# Single top production and properties at hadron colliders

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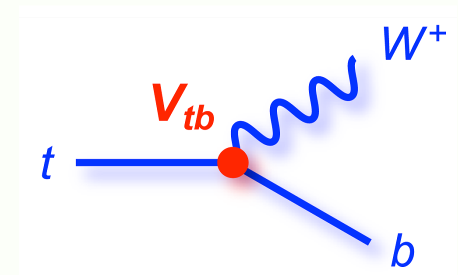
# Why study single top ?

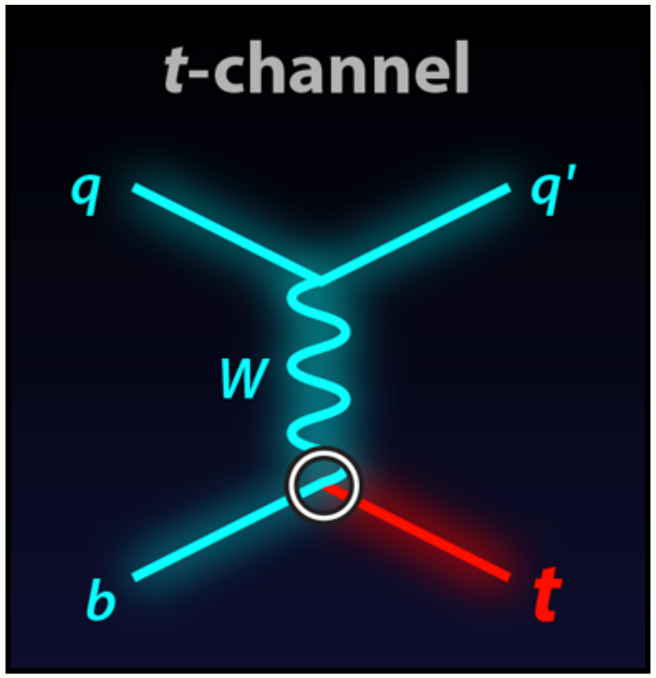
- **Direct probe of electroweak interactions** (in contrary to ttbar production which is of strong type)
- **Wtb vertex** is involved in all SM single top production mechanism → **determination of CKM matrix element $|V_{tb}|$** from the measured cross sections



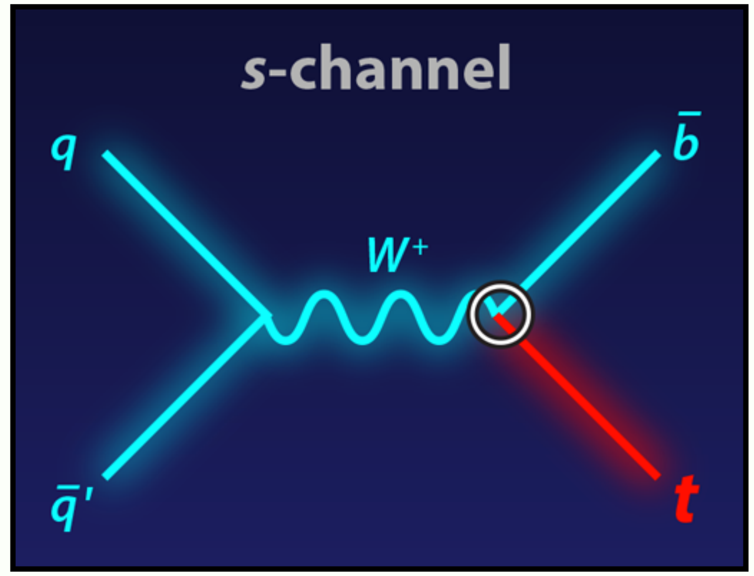

- **Probe the PDFs**
- **Test anomalous Wtb couplings** in the production rates of top and antitop quarks
- Search for **FCNC** interactions

More details on single top related results could be found in the talks already given by ***Mohsen Naseri***, ***Fabian-Phillipp Tepel***, ***Matthias Komm*** and ***Peter Uwer***

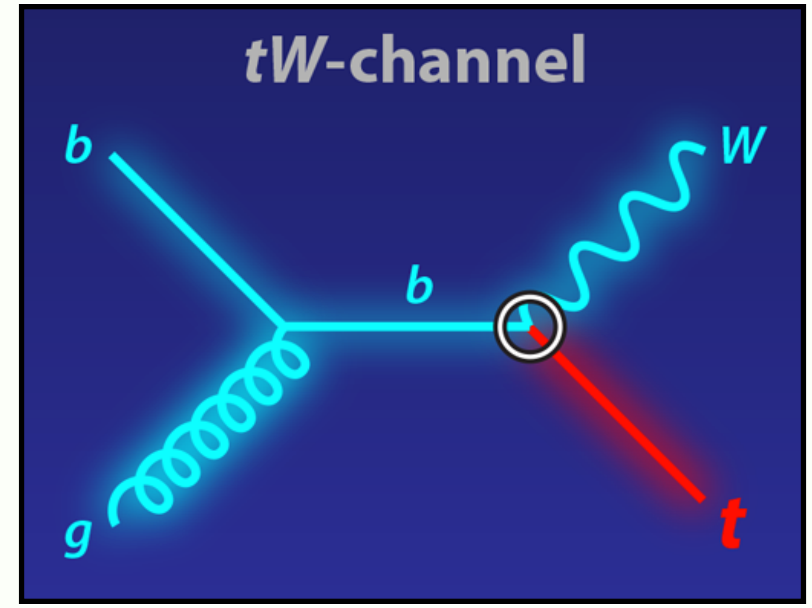
# Single top production




*Light jet in forward direction*




*Two b jets within the central region*

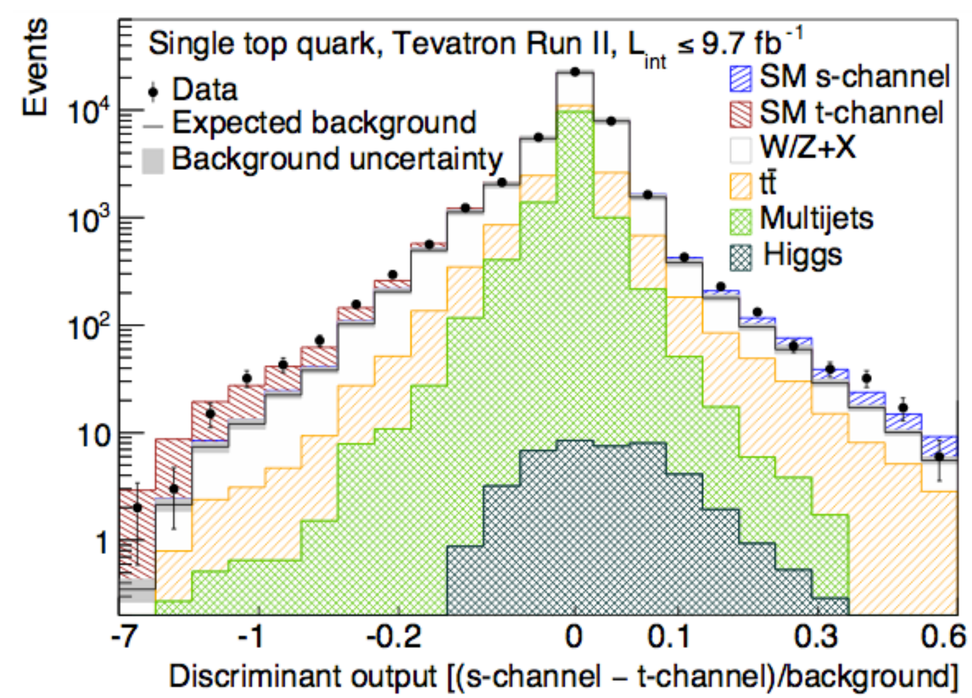


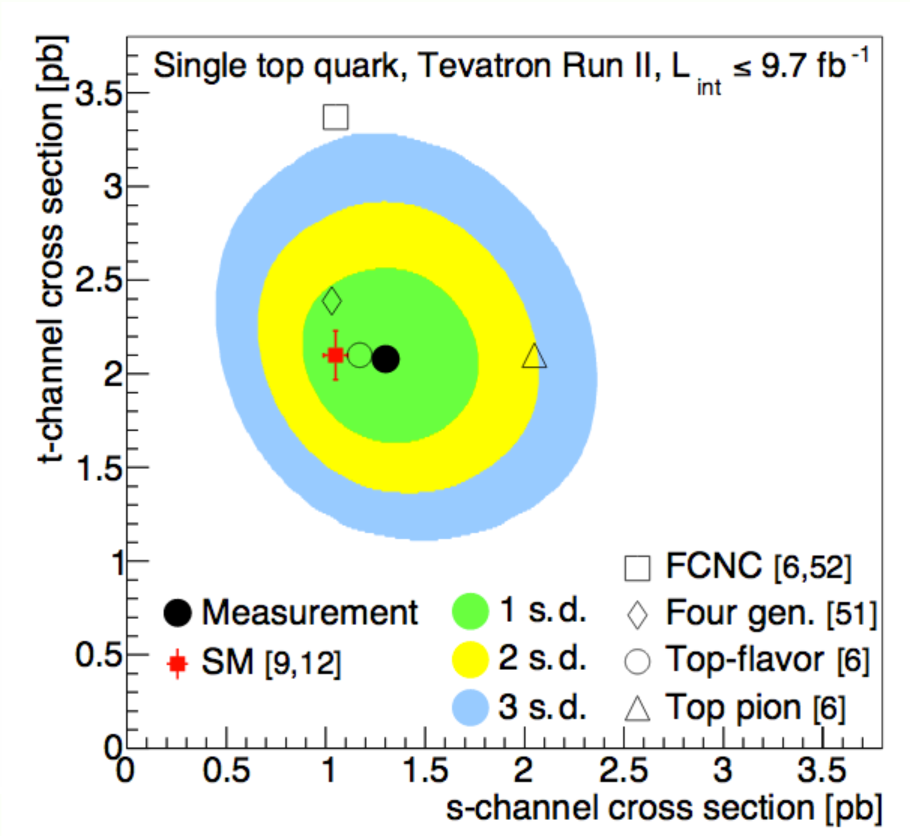

| Energy | Process | Cross section [pb] | Reference |
|---|---|---|---|
| Tevatron (1.96 TeV) | t | $2.10 \pm 0.13$ | Phys. Rev. D 83, 091503 (2011) |
| | s | $1.05 \pm 0.06$ | Phys. Rev. D 81, 054028 (2010) |
| | Wt | $0.25 \pm 0.03$ | Phys. Rev. D 74, 114012 (2006) |
| LHC (7 TeV) | t | $65.9\ ^{+2.1}_{-0.7}$ (scale) $^{+1.5}_{-1.7}$ (PDF) | Phys. Part. Nucl. 45, 714 (2014) |
| | s | $4.56 \pm 0.07$ (scale) $^{+0.18}_{-0.17}$ (PDF) | |
| | Wt | $15.6 \pm 0.4$ (scale) $\pm 1.1$ (PDF) | |
| LHC (8 TeV) | t | $87.2\ ^{+2.8}_{-1.0}$ (scale) $^{+2.0}_{-2.2}$ (PDF) | Phys. Part. Nucl. 45, 714 (2014) |
| | s | $5.55 \pm 0.08$ (scale) $\pm 0.21$ (PDF) | |
| | Wt | $22.2 \pm 0.6$ (scale) $\pm 1.4$ (PDF) | |
| LHC (13 TeV) | t | $216.99^{+6.62}_{-4.64}$ (scale) $\pm 6.16$ (PDF) | Phys. Rev. Lett. 102, 182003 (2009) |
| | s | $10.3 \pm 0.4$ | Phys. Rev. D 82 054018 (2010) |
| | Wt | $71.1 \pm 3.8$ | Phys. Rev. D 82 054018 (2010) |

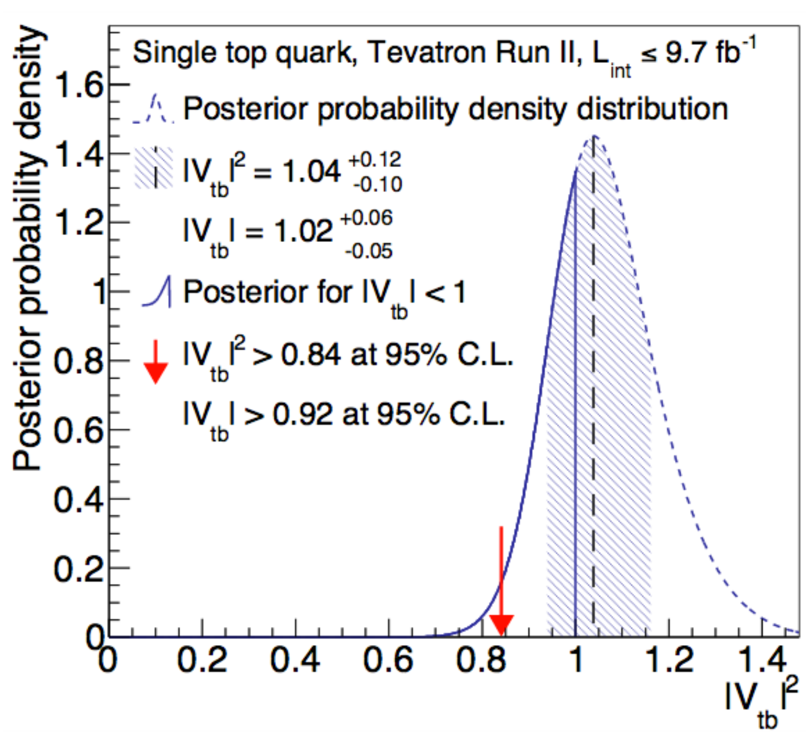
- Predicted cross sections depend on PDF, 4FS/5FS, scale choice, top quark mass, etc.
- Common efforts within ***LHCtopWG*** and ***Tevatron Top WG*** to harmonize the comparison to theoretical predictions with Hathor v2.1 (**NLO**), will proceed at **NNLO**: *Phys. Lett. B 736, 58-63 (2014)*
- Calculations for Wt are available at **NLO+NNLL**

# Single top at Tevatron

- Final single top combination for **t** and **s+t** channels from Tevatron [1]
- Does not include already reported **s channel** results [2]
- Statistically independent combination of **l+jets** (CDF and D0) and **$E_T^{miss}$+jets** (CDF) final states
- Combined MVA based **t** and **s** channel discriminants
- Measured cross sections and |Vtb| are **consistent with SM predictions**



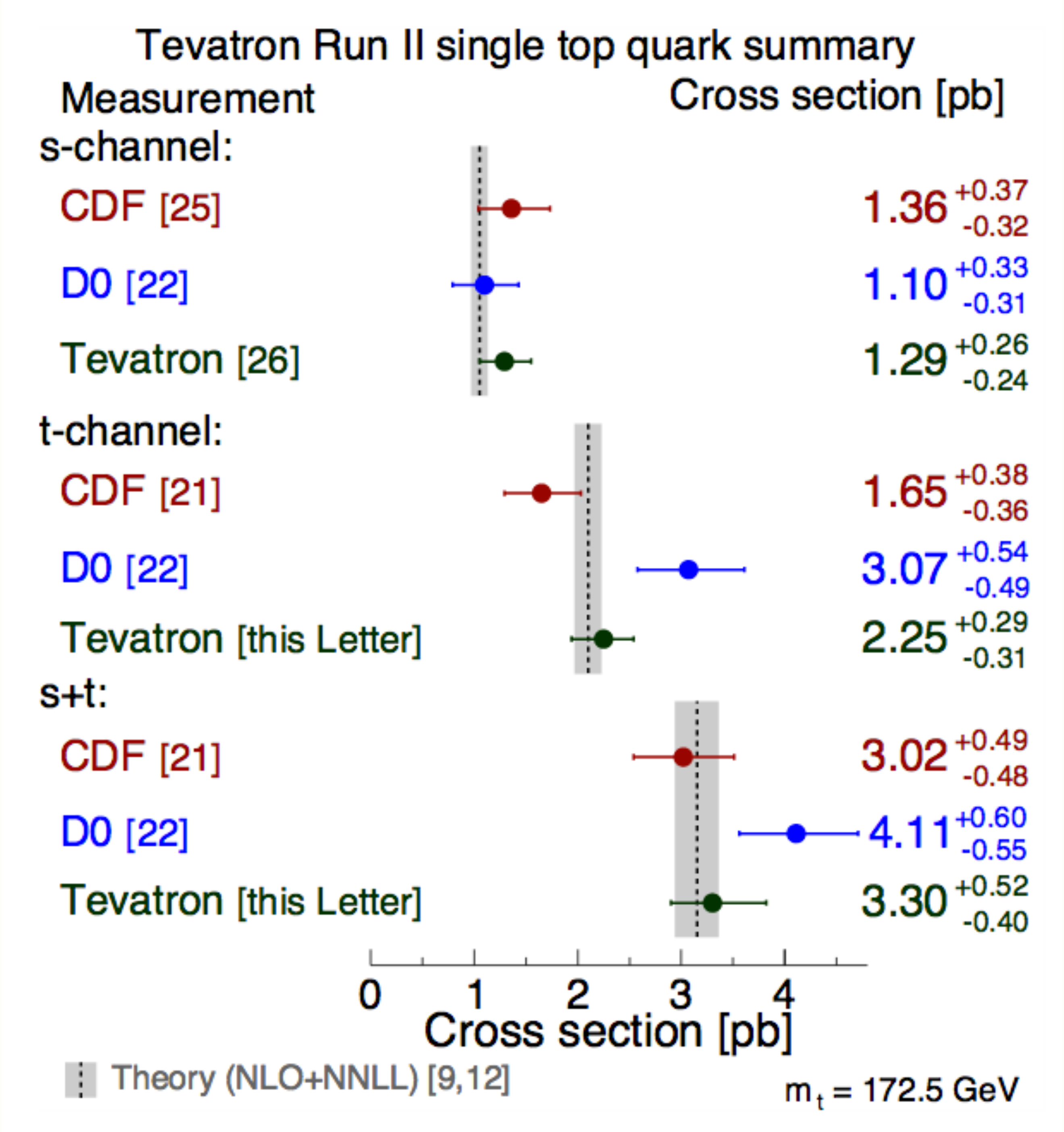





*[1] T. Aaltonen et al., CDF Collaboration, D0 Collaboration, Phys. Rev. Lett. 115, 152003 (2015)*

*[2] T. Aaltonen et al., CDF Collaboration, D0 Collaboration, Phys. Rev. Lett. 112, 231803 (2014)*

# Summary on single top at Tevatron




*[this Letter]* *Phys. Rev. Lett. 115, 152003 (2015)*

*[21]* *Phys. Rev. D 93, 032011 (2016)*

*[22]* *Phys. Lett. B 726, 656 (2013)*

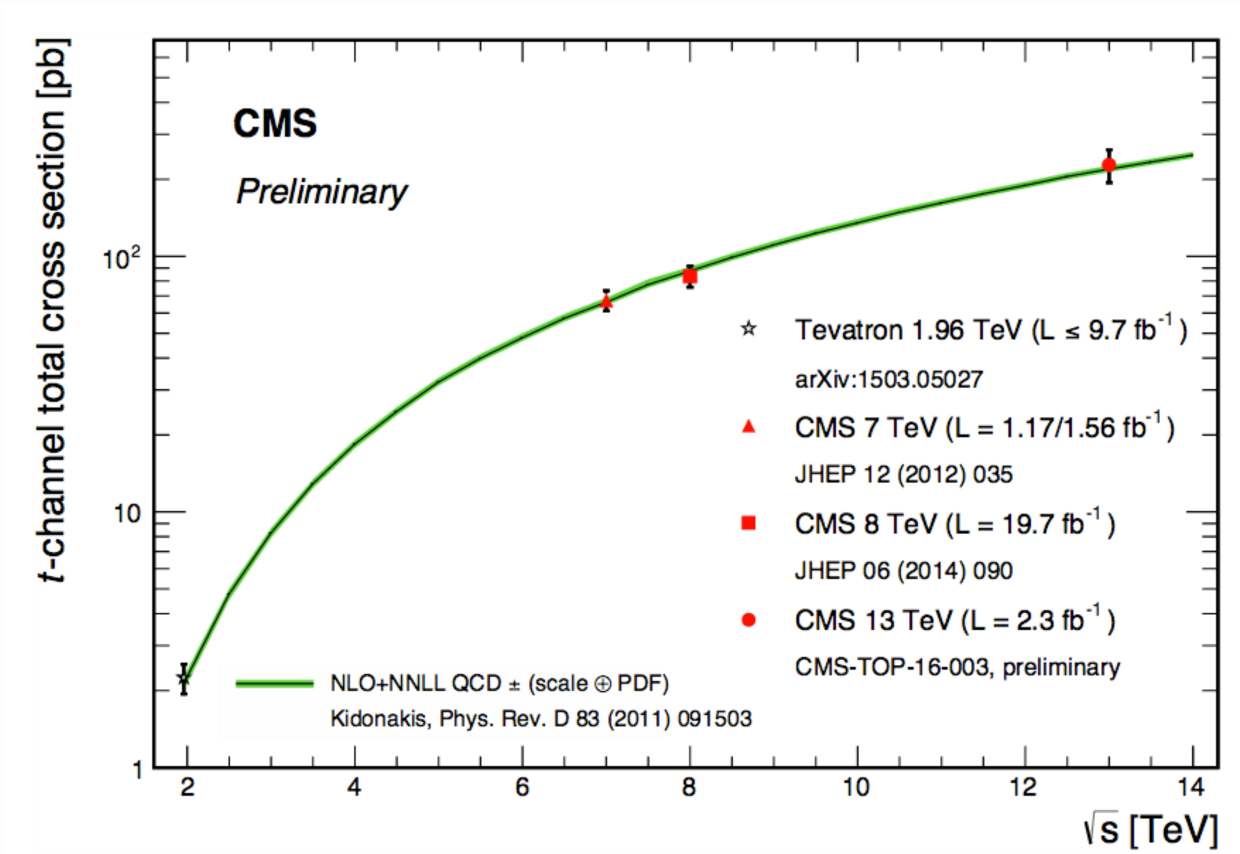
*[25]* *Phys. Rev. Lett.112, 231805 (2014)*

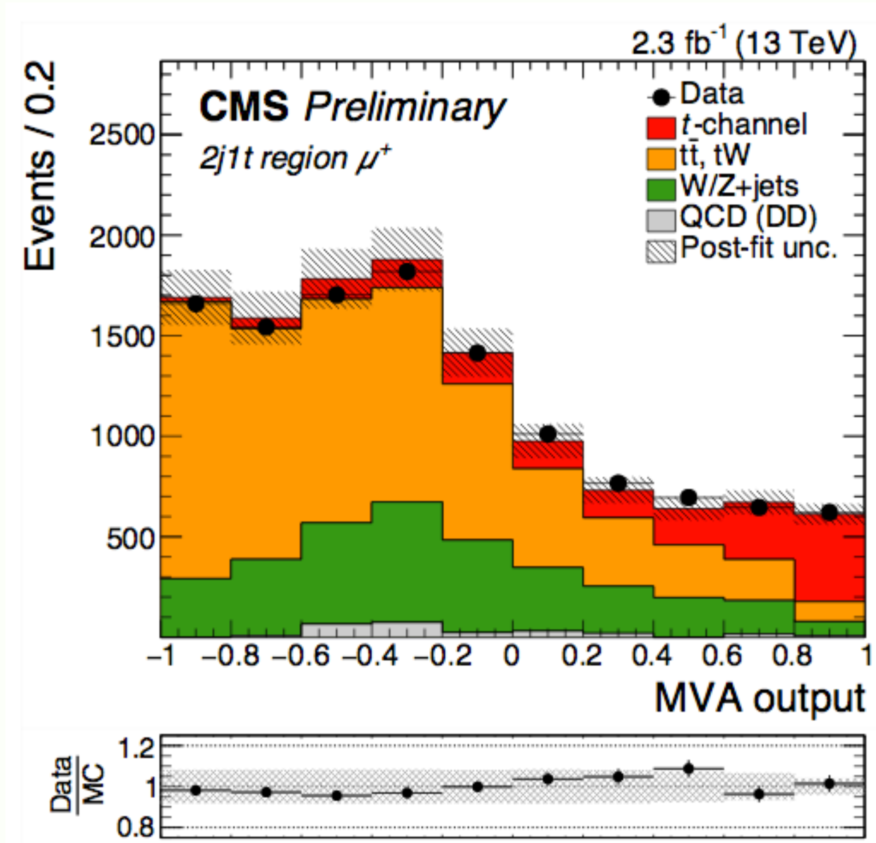
*[26]* *Phys. Rev. Lett. 112, 231803 (2014)*

# t channel at CMS

**13 TeV**

- **Measurement with full 2015 data (2.3 fb$^{-1}$)** [1] following the **first t channel measurement at 13 TeV** (42 pb$^{-1}$) [2] at **CMS**
- Measured in **muon+jets** channel
- Event categorization according to the number of jets and b tagged jets
- Signal extracted through binned likelihood fit to a Neural Net discriminant




$$|f_{LV} V_{tb}| = 1.02 \pm 0.07(\text{exp.}) \pm 0.02(\text{theo.})$$ **7%**

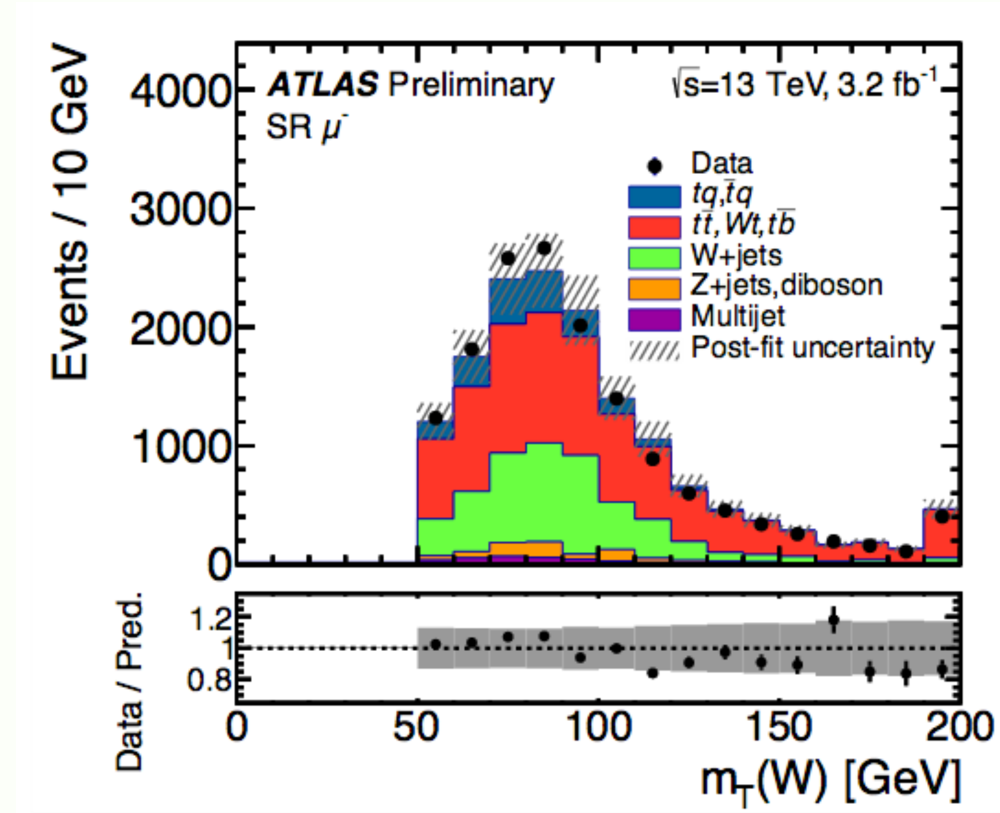
$$\sigma_{t\text{-ch.}} = 227.8 \pm 9.1\,(\text{stat.}) \pm 14.0\,(\text{exp.})\,^{+28.7}_{-27.7}\,(\text{theo.}) \pm 6.2\,(\text{lumi.})\,\text{pb} = 227.8\,^{+33.7}_{-33.0}\,\text{pb}$$ **15%**


[1] CMS-PAS-TOP-16-003
[2] CMS-PAS-TOP-15-004

# t channel at ATLAS

**13 TeV**

- **First separate top-quark and top-antiquark t channel measurement at 13 TeV** [1]
- Measurement is done in **muon+jets** channel
- Event categorization according to the number of jets and b tagged jets
- Signal extracted through a binned likelihood fit to a Neural Net discriminant




$$\sigma(tq) = 133 \pm 6\,(\text{stat.}) \pm 24\,(\text{syst.}) \pm 7\,(\text{lumi.})\ \text{pb}$$

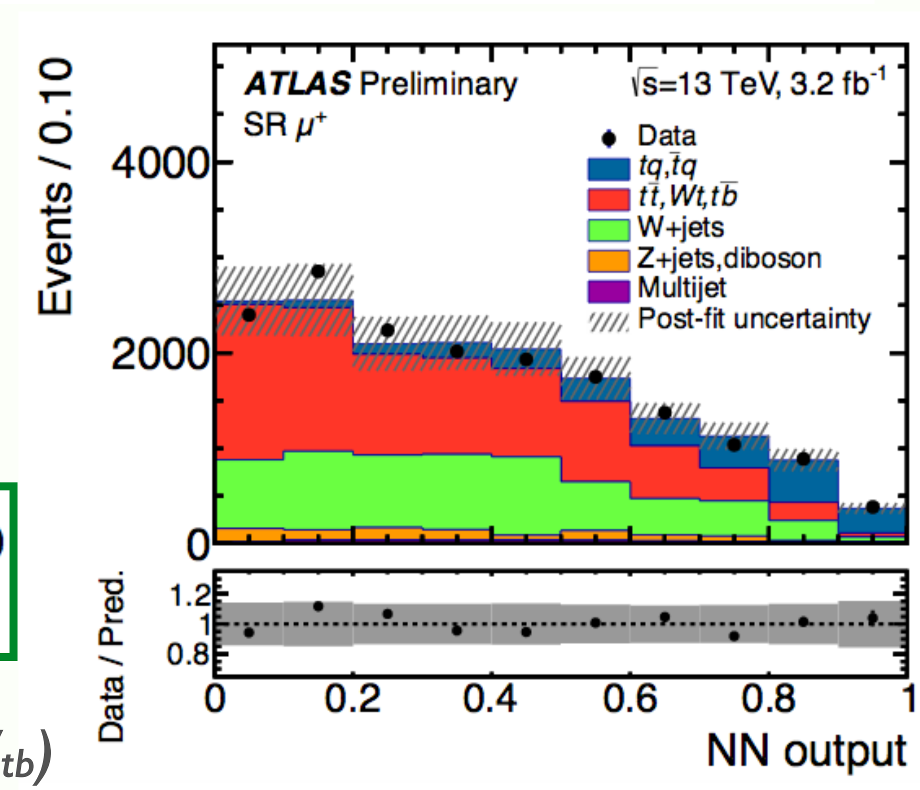
$$\sigma(\bar{t}q) = 96 \pm 5\,(\text{stat.}) \pm 23\,(\text{syst.}) \pm 5\,(\text{lumi.})\ \text{pb}$$

$$\sigma(tq+\bar{t}q) = 229 \pm 48\ \text{pb}$$

**21%**

$$|f_{\rm LV} \cdot V_{tb}| = 1.03 \pm 0.02\,(\text{stat.}) \pm 0.11\,(\text{syst.}) \pm 0.02\,(\text{theor.}) \pm 0.03\,(\text{lumi.})$$
$$= 1.03 \pm 0.11.$$

**11%**



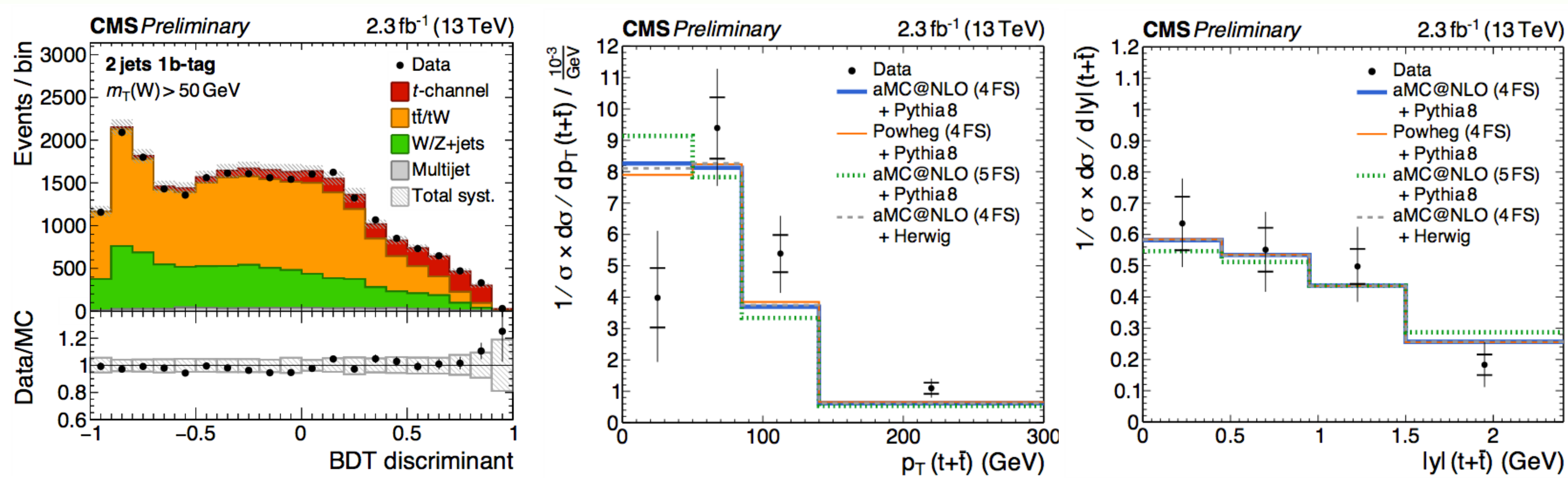

[1] ATLAS-CONF-2015-079

***$|V_{tb}| > 0.75$ @95% CL ($f_{LV} = 1$, $V_L = V_{tb}$)***

# t channel at CMS

**13 TeV**

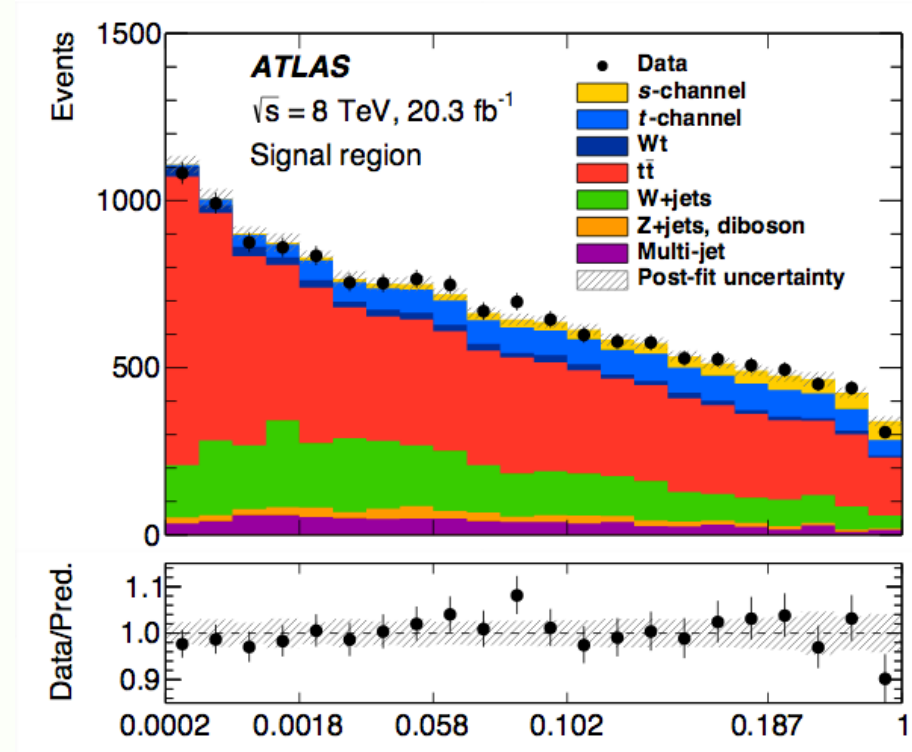
- **First t channel differential cross section measurement at 13 TeV** [1]
- Analysis is done in **muon+jets** events
- Signal is extracted with binned maximum likelihood fit to **BDT** discriminator ($m_T(W) > 50$ GeV) and to $\mathbf{m_T(W)}$ in the signal and background control regions
- Unfolded cross section is measured as a function of the **top quark $p_T$** and **rapidity**



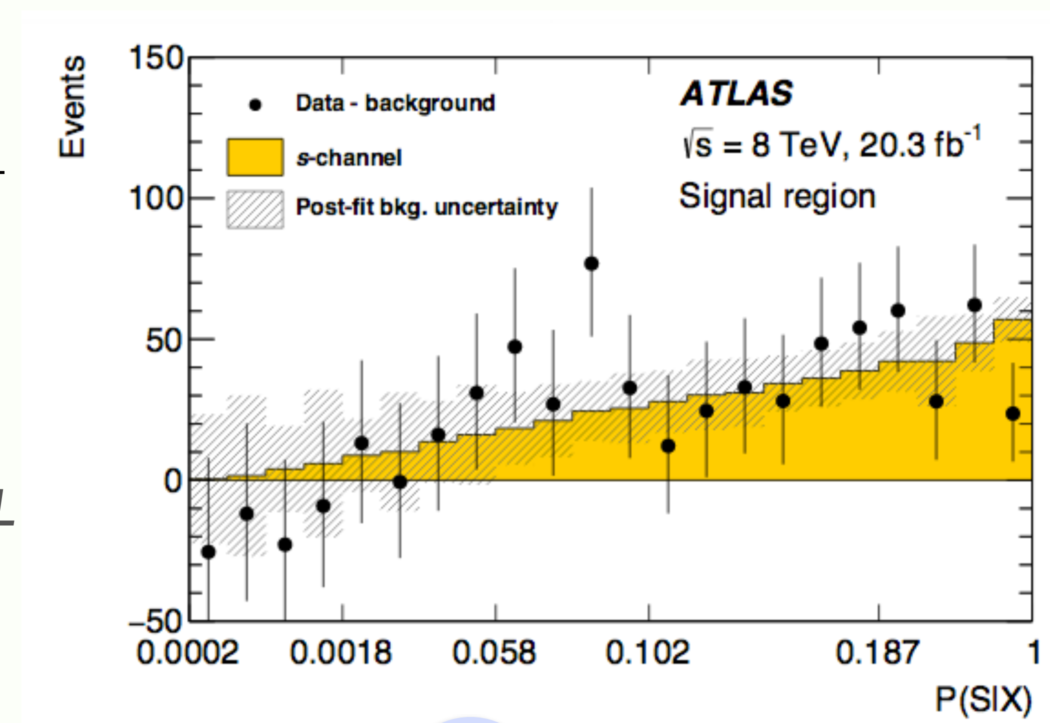

[1] CMS-PAS-TOP-16-004

# s channel at ATLAS

- **Evidence** for **s channel** at 8 TeV [1]
- Previous ATLAS result based on the same dataset using **BDT** gave **1.3σ** observed significance [2]
- Analysis in **lepton+jets** channels
- **Matrix element (ME) method** to define discriminant (contributes up to ≈50% improvement with respect to BDT analysis)
- Another ≈50% of improvement comes from the latest calibrations, optimized event selection and simulated samples
- Signal extracted from simultaneous binned maximum-likelihood fit to ME discriminant and lepton charge in signal and control regions




*P(S|X) - ME discriminant*




***Observed significance is 3.2σ (3.9σ expected)***

*$|V_{tb}| > 0.5$ @95% CL*
*($f_{LV} = 1$, $V_L = V_{tb}$)*

$$\sigma_s = 4.8 \pm 0.8(\text{stat.})^{+1.6}_{-1.3}(\text{syst.})\ \text{pb}$$

**35%**


[1] ATLAS Collaboration, Phys. Lett. B (2016) 228-246
[2] ATLAS Collaboration, Phys. Lett. B740 (2015) 118

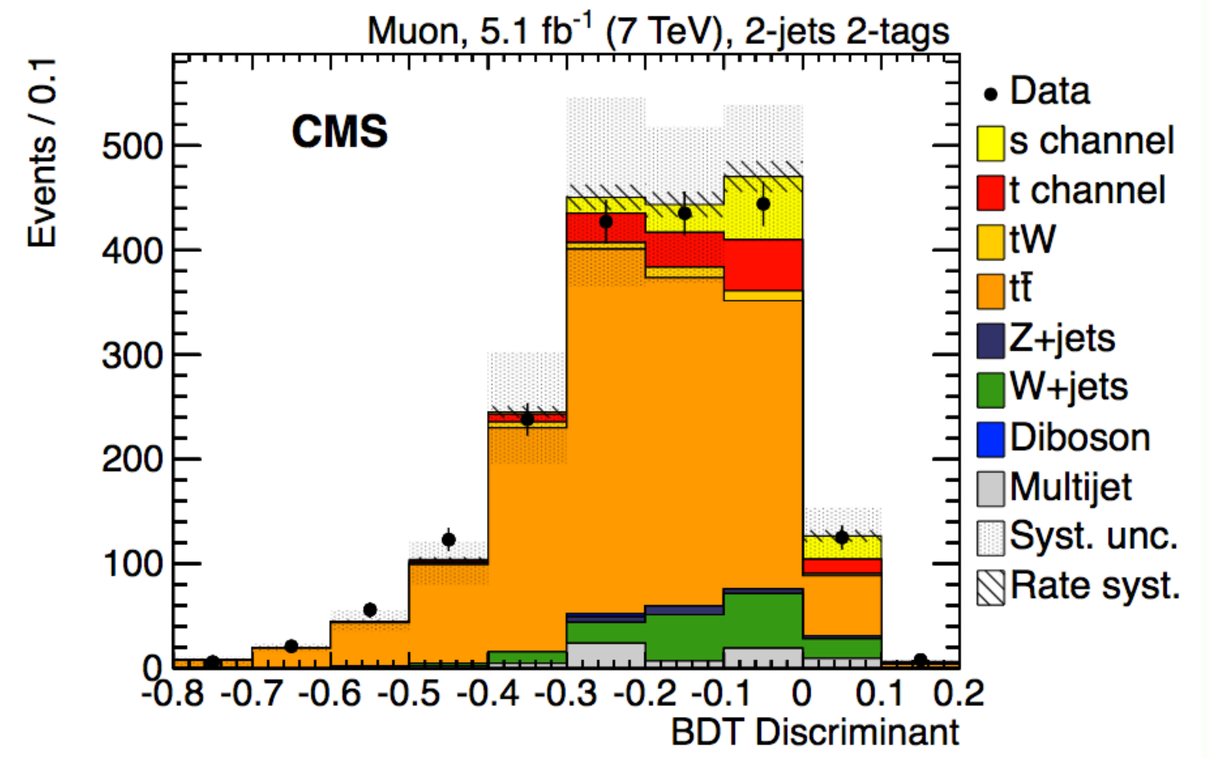
# s channel at CMS

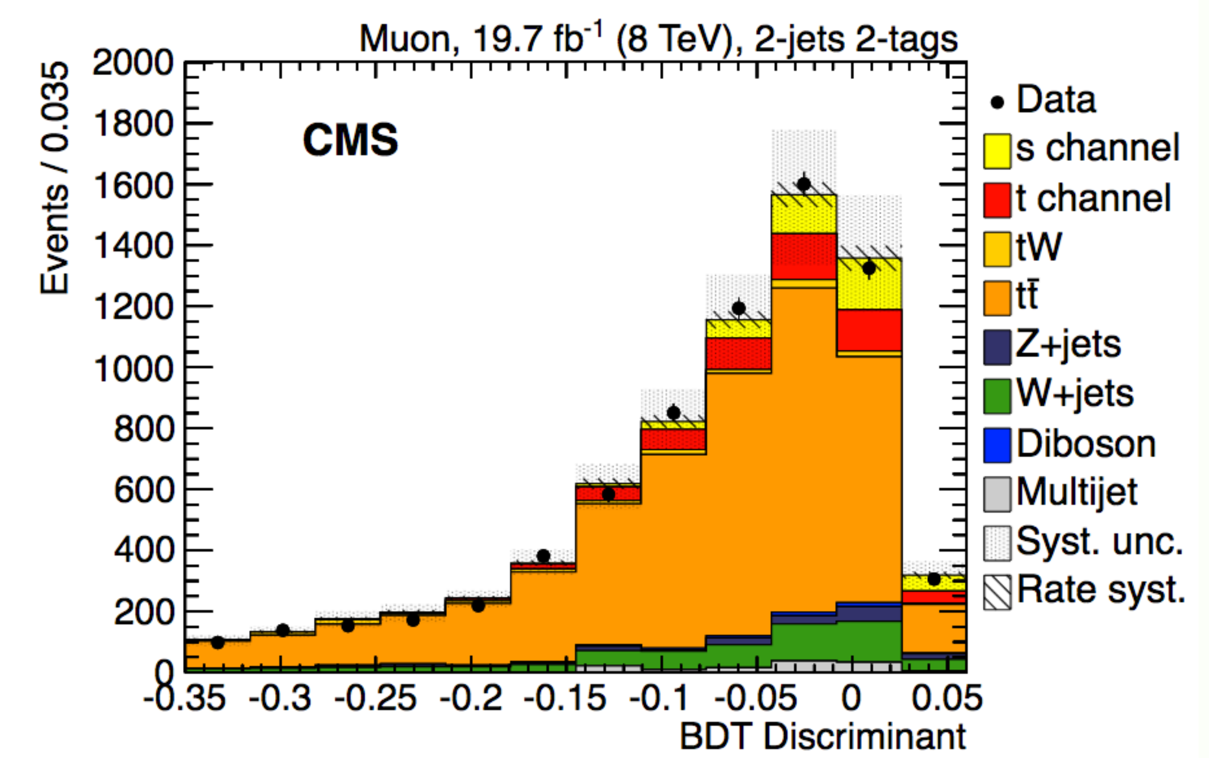
- **Combined fit** of **7 TeV** (**muon** channel) and **8 TeV** (**electron and muon** channels) data results [1]
- Categorization of events by the number of b tagged jets
- Signal extracted through a binned maximum-likelihood fit to a signal vs background BDT discriminant

$$\sigma_s = 7.1 \pm 8.1\,(\text{stat}+\text{syst})\,\text{pb}, \quad \text{muon channel, 7 TeV;}$$
$$\sigma_s = 11.7 \pm 7.5\,(\text{stat}+\text{syst})\,\text{pb}, \quad \text{muon channel, 8 TeV;}$$
$$\sigma_s = 16.8 \pm 9.1\,(\text{stat}+\text{syst})\,\text{pb}, \quad \text{electron channel, 8 TeV;}$$
$$\sigma_s = 13.4 \pm 7.3\,(\text{stat}+\text{syst})\,\text{pb}, \quad \text{combined, 8 TeV.}$$

**54%**

*Observed significance is*
*2.5σ (1.1σ expected)*

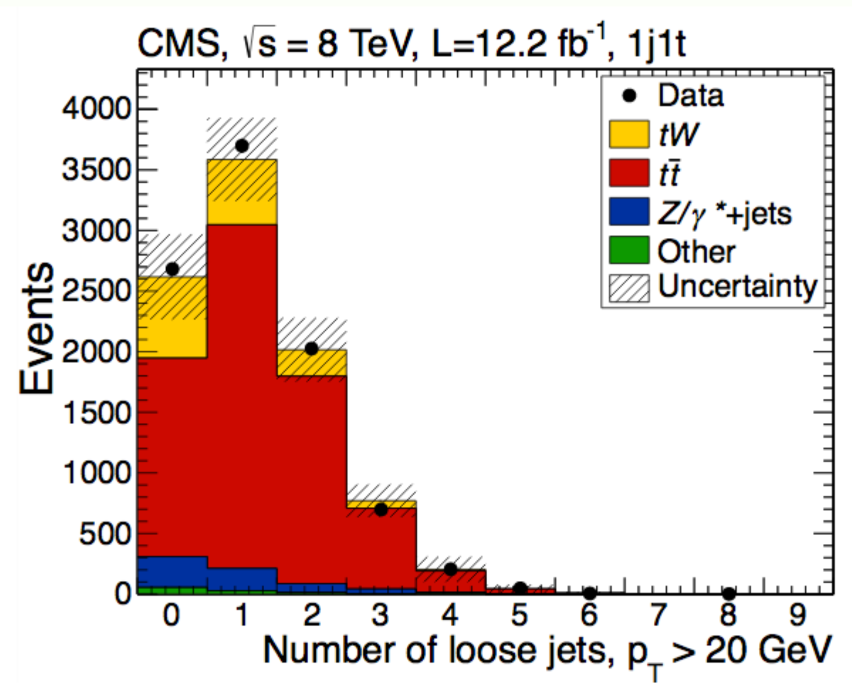


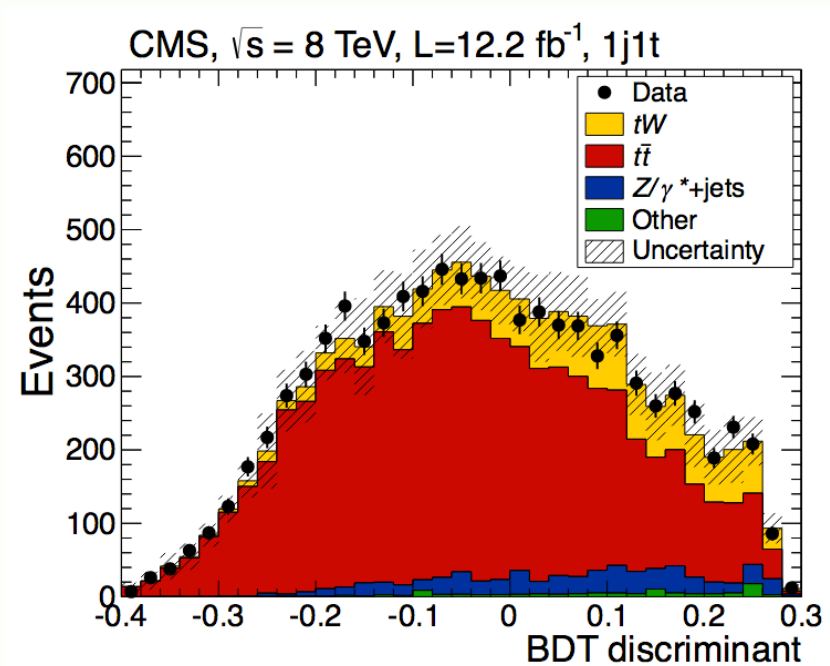



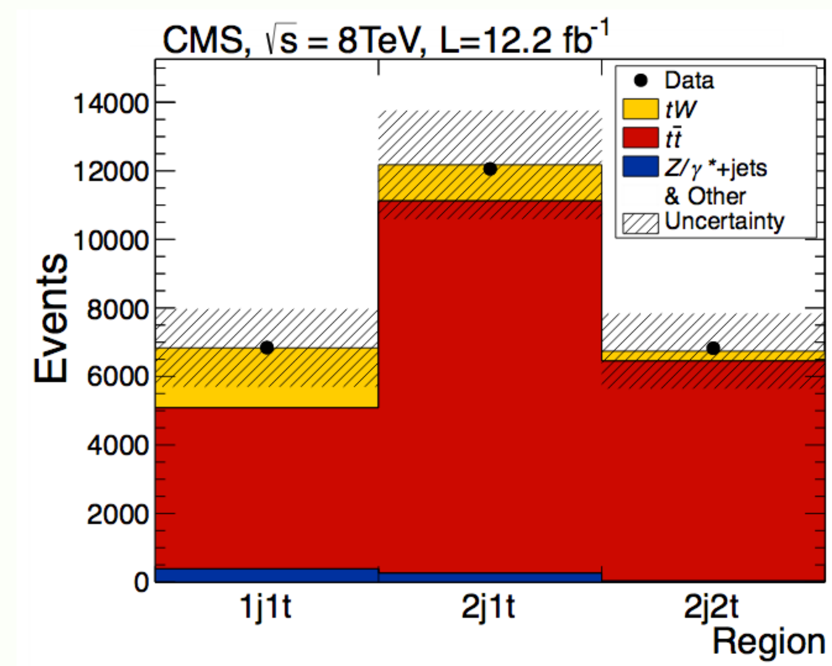

[1] CMS-TOP-13-009 (Submitted to J. High Energy Phys.)

# Wt channel at CMS

- **First observation** of **Wt production channel** at 8 TeV [1]
- Analysis of events with **two oppositely charged leptons**
- Signal extracted from a simultaneous binned likelihood fit to BDT discriminant over the signal and background control regions




$$|f_{\mathrm{LV}} V_{tb}| = 1.03 \pm +0.12(exp.) + 0.04(th.)$$ **13%**

$$\sigma(\mathrm{Wt}) = 23.4 \pm 5.4\ \mathrm{pb}$$ **23%**

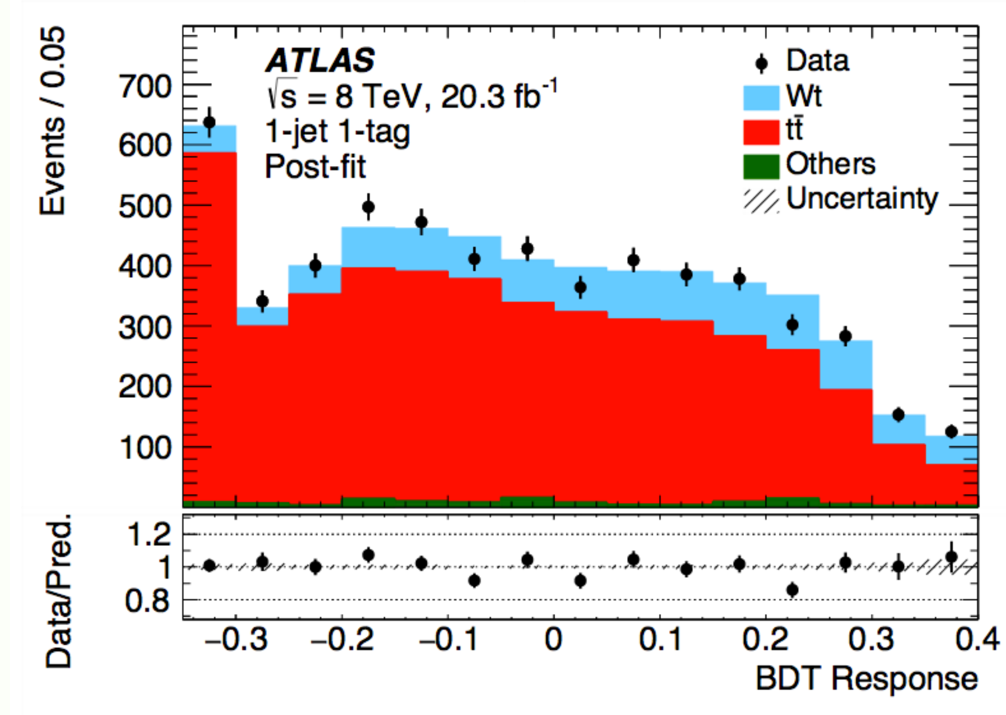
***$|V_{tb}| > 0.78$ @95% CL ($f_{LV} = 1$, $V_L = V_{tb}$)***

***Observed significance is 6.1σ (5.4σ expected)***

[1] CMS Collaboration, Phys. Rev. Lett. 112 (2014) 231802

# Wt channel at ATLAS

- **Observation** of **Wt production channel** at 8 TeV [1]
- **Two oppositely charged leptons** are considered
- Signal extracted via profile likelihood fit over the signal and background control regions
- **First fiducial cross section** (Wt+ttbar) measured for two selected leptons with *$p_T$ > 25 GeV, |η| < 2.5, one b jet with $p_T$ > 20 GeV, |η| < 2.5 and $E_T^{miss}$ > 20 GeV*



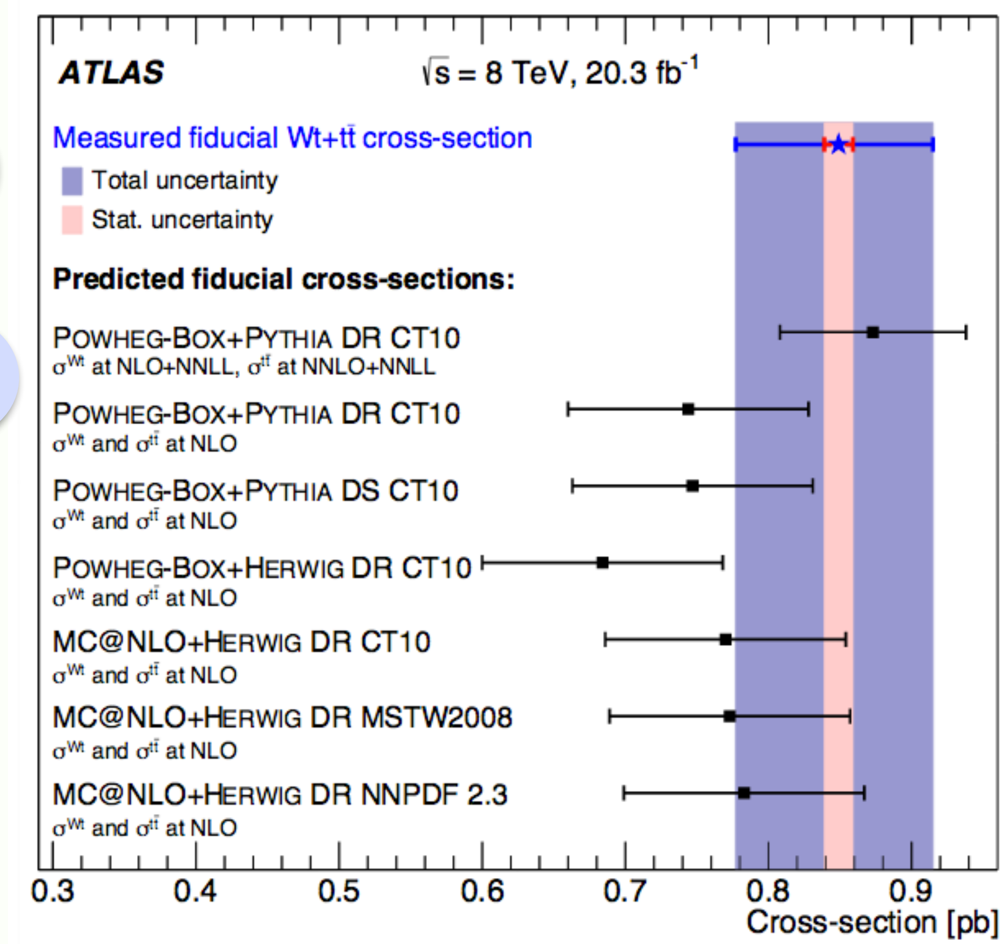

$$\sigma(\mathrm{Wt}) = 23.0 \pm 1.3(\mathrm{stat.})^{+3.2}_{-3.5}(\mathrm{syst.}) \pm 1.1(\mathrm{lumi.})\ \mathrm{pb}$$ **17%**

$$\sigma_{\mathrm{fiducial}} = 0.85 \pm 0.01(\mathrm{stat.})^{+0.06}_{-0.07}(\mathrm{syst.}) \pm 0.03(\mathrm{lumi.})\ \mathrm{pb}$$ **9%**

$$|f_{\mathrm{LV}} V_{tb}| = 1.01 \pm 0.10$$ **10%**

*Observed significance is* ***7.7σ (6.9σ*** *expected)*

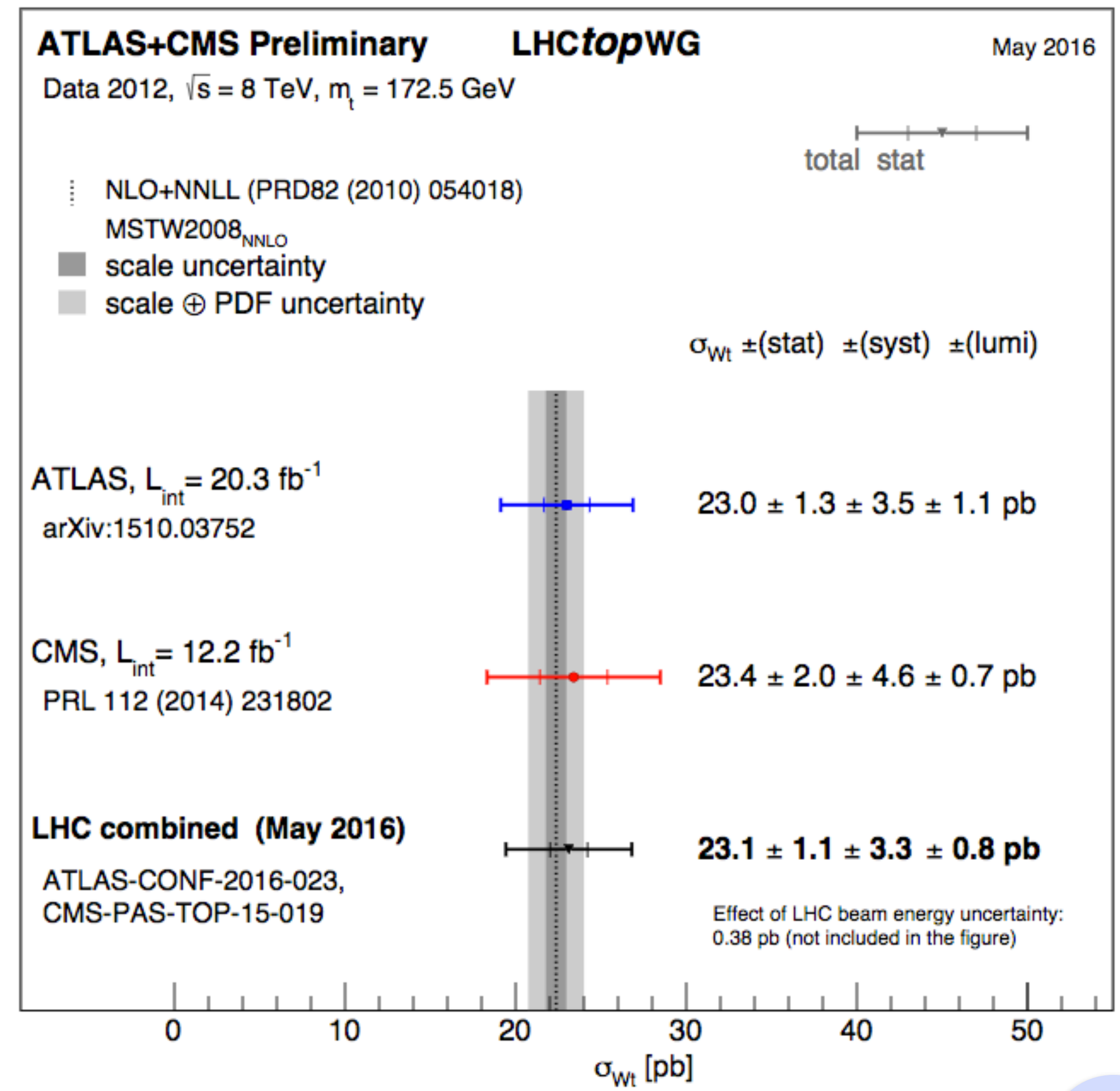
***$|V_{tb}|$ > 0.80 @95% CL ($f_{LV}$ = 1, $V_L$ = $V_{tb}$)***




*[1] ATLAS Collaboration, JHEP 01 (2016) 064*

# Wt combination at LHC

- **New LHC combination for Wt production cross sections at 8 TeV** [1]
- Results are combined using the best linear unbiased estimator (**BLUE**) method
- Combination results in an improved precision of 16% (ATLAS - 17%, CMS - 23%)
- The dominant uncertainties are due to **theory modeling** (ISR/FSR, Scale, Parton shower, etc.)




| Source | Uncertainty (%) | Uncertainty (pb) |
|---|---|---|
| Data statistics | 4.7 | 1.1 |
| Simulation statistics | 0.8 | 0.2 |
| Luminosity | 3.6 | 0.8 |
| Theory modelling | 11.8 | 2.7 |
| Background normalization | 2.2 | 0.5 |
| Jets | 6.2 | 1.4 |
| Detector modelling | 4.9 | 1.1 |
| Total systematics (excl. lumi) | 14.4 | 3.3 |
| Total systematics (incl. lumi) | 14.8 | 3.4 |
| Total uncertainty | 15.6 | 3.6 |

16%

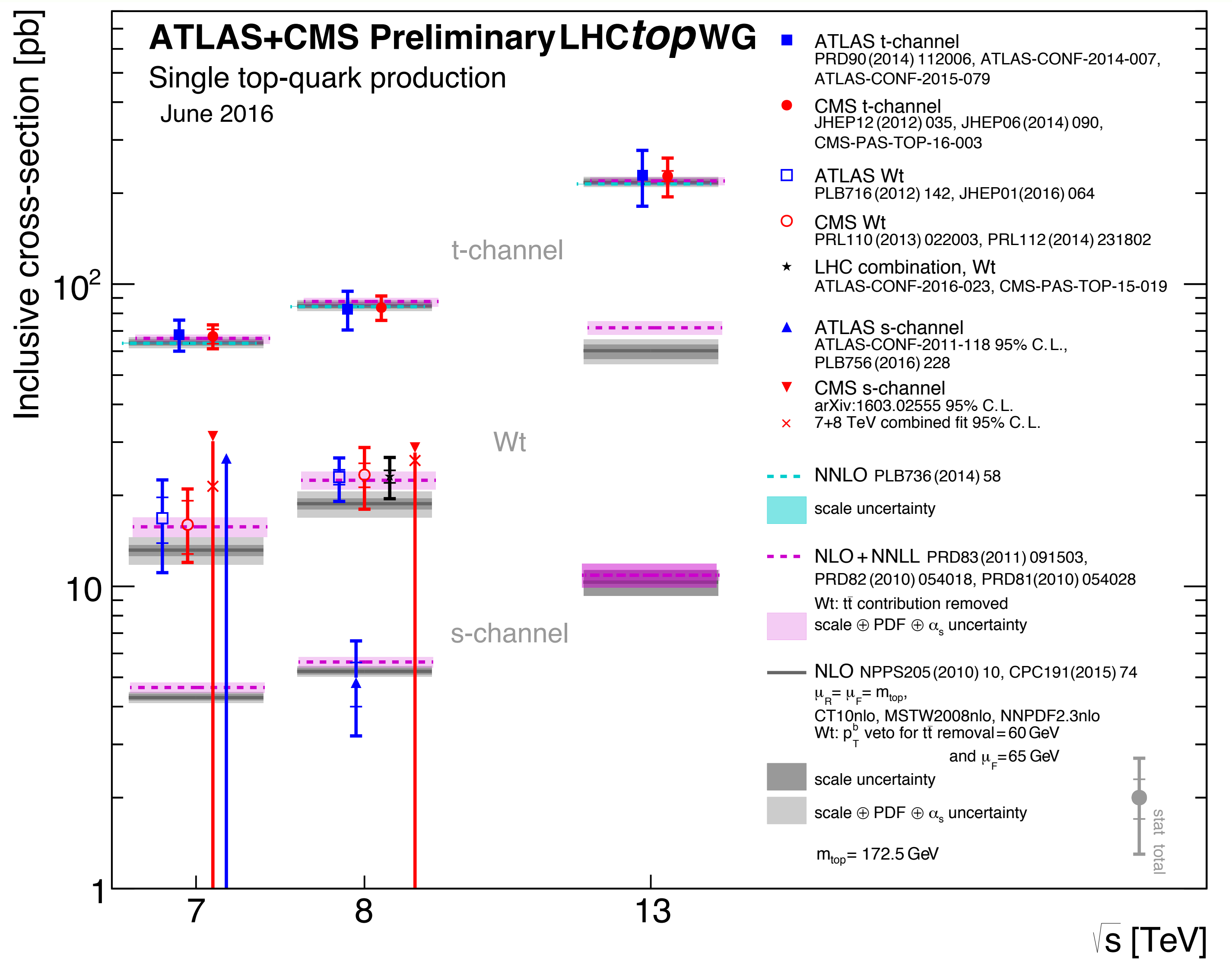
$$\sigma_{\mathrm{Wt}} = 23.1 \pm 1.1\ (\mathrm{stat.}) \pm 3.3\ (\mathrm{syst.}) \pm 0.8\ (\mathrm{lumi.})\ \mathrm{pb} = 23.1 \pm 3.6\ \mathrm{pb}$$

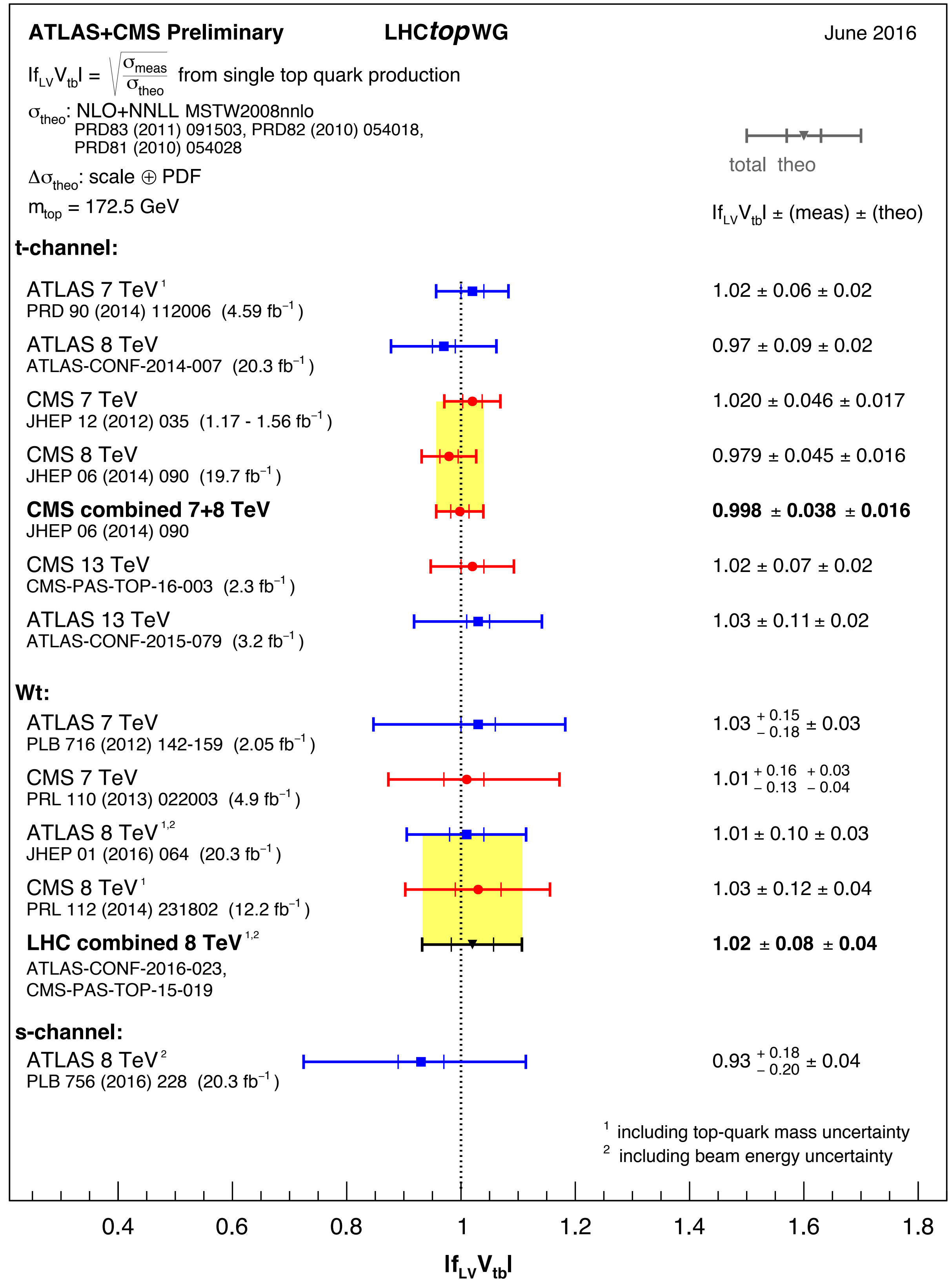
$$|f_{\mathrm{LV}} V_{\mathrm{tb}}| = 1.02 \pm 0.09$$

9%

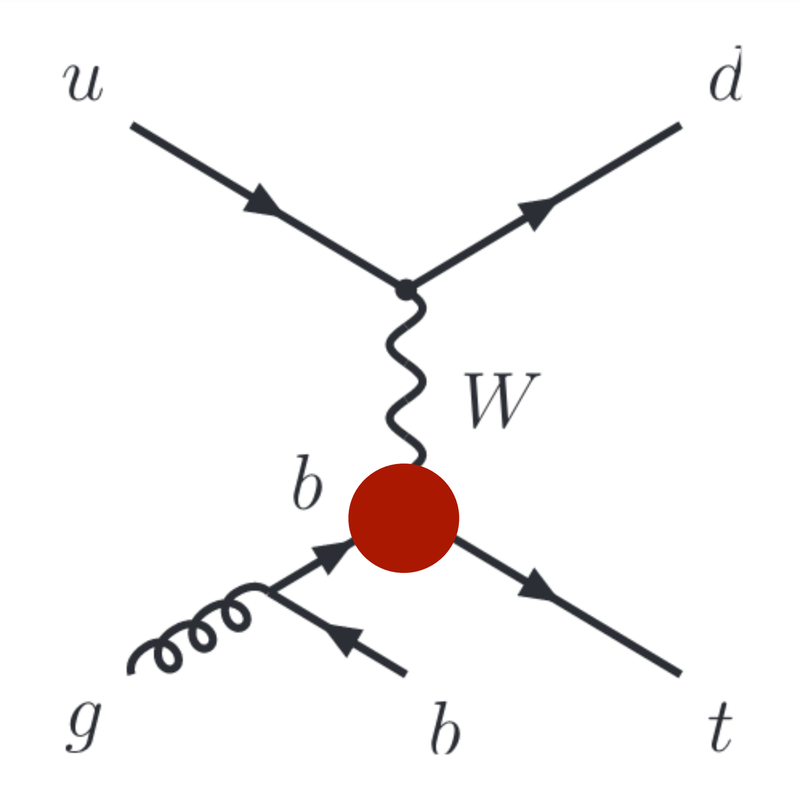
*[1] CMS-PAS-TOP-15-019, ATLAS-CONF-2016-023*

# Summary on single top production at LHC



# Anomalous Wtb couplings



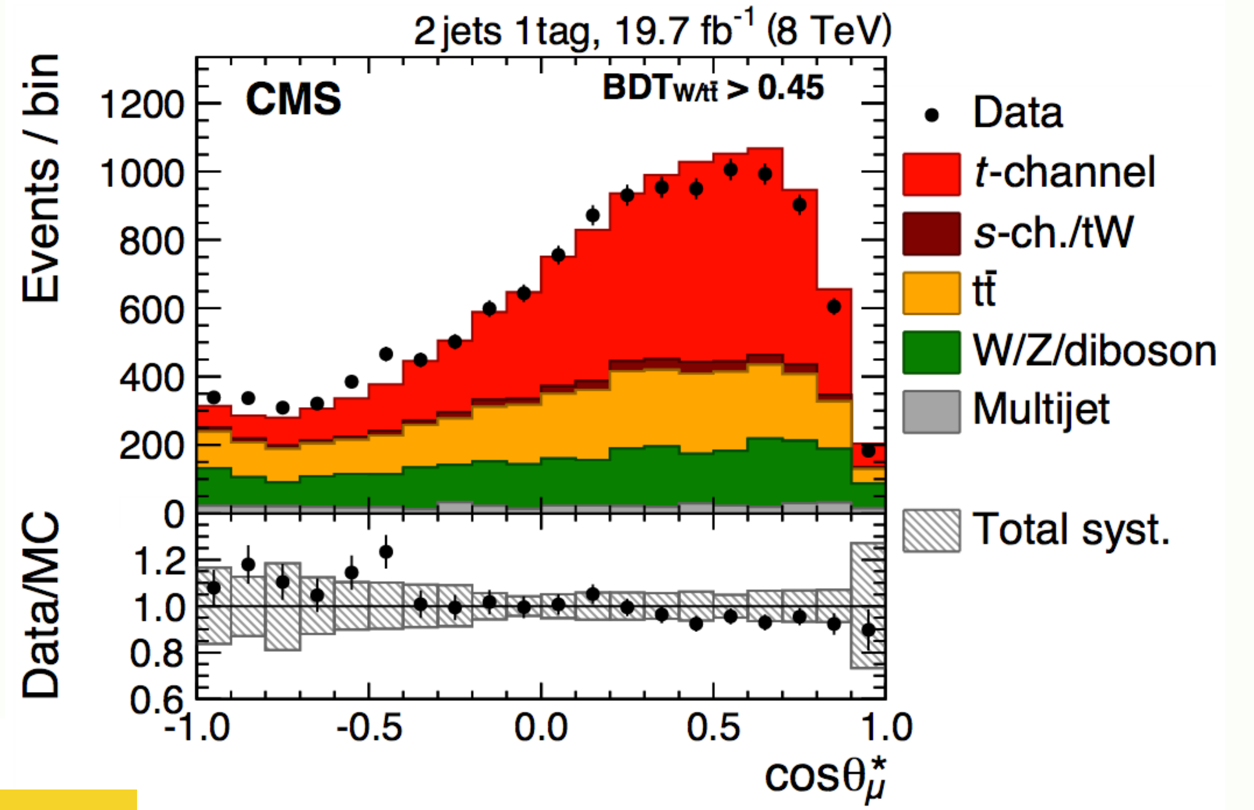

- Single top production cross section is proportional to the size of Wtb interaction
- Provides the direct measurement of $|V_{tb}|$ and allows one to **probe anomalous Wtb couplings**: vector ($V_R$) and tensor ($g_L$, $g_R$)
- Top quarks are **polarized** in the single top production ($P \approx 0.9$)
- Look for differences in kinematical and angular distributions in the presence of anomalous couplings

$$\mathcal{L}_{\mathrm{tWb}}^{\mathrm{anom.}} = -\frac{g}{\sqrt{2}}\bar{\mathrm{b}}\gamma^{\mu}(V_{\mathrm{L}}P_{\mathrm{L}} + V_{\mathrm{R}}P_{\mathrm{R}})\mathrm{t}W^{-}{}_{\mu} - \frac{g}{\sqrt{2}}\bar{\mathrm{b}}\frac{i\sigma^{\mu\nu}q_{\nu}}{m_{\mathrm{W}}}(g_{\mathrm{L}}P_{\mathrm{L}} + g_{\mathrm{R}}P_{\mathrm{R}})\mathrm{t}W^{-}{}_{\mu} + \mathrm{h.c.}$$

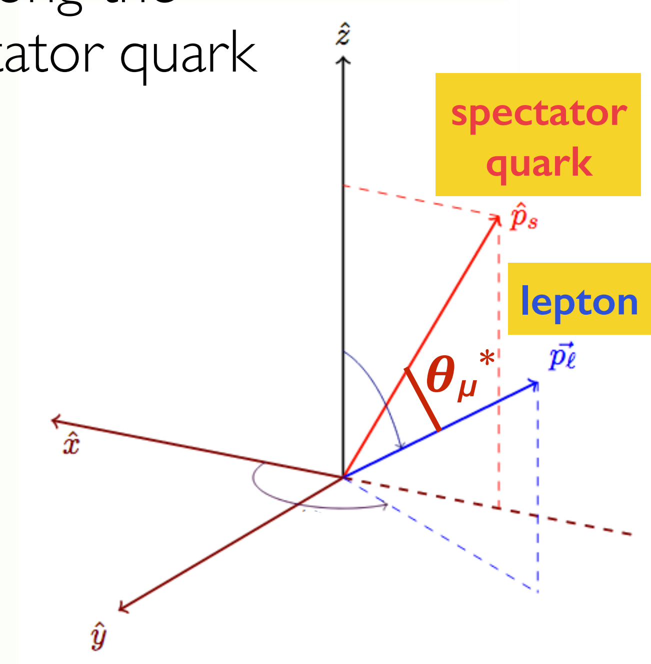
In SM: $\mathbf{V_L = V_{tb} \approx 1}$ with $\mathbf{V_R}$, $\mathbf{g_L}$ and $\mathbf{g_R}$ **vanishing** at LO

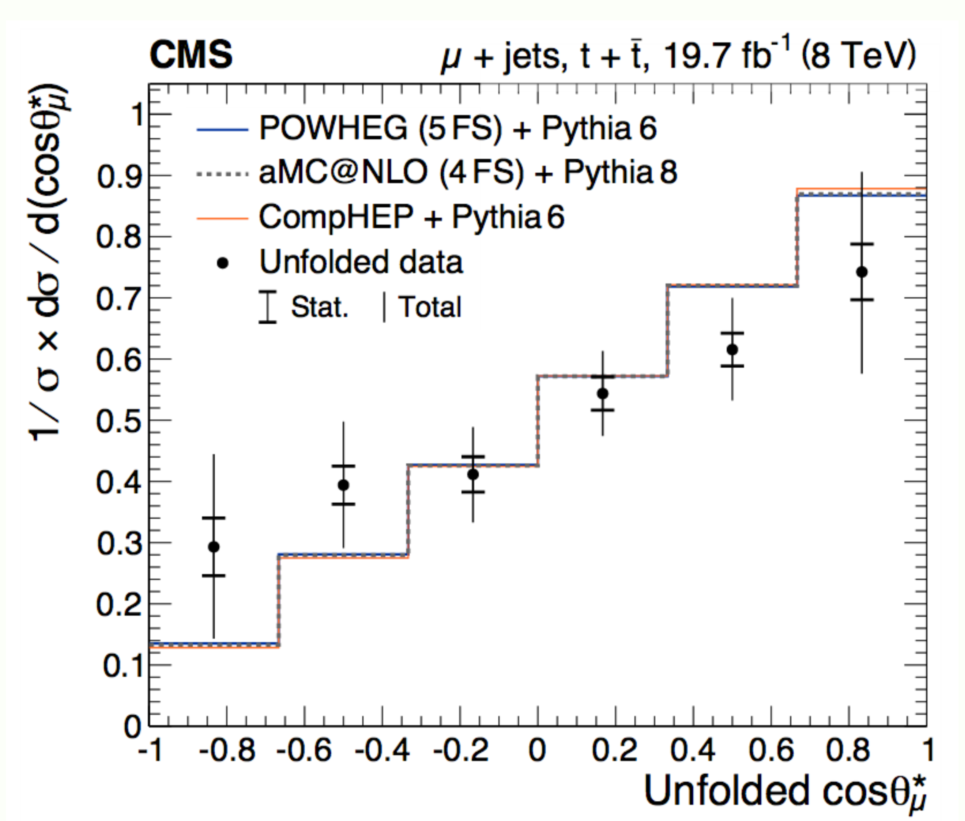
# Top quark polarization at CMS

- **First measurement of top quark spin asymmetry** (sensitive to top quark polarization) in high purity **t channel** [1]
- **Probe the coupling structure** via spin asymmetry
- Analysis in **muon+jets** events
- Spin projection is measured along the direction of the recoiling spectator quark momentum




$$A_X \equiv \frac{N(\uparrow) - N(\downarrow)}{N(\uparrow) + N(\downarrow)}$$



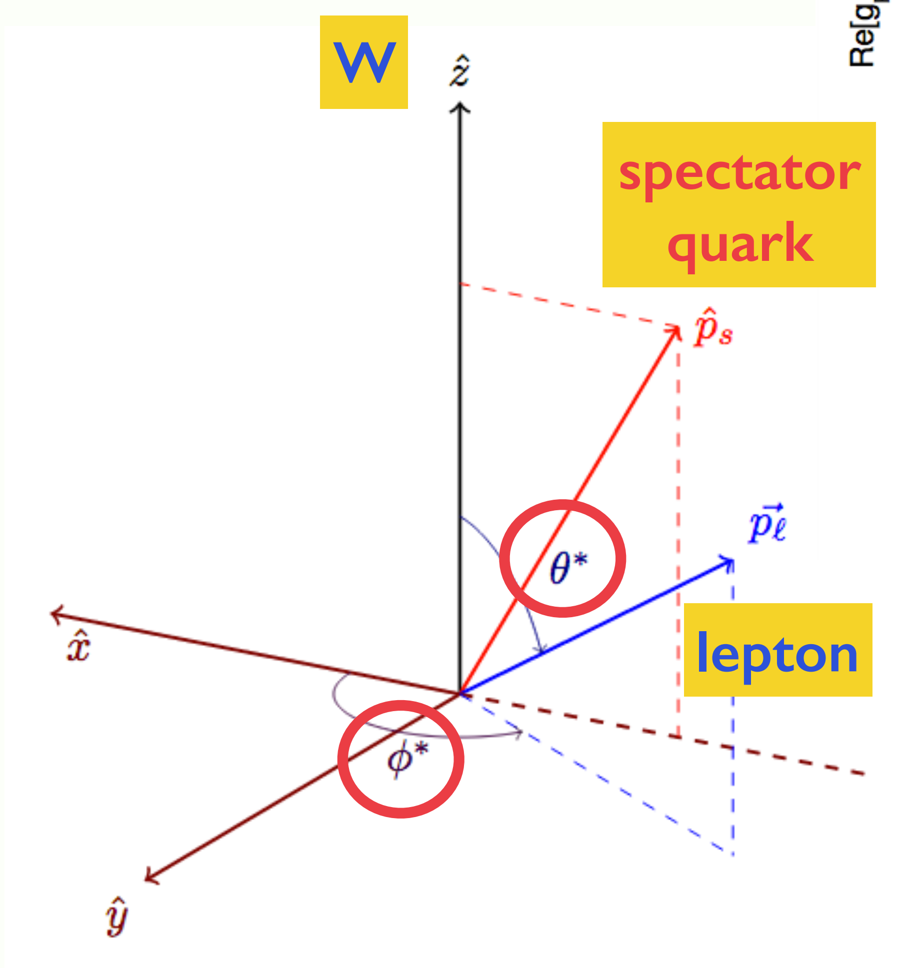

$$A_\mu(\mathrm{t}+\bar{\mathrm{t}}) = 0.26 \pm 0.03\,(\mathrm{stat}) \pm 0.10\,(\mathrm{syst}) = 0.26 \pm 0.11$$

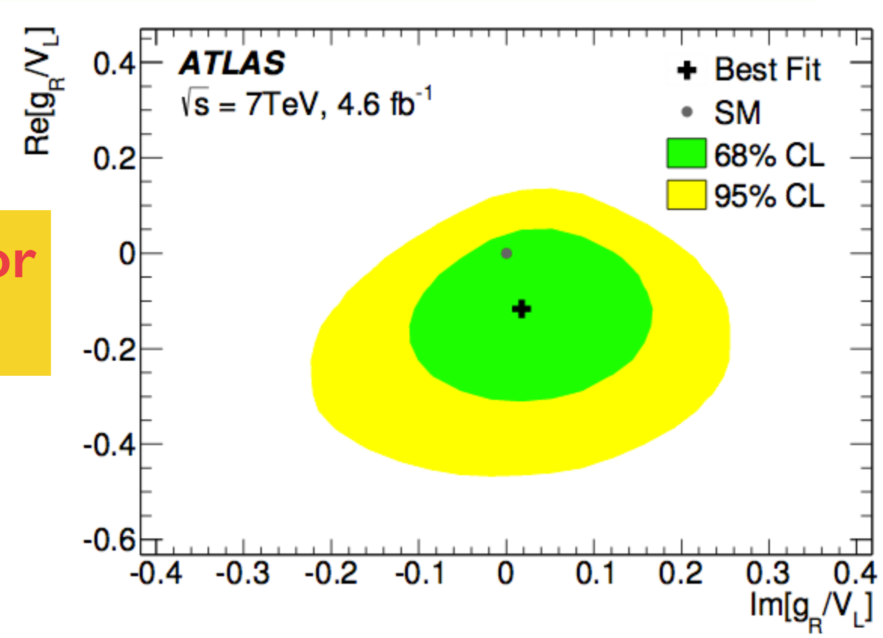
***Results are consistent with SM ($A_\mu^{SM}$ = 0.44), p-value = 4.6%***

[1] CMS Collaboration, JHEP 04 (2016) 073

# Double differential asymmetry at ATLAS

- Perform a **normalized double differential angular measurement** in ***θ**** and **ϕ*** in single top events
- The triple differential decay rate of the top quark is expressed in the form of parametrized spherical harmonics

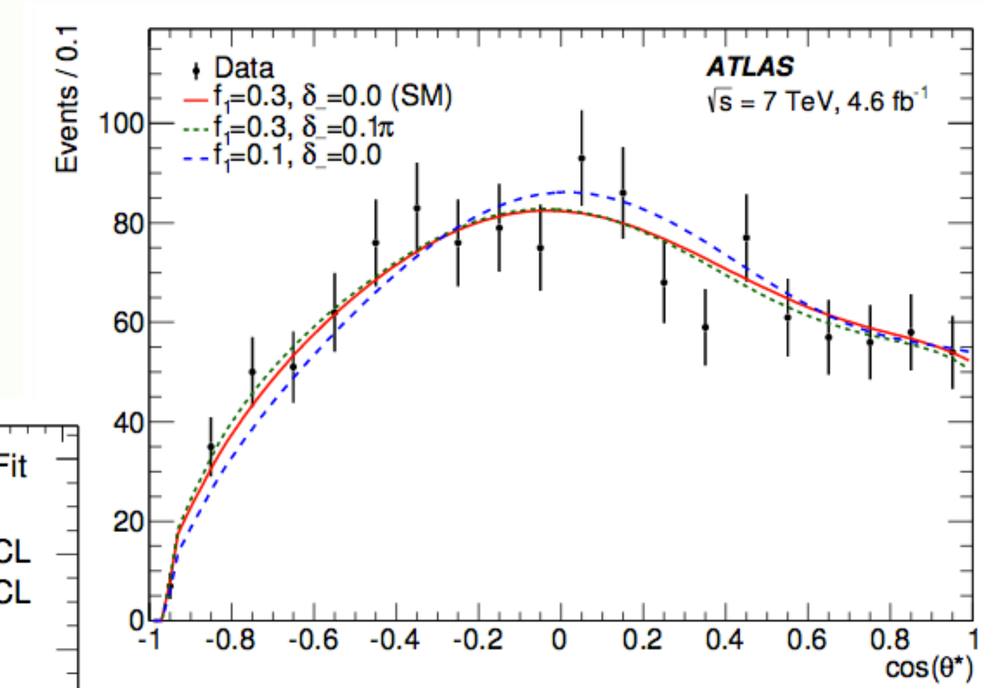


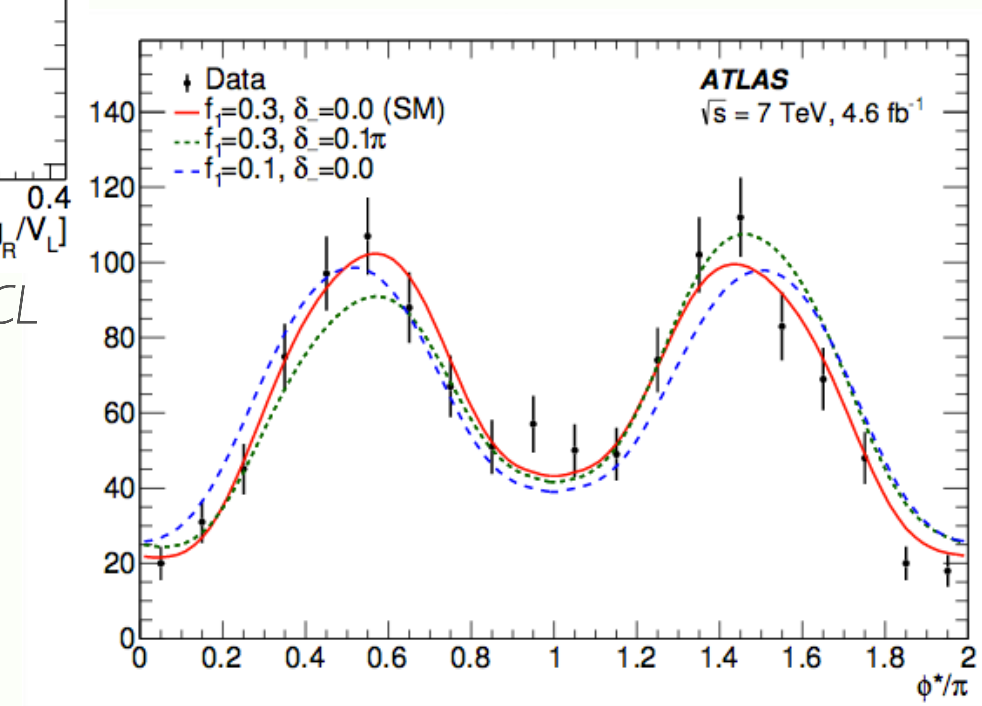




*Two-dimensional limits at 95% CL*
*correlation = 0.11*

$$\mathrm{Re}\left[\frac{g_R}{V_L}\right] \in [-0.36, 0.10]$$

$$\mathrm{Im}\left[\frac{g_R}{V_L}\right] \in [-0.17, 0.23]$$

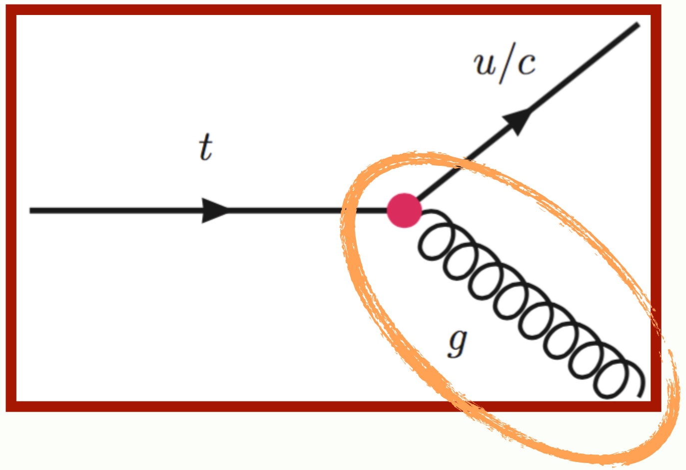


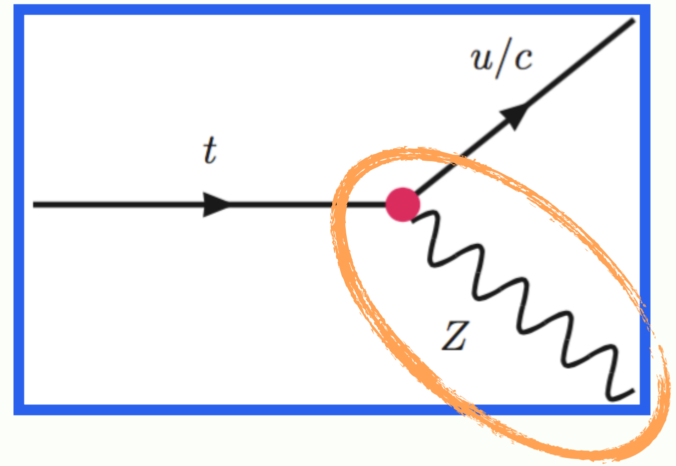




*[1] ATLAS Collaboration, JHEP 04 (2016) 023*

# FCNC with top quarks

**Top + gluon**



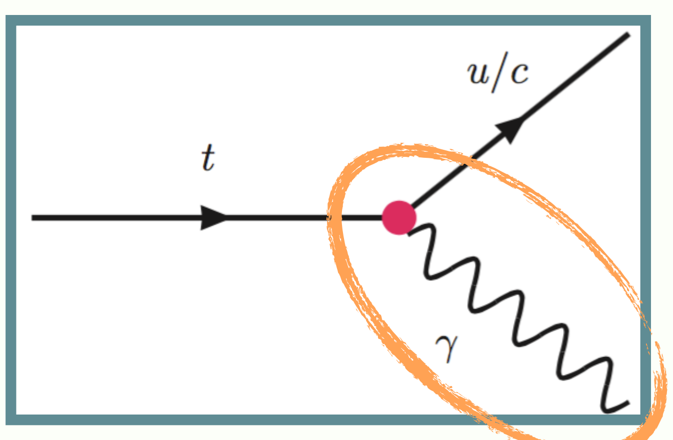



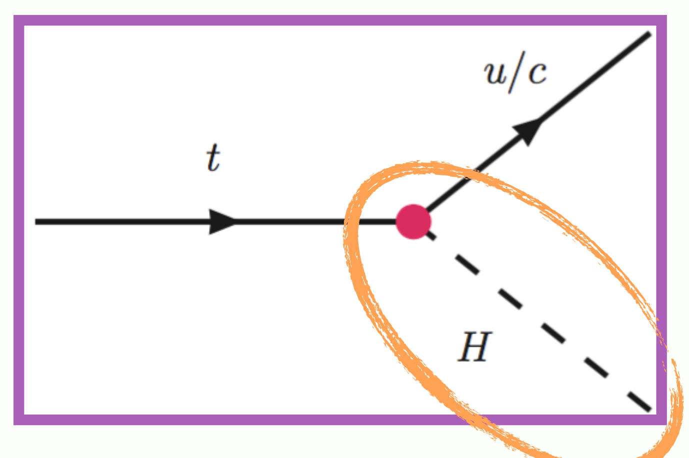

**Top + Z**

- **Flavour-changing neutral current** (**FCNC**) **is forbidden** in SM at tree level by the Glashow-Iliopoulos-Maiani (GIM) mechanism
- Only possible at higher orders via loops induced processes → **highly suppressed**
- **FCNC decays could be enhanced in various BSM**

$$
\begin{aligned}
\mathcal{L} \;=\; \sum_{q=u,c} \Big[ & \sqrt{2}\, g_s \frac{\kappa_{gqt}}{\Lambda} \bar{t}\, \sigma^{\mu\nu}\, T_a (f^L_{Gq} P_L + f^R_{Gq} P_R)\, q\, G^a_{\mu\nu} \\
+ & \frac{g}{\sqrt{2} c_W} \frac{\kappa_{zqt}}{\Lambda} \bar{t} \sigma^{\mu\nu} (f^L_{Zq} P_L + f^R_{Zq} P_R)\, q\, Z_{\mu\nu} \\
- & e \frac{\kappa_{\gamma qt}}{\Lambda} \bar{t}\, \sigma^{\mu\nu} (f^L_{\gamma q} P_L + f^R_{\gamma q} P_R)\, q\, A_{\mu\nu} \\
+ & \frac{g}{\sqrt{2}} \bar{t}\, \kappa_{Hqt} (f^L_{Hq} P_L + f^R_{Hq} P_R)\, q\, H \Big] + \text{h.c.}
\end{aligned}
$$

**Top + gamma**

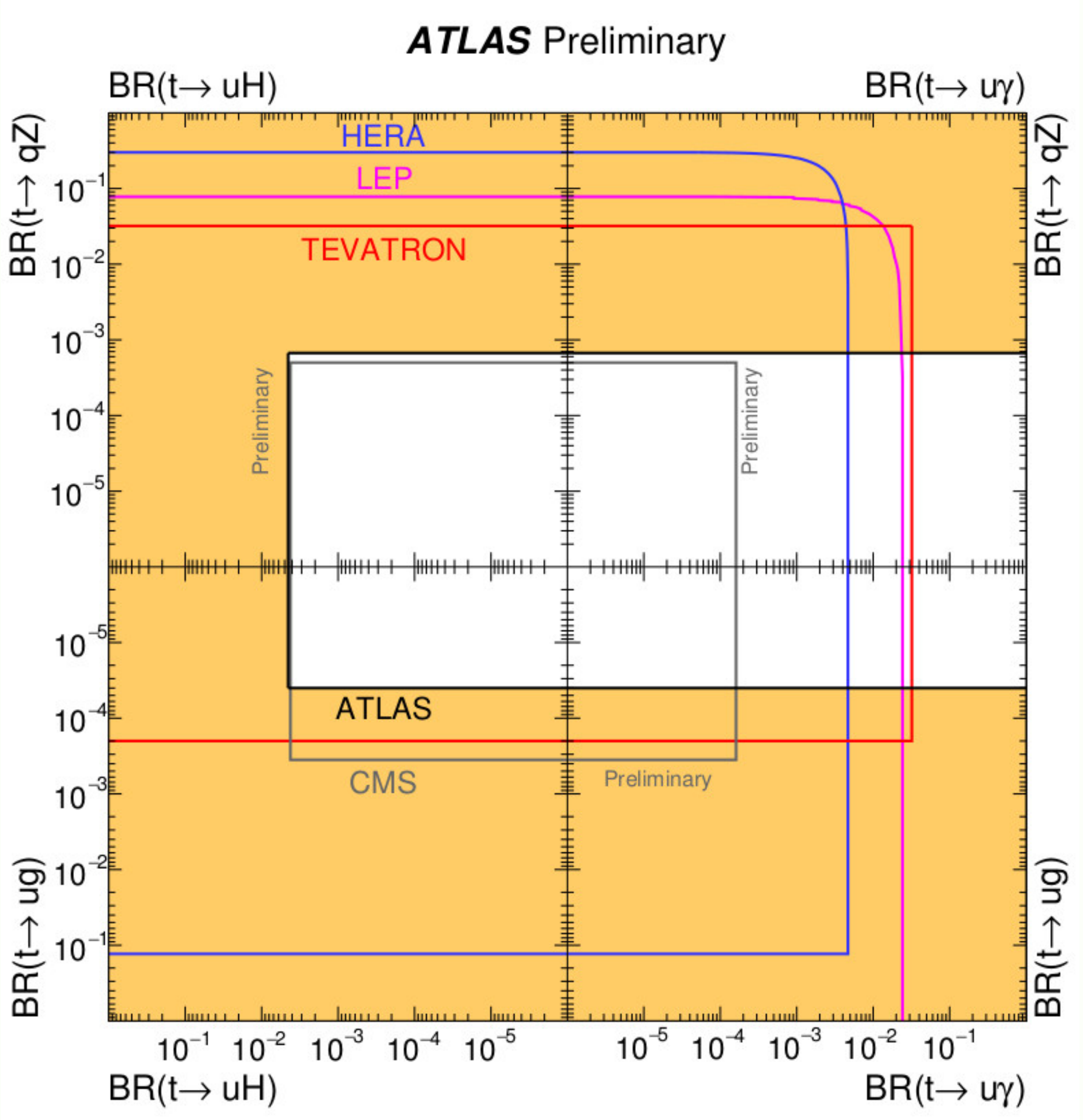


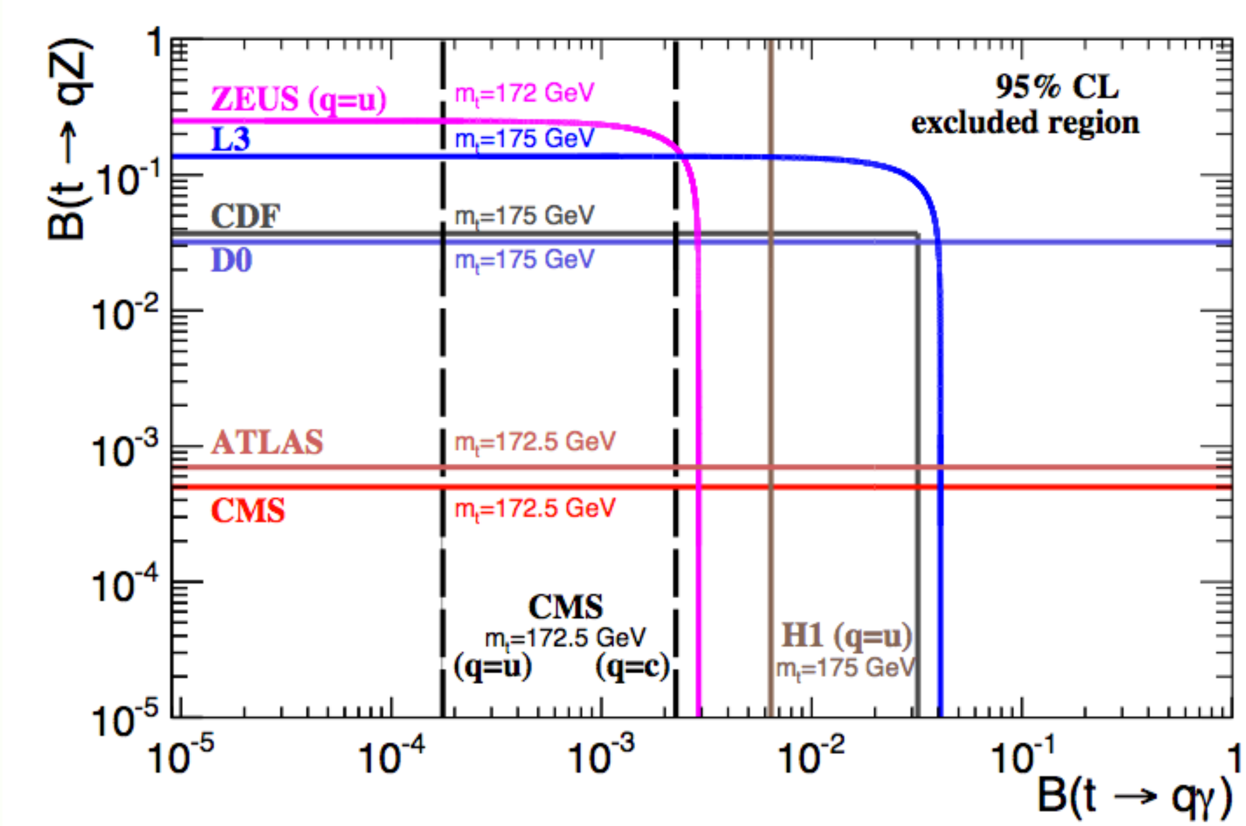

**Top + Higgs**

# Summary on FCNC searches

ATLAS Top Combined Summary Plots




CMS Collaboration, JHEP 04 (2016) 035




**Latest results:**

- *t→gq* (***ATLAS*** *Collaboration, Eur. Phys. J. C (2016) 76:55): the most stringent limit on this decay*
- *t→γq* (***CMS*** *Collaboration, JHEP 04 (2016) 035): the only existing analysis to probe this coupling*

# Conclusion

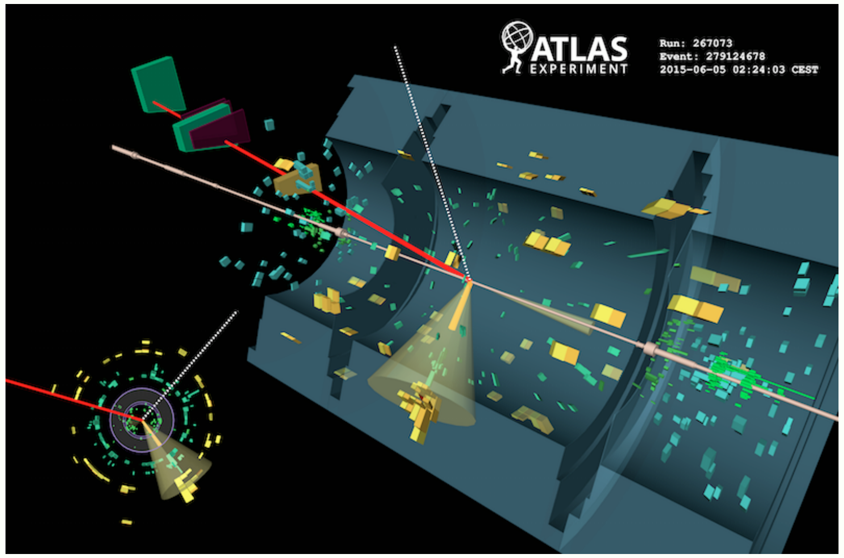
- Single top production provides unique environment to test the SM and to search for new physics by probing anomalous couplings
- Several new single top results are available from **LHC Run 2** experiments: **t channel inclusive and differential cross sections**
- All results show **good agreement with SM** predictions
- Looking forward to more data, more results and only **good** surprises

**Top quark public results**: ATLAS, CMS, CDF, D0

# Backup slides

# Top quark has special powers

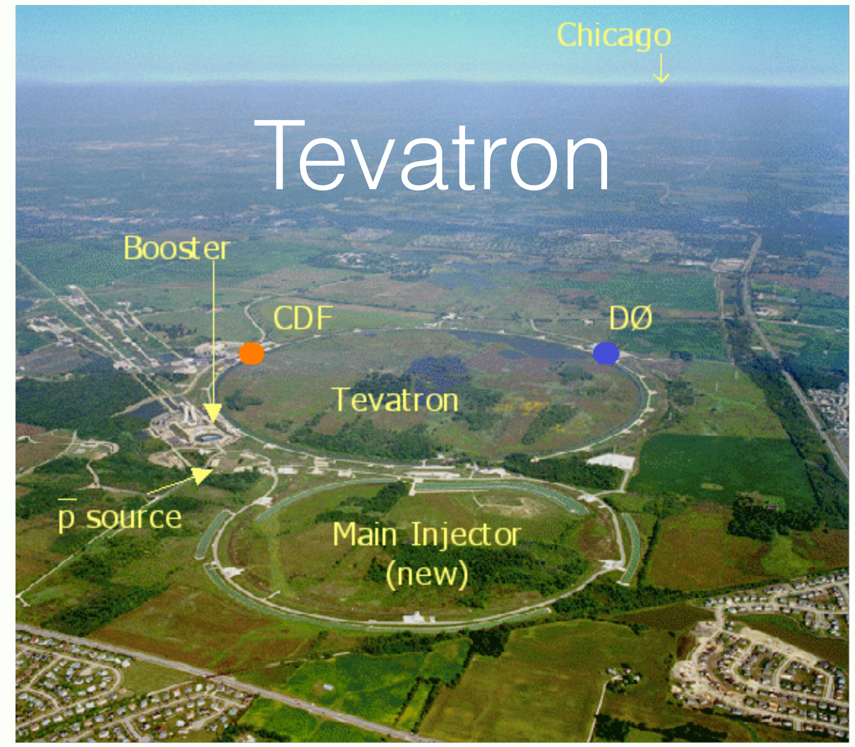
- ☆ Top quark is the **heaviest** elementary particle known
- ☆ An excellent candidate to study **EW symmetry breaking mechanism** and **fermion mass hierarchy** due to its large Yukawa coupling ($y_t \approx 1$)
- ☆ Almost exclusively decays to **W boson** and **b quark**
- ☆ The **short lifetime** ($\tau \approx 4 \times 10^{-25}$ s) of a top quark makes it decay before any hadronization occurs to produce bound states
- ☆ **Distinctive experimental signature**
- ☆ The **new physics** could manifest itself in observed anomalies of the top quark production and decays

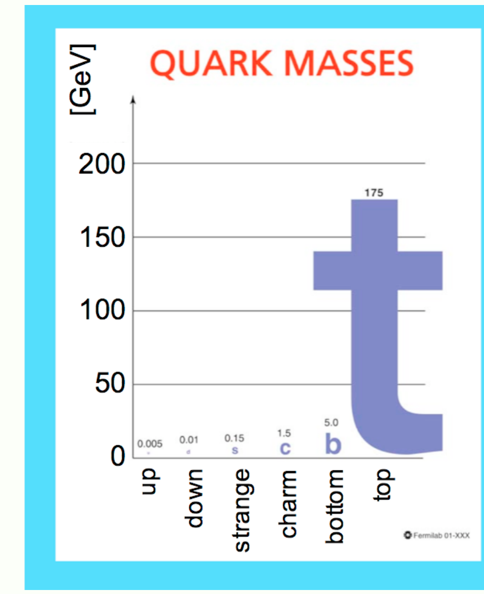




Single top event candidate in 13 TeV data

# Single top quark manufacturing

- **Top quark discovered** at Fermilab [1]
- Observation of ***inclusive single top*** production at Tevatron [2]
- Rediscovered ***t channel*** at LHC [3]
- Observation of ***Wt production*** at LHC [4]
- Observation of ***s channel*** at Tevatron [5]





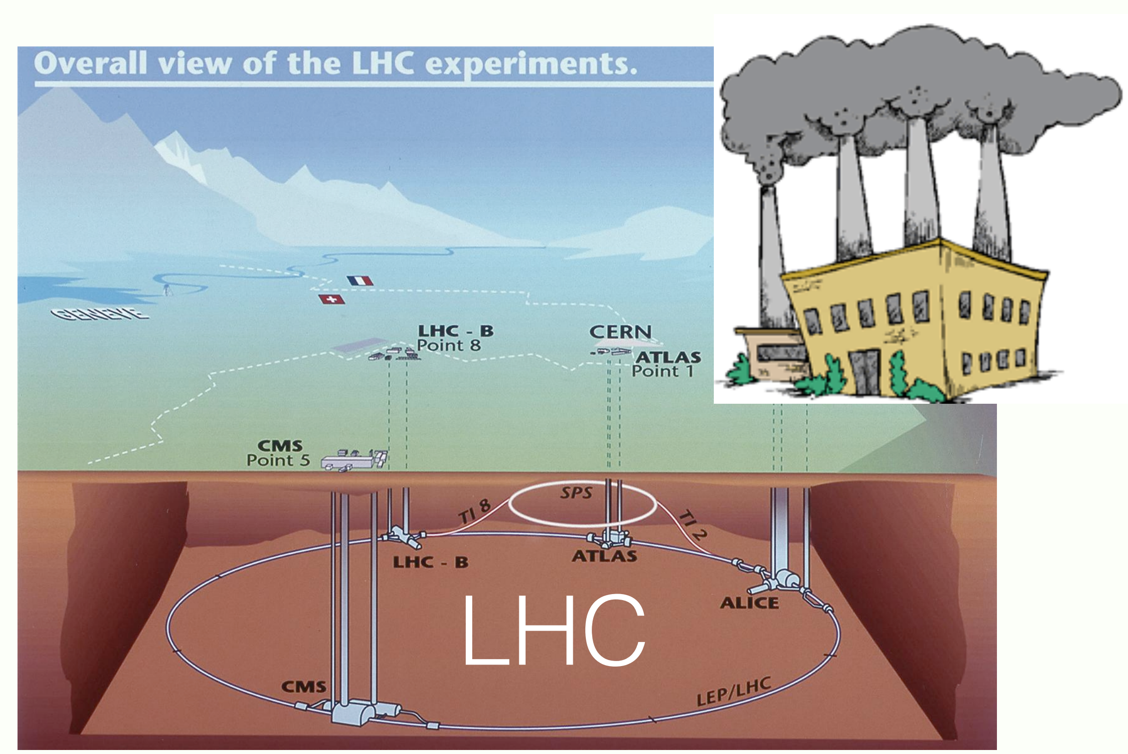
[1] F. Abe et al., CDF Collaboration, Phys. Rev. Lett. 74, 2626 (1995); S. Abachi et al., D0 Collaboration, Phys. Rev. Lett. 74, 2632 (1995)

[2] T. Aaltonen et al., CDF Collaboration, Phys. Rev. Lett. 103, 092002 (2009); V. M. Abazov et al., D0 Collaboration, Phys. Rev. Lett. 103, 092001 (2009)

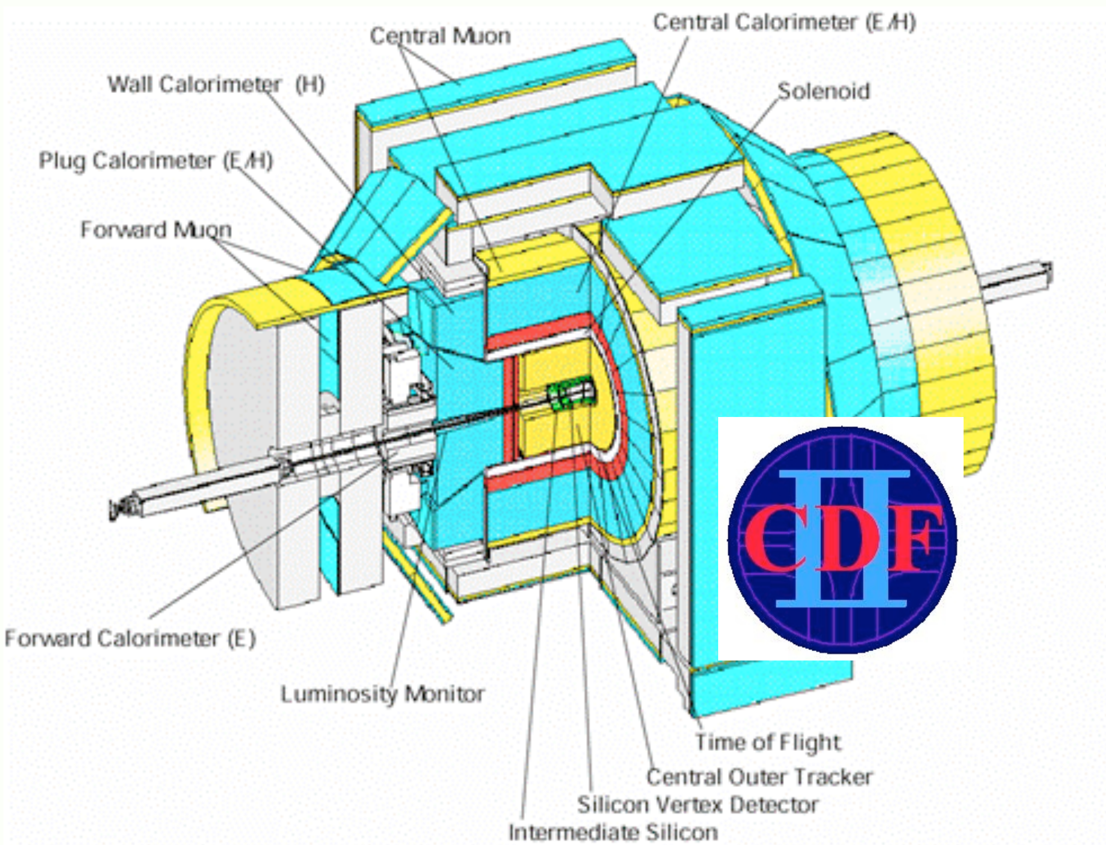
[3] ATLAS Collaboration, Phys. Lett. B 717, 330-350 (2012); CMS Collaboration, JHEP 12 (2012) 035

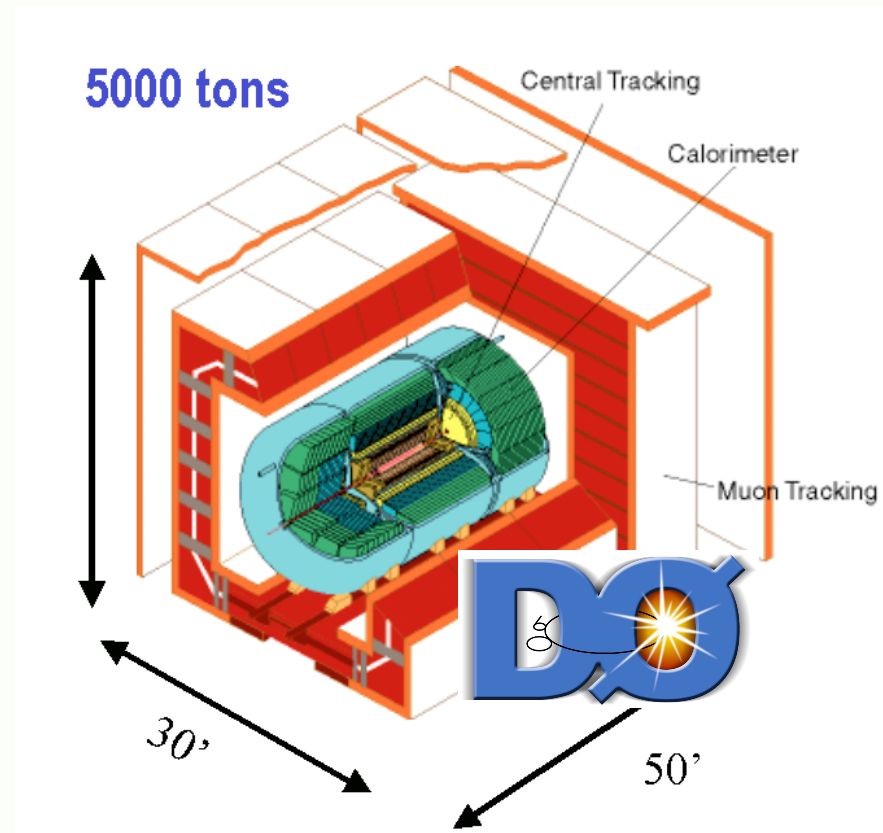
[4] CMS Collaboration, Phys. Rev. Lett. 112 (2014) 231802; CMS Collaboration, Phys. Rev. Lett. 110, 022003 (2013)

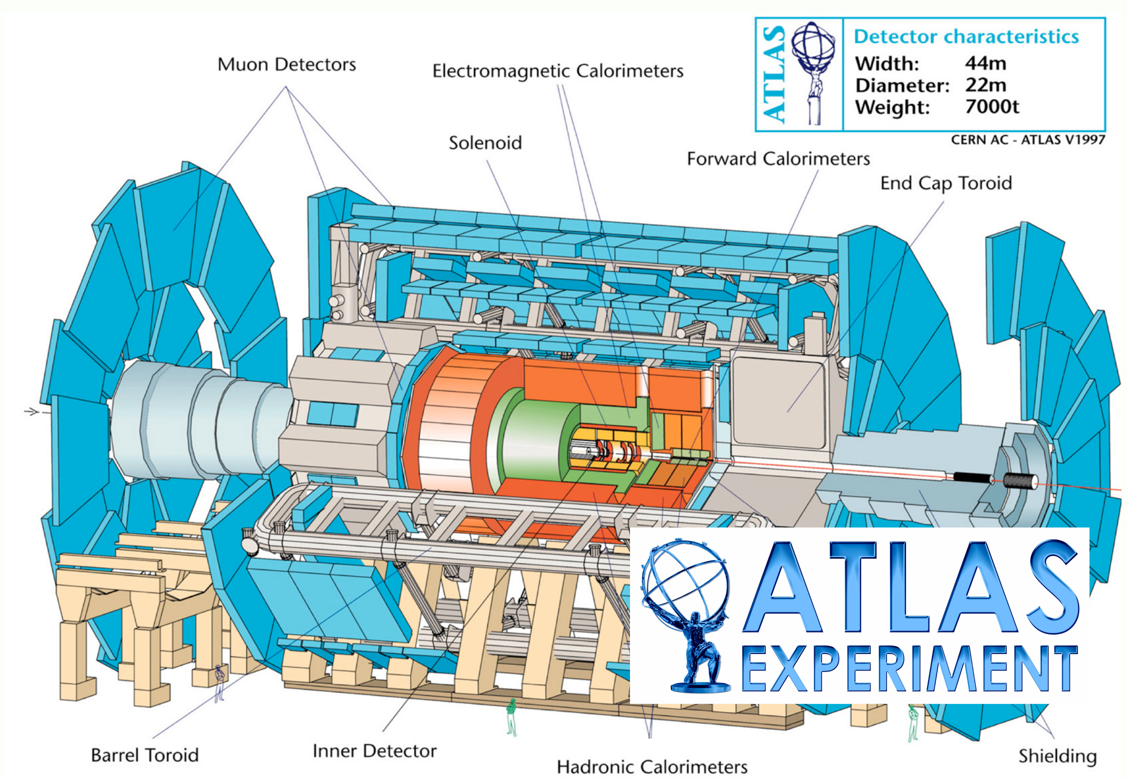
[5] T. Aaltonen et al., CDF and D0 Collaborations, Phys. Rev. Lett. 112, 231803 (2014)

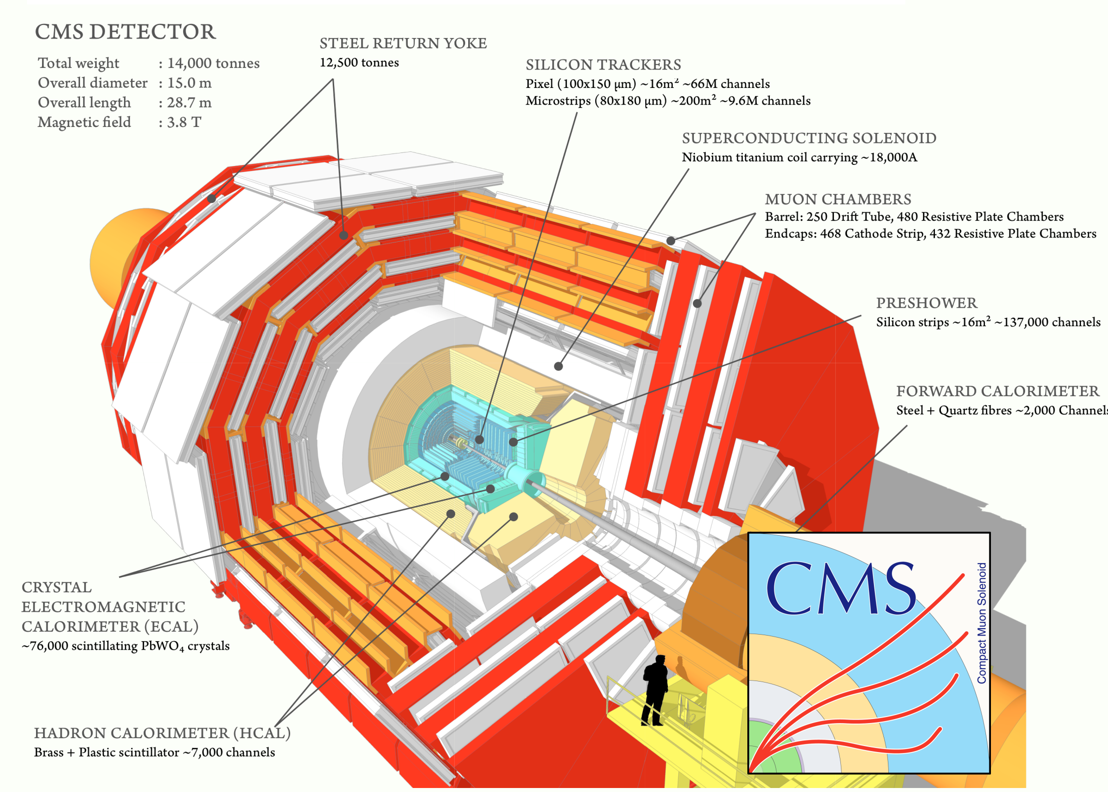



# Tools


Central Muon
Central Calorimeter (E/H)
Wall Calorimeter (H)
Solenoid
Plug Calorimeter (E/H)
Forward Muon
Forward Calorimeter (E)
Luminosity Monitor
Time of Flight
Central Outer Tracker
Silicon Vertex Detector
Intermediate Silicon
CDF II

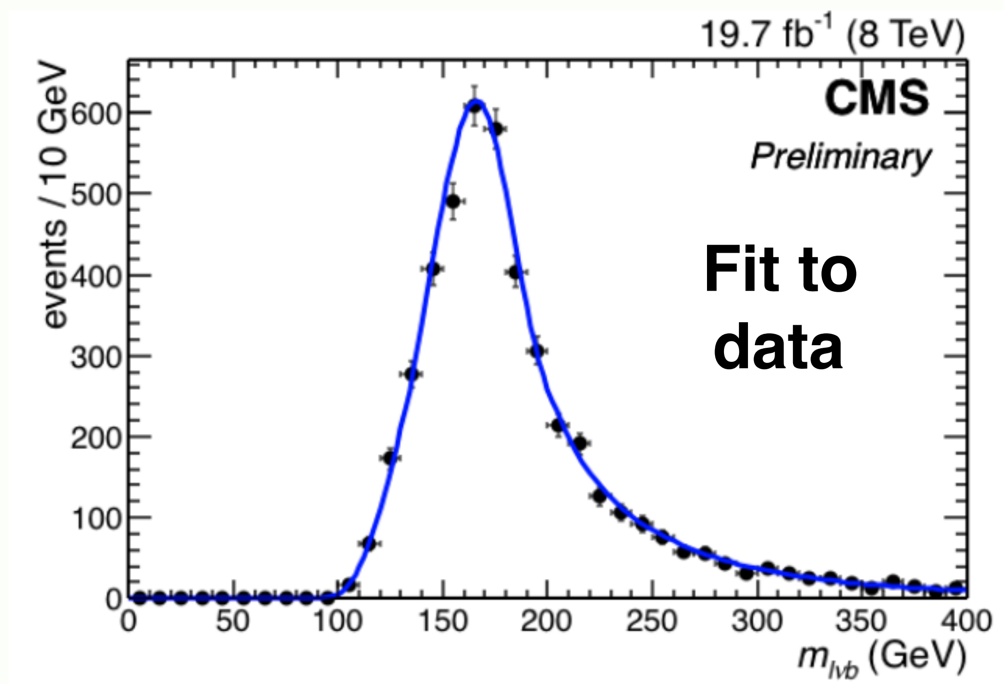

5000 tons
Central Tracking
Calorimeter
Muon Tracking
30'
50'
DØ


ATLAS
Detector characteristics
Width: 44m
Diameter: 22m
Weight: 7000t
CERN AC - ATLAS V1997
Muon Detectors
Electromagnetic Calorimeters
Solenoid
Forward Calorimeters
End Cap Toroid
Barrel Toroid
Inner Detector
Hadronic Calorimeters
Shielding
ATLAS EXPERIMENT

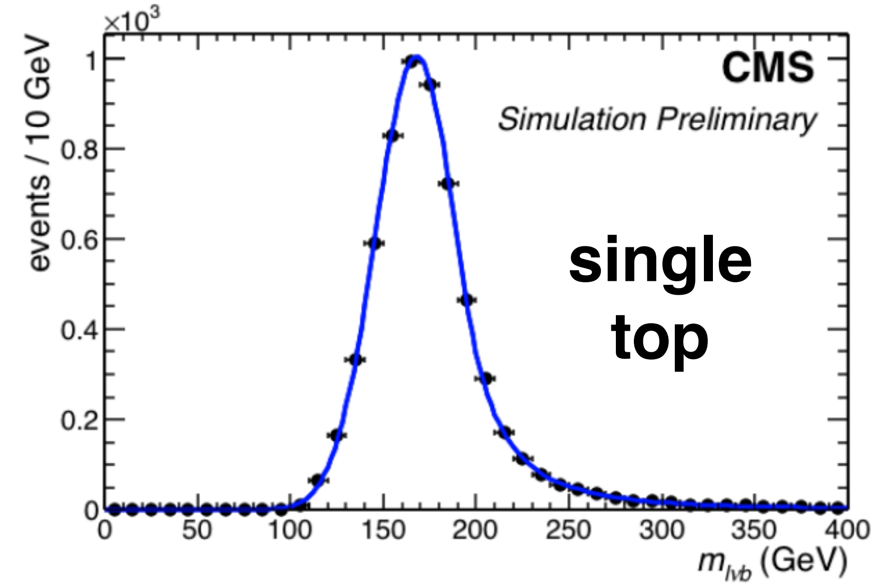

CMS DETECTOR
Total weight : 14,000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T
STEEL RETURN YOKE
12,500 tonnes
SILICON TRACKERS
Pixel (100x150 μm) ~16m² ~66M channels
Microstrips (80x180 μm) ~200m² ~9.6M channels
SUPERCONDUCTING SOLENOID
Niobium titanium coil carrying ~18,000A
MUON CHAMBERS
Barrel: 250 Drift Tube, 480 Resistive Plate Chambers
Endcaps: 468 Cathode Strip, 432 Resistive Plate Chambers
PRESHOWER
Silicon strips ~16m² ~137,000 channels
FORWARD CALORIMETER
Steel + Quartz fibres ~2,000 Channels
CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)
~76,000 scintillating PbWO4 crystals
HADRON CALORIMETER (HCAL)
Brass + Plastic scintillator ~7,000 channels
CMS
Compact Muon Solenoid

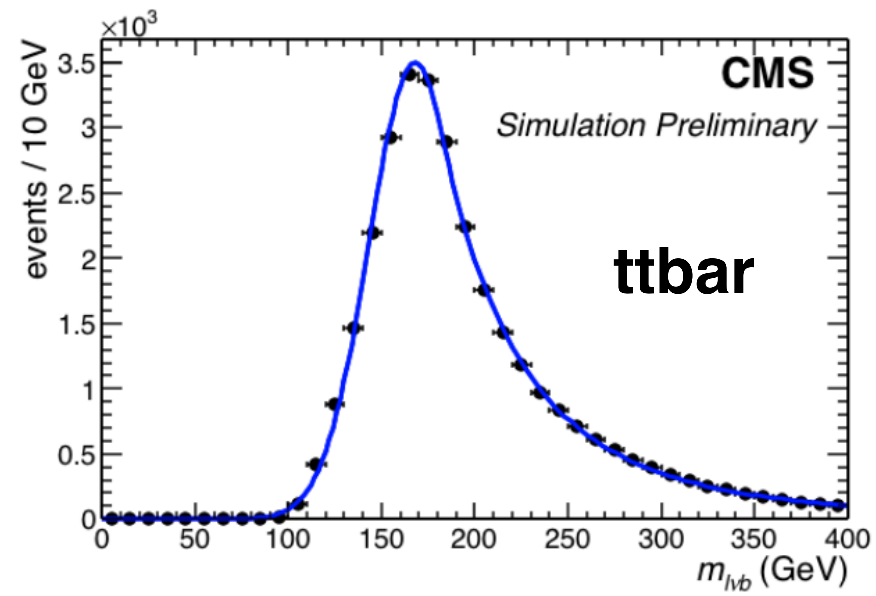
# Top quark mass in single top at CMS

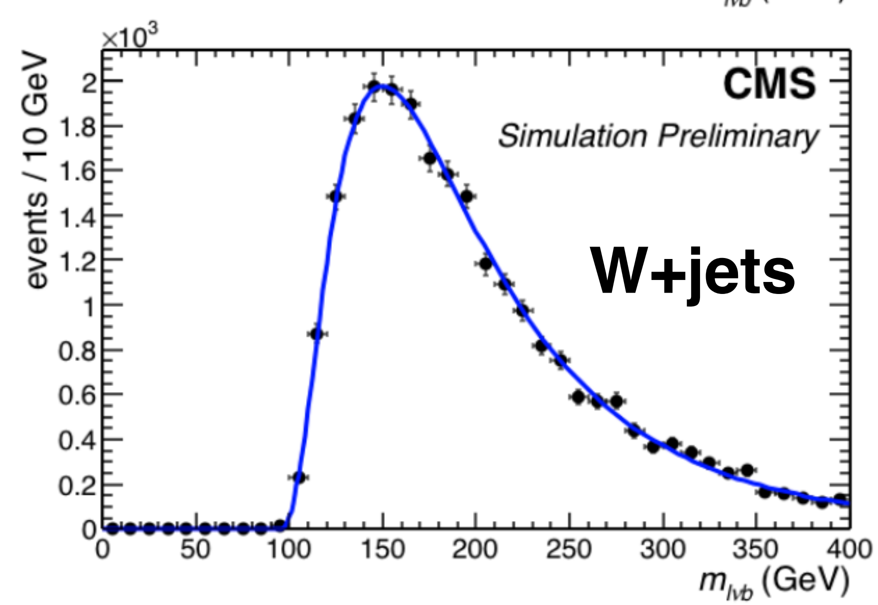
- Measurement of top quark mass in **t channel** (purity ≈ 75%) [1]
- **Muon+jets** channel is considered
- Mass extracted from the reconstructed top quark mass through an extended unbanned maximum likelihood fit
- Signal parametrization is done with Crystal Ball function
- Total uncertainty on the measurement is driven by several sources (JES, signal modelling, fit calibration, etc.)




$$m_t = 172.60 \pm 0.77\ (\text{stat})\ ^{+0.97}_{-0.93}\ (\text{syst})\ \text{GeV}$$



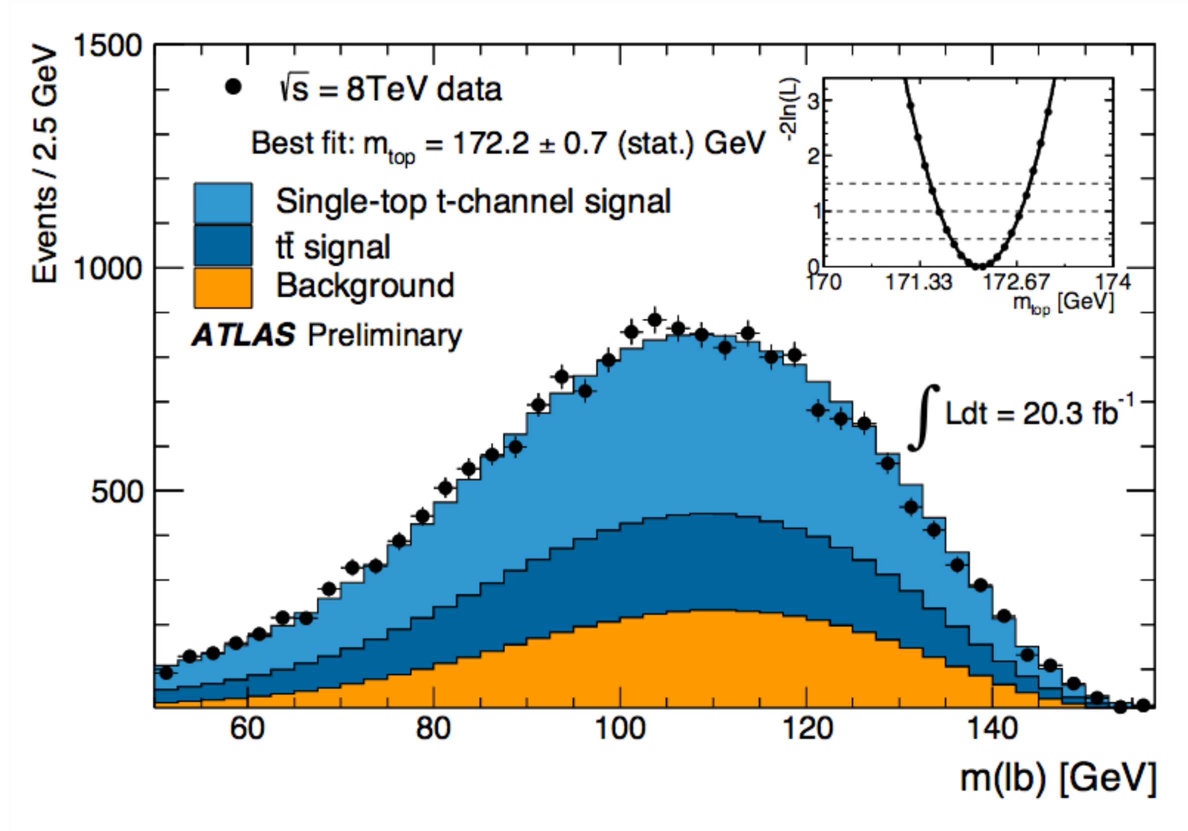



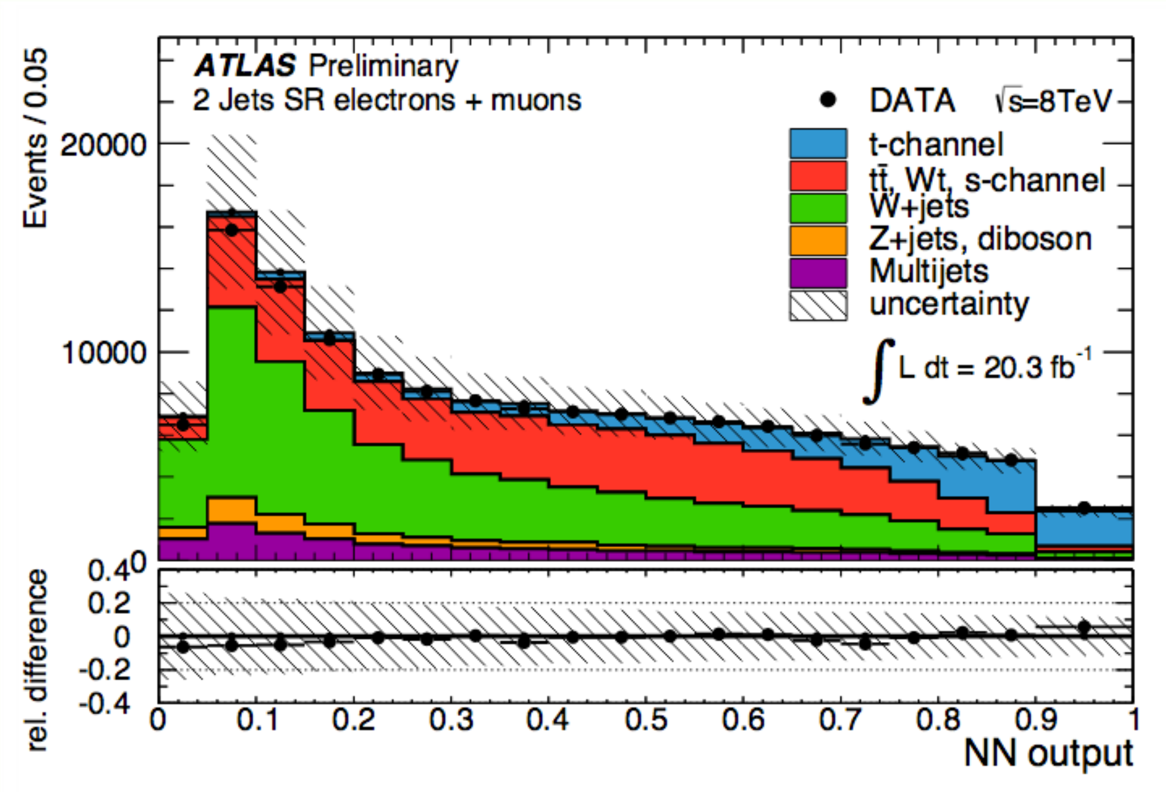




*[1] CMS-PAS-TOP-15-001*

# Top quark mass in single top at ATLAS

- Measurement of top quark mass in **t channel** (purity ≈ 70%) [1]
- Neural network to reduce the background (ttbar not included in the training)
- Invariant mass of charged lepton and b jet as an estimator for top quark mass
- Template method to determine the mass via likelihood fit
- Main systematic uncertainties: JES, signal modelling, background normalization, etc.

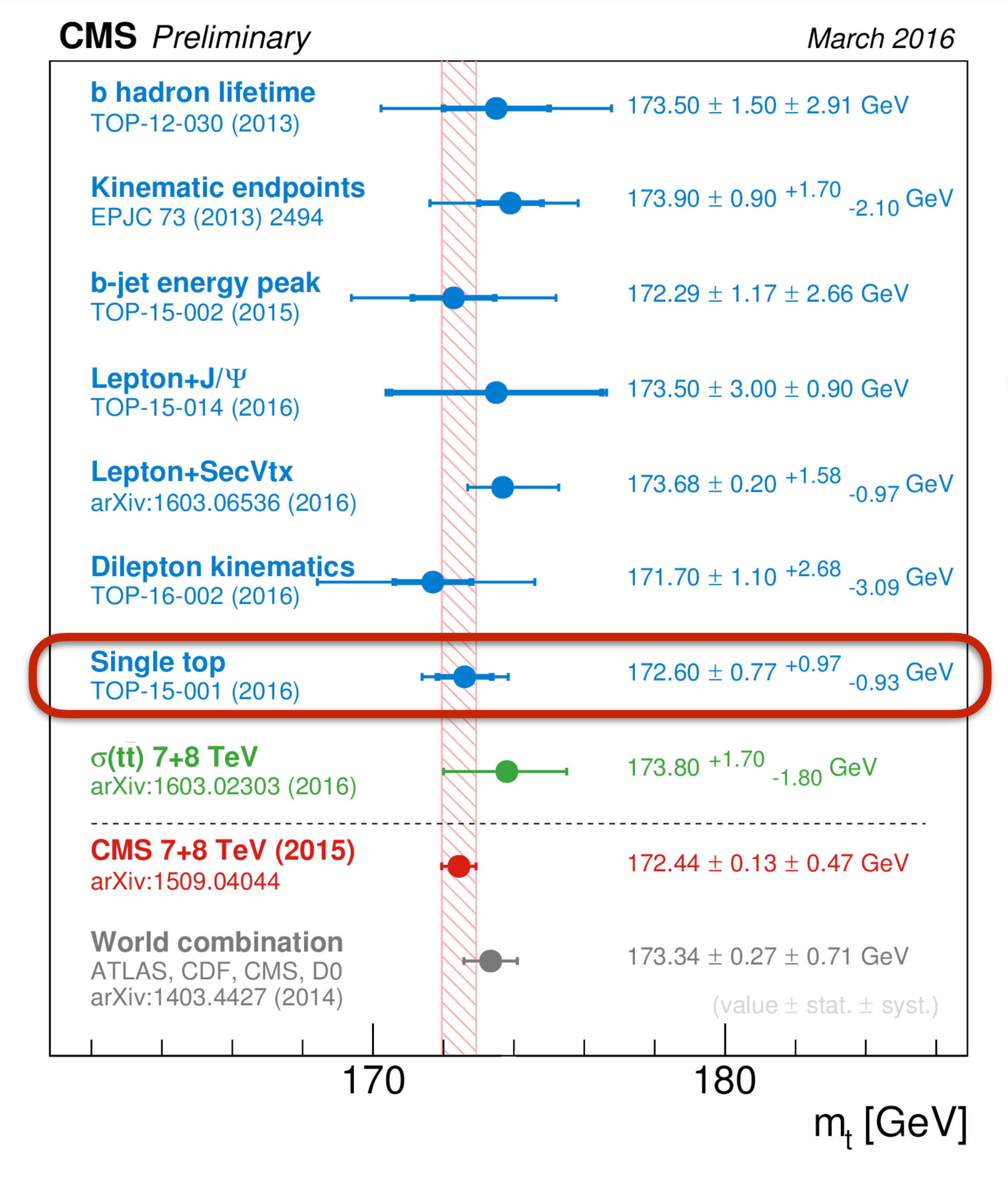


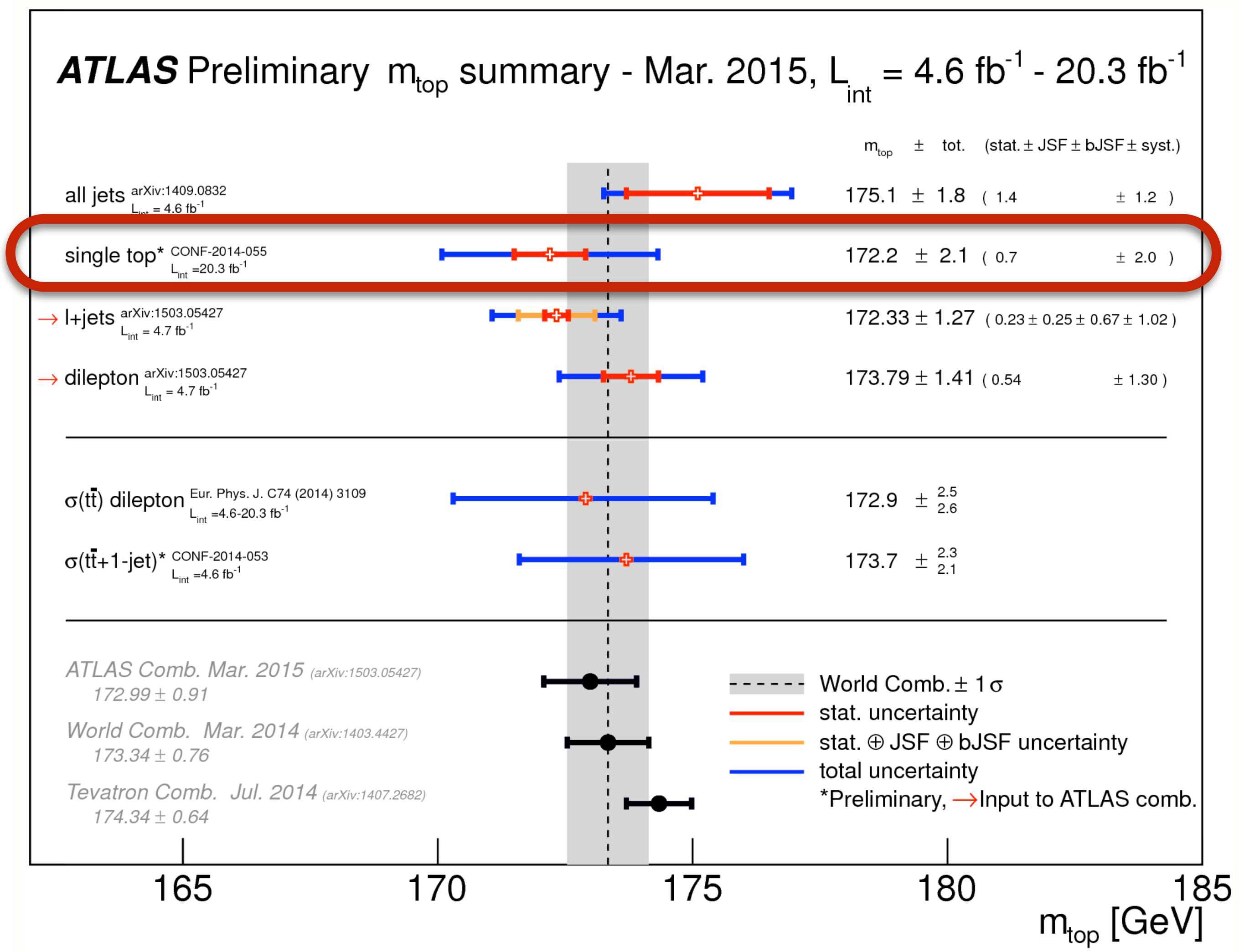




[1] ATLAS-CONF-2014-055

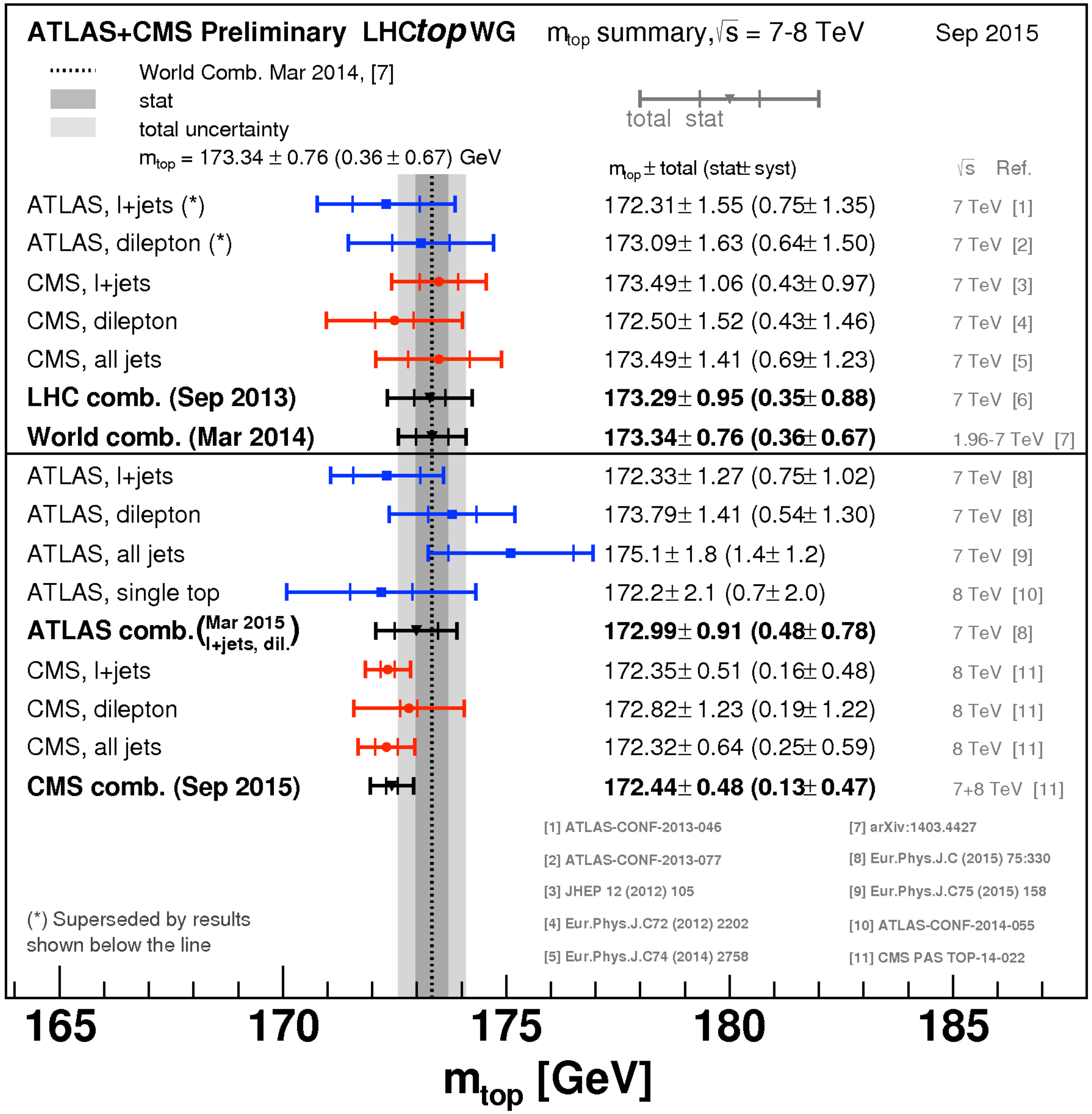
$$m_{top} = 172.2 \pm 0.7(\text{stat.}) \pm 2.0(\text{syst.})\ \text{GeV}$$

# Summary on top quark mass measurements



# Summary on top quark mass measurements

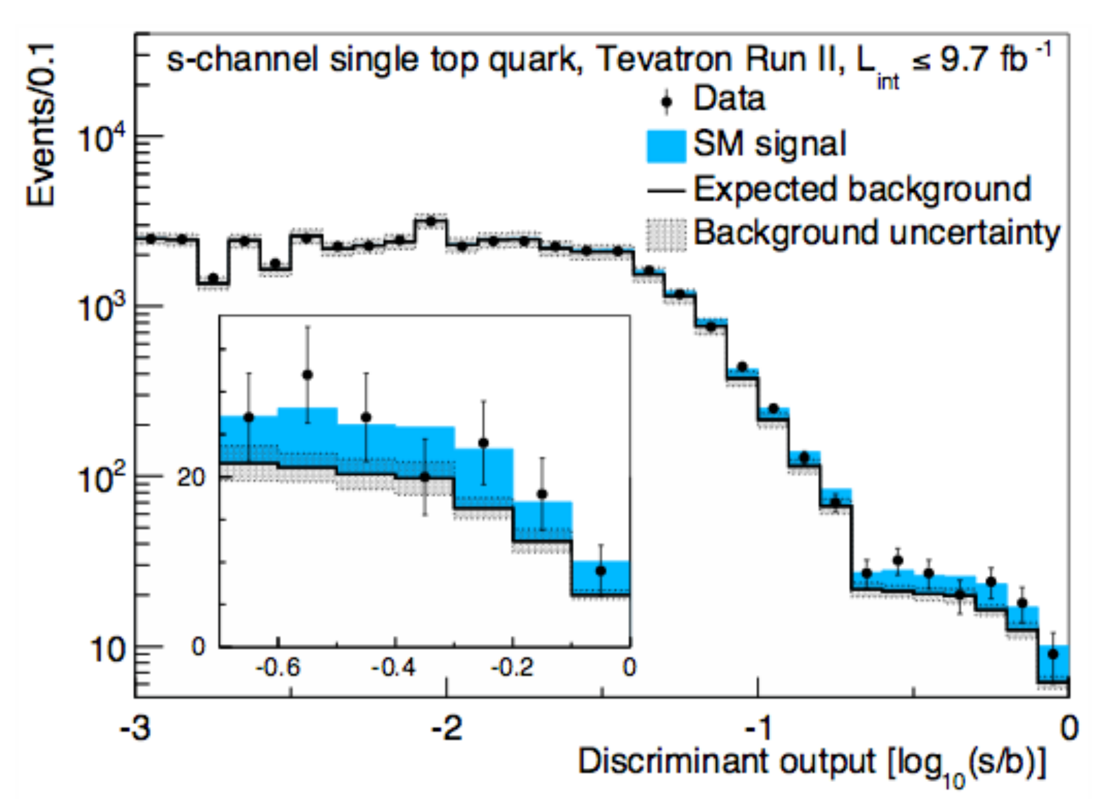


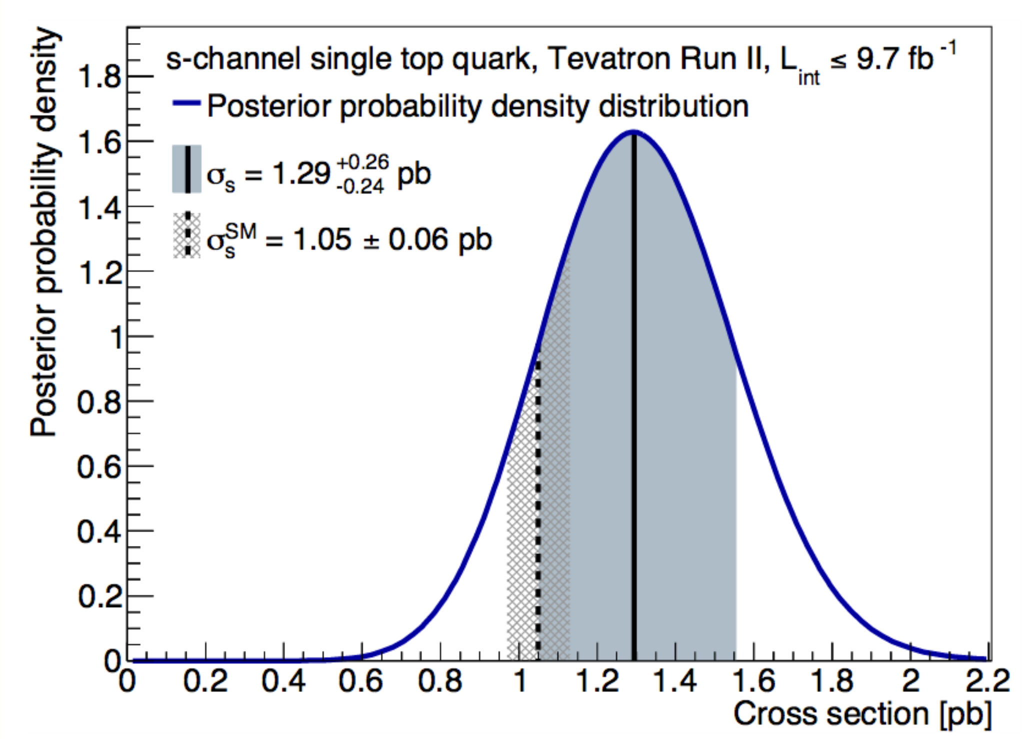
# Single top event generation

| Experiment | Generator | Order |
|---|---|---|
| CDF | POWHEG-BOX | NLO |
| DO | SINGLETOP | NLO |
| ATLAS | POWHEG-BOX, MG5_aMC@NLO | NLO |
| CMS | MG5_aMC@NLO, POWHEG-BOX | NLO |

# s channel at Tevatron

- Observation of **s channel** at Tevatron [1]
- Combination of **l+jets** (CDF and D0) and **$E_T^{miss}$ +jets** (CDF) channels
- **W+jets** backgrounds normalized to data
- Observed with S = 6.3**σ** (expected 5.1**σ**)
- Probability to observe an excess in the absence of signal is $1.8 \times 10^{-10}$




| Systematic uncertainty | CDF Norm | CDF Dist | D0 Norm | D0 Dist | Correlated |
|---|---|---|---|---|---|
| Lumi from detector | 4.5% | | 4.5% | | No |
| Lumi from cross section | 4.0% | | 4.0% | | Yes |
| Signal modeling | 2–10% | • | 3–8% | | Yes |
| Background (simulation) | 2–12% | • | 2–11% | • | Yes |
| Background (data) | 15–40% | • | 19–50% | • | No |
| Detector modeling | 2–10% | • | 1–5% | • | No |
| *b*-jet-tagging | 10–30% | | 5–40% | • | No |
| JES | 0–20% | • | 0–40% | • | No |

$$p(\sigma_s) = \int L(\sigma_s, \{\theta\}|\text{data})\pi(\sigma_s)\Pi(\{\theta\})d\{\theta\}$$


*[1] T. Aaltonen et al., CDF Collaboration, D0 Collaboration, Phys. Rev. Lett. 112, 231803 (2014)*

# t channel measurement (uncertainties)

ATLAS

| Source | $\Delta\sigma_{tq}/\sigma_{tq}$ [%] | $\Delta\sigma_{\bar{t}q}/\sigma_{\bar{t}q}$ [%] |
|---|---|---|
| Data statistics | ± 4.6 | ± 5.0 |
| MC statistics | ± 6.3 | ± 6.5 |
| Multijet normalisation | ± 0.8 | ± 2.4 |
| Other background normalisation | ± 1.4 | ± 0.5 |
| Muon uncertainties | ± 1.6 | ± 1.6 |
| JES | ± 5.5 | ± 1.6 |
| Jet energy resolution | ± 4.3 | ± 3.1 |
| $E_T^{miss}$ modelling | ± 4.2 | ± 4.5 |
| *b*-tagging efficiency | ± 7.1 | ± 7.5 |
| *c*-tagging efficiency | < 0.5 | < 0.5 |
| Light-jet tagging efficiency | < 0.5 | < 0.5 |
| Pile-up reweighting | ± 1.2 | ± 3.2 |
| *W*+jets modelling | ± 2.3 | ± 1.0 |
| $t\bar{t}$,*Wt* and *s*-channel shower generator | < 0.5 | ± 2.3 |
| $t\bar{t}$,*Wt* and *s*-channel NLO matching | ± 2.7 | ± 7.0 |
| $t\bar{t}$,*Wt* and *s*-channel scale | ± 2.6 | ± 0.9 |
| *t*-channel scale | ± 5.9 | ± 7.7 |
| *t*-channel generator | ± 11.0 | ± 15.0 |
| PDF | < 0.5 | ± 1.0 |
| Luminosity | ± 5.0 | ± 5.0 |
| Total systematic uncertainty | ± 18.4 | ± 24.4 |
| Total uncertainty | ± 19.0 | ± 25.0 |

CMS

| uncertainty source | $\Delta\sigma_{t-ch.,t+\bar{t}}/\sigma^{obs}_{t-ch.,t+\bar{t}}$ | $\Delta\sigma_{t-ch.,t}/\sigma^{obs}_{t-ch.,t}$ | $\Delta\sigma_{t-ch.,\bar{t}}/\sigma^{obs}_{t-ch.,\bar{t}}$ |
|---|---|---|---|
| uncertainty of the fit (stat. + prof. unc.) | ±6.8% | ±7.4% | ±11.9% |
| statistical uncertainty | ±4.0% | ±4.7% | ±7.6% |
| profiled uncertainties | ±5.5% | ±5.7% | ±9.2% |
| MC statistics | ±2.8% | ±3.4% | ±4.0% |
| pileup | -0.2/+0.1% | -0.5/+0.4% | -0.1/+0.7% |
| experimental uncertainty | -6.2/+6.2% | -6.7/+6.7% | -10.0/+10.0% |
| Signal modeling | ±7.9% | ±10.1% | ±8.2% |
| $t\bar{t}$ modeling | ±4.3% | ±3.9% | ±4.6% |
| W+jets modeling | -2.1/+1.7% | -1.6/+1.1% | -2.8/+2.3% |
| $Q^2$ scale *t*-channel | -5.7/+7.0% | -7.1/+5.1% | -6.1/+6.9% |
| $Q^2$ scale $t\bar{t}$ | -2.7/+4.1% | -2.5/+4.0% | -3.9/+3.4% |
| $Q^2$ scale tW | -0.3/+0.5% | -0.4/+0.3% | -1.1/+0.4% |
| $Q^2$ scale W+jets | -2.7/+3.0% | -2.5/+4.2% | -5/+2.4% |
| PDF uncertainty | -3.0/+2.6% | -3.1/+3.2% | -3.7/+4.2% |
| top $p_T$ modeling | ±0.1% | ±0.1% | ±0.2% |
| total theory uncertainties | -12.1/+12.6 | -13.8/+13.6 | -13.5/+13.4% |
| luminosity | ±2.7% | ±2.7% | ±2.7% |
| total uncertainty | -14.5/+14.8% | -16.3/+16.1% | -18.6/+18.6% |

| uncertainty source | $\Delta\sigma_{t-ch.,t+\bar{t}}/\sigma^{obs}_{t-ch.,t+\bar{t}}$ | $\Delta\sigma_{t-ch.,t}/\sigma^{obs}_{t-ch.,t}$ | $\Delta\sigma_{t-ch.,\bar{t}}/\sigma^{obs}_{t-ch.,\bar{t}}$ |
|---|---|---|---|
| JES | ±4.9% | ±5.6% | ±3.7% |
| JER | ±0.7% | ±0.2% | ±1.5% |
| b-tagging efficiency | ±2.3% | ±2.1% | ±1.6% |
| mis-tagging efficiency | ±0.8% | ±1.2% | ±0.4% |
| lepton reconstruction/trigger | ±2.5% | ±2.0% | ±2.9% |

# s channel measurement (uncertainties)

CMS

| Source | Uncertainty (%) | | | | |
|---|---|---|---|---|---|
| | $\mu$, 7 TeV | $\mu$, 8 TeV | e, 8 TeV | $\mu$ + e, 8 TeV | 7+8 TeV |
| Statistical | 34 | 15 | 14 | 10 | 11 |
| $t\bar{t}$, single top quark rate | 29 | 15 | 14 | 12 | 14 |
| W/Z+jets, diboson rate | 23 | 11 | 13 | 12 | 12 |
| Multijet rate | 9 | 3 | 5 | 2 | 2 |
| Lepton efficiency | 14 | 1 | 2 | 1 | 3 |
| Hadronic trigger | 5 | — | — | — | 1 |
| Luminosity | 10 | 5 | 6 | 4 | 6 |
| JER & JES | 66 | 39 | 29 | 34 | 18 |
| b tagging & mistag | 34 | 15 | 14 | 14 | 16 |
| Pileup | 6 | 11 | 7 | 9 | 7 |
| Unclustered $\not{E}_T$ | 5 | 8 | 2 | 6 | 5 |
| $\mu_R$, $\mu_F$ scales | 54 | 34 | 31 | 30 | 28 |
| Matching thresholds | 43 | 11 | 12 | 7 | 17 |
| PDF | 12 | 8 | 7 | 7 | 9 |
| Top quark $p_T$ reweighting | 3 | 5 | 7 | 6 | 6 |
| Total uncertainty | 115 | 64 | 54 | 55 | 47 |

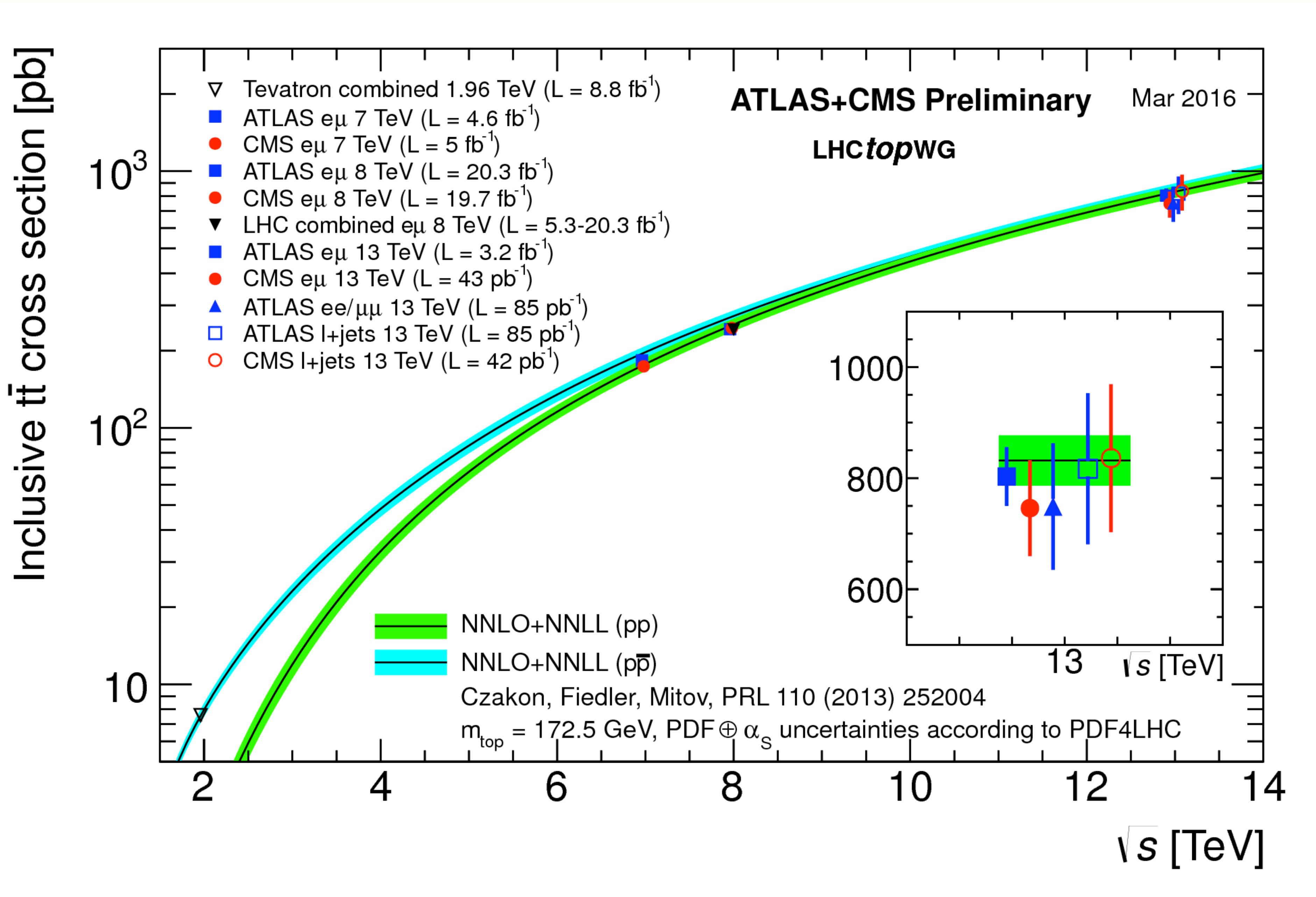
| Type | $\pm\Delta\sigma/\sigma$ [%] |
|---|---|
| Data statistics | 16 |
| MC statistics | 12 |
| Jet energy resolution | 12 |
| *t*-channel generator choice | 11 |
| *b*-tagging | 8 |
| *s*-channel generator scale | 7 |
| *W*+jets normalization | 6 |
| Luminosity | 5 |
| *t*-channel normalization | 5 |
| Jet energy scale | 5 |
| PDF | 3 |
| Lepton identification | 2 |
| Electron energy scale | 1 |
| $t\bar{t}$ generator choice | 1 |
| Lepton trigger | 1 |
| Charm tagging | 1 |
| Other | < 1 |
| Total | 34 |

ATLAS

# Wt combination at LHC (uncertainties)

| Category | ATLAS | | CMS | | $\rho$ |
|---|---|---|---|---|---|
| Data statistics | Data statistics | 5.8% | Fit statistics | 8.1% | 0.0 |
| Category subtotal | | **5.8%** | | **8.1%** | **0.0** |
| Simulation statistics | Sim. statistics | 0.5% | Sim. statistics | 2.4% | 0.0 |
| Category subtotal | | **0.5%** | | **2.4%** | **0.0** |
| Luminosity | | 4.6% | | 3.0% | — |
| Category subtotal | | **4.6%** | | **3.0%** | **0.31** |
| Theory modelling | ISR/FSR | 8.8% | Ren./fact. scale | 12.4% | 1.0 |
| | NLO matching method | 2.5% | | | — |
| | Parton shower | 1.7% | ME/PS match. thr. | 14.1% | 1.0 |
| | PDF | 0.6% | PDF | 1.7% | 1.0 |
| | Wt/$t\bar{t}$ overlap | 3.5% | DR/DS scheme | 2.1% | 1.0 |
| | | | Top $p_T$ reweight. | 0.4% | — |
| Category subtotal | | **10.0%** | | **19.0%** | **0.75** |
| Background normalization | bkg. mod. | 2.8% | $t\bar{t}$ cross section | 1.7% | 0.0 |
| | | | Z+jets | 2.6% | — |
| Category subtotal | | **2.8%** | | **3.1%** | **0.0** |
| Jets | JES common | 5.3% | JES | 3.8% | 0.0 |
| | JES flavour | 1.9% | | | — |
| | Jet id | 0.2% | | | — |
| | Jet res. | 6.5% | Jet resolution | 0.9% | 0.0 |
| Category subtotal | | **8.6%** | | **3.9%** | **0.0** |
| Detector modelling | Lepton modelling | 3.0% | Lepton modelling | 1.8% | 0.0 |
| | MET scale | 5.5% | MET modelling | 0.4% | 0.0 |
| | MET resolution | 0.2% | | | — |
| | b-tagging | 1.0% | b tagging | 0.9% | 0.0 |
| | Pileup | 2.7% | Pileup | 0.4% | 0.0 |
| Category subtotal | | **6.9%** | | **2.0%** | **0.0** |
| Total | | **16.8%** | | **21.7%** | **0.40** |

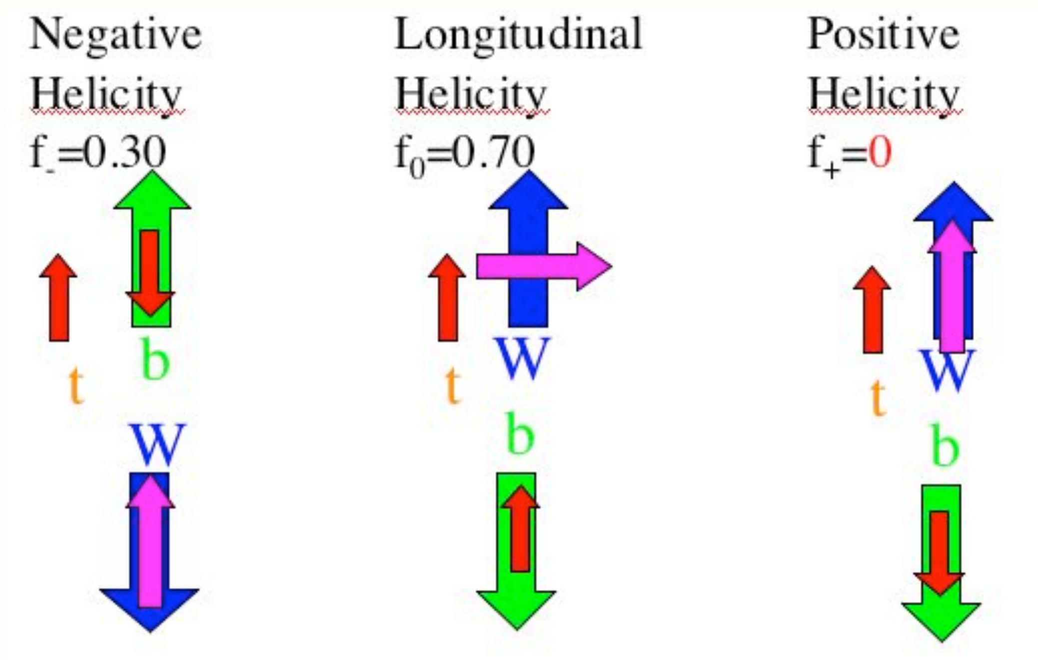
# ttbar production at LHC




$$\frac{\sigma_{t\bar{t}}(13\text{TeV})}{\sigma_{t\bar{t}}(8\text{TeV})} \simeq 3.2 \quad \frac{\sigma_{\text{s}}(13\text{TeV})}{\sigma_{\text{s}}(8\text{TeV})} \simeq 2 \quad \frac{\sigma_{\text{t}}(13\text{TeV})}{\sigma_{\text{t}}(8\text{TeV})} \simeq 2.5 \quad \frac{\sigma_{\text{Wt}}(13\text{TeV})}{\sigma_{\text{Wt}}(8\text{TeV})} \simeq 3.2$$

# W boson helicity

- W helicity - projection of W's spin on its momentum
- Helicity fractions: $\mathbf{F_{L,R,0}} = \Gamma_{L,R,0} / \Gamma(t \rightarrow Wb)$, $\Sigma F_i = 1$
- Helicity is sensitive to the **real part** of **Wtb anomalous couplings**

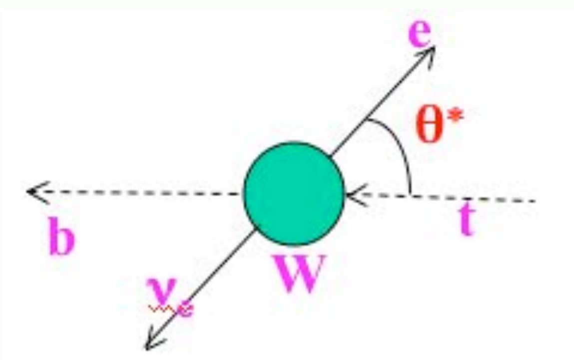


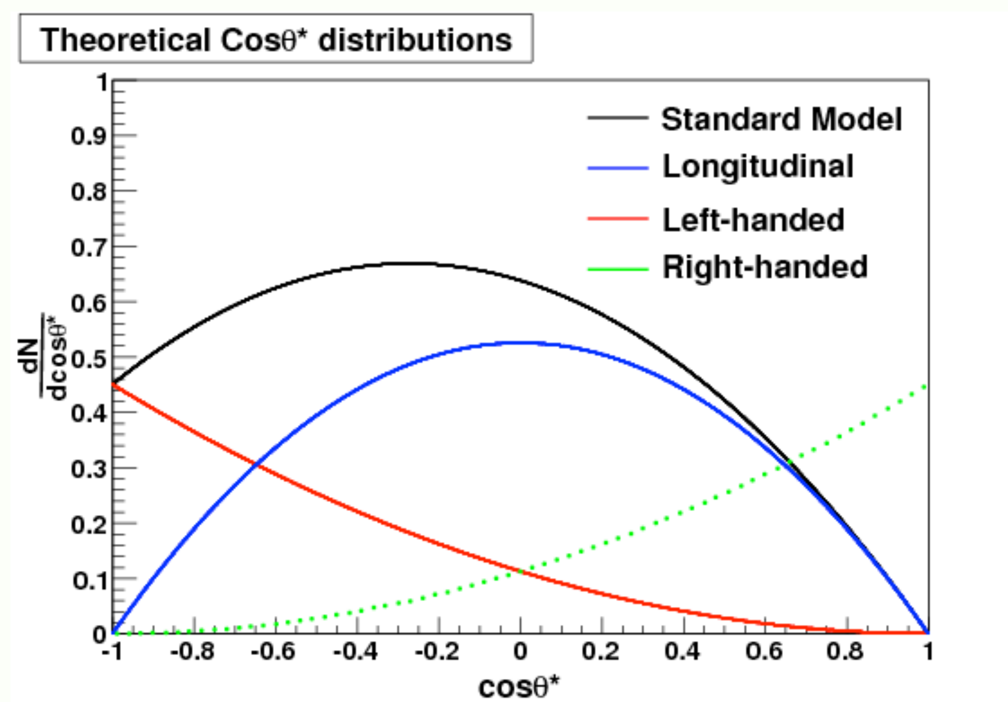

$$\rho(\cos\theta^*_\ell) \equiv \frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta^*_\ell} = \frac{3}{8}(1-\cos\theta^*_\ell)^2 F_L + \frac{3}{4}\sin^2\theta^*_\ell F_0 + \frac{3}{8}(1+\cos\theta^*_\ell)^2 F_R$$

@NNLO
$F_0 = 0.687 \pm 0.005$
$F_L = 0.311 \pm 0.005$
$F_R = 0.0017 \pm 0.0001$

*Phys. Rev. D 81 (2010) 111503*

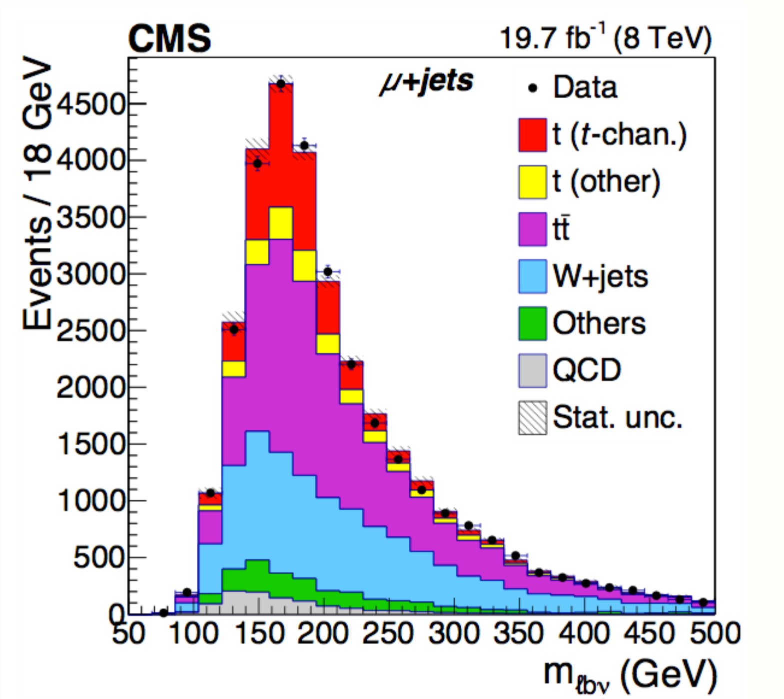
$\theta^*$ helicity angle:

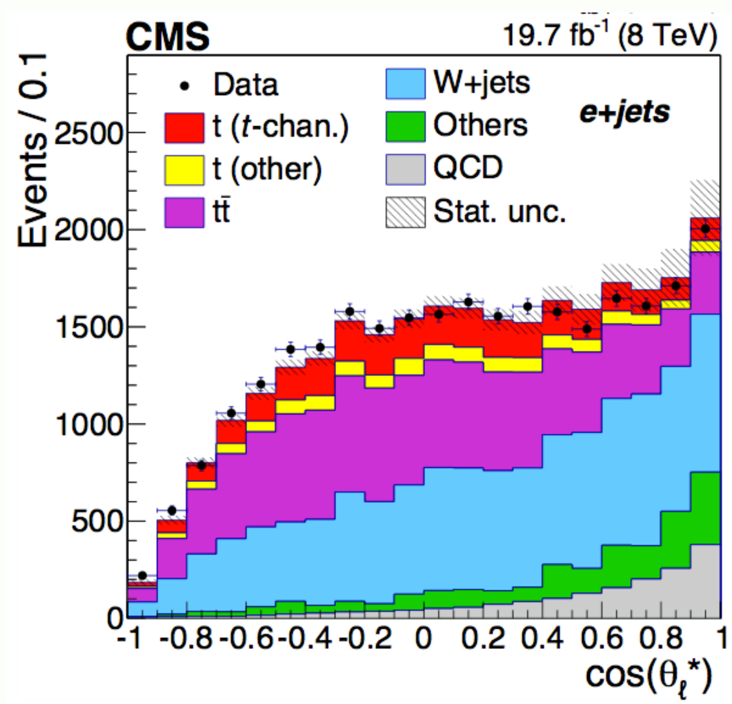


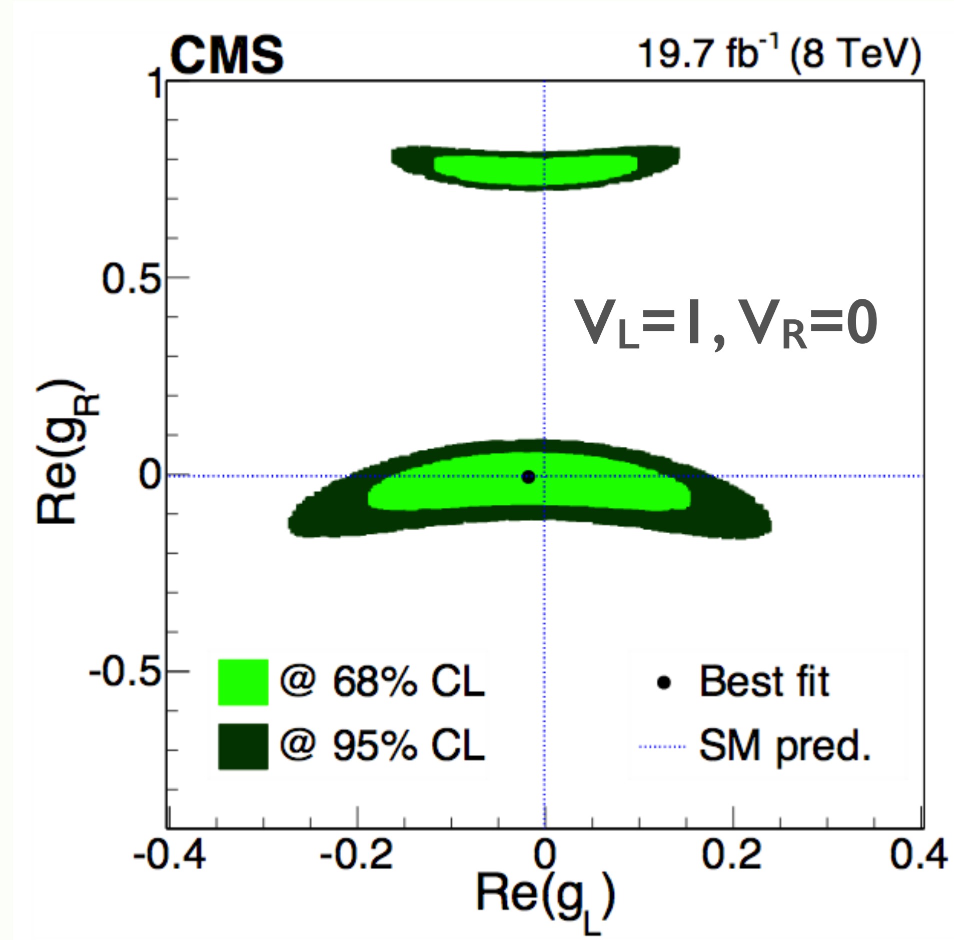



# W boson helicity in t channel at CMS

- **First measurement** of W boson helicity in **single top quark event topology**
- Single top statistics accompanied by ttbar events also used to extract helicity fractions
- $F_0$, $F_L$ and W+jets fraction are free parameters in the fit




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

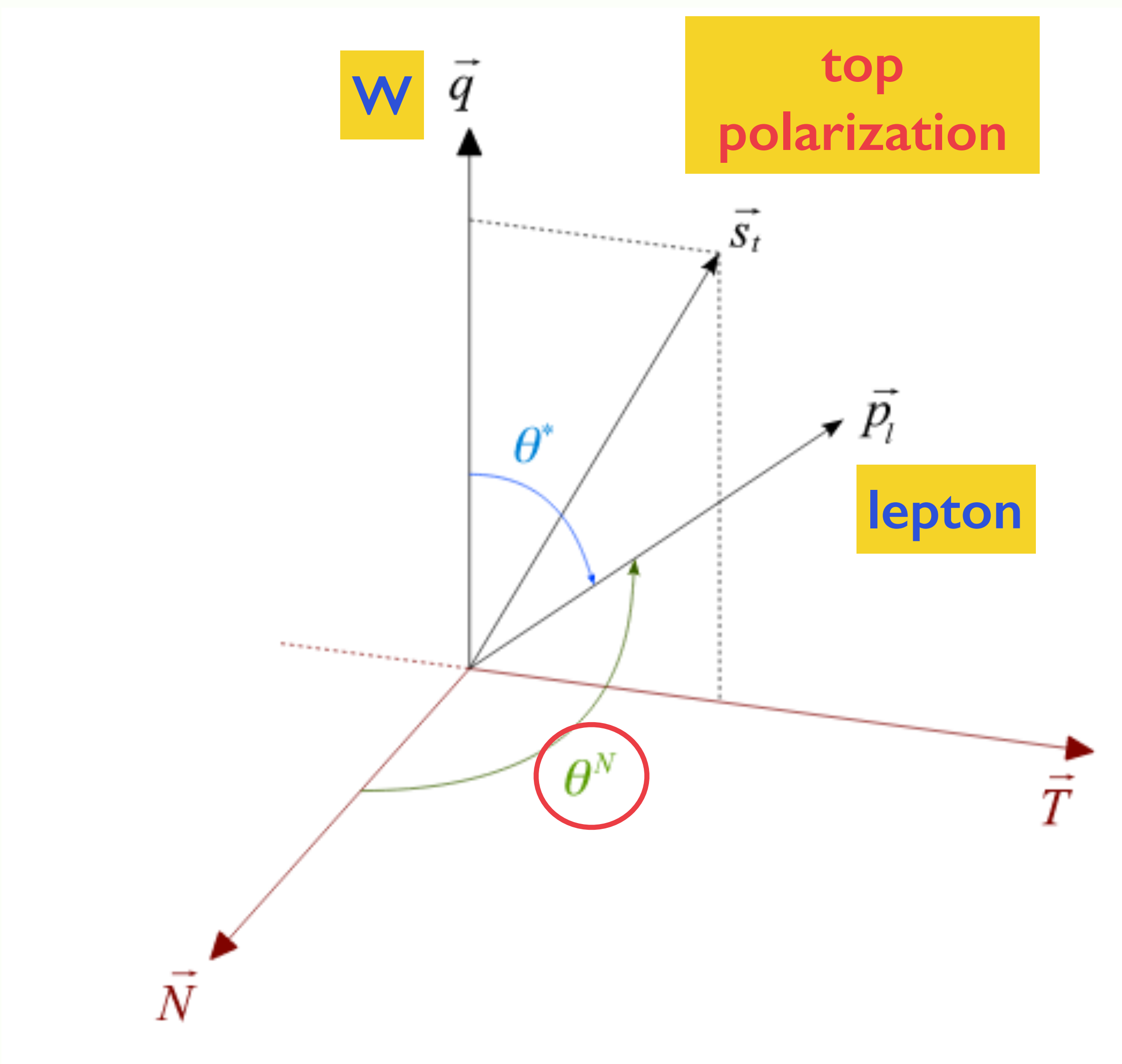
Best fit gives **Re($g_L$) = -0.017**, **Re($g_R$) = -0.008**

*Measured helicity fractions are consistent with SM*

*[1] CMS Collaboration, J. High Energy Phys. 01 (2015) 053*

# Forward-backward asymmetry

- Measure forward-backward asymmetry in the normal direction ($A^N_{FB}$) in **single top** events → **probe complex phase of $g_R$**
- **In ttbar**:
  - Top quarks are only slightly polarized due to EW corrections → no $A_{FB}$ asymmetry
- **In single top**:
  - Top quark is highly polarized ($P \approx 0.9$)
  - Two new reference directions: ***N*** and ***T***
- **A presence of FB asymmetry** would be a sign of **CP violation** in top quark decays

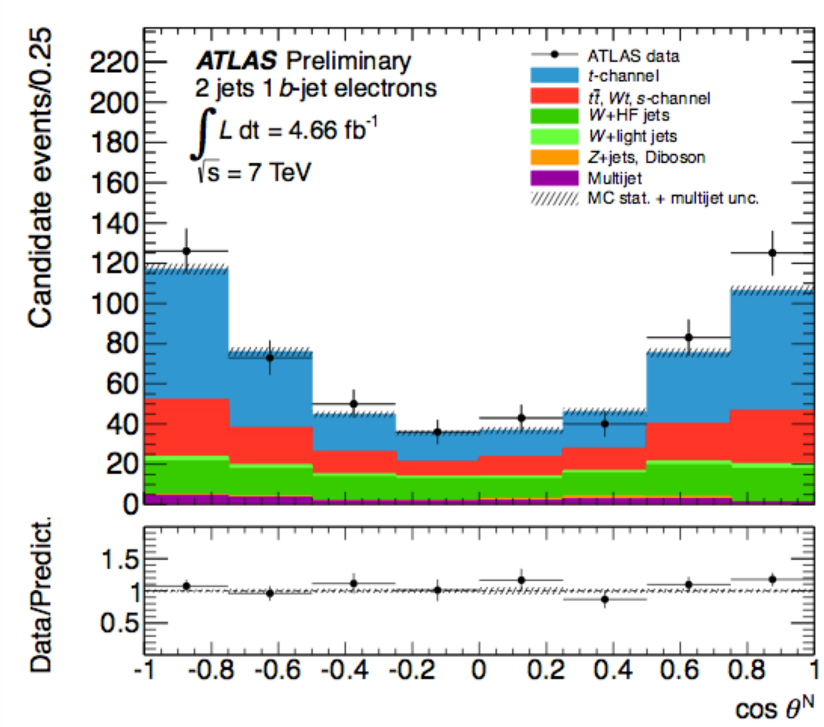


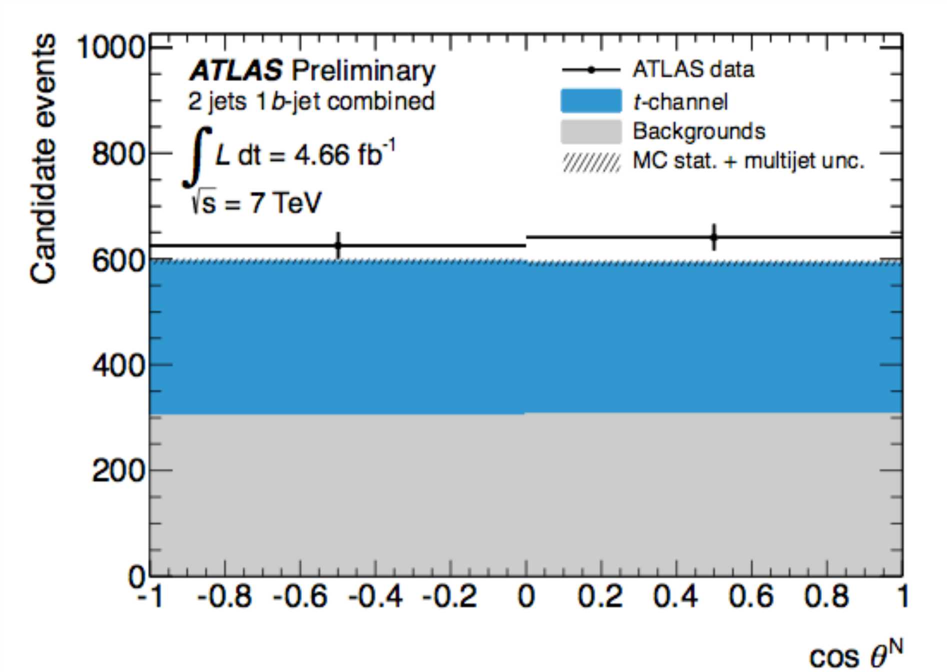

$$A^N_{FB} \equiv \frac{N_{evt}(cos\theta^N > 0) - N_{evt}(cos\theta^N < 0)}{N_{evt}(cos\theta^N > 0) + N_{evt}(cos\theta^N < 0)}$$

$$\vec{N} = \vec{s}_t \times \vec{q}$$
$$\vec{T} = \vec{q} \times \vec{N}$$

# $A_{FB}$ in single top at ATLAS

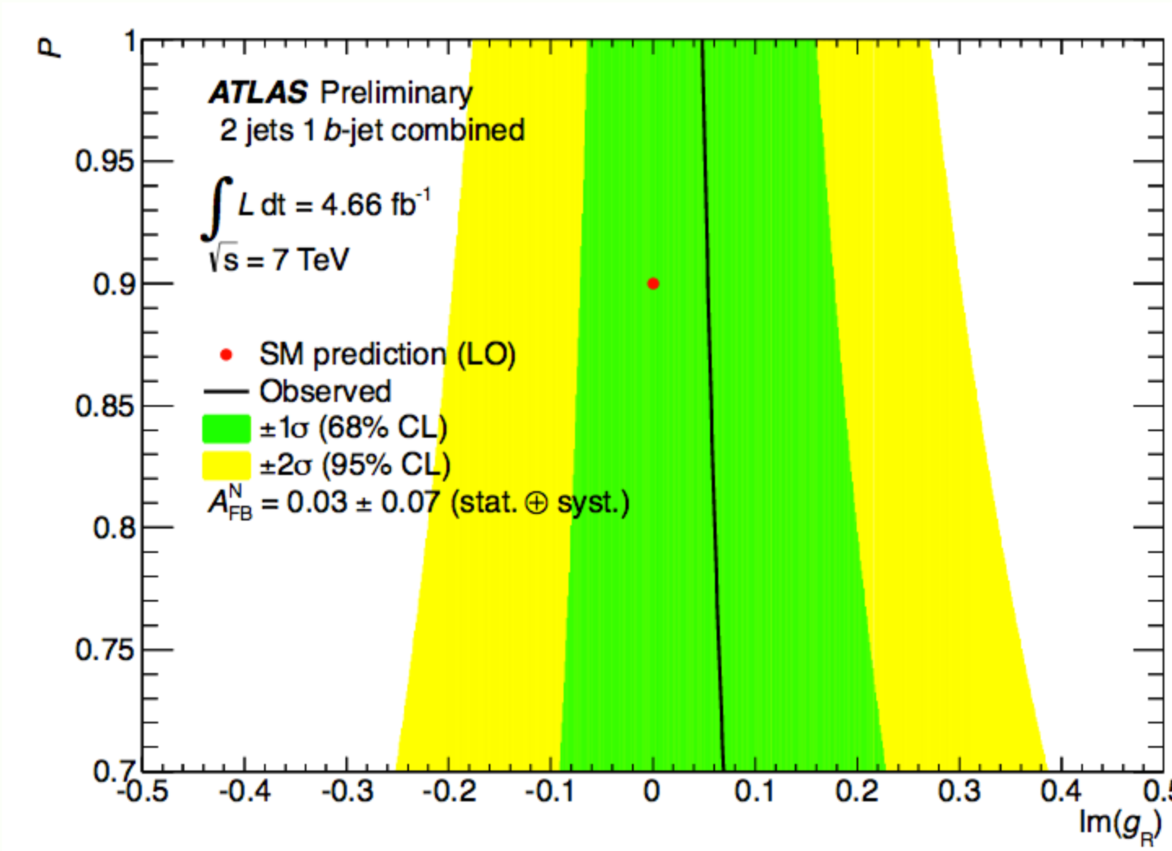
- Measure $A_{FB}$ asymmetry in lepton+jets events
- Asymmetry extracted with unfolding the **$\cos\theta^N$** distribution
- $g_R$ assumed to be purely **imaginary**




$$A_{FB}^{N} = 0.031 \pm 0.065\,(\text{stat.})\,^{+0.029}_{-0.031}\,(\text{syst.})$$

**First experimental limit on Im($g_R$)** of [**-0.20**, **0.30**] at 95% CL

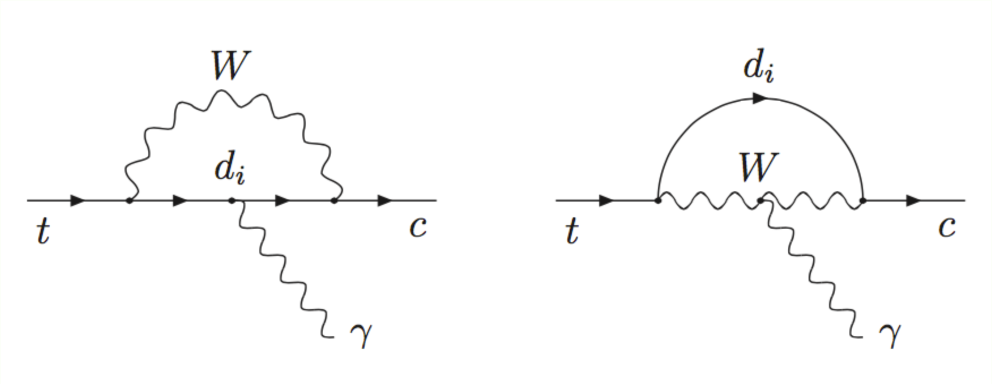



[1] ATLAS-CONF-2013-032

# Summary on FCNC searches

- **Flavour-changing neutral current (FCNC) →** process where a fermion changes its flavour with preserving its charge
- **FCNC amplitudes are forbidden** at tree level by the Glashow-Iliopoulos-Maiani (GIM) mechanism [Phys. Rev. D2 (1970) 1285] in SM
- FCNC is only possible in SM at higher orders via loops induced processes → **highly suppressed**
- **FCNC decays could be enhanced in various BSM**

## FCNC in SM




$BR(t\to c\mathbf{g}) \simeq 5 \times 10^{-12}$

$BR(t\to c\mathbf{Z}) \simeq 1 \times 10^{-14}$

$BR(t\to c\boldsymbol{\gamma}) \simeq 5 \times 10^{-14}$

$BR(t\to c\mathbf{H}) \simeq 3 \times 10^{-15}$

$BR(t\to \mathbf{u}X) \simeq BR(t\to \mathbf{c}X)\ |V_{ub}/V_{cb}|^2$ ($\simeq 0.008$)

*J.A. Aguilar-Saavedra, Acta Phys. Polon. B35 (2004) 2695-2710*

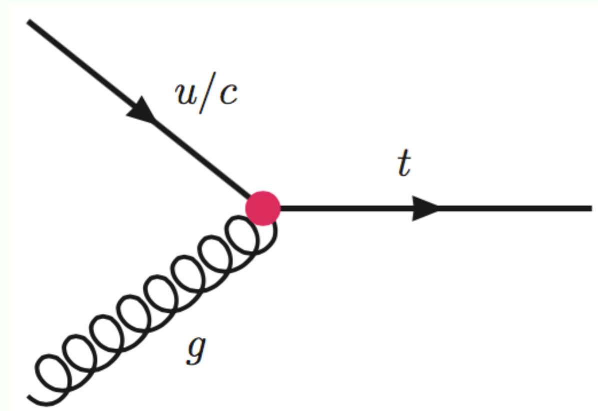
## FCNC in BSM

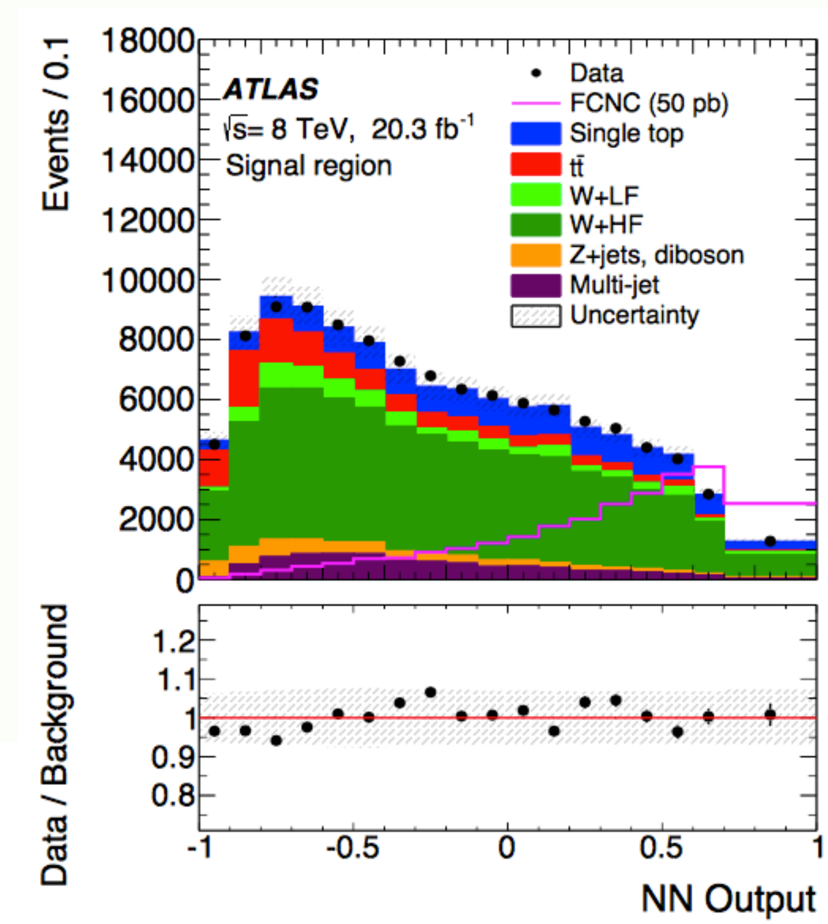
| | 2HDM | MSSM | RS |
|---|---|---|---|
| $BR(t\to cg)$ | $10^{-8}$ - $10^{-4}$ | $10^{-7}$ - $10^{-6}$ | $10^{-10}$ |
| $BR(t\to cZ)$ | $10^{-10}$ - $10^{-6}$ | $10^{-7}$ - $10^{-6}$ | $10^{-5}$ |
| $BR(t\to c\gamma)$ | $10^{-9}$ - $10^{-7}$ | $10^{-9}$ - $10^{-8}$ | $10^{-9}$ |
| $BR(t\to cH)$ | $10^{-5}$ - $10^{-3}$ | $10^{-9}$ - $10^{-5}$ | $10^{-4}$ |

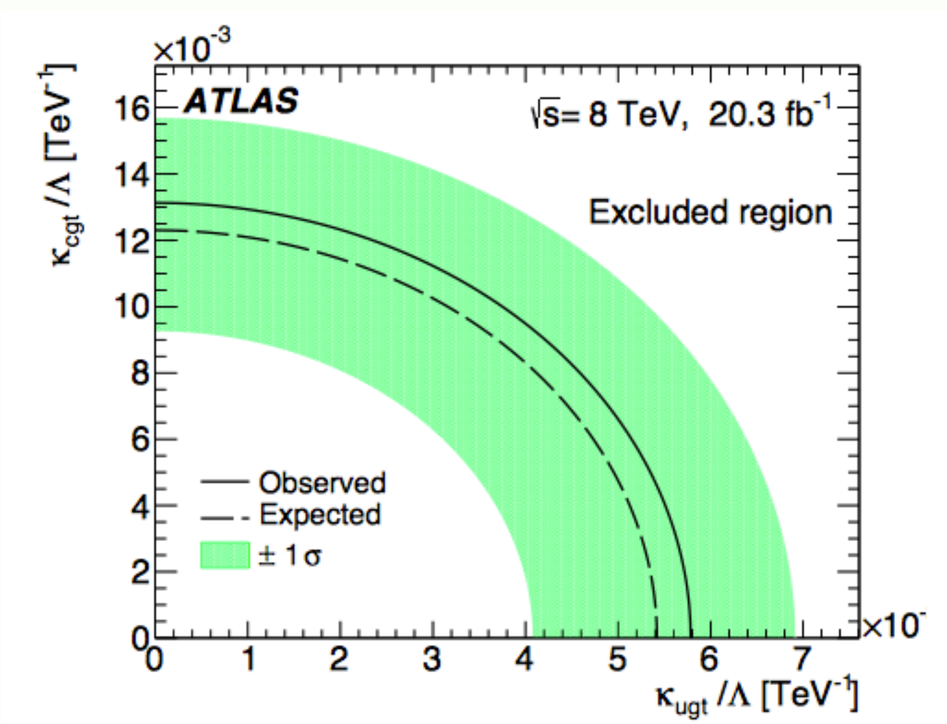
*K. Agashe et al., arXiv:1311.2028*

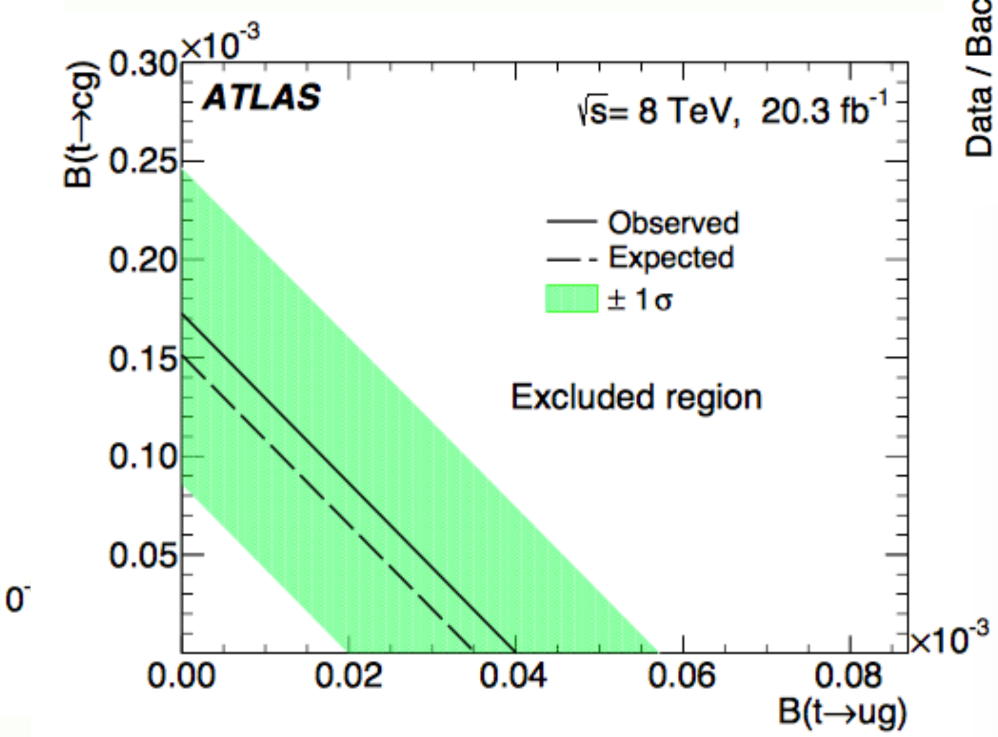
# Search for single top FCNC at ATLAS

- Search for flavor changing neutral currents (FCNC) in single top events [1]
- Event topology is a top quark leptonic decay
- Main background is W+jets
- **Most stringent limits to date on FCNC t→gq BR**



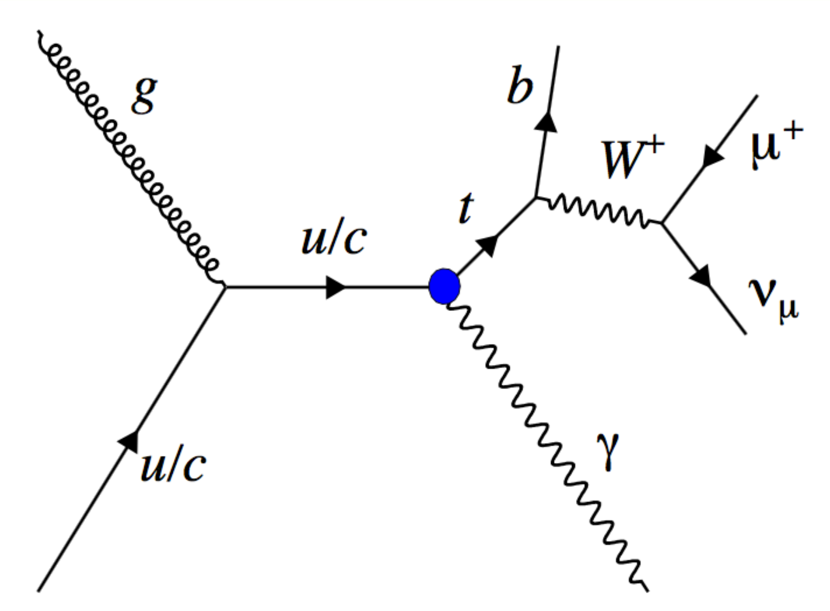




BR(t→gu) < 0.0040 % (obs)
0.0035 % (exp)
BR(t→gc) < 0.017 % (obs)
0.015 % (exp)

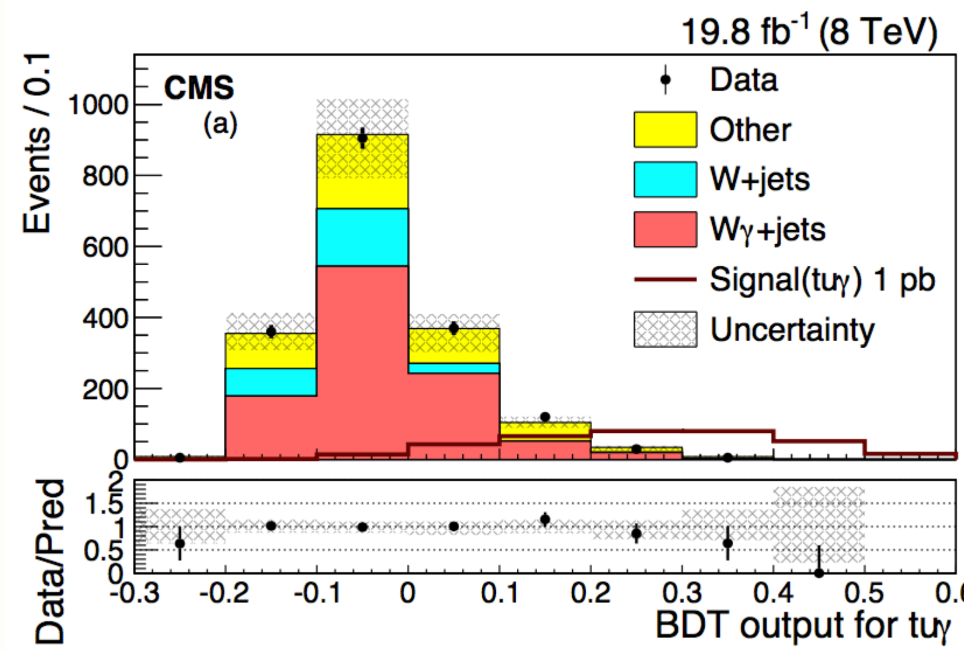

*[1] ATLAS Collaboration, Eur. Phys. J. C (2016) 76:55*

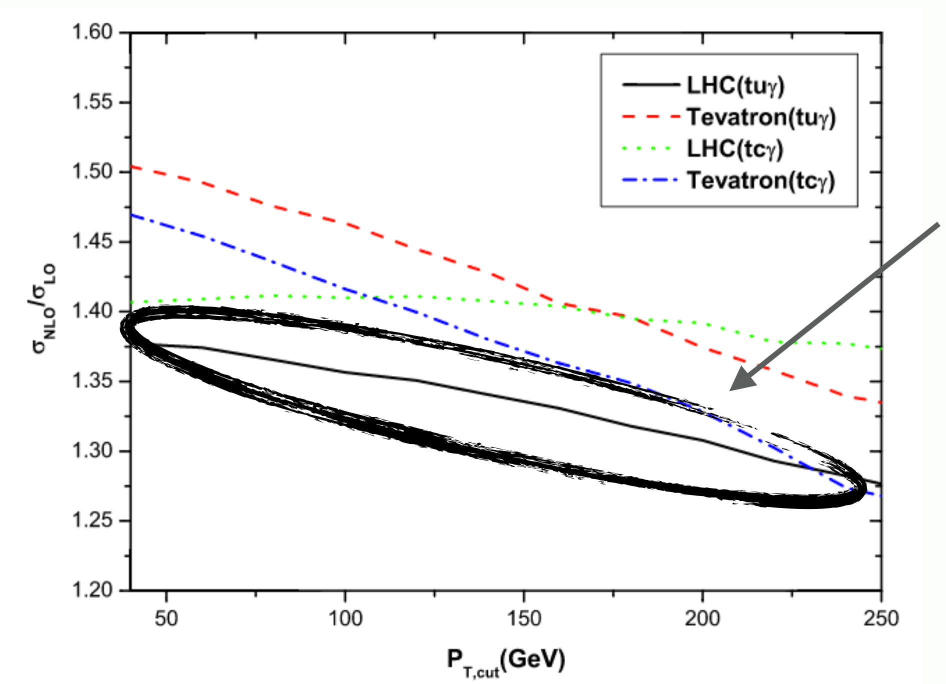
# Search for top+gamma FCNC at CMS




- Search for FCNC in single top+γ events [1]
- Main background is W(γ)+jets
- **The only existing analysis to search for t→γq decays**

**Wγ+jets and W+jets measured from data**
using cos(W,γ) template fit




FCNC NLO corrections are sizable (k≈1.375 @ 50GeV)

**Limits @NLO**

$\kappa_{u\gamma t}/\Lambda < 0.025\ \mathrm{TeV}^{-1}$

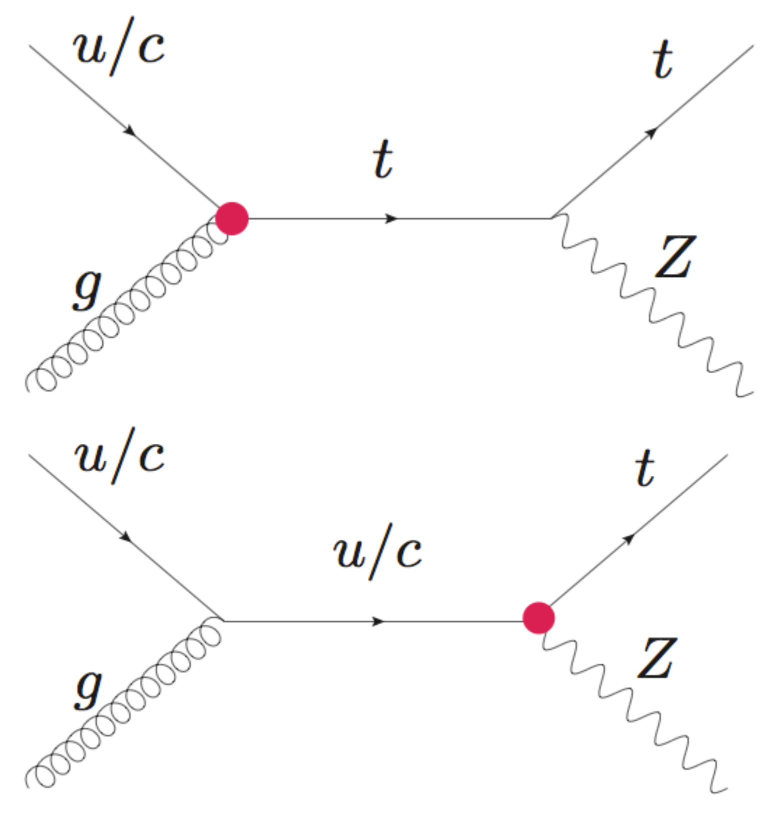
$\kappa_{c\gamma t}/\Lambda < 0.091\ \mathrm{TeV}^{-1}$

BR(t→γu) < 0.01 % (obs)
0.02 % (exp)

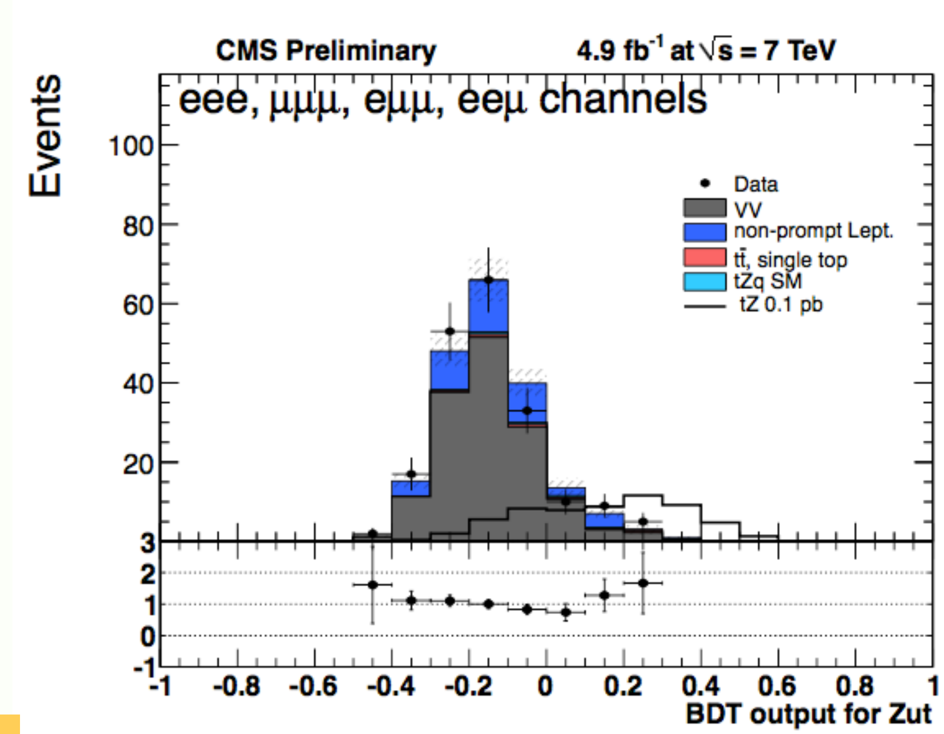
BR(t→γc) < 0.17 % (obs)
0.20 % (exp)

[1] CMS Collaboration, JHEP 04 (2016) 035

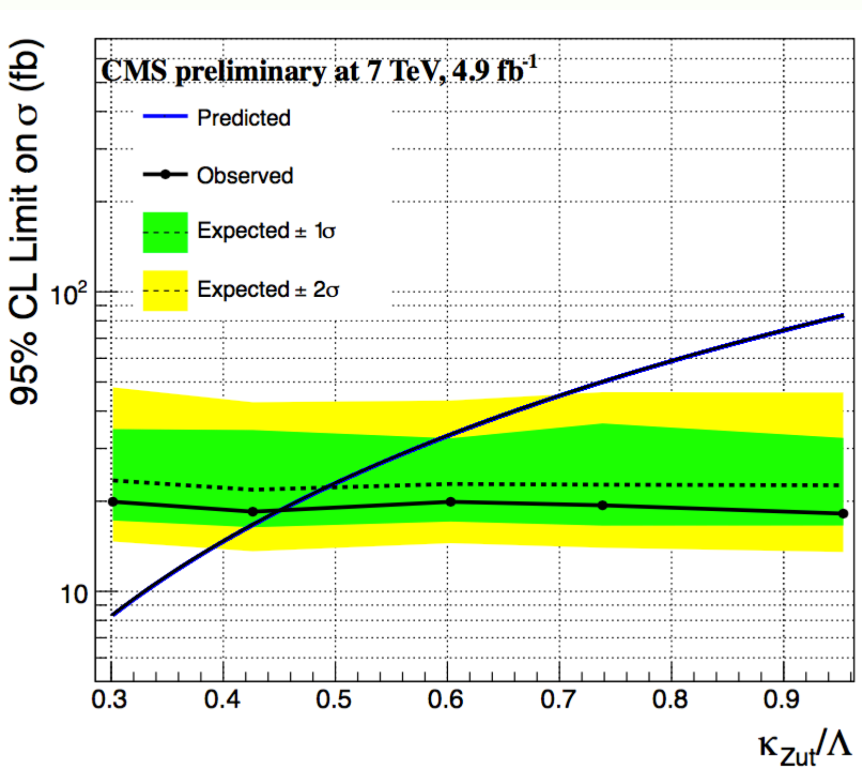
# Search for top+Z FCNC at CMS




- Search for FCNC in single top+Z events in trilepton channel [1]
- Main background is WZ +jets, fake leptons




$BR(t \to Zu) < 0.51$ % (obs)
0.61 % (exp)
$BR(t \to Zc) < 0.11$ % (obs)
0.16% (exp)




$BR(t \to gu) < 0.56$ % (obs)
0.56 % (exp)
$BR(t \to gc) < 0.71$ % (obs)
1.03 % (exp)

$\kappa_{Zut}/\Lambda < 0.45\ \mathrm{TeV}^{-1}$

$\kappa_{Zct}/\Lambda < 2.27\ \mathrm{TeV}^{-1}$

$\kappa_{ugt}/\Lambda < 0.10\ \mathrm{TeV}^{-1}$

$\kappa_{cgt}/\Lambda < 0.35\ \mathrm{TeV}^{-1}$

[1] CMS-PAS-TOP-12-021

# Summary on FCNC searches (references)


- HERA:
  ZEUS Collaboration, Phys. Lett. B708 (2012) 27; H1 Collaboration, Phys. Lett. B 678 (2009) 450; A.A. Ashimova and S.R. Slabospitsky, Phys. Lett. B668 (2008) 282
- LEP:
  ALEPH Collaboration, Phys. Lett. B543 (2002) 173; DELPHI Collaboration, Phys. Lett. B590 (2004) 21; OPAL Collaboration, Phys. Lett. B521 (2001) 181; L3 Collaboration, Phys. Lett. B549 (2002) 290; LEP Exotica WG, LEP Exotica WG 2001-01
- TEVATRON:
  CDF Collaboration, Phys. Rev. Lett. 101 (2008) 192002; DØ Collaboration, Phys. Lett. B701 (2011) 313; CDF Collaboration, Phys. Rev. Lett. 102 (2009) 151801; DØ Collaboration, Phys. Lett. B693 (2010) 81; CDF Collaboration, Phys. Rev. Lett. 80 (1998) 2525
- CMS:
  CMS Collaboration, Phys. Rev. Lett. 112 (2014) 171802; *CMS Collaboration, CMS-PAS-TOP-14-007*; *CMS Collaboration, CMS-PAS-TOP-14-003*; *CMS Collaboration, CMS-PAS-TOP-14-019*
- ATLAS:
  ATLAS Collaboration, arXiv:1509.00294; ATLAS Collaboration, arXiv:1508.05796; *ATLAS Collaboration, TOPQ-2014-14*