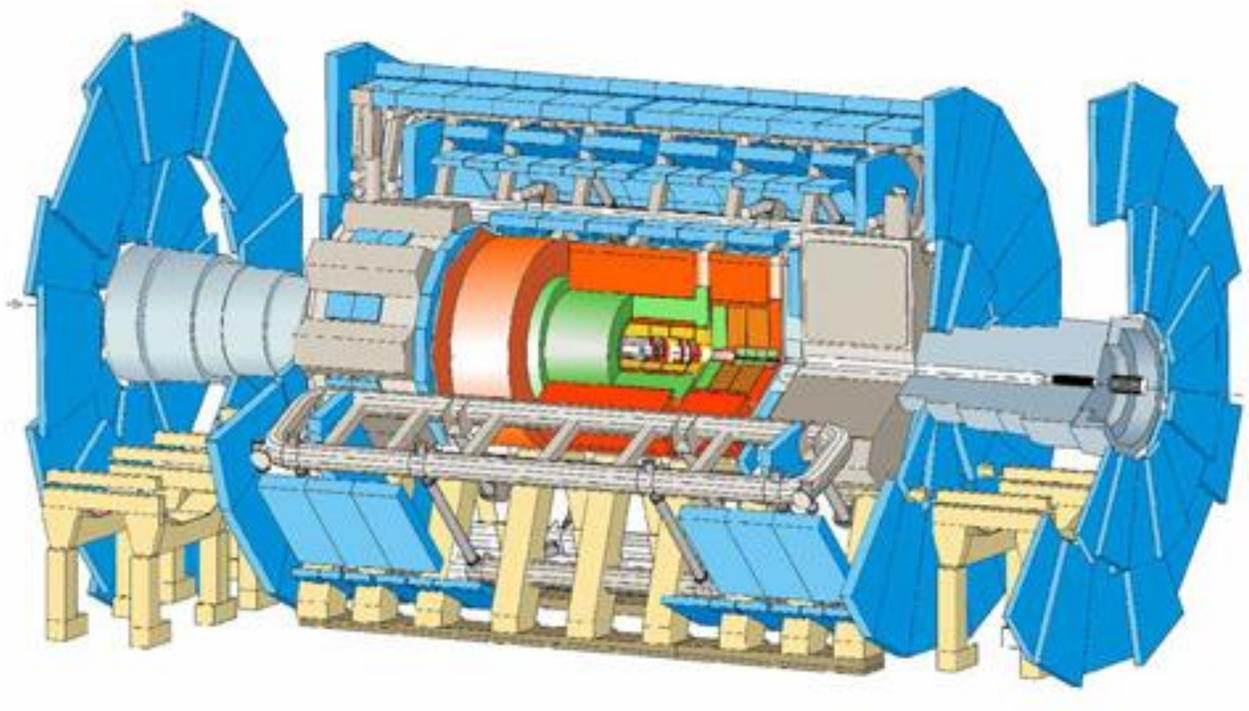
Nikhef

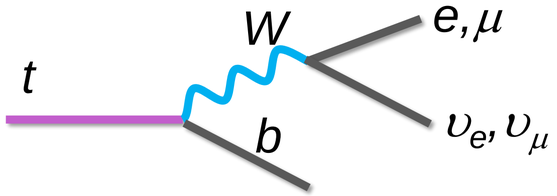


Single top-quark production and properties measurements using the ATLAS detector

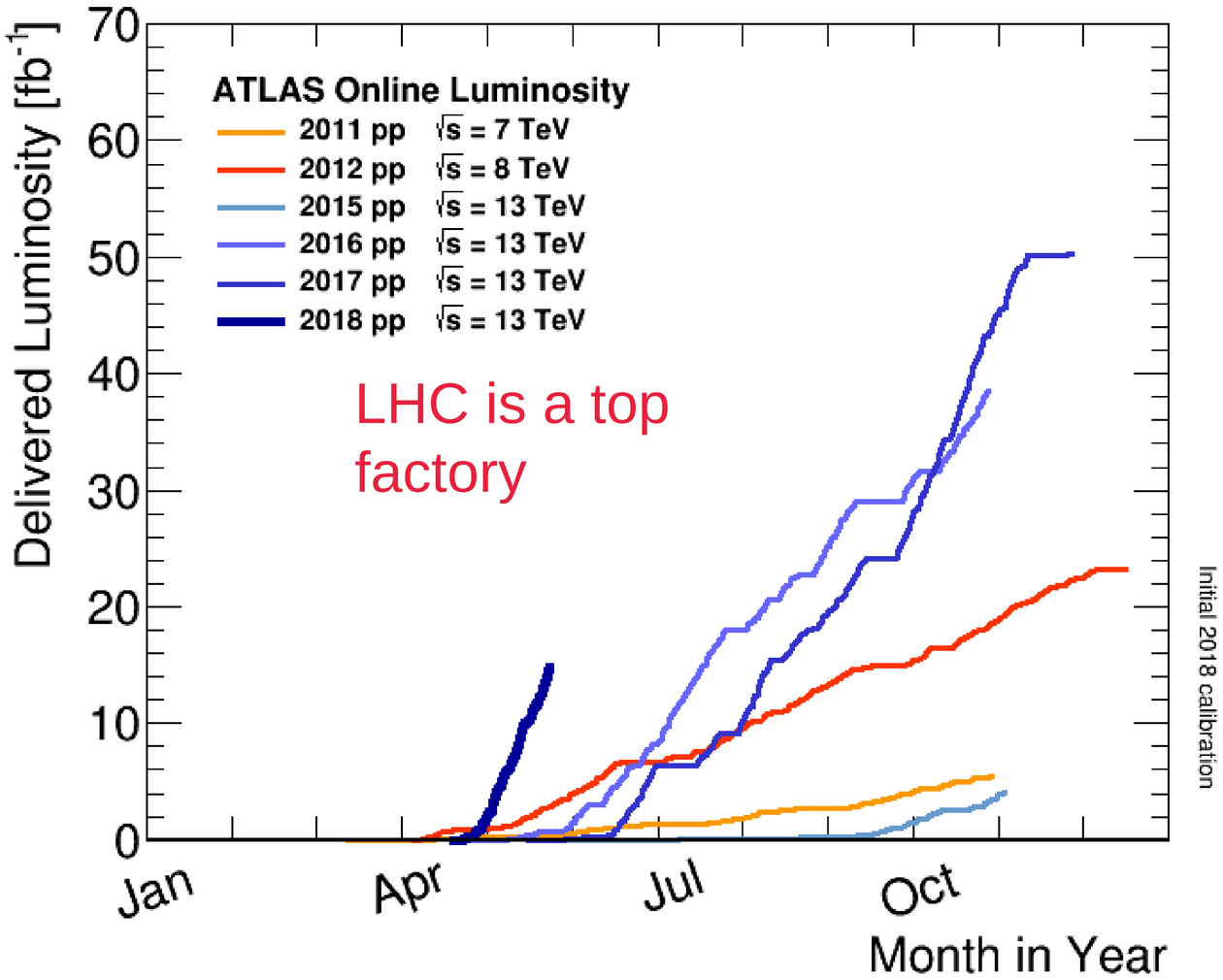
By Marcel Vreeswijk (Nikhef/UvA-IoP)
on behalf of the ATLAS Collaboration

Top quarks in ATLAS

- Top Quarks are abundantly produced in ATLAS at the LHC.
- Production in pairs (strong, $\sigma \sim 800\text{pb}$ @ 13TeV) or single (weak, $\sigma \sim 300\text{pb}$ @ 13TeV).
- Unique: top quark decays before it hadronizes
- Standard Model decay: $t \rightarrow Wb$ (~100%) W leptonic (~33%) or hadronic (~66%)



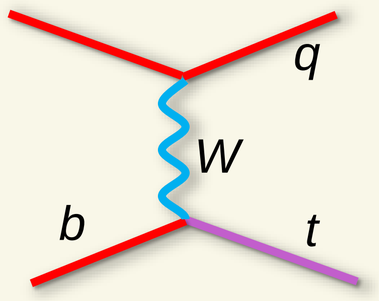
- Measurements in this talk: W decay to $e+\upsilon_e$ or $\mu+\upsilon_\mu$ (~22%)



LHC is a top factory

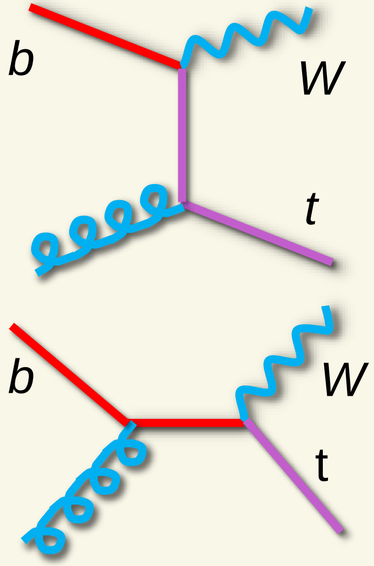
Single top-quark production

t-channel



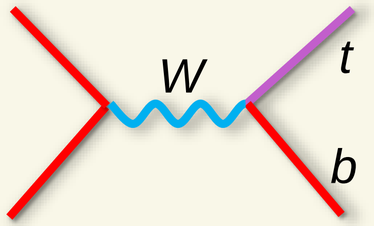
$\sigma(13\text{TeV}) = 217^{+10}_{-10}\text{pb}$

tW-channel



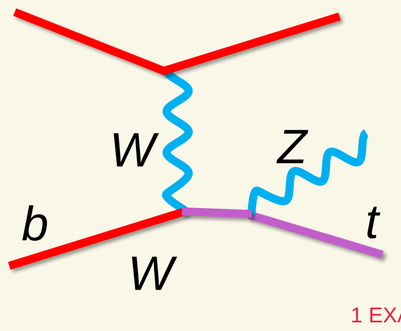
$\sigma(13\text{TeV}) = 72^{+4}_{-4}\text{pb}$

s-channel



$\sigma(13\text{TeV}) = 10.3^{+0.4}_{-0.4}\text{pb}$

tZq channel
(rare SM process)



$\sigma(13\text{TeV}) = 0.8^{+0.05}_{-0.05}\text{pb}$

All interesting processes by themselves: enable tests of the Standard Model *Wtb* vertex

Sensitive to Beyond Standard Model physics:

- Direct: Flavour Changing Neutral Currents, Heavy Bosons, Charged Higgs
- Indirect: Effective Field Theory operators

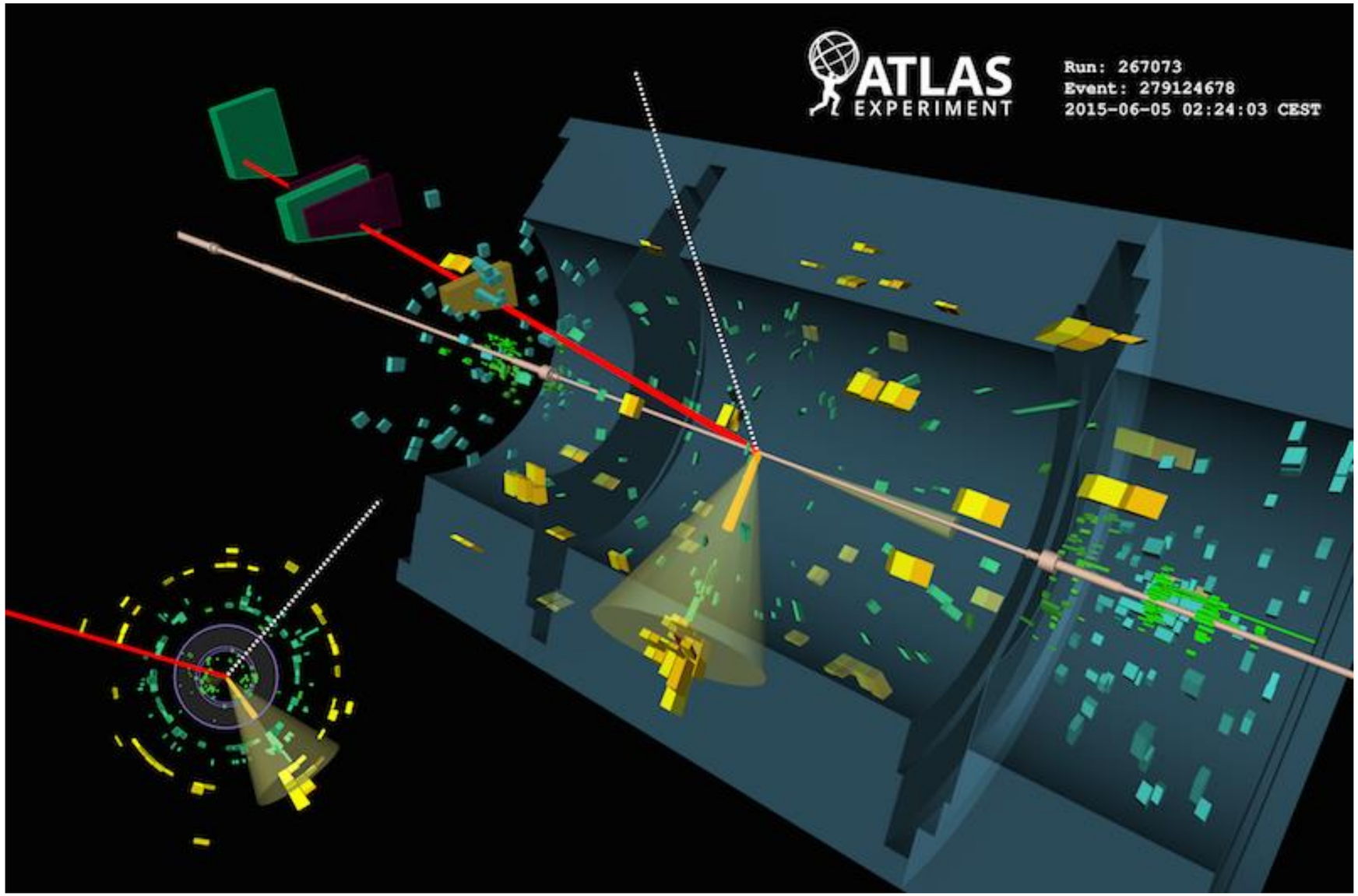
Single top-quark measurements

ATLAS	t-channel	*tW*-channel	s-channel	*tZq*-channel (rare SM process)
7 TeV (2011)	Inclusive σ	Evidence	Search	-
8 TeV (2012)	Differential σ *Wtb*-vertex	Inclusive σ	Evidence	-
13 TeV (2015-2016)	Inclusive σ	Differential σ	-	Evidence

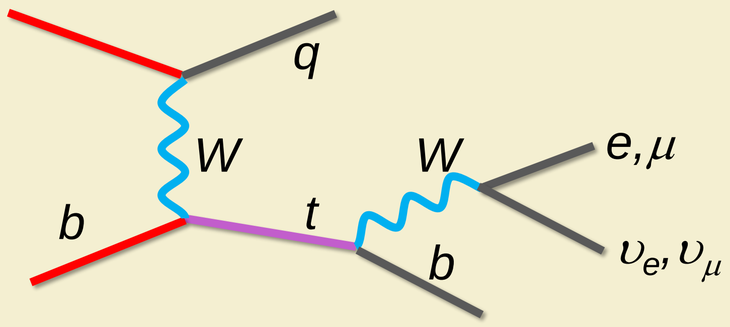
In this talk we focus on the indicated results

All Publications and public notes can be googled:
ATLAS Public Top Physics

t-channel


ATLAS
EXPERIMENT
Run: 267073
Event: 279124678
2015-06-05 02:24:03 CEST

t-channel: analysis @8TeV (and 13 TeV)



Signal Region (8TeV):

- Forward untagged jet (P_T>30GeV)
- Isolated e, μ (P_T>25GeV)
  (isolation eff: 90%[99%]for pT = 25[60]GeV)
- Missing E_T (MET>30GeV)
- 1 tagged *b*-jet (P_T>30GeV)
  (eff 50%, mis-eff: 3.9%charm, 0.07% light)

- Analysis separately for l^+ and l^-
- Neural Net (NN) to separate signal from background
- Signal obtained from binned likelihood fit.
- Multijet determined data driven.
- Largest Backgrounds: ttbar, *W*+jets checked in Validation Regions and normalisations simultaneously obtained in fit.

$$\left\{\begin{array}{l} m(jb) \\ |\eta(j)| \\ m(\ell\nu b) \\ m_{\mathrm{T}}(\ell E_{\mathrm{T}}^{\mathrm{miss}}) \\ |\Delta\eta(\ell\nu, b)| \\ m(\ell b) \\ \cos\theta^*(\ell, j) \end{array}\right.$$

(13 TeV analysis in a manner similar)

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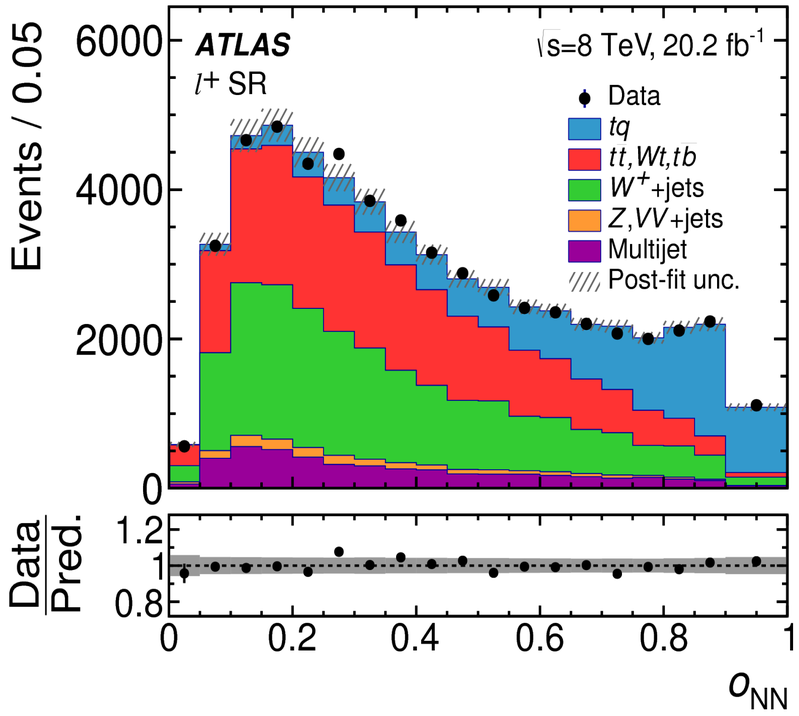


t-channel: cross sections @8TeV and 13TeV

8 TeV: [EPJC 77 (2017) 531]

Cross section obtained in Fiducial region with uncertainty ~5%

Main systematic unc sources:
jet energy scale, lepton reco., flavour tagging

Total cross section @8TeV

$$\sigma = 89.6 \pm 1.2\,(\text{stat.}) \pm 5.1\,(\text{exp.})\,^{+4.1}_{-2.5}\,(\text{scale})$$
$$\pm 0.7\,(\text{PDF})$$
$$\pm\,^{+1.7}_{-1.6}\,(\text{NLO-matching method})$$
$$\pm 1.6\,(\text{parton shower}) \pm 1.7\,(\text{lumi.})\ \text{pb}$$
$$= 89.6^{+7.1}_{-6.3}\ \text{pb.} \quad \sim 7.5\%$$

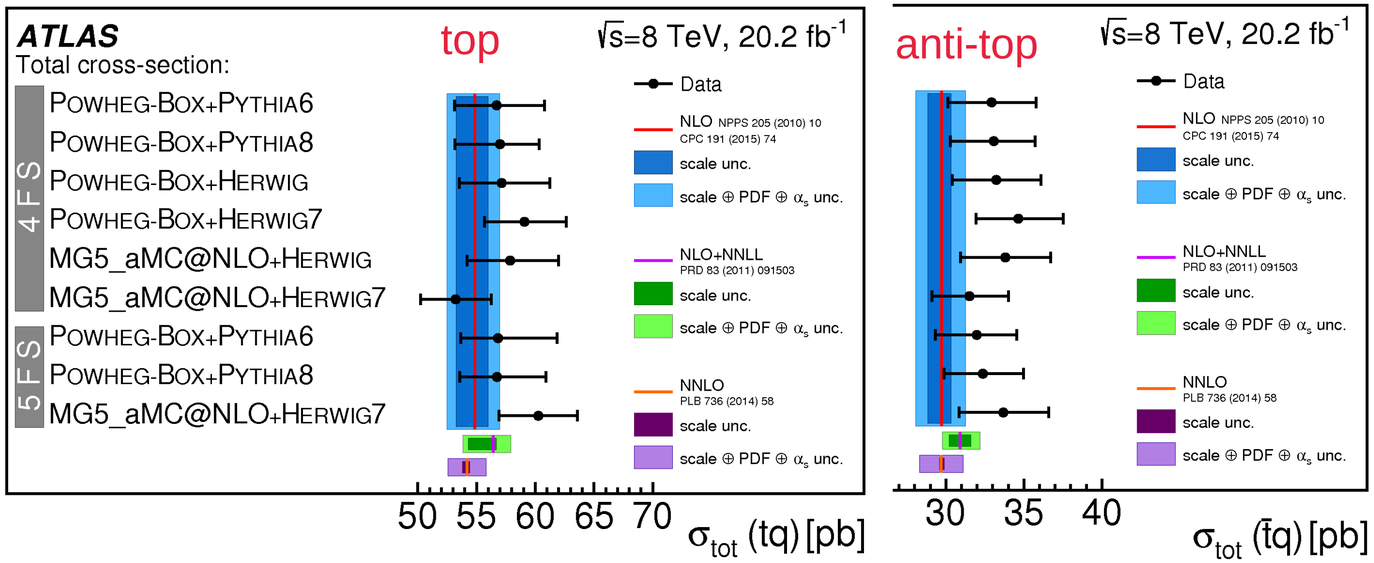
Predicted $\sigma(8\text{TeV}) = 84.6^{+3.9}_{-3.4}\text{pb}$

[JHEP 04 (2017) 086]

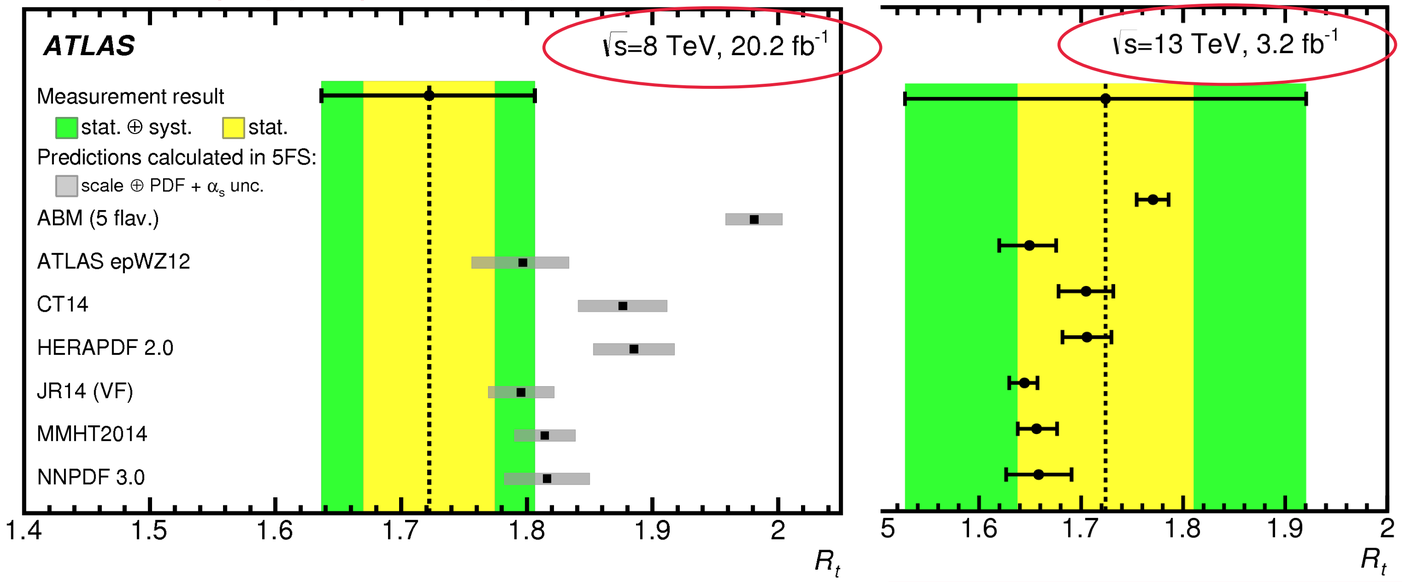
Also **13 TeV** result available

$$\sigma = 247 \pm 6\,(\text{stat.}) \pm 45\,(\text{syst.}) \pm 5\,(\text{lumi.})\ \text{pb}$$

Predicted $\sigma(13\text{TeV}) = 217^{+10}_{-10}\text{pb}$



Ratio σ(top)/σ(antitop) 8TeV and **13TeV**:



t-channel: differential cross sections @8TeV

Differential Cross section at particle level.
Iterative Bayesian unfolding uses events with NN> 0.8.
(distributions also available at parton level)

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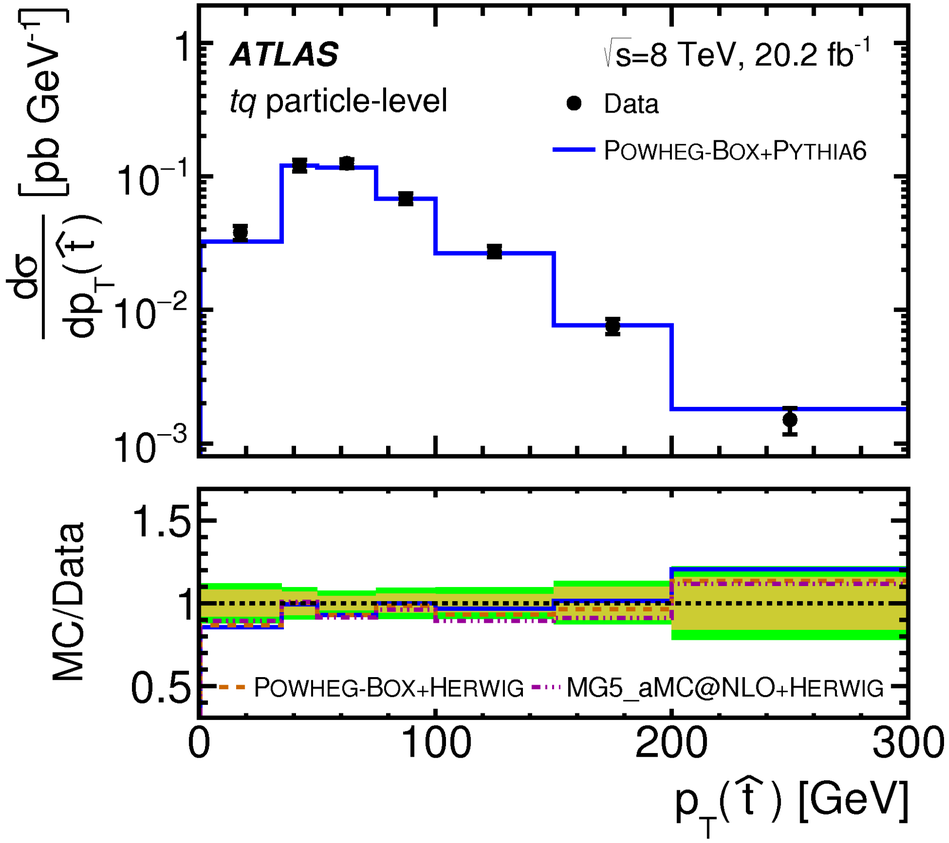

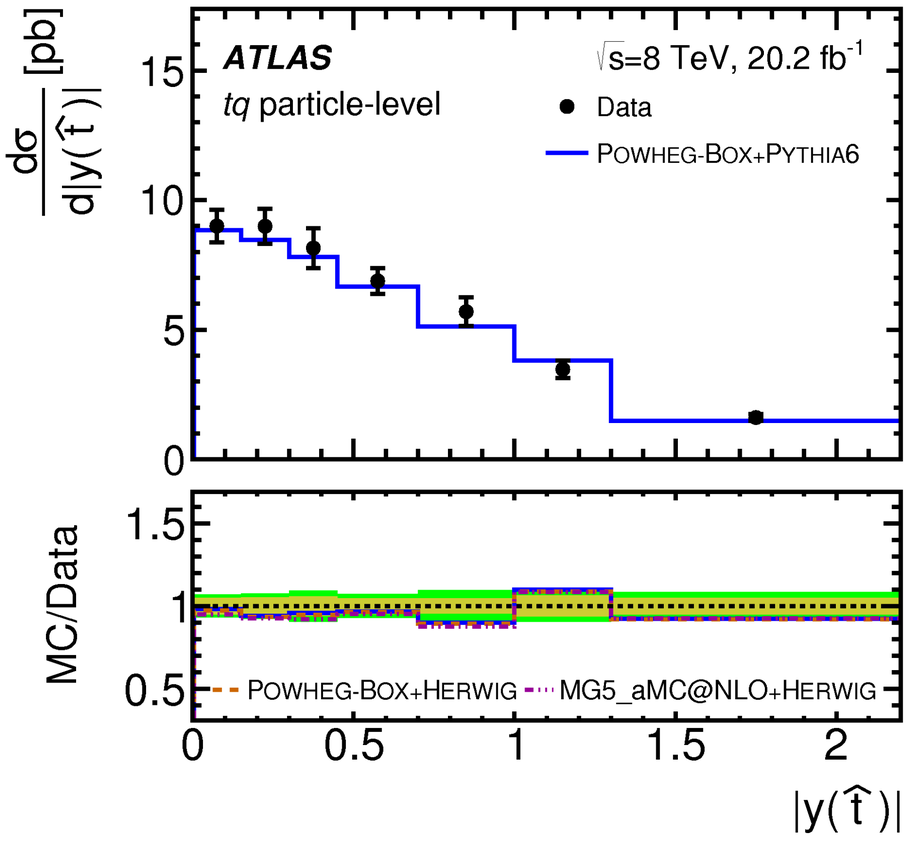

t-channel

-- *Wtb* vertex--

t-channel: *Wtb* vertex

(Very) brief summary of 8 TeV analysis

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Top quark is spin polarized at production.
Spin information is transferred to its decay products

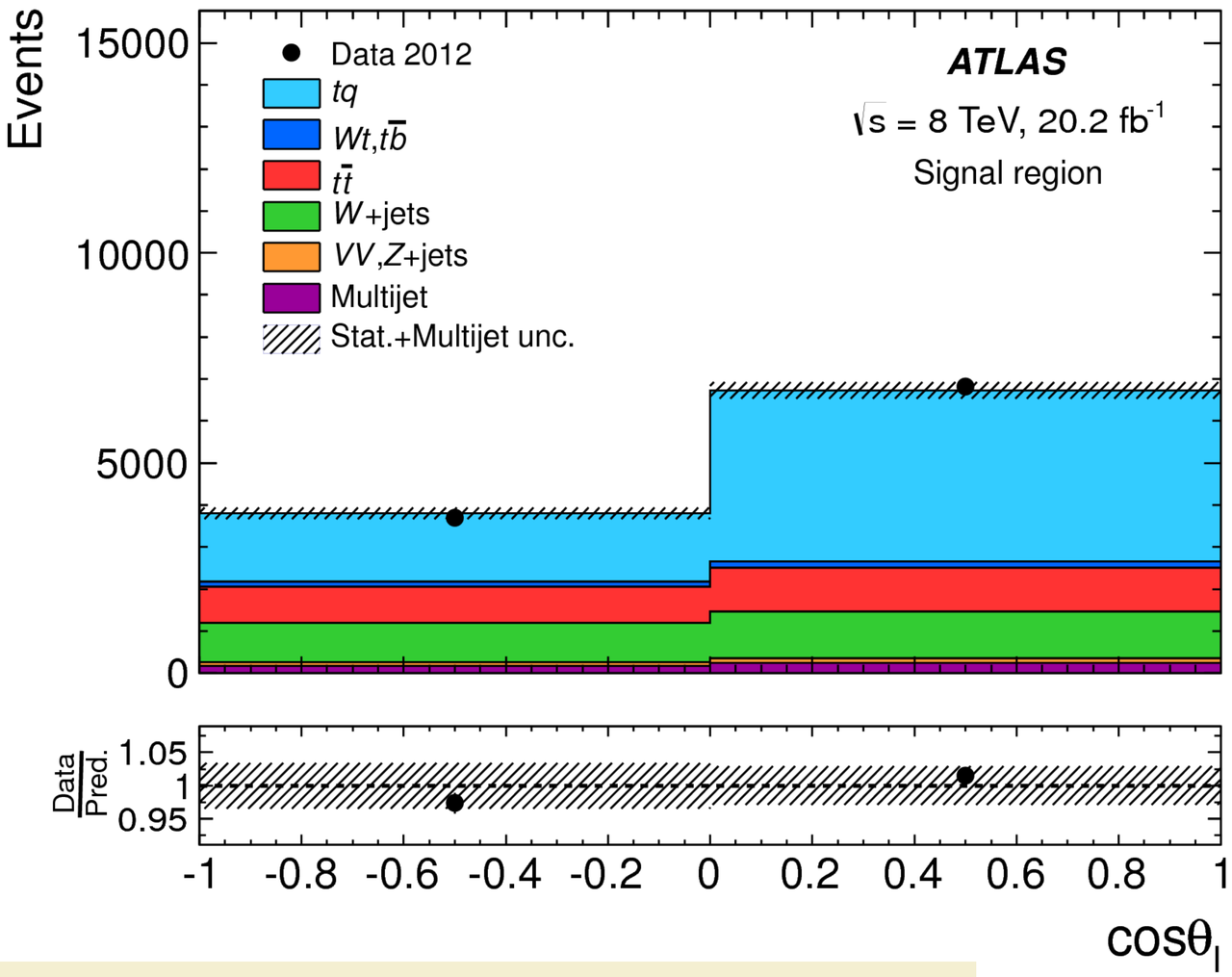
- the untagged jet is taken as the spin direction in top rest frame
- For any decay product:

For charged lepton $\alpha \sim 1$

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

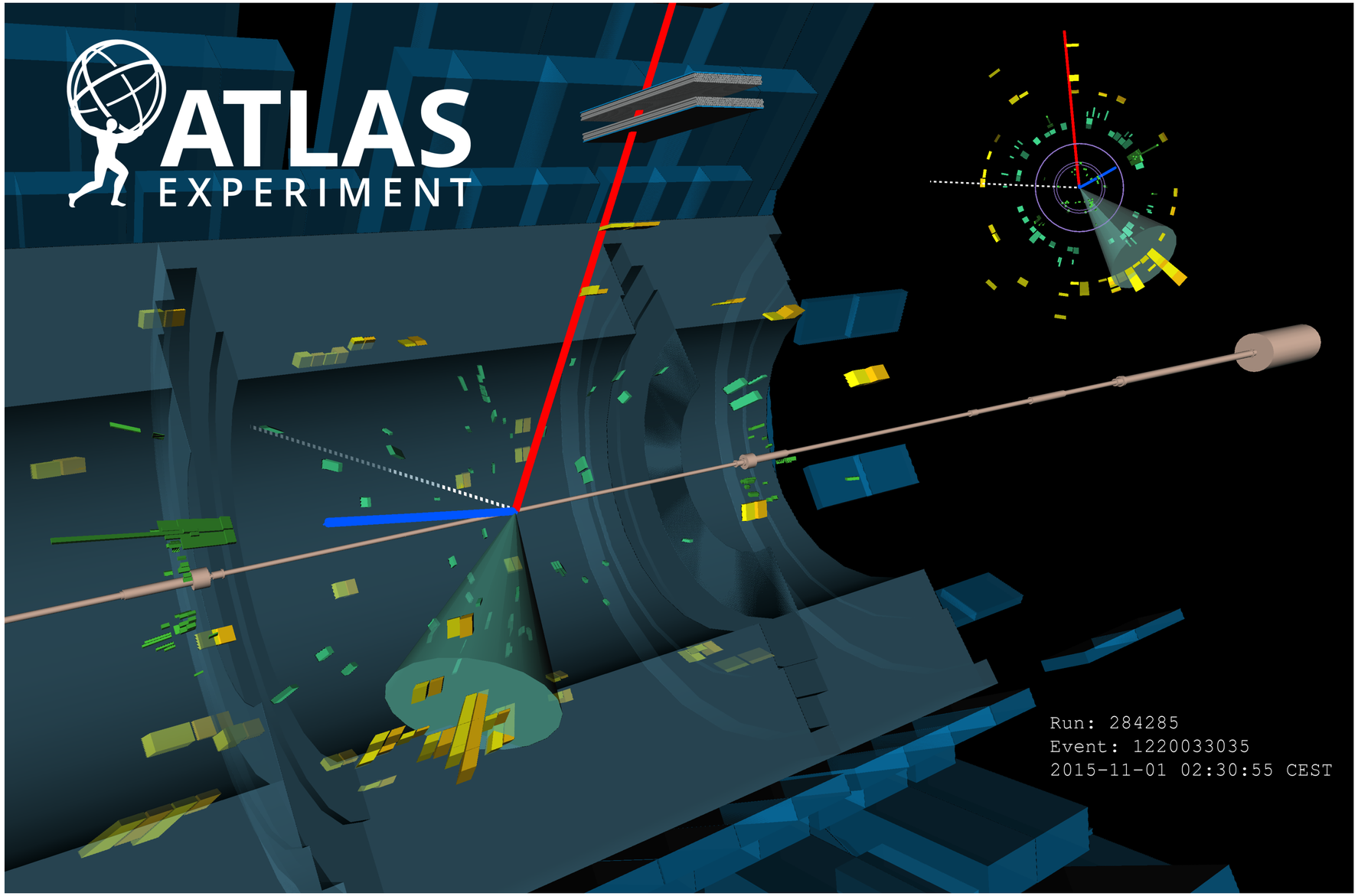
Top quark polarisation: P=0.97±0.12
Predicted NLO: P~0.9

Main systematics:
- MC stats
- Jet Reconstruction
- ttbar generator

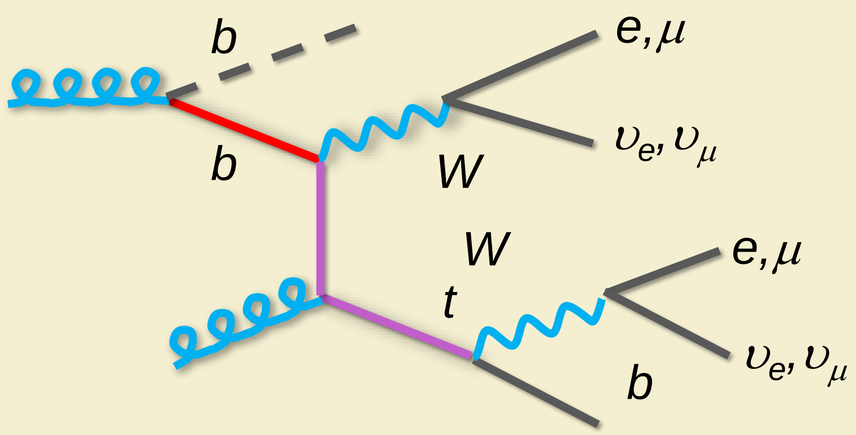


ALSO RESULTS AVAILABLE ON ANGULAR DISTRIBUTION RELATED TO BSM-COUPLINGS/ EFT OPERATORS.

tW-channel


ATLAS
EXPERIMENT
Run: 284285
Event: 1220033035
2015-11-01 02:30:55 CEST

tW-channel: analysis @13TeV

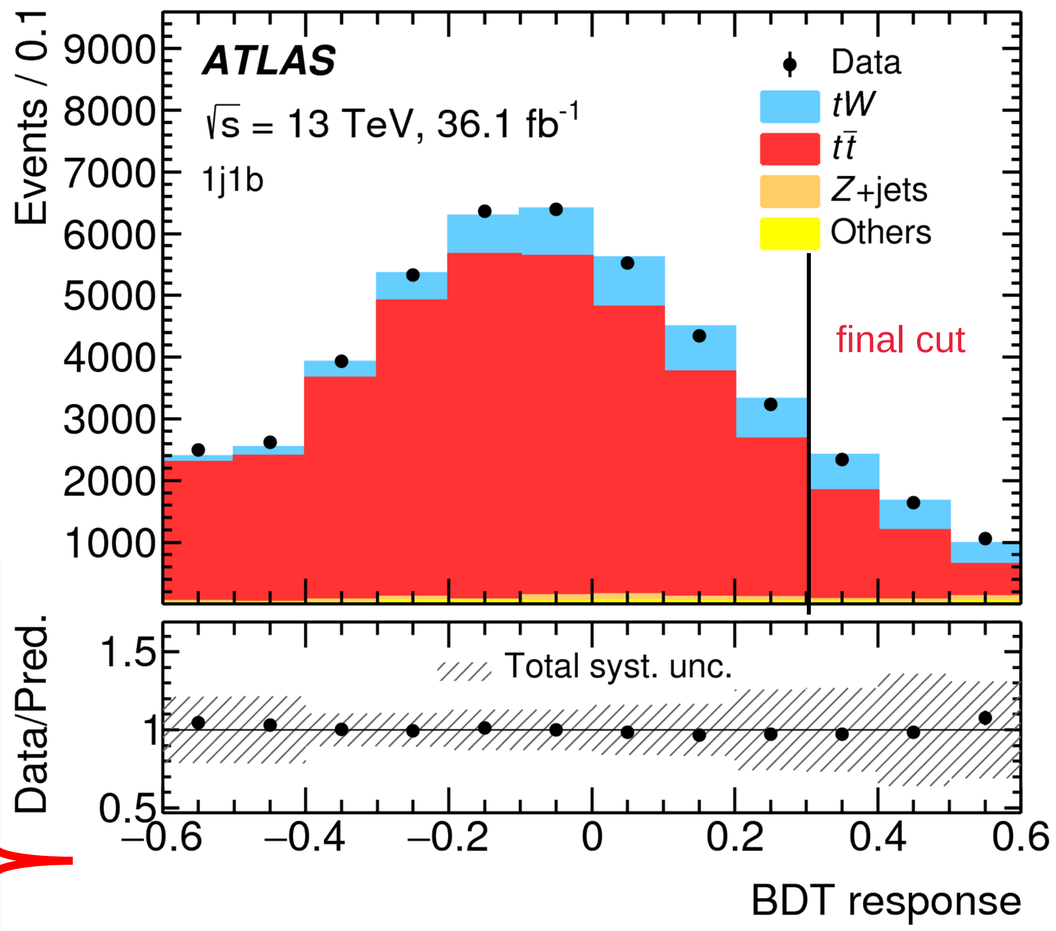


Signal Region:

- Exactly two isolated *e* and/or μ.
- MET>20 GeV
- 1 jet which is *b*-tagged (pt>25 GeV)
  (EFF 77%, CHARM 22%, LIGHT 0.07%)
- mass(*ll*) vs MET cuts to reduce Z+jets.

- BDT used to separate Signal and Background
- Main background ttbar

$p_T(\ell_1\ell_2 E_T^{miss} b)$
$\Delta p_T(\ell_1\ell_2 b, E_T^{miss})$
$\sum E_T$
$\eta(\ell_1\ell_2 E_T^{miss} b)$
$\Delta p_T(\ell_1\ell_2, E_T^{miss})$
$p_T(\ell_1\ell_2 b)$
$C(\ell_1\ell_2)$
$m(\ell_2, b)$
$m(\ell_1, b)$



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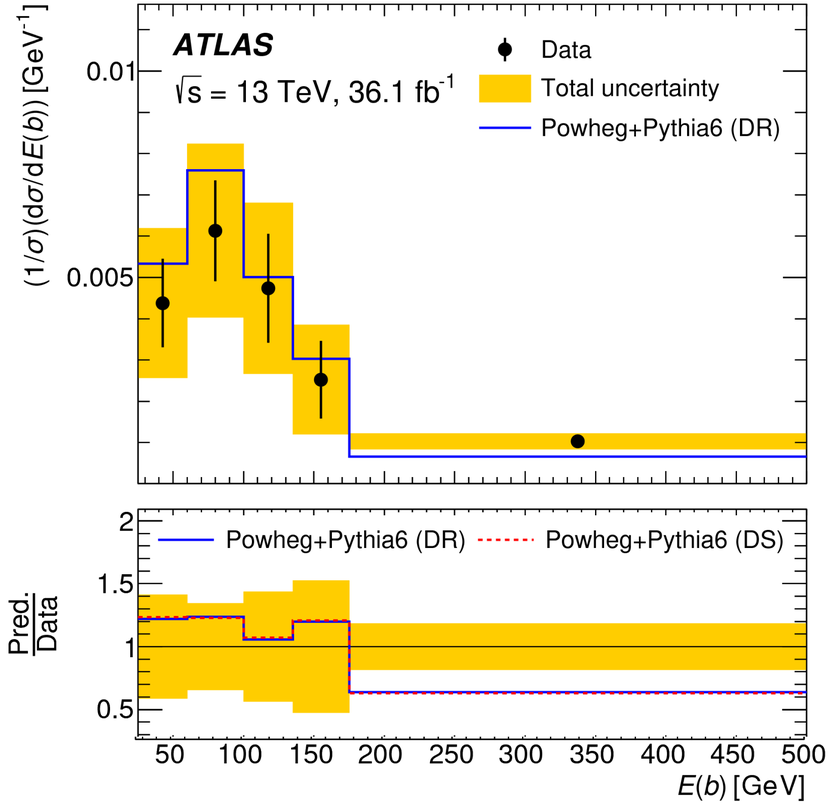
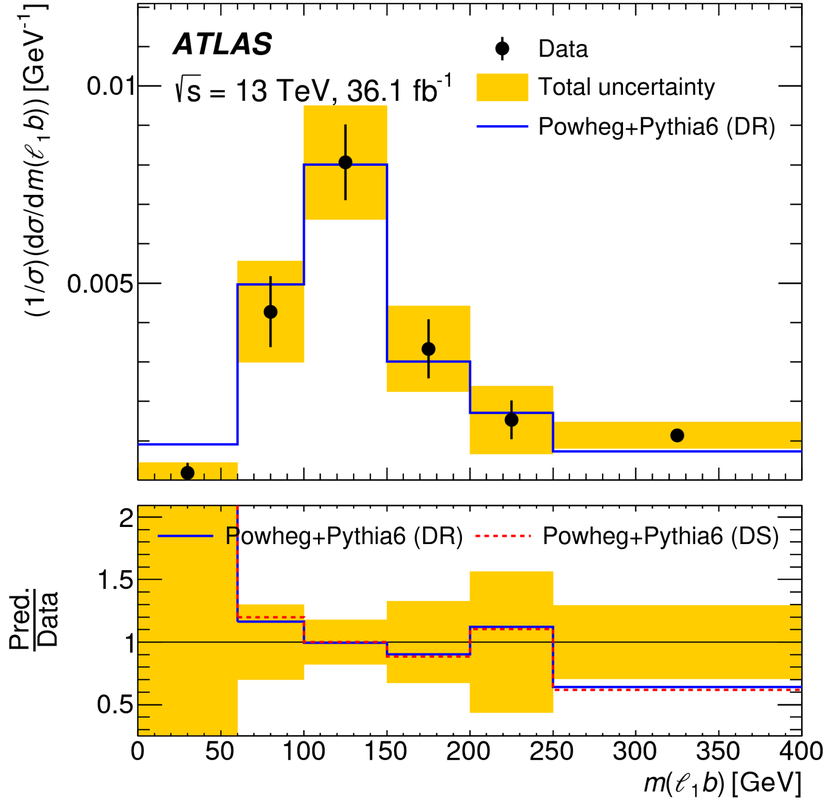
tW channel: differential cross section @13 TeV

Cut on BDT>0.3 to reduce syst
Unfolding with Iterative Bayesian method
Differential cross section are normalised by the fiducial cross section





In high tail mc<data
Also seen in $M(\ell_2\, b)$, and $E(\ell\, b)$

Largest systematic:
- *tW* generator parton shower,
- ttbar modelling (ISR/FSR)

Results are sensitive to quantum interference *tW* and ttbar.
Nominal MC: Diagram-Removal (DR)
For syst. Check:
Diagram-Substraction (DS)

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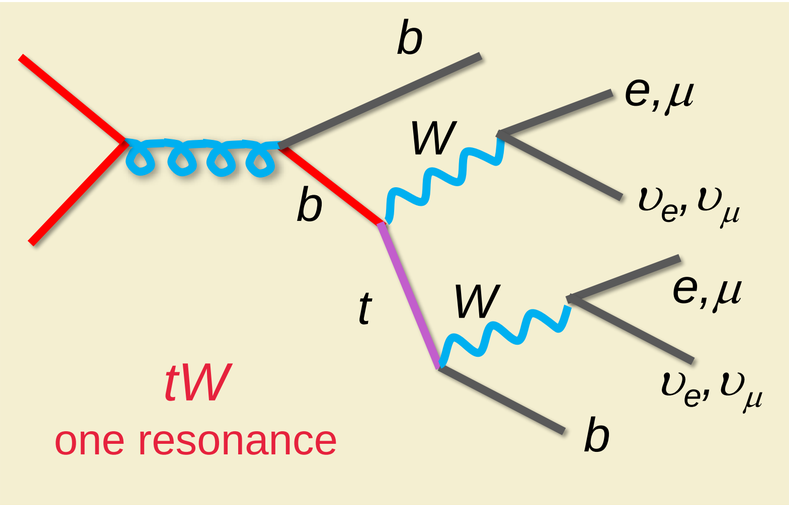
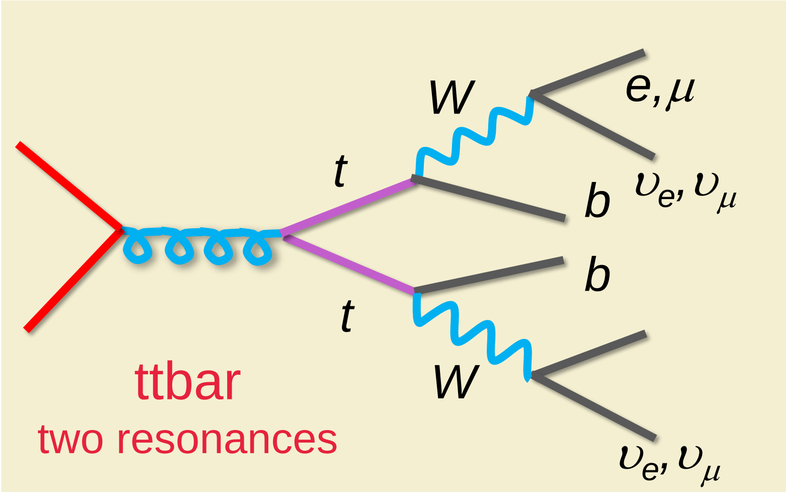
tW MC: powheg-box v1 for ME; ct10 DR; PS: Pythia6.428 CTEQ6l1pdfset

tW-channel: interference with ttbar



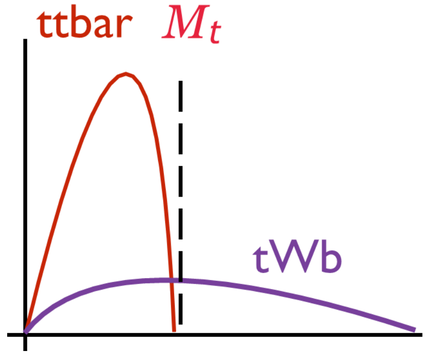


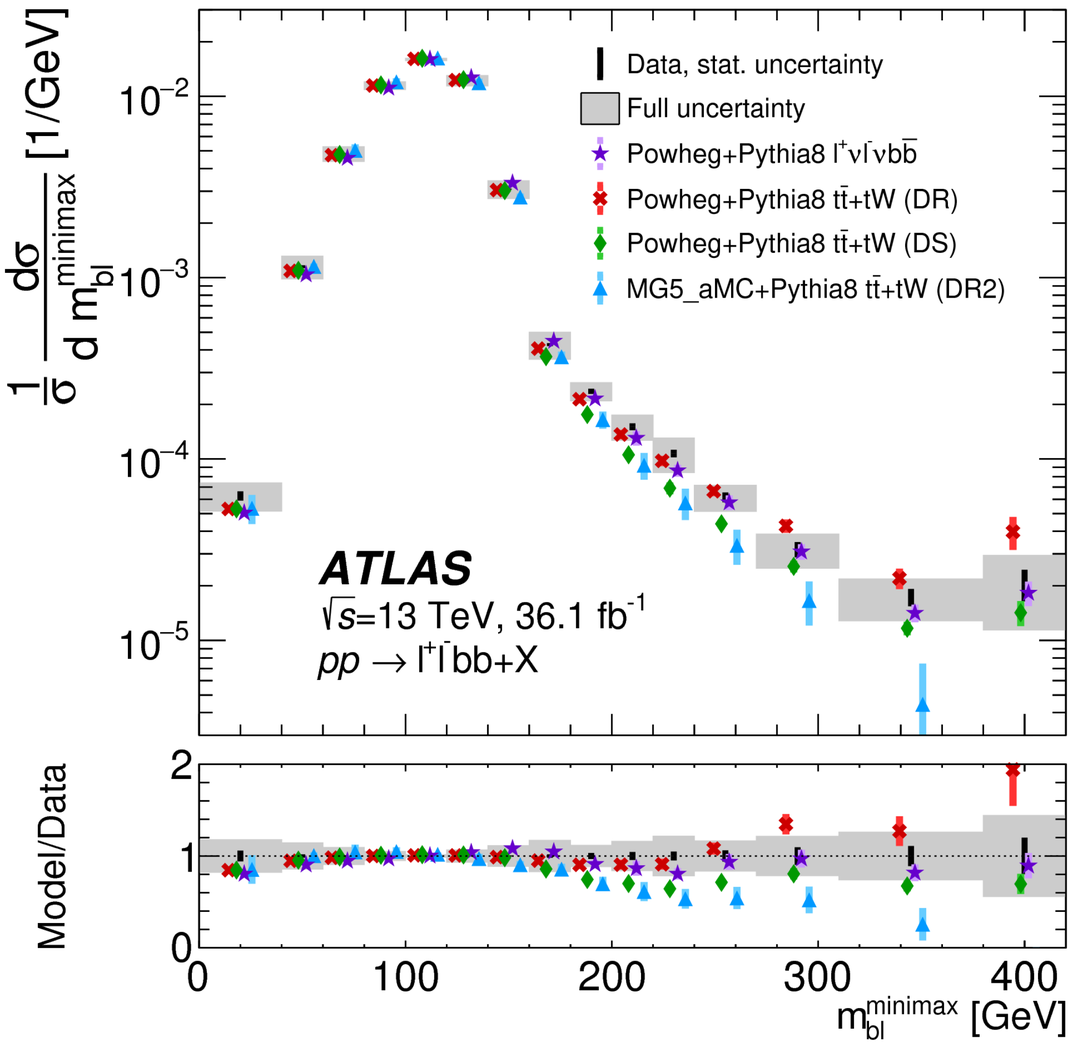
SAME FINAL STATE @LO

Novel method to study interference

submitted to prl

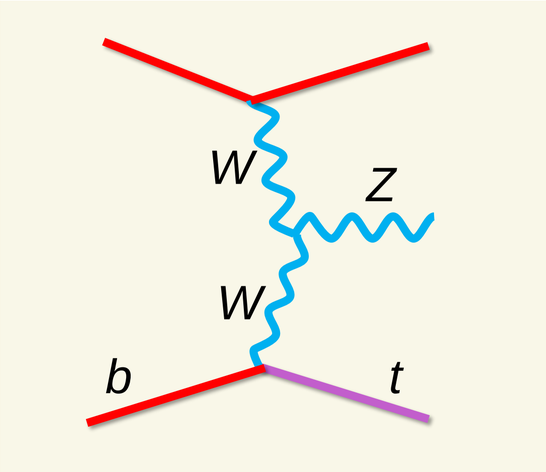
$$m_{b\ell}^{\text{minimax}} \equiv \min\{ \max(m_{b_1\ell_1}, m_{b_2\ell_2}), \max(m_{b_1\ell_2}, m_{b_2\ell_1}) \}$$

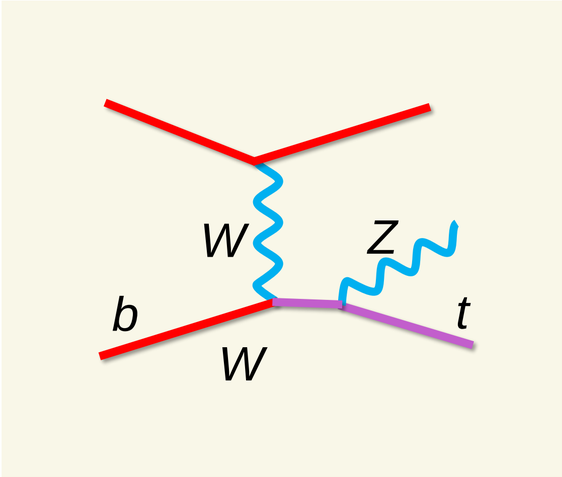




tZq production
--a rare SM channel--

13TeV

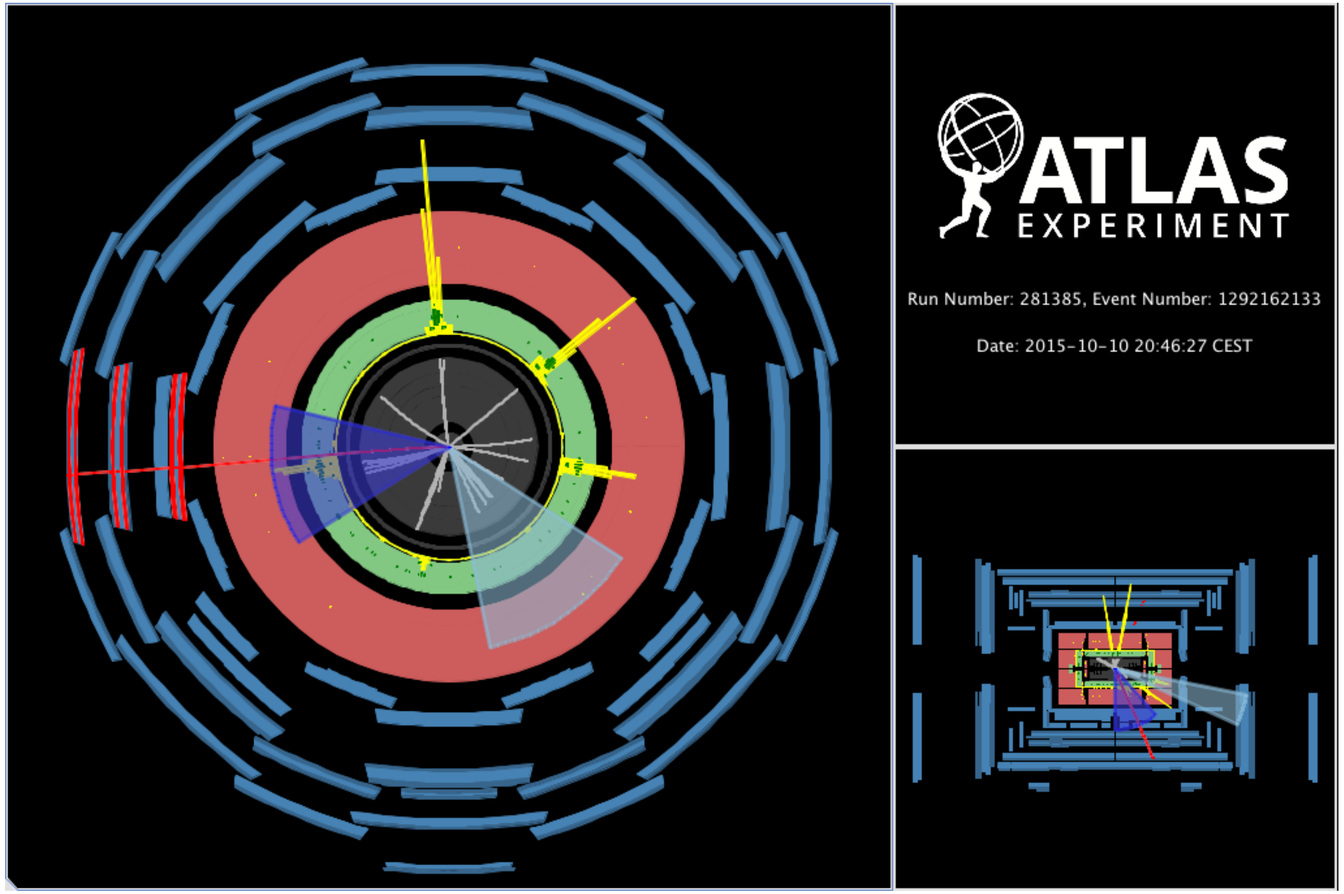




Sensitive to *WWZ* and *tZ* coupling
→ Not seen before
→ Background to *tH* channel

Signal Region

- Three charged leptons in final state P_T>28, 25, 15GeV
- 1 b-tagged jet (P_T>30GeV) (eff 77%, charm 17%, light 1%)
- 1 untagged jet (P_T>30GeV)
- Transverse mass W, M_T(lepton,MET) >20GeV
- Z mass window 80-100GeV (and a opposite charge, same lepton flavour pair)



tZq production: analysis

Two Control Regions for Backgrounds:

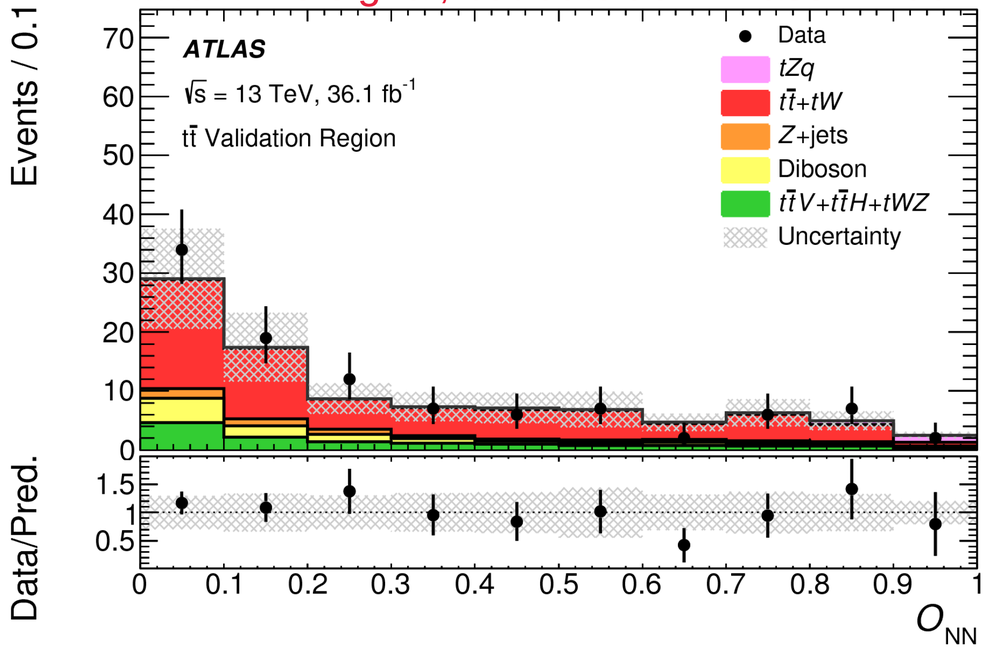
- ''Fake Z'' background from **ttbar**: opposite flavour lepton combination
- ''Real Z'' background **diboson**: 1 untagged jet, tightened M_T

Background Z+jets from ratio in data (M_T <20) with a third lepton failing isolation criteria.

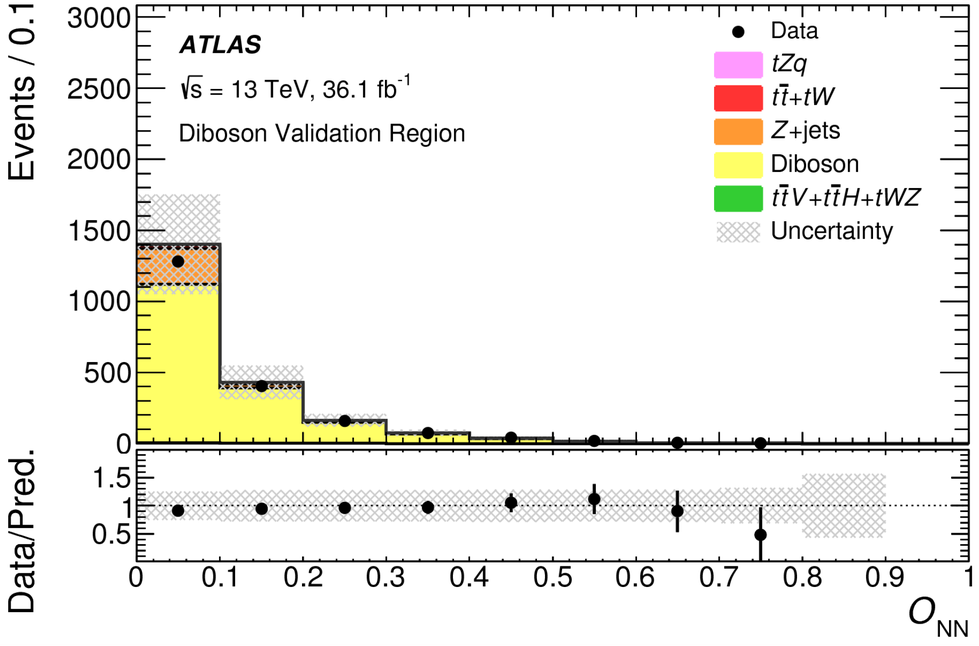
$|\eta(\mathrm{j})|$
$p_{\mathrm{T}}(\mathrm{j})$
m_t
$p_{\mathrm{T}}(\ell^W)$
$\Delta R(\mathrm{j}, Z)$
$m_{\mathrm{T}}(\ell, E_{\mathrm{T}}^{\mathrm{miss}})$
$p_{\mathrm{T}}(t)$
$p_{\mathrm{T}}(b)$
$p_{\mathrm{T}}(Z)$
$|\eta(\ell^W)|$

Neural net to separate signal and background
Output checked in validation regions (VR)

VR ttbar: like signal, but outside *Z*-mass window



VR diboson: like signal, only 1 jet, (no *b*-tagging)



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tZq production, cross section @13 TeV

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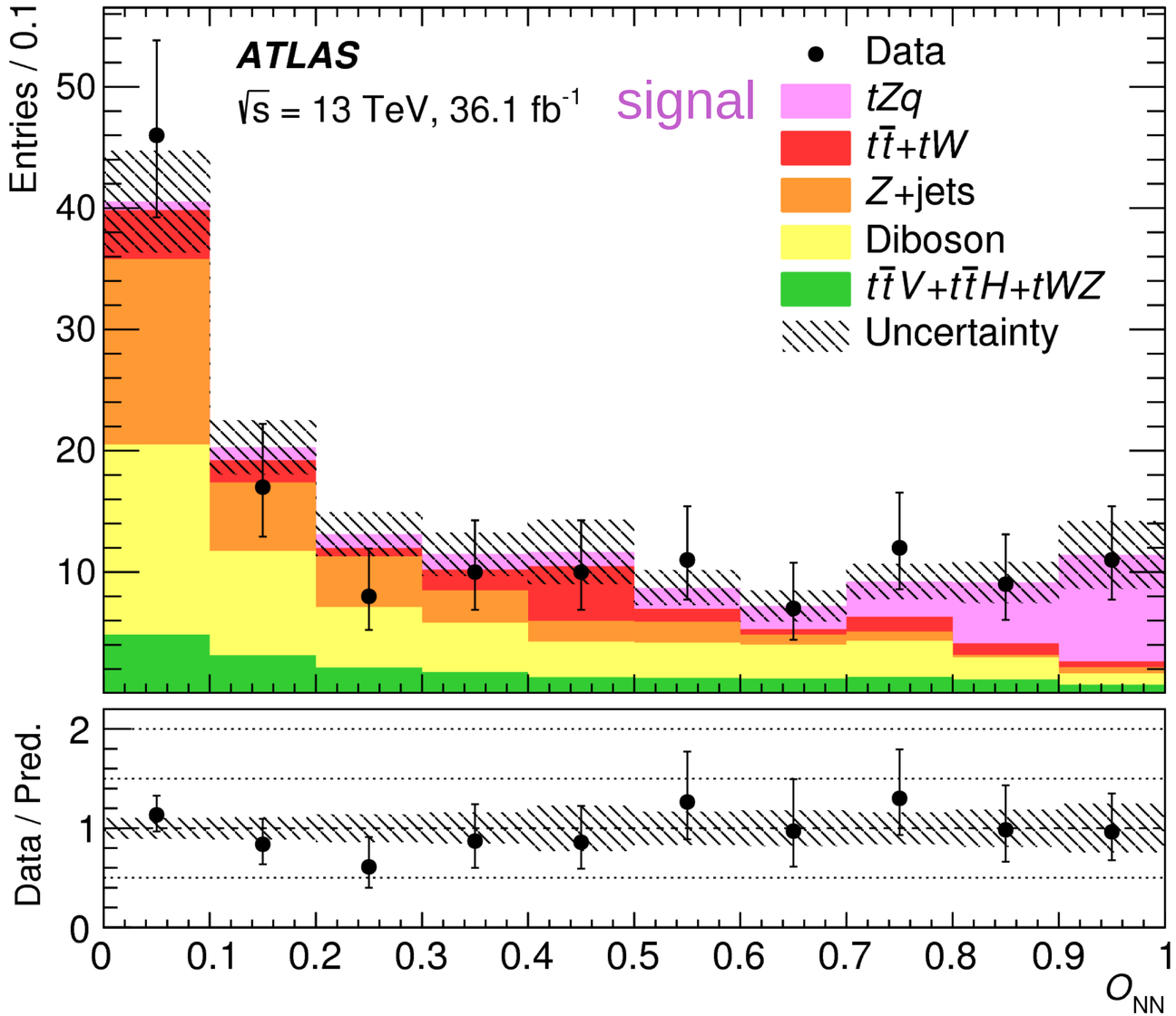


Signal obtained in Likelihood fit
Background also fitted with constrains according to uncertainties

σ=600±170 (stat.)±140 (syst.) fb
(theory NLO 800fb ±7% (scale))

Main systematics:

- Radiation signal MC
- Jet Energy Scale
- b-tagging

Significance 4.2 (5.4 expected)

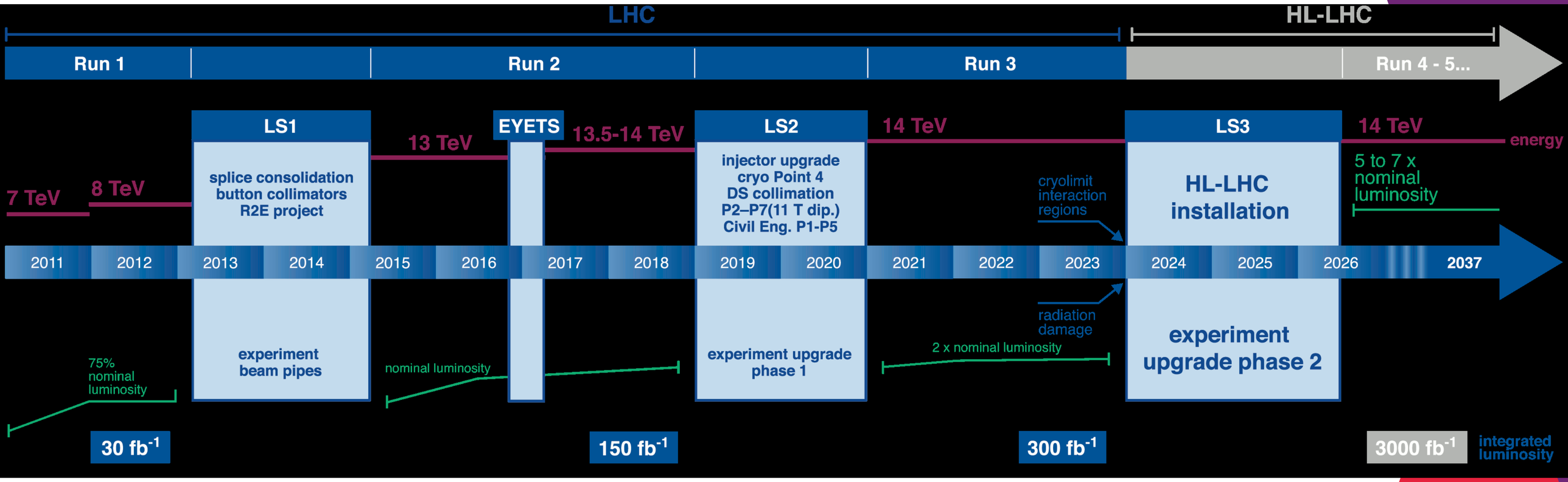
EVIDENCE

SIGNAL MC:
LO MG5_AMC@NLO2.2.1, 4FS; PS: CTEQ6L1 (LO)

Summary

- Main three single top channel being pinned down
- Many results available
- The hunt for rare single-top processes started

LHC SCHEDULE



t-channel: CROSS-SECTION MEASUREMENT @8TEV

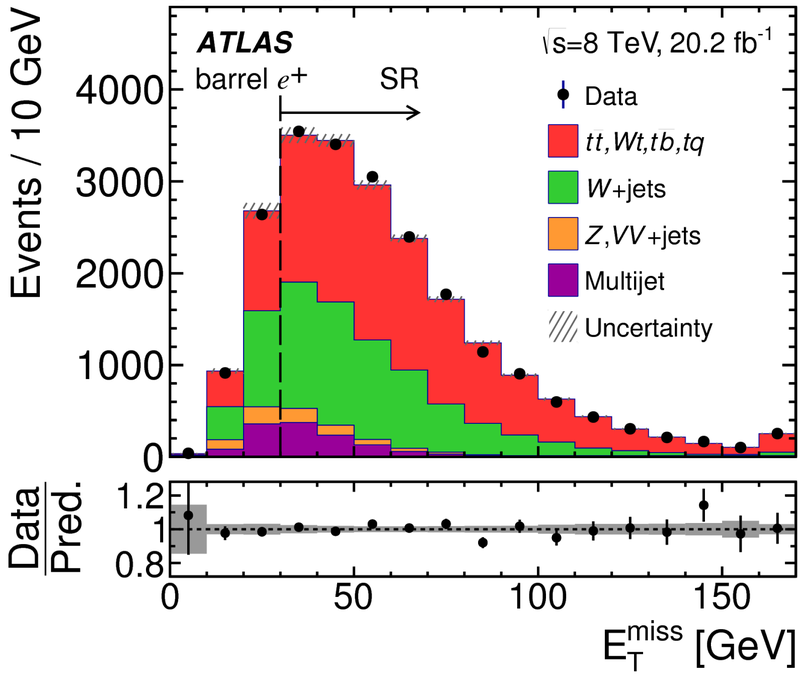
BACKGROUND (DATA-DRIVEN)

Multijet shape from di-jet MC.
Multijet normalisation from MET distribution

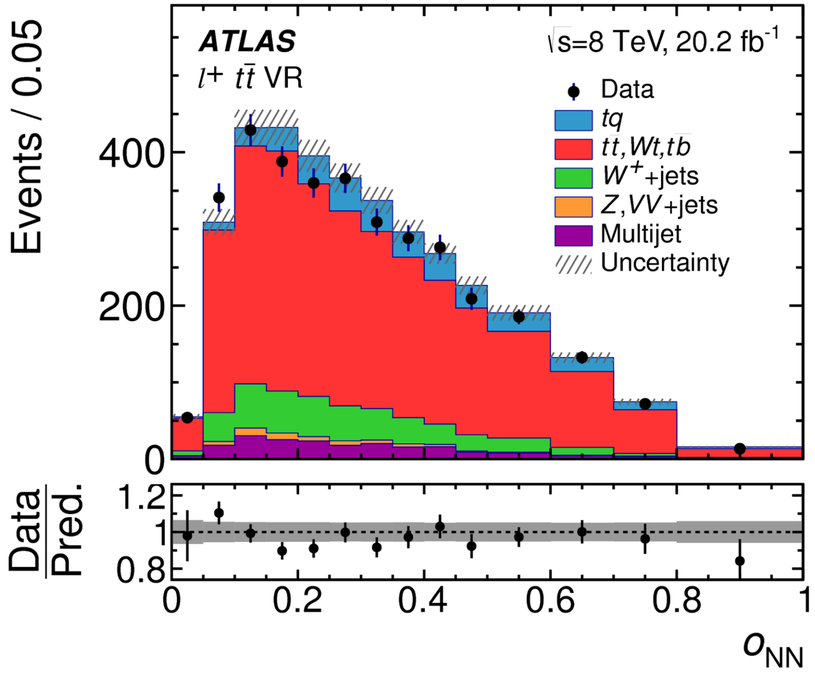
ttbar shape from NLO MC
Validation Region (VR) to check NN
(VR is SR but with 2 *b*-jets)

W+jets shape from NLO MC
Validation Region (VR) to check NN
(VR uses relaxed *b*-jet requirement)

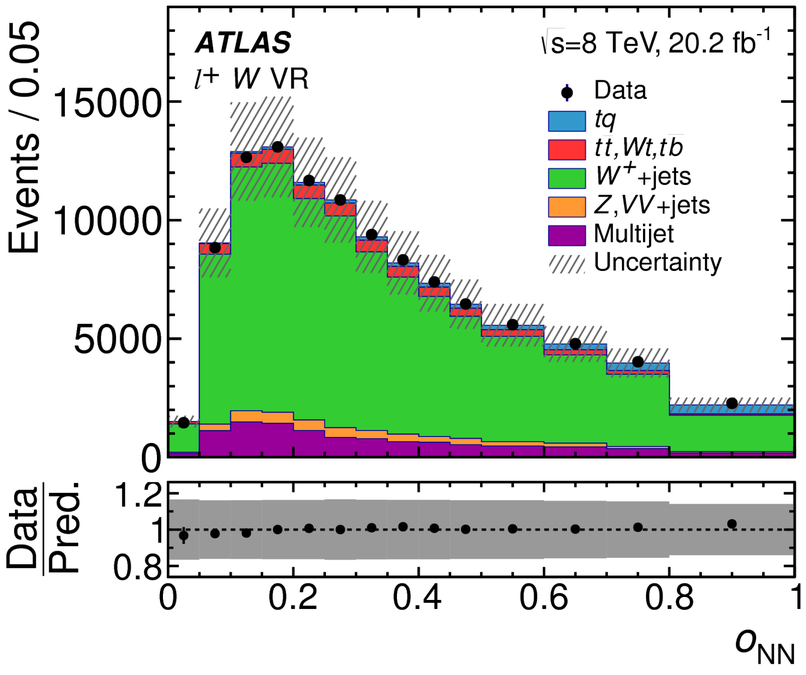
Signal Region (SR), without MET cut



NN output in ttbar VR



NN output in *W*+jets VR



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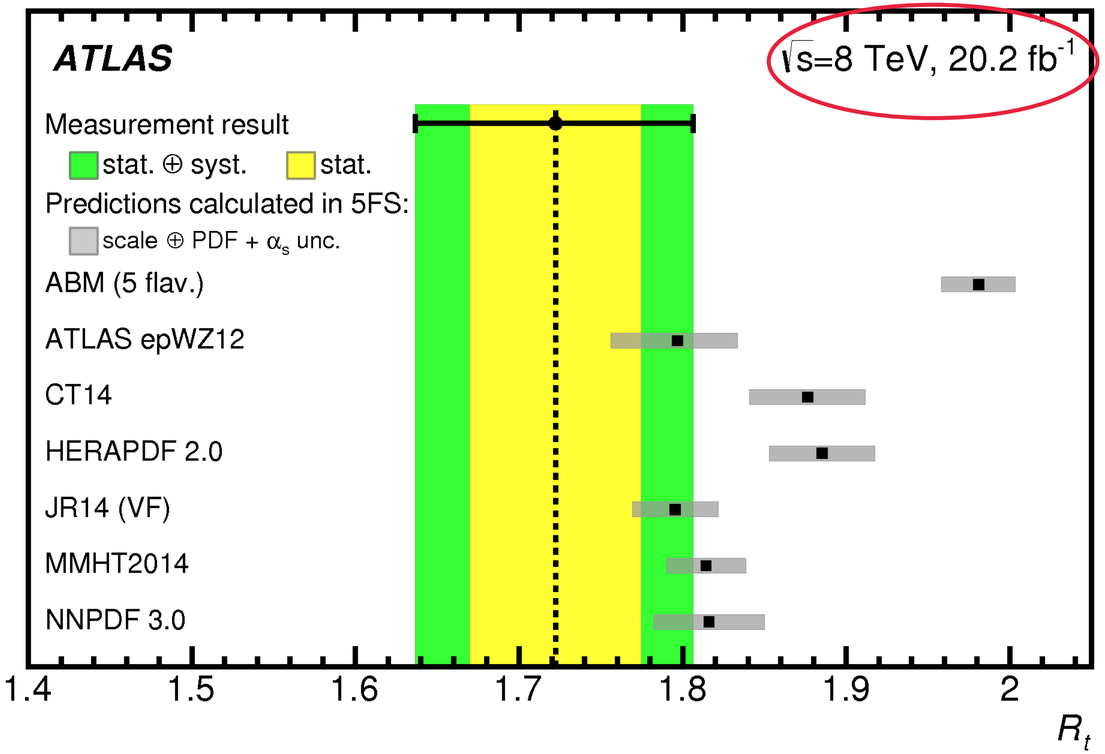
t-channel: ratio σ(top)/σ(antitop) 8TeV and 13TeV

Many additional result available
Shown here: ratio σ(top)/σ(antitop)



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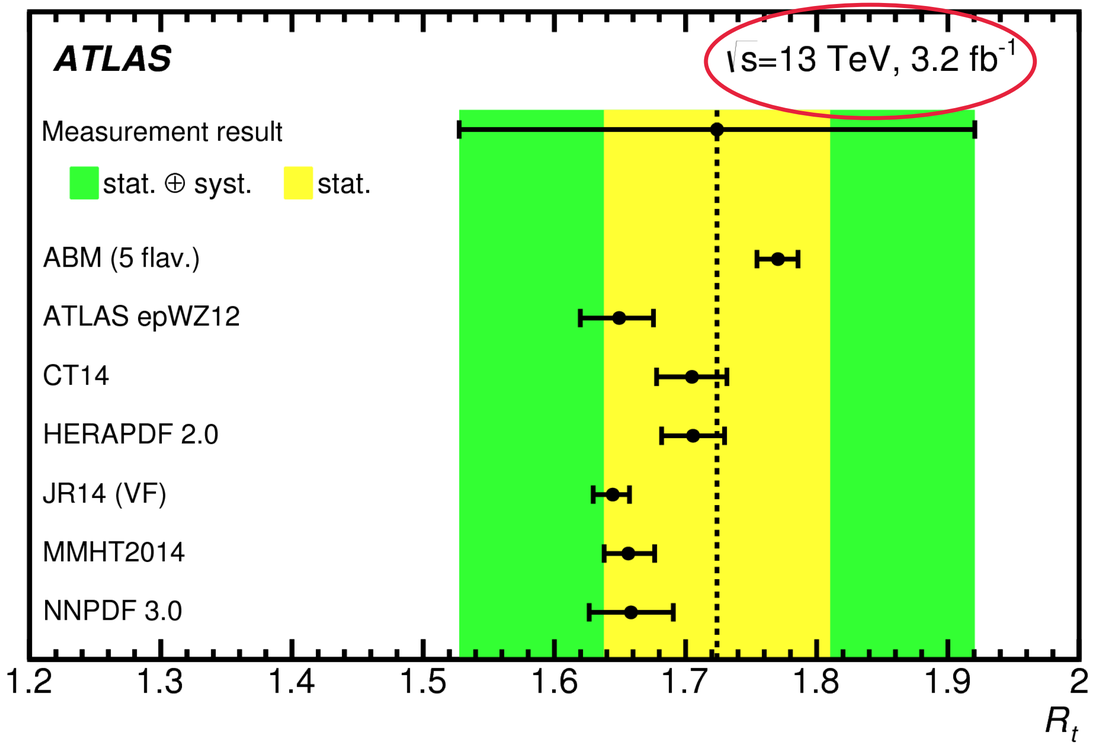
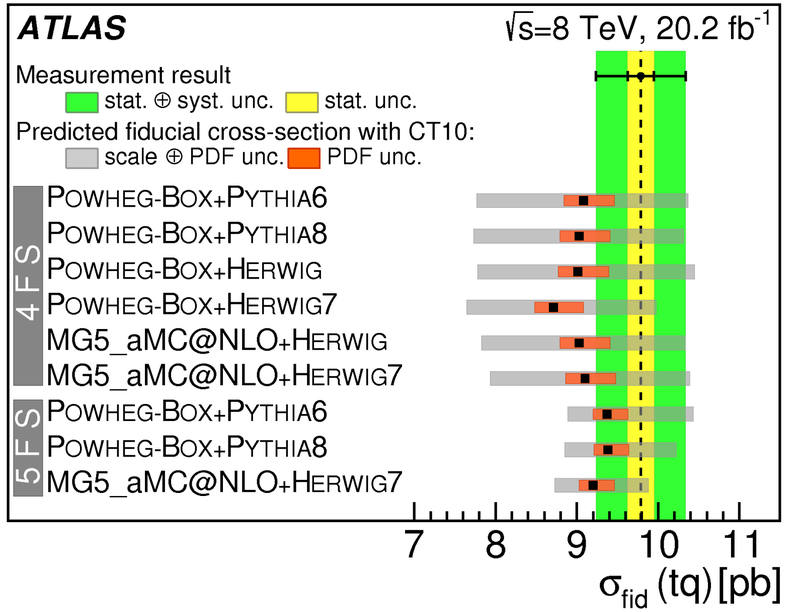
Note: also 13TeV paper is out!
In a manner similar analysis as 8 TeV
(cross section shown later this talk)

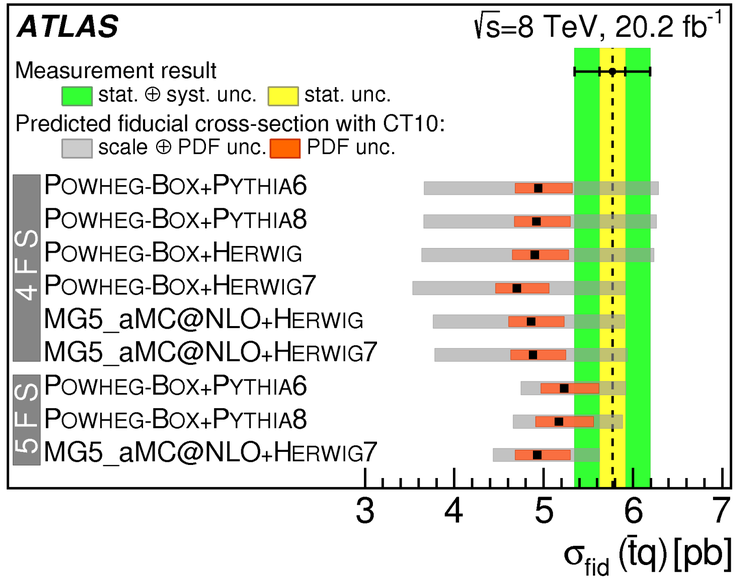


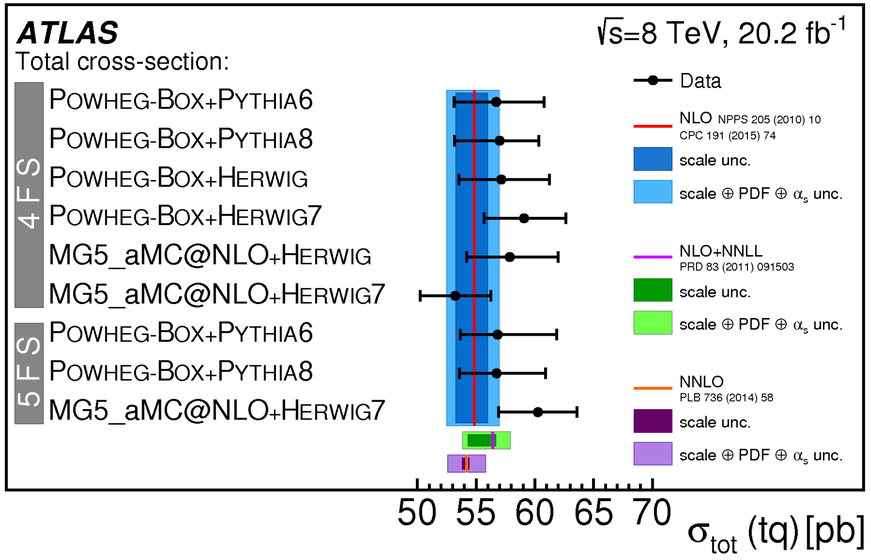
JHEP 04 (2017) 086

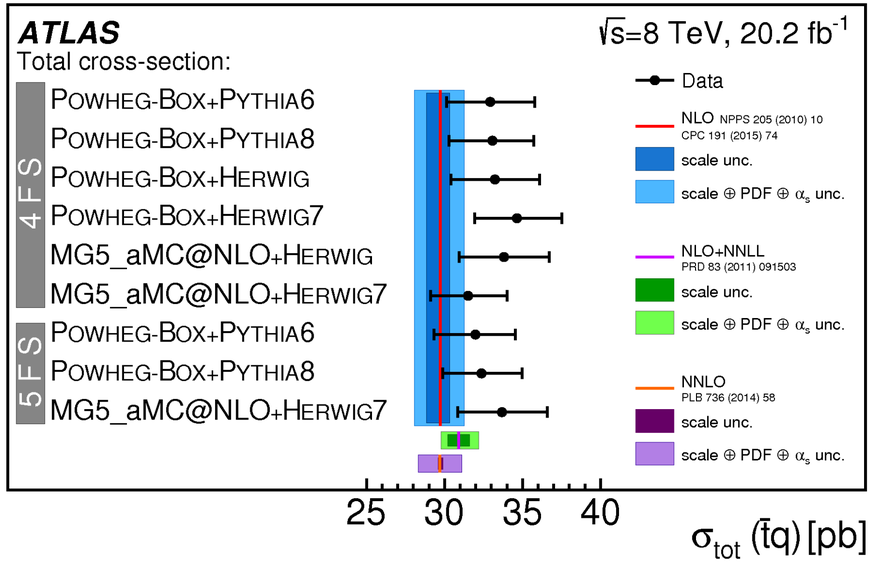
Main systematic unc.: Background modelling, Jet Reconstruction, MET modelling

t-CHANNEL


ATLAS
√s=8 TeV, 20.2 fb-1
Measurement result
stat. ⊕ syst. unc.
stat. unc.
Predicted fiducial cross-section with CT10:
scale ⊕ PDF unc.
PDF unc.
4FS
POWHEG-BOX+PYTHIA6
POWHEG-BOX+PYTHIA8
POWHEG-BOX+HERWIG
POWHEG-BOX+HERWIG7
MG5_aMC@NLO+HERWIG
MG5_aMC@NLO+HERWIG7
5FS
POWHEG-BOX+PYTHIA6
POWHEG-BOX+PYTHIA8
MG5_aMC@NLO+HERWIG7
7 8 9 10 11
σfid (tq) [pb]


ATLAS
√s=8 TeV, 20.2 fb-1
Measurement result
stat. ⊕ syst. unc.
stat. unc.
Predicted fiducial cross-section with CT10:
scale ⊕ PDF unc.
PDF unc.
4FS
POWHEG-BOX+PYTHIA6
POWHEG-BOX+PYTHIA8
POWHEG-BOX+HERWIG
POWHEG-BOX+HERWIG7
MG5_aMC@NLO+HERWIG
MG5_aMC@NLO+HERWIG7
5FS
POWHEG-BOX+PYTHIA6
POWHEG-BOX+PYTHIA8
MG5_aMC@NLO+HERWIG7
3 4 5 6 7
σfid (t̄q) [pb]


ATLAS
√s=8 TeV, 20.2 fb-1
Total cross-section:
4FS
POWHEG-BOX+PYTHIA6
POWHEG-BOX+PYTHIA8
POWHEG-BOX+HERWIG
POWHEG-BOX+HERWIG7
MG5_aMC@NLO+HERWIG
MG5_aMC@NLO+HERWIG7
5FS
POWHEG-BOX+PYTHIA6
POWHEG-BOX+PYTHIA8
MG5_aMC@NLO+HERWIG7
Data
NLO NPPS 205 (2010) 10
CPC 191 (2015) 74
scale unc.
scale ⊕ PDF ⊕ αs unc.
NLO+NNLL
PRD 83 (2011) 091503
scale unc.
scale ⊕ PDF ⊕ αs unc.
NNLO
PLB 736 (2014) 58
scale unc.
scale ⊕ PDF ⊕ αs unc.
50 55 60 65 70
σtot (tq) [pb]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Data
NLO NPPS 205 (2010) 10
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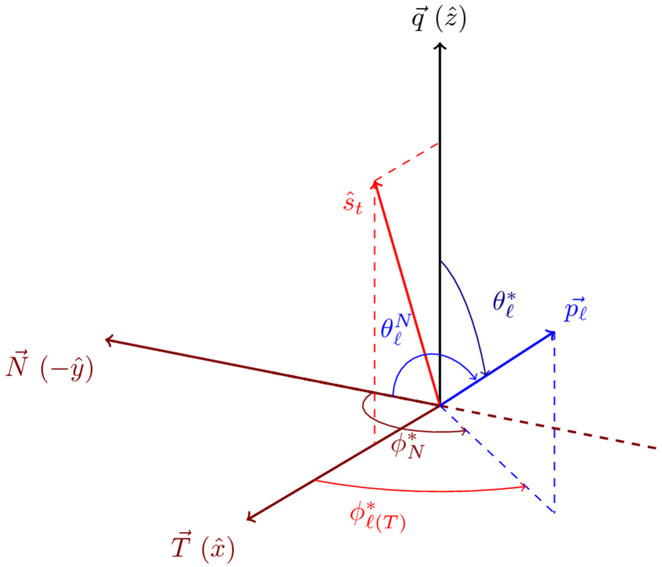
scale unc.
scale ⊕ PDF ⊕ αs unc.
NLO+NNLL
PRD 83 (2011) 091503
scale unc.
scale ⊕ PDF ⊕ αs unc.
NNLO
PLB 736 (2014) 58
scale unc.
scale ⊕ PDF ⊕ αs unc.
25 30 35 40
σtot (t̄q) [pb]

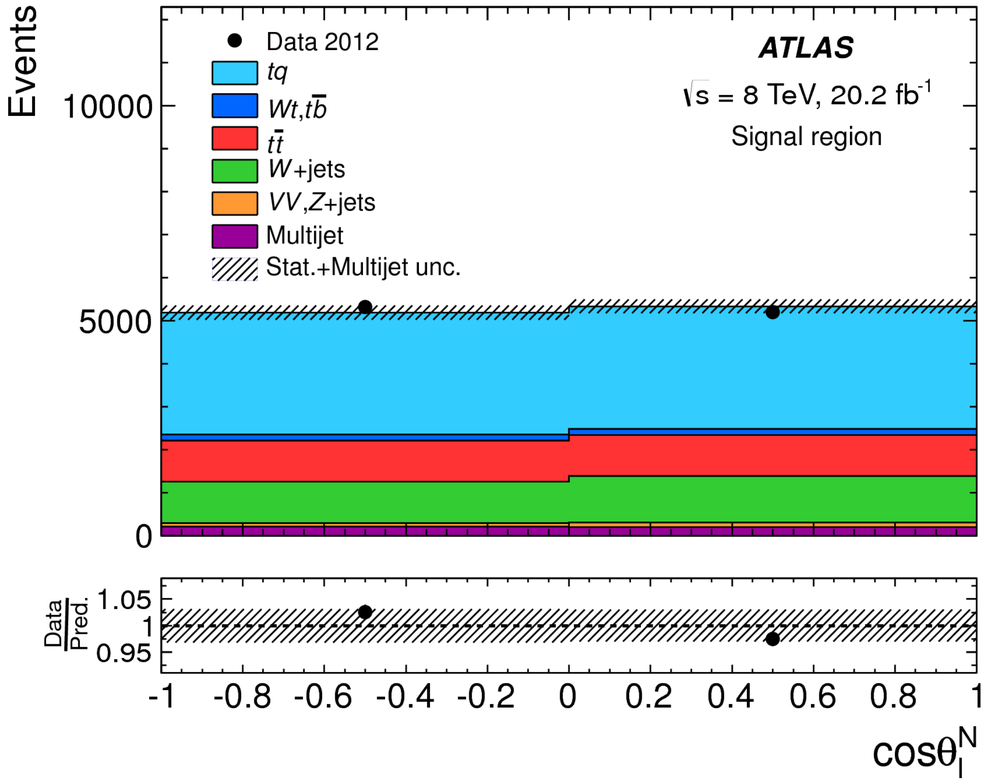
SINGLE TOP-QUARK MEASUREMENTS: t-channel

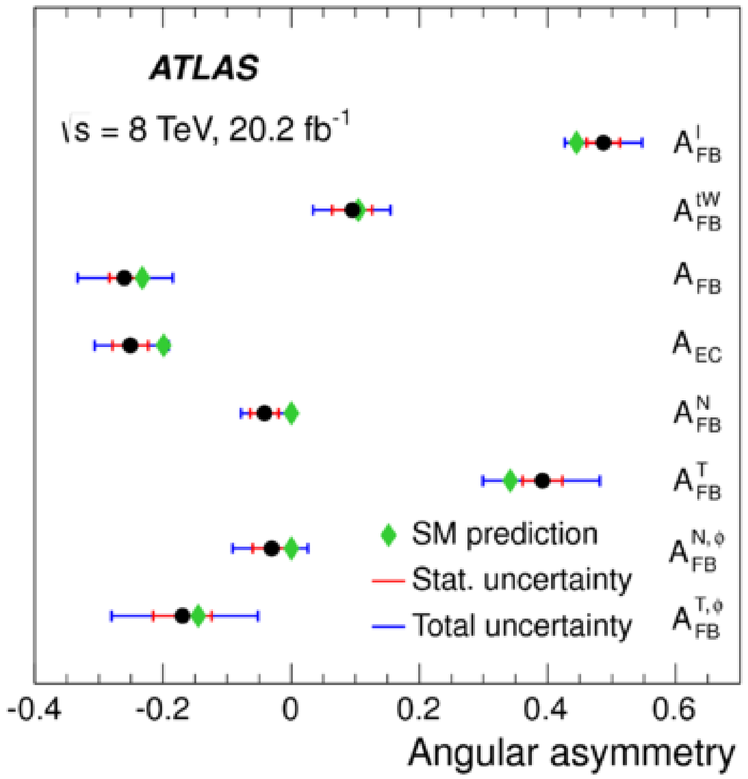
$$\mathcal{L}_{Wtb} = -\frac{g}{\sqrt{2}}\,\bar{b}\gamma^{\mu}\left(V_L P_L + V_R P_R\right) t W^-_{\mu} - \frac{g}{\sqrt{2}}\,\bar{b}\,\frac{i\sigma^{\mu\nu}q_{\nu}}{m_W}\left(g_L P_L + g_R P_R\right) t W^-_{\mu}$$

Example: g_R is CP violating

$$A^N_{FB} = 0.64\, P\, \mathrm{Im}\, g_R$$







Main systematic unc. (on A_{FB}^N):

MC stats, Jet reconstruction, ttbar parton shower, t-channel (scales)

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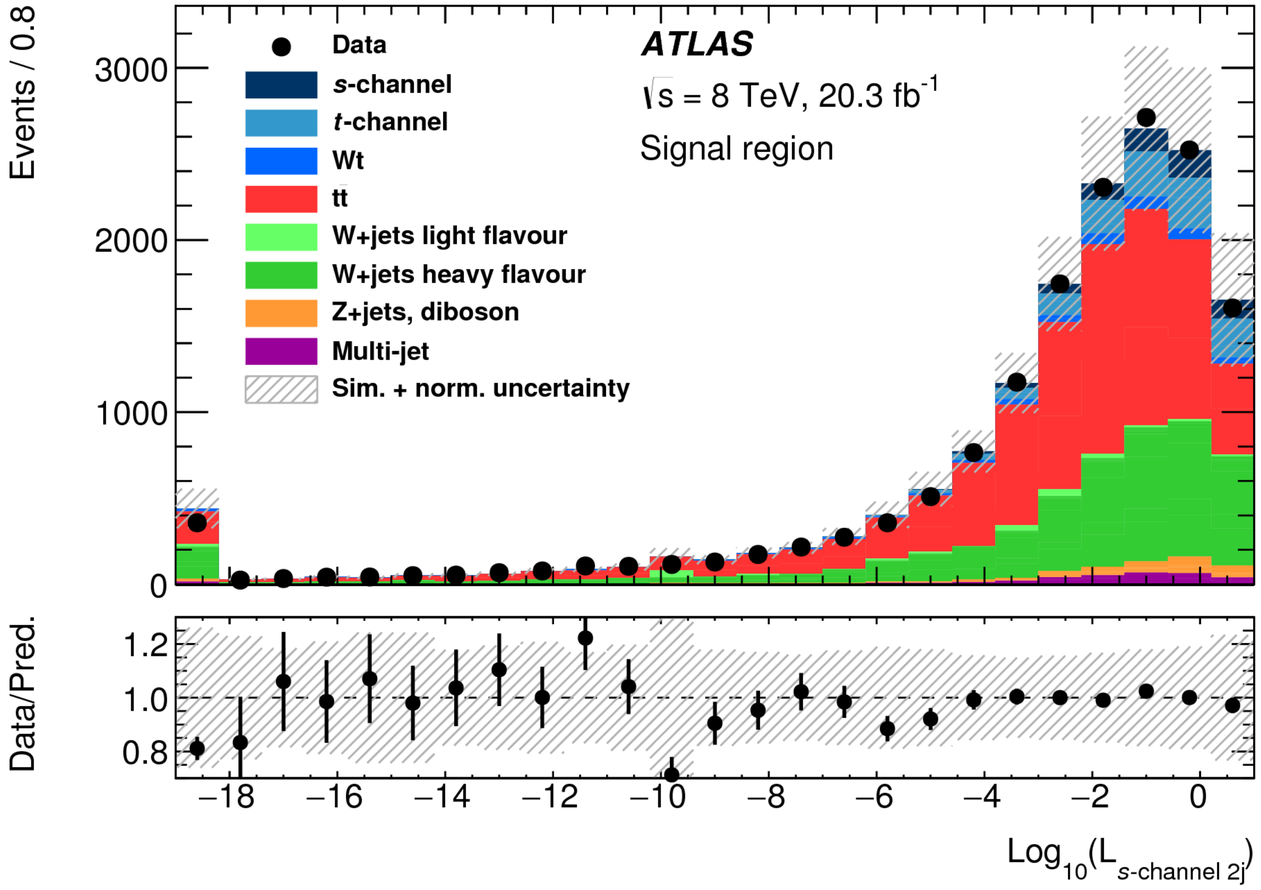
s-CHANNEL

s-channel evidence 8 TeV



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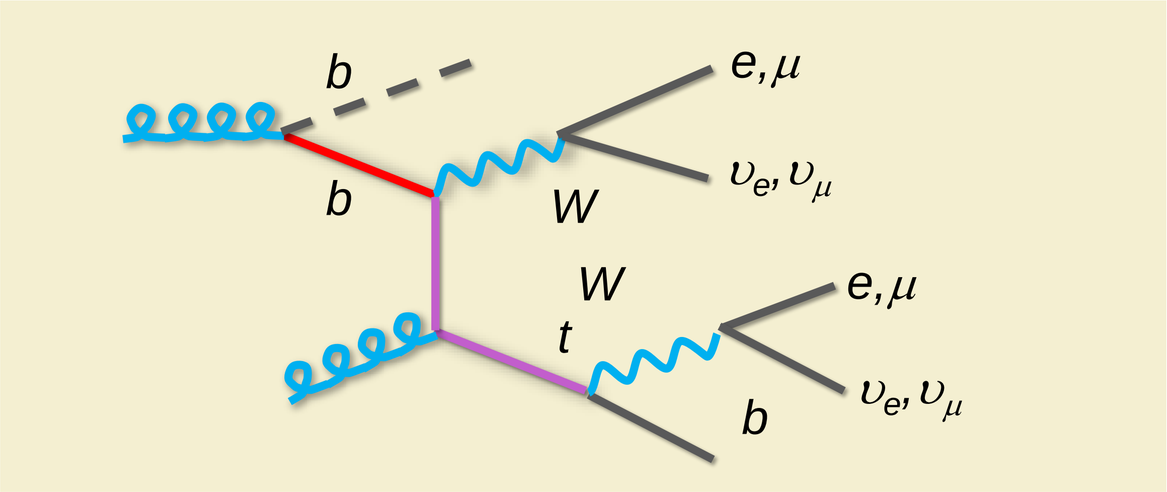
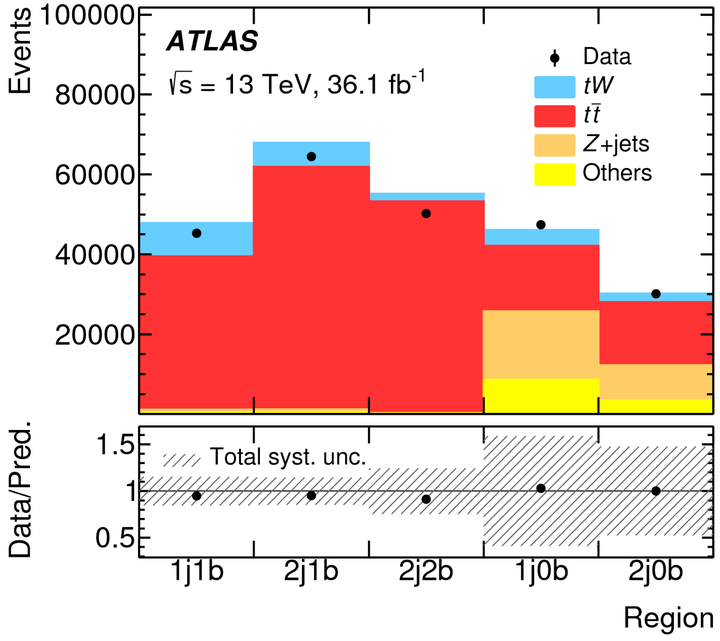
tW-channel: differential cross section @13TeV



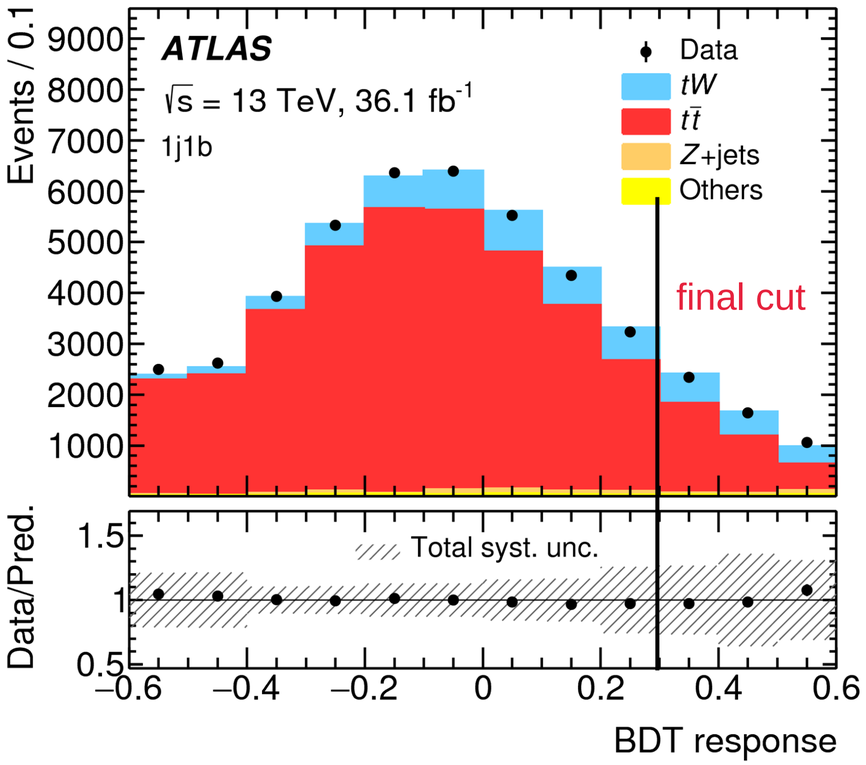
Fiducial cuts=Signal Region:

- Exactly two isolated *e* and/or μ.
- MET>20 GeV
- 1 jet which is *b*-tagged (pt>25 GeV)
  (EFF 77%, CHARM 22%, LIGHT 0.07%)
- mass(*ll*) vs MET cuts to reduce Z+jets.



- Main background ttbar
- Several Validation Regions for checks, one Signal Region ''1j1b''
- Separation in SR with BDT

$p_T(\ell_1\ell_2 E_T^{miss} b)$
$\Delta p_T(\ell_1\ell_2 b, E_T^{miss})$
$\sum E_T$
$\eta(\ell_1\ell_2 E_T^{miss} b)$
$\Delta p_T(\ell_1\ell_2, E_T^{miss})$
$p_T(\ell_1\ell_2 b)$
$C(\ell_1\ell_2)$
$m(\ell_2, b)$
$m(\ell_1, b)$



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