Top-quark physics results from CMS

PANIC 2014

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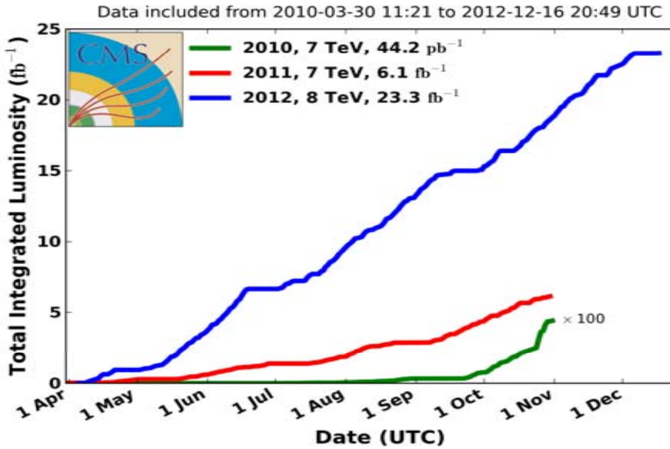
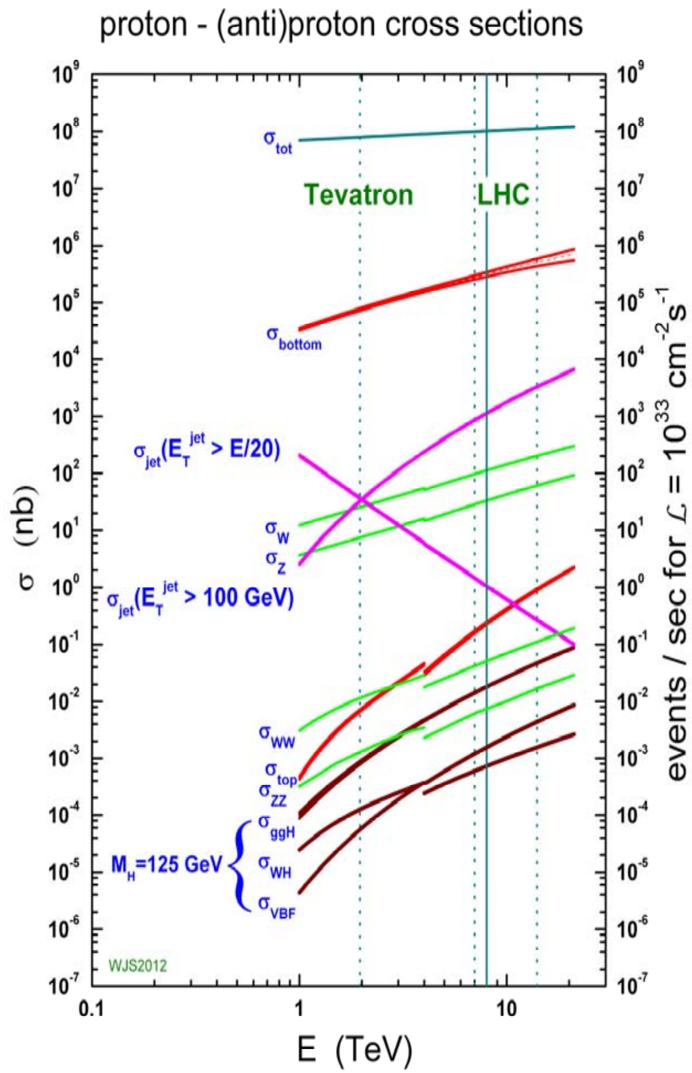
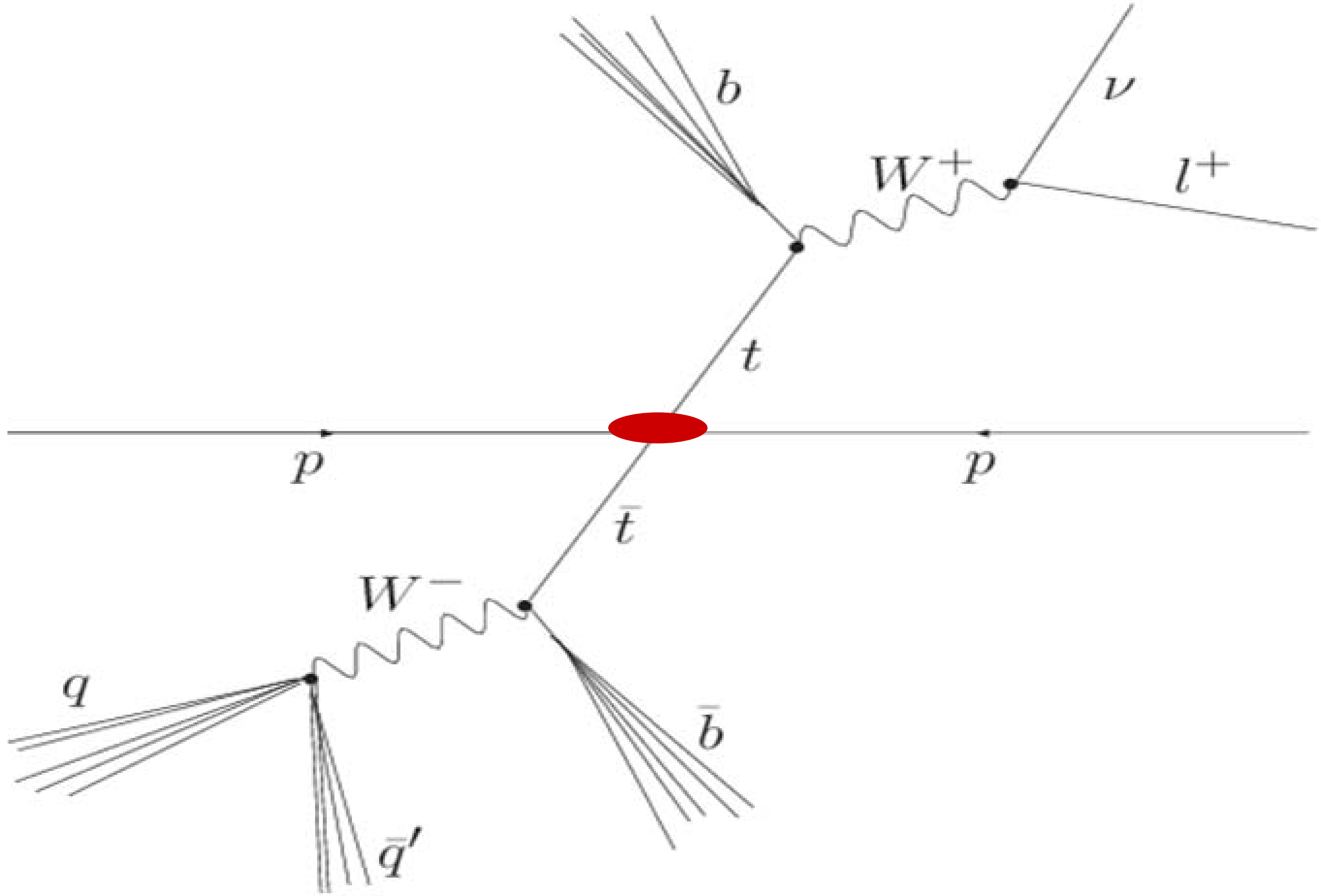
Introduction

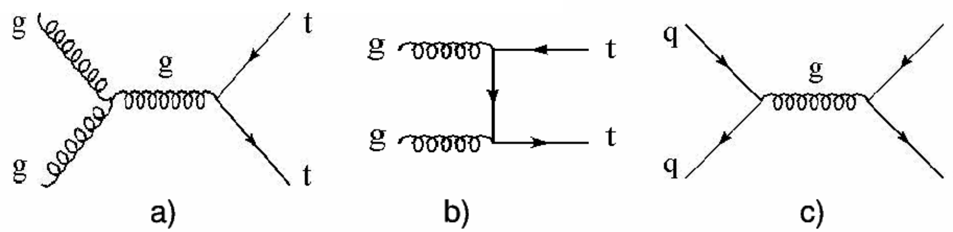
- The top-quark is the heaviest observed particle.
- In many aspects, it is of a special interest for particle physics :
  - Decays before it hadronizes : measurement of top-quark properties,
  - Large coupling with the Higgs-boson,
  - Precision measurements : search for deviations and understanding of MC generators, theoretical calc.,
  - Important for direct BSM searches : signatures with top quarks, backgrounds,
- Copiously produce at the LHC ! (≈5.10^6 top pairs)





Top-quark analyses in $t\bar{t}$ events





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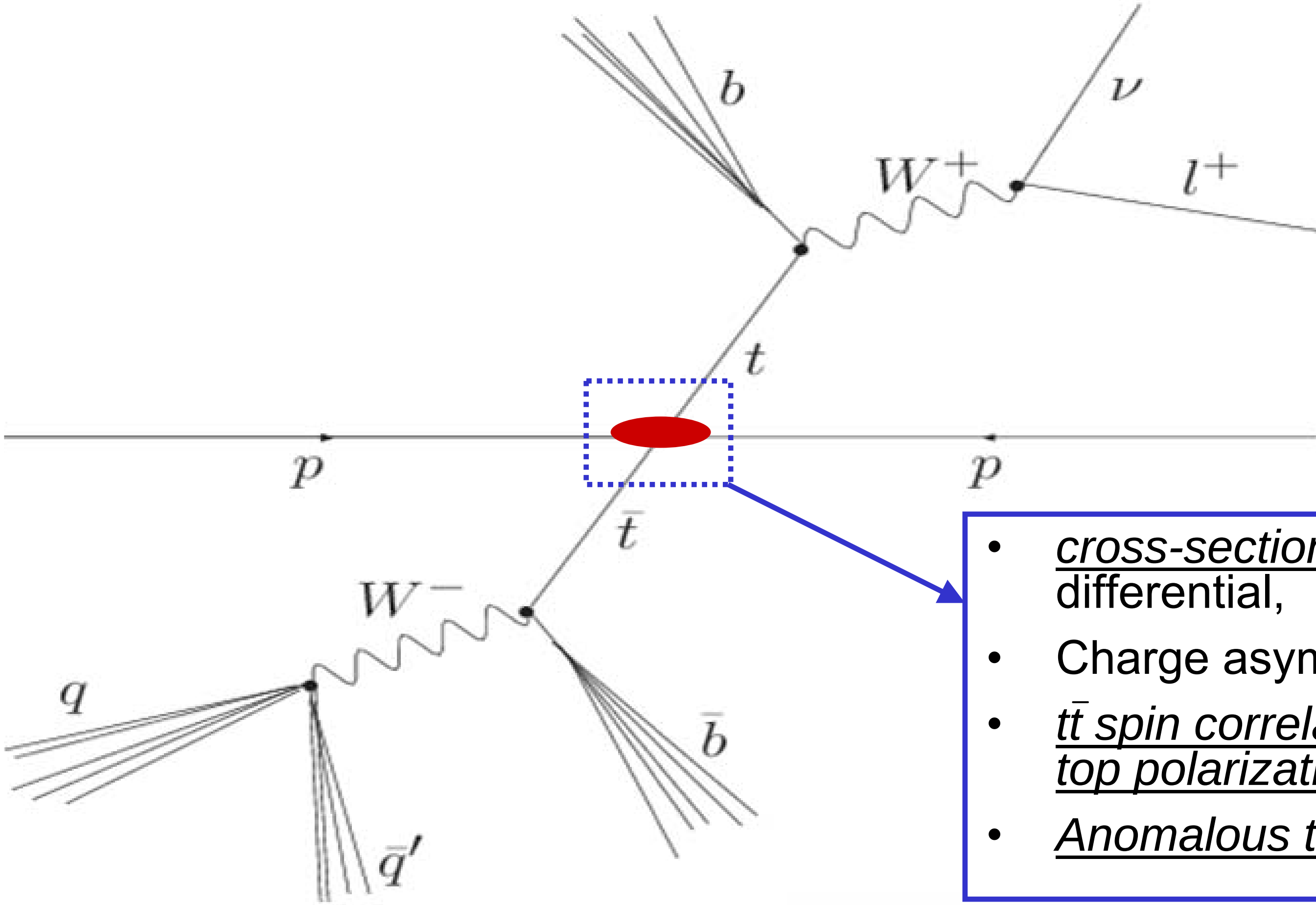
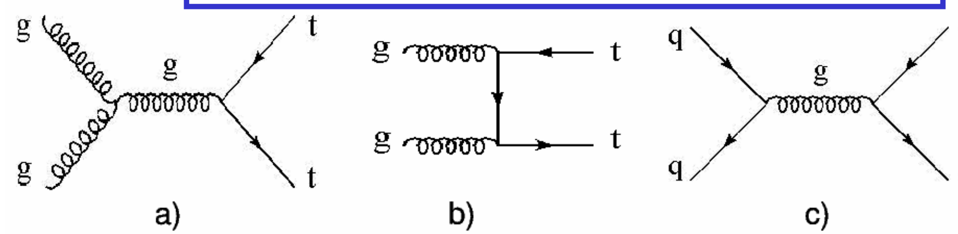
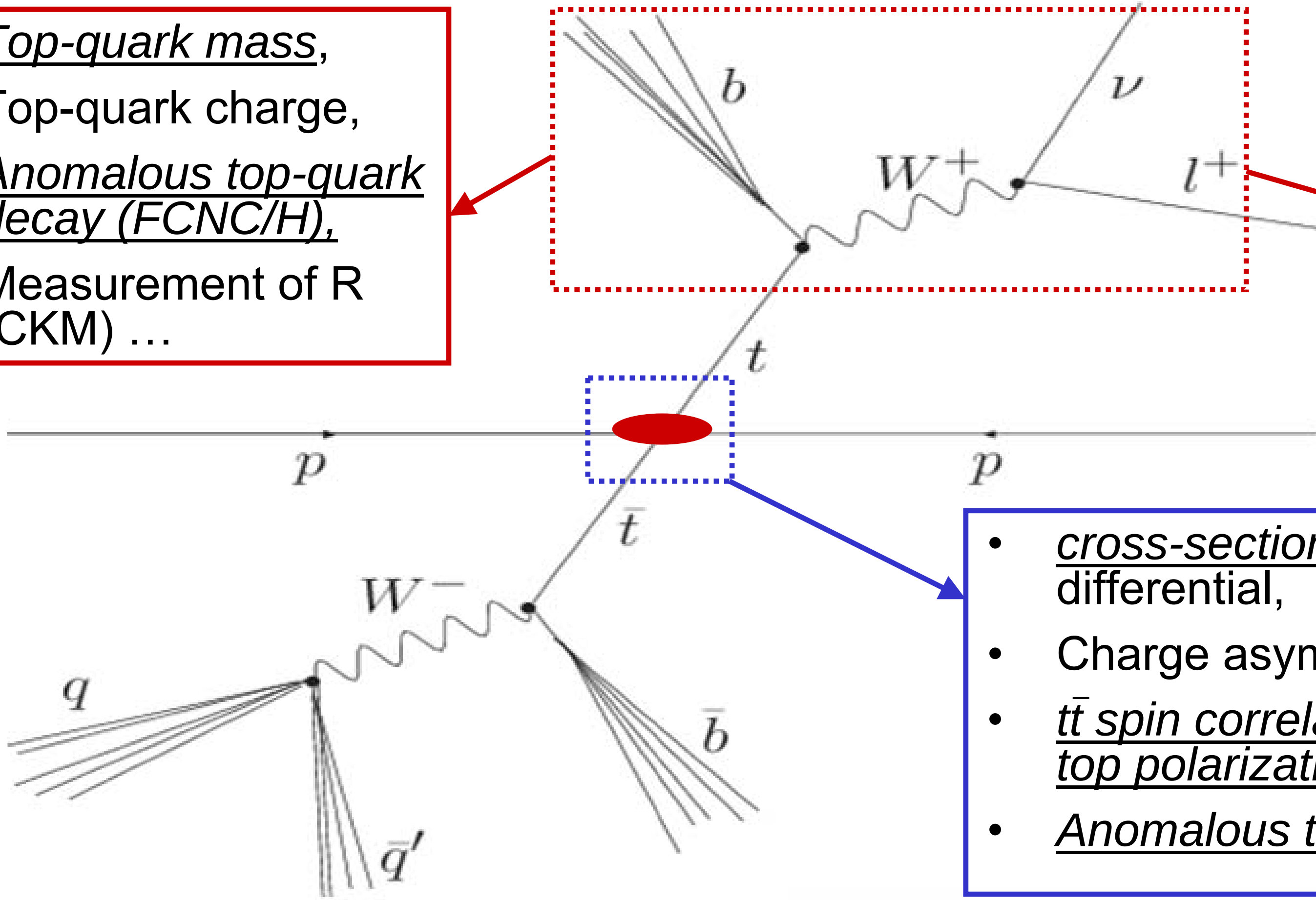


- *cross-section: inclusive* and differential,
- Charge asymmetry,
- *$t\bar{t}$ spin correlation, top polarization*
- *Anomalous $t\bar{t}g$ couplings*…



Top-quark analyses in $t\bar{t}$ events

- *Top-quark mass*,
- Top-quark charge,
- *Anomalous top-quark decay (FCNC/H),*
- Measurement of R (CKM) …



- W-helicity,
- Anomalous tWb couplings…

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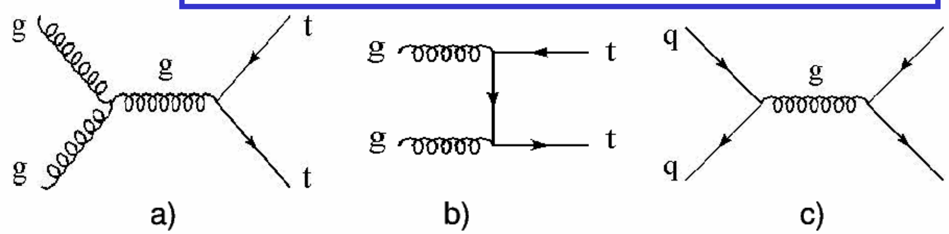

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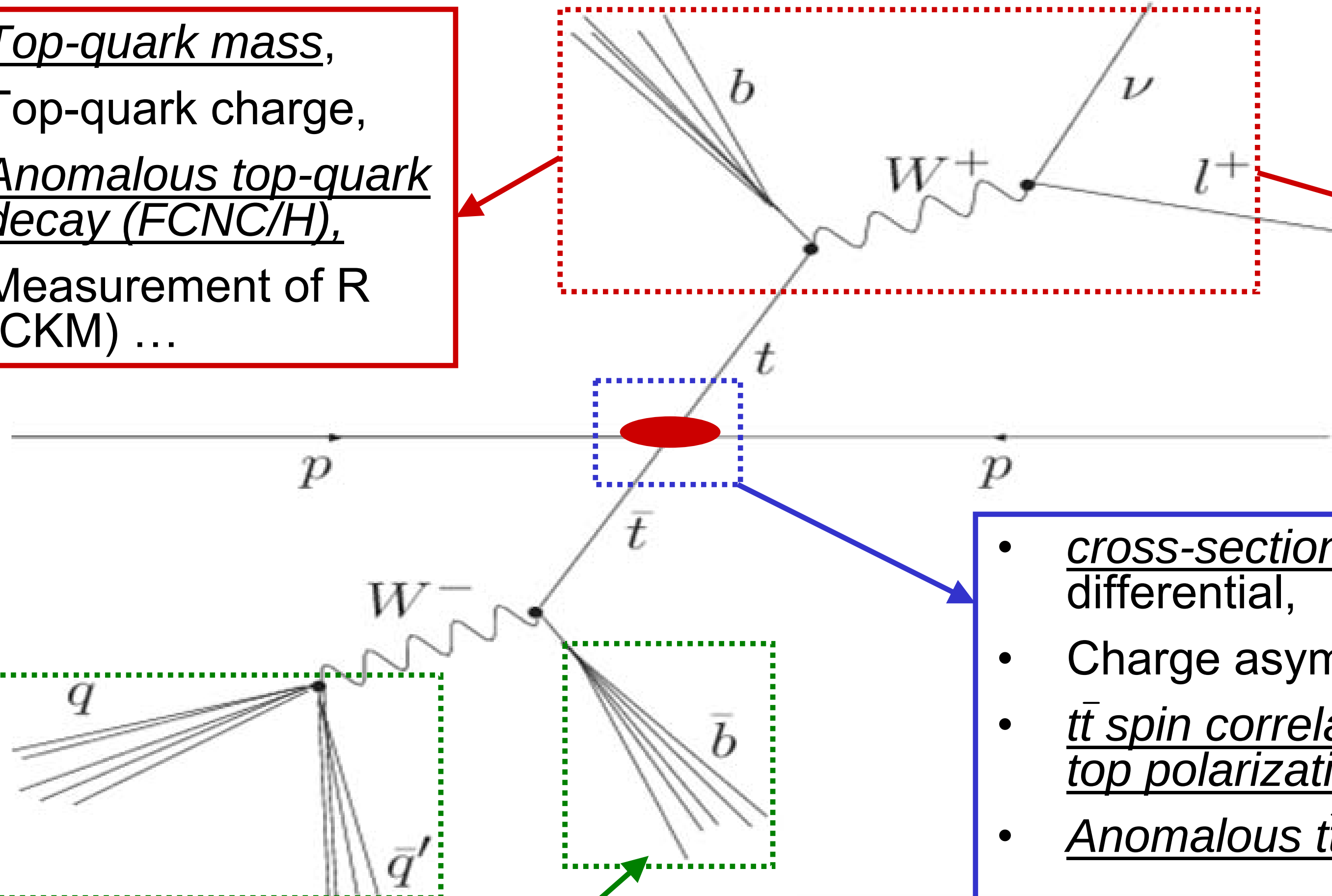

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- *cross-section: inclusive* and differential,
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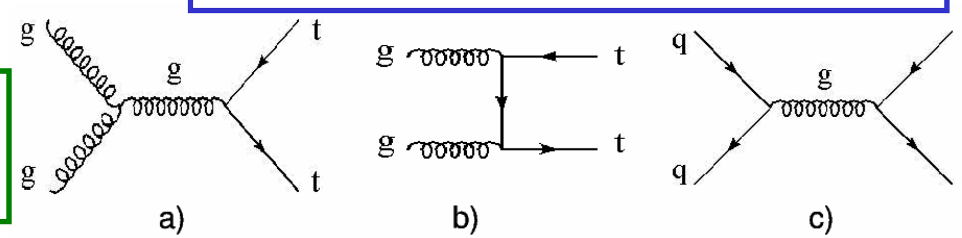
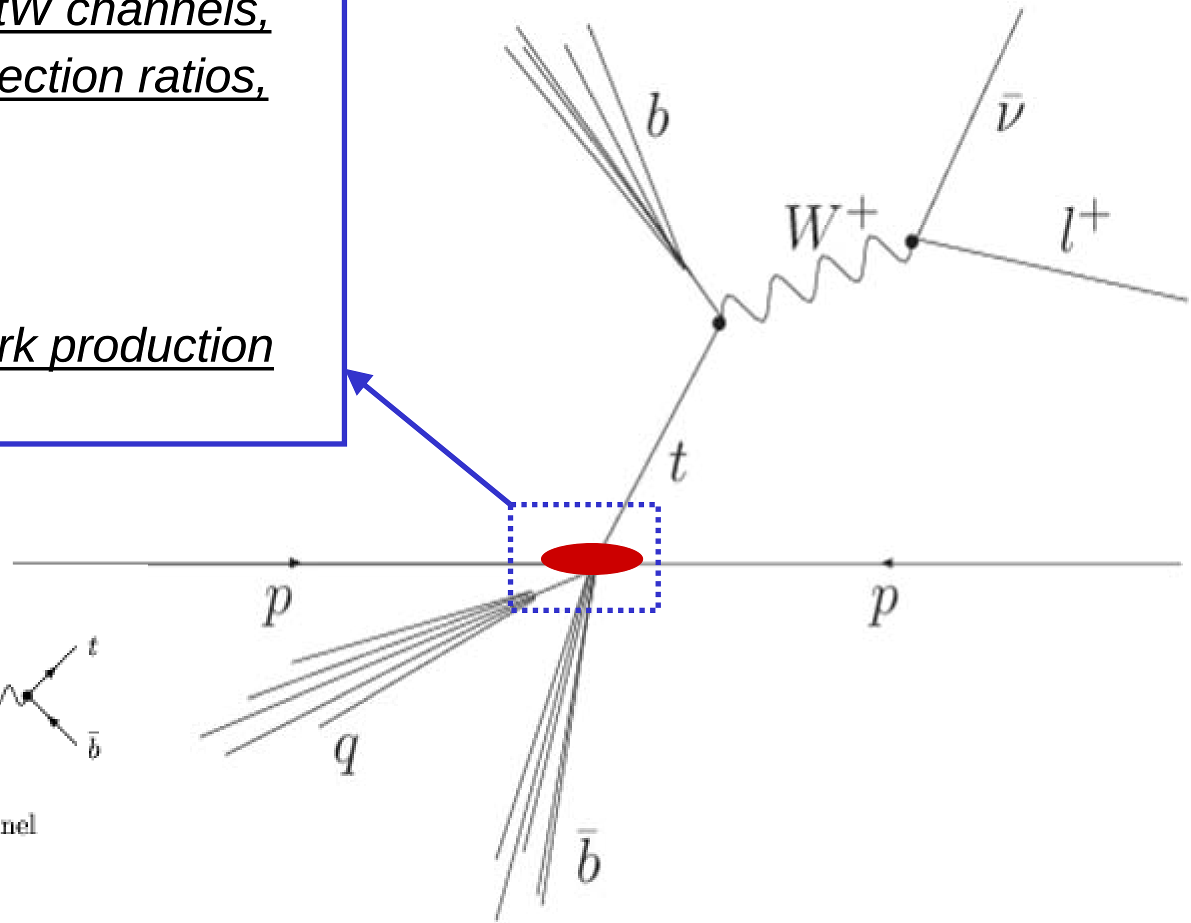
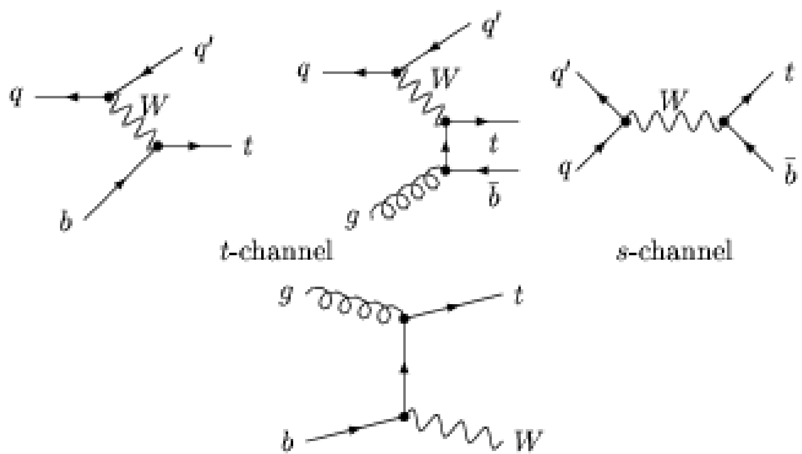
- Calibration of b-tagging algorithms,
- *In situ jet energy corrections*…



Top-quark analyses in single-top events

- *Cross-sections of t, s and tW channels,*
- *Top/anti-top quark cross-section ratios,*
- *Measurement of |Vtb|,*
- Anomalous tWb coupling,
- Top polarization,
- *Anomalous single-top-quark production (FCNC/H),*





t-channel

s-channel

Wt associated production

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$t\bar{t}$ cross section

$t\bar{t}$ cross-section in dilepton 8TeV, L=5.3 pb^{-1}

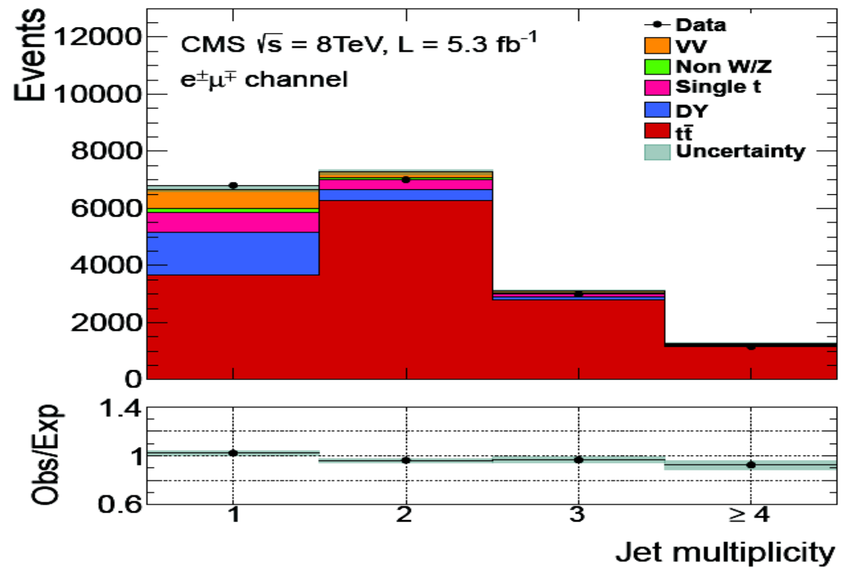
TOP-12-007

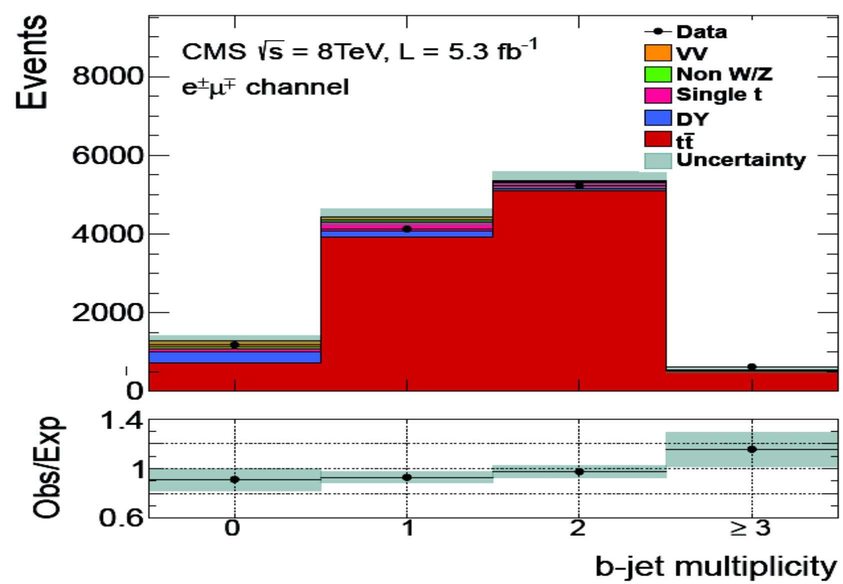
- Most precise measurement in the dilepton channel.
- Event selection : dilepton-trigger, 2 isolated leptons (Z mass veto), ≥2 jets, ≥ 1 b-tagged jet, large missing E_T (MET, only for ee and μμ).
- QCD multijets background estimated using fake-rate method, Z+jets background estimated using a control region enriched in Z events.

$$\sigma=239.0\pm2.1(\text{stat})\pm11.3(\text{syst.})\pm6.2(\text{lumi})\ \text{pb}$$

$$\sigma_{tot}= 5.8\%$$

- Simple cut&count method.
- Main systematics : Jet Energy Scale (JES), signal modeling (renorm./fact. scales, matching).





Top-quark mass

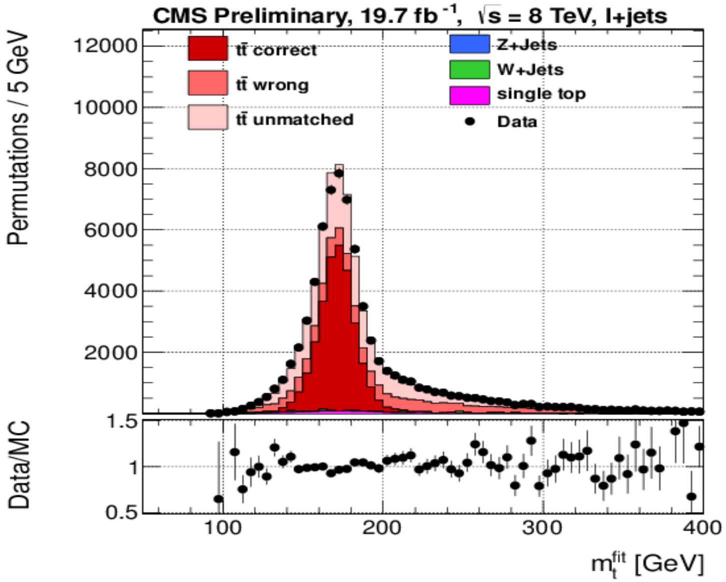
Top mass with lepton+jets events 8TeV, L=19.7 fb^{-1}

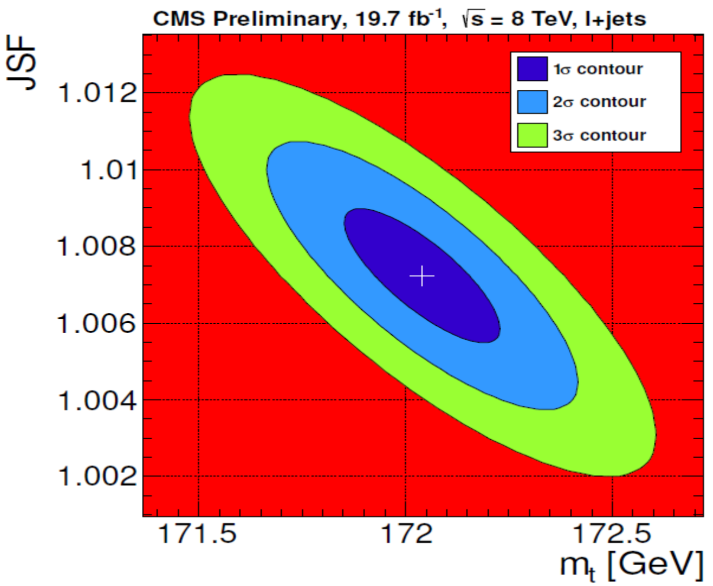
TOP-14-001

- Measurement of the top-quark mass in the lepton+jets.
- Event selection : 1 lepton (e or μ), ≥4 jets, 2 b-tagged jets => high purity sample (≈95%).
- Kinematic fit : constrains 4-momenta, improves the correct jets-parton assignments (cut on the goodness of fit).
- Top-quark mass and Jet Energy Scaling Factor (JSF) simultaneously estimated using a likelihood fit (Ideogram).

$$m_t = 172.04 \pm 0.19\,(\text{stat.+JSF}) \pm 0.75\,(\text{syst.})\ \text{GeV},$$
$$\text{JSF} = 1.007 \pm 0.002\,(\text{stat.}) \pm 0.012\,(\text{syst.}).$$

$\sigma_{tot} = 0.77$ GeV





Top mass with lepton+jets events 8TeV, L=19.7 fb^{-1}

	δm_t^{2D} (GeV)	δJSF	δm_t^{1D} (GeV)
Experimental uncertainties			
Fit calibration	0.10	0.001	0.06
p_T- and η-dependent JES	0.18	0.007	1.17
Lepton energy scale	0.03	<0.001	0.03
MET	0.09	0.001	0.01
Jet energy resolution	0.26	0.004	0.07
b tagging	0.02	<0.001	0.01
Pileup	0.27	0.005	0.17
Non-$t\bar{t}$ background	0.11	0.001	0.01
Modeling of hadronization			
Flavor-dependent JSF	0.41	0.004	0.32
b fragmentation	0.06	0.001	0.04
Semi-leptonic B hadron decays	0.16	<0.001	0.15
Modeling of the hard scattering process			
PDF	0.09	0.001	0.05
Renormalization and factorization scales	0.12±0.13	0.004±0.001	0.25±0.08
ME-PS matching threshold	0.15±0.13	0.003±0.001	0.07±0.08
ME generator	0.23±0.14	0.003±0.001	0.20±0.08
Modeling of non-perturbative QCD			
Underlying event	0.14±0.17	0.002±0.002	0.06±0.10
Color reconnection modeling	0.08±0.15	0.002±0.001	0.07±0.09
Total	0.75	0.012	1.29

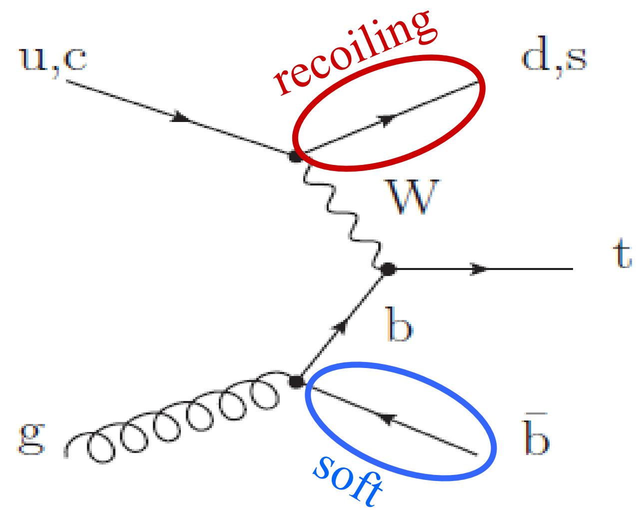
MG vs Powheg

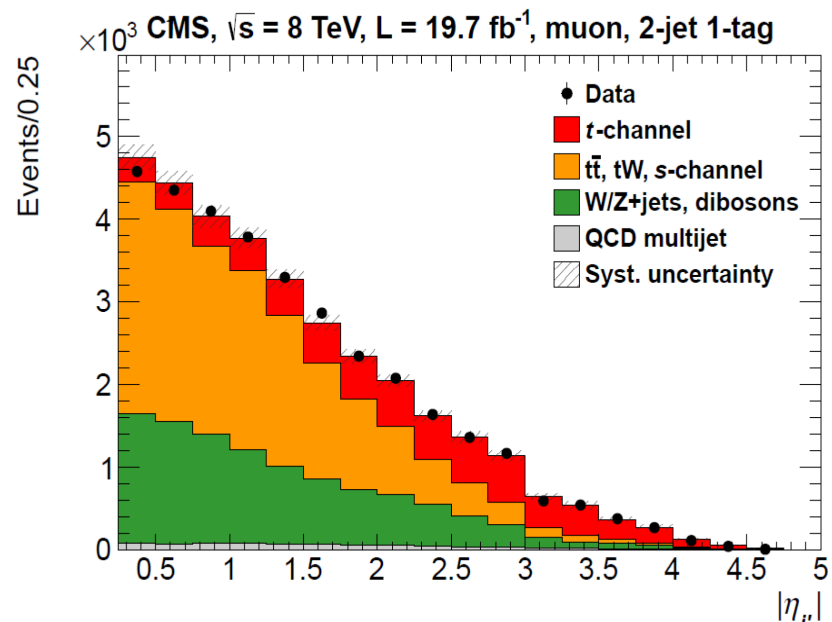
Single-top cross sections

t-channel cross-section 8TeV, L=19.7 fb^{-1}

TOP-12-038

- Dominant single-top process.
- Event selection : single-lepton trigger, 1 isolated lepton (e or μ), large MET and transverse mass m_T, ≥2 jets.
- Signal and background extraction :
  - Signal region, 2jets-1tag, reconstructed $m_{lnb} \approx m_t$,
  - control regions to constrain the backgrounds, njets+mtag, reconstructed $m_{lnb} \neq m_t$,
  - Cross section from a fit on η of the recoiling light-jet.
- Main backgrounds : $t\bar{t}$, W+jets, tW, QCD (fit of MET and m_T).





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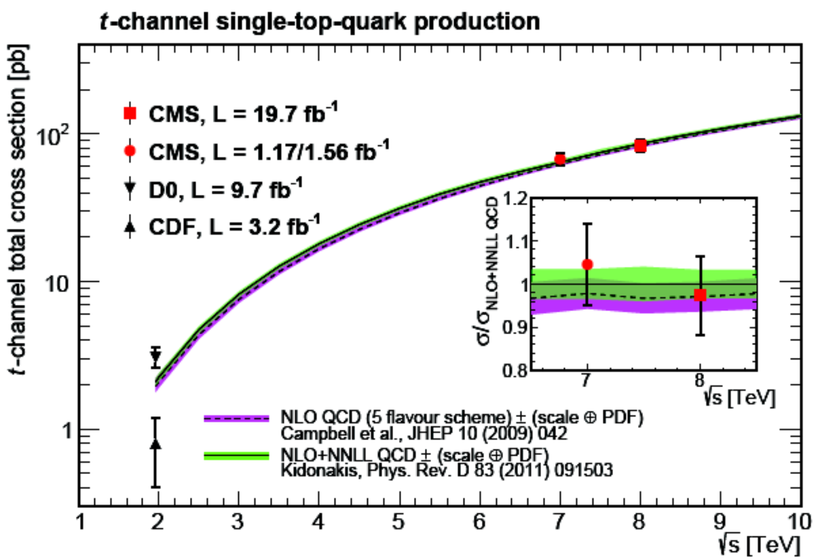
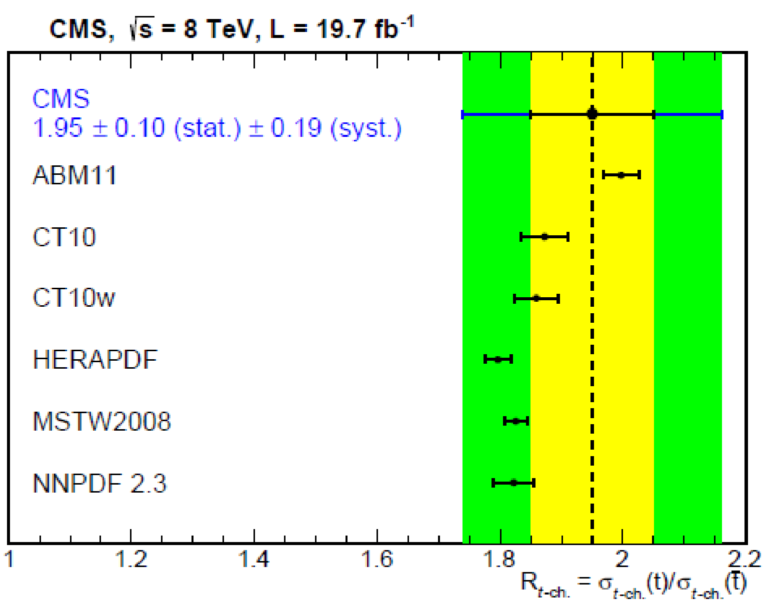
t-channel cross-section (2)

TOP-12-038





- Dominant systematic : signal modeling, jet selection, b-tagging.
- Inclusive single-top-quark production cross section :

$$\boxed{\sigma_{t\text{-ch.}} = 83.6 \pm 2.3\,(\mathrm{stat}) \pm 7.4\,(\mathrm{syst})\,\mathrm{pb}}$$

- top ant anti-top cross section ratio => probe PDF sets.

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

- Measurement of |Vtb|. $|V_{\mathrm{td}}|, |V_{\mathrm{ts}}| \ll |V_{\mathrm{tb}}|$

$$|f_{\mathrm{Lv}} V_{\mathrm{tb}}| = 0.998 \pm 0.038\,(\mathrm{exp.}) \pm 0.016\,(\mathrm{theo.})$$

$\boxed{|V_{\mathrm{tb}}| > 0.92}$ At 95% C.L.

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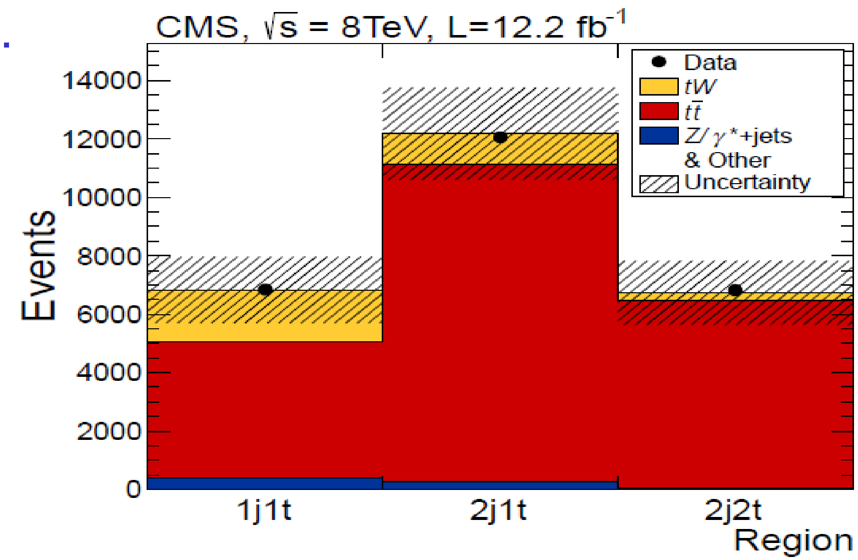
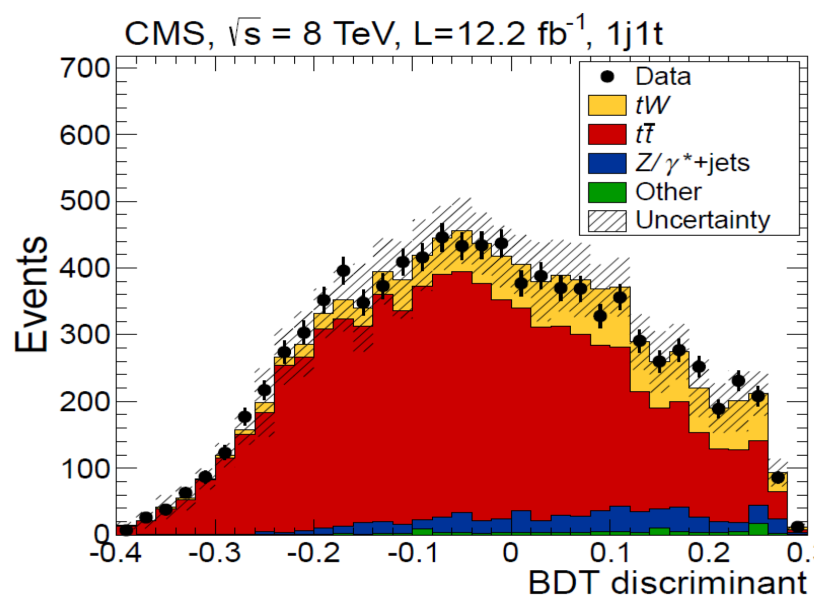
Observation of the tW channel 8TeV, 12.2 fb^{-1}

TOP-12-040

- First observation in the di-leptonic channel.
- Event selection : very similar to the $t\bar{t}$ dilepton cross-section.
- Signal and control regions :
  - Signal : 1jet-1tag.
  - Backgrounds and b-tag efficiency : 2jets-1tag,2jets-2tags,
- Signal extraction : fit of a BDT discriminant.
- Main backgrounds : $t\bar{t}$ (estimated from the fit) , Z+jets (rescaled using events compatible with a Z decay (MET)).
- **First Observation** : $\boxed{6.1\sigma,\ 23.4\pm5.4\ \text{pb}}$





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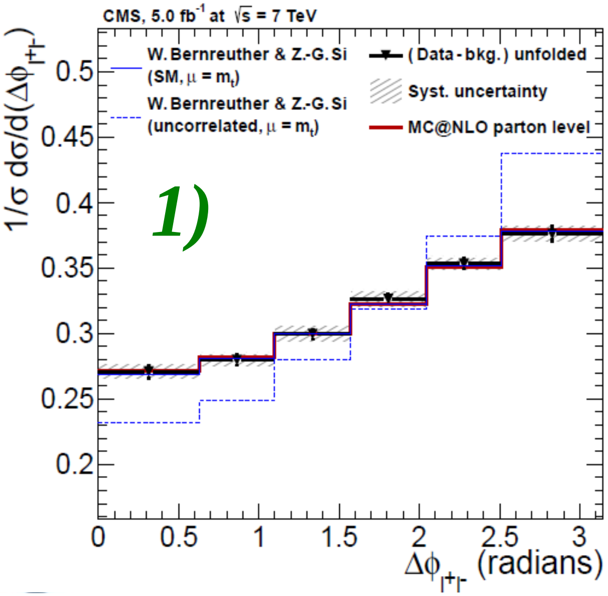
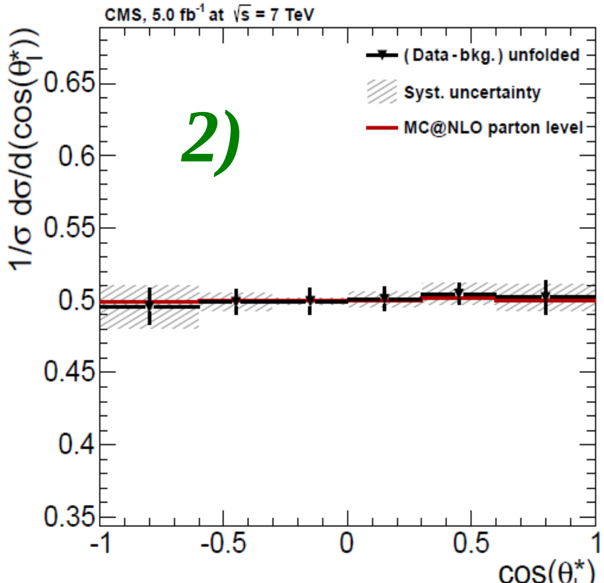
Top-quark “properties”

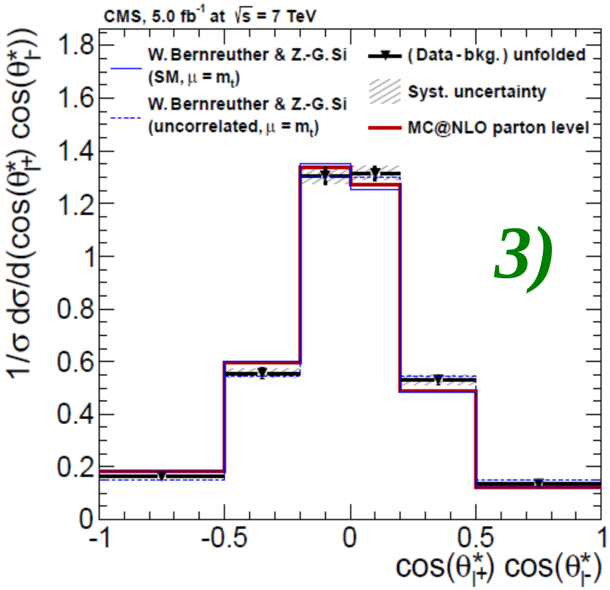
$t\bar{t}$ spin correlation and top polarization 7TeV, 5.0fb^{-1}

TOP-13-003

- In the dileptonic channel : leptons have the highest spin analyzing power.
- Event selection : very similar to the $t\bar{t}$ dilepton cross section analysis.
- Event reconstruction : constrains from W, top masses, PDF.
- Unfolded at parton level and compared to theoretical predictions.
- ***1)*** $\Delta\varphi(ll)$, ***2)*** $\cos\theta^*$, ***3)*** $\cos\theta^*_{l+}$ $\cos\theta^*_{l-}$ => good agreement with the SM.





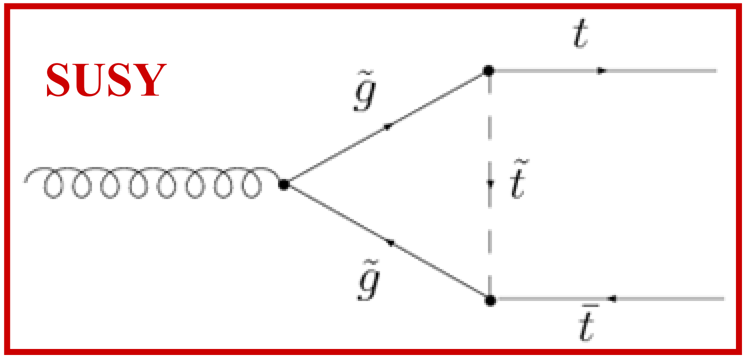


Limits on CMDM from the $t\bar{t}$ spin correlation

- CMDM/CEDM model from effective lagrangian.

$$\mathcal{L}_{eff} = -\frac{\tilde{\mu}_t}{2}\bar{t}\sigma^{\mu\nu}T^a t G^a_{\mu\nu} - \frac{\tilde{d}_t}{2} i\sigma^{\mu\nu}\gamma_5 T^a t G^a_{\mu\nu}, \qquad \tilde{\mu}_t(\tilde{d}_t) = \frac{g_s}{m_t}\hat{\mu}_t(\hat{d}_t)$$

- Effective Field Theory : new particles enter in loops of $t\bar{t}g$ diagrams.
- Loops can be modeled by effective operators (can probe heavy new particles).
- Example of loops contributing to CMDM ($Re(\mu_t)$):

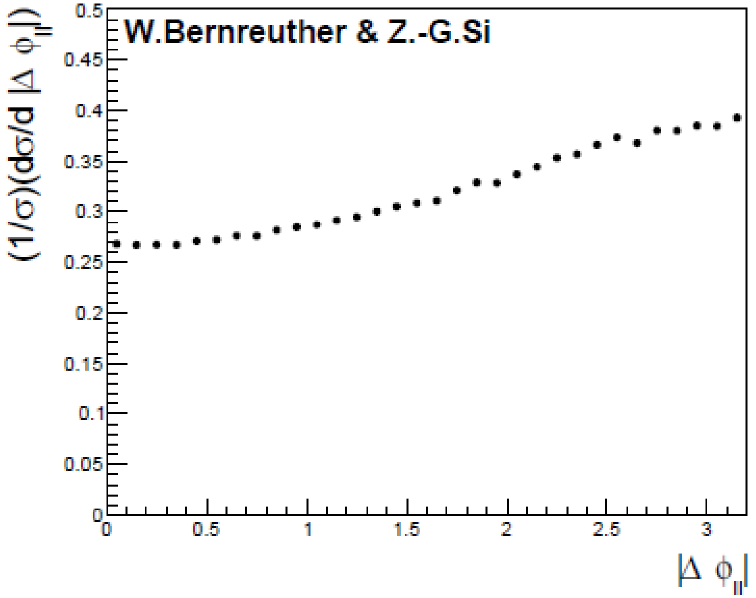


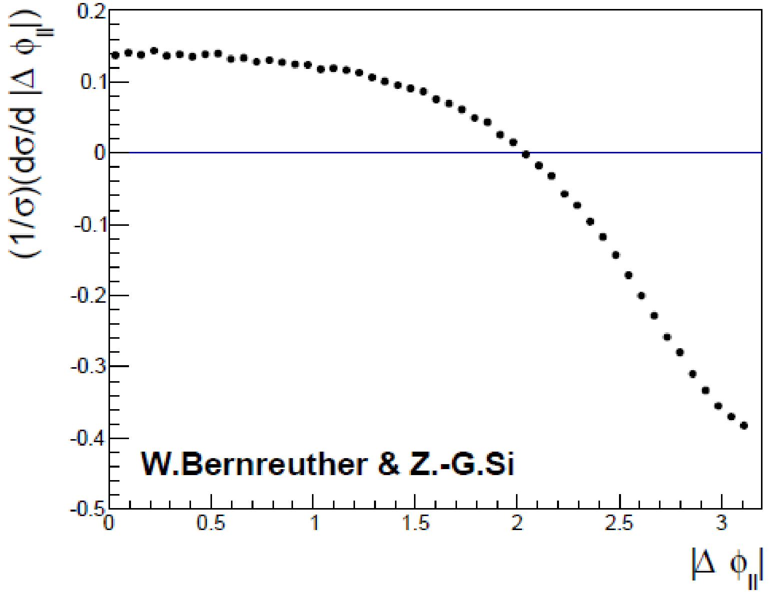
- Expectations for some models (**R. Martinez&al., Eur. Phys. J. C53 221 (2008), Phys.Rev. D65 (2002) 057301**)

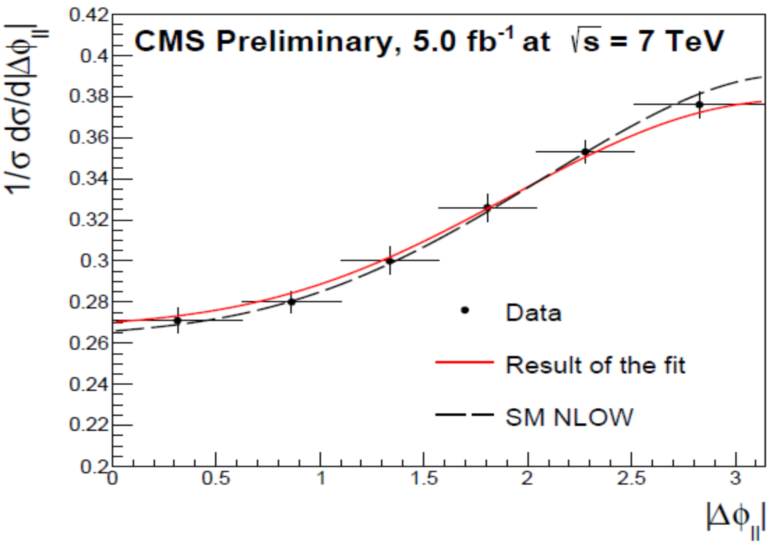
Model	2HDM	Extra-dim	SUSY
$Re(\mu_t)$	-1.3×10^{-2}	-1.9×10^{-2}	$\approx10^{-1}$

Limits on CMDM 7TeV, 5.0fb^{-1}

TOP-14-005







- Fit of the unfolded distribution with 2 templates : SM and NP.

For Re(μ)<<1

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

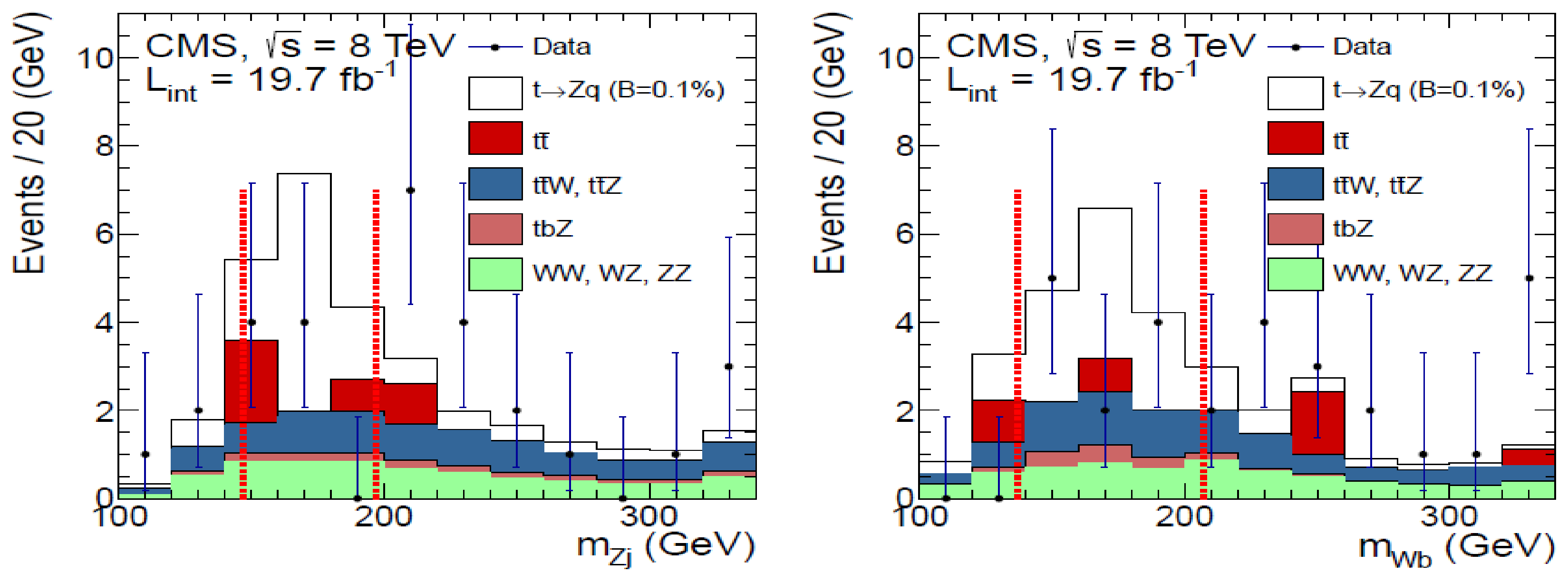
- Limits on the real part of the CMDM

$$\boxed{-0.043 < \mathrm{Re}(\hat{\mu}_t) < 0.117}$$

Search for FCNC in top decays 8TeV, L=19.7 pb^{-1}

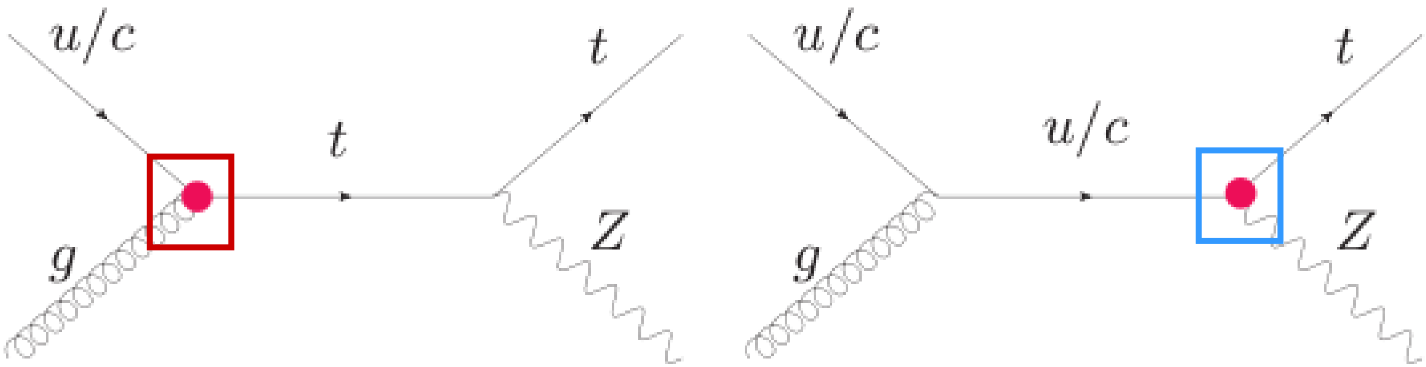
TOP-12-037

- Search for Flavor Changing Neutral Current (FCNC) in top decays in $t\bar{t}$ events.
- $t \rightarrow Zq$ highly suppressed by the GIM mechanism, any **observation == new physics** !
- Event selection : dilepton trigger, 3 isolated leptons (2 o.s. compatible with a Z), ≥2 jets and 1 b-tagged jet, high MET and cuts on top mass. Backgrounds estimated from samples with 0 and ≥ b-tagged jets.
- No excess over the SM background is observed. Limit on $\boxed{Br(t \rightarrow Zq) < 0.05\%}$ at 95% C.L. (combining 7+8TeV data), 0.09% expected.



Search for top FCNC at CMS

Probe separately tZc and tZu couplings using the charge asymmetry !



- tZ production through 2 types of anomalous couplings :
  - **gu(c)t** :
  - **Zu(c)t** :

$$\mathcal{L} = \sum_{q=u,c} \left[\boxed{\sqrt{2} g_s \frac{\kappa_{gqt}}{\Lambda} \bar{t} \sigma^{\mu\nu} T_a (f_q^L P_L + f_q^R P_R) q \, G^a_{\mu\nu}} \right.$$

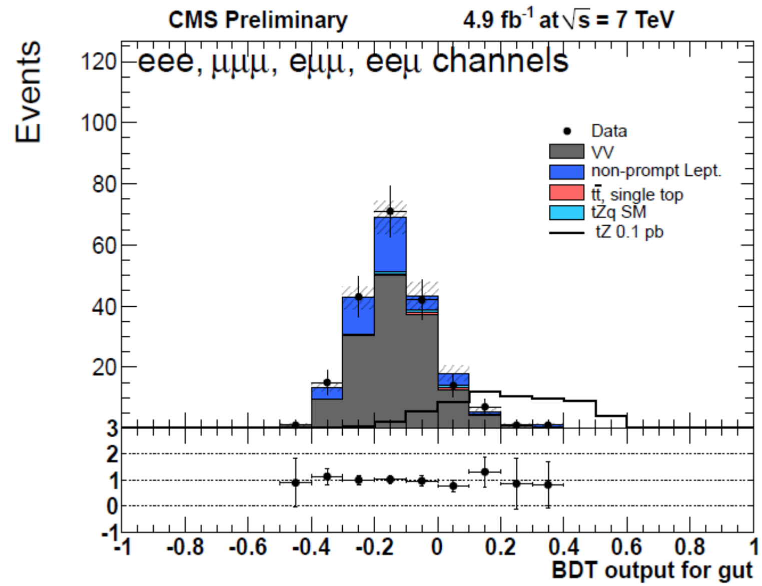
$$\boxed{\left. + \frac{g}{\sqrt{2} c_W} \frac{\kappa_{zqt}}{\Lambda} \bar{t} \sigma^{\mu\nu} (\hat{f}_q^L P_L + \hat{f}_q^R P_R) q \, Z_{\mu\nu} \right]} + \text{h.c.}$$

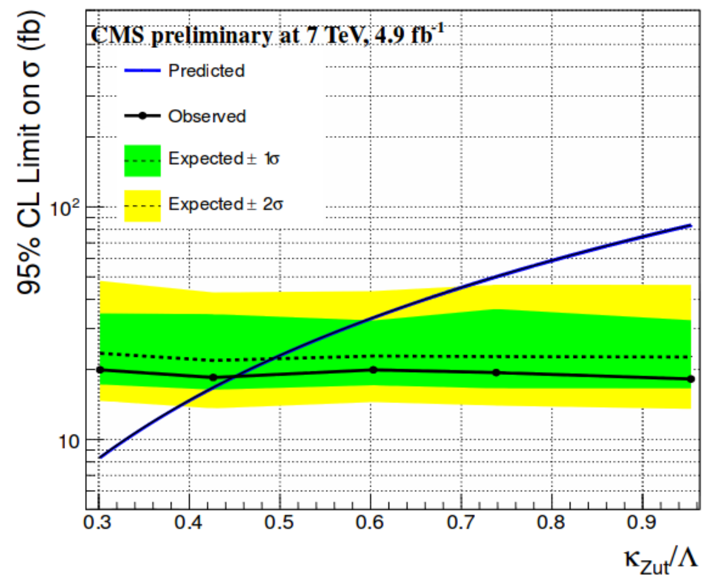
Search for FCNC in top production tZ, 7TeV, L=5.0 fb^{-1}

TOP-12-021

- Event selection : 3 isolated leptons (2 o.s. compatible with a Z), ≥1 jet, no more than 1 b-tagged jet.
- Signal vs background determination : BDT from kinematic variables.
- Main backgrounds : WZ+jets, Z+jets, $t\bar{t}$.
- Z+jets estimated from a fit of the m_T.
- No excess over the SM background observed. Limits from a fit of the BTD (WZ+jets floating).

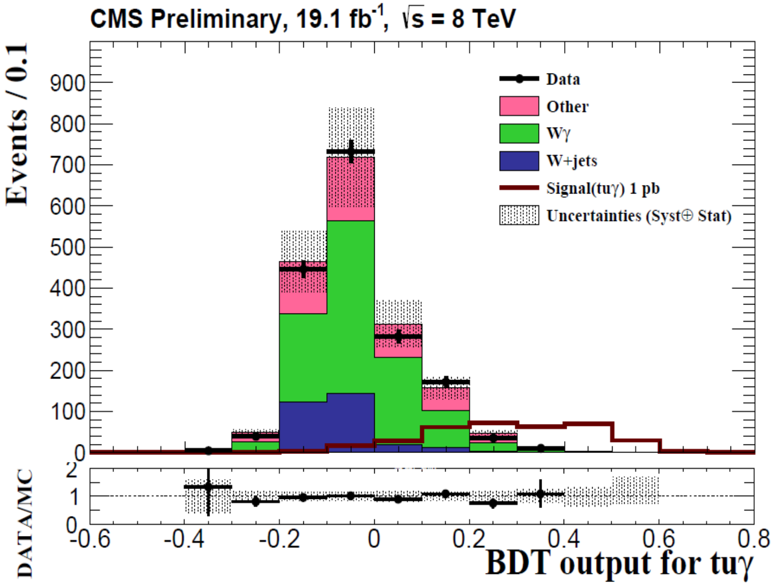
couplings	Expected	Observed	$\mathcal{B}(t \to gq/Zq)$
κ_{gut}/Λ	0.096	0.096	0.56 %
κ_{gct}/Λ	0.427	0.354	7.12 %
κ_{Zut}/Λ	0.492	0.451	0.51 %
κ_{Zct}/Λ	2.701	2.267	11.40 %

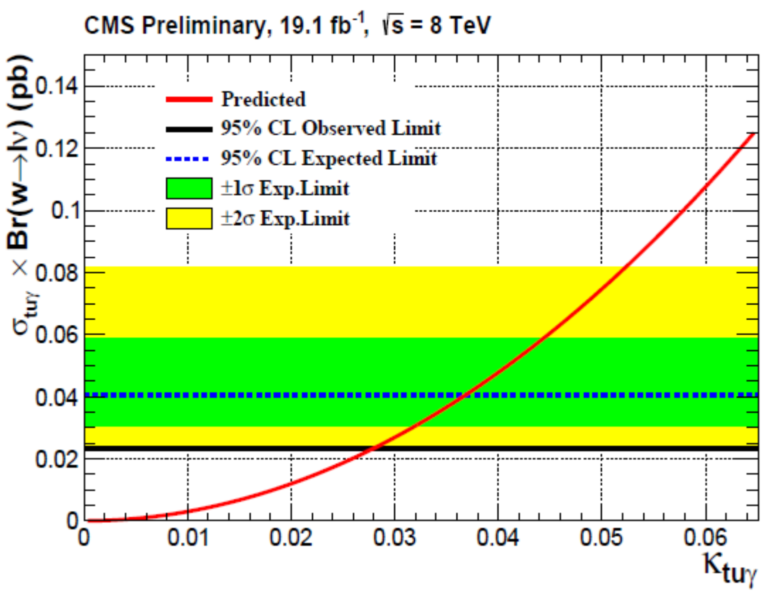




Search for FCNC in top production tγ, 8TeV, L=19.1 fb^{-1}

TOP-14-003



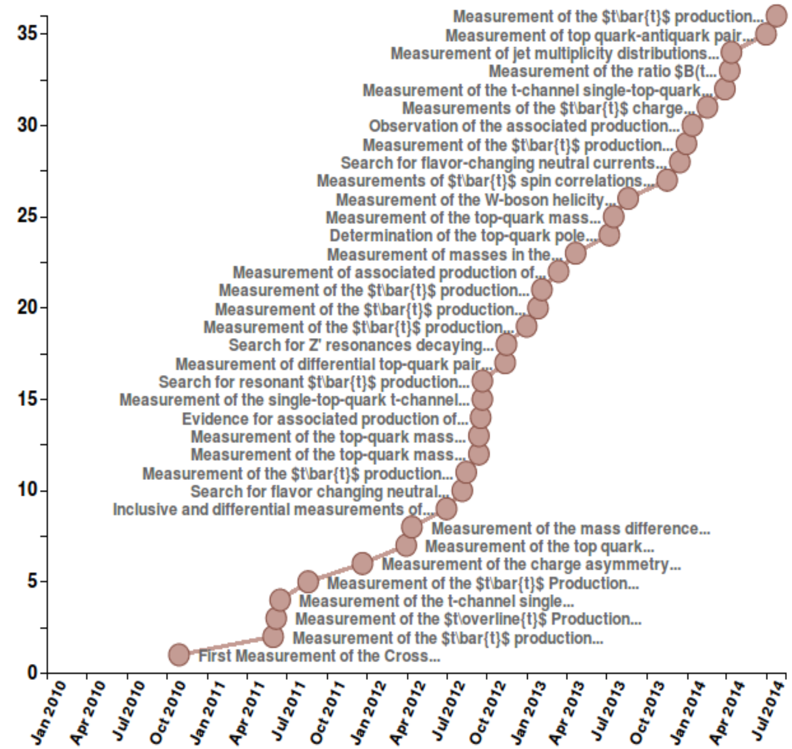


- Search for FCNC in single top tγ in the muon channel.
- Event selection : single muon trigger, 1 isolated muon, 1 high p_T photon, ≥1 jets with 0-1 b-tagged jet.
- Main background : W(γ)+jets, estimated from a control region.
- Similar strategy as for tZ : BDT discriminant and exclusion limits.

	Exp.	Obs.
Br(t→uγ)	0.0279%	0.0161%
Br(t→cγ)	0.261%	0.182%

Conclusions and prospective

- The CMS collaboration covers a wide range of top-related topics.
- 36 publications : only a small subset was presented in this talk.
- A lot of interesting physics still to be investigated :
  - More precision measurements : cross sections, mass, charge asymmetry, spin correlation…
  - BSM searches : FCNC, anomalous couplings …
  - Observation of rare top SM processes : tt+W/Z, tZq, single top s-channel, 4 tops…
- New top processes (and new physics!!!) **<u>might be accessible with the 13 TeV collisions !</u>**



https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsTOP

Expected limits on top FCNC at 14 TeV

$\mathcal{B}(t \to Zq)$	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	$< 0.10\%$	$< 0.027\%$	$< 0.010\%$

Backup

Bibliography

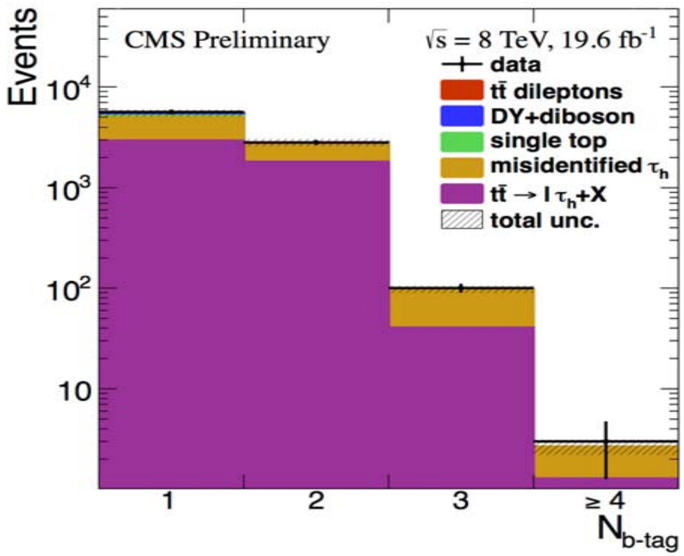
- **TOP-12-007** : Measurement of the t t-bar production cross section in the dilepton channel in pp collisions at sqrt(s)=8 TeV, JHEP 02 (2014) 024.
- **TOP-14-001** : Measurement of the top mass in the lepton+jets channel at 8 TeV, CMS PAS TOP-14-001.
- **TOP-12-038** : Measurement of the top/antitop production ratio in single top t-channel production at 8 TeV , JHEP 06 (2014) 090.
- **TOP-12-040** : Observation of the associated production of a single top quark and a W boson in pp collisions at sqrt(s)=8 TeV, PRL 112 (2014) 231802.
- **TOP-13-003** : Measurements of t t-bar spin correlations and top-quark polarization using dilepton final states in pp collisions at sqrt(s)=7 TeV, PRL 112 (2014) 182001.
- **TOP-14-005** : Limits on top-quark chromomagnetic dipole moments from angular distributions, CMS PAS TOP-14-002.
- **TOP-12-037** : Search for flavor-changing neutral currents (FCNC) in top-quark decays t to Zq in pp collisions at sqrt(s)=8 TeV, PRL 112 (2014) 171802.
- **TOP-12-021** : Search for Flavor Changing Neutral Currents in tZ events in proton-proton collisions at 7 TeV, CMS PAS TOP-12-021.
- **TOP-14-003** : Search for anomalous single top + photon production (FCNC) , CMS PAS TOP-14-003.

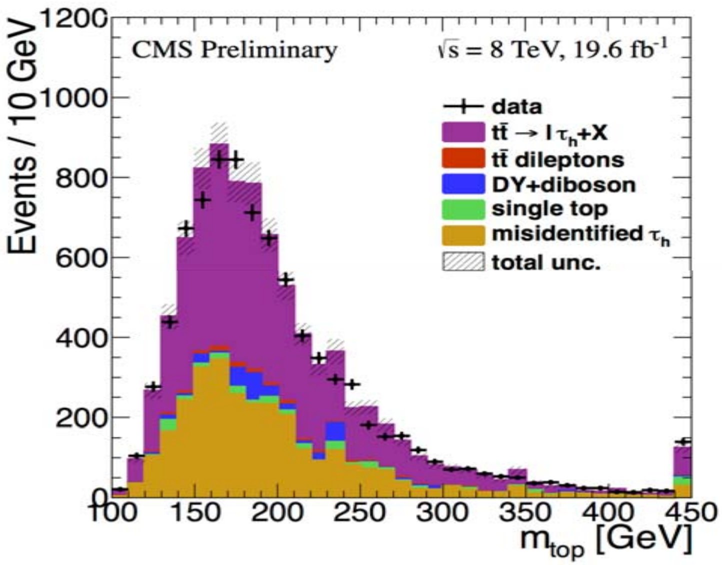
Comments on this draft

- Preliminary version. Still needs to :
  - Search for typos,

tt cross-section in tau+lepton, 8TeV, 19.6fb^{-1}

TOP-12-026





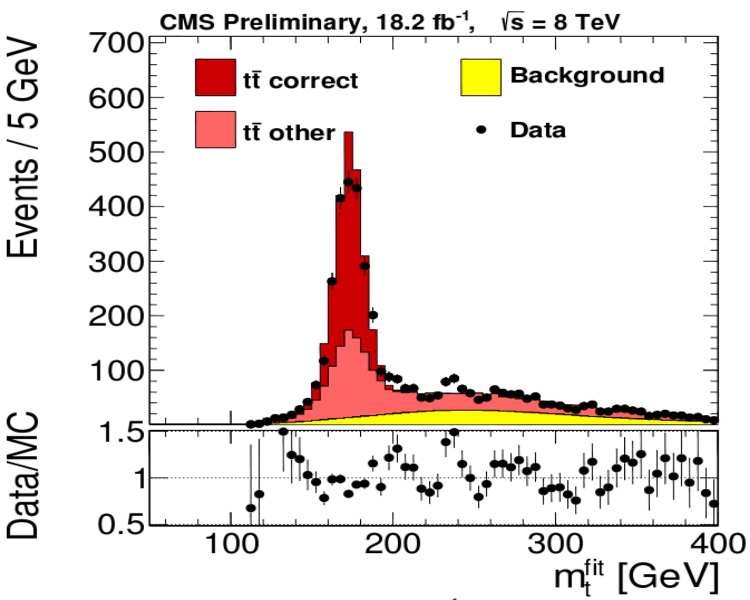
- Example of a more challenging channel : dilepton with a hadronic tau (background for charged Higgs search).
- Event selection: single-lepton trigger, 1 isolated lepton (e or μ), 1 identified and isolated tau, ≥2 jets, ≥ 1 b-tagged jet, large MET.
- Main backgrounds : QCD/W+jets with one mis-identified tau, estimated using the fake-tau probability.
- Main systematic sources : tau selection and energy scale, backgrounds, signal modeling.

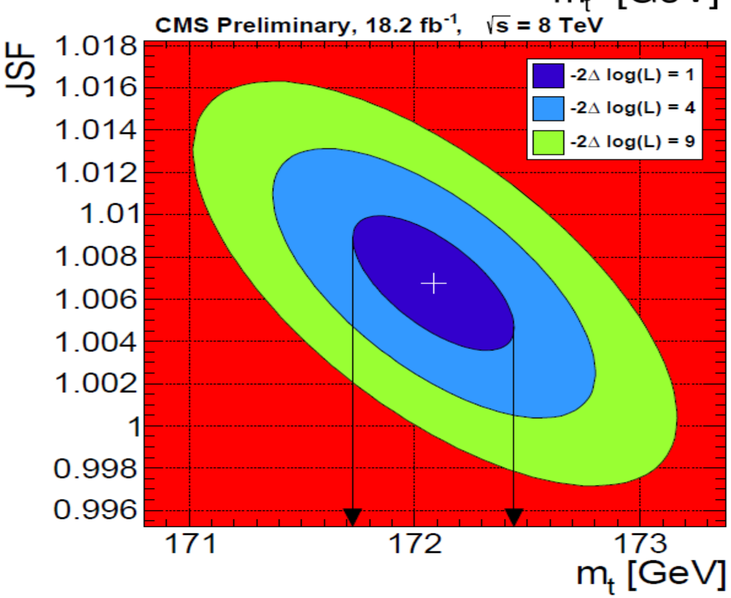
$$\boxed{\sigma_{t\bar{t}} = 257 \pm 3\,(\text{stat}) \pm 24\,(\text{syst}) \pm 7\,(\text{lumi})\,\text{pb}}$$

$$\boxed{\sigma_{tot} = 9.7\%}$$

Top mass with full-hadronic events 8TeV, L=18.2fb^{-1}

TOP-14-002



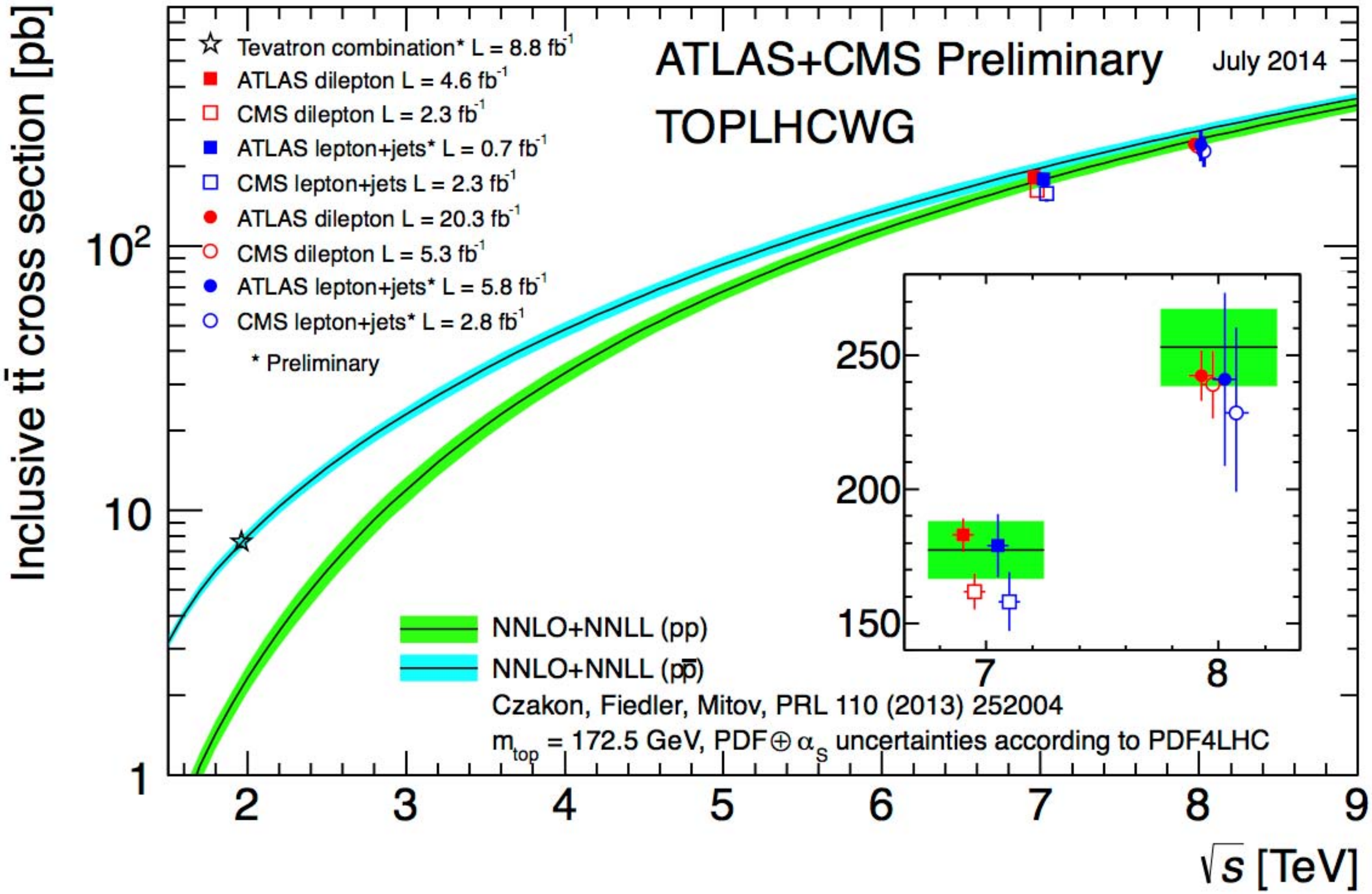


- The same strategy followed for the top-quark mass measurement in the all-hadronic channel.
- Event selection : 4-jets trigger, ≥6-jets, 2 b-tagged jets => low purity (≈15%).
- After kinematic fit and cut on the goodness of fit : purity ≈80%.
- Main background : QCD-multijets
  - modeled using a mixing technique (mixing randomly jets from a data-pool, random permutations).
  - Fraction of QCD estimated from the likelihood fit.

$$m_t = 172.08 \pm 0.36\,(\text{stat.+JSF}) \pm 0.83\,(\text{syst.})\ \text{GeV},$$
$$\text{JSF} = 1.007 \pm 0.003\,(\text{stat.}) \pm 0.011\,(\text{syst.}).$$

σ_{tot}= 0.90 GeV

- Main systematics : flavor dependence of JSF, pileup, JES, signal modeling.



Inclusive tt̄ cross section [pb]
Tevatron combination* L = 8.8 fb-1
ATLAS dilepton L = 4.6 fb-1
CMS dilepton L = 2.3 fb-1
ATLAS lepton+jets* L = 0.7 fb-1
CMS lepton+jets L = 2.3 fb-1
ATLAS dilepton L = 20.3 fb-1
CMS dilepton L = 5.3 fb-1
ATLAS lepton+jets* L = 5.8 fb-1
CMS lepton+jets* L = 2.8 fb-1
* Preliminary
ATLAS+CMS Preliminary
July 2014
TOPLHCWG
NNLO+NNLL (pp)
NNLO+NNLL (pp̄)
Czakon, Fiedler, Mitov, PRL 110 (2013) 252004
m_top = 172.5 GeV, PDF ⊕ α_S uncertainties according to PDF4LHC
√s [TeV]

Ttbar dilepton xs

Source	e^+e^-	$\mu^+\mu^-$	$e^\pm\mu^\mp$
Trigger efficiencies	4.1	3.0	3.6
Lepton efficiencies	5.8	5.6	4.0
Lepton energy scale	0.6	0.3	0.2
Jet energy scale	10.3	10.8	5.2
Jet energy resolution	3.2	4.0	3.0
b-jet tagging	1.9	1.9	1.7
Pileup	1.7	1.5	2.0
Scale (μ_F and μ_R)	5.7	5.5	5.6
Matching partons to showers	3.9	3.8	3.8
Single top quark	2.6	2.4	2.3
VV	0.7	0.7	0.5
Drell–Yan	10.8	10.3	1.5
Non-W/Z leptons	0.9	3.2	1.9
Total systematic	18.6	18.6	11.4
Integrated luminosity	6.4	6.1	6.2
Statistical	5.2	4.5	2.6

$$\sigma_{t\bar{t}}/\sigma_{t\bar{t}}(m_t = 172.5) = 1.00 - 0.009 \times (m_t - 172.5) - 0.000168 \times (m_t - 172.5)^2$$

Ttbar tau+jets xs

Source	Uncertainty [%]		
	$e\tau_h$	$\mu\tau_h$	combined
Experimental uncertainties:			
τ_h-jet identification	6.0	6.0	6.0
τ_h misidentification background	4.3	4.3	4.3
τ_h energy scale	2.4	2.5	2.5
b-jet tagging, jet misidentification	1.6	1.6	1.6
jet energy scale, jet energy resolution, MET	1.9	1.9	1.9
other backgrounds	0.6	0.7	0.7
lepton reconstruction	0.8	0.6	0.5
luminosity	2.6	2.6	2.6
Theoretical uncertainties:			
matrix element-parton shower matching	1.7	1.3	1.5
factorization/renormalization Q^2 scale	2.9	2.9	2.9
top quark p_T modeling	0.7	0.5	0.6
parton distribution functions	0.8	0.7	0.7
generator	1.5	1.5	1.5
hadronization	1.7	1.7	1.7
Total systematic uncertainty	**9.6**	**9.5**	**9.5**

Top mass all jets

	δm_t^{2D} (GeV)	δJSF	δm_t^{1D} (GeV)
Experimental uncertainties			
Fit calibration	0.06	<0.001	0.06
p_T- and η-dependent JES	0.28	0.006	0.86
Jet energy resolution	0.10	0.001	0.01
b tagging	0.02	<0.001	<0.01
Pileup	0.31	0.001	0.30
Calorimeter JES of trigger confirmation	0.18	0.003	0.07
Non-$t\bar{t}$ background	0.22	0.002	0.08
Modeling of hadronization			
Flavor-dependent JSF	0.36	0.004	0.30
b fragmentation	0.07	0.001	0.03
Semi-leptonic B hadron decays	0.12	<0.001	0.12
Modeling of the hard scattering process			
PDF	0.02	<0.001	0.01
Renormalization and factorization scales	0.19±0.19	0.004±0.002	0.18±0.14
ME-PS matching threshold	0.20±0.19	0.002±0.002	0.09±0.14
ME generator	0.09±0.21	0.003±0.002	0.17±0.15
Modeling of non-perturbative QCD			
Underlying event	0.13±0.28	0.000±0.002	0.11±0.20
Color reconnection modeling	0.00±0.25	0.000±0.002	0.03±0.18
Total	0.83	0.011	1.05

t-channel xs

$$\sigma_{t\text{-ch.}} = 83.6 \pm 2.3\,(\text{stat}) \pm 7.4\,(\text{syst})\,\text{pb}$$

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

Uncertainty source	$\sigma_{t\text{-ch.}}$ (%)
Statistical uncertainty	$\pm$ 2.7
JES, JER, MET, and pileup	$\pm$ 4.3
b-tagging and mis-tag	$\pm$ 2.5
Lepton reconstruction/trig.	$\pm$ 0.6
QCD multijet estimation	$\pm$ 2.3
W+jets, $t\bar{t}$ estimation	$\pm$ 2.2
Other backgrounds ratio	$\pm$ 0.3
Signal modeling	$\pm$ 5.7
PDF uncertainty	$\pm$ 1.9
Simulation sample size	$\pm$ 0.7
Luminosity	$\pm$ 2.6
Total systematic	$\pm$ 8.9
Total uncertainty	$\pm$ 9.3
Measured cross section	83.6 ± 7.8 pb

$$|f_{\text{L}v} V_{\text{tb}}| = 0.998 \pm 0.038\,(\text{exp.}) \pm 0.016\,(\text{theo.})$$

$$|V_{\text{tb}}| > 0.92$$

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

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

T-channel xs

Uncertainty source	$\sigma_{t\text{-ch.}}(\mathrm{t})$ (%)	$\sigma_{t\text{-ch.}}(\bar{\mathrm{t}})$ (%)	$R_{t\text{-ch.}}$ (%)
Statistical uncertainty	± 2.7	± 4.9	± 5.1
JES, JER, MET, and pileup	± 4.2	± 5.2	± 1.1
b-tagging and mis-tag	± 2.6	± 2.6	± 0.2
Lepton reconstruction/trig.	± 0.5	± 0.5	±0.3
QCD multijet estimation	± 1.6	± 3.5	±1.9
W+jets, $\mathrm{t\bar{t}}$ estimation	± 1.7	± 3.6	± 3.0
Other backgrounds ratio	± 0.1	± 0.2	± 0.6
Signal modeling	± 4.9	± 9.4	± 6.1
PDF uncertainty	± 2.5	± 4.8	± 6.2
Simulation sample size	± 0.6	± 1.1	± 1.2
Luminosity	± 2.6	± 2.6	—
Total systematic	± 8.2	± 13.4	± 9.6
Total uncertainty	± 8.7	± 14.2	± 10.9
Measured cross section or ratio	53.8 ± 4.7 pb	27.6 ± 3.9 pb	1.95 ± 0.21

Ttbar spin correlation limits

$$A_{\Delta\phi} = \frac{N(\Delta\phi_{\ell^+\ell^-} > \pi/2) - N(\Delta\phi_{\ell^+\ell^-} < \pi/2)}{N(\Delta\phi_{\ell^+\ell^-} > \pi/2) + N(\Delta\phi_{\ell^+\ell^-} < \pi/2)} \qquad A_{c_1c_2} = \frac{N(c_1c_2 > 0) - N(c_1c_2 < 0)}{N(c_1c_2 > 0) + N(c_1c_2 < 0)}$$

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

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

Asymmetry variable	$A_{\Delta\phi}$	$A_{c_1c_2}$	A_P
Jet energy scale	0.002	0.012	0.009
Lepton energy scale	0.001	0.001	0.001
Background	0.003	0.001	0.006
Fact. and renorm. scales	0.001	0.010	0.004
Top-quark mass	0.001	0.003	0.005
Parton distribution functions	0.002	0.002	0.001
Jet energy resolution	<0.001	<0.001	<0.001
Pileup	0.002	0.002	0.004
b-tagging scale factor	<0.001	<0.001	0.001
Lepton selection	<0.001	<0.001	<0.001
τ decay polarization	0.001	0.002	0.001
Unfolding	0.004	0.020	0.002
Total systematic uncertainty	0.006	0.025	0.014
Top p_T reweighting uncertainty	0.012	0.010	0.008

Ttbar FCNC

Source	Uncertainty %
Renormalization/factorization scales	12
Parton distribution functions	7
$t\bar{t}$ cross section	7
Parton matching threshold	6
Lepton selection	6
Trigger efficiency	5
b-tagging	5
Top-quark mass	4
Jet energy scale	4
Missing transverse energy resolution	3
Pileup modeling	3
Total	20

Summary of top FCNC search at CMS

<table>
<tr><th></th><th>7TeV
single top tZ</th><th>7TeV
single top tq</th><th>7TeV
ttbar</th><th>7+8 TeV
ttbar</th><th>8TeV
single top tγ</th></tr>
<tr><td>Br(t→ug)</td><td>0.56%</td><td>0.0355%</td><td></td><td></td><td></td></tr>
<tr><td>Br(t→cg)</td><td>7.12%</td><td>0.0344%</td><td></td><td></td><td></td></tr>
<tr><td>Br(t→uZ)</td><td>0.51%</td><td></td><td rowspan="2">0.21%
(u+c)</td><td rowspan="2">0.05%
(u+c)</td><td></td></tr>
<tr><td>Br(t→cZ)</td><td>11.40%</td><td></td><td></td></tr>
<tr><td>Br(t→uγ)</td><td></td><td></td><td></td><td></td><td>0.016%</td></tr>
<tr><td>Br(t→cγ)</td><td></td><td></td><td></td><td></td><td>0.182%</td></tr>
</table>