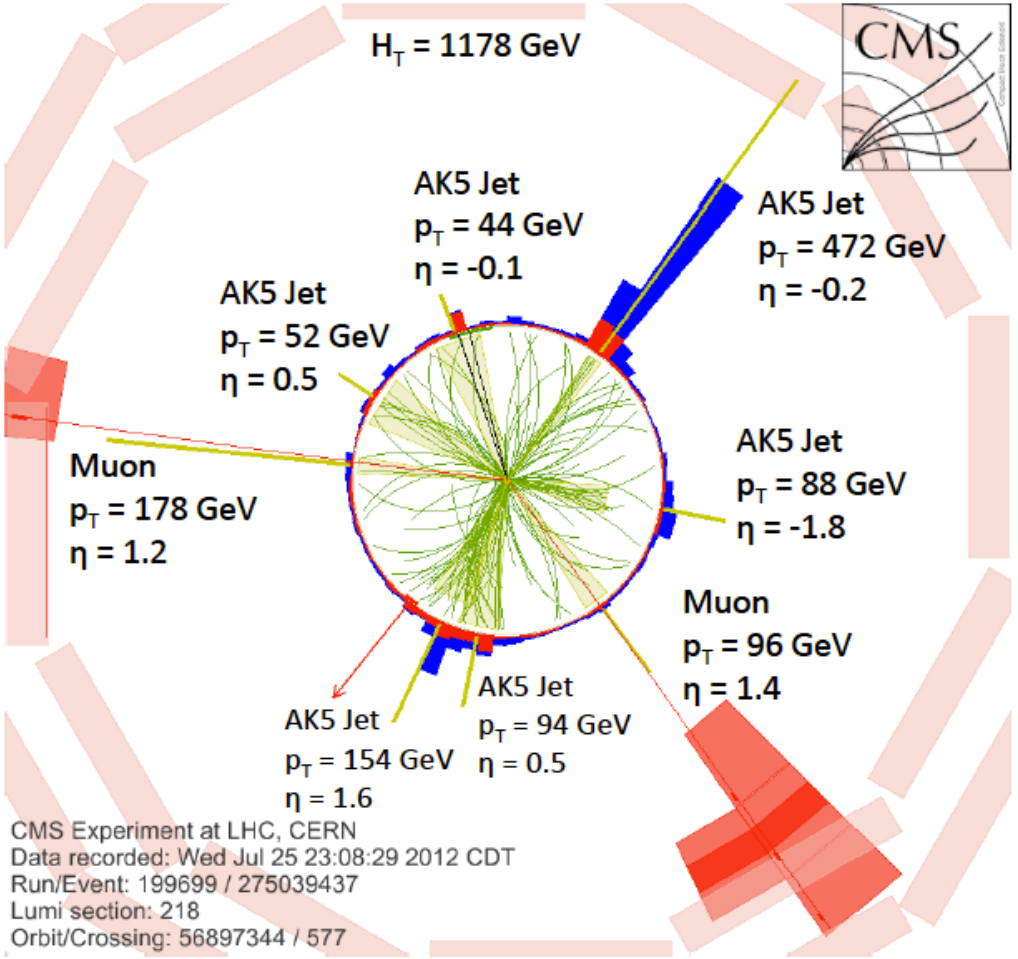
Top Quark Physics in CMS

Jorgen D'Hondt



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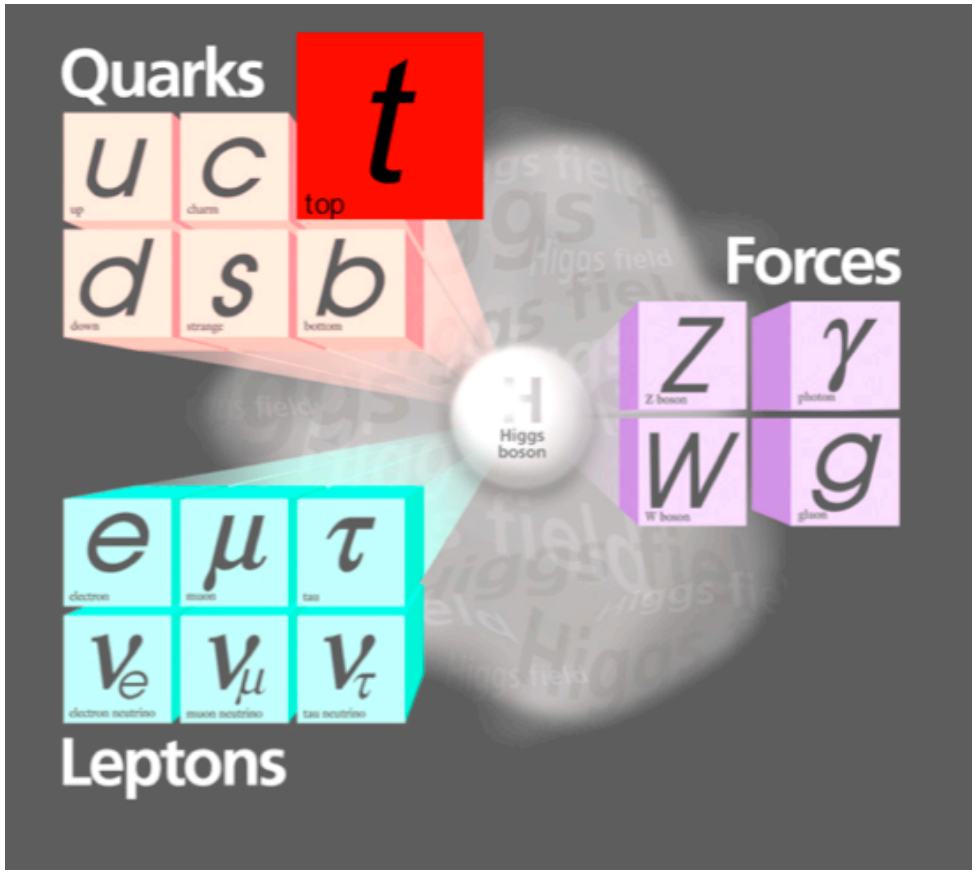
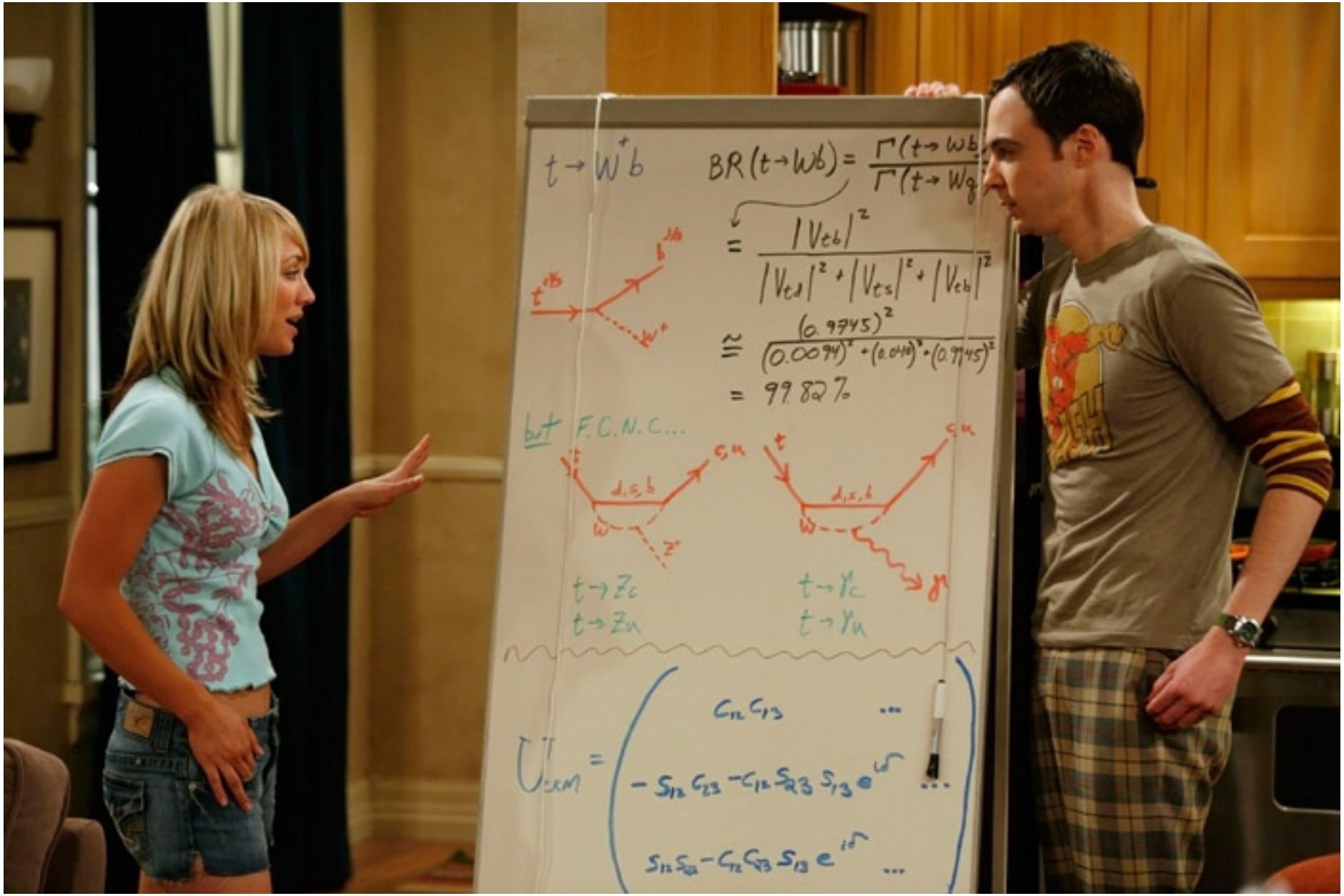
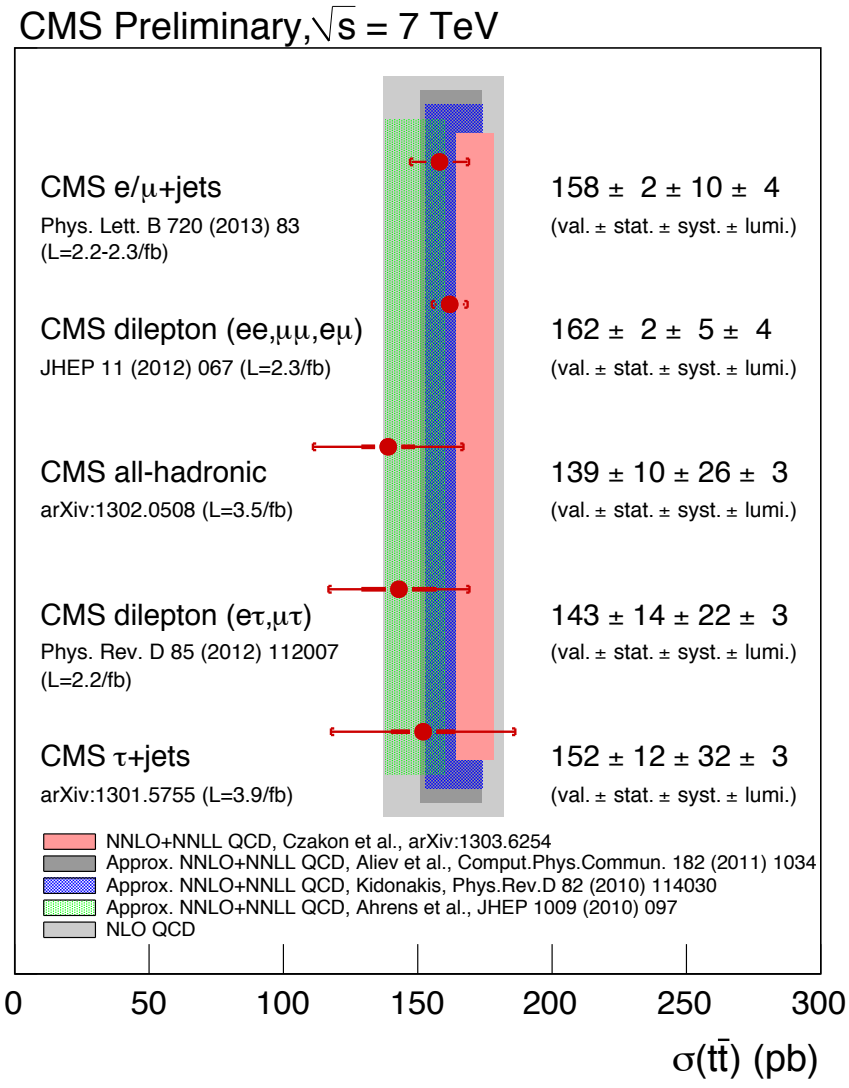
The Top Quark in the Standard Model

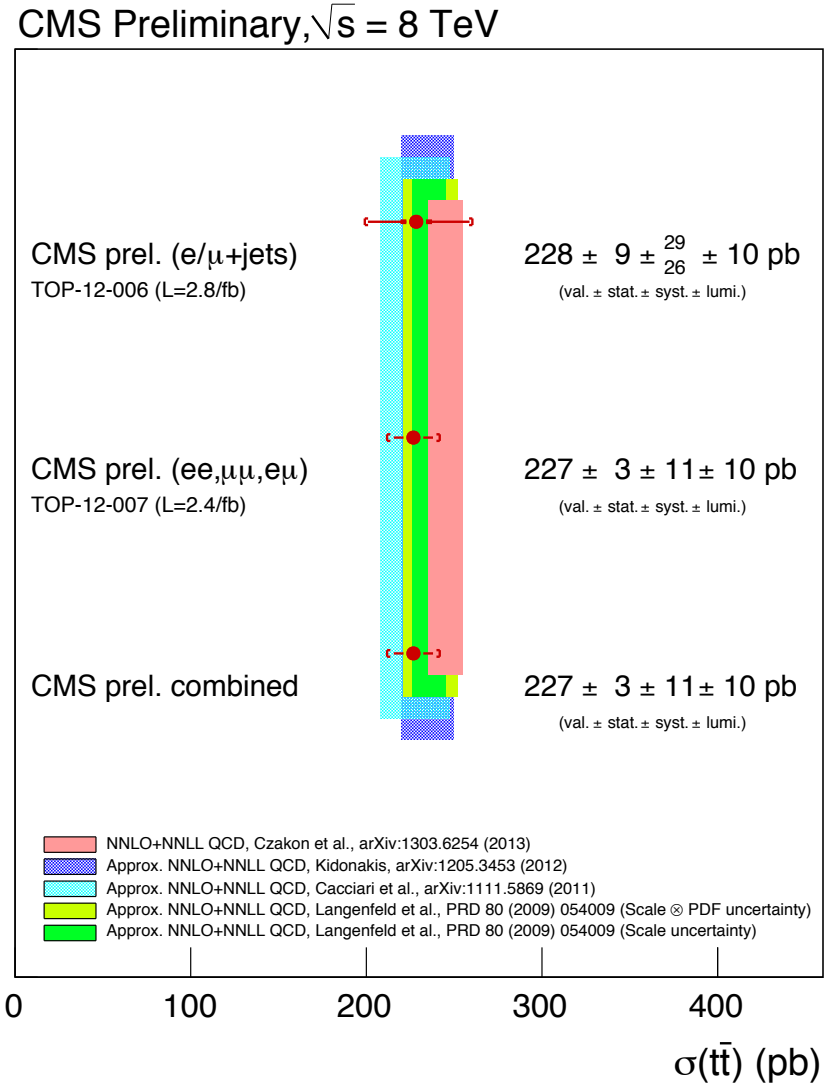


cfr. presentation of Roberto Tenchini

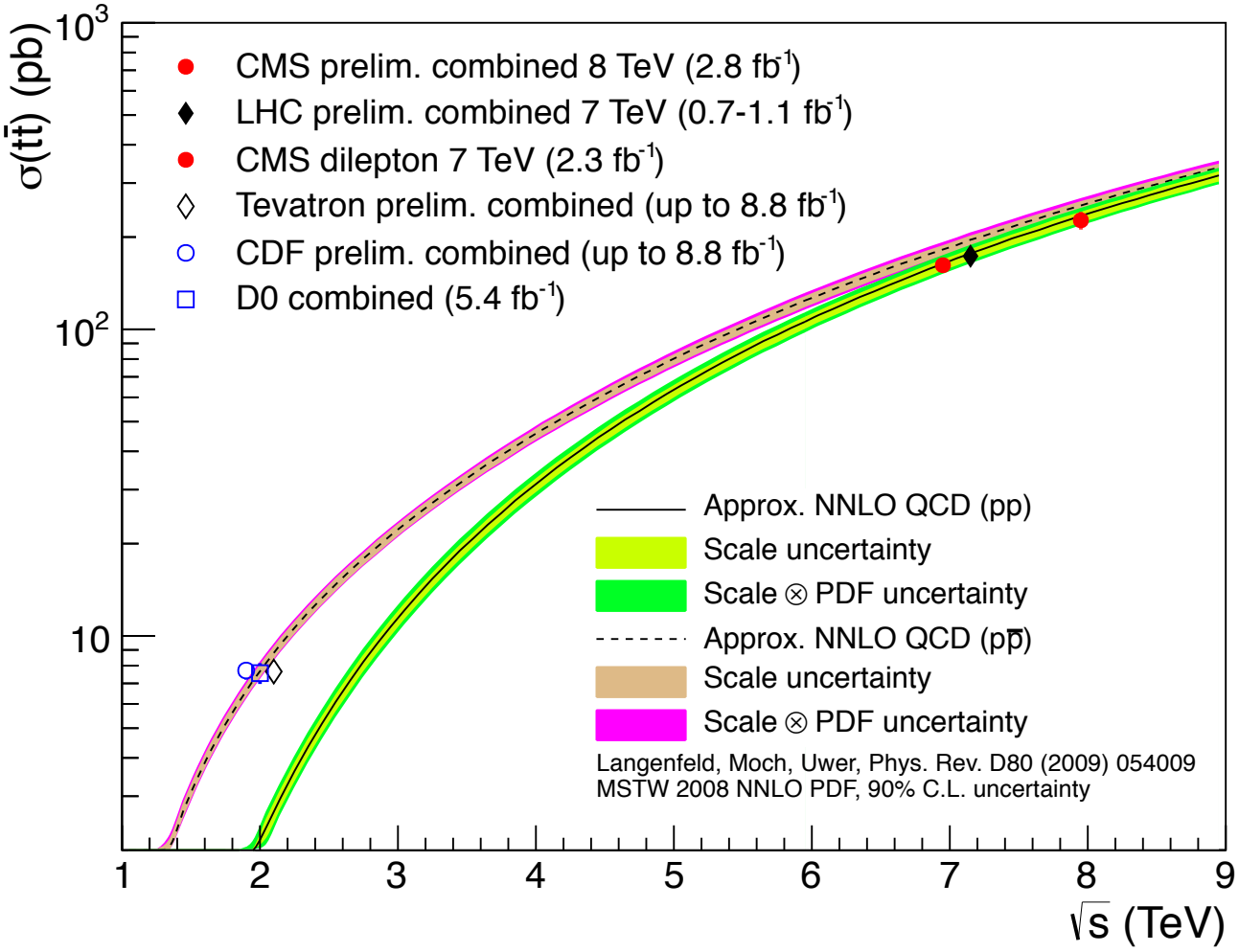

$t \to W^+ b$
$BR(t \to Wb) = \frac{\Gamma(t \to Wb)}{\Gamma(t \to Wq)}$
$= \frac{|V_{tb}|^2}{|V_{td}|^2 + |V_{ts}|^2 + |V_{tb}|^2}$
$\simeq \frac{(0.9745)^2}{(0.0094)^2 + (0.040)^2 + (0.9745)^2}$
$= 99.82\%$
but F.C.N.C...
$t \to Zc$
$t \to Zu$
$t \to \gamma c$
$t \to \gamma u$
$U_{CKM} = \begin{pmatrix} c_{12}c_{13} & \cdots \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & \cdots \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & \cdots \end{pmatrix}$

Top quark pair cross section

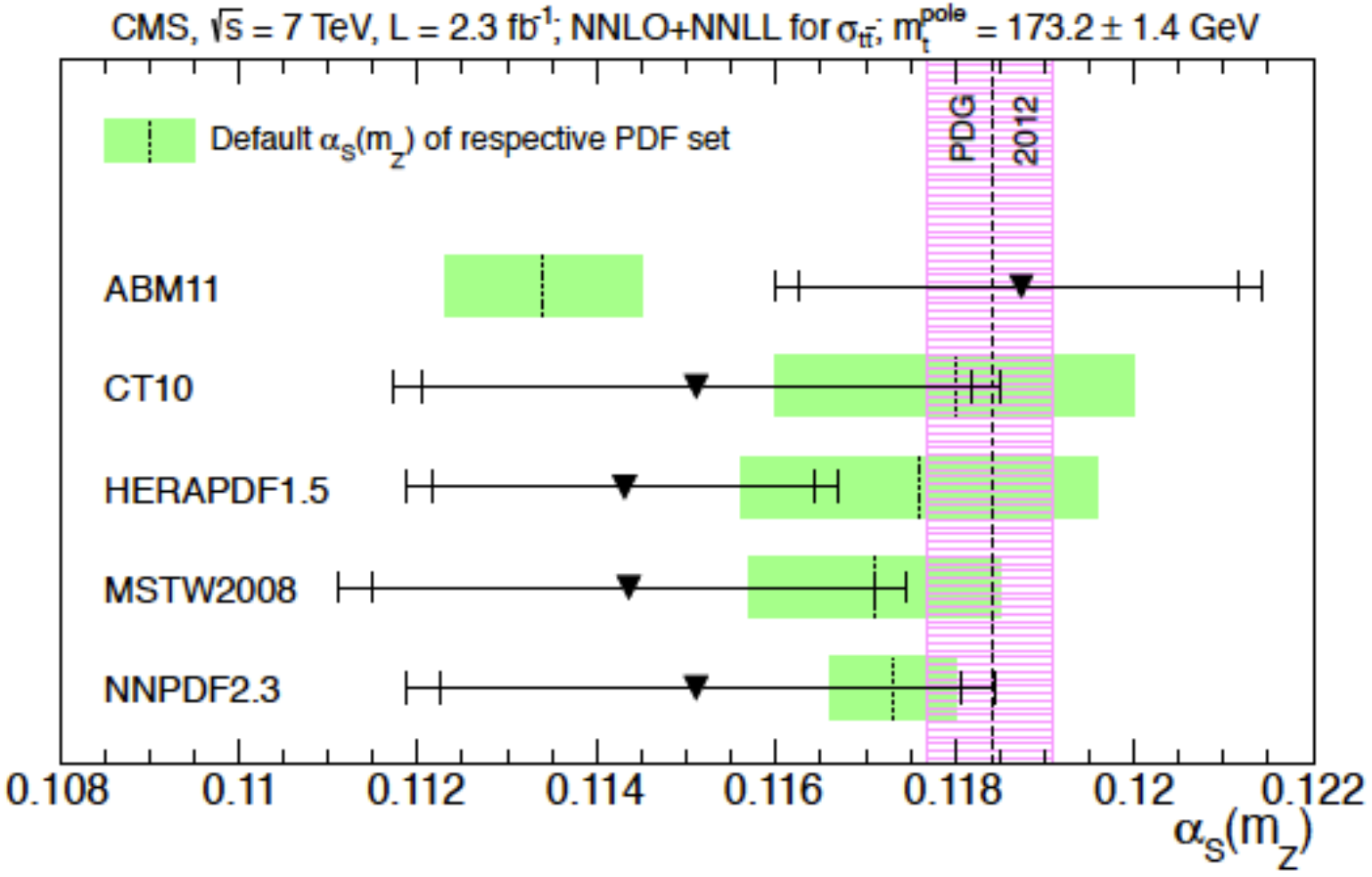




Top quark pair cross section



Top quark pair cross section



CMS PAS TOP-13-010

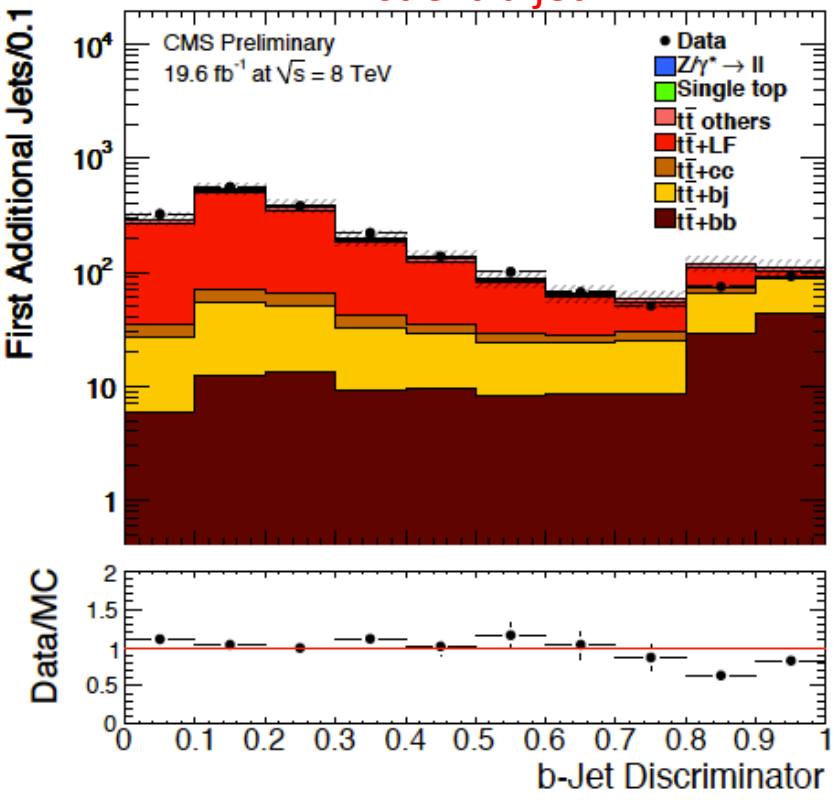
Di-lepton

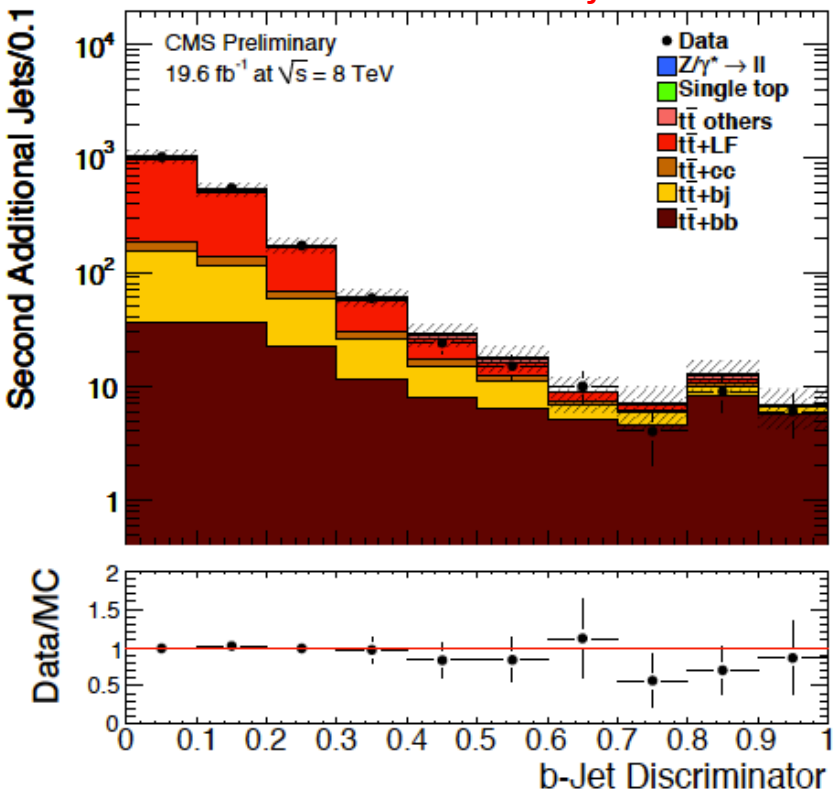
Top quark pair + jets cross section

First extra jet

pT > 20 GeV

Second extra jet



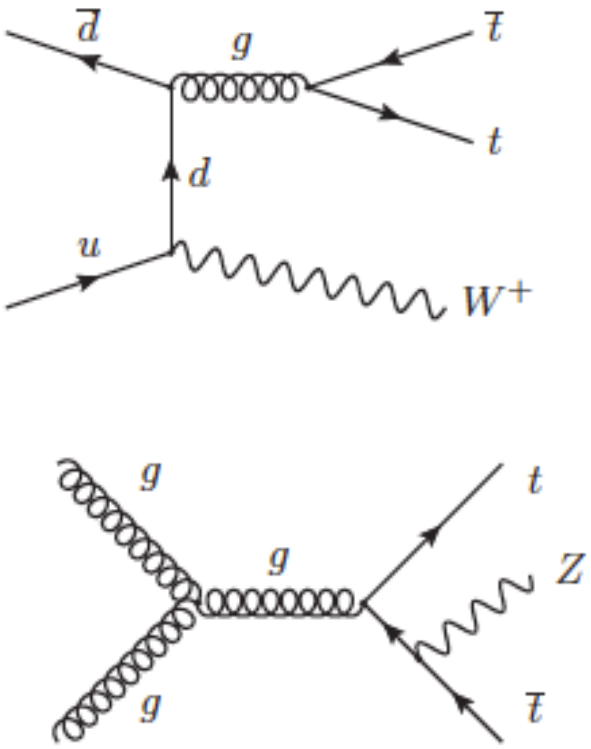


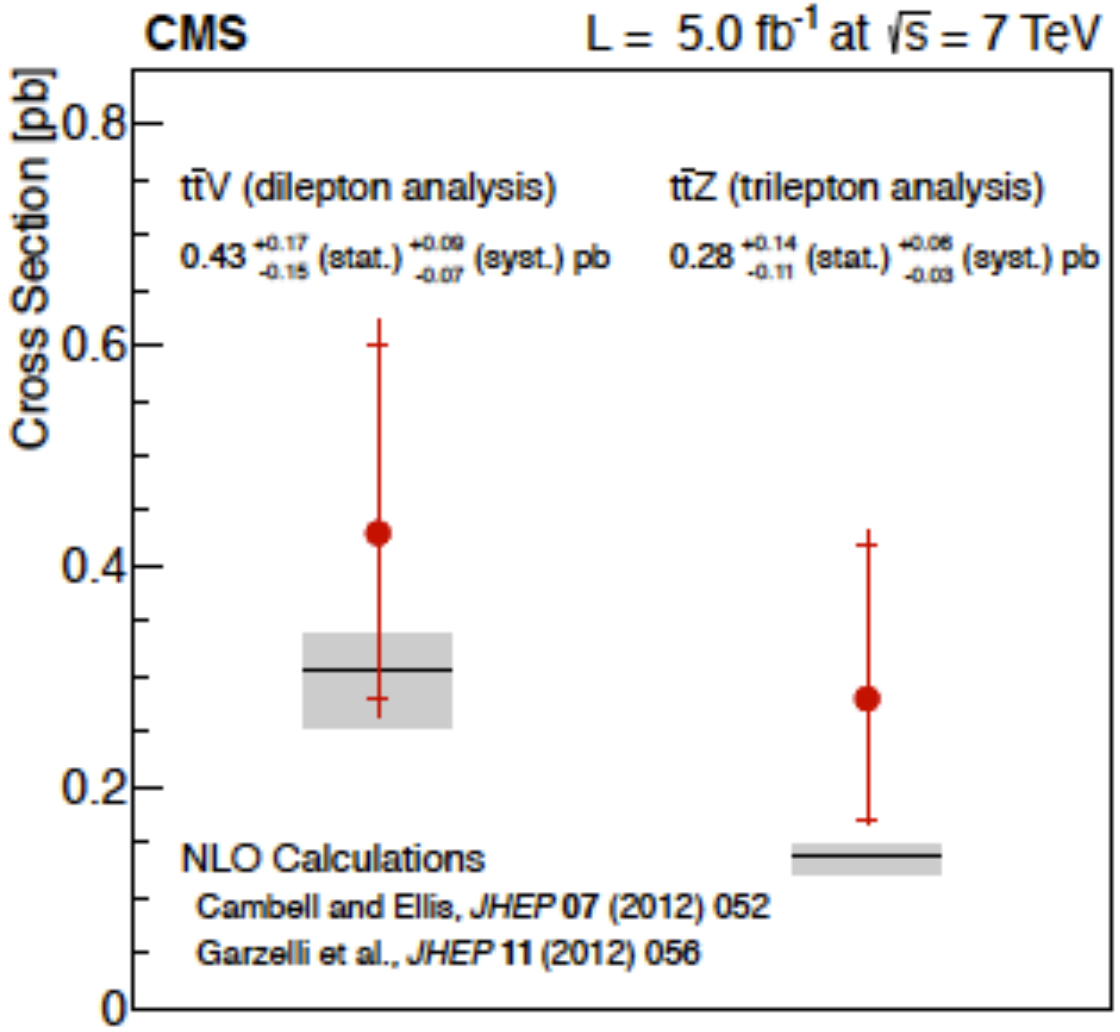
$$\sigma(t\bar{t}b\bar{b})/\sigma(t\bar{t}jj) = 0.023 \pm 0.003(\text{stat.}) \pm 0.005(\text{syst.}) \text{ at } p_T > 20\,\text{GeV}/c$$ 0.016±0.002 (MadGraph)

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

arXiv:1303.3239v2

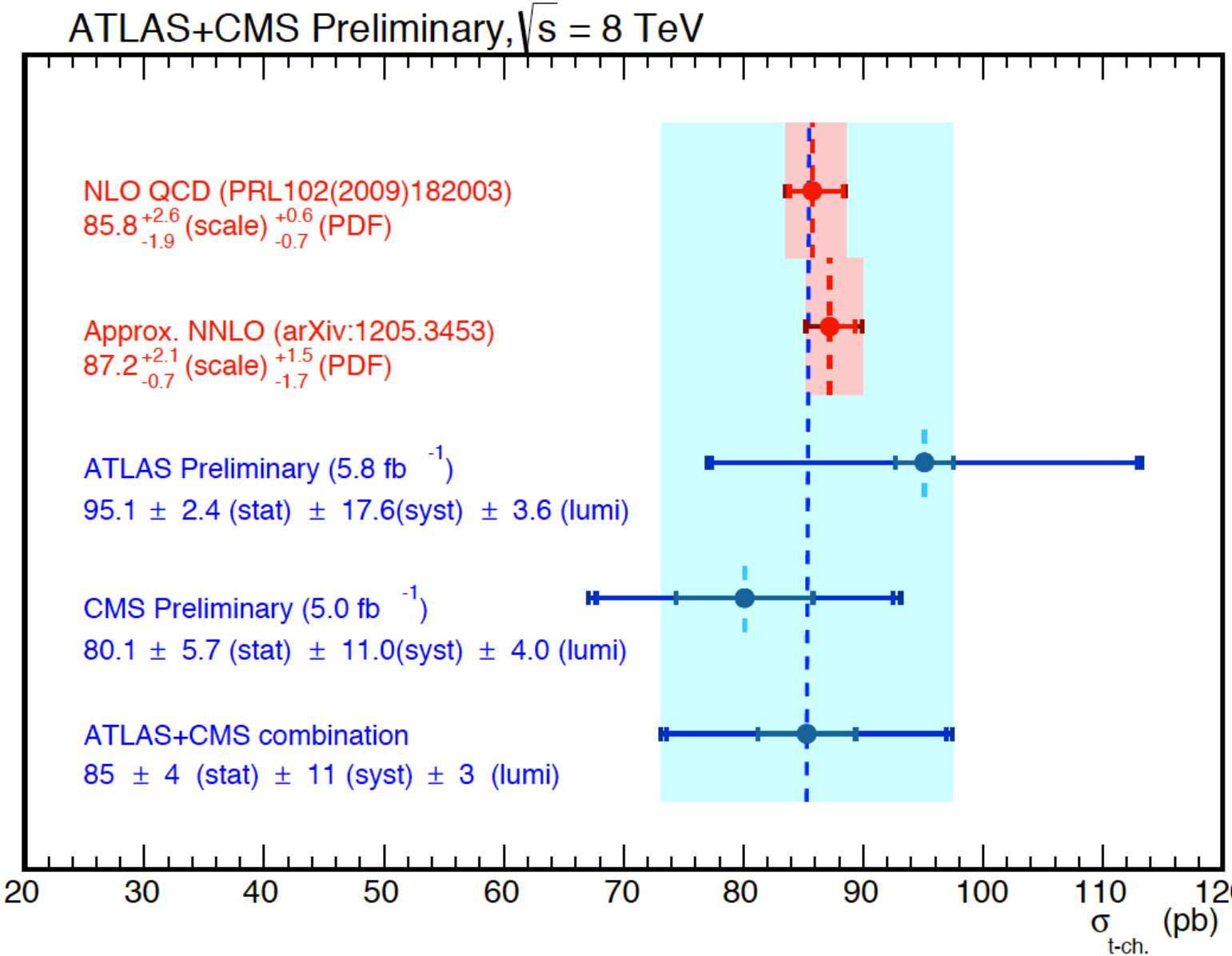
Top quark pair + Vector Bosons cross section



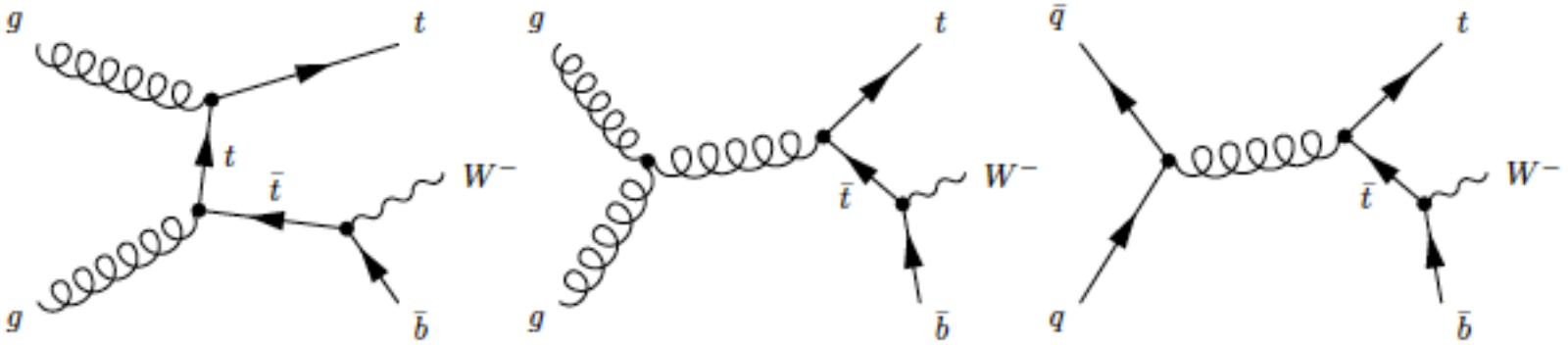


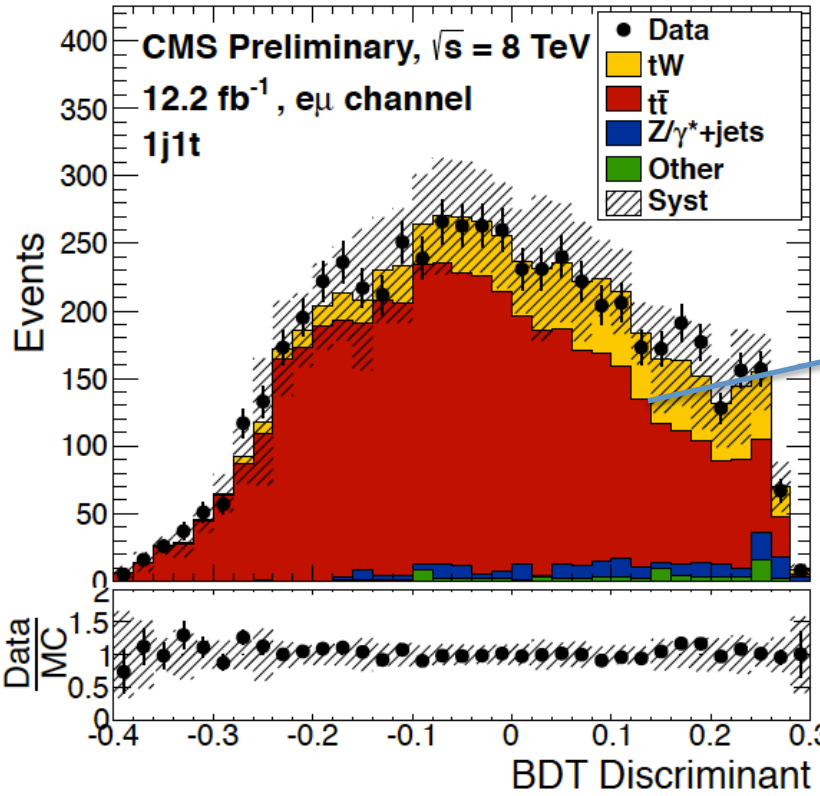
Presentation from A. Jafari on “Single-top”

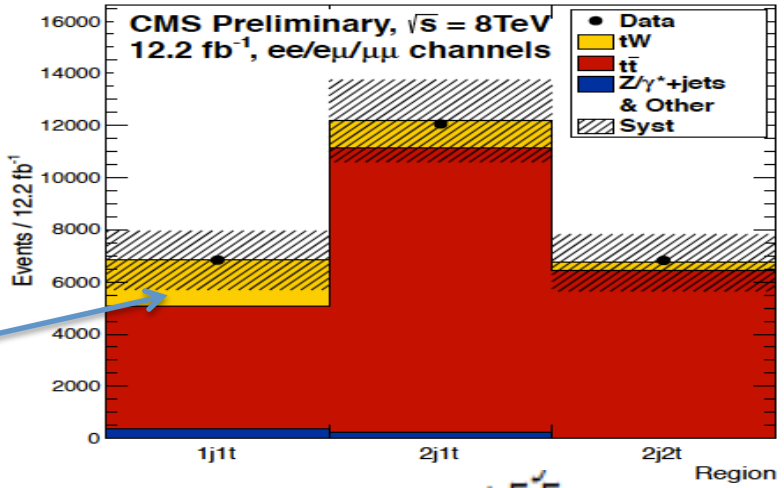
Single top quark cross section (t-channel)



Single top quark (tW) cross section







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

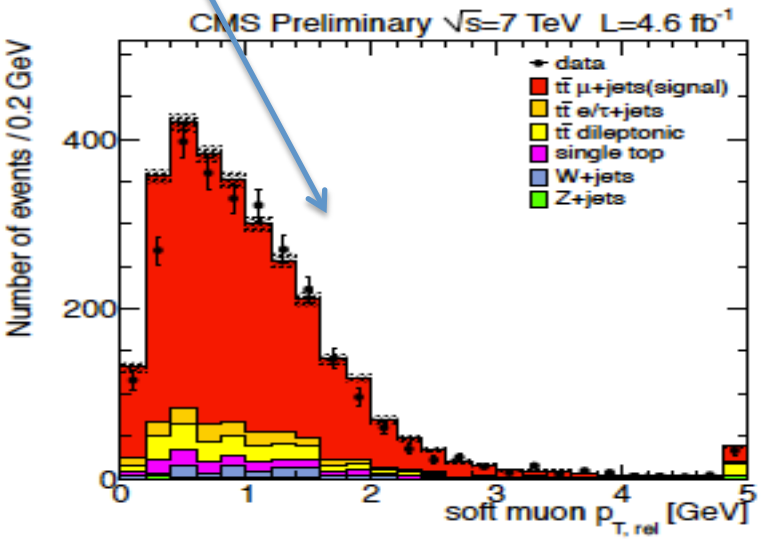
6σ significance

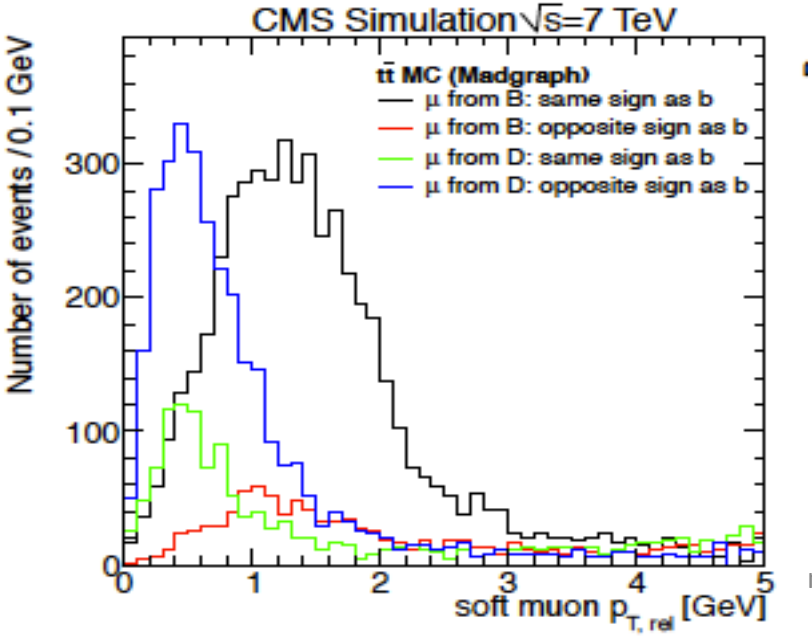
$$|V_{tb}| = \sqrt{\frac{\sigma_{tW}}{\sigma^{th}_{tW}}} = 1.03 \pm 0.12(exp.) \pm 0.04(th.)$$

SM(Q) = +2/3

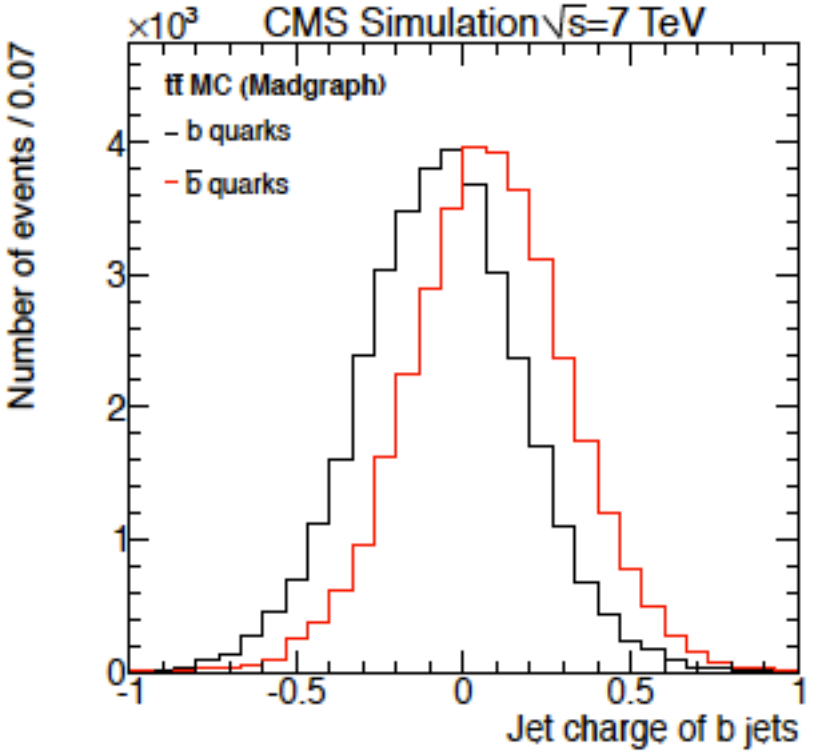
Top Quark charge

$$BR(b \to \mu + \nu + X) \sim 11\%$$





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



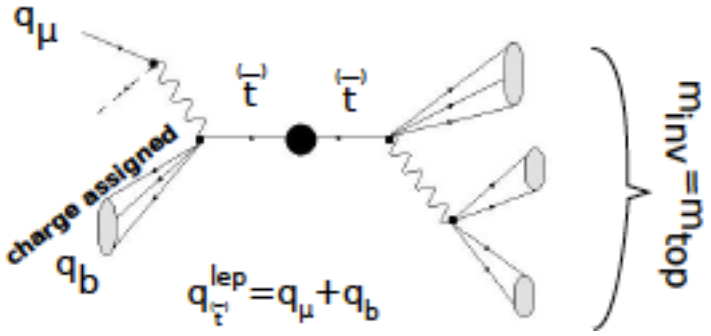
Combine both pieces of information

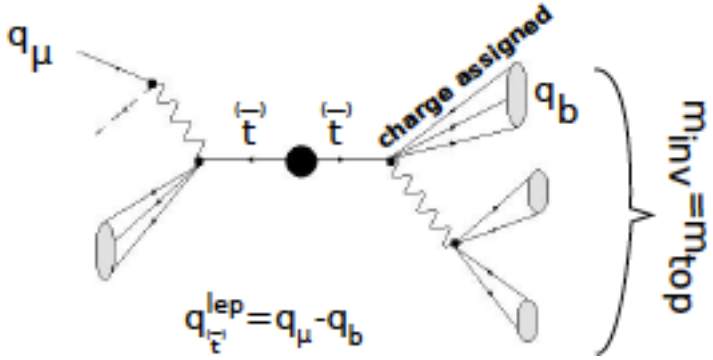
SM(Q) = +2/3

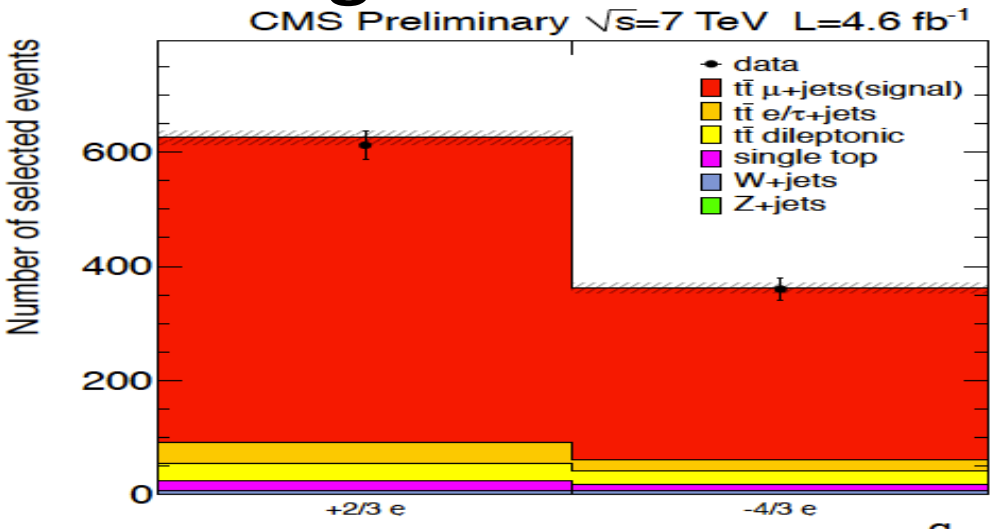
Top Quark charge

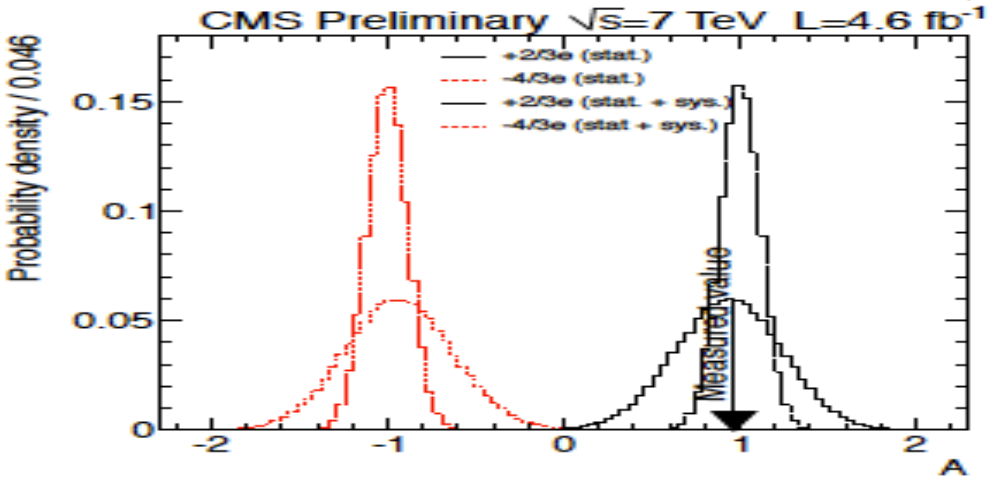
A is an "asymmetry" test statistics

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





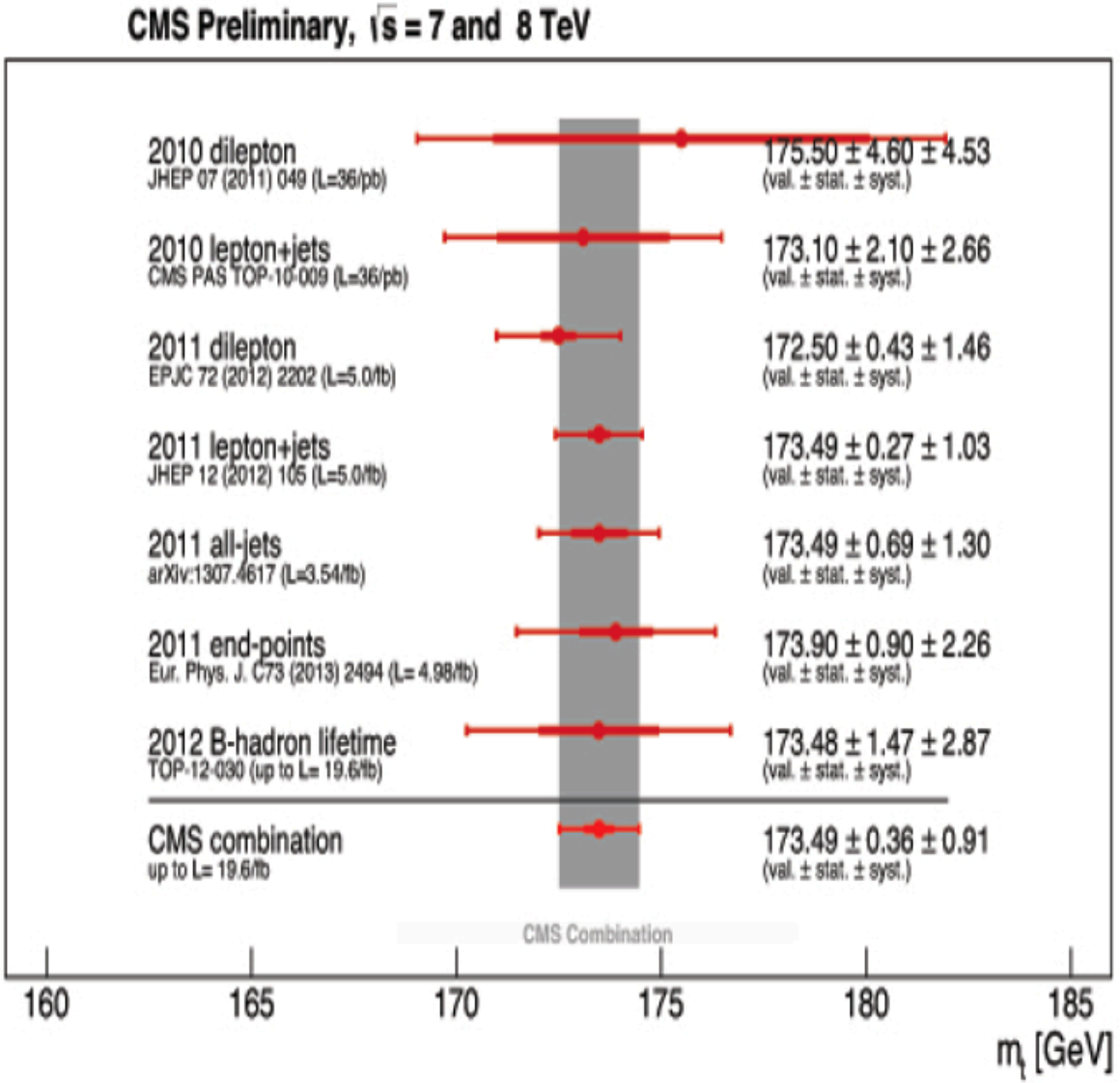




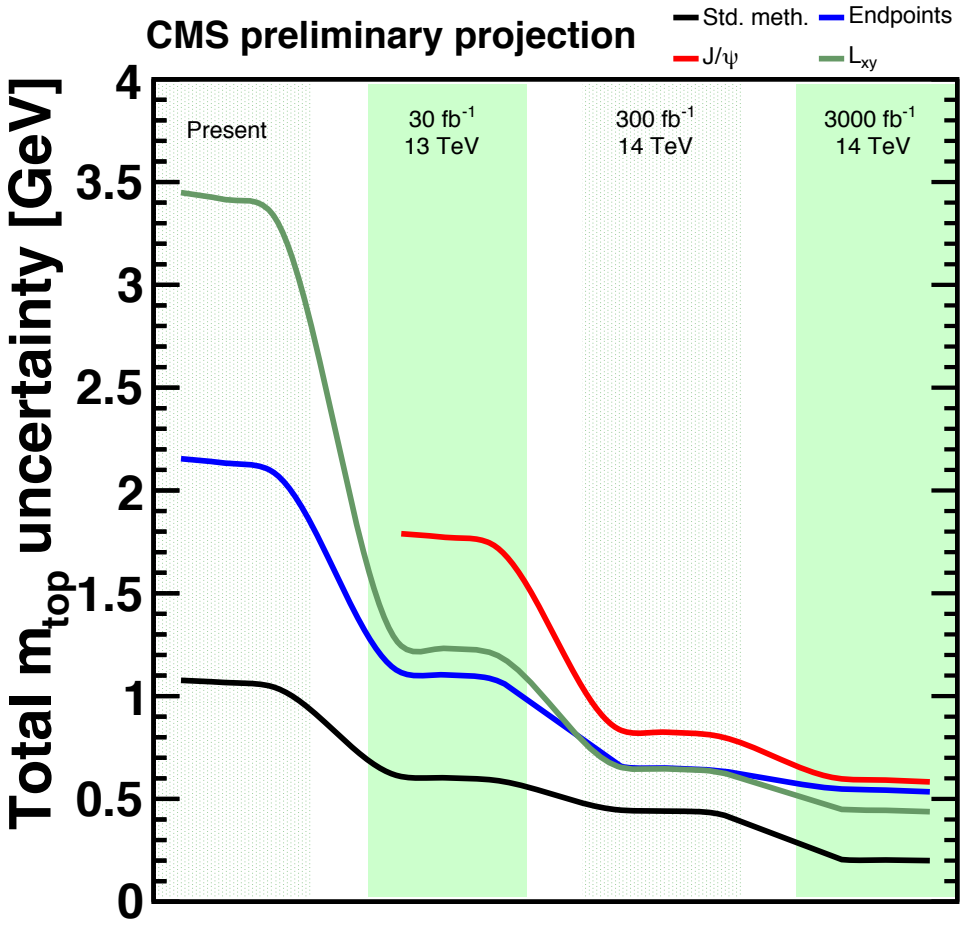
Charge -4/3 more then 5σ excluded

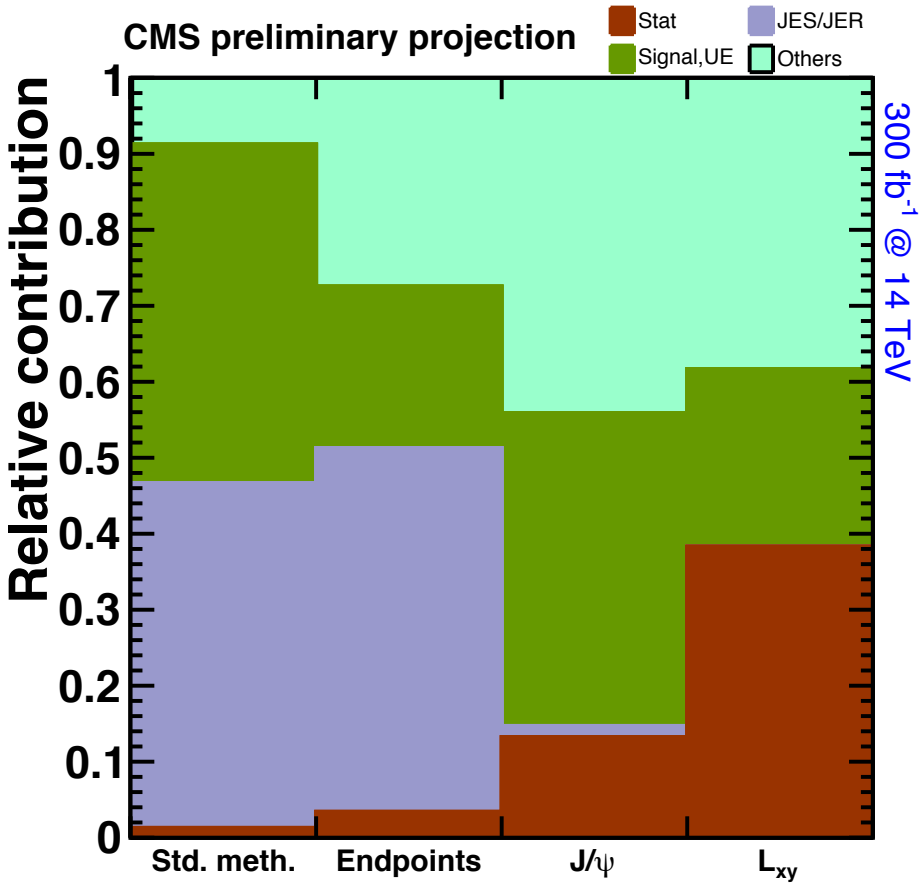
CMS PAS TOP-13-002

Top quark mass



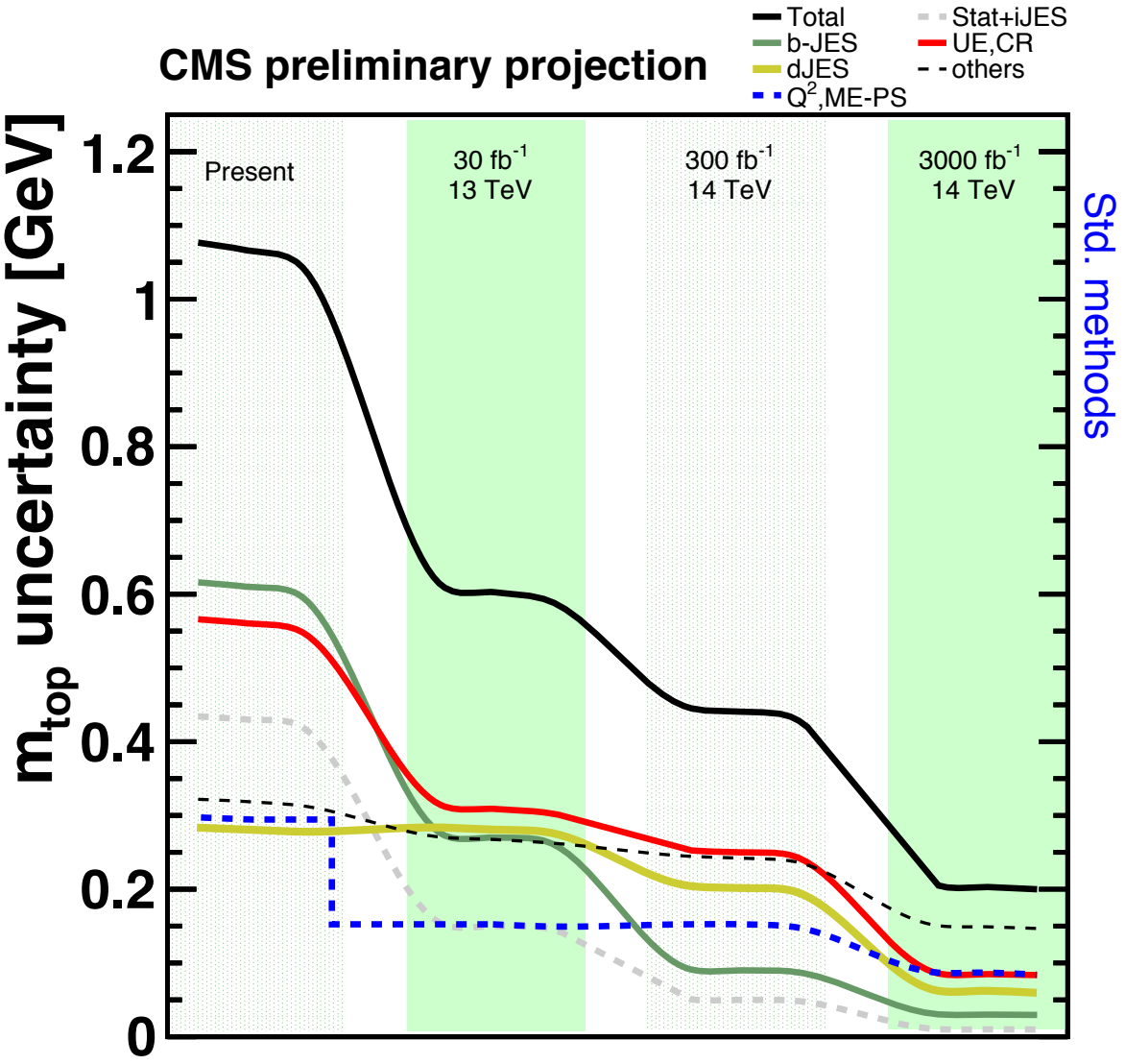
Top quark mass prospects





CMS PAS FTR-13-017

Top quark mass prospects



Top quark versus anti-quark mass

Ideogram method

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

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

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

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

Parameters in the kinematic fit

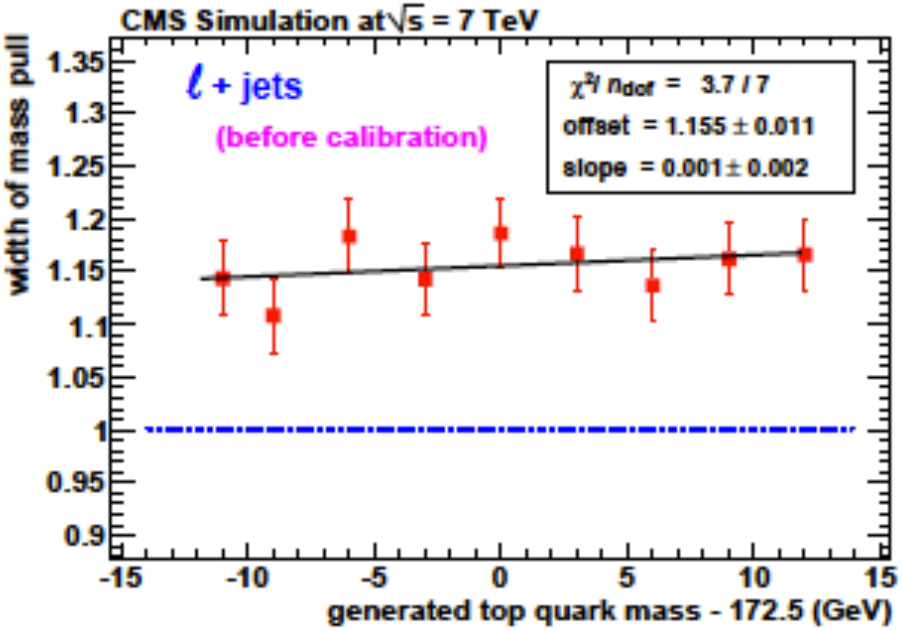
Probability of btagging $w_b = \prod_j p^j,$

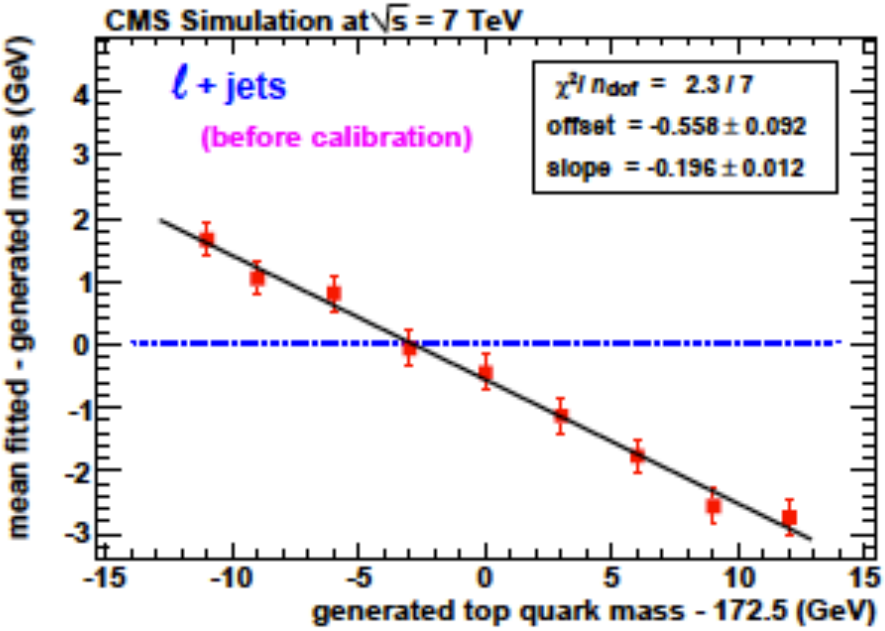
$$P_{t\bar{t}}(x_{\text{mass}};y \mid m_t) = \sum_{i=1}^{12} w_i \left(f_{gc} \int dm' G(m_i \mid m', \sigma_i) B(m' \mid m_t, \Gamma_t) + (1 - f_{gc}) W(m_i \mid m_t) \right)$$

Gauss distr. Breit-Wigner distr. Wrong jet combinations

Top quark versus anti-quark mass

Calibration of the properties of the M_t estimator





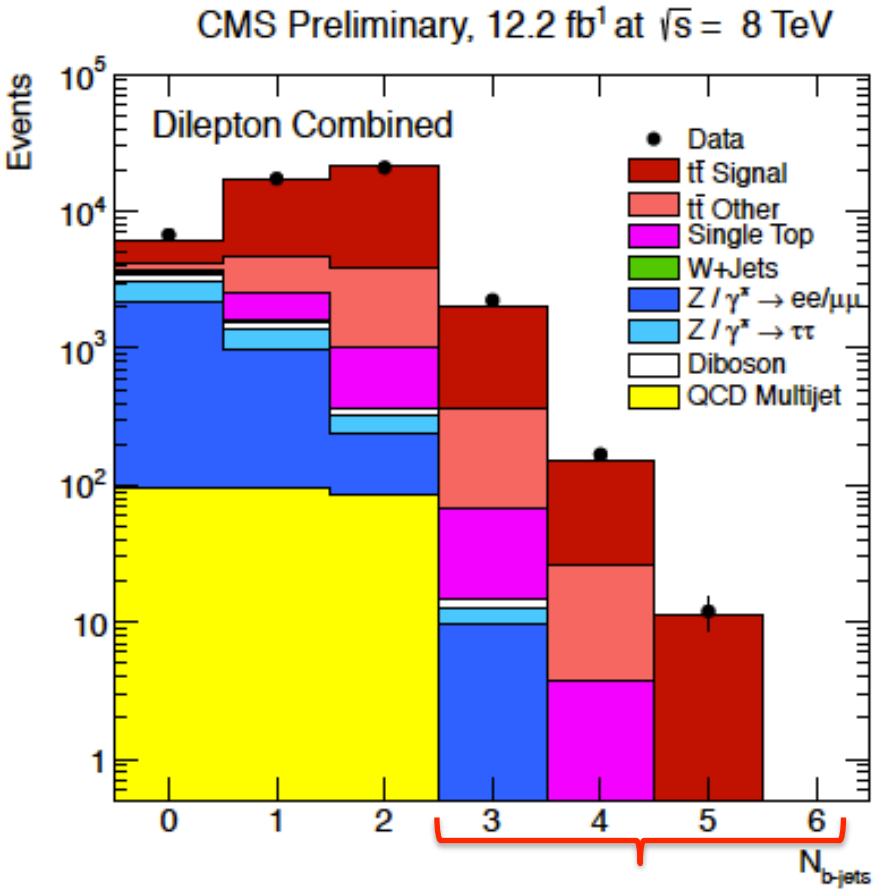
$$\Delta m_t = -272 \pm 196 \text{ (stat.)} \pm 122 \text{ (syst.) MeV}$$

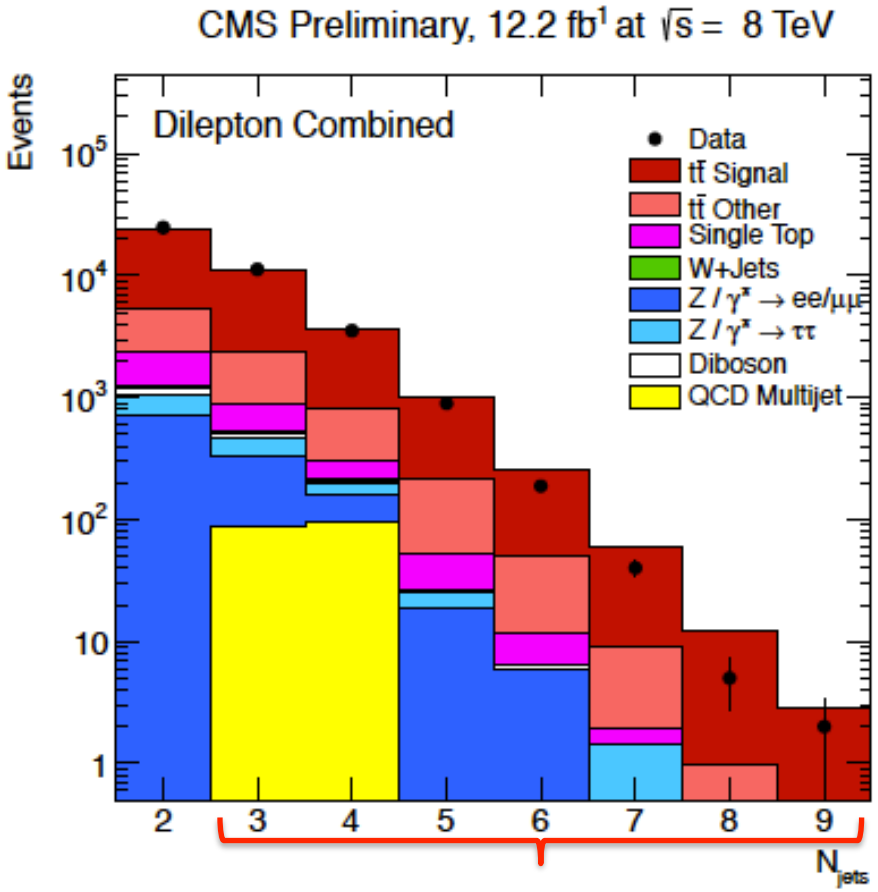
Dominated by statistical uncertainties, hence need measurement at 13-14 TeV

CMS PAS TOP-12-028

Di-lepton

Differential cross-sections in top quark events



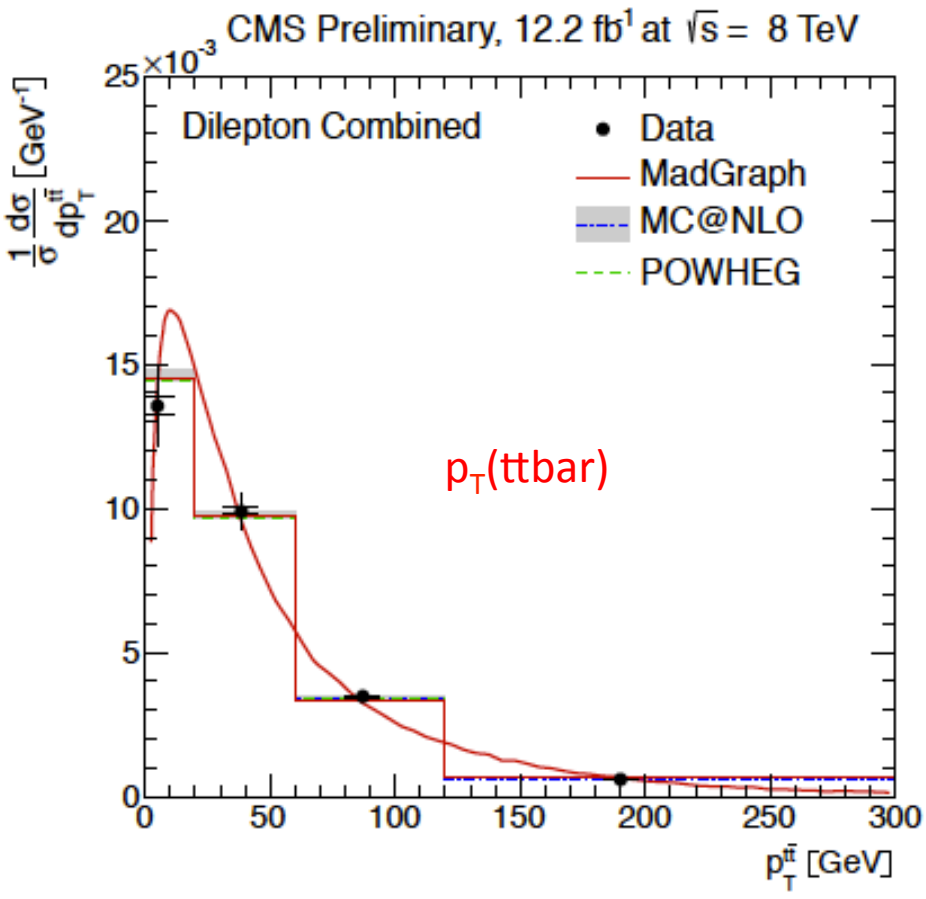


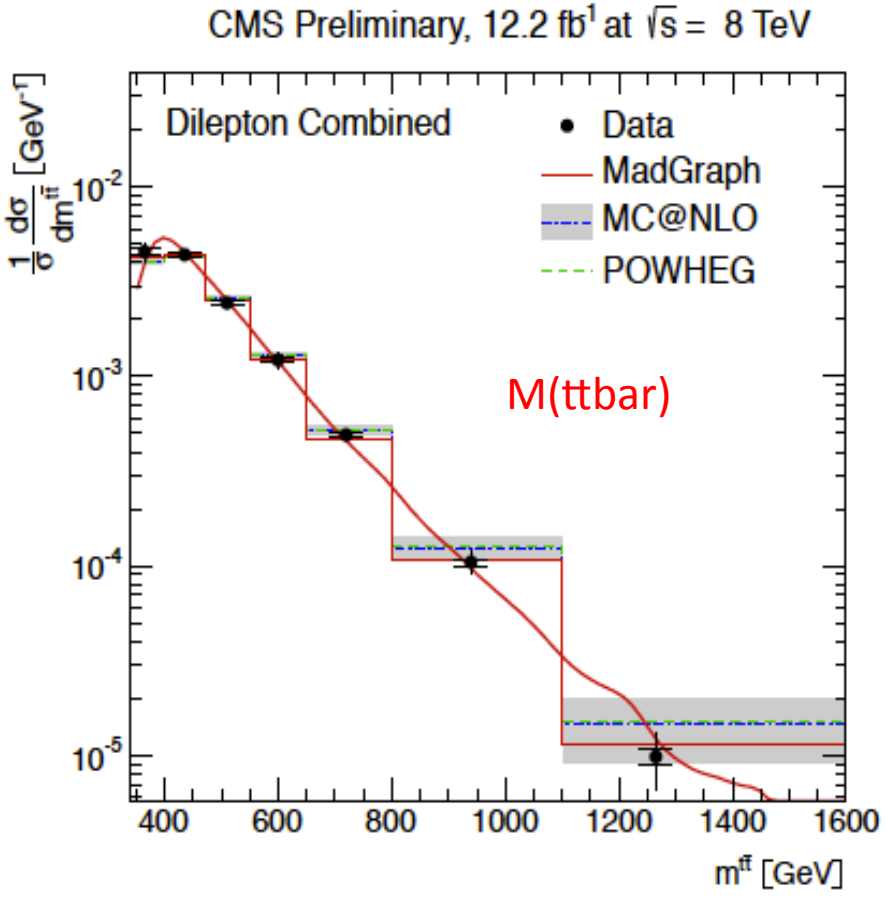
Region of extra (b-)jets

CMS PAS TOP-12-028

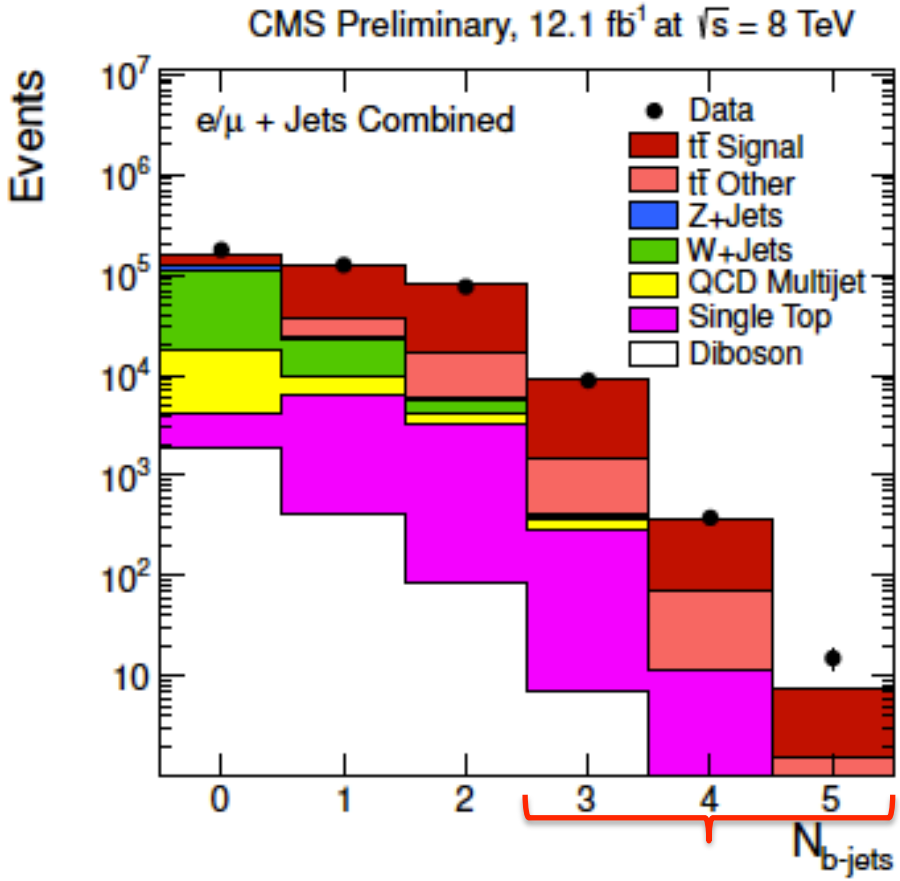
Di-lepton

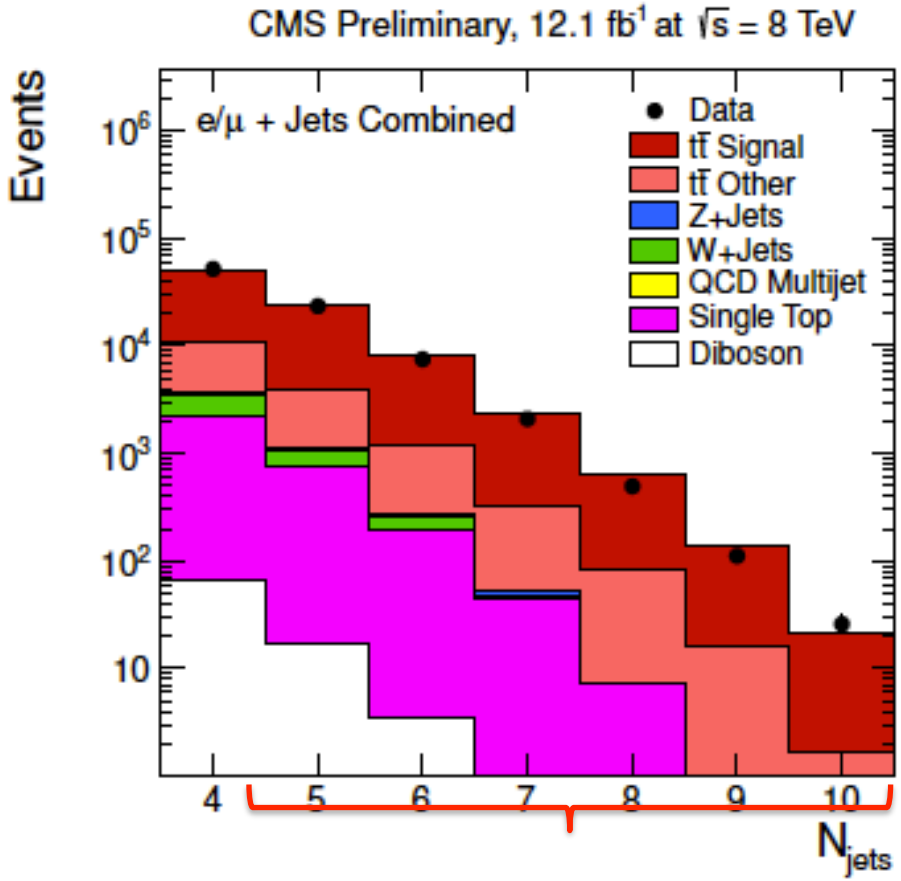
Differential cross-sections in top quark events





Differential cross-sections in top quark events



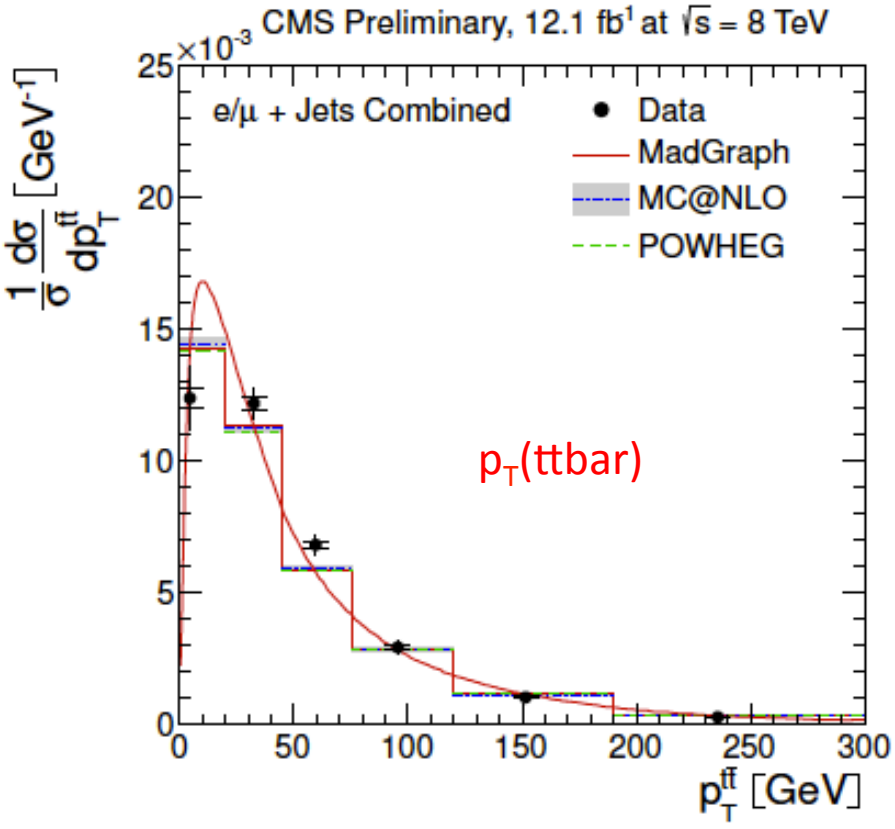


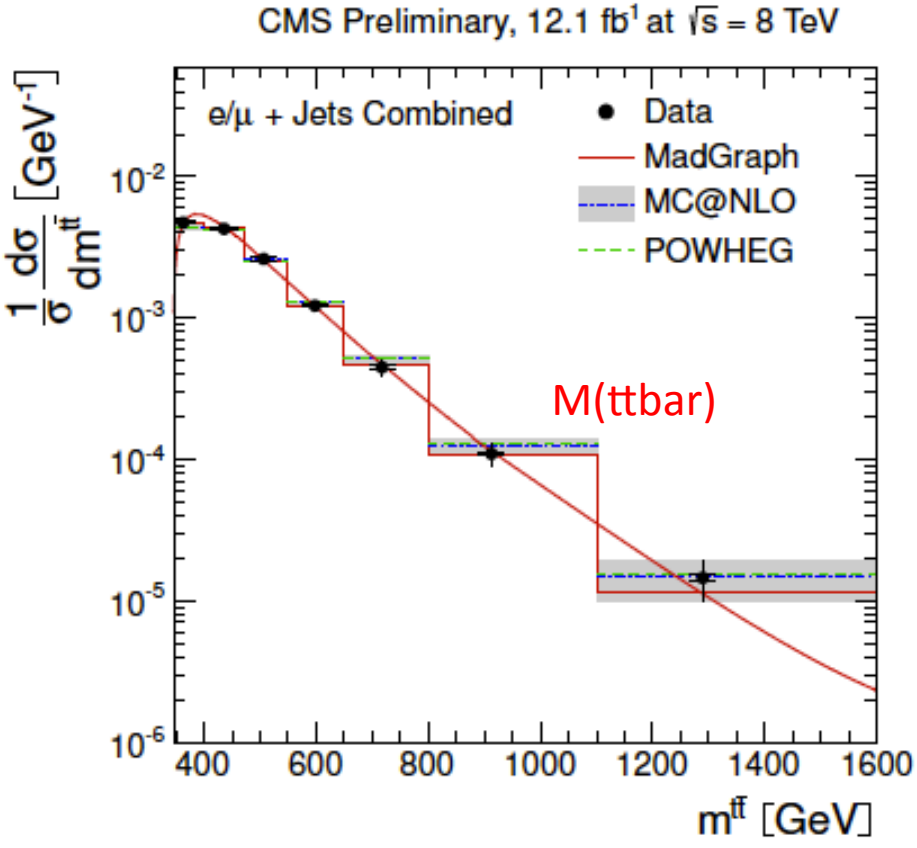
Region of extra (b-)jets

CMS PAS TOP-12-027

Lepton+jets

Differential cross-sections in top quark events



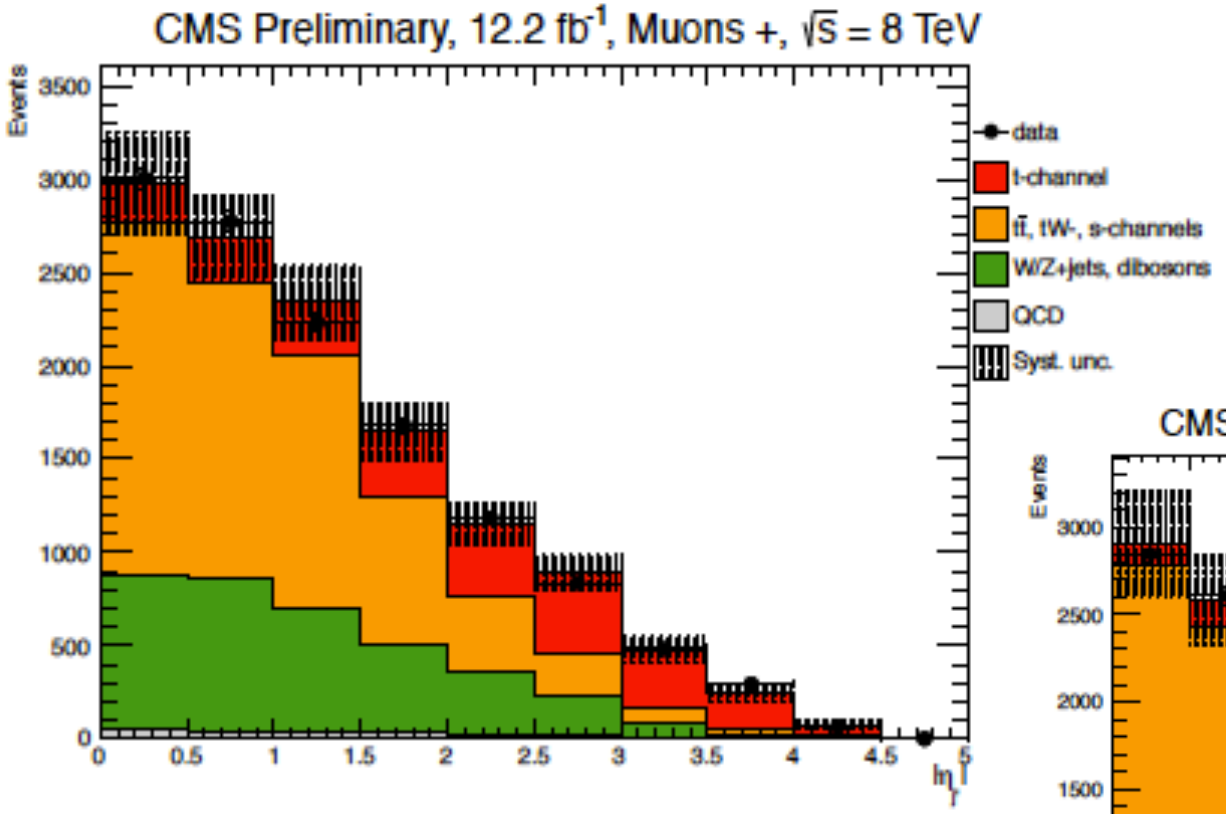


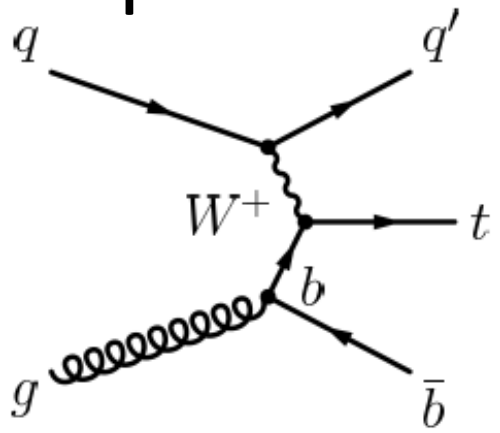
CMS PAS TOP-12-038

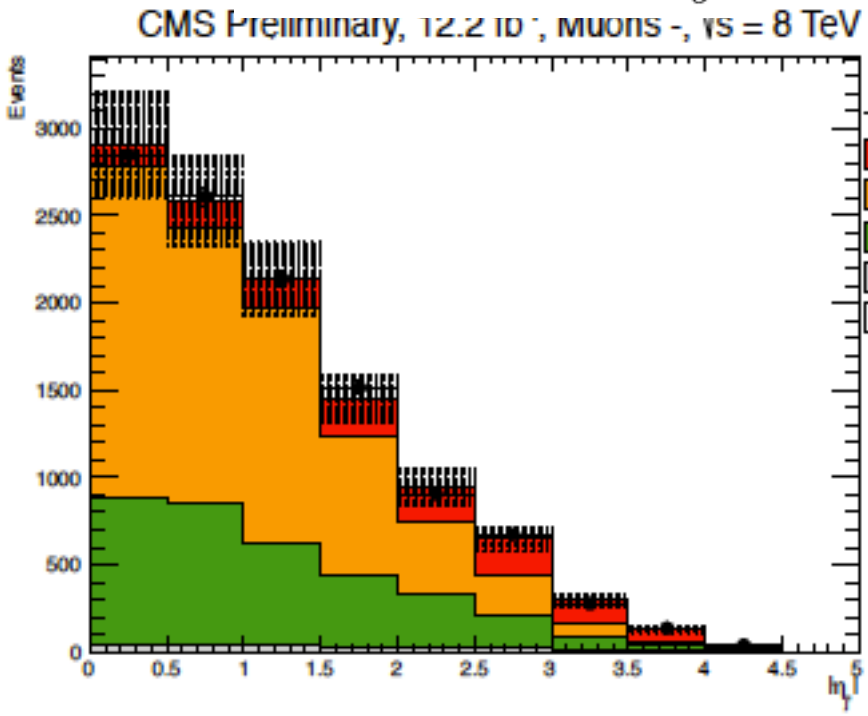
$$\sigma^{\text{th}}_{t\text{-ch.,top}} = 56.4^{+2.1}_{-0.3}\,(\text{scale})^{+1.1}_{-1.1}\,(\text{PDF})\text{pb}$$

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

Single top versus anti-top



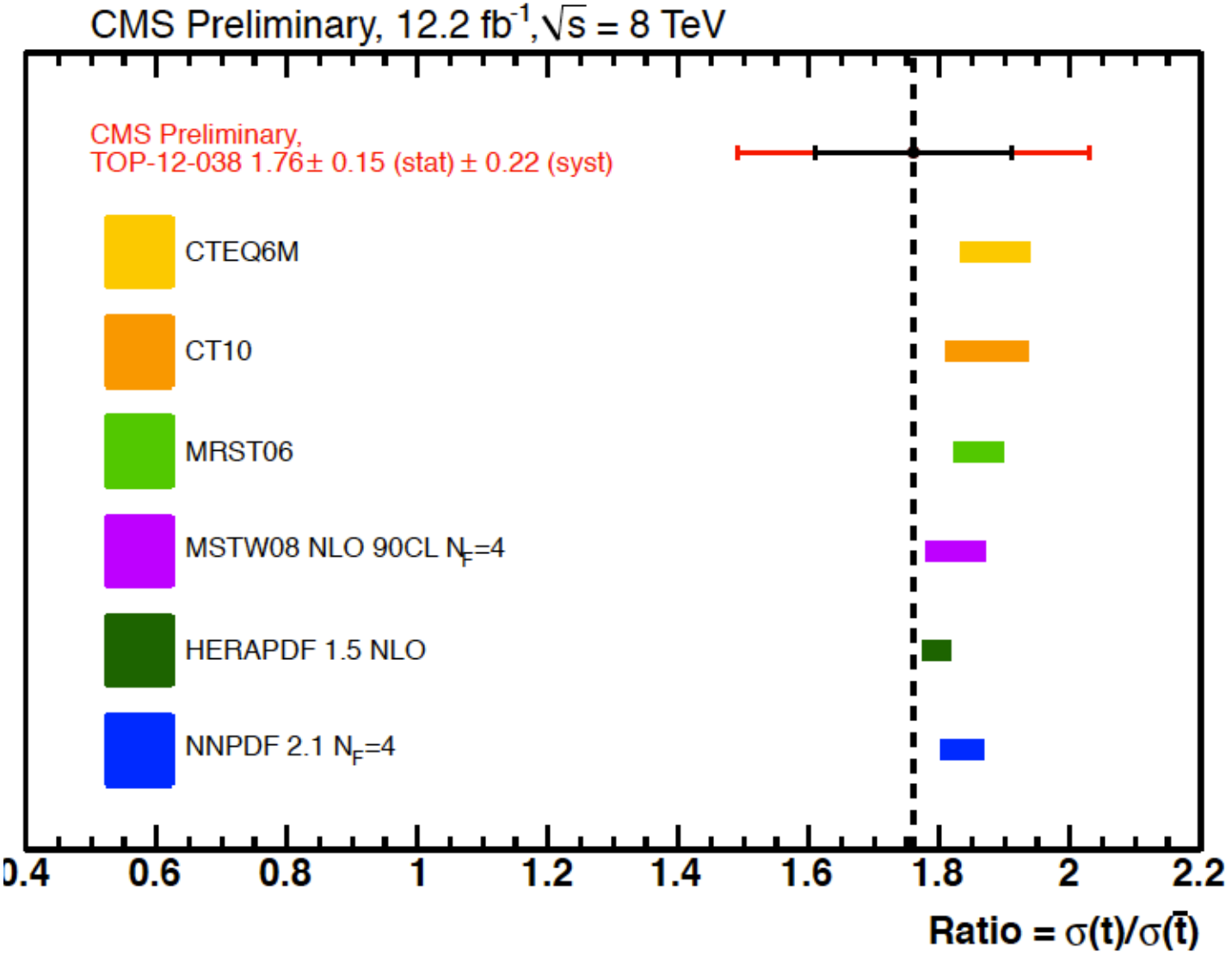




Fitting simultaneous the top and anti-top component on the pseudo-rapidity distribution

CMS PAS TOP-12-038

Single top versus anti-top

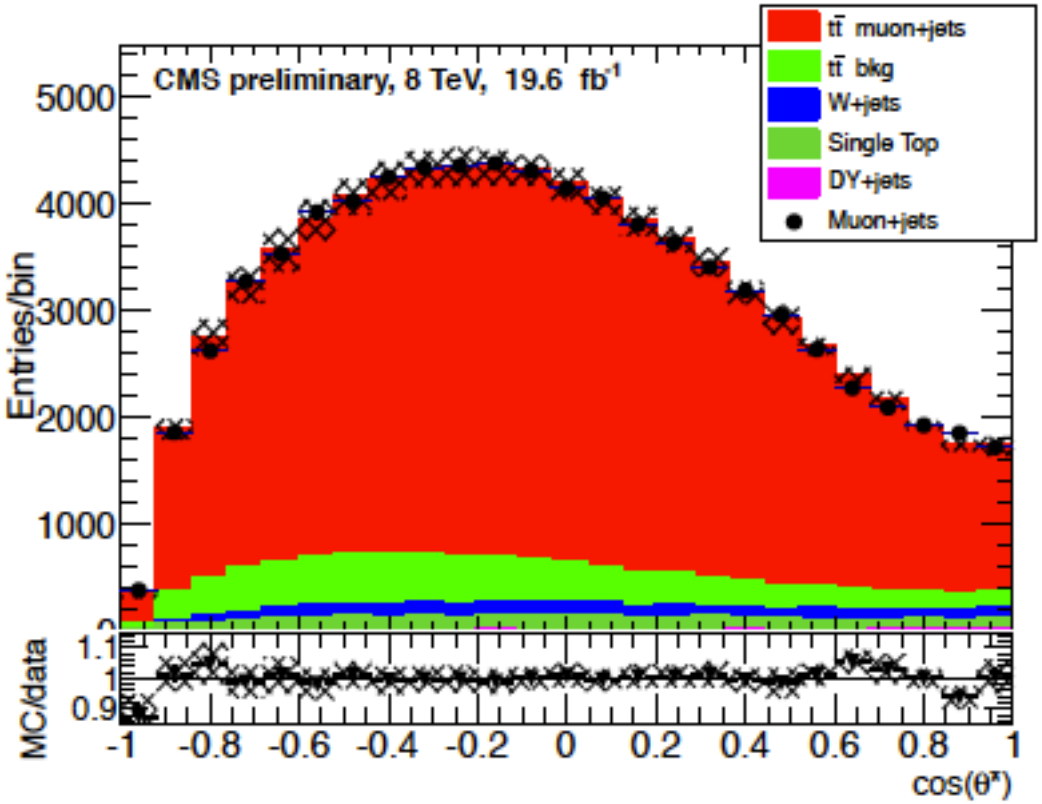


Presentation from M. Zeinali on "W decays in top events"

W helicity (in top quark pair events)

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

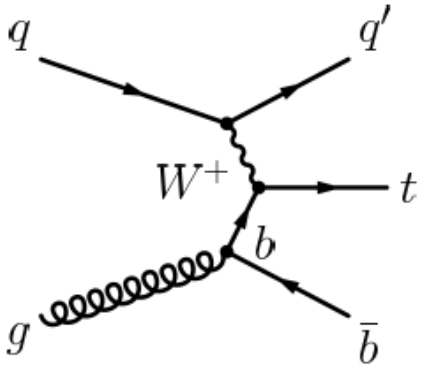
$$\mathcal{L}_{tWb}^{anom.} = -\frac{g}{\sqrt{2}}\bar{b}\gamma^\mu(V_L P_L + V_R P_R)tW_\mu^- - \frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}q_\nu}{m_W}(g_L P_L + g_R P_R)tW_\mu^- + H.C,$$



Reweighting method to fit this distribution with 2 free parameters:

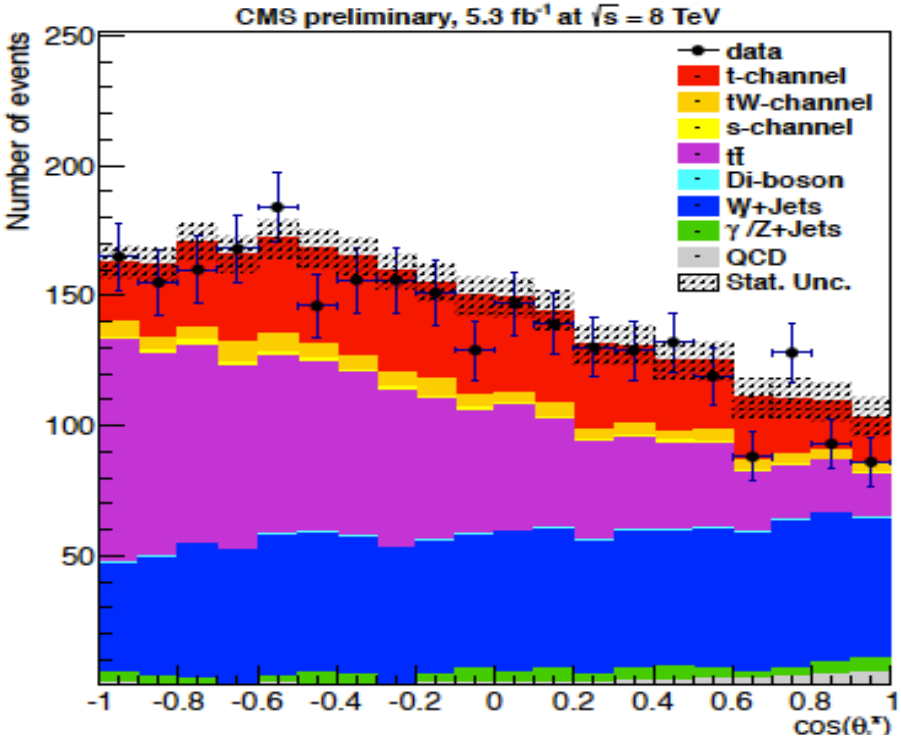
$$F_0 = 0.659 \pm 0.015(\text{stat.}) \pm 0.023(\text{syst.}),$$
$$F_L = 0.350 \pm 0.010(\text{stat.}) \pm 0.024(\text{syst.}),$$

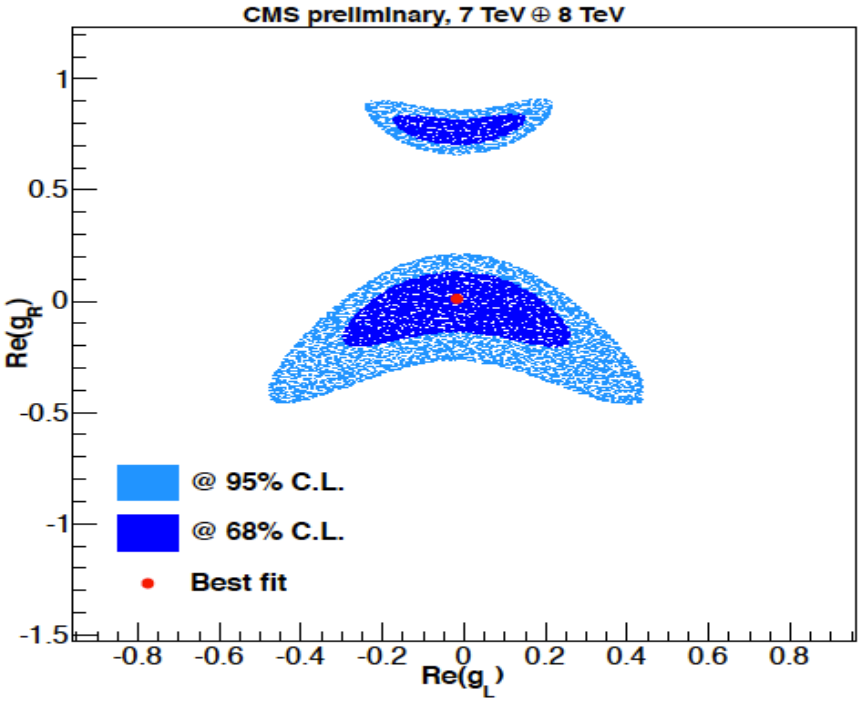
Theoretical uncertainties dominate and the MET shape



W helicity in Single Top

$$F_L^{\text{Comb.}} = 0.293 \pm 0.069(\text{stat.}) \pm 0.030(\text{syst.}),$$
$$F_0^{\text{Comb.}} = 0.713 \pm 0.114(\text{stat.}) \pm 0.023(\text{syst.}),$$
$$F_R^{\text{Comb.}} = -0.006 \pm 0.057(\text{stat.}) \pm 0.027(\text{syst.}),$$

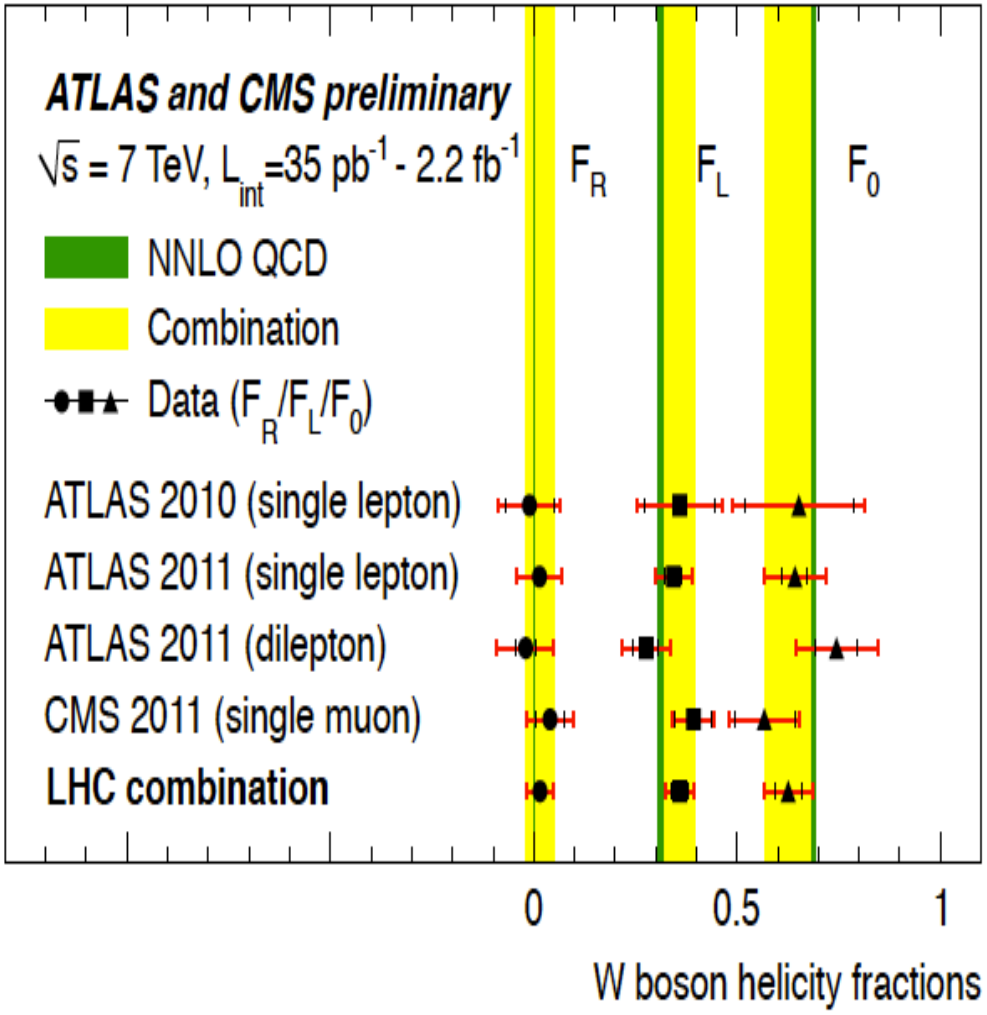


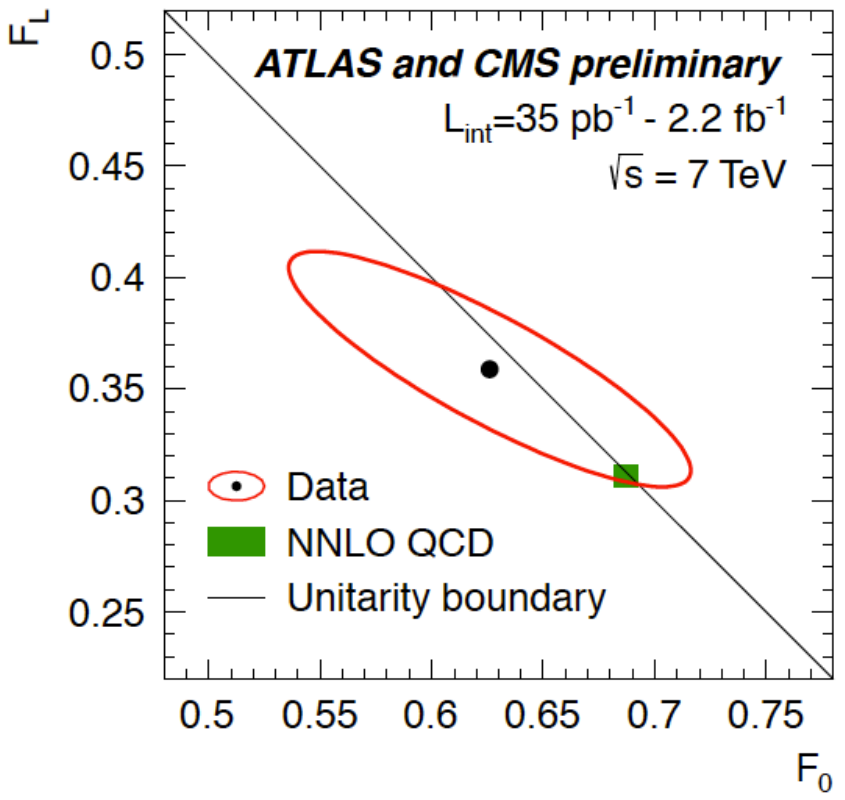


$$\mathcal{L}_{tWb}^{anom.} = -\frac{g}{\sqrt{2}}\bar{b}\gamma^{\mu}(V_L P_L + V_R P_R)tW_{\mu}^{-} - \frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}q_{\nu}}{m_W}(g_L P_L + g_R P_R)tW_{\mu}^{-} + H.C,$$

CMS PAS TOP-12-025

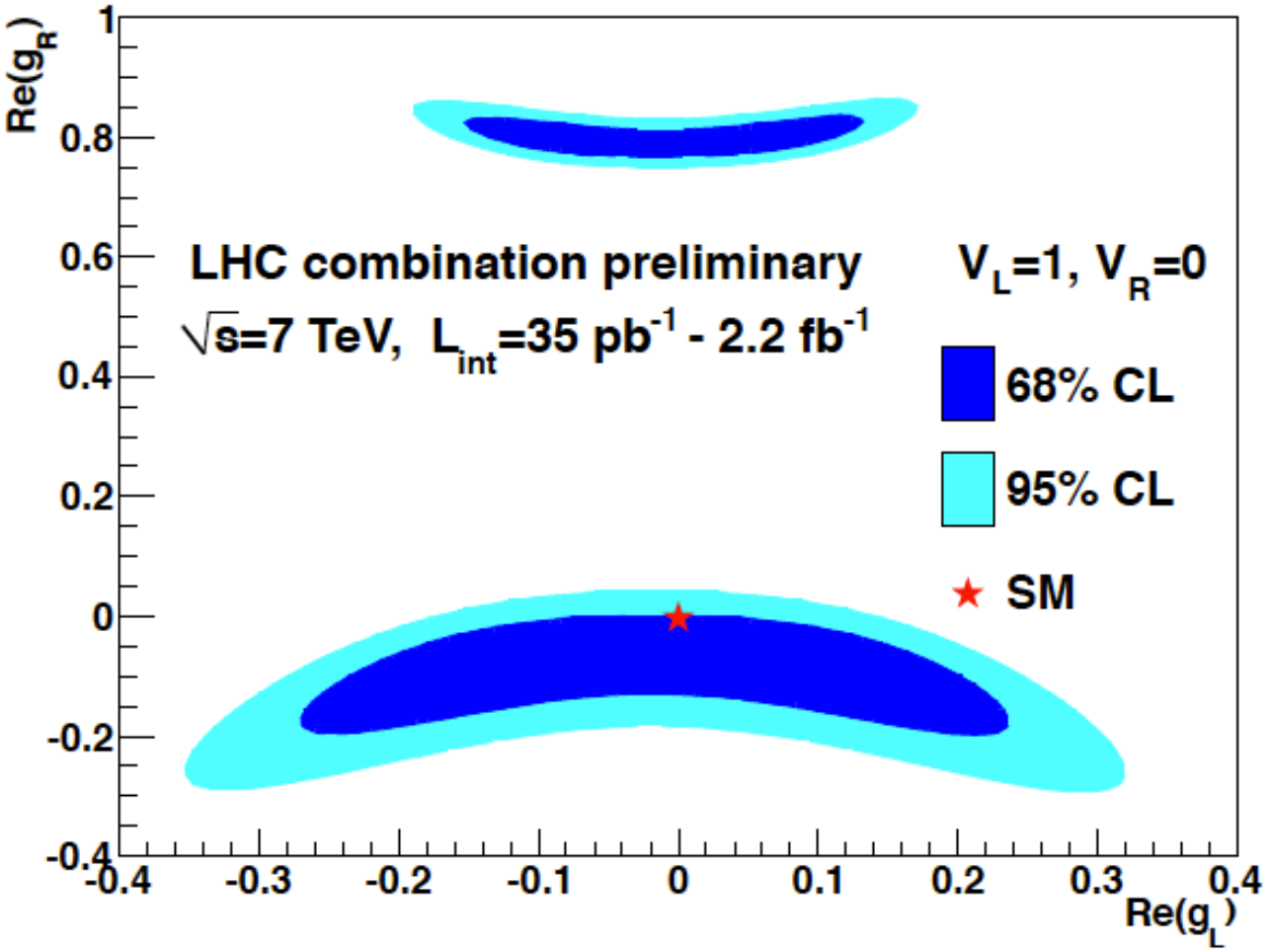
W helicity: LHC combination





$$F_0 = 0.626 \pm 0.034\,(\text{stat.}) \pm 0.048\,(\text{syst.}),$$
$$F_L = 0.359 \pm 0.021\,(\text{stat.}) \pm 0.028\,(\text{syst.}).$$

W helicity: LHC combination



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

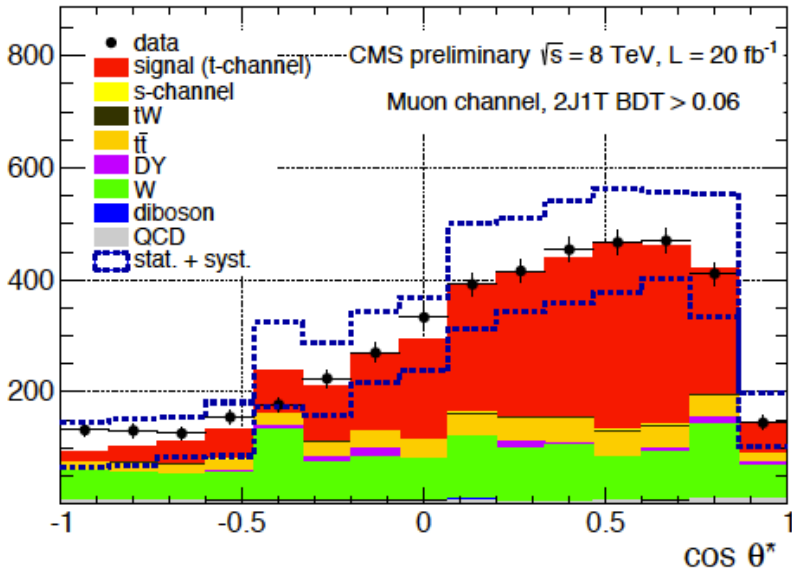
CMS PAS TOP-13-001

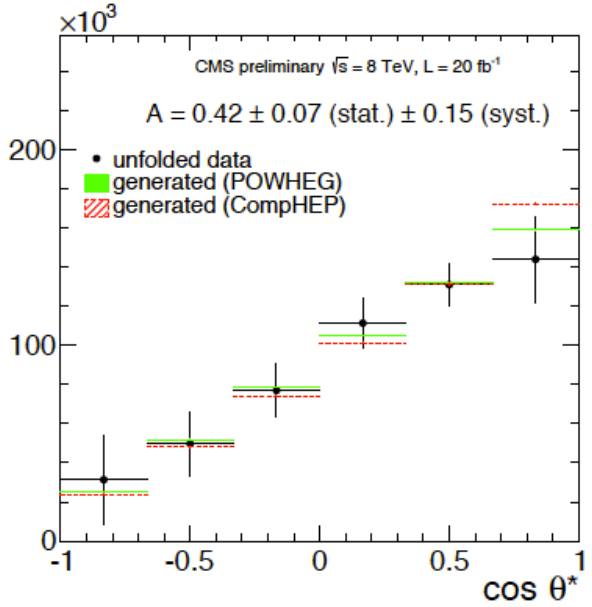
t-channel

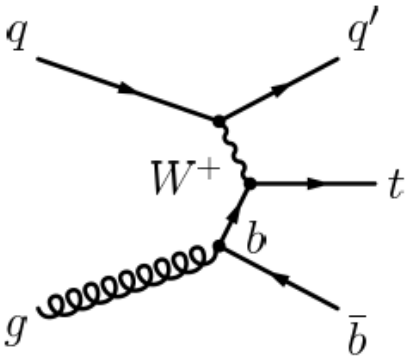
$$\frac{d\Gamma}{d\cos\theta_X} = \frac{\Gamma}{2}(1 + P_t \alpha_X \cos\theta_X) \qquad X\,(= W, \ell, \nu, b)$$

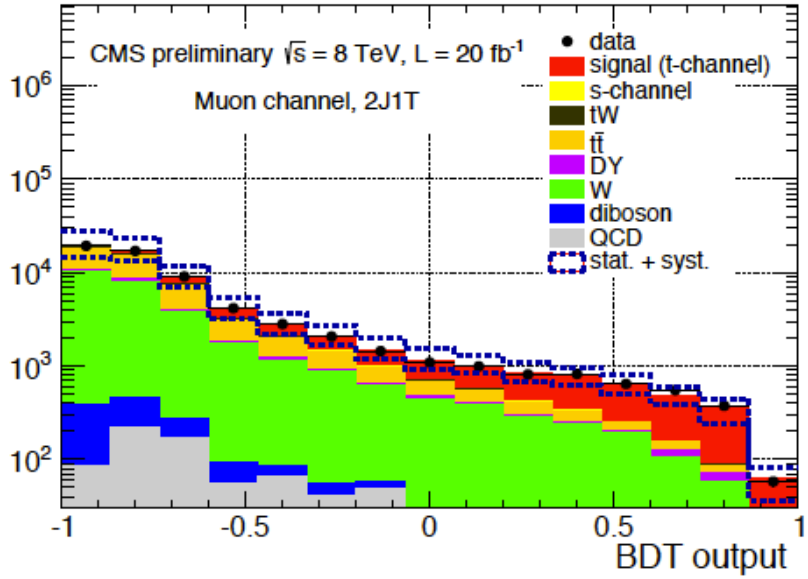
$$A_l \equiv \frac{1}{2} \cdot P_t \cdot \alpha_l = \frac{N(\uparrow) - N(\downarrow)}{N(\uparrow) + N(\downarrow)}$$

Top polarization in Single Top events









$$A_l = \frac{N(\cos\theta^*_{unfolded} > 0) - N(\cos\theta^*_{unfolded} < 0)}{N(\cos\theta^*_{unfolded} > 0) + N(\cos\theta^*_{unfolded} < 0)}.$$

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

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

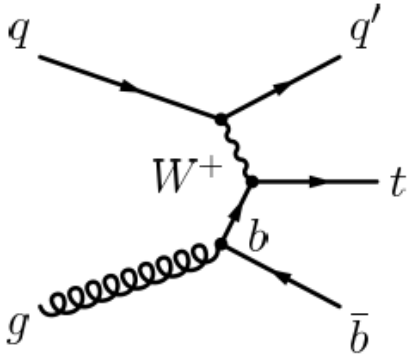
$$\alpha_l = 1$$

100% polarization expected

ADDENDUM

t-channel

Top polarization in Single Top events



In this analysis, the top-quark spin asymmetry

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

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 α_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].

CMS PAS TOP-12-004

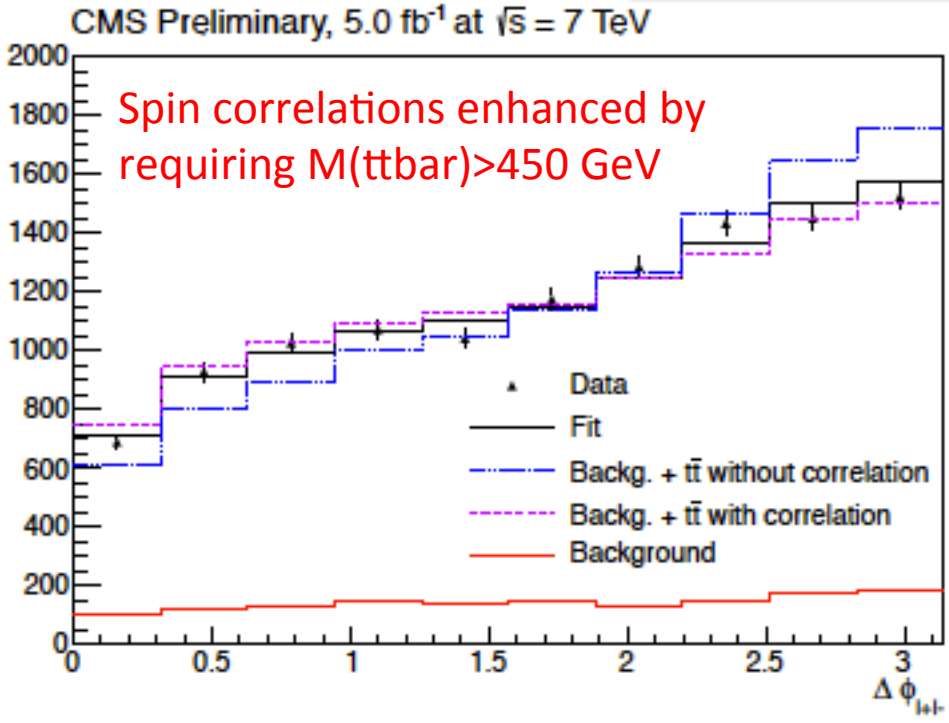
Di-lepton

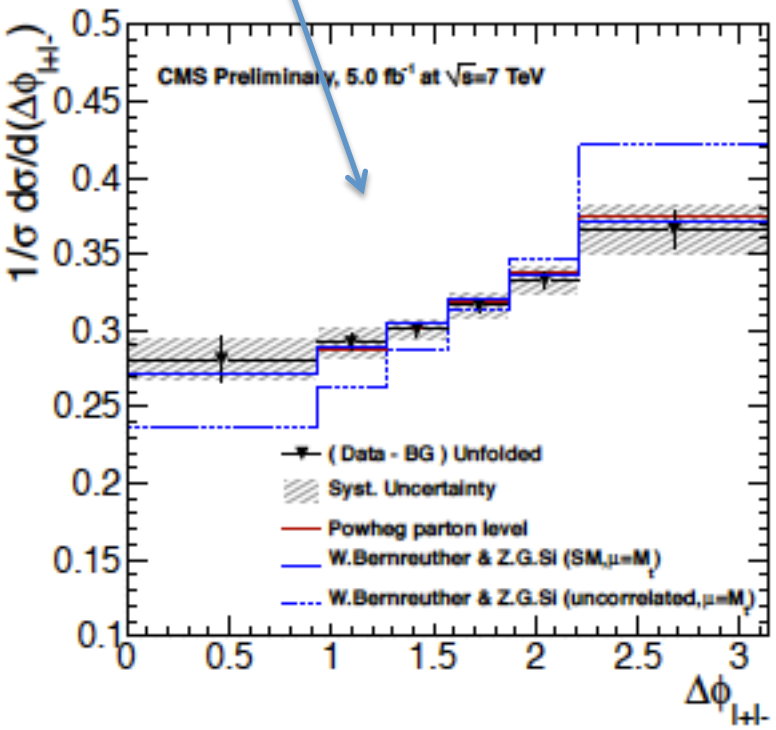
$t\bar{t} \rightarrow l^+\nu l^-\bar{\nu}b\bar{b},$

$(\Delta\phi_{l^+l^-} = |\phi_{l^+} - \phi_{l^-}|)$

Spin correlations

Background-subtracted and unfolded differential cross-sections





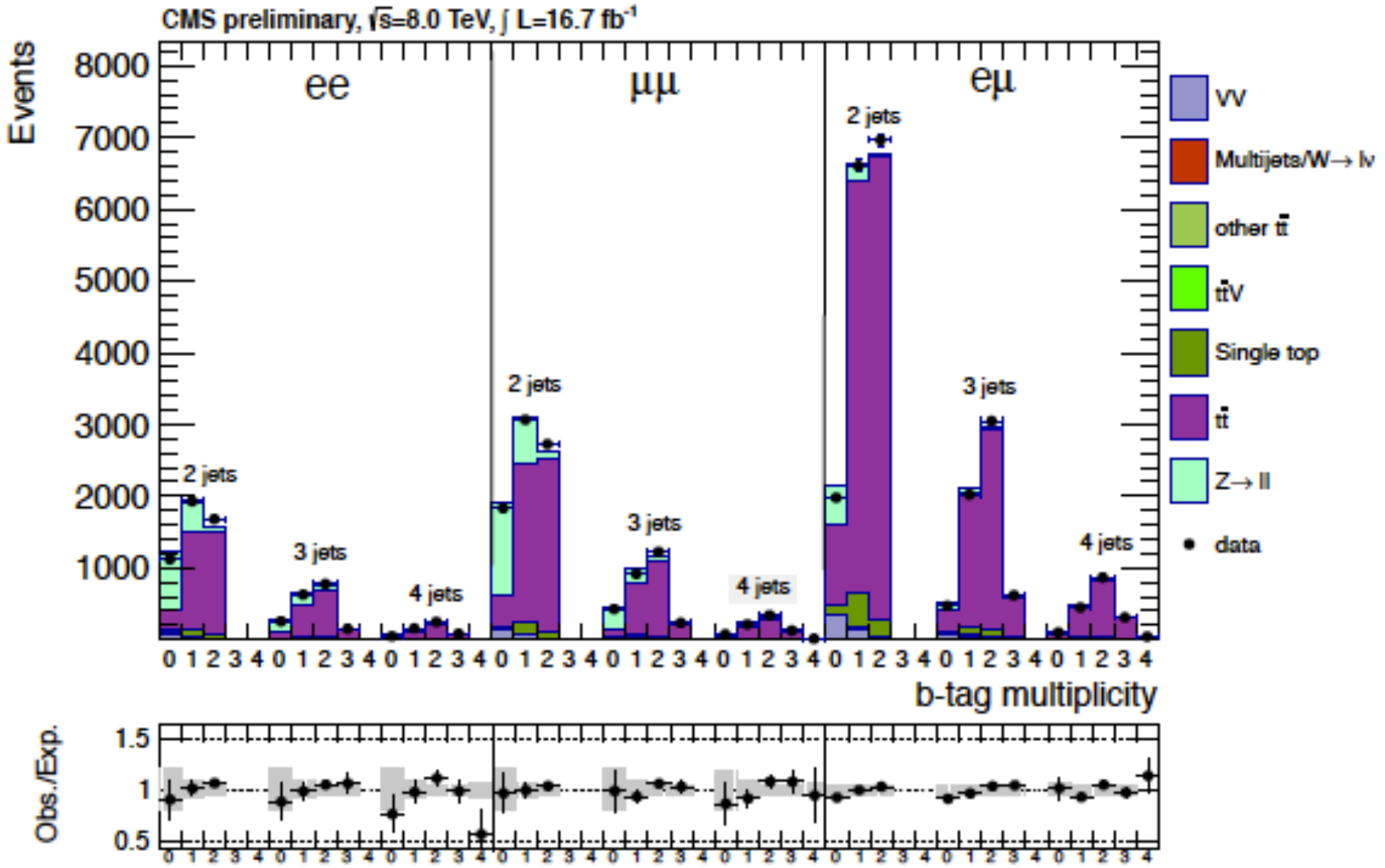
Correlation coefficient in the helicity basis: $0.24 \pm 0.02(\text{stat.}) \pm 0.08(\text{syst.})$

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

CMS PAS TOP-12-035

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

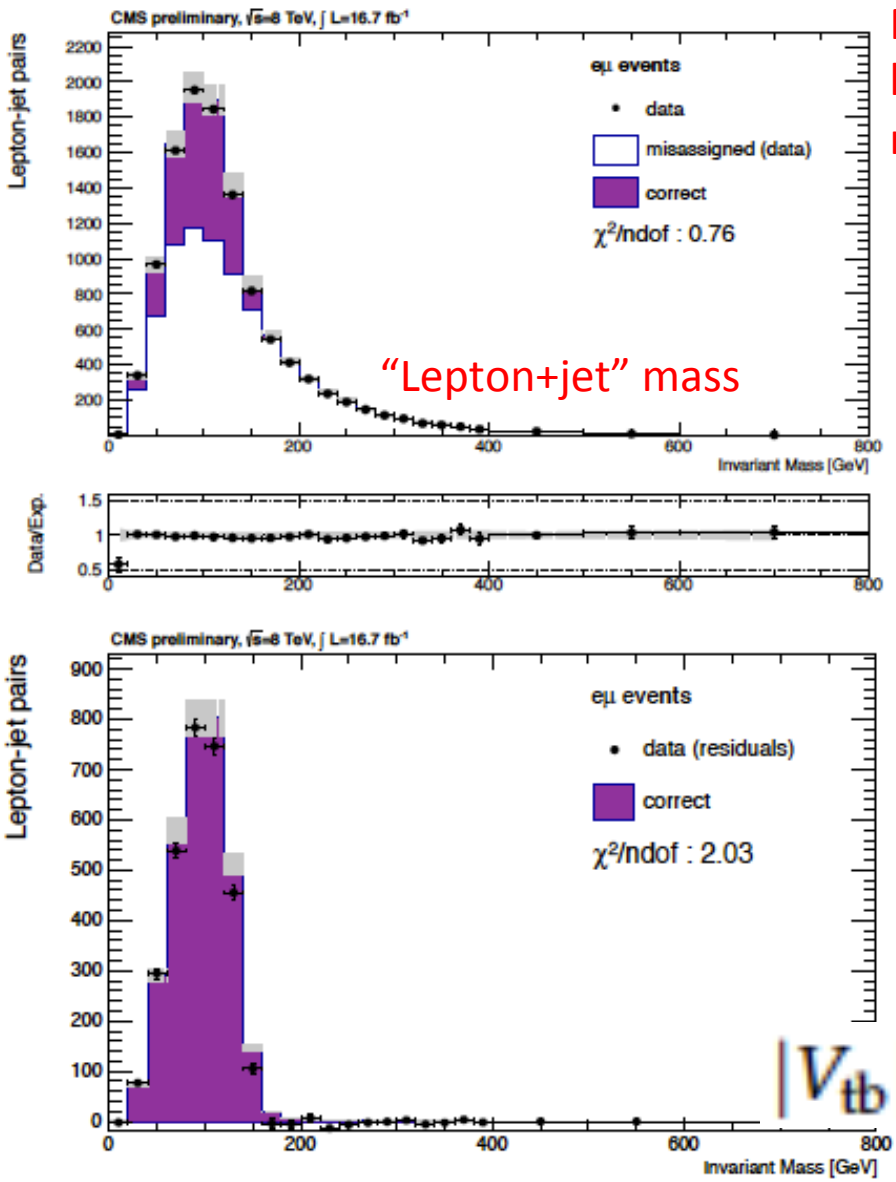
Ratio of top decays to Wb and Wq



CMS PAS TOP-12-035

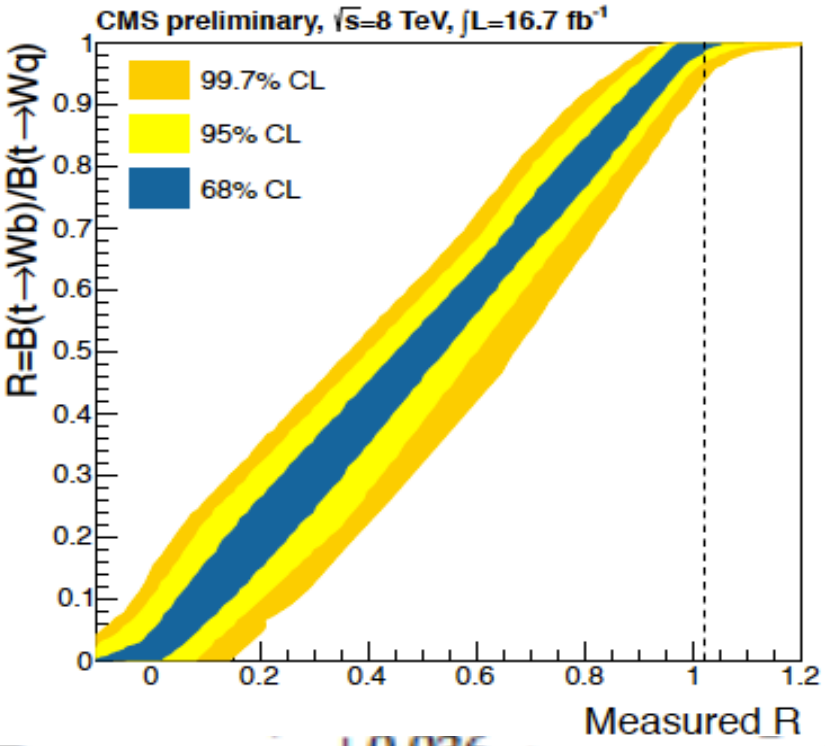
Di-lepton $t\bar{t} \rightarrow l^+\nu l^-\bar{\nu}b\bar{b}$,

Ratio of top decays to Wb and Wq



"Lepton+jet" mass

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



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

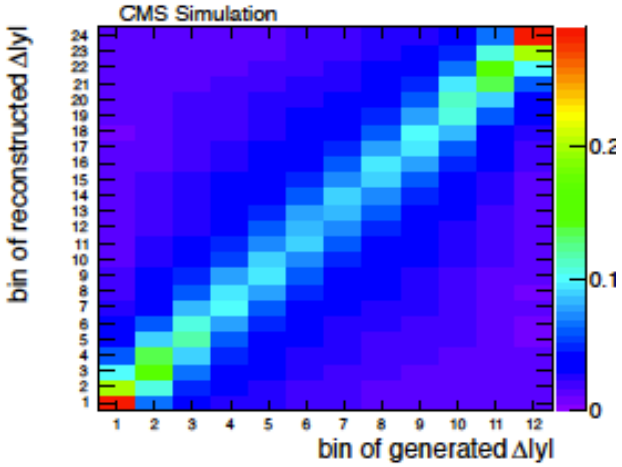
$|V_{tb}| > 0.972$ is obtained at 95% CL

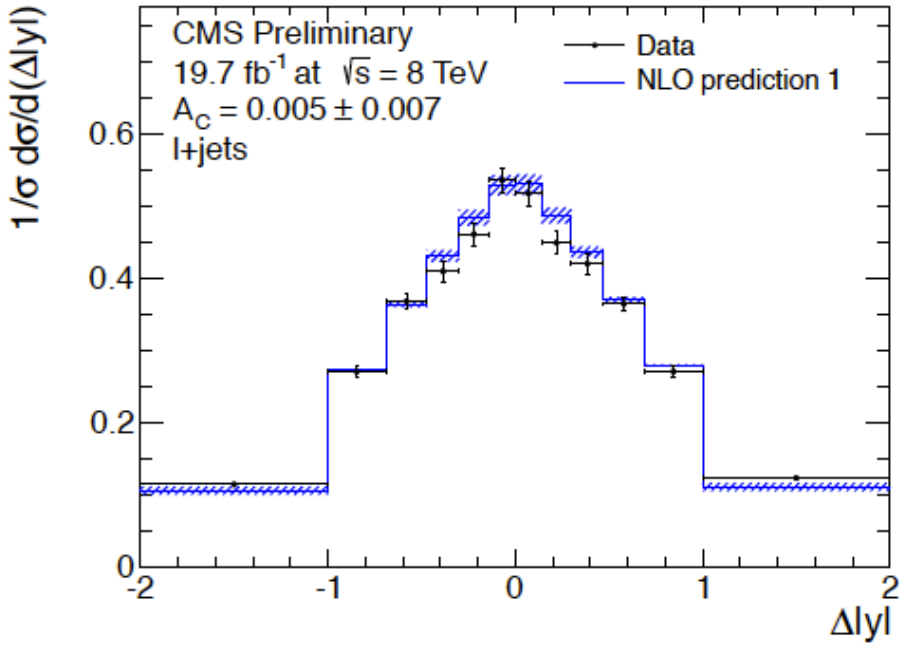
Lepton+jets

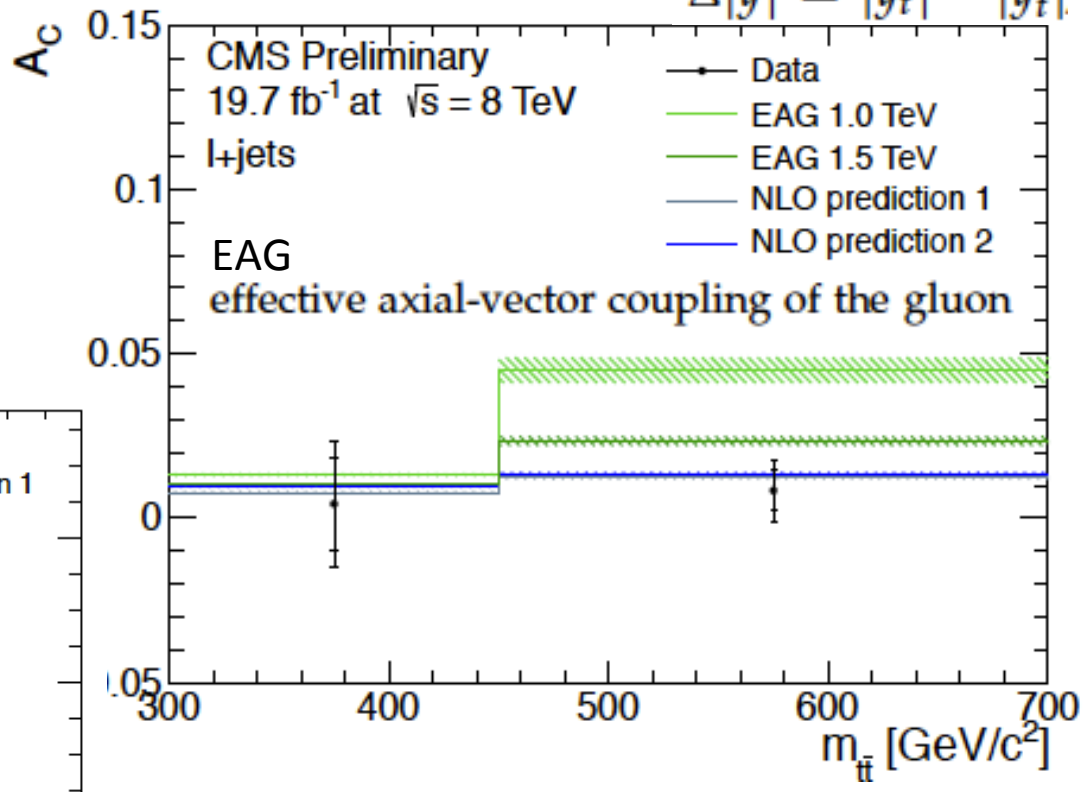
Charge asymmetry

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

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







Measured charge asymmetry

$$0.005 \pm 0.007\ (\text{stat.}) \pm 0.006\ (\text{syst.})$$

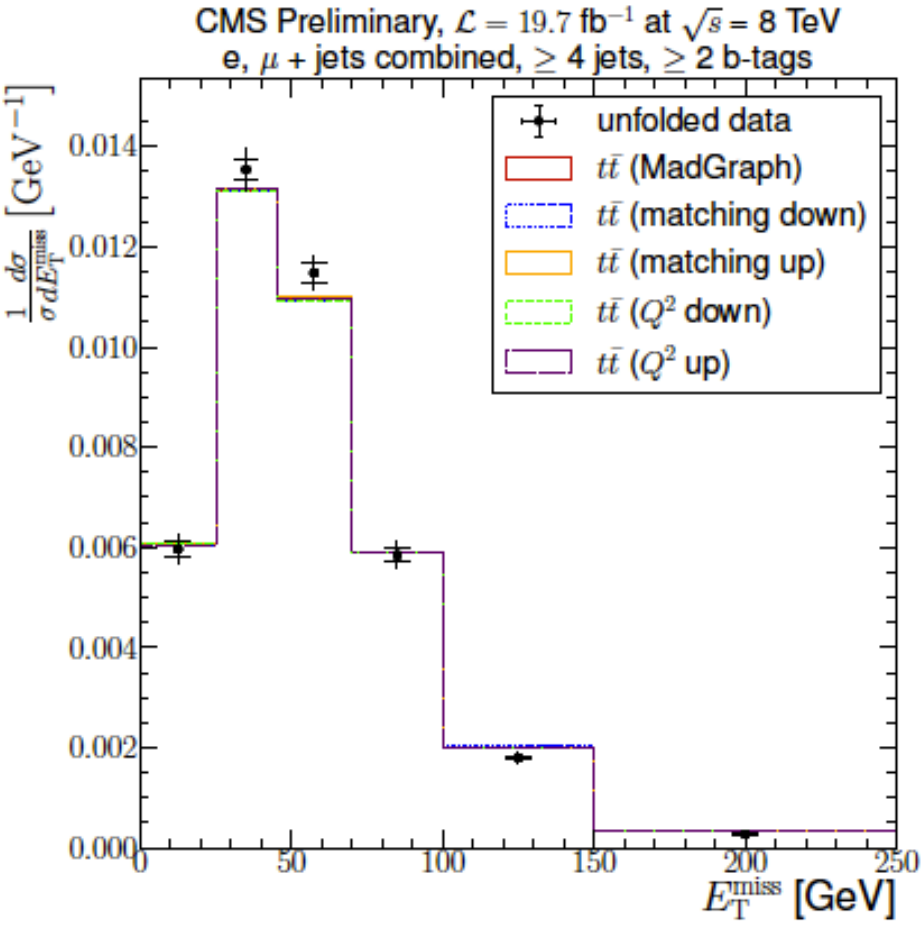
Theory prediction ~1%

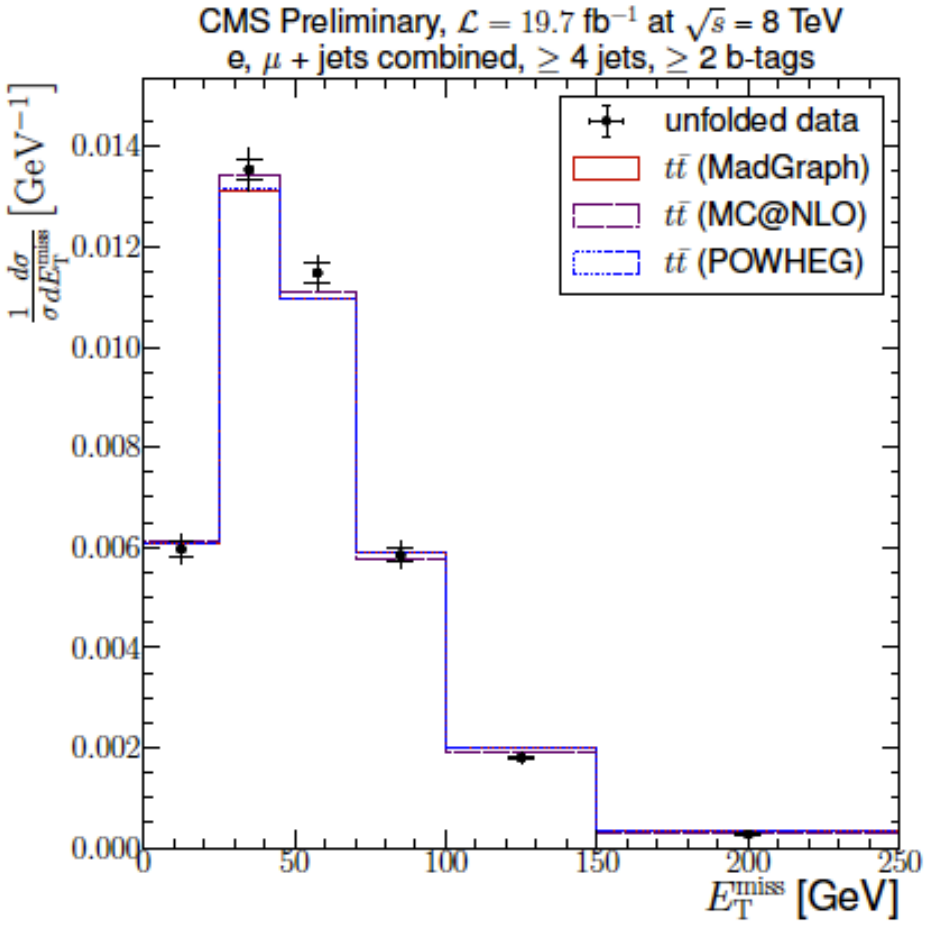
$$\Delta|y| = |y_t| - |y_{\bar{t}}|$$

Lepton+jets

Kinematics of top quark events

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

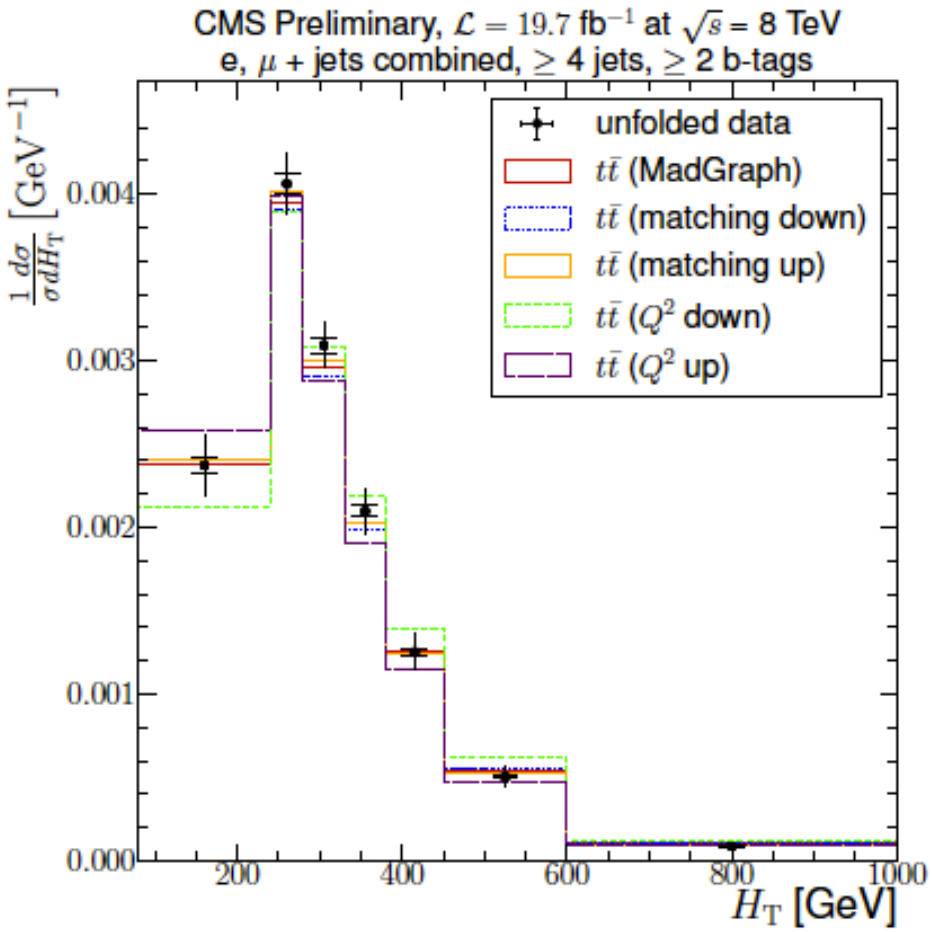


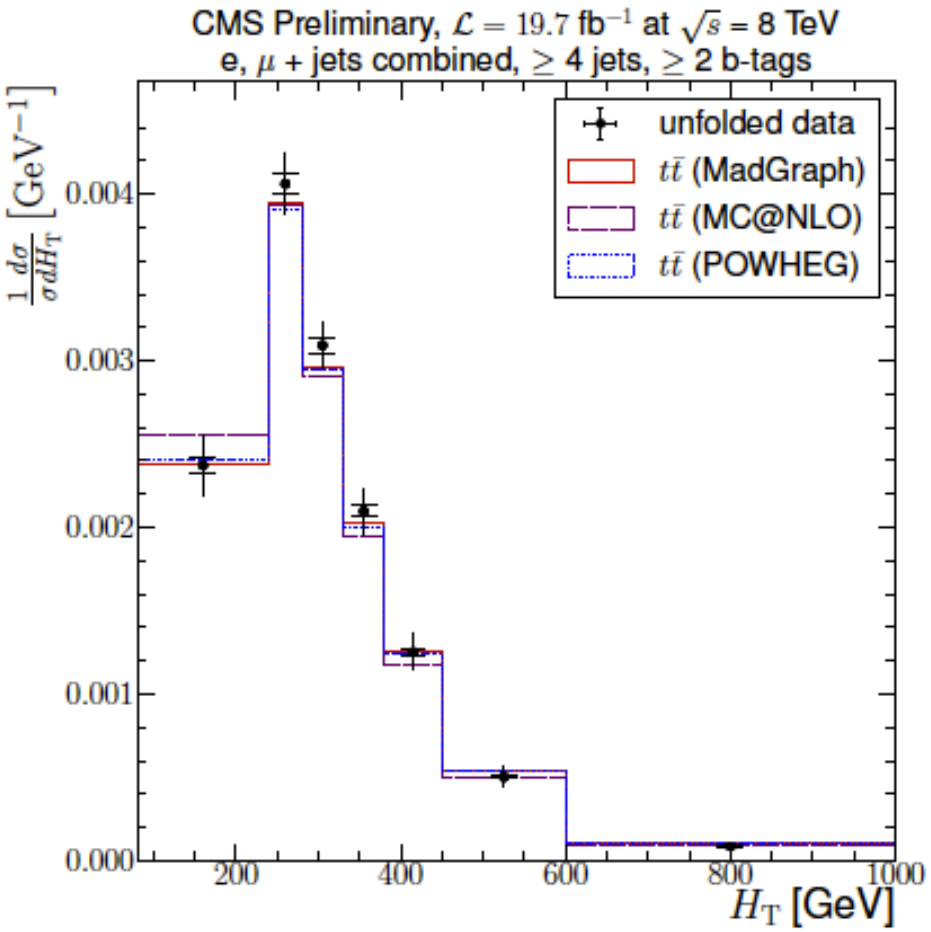


Lepton+jets

Kinematics of top quark events

$$H_{\mathrm{T}} = \sum_{\mathrm{alljets}} p_{\mathrm{T}}^{\mathrm{jet}}$$

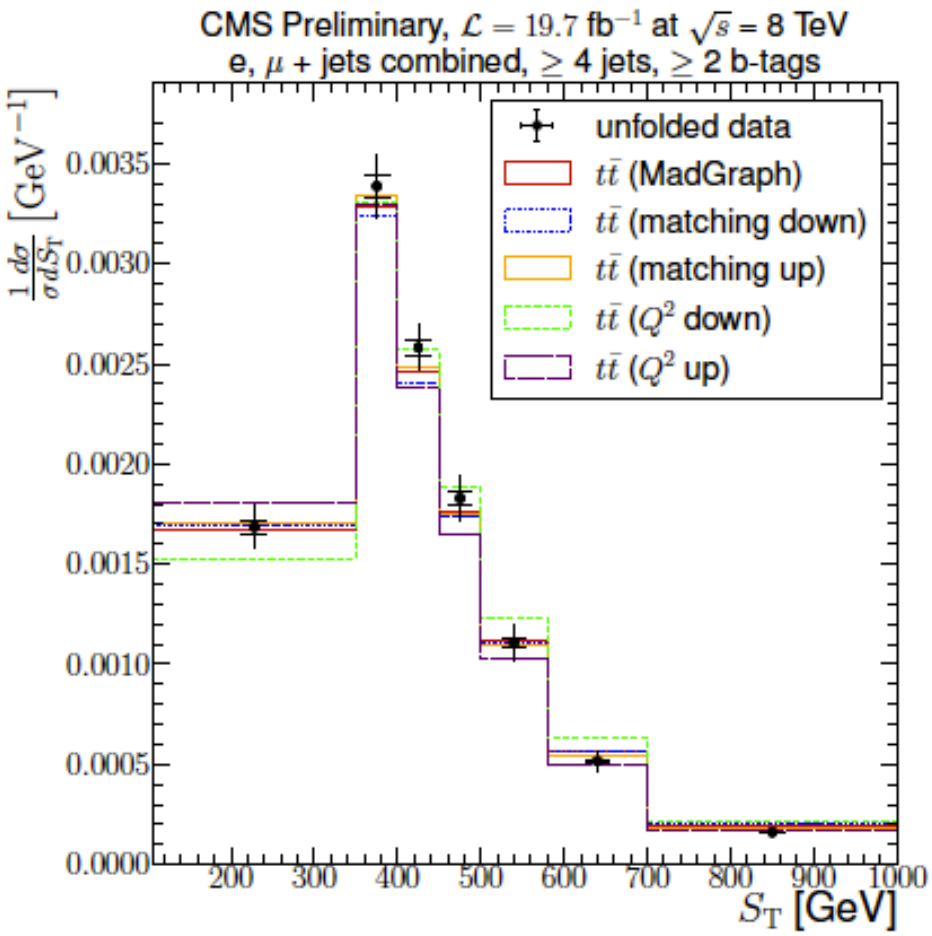


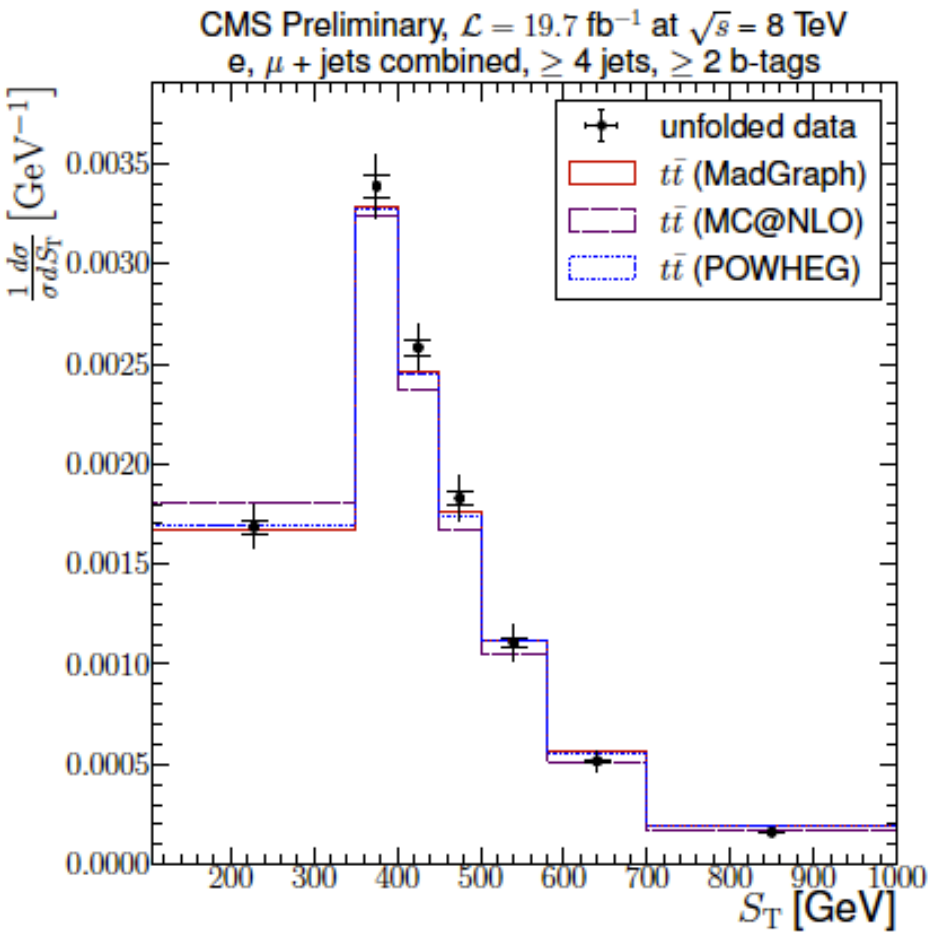


Lepton+jets

Kinematics of top quark events

$$S_{\mathrm{T}} = H_{\mathrm{T}} + E_{\mathrm{T}}^{\mathrm{miss}} + p_{\mathrm{T}}^{\mathrm{lepton}}$$

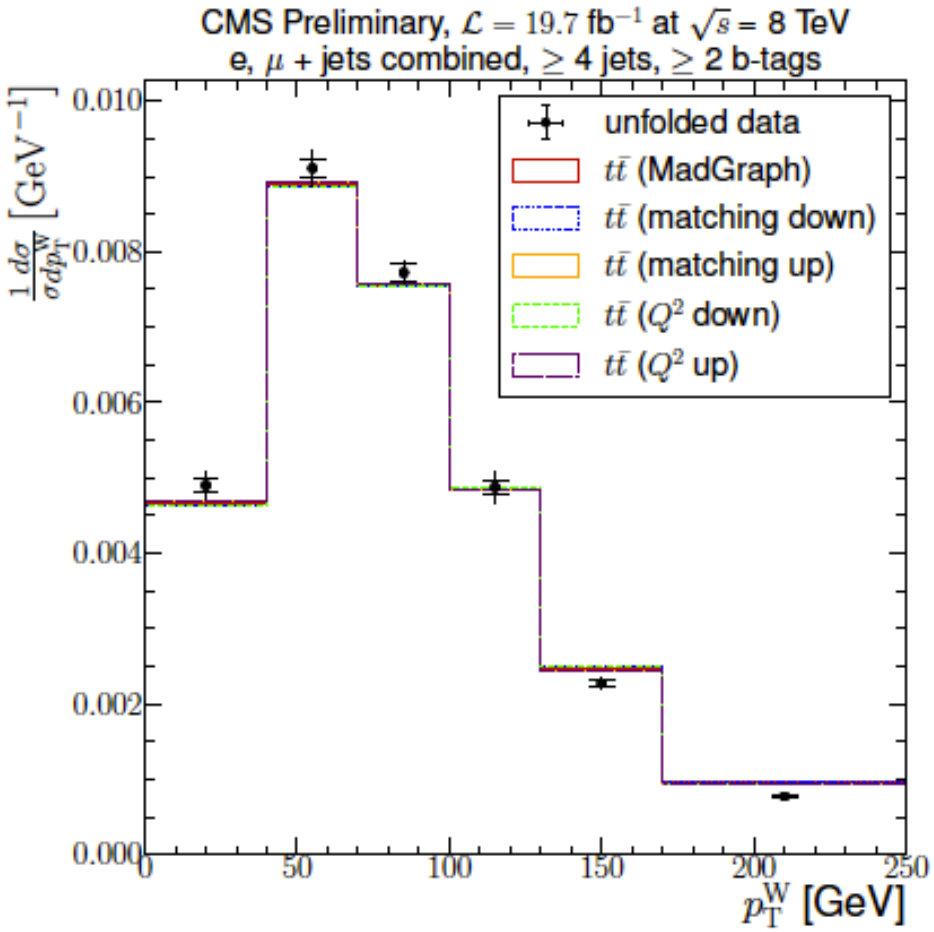


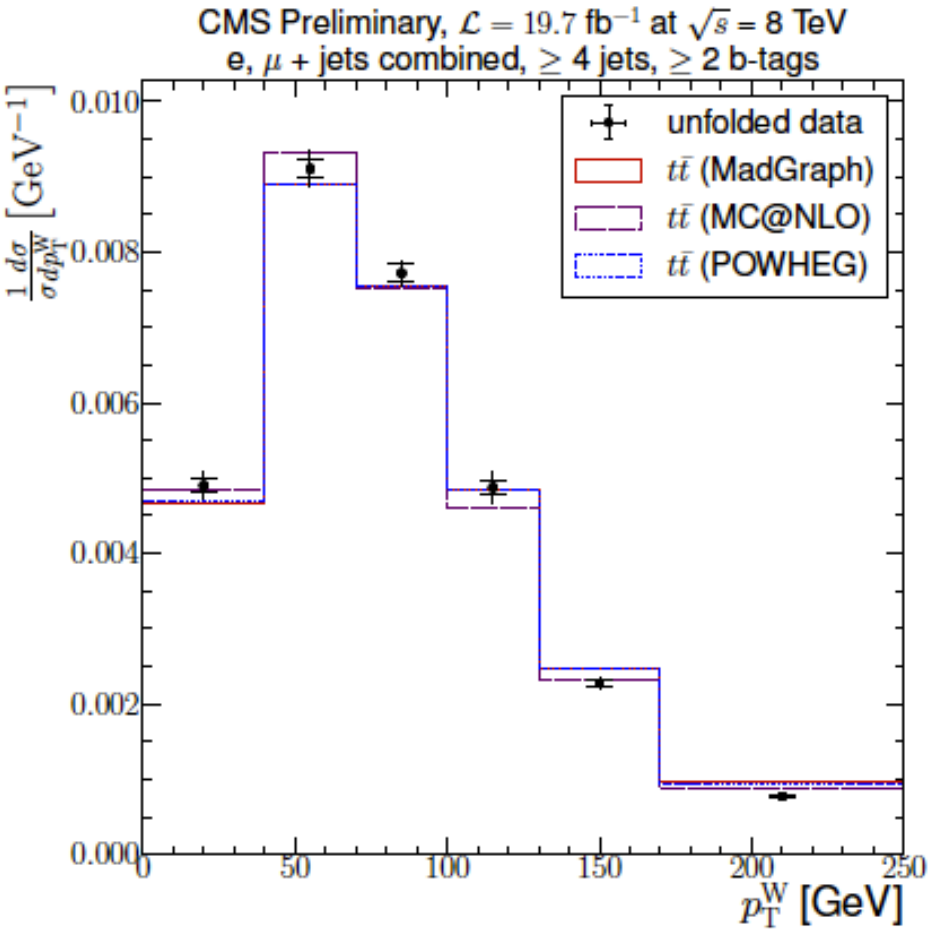


Lepton+jets

Kinematics of top quark events

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

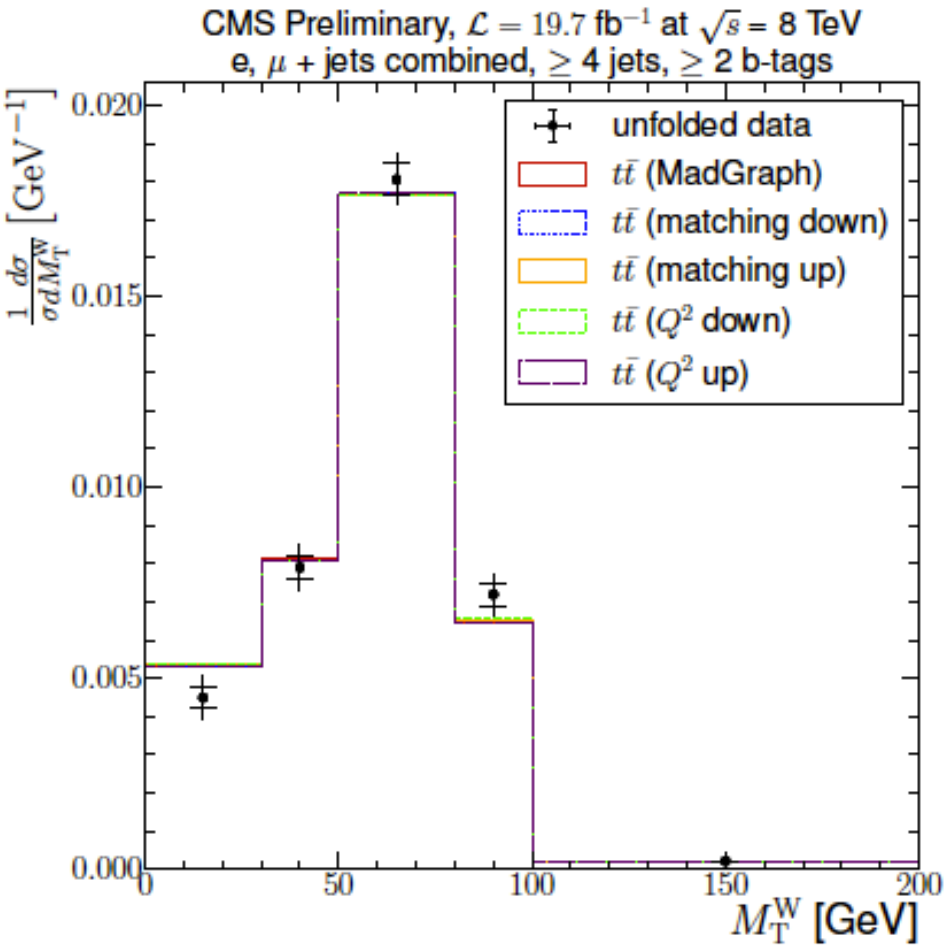


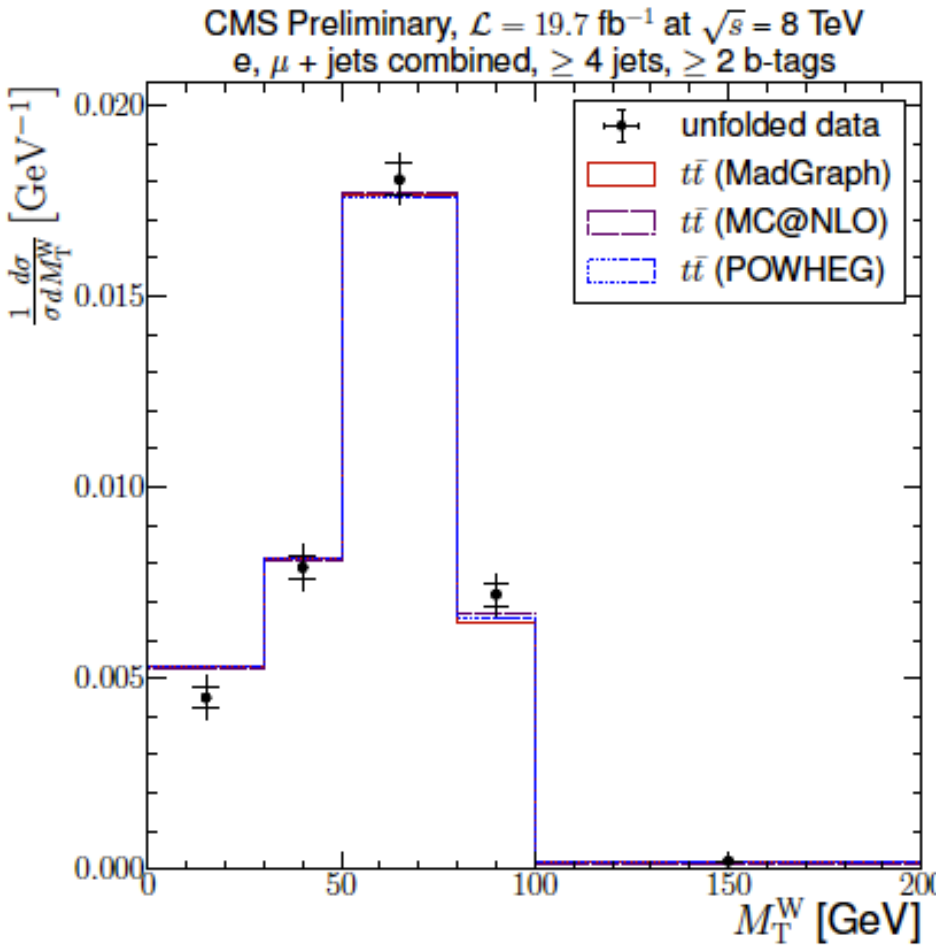


Lepton+jets

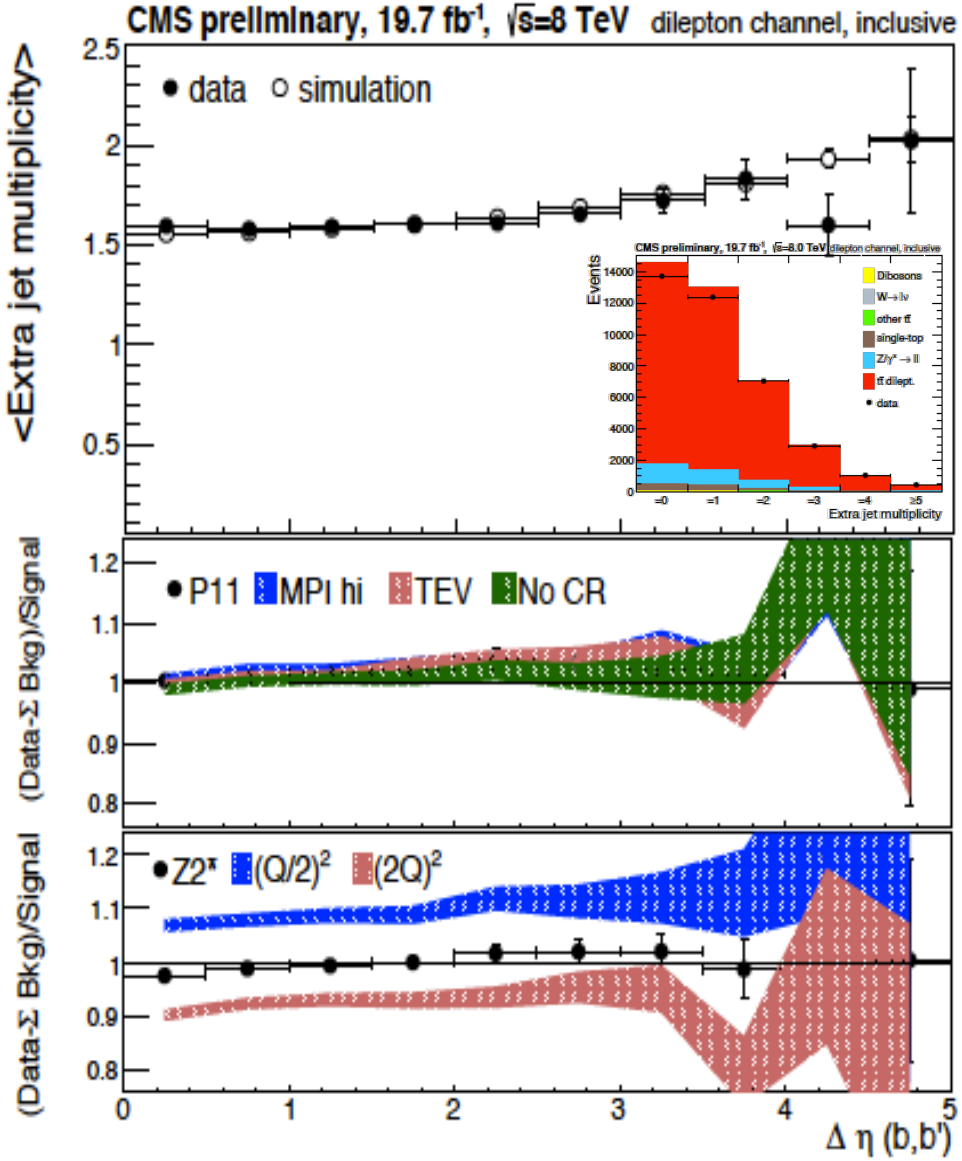
Kinematics of top quark events

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

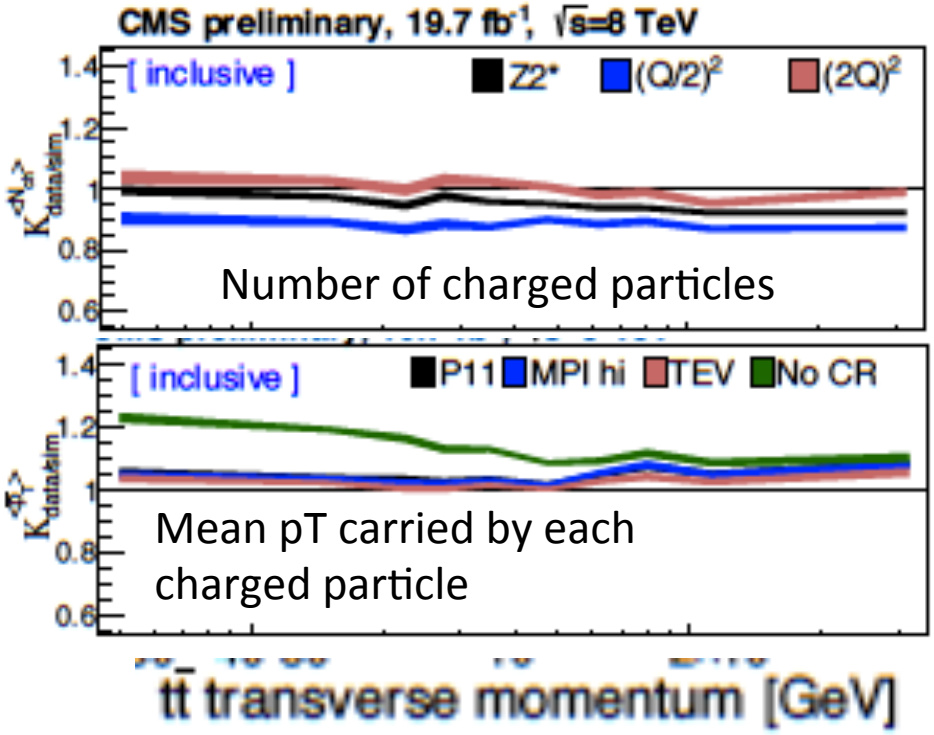




Study of systematic in top quark events



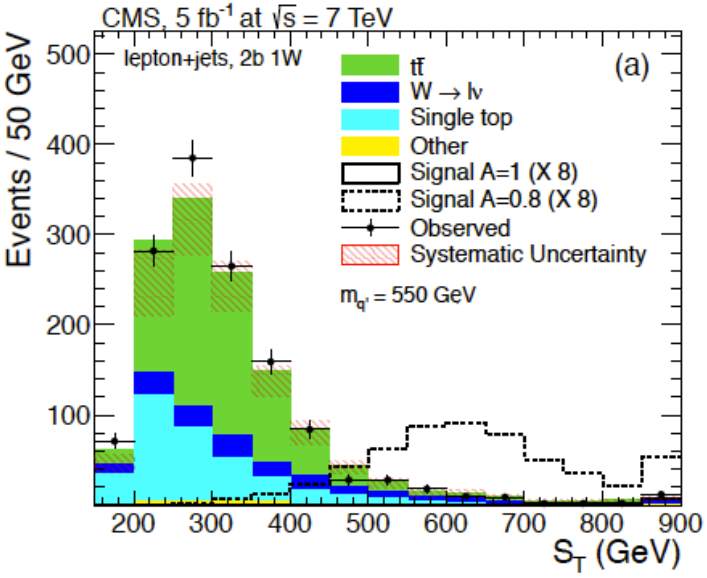
$$\kappa^{x}_{\mathrm{data/sim}}\left(\langle p_{\mathrm{T}}(\mathrm{t\bar{t}})\rangle\right) = \frac{\langle x^{\mathrm{obs}}\rangle\left(\langle p_{\mathrm{T}}(\mathrm{t\bar{t}})\rangle\right)}{\langle x^{\mathrm{exp}}\rangle\left(\langle p_{\mathrm{T}}(\mathrm{t\bar{t}})\rangle\right)}$$



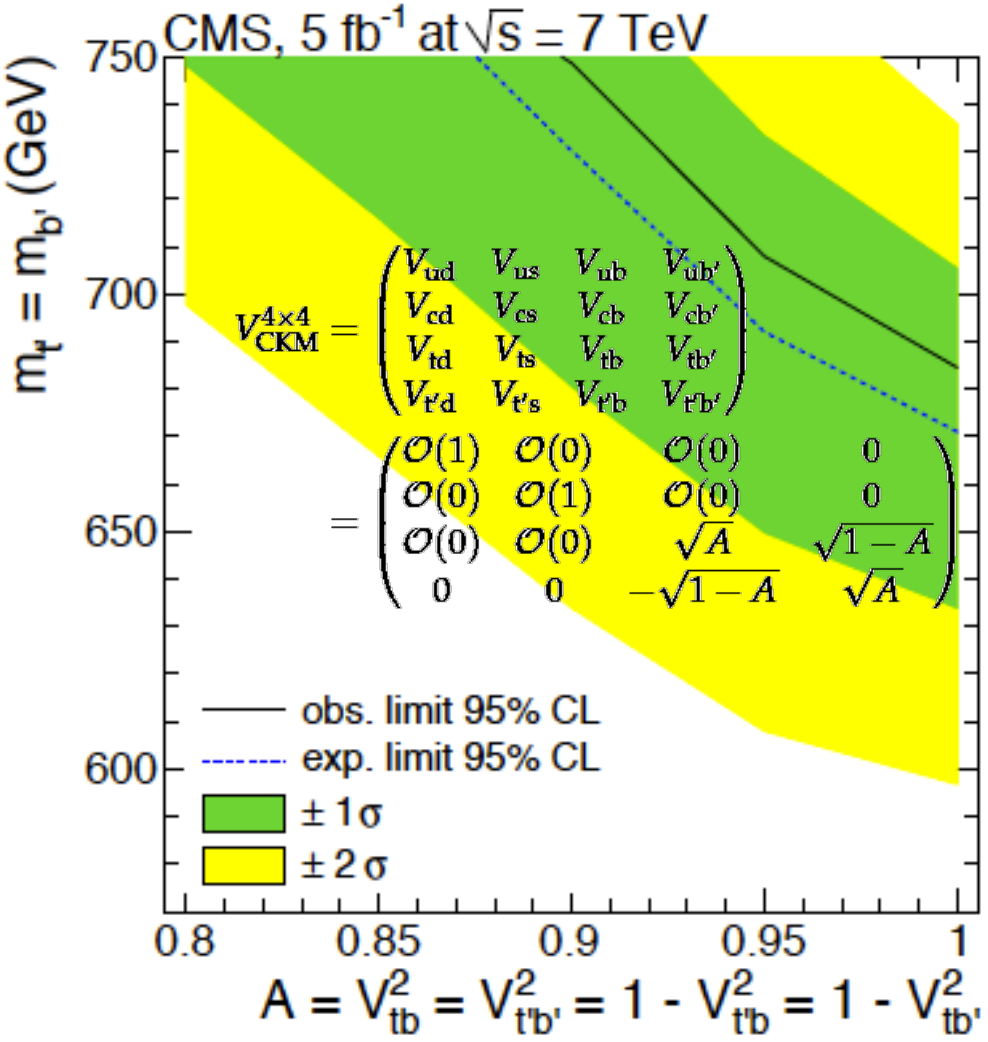
These studies are crucial to enter the precision era of top quark physics at the LHC

arXiv:1209.1062v2

Fourth generation top quarks?

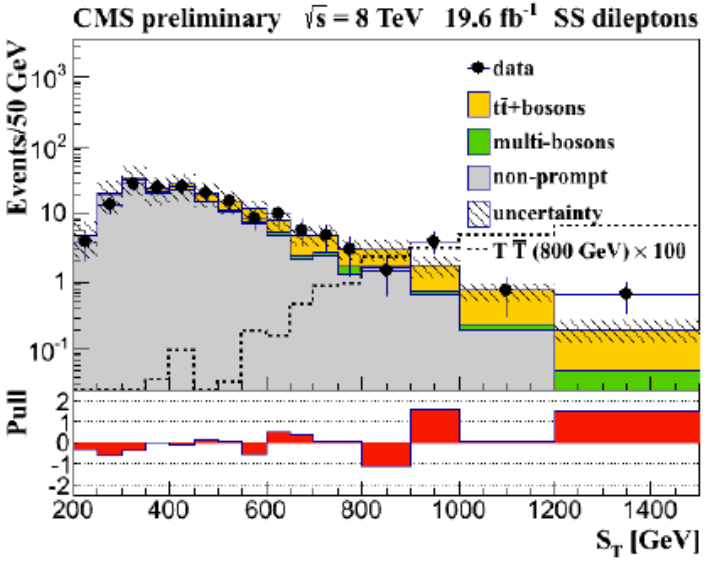


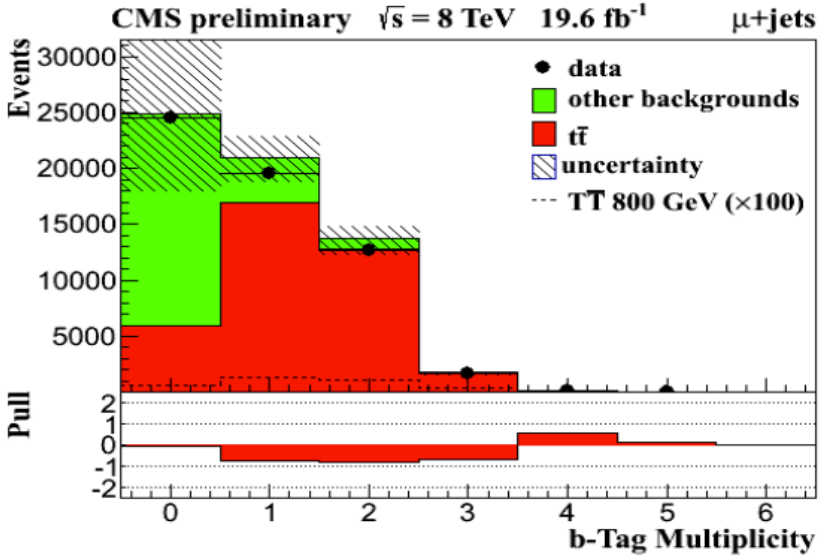
subsample	observable
single-lepton 1W	S_T
single-lepton 2W	S_T and m_{bW}
single-lepton 3W	S_T
single-lepton 4W	event yield
same-sign dilepton	event yield
trilepton	event yield

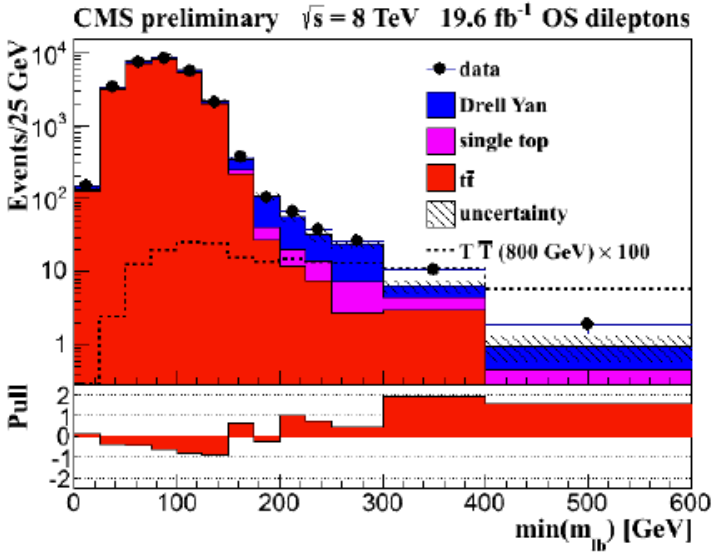


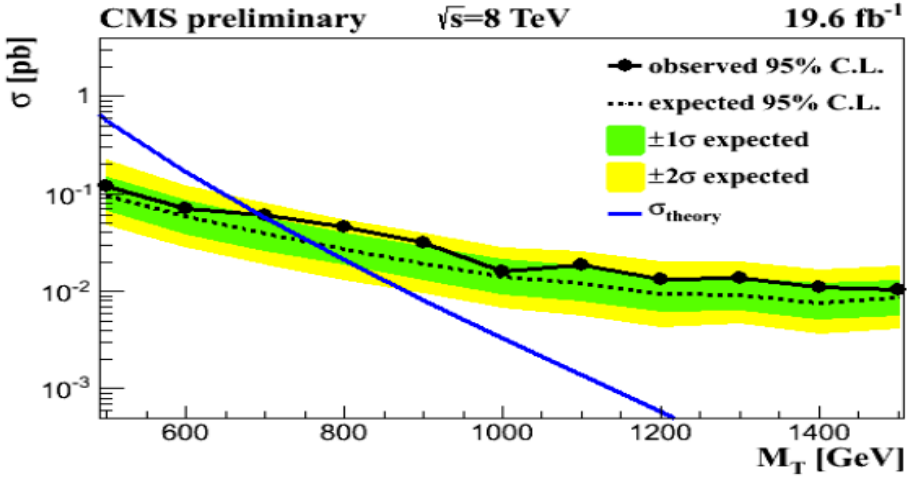
$$V_{\mathrm{CKM}}^{4\times4} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} & V_{ub'} \\ V_{cd} & V_{cs} & V_{cb} & V_{cb'} \\ V_{td} & V_{ts} & V_{tb} & V_{tb'} \\ V_{t'd} & V_{t's} & V_{t'b} & V_{t'b'} \end{pmatrix} = \begin{pmatrix} \mathcal{O}(1) & \mathcal{O}(0) & \mathcal{O}(0) & 0 \\ \mathcal{O}(0) & \mathcal{O}(1) & \mathcal{O}(0) & 0 \\ \mathcal{O}(0) & \mathcal{O}(0) & \sqrt{A} & \sqrt{1-A} \\ 0 & 0 & -\sqrt{1-A} & \sqrt{A} \end{pmatrix}$$

Inclusive vector-like T quarks ? Charge 2/3





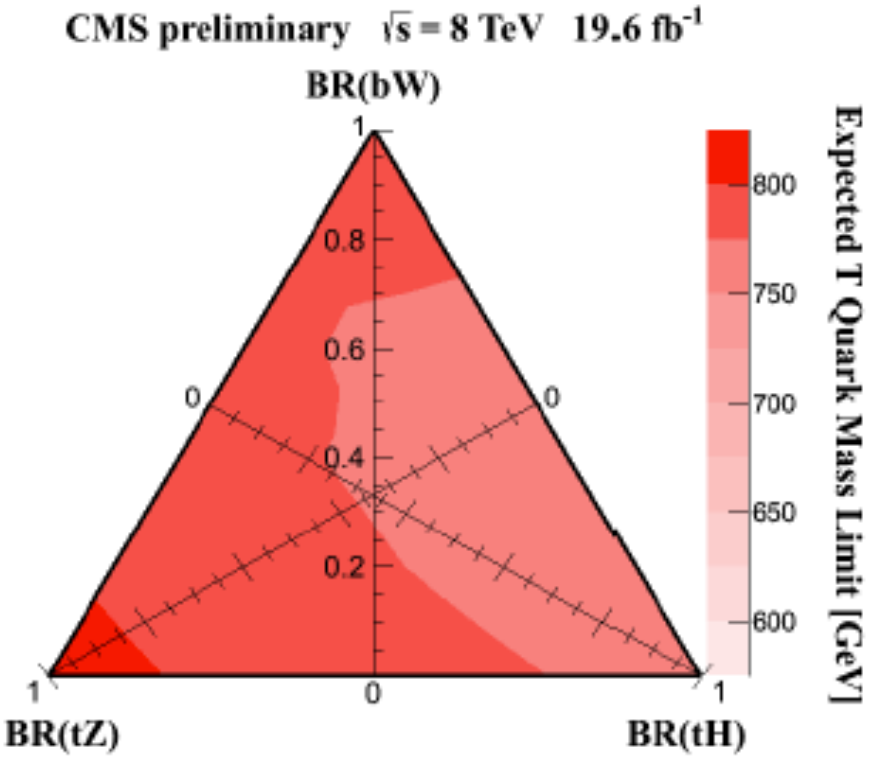


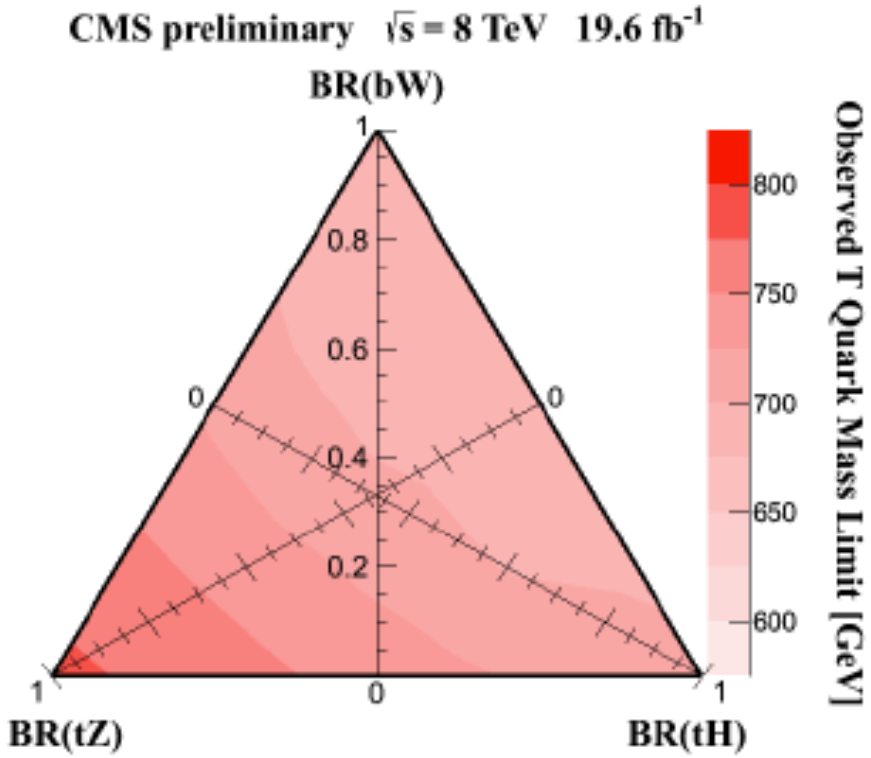


for branching fractions into bW, tH, tZ of 50%, 25%, 25%.

CMS PAS B2G-12-015

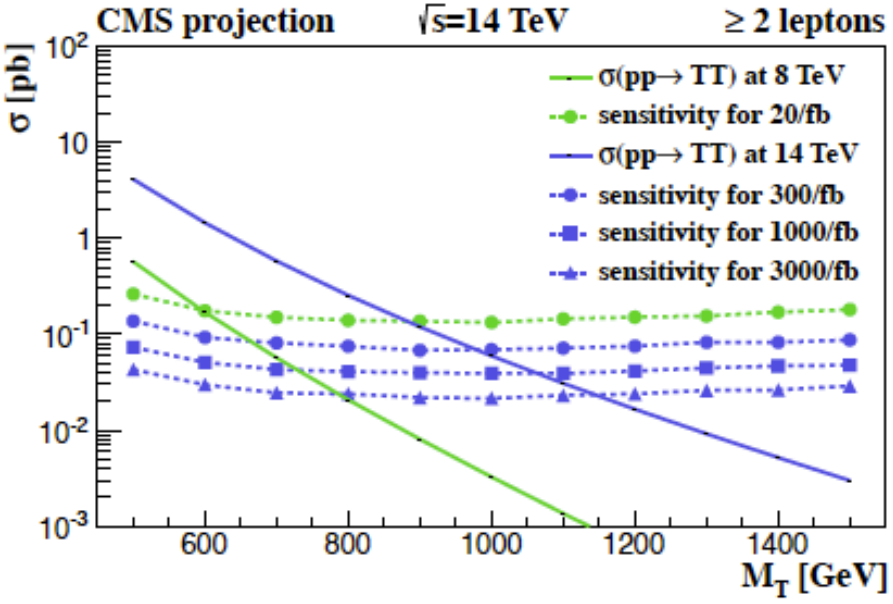
Inclusive vector-like T quarks ?



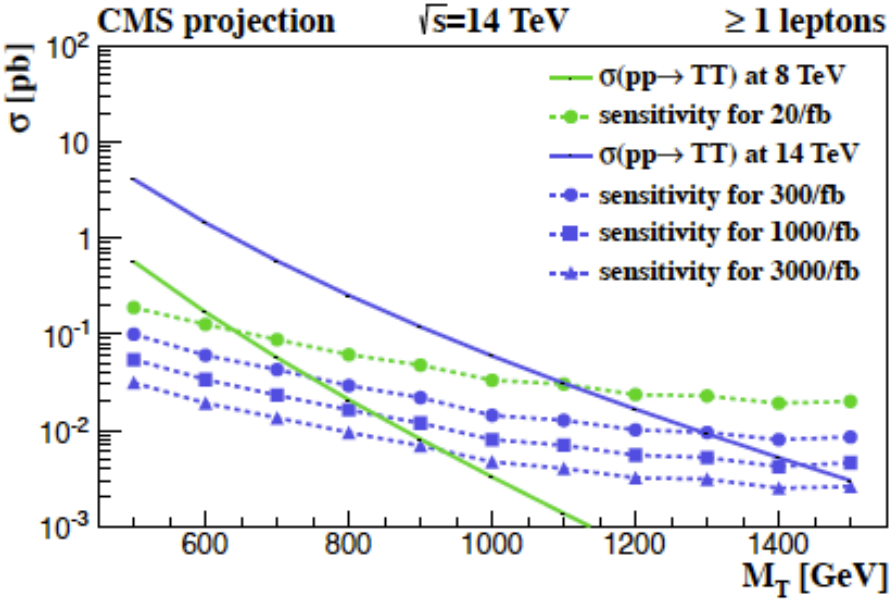


arXiv:1307.7135v2

Inclusive vector-like T quarks: prospects ?

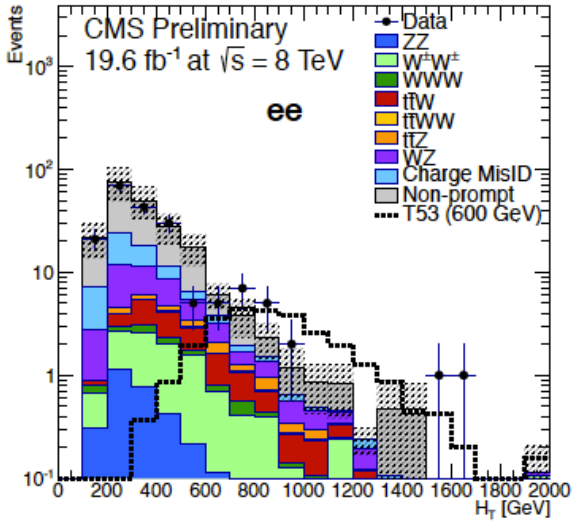


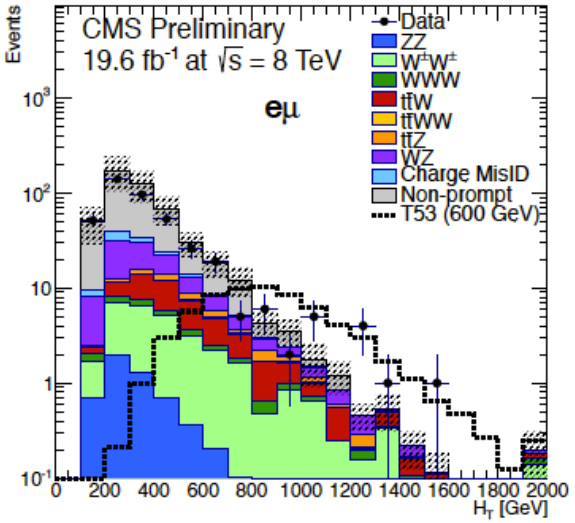
All channels combined

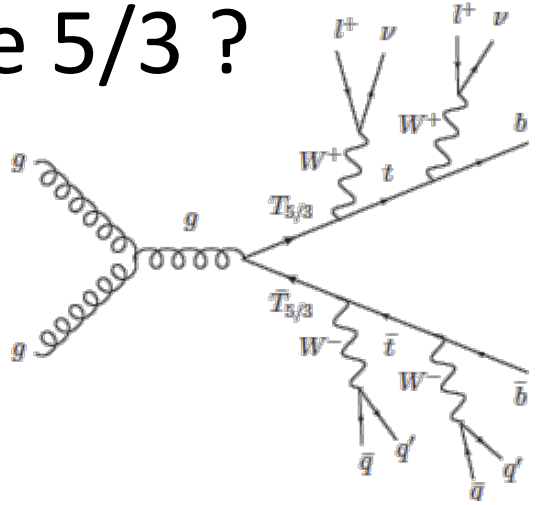


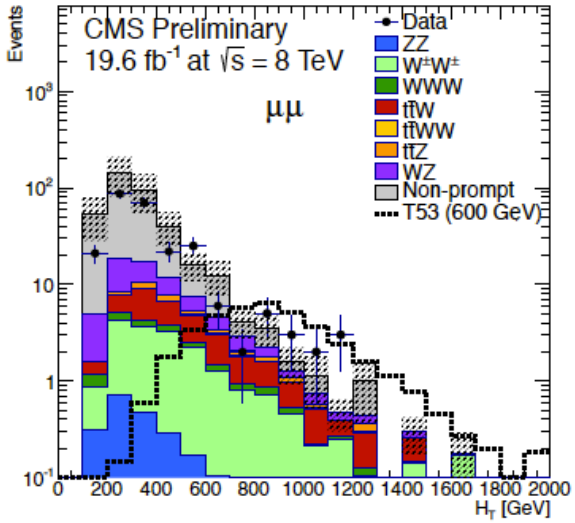
Discovery reach up to 1.2 TeV

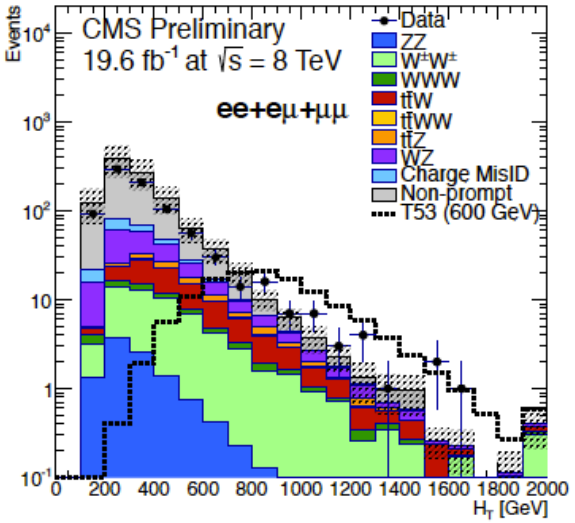
Top Partners with charge 5/3 ?

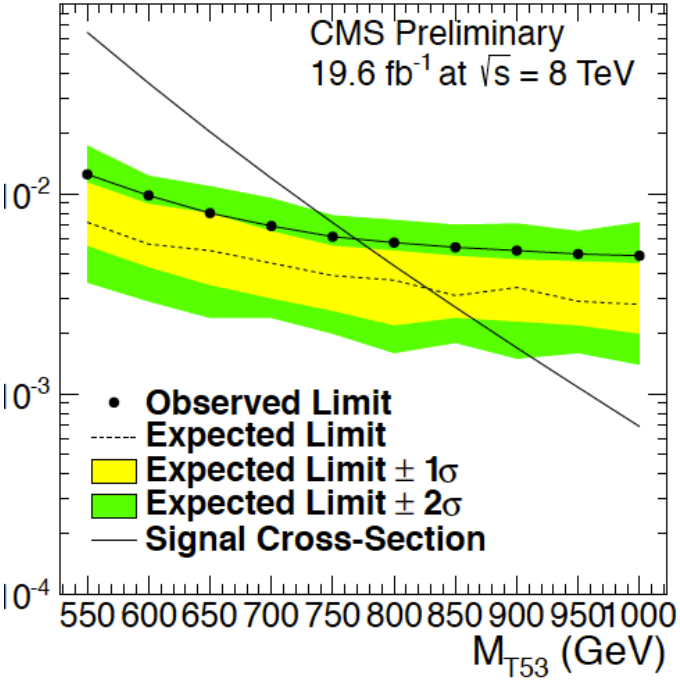








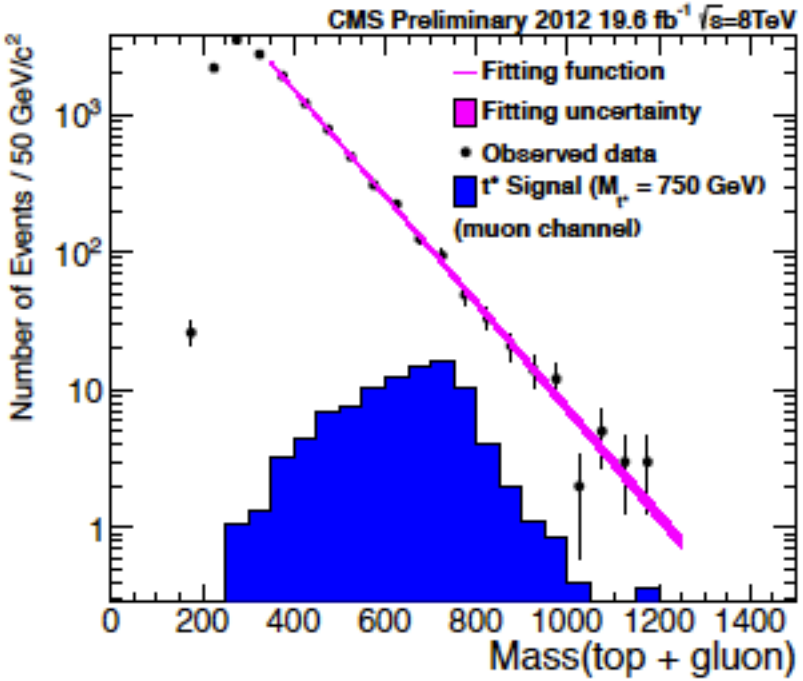


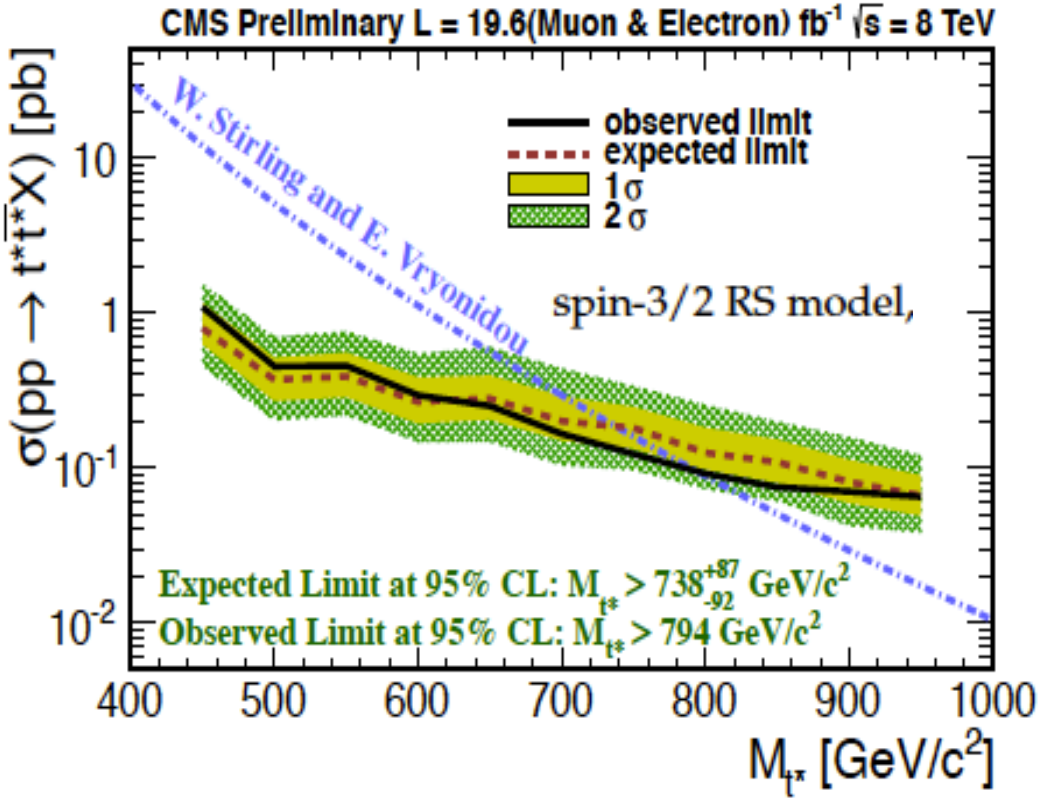


Resonances decaying into top+jets ?

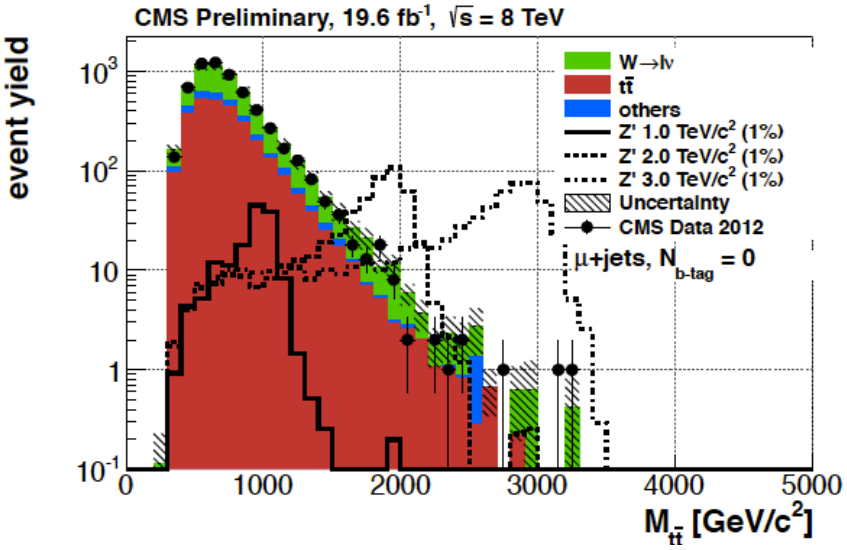
$$m(\ell\nu) = m(q\bar{q}) = M_W$$
$$m(\ell\nu b) = m(q\bar{q}b) = M_t$$
$$m(\ell\nu bg) = m(q\bar{q}bg) = M_{t+g},$$

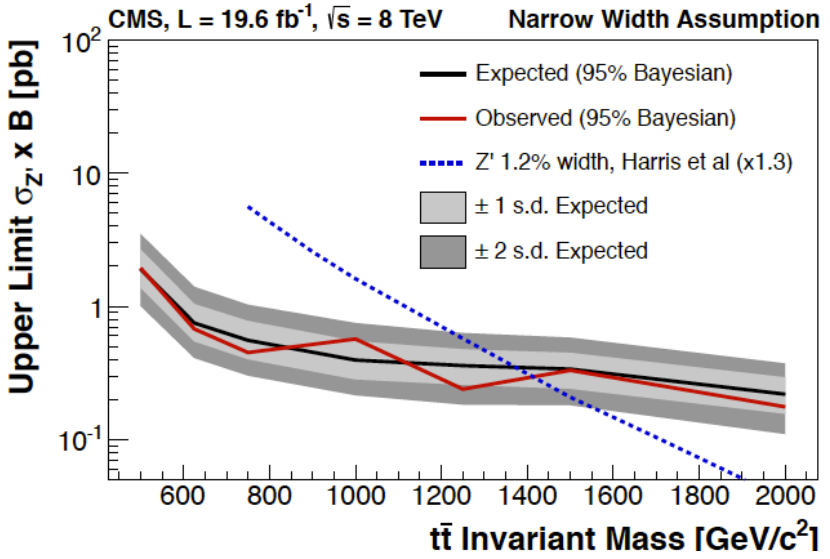
Existed top quark which receives a non-zero mass before applying the Brout-Englert-Higgs mechanism

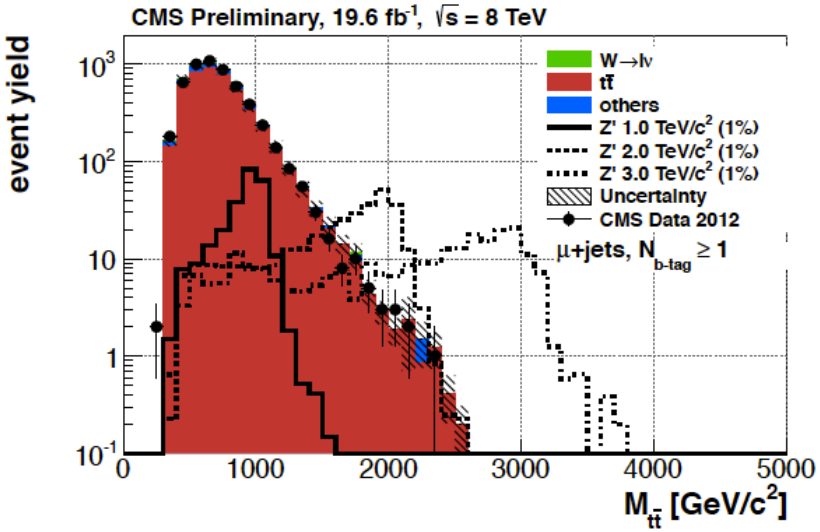


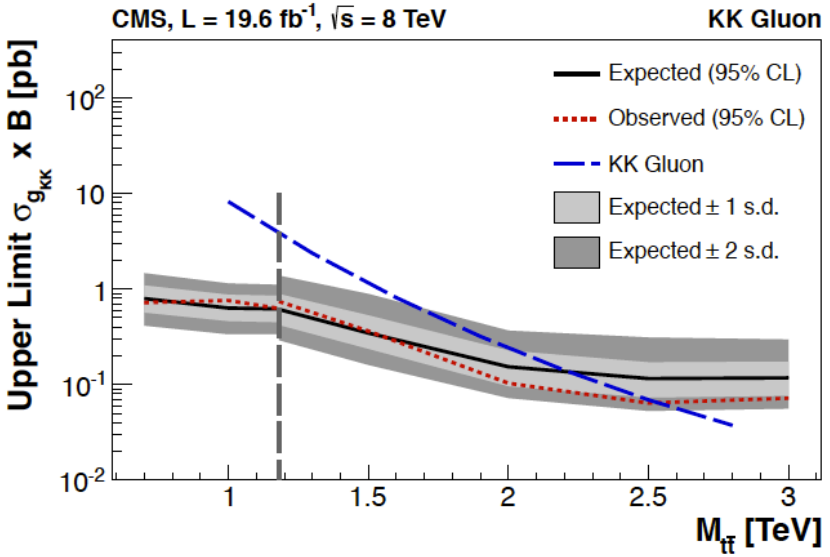


Ttbar resonances ?

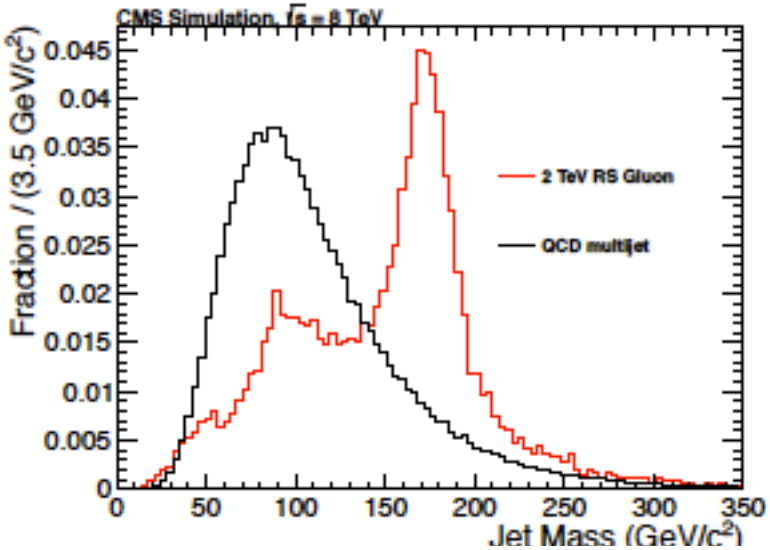


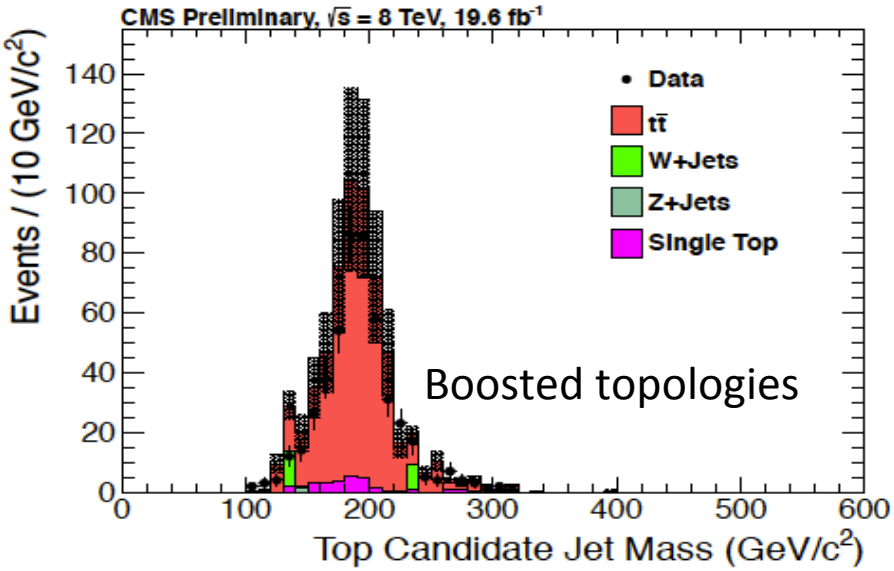


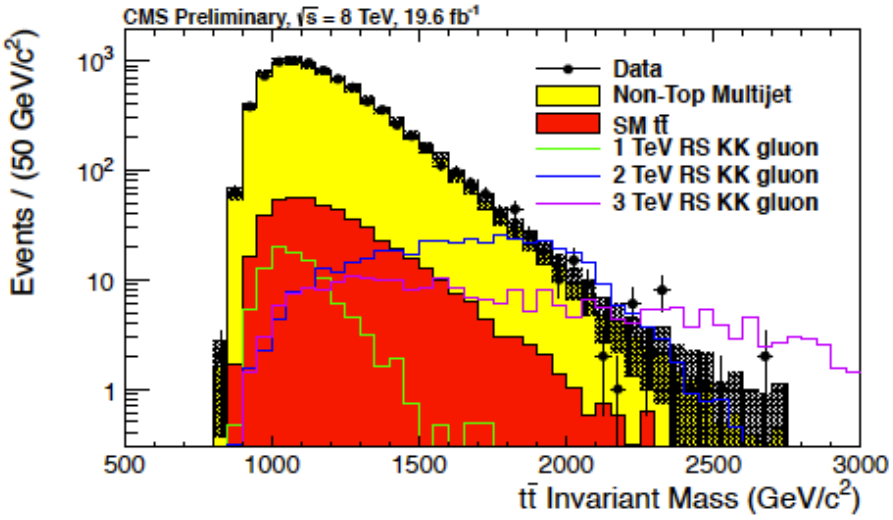


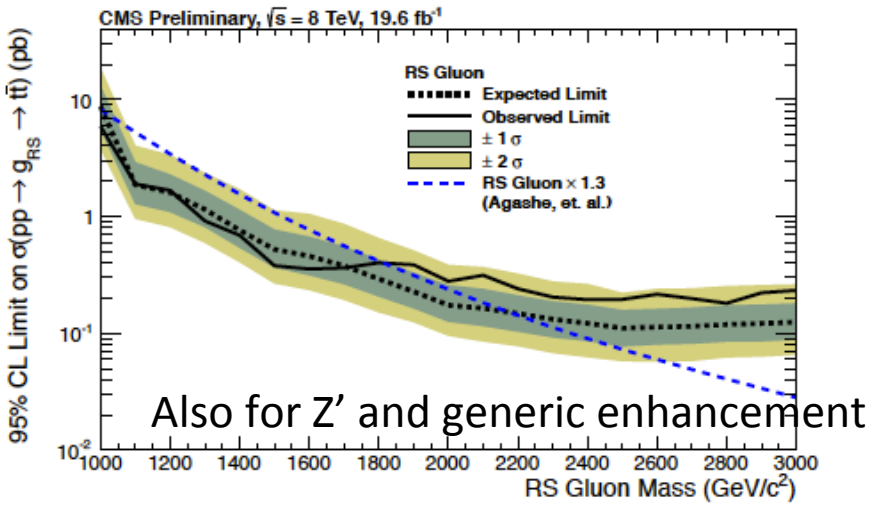


Anomalous top quark production ?









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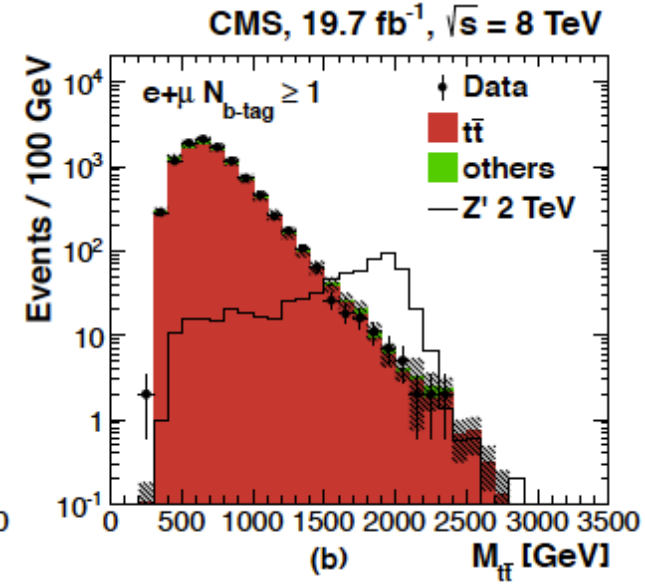
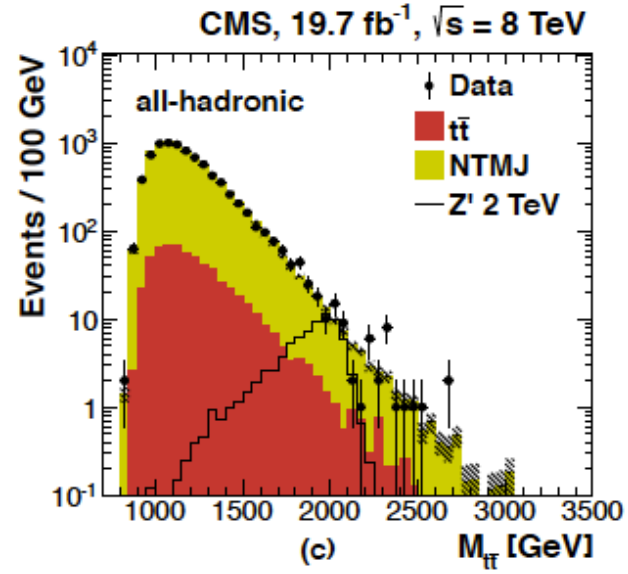
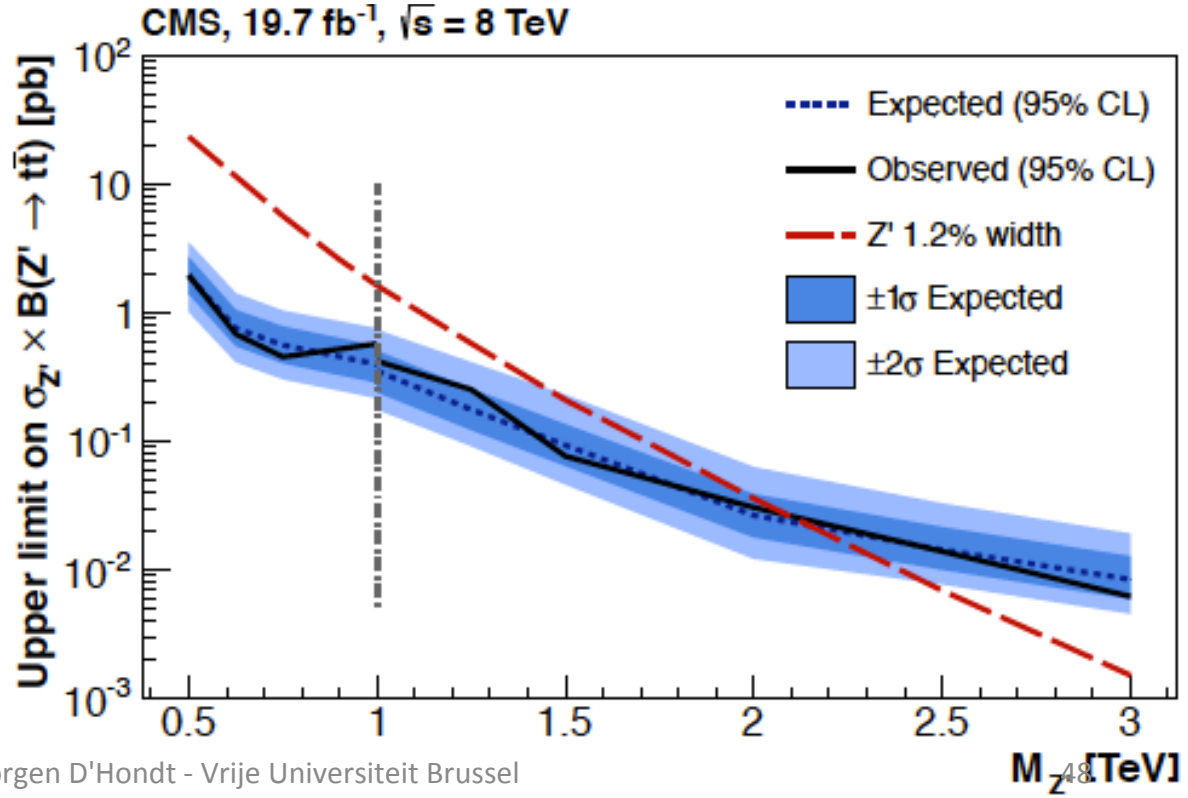




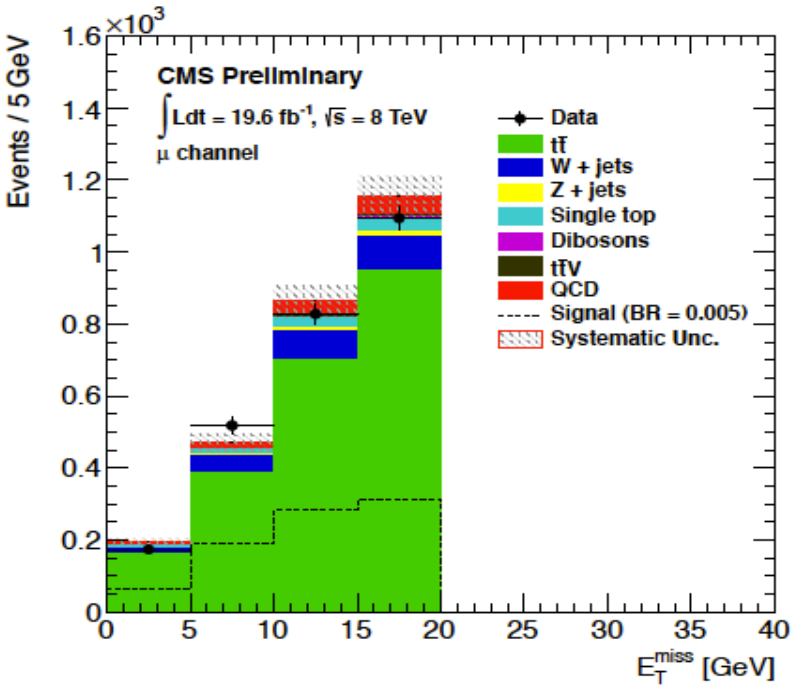
Combined boosted and resolved topology

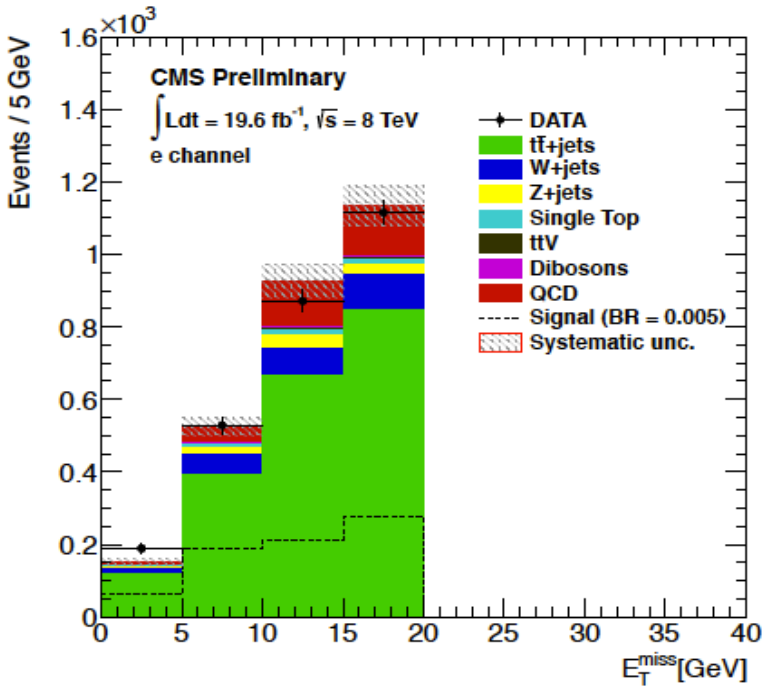
Model	Observed Limit	Expected Limit
$Z', \Gamma_{Z'}/M_{Z'} = 1.2\%$	2.1 TeV	2.1 TeV
$Z', \Gamma_{Z'}/M_{Z'} = 10\%$	2.7 TeV	2.6 TeV
RS KK gluon	2.5 TeV	2.4 TeV



$t \to \bar{b}\bar{c}\mu^+ \; (\bar{t} \to b c \mu^-)$
$t \to \bar{b}\bar{u}e^+ \; (\bar{t} \to b u e^-)$

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]

CMS PAS B2G-12-021

Di-lepton

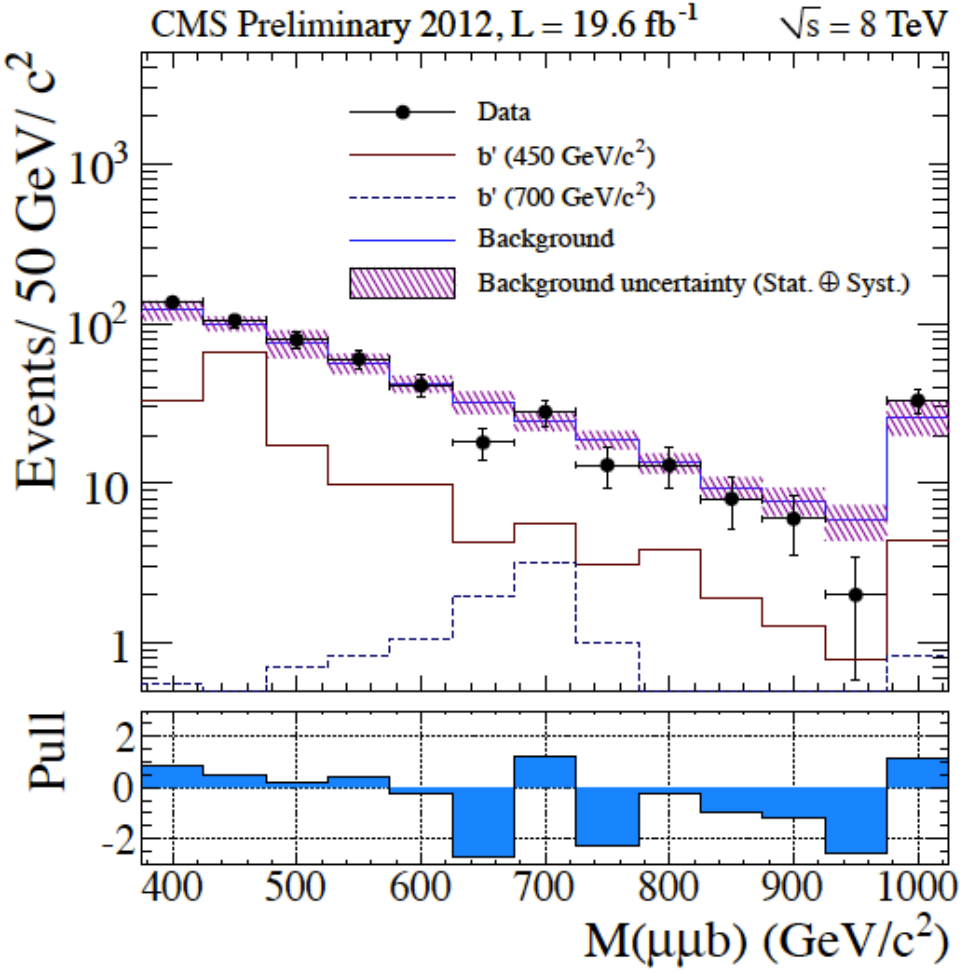
$b' \to bZ$

$BR(b' \to bZ) = 100\%$

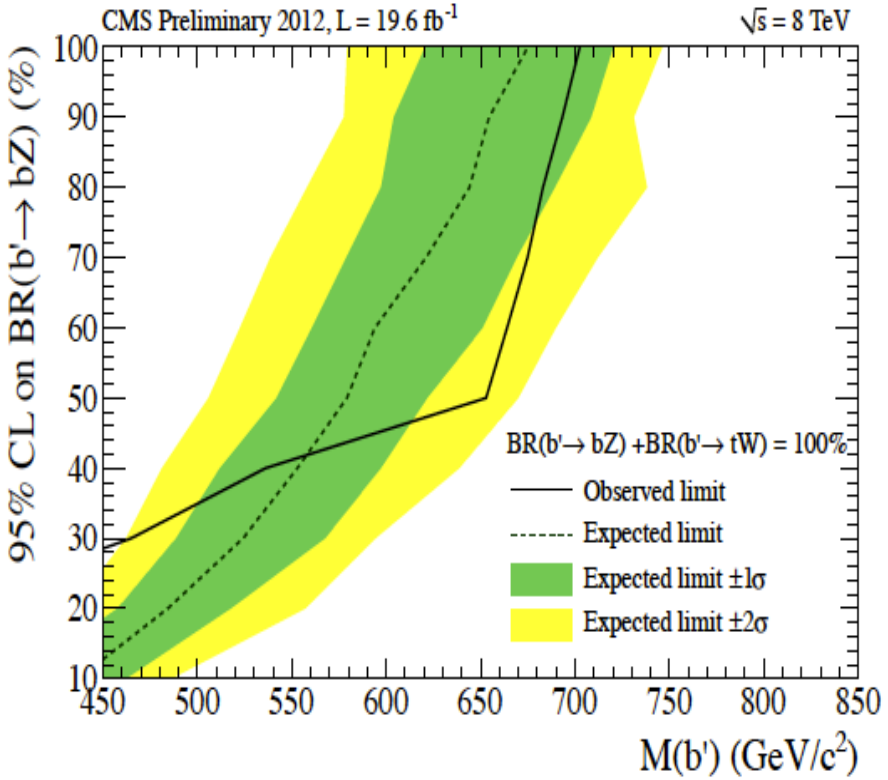
Vector-like b' quarks ?

Charge -1/3

Pair production, single production not yet included



$BR(b' \to bZ) + BR(b' \to tW) = 100\%$



CMS PAS B2G-12-019

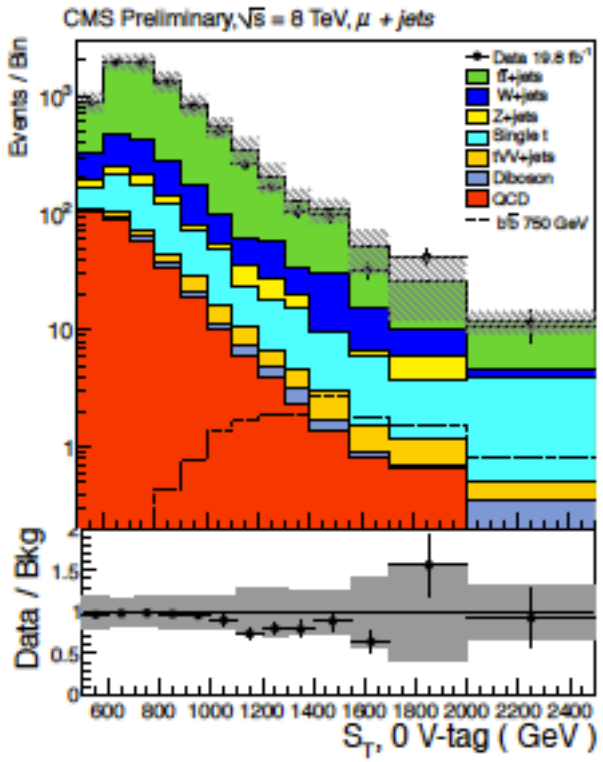
Lepton+jets

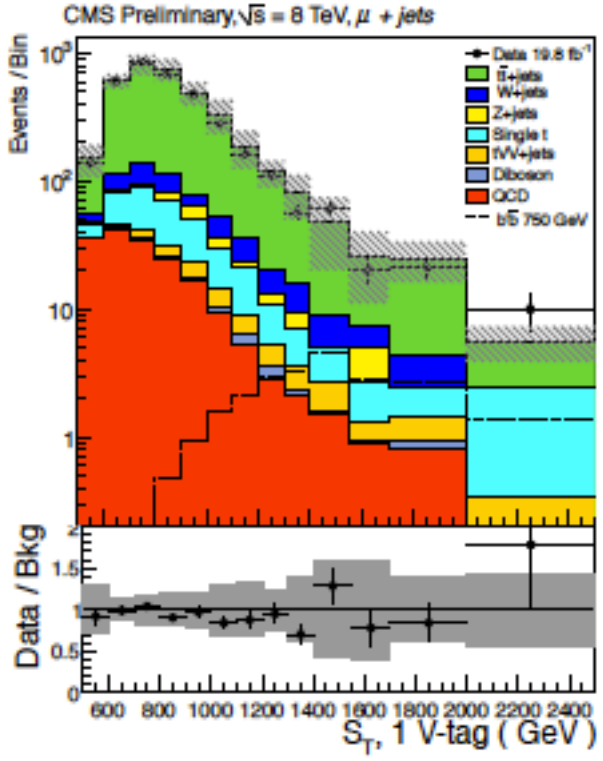
Vector-like b’ quarks ?

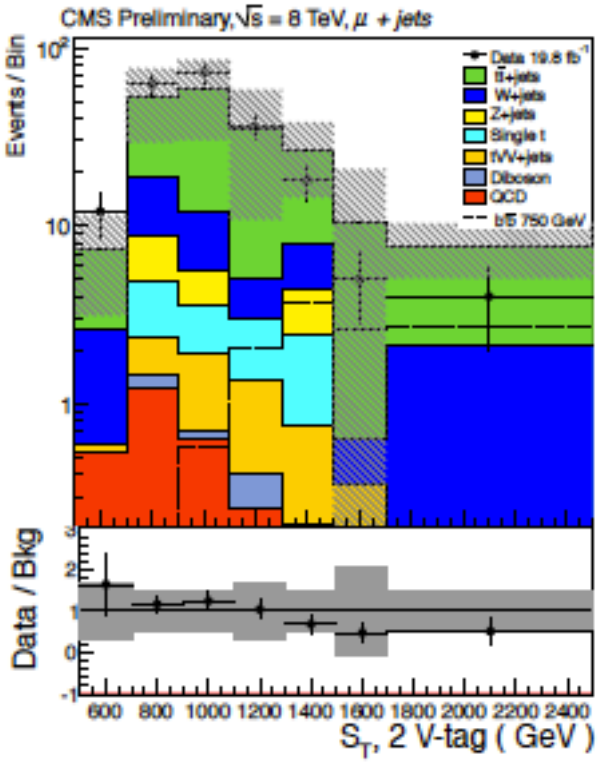
Charge -1/3

Pair production, single production not yet included

b' decays to tW, bH, and bZ







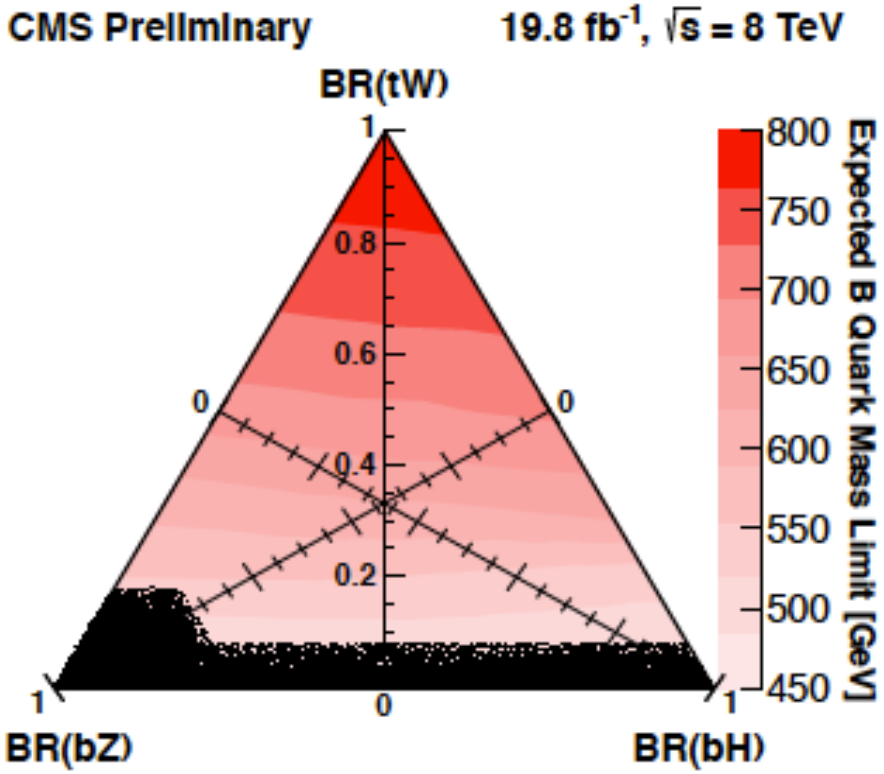
CMS PAS B2G-12-019

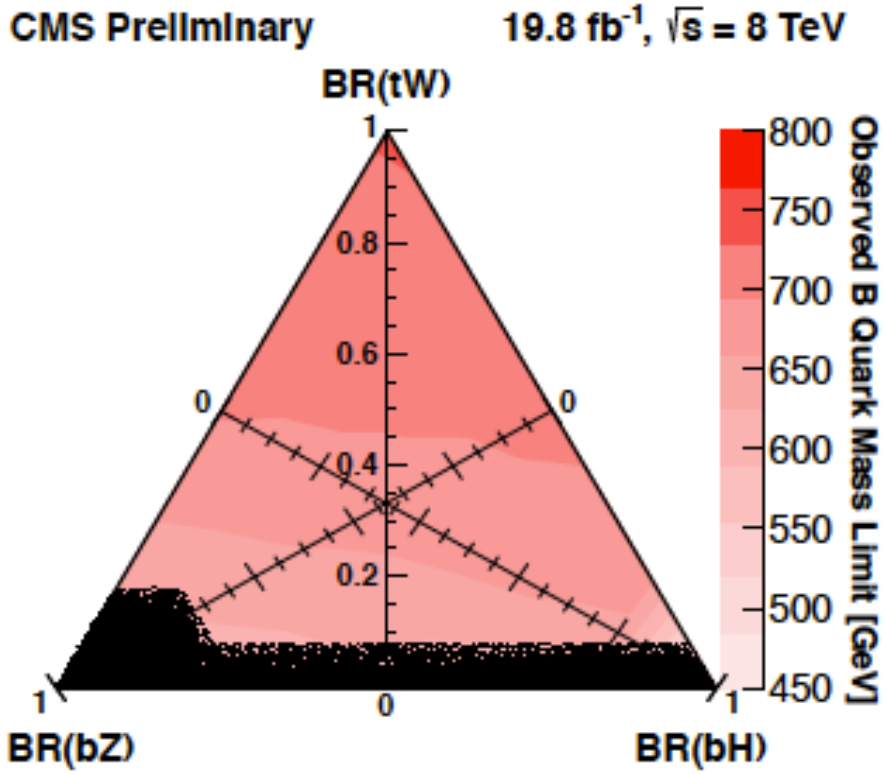
Lepton+jets

Vector-like b' quarks ?

Charge -1/3

Pair production, single production not yet included

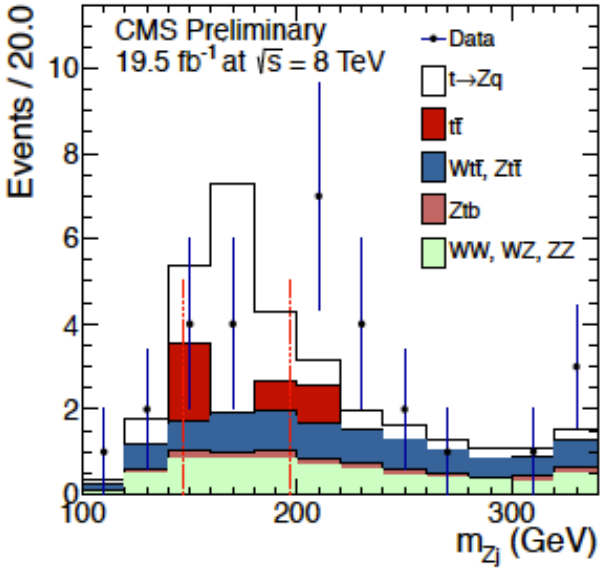


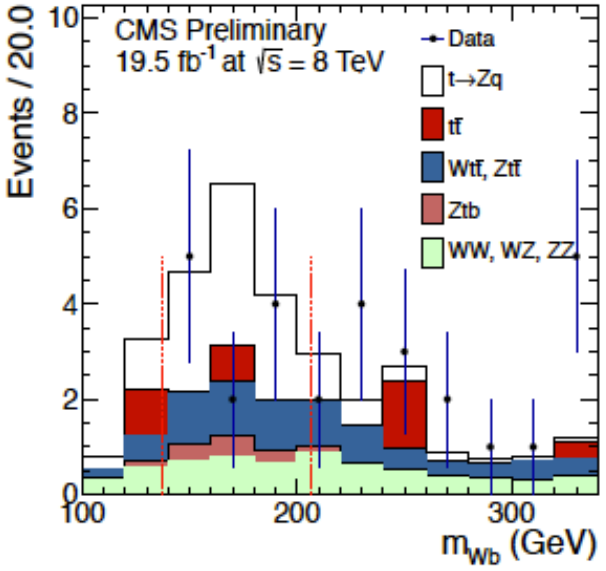


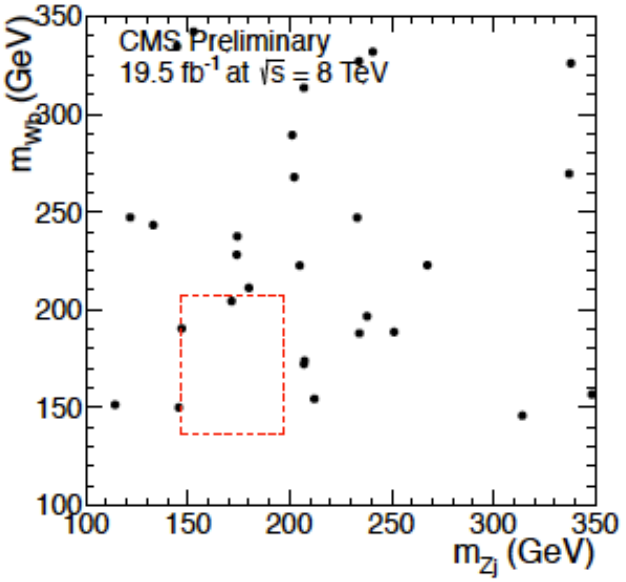
Presentation from R. Goldouzian on "FCNC"

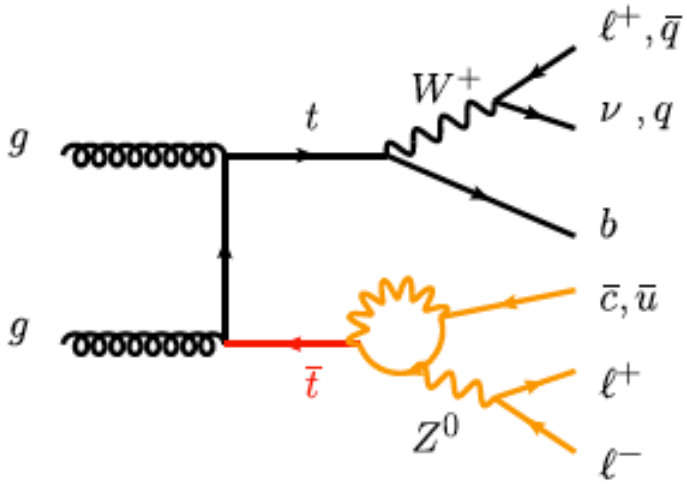
Flavour Changing Neutral Currents ?

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





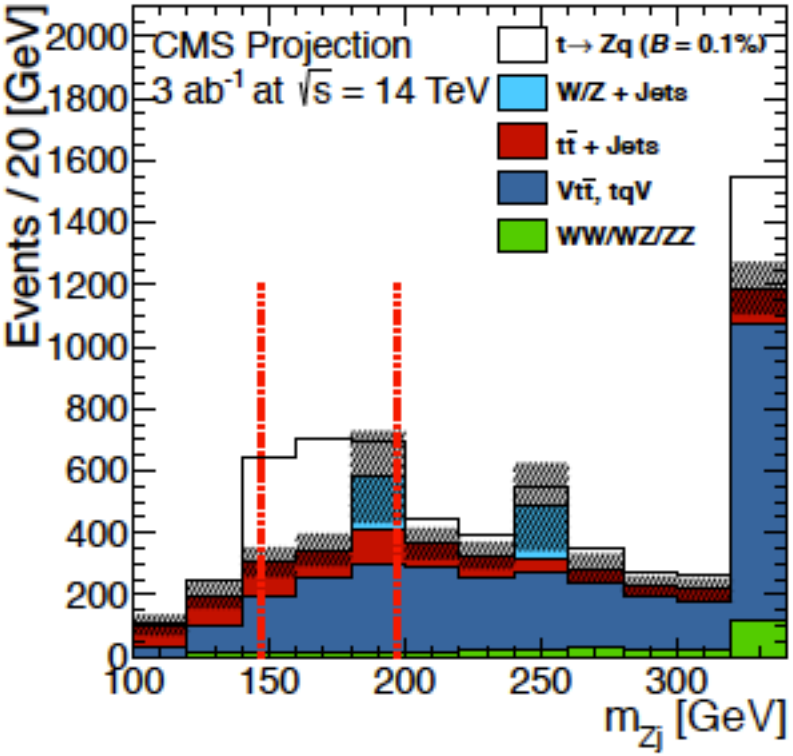


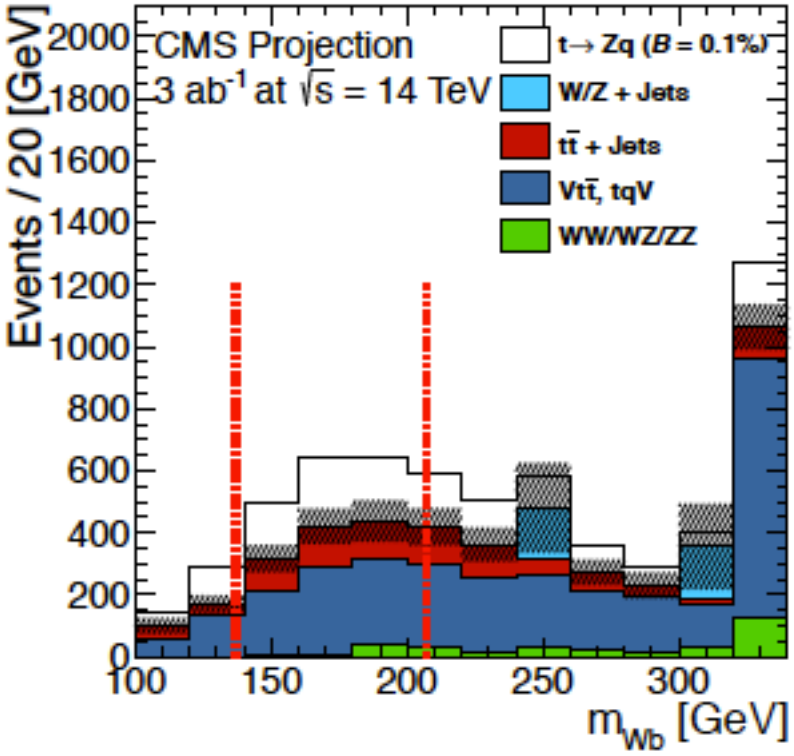


BR(t→Zq) > 0.07% excluded @ 95% CL
(main uncertainty due
to event Q^2 modeling)

$t\bar{t} \to Zq + Wb \to \ell\ell q + \ell'\nu b \; (\ell = e, \mu)$

Flavour Changing Neutral Currents @ 3000/fb ?





$\mathcal{B}(t \to Zq)$	19.5 fb^{-1} @ 8 TeV	300 fb^{-1} @ 14 TeV	3000 fb^{-1} @ 14 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	$0.05 - 0.20\%$	$0.013 - 0.051\%$	$0.005 - 0.020\%$

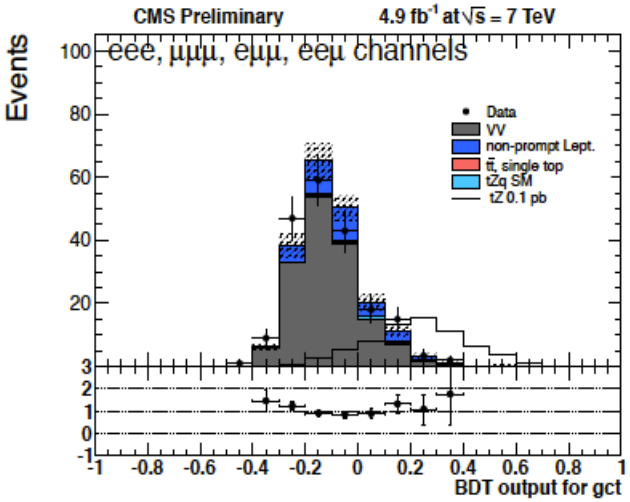
5σ observation from 0.02%

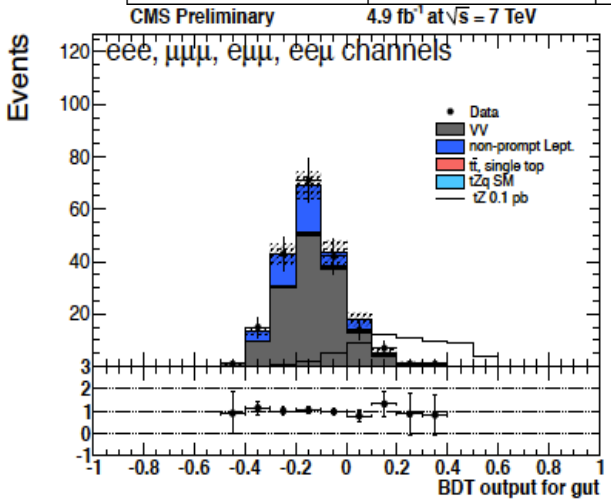
Coupling in the production via an effective Lagrangian

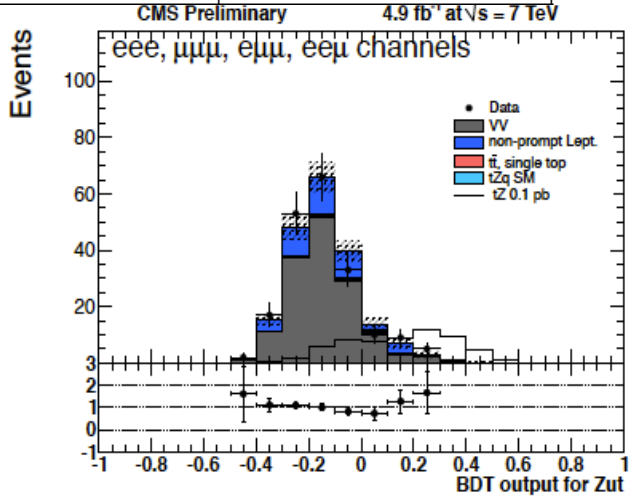
Flavour Changing Neutral Currents in tZ events ?

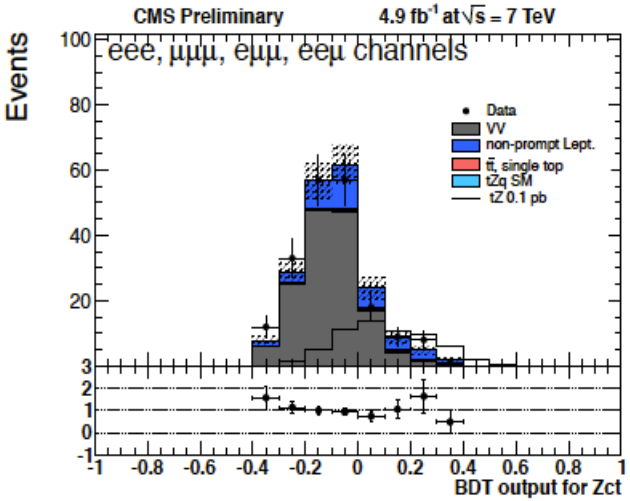
$$\mathcal{L} = \sum_{q=u,c} \left[\sqrt{2} g_s \frac{\kappa_{gqt}}{\Lambda} \bar{t} \sigma^{\mu\nu} T_a (f_q^L P_L + f_q^R P_R) q \, G^a_{\mu\nu} + \frac{g}{\sqrt{2} c_W} \frac{\kappa_{Zqt}}{\Lambda} \bar{t} \sigma^{\mu\nu} (\hat{f}_q^L P_L + \hat{f}_q^R P_R) q \, Z_{\mu\nu} \right] + \text{h.c.}$$

couplings	Expected	Observed	$\mathcal{B}(t \to gq/Zq)$
κ_{gut}/Λ	0.096	0.096	0.56 %
κ_{gct}/Λ	0.427	0.354	7.12 %
κ_{Zut}/Λ	0.492	0.451	0.51 %
κ_{Zct}/Λ	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→Zq) < 0.07% (systematics!)

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