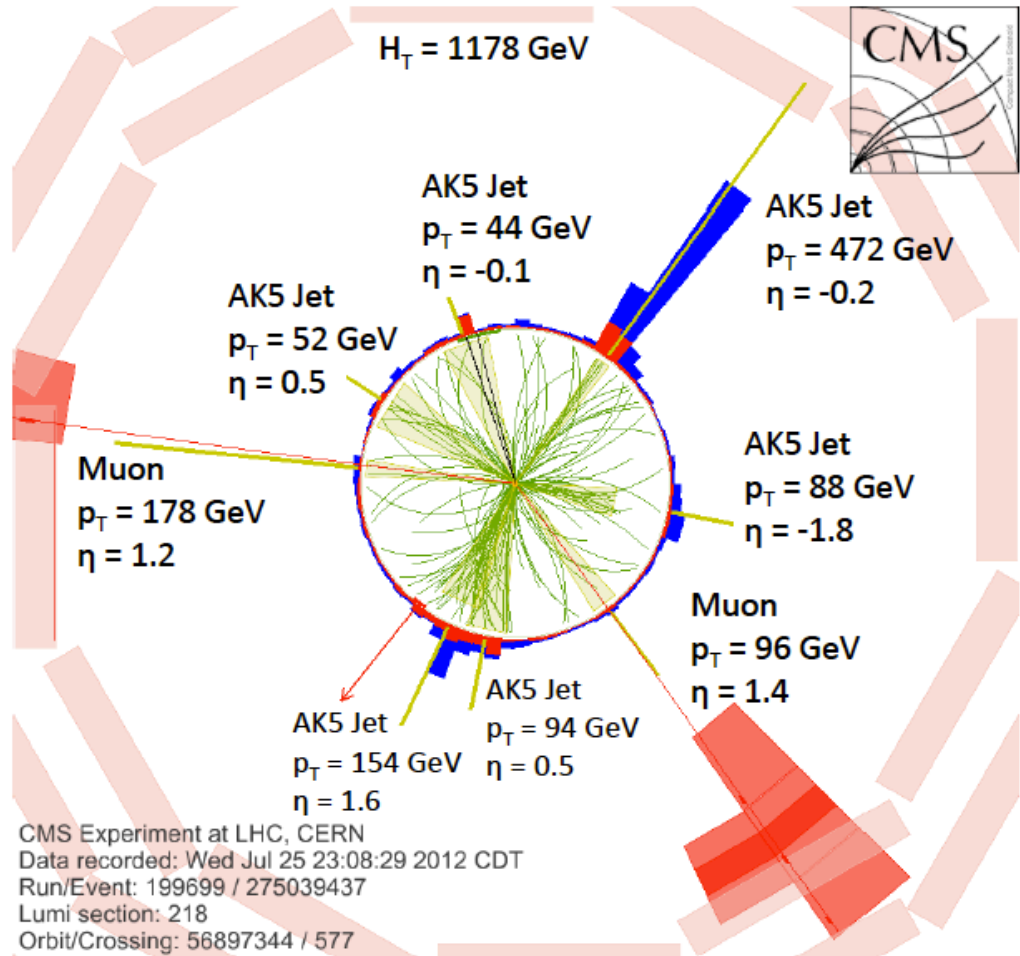
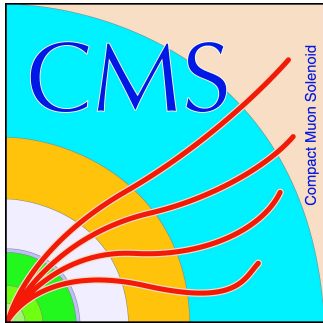


# Top Quark Physics in CMS

Jorgen D'Hondt

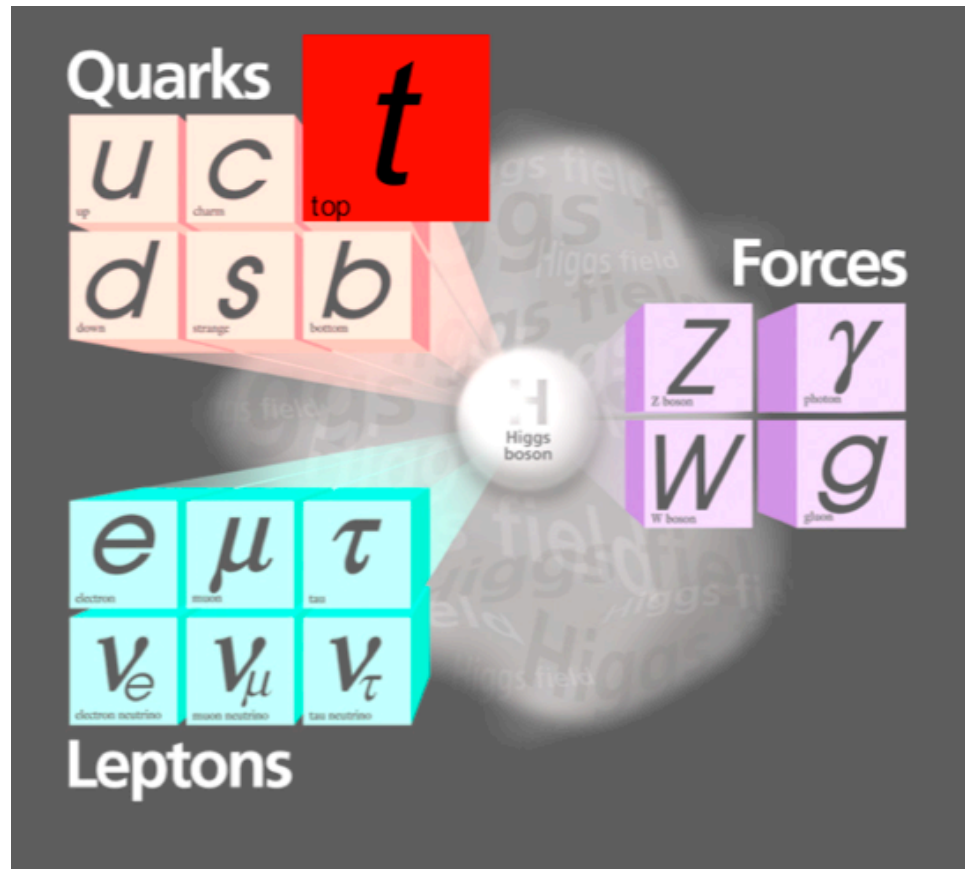


*iihe*  
BRUXELLES BRUSSEL

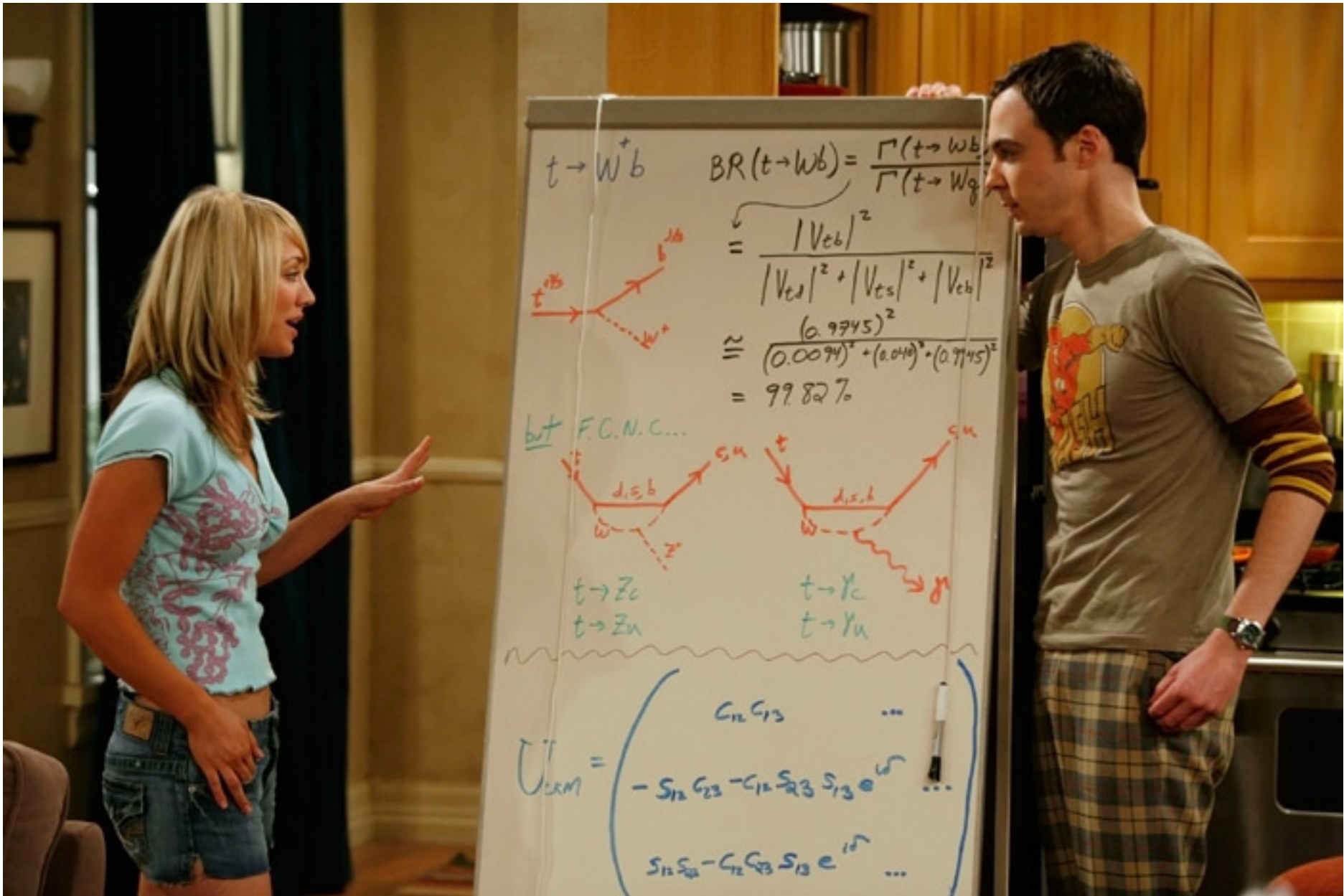


Vrije Universiteit Brussel

# The Top Quark in the Standard Model

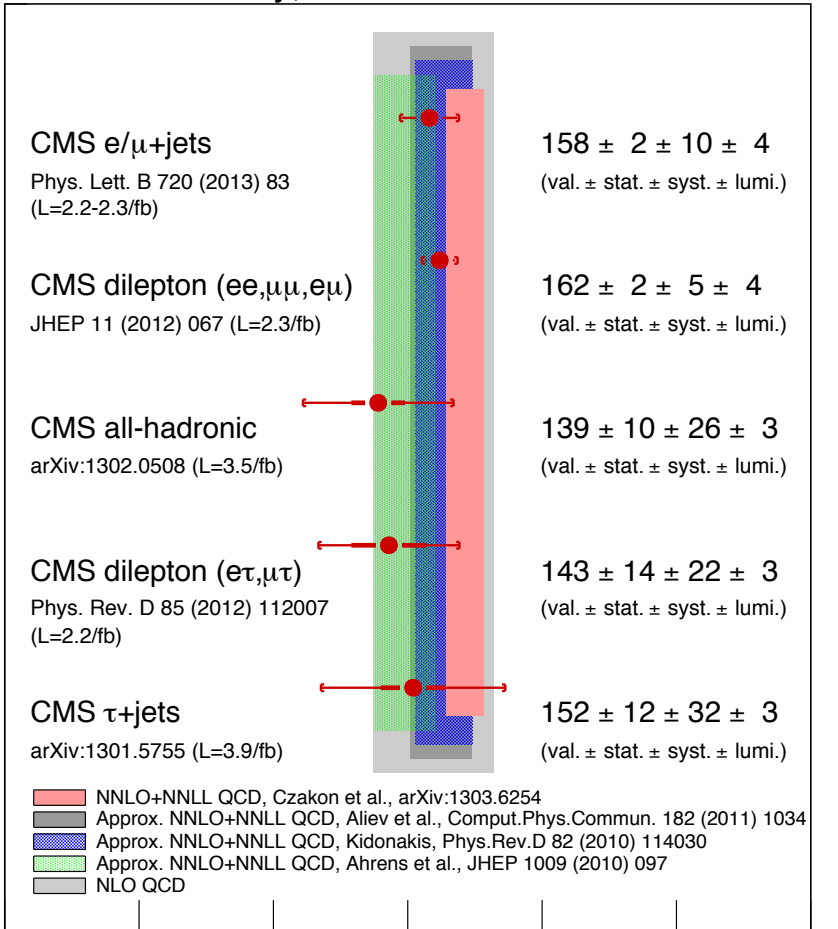


cfr. presentation of Roberto Tenchini

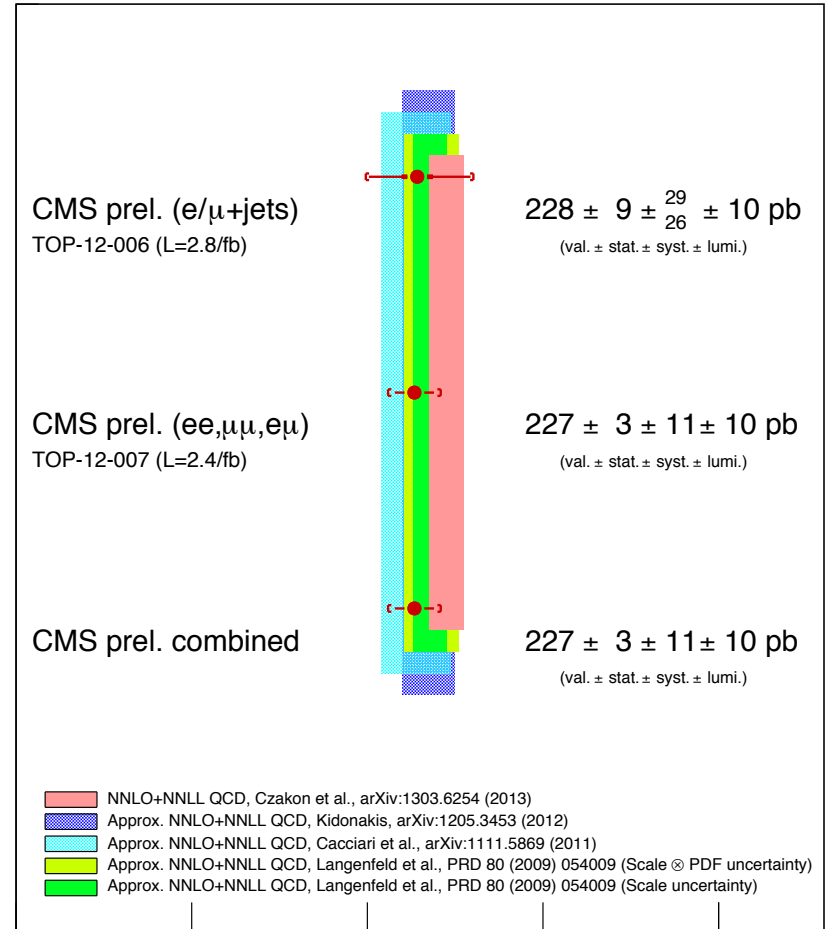


# Top quark pair cross section

CMS Preliminary,  $\sqrt{s} = 7$  TeV



CMS Preliminary,  $\sqrt{s} = 8$  TeV

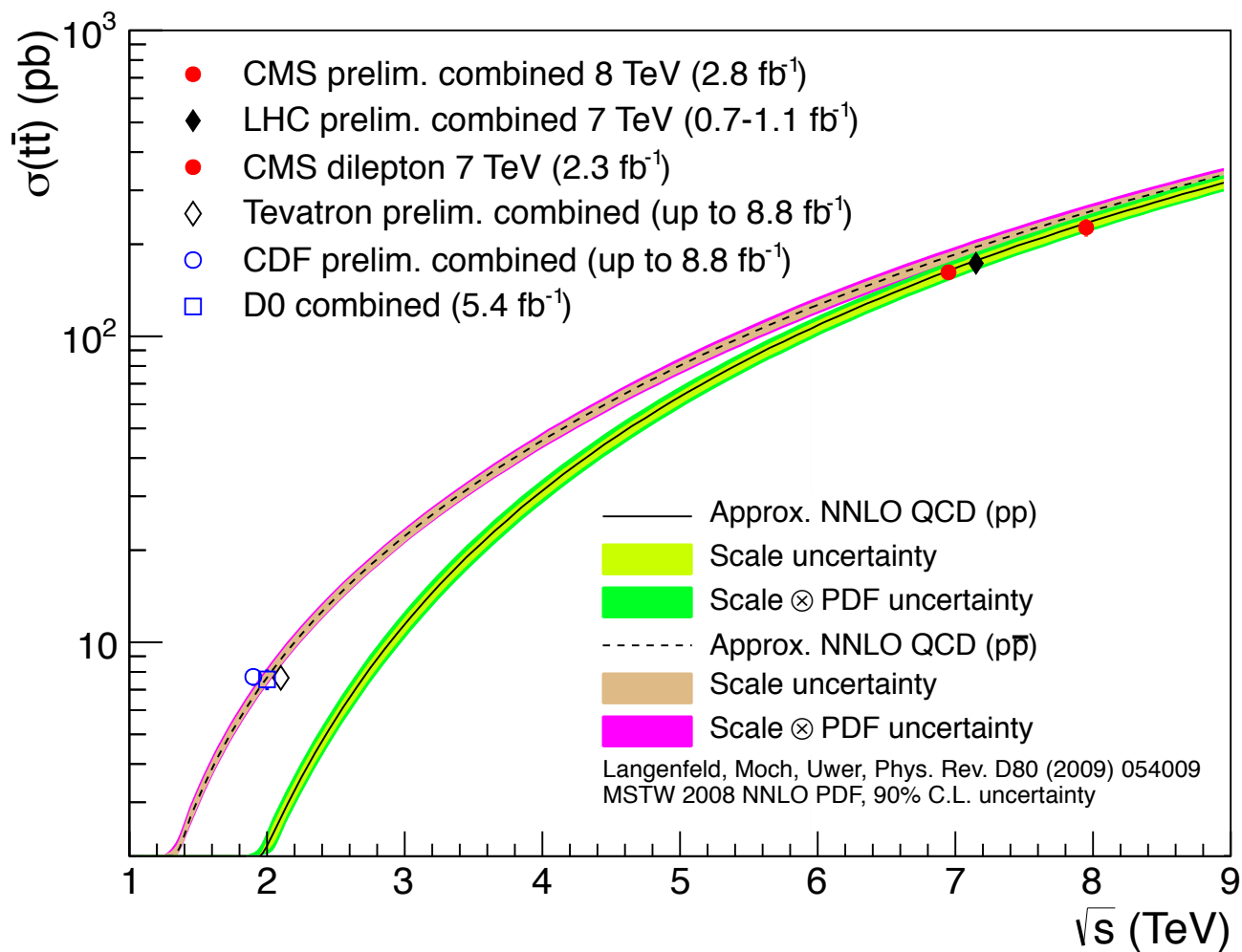


0 50 100 150 200 250 300  
 $\sigma(t\bar{t})$  (pb)

0 100 200 300 400  
 $\sigma(t\bar{t})$  (pb)

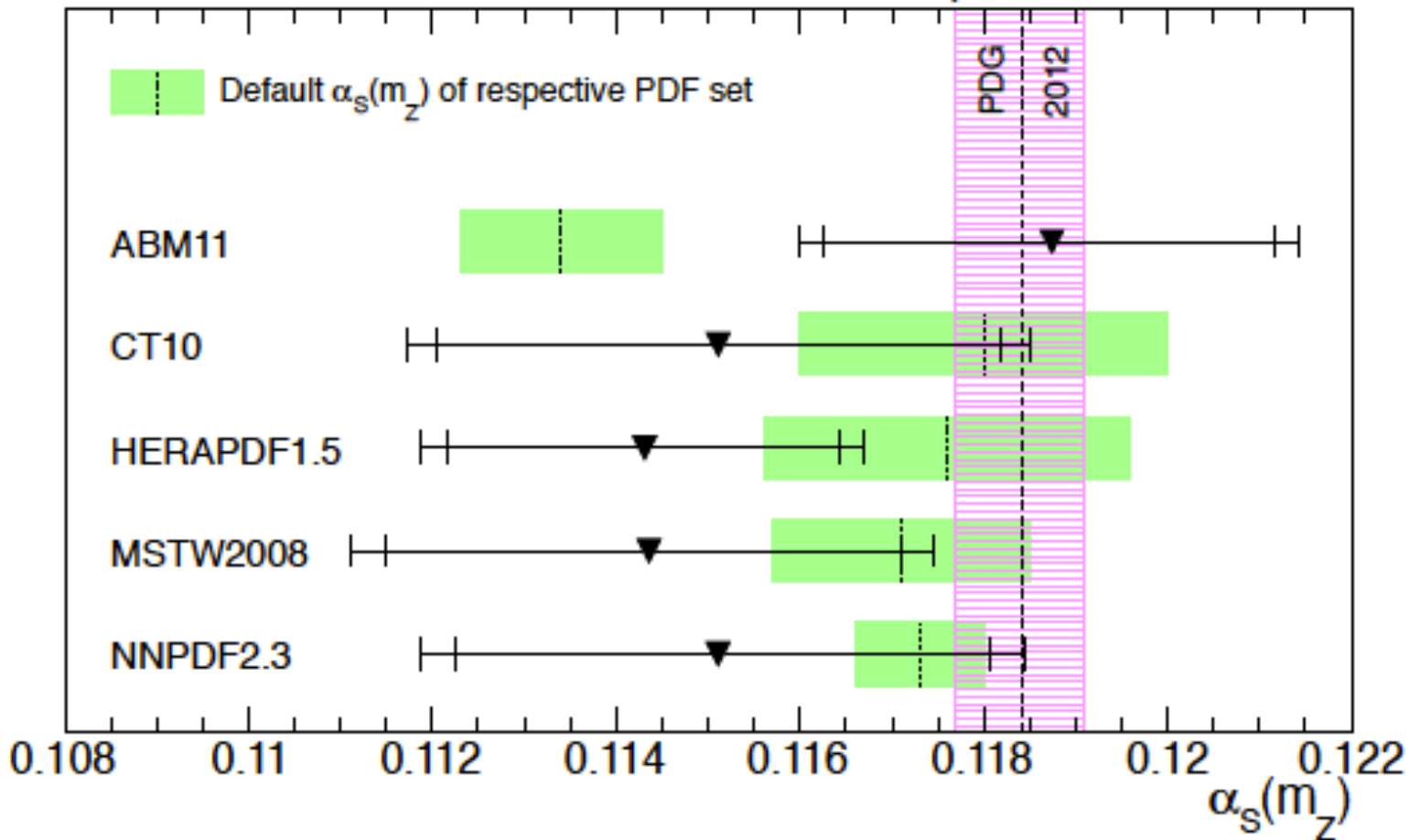


# Top quark pair cross section



# Top quark pair cross section

CMS,  $\sqrt{s} = 7$  TeV,  $L = 2.3 \text{ fb}^{-1}$ ; NNLO+NNLL for  $\sigma_{t\bar{t}}$ ;  $m_t^{\text{pole}} = 173.2 \pm 1.4$  GeV

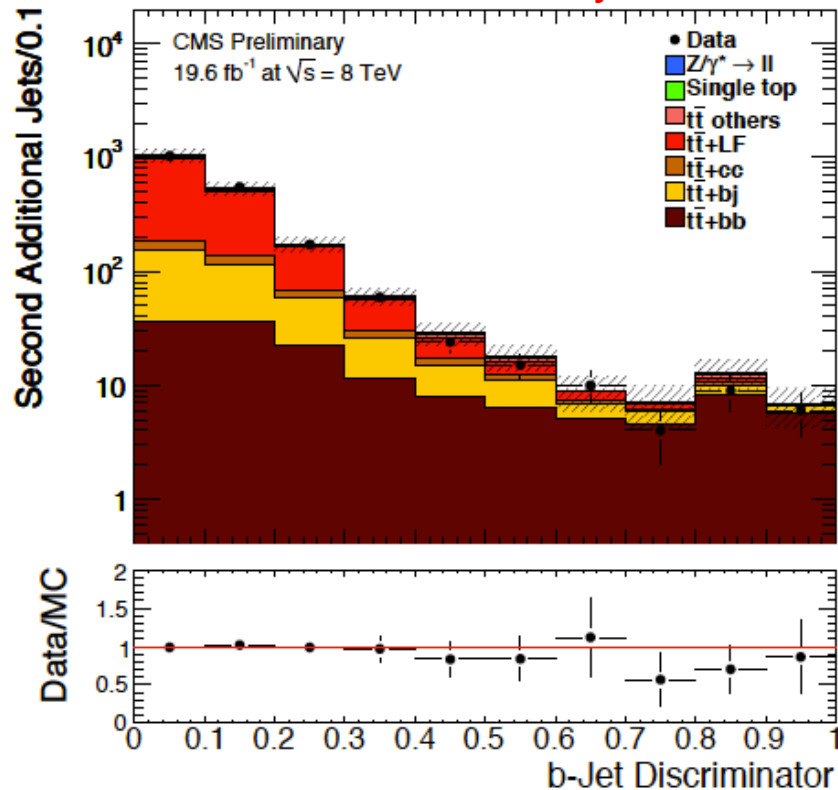
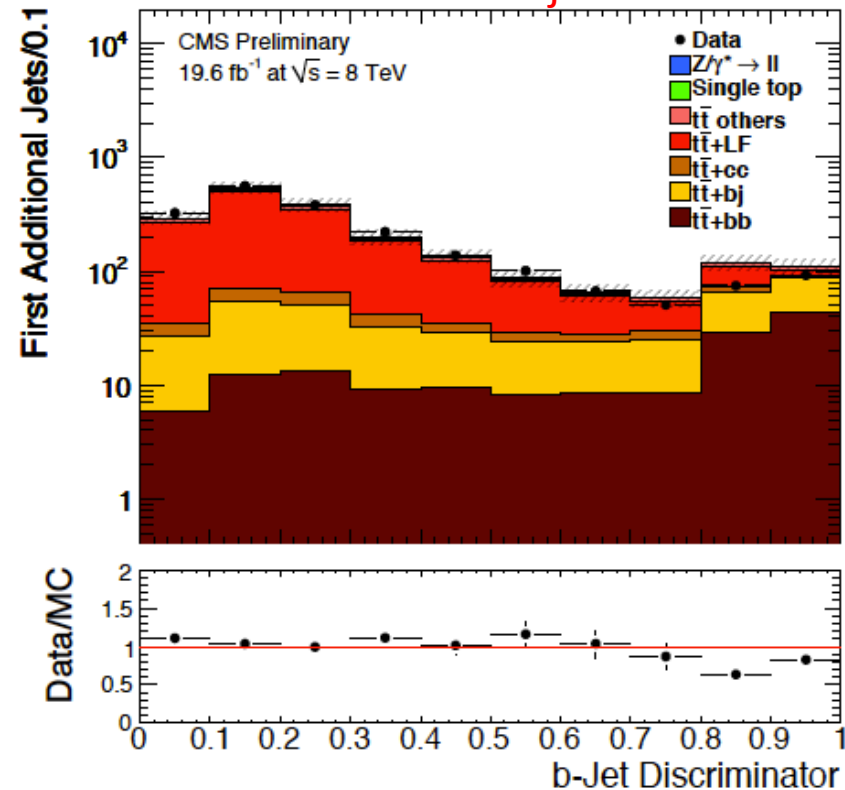


# Top quark pair + jets cross section

First extra jet

$p_T > 20$  GeV

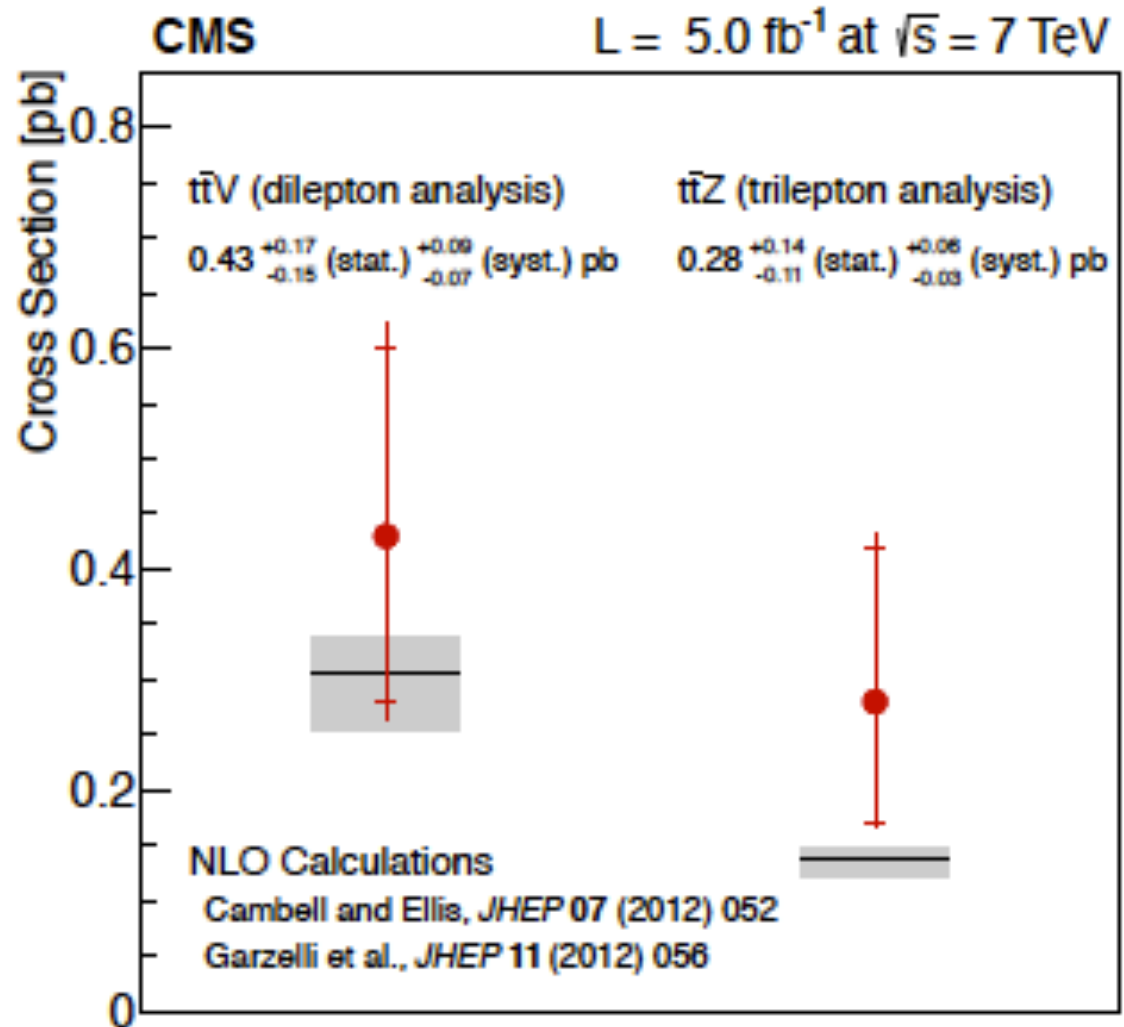
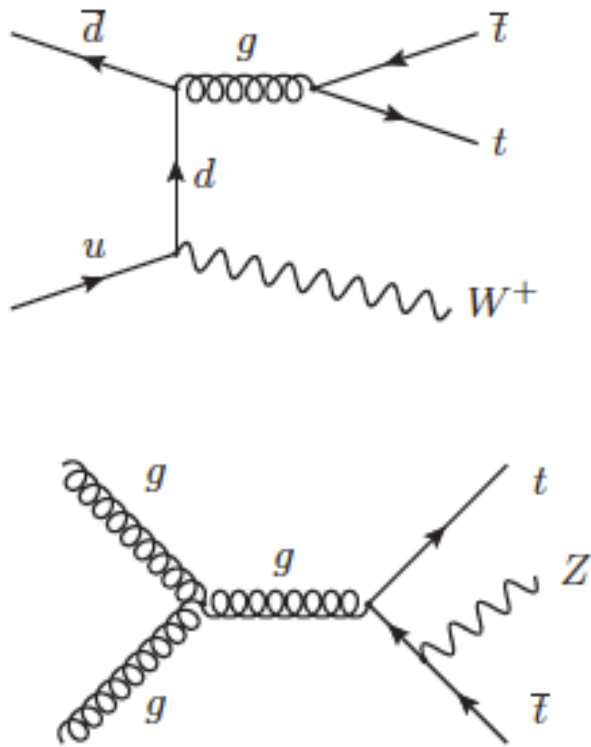
Second extra jet



$$\sigma(t\bar{t}b\bar{b})/\sigma(t\bar{t}jj) = 0.023 \pm 0.003(\text{stat.}) \pm 0.005(\text{syst.}) \text{ at } p_T > 20 \text{ GeV}/c \quad 0.016 \pm 0.002 \text{ (MadGraph)}$$

$$\sigma(t\bar{t}b\bar{b})/\sigma(t\bar{t}jj) = 0.022 \pm 0.004(\text{stat.}) \pm 0.005(\text{syst.}) \text{ at } p_T > 40 \text{ GeV}/c \quad 0.013 \pm 0.002 \text{ (MadGraph)}$$

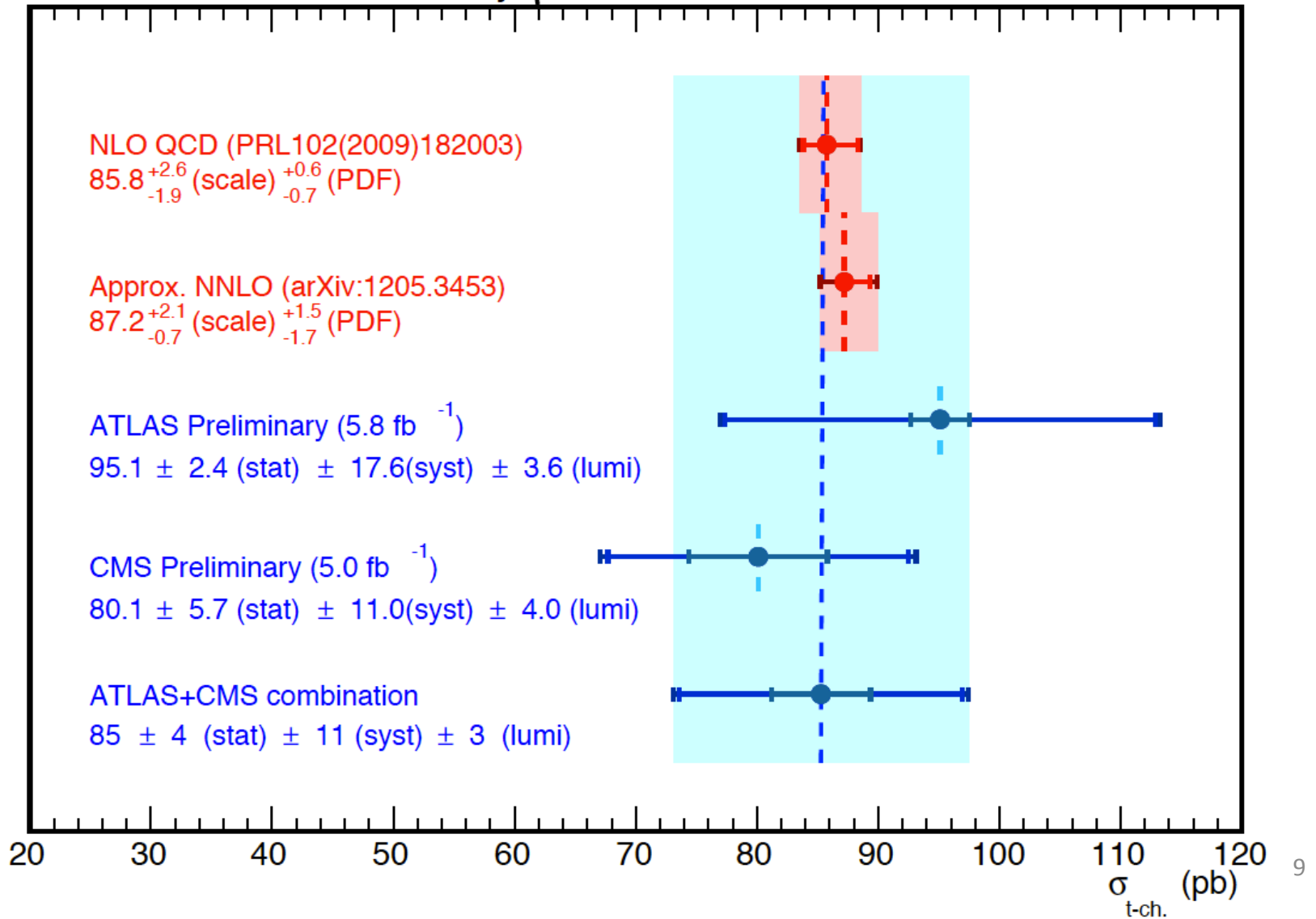
# Top quark pair + Vector Bosons cross section





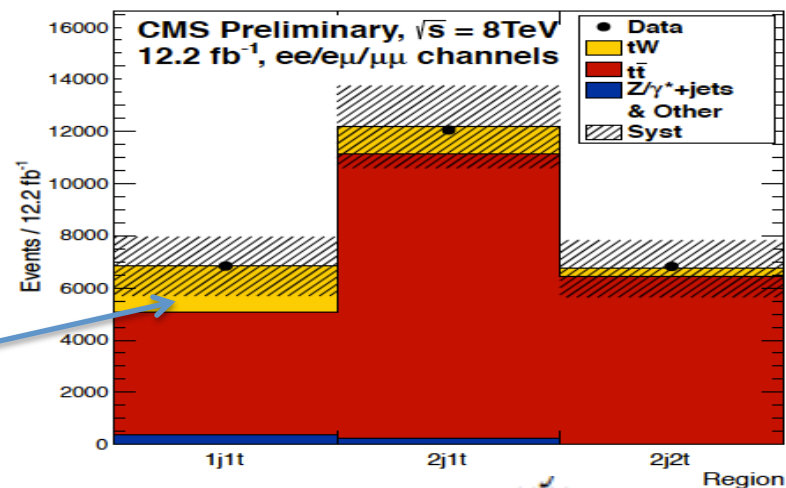
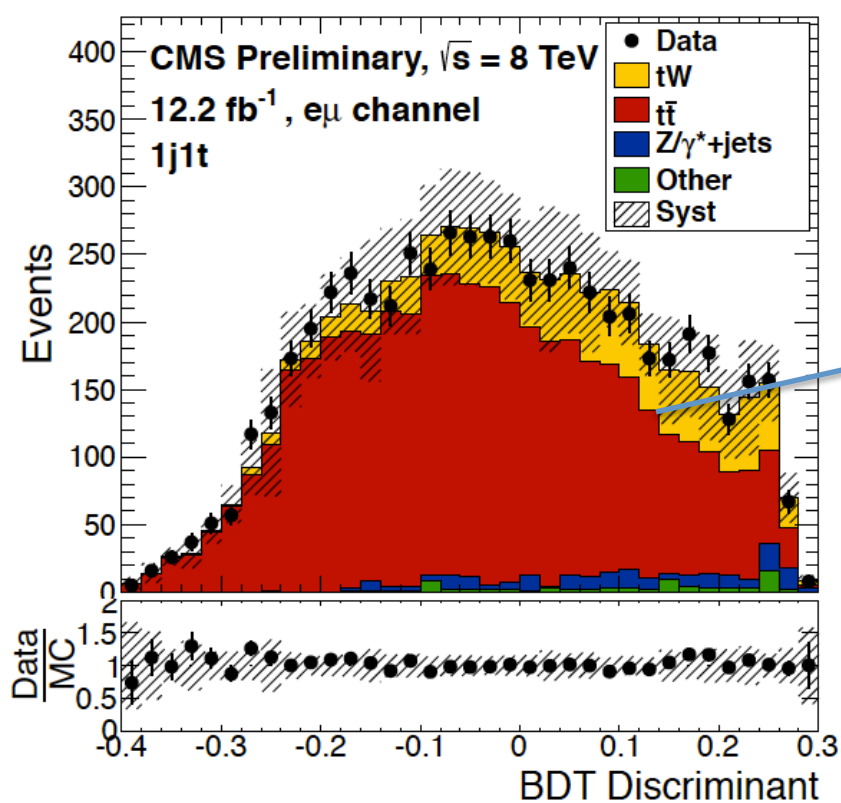
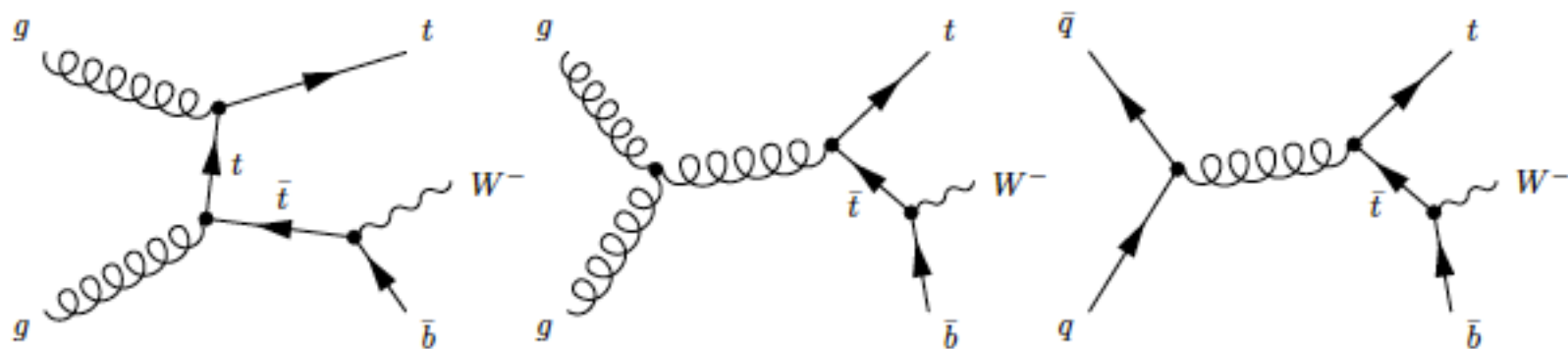
# Single top quark cross section (t-channel)

ATLAS+CMS Preliminary,  $\sqrt{s} = 8$  TeV





# Single top quark (tW) cross section



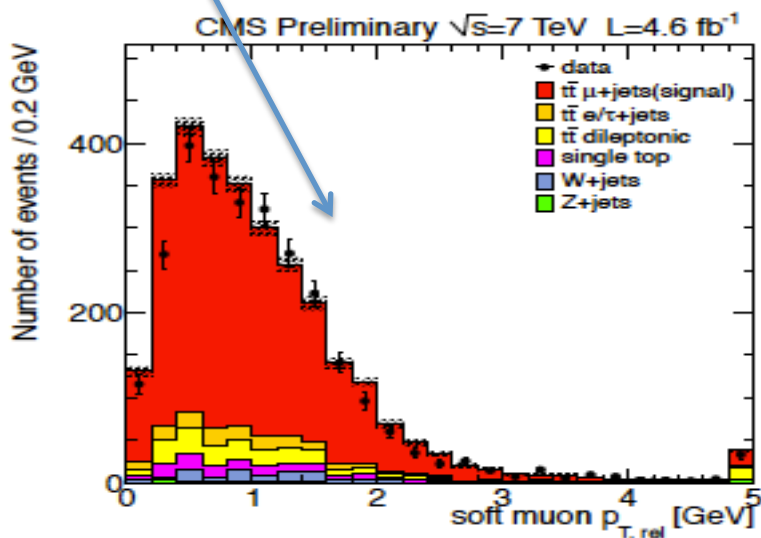
$$\sigma_{tW} = 23.4^{+5.5}_{-5.4} \text{ pb}$$

6 $\sigma$  significance

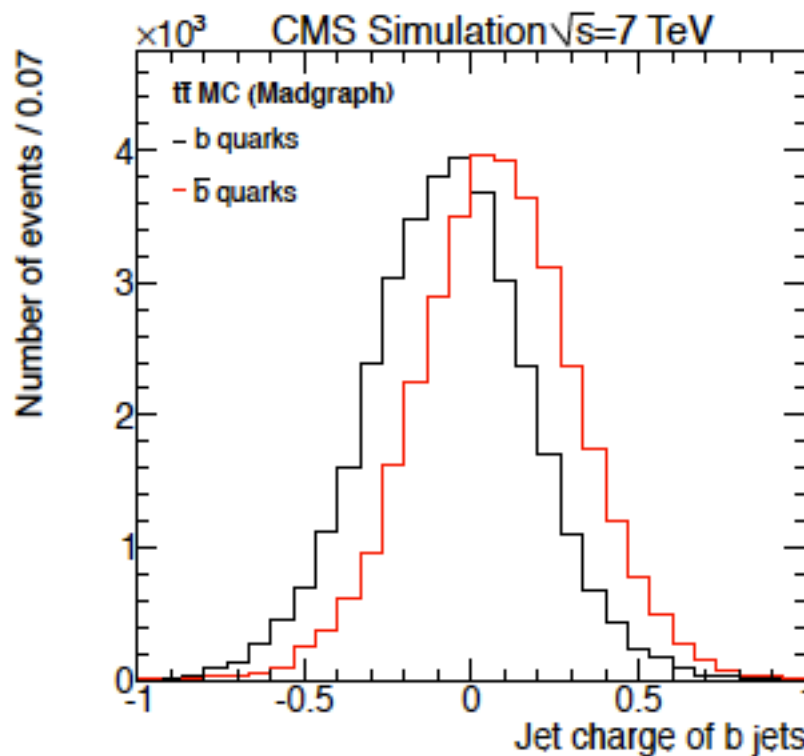
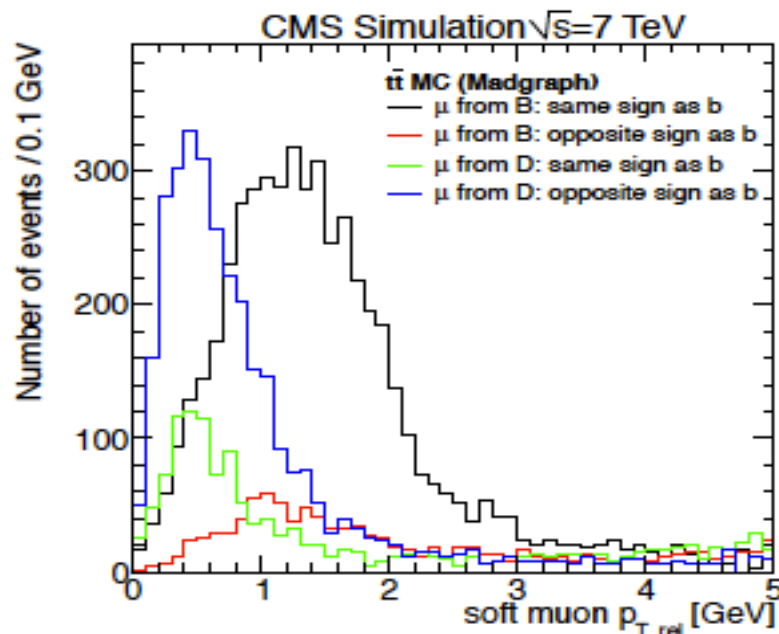
$$|V_{tb}| = \sqrt{\frac{\sigma_{tW}}{\sigma_{tW}^{th}}} = 1.03 \pm 0.12(\text{exp.}) \pm 0.04(\text{th.})$$

$$BR(\check{b} \rightarrow \mu + \nu + \check{X}) \sim 11\%$$

# Top Quark charge



$$JC = \frac{\sum_{\text{tracks}} (\vec{p}_i \cdot \vec{j})^{0.7} \cdot q}{\sum_{\text{tracks}} (\vec{p}_i \cdot \vec{j})^{0.7}}$$

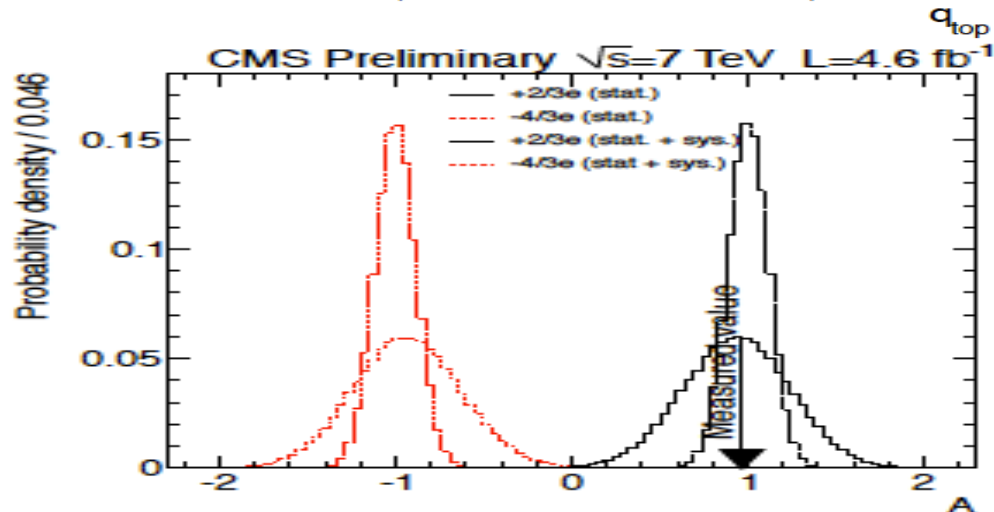
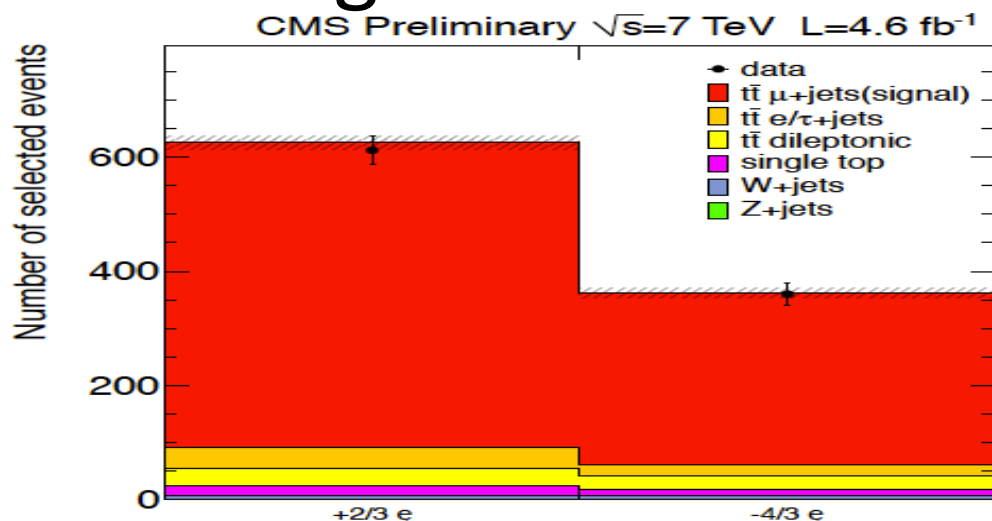
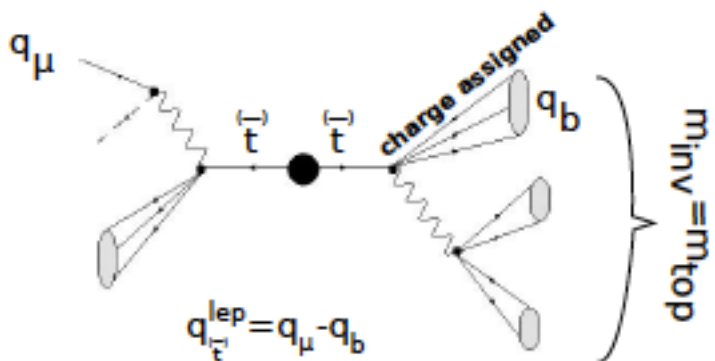
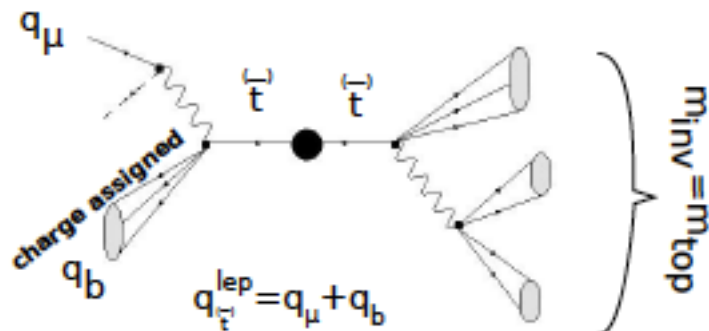


Combine both pieces of information

# Top Quark charge

A is an "asymmetry" test statistics

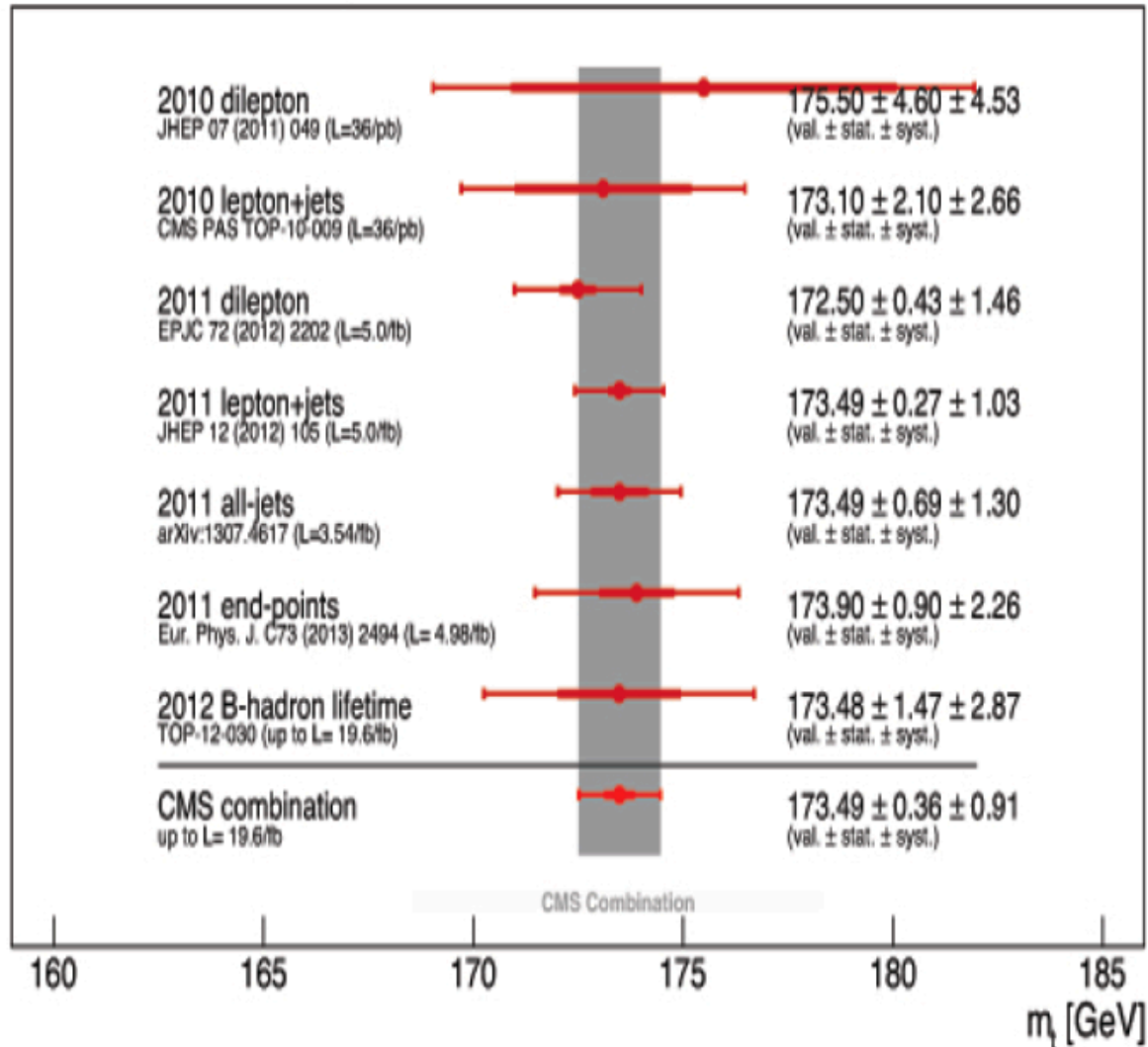
$$A = \frac{1}{D_S} \frac{N_{SM} - N_{XM} - \langle N_{BG} \rangle D_B}{N_{SM} + N_{XM} - \langle N_{BG} \rangle}$$



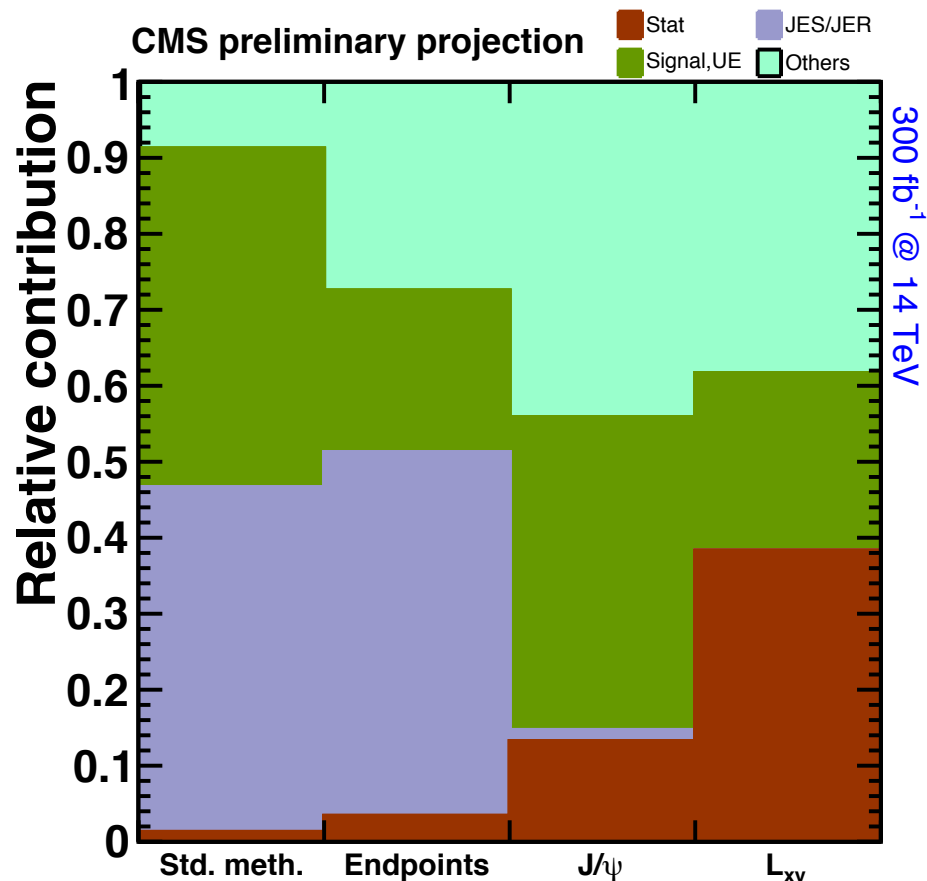
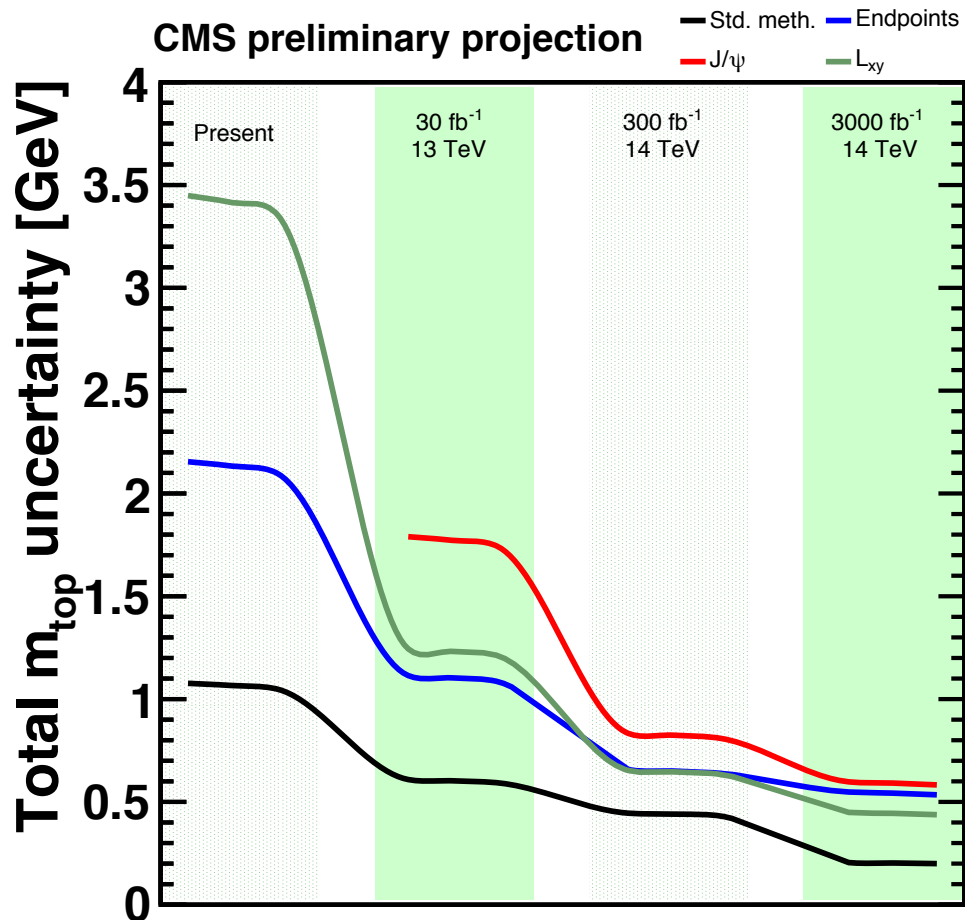
Charge -4/3 more then  $5\sigma$  excluded

# Top quark mass

CMS Preliminary,  $\sqrt{s} = 7$  and 8 TeV

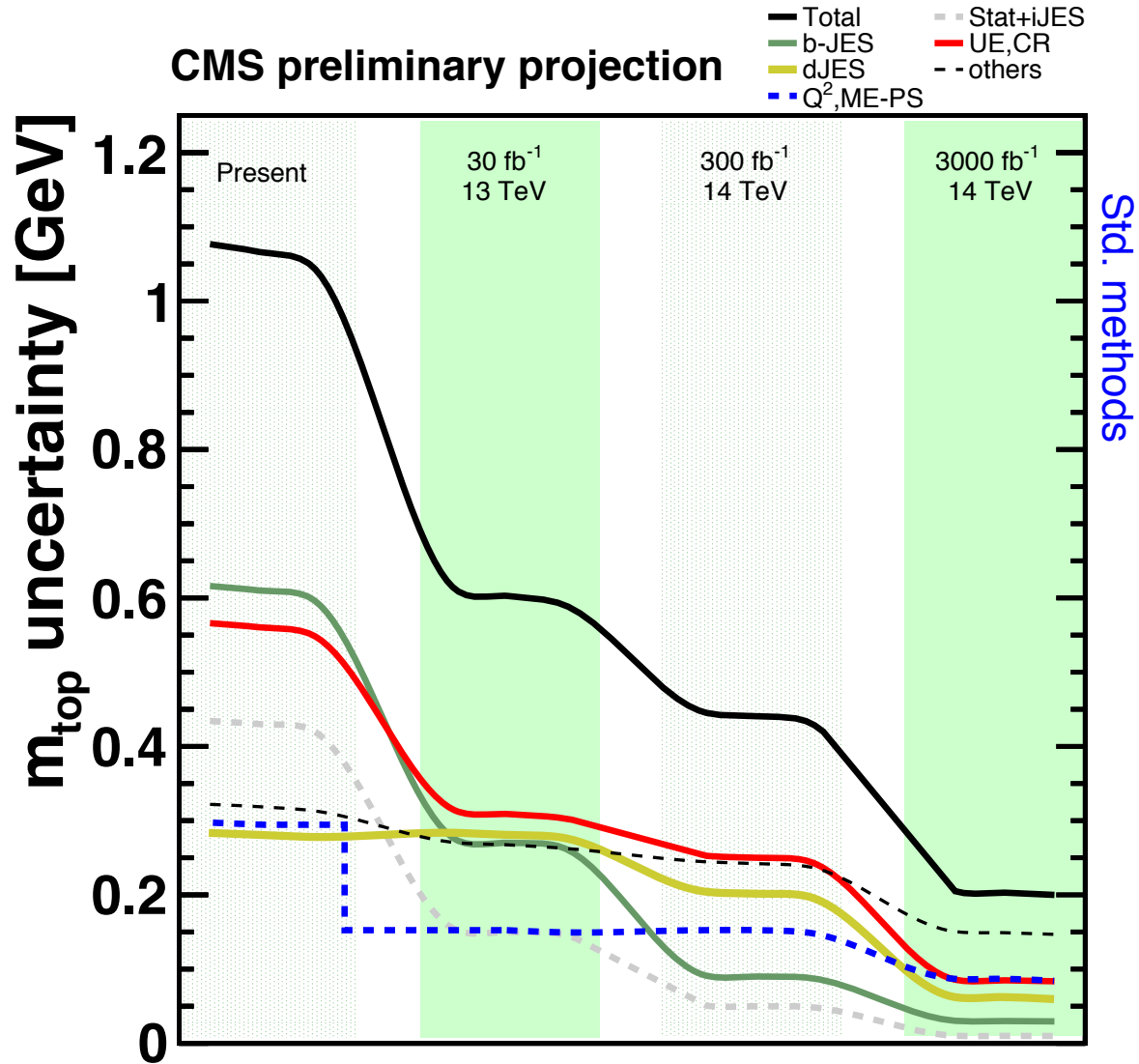


# Top quark mass prospects





# Top quark mass prospects



# Top quark versus anti-quark mass

## Ideogram method

$$\mathcal{L}_{\text{event}}(x; y | m_t) = f_{\bar{t}\bar{t}} P_{\bar{t}\bar{t}}(x; y | m_t) + (1 - f_{\bar{t}\bar{t}}) P_{\text{bkg}}(x).$$

$$P_{\bar{t}\bar{t}}(x; y | m_t) = P_{\bar{t}\bar{t}}(n_b) \cdot P_{\bar{t}\bar{t}}(q^\ell) \cdot P_{\bar{t}\bar{t}}(x_{\text{mass}}; y | m_t)$$

$$P_{\text{bkg}}(x) = P_{\text{bkg}}(n_b) \cdot P_{\text{bkg}}(q^\ell) \cdot P_{\text{bkg}}(x_{\text{mass}}).$$

$$w_i = \exp\left(-\frac{1}{2} \chi_i^2\right) w_b.$$

Probability of btagging  $w_b = \prod_j p^j,$

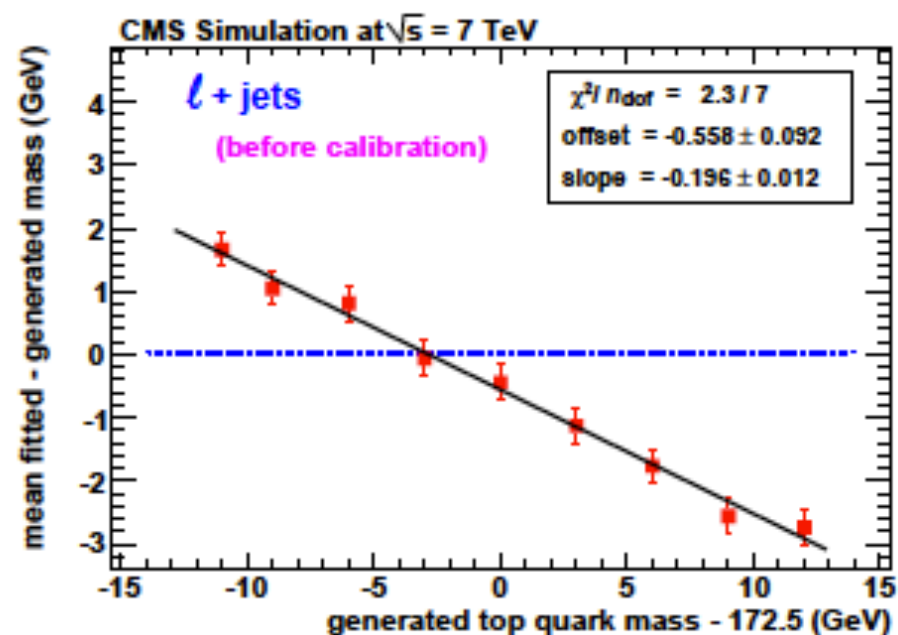
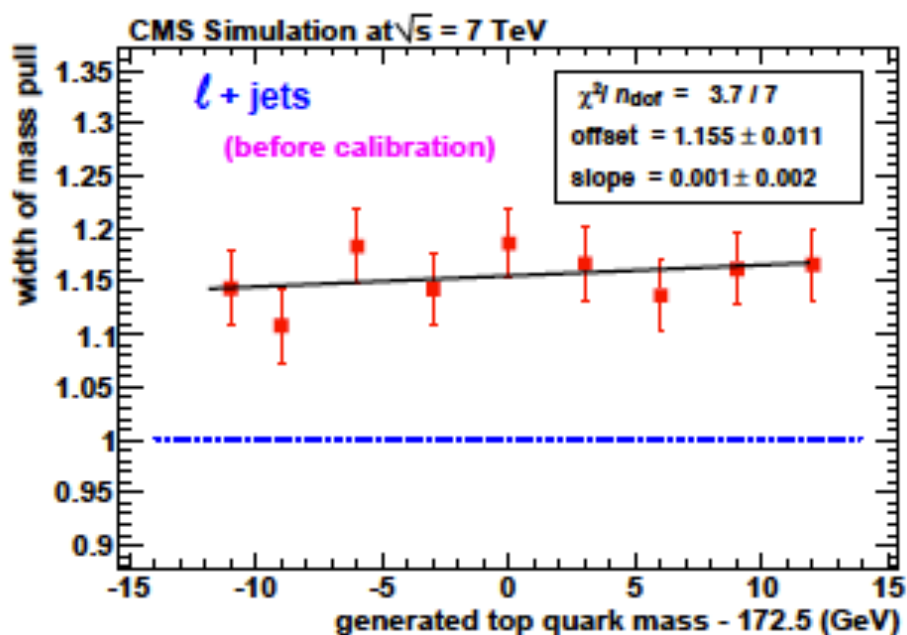
$$P_{\bar{t}\bar{t}}(x_{\text{mass}}; y | m_t) = \sum_{i=1}^{12} w_i \left( f_{\text{gc}} \int dm' \underbrace{G(m_i | m', \sigma_i)}_{\text{Gauss distr.}} \underbrace{B(m' | m_t, \Gamma_t)}_{\text{Breit-Wigner distr.}} + (1 - f_{\text{gc}}) \underbrace{W(m_i | m_t)}_{\text{Wrong jet combinations}} \right)$$

Gauss distr.    Breit-Wigner distr.    Wrong jet combinations

Parameters in the kinematic fit

# Top quark versus anti-quark mass

Calibration of the properties of the  $M_t$  estimator

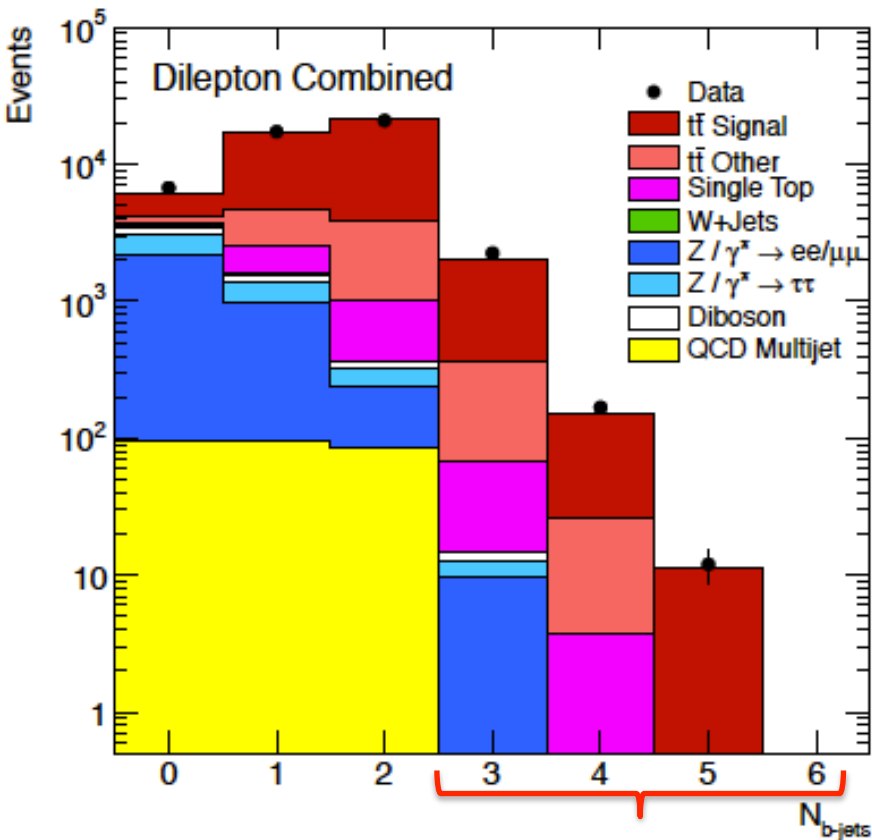


$$\Delta m_t = -272 \pm 196 \text{ (stat.)} \pm 122 \text{ (syst.) MeV}$$

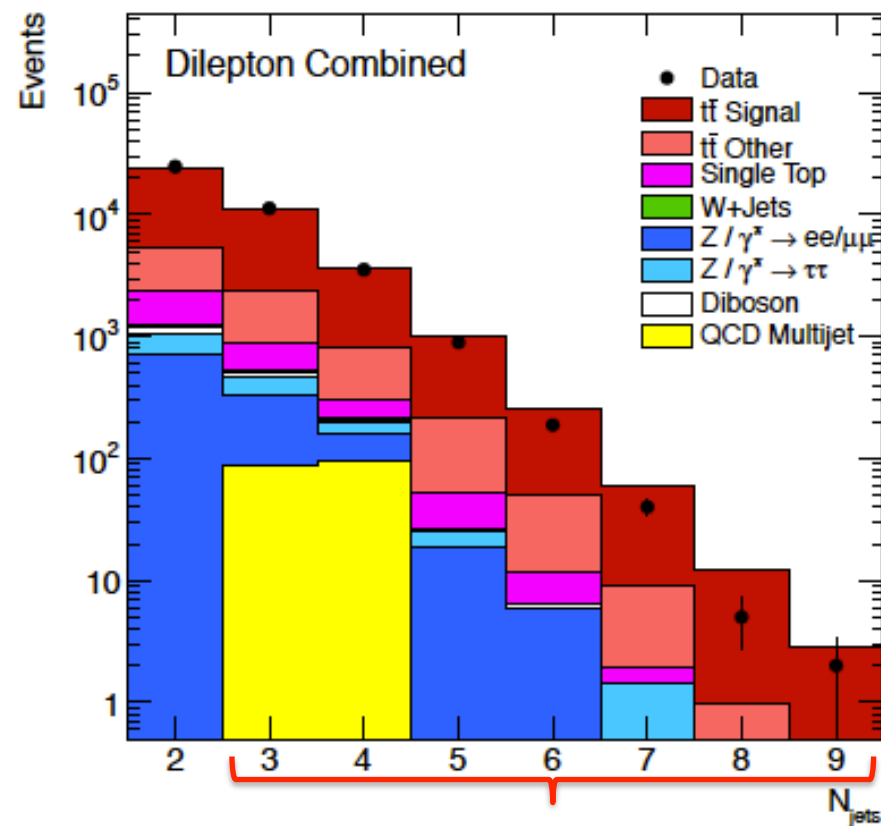
Dominated by statistical uncertainties, hence need measurement at 13-14 TeV

# Differential cross-sections in top quark events

CMS Preliminary, 12.2 fb<sup>1</sup> at  $\sqrt{s} = 8$  TeV

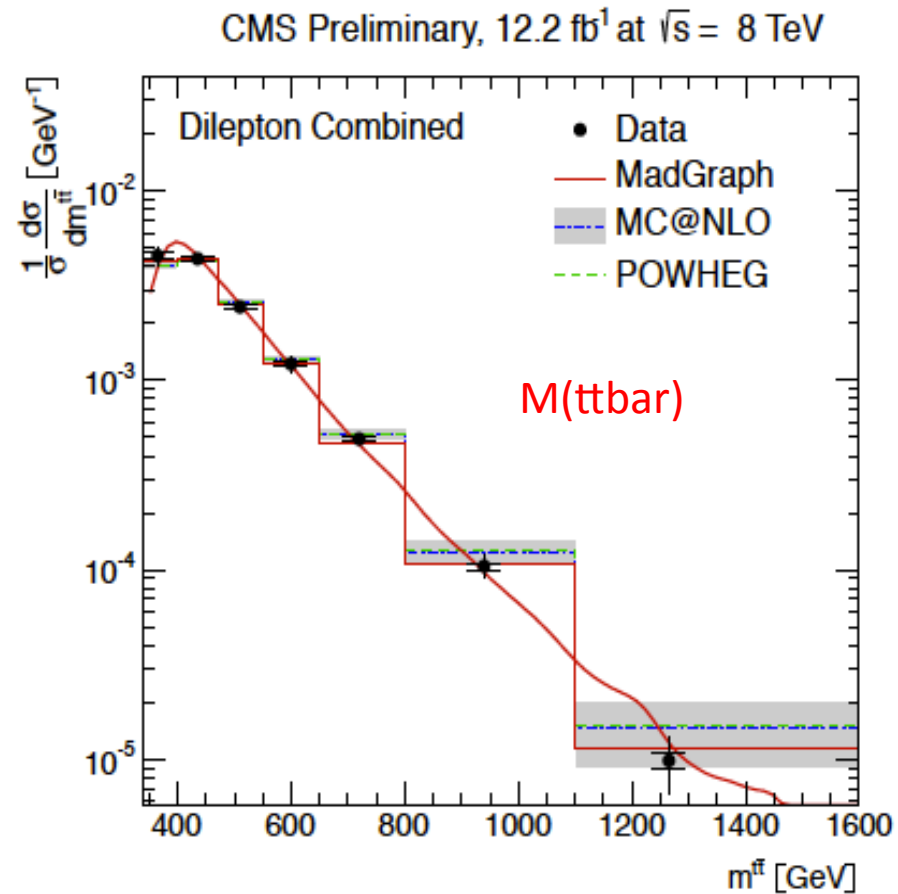
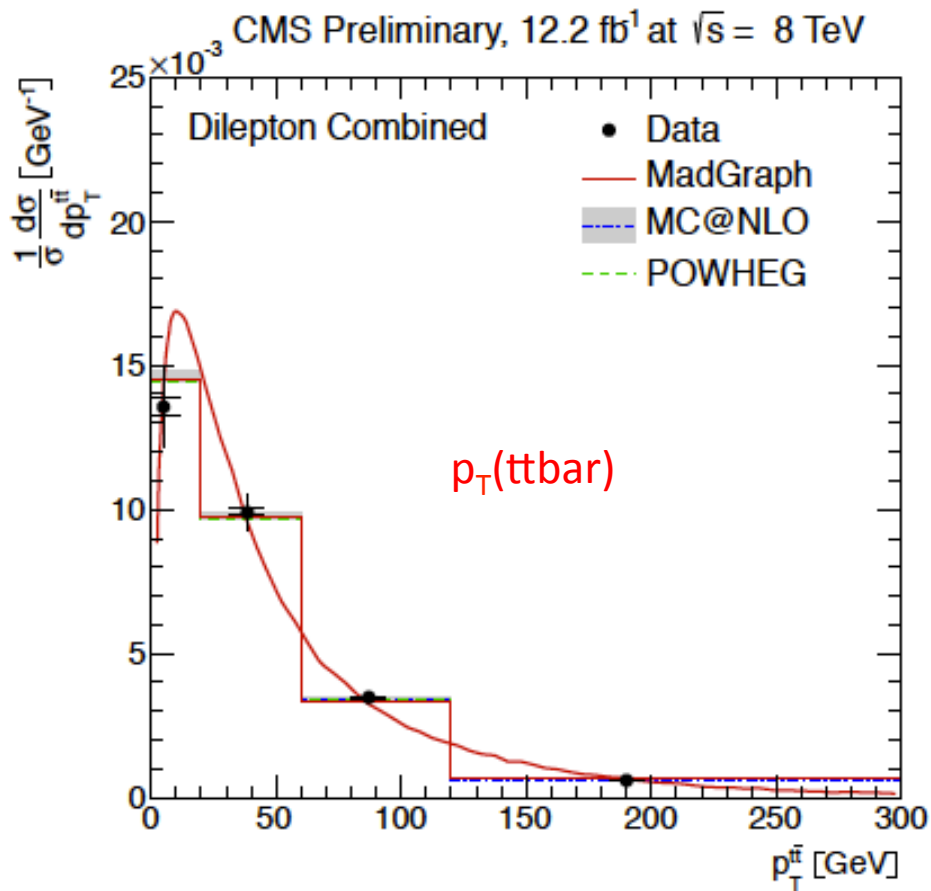


CMS Preliminary, 12.2 fb<sup>1</sup> at  $\sqrt{s} = 8$  TeV



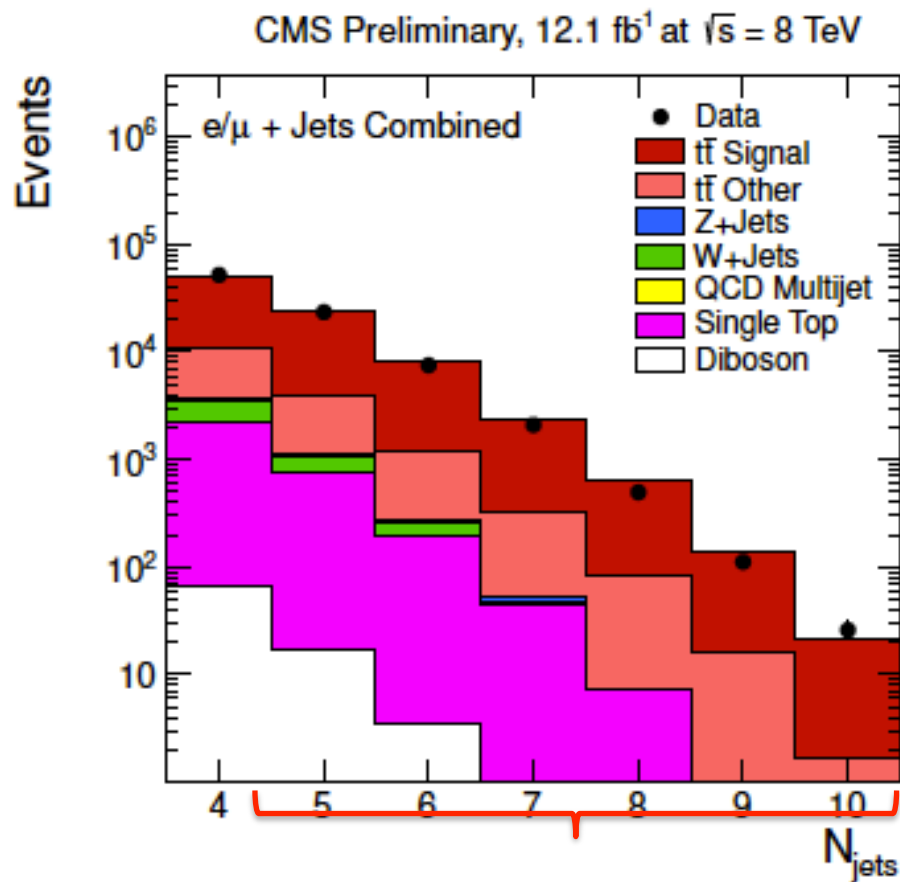
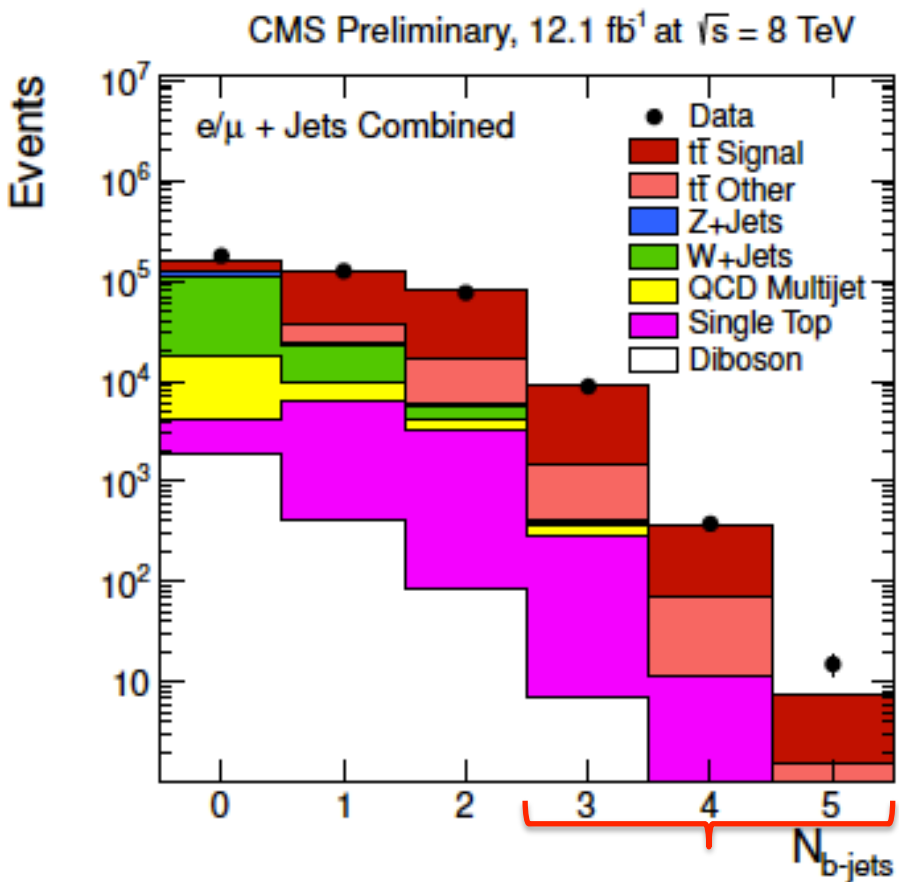
Region of extra (b-)jets

# Differential cross-sections in top quark events



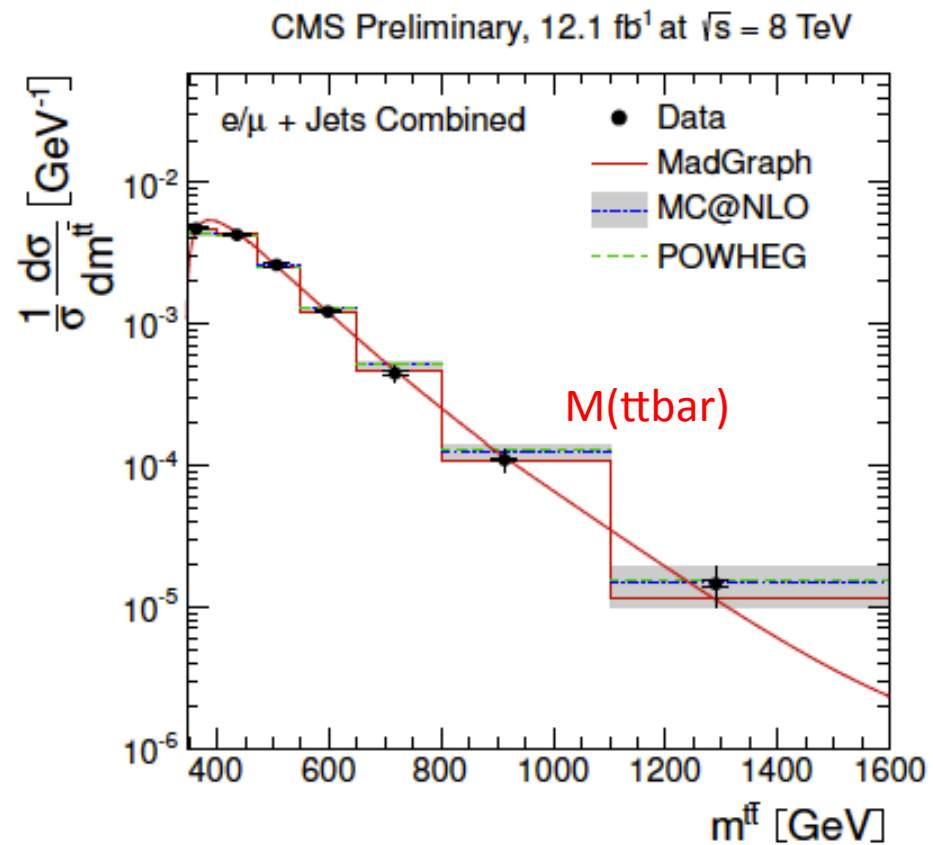
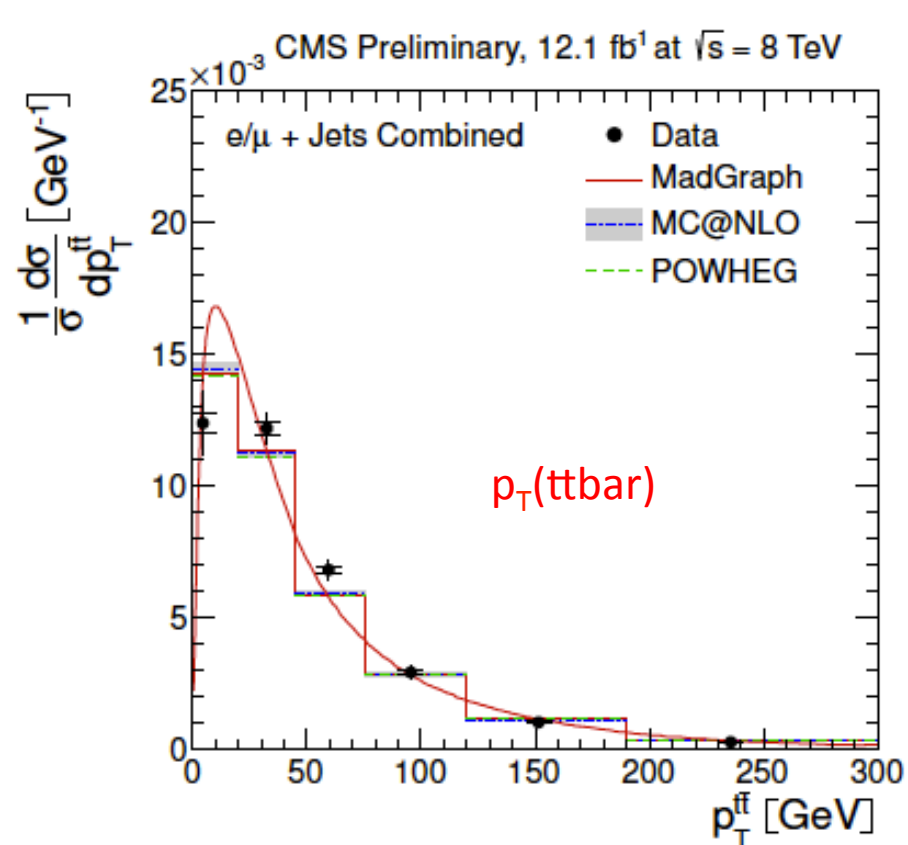


# Differential cross-sections in top quark events



Region of extra (b-)jets

# Differential cross-sections in top quark events

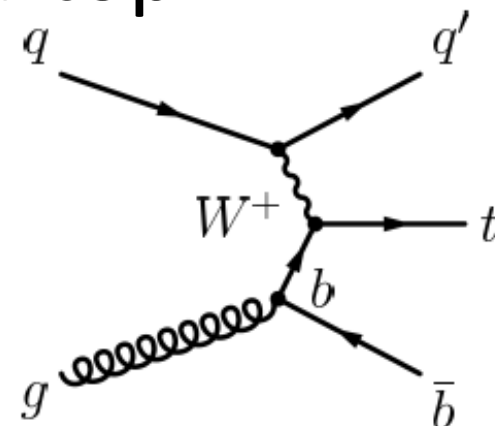
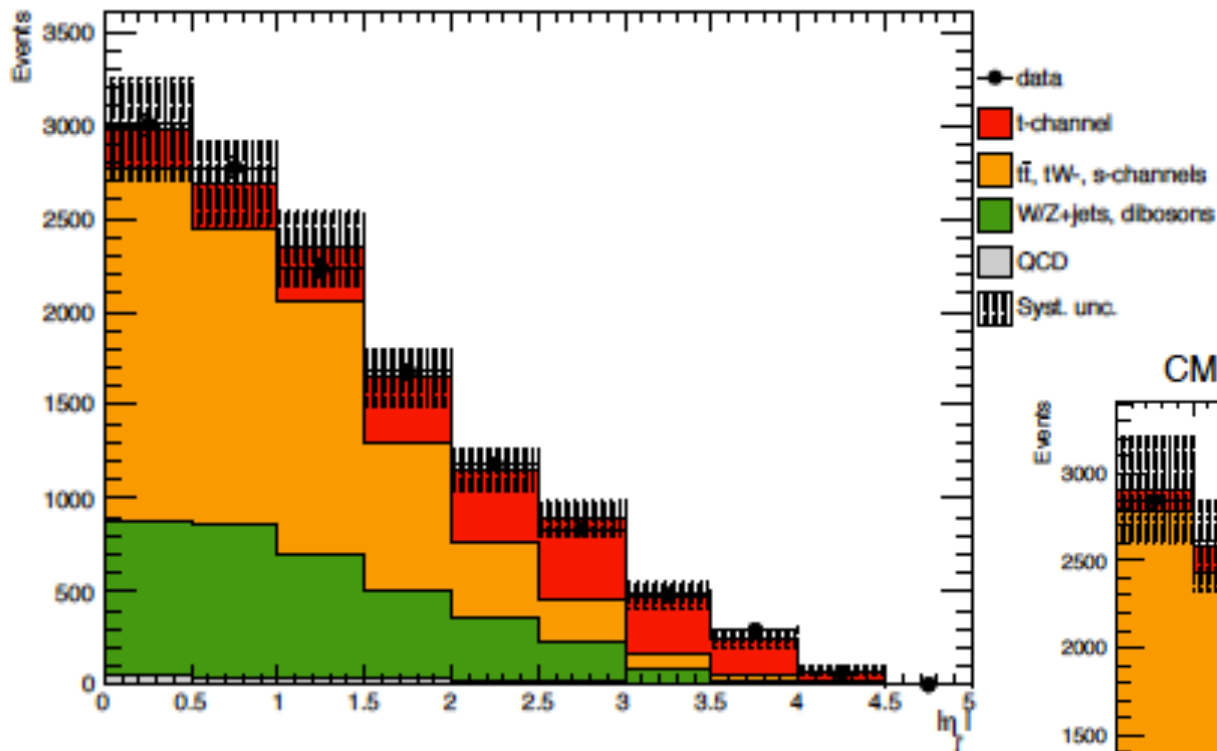


$$\sigma_{t\text{-ch,top}}^{\text{th}} = 56.4_{-0.3}^{+2.1} (\text{scale})_{-1.1}^{+1.1} (\text{PDF}) \text{pb}$$

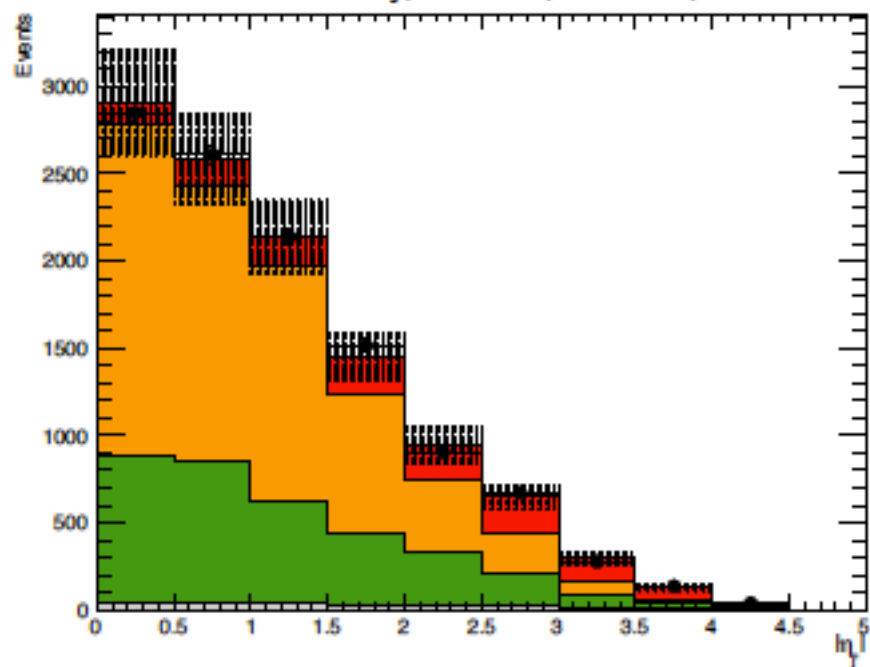
$$\sigma_{t\text{-ch,anti-top}}^{\text{th}} = 30.7_{-0.7}^{+0.7} (\text{scale})_{-1.1}^{+0.9} (\text{PDF}) \text{pb}$$

# Single top versus anti-top

CMS Preliminary, 12.2 fb<sup>-1</sup>, Muons +,  $\sqrt{s} = 8 \text{ TeV}$



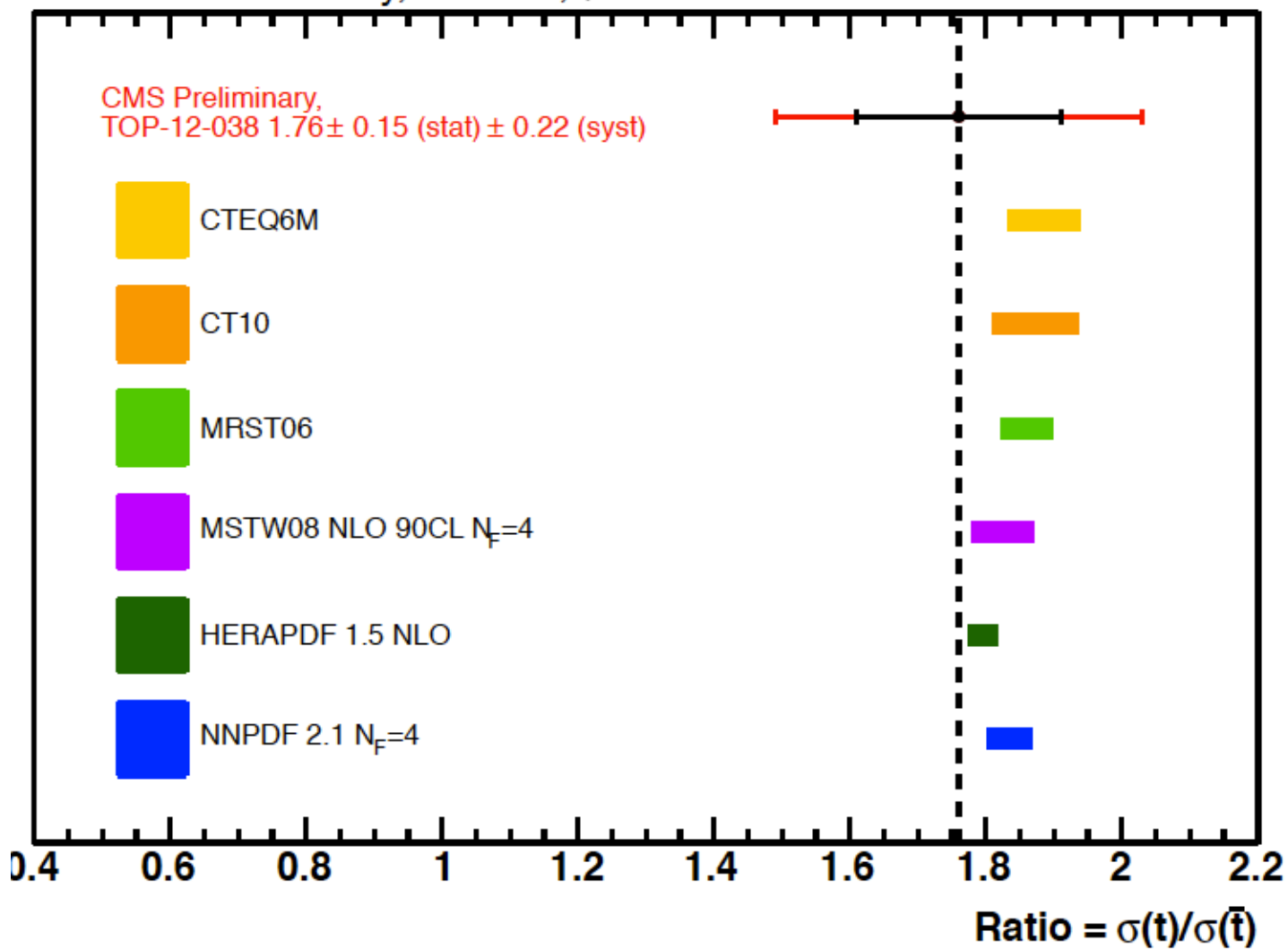
CMS Preliminary, 12.2 fb<sup>-1</sup>, MUONS -,  $\sqrt{s} = 8 \text{ TeV}$



Fitting simultaneous the top and anti-top component on the pseudo-rapidity distribution

# Single top versus anti-top

CMS Preliminary,  $12.2 \text{ fb}^{-1}, \sqrt{s} = 8 \text{ TeV}$

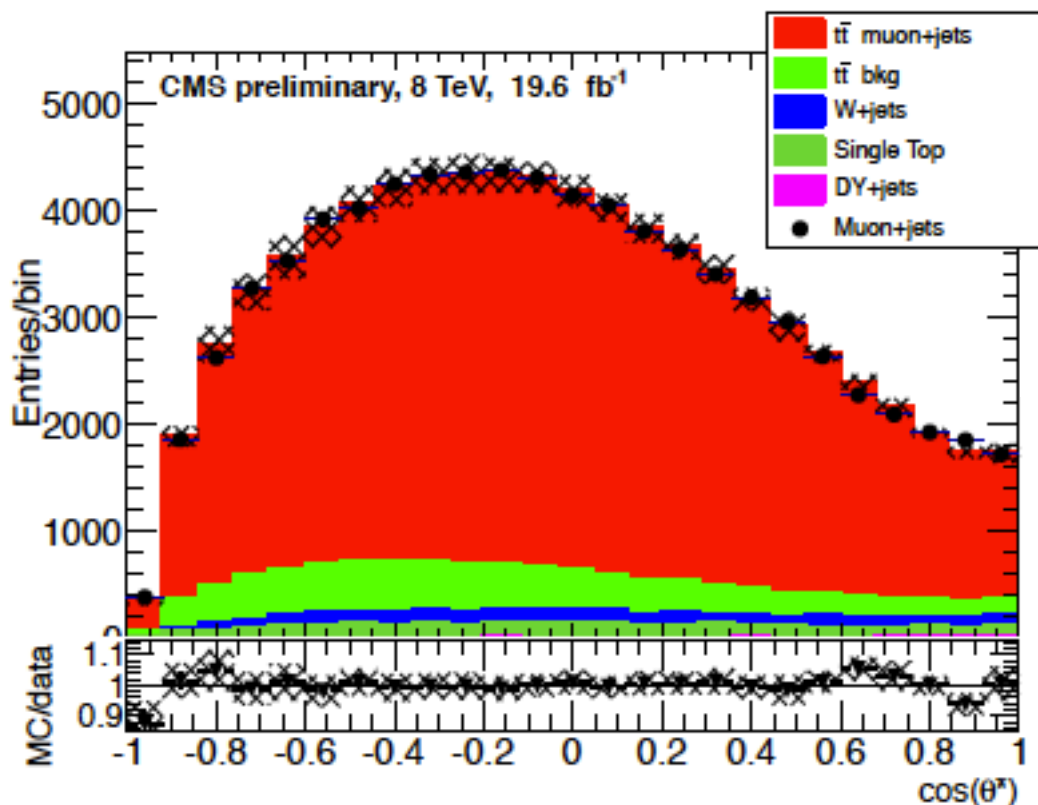




# W helicity (in top quark pair events)

$$\rho(\cos \theta_1^*) \equiv \frac{1}{\Gamma} \frac{d\Gamma}{d \cos \theta_1^*} = \frac{3}{8}(1 - \cos \theta_1^*)^2 F_L + \frac{3}{8}(1 + \cos \theta_1^*)^2 F_R + \frac{3}{4} \sin^2 \theta_1^* F_0,$$

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



Reweighting method to fit this distribution with 2 free parameters:

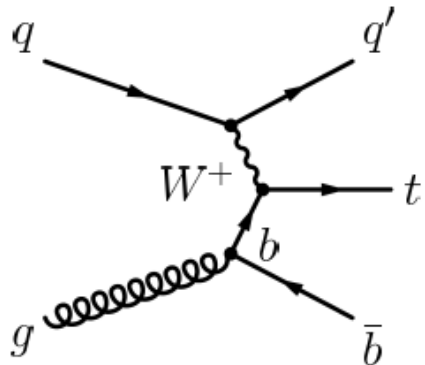
$$F_0 = 0.659 \pm 0.015(\text{stat.}) \pm 0.023(\text{syst.}),$$

$$F_L = 0.350 \pm 0.010(\text{stat.}) \pm 0.024(\text{syst.}),$$

Theoretical uncertainties dominate and the MET shape



# W helicity in Single Top

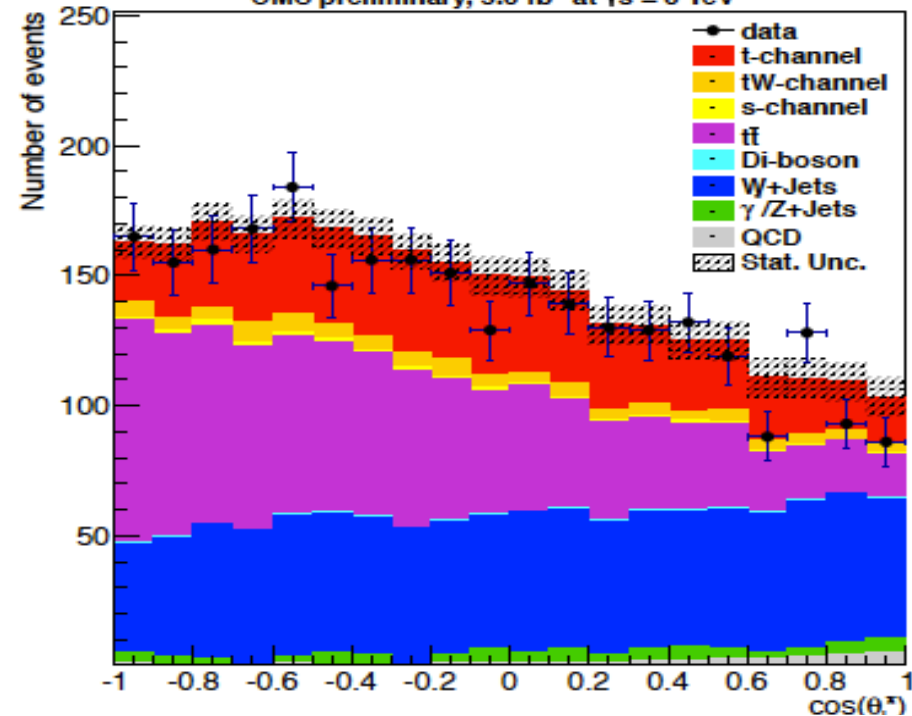


$$F_L^{\text{Comb.}} = 0.293 \pm 0.069(\text{stat.}) \pm 0.030(\text{syst.}),$$

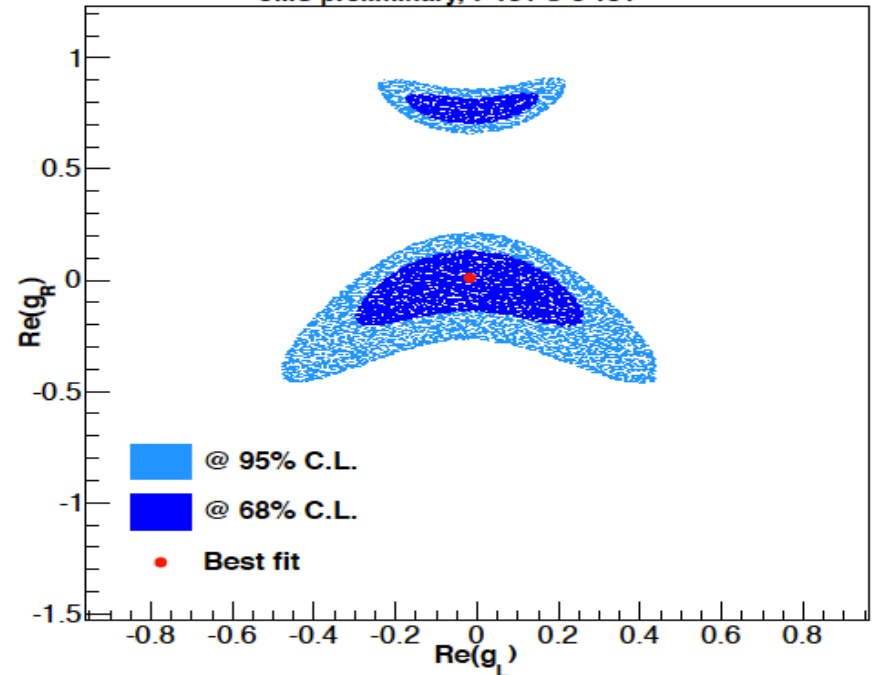
$$F_0^{\text{Comb.}} = 0.713 \pm 0.114(\text{stat.}) \pm 0.023(\text{syst.}),$$

$$F_R^{\text{Comb.}} = -0.006 \pm 0.057(\text{stat.}) \pm 0.027(\text{syst.}),$$

CMS preliminary, 5.3 fb<sup>-1</sup> at  $\sqrt{s} = 8$  TeV

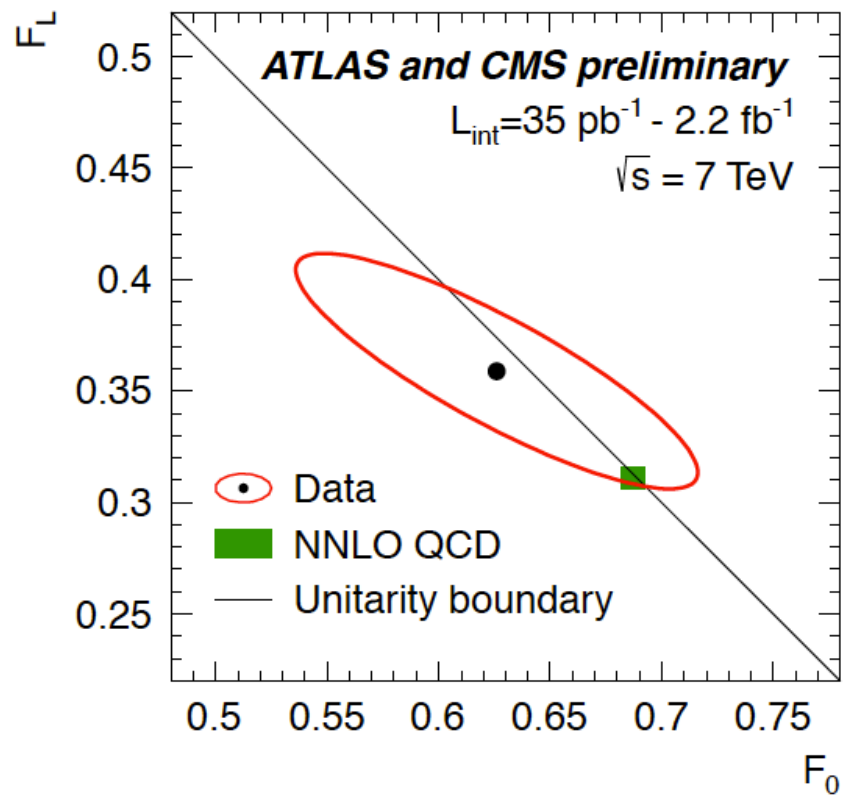
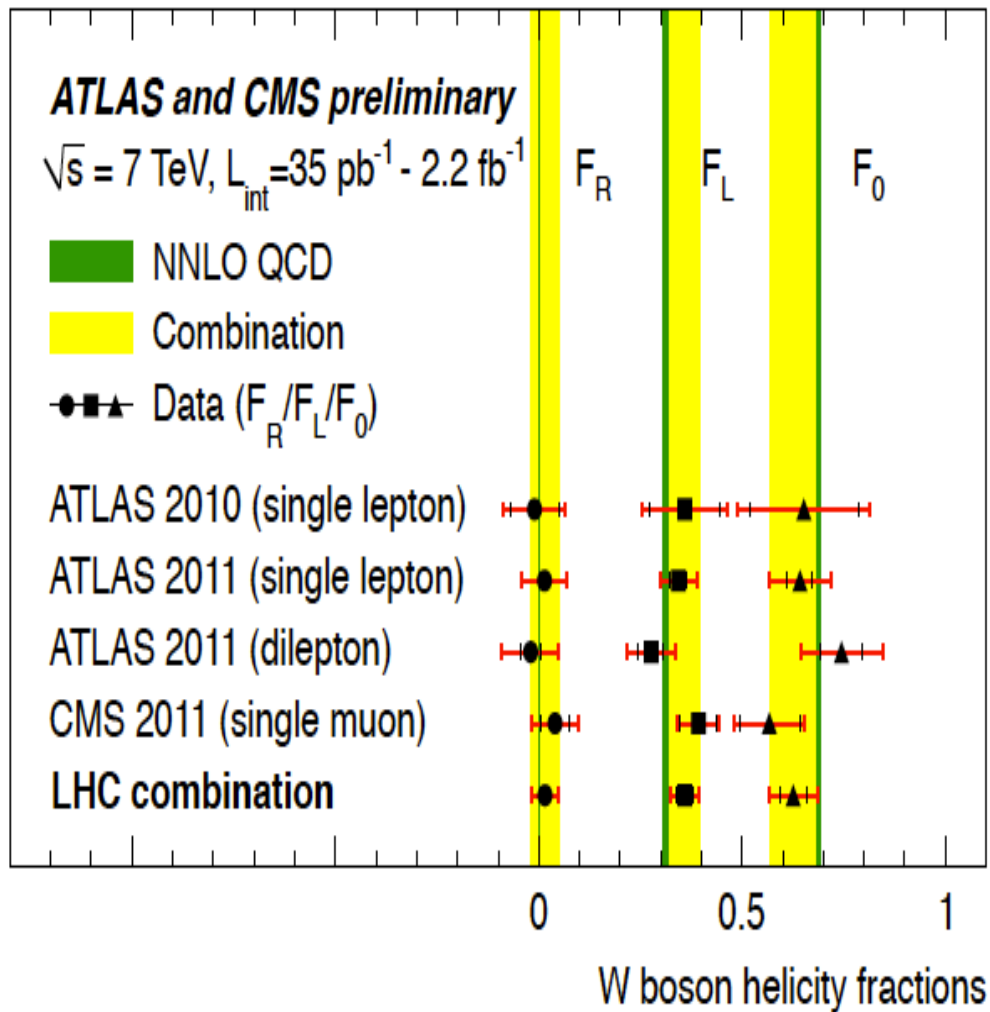


CMS preliminary, 7 TeV  $\oplus$  8 TeV



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

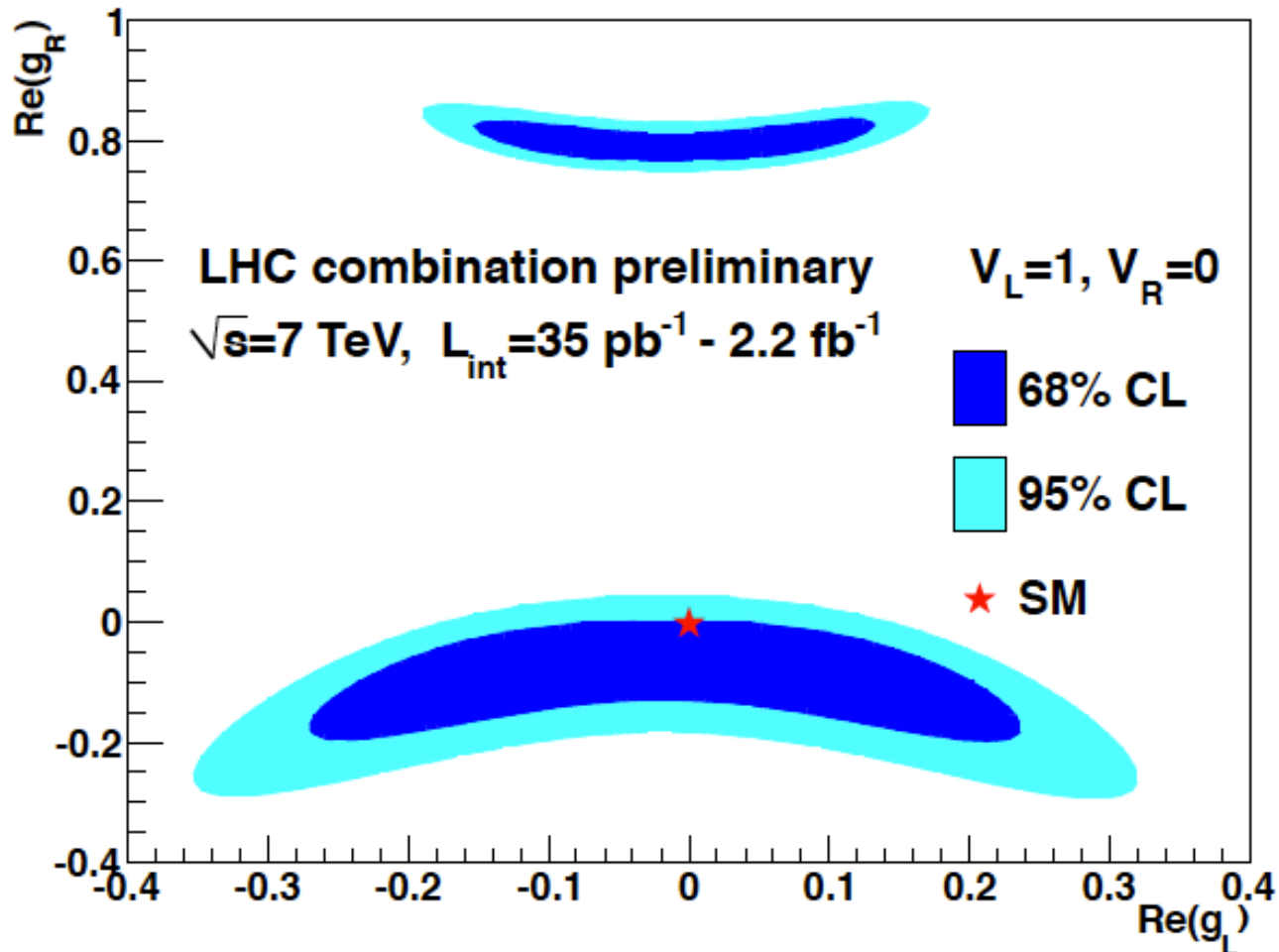
# W helicity: LHC combination



$$F_0 = 0.626 \pm 0.034 \text{ (stat.)} \pm 0.048 \text{ (syst.)},$$

$$F_L = 0.359 \pm 0.021 \text{ (stat.)} \pm 0.028 \text{ (syst.)}.$$

# W helicity: LHC combination



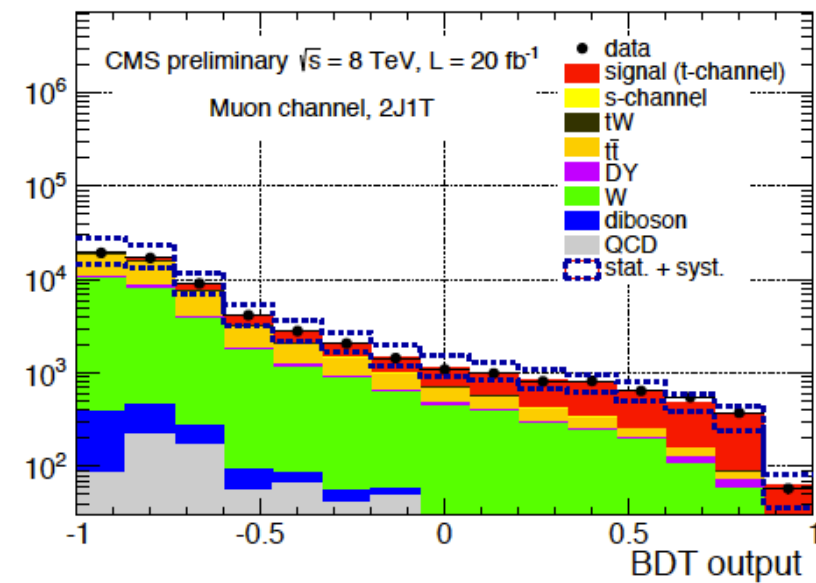
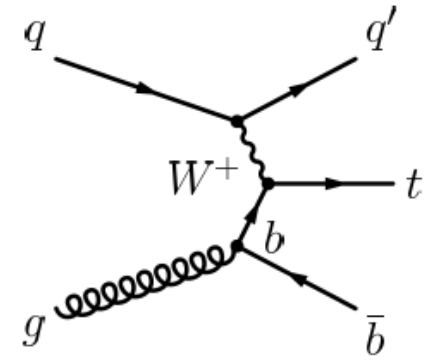
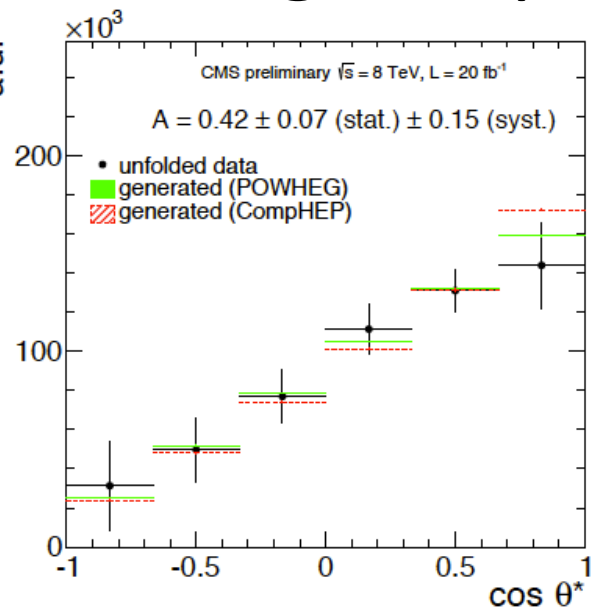
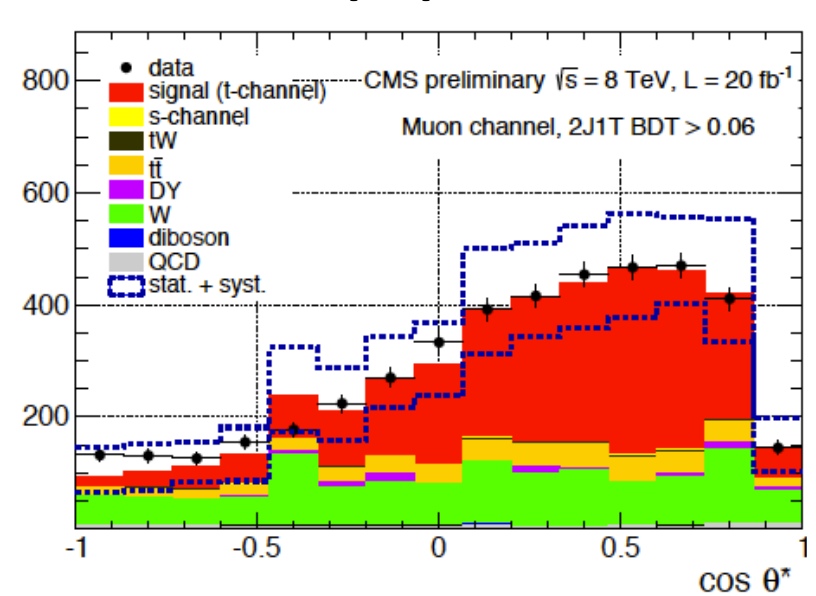
$$\mathcal{L}_{tWb}^{\text{anom.}} = -\frac{g}{\sqrt{2}} \bar{b} \gamma^\mu (V_L P_L + V_R P_R) t W_\mu^- - \frac{g}{\sqrt{2}} \bar{b} \frac{i\sigma^{\mu\nu} q_\nu}{m_W} (g_L P_L + g_R P_R) t W_\mu^- + H.C.,$$

t-channel

$$\frac{d\Gamma}{d \cos \theta_X} = \frac{\Gamma}{2} (1 + P_t \alpha_X \cos \theta_X) \quad A_l \equiv \frac{1}{2} \cdot P_t \cdot \alpha_l = \frac{N(\uparrow) - N(\downarrow)}{N(\uparrow) + N(\downarrow)}$$

$X (= W, \ell, \nu, b)$

# Top polarization in Single Top events



$$A_l = \frac{N(\cos \theta_{unfolding}^* > 0) - N(\cos \theta_{unfolding}^* < 0)}{N(\cos \theta_{unfolding}^* > 0) + N(\cos \theta_{unfolding}^* < 0)}$$

$$A_l = 0.41 \pm 0.06(stat.) \pm 0.16(syst.)$$

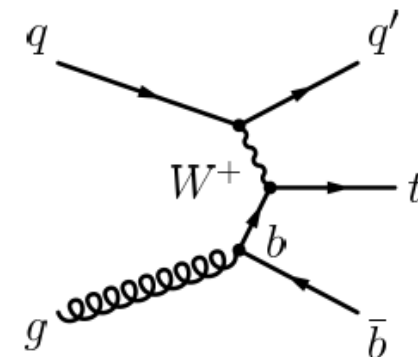
$$P_t = 0.82 \pm 0.12(stat.) \pm 0.32(syst.)$$

$$\alpha_l = 1$$

100% polarization expected

t-channel

# Top polarization in Single Top events



In this analysis, the top-quark spin asymmetry

$$A_l \equiv \frac{1}{2} \cdot P_t \cdot \alpha_l = \frac{N(\uparrow) - N(\downarrow)}{N(\uparrow) + N(\downarrow)} \quad (1)$$

is used to probe the top-quark coupling structure, where:  $P_t$  represents the top-quark polarization;  $N(\uparrow)$  and  $N(\downarrow)$  respectively denote the number of charged leptons aligned or counter-aligned with the direction of the spectator quark that recoils against the single top quark in the top-quark rest frame, which is a good approximation of the top-quark spin axis [2, 3]; and  $\alpha_X$  denotes the spin-analyzing power of a decay product  $X$ , i.e. the degree of correlation of its angular distributions with respect to the spin of the top quark. The latter is exactly 1 in the SM when  $X$  is a charged lepton but its value is in general modified by anomalous top-quark couplings that can arise through an effective extension of the coupling structure at the  $Wtb$  vertex [4].

Di-lepton

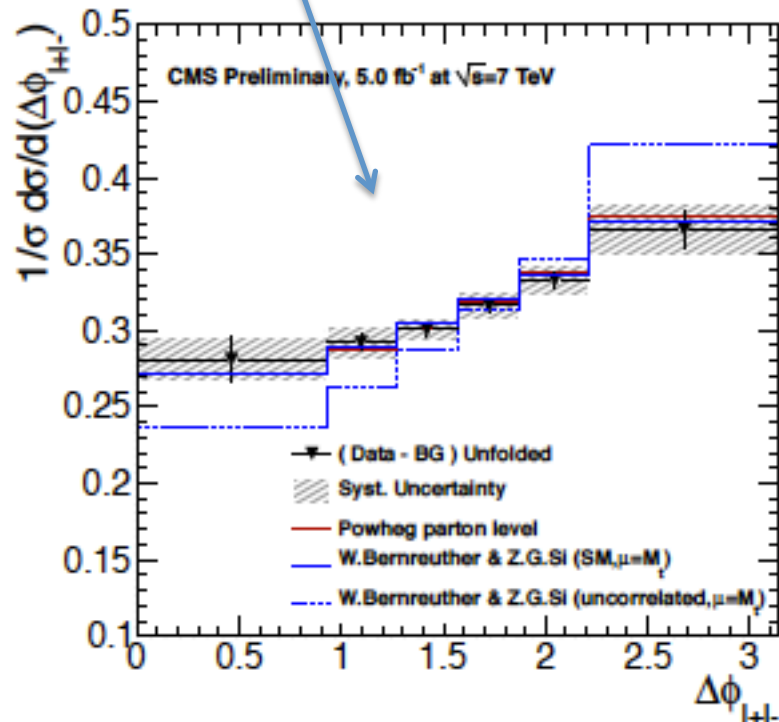
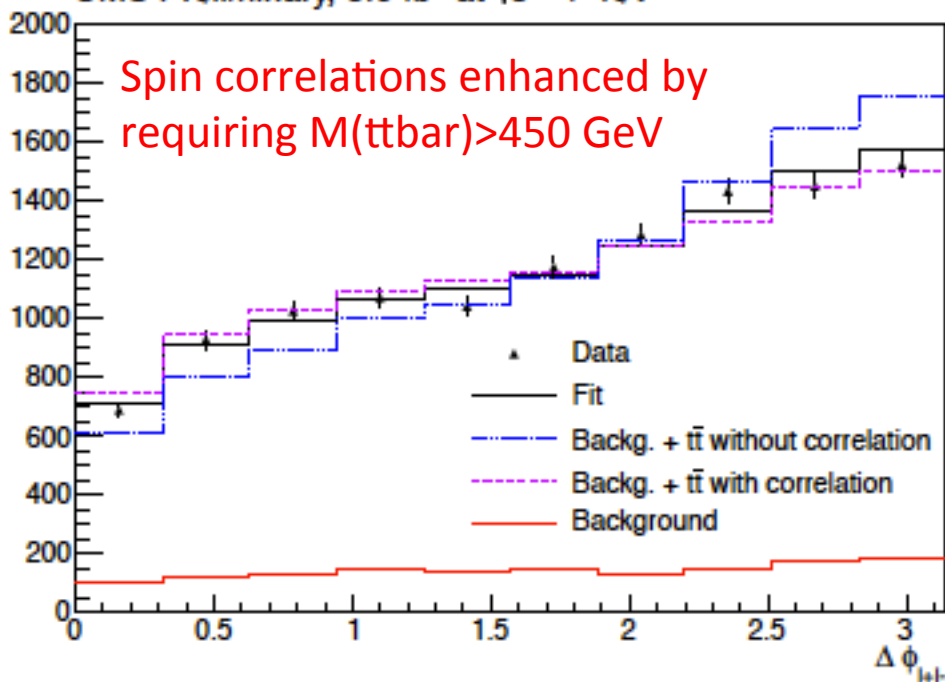
$$t\bar{t} \rightarrow l^+ \nu l^- \bar{\nu} b\bar{b},$$

$$[\Delta\phi_{l+l^-} = |\phi_{l^+} - \phi_{l^-}|]$$

# Spin correlations

Background-subtracted and unfolded differential cross-sections

CMS Preliminary, 5.0 fb<sup>-1</sup> at  $\sqrt{s} = 7$  TeV



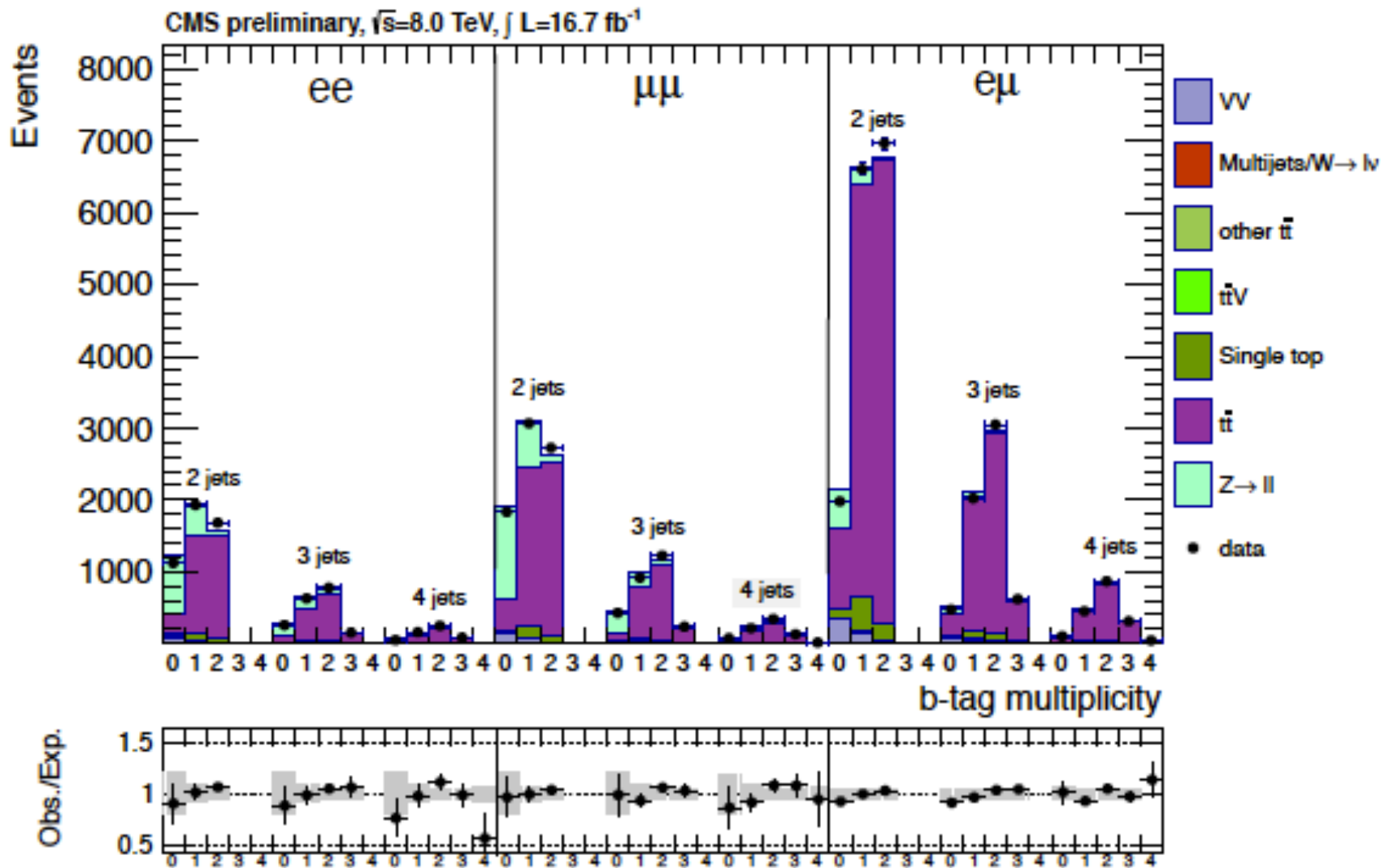
Correlation coefficient in the helicity basis:  $0.24 \pm 0.02(\text{stat.}) \pm 0.08(\text{syst.})$

$$A_{hel}^{SM} = 0.31$$



Di-lepton  $t\bar{t} \rightarrow l^+ \nu l^- \bar{\nu} b \bar{b}$ ,

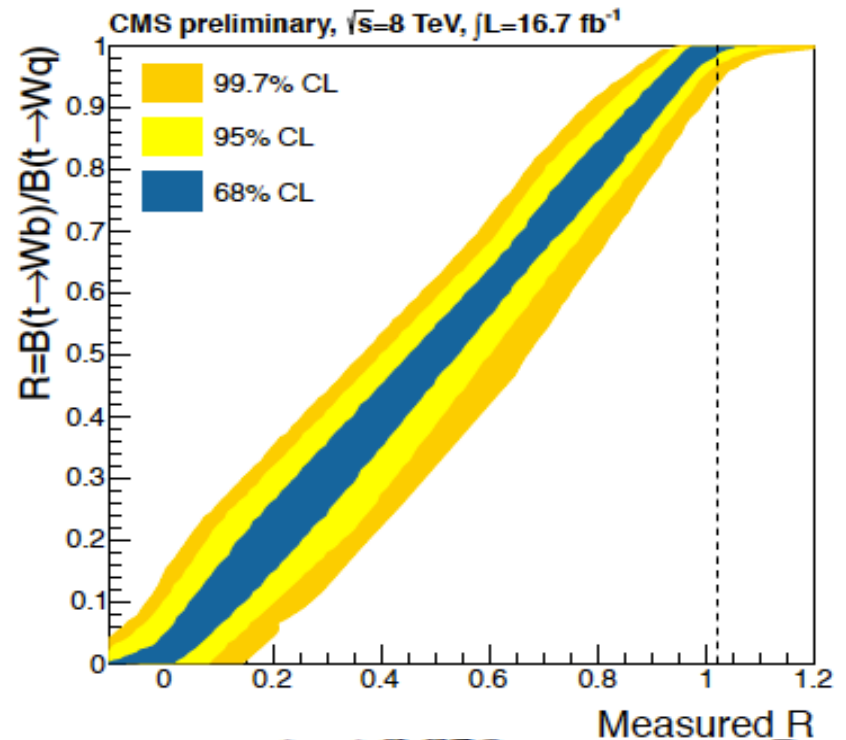
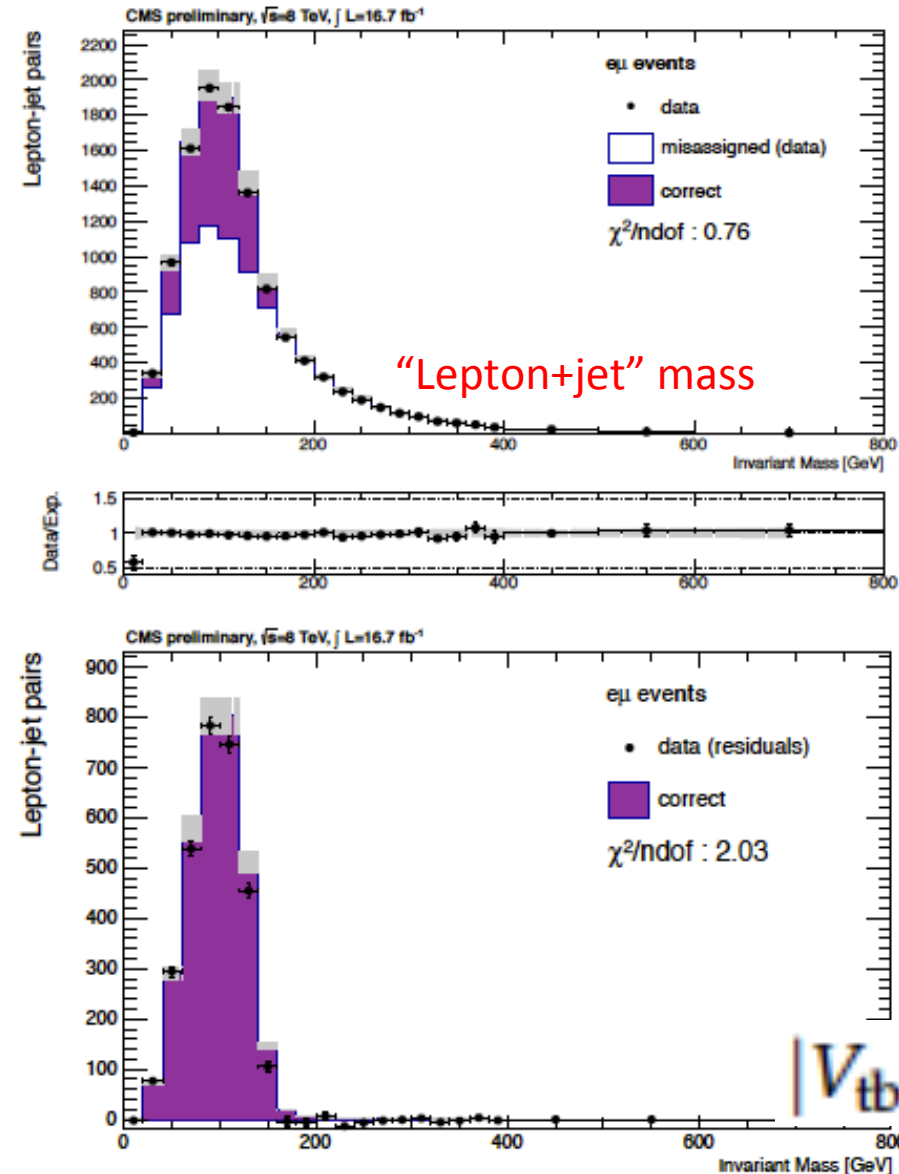
# Ratio of top decays to Wb and Wq



Di-lepton  $t\bar{t} \rightarrow l^+ \nu l^- \bar{\nu} b\bar{b}$ ,

# Ratio of top decays to Wb and Wq

Mis-reconstructions taken into account in likelihood fit (jet assignment & flavor tagging matching).



$$\mathcal{R} = 1.023^{+0.036}_{-0.034} \text{ (stat+syst)}$$

$|V_{tb}| > 0.972$  is obtained at 95% CL



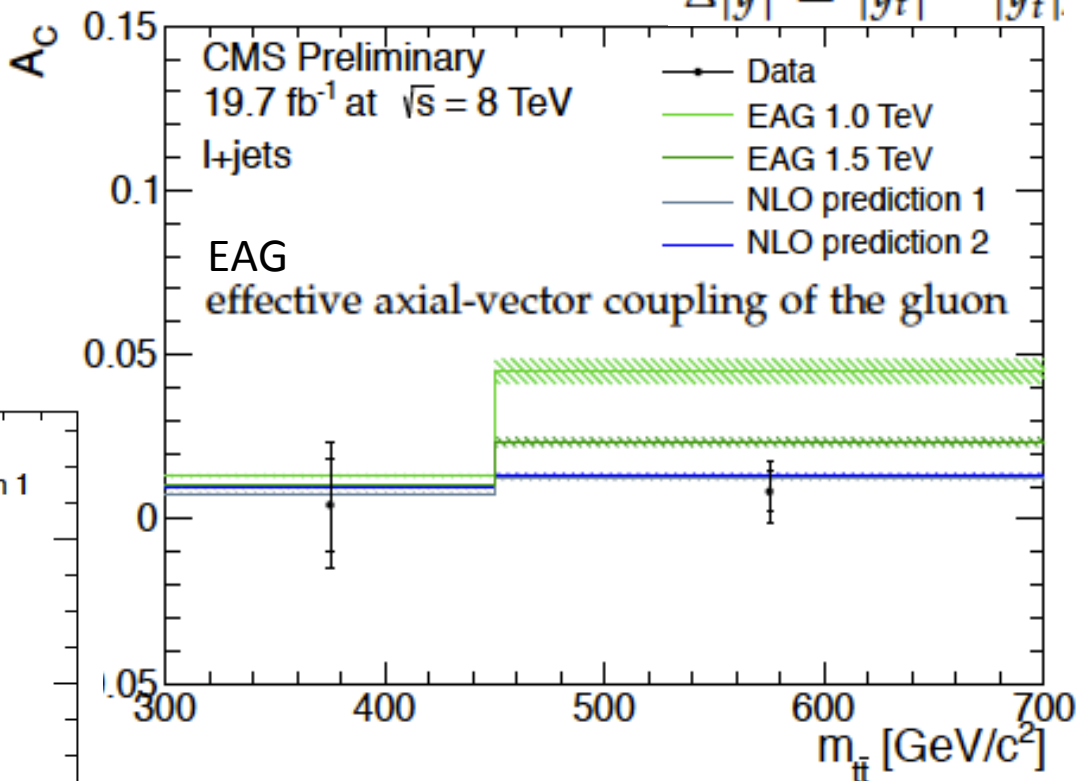
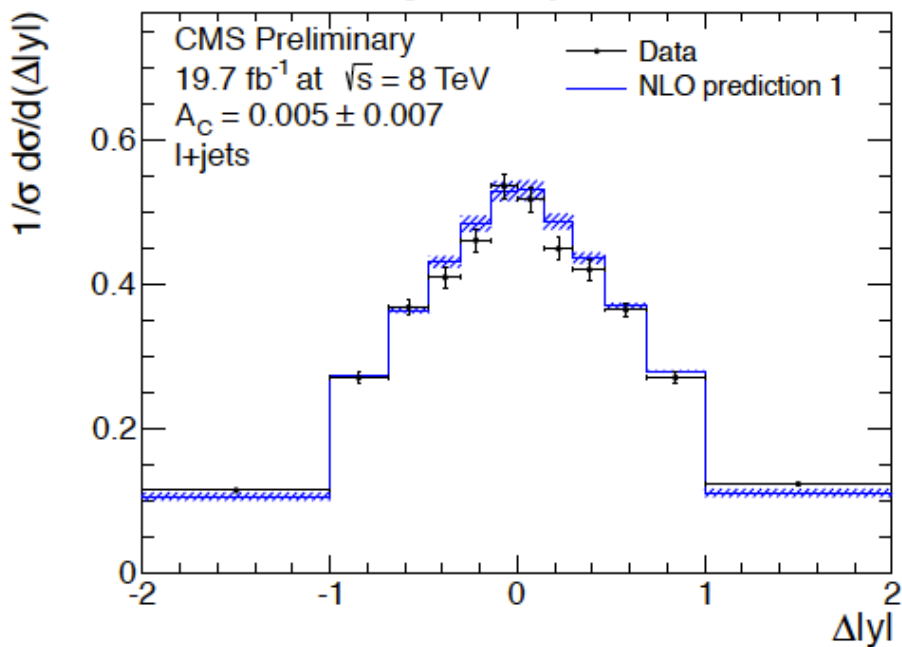
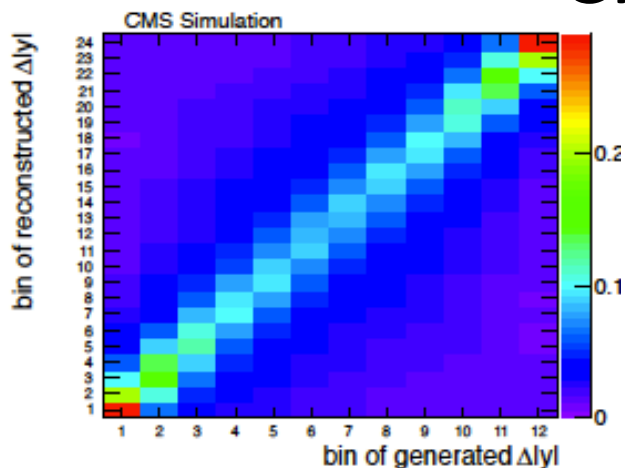


Lepton+jets

# Charge asymmetry

$$A_C = \frac{N^+ - N^-}{N^+ + N^-}$$

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



Measured charge asymmetry  
 $0.005 \pm 0.007$  (stat.)  $\pm 0.006$  (syst.)

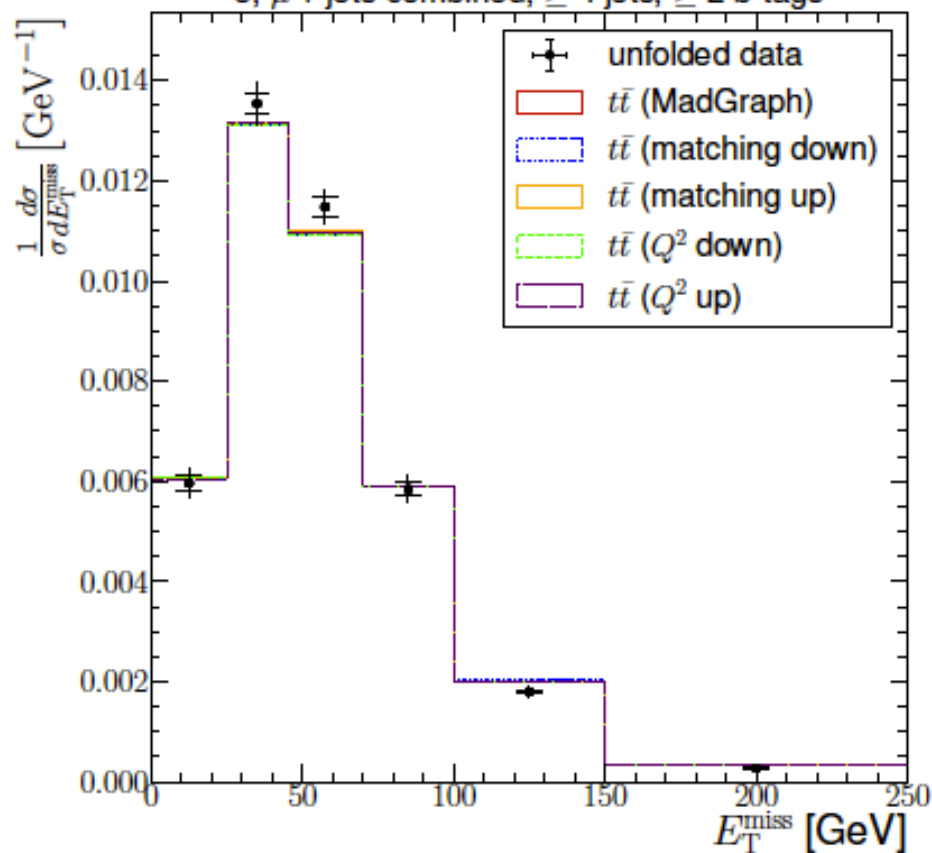
Theory prediction  $\sim 1\%$

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

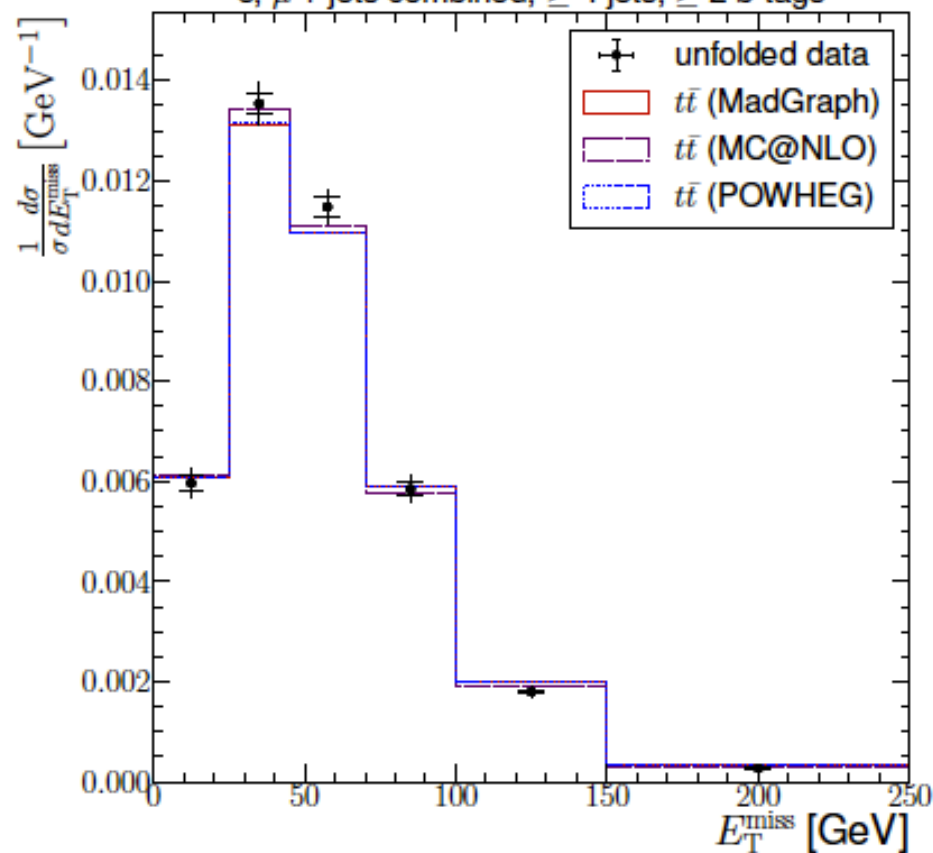
# Kinematics of top quark events

$$E_T^{\text{miss}} = - \left[ \left( \sum_i p_x^i \right)^2 + \left( \sum_i p_y^i \right)^2 \right]^{\frac{1}{2}}$$

CMS Preliminary,  $\mathcal{L} = 19.7 \text{ fb}^{-1}$  at  $\sqrt{s} = 8 \text{ TeV}$   
 $e, \mu + \text{jets combined, } \geq 4 \text{ jets, } \geq 2 \text{ b-tags}$



CMS Preliminary,  $\mathcal{L} = 19.7 \text{ fb}^{-1}$  at  $\sqrt{s} = 8 \text{ TeV}$   
 $e, \mu + \text{jets combined, } \geq 4 \text{ jets, } \geq 2 \text{ b-tags}$

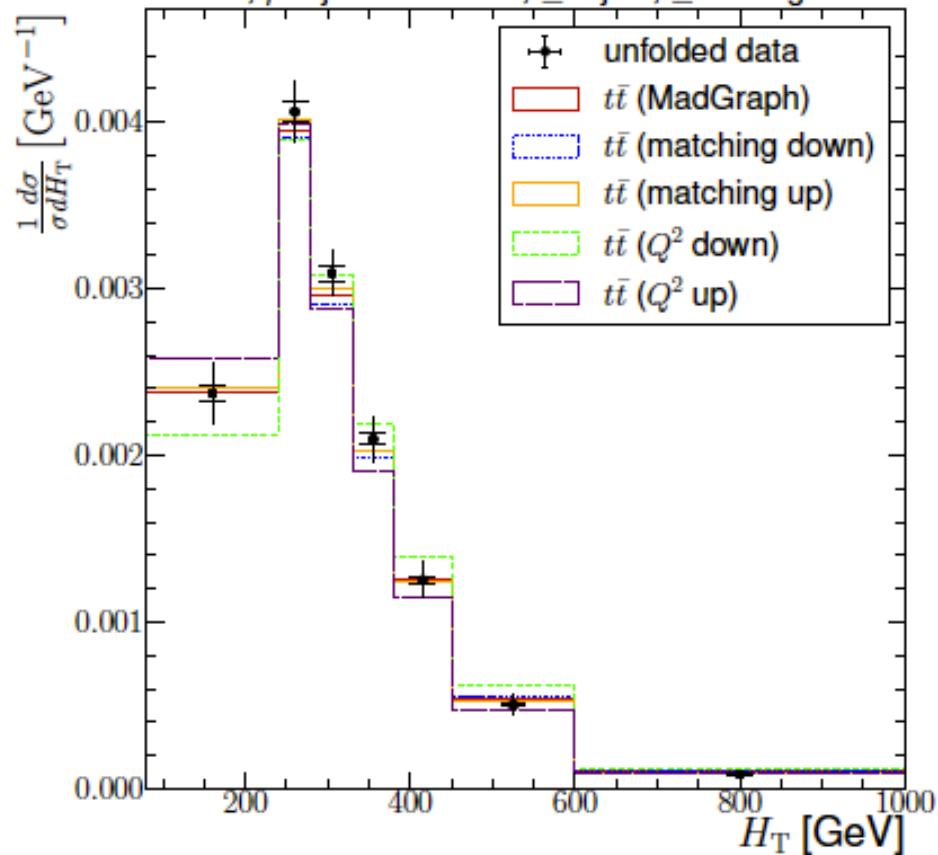


Lepton+jets

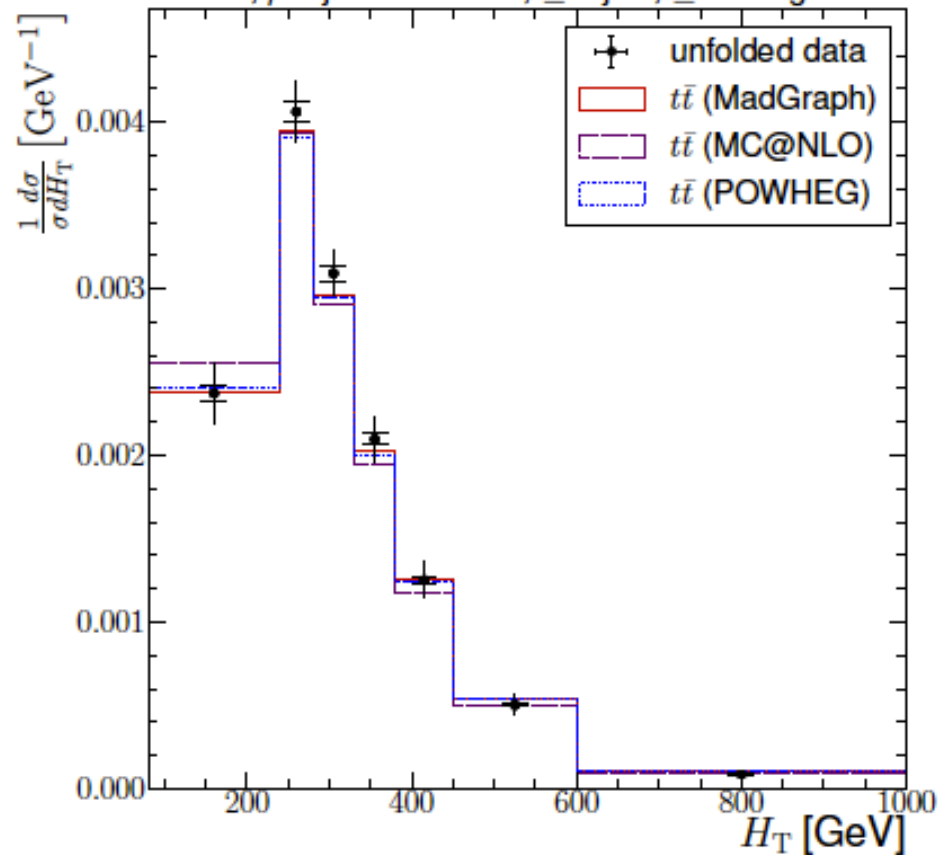
# Kinematics of top quark events

$$H_T = \sum_{\text{all jets}} p_T^{\text{jet}}$$

CMS Preliminary,  $\mathcal{L} = 19.7 \text{ fb}^{-1}$  at  $\sqrt{s} = 8 \text{ TeV}$   
 $e, \mu + \text{jets combined, } \geq 4 \text{ jets, } \geq 2 \text{ b-tags}$



CMS Preliminary,  $\mathcal{L} = 19.7 \text{ fb}^{-1}$  at  $\sqrt{s} = 8 \text{ TeV}$   
 $e, \mu + \text{jets combined, } \geq 4 \text{ jets, } \geq 2 \text{ b-tags}$

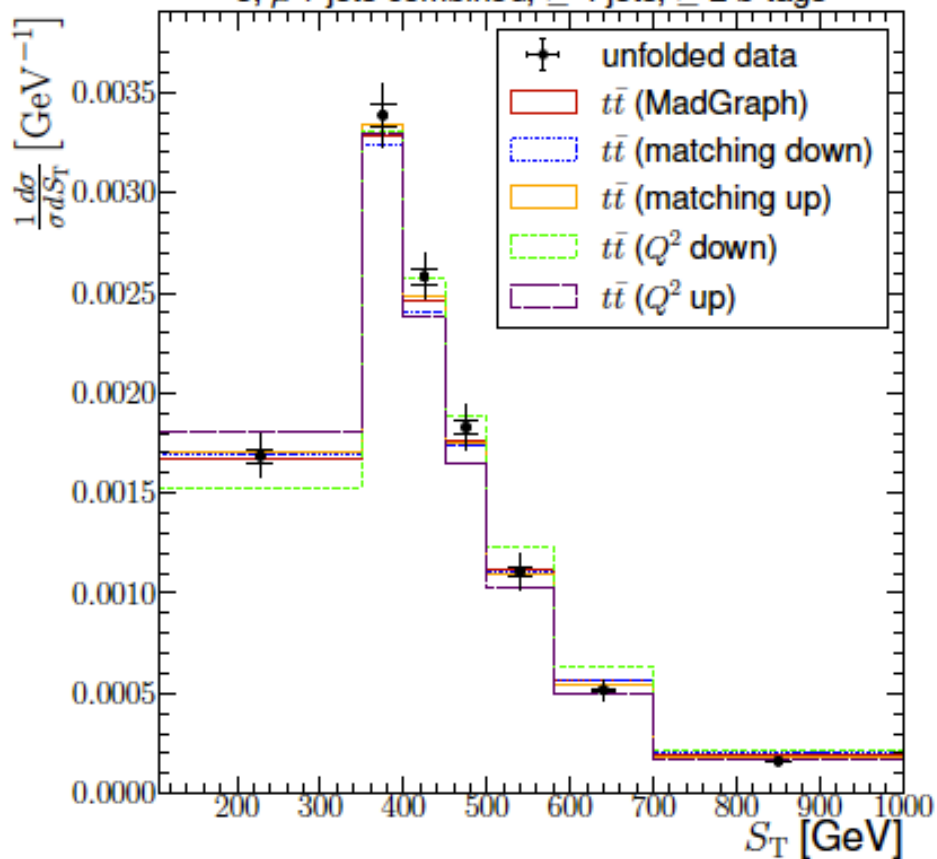


Lepton+jets

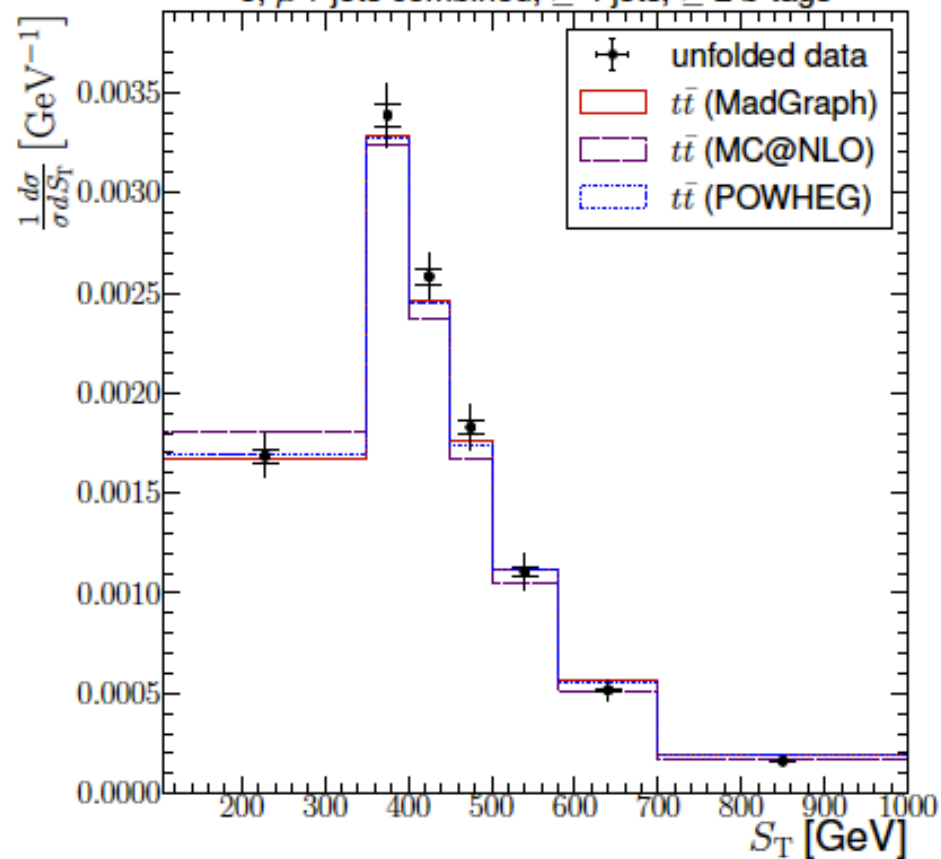
# Kinematics of top quark events

$$S_T = H_T + E_T^{\text{miss}} + p_T^{\text{lepton}}$$

CMS Preliminary,  $\mathcal{L} = 19.7 \text{ fb}^{-1}$  at  $\sqrt{s} = 8 \text{ TeV}$   
 $e, \mu + \text{jets combined, } \geq 4 \text{ jets, } \geq 2 \text{ b-tags}$



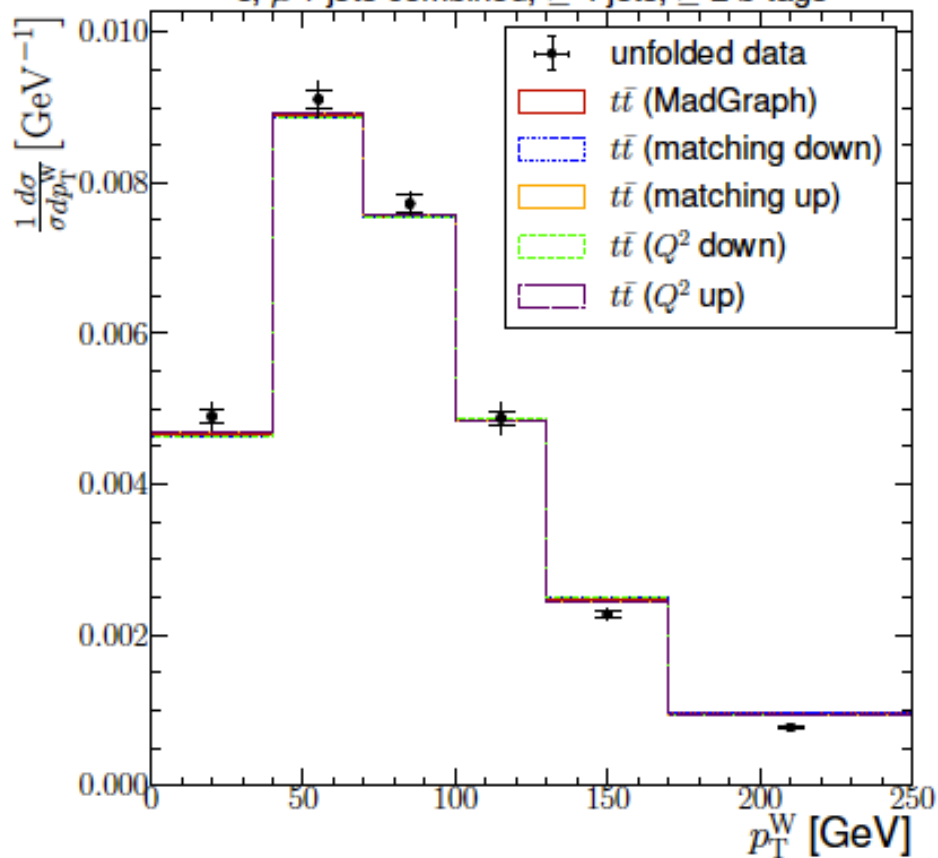
CMS Preliminary,  $\mathcal{L} = 19.7 \text{ fb}^{-1}$  at  $\sqrt{s} = 8 \text{ TeV}$   
 $e, \mu + \text{jets combined, } \geq 4 \text{ jets, } \geq 2 \text{ b-tags}$



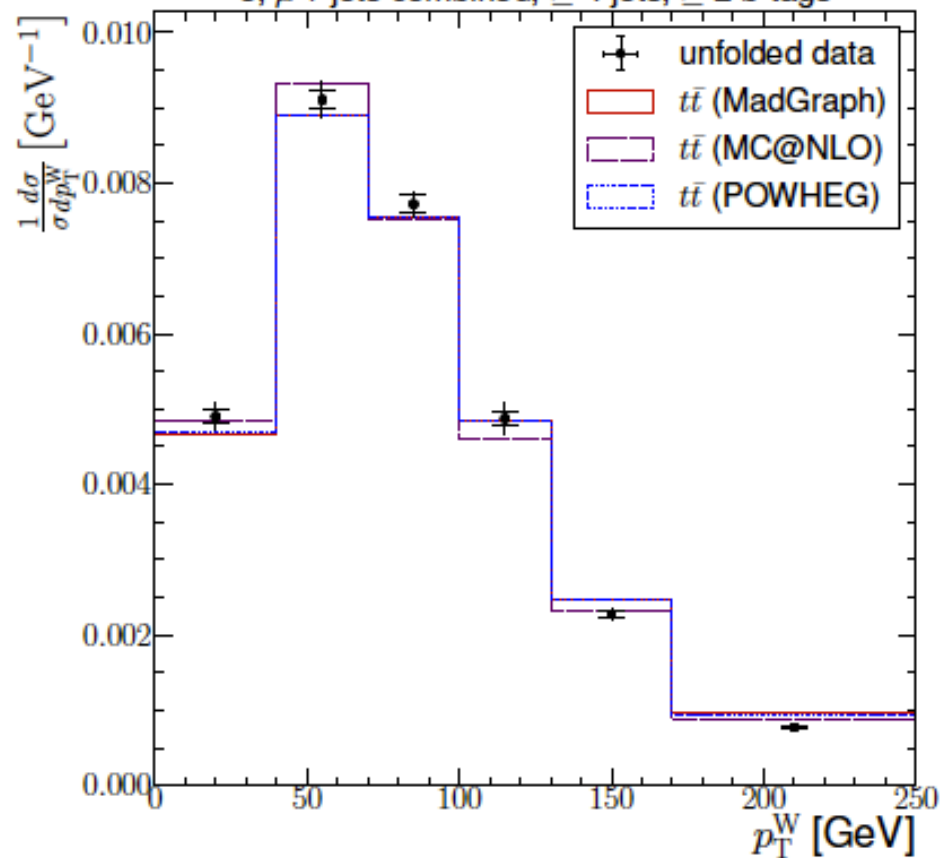
# Kinematics of top quark events

$$p_T^W = \sqrt{(p_x^{\text{lepton}} + p_x^{\text{miss}})^2 + (p_y^{\text{lepton}} + p_y^{\text{miss}})^2}$$

CMS Preliminary,  $\mathcal{L} = 19.7 \text{ fb}^{-1}$  at  $\sqrt{s} = 8 \text{ TeV}$   
 $e, \mu + \text{jets combined, } \geq 4 \text{ jets, } \geq 2 \text{ b-tags}$



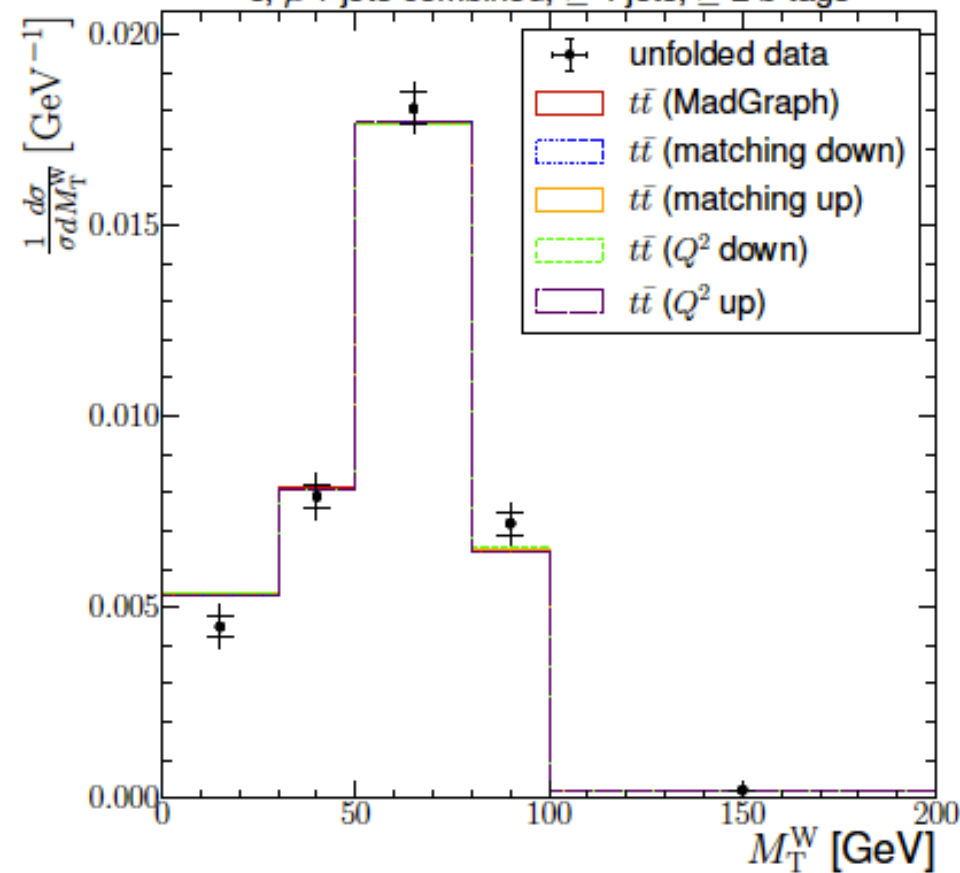
CMS Preliminary,  $\mathcal{L} = 19.7 \text{ fb}^{-1}$  at  $\sqrt{s} = 8 \text{ TeV}$   
 $e, \mu + \text{jets combined, } \geq 4 \text{ jets, } \geq 2 \text{ b-tags}$



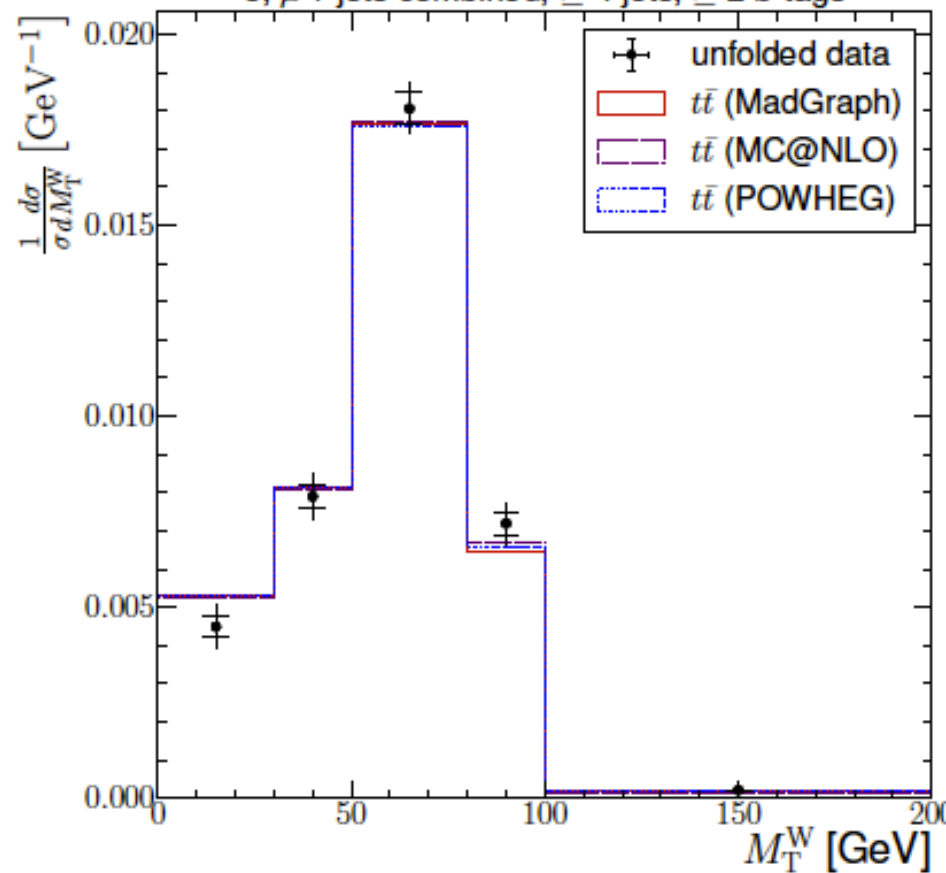
# Kinematics of top quark events

$$M_T^W = \sqrt{(E_T^{\text{lepton}} + E_T^{\text{miss}})^2 - p_T^W{}^2}$$

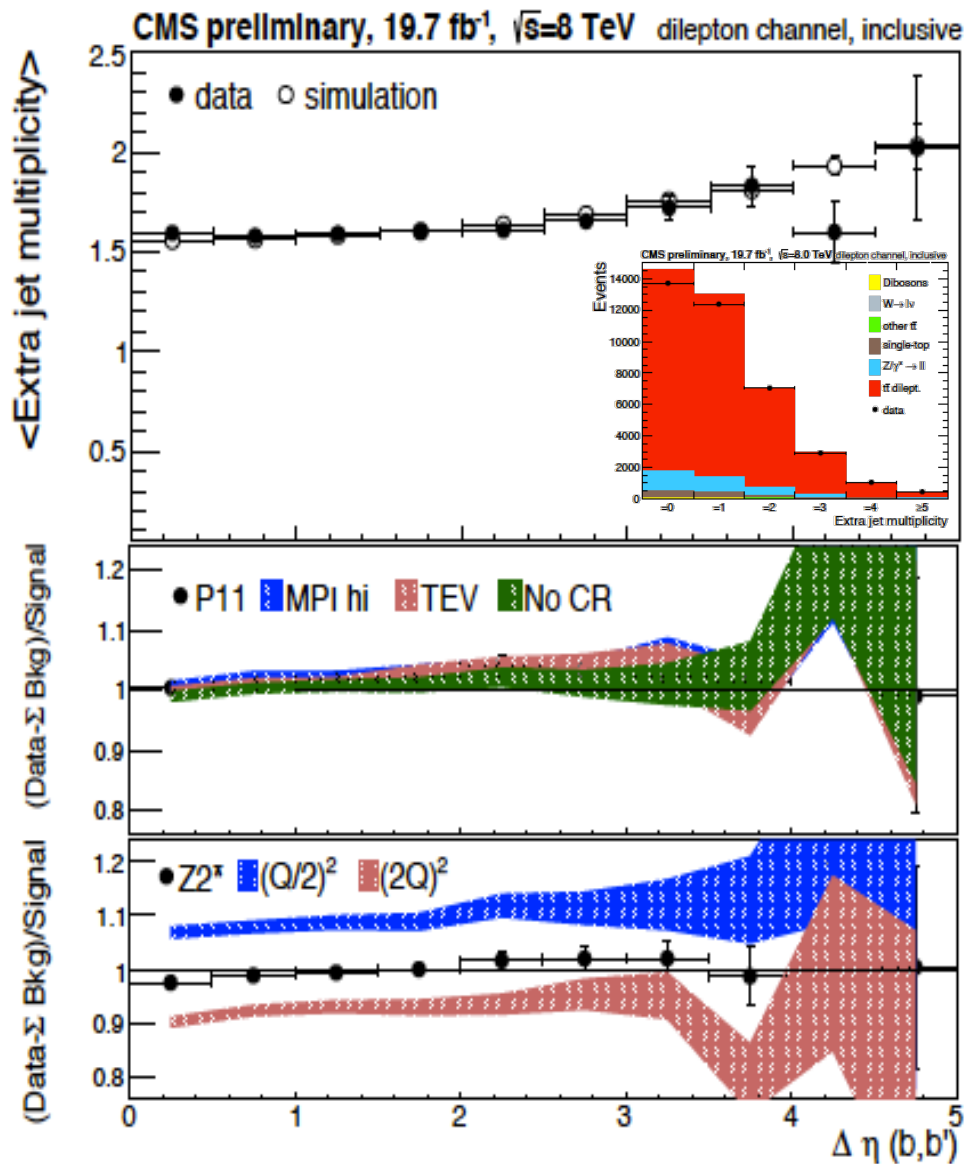
CMS Preliminary,  $\mathcal{L} = 19.7 \text{ fb}^{-1}$  at  $\sqrt{s} = 8 \text{ TeV}$   
 $e, \mu + \text{jets combined, } \geq 4 \text{ jets, } \geq 2 \text{ b-tags}$



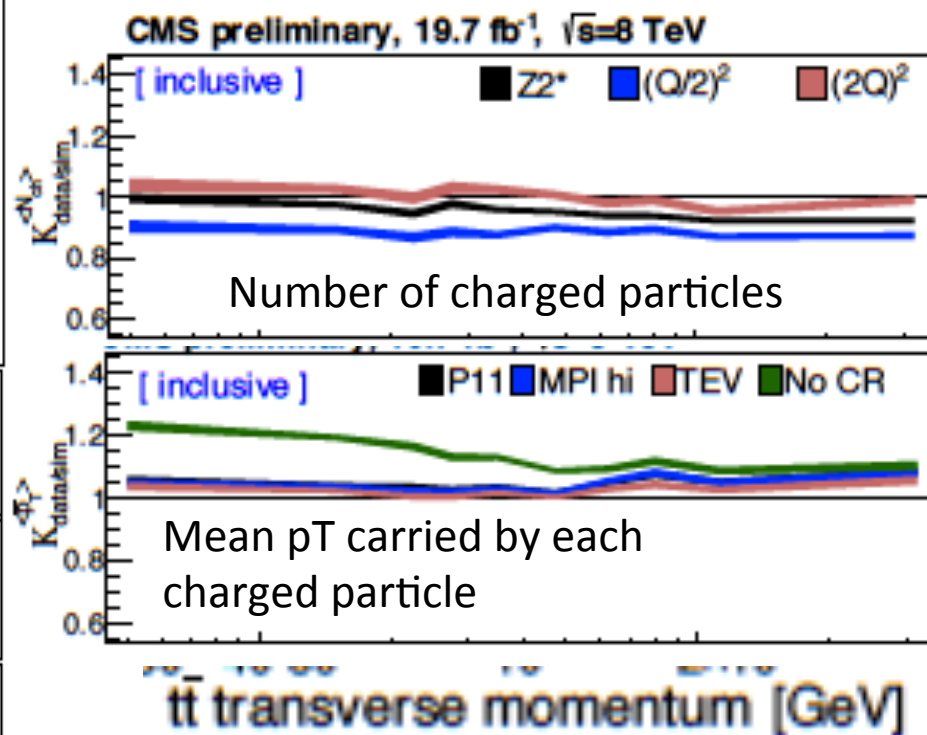
CMS Preliminary,  $\mathcal{L} = 19.7 \text{ fb}^{-1}$  at  $\sqrt{s} = 8 \text{ TeV}$   
 $e, \mu + \text{jets combined, } \geq 4 \text{ jets, } \geq 2 \text{ b-tags}$



# Study of systematic in top quark events



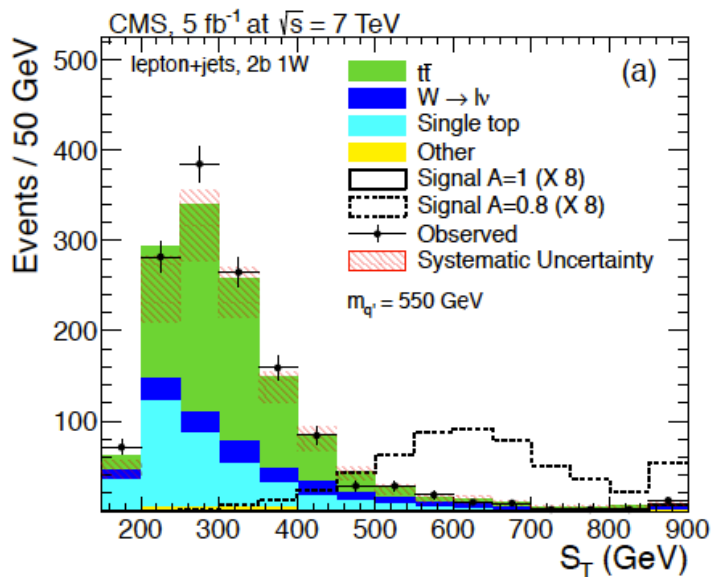
$$K_{\text{data/sim}}^x (\langle p_T(t\bar{t}) \rangle) = \frac{\langle x^{\text{obs}} \rangle (\langle p_T(t\bar{t}) \rangle)}{\langle x^{\text{exp}} \rangle (\langle p_T(t\bar{t}) \rangle)}$$



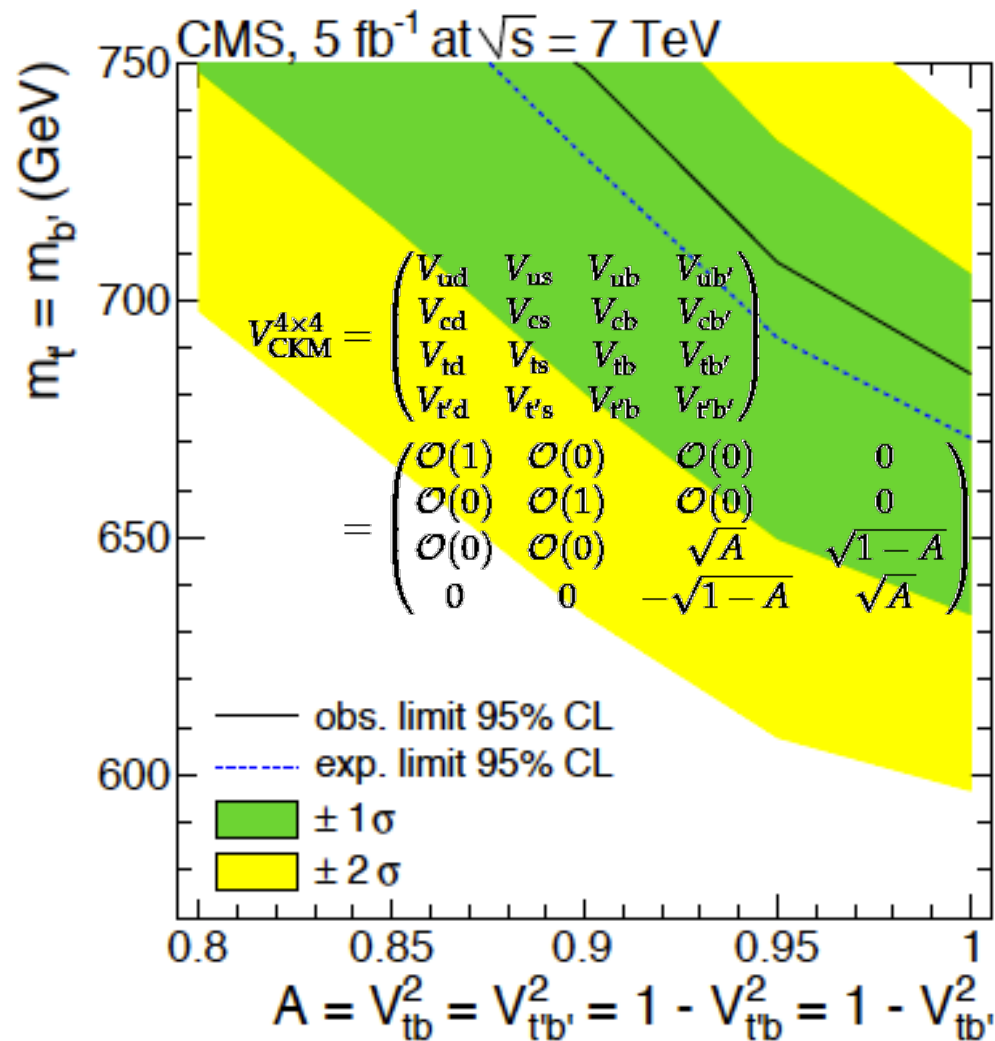
These studies are crucial to enter the precision era of top quark physics at the LHC



# Fourth generation top quarks?

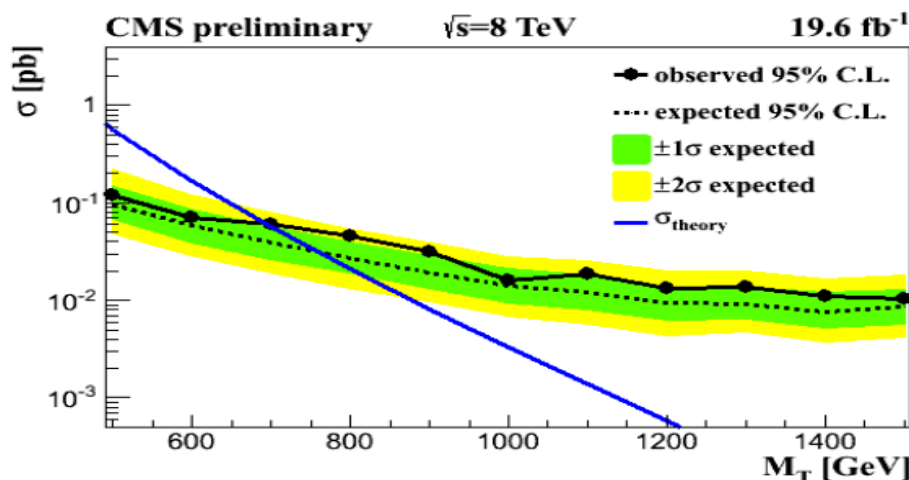
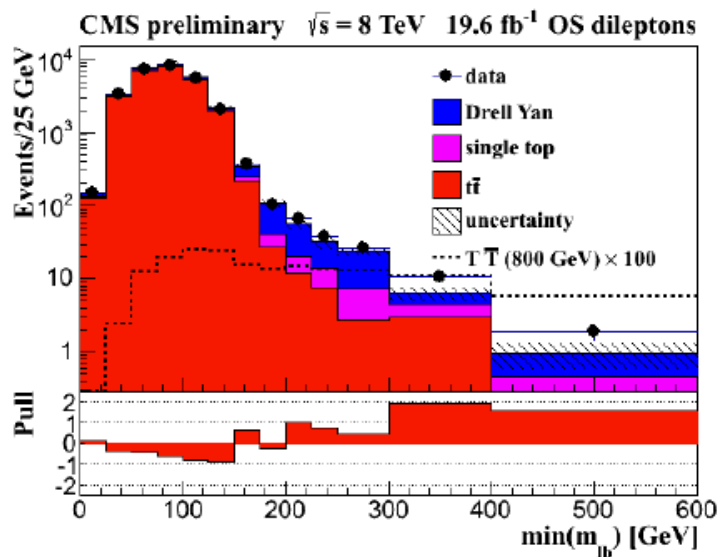
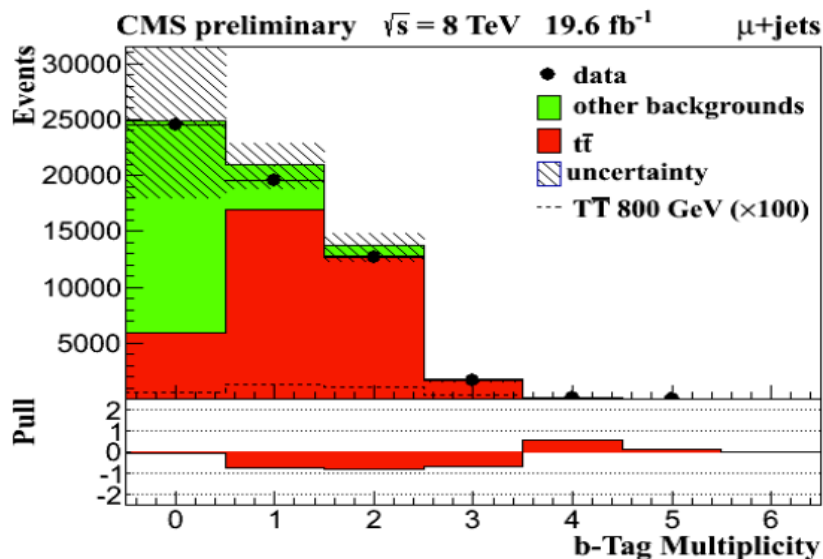
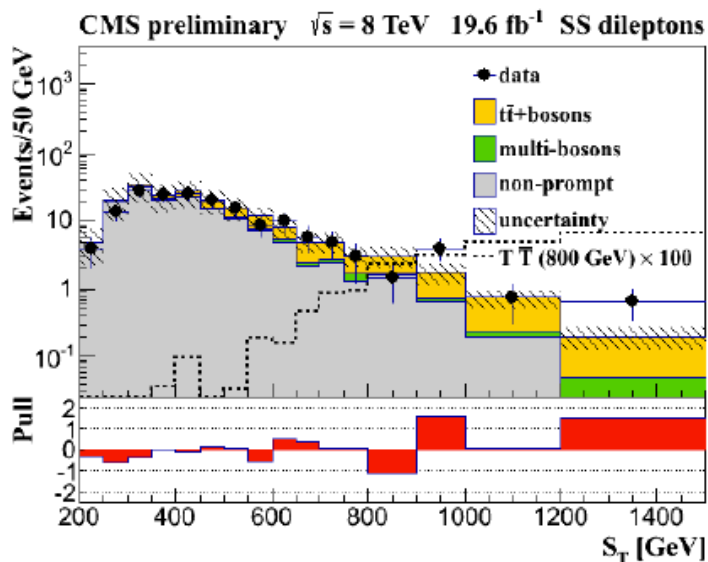


subsample	observable
single-lepton 1W	$S_T$
single-lepton 2W	$S_T$ and $m_{bW}$
single-lepton 3W	$S_T$
single-lepton 4W	event yield
same-sign dilepton	event yield
trilepton	event yield





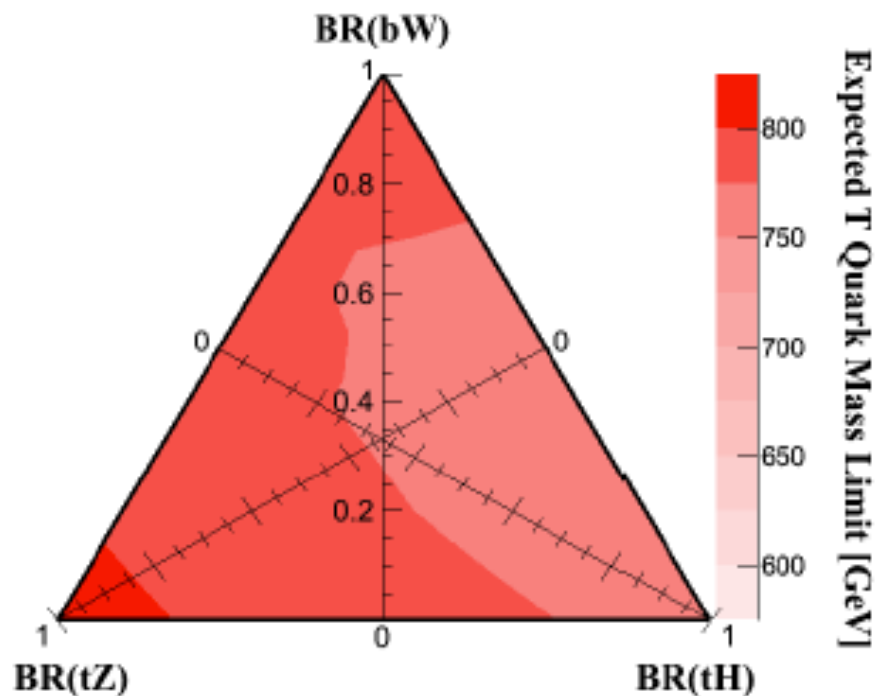
# Inclusive vector-like T quarks ? Charge 2/3



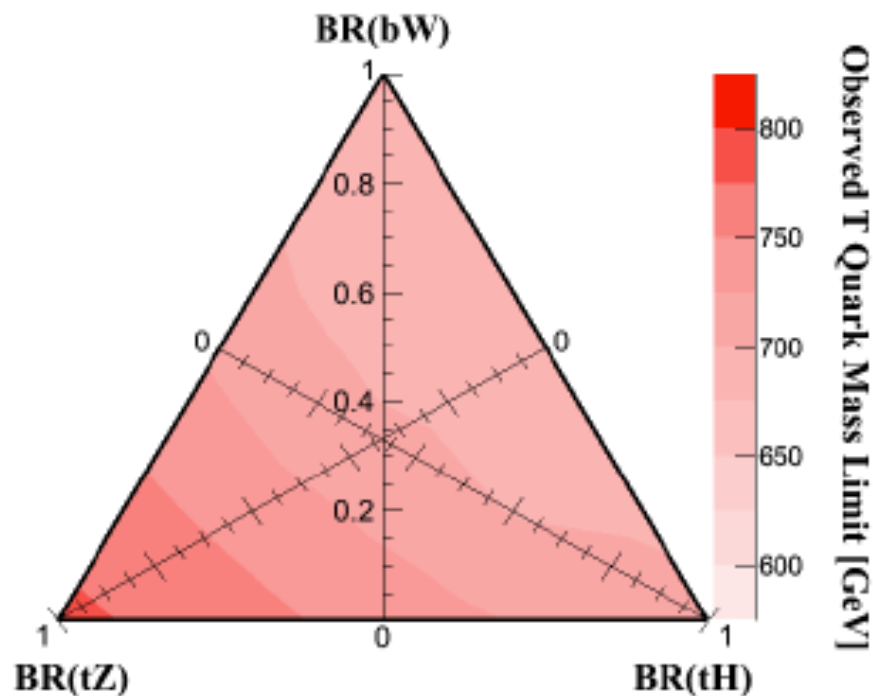
for branching fractions into bW, tH, tZ of 50%, 25%, 25%.

# Inclusive vector-like T quarks ?

CMS preliminary  $\sqrt{s} = 8 \text{ TeV}$   $19.6 \text{ fb}^{-1}$

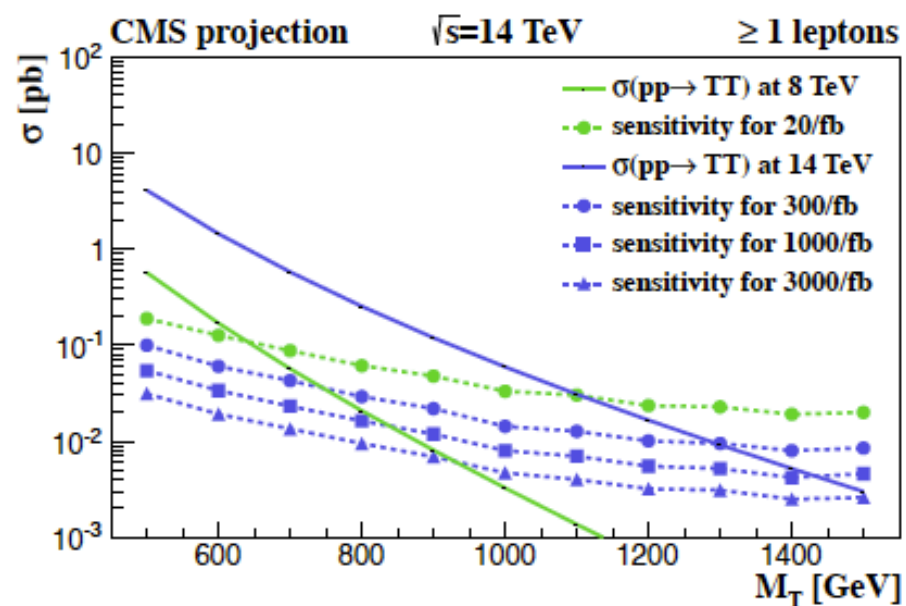
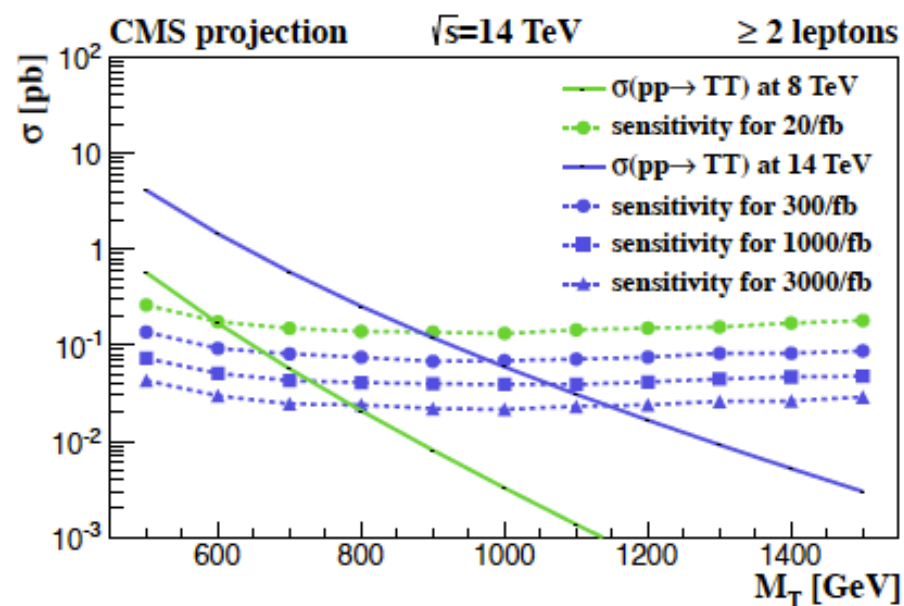


CMS preliminary  $\sqrt{s} = 8 \text{ TeV}$   $19.6 \text{ fb}^{-1}$



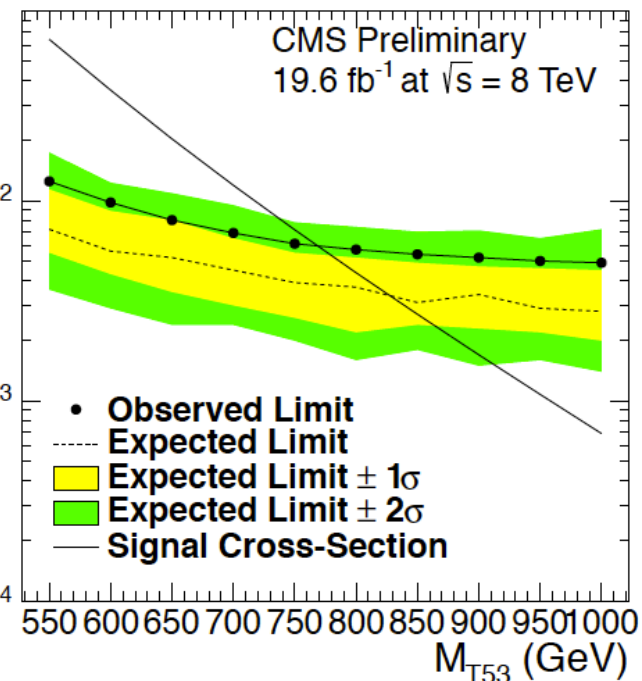
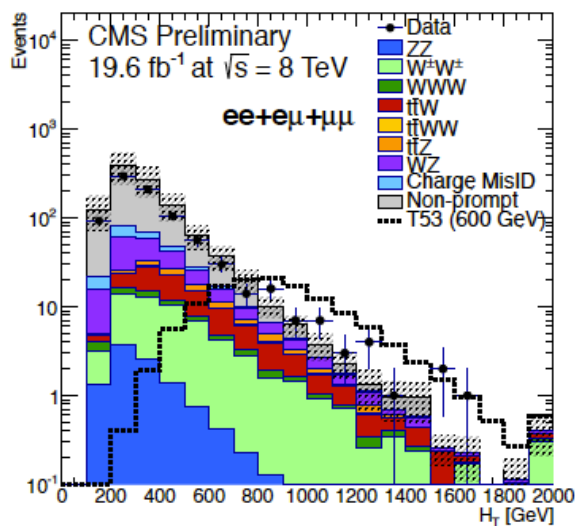
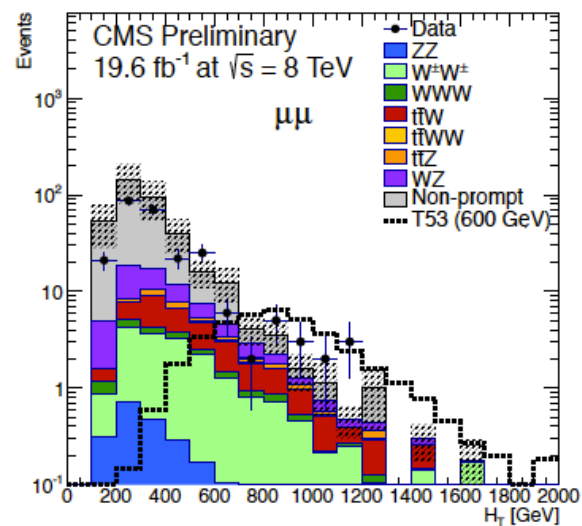
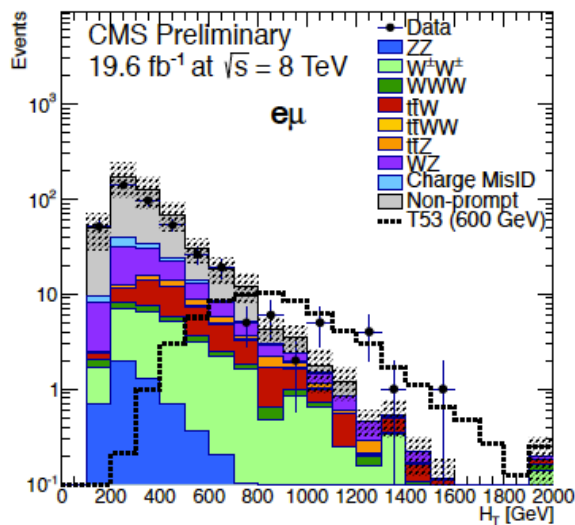
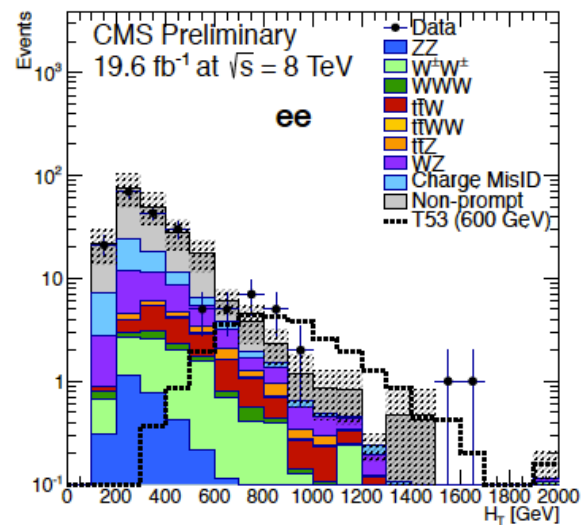
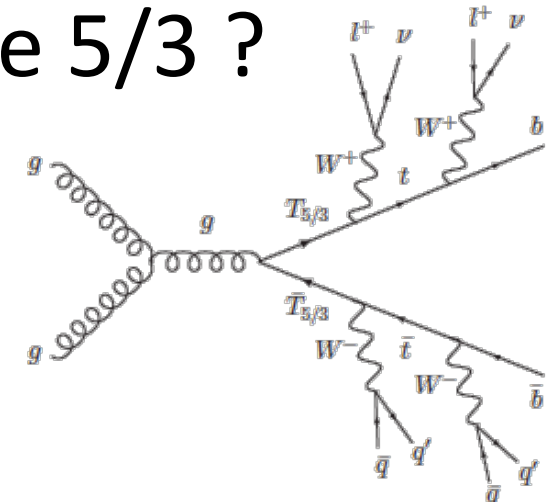
# Inclusive vector-like T quarks: prospects ?

All channels combined



Discovery reach up to 1.2 TeV

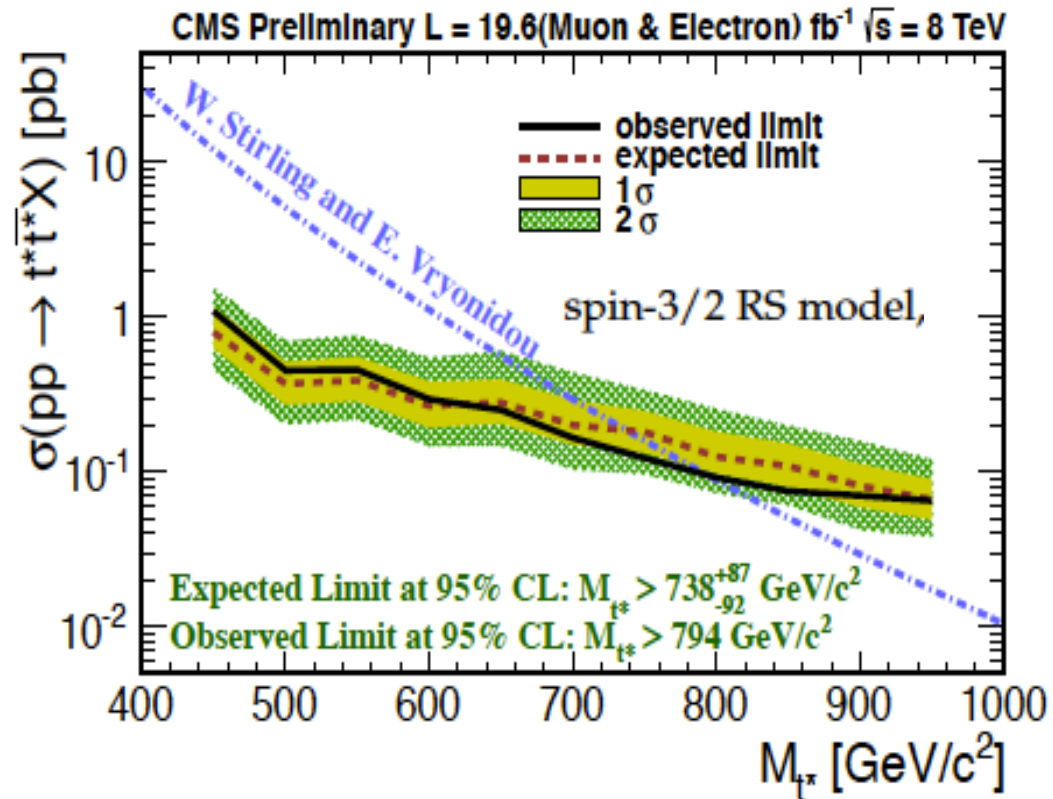
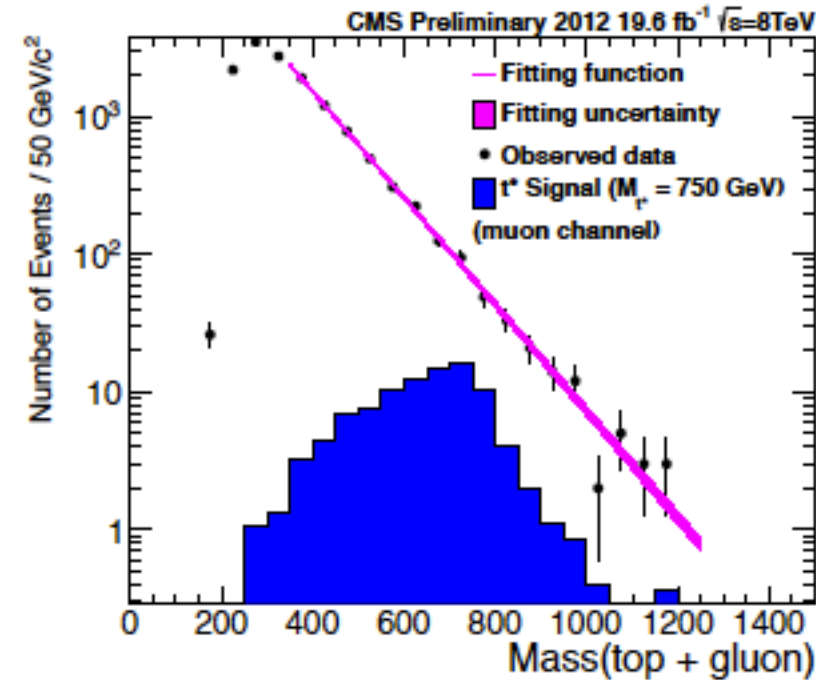
# Top Partners with charge 5/3 ?



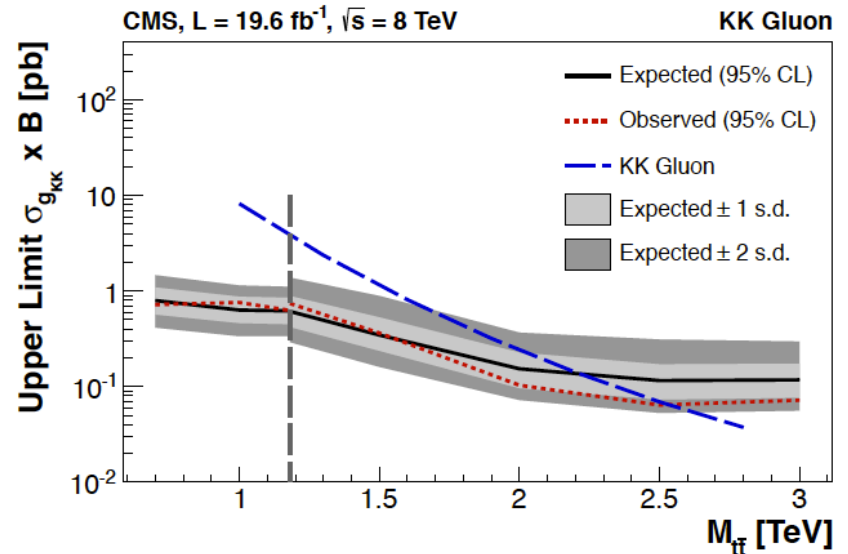
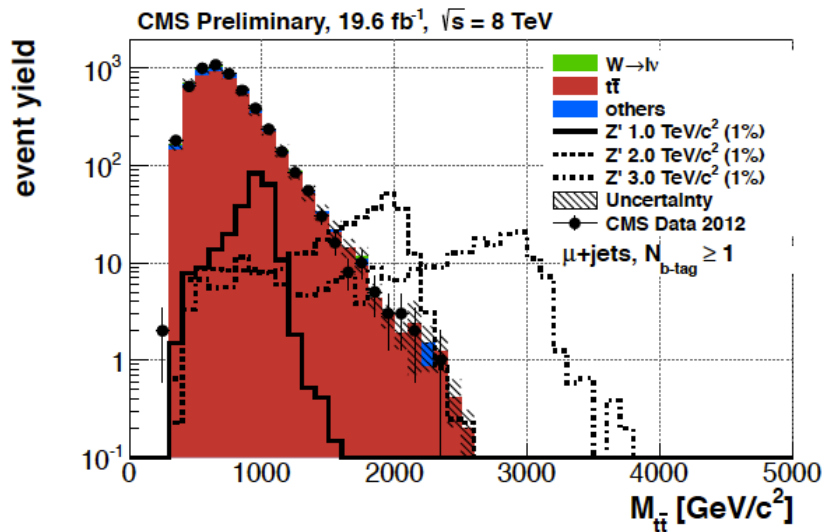
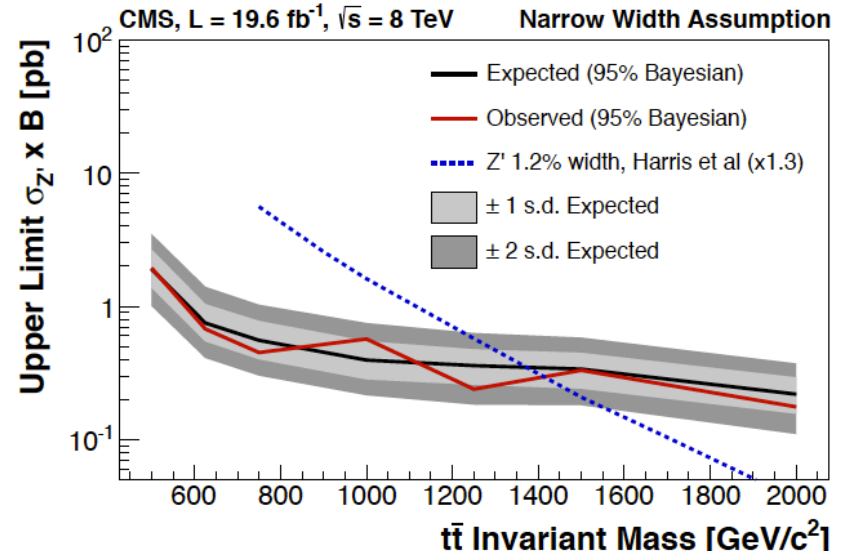
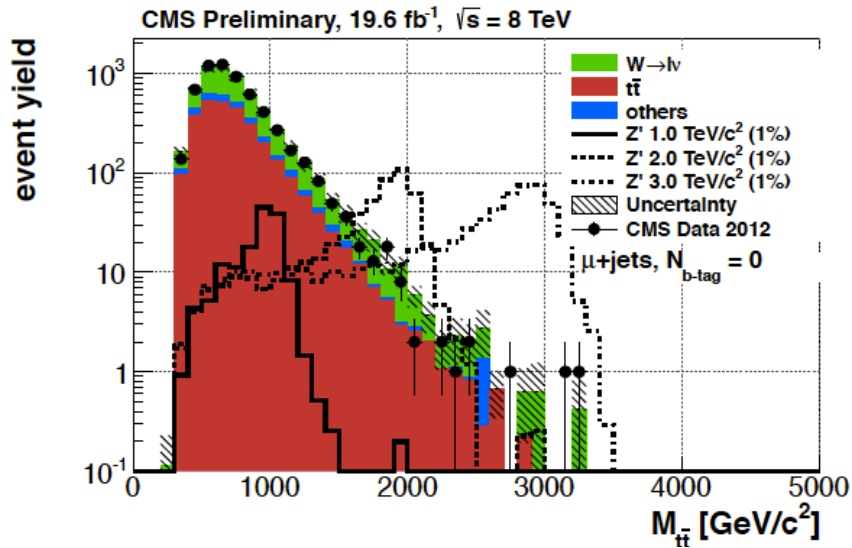
# Resonances decaying into top+jets ?

$$\begin{aligned}
 m(lv) = m(q\bar{q}) &= M_W \\
 m(lvb) = m(q\bar{q}b) &= M_t \\
 m(lvbg) = m(q\bar{q}bg) &= M_{t+g},
 \end{aligned}$$

Existed top quark which receives a non-zero mass before applying the Brout-Englert-Higgs mechanism

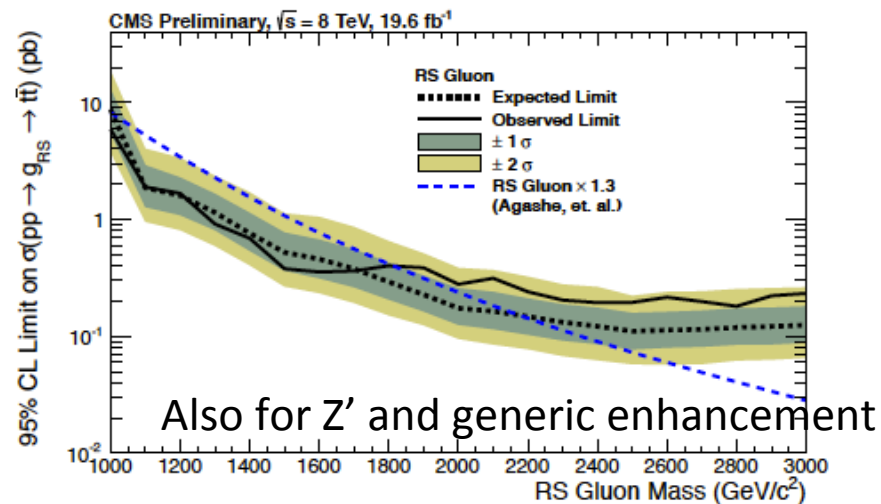
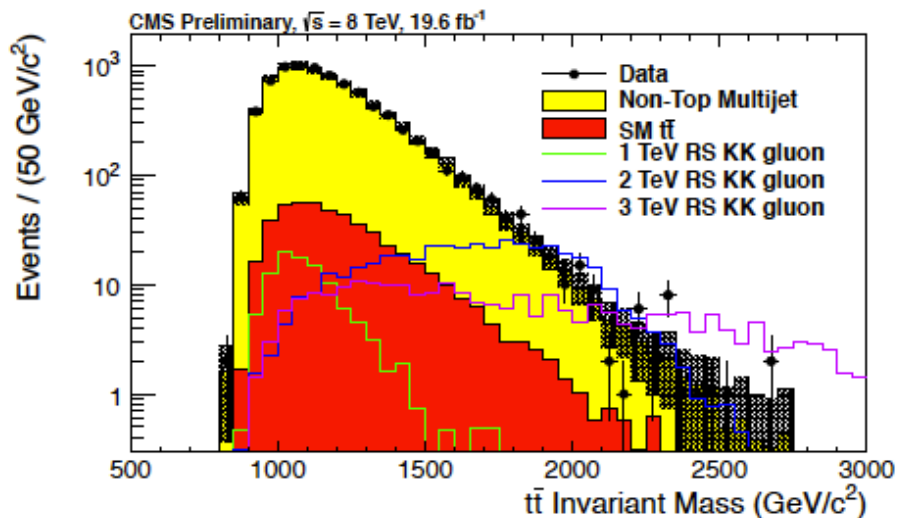
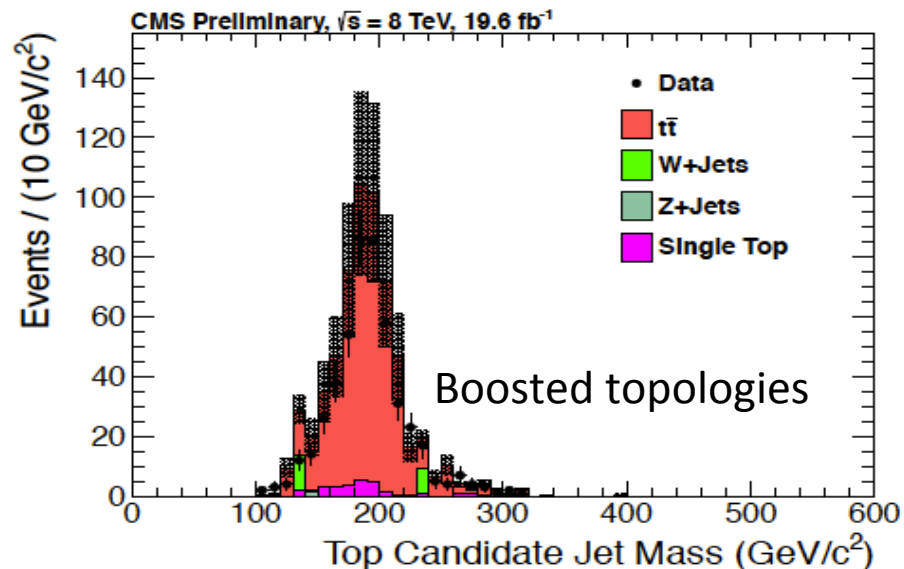
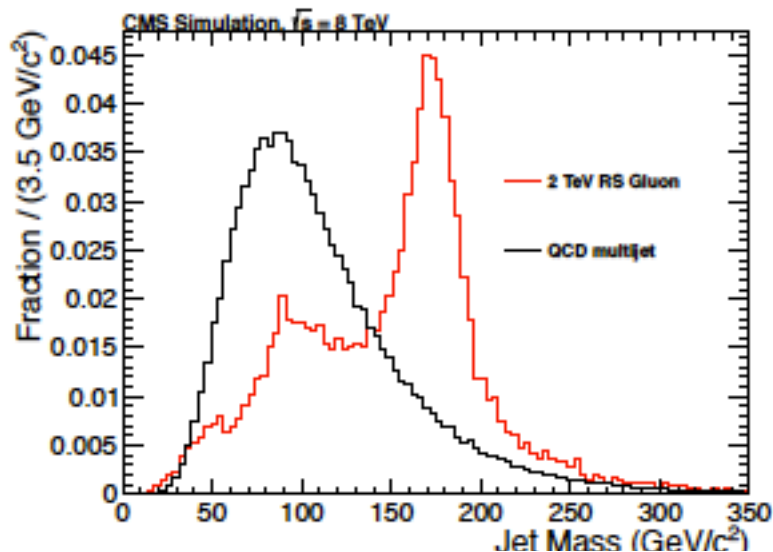


# Ttbar resonances ?



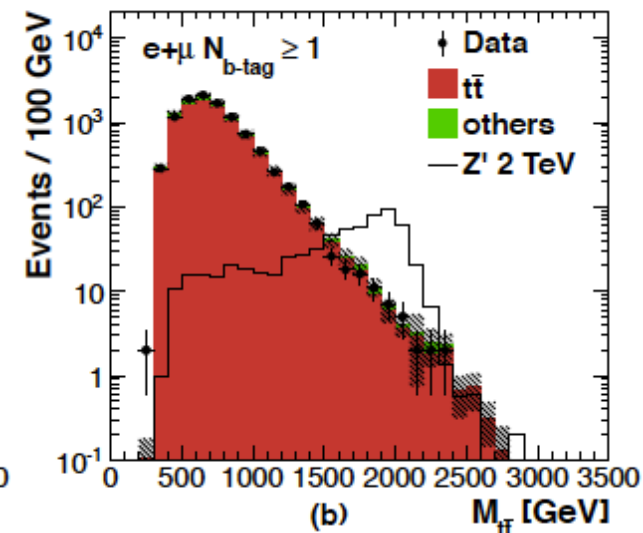


# Anomalous top quark production ?

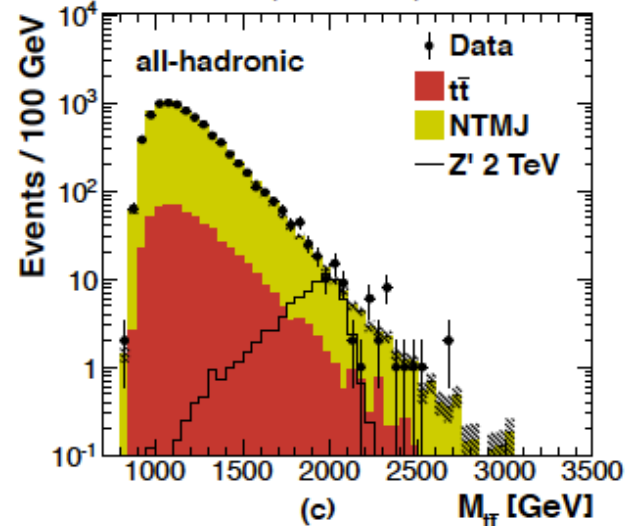


# Anomalous top quark production ?

CMS,  $19.7 \text{ fb}^{-1}$ ,  $\sqrt{s} = 8 \text{ TeV}$



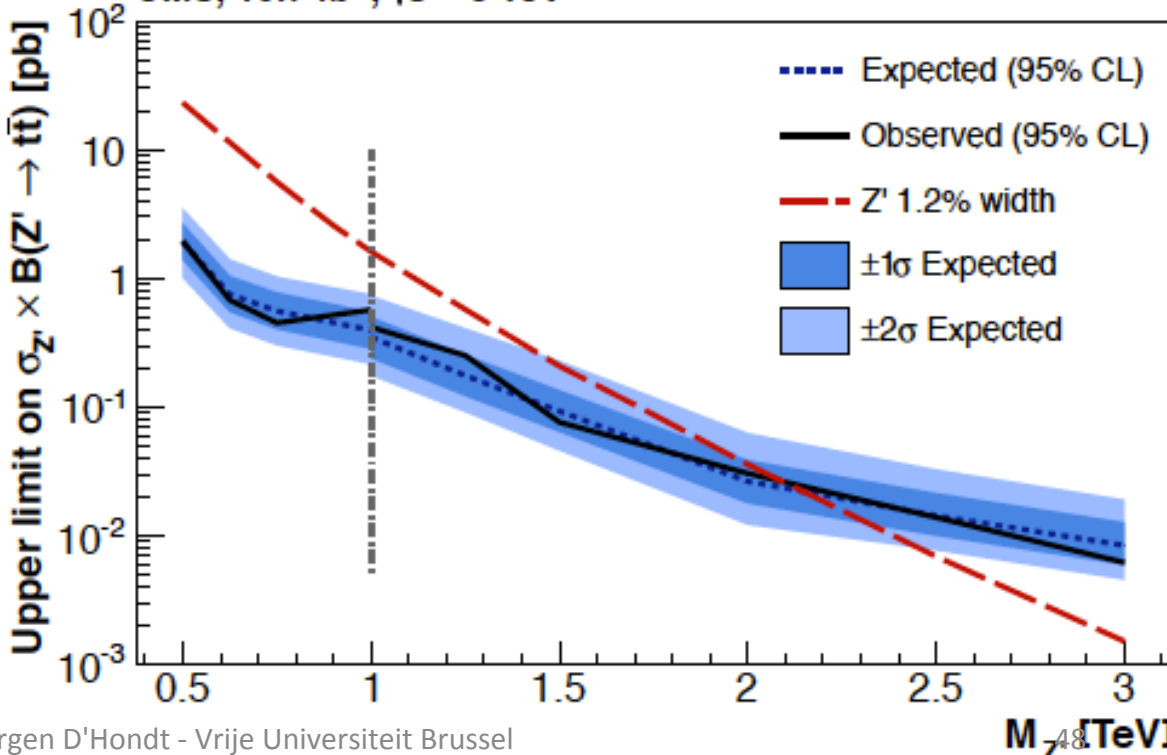
CMS,  $19.7 \text{ fb}^{-1}$ ,  $\sqrt{s} = 8 \text{ TeV}$



Combined boosted and resolved topology

Model	Observed Limit	Expected Limit
$Z', \Gamma_{Z'}/M_{Z'} = 1.2\%$	2.1 TeV	2.1 TeV
$Z', \Gamma_{Z'}/M_{Z'} = 10\%$	2.7 TeV	2.6 TeV
RS KK gluon	2.5 TeV	2.4 TeV

CMS,  $19.7 \text{ fb}^{-1}$ ,  $\sqrt{s} = 8 \text{ TeV}$

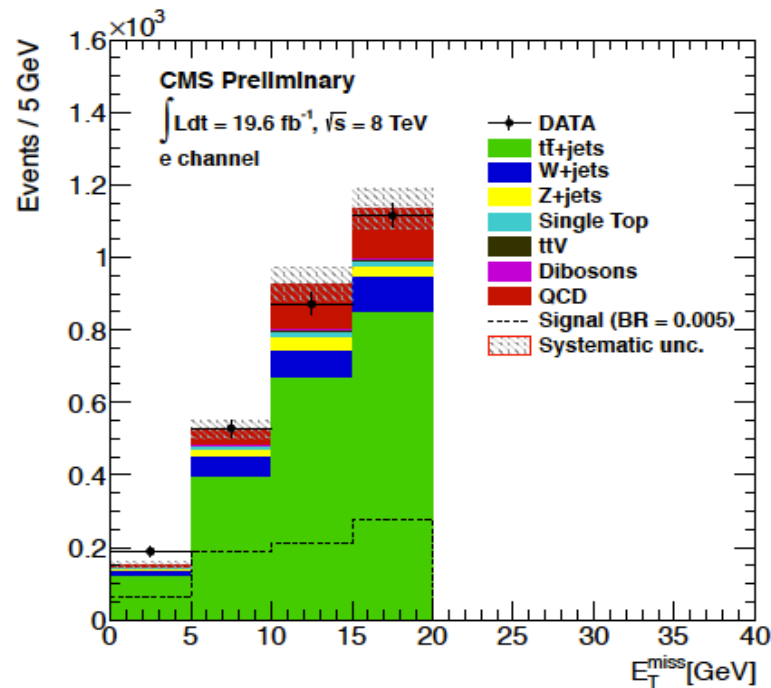
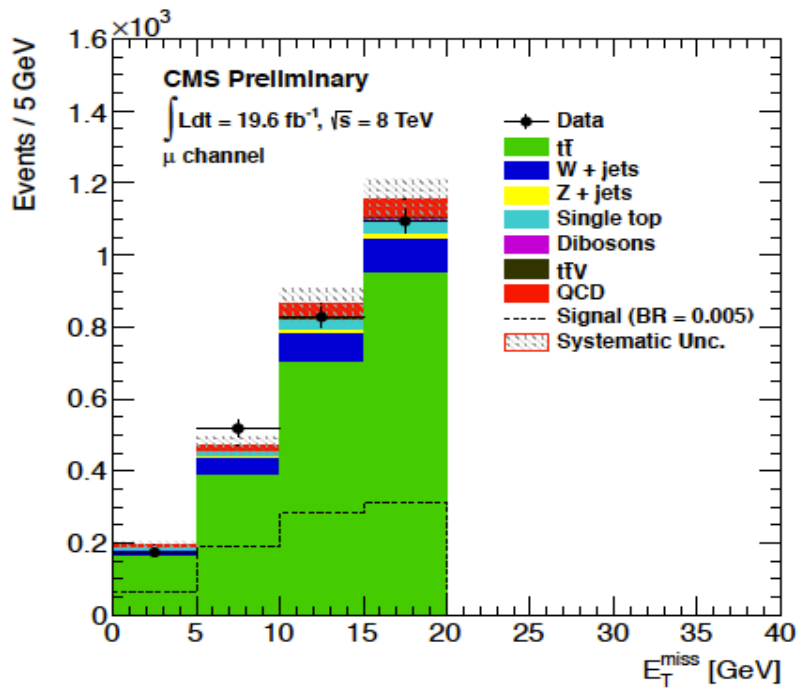




$$t \rightarrow \bar{b}c\mu^+ \quad (\bar{t} \rightarrow bc\mu^-)$$

$$t \rightarrow \bar{b}ue^+ \quad (\bar{t} \rightarrow bue^-)$$

# Baryon Number Violation in top decays ?



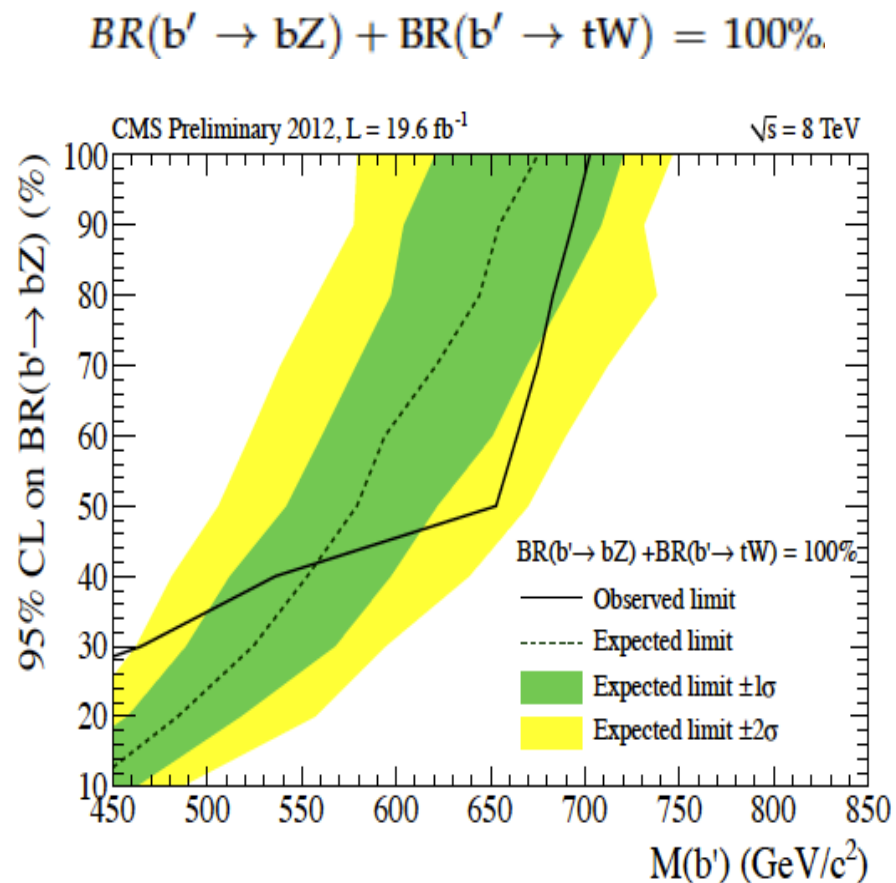
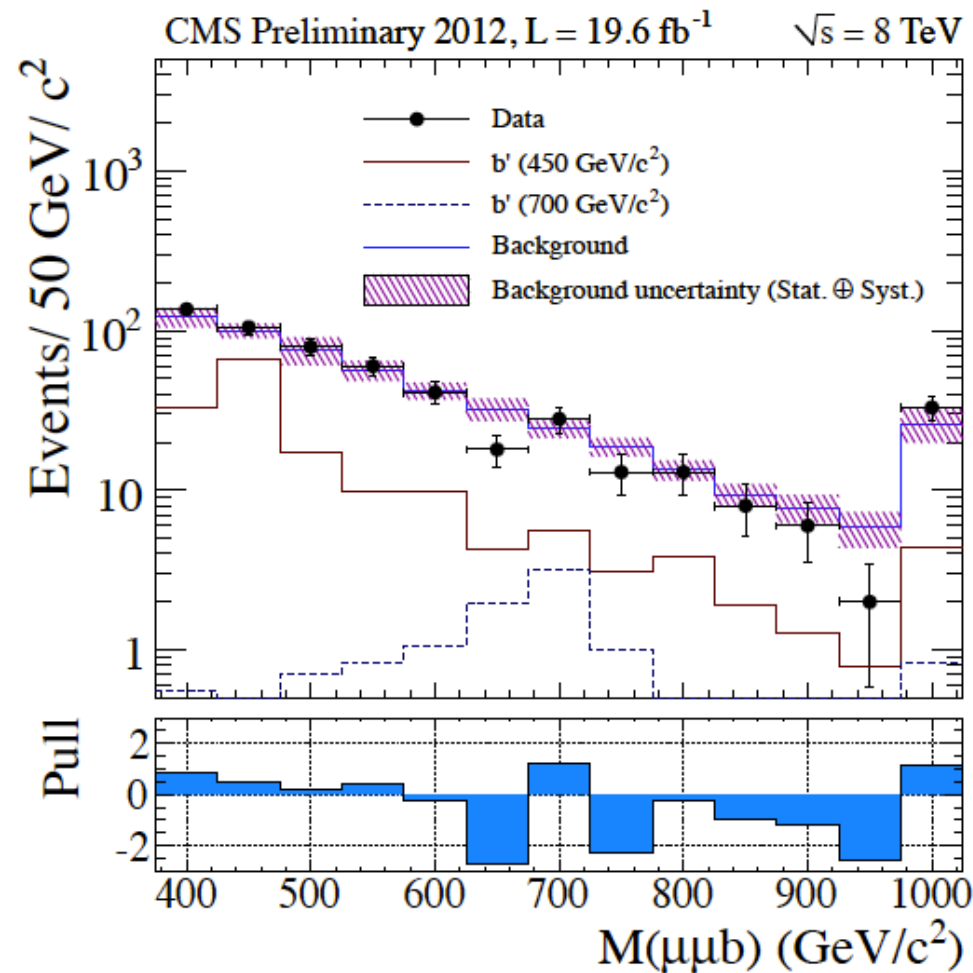
Data driven background

	95% CL Upp. lim.	Exp. lim.	68% exp. lim. range
Muon ch.	0.0016	0.0029	[0.0017, 0.0042]
Electron ch.	0.0017	0.0031	[0.0018, 0.0045]
Combined	0.0015	0.0029	[0.0016, 0.0042]

# Vector-like $b'$ quarks ?

Charge  $-1/3$

Pair production, single production not yet included

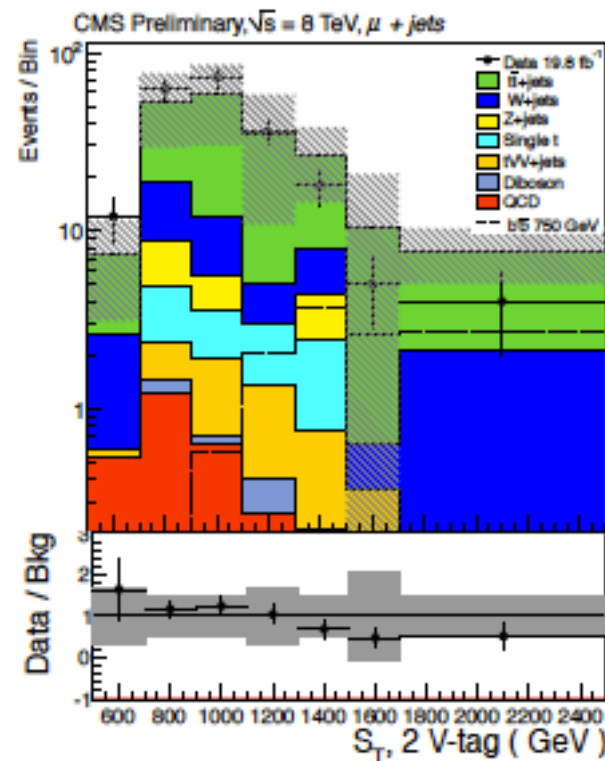
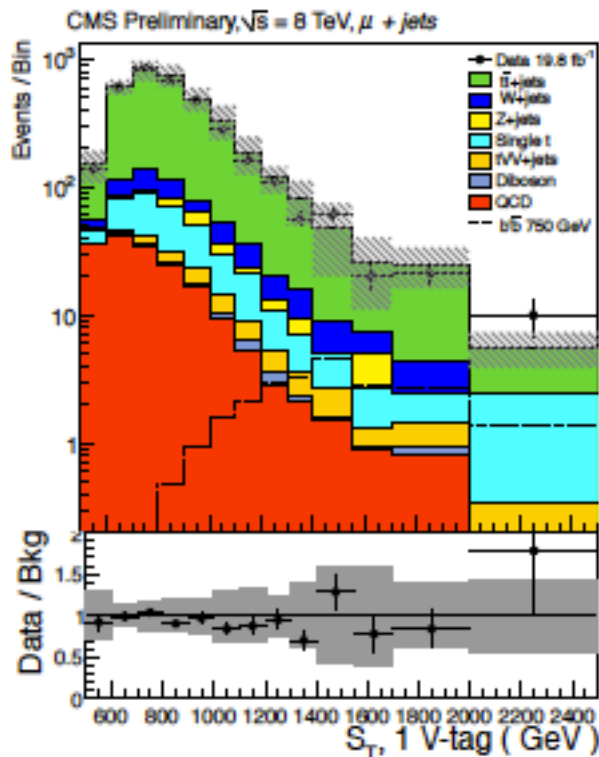
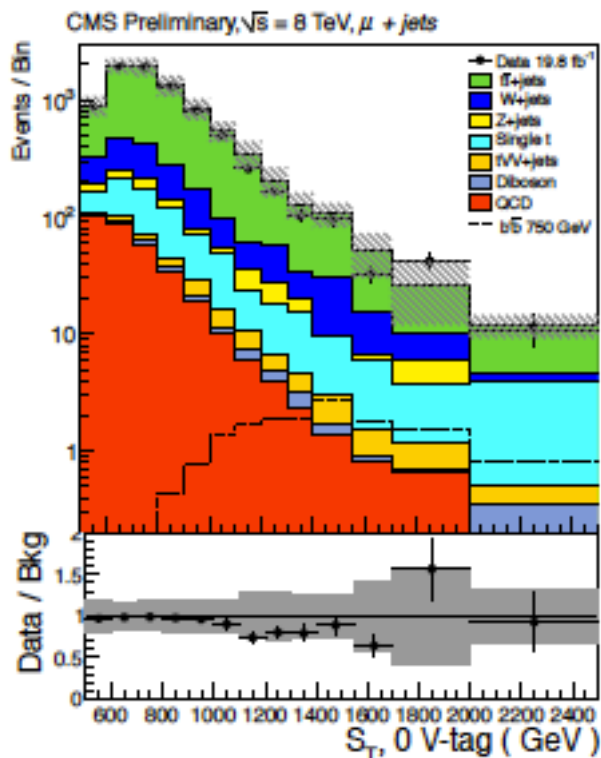


# Vector-like $b'$ quarks ?

Charge -1/3

Pair production, single production not yet included

## $b'$ decays to $tW$ , $bH$ , and $bZ$

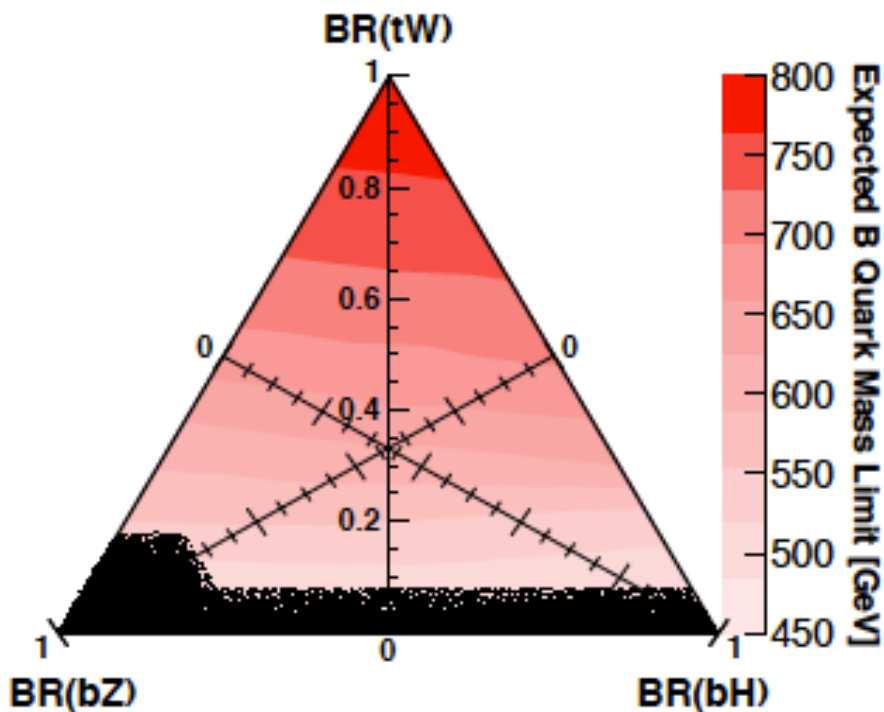


# Vector-like b' quarks ?

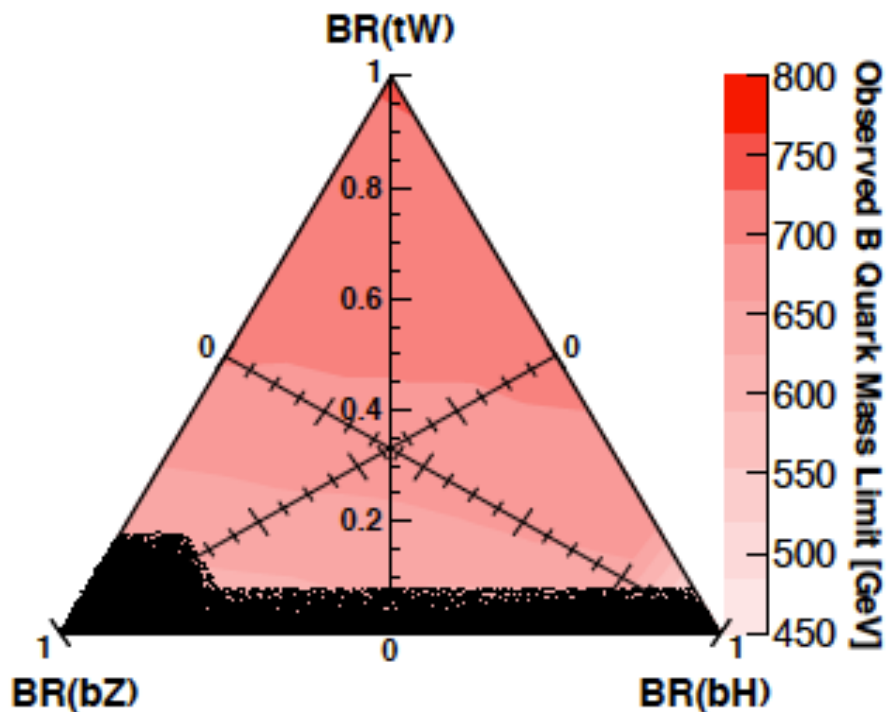
Charge -1/3

Pair production, single production not yet included

CMS Preliminary 19.8 fb<sup>-1</sup>,  $\sqrt{s} = 8$  TeV



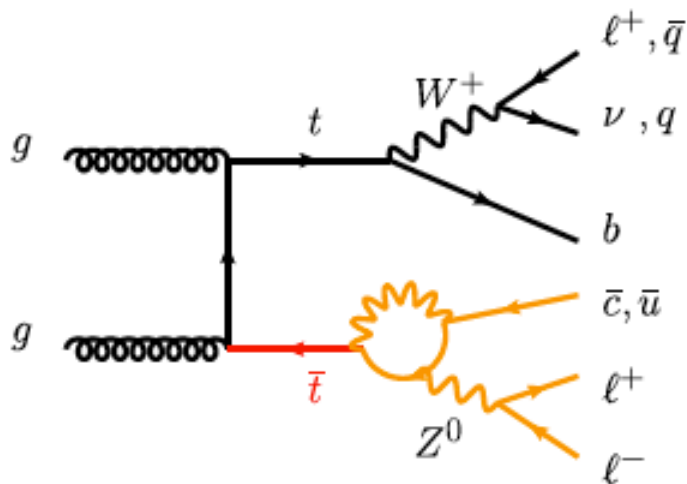
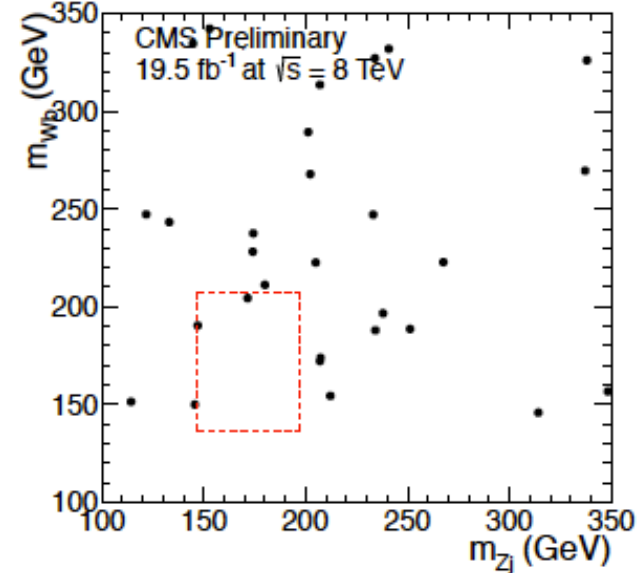
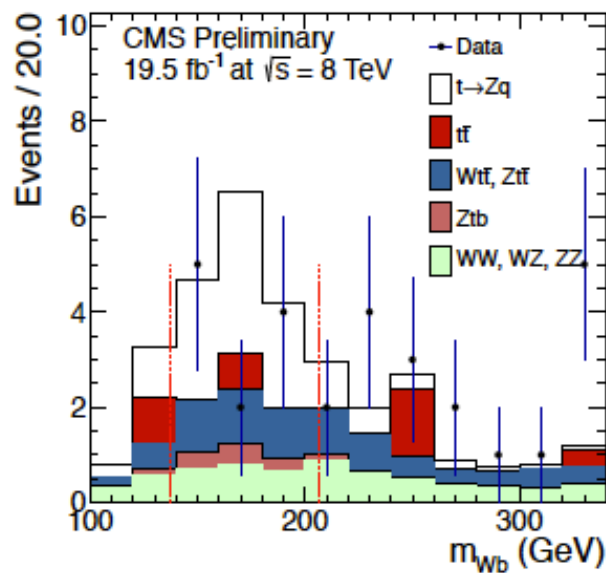
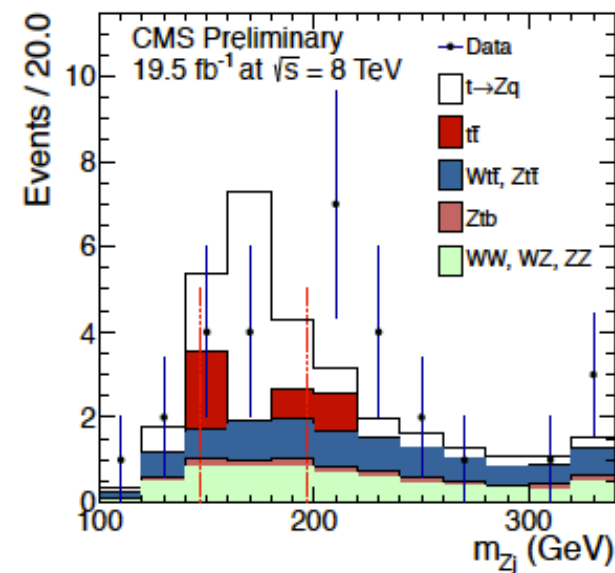
CMS Preliminary 19.8 fb<sup>-1</sup>,  $\sqrt{s} = 8$  TeV





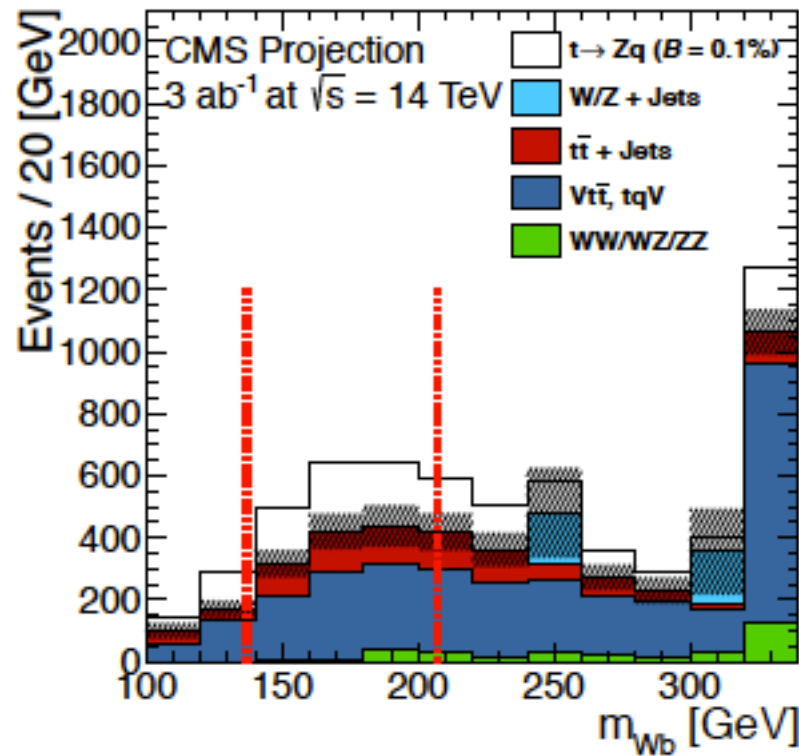
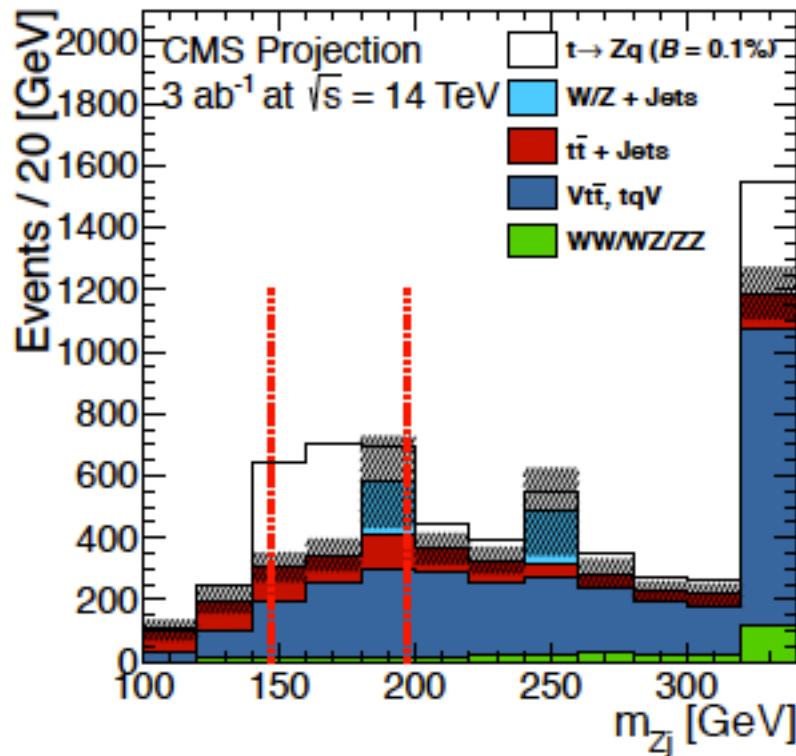
# Flavour Changing Neutral Currents ?

$$t\bar{t} \rightarrow Wb + Zq$$



**BR( $t \rightarrow Zq$ ) > 0.07% excluded @ 95% CL  
(main uncertainty due to event  $Q^2$  modeling)**

# Flavour Changing Neutral Currents @ 3000/fb ?



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

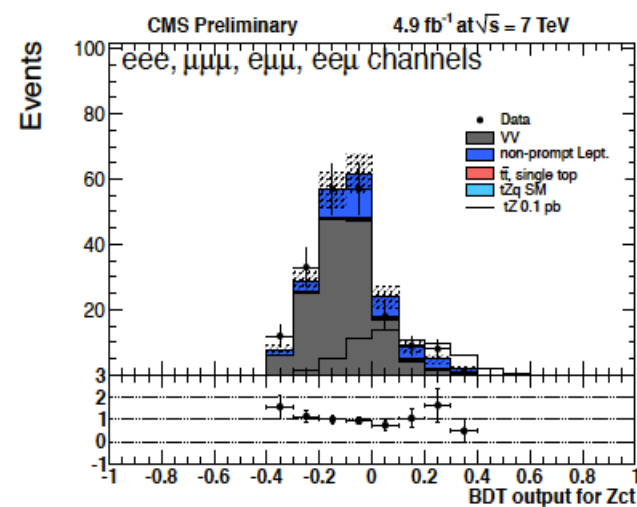
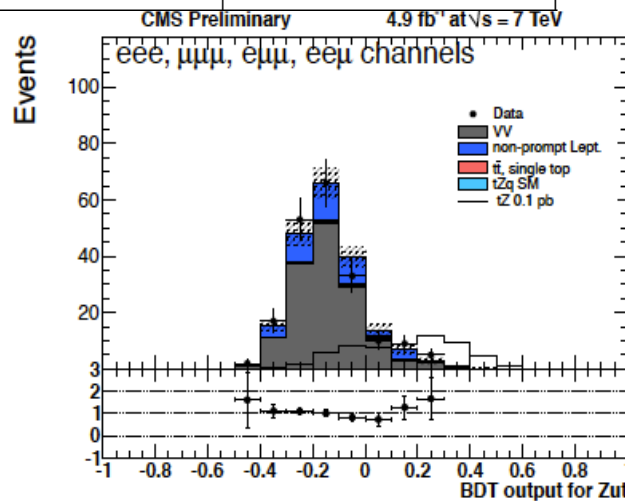
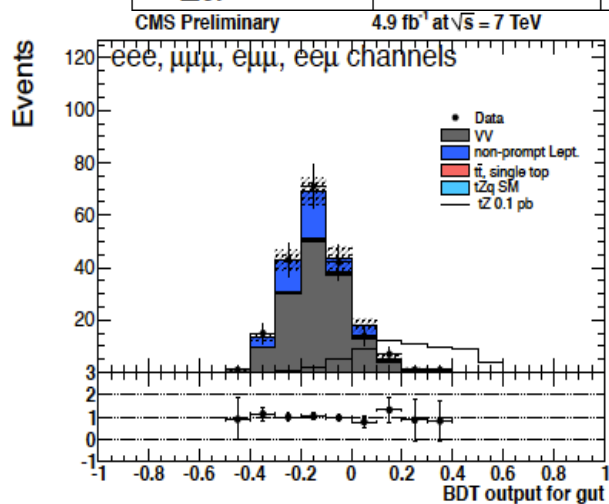
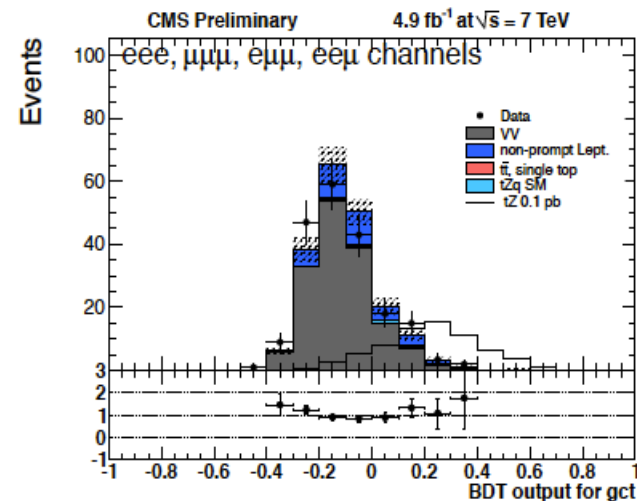
5 $\sigma$  observation from 0.02%



# Flavour Changing Neutral Currents in tZ events ?

$$\mathcal{L} = \sum_{q=u,c} \left[ \sqrt{2}g_s \frac{\kappa_{gqt}}{\Lambda} \bar{t} \sigma^{\mu\nu} T_a (f_q^L P_L + f_q^R P_R) q G_{\mu\nu}^a + \frac{g}{\sqrt{2}c_W} \frac{\kappa_{Zqt}}{\Lambda} \bar{t} \sigma^{\mu\nu} (f_q^L P_L + f_q^R P_R) q Z_{\mu\nu} \right] + \text{h.c.}$$

couplings	Expected	Observed	$\mathcal{B}(t \rightarrow gq/Zq)$
$\kappa_{gut}/\Lambda$	0.096	0.096	0.56 %
$\kappa_{gct}/\Lambda$	0.427	0.354	7.12 %
$\kappa_{Zut}/\Lambda$	0.492	0.451	0.51 %
$\kappa_{Zct}/\Lambda$	2.701	2.267	11.40 %



# Putting things together (i.e. conclusion)

- Top quark pair cross section (+ vector bosons & extra jets, systematics!)
- Differential cross sections (incl. unfolding)
- Single Top cross section (incl. tW channel & top versus anti-top, systematics!)
- Top charge (+2/3) and mass (precision < 1 GeV, systematics!)
- Top versus anti-top mass (precision ~ 200 MeV)
- W helicity in top decays (precision < 10%, systematics!)
- Top polarization (precision ~ 40%, systematics!)
- Spin correlations (observed, systematics!)
- Top to Wb and Wq decays (precision ~ 3-4%, systematics!)
- Charge asymmetry (precision < 1%)
- Kinematics of top quark events are well predicted
- Fourth generation top quarks > ~700 GeV
- Vector-like T quarks (decay into tZ, tH, bW) > ~ 700 GeV
- Top partners with charge 5/3 > ~ 800 GeV
- Resonances (spin-3/2 RS model) decaying into top+jets > ~ 750 GeV
- Ttbar resonances > ~ 1.5-2 TeV
- Baryon number violating top decays < 0.15%
- Flavour Changing Neutral Currents ( $t \rightarrow Zq$ ) < 0.07% (systematics!)



# Putting things together (i.e. conclusion)

- Top quark pair cross section (+ vector bosons & extra jets, **systematics!**)
- Differential cross sections (incl. unfolding)
- Single Top cross section (incl. tW channel & top versus anti-top, **systematics!**)
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- Baryon number violating top decays < 0.15%
- Flavour Changing Neutral Currents ( $t \rightarrow Zq$ ) < 0.07% (**systematics!**)