Top-quark properties and single top at CMS

Kirill Skovpen (IPHC Strasbourg, CNRS)
on behalf of the CMS collaboration

Les Rencontres de Physique de la Vallée d'Aoste

La Thuile, March 1-7, 2015

Outline

Top-quark properties

- W-boson helicity
- Polarisation and spin correlations
- Charge asymmetry

Single top production

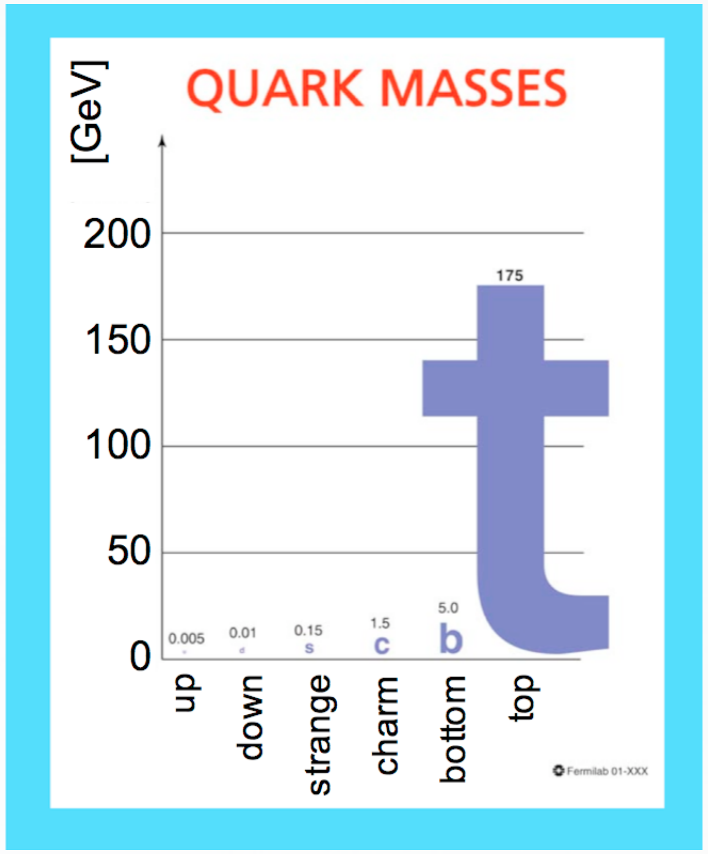
- t-channel
- tW production
- s-channel

.. and searches for new physics

(FCNC and anomalous couplings)

Top quark

- Top quark is the **heaviest** elementary particle ever discovered
- An excellent candidate to study EW symmetry breaking mechanism and fermion mass hierarchy due to its **large Yukawa coupling** ($y_t \approx 1$)
- Almost exclusively decays to W-boson and b-quark
- The **lifetime of a top-quark is much shorter** than hadronisation and spin decorrelation time scales which results in a rather clean experimental signature
- Properties of the top quarks could be studied directly with the decay objects
- The **new physics** could appear in observed anomalies of the top-quark properties



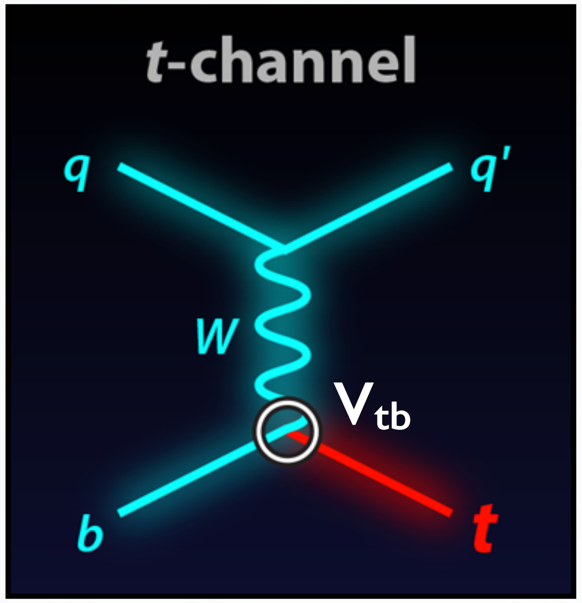
1977: b-quark discovered at Fermilab (E288), the sixth quark is out there …

1995: discovery of top-quark at Fermilab

2010: LHC is a top factory

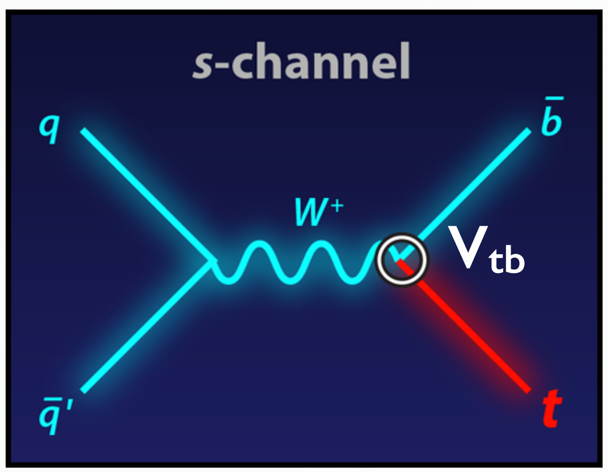
Single top production at the LHC

Three production mechanisms

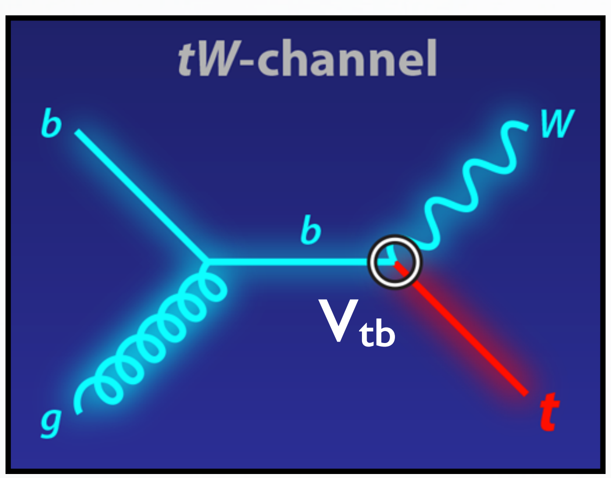


$\sigma_{t\text{-ch}}$(8TeV) = **87.2** ± 2.8 (scale) ± 2.2 (PDF) pb

t- and s-channels were observed for the first time at Tevatron

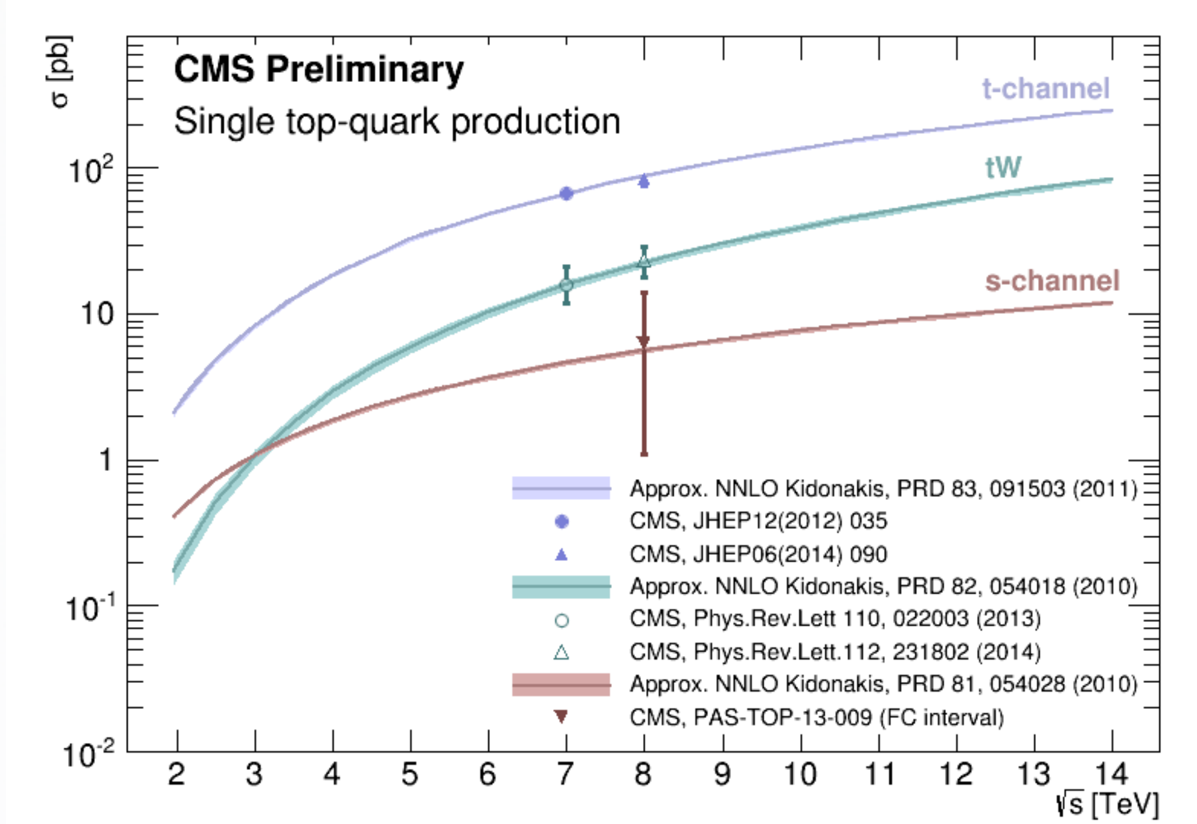


$\sigma_{s\text{-ch}}$(8TeV) = **5.55** ± 0.08 (scale) ± 0.21 (PDF) pb



σ_{tW}(8TeV) = **22.2** ± 0.6 (scale) ± 1.4 (PDF) pb

tW production first observed by CMS

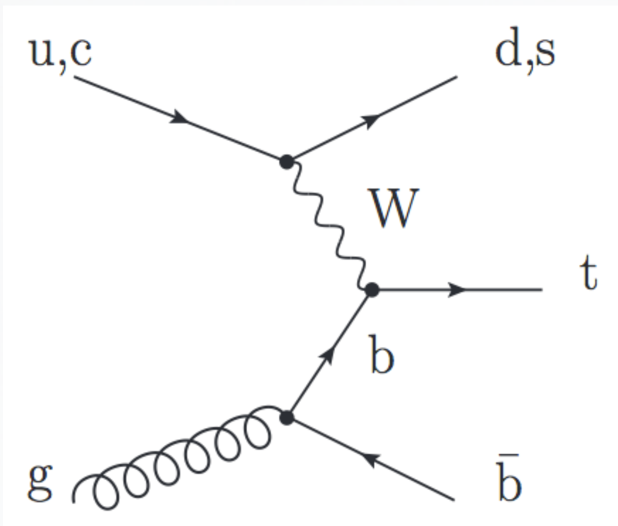


N. Kidonakis, "Differential and total cross sections for top pair and single top production", arXiv:1205.3453.

- Direct probe of electroweak interactions (as opposed to ttbar production which is of strong-type)
- Search for new physics
- Wtb vertex is involved in all SM single top production mechanism - determination of CKM matrix element $|V_{tb}|$ from the measured cross-sections
- Test anomalous Wtb couplings

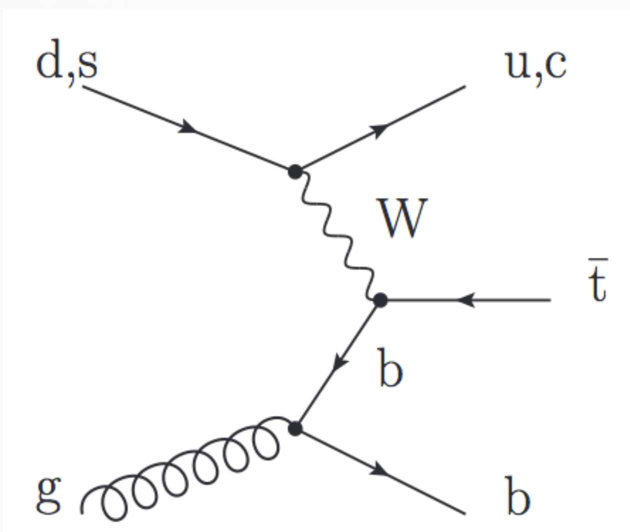
Single top in t-channel

[JHEP 06 (2014) 090]
8 TeV, 20 fb^{-1}



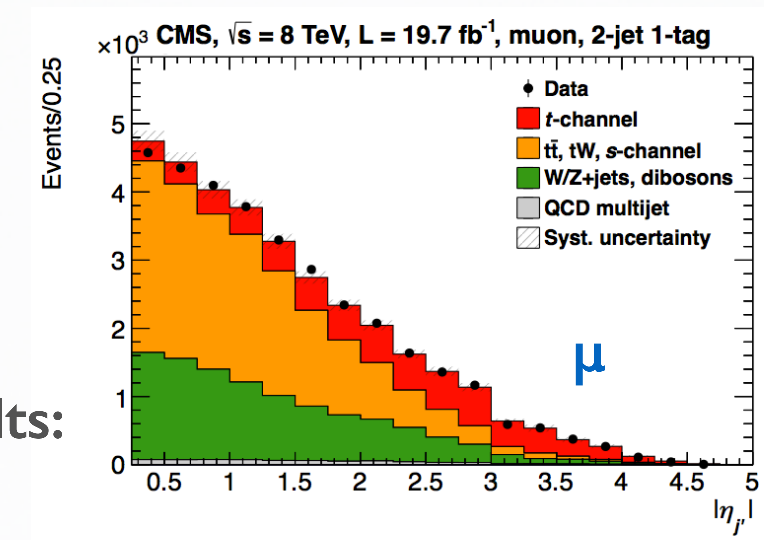
- Exactly one isolated lepton and at least two jets
- Missing E_T > 45 GeV (electron channel), $m_T(W)$ > 50 GeV (muon channel)
- Categorisation on the number of b-tagged jets: 2-jet 1-tag (enriched in signal); 3-jet 1-tag, 3-jet 2-tag, 2-jet 0-tag (control samples)

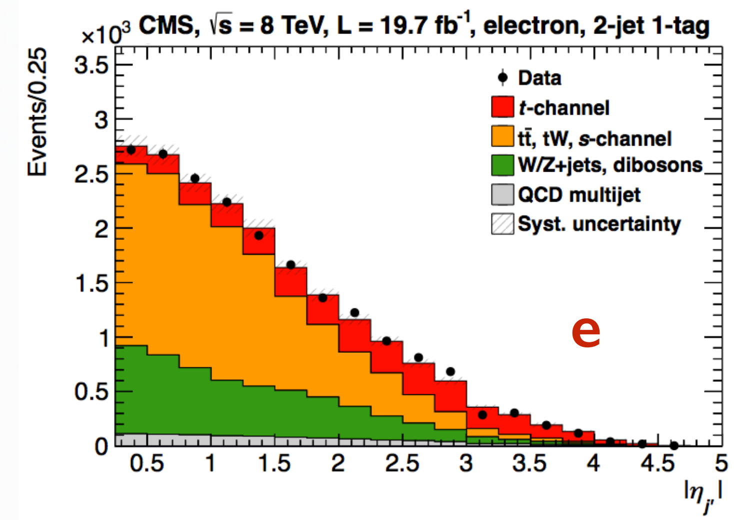
Main backgrounds: ttbar, W/Z+jets and QCD multijet production



POWHEG
+PYTHIA

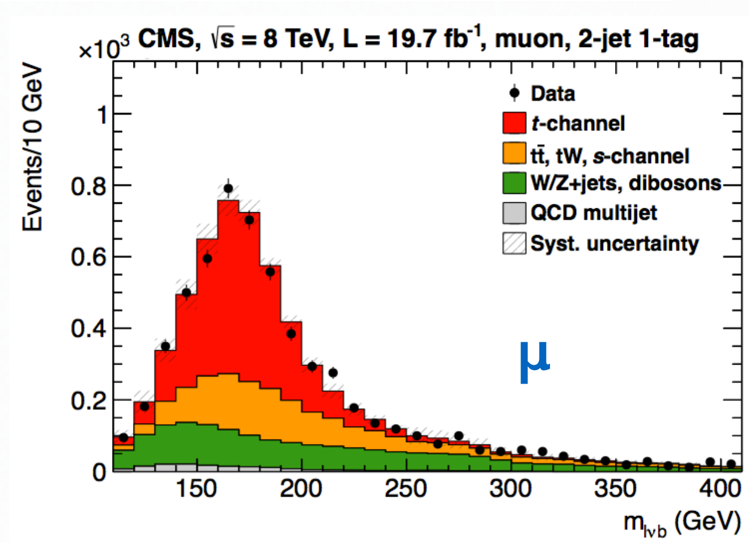
Fit results:

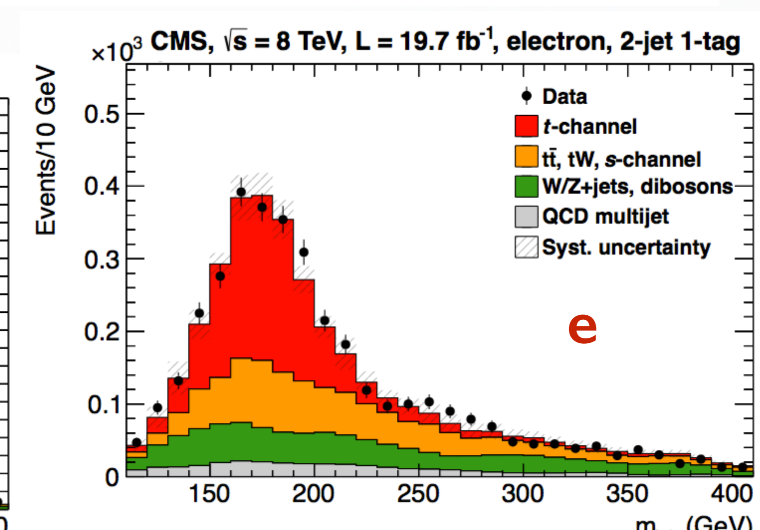




QCD is estimated from data from a template fit with missing E_T (electrons) and $m_T(W)$ (muons)

Data/MC correction factors are measured for **ttbar** and **W/Z+jets backgrounds**

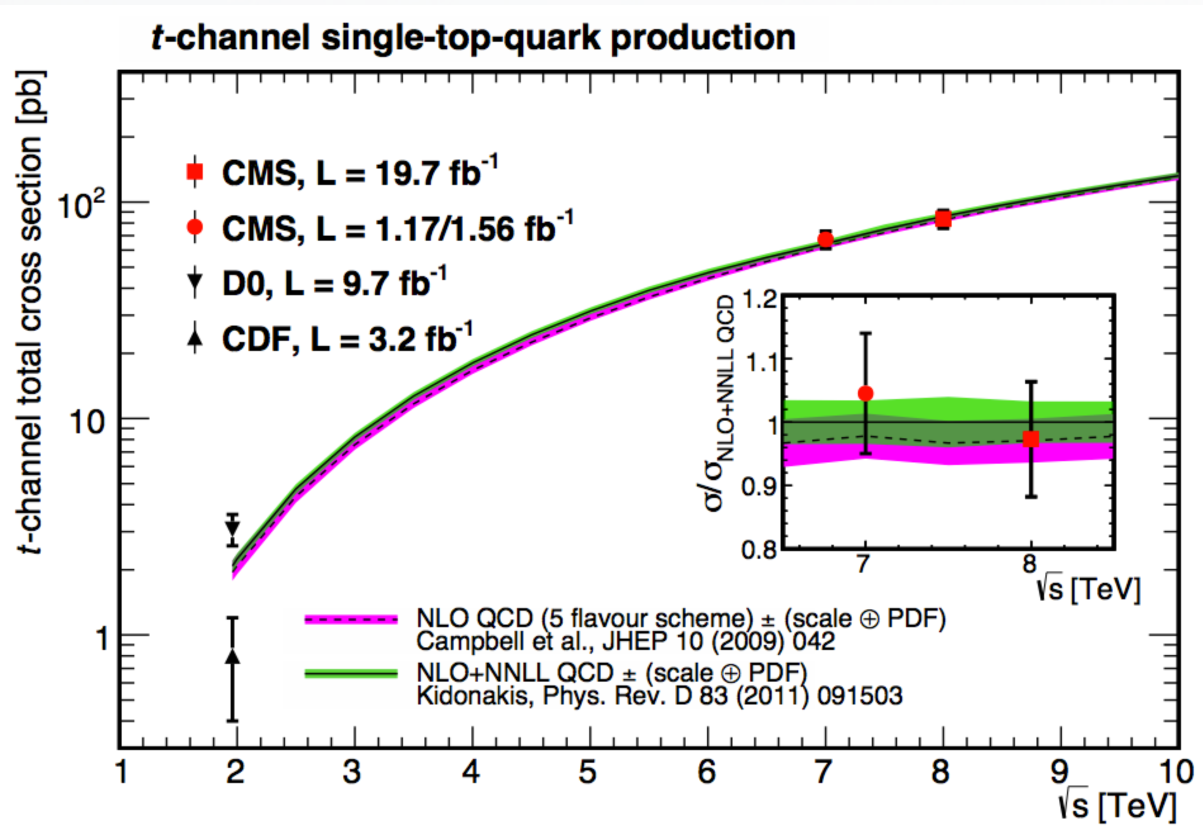


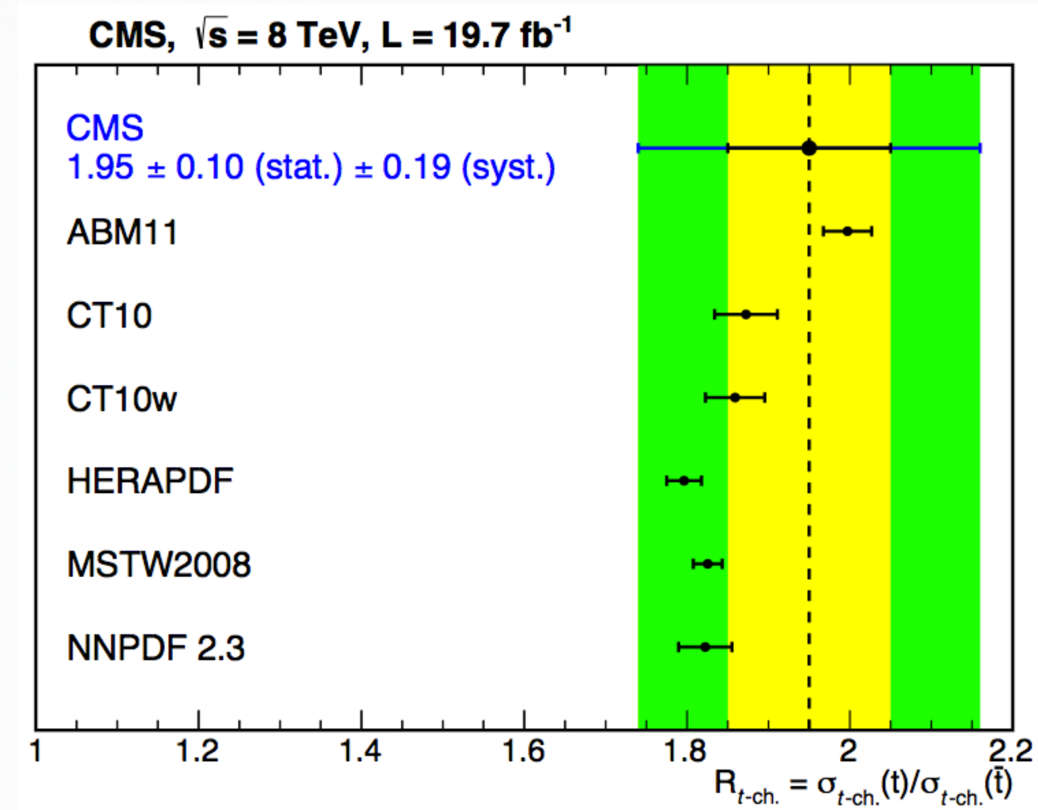


Reconstructed top mass after $|\eta_{j'}| > 2.5$

Single top in t-channel

JHEP 06 (2014) 090
8 TeV, 20 fb^{-1}





$$R^{\text{theo.}}_{8/7} = 1.32^{+0.06}_{-0.02}\,(\text{scale})^{+0.04}_{-0.05}\,(\text{PDF}).$$

$$R_{t\text{-ch.}} = \sigma_{t\text{-ch.}}(\text{t})/\sigma_{t\text{-ch.}}(\bar{\text{t}}) = 1.95 \pm 0.10\,(\text{stat}) \pm 0.19\,(\text{syst})$$

$$R_{8/7} = \sigma_{t\text{-ch.}}(8\,\text{TeV})/\sigma_{t\text{-ch.}}(7\,\text{TeV}) = 1.24 \pm 0.08\,(\text{stat}) \pm 0.12\,(\text{syst.})$$

Measured:

$$\sigma_{t\text{-ch.}} = 83.6 \pm 2.3\,(\text{stat}) \pm 7.4\,(\text{syst})\,\text{pb}$$
$$\sigma_{t\text{-ch.}}(\text{t}) = 53.8 \pm 1.5\,(\text{stat}) \pm 4.4\,(\text{syst})\,\text{pb}$$
$$\sigma_{t\text{-ch.}}(\bar{\text{t}}) = 27.6 \pm 1.3\,(\text{stat}) \pm 3.7\,(\text{syst})\,\text{pb}$$

Predicted:

$$\sigma^{\text{theo.}}_{t\text{-ch.}} = 87.2^{+2.8}_{-1.0}\,(\text{scale})^{+2.0}_{-2.2}\,(\text{PDF})\,\text{pb}$$
$$\sigma^{\text{theo.}}_{t\text{-ch.}}(\text{t}) = 56.4^{+2.1}_{-0.3}\,(\text{scale}) \pm 1.1\,(\text{PDF})\,\text{pb}$$
$$\sigma^{\text{theo.}}_{t\text{-ch.}}(\bar{\text{t}}) = 30.7 \pm 0.7\,(\text{scale})^{+0.9}_{-1.1}\,(\text{PDF})\,\text{pb}$$

$$|f_{\text{Lv}} V_{\text{tb}}| = \sqrt{\sigma_{t\text{-ch.}}/\sigma^{\text{theo.}}_{t\text{-ch.}}}$$

anomalous form factor

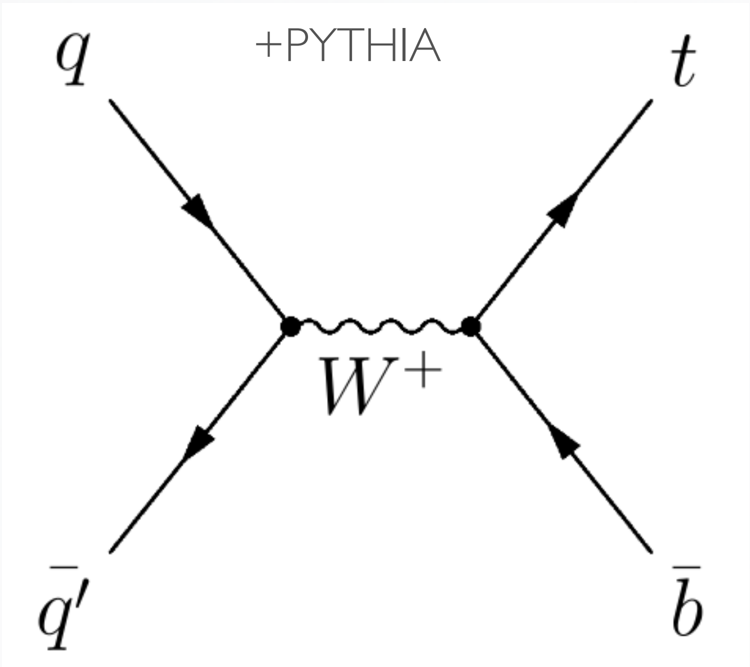
$$|f_{\text{Lv}} V_{\text{tb}}| = 0.998 \pm 0.038\,(\text{exp.}) \pm 0.016\,(\text{theo.})$$ **7+8 TeV combination**

$|V_{tb}|$ > 0.92 at 95% C.L. (f_{Lv} = 1)

Single top in s-channel

PAS TOP-13-009
8 TeV, 20 fb^{-1}

POWHEG
+PYTHIA



- Exactly one isolated lepton
- Jets with E_T > 30 GeV (40 GeV for the most two energetic jets) and $|\eta|$ < 4.5
- Several categories: 2-jet 2-tag, 3-jet 2-tag (signal regions & ttbar-enriched), 2-jet 0-tag (enriched in W+jets)

Main backgrounds: ttbar, W/Z+jets and QCD multijet production

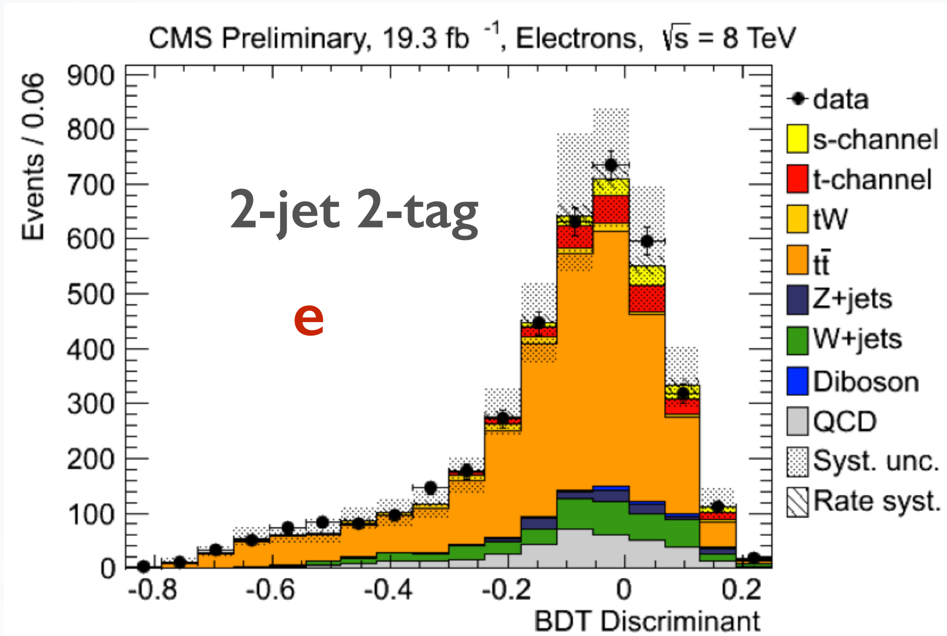
Top mass reconstruction is done with a b-jet which gives closest mass to the nominal top quark mass used

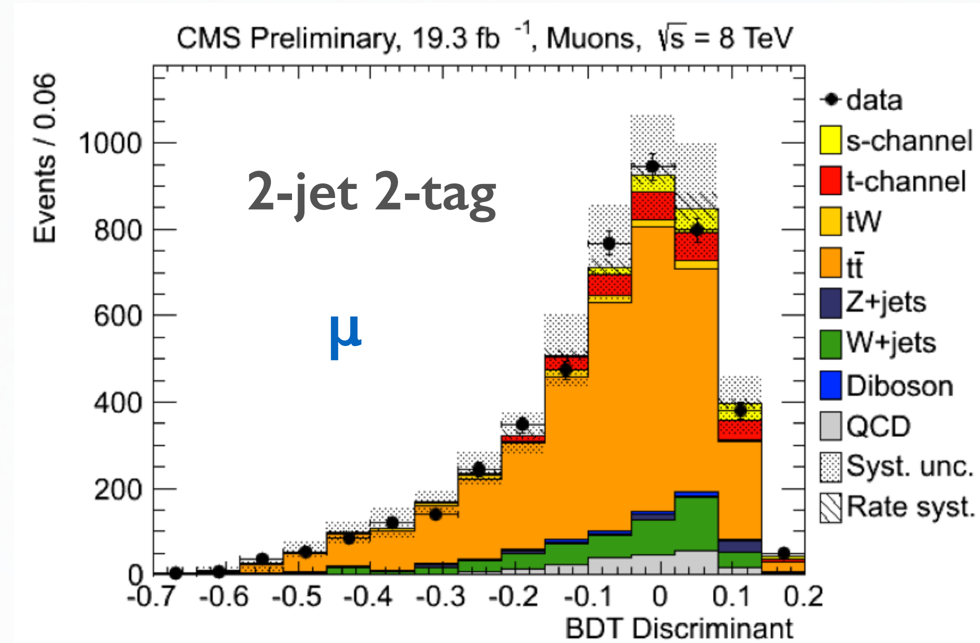
Multijet QCD background is estimated from template fit to $m_T(W)$ (muon channel) and missing E_T (electron channel) in QCD-enriched data with lepton inverted isolation

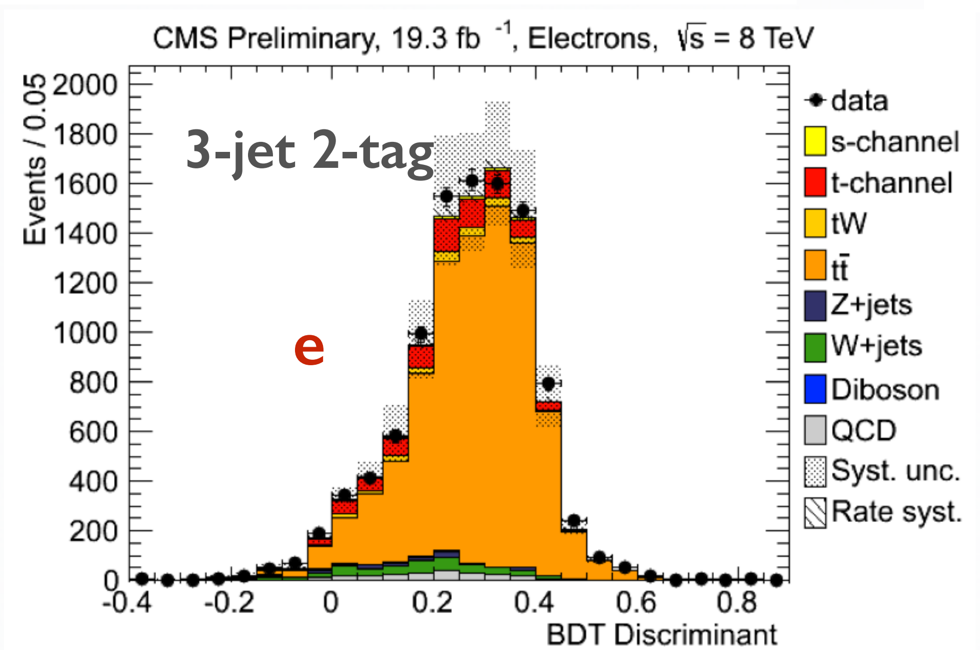
BDT is used to suppress the background and extract the signal cross-section with binned maximum-likelihood fit in 2-jet 2-tag and 3-jet 2-tag:

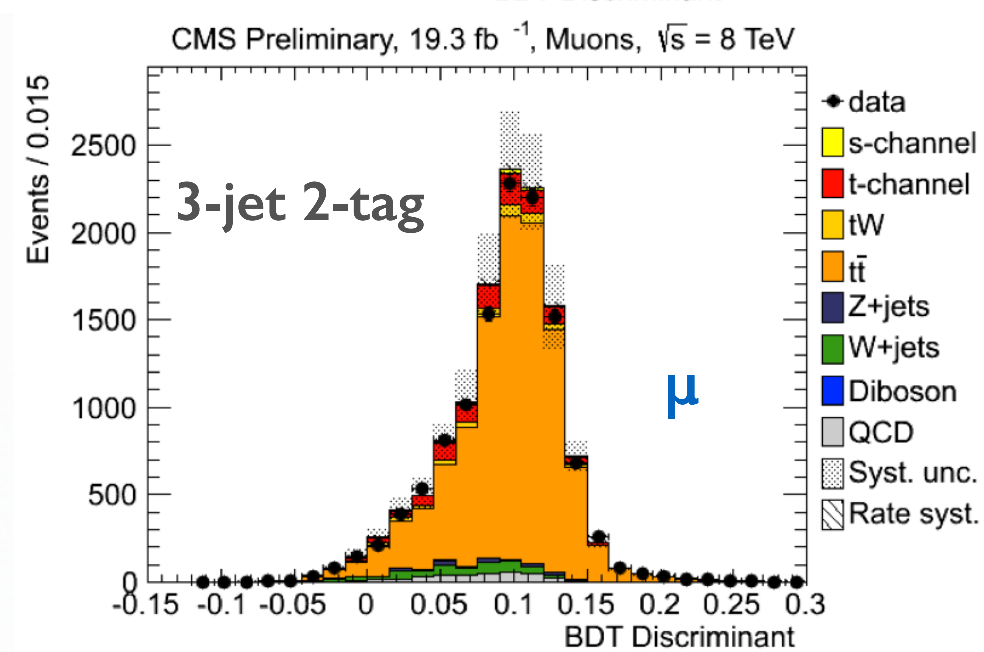
Single top in s-channel

PAS TOP-13-009
8 TeV, 20 fb^{-1}









68% C.L. intervals:

$$\sigma_{s\text{-ch.}} = 5.9^{+8.6}_{-5.1} \text{ pb} \quad \text{muon channel}$$
$$\sigma_{s\text{-ch.}} = 6.9^{+8.7}_{-5.7} \text{ pb} \quad \text{electron channel}$$
$$\sigma_{s\text{-ch.}} = 6.2^{+8.0}_{-5.1} \text{ pb} \quad \text{combined}$$

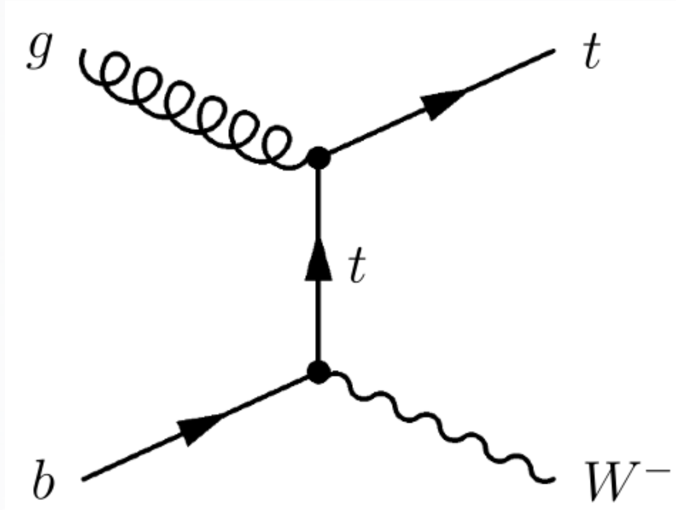
Observed significance is 0.7σ

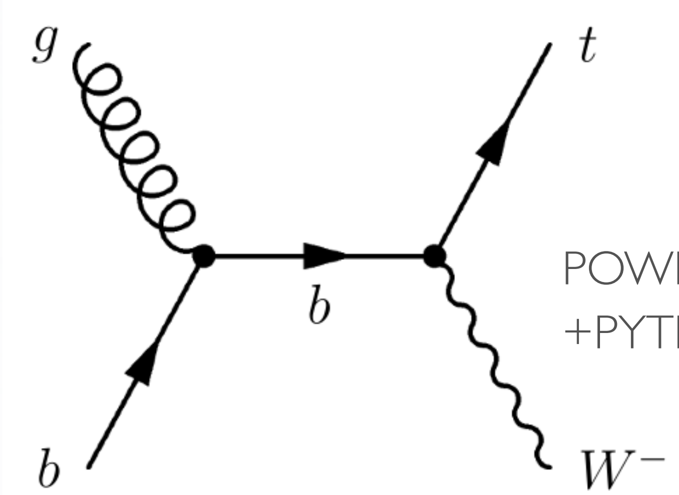
$$\sigma_{s\text{-ch.}} = 5.9 \pm 7.1(\text{exp.}) \pm 5.0(\text{th.}) \text{ pb} = 5.9 \pm 8.7 \text{ pb} \quad \text{muon channel}$$
$$\sigma_{s\text{-ch.}} = 6.9 \pm 5.6(\text{exp.}) \pm 6.5(\text{th.}) \text{ pb} = 6.9 \pm 8.7 \text{ pb} \quad \text{electron channel}$$
$$\sigma_{s\text{-ch.}} = 6.2 \pm 5.4(\text{exp.}) \pm 5.9(\text{th.}) \text{ pb} = 6.2 \pm 8.0 \text{ pb} \quad \text{combined}$$

Single top in tW production

PRL 112 (2014) 231802
8 TeV, 12 fb^{-1}

- Exactly two isolated opposite-sign leptons
- m(ll) > 20 GeV, veto 81 < m(ll) < 101 GeV
- Missing E_T > 50 GeV (dielectron and dimuon channels)
- Several categories: 1-jet 1-tag (signal region), 2-jet 1-tag, 2-jet 2-tag (enriched in ttbar events)

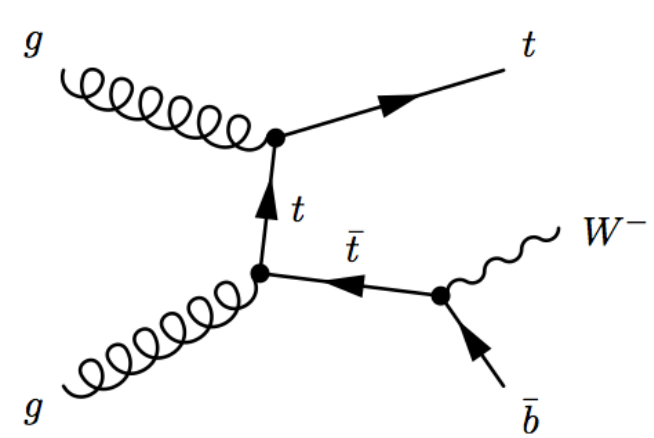




POWHEG +PYTHIA

Main backgrounds: ttbar, W/Z+jets and QCD multijet production

BDT is trained with ttbar and tW events in 1-jet 1-tag selection



@NLO there is an interference with ttbar: diagram removal (DR) scheme is used

DY+jets background is semi-data driven: data/MC EtMiss corrections factors are measured in 81 < m(ll) < 101 GeV

Cross-section is extracted from the **fit to BDT discriminant**

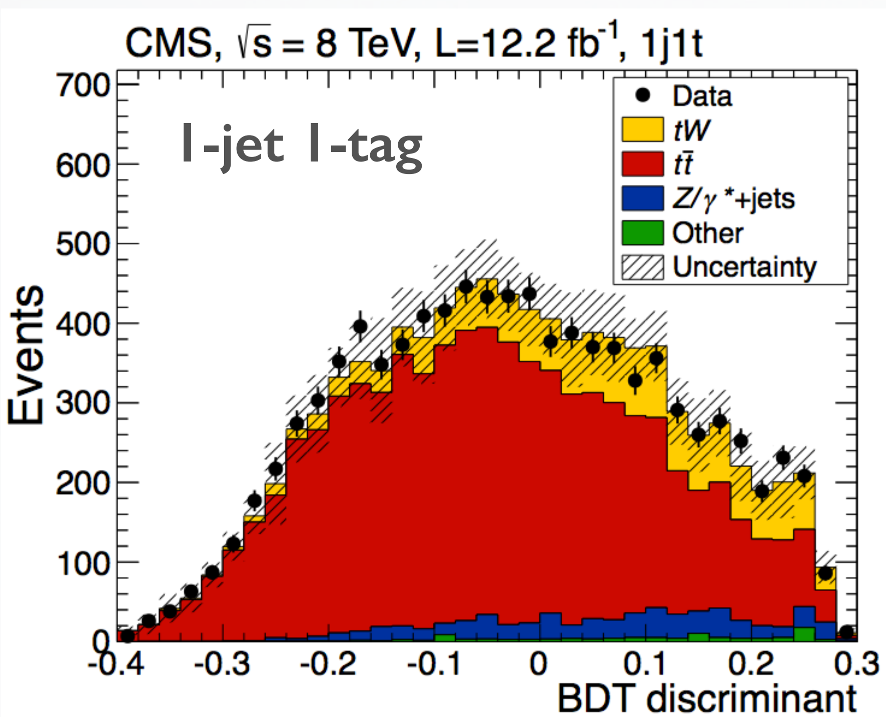
Additional checks are performed in 1-jet 0-tag and 2-jet 0-tag regions

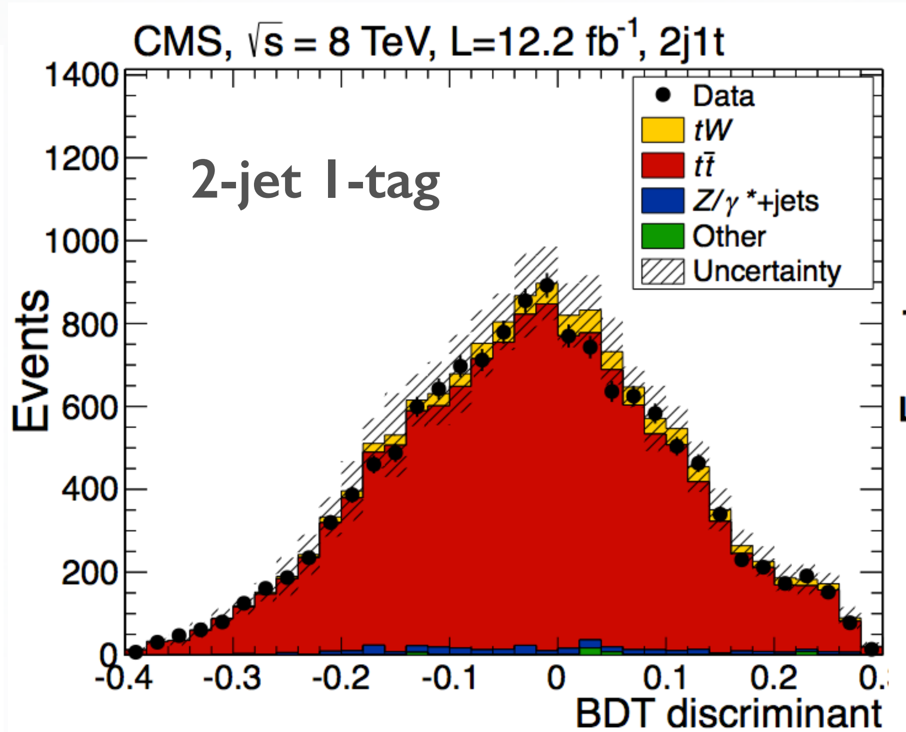
Single top in tW production

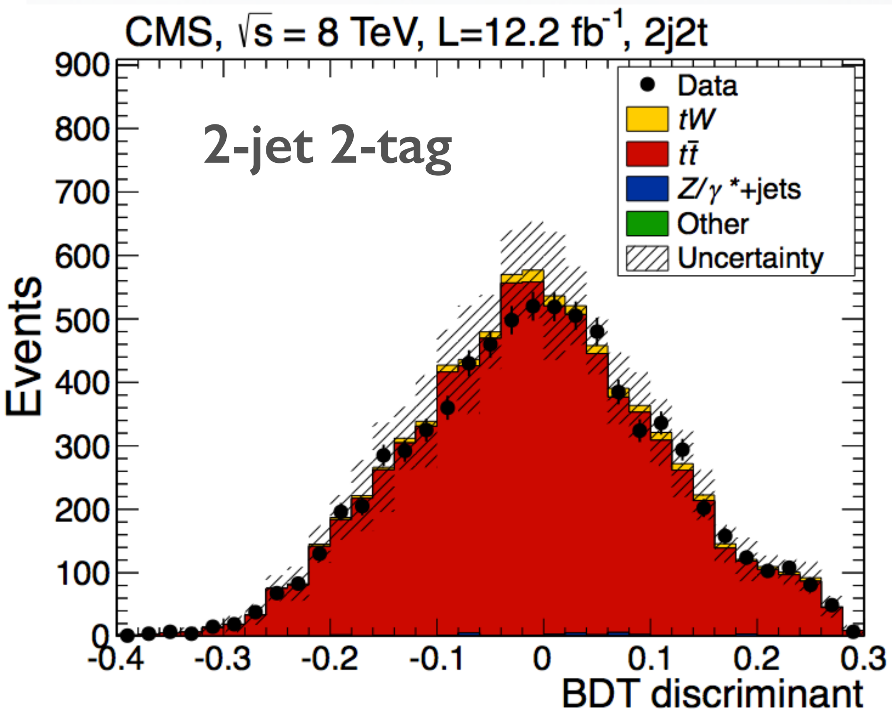
PRL 112 (2014) 231802
8 TeV, 12 fb^{-1}

First observation of this process

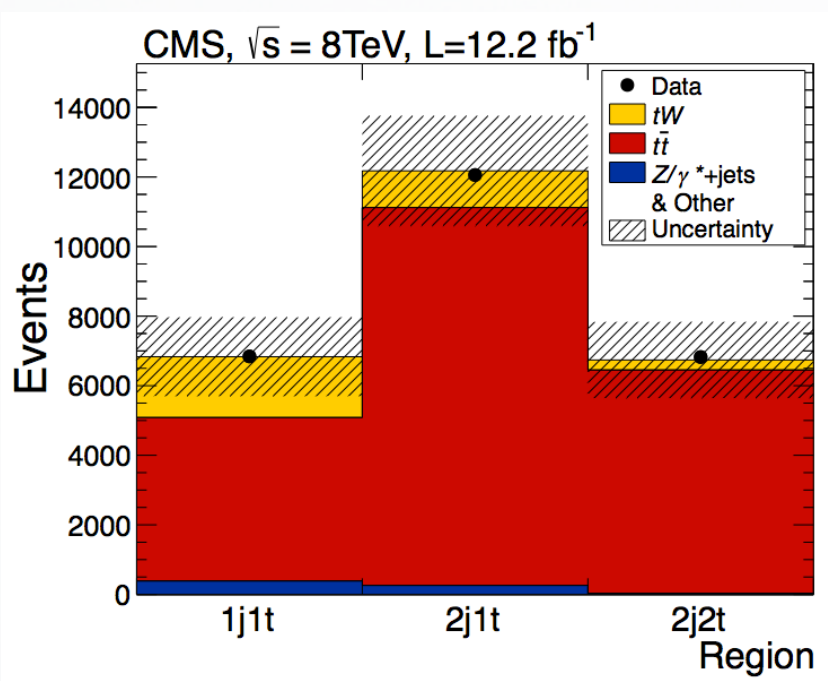
Binned Likelihood fit for BDT distribution in three regions:







Cut-based analysis result fit:



Two cross-check analyses have been performed: **cut-based analysis** and **fit to the distribution of pT of the system**

Result cross-sections:

Main analysis: **23.4 +5.5 -5.4** pb

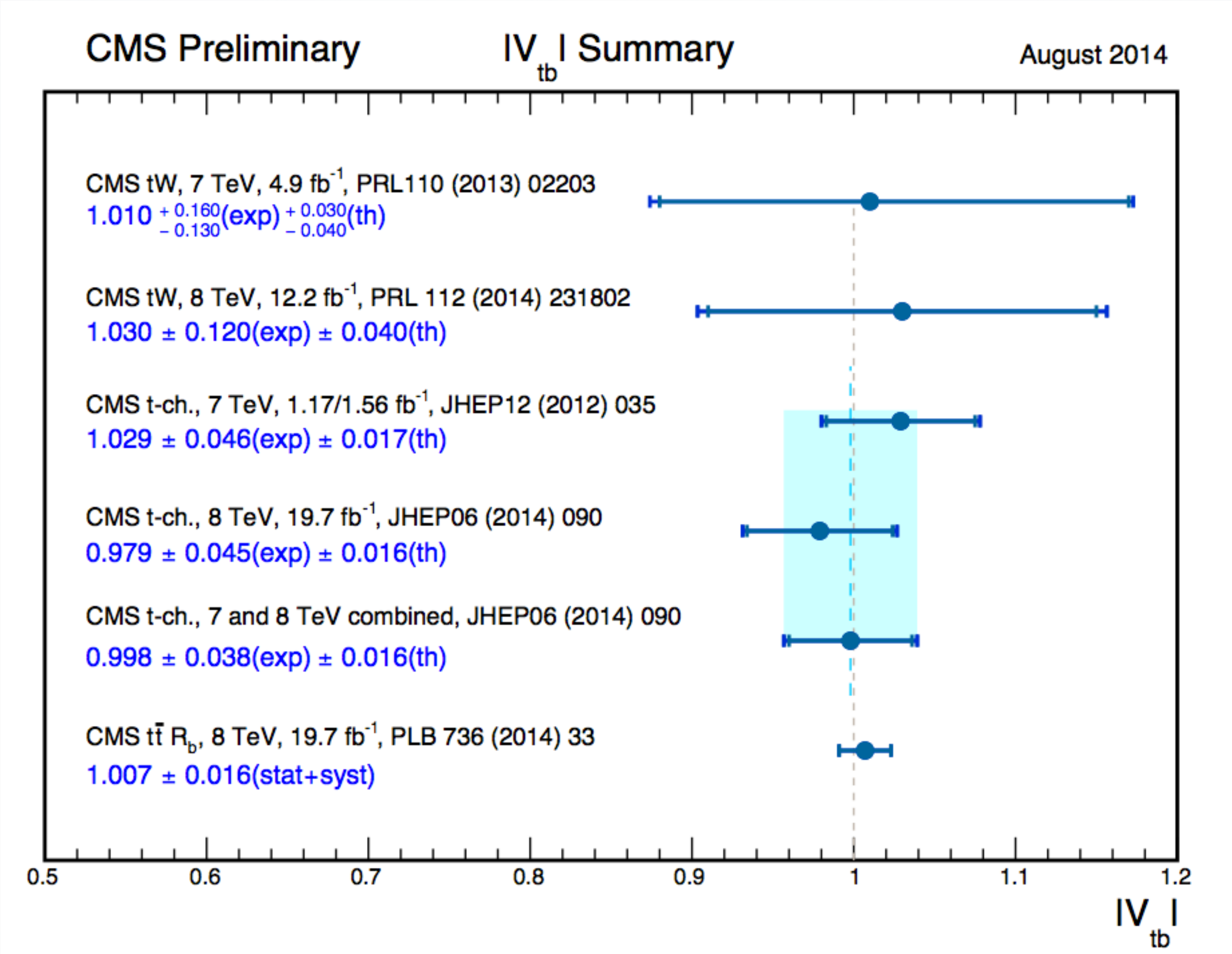
Cut-based analysis: **33.9 +8.6 -8.6** pb

pT-fit analysis: **24.3 +8.6 -8.8** pb

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

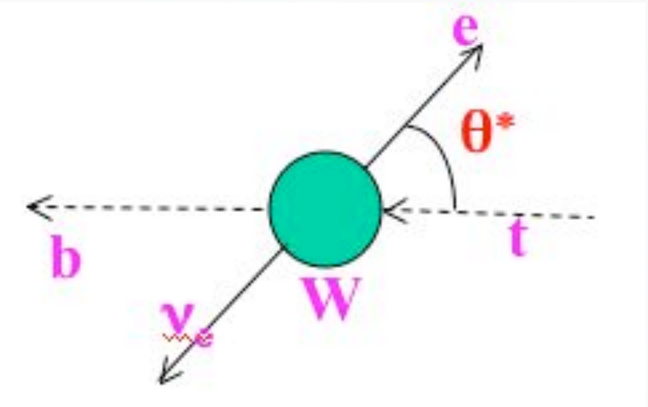
$|V_{tb}| > 0.78$ at 95% C.L.

Summary of $|V_{tb}|$ measurements by CMS



W-boson helicity

- Helicity is a projection of particle's spin onto its momentum
- The W-boson helicity fractions, $F_{L,R,0}=\Gamma_{L,R,0}/\Gamma(t\rightarrow Wb)$, with $\Sigma F_i=1$, could be extracted from **angular distributions** of the top-quark decay products:



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

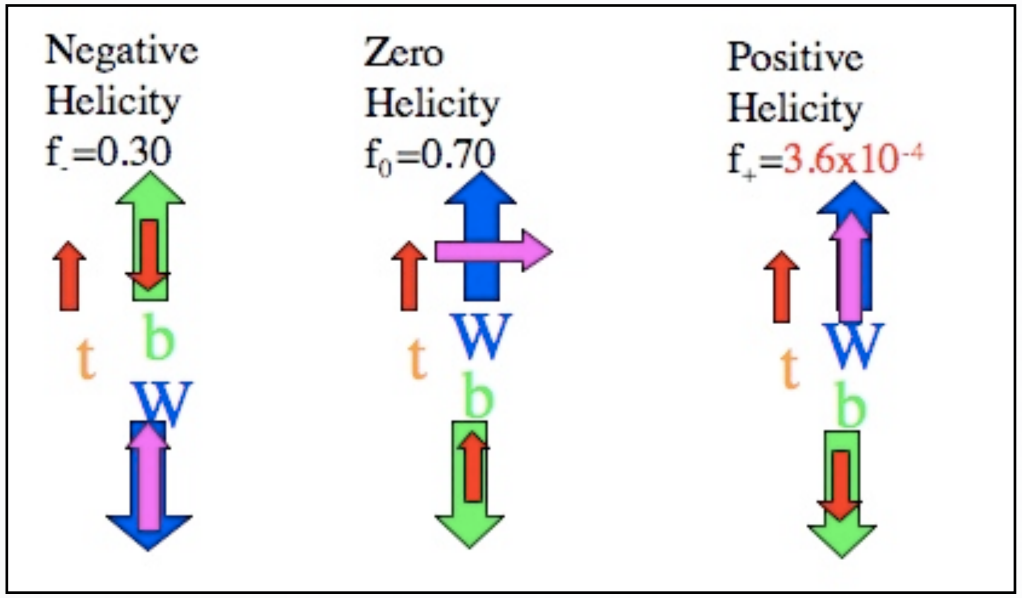
Helicity angle θ^*: angle between W momentum in the t-rest frame and lepton in the rest frame of W

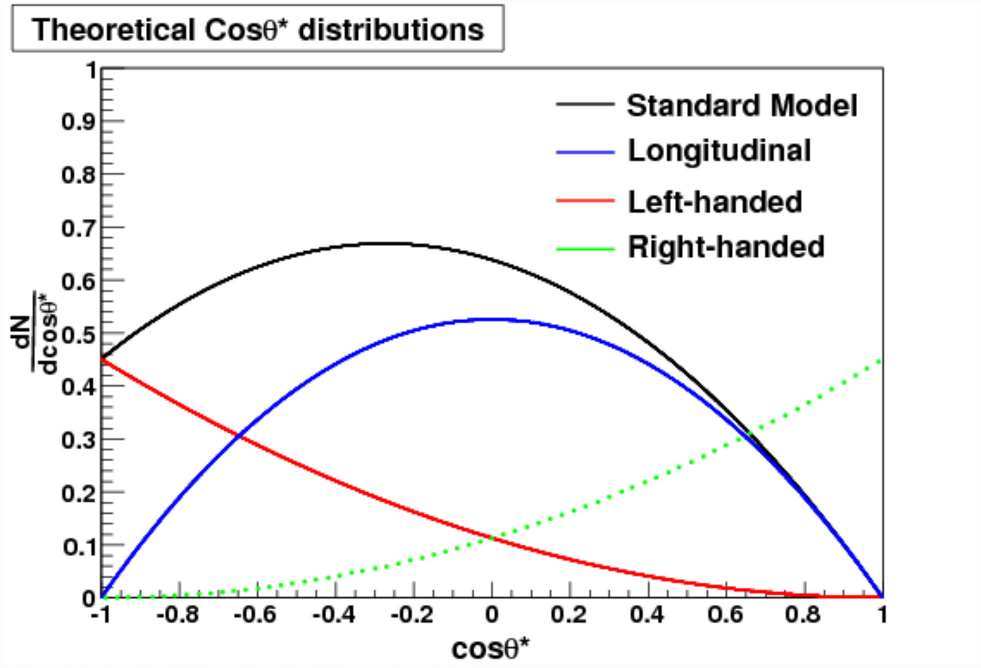
- Helicity fractions are sensitive to **Wtb anomalous couplings**:

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

$V_L=V_{tb}\approx 1$ in SM

Theoretical predictions on W-boson helicity:





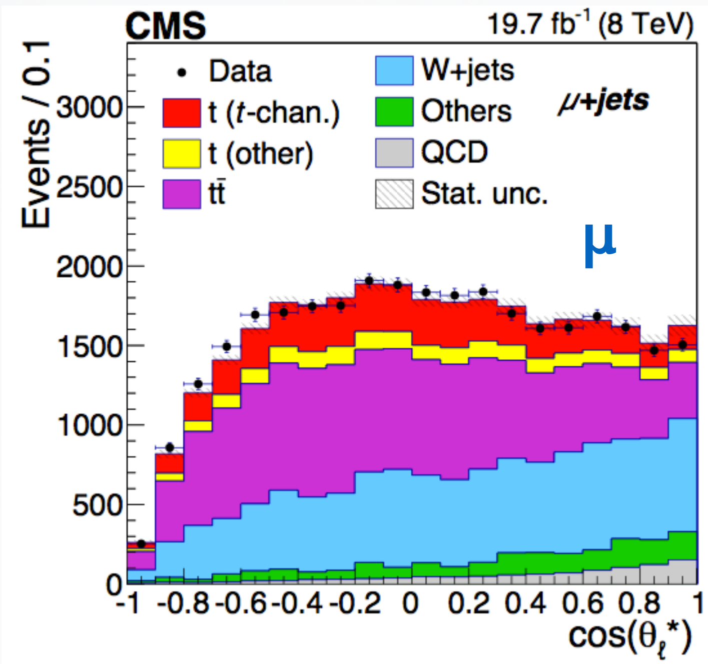
@NNLO:
$F_0=0.687\pm0.005$
$F_L=0.311\pm0.005$
$F_R=0.0017\pm0.0001$

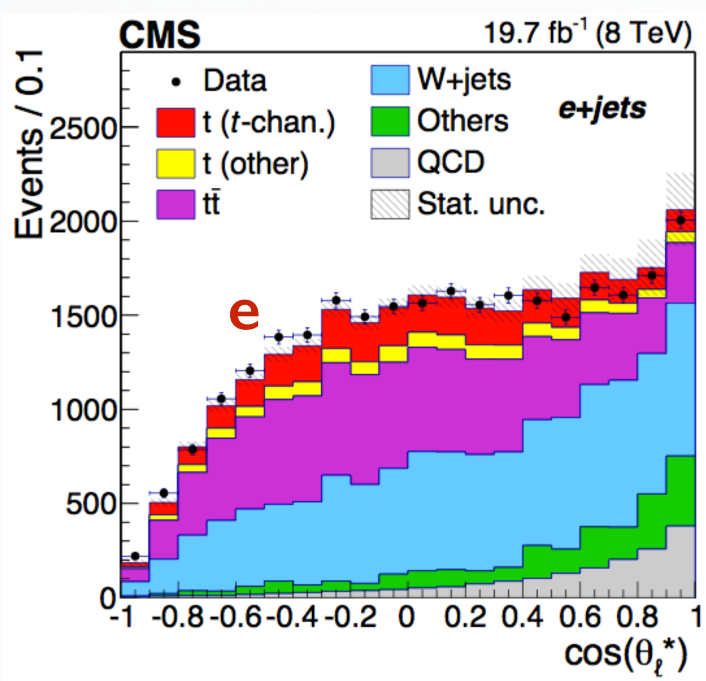
W-boson helicity in single top

JHEP 01 (2015) 053
8 TeV, 20 fb^{-1}

- Exactly one isolated electron (muon) and exactly two jets
- Exactly one of two jets is b-tagged
- $M_T(W)$ > 50 GeV (QCD background rejection)

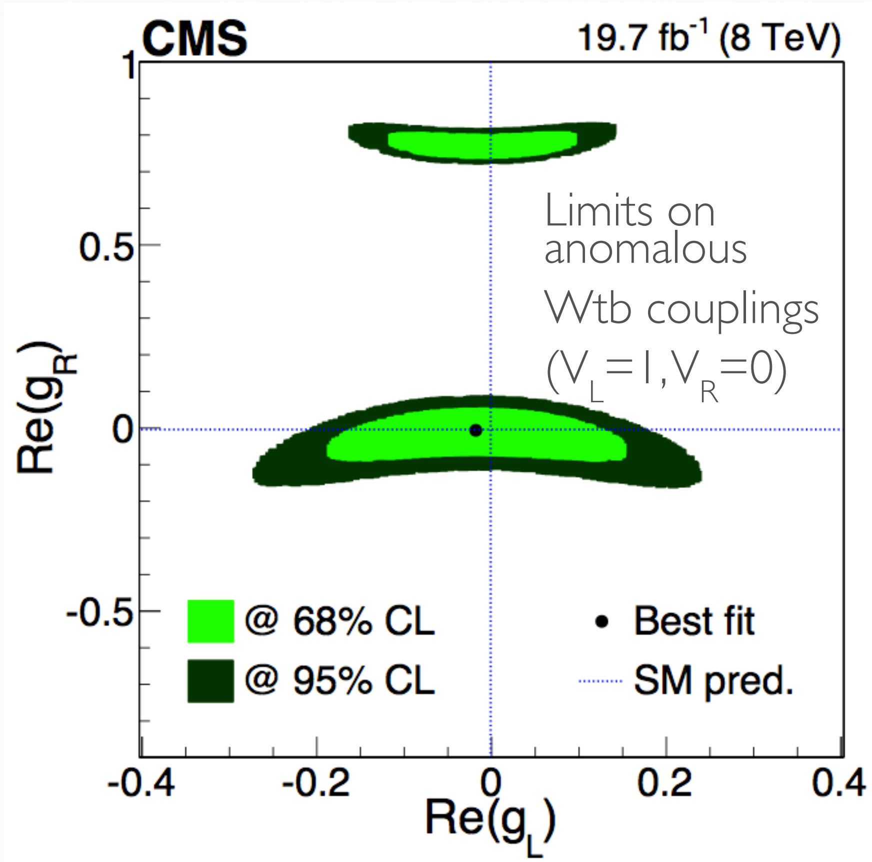
t-channel events are used

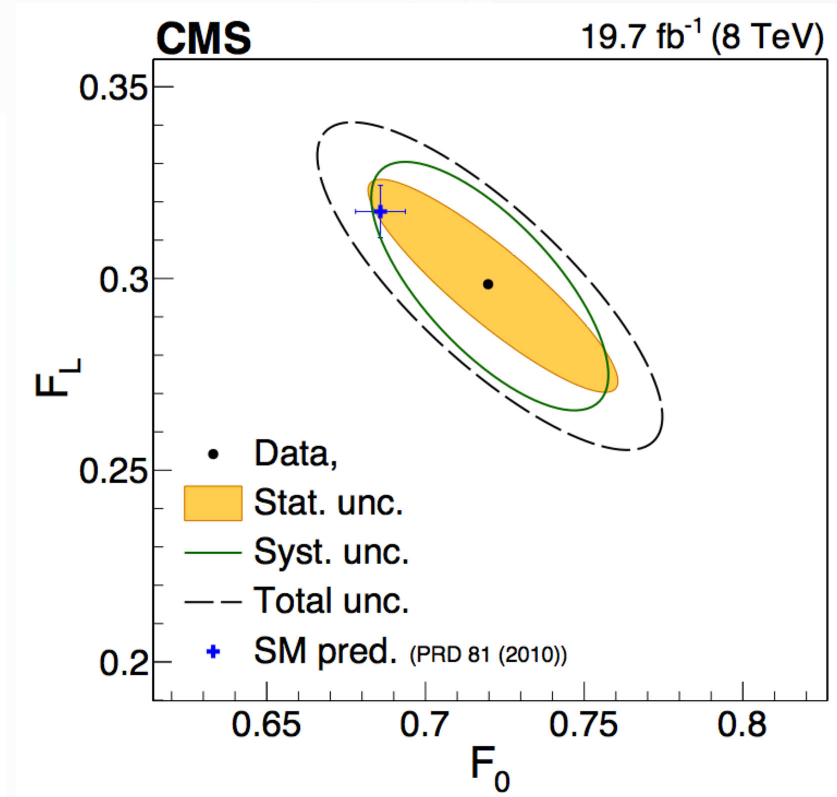




Extract cosθ^* from the fit

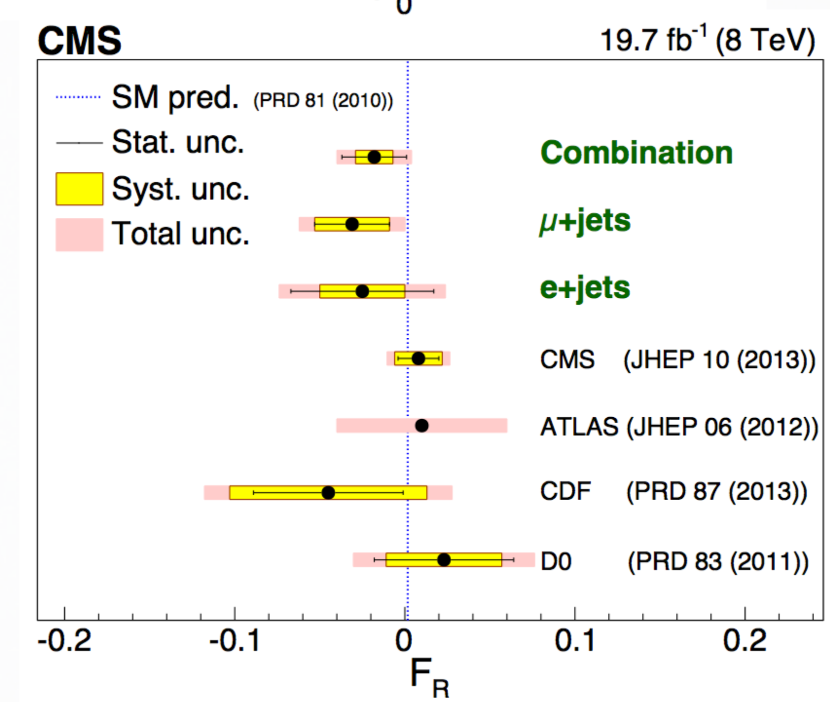
(F_L,F_0 and W+jets fraction are free parameters)





Combination:

$$F_L = 0.298 \pm 0.028\,(\text{stat}) \pm 0.032\,(\text{syst}),$$
$$F_0 = 0.720 \pm 0.039\,(\text{stat}) \pm 0.037\,(\text{syst}),$$
$$F_R = -0.018 \pm 0.019\,(\text{stat}) \pm 0.011\,(\text{syst})$$



Top-quark polarisation and spin correlations

In the SM top-quarks are produced with a **small amount of polarisation** arising from EW corrections (for QCD production dominated processes), while in single top production quarks are ≈100% polarised, but some **new models can alter the spin**

Top-quark polarisation (**P=2A$_P$**) in helicity basis is given by asymmetry variable:

$$A_P = \frac{N\left[\cos(\theta^\star_\ell) > 0\right] - N\left[\cos(\theta^\star_\ell) < 0\right]}{N\left[\cos(\theta^\star_\ell) > 0\right] + N\left[\cos(\theta^\star_\ell) < 0\right]}$$

Discriminating kinematic variable to separate correlated and uncorrelated top and anti-top quark spins:

$$A_{\Delta\phi} = \frac{N(\Delta\phi_{\ell^+\ell^-} > \pi/2) - N(\Delta\phi_{\ell^+\ell^-} < \pi/2)}{N(\Delta\phi_{\ell^+\ell^-} > \pi/2) + N(\Delta\phi_{\ell^+\ell^-} < \pi/2)}$$

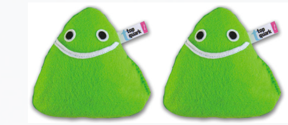
Spin correlation coefficient (**C$_{hel}$= - 4A$_{c1c2}$**) is given by:

$$A_{c_1c_2} = \frac{N(c_1c_2 > 0) - N(c_1c_2 < 0)}{N(c_1c_2 > 0) + N(c_1c_2 < 0)}$$

$c_1 = \cos(\theta_{l+})$

$c_2 = \cos(\theta_{l-})$

Phys.Rev.Lett. 112 182001
7 TeV, 5 fb^{-1}

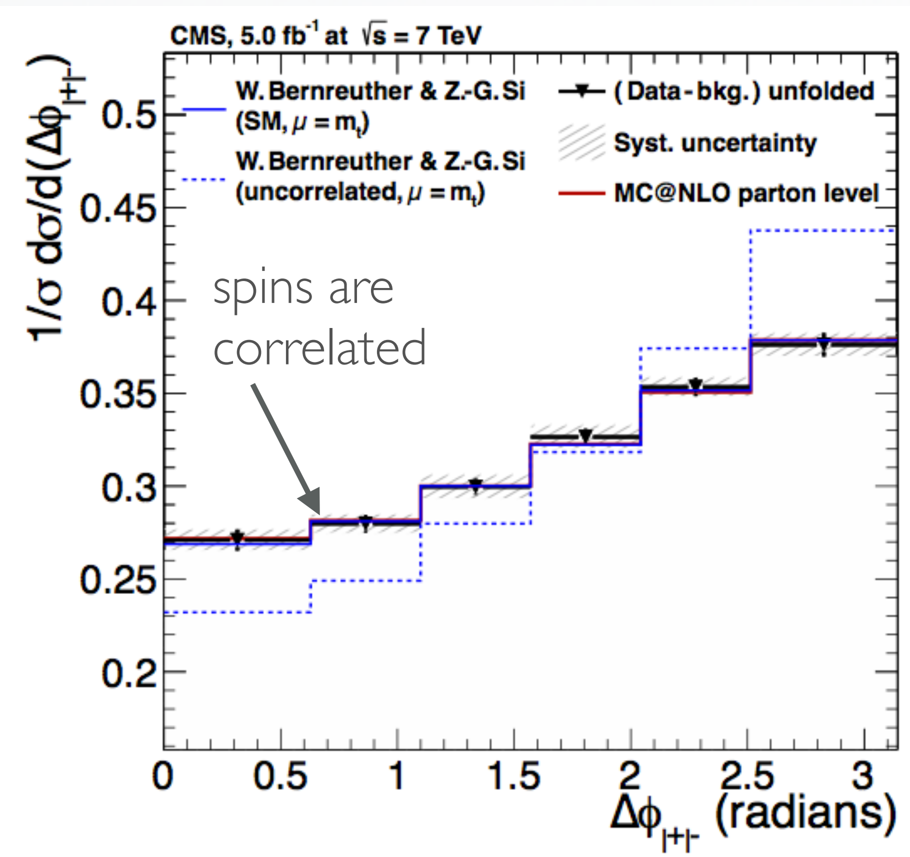


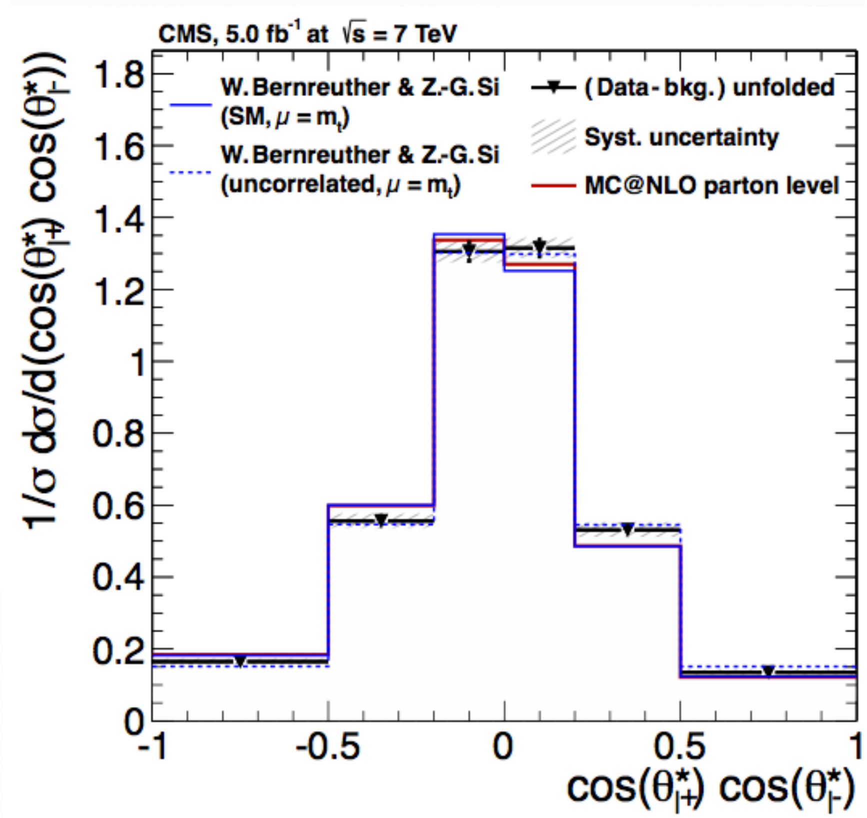
Unfolding is applied to correct for finite resolution and detector acceptance

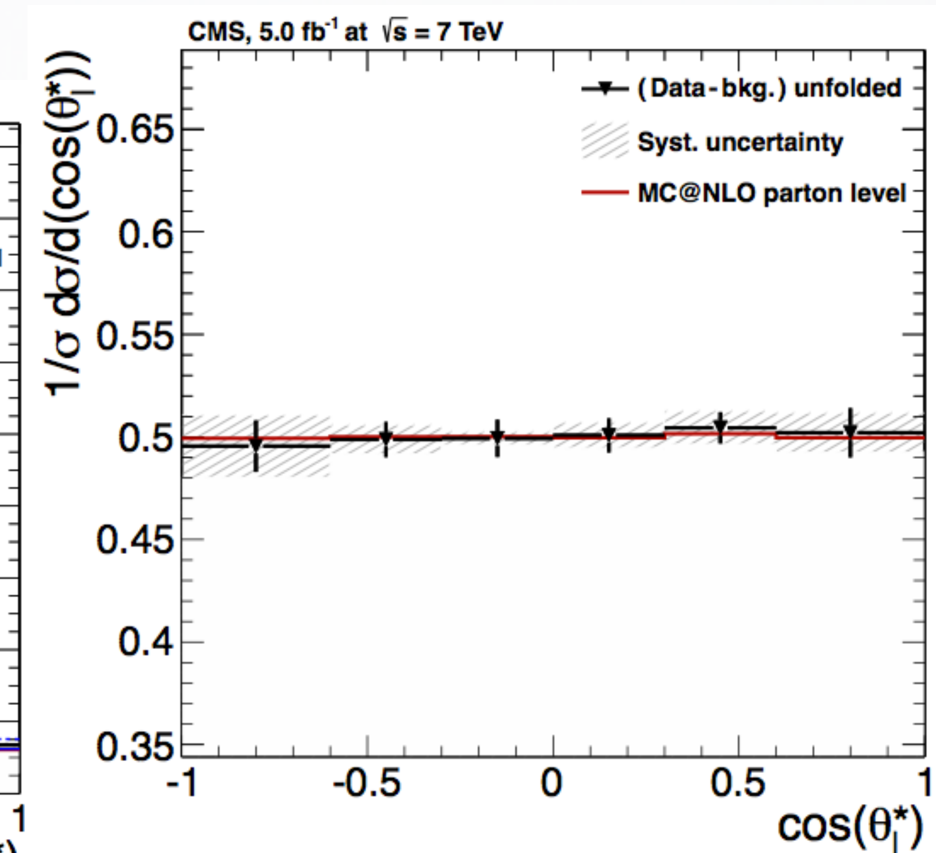
$$\vec{b} = S A \vec{x}$$

- $\vec{x}$: underlying parton-level distribution
- $\vec{b}$: background-subtracted measured distribution
- $S A$: resolution and acceptance matrices

uncertainties are estimated by rederiving matrices





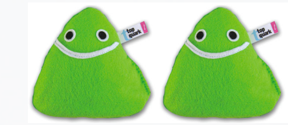


Extracted parton-level asymmetry after unfolding procedure:

Asymmetry	Data (unfolded)	MC@NLO	NLO (SM, correlated)	NLO (uncorrelated)
$A_{\Delta\phi}$	$0.113 \pm 0.010 \pm 0.006 \pm 0.012$	0.110 ± 0.001	$0.115^{+0.014}_{-0.016}$	$0.210^{+0.013}_{-0.008}$
$A_{c_1c_2}$	$-0.021 \pm 0.023 \pm 0.025 \pm 0.010$	-0.078 ± 0.001	-0.078 ± 0.006	0
A_P	$0.005 \pm 0.013 \pm 0.014 \pm 0.008$	0.000 ± 0.001	N/A	N/A

Limits on top-quark chromo-magnetic dipole moment

TOP PAS-14-005
7 TeV, 5 fb^{-1}



Search for **ttbarg anomalous couplings** in the framework of Chromo-Magnetic Dipole Moments effective model (CMDM) which could significantly modify ttbar spin correlations

$$\mathcal{L}_{eff} = -\frac{\tilde{\mu}_t}{2}\bar{t}\sigma^{\mu\nu}T^a t G^a_{\mu\nu} - \frac{\tilde{d}_t}{2}\bar{t}i\sigma^{\mu\nu}\gamma_5 T^a t G^a_{\mu\nu}$$

CMDM (CP-conserving) **CEDM** (CP-violating)

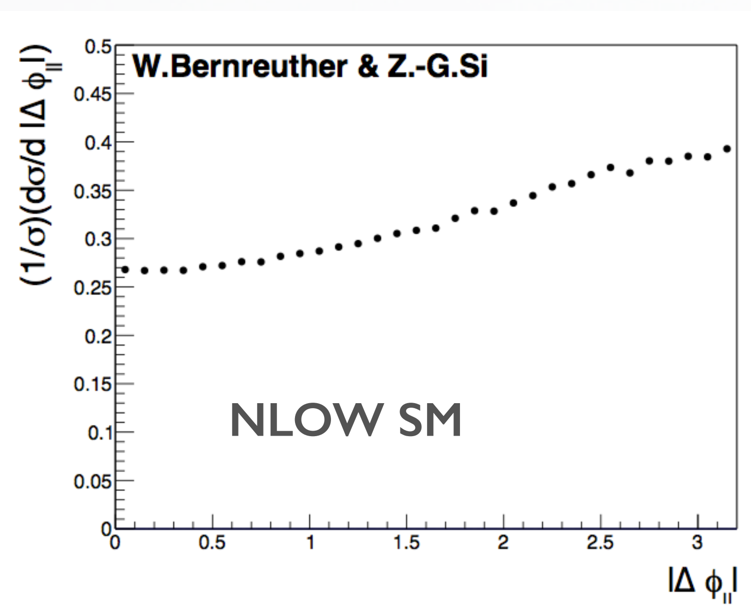
form factors in time-like kinematic domain

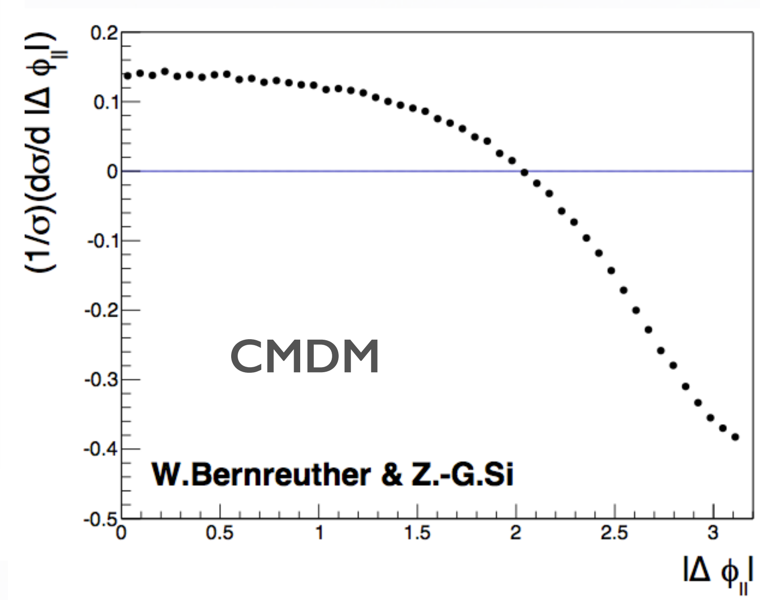
$$\tilde{\mu}_t(\tilde{d}_t) \equiv \frac{g_s}{m_t}\hat{\mu}_t(\hat{d}_t)$$

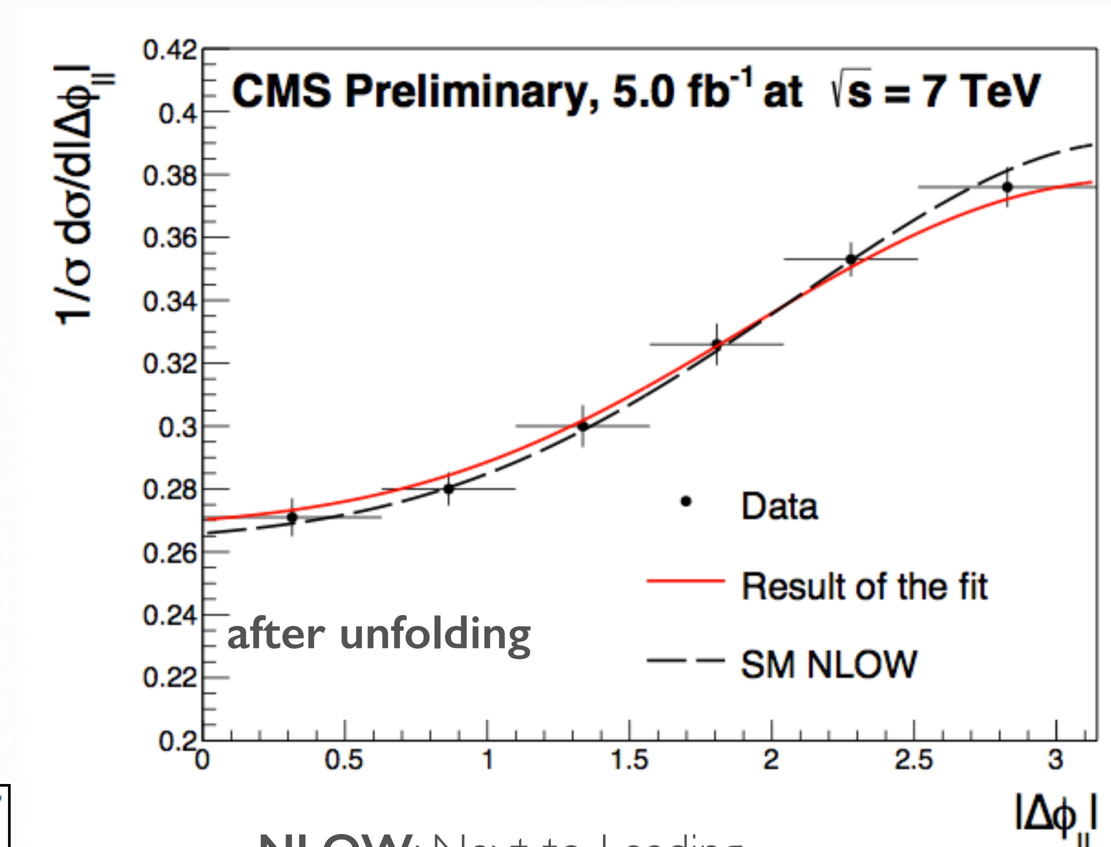
Experimental results and unfolding matrices are taken from Phys.Rev.Lett. 112 182001

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

Cross-section with a small contribution of NP, **CEDM** does not contribute to $\Delta\phi_{ll}$ distribution



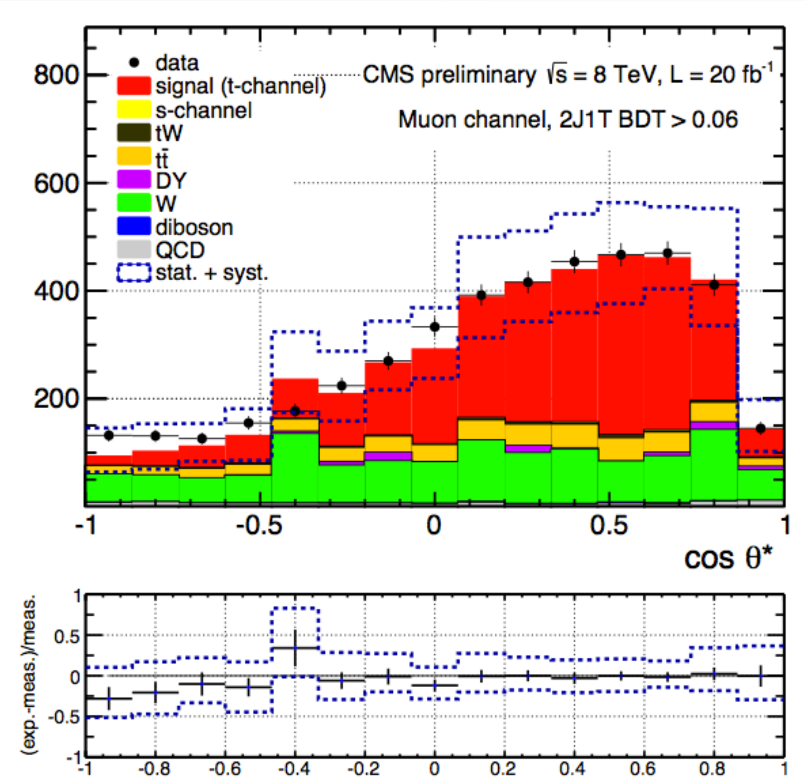


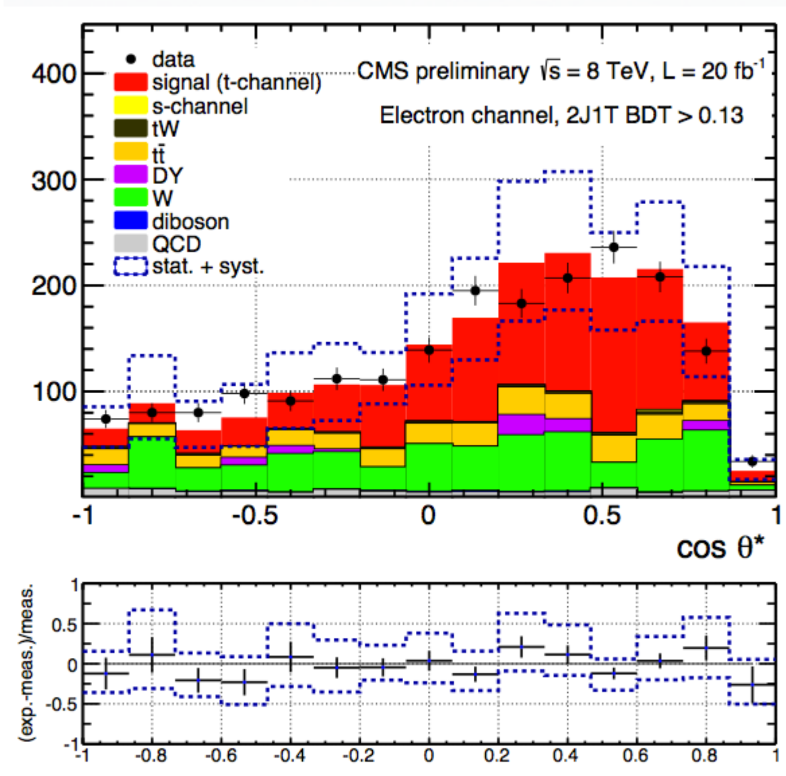


Excluded at 95% C.L. outside the range: $-0.043 < \mathrm{Re}(\hat{\mu}_t) < 0.117$

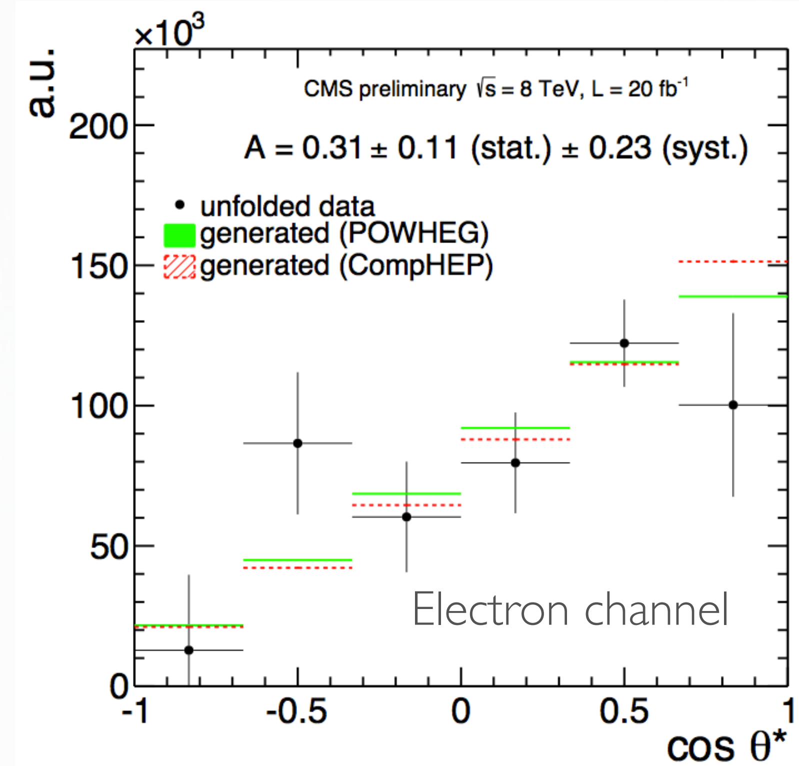
NLOW: Next-to-Leading order QCD and weak

Top-quark polarisation in single top





Binned likelihood fit is performed on BDT, unfolding is done to extract cosθ^*

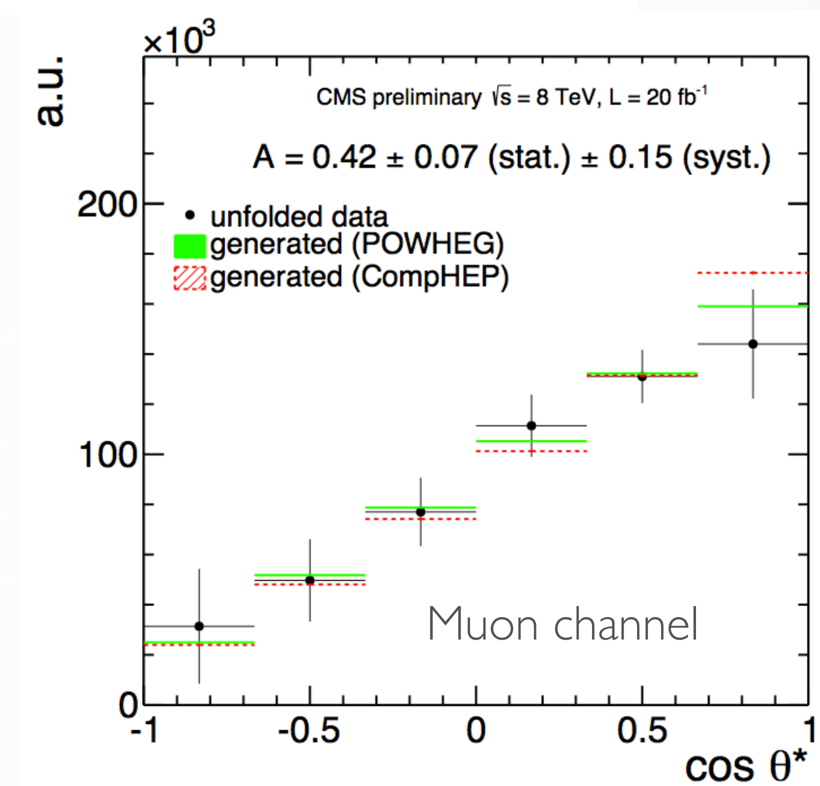


$$A_l = \frac{N(\cos\theta^*_{unfolded} > 0) - N(\cos\theta^*_{unfolded} < 0)}{N(\cos\theta^*_{unfolded} > 0) + N(\cos\theta^*_{unfolded} < 0)}$$

After unfolding:

$$A_l^{\mu} = 0.42 \pm 0.07(stat.) \pm 0.15(syst.)$$
$$A_l^{e} = 0.31 \pm 0.11(stat.) \pm 0.23(syst.)$$

Combination is done with BLUE

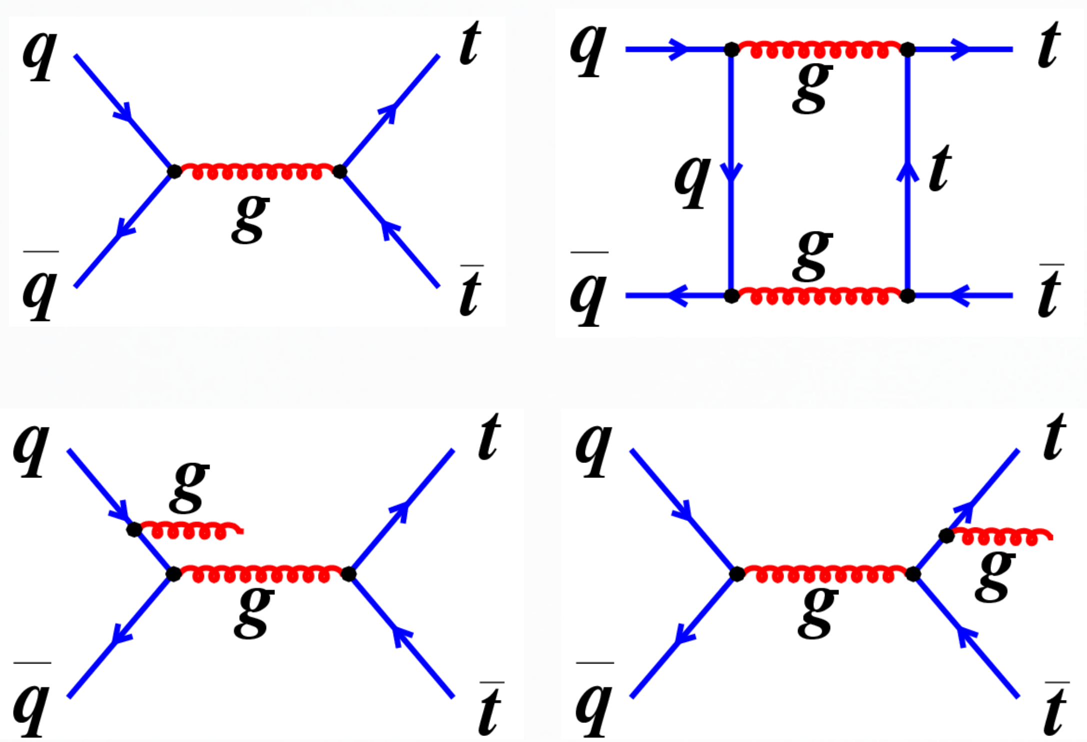


Measured polarisation: $P_t = 0.82 \pm 0.12(stat.) \pm 0.32(syst.)$

$$A_l = 0.41 \pm 0.06(stat.) \pm 0.16(syst.) = 0.41 \pm 0.17$$

Charge asymmetry

- Occurs only in **quark-antiquark or quark-gluon initial states** (the dominant gluon-gluon production is charge symmetric)
- At the LHC, initial quarks are mainly valence quarks, antiquarks are always sea quarks
- This leads to an excess of top quarks produced in the forward directions
- Important to measure differential asymmetry in addition to inclusive measurement as this charge asymmetry is enhanced in specific kinematic regions (e.g. wrt ttbar system kinematic variables)
- In the SM **charge asymmetry** is explained by **interference** between LO and box, and FSR and ISR, and EW corrections enhance the asymmetry by about 20%

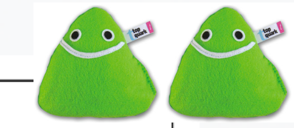


Charge asymmetry:

$$A_C = \frac{N(|y_t| > |y_{\bar{t}}|) - N(|y_t| < |y_{\bar{t}}|)}{N(|y_t| > |y_{\bar{t}}|) + N(|y_t| < |y_{\bar{t}}|)}$$

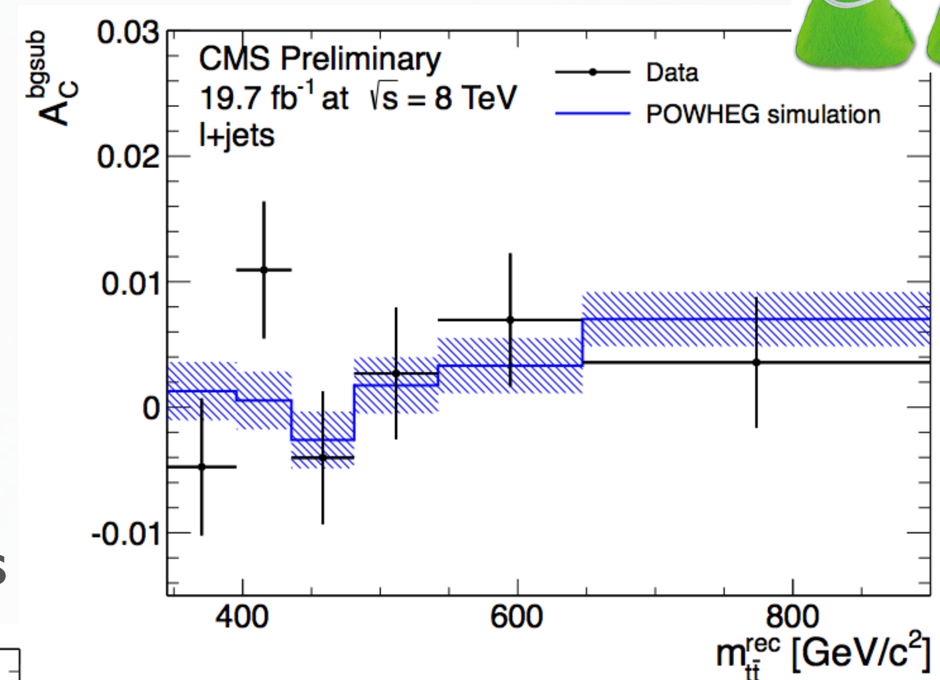
Charge asymmetry in lepton+jets

TOP PAS-12-033
8 TeV, 20 fb^{-1}

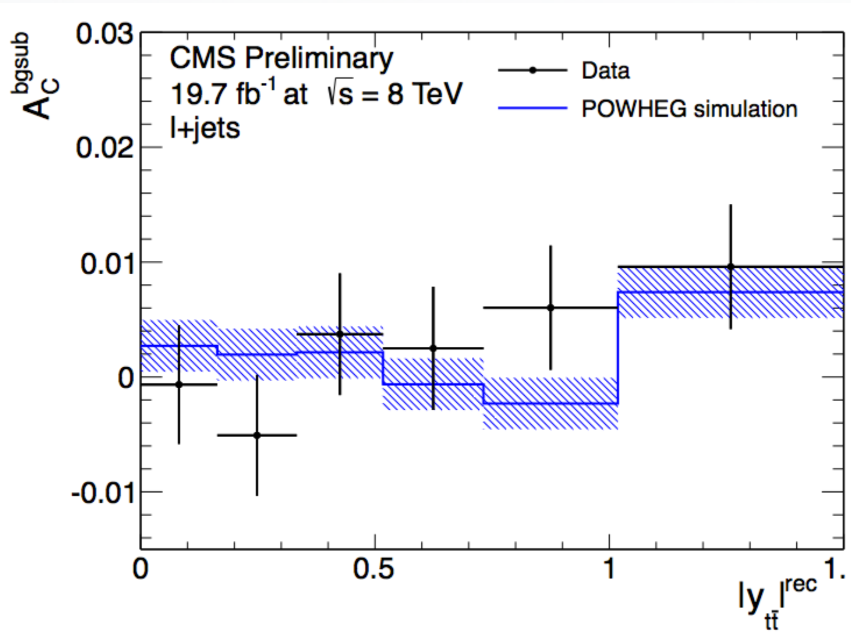


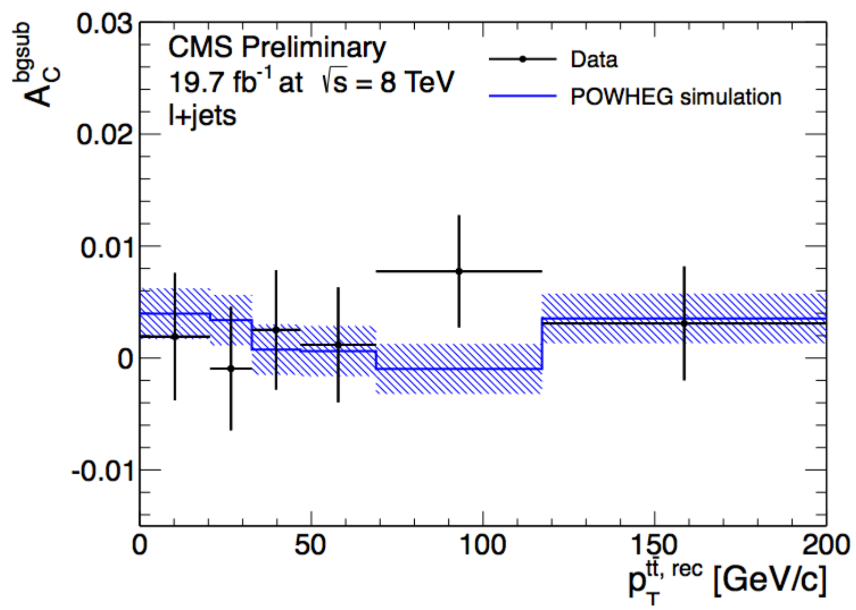
- Exactly one isolated lepton and at least four jets
- At least one jet is b-tagged
- mT > 50 GeV

QCD multijet background is estimated from a simultaneous fit of $m_T(W)$ ($m_T(W)$ < 50 GeV) and M3 ($m_T(W)$ > 50 GeV)



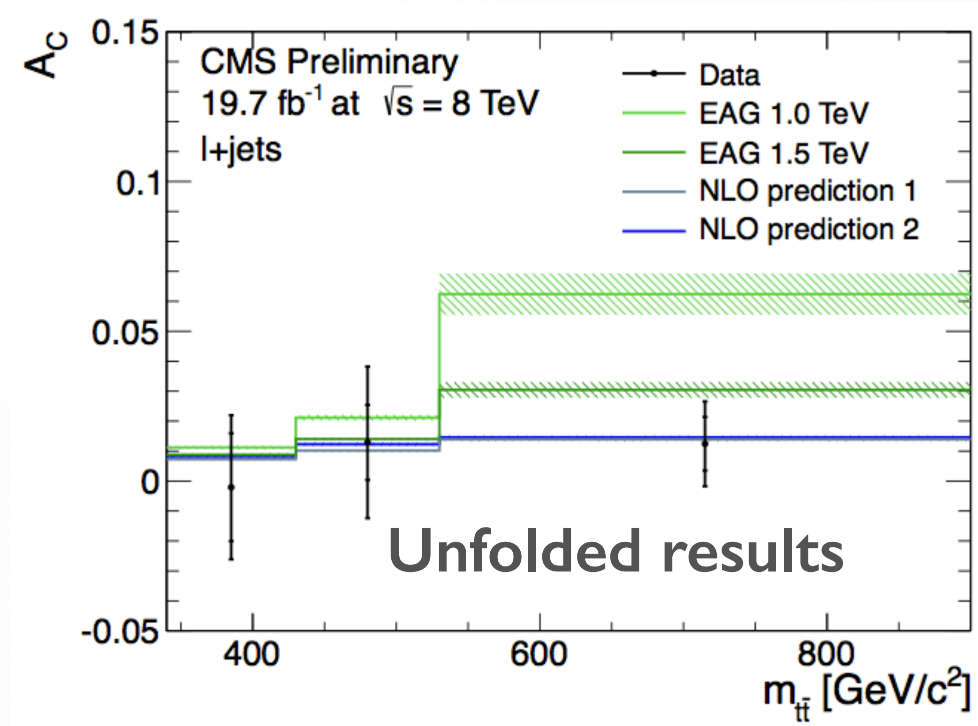
Background subtracted non-unfolded results





The matrix-inversion with regularization method is used to perform an unfolding procedure

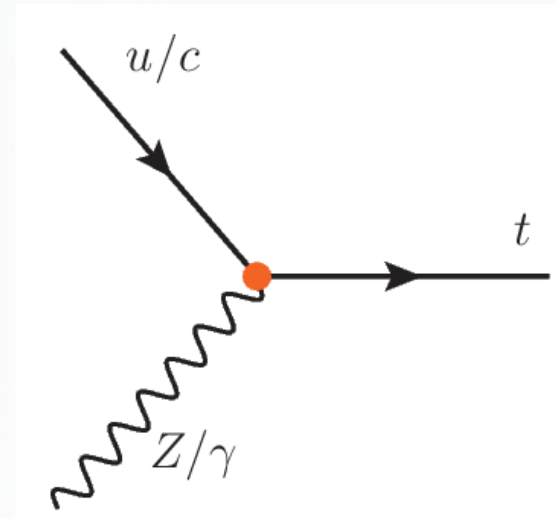
Asymmetry	A_C
Reconstructed	0.003 ± 0.002 (stat.)
BG-subtracted	0.002 ± 0.002 (stat.)
Unfolded	0.005 ± 0.007 (stat.) ± 0.006 (syst.)
Theory prediction [Kühn, Rodrigo] [9, 33]	0.0102 ± 0.0005
Theory prediction [Bernreuther, Zi] [34, 35]	0.0111 ± 0.0004

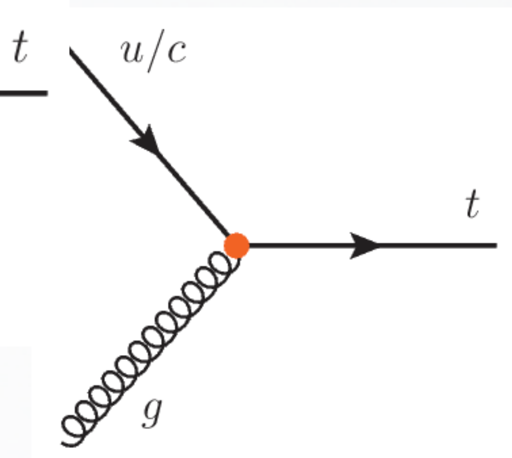


EAG: model with axial-vector gluon coupling (E. Gabrielli, M. Raidal, and A. Racioppi)

Search for FCNC interactions

- Flavour-changing neutral current (**FCNC**) transition is an interaction process where a fermion undergoes the **change of flavour without alteration of the charge**
- FCNC amplitudes at tree level are **forbidden** by the Glashow-Iliopoulos-Maiani (GIM) mechanism in the Standard Model (SM)
- However, highly GIM-suppressed FCNC transitions are possible in the SM in the higher orders via penguin and box diagrams
- Some extensions of the SM could introduce FCNC decays at tree level including **new particles**





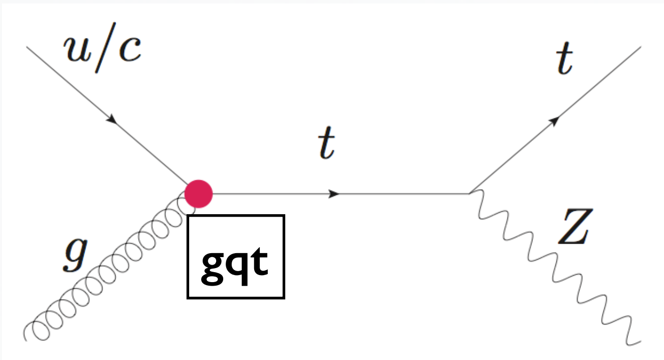
- Fourth-generation models
- Extended technicolor models
- Leptoquark models
- Extra dimensions
- Extra quark models
- Supersymmetry
- Two-Higgs-Doublet models

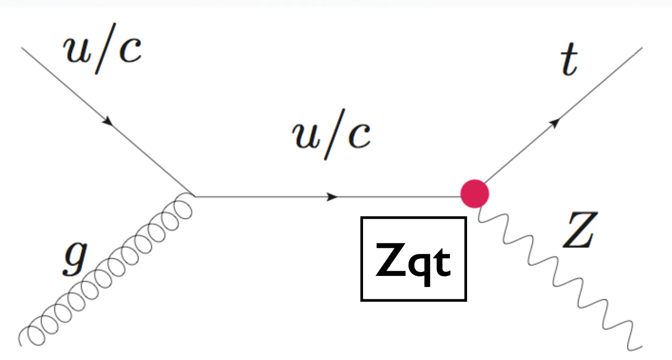
$$\Delta\mathcal{L}_{\text{eff}} = e\ e_t\ \bar{t}\frac{i\sigma_{\mu\nu}p^\nu}{\Lambda}\ \kappa_\gamma\ u\ A^\mu + \frac{g}{2\cos\theta_W}\ \bar{t}\gamma_\mu\ v_Z\ uZ^\mu\ + \text{h.c.}$$

GIM mechanism: S. L. Glashow, J. Iliopoulos and L. Maiani, Phys. Rev. D 2 (1970) 1285

Search for FCNC tZ events

TOP PAS-12-021
7 TeV, 5 fb^{-1}

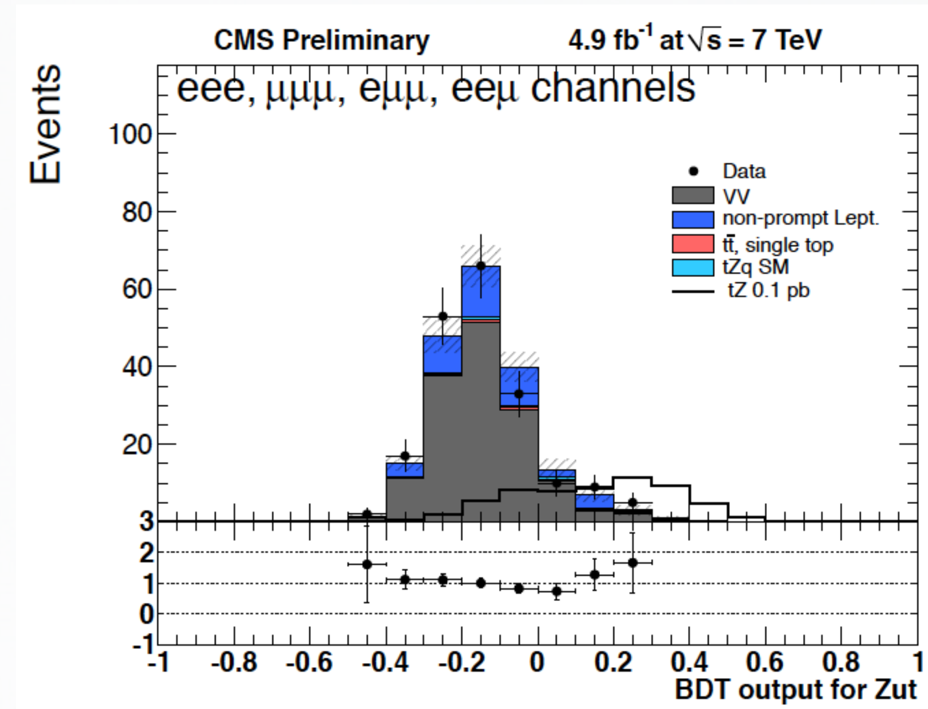




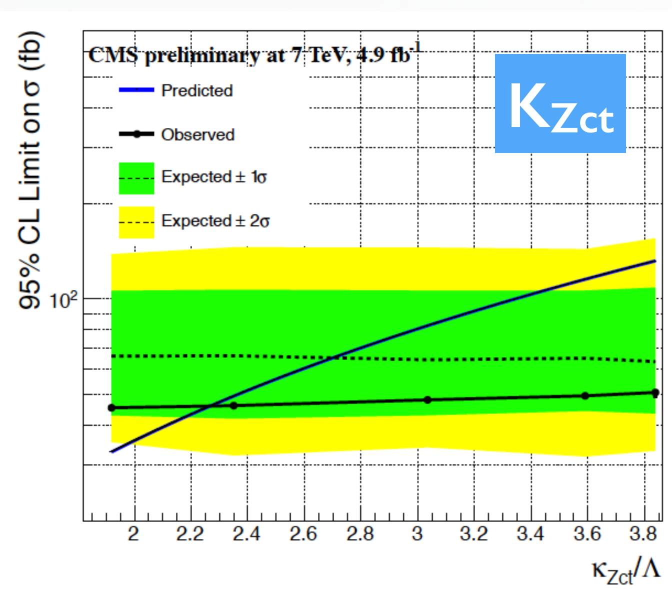
BDT is used to suppress background

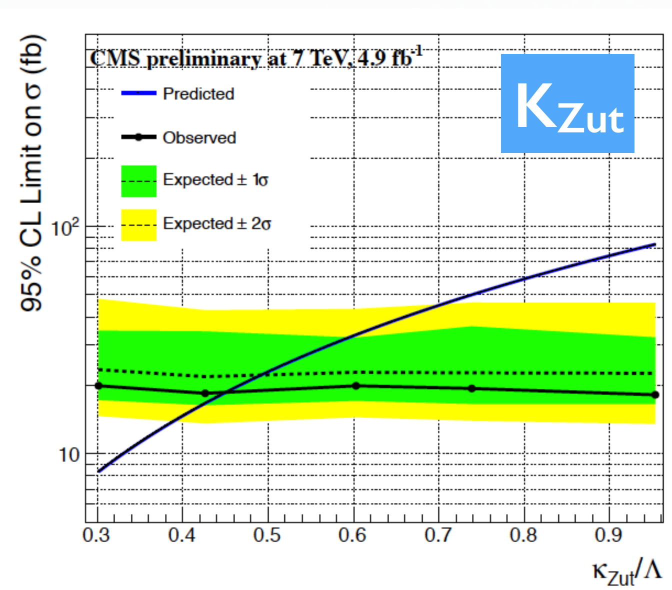
- At least three isolated leptons
- Restrict two leptons to be consistent with Z-peak
- Up to one b-tagged jet
- $m_T(W) > 20$ GeV

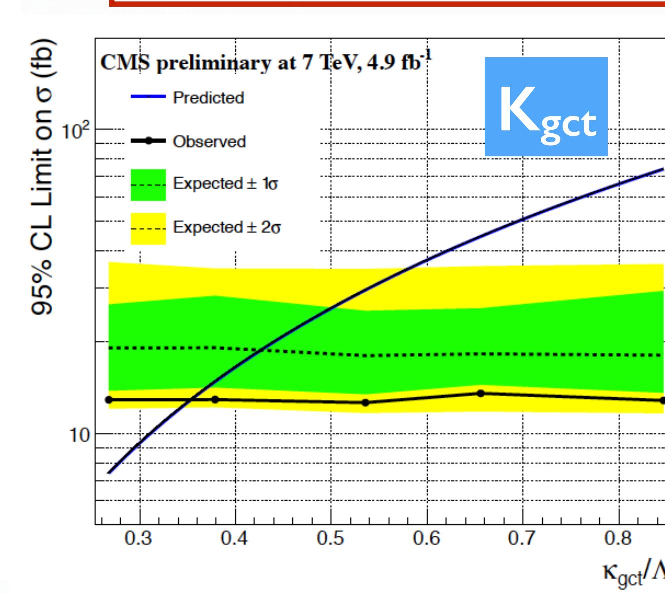
Main backgrounds: WZ/ZZ+jets, tZq, Z +jets

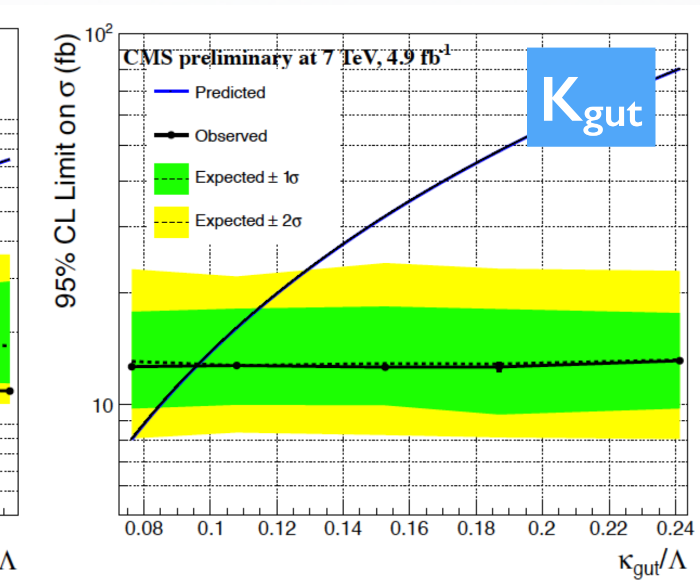


couplings	Expected	Observed	$\mathcal{B}(t \to gq/Zq)$
κ_{gut}/Λ	0.096	0.096	0.56 %
κ_{gct}/Λ	0.427	0.354	7.12 %
κ_{Zut}/Λ	0.492	0.451	0.51 %
κ_{Zct}/Λ	2.701	2.267	11.40 %



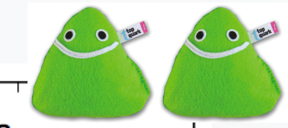






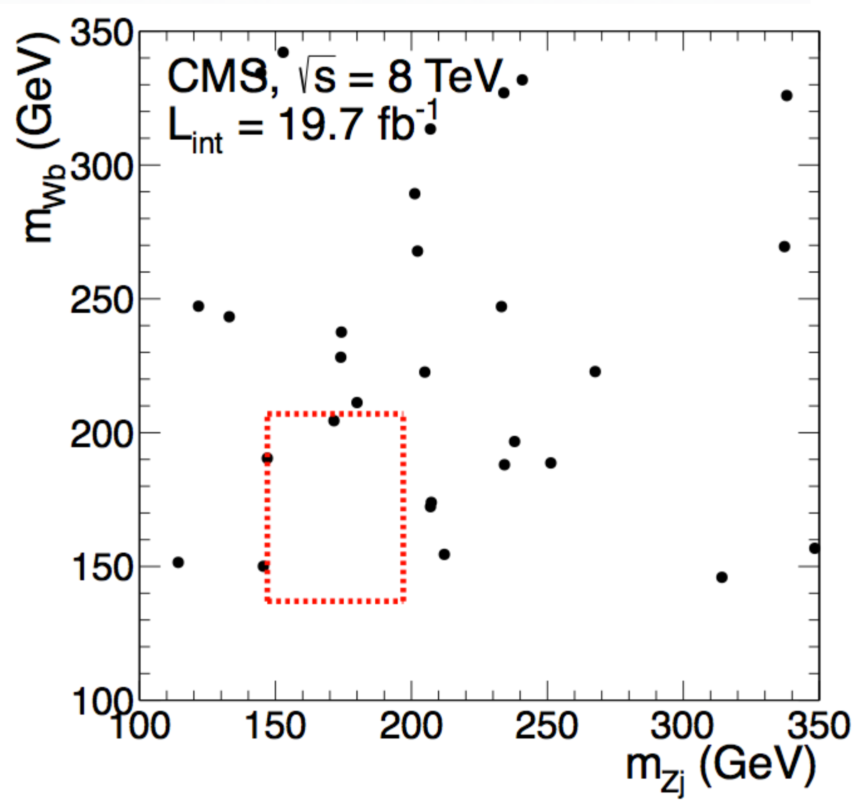
Search for FCNC t→Zq in ttbar events

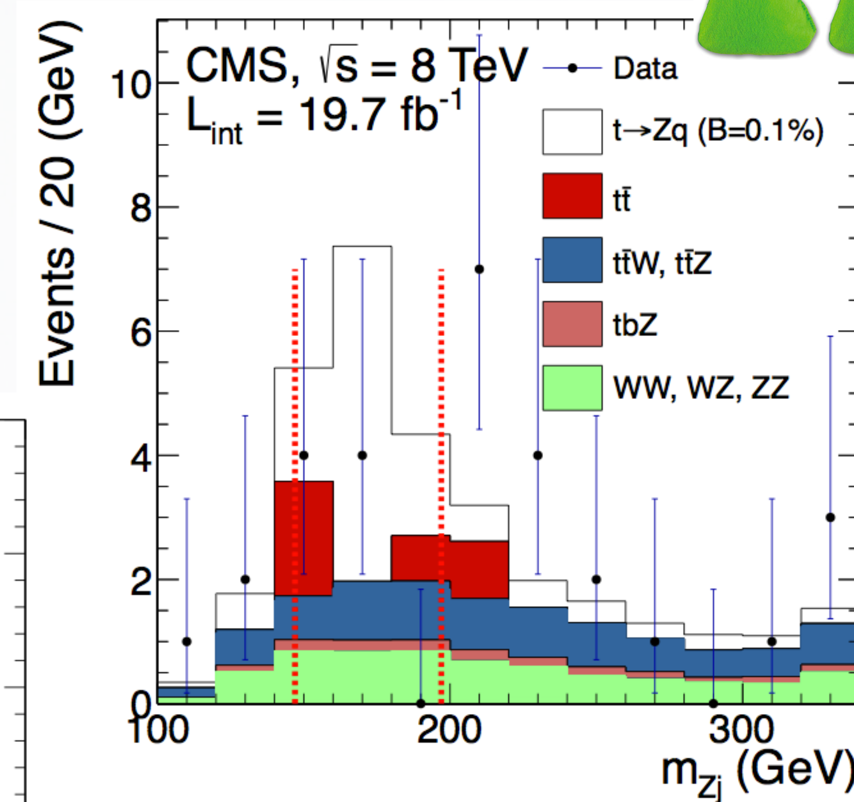
PRL 112 (2014) 171802
8 TeV, 20 fb^{-1}

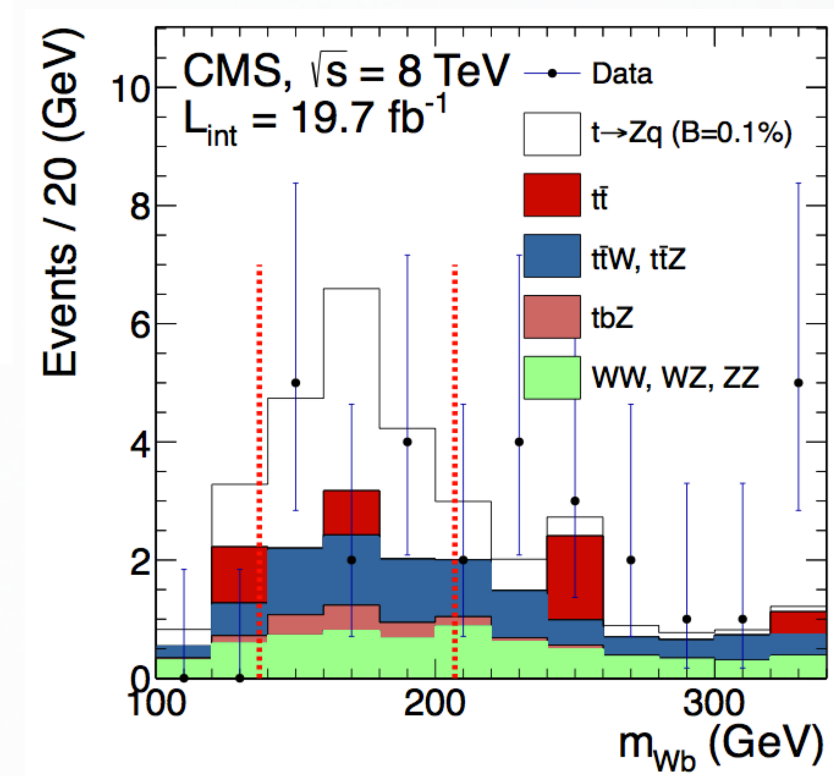


- At least three isolated leptons and at least two jets
- Restrict two leptons to be consistent with Z-peak
- Exactly one jet is b-tagged
- 137.5 < m(Wb) < 207.5 GeV
- 147.5 < m(Zq) < 197.5 GeV

Main backgrounds:
WZ/ZZ+jets,
ttbarW/Z, ttbar





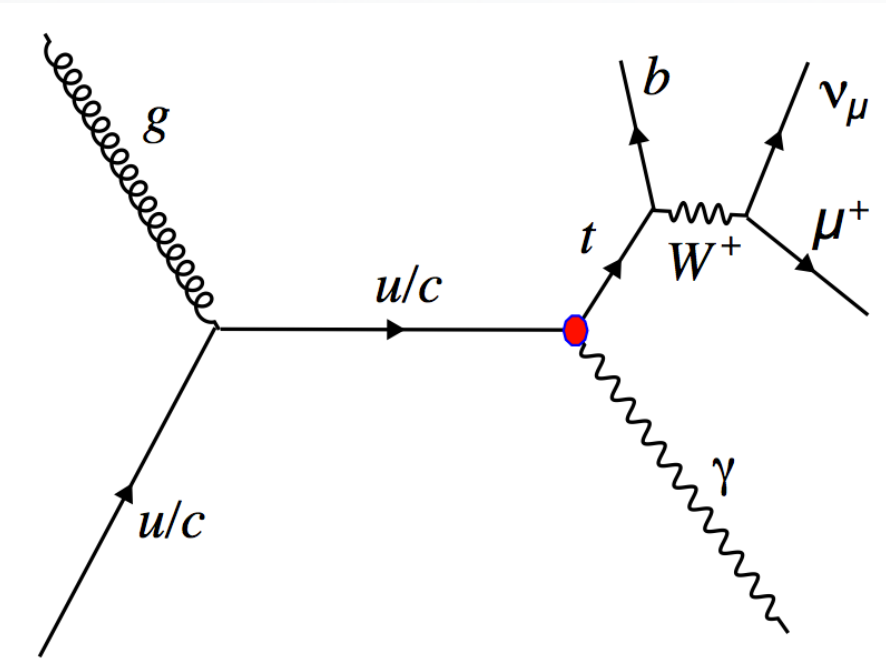


Result limits:

$\mathcal{B}(t \to Zq)$	8 TeV	7 TeV + 8 TeV
Expected upper limit	<0.10%	<0.09%
Observed upper limit	<0.06%	<0.05%
1 σ boundary	0.06–0.13%	0.06–0.13%
2 σ boundary	0.05–0.20%	0.05–0.18%

Search for FCNC tγ events

TOP PAS-14-003
8 TeV, 19 fb^{-1}

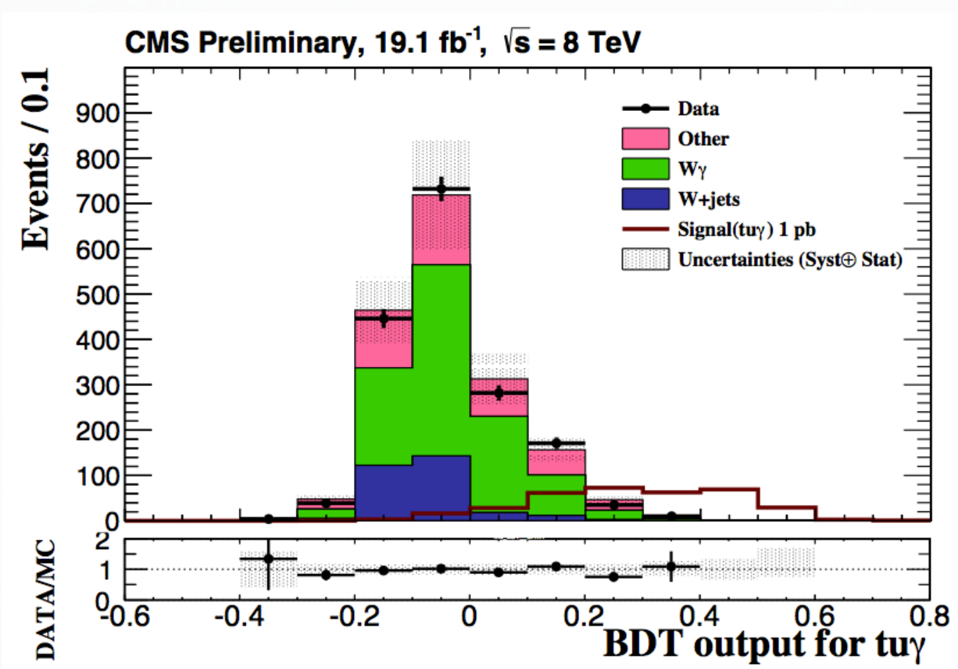


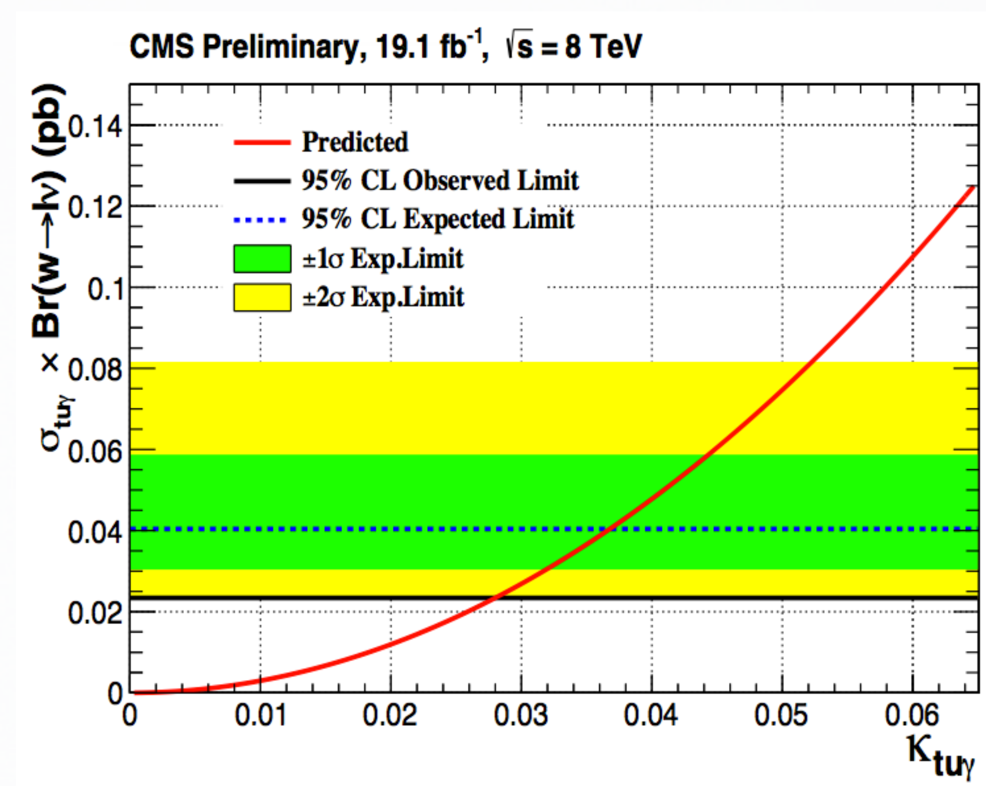
- Exactly one isolated photon, exactly one muon
- Up to one b-tagged jet in event
- Missing E_T > 30 GeV
- 130 < m(top) < 220 GeV

The main backgrounds are estimated from **data template fit** in W+jets control region (looser photon requirement and no b-tagging) using cos(W,γ)

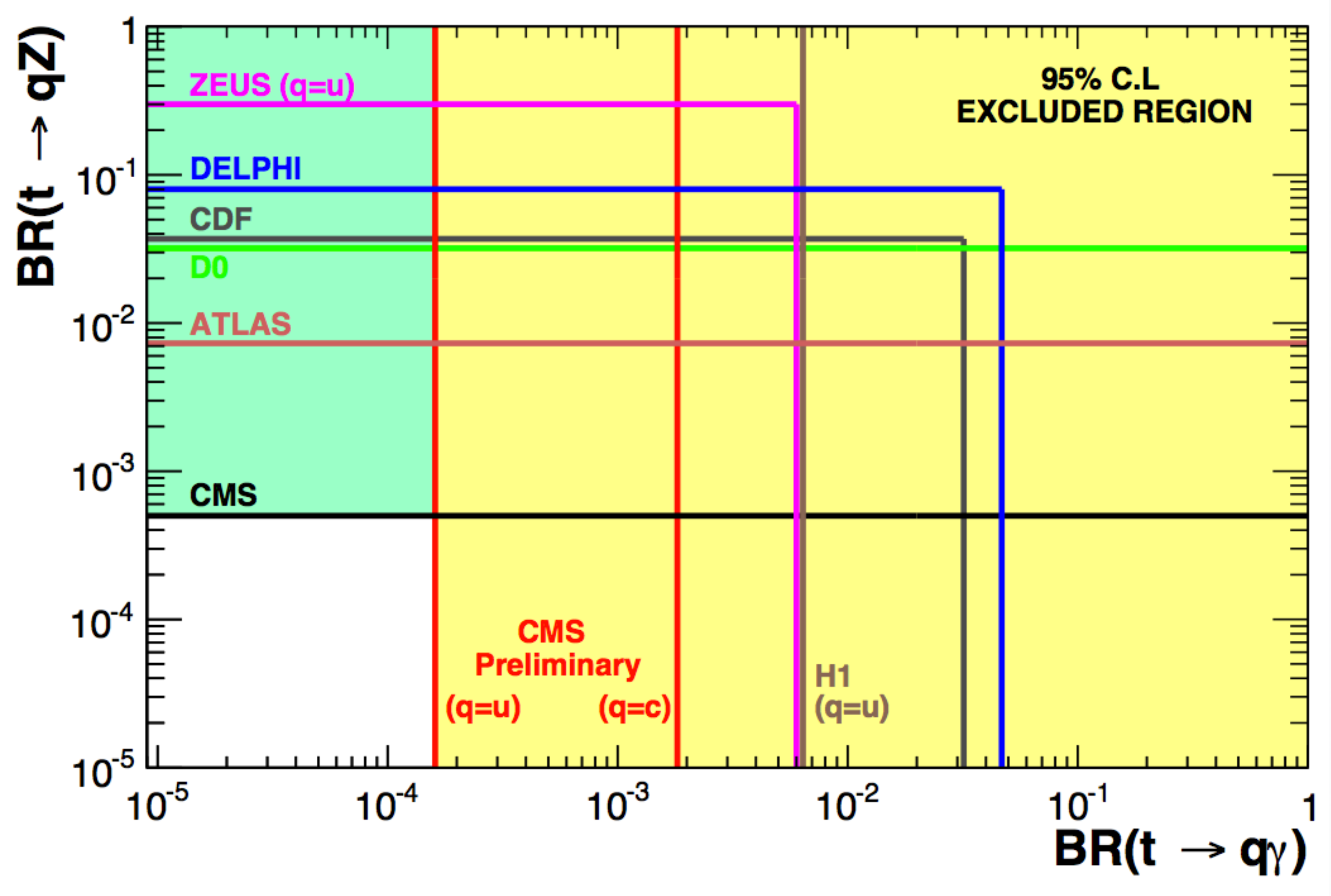
Main backgrounds:
W+jets, Wγ+jets

BDT is used as a final discriminant





Search for FCNC events

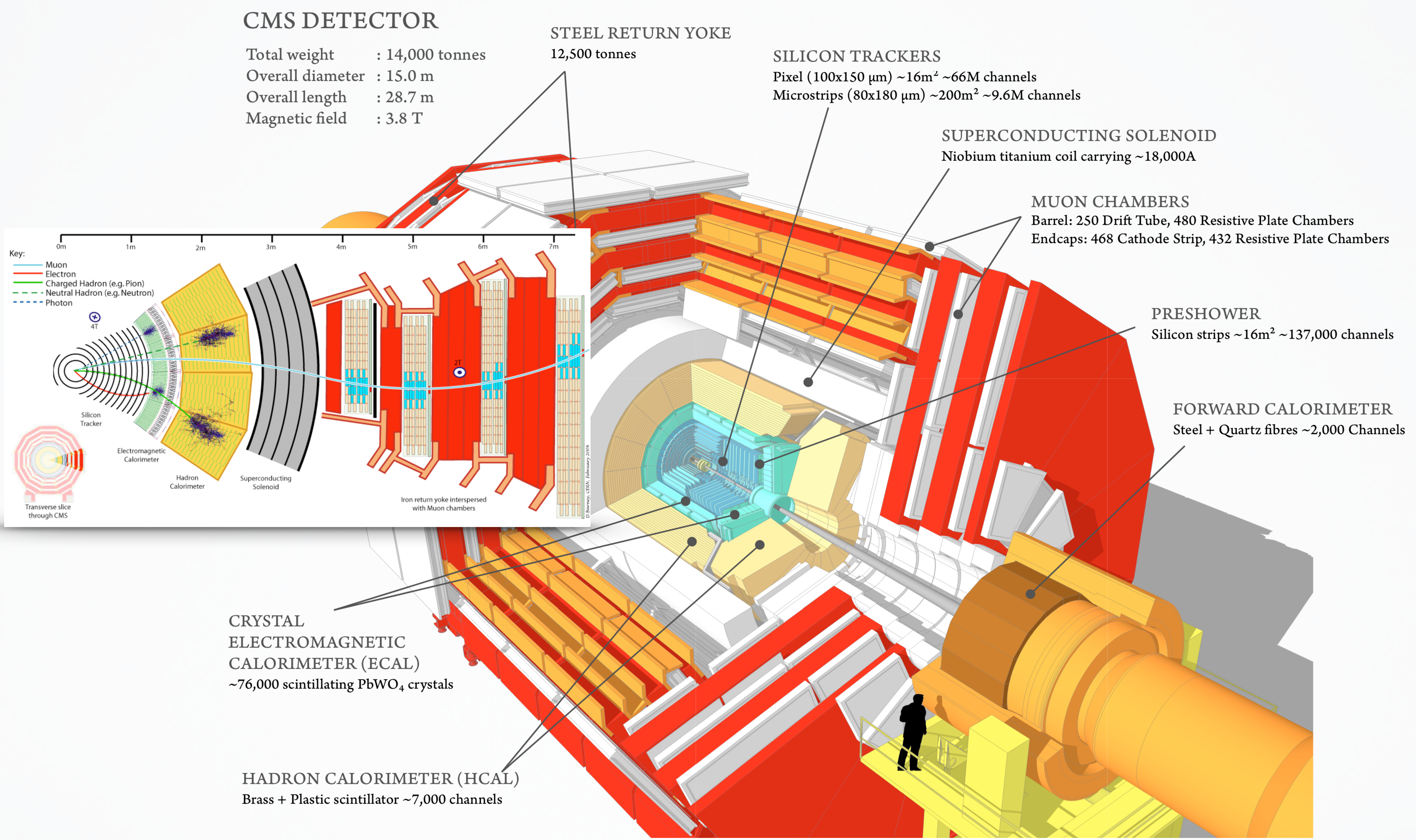


Conclusion

- The latest results on top-quark properties and single top production cross-sections at CMS using Run I data were presented
- Several analyses with the search for FCNC interactions involving top-quarks were presented as well
- All obtained results are in a good agreement with the SM predictions
- More new top-analyses based on 8 TeV data are expected to be released soon from the CMS collaboration
- Run II data should allow to improve the precision of these results and hopefully to lead to unexpected observations

Backup

The CMS experiment



Top-quark polarisation in single top

TOP PAS-13-001
8 TeV, 20 fb^{-1}

- Exactly one isolated lepton and at least two jets
- Missing E_T > 45 GeV (QCD suppression in electron channel)
- $m_T(W)$ > 50 GeV (muon channel)
- Events are classified by the number of b-tagged jets: 2-jet 1-tag (signal region), 2-jet 0-tag (W+jets), 3-jet 1-tag and 3-jet 2-tag (ttbar)

Angular distribution of decay products in the top-quark rest frame:

$$\frac{d\Gamma}{d\cos\theta_X} = \frac{\Gamma}{2}(1 + P_t\alpha_X\cos\theta_X) \equiv \Gamma(\frac{1}{2} + A_X\cos\theta_X)$$

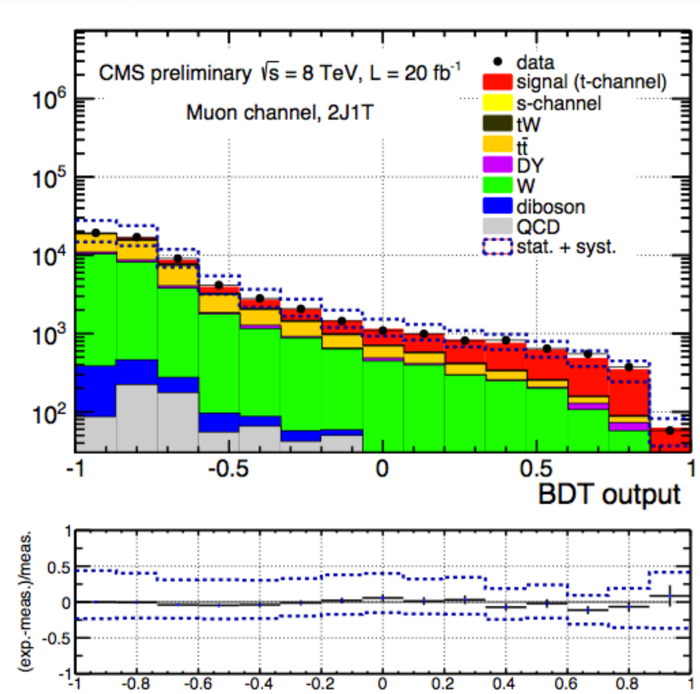
Top-quark polarisation

Degree of correlation of angular distributions wrt top-quark spin

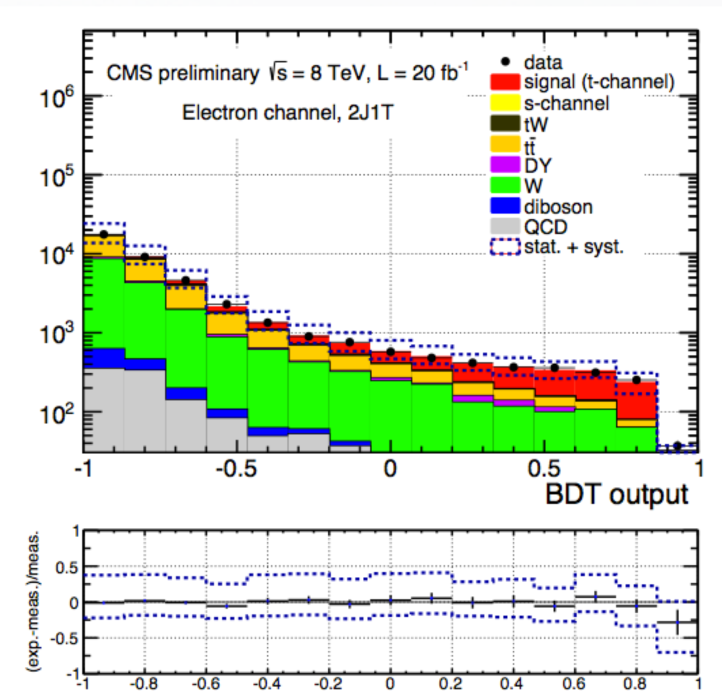
QCD multijet background is estimated from template fit in data by reversing lepton isolation requirement

Additional background suppression is done by BDT

Muon, 2-jet 1-tag

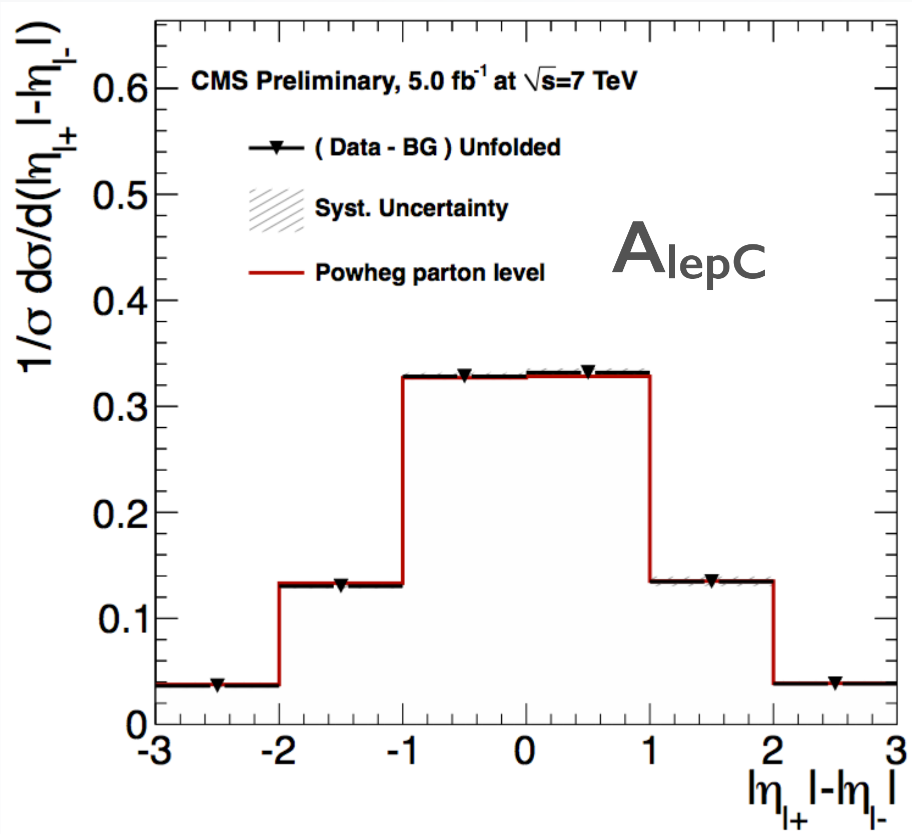


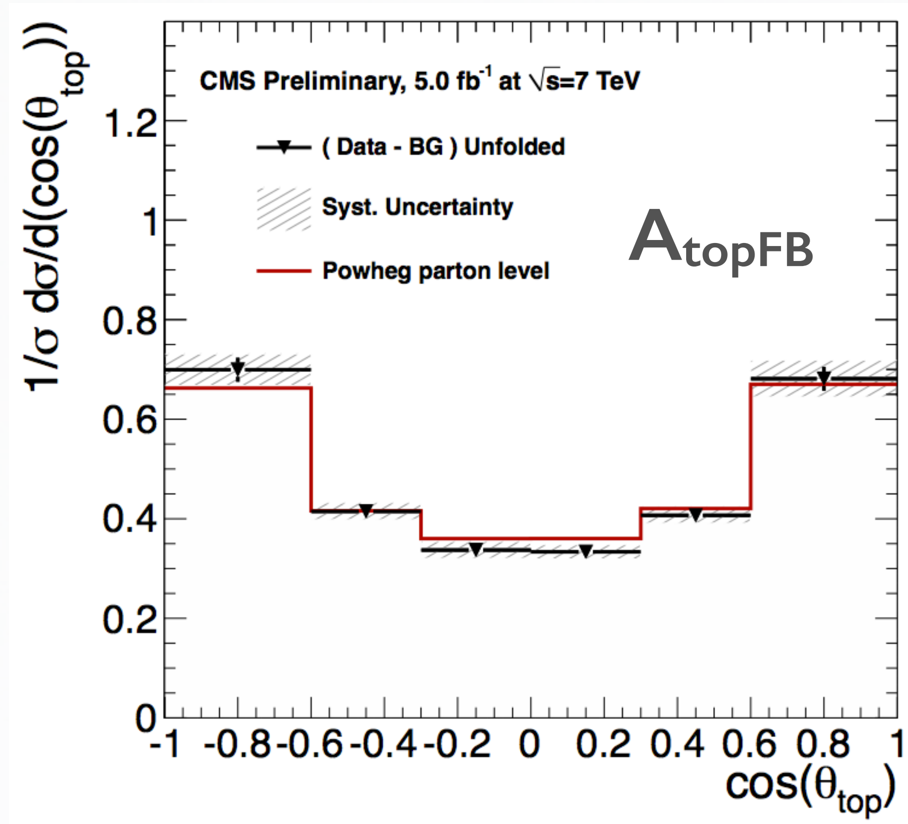
Electron, 2-jet 1-tag



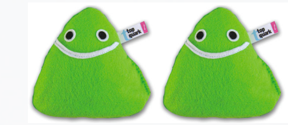
Charge asymmetry in dilepton+jets

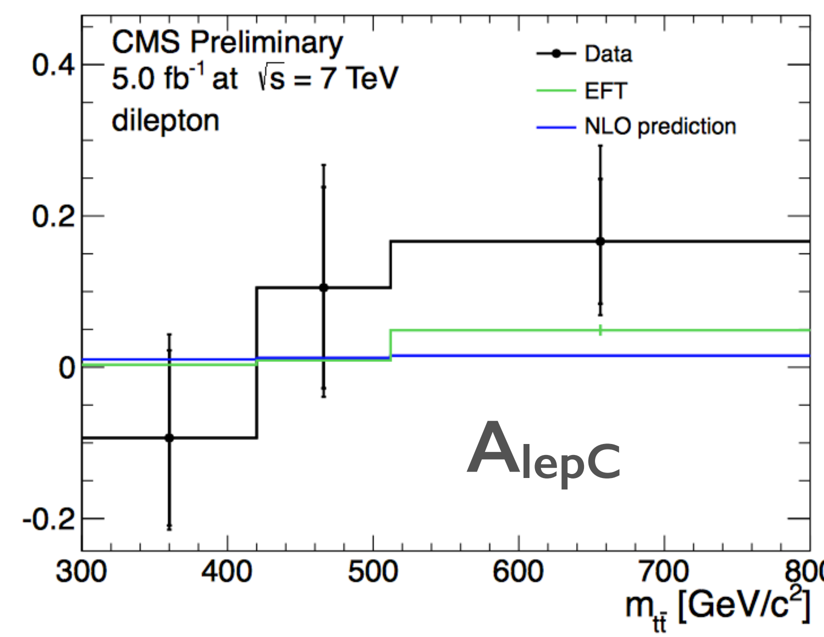
TOP PAS-12-010
7 TeV, 5 fb^{-1}





Unfolded results





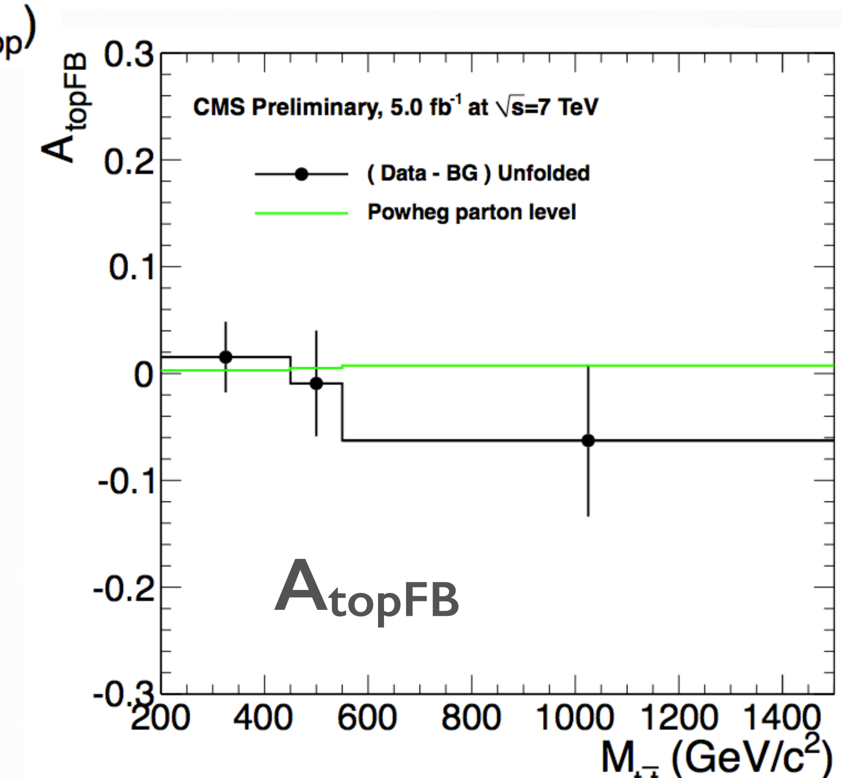
Charge asymmetry

$$A_{lepC} = \frac{N(|\eta_{l+}| > |\eta_{l-}|) - N(|\eta_{l+}| < |\eta_{l-}|)}{N(|\eta_{l+}| > |\eta_{l-}|) + N(|\eta_{l+}| < |\eta_{l-}|)}$$

forward-backward asymmetry

$$A_{topFB} = \frac{N(\cos(\theta_t) > 0) - N(\cos(\theta_t) < 0)}{N(\cos(\theta_t) > 0) + N(\cos(\theta_t) < 0)}$$

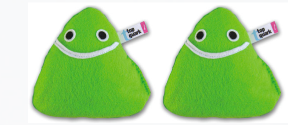
Unfolded asymmetries	Data	POWHEG
A_{lepC}	$0.010 \pm 0.015 \pm 0.006$	0.004 ± 0.0004
A_{topFB}	$-0.011 \pm 0.034 \pm 0.026$	0.005 ± 0.0004
$A_{topFB}(M_{t\bar{t}} < 450$ GeV)	$0.015 \pm 0.033 \pm 0.034$	0.003 ± 0.001
$A_{topFB}(450 \leq M_{t\bar{t}} < 550$ GeV)	$-0.009 \pm 0.050 \pm 0.055$	0.005 ± 0.001
$A_{topFB}(M_{t\bar{t}} \geq 550$ GeV)	$-0.063 \pm 0.071 \pm 0.081$	0.007 ± 0.001



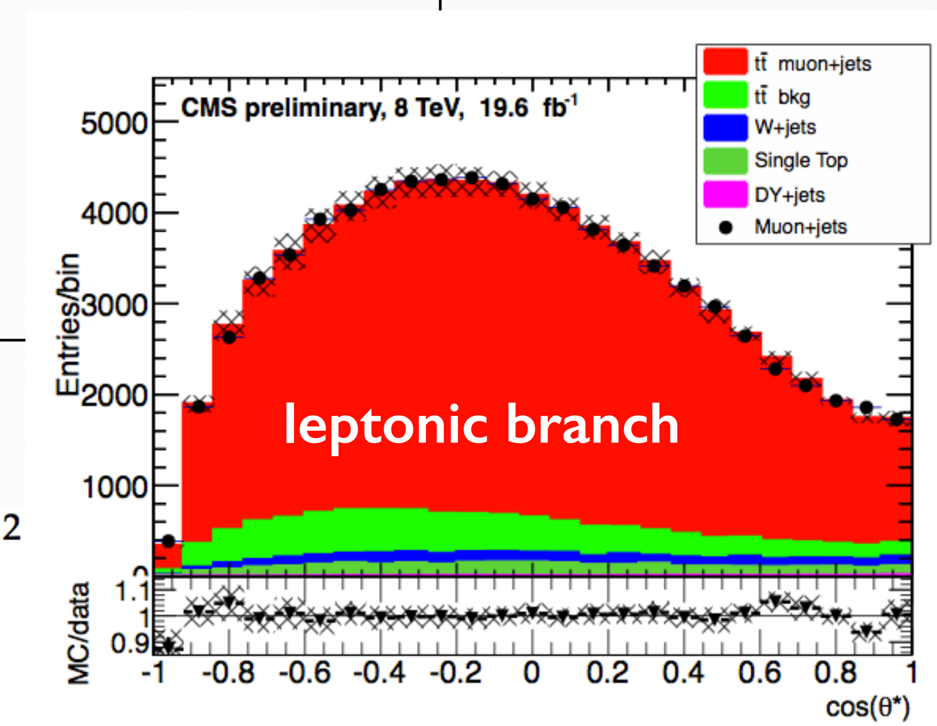
EFT: model with axial-vector gluon coupling with effective scale 1 TeV (E. Gabrielli, M. Raidal, and A. Racioppi)

W-boson helicity in ttbar

PAS TOP-13-008
8 TeV, 20 fb^{-1}



- Analysis is done in **muon+jets** channel (top-quark semi-leptonic and hadronic decays)
- Isolated muon
- $m_T(W) > 30$ GeV (QCD background rejection)
- $m_T(W) < 200$ GeV (suppression of dileptonic modes in ttbar)
- At least two jets are b-tagged (suppression of W+jets and QCD)



Top-quark reconstruction uses kinematic fit:

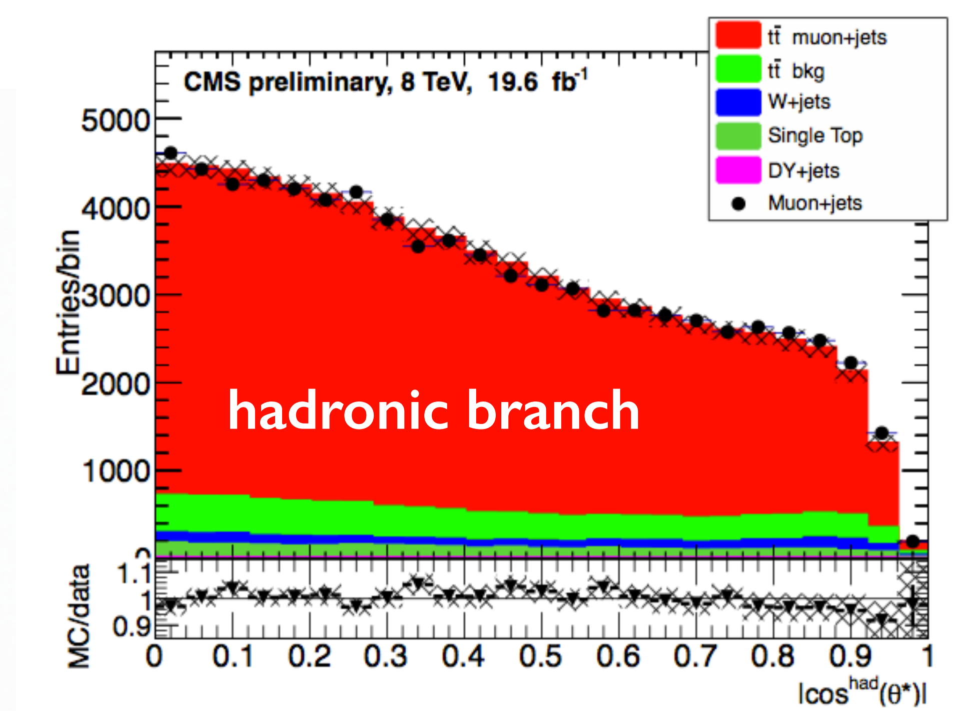
$$\chi^2_{\mathrm{comb}} = \left(\frac{m_t - m_t^{\mathrm{ref}}}{\sigma_{m_t}}\right)^2 + \left(\frac{m_{\bar{t}} - m_{\bar{t}}^{\mathrm{ref}}}{\sigma_{m_{\bar{t}}}}\right)^2 + \left(\frac{M_W^{\mathrm{lep}} - 80.4}{\sigma_{M_W^{\mathrm{lep}}}}\right)^2 + \left(\frac{M_W^{\mathrm{had}} - 80.4}{\sigma_{M_W^{\mathrm{had}}}}\right)^2 - \sum_{i=1,4} 2 \ln p_i(\mathrm{disc}|f),$$

b-tagging requirement

experimental mass resolution

neutrino momentum is constrained by W→ℓν

$$\vec{p}^{\nu} = (\vec{p}_T^{\mathrm{miss}}, p_z^{\nu})$$

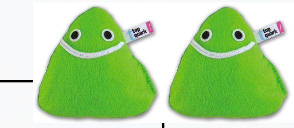


$$\begin{aligned} F_0 &= 0.659 \pm 0.015(\mathrm{stat.}) \pm 0.023(\mathrm{syst.}) \\ F_L &= 0.350 \pm 0.010(\mathrm{stat.}) \pm 0.024(\mathrm{syst.}) \\ F_R &= -0.009 \pm 0.006(\mathrm{stat.}) \pm 0.020(\mathrm{syst.}) \end{aligned}$$

total systematic uncertainties are reduced if compare to 7 TeV result

Top-quark polarisation and spin correlations

Phys.Rev.Lett. 112 182001
7 TeV, 5 fb^{-1}



- Exactly two isolated opposite-sign leptons and at least two jets
- For same-flavour lepton final state veto events with 76 < m(ll) < 106 GeV (DY+jets suppression)
- At least one jet is b-tagged
- Missing E_T > 40 GeV in events with same-flavour leptons (DY+jets suppression)

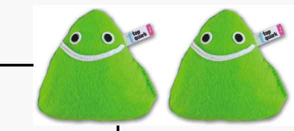
Top-quark reconstruction is done with **matrix weighting technique**: perform a scan of top-quark mass in the region from 100 to 300 GeV and calculate the weight per event (the max value is chosen for reconstructed m_{top})

DY+jets background is corrected from data by scaling to MC Z-window/Z-sideband yield

Fake lepton background is estimated from data via p_T/η-parametrised misidentification rates

Charge asymmetry in dilepton+jets

TOP PAS-12-010
7 TeV, 5 fb^{-1}



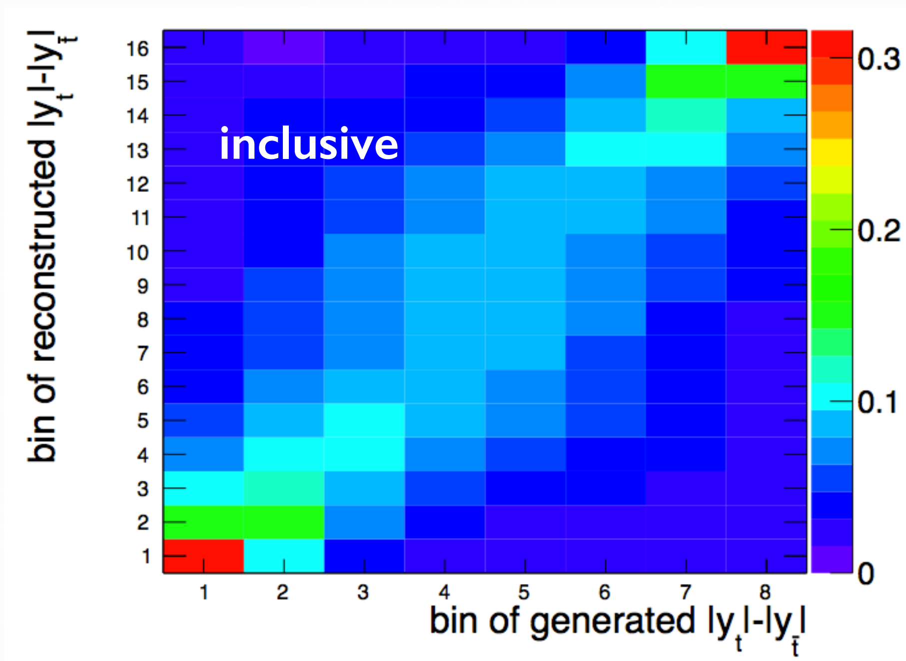
- At least one pair of opposite-sign isolated leptons (the highest-P_T pair is used)
- At least two AntiKt5 jets
- m(ll) > 12 GeV and 76 < m(ll) < 106 GeV (for dielectron and dimuon channels)
- Missing E_T > 30 GeV (for dielectron and dimuon channels)

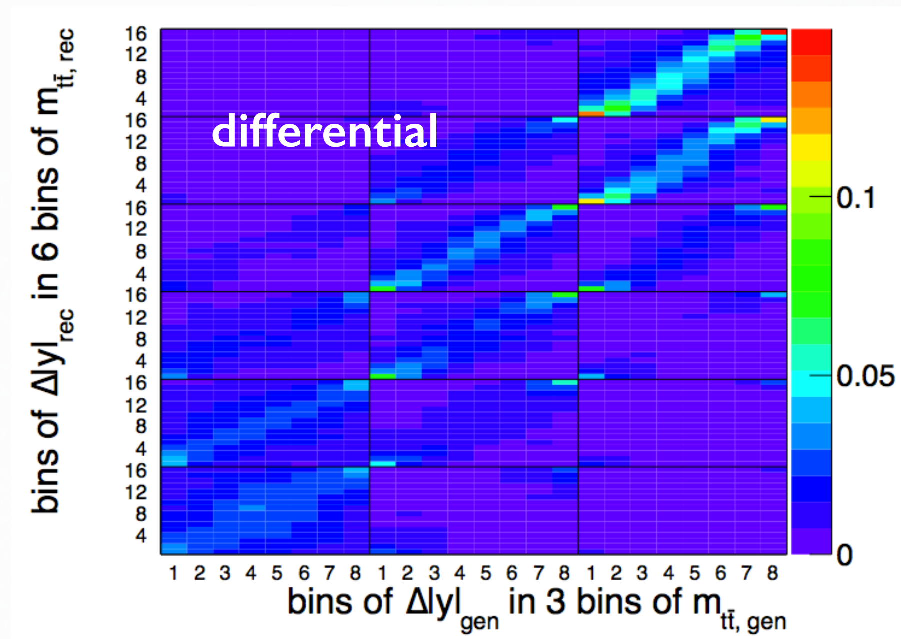
Top-quark reconstruction is done with matrix weighting technique (as in top quark polarisation and spin correlations analysis)

Fake Matrix Method is used to estimate QCD multilepton background

The matrix-inversion method (as in lepton+jets analysis) is used to perform an unfolding procedure

migration matrices

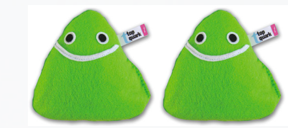




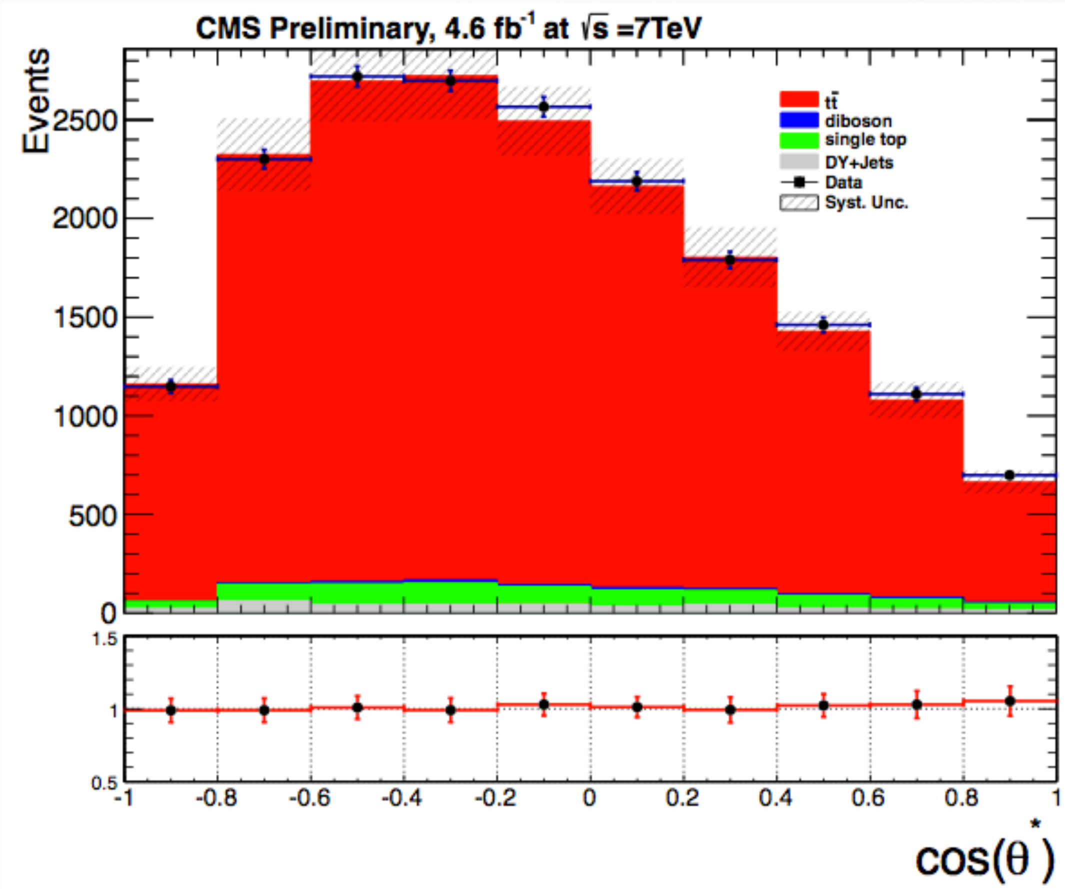
W-boson helicity in ttbar

PAS TOP-12-015

7 TeV, 5 fb^{-1}



- Analysis is done in **dileption** channel
- Two isolated leptons
- Veto events with 76 < m(ll) < 106 GeV (to reject DY background, applied only for ee and μμ channels)
- At least one jet is b-tagged (suppression of W +jets and QCD)
- Missing E_T > 30 GeV (ee, μμ) and > 20 GeV (eμ)
- The same reweighting method to extract the helicity of W-boson as in muon+jets analysis at 8 TeV



Results for W-boson helicity fractions:

$$F_L = 0.288 \pm 0.035(\text{stat}) \pm 0.040(\text{syst})$$
$$F_0 = 0.698 \pm 0.057(\text{stat}) \pm 0.063(\text{syst})$$
$$F_R = 0.014 \pm 0.027(\text{stat}) \pm 0.042(\text{syst})$$

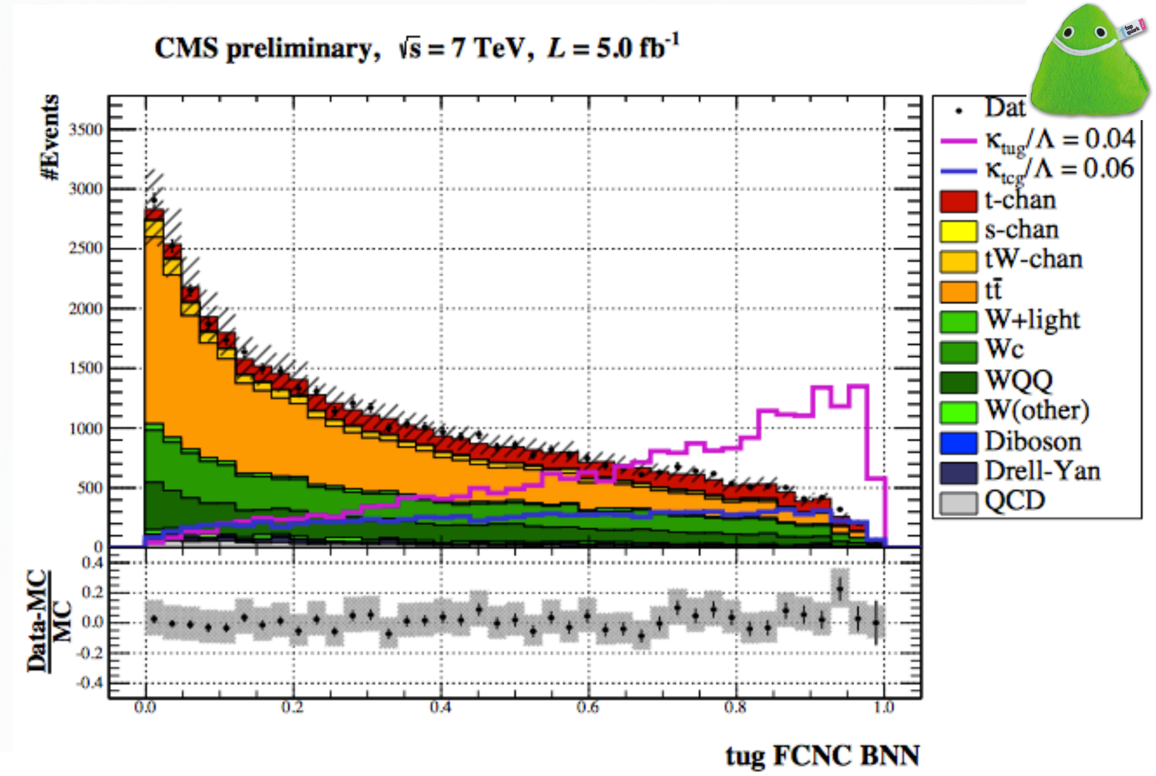
Search for anomalous couplings in t-channel

- Exactly one isolated muon with $P_T > 20$ GeV and $|\eta| < 2.1$
- Events with loose electrons are vetoed
- Two or three AntiKt5 jets with $P_T > 30$ GeV and $|\eta| < 4.7$
- At least one b-tagged jet and one non-b-tagged jet

BNN is used as a final discriminant

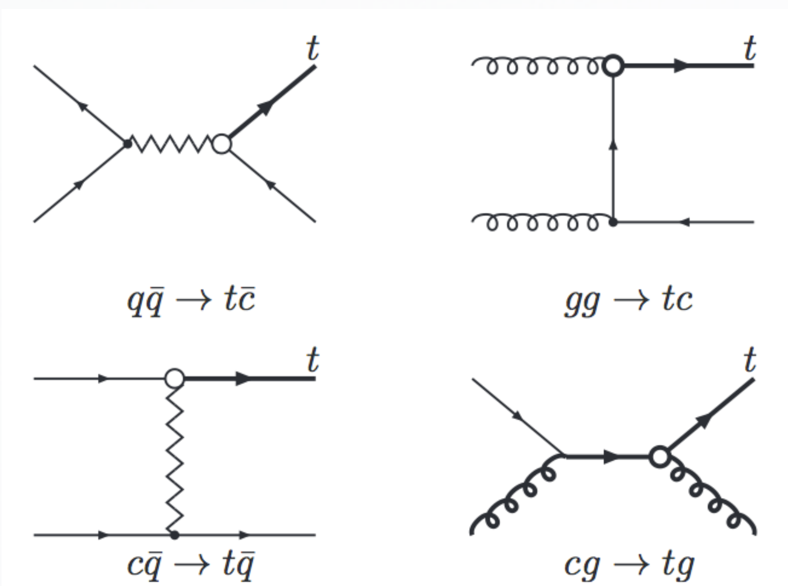
Main backgrounds: W+jets, ttbar, single top, QCD, DY+jets

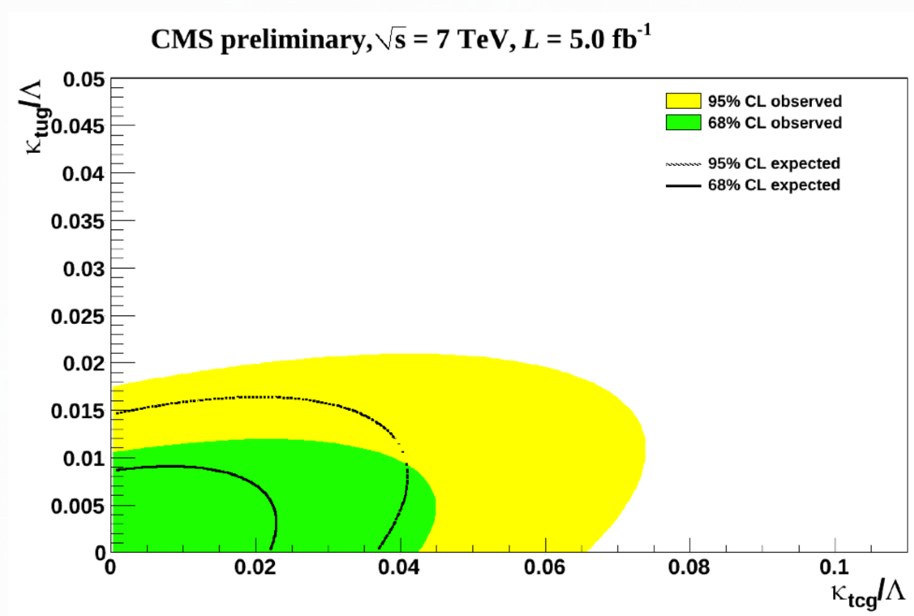
QCD background is suppressed by a dedicated BNN

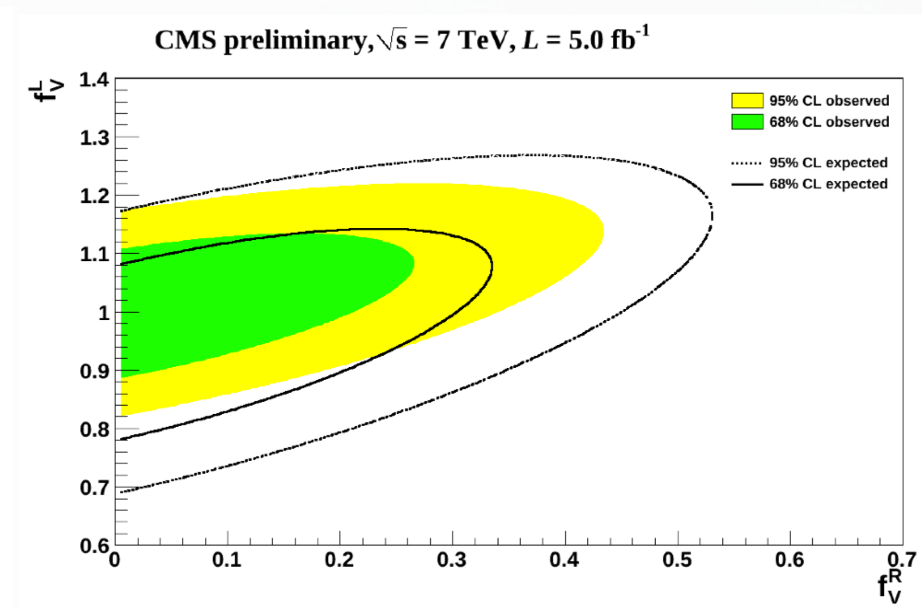


$$\mathfrak{L} = -\frac{g}{\sqrt{2}}\bar{b}\gamma^{\mu}\left(f_V^L P_L + f_V^R P_R\right) t W_{\mu}^- - \frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}\partial_{\nu}W_{\mu}^-}{M_W}\left(f_T^L P_L + f_T^R P_R\right) t + h.c.$$

QCD background normalisation is extracted from template fit to QCD BNN discriminator







Search for anomalous couplings in t-channel

TOP PAS-14-007
7 TeV, 5 fb^{-1}

Wtb anomalous couplings limits:

Observed (expected) 95% C.L. limits:

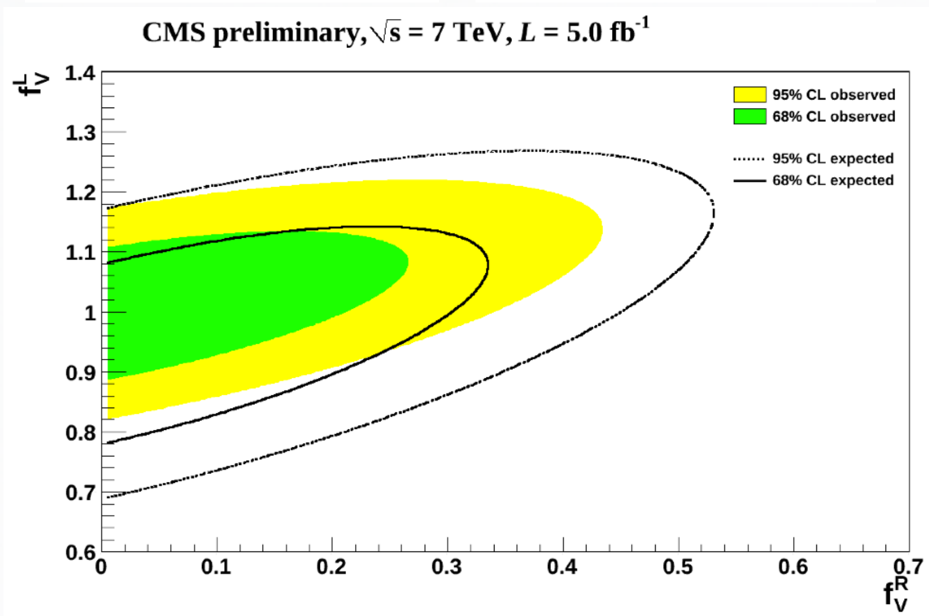
$|f_V^L| > 0.90\ (0.88)$
$|f_V^R| < 0.34\ (0.39)$

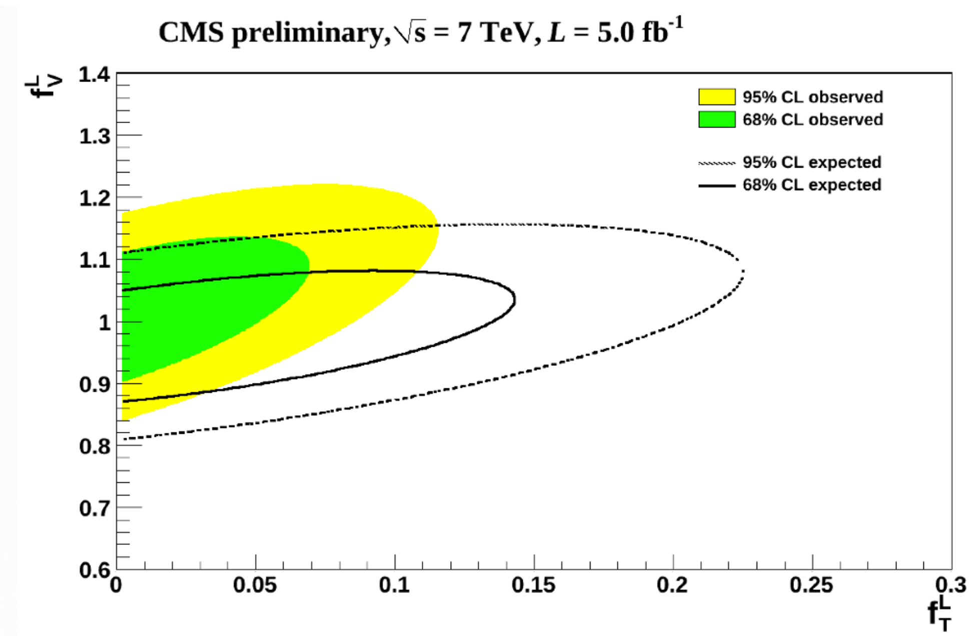
$|f_V^L| > 0.92\ (0.88)$
$|f_T^L| < 0.09\ (0.16)$

$$\sigma = \left((f_V^L)^2 A_p + (f_V^R)^2 B_p \right) Br(t \to l, \nu, b)$$

$$Br(t \to l, \nu, b) = \left((f_V^L)^2 A_d + (f_V^R)^2 B_d \right) / w_{tot}$$

$$\sigma(f_V^L, f_V^R) = m(1000) + n(artificial) + k(0100)$$





FCNC limits:

$$\frac{\kappa_{tug}}{\Lambda} < 1.8 \cdot 10^{-2}\ (1.2 \cdot 10^{-2})\ \text{TeV}^{-1},$$
$$\frac{\kappa_{tcg}}{\Lambda} < 5.6 \cdot 10^{-2}\ (3.1 \cdot 10^{-2})\ \text{TeV}^{-1}.$$

$$Br(t \to u + g) < 3.55 \times 10^{-4}\ (1.58 \times 10^{-4}),$$
$$Br(t \to c + g) < 3.44 \times 10^{-3}\ (1.05 \times 10^{-3})$$