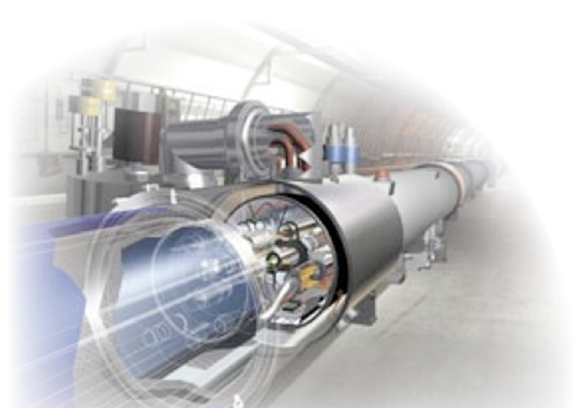
SM and BSM physics in single top quark at the LHC

LHCP2017 May 15-20, 2017. Shanghai, China

C. Escobar on behalf of the ATLAS and CMS Collaborations

Instituto de Física Corpuscular (IFIC) - CSIC/UV



Contents

- Single top-quark production cross-section:
  - *s*-channel (evidence at 8 TeV).
  - *tW* associated production (8, 13 TeV).
  - *t*-channel (inclusive at 8 TeV and fiducial at 13 TeV)
  - $|V_{tb}|$ measurements (8 TeV).
  - *t*-channel differential (8, 13 TeV).

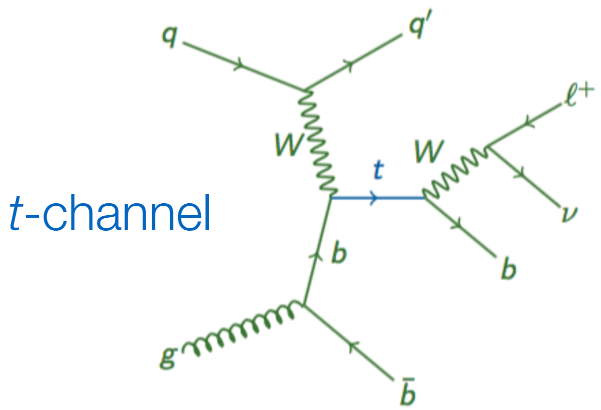
- Search for SM *tZq* (8 TeV).

- Top-quark polarization, *W* boson spin observables measurements and searches for anomalous couplings (7, 8TeV).

The top quark was discovered by CDF/D0, at Fermilab in 1995.

The single top-quark production was discovered in 2009 by CDF/D0 and observed in 2011 by ATLAS/CMS.

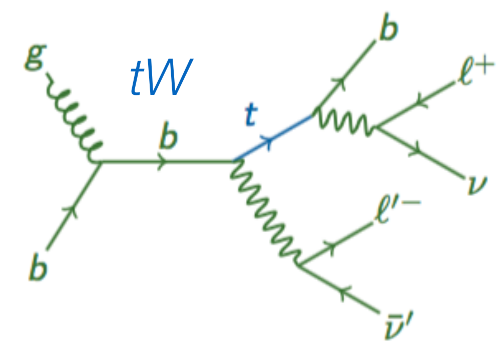
- Three production mechanisms (@ LO):



$\sigma_{t\text{-}ch}$ (8 TeV) = $87.7^{+3.4}_{-1.9}$ pb

$\sigma_{t\text{-}ch}$ (13 TeV) = $217.0^{+9.1}_{-7.7}$ pb

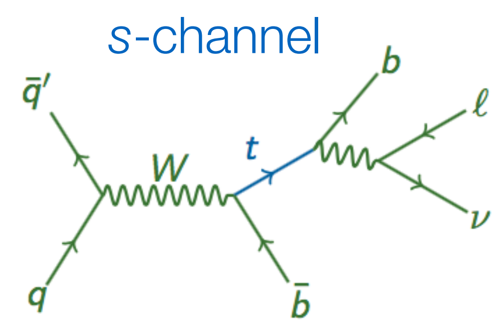
Golden channel



σ_{Wt} (8 TeV) = 22.4 ± 1.5 pb

σ_{Wt} (13 TeV) = 71.7 ± 3.8 pb

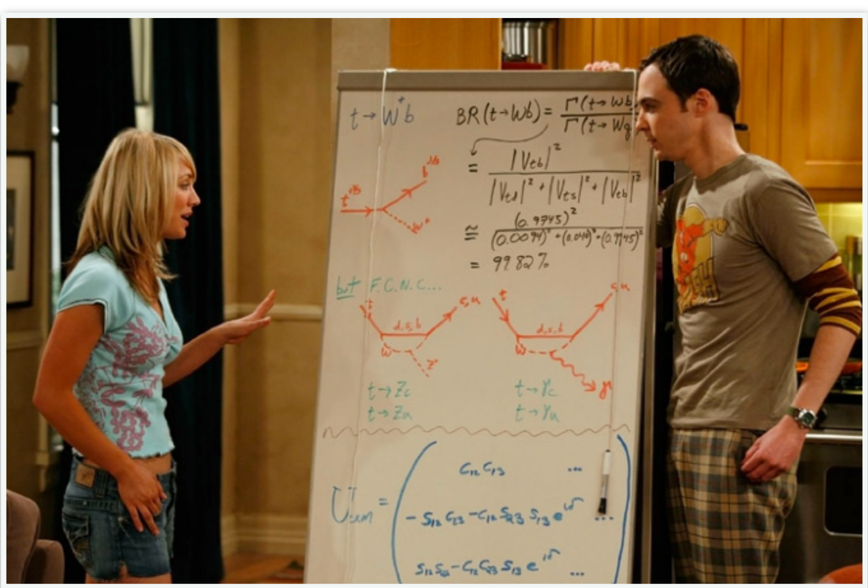
Observed at the LHC



$\sigma_{s\text{-}ch}$ (8 TeV) = 5.6 ± 0.2 pb

$\sigma_{s\text{-}ch}$ (13 TeV) = 10.3 ± 0.4 pb

Challenging at the LHC



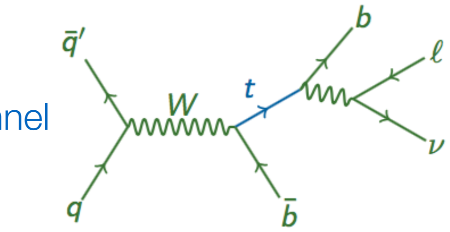
Why is the single top quark is interesting?

- Probe *Wtb* vertex: $|V_{tb}|$ and V—A structure.
- Top quark is polarised.
- Production modes sensitive to new physics.
- *Wtb* anomalous couplings / FCNC.
- Constrains PDFs and tune MC generators.
- Background for searches in Higgs and SUSY analyses.

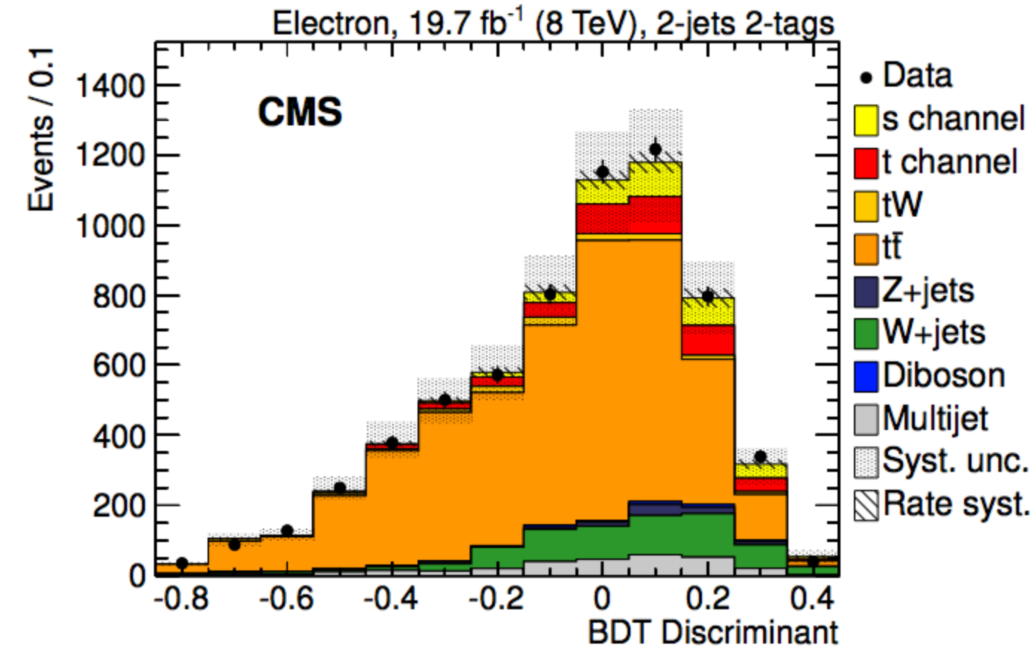
See Kevin's slides

5.1 fb^{-1}, 7 TeV
19.7 fb^{-1}, 8 TeV
JHEP09 (2016) 027

s-channel



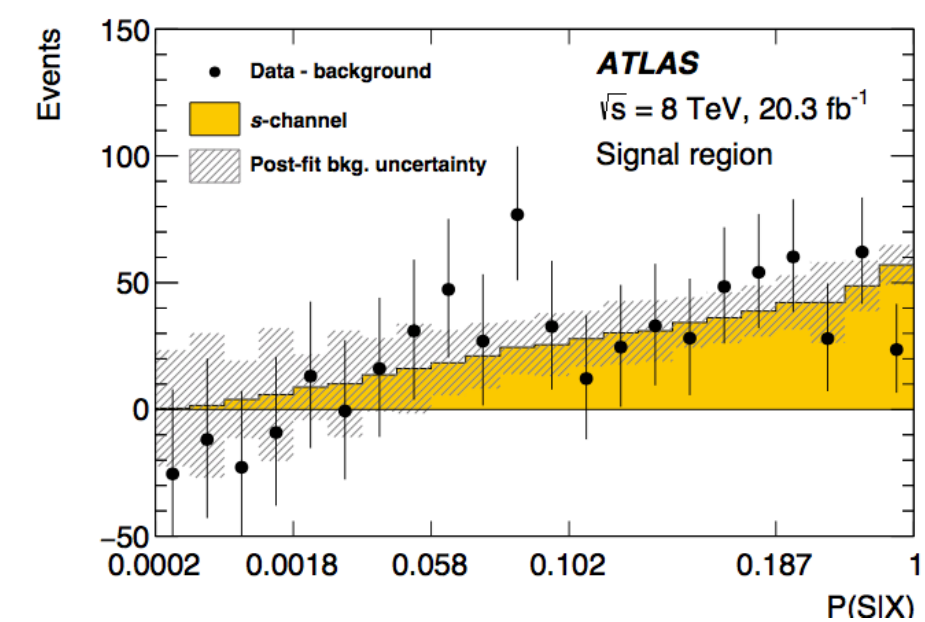
- BDT for further S/B separation.
  - Dedicated BDT to suppress QCD@8TeV (m_T(W)@7TeV).
- BDT to reject $t\bar{t}$ and *W*+jets.
- Combined maximum likelihood fit in SR and CRs.
- Dominant systematics: $t\bar{t}$ fact./renorm. scales (30%), JES/JER (35%).
- **Upper limit $\sigma_{s\text{-ch}}$ (7 TeV) at 95% CL is 31.4 pb.**
- **Upper limit $\sigma_{s\text{-ch}}$ (8 TeV) at 95% CL is 28.8 pb.**
- 2.5σ observed significance (1.1σ expected).



20.3 fb^{-1}, 8 TeV
PLB (2016) 228

$$P(S|X) = \frac{\sum_i \alpha_{S_i} \mathcal{P}(X|S_i)}{\sum_i \alpha_{S_i} \mathcal{P}(X|S_i) + \sum_j \alpha_{B_j} \mathcal{P}(X|B_j)}$$

- Matrix element method for S/B separation.
  - Build likelihood from partonic cross-sections of the hard scatter.
- Combined maximum likelihood fit to P(S|X) + lepton charge (CR).
- Dominant systematics: MC stat (12%), JER (12%) and t-ch. (11%).
- **$\sigma_{s\text{-ch}}$ = 4.8 ± 0.8 (stat.) $^{+1.6}_{-1.3}$ (syst.) pb (total unc.: 38%)**
- 3.2σ observed significance (3.9σ expected).
- **First evidence at the LHC.**

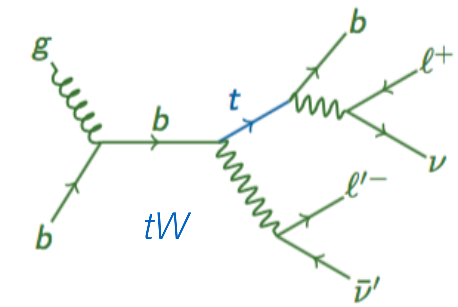


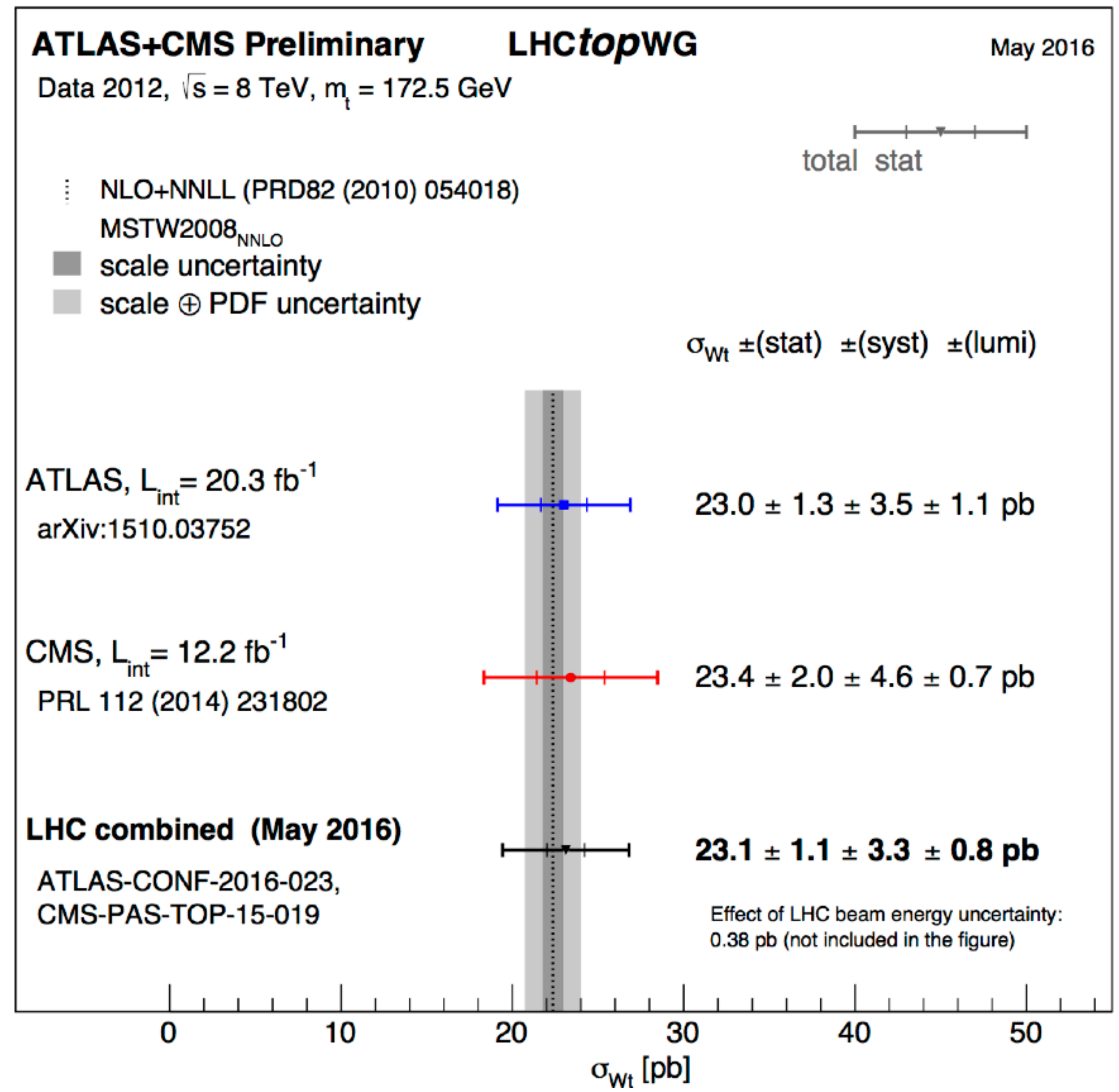
- *tW* cross-section measurement done by combining:
  - CMS: PRL112 (2014) 231802 (12.2 fb^{-1}, 8 TeV).
    - BDT for further S/B separation.
    - Maximum likelihood fit in SR and CR.
    - σ_{tW} = 23.4 ± 5.4 pb (total unc. 23%).
  - ATLAS: JHEP01 (2016) 064 (20.3 fb^{-1}, 8 TeV)
    - BDT for further S/B separation.
    - Profile likelihood fit in SR and CR.
    - σ_{tW} = 23.0 ± 1.3 (stat.)$^{+3.2}_{-3.5}$ (syst.) (total unc. 16%).
- BLUE method used for the combination.
- Dominant systematics:

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

ATLAS-CONF-2016-023

CMS-PAS-TOP-15-019

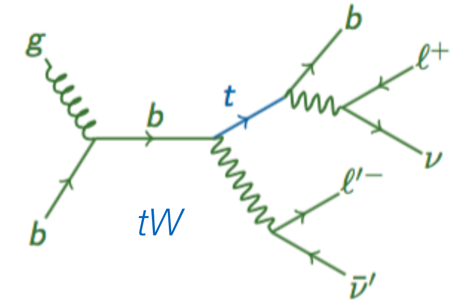




LHC combination:

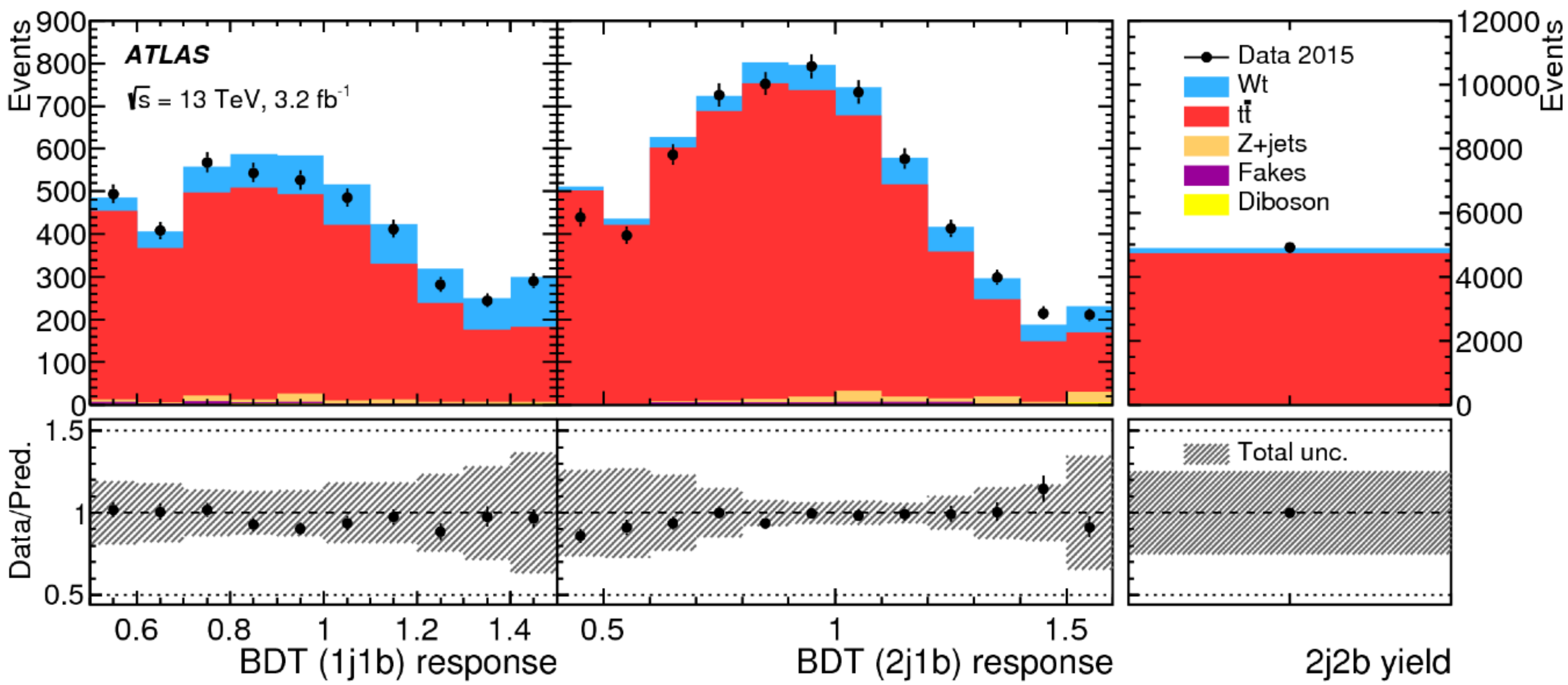
- **σ_{tW} = 23.1 ± 1.1 (stat) ± 3.3 (syst.) pb (total unc. 15%).**

3.2 fb[-1], 13 TeV
arXiv:1612.07231



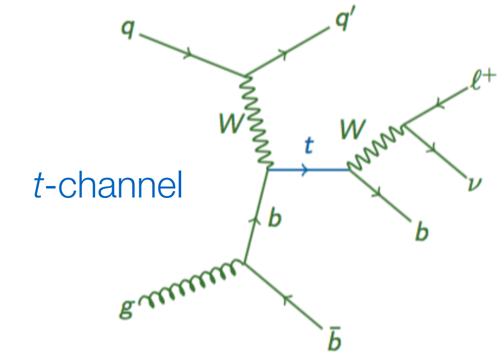
# b-tag jets	# jets: 1	# jets: 2
0	VR (1j0b) others	VR (2j0b) others
0	SR (1j1b) Wt-channel (20%)	SR (2j1b) Wt-channel (10%)
2		CR (2j2b) ttbar

- BDT for further S/B separation.
- 5 independent regions: 2 SR, 1 CR and 2 VR.
- Combined maximum likelihood fit in SRs and CRs (constrains $t\bar{t}$).



- Dominant systematics: JES (21%), NLO ME (18%), JER (9%) and PS (7%).
- **σ_{tW} = 94 ± 10 (stat.) $^{+28}_{-22}$ (syst.) ± 2 (lumi.) pb (total unc.: 32 %).**

Fiducial measurement is less sensitive to PDF, ME, PS and scale variations.



CMS: 19.7 fb^{-1}, 8 TeV
CMS-PAS-TOP-15-007

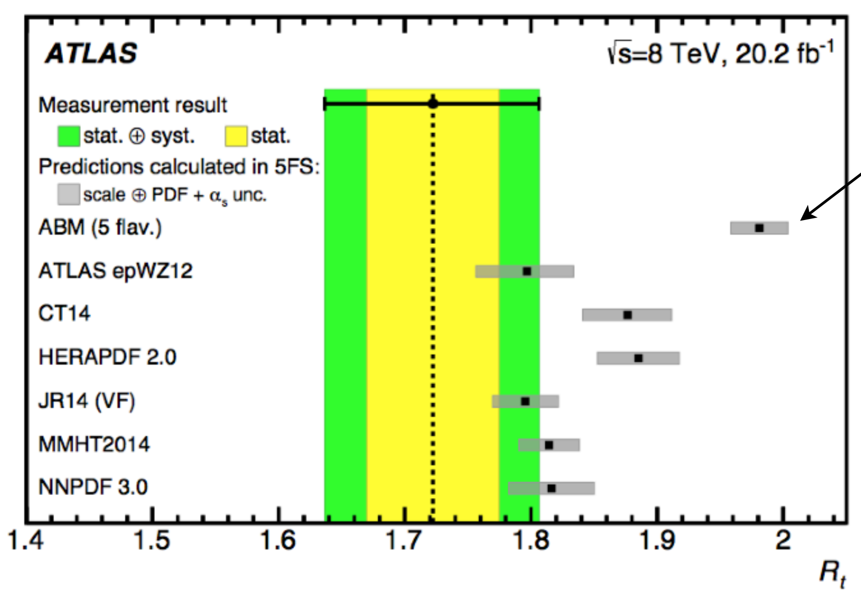
- **$\sigma_{t\text{-ch}}$ (fiducial) = 3.38 ± 0.32 pb (total unc. 9%).**

ATLAS: 20.2 fb^{-1}, 8 TeV
arXiv:1702.02859

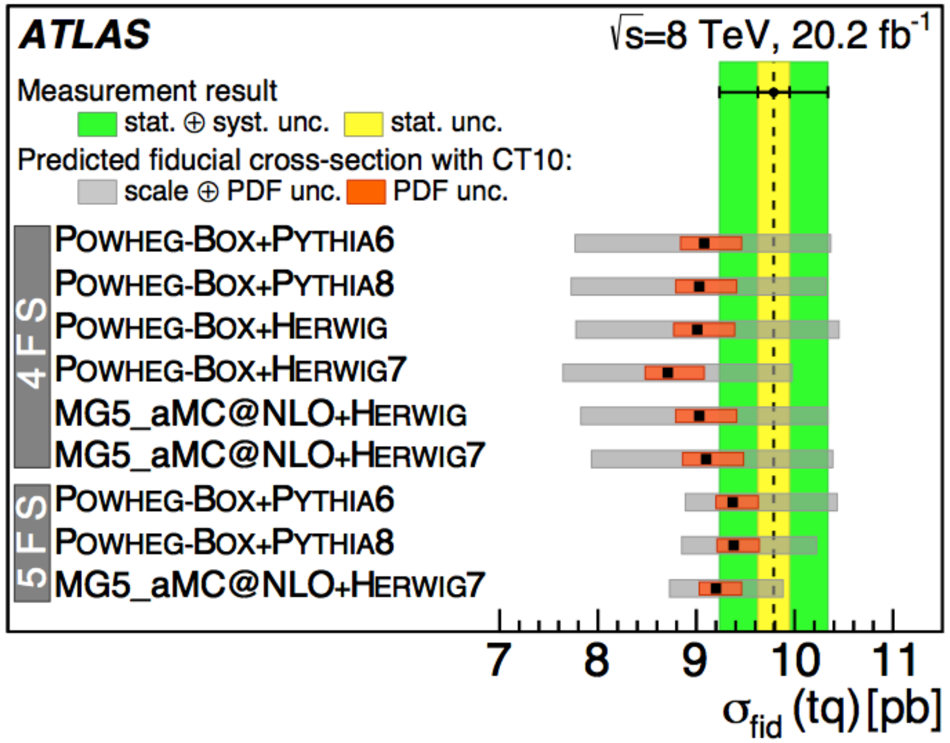
- NN for further S/B separation.
  - Cut on NN > 0.8.
- 3 independent regions: 1 SR, 1 CR and 1 VR.
  - separated for lepton charge.
- Maximum likelihood fit in SR.
- Dominant systematics: JES (4%).

- **$\sigma^{t}_{t\text{-ch}}$ (fiducial) = 9.78 ± 0.57 pb (total unc. 5.8%).**
- **$\sigma^{\bar{t}}_{t\text{-ch}}$ (fiducial) = 5.77 ± 0.45 pb (total unc. 7.8%).**

- **R_t = 1.72 ± 0.09 (total unc. 5%).**



Different treatment of the *b*-quark PDF and the value of α_S.



- Most predictions agree at the 1σ level with the measured value.
  - Predictions based on the 5FS feature strongly reduced scale uncertainties.

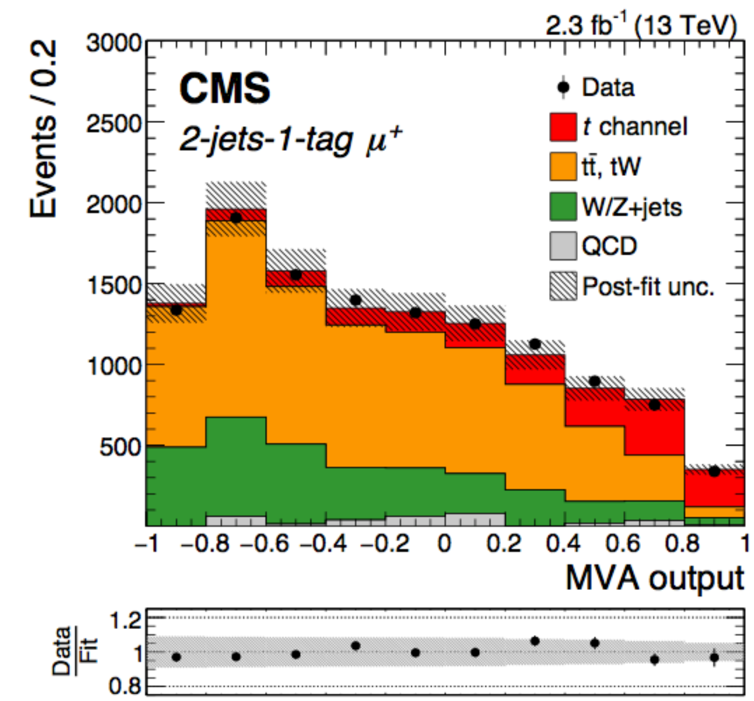
Carlos Escobar
Instituto de Física Corpuscular (IFIC) - CSIC/UV

See Nils' slides

2.3 fb^{-1}, 13 TeV
arXiv:1610.00678

- NN for further S/B separation.
- 4 independent regions: 1 SR, 2 CRs and 1 VR.
  - Separated for lepton charge.
- Maximum likelihood fit in SR and CRs (constrains $t\bar{t}$).
- Dominant systematics: *t*-channel and $t\bar{t}$ modelling (9%) and *t*-channel factor./renorm. scales (6%).

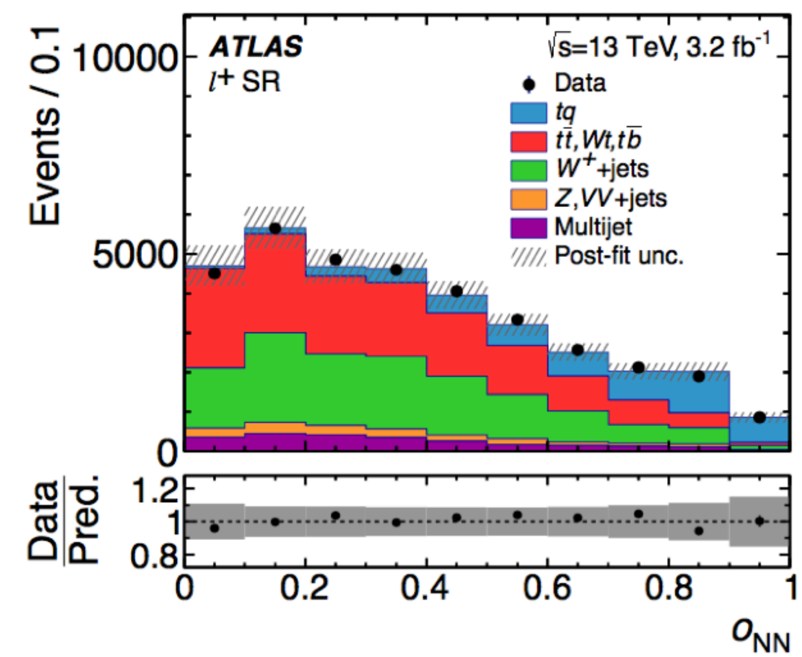
# b-tag jets \ # jets	1	2	3
0		VR (2j0b) W+jets	
1		SR (2j1b) t-channel	CR (3j1b) ttbar
2			CR (3j2b) ttbar



3.2 fb^{-1}, 13 TeV
JHEP04 (2017) 086

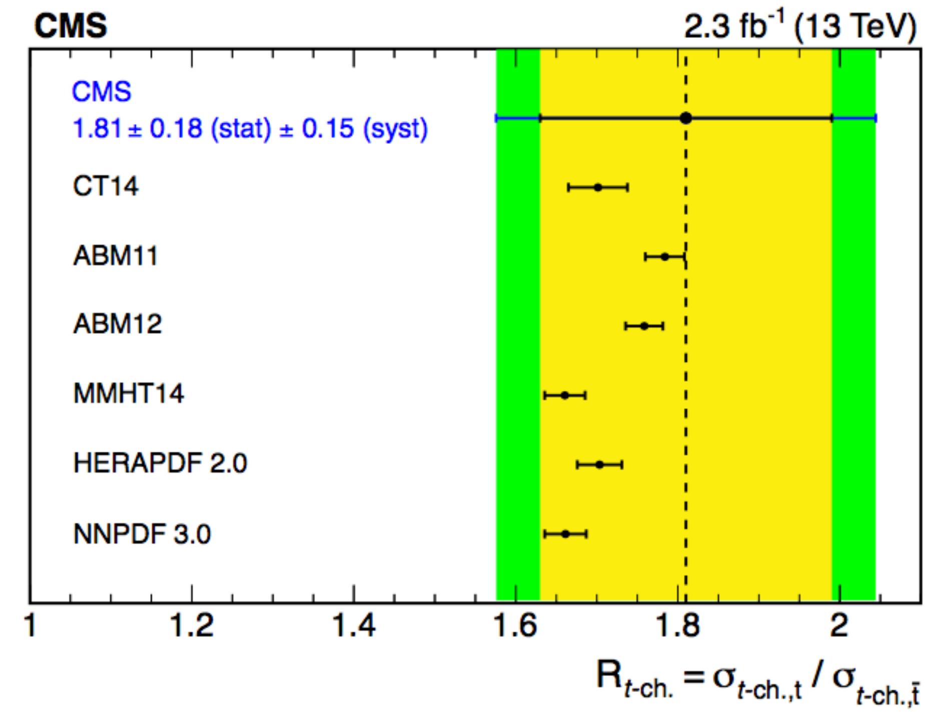
- NN for further S/B separation.
- 3 independent regions: 1 SR, 1 CR and 1 VR.
  - separated for lepton charge.
- Maximum likelihood fit in SR and CRs (constraint $t\bar{t}$).
- Dominant systematics: PS (14%) and *b*-tagging eff. (7%).

# b-tag jets \ # jets	1	2	3
0			
1 b-tagWP (85%)		VR ($2j1b_{loose}$) W+jets	
1 b-tagWP (60%)		SR (2j1b) t-channel	
2			VR (3j2b) ttbar



2.3 fb^{-1}, 13 TeV
arXiv:1610.00678

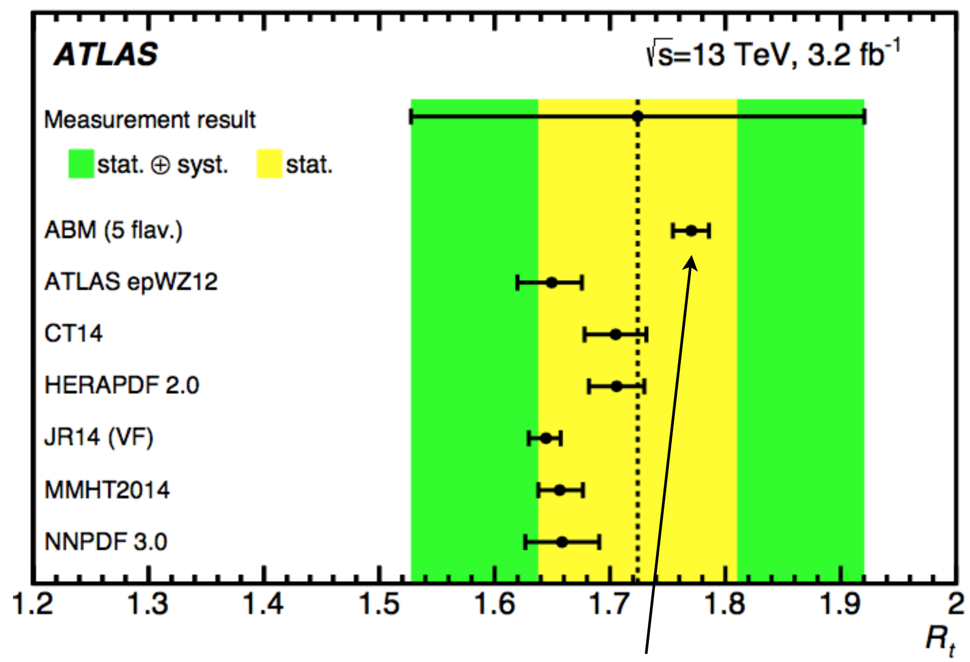
- $\sigma^{t}_{t\text{-ch}}$ = 150 ± 22 pb (total unc. 15%).
- $\sigma^{\bar{t}}_{t\text{-ch}}$ = 82 ± 16 pb (total unc. 20%).
- $\sigma_{t\text{-ch}}$ = 232 ± 13 (stat.) ± 28 (syst.) pb (total unc. 13%).
- R_t = 1.81 ± 0.18 (stat.) ± 0.15 (syst.) (total unc. 13%).



Uncertainty is too large to differentiate between predictions.

3.2 fb^{-1}, 13 TeV
JHEP04 (2017) 086

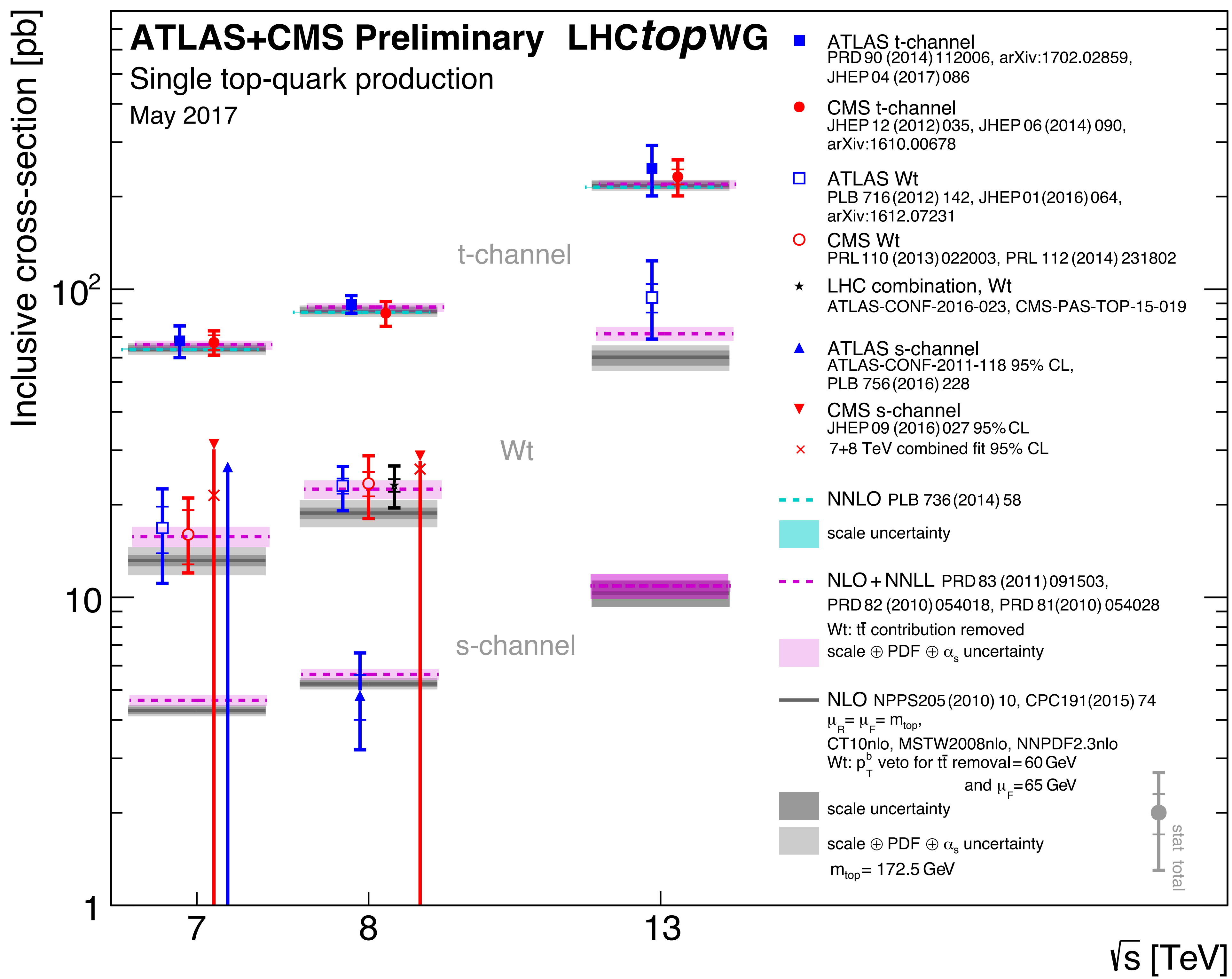
- $\sigma^{t}_{t\text{-ch}}$ = 156 ± 5 (stat.) ± 27 (syst.) ± 3 (lumi.) pb (total unc. 18%).
- $\sigma^{\bar{t}}_{t\text{-ch}}$ = 91 ± 4 (stat.) ± 18 (syst.) ± 2 (lumi.) pb (total unc. 20%).
- $\sigma_{t\text{-ch}}$ = 247 ± 6 (stat.) ± 45 (syst.) ± 5 (lumi.) pb (total unc. 19%).
- R_t = 1.72 ± 0.09 (stat.) ± 0.18 (syst.) (total unc. 12%).



Different treatment of the *b*-quark PDF and the value of α_S.

Generally:

- Generator uncertainties dominate.
- Agreement with SM predictions.



Cross-section results from all three single top-quark production processes are in agreement with the SM predictions.

- Single top-quark cross-section is proportional to $|V_{tb}|$:

$$|V_{tb} \cdot f_{LV}|^2 = \frac{\sigma^{obs.}}{\sigma^{theory}}$$

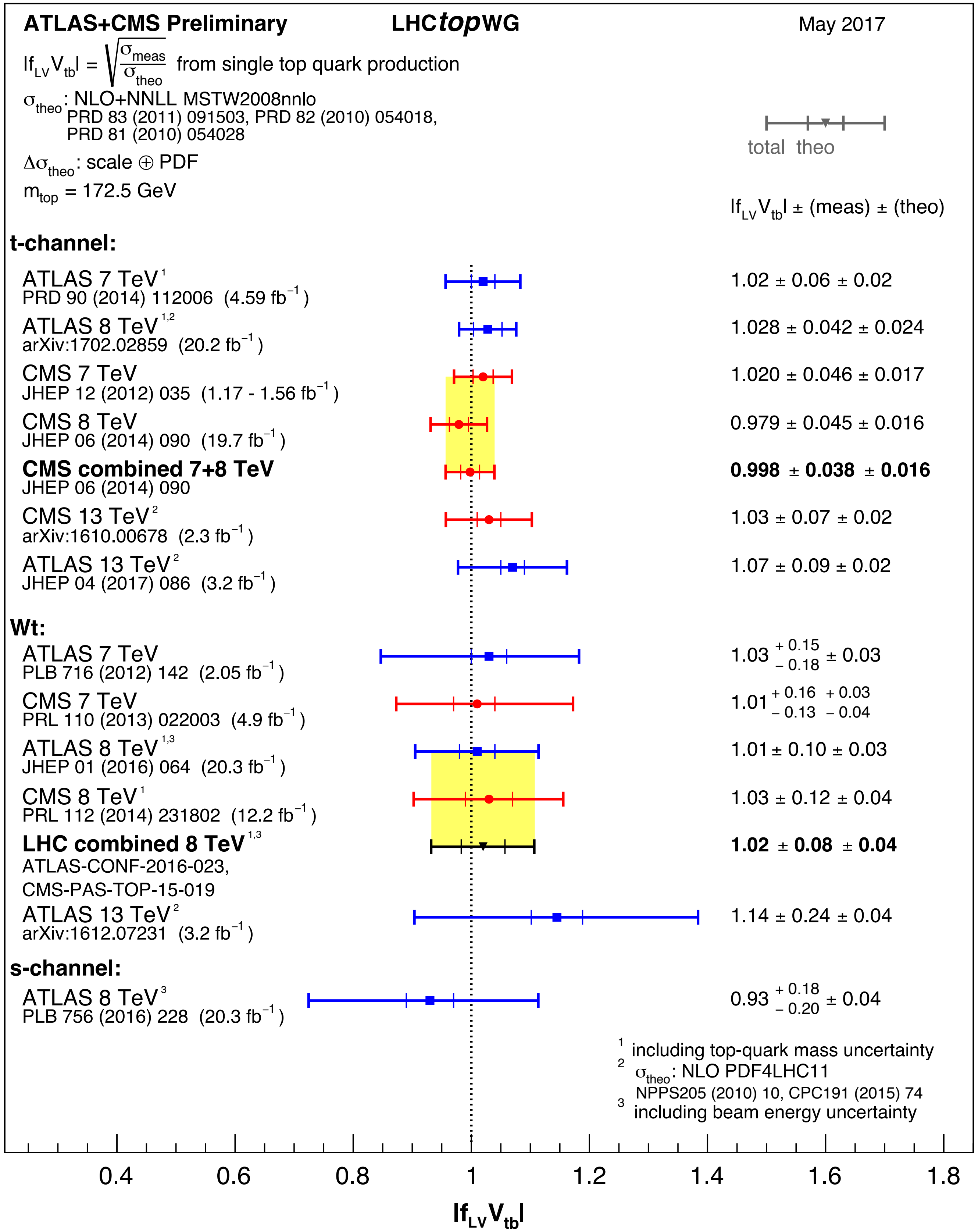
where f_{LV} is a (real) left-handed form factor that can encapsulate non-SM contributions.

- Independent of assumptions about the number of quark generations or about the unitarity of the CKM matrix.

Assumptions for the extraction:

- *Wtb* interaction is a SM-like left-handed weak coupling.
- $|V_{tb}| \gg |V_{td}|, |V_{ts}|$
- $BR(t \rightarrow Wb) = 1$.

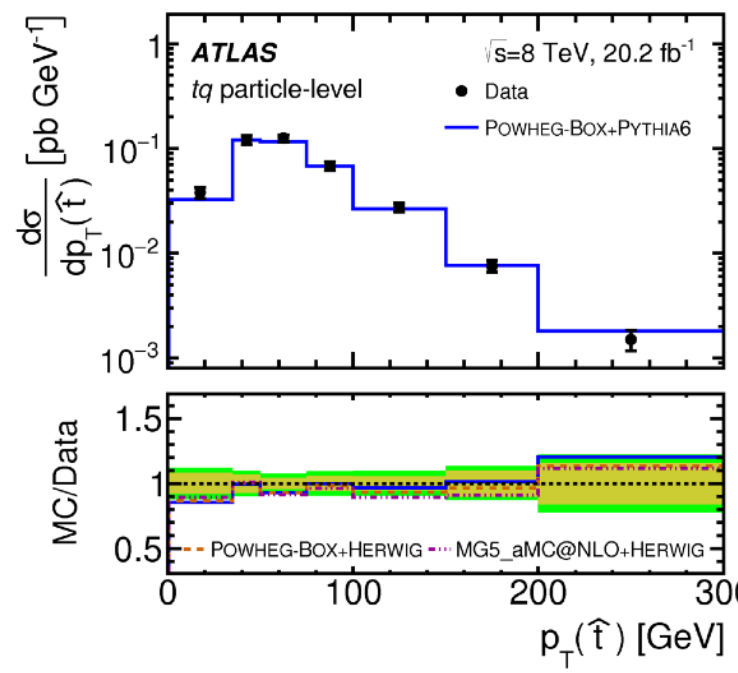
$|V_{tb}|$ results from all three single top-quark production processes are in agreement with the SM predictions.

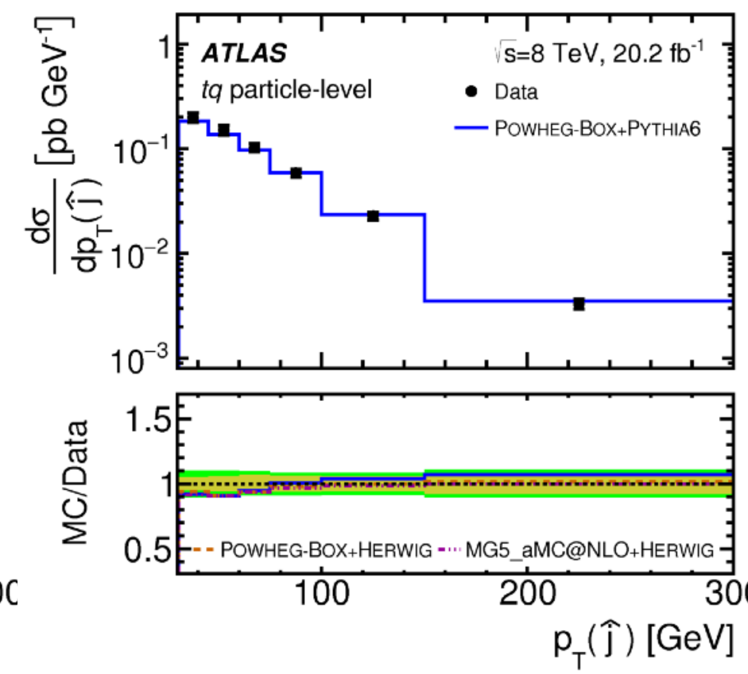


20.2 fb^{-1}, 8 TeV
arXiv:1702.02859

- Diff. cross-section measured as a function of:
  - p_T and *y* of top quark and top antiquark.
  - p_T and *y* for the forward light-jet.
- NN for further S/B separation.
  - Same NN as for the fiducial without the $\eta_{\text{light-jet}}$.
  - Cut on NN > 0.8.

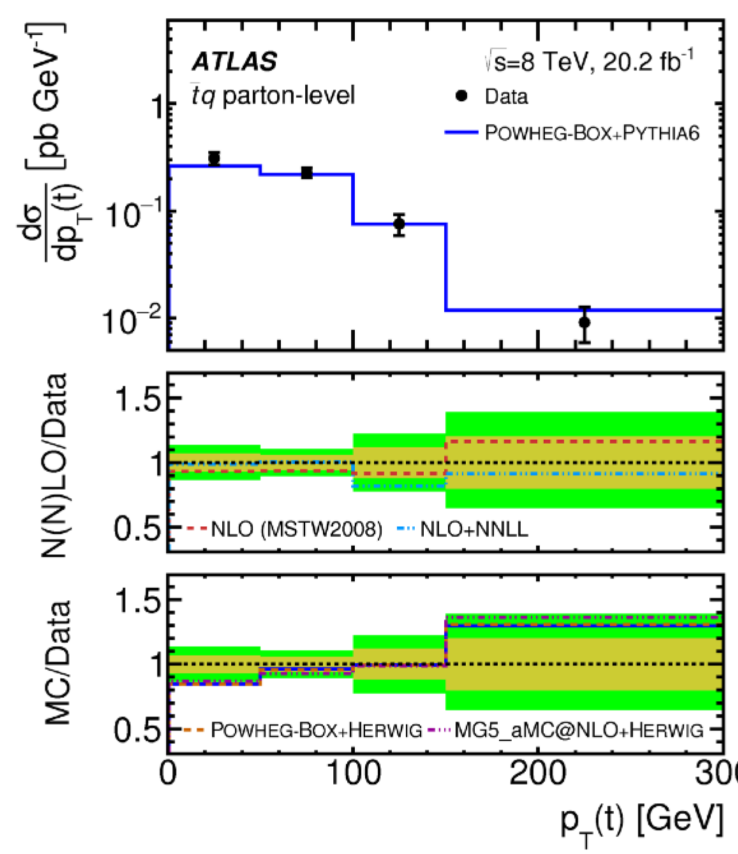
Parton level

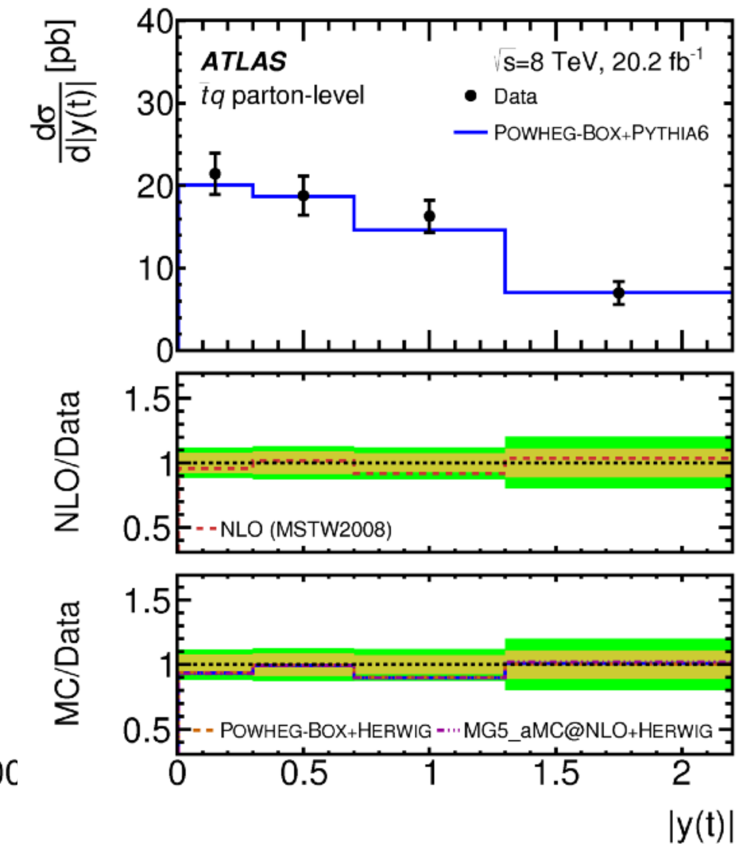




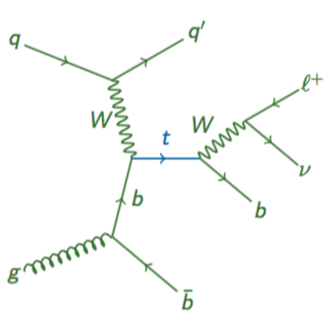
- Unfolding to parton and particle level.
- Dominant systematics:
  - JES calibration
  - *t*-ch. and $t\bar{t}$ modelling.

Particle level





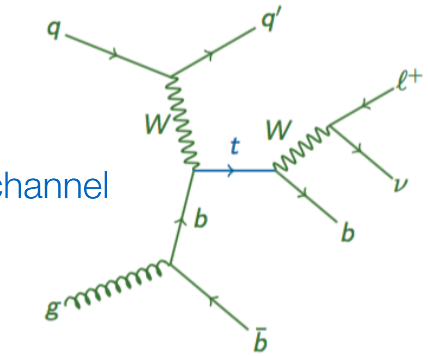
t-channel



NLO prediction by MCFM
Yellow bands: stat. unc.
Green bands: total unc.

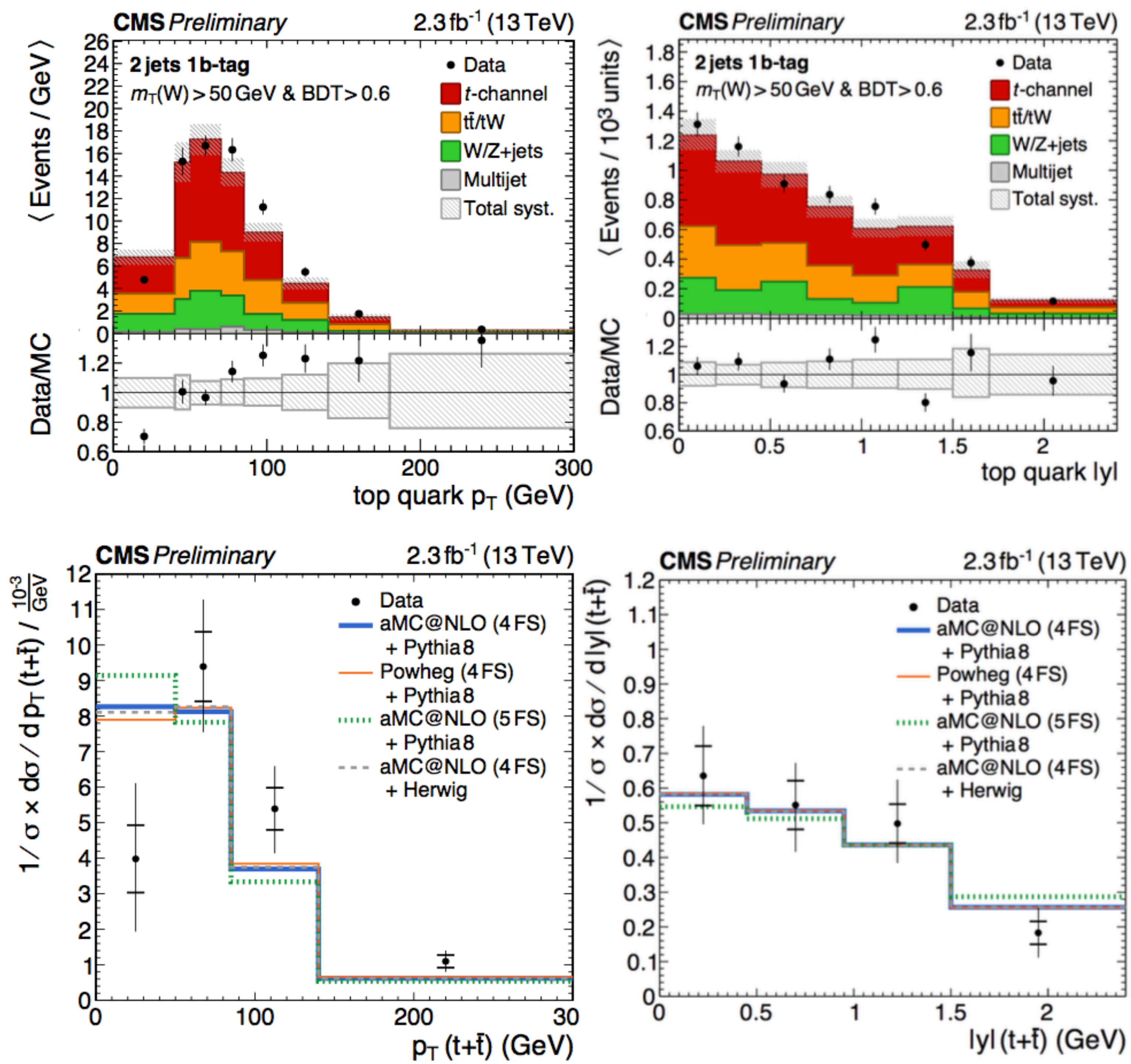
2.3 fb^{-1}, 13 TeV
CMS-PAS-TOP-16-004

t-channel



- Differential cross-section measured as a function of:
  - p_T and y of top quark and top antiquark.
- BDT for further S/B separation.
  - Cut on BDT> 0.6.

- Unfolding to parton level. (correct detector res./sel. eff.).
- Dominant systematics:
  - data statistics (10-25%)
  - *t*-ch. renorm./factor. scales(10-15%)
  - m_{top} variation (10-20%)
  - jet energy corrections (10-15%).

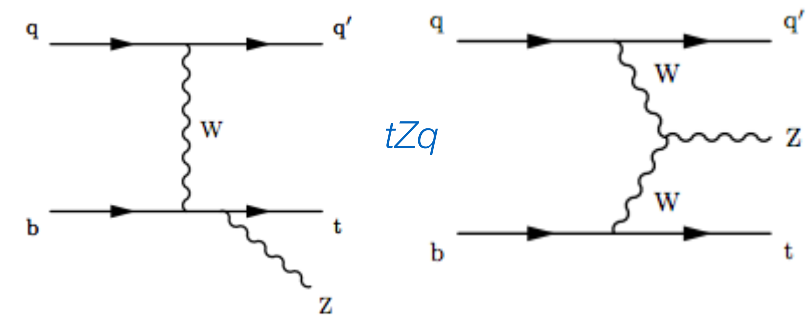


Parton level

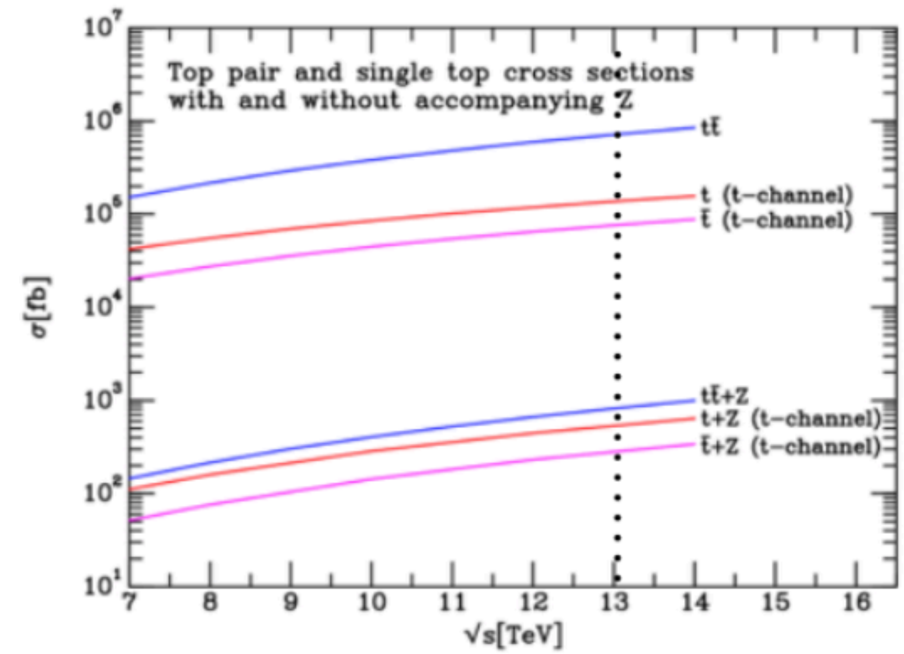
See Kevin's slides
See Maksim's slides

19,7 fb^{-1}, 8 TeV
arXiv:1702.01404

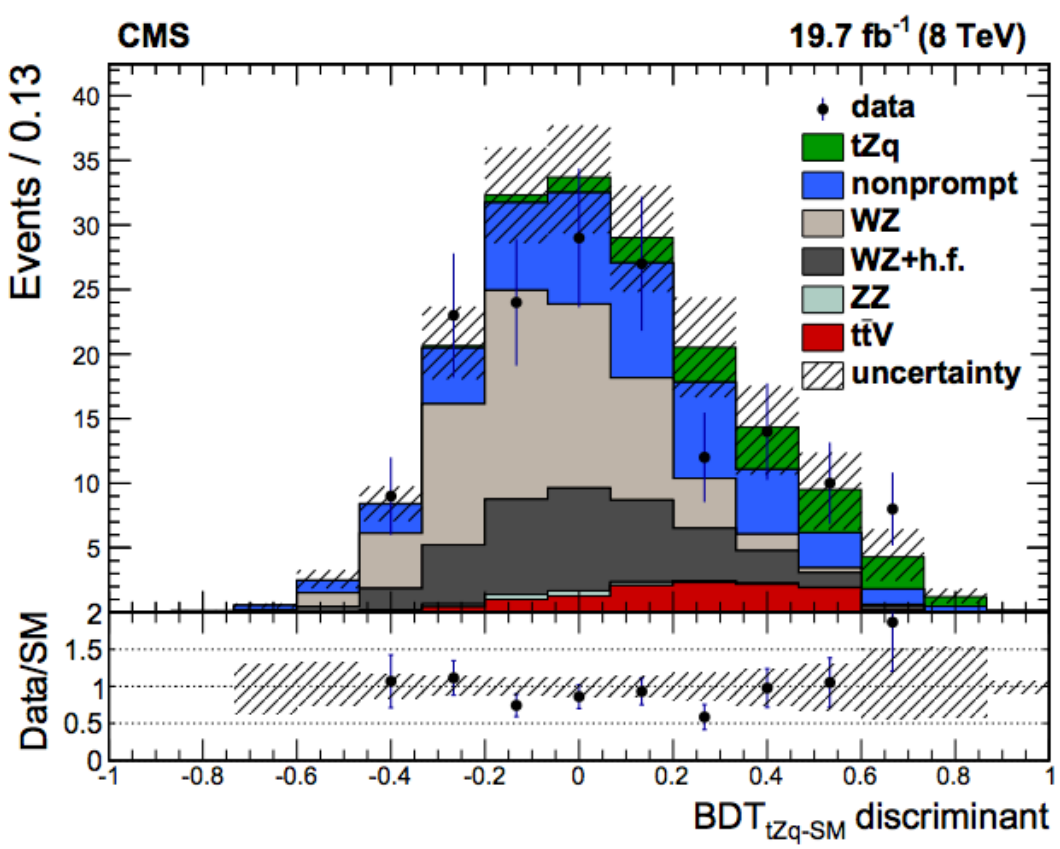
σ_{tZq} = 8.2 fb



- Search for rare process *tZq* → test of the SM and search for FCNCs.



- ***tZq* signature** (trileptonic decay):
  - 3 high-p_T isolated leptons.
  - 1 high-p_T and central |η| jet (*b*-jet).
  - 1 high-p_T and forward |η| jet (light jet).
  - E_T^{miss} from the neutrino.
- Main background: *WZ*.



- BDT for further S/B separation.
- Two regions (SR and CR).
- Fit to BDT discriminant.
- Final uncertainties driven by data statistics.
- **σ_{tZq} = 10 $^{+8}_{-7}$ (stat.+syst.) pb (total unc.: 80%).**
- 2.4σ observed significance (1.8σ expected).

95% exclusion limits of the *tZ*-FCNC couplings.

- BR(*t*→*Zu*) < 0.022% (expected 0.027%)
- BR(*t*→*Zc*) < 0.049% (expected 0.118%)

Top-quark polarization and W boson spin observables (8 TeV)

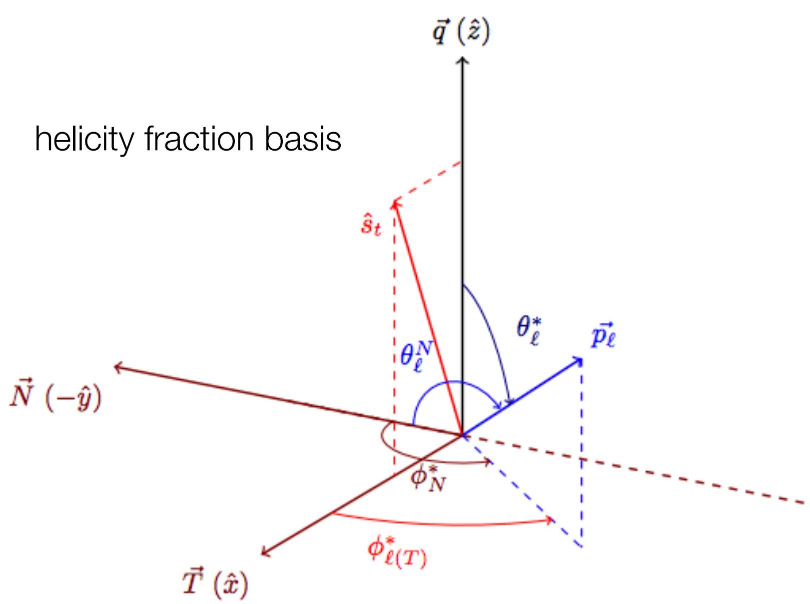
- Measurement of angular asymmetries (top-quark polarisation) and of the W boson spin observables with the SM-based unfolding to check the consistency with the SM predictions.

20.2 fb^{-1}, 8 TeV
JHEP04 (2017) 124

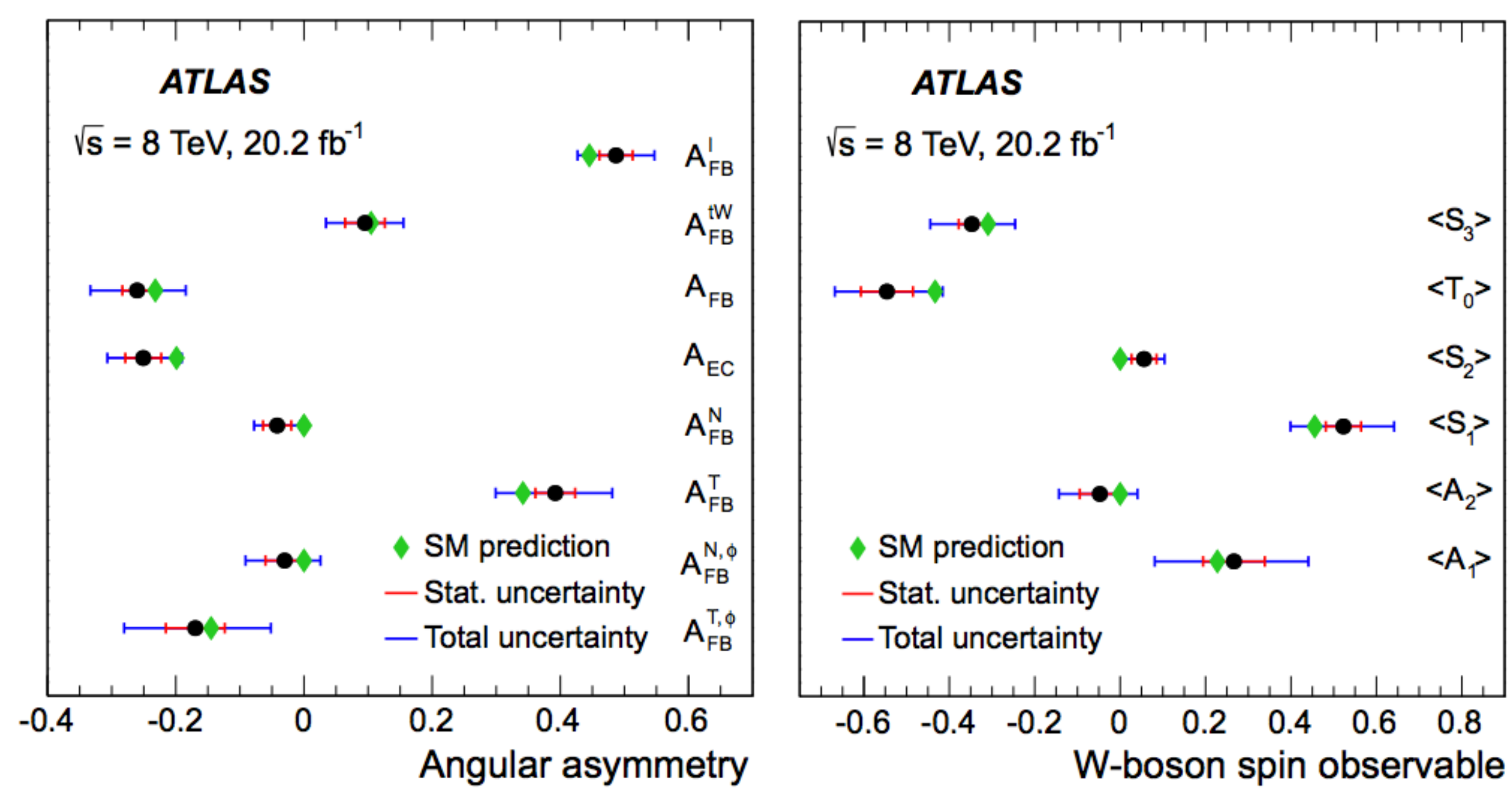
- Cut-based analysis for S/B separation.
- 4 independent regions.
- Unfolding done at parton level.
- Dominant systematics: $t\bar{t}$ modelling, JES, MC statistics.

Asymmetry	Angular observable	Polarisation observable	SM prediction
A_{FB}^{ℓ}	$\cos\theta_\ell$	$\frac{1}{2}\alpha_\ell P$	0.45
A_{FB}^{tW}	$\cos\theta_W \cos\theta_\ell^*$	$\frac{3}{8}P(F_R+F_L)$	0.10
A_{FB}	$\cos\theta_\ell^*$	$\frac{3}{4}\langle S_3\rangle = \frac{3}{4}(F_R-F_L)$	−0.23
A_{EC}	$\cos\theta_\ell^*$	$\frac{3}{8}\sqrt{\frac{3}{2}}\langle T_0\rangle = \frac{3}{16}(1-3F_0)$	−0.20
A_{FB}^{T}	$\cos\theta_\ell^T$	$\frac{3}{4}\langle S_1\rangle$	0.34
A_{FB}^{N}	$\cos\theta_\ell^N$	$-\frac{3}{4}\langle S_2\rangle$	0
$A_{FB}^{T,\phi}$	$\cos\theta_\ell^* \cos\phi_T^*$	$-\frac{2}{\pi}\langle A_1\rangle$	−0.14
$A_{FB}^{N,\phi}$	$\cos\theta_\ell^* \cos\phi_N^*$	$\frac{2}{\pi}\langle A_2\rangle$	0

helicity fraction basis



αP = 0.97 ± 0.05 (stat.) ± 0.11(syst.)



From A^N_{FB} and A^l_{FB} (measured independently of any assumption on Im[g_R]) and assuming $V_L = 1$ and $V_R = g_L = \mathrm{Re}[g_R] = 0$:

Im[g_R] ∈ [−0.18, 0.06] @ 95 C.L.

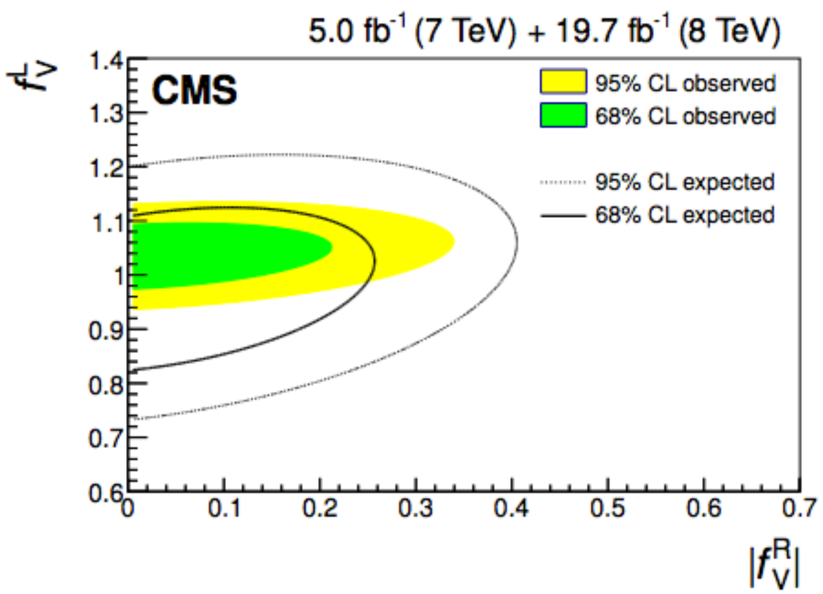
- In agreement with SM predictions.

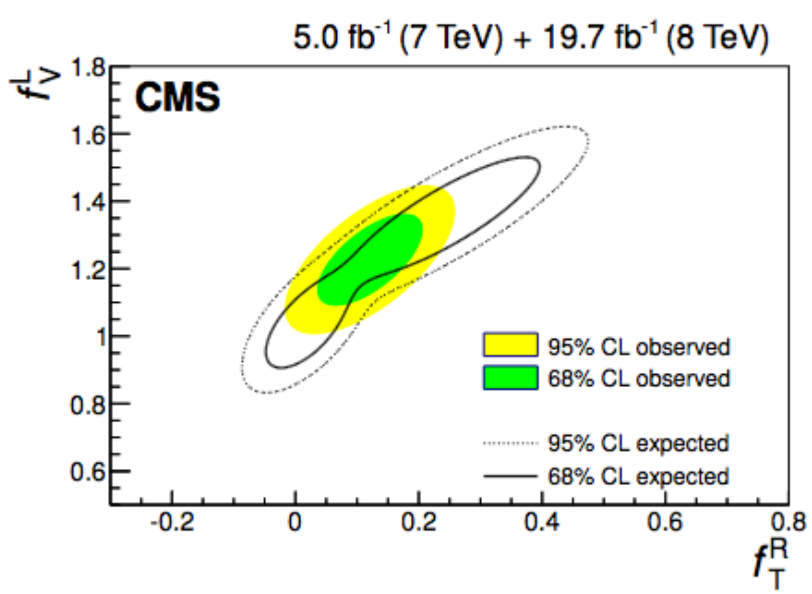
5.0 fb^{-1}, 7 TeV
19,7 fb^{-1}, 8 TeV
JHEP02 (2017) 028

- Using *t*-channel events (muon channel only and 2 or 3 jets).

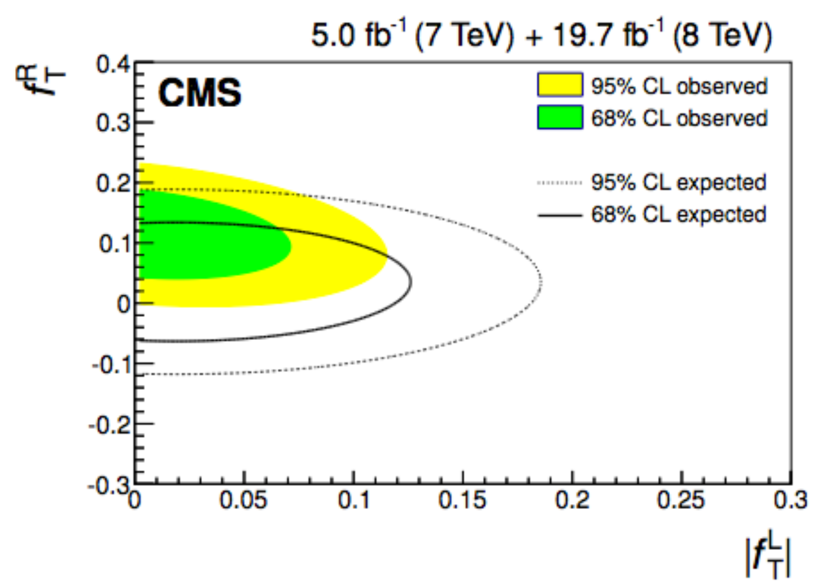
- Bayesian NN (BNN) for further S/B separation.
- Dedicated anomalous *Wtb* BNNs are used in each scenario.
- Limits are extracted from a simultaneous two- or three-dimensional fit to the SM BNN and (real-only) anomalous *Wtb* BNNs outputs.
  - Assumption: remaining couplings set to the SM values.

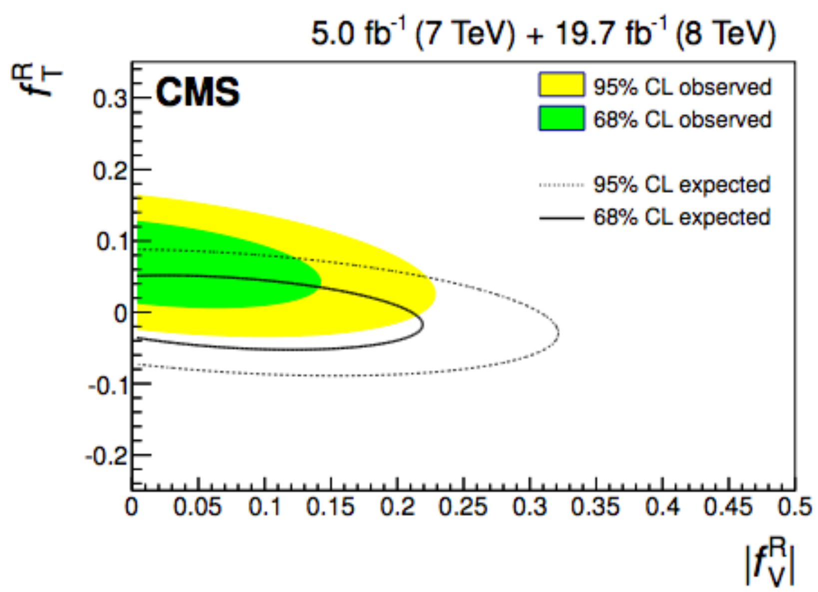
Two-dimensional fit.





Three-dimensional fit.





$|V_R| < 0.16$ @ 95 C.L.
$|g_L| < 0.057$ @ 95 C.L.
$g_R \in [-0.049, 0.048]$ @ 95 C.L.

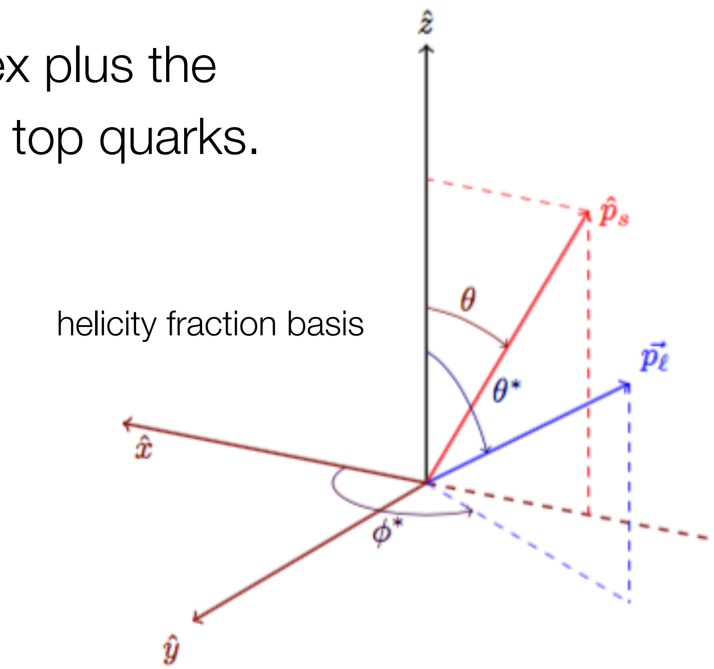
95% CL, FCNC upper limits:
- BR($t \to ug$) $< 2.0 \times 10^{-5}$.
- BR($t \to cg$) $< 4.1 \times 10^{-4}$.

- In agreement with SM predictions.

Complete description of the full space of anomalous couplings governing the *Wtb* vertex plus the top-quark polarisation by using the normalised triple-differential (θ, θ^*, ϕ^*) decay rate of top quarks.

$$\begin{aligned}
\varrho(\theta,\theta^*,\phi^*;P) = \frac{1}{N}\frac{d^3N}{d(\cos\theta)d\Omega^*} &= \frac{1}{8\pi}\Bigg\{\frac{3}{4}\left|A_{1,\frac{1}{2}}\right|^2(1+P\cos\theta)(1+\cos\theta^*)^2 \\
&+ \frac{3}{4}\left|A_{-1,-\frac{1}{2}}\right|^2(1-P\cos\theta)(1-\cos\theta^*)^2 \\
&+ \frac{3}{2}\left(\left|A_{0,\frac{1}{2}}\right|^2(1-P\cos\theta)+\left|A_{0,-\frac{1}{2}}\right|^2(1+P\cos\theta)\right)\sin^2\theta^* \\
&- \frac{3\sqrt{2}}{2}P\sin\theta\sin\theta^*(1+\cos\theta^*)\,\mathrm{Re}\left[e^{i\phi^*}A_{1,\frac{1}{2}}A^*_{0,\frac{1}{2}}\right] \\
&- \frac{3\sqrt{2}}{2}P\sin\theta\sin\theta^*(1-\cos\theta^*)\,\mathrm{Re}\left[e^{-i\phi^*}A_{-1,-\frac{1}{2}}A^*_{0,-\frac{1}{2}}\right]\Bigg\} \\
&= \sum_{k=0}^{1}\sum_{l=0}^{2}\sum_{m=-k}^{k} a_{k,l,m}M^m_{k,l}(\theta,\theta^*,\phi^*),
\end{aligned}$$

Finite series of (orthonormal) *M*-functions.



20.2 fb^{-1}, 8 TeV
Preliminary

- Helicity amplitudes ($A_{\lambda b,\lambda W}$) from the $t \to Wb$ transition.
- Relative phases can only be measured with polarised top quarks (i.e. in single top-quark events).

Only nine of the coefficients $a_{k,l,m}$ are nonzero and can be parameterised by three amplitude fractions and two phases:

- 3 observable amplitude fractions: f_1, f_1^+, f_0^+.
- 1 observable phase: δ_-.
- 1 likely unobservable phase: δ_+.
- 1 observable "nuisance" parameter (P).

From f_1, f_1^+, traditional helicity fractions (F_+, F_-, F_0) can be extracted, while f_0^+ has not been measured before! F_0 only measures combinations of fractions but this analysis separates them.

Non-zero phase could imply CP-violation (at first order).

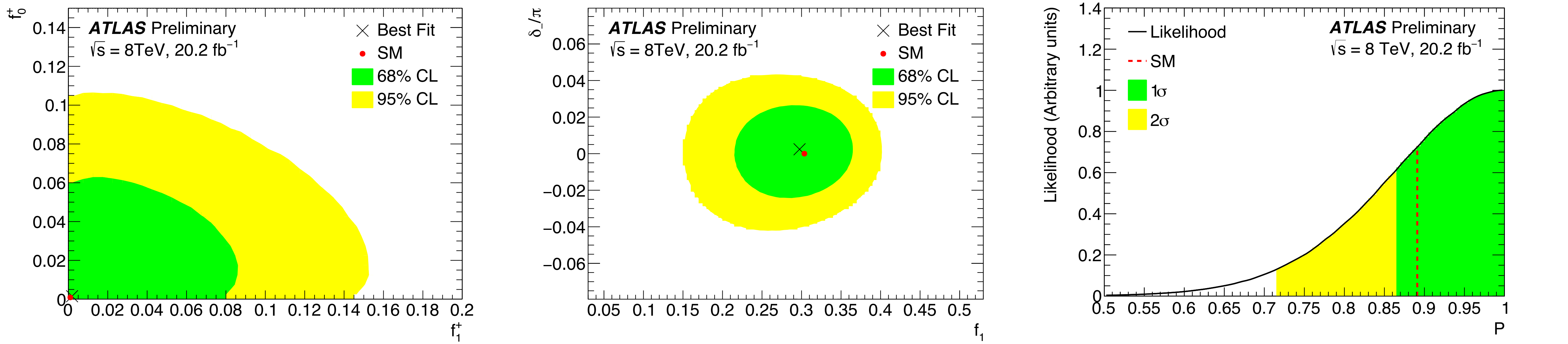
No sensitivity to this parameter since it is related to right-handed *b*-quarks.

- Detector effects are deconvolved from data by measuring differential rates using Fourier techniques.
- All amplitudes and phases (and couplings) + P are determined simultaneously and include all correlations.

20.2 fb^{-1}, 8 TeV
Preliminary

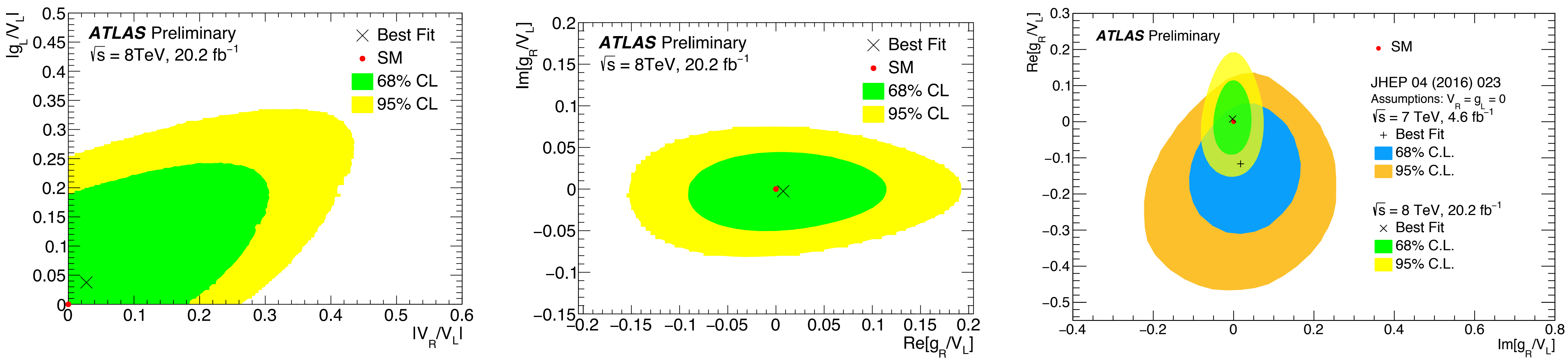
Global fit → Likelihood function with all correlations (covariance matrix).

- Distributions are obtained from numerical calculations of the likelihood function.



Interpretation in terms of anomalous couplings by propagating the statistical and systematic uncertainties.

- Limits are placed simultaneously on the possible complex values of the ratio of the anomalous couplings.
- No assumptions on values of the other anomalous couplings.



- In agreement with SM predictions.

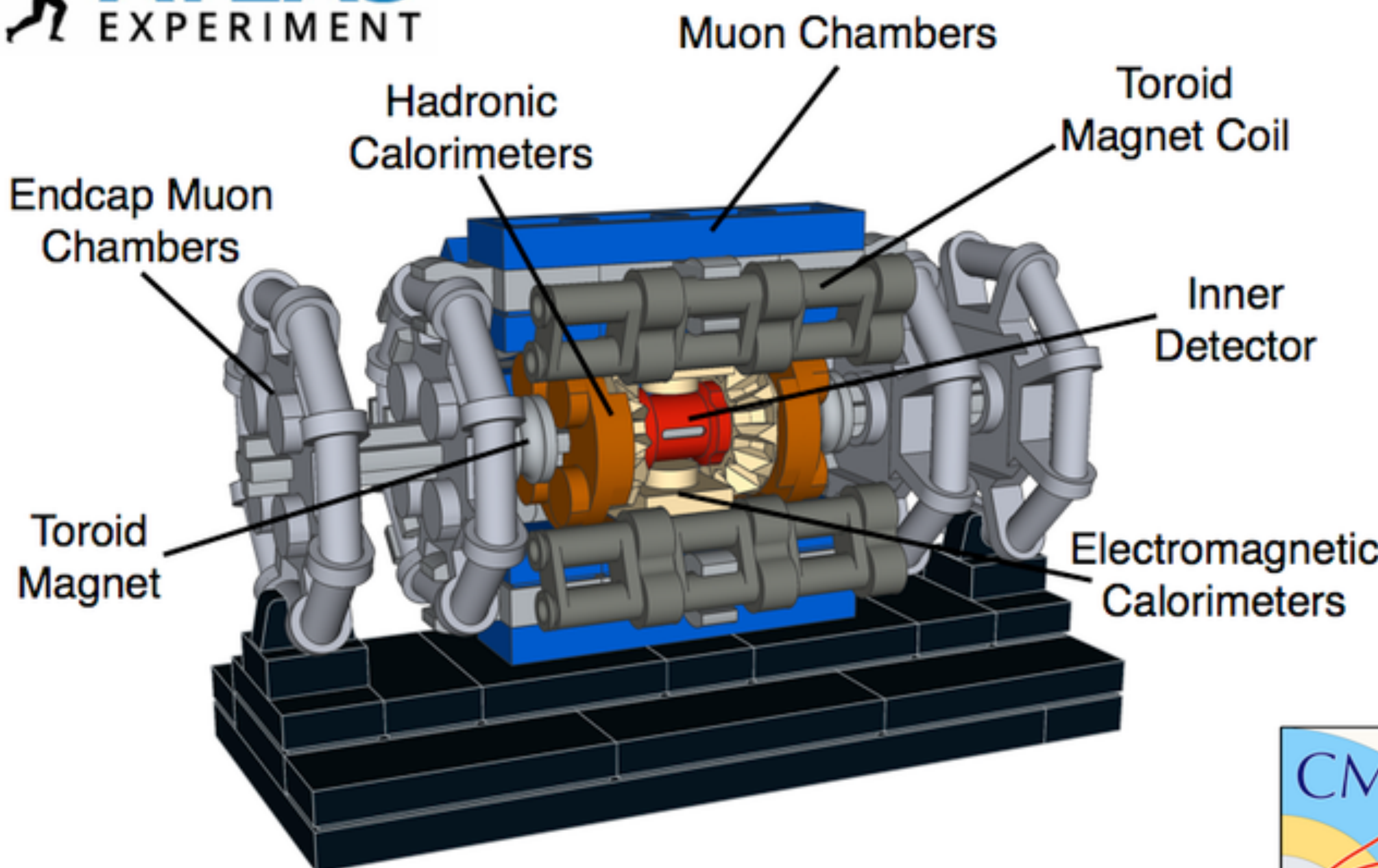
- LHC experiments are performing extensive studies using single top-quark events.

- Cross-sections measured in all three single top-quark signatures.
- Differential measurements of the *t*-channel cross-section.
- Measuring top-quark polarisation.
- Search for SM *tZq*.
- Searches for anomalous couplings.

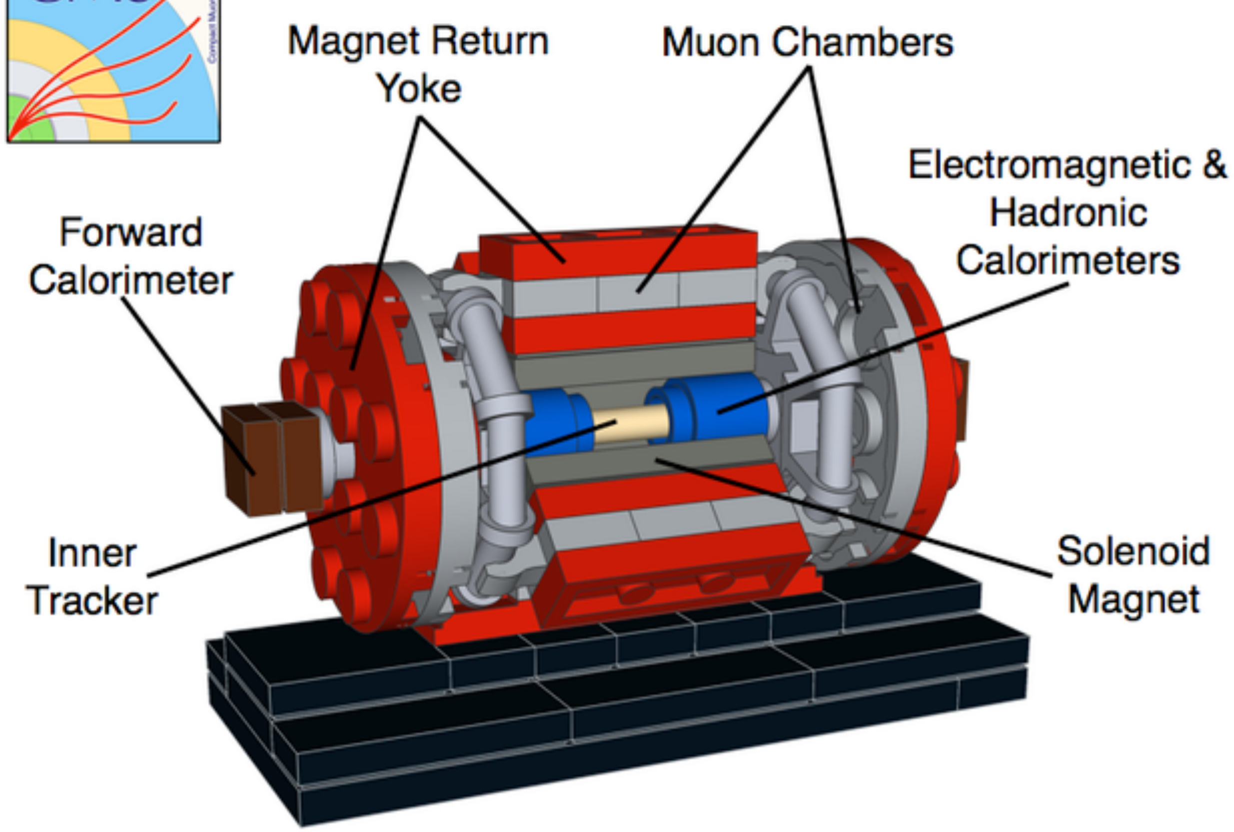
- All measurements are so far consistent with the SM predictions.
    - No sign of new physics has been found yet.

- More results will arrive soon! Stay tuned!
    - ATLAS Top Physics Results: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TopPublicResults.
    - CMS Top Physics Results: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsTOP.

Backup slides



ATLAS (general purpose detector)
- Length: 44 m, diameter: 25 m
- Mass: ~7.0 ktons
- Two magnet fields:
  - Solenoid (ID): 2 T
  - Toroid (Muon System): 2-8 Tm



CMS (general purpose detector)
- Length: 21 m, diameter: 15 m
- Mass: ~ 12.5 ktons
- Solenoid: 4 T

The top quark was discovered by CDF/D0, at Fermilab in 1995.

The single top-quark production was discovered in 2009 by CDF/D0 and observed in 2011 by ATLAS/CMS.

The LHC is a top-quark factory:

- Tevatron Run-II (10^{32} cm^{-2} s^{-1} @ 1.96 TeV): ~1 single top quark/hr.
- LHC @ low luminosity (10^{32} cm^{-2} s^{-1} @ 7 TeV): ~40 single top quark/hr.
- LHC @ design luminosity (10^{34} cm^{-2} s^{-1} @ 14 TeV): ~4k single top quark/hr.
- Top-quark prod. is dominated by gluon fusion (~85% $gg \rightarrow tt$, ~15% $qq \rightarrow tt$).

Top quark unique features:

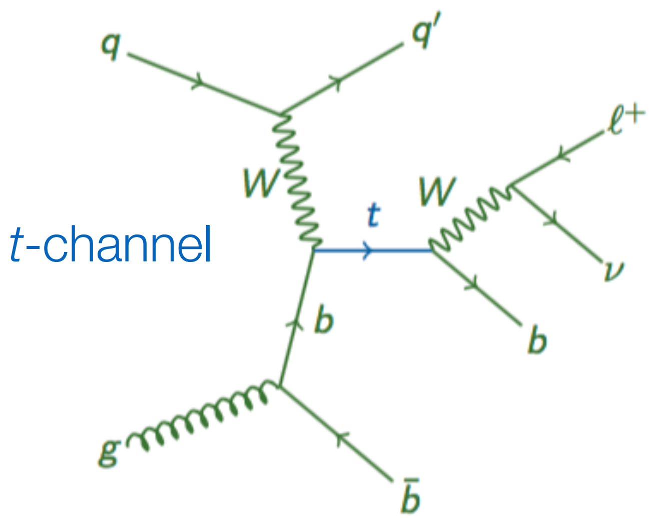
- Heaviest known elementary particle with the smallest cross-section of all of the SM particles.
- Short lifetime ($5 \cdot 10^{-25}$ s) $\Longrightarrow$ top quark decays into high p_T particles before hadronizing.
- Unique quark: only quark whose most of its properties can be directly measured!!!
- Top-quark pair production via strong interaction (dominant) and single top quark via EW interaction (sub-dominant).

Why single top quark?

- Good scenario for unique SM measurements:
  - Cross-section measurement allows to directly access a CKM matrix element: $\sigma \propto |V_{tb}|^2$.
  - Properties: top-quark polarizartion, *W* boson helicity, *Wtb* anomalous couplings, etc…
- Powerful probe for physics BSM related to EWSB.
  - All production modes are sensitive to different forms of new physics: cross-sections, polarization,
  - *Wtb* anomalous couplings, FCNC, new particles (*W*', H$^+$, etc…).
- Background in searches: Higgs and SUSY.

Single top-quark production modes and signature

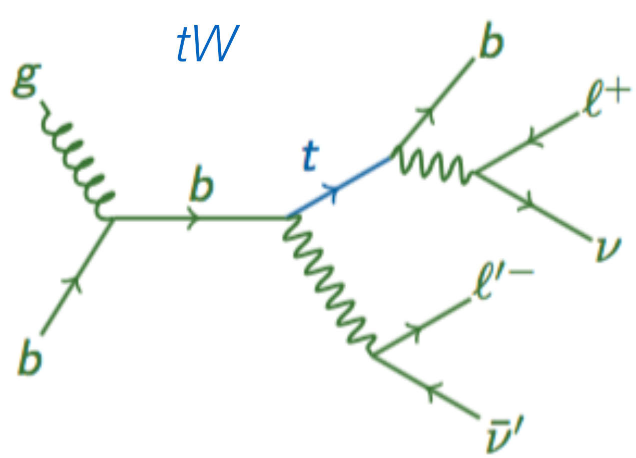
Three production mechanisms (@ LO):



***t*-channel signature:**

- 1 isolated and high-p_T lepton.
- 1 high-p_T and forward $|\eta|$ jet (light jet).
- 1 high-p_T and central $|\eta|$ jet (b-jet).
- An additional soft b-quark with high $|\eta|$ (not usually detected).
- MET from the neutrino.
- Main backgrounds: $t\bar{t}$ and W+jets.

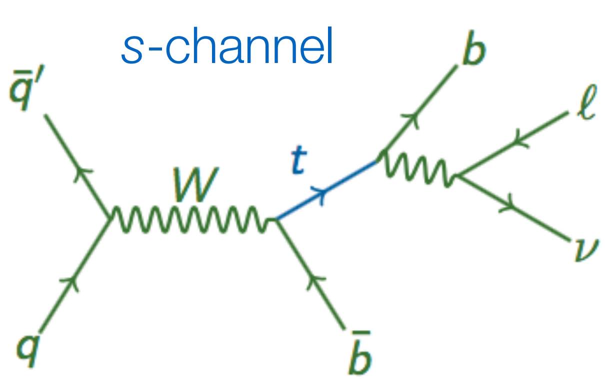
Golden channel



***tW* signature:**

- 2 isolated and high-p_T leptons.
- 1 high-p_T and central $|\eta|$ jet (b-jet).
- MET from the two neutrinos.
- Main backgrounds: $t\bar{t}$.

Observed at the LHC



***s*-channel signature:**

- 1 isolated and high-p_T lepton.
- 2 high-p_T and central $|\eta|$ jets (b-jets).
- MET from the neutrino.
- Main backgrounds: $t\bar{t}$, W+jets and t-channel.

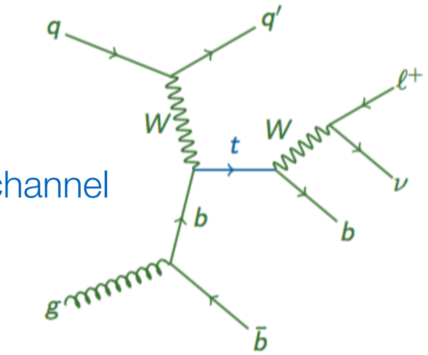
Challenging at the LHC

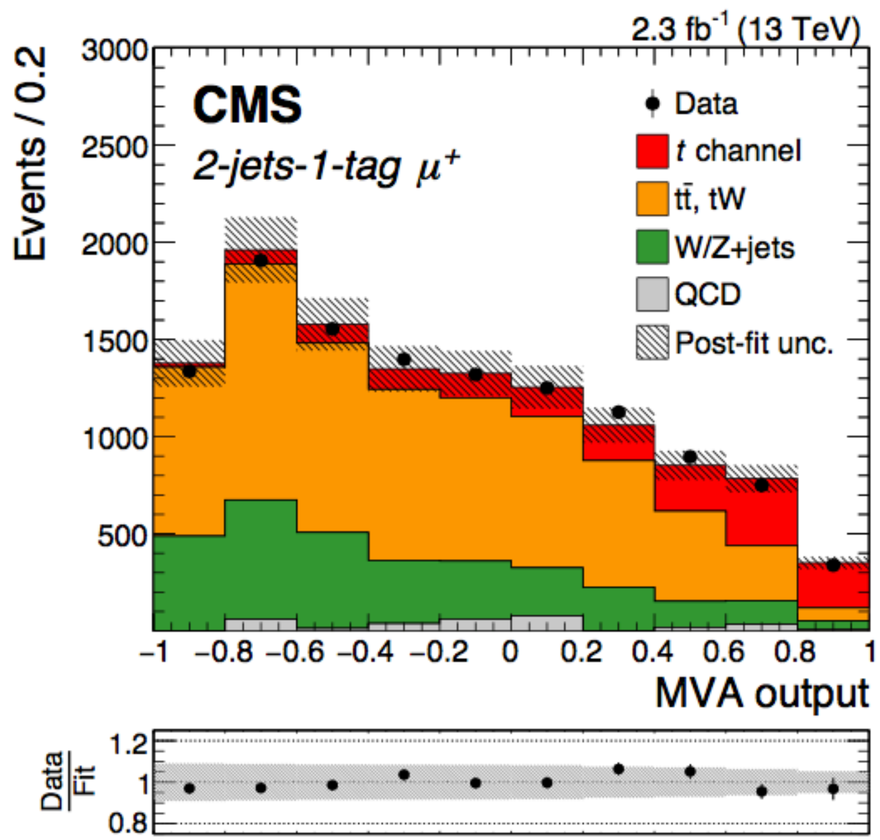
2.3 fb^{-1}, 13 TeV
arXiv:1610.00678

- NN for further S/B separation.
- 4 independent regions: 1 SR, 2 CRs and 1 VR.
  - Separated for lepton charge.
- Maximum likelihood fit in SR and CRs (constrains $t\bar{t}$).
- Dominant systematics: *t*-channel and $t\bar{t}$ modelling (9%) and *t*-channel factor./renorm. scales (6%).

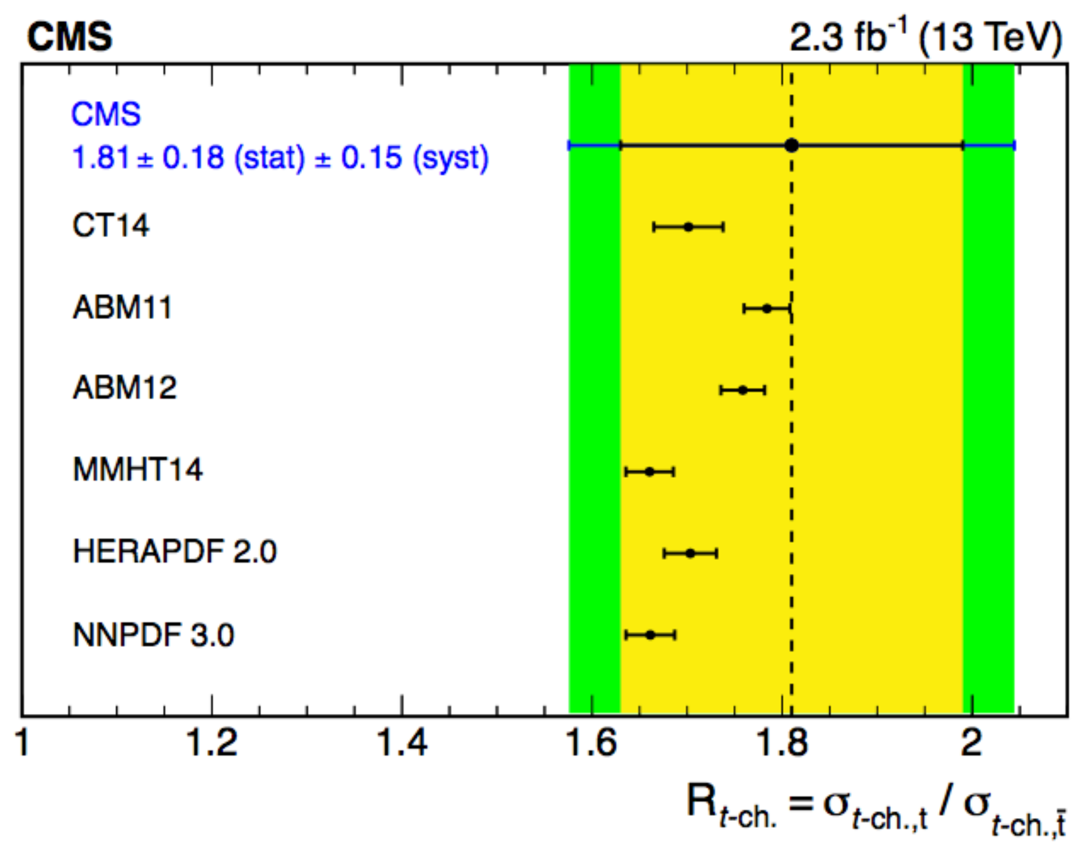
# b-tag jets \ # jets	1	2	3
0		VR (2j0b) W+jets	
1		SR (2j1b) t-channel	CR (3j1b) ttbar
2			CR (3j2b) ttbar

t-channel





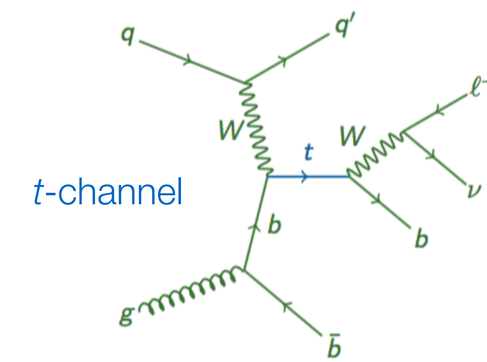
- **R_t = 1.81 ± 0.18 (stat.) ± 0.15 (syst.) (total unc. 13%).**



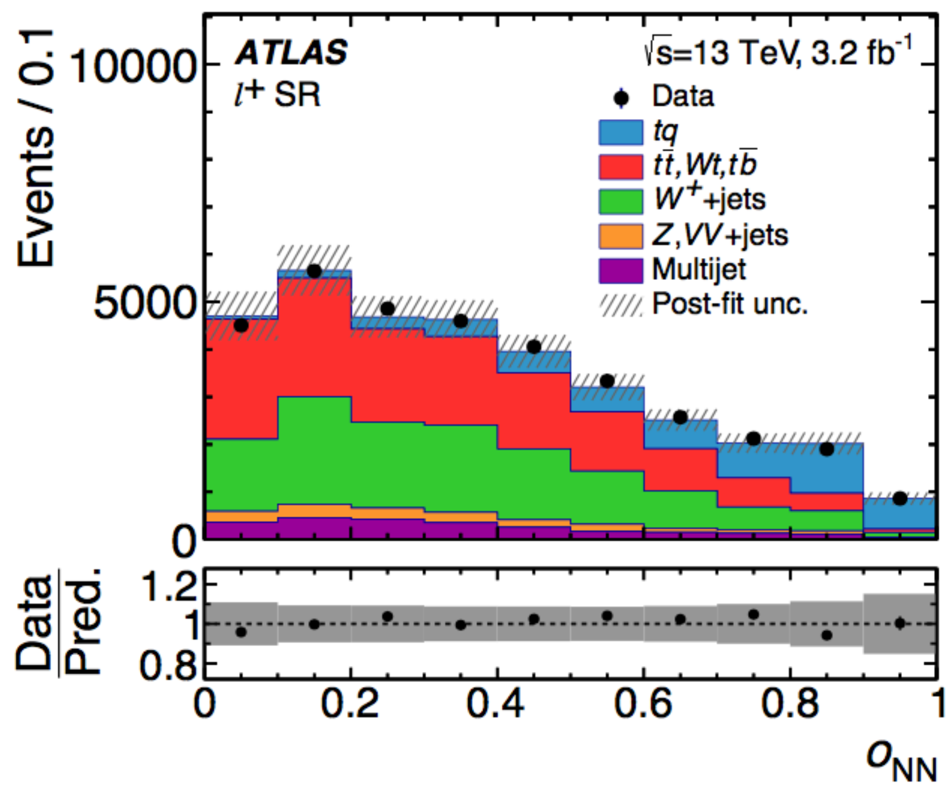
- **$\sigma^{t}_{t\text{-ch}}$ = 150 ± 22 pb (total unc. 15%).**
- **$\sigma^{\bar{t}}_{t\text{-ch}}$ = 82 ± 16 pb (total unc. 20%).**
- **$\sigma_{t\text{-ch}}$ = 232 ± 13 (stat.) ± 28 (syst.) pb (total unc. 13%).**

3.2 fb^{-1}, 13 TeV
JHEP04 (2017) 086

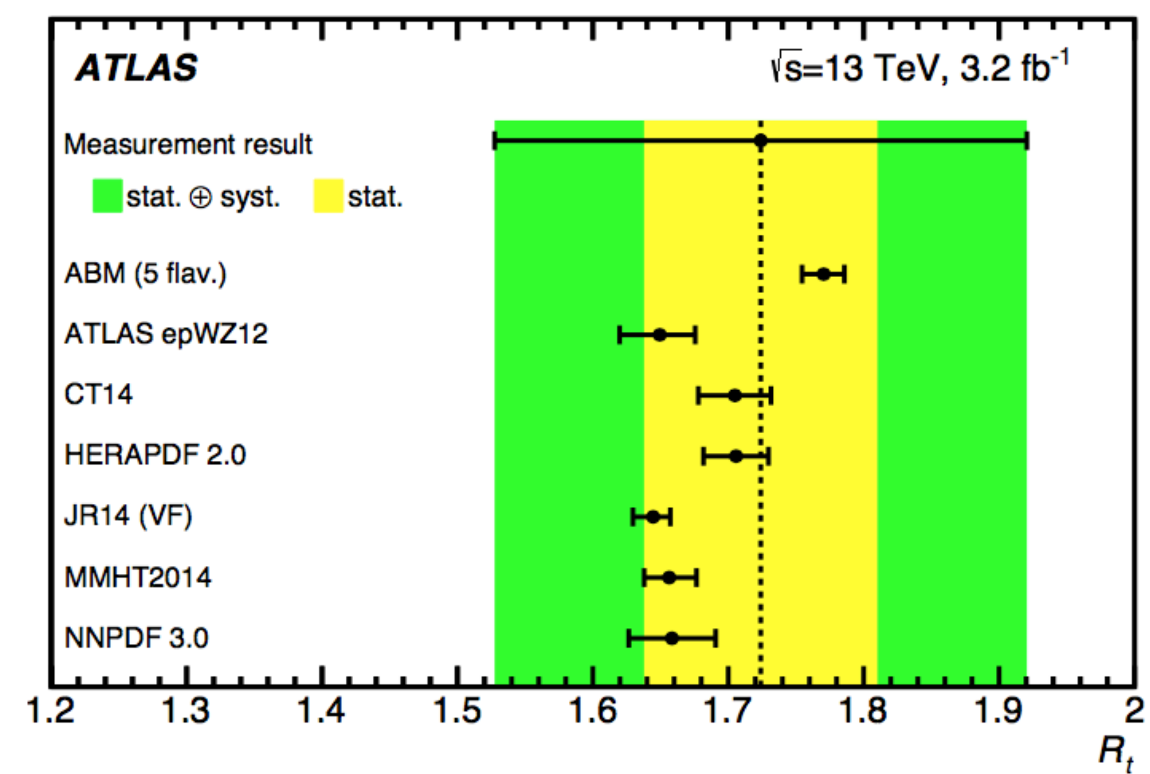
# b-tag jets \ # jets	1	2	3
0			
1 b-tagWP (85%)		VR ($2j1b_{loose}$) W+jets	
1 b-tagWP (60%)		SR (2j1b) t-channel	
2			VR (3j2b) ttbar



- NN for further S/B separation.
- 3 independent regions: 1 SR, 1 CR and 1 VR.
  - separated for lepton charge.
- Maximum likelihood fit in SR and CRs (constraint $t\bar{t}$).
- Dominant systematics: PS (14%) and b-tagging eff. (7%).



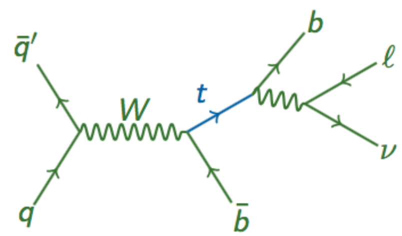
- **R_t = 1.72 ± 0.09 (stat.) ± 0.18 (syst.) (total unc. 12%).**



- **$\sigma^{t}_{t\text{-ch}}$ = 156 ± 5 (stat.) ± 27 (syst.) ± 3 (lumi.) pb (total unc. 18%).**
- **$\sigma^{\bar{t}}_{t\text{-ch}}$ = 91 ± 4 (stat.) ± 18 (syst.) ± 2 (lumi.) pb (total unc. 20%).**
- **$\sigma_{t\text{-ch}}$ = 247 ± 6 (stat.) ± 45 (syst.) ± 5 (lumi.) pb (total unc. 19%).**

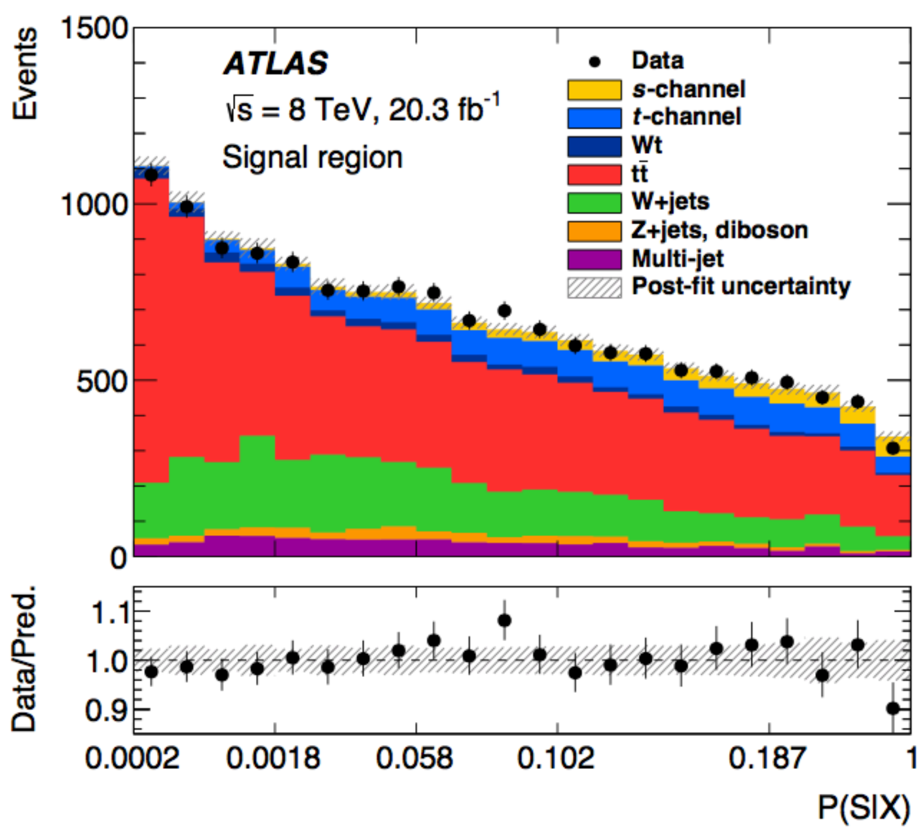
20.3 fb^{-1}, 8 TeV
PLB (2016) 228

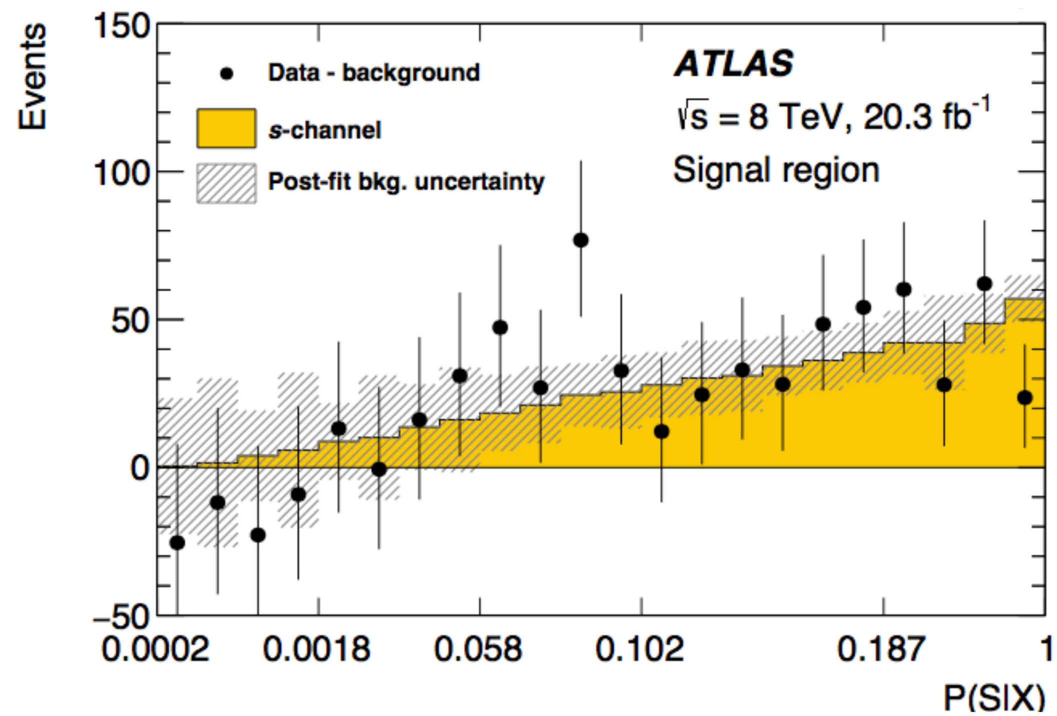
s-channel



- Matrix element method for S/B separation.
- Three independent regions.
- Maximum likelihood fit of P(S|X): $P(S|X) = \dfrac{\sum_i \alpha_{S_i} \mathcal{P}(X|S_i)}{\sum_i \alpha_{S_i} \mathcal{P}(X|S_i) + \sum_j \alpha_{B_j} \mathcal{P}(X|B_j)}$

# b-tag jets \ # jets	1	2	3	4
0				
1				
2 b-tagWP (80%)		**CR** (2j2b) W+jets		
2 b-tagWP (70%)		**SR** (2j2b) s-channel		**VR** (4j2b) ttbar

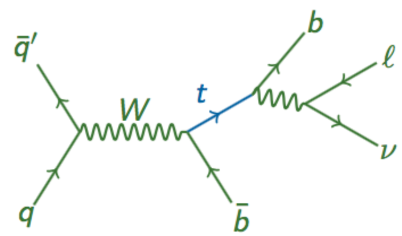




- Dominant systematics: MC stat (12%), JER (12%) and t-ch. (11%).
- **$\sigma_{s\text{-ch}}$ = 4.8 ± 0.8 (stat.) $^{+1.6}_{-1.3}$ (syst.) pb (total unc.: 86%)**
- 3.2σ observed significance (3.9σ expected).
- **First evidence at the LHC.**

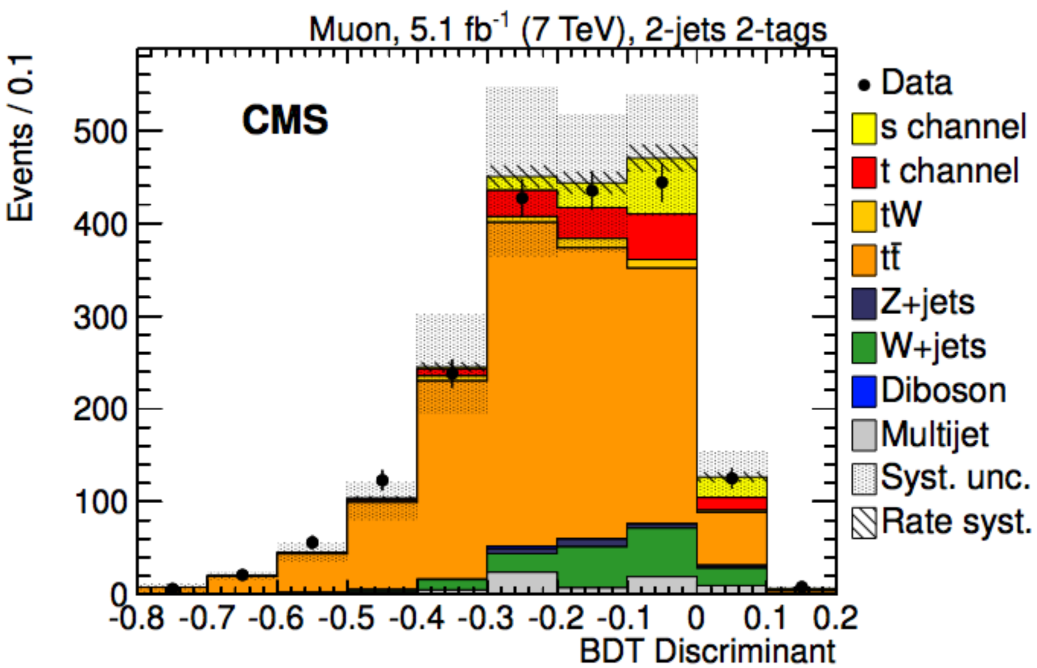
5.1 fb^{-1}, 7 TeV
19.7 fb^{-1}, 8 TeV
JHEP09 (2016) 027

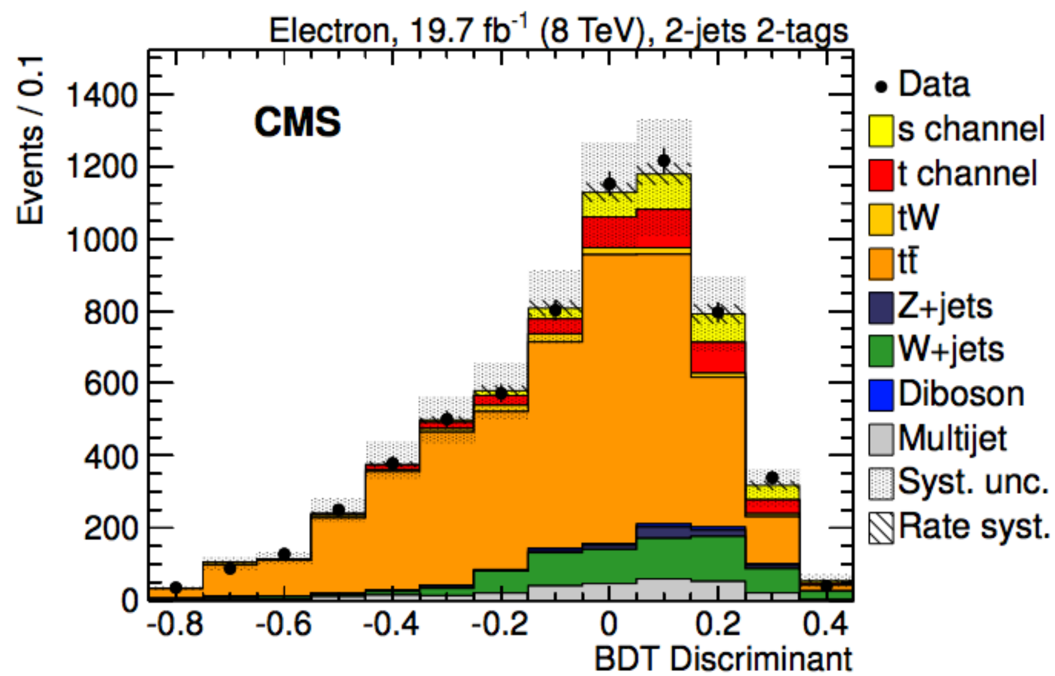
s-channel



# b-tag jets \ # jets	1	2	3
0			
1		CR (2j1b) t-channel & W+jets	
2		SR (2j2b) s-channel	CR (3j2b) ttbar

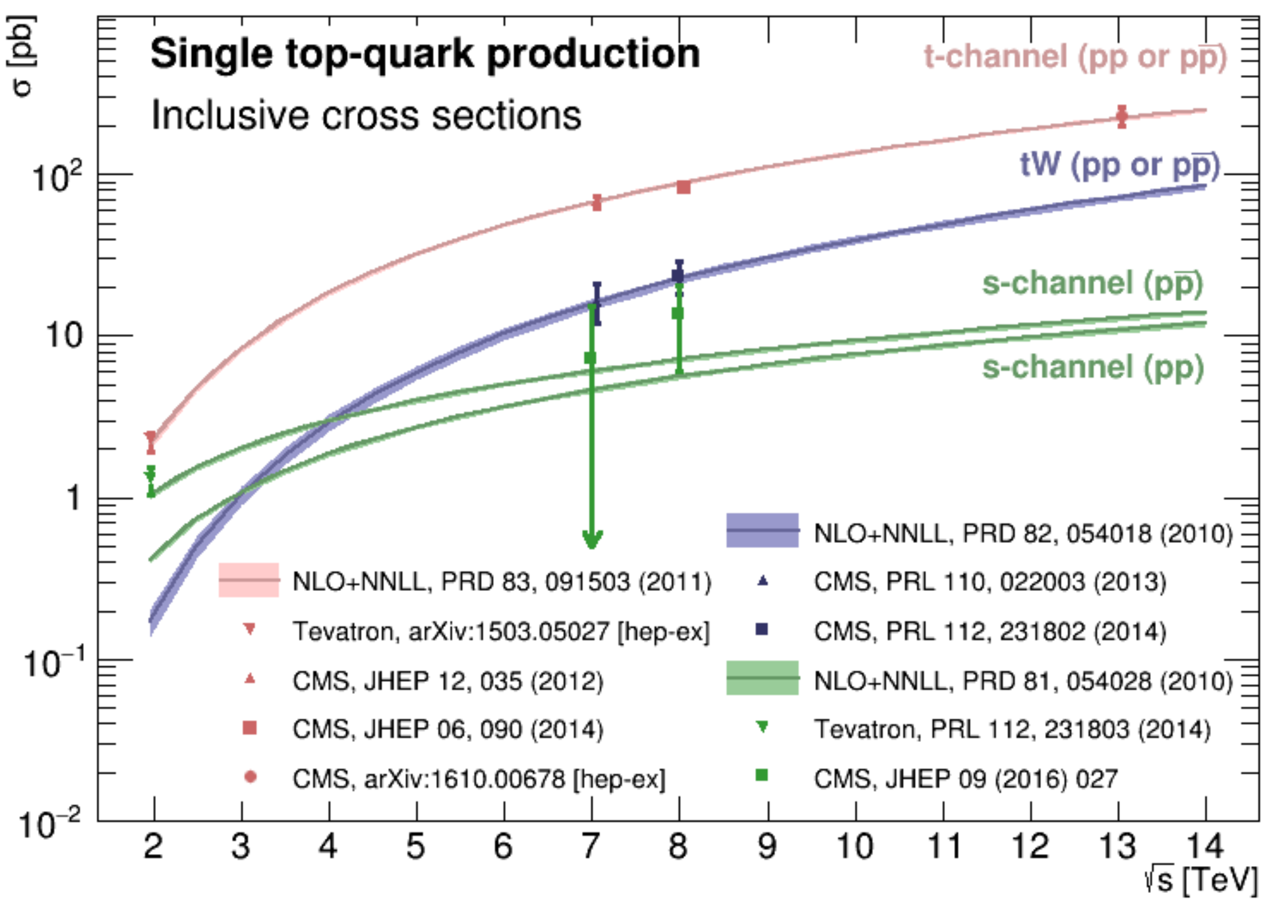
- BDT for further S/B separation.
  - BDT dedicated suppress QCD@8TeV (m_T(W)@7TeV).
- BDT to reject $t\bar{t}$ and W+jets.
- Three independent regions.
- Maximum likelihood fit in SR and CRs.



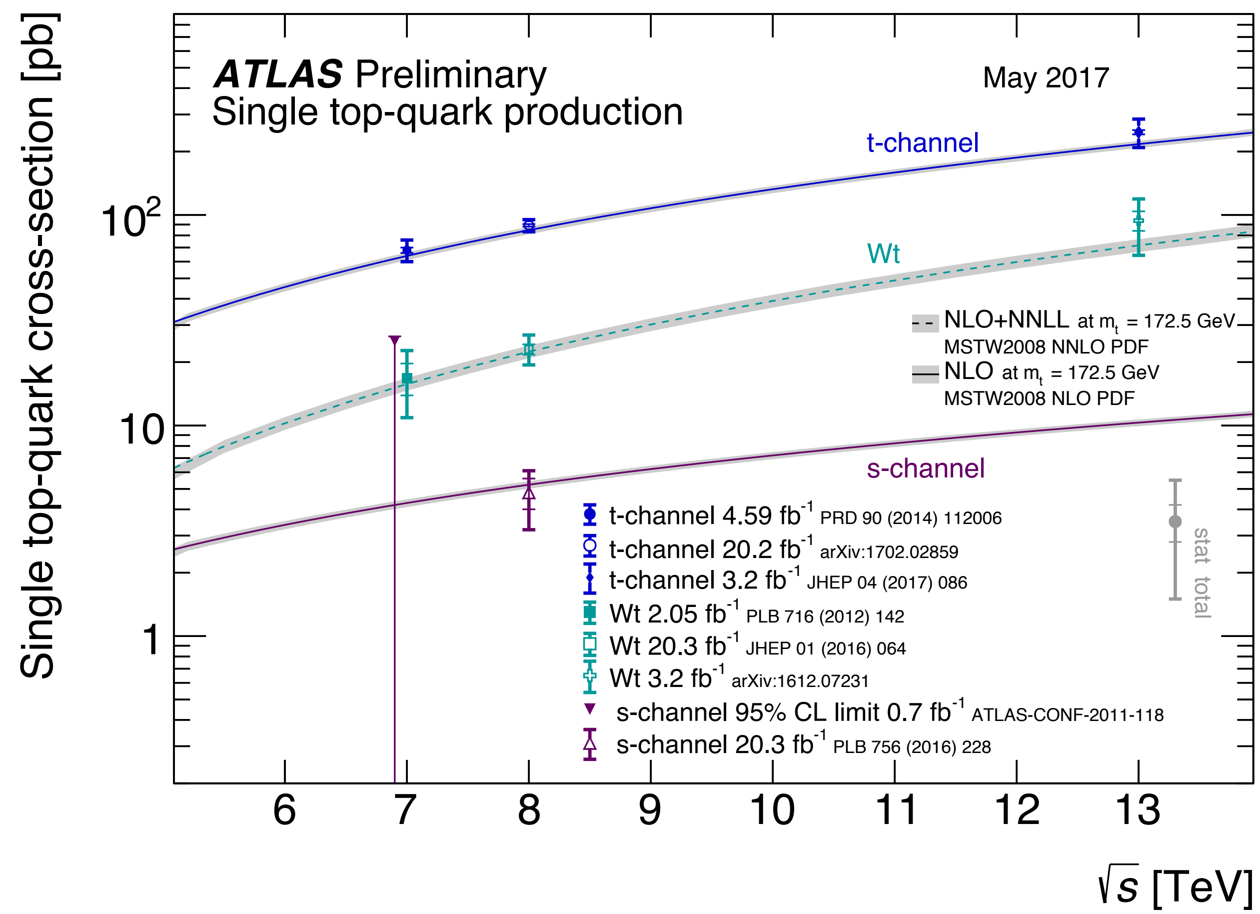


- Dominant systematics: $t\bar{t}$ fact./renorm. scales (30%), JES/JER (35%).
- **$\sigma_{s\text{-ch}}$ (7 TeV) = 7.1 ± 8.1 (stat.+syst.) pb (total unc.: XX%).**
- **$\sigma_{s\text{-ch}}$ (8 TeV) = 13.4 ± 7.3 (stat.+syst.) pb (total unc.: XX%).**
- 2.5σ observed significance.

Summary of single top-quark cross-section measurements by CMS, as function of centre-of-mass energy.



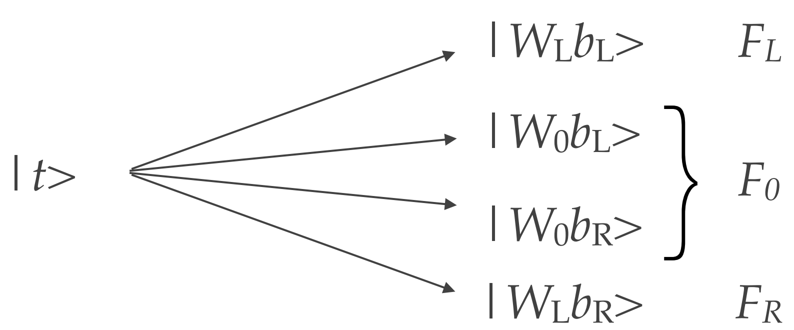
Summary of single top-quark cross-section measurements by ATLAS, as function of centre-of-mass energy.



The differential decay rate of the decaying top quark considering the angle θ^*_ℓ is given by:

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

JHEP 01 (2015) 053

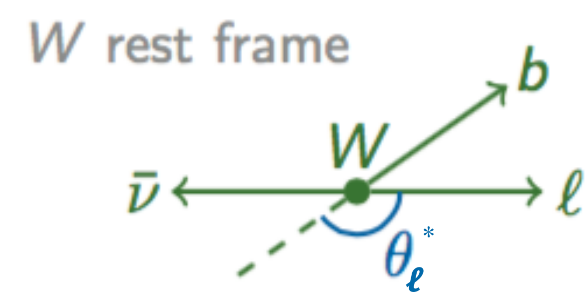


Partial widths of the top quark decay:

$\Gamma(t \to Wb) = \Gamma_L + \Gamma_0 + \Gamma_R$

$F_i = \Gamma_i / \Gamma$ where i = L, 0, or R

$\sum F_i = 1$

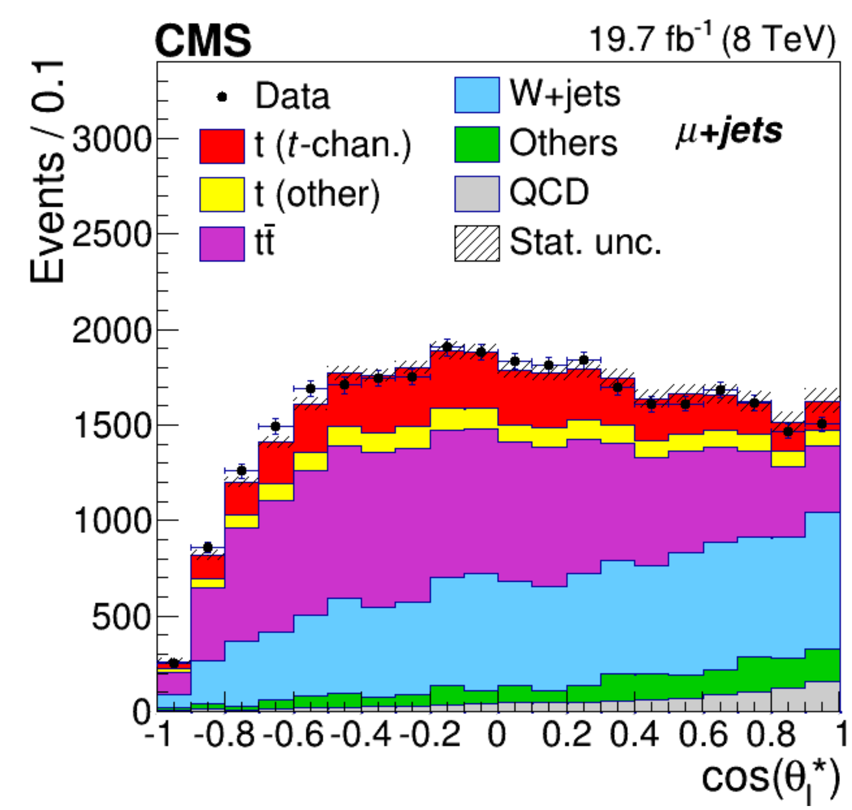


The angle θ^*_ℓ is defined as the angle between the W boson momentum in the top-quark rest frame and the momentum of the lepton in the rest frame of the W boson.

The helicity fractions are well-known parameters in top-quark physics. They refer to a decomposition of the decay rate into three classes (two independent parameters).

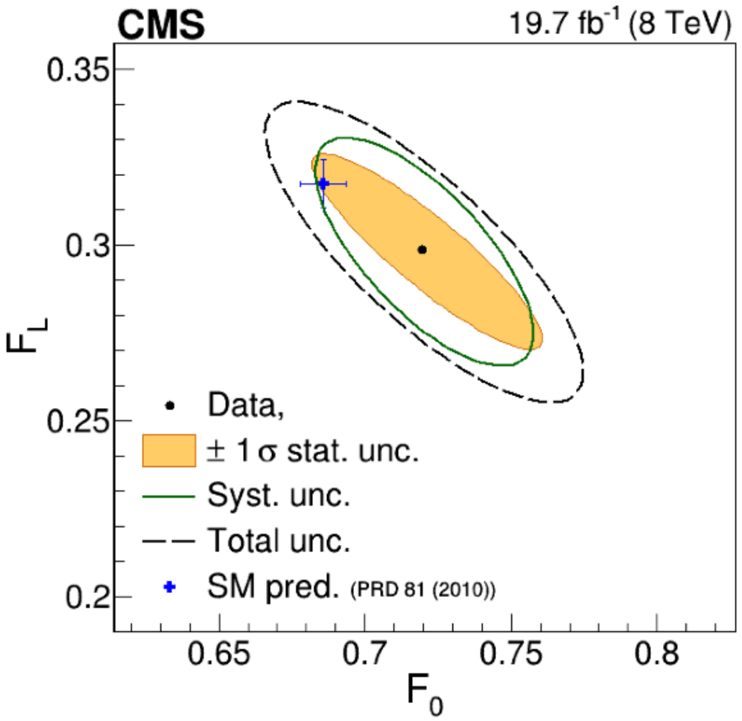
First measurement of *W* boson helicity in single top-quark topology (19.7 fb^{-1}, 8 TeV).

- A reweighting method used in a binned likelihood fit using cos θ^*_ℓ.
- Contributions from $t\bar{t}$ are taken into account.
- Results from the e and μ channels are combined using their likelihoods.
- Anomalous couplings in the Wtb vertex can be constrained with the W boson helicity (next slide).



- Dominant systematics: Modelling
- In agreement, within their uncertainties, with the standard model NNLO predictions.

$19.7\ fb^{-1}$, 8 TeV
JHEP 01 (2015) 053



Combination (likelihood) of the e and μ channels:

- F_L **= 0.298 ± 0.028 (stat.) ± 0.032 (syst.)**
- F_0 **= 0.720 ± 0.039 (stat.) ± 0.037 (syst.)**
- F_R **= –0.018 ± 0.019 (stat.) ± 0.011 (syst.)**

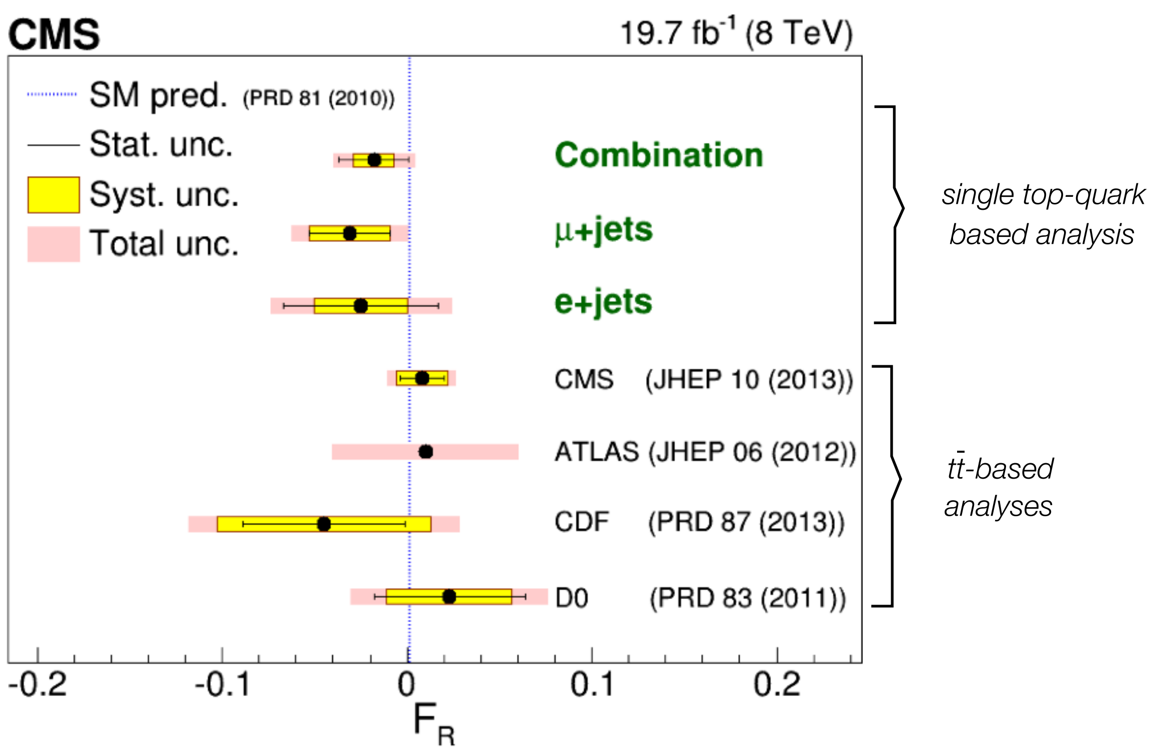
The SM predictions for the W boson helicity fractions at NNLO, including the finite b-quark mass (m_b = 4.8 GeV) and EW effects, with m_t = 172.8 ± 1.3 GeV, are:

- F_L = 0.311 ± 0.005
- F_0 = 0.687 ± 0.005
- F_R = 0.0017 ± 0.0001

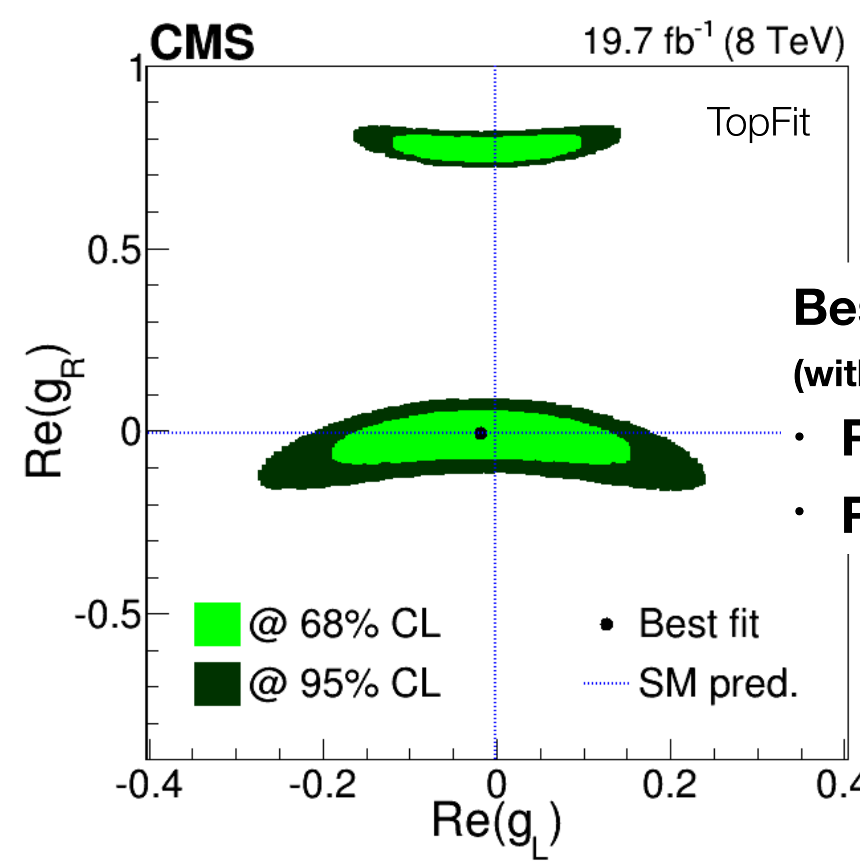
Phys. Rev. D 81 (2010) 111503

Comparison with previous $t\bar{t}$ measurements.

- Similar precision (with less stats) to those based on $t\bar{t}$ events.



Exclusion limits on the Re(g_L) and Re(g_R), with V_L = 1 and V_R = 0. Dashed blue lines show g_L = 0 and g_R = 0 as predicted by the SM at tree level.



Best fit values:

(with mentioned assumptions)

- **Re(g_L) = -0.017**
- **Re(g_R) = -0.008**

19.7 fb^{-1}, 8 TeV
JHEP 04 (2016) 073

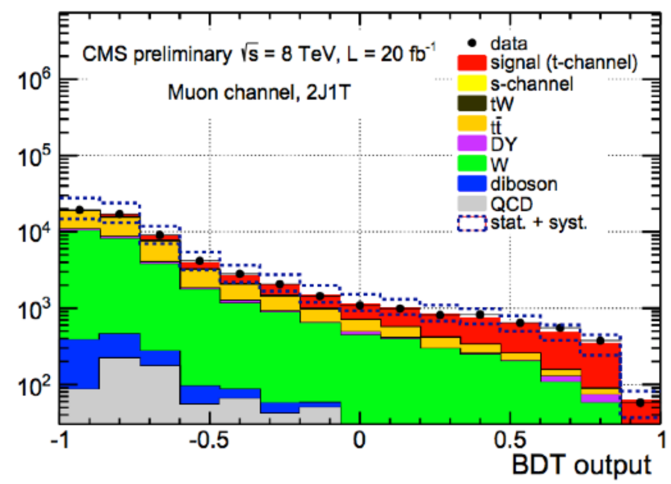
The differential decay rate of the decaying top quark considering the angle θ^* is given by:

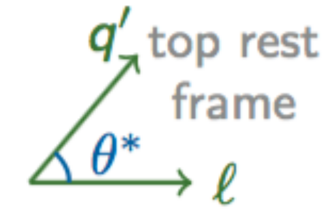
$$\frac{d\Gamma}{d\cos\theta_X} = \frac{\Gamma}{2}(1 + P_t\alpha_X\cos\theta_X) \equiv \Gamma(\frac{1}{2} + A_X\cos\theta_X)$$

where α_X *is the spin analyzing power.*

- The spin asymmetry is measured:

$$A_X = \frac{N(\cos\theta_X > 0) - N(\cos\theta_X < 0)}{N(\cos\theta_X > 0) + N(\cos\theta_X < 0)} = \frac{1}{2}P_t\alpha_X$$

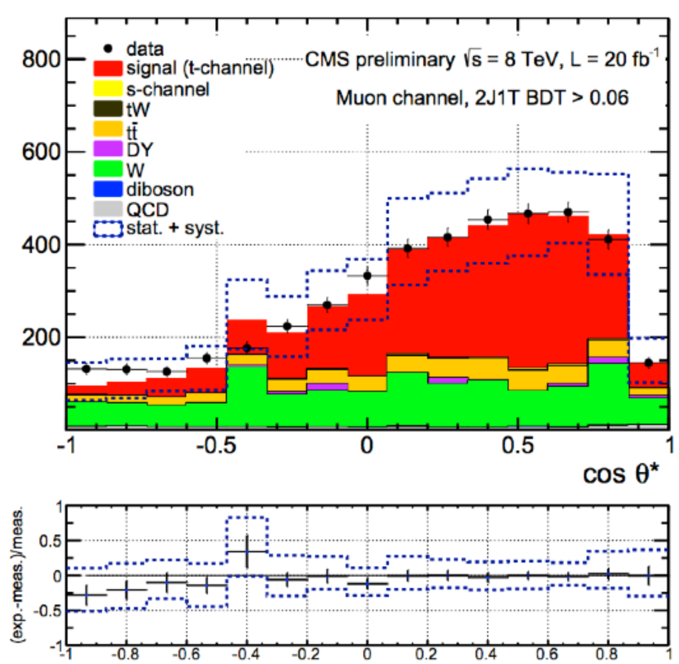




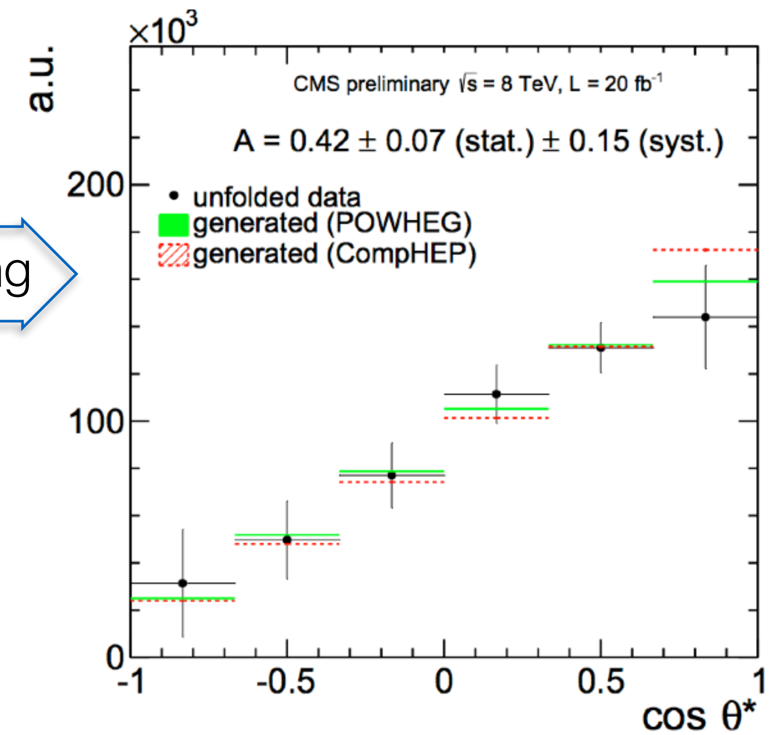
The angle θ^* is defined as the angle between the spectator quark and the direction of motion of the chosen decay product X (spin analyzer), which in this case is $X=\ell$, in the top-quark rest frame.

First measurement of top-quark polarization in single top quark (19.7 fb^{-1}, 8 TeV).

- The cos θ^* distribution is unfolded to parton-level to extract the top-quark spin asymmetry.
- BDT is used to determine the background contributions and enrich the signal sample.
- Dominant systematics: JES and QCD fraction (*e* channel only).



unfolding



Combination (BLUE) of the *e* and *μ* channels:

$$A_\ell = 0.26 \pm 0.03\ (\text{stat.}) \pm 0.10\ (\text{syst.})$$

Compatible with a *p*-value of 4.6% with the standard model prediction of 0.44