Top quark couplings and Polarization

Giuseppe Codispoti
for the *CMS* Collaboration

Bologna INFN Istituto Nazionale di Fisica Nucleare

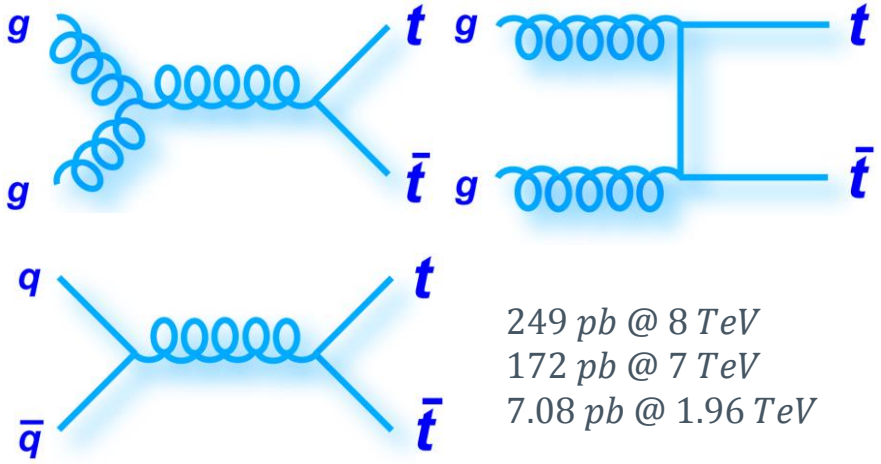
ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA

The Top Quark in short

- The **heaviest** known fundamental particle:
  - $M_t \sim 173.34 \pm 0.76\ GeV$
- **Short lived**: decays before hadronization
  - study as a free quark
  - $\Gamma_t^{NLO} = 1.42\ GeV$
  - $\tau_t = \frac{1}{\Gamma_t} = \sim 10^{-24} s\ > \Lambda_{QCD}^{-1} \sim (100 MeV)^{-1} \sim 10^{-23} s$
  - Bare **properties directly accessible**: mass, charge, spin, polarization…
    - Their precise measurement provides a powerful test of the SM
- Decays (almost exclusively) through: $\mathbf{t} \rightarrow \boldsymbol{Wb} \propto |\boldsymbol{V_{tb}}|^2$
- Large mass implies large **coupling to Higgs:**
  - $\lambda_t \frac{\sqrt{2} m_t}{v} \sim 1$
    - special role in EWSB?
  - Special role in new physics models
- **Main background for SM** processes, (e.g. especially Higgs) and beyond SM

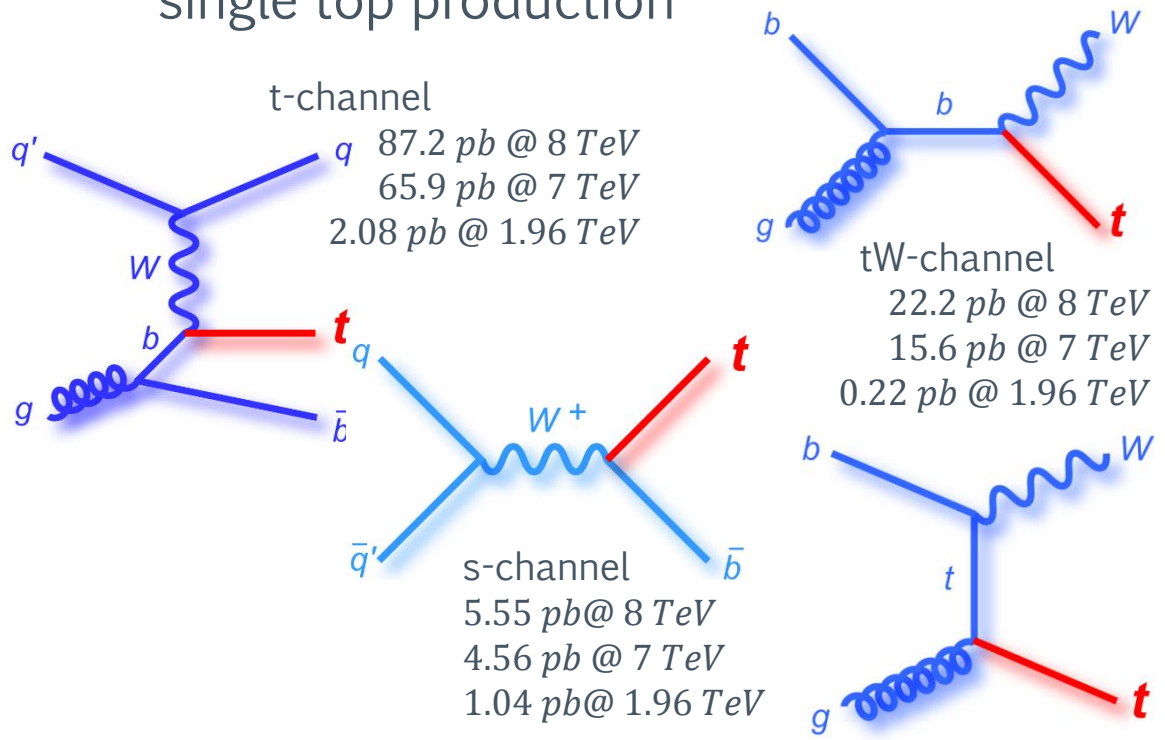
Production and decay

$t\bar{t}$ pair production

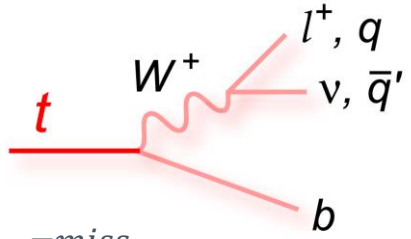


249 pb @ 8 TeV
172 pb @ 7 TeV
7.08 pb @ 1.96 TeV

single top production



- Top Decay
  - Hadronic: 3 jets (1 b-jet)
  - Lepton + jets : b-jet, lepton, E_T^{miss}
- => $t\bar{t}$ final states
  - Hadronic (45.7%): 6 jets
  - Lepton+jets (34.5%) : 1 lepton, 3 jets, E_T^{miss}
  - Dilepton (6.5%): 2 leptons, 2 jets, E_T^{miss}
  - Also relevant the transverse mass of the reconstructed W



- Main Backgrounds:
  - QCD multijet
  - Boson+jets (V+jets)
  - Di-Bosons (VV)
  - Single-t for $t\bar{t}$ pairs
  - $t\bar{t}$ pairs for single-t

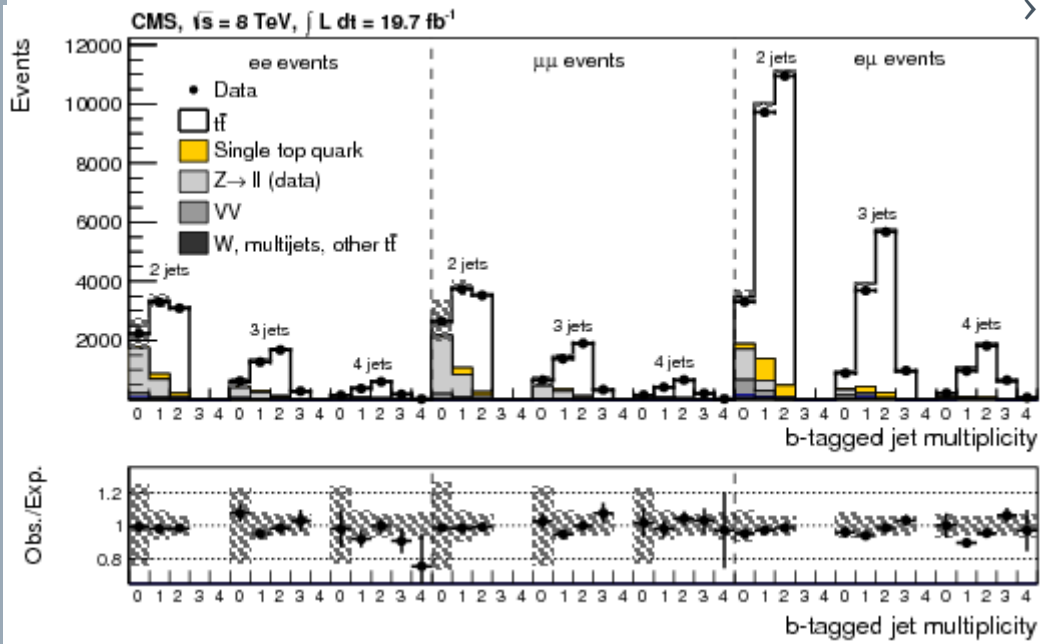
In this talk

- CMS recent measurements:
  - $|V_{tb}|$ measurements:
    - $R = (t \to Wb)/(t \to Wq)$
    - in t-channel
    - in tW associated production
  - $t\bar{t}$ and W/Z/γ associated production
  - Properties
    - spin correlation in $t\bar{t}$
    - polarization in $t\bar{t}$ and single top
    - W helicity in $t\bar{t}$

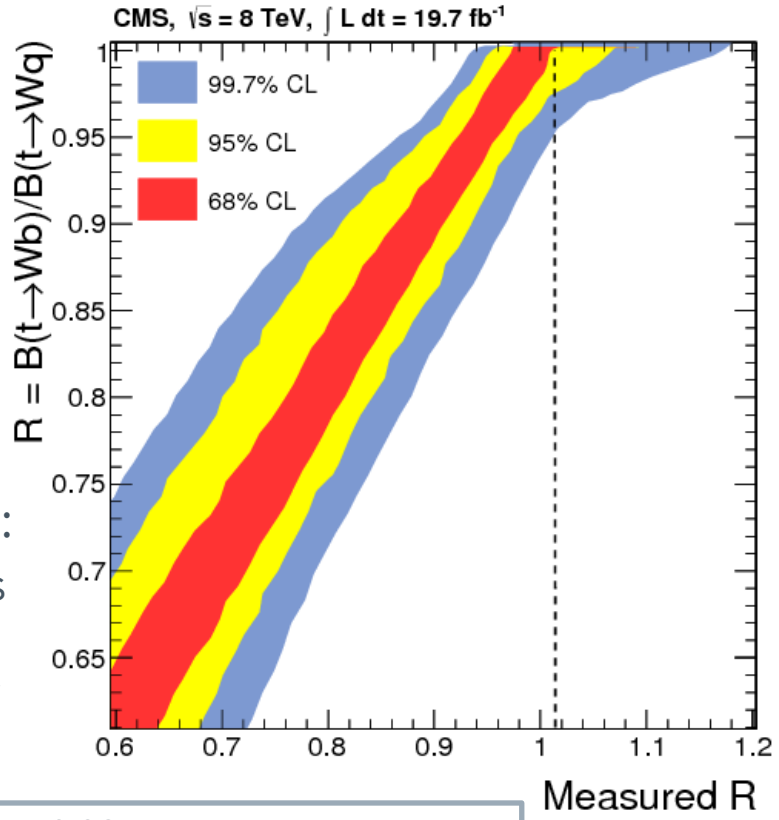
$R = (t \to Wb)/(t \to Wq)$ in dilepton channel

CMS PAS TOP-12-035
PLB 736 (2014) 33

- Top dominant decay W+b: $|Vtb| = 0.999146^{+0.000021}_{-0.000046}$
  - **Tension** in the most precise measurement **in D0**
    - R = 0.90±0.04 (stat.+syst.) [*Phys.Rev.Lett.* **107** (2011) 121802]
- **Likelihood fit** on jet multiplicity accounting for
  - Fraction of $t\bar{t}$ signal and single-top
  - Fraction of event with correct jet assignment
  - b-tag efficiency and mis-identification
- $|V_{tb}|$ calculated assuming unitarity of the CKM matrix and its three-generation structure



- Main systematics:
  - t-channel cross section
  - B tag efficiency



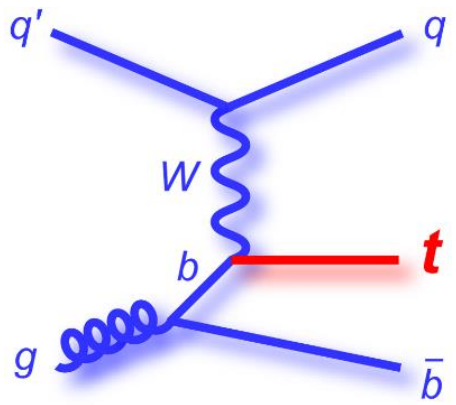
$R = 1.023^{+0.036}_{-0.034}(stat.+syst.)$

$|V_{tb}| = 1.011^{+0.018}_{-0.017}(stat.+syst.)$

$R \leq 1 \Rightarrow R > 0.945$ at 95% CL

$|V_{tb}| > 0.972$ @ 95% CL

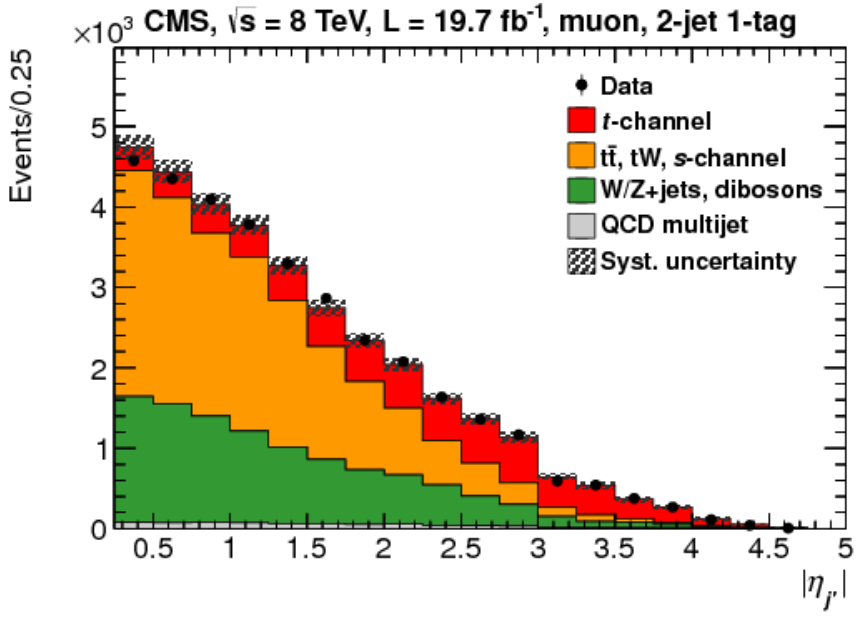
$|V_{tb}|$ measurement in t-channel



- lepton+jets final state
  - 1 isolated lepton
  - 1 light forward jet
  - 1 central b-jet (second b-jet escapes detection)
  - E_T^{miss}

~~CMS PAS TOP-12-038~~
JHEP 06 (2014) 090

- Template analysis $|\eta_{j'}|$
  - fit to the η of the recoil jet in the signal region
    $130 < m_t < 220\ GeV$
  - W/Z+jets from sidebands
  - $t\bar{t}$ background shapes are estimated from 3-jets data
  - QCD from a control sample with inverted isolation cut



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

$[\ \sigma_{tW}^{NNLO} = 87.2^{+2.8}_{-1.0}(scale)^{+2.0}_{-2.2}(PDF)pb]$

8 TeV

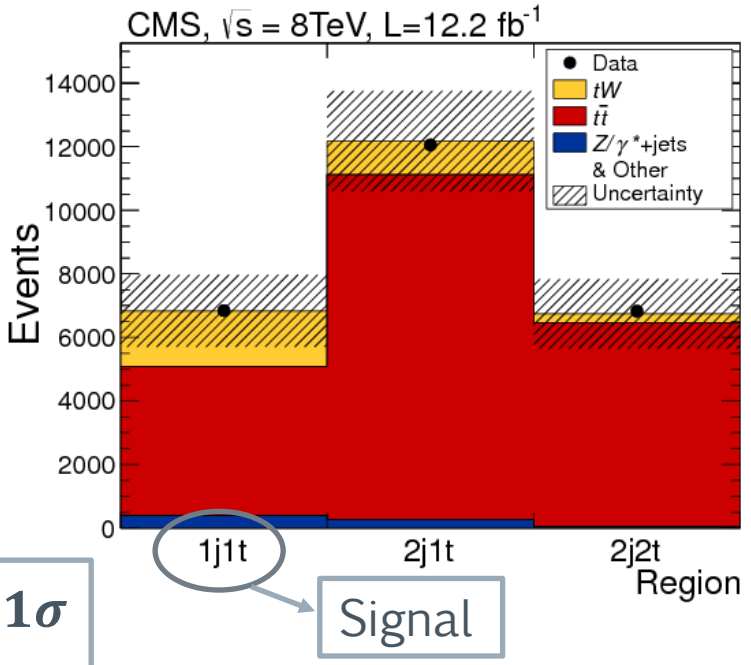
Combination 7+8 TeV for t-channel assuming $|V_{td}|, |V_{ts}| \ll |V_{tb}| \approx 1$

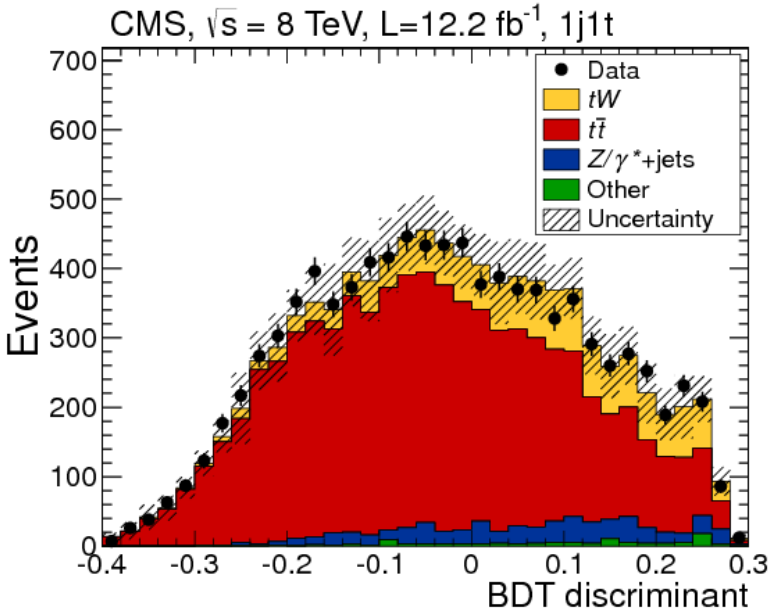
- $\boldsymbol{|V_{tb}| = \sqrt{\frac{\sigma_{t-ch}}{\sigma_{t-ch}^{th}}} = 0.998 \pm 0.038(exp.) \pm 0.016(th.)}$
- $\boldsymbol{|V_{tb}| > 0.92}$ @ **95% CL** after $|V_{tb}| \leq 1\ and\ |f_{Lv}|$=1

Single top and W associated production (tW)

- 2 leptons 1 b-jet signal ('*1j1tag*')
  - Excluded resonant single-top/$t\bar{t}$ NLO diagrams
- '*2jet1tag*' and '*2jets2tags*' events used as $t\bar{t}$ control region
  - simultaneously constrains the $t\bar{t}$ normalization and the b-tagging efficiency in situ
- DY+ jets corrected using Z/γ^* +jets enriched
  - E_T^{miss} from Z/γ^* +jets enriched region $|m_{ll} - m_z| < 20GeV$
- Fit of a discriminant built from kinematic quantities combined with a multivariate technique
  - cross-checks using event-counting and a kinematic variable fit

~~CMS PAS TOP-12-040~~
Phys. Rev. Lett. 112 (2014) 231802



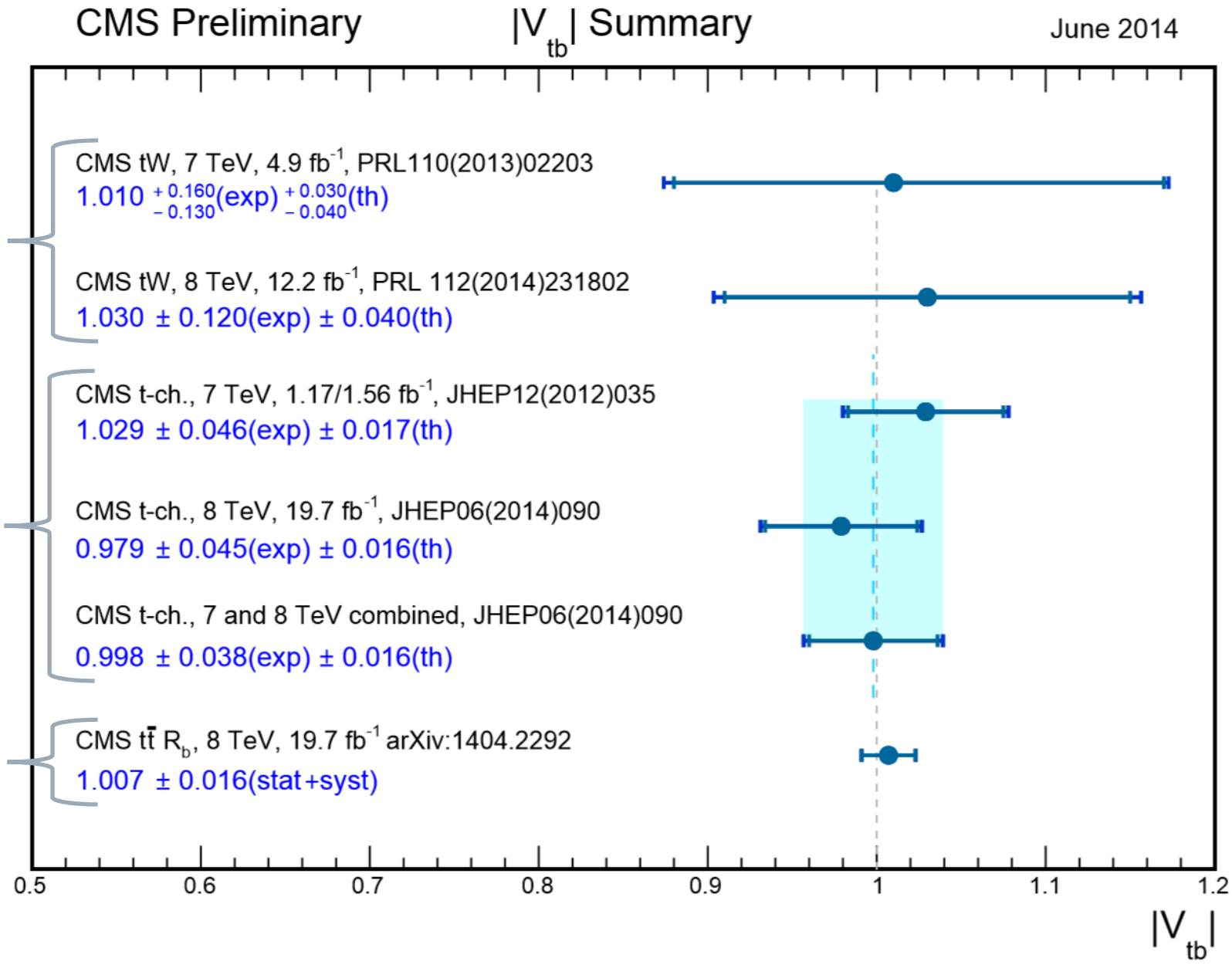


$$\sigma_{tW} = 23.4^{+5.5}_{-5.4} pb, \text{ sig.} = 6.1\sigma$$
$$[\,\sigma_{tW}^{NNLO} = 22.2 \pm 1.5 pb]$$

Assuming $|V_{tb}| = 1$ for σ_{tW}^{th} calculation:

- $|V_{tb}| = \sqrt{\frac{\sigma_{tW}}{\sigma_{tW}^{th}}} = 1.003 \pm 0.12(exp.) \pm 0.04(th.)$
- $|V_{tb}| > 0.78$ @ 95% CL

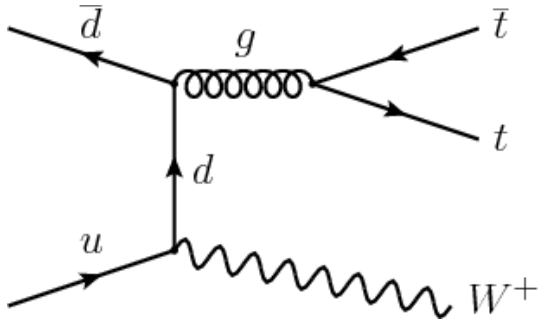
Summary of $|V_{tb}|$ measurements

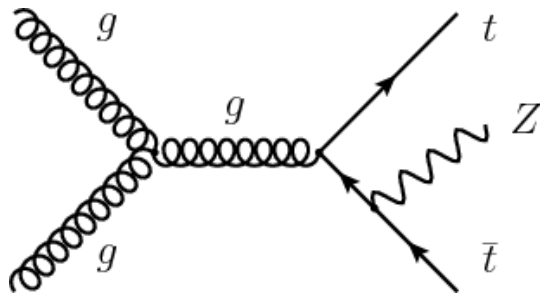


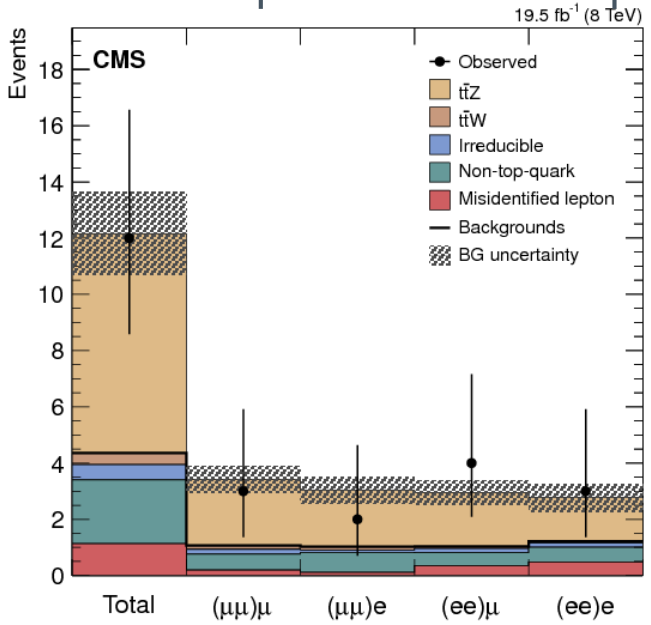
$t\bar{t}$ and W/Z boson associated production

CMS PAS TOP-12-036

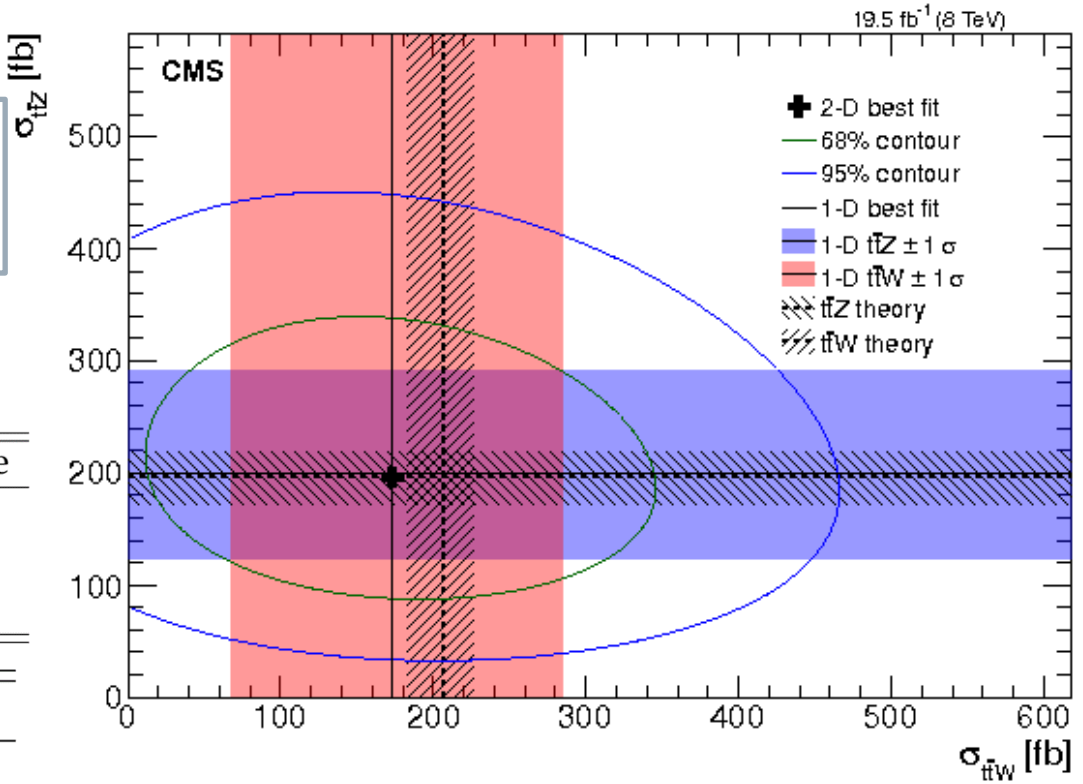
- $t\bar{t}W$:same-sign dileptons (lepton+jets only top decay)
- $t\bar{t}Z$: 3-leptons and 4-leptons







- $\sigma_{t\bar{t}W}^{NLO} = 202^{+21}_{-23} fb$
- $\sigma_{t\bar{t}Z}^{NLO} = 197^{+22}_{-25} fb$



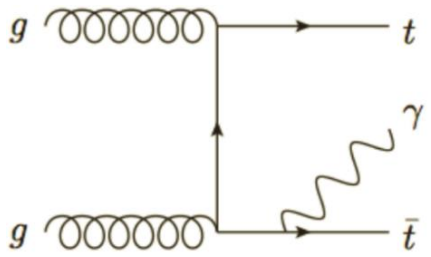
Channels used	Process	Cross section	Significance
2ℓ	$t\bar{t}W$	$170^{+90}_{-80}(\text{stat.})^{+70}_{-70}(\text{syst.})$ fb	1.6 σ
3ℓ+4ℓ	$t\bar{t}Z$	$200^{+80}_{-70}(\text{stat.})^{+40}_{-30}(\text{syst.})$ fb	3.1 σ
2ℓ+3ℓ+4ℓ	$t\bar{t}W + t\bar{t}Z$	$380^{+100}_{-90}(\text{stat.})^{+80}_{-70}(\text{syst.})$ fb	3.7 σ

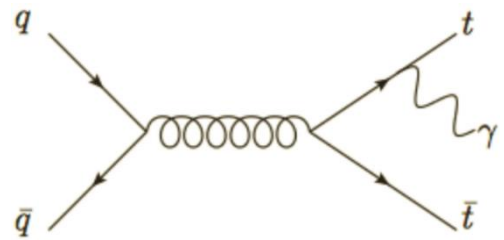
Channels used	$t\bar{t}W$ cross section	$t\bar{t}Z$ cross section
2ℓ+3ℓ+4ℓ	$170^{+110}_{-100}(\text{total})$ fb	$200^{+90}_{-90}(\text{total})$ fb

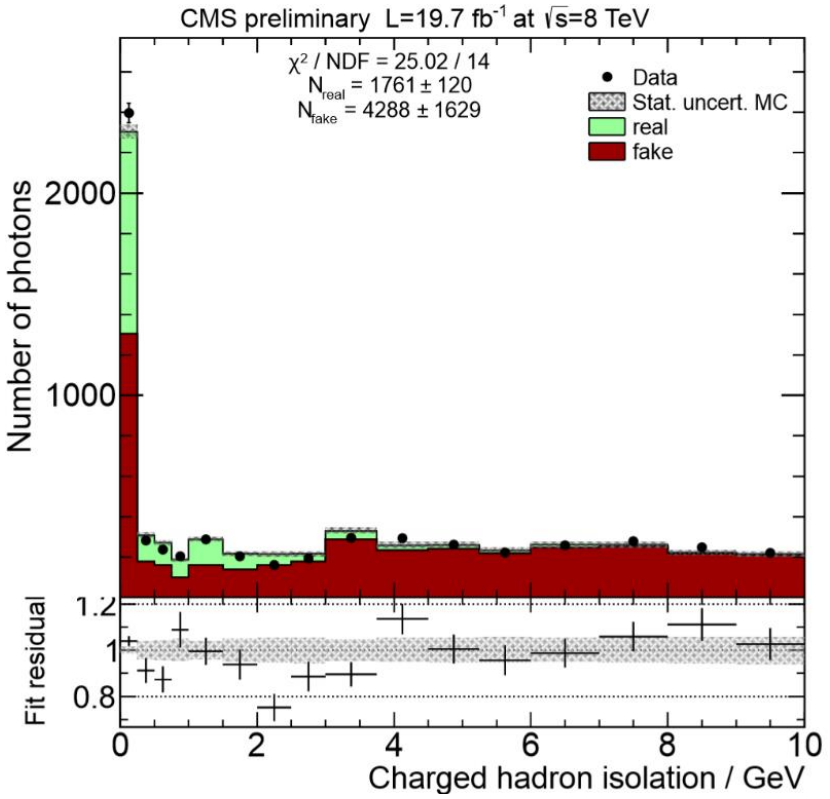
$t\bar{t}$ and photon associated production in μ+jets

CMS PAS TOP-13-011

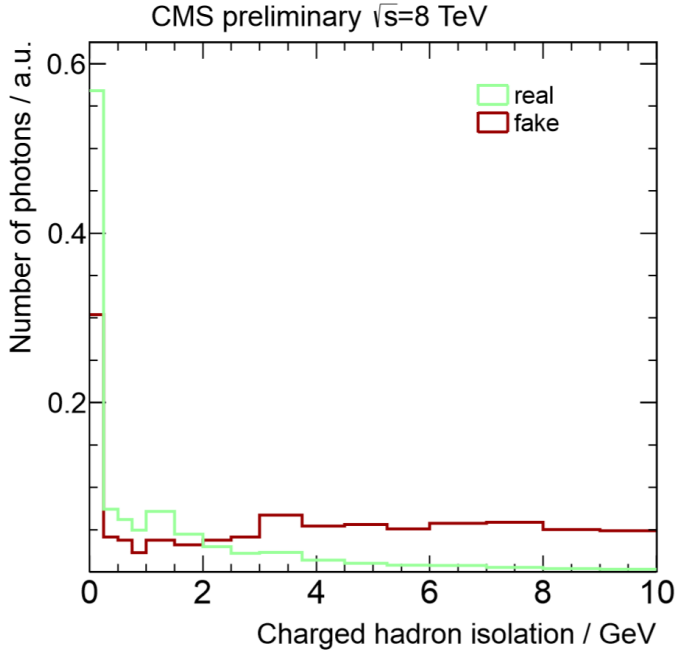
- μ+jets channel
- High p_T photon ($> 20GeV$)
- Template fit on the hadronic isolation
  - main source of mis-identified photons is hadronic







- Signal from MC
  - Normalization is the dominant systematic
- Background from sidebands
  - Modeling is second source of systematic



$Measured: R = {}^{\sigma_{t\bar{t}\gamma}}/_{\sigma_{t\bar{t}}}$

Assuming $\sigma_{t\bar{t}}^{CMS} = 227 \pm 15\ pb$

$$\boldsymbol{\sigma_{t\bar{t}\gamma} = 2.4 \pm 0.2(stat.) \pm 0.6(syst.)pb}$$

$$\sigma_{t\bar{t}\gamma}^{LO} = 1.8 \pm 0.5pb$$

Polarization and spin correlation in dilepton

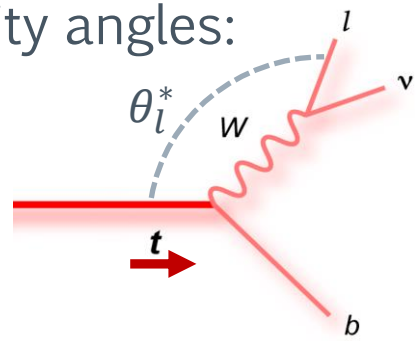
- SM predicts small polarization and ~100% spin correlation between top and anti-top
- $\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_i} = \frac{1}{2}(1+\alpha_i\cos\theta_i)$,
  - α_i is the spin analyzing power

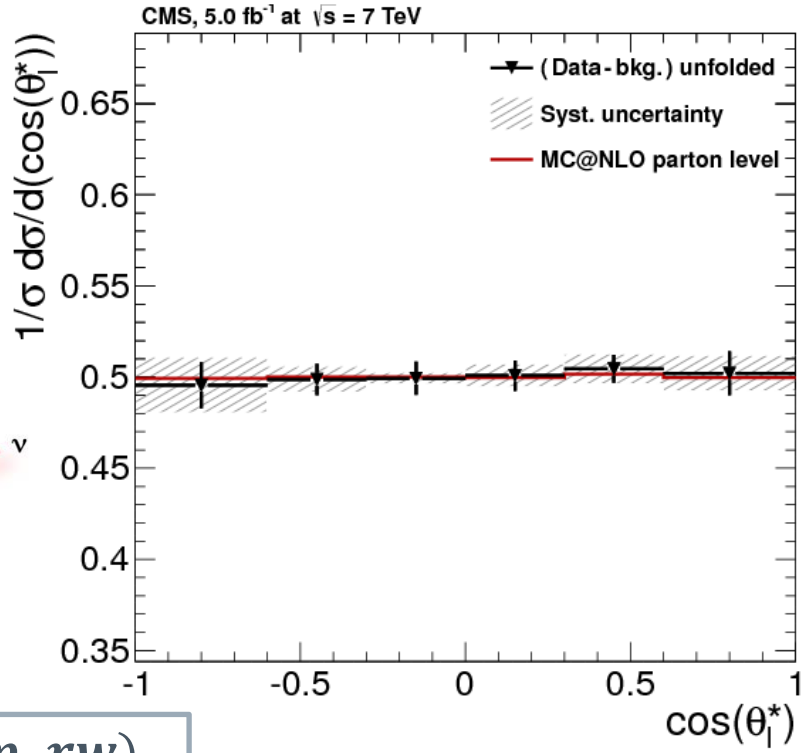
CMS PAS TOP-13-003
Phys. Rev. Lett. 112 (2014) 182001

- $\frac{1}{\sigma}\frac{d^2\sigma}{d\cos\theta_+ d\cos\theta_-} = \frac{1}{4}(1+\cancel{\alpha_+ P_+\cos\theta_+} + \cancel{\alpha_- P_-\cos\theta_-} + A\alpha_+\alpha_-\cos\theta_+\cos\theta_-)$

- Studied through angular asymmetry variables
  - Angular asymmetry variables unfolded to the parton level
  - Backgrounds from MC, validated using data
  - Top p_T modeling is the major source of uncertainties

- Polarization as a function of the helicity angles:
  - Requires full event reconstruction
  - $\boldsymbol{P = 2A_P} \equiv 2\cdot\frac{N[\cos(\theta_l^*)>0]-N[\cos(\theta_l^*)<0]}{N[\cos(\theta_l^*)>0]+N[\cos(\theta_l^*)<0]}$





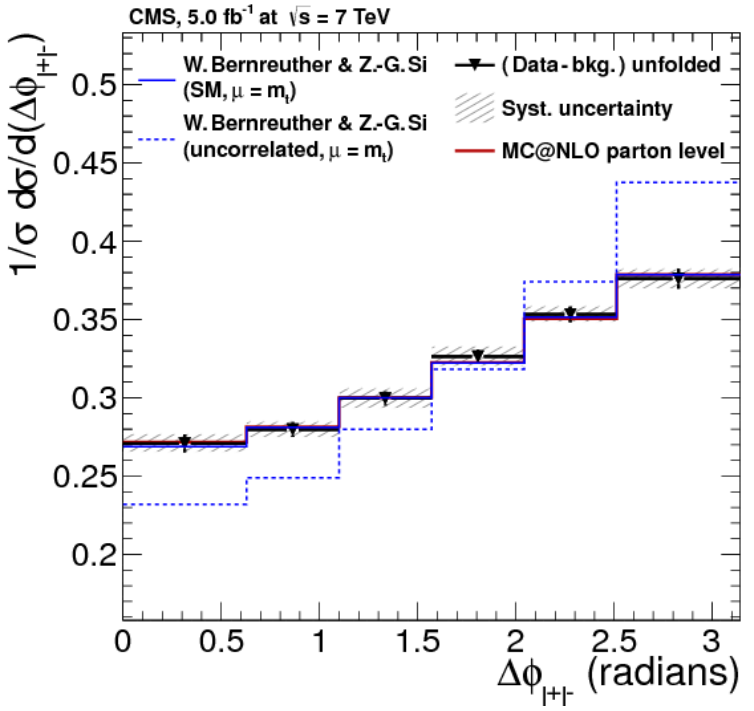
- $\boldsymbol{A_P = 0.005 \pm 0.013(stat.) \pm 0.014(syst.) \pm 0.008(p_T rw)}$

Spin correlation in dilepton

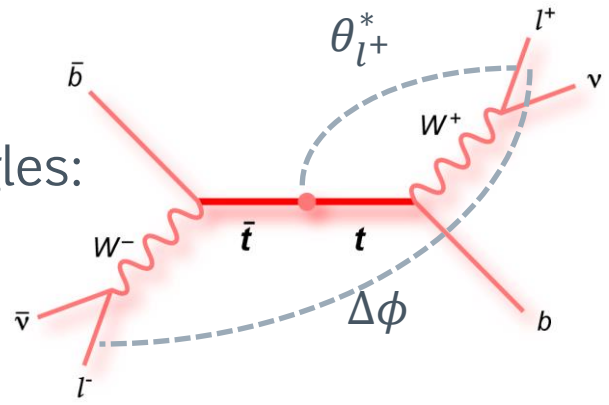
- As a function of pure leptons angular variables:
  - $A_{\Delta\phi} = \frac{N\left[\Delta\phi^*_{l^+l^-} > \pi/2\right] - N\left[\Delta\phi^*_{l^+l^-} < \pi/2\right]}{N\left[\Delta\phi^*_{l^+l^-} > \pi/2\right] + N\left[\Delta\phi^*_{l^+l^-} < \pi/2\right]}$

$$\boldsymbol{A_{\Delta\phi} = 0.113 \pm 0.010(stat.) \pm 0.006(syst.) \pm 0.012(p_T rw)}$$

NLO
$$\begin{cases} \boldsymbol{A^{corr.}_{\Delta\phi} = 0.115^{+0.014}_{-0.016}} \\ A^{unc.}_{\Delta\phi} = 0.210^{+0.013}_{-0.008} \end{cases}$$

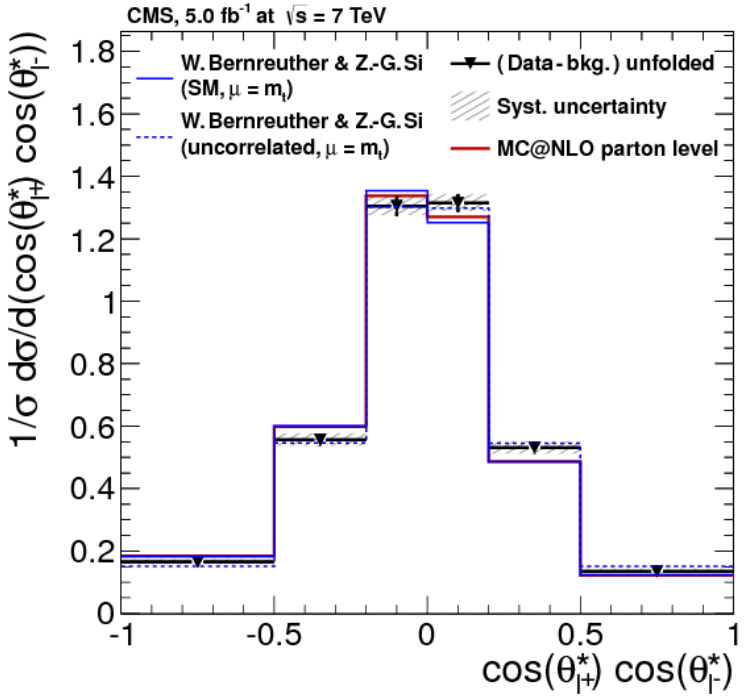


- As a function of the helicity angles:
  - requires full event recontruction
  - $A_{c_1c_2} = \frac{N[c_1c_2>0] - N[c_1c_2<0]}{N[c_1c_2>0] + N[c_1c_2<0]}$
  - $c_1 = \cos\left(\theta^*_{l^+}\right)$ *and* $c_2 = \cos(\theta^*_{l^-})$



$$\boldsymbol{A_{c_1c_2} = -0.021 \pm 0.023(stat.) \pm 0.025(syst.) \pm 0.010(p_T rw)}$$

NLO
$$\begin{cases} A^{corr.}_{c_1c_2} = -0.078 \pm 0.006 \\ A^{unc.}_{c_1c_2} = 0 \end{cases}$$



Top Polarization in single top

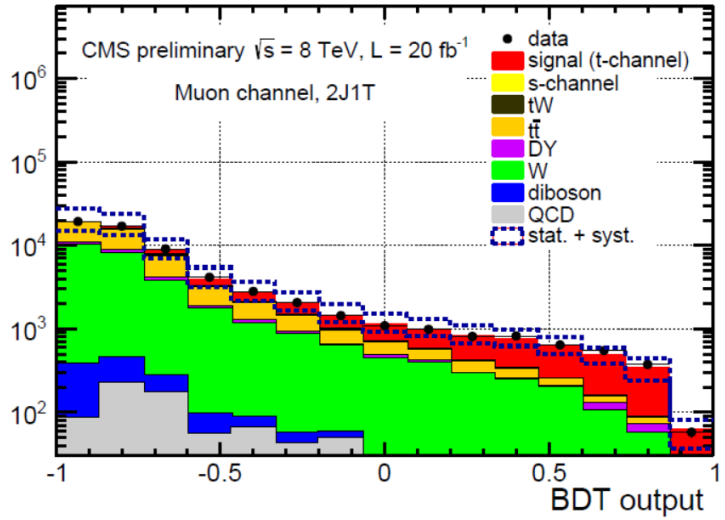
CMS PAS TOP-13-001

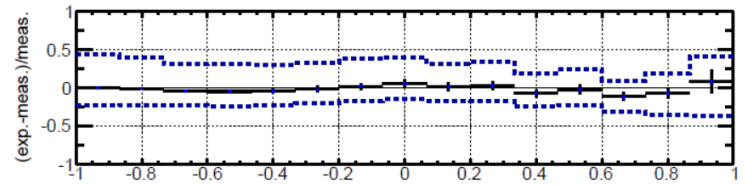
- $\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_l} = \frac{1}{2}(1 + P_t\alpha_l\cos\theta_l) \equiv \frac{1}{2} + A_l\cos\theta_l$
  - $\boldsymbol{\alpha_l}$: analyzing power of the angular variable
  - $\boldsymbol{\theta_l}$: angle between charged lepton and untagged jet
  - Calculated in the top R.F. $\Rightarrow$ $\boldsymbol{\theta_l^*}$

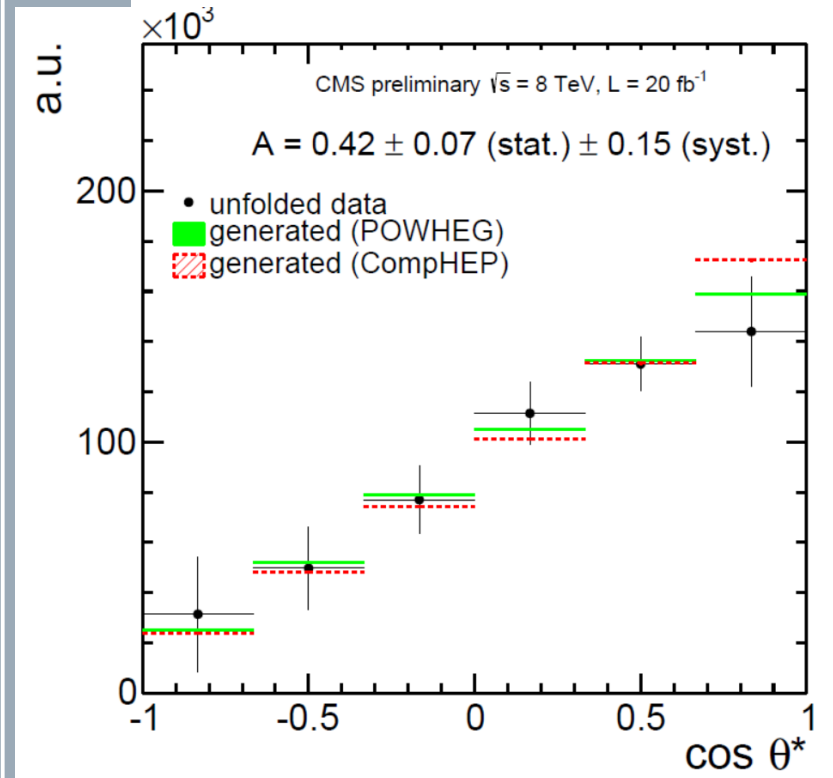
SM : ~100% polarized

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

the light-quark recoiling against the top-quark tend to have a direction parallel to the spin direction of the top





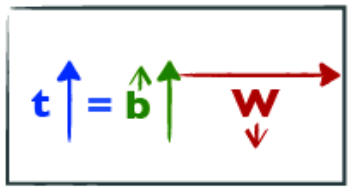


- QCD orthogonal sample
  - Lepton isolation cut reverted
- Other backgrounds from MC
  - W+jets reweighted w.r.t flavor content
  - $t\bar{t}$ validated in sample with 3 jets and 1 or 2 b-tags
- Signal, other-top and VV/V+jets relative contributions are extracted through a likelihood fit on BDT discriminant

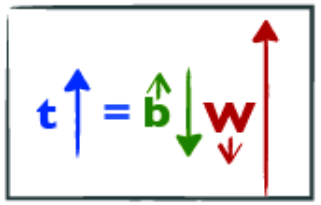
- $e + \mu$ combined results:
- $\boldsymbol{A_l = 0.41 \pm 0.06(stat.) \pm 0.16(syst.) = 0.41 \pm 0.17}$
- $\alpha_l = 1 \Rightarrow \boldsymbol{P_t = 0.82 \pm 0.12\,(stat.) \pm 0.32(syst.) = 0.82 \pm 0.34}$

W helicity fractions in top decays

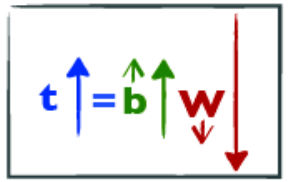
- Directly related to V-A electroweak structure
- High sensitivity to BSM physics



F_0 [SM≃0.687]

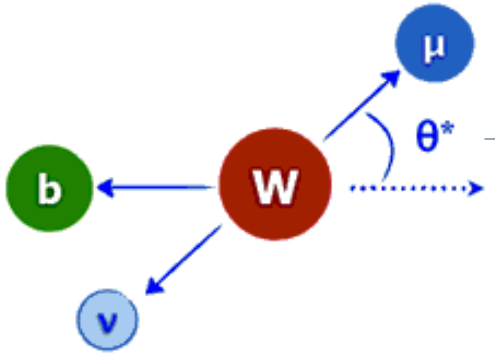


F_L [SM≃0.311]

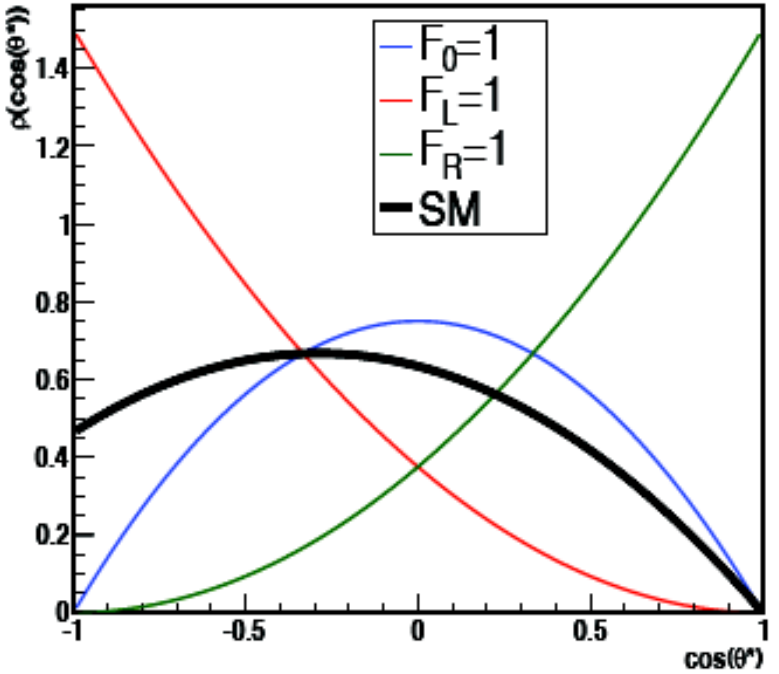


F_R [SM≃0.001]

- $F_x = \frac{\Gamma^x}{\Gamma} \Rightarrow F_L + F_R + F_0 = 1$



direction of the charged lepton
in the W rest frame w.r.t
the W direction in the top rest frame

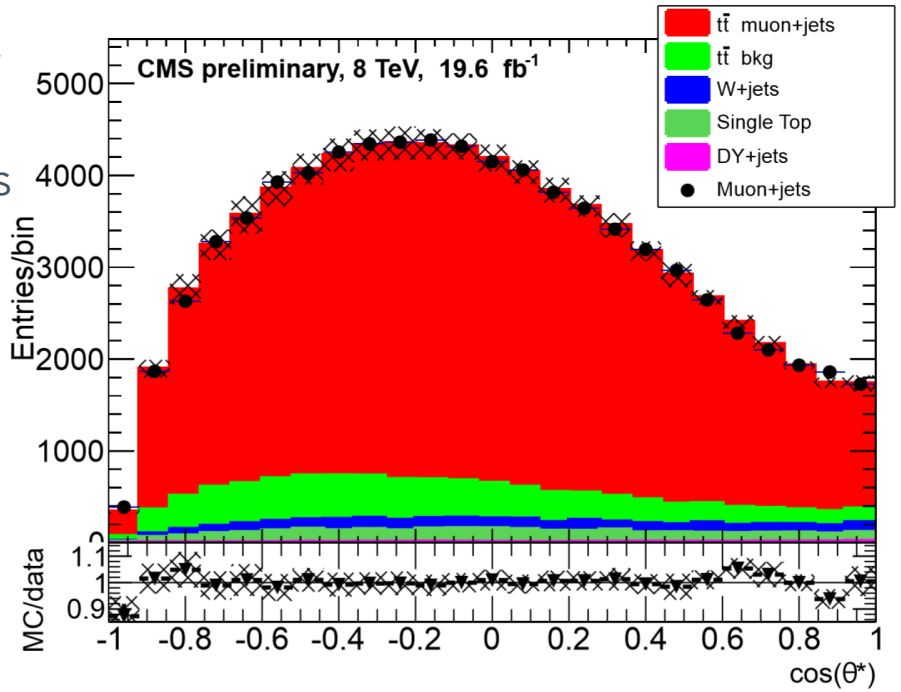


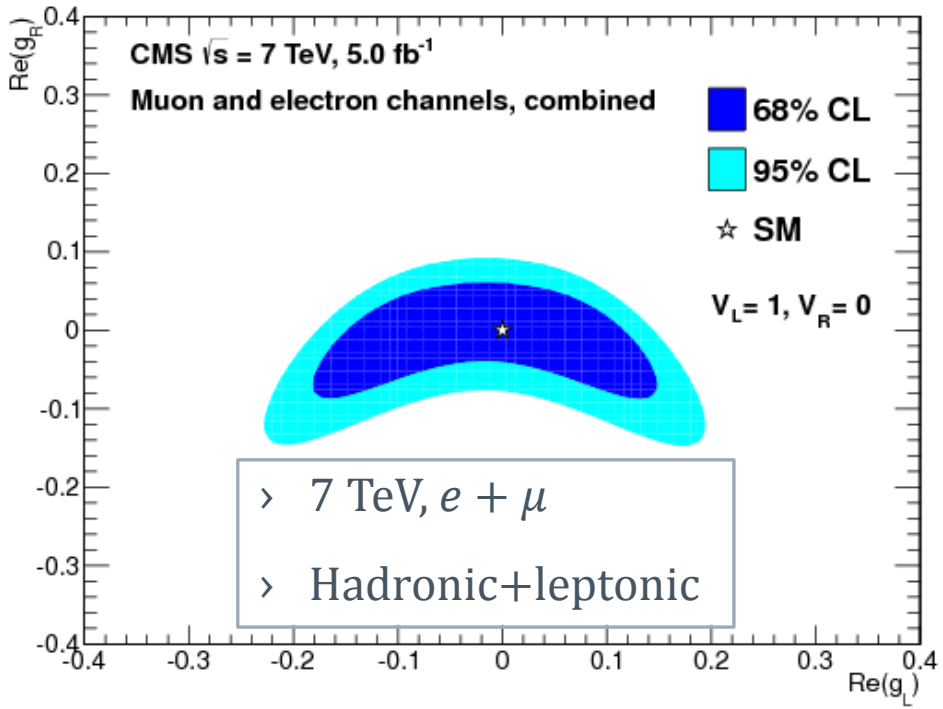
- $\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta^*} = \frac{3}{4}(1-\cos^2\theta^*)F_0 + \frac{3}{8}(1-\cos\theta^*)^2 F_L + \frac{3}{8}(1+\cos\theta^*)^2 F_R$

W-helicity lepton+jets results

JHEP 10 (2013) 167
CMS PAS TOP-13-008

- Poisson binned likelihood maximization
  - Reweight based on observed and expected events in bins of $cos\,\theta^*$
  - accounts for simulated detector acceptance and efficiencies
- Major background from di-leptons
- Other backgrounds reduced through b-tag and m_T
  - Data driven validations provided





- 7 TeV, $e + \mu$
- Hadronic+leptonic

8 TeV μ − only, leptonic branch

- $\mathbf{F_0 = 0.659 \pm 0.015^{(stat)} \pm 0.0023^{(syst)}}$
- $\mathbf{F_L = 0.350 \pm 0.010^{(stat)} \pm 0.024^{(syst)}}$
- $\mathbf{F_R = -0.009 \pm 0.006^{(stat)} \pm 0.020^{(syst)}}$

Conclusions

- CMS has a **wide range of measurements** of the top quark properties
  - In the $t\bar{t}$ *strong* production
    - Presented : R and $|V_{tb}|$, $t\bar{t}$ + W/Z/γ production, polarization and spin correlation, W-helicity
  - In the **single top** *electroweak* production
    - Presented : $|V_{tb}|$ in t-channel and tW production, polarization

- They provide **thorough tests to the Standard Model**
  - **high sensitivity to new physics** through variations from SM predictions

- All the measurements show ***good agreement*** with the Standard Model, both with $\mathbf{7\ TeV}$ and $\mathbf{8\ TeV}$ collisions data

- CMS is preparing for LHC-Run2: **new results** will come!

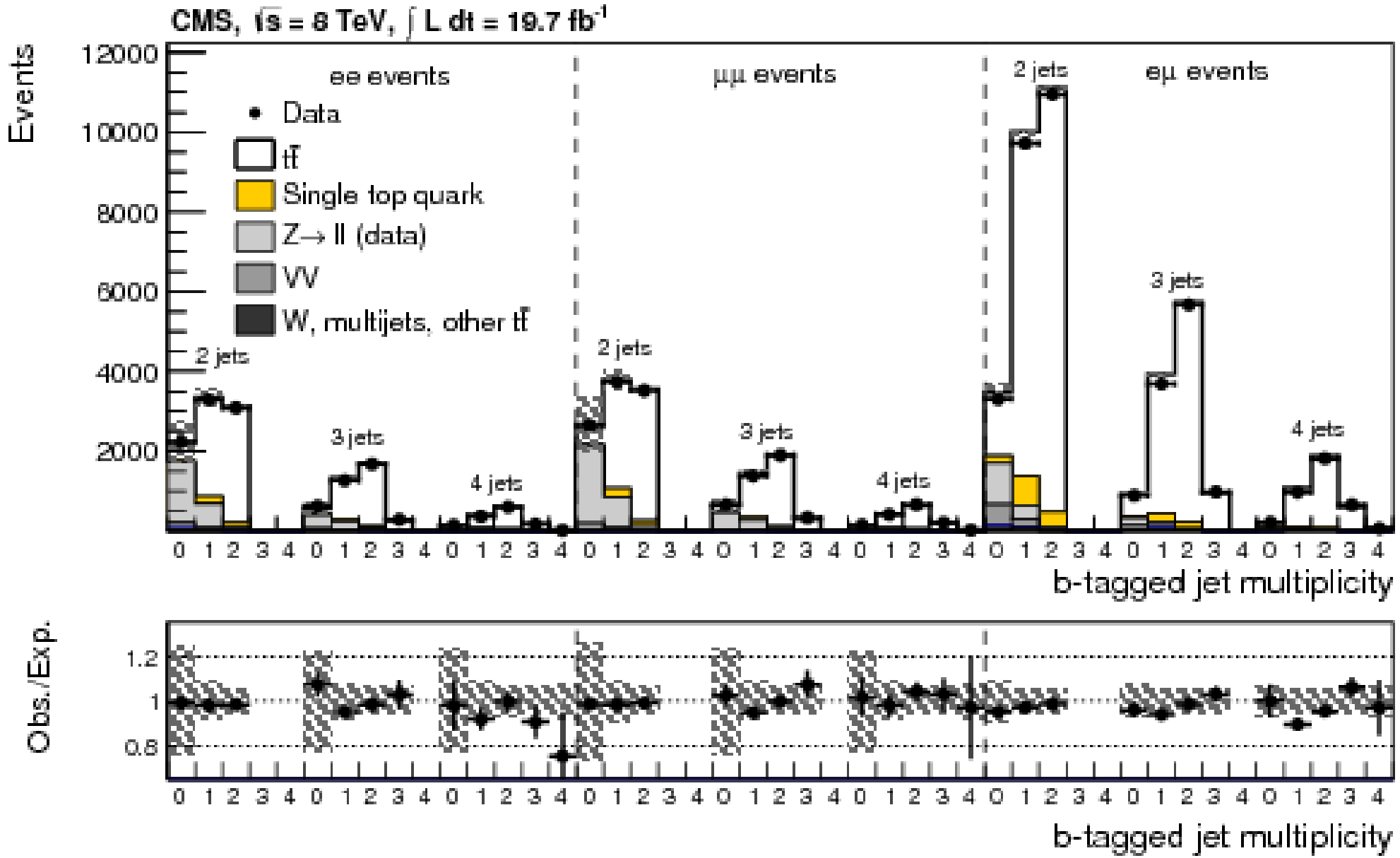
thanks

G. Codispoti for the CMS Collaboration
BEACH14, Birmingham – UK
22/07/2014

BACKUP SLIDES

G. Codispoti for the CMS Collaboration
BEACH14, Birmingham – UK
22/07/2014

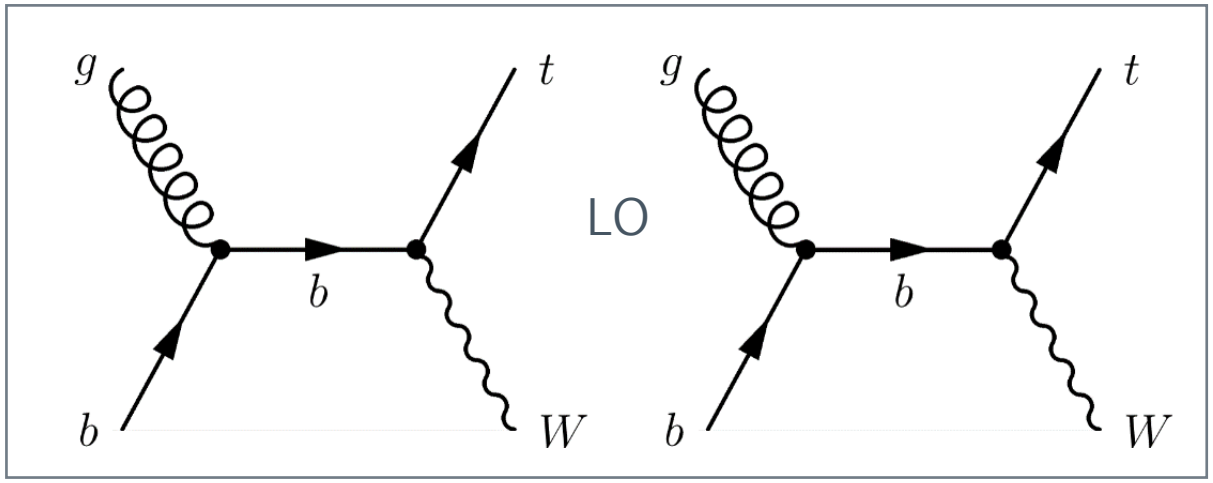
B-jet multiplicity in tW analysis

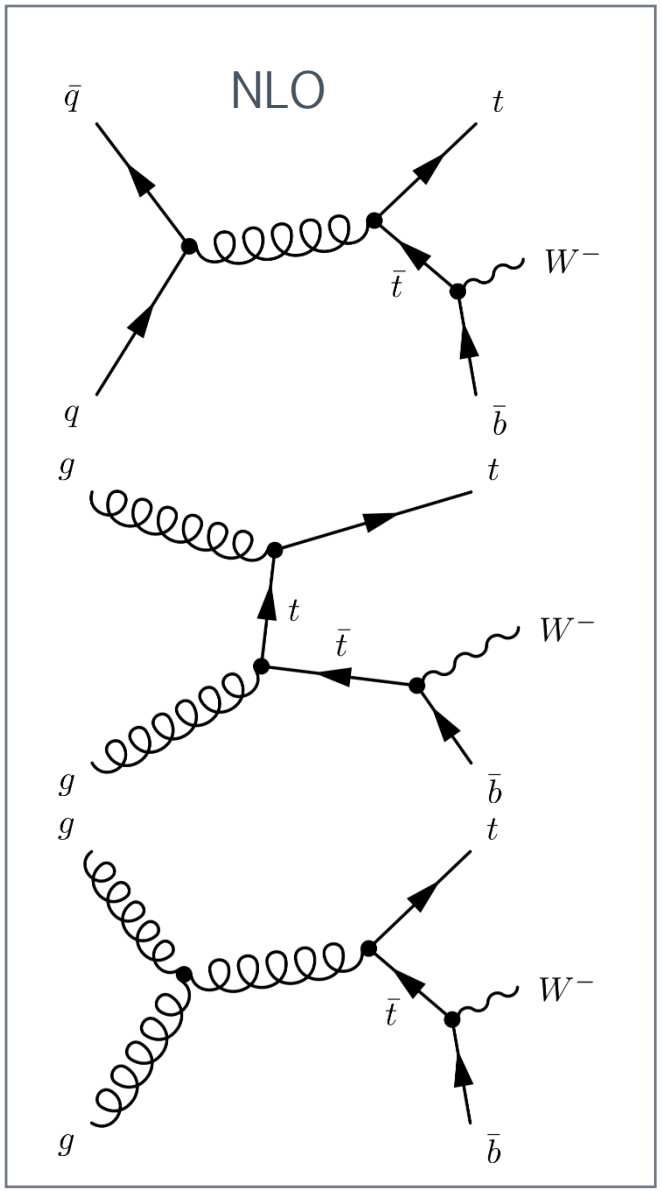


tW production additional information

- Signature:
  - 2 opposite charge isolated leptons
  - b-jet from top + light jet
- NLO diagrams mixes single top and $t\bar{t}$
  - Diagram removal approach: resonant NLO diagrams are not considered signal

Systematic Uncertainty	$\Delta\sigma$ (pb)	$\frac{\Delta\sigma}{\sigma}$
ME/PS matching thresholds	3.25	14%
Q^2 scale	2.68	11%
Top quark mass	2.28	10%
Statistical	2.13	9%
Luminosity	1.13	5%
JES	0.91	4%
$t\bar{t}$ cross section	0.87	4%
Z+jet data/MC scale factor	0.56	2%
tW DR/DS scheme	0.45	2%
PDF	0.33	1%
Lepton identification	0.31	1%
JER	0.27	1%
B-tagging data/MC scale factor	0.20	$< 1\%$
$t\bar{t}$ Spin Correlations	0.12	$< 1\%$
Top Pt Reweighting	0.12	$< 1\%$
Event pile up	0.11	$< 1\%$
$E_{\mathrm{T}}^{\mathrm{miss}}$ modeling	0.07	$< 1\%$
Lepton energy scale	0.02	$< 1\%$
Total	5.58	24%

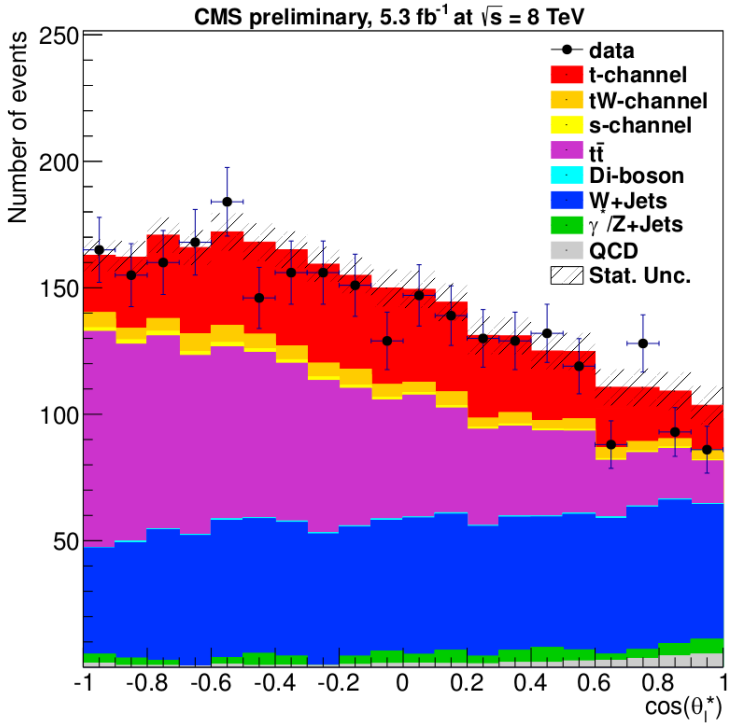


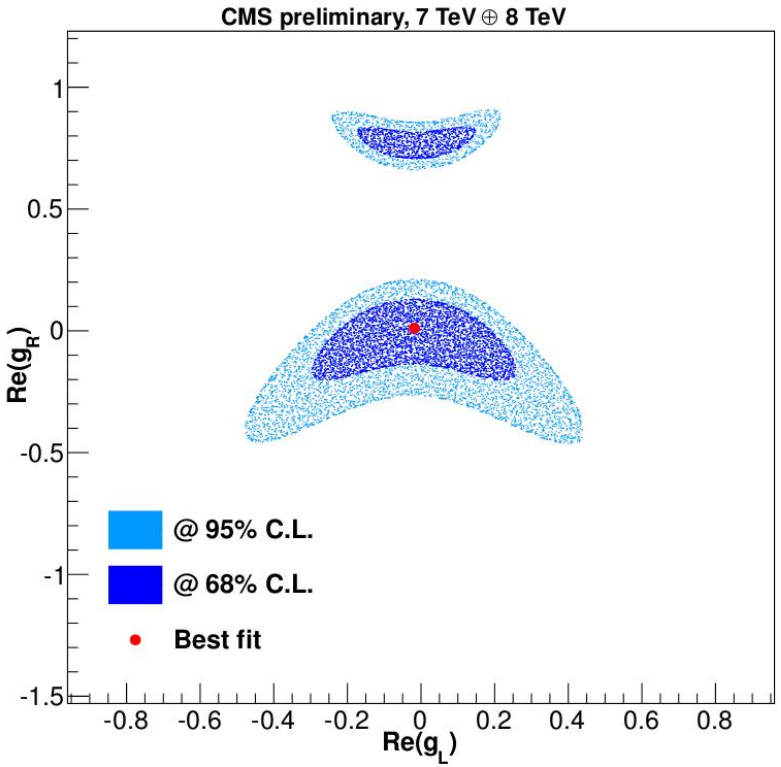


W-helicity in single top, μ+jets

CMS PAS TOP-12-020

- Electroweak process involving Wtb vertex
  - alternative to $t\bar{t}$ strong production (qq, gg)
  - sensitive to non-SM couplings
- Fractions obtained from likelihoods with reweighted signal
  - Normalization of W+jets also free parameter of the fit, shape validated using data from control region with no b-tag request





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