

**XXVII International Symposium on Lepton Photon  
Interactions at High Energies**

17-22 August 2015 Ljubljana Exhibition and Convention Centre



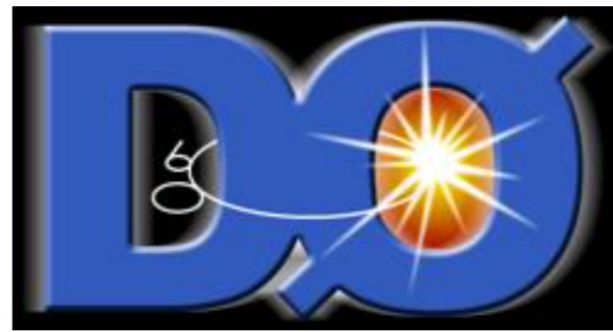
# Top-quark production measurements

**Markus Cristinziani\* (Bonn)**

on behalf of the Collaborations

Lepton Photon 2015

Ljubljana, 20-Aug-2015



\* supported by the European Research Council under contract ERC-CoG-617185

## Discovered at Tevatron in 1995

## LHC is a top quark factory

- $t\bar{t}$  production: inclusive
- $t\bar{t}$  production: differential

## Single top quark production

- total cross section:  $t$ -,  $Wt$  and  $s$ -channel
- differential cross section

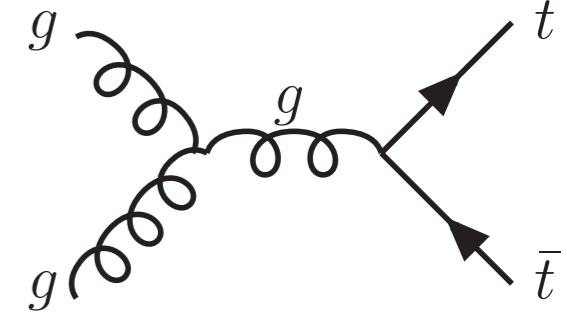
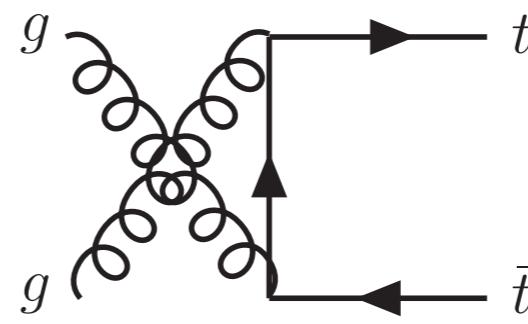
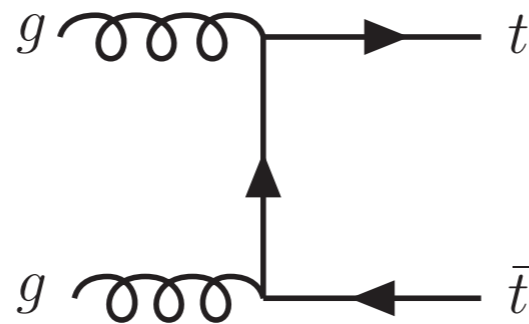
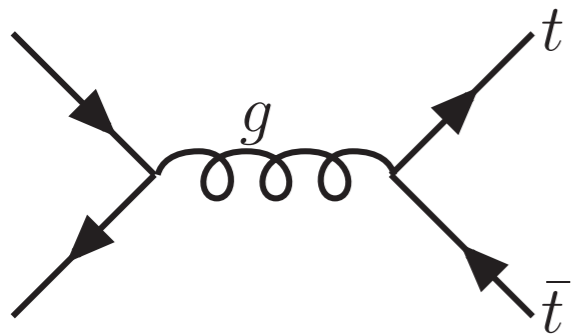
## Associated production

- $\gamma, W, Z, b, t$

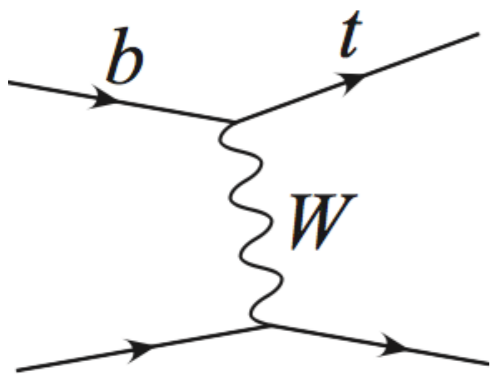
## In this talk

- highlighting results released in the last year

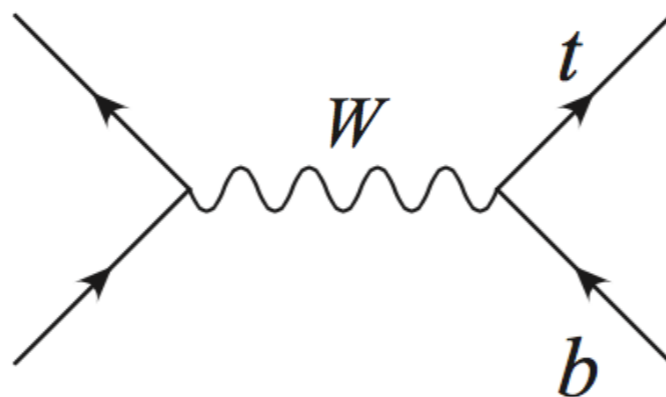
## Top-quark pairs via **strong interaction**



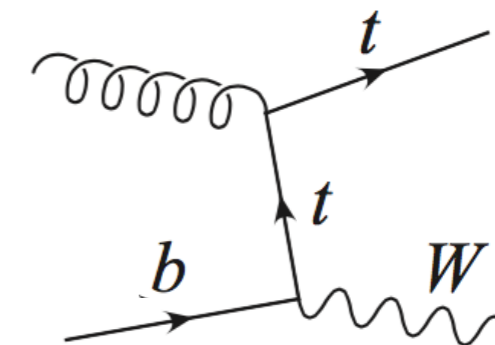
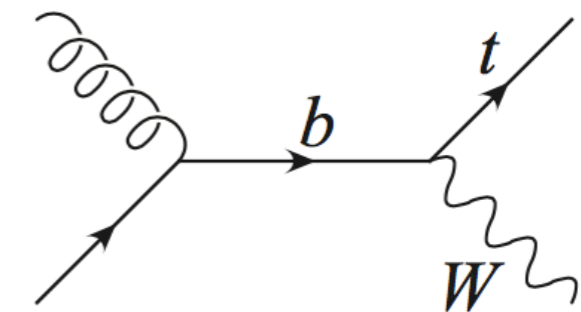
## Single-top quarks via **weak interaction**



t-channel



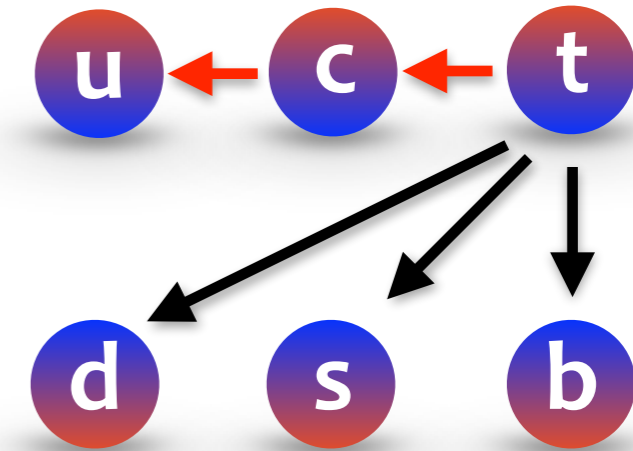
s-channel



Wt channel

## Weak decay

- governed by CKM matrix,  $\text{BF}(t \rightarrow Wb) \sim 1$
- no FCNC transitions at tree level
- $W \rightarrow \ell\nu, \tau_{\text{had}}\nu$  or  $q\bar{q}$



W decay mode	qq'	lepton plus jets	tau plus jets	all hadronic	
		eτ/μτ	ττ		tau plus jets
		eν/μν	eτ/μτ		lepton plus jets
		eν/μν	τν	qq'	
		W decay mode			

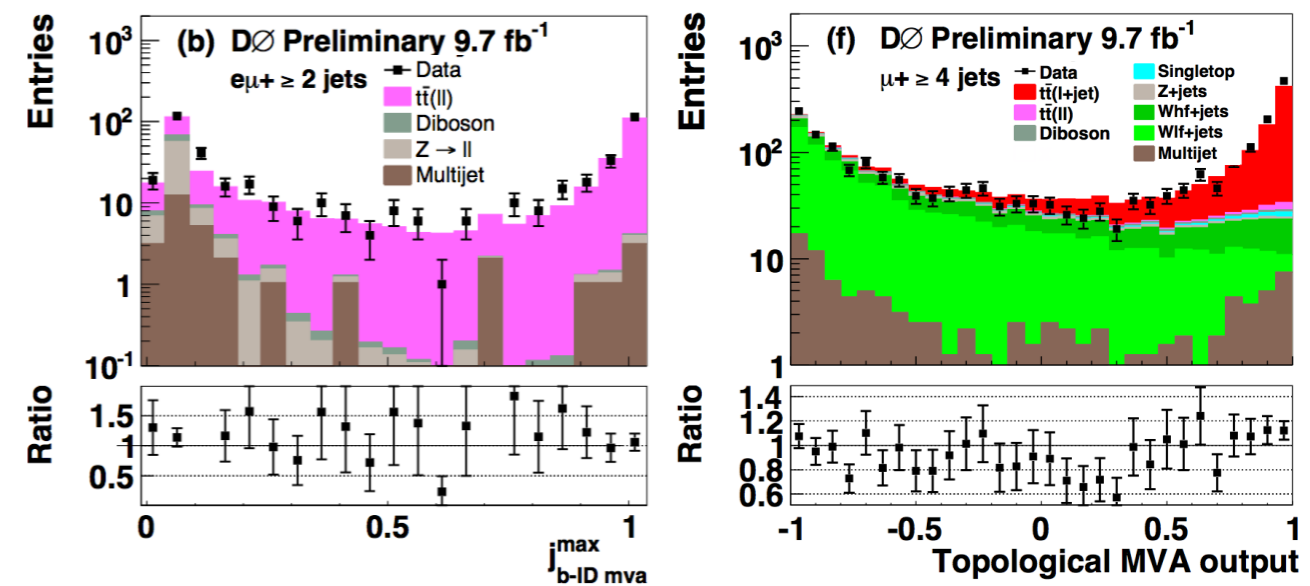
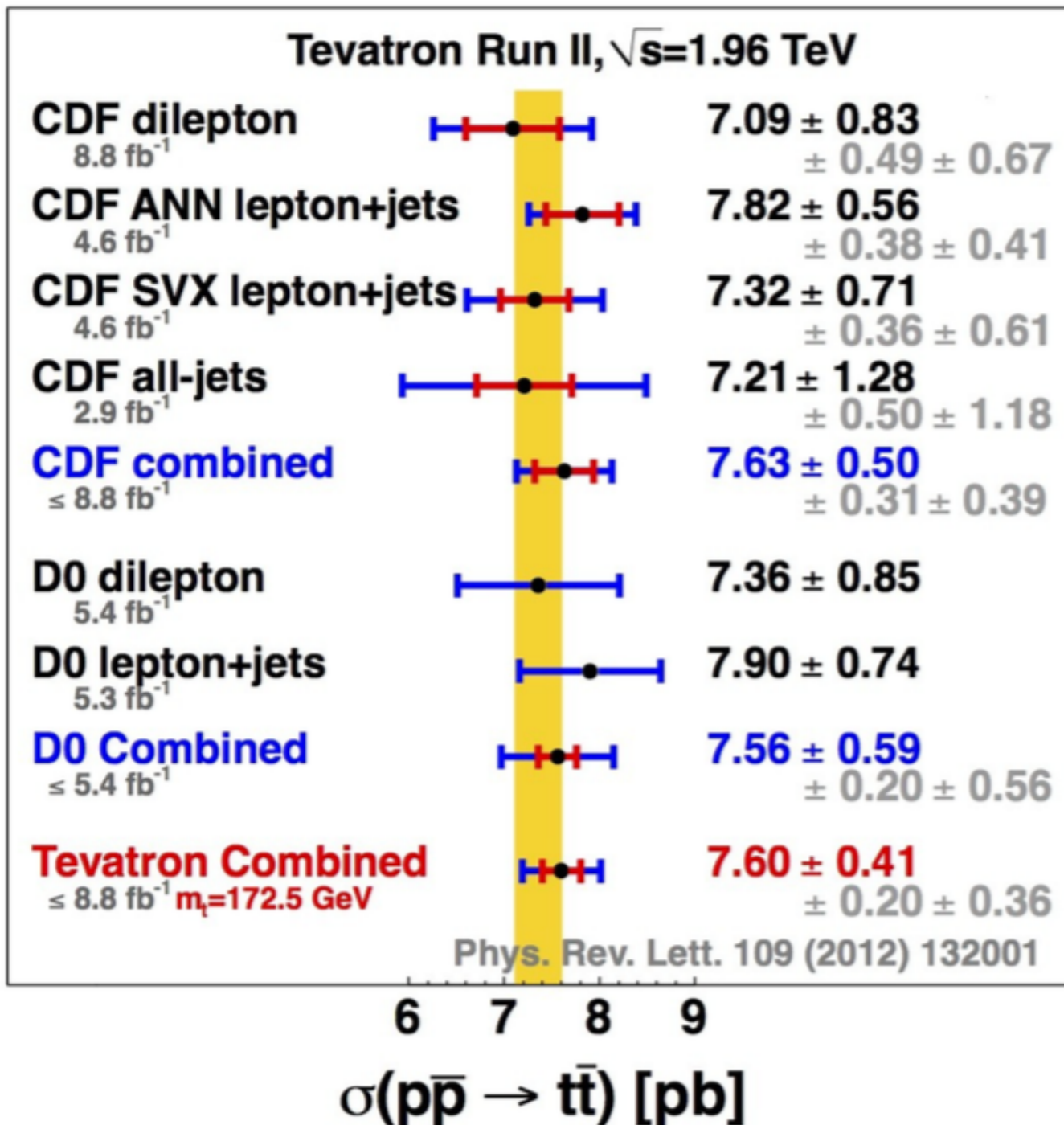
## $t\bar{t}$ final states

- all hadronic (2b, 4q)
- $\ell$ +jets (2b, 2q, 1 $\ell$ , 1 $\nu$ )
- dilepton (2b, 2 $\ell$ , 2 $\nu$ )
- with a  $\tau_{\text{had}}$  lepton

+ extra jets

## Do inclusive measurement

- full dataset ( $9.7 \text{ fb}^{-1}$ ), combination
- dilepton
  - ▶  $b$ -tag MVA
- $\ell$ +jets
  - ▶  $b$ -tag MVA + topological discriminant
  - ▶ split in 2, 3,  $\geq 4$  jets



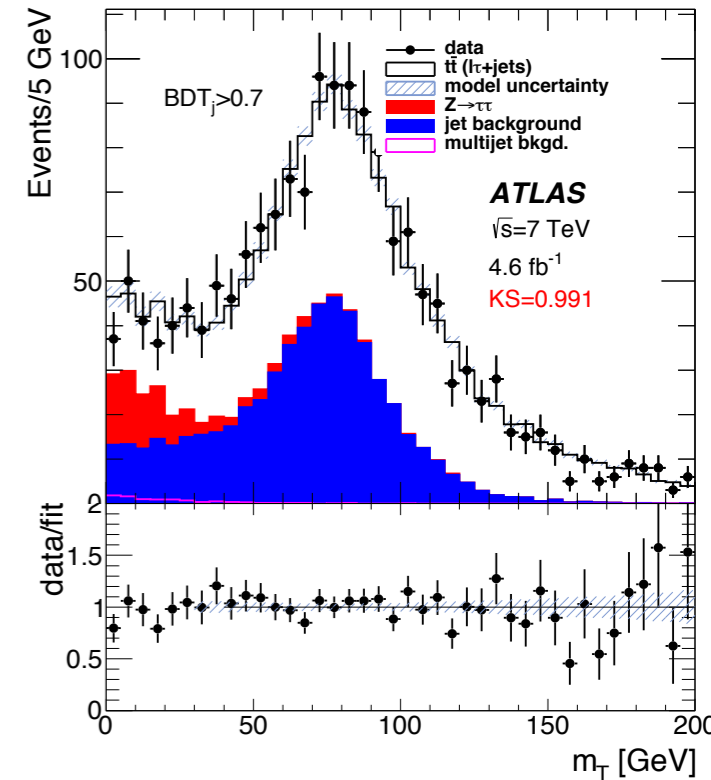
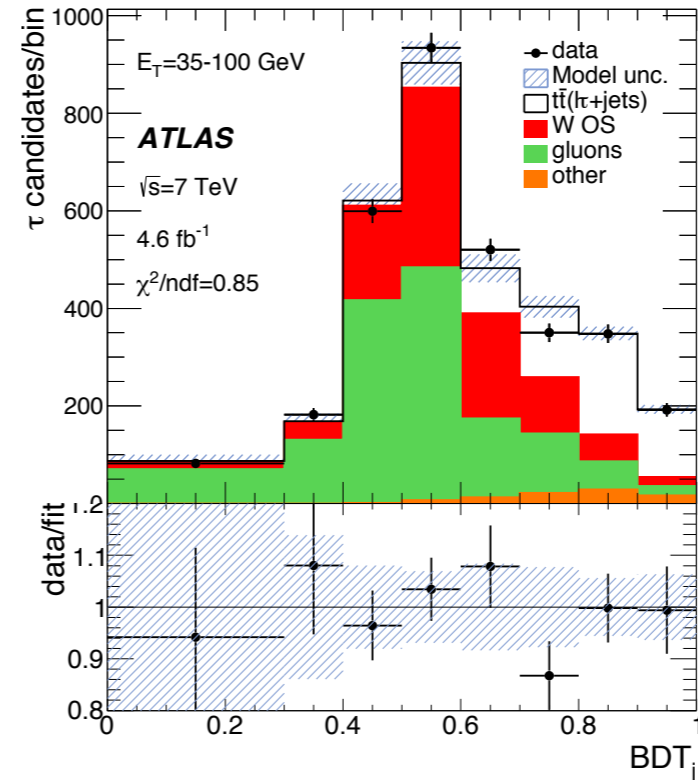
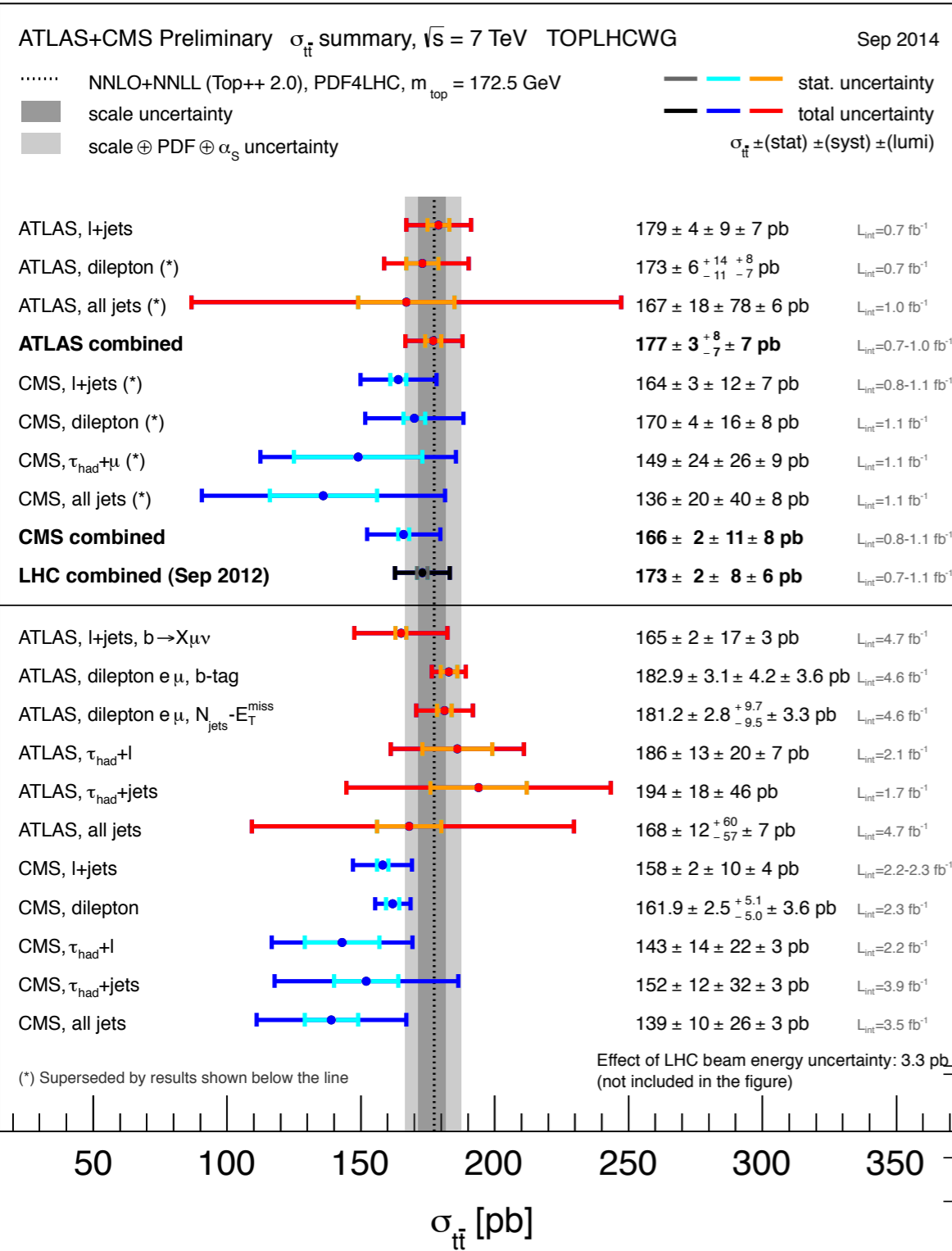
- $\sigma_{t\bar{t}} = 7.73 \pm 0.13_{\text{stat}} \pm 0.55_{\text{syst}} \text{ pb}$ 
  - ▶ uncertainty: 7.3%
  - ▶ largest syst. from hadronisation

# $t\bar{t}$ production at 7 TeV



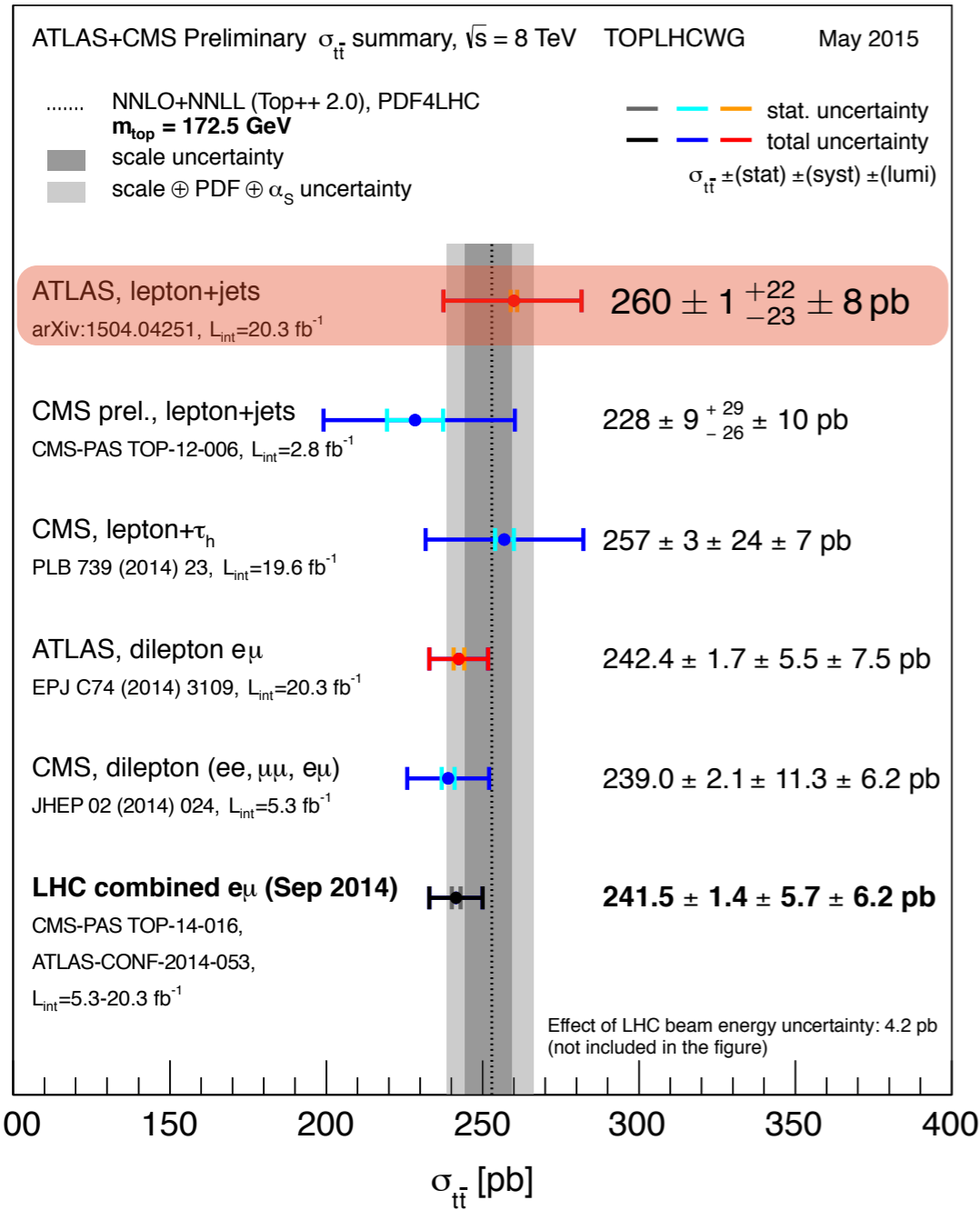
arXiv:1506.05074  
submitted to PRD

## New measurement in $t\bar{t} \rightarrow \ell\tau_{had}$



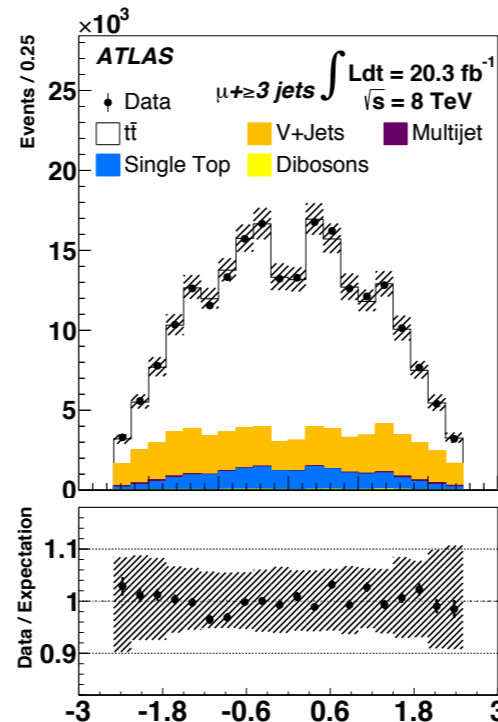
- $\sigma_{t\bar{t}} = 183 \pm 9_{\text{stat}} \pm 23_{\text{syst}} \pm 3_{\text{lumi}} \text{ pb}$
- also extract  $BF(t \rightarrow \ell\nu b)$  and  $BF(t \rightarrow q\bar{q}b)$ 
  - ▶ similar selection criteria for  $\ell$ +jets and dilepton

	Measured (top quark)	SM	LEP (W)
$\sigma_{t\bar{t}}$	$178 \pm 3$ (stat.) $\pm 16$ (syst.) $\pm 3$ (lumi.) pb	$177.3 \pm 9.0^{+4.6}_{-6.0}$ pb	
$B_j$	$66.5 \pm 0.4$ (stat.) $\pm 1.3$ (syst.)	$67.51 \pm 0.07$	$67.48 \pm 0.28$
$B_e$	$13.3 \pm 0.4$ (stat.) $\pm 0.5$ (syst.)	$12.72 \pm 0.01$	$12.70 \pm 0.20$
$B_\mu$	$13.4 \pm 0.3$ (stat.) $\pm 0.5$ (syst.)	$12.72 \pm 0.01$	$12.60 \pm 0.18$
$B_\tau$	$7.0 \pm 0.3$ (stat.) $\pm 0.5$ (syst.)	$7.05 \pm 0.01$	$7.20 \pm 0.13$

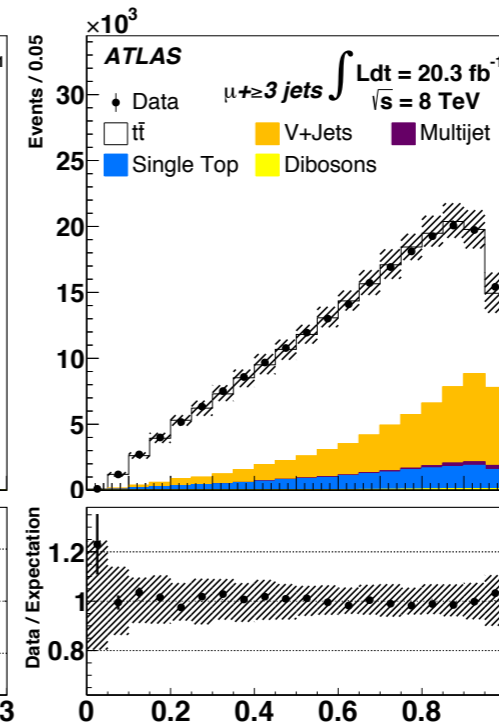


## Recent measurement in $t\bar{t} \rightarrow \ell + \text{jets}$

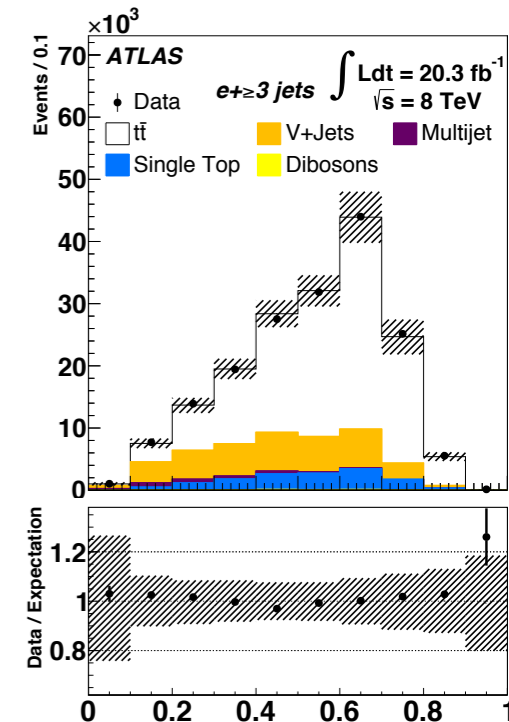
- require  $\geq 3$  jets,  $\geq 1$   $b$ -tag
- extract  $e + \text{jets}$  and  $\mu + \text{jets}$  independently
- template fit to likelihood discriminant with only two variables



$\eta_e$



$\exp(-8 \text{ aplanarity})$



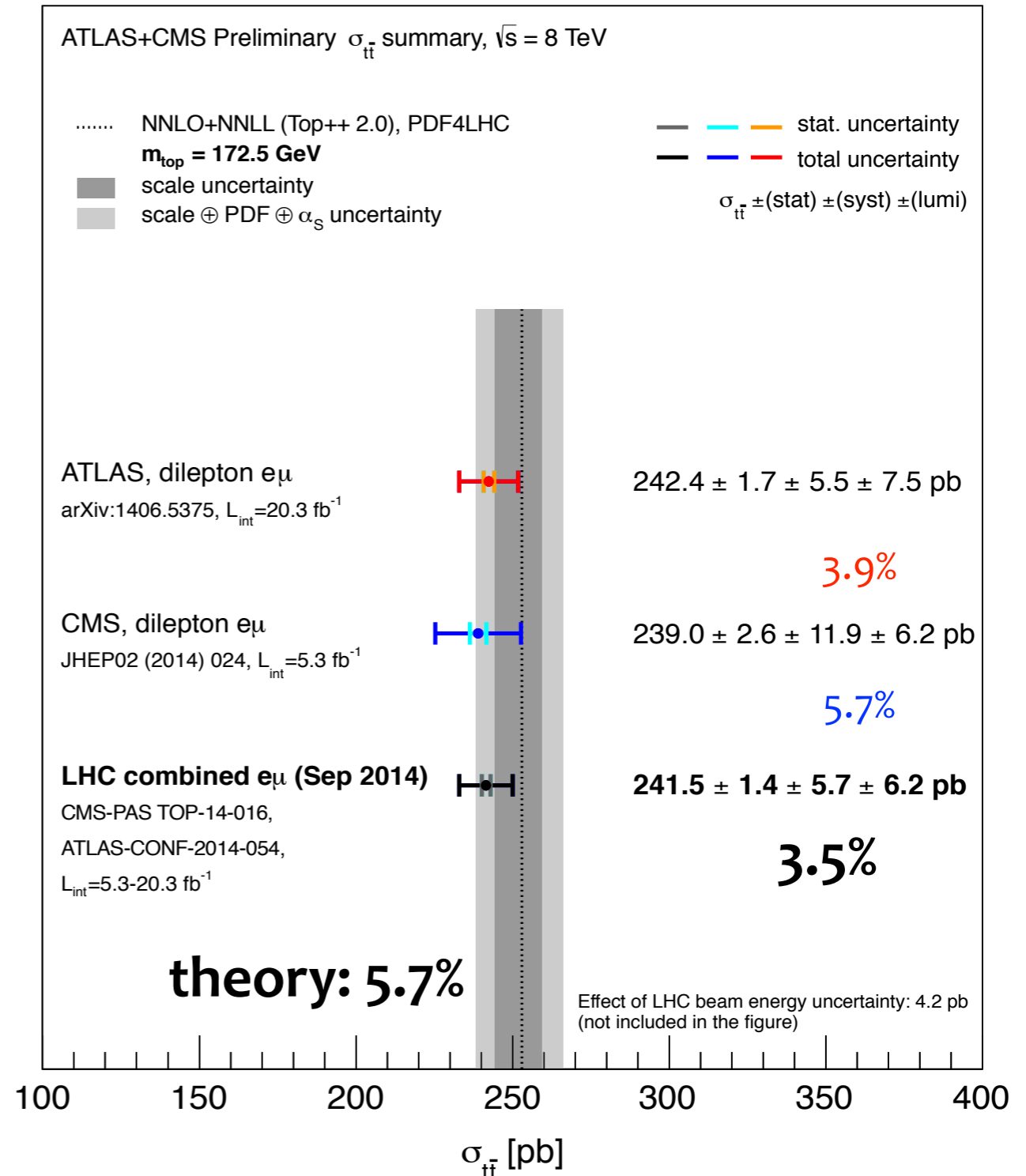
LHD

## TOPLHCWG combination of best $\sigma_{t\bar{t}}$ determinations

ATLAS-CONF-2014-054  
CMS PAS TOP-14-016

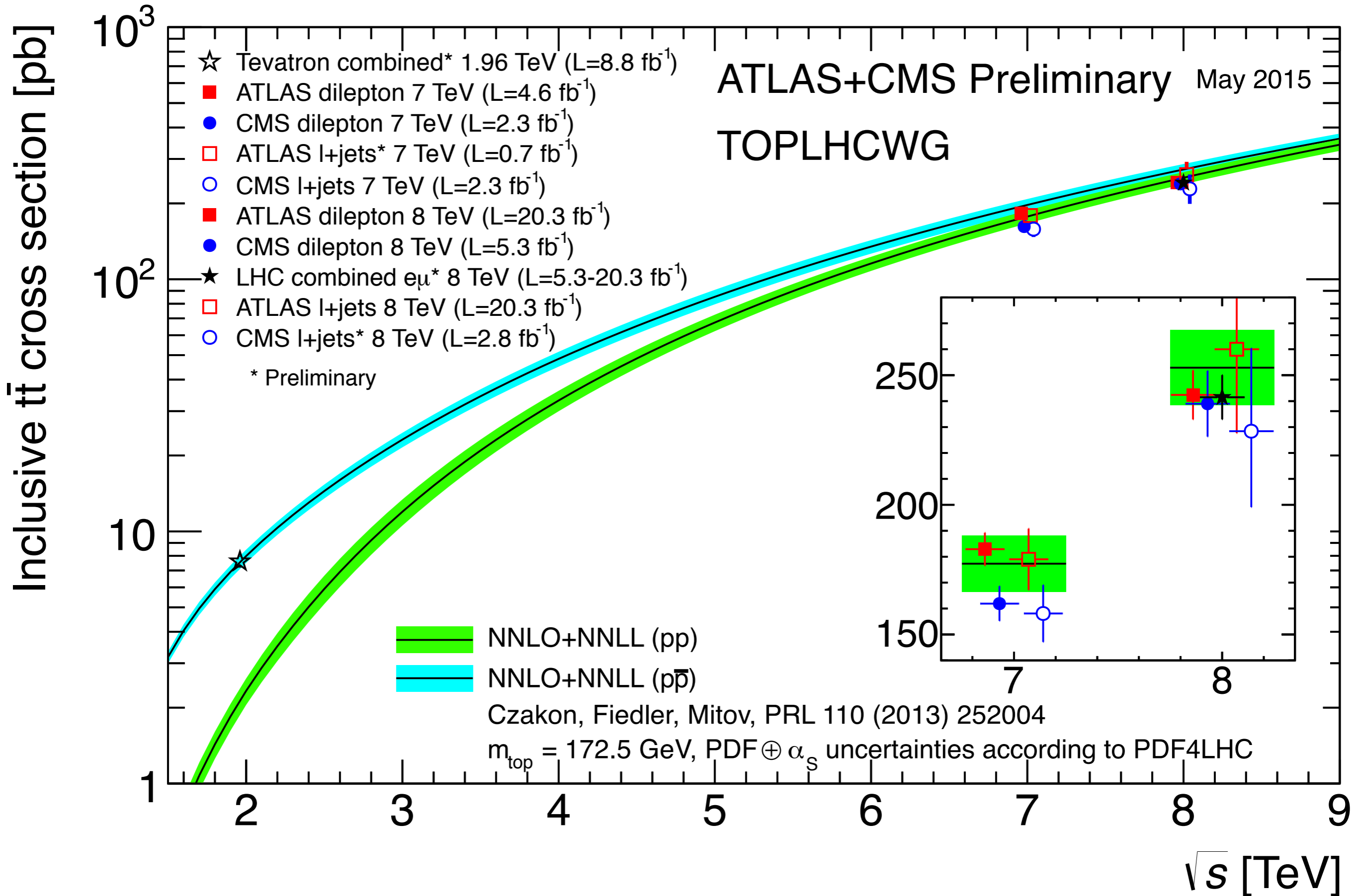
- mapping of systematic uncertainties; study effect of correlations

	ATLAS	CMS	Correlation	LHC combination
Cross section [pb]	242.4	239.0		241.5
Uncertainty [pb]				
Statistical	1.7	2.6	0	1.4
Detector model				
Trigger	0.4	3.6	0	1.0
Lepton scale and resolution	1.2	0.2	0	0.9
Lepton identification	1.7	4.0	0	1.6
Jet resolution	1.2	3.0	0	1.2
Jet identification	0.1	–	–	0.1
b-tagging	1.0	1.7	0	0.8
Pileup	–	2.0	–	0.5
Non-JES subtotal	2.6	6.7	0	2.6
UncorrJES	0.6	4.3	0	1.2
InsituJES	0.6	0.6	0	0.5
IntercalibJES	0.3	0.1	0.5	0.2
FlavourJES	0.9	2.9	1	1.4
bJES	0.1	–	–	0.1
JES subtotal	1.3	5.2	0.4	1.9
Class subtotal	2.9	8.5		3.2
Signal model				
Scale	0.7	5.6	0.5	1.9
Radiation	–	3.8	–	1.0
Generator and parton shower	3.0	3.3	0.5	2.7
PDF	2.7	0.5	1	2.1
Class subtotal	4.1	7.5	0.3	4.0
Background from data				
Z+jets	<0.1	1.5	0	0.4
Lepton misidentification	0.8	1.9	0	0.8
Class subtotal	0.8	2.4	0	0.9
Background from simulation				
Dibosons	0.3	0.5	1	0.4
Single top quark	2.0	2.3	1	2.1
Class subtotal	2.0	2.4	1	2.1
Luminosity				
Beam modelling	2.9	5.0	1	3.5
Luminosity determination	6.9	3.6	0	5.1
Class subtotal	7.5	6.2	0.3	6.2
Total systematic	9.3	13.4		8.4
Total	9.4	13.6		8.5





# $t\bar{t}$ inclusive production



# LHCb joins the top family

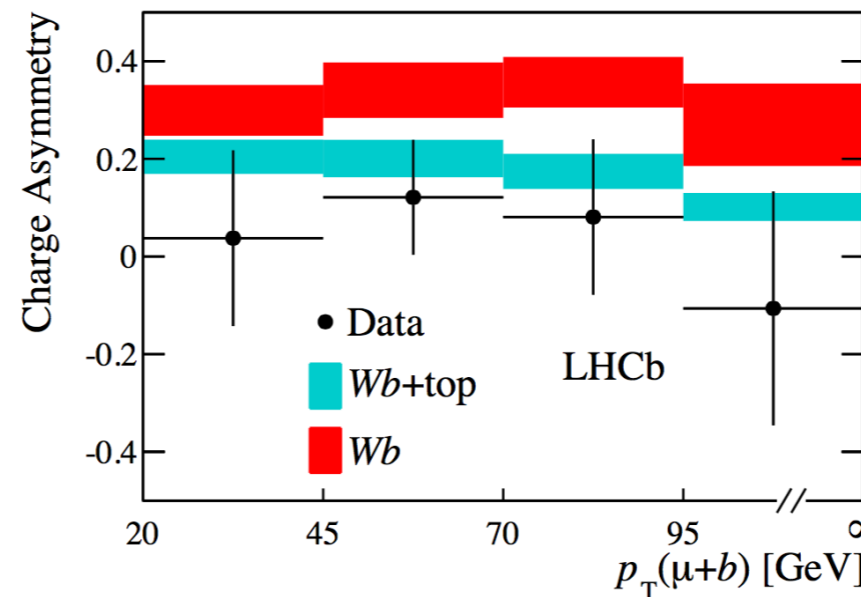
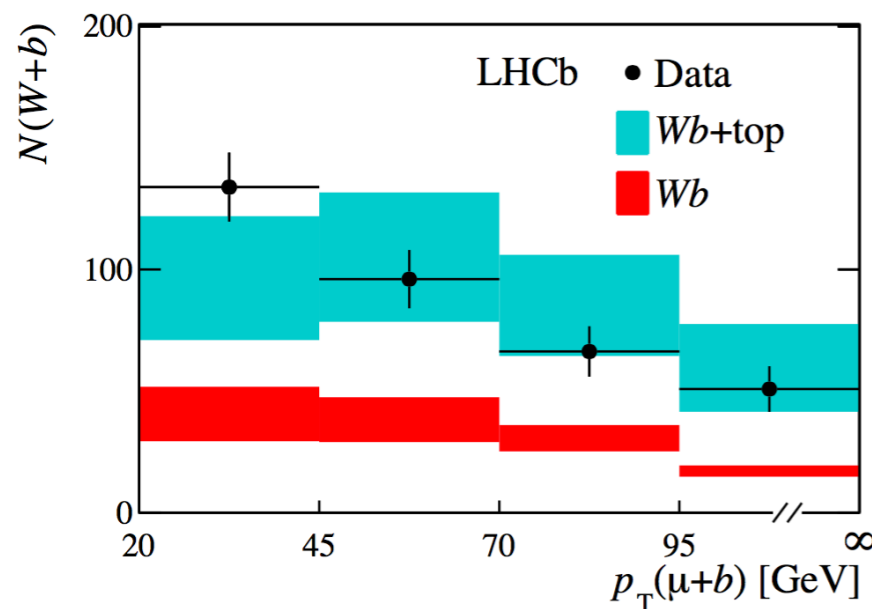
## Forward region interesting

- enhanced sensitivity to BSM ( $q\bar{q}$  and  $qg$  production)
- constrain PDF at large  $x \rightarrow$  improves background to high-mass particles

## LHCb observation

- can identify  $W$  bosons and tag  $b$ - and  $c$ -jets  $\rightarrow$  combine to top quark search
- likelihood fit of  $N(\mu b)$  and  $A(\mu b)$  in fiducial region
- $Wb$ -only hypothesis is excluded at  $5.4 \sigma$

$$\mathcal{A}(Wq) = \frac{\sigma(W^+q) - \sigma(W^-q)}{\sigma(W^+q) + \sigma(W^-q)}$$

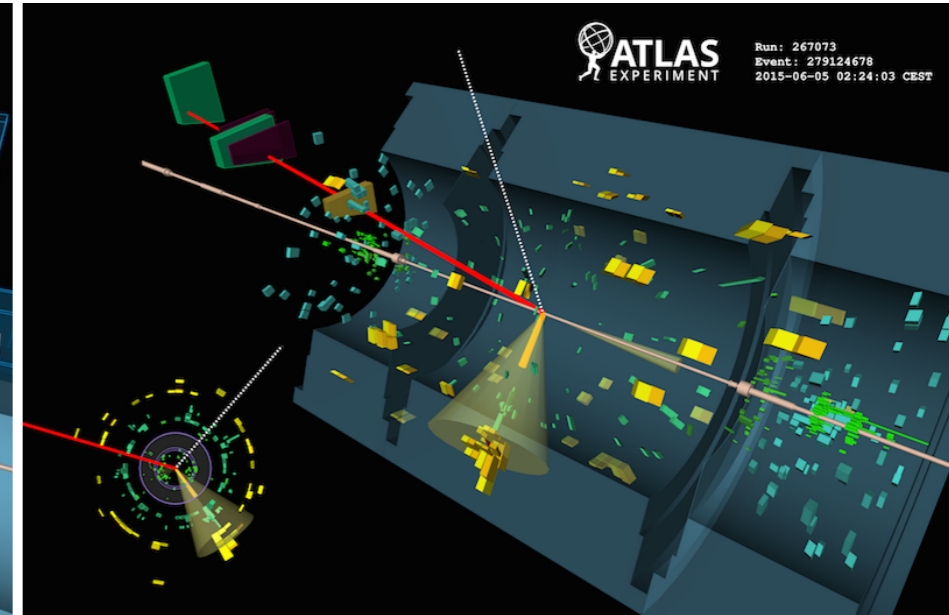
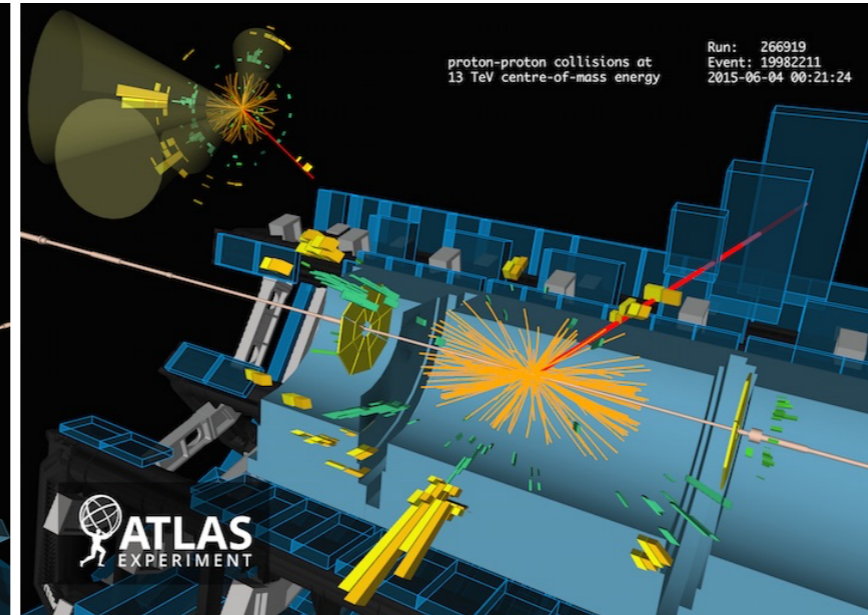
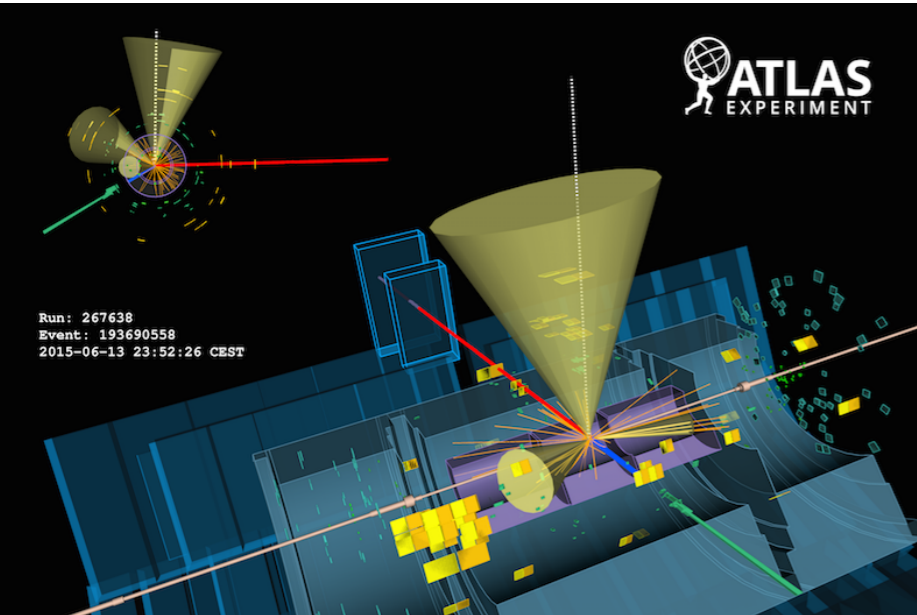


compatible with  
MCFM NLO

$p_T(\mu) > 25 \text{ GeV}$ ,  $2.0 < \eta(\mu) < 4.5$   
 $\Delta R(\mu, b) > 0.5$ , and  $p_T(\mu + b) > 20 \text{ GeV}$   
 $50 < p_T(b) < 100 \text{ GeV}$ ,  $2.2 < \eta(b) < 4.2$

$\sigma(\text{top})[7 \text{ TeV}] = 239 \pm 53 \text{ (stat)} \pm 38 \text{ (syst) fb}$ ,  
 $\sigma(\text{top})[8 \text{ TeV}] = 289 \pm 43 \text{ (stat)} \pm 46 \text{ (syst) fb}$ .

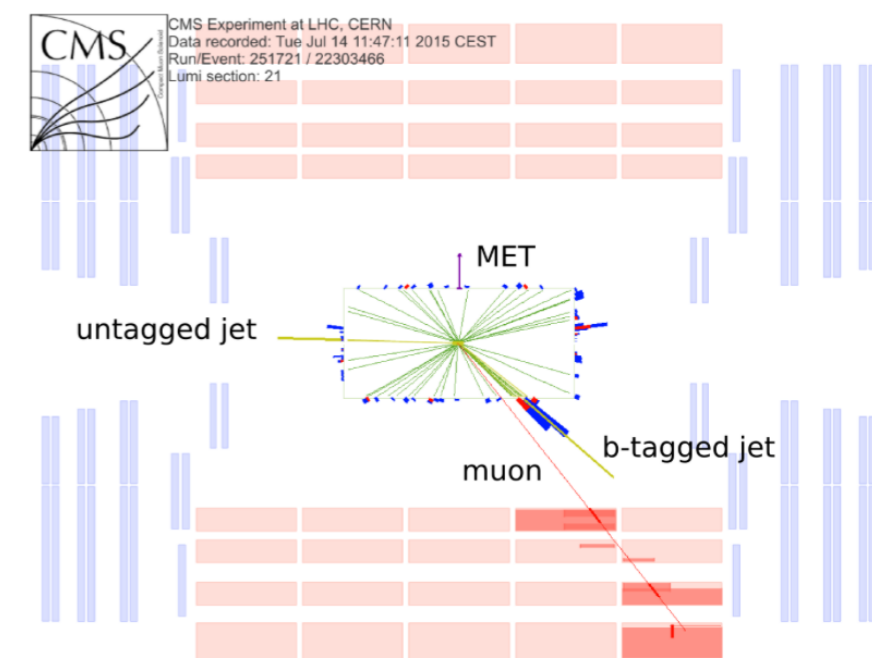
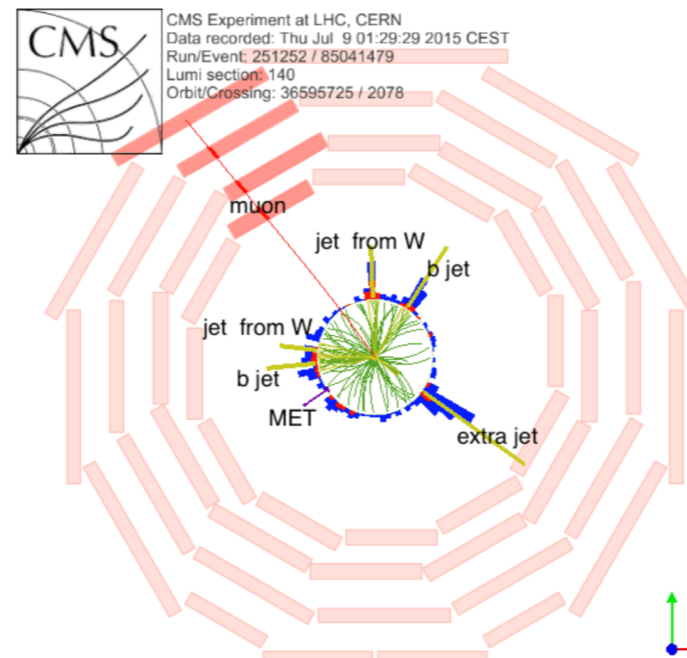
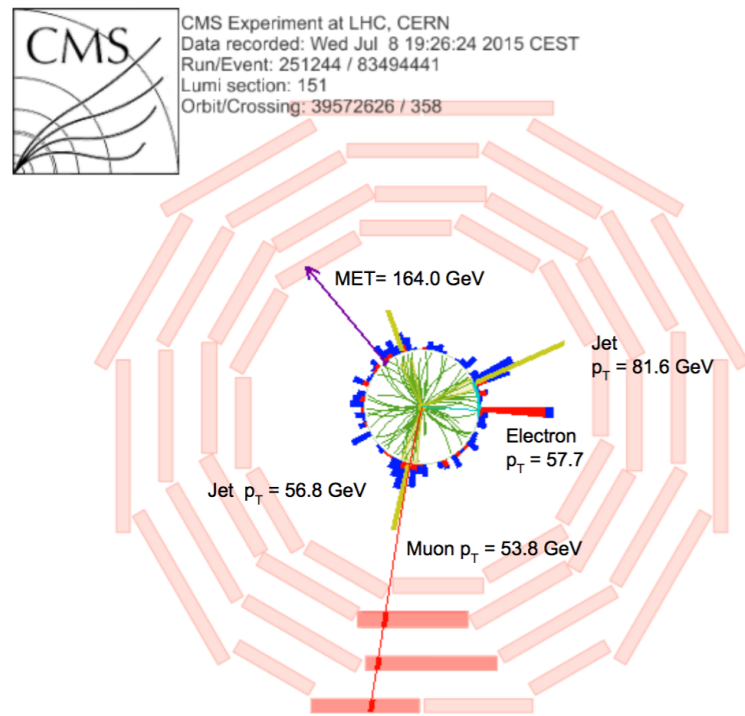
# First 13 TeV top quark candidates



$e\mu + 2 b\text{-tags}$

$\mu + \geq 4 \text{ jets}$

single top candidate



# $t\bar{t}$ production at 13 TeV

## Analysis strategy follows Run-1 best measurement

ATLAS-CONF-2015-033

- select OS  $e\mu$ ,  $p_T(\ell) > 25$  GeV, jets (25 GeV),  $\geq 1$   $b$ -tag, no  $E_T^{\text{miss}}$  required

## Count number of $e\mu$ events with

- exactly one ( $N_1$ ) and exactly two ( $N_2$ )  $b$ -tagged jets
- extract  $\sigma_{t\bar{t}}$  and prob. to  $b$ -tag  $q$  from  $t \rightarrow Wq$  ( $\epsilon_b$ )

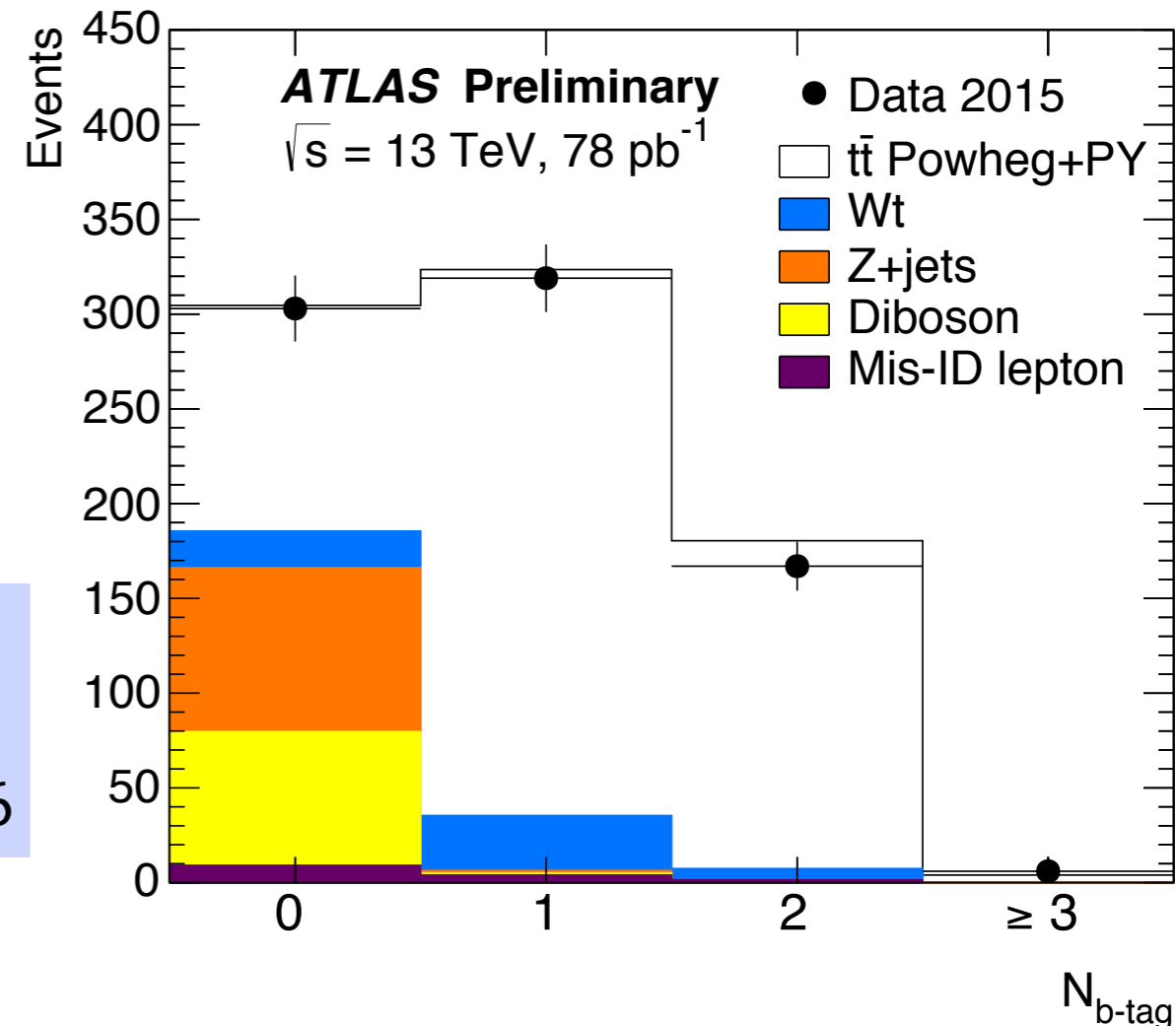
$$N_1 = L\sigma_{t\bar{t}} \epsilon_{e\mu} 2\epsilon_b (1 - C_b \epsilon_b) + N_1^{\text{bkg}}$$

$$N_2 = L\sigma_{t\bar{t}} \epsilon_{e\mu} C_b \epsilon_b^2 + N_2^{\text{bkg}}$$

luminosity of data sample

sel. eff.+acc. incl. BR (0.9%)

non-factorisation correction from MC  $\epsilon_{bb}/\epsilon_b^2 = 1.005 \pm 0.006$



- $\epsilon_b = 0.527 \pm 0.026_{\text{stat}} \pm 0.006_{\text{syst}}$

▶ in good agreement with simulation (0.543), includes jet acceptance

# $t\bar{t}$ production at 13 TeV

CMS PAS TOP-15-003

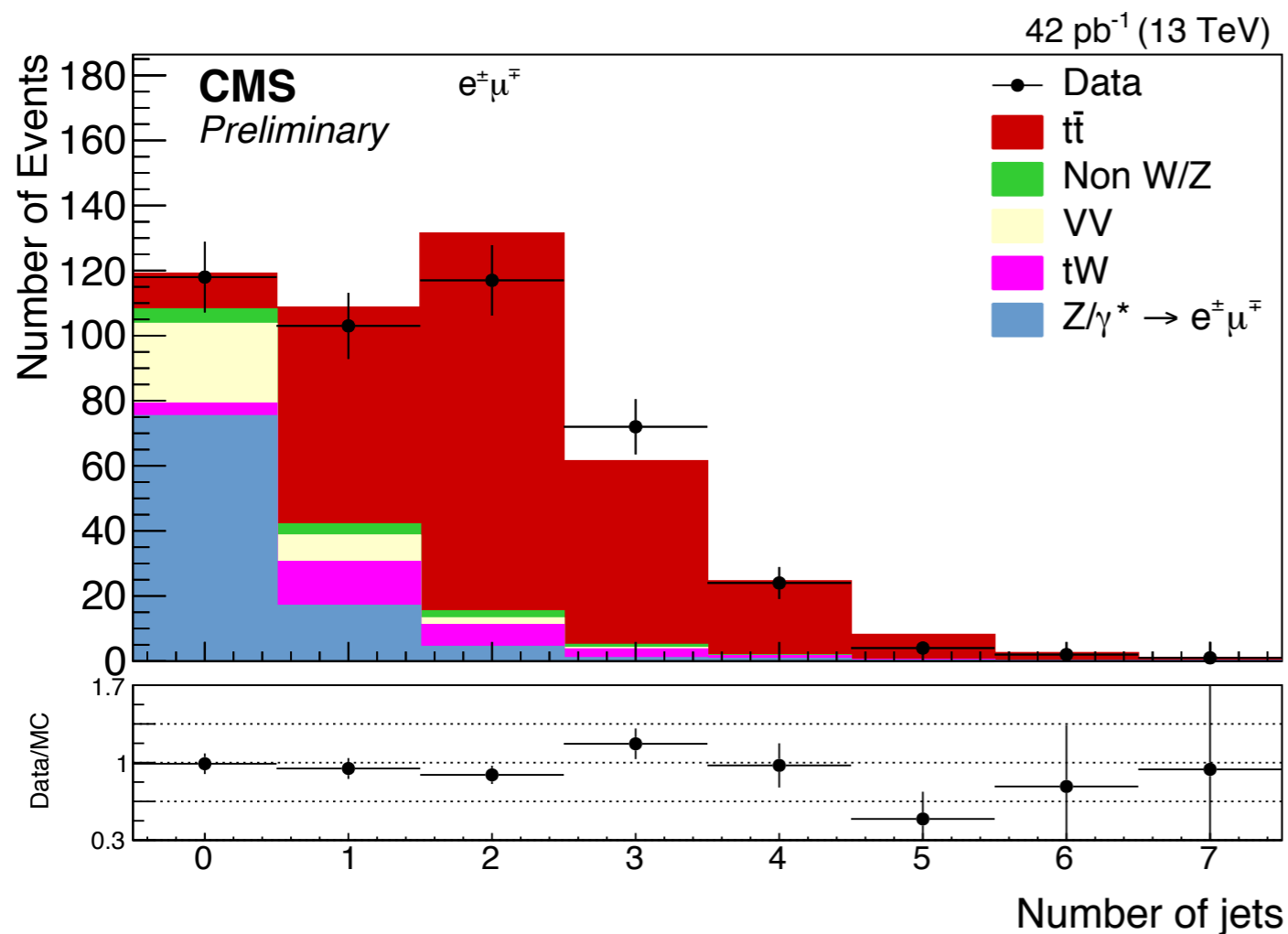
NEW FOR THIS CONFERENCE

LEPTON PHOTON 2015



## Analysis strategy focussing on simplicity

- also use very clean  $e\mu$  channel  $p_T(\ell) > 20$  GeV,
- $\geq 2$  jets (30 GeV)
- dilepton trigger, no b-tagging, no  $H_T$  required
- extract  $\sigma_{t\bar{t}}$  by counting events



Source	Number of events $e^\pm\mu^\mp$
Drell–Yan	$6.4 \pm 1.2$
Non-W/Z leptons	$8.5 \pm 4.3$
Single top quark	$10.6 \pm 3.4$
VV (V = W or Z)	$2.6 \pm 0.9$
Total background	$28.1 \pm 5.7$
$t\bar{t}$ dilepton signal	$206.7 \pm 16.0$
Data	220

**ATLAS** and **CMS** analyses presented already on Monday

## Comparing uncertainties

- **luminosity uncertainty is dominating (9%, 12%)**
  - ▶ will be reduced with dedicated scans this month
- **$t\bar{t}$  modeling**
  - ▶  $t\bar{t}$  hadronisation (4.5%, 1.8%)
  - ▶  $t\bar{t}$  NLO modeling, ISR/FSR radiation & PDF (2.9%, 2.4%)
- **detector-related**
  - ▶ lepton triggers (1.3%, 5.0%)
  - ▶ electron ID and isolation (4.2%), muon ID and isolation (1.6%); lepton efficiency (4.3%)
  - ▶ lepton mis-ID (1.3%, 1.0%)
  - ▶ jet energy scale (0.3%, 2.6%)
- **statistical uncertainty**
  - ▶ ATLAS analysed 78 pb<sup>-1</sup> (6.0%), CMS 42 pb<sup>-1</sup> (7.7%)

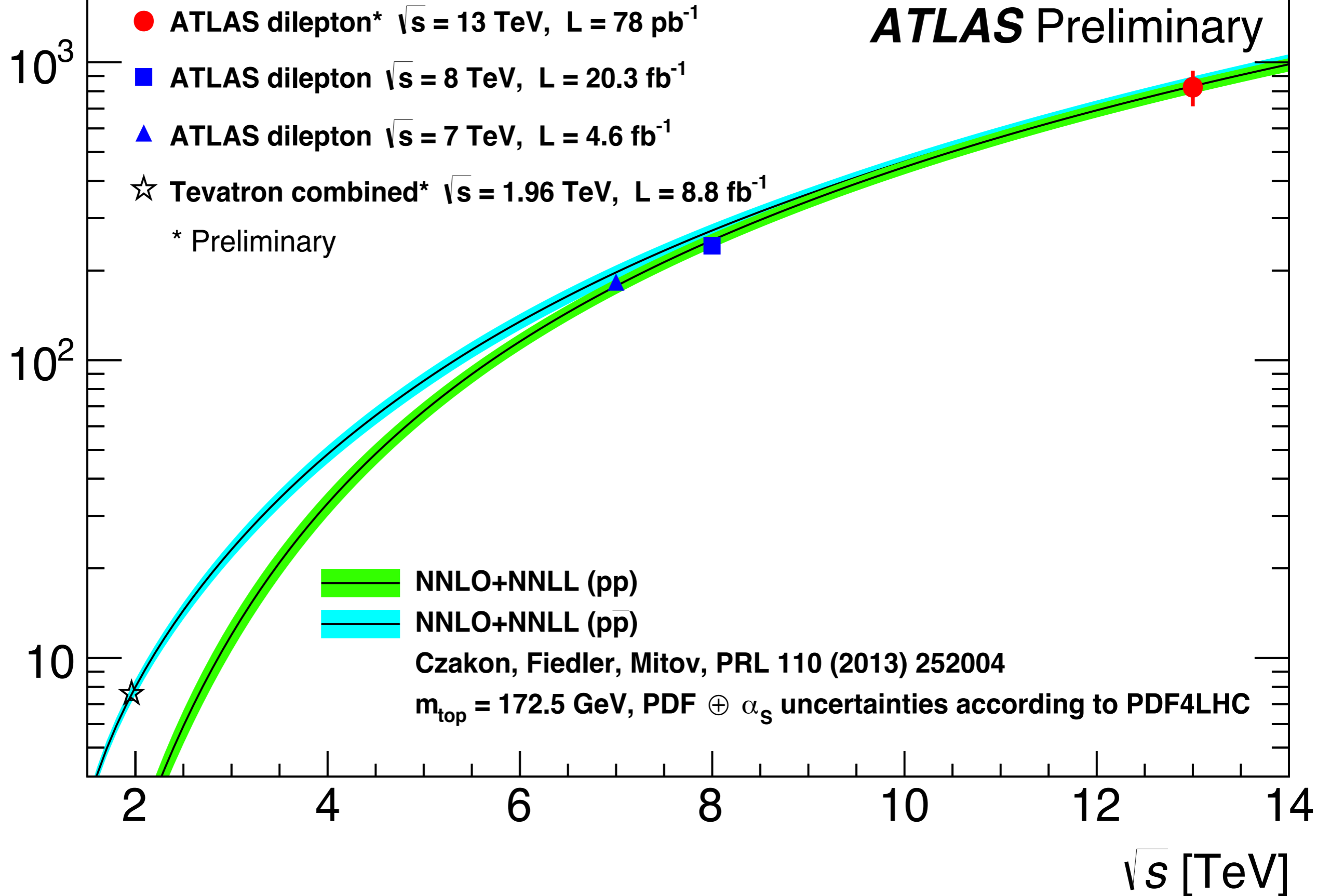
## Resulting in

- $\sigma_{t\bar{t}} = 825 \pm 49_{\text{stat}} \pm 60_{\text{syst}} \pm 83_{\text{lumi}} \text{ pb}$  ,  $\Delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}} = 14\%$  (ATLAS)
- $\sigma_{t\bar{t}} = 772 \pm 60_{\text{stat}} \pm 62_{\text{syst}} \pm 93_{\text{lumi}} \text{ pb}$  ,  $\Delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}} = 16\%$  (CMS)

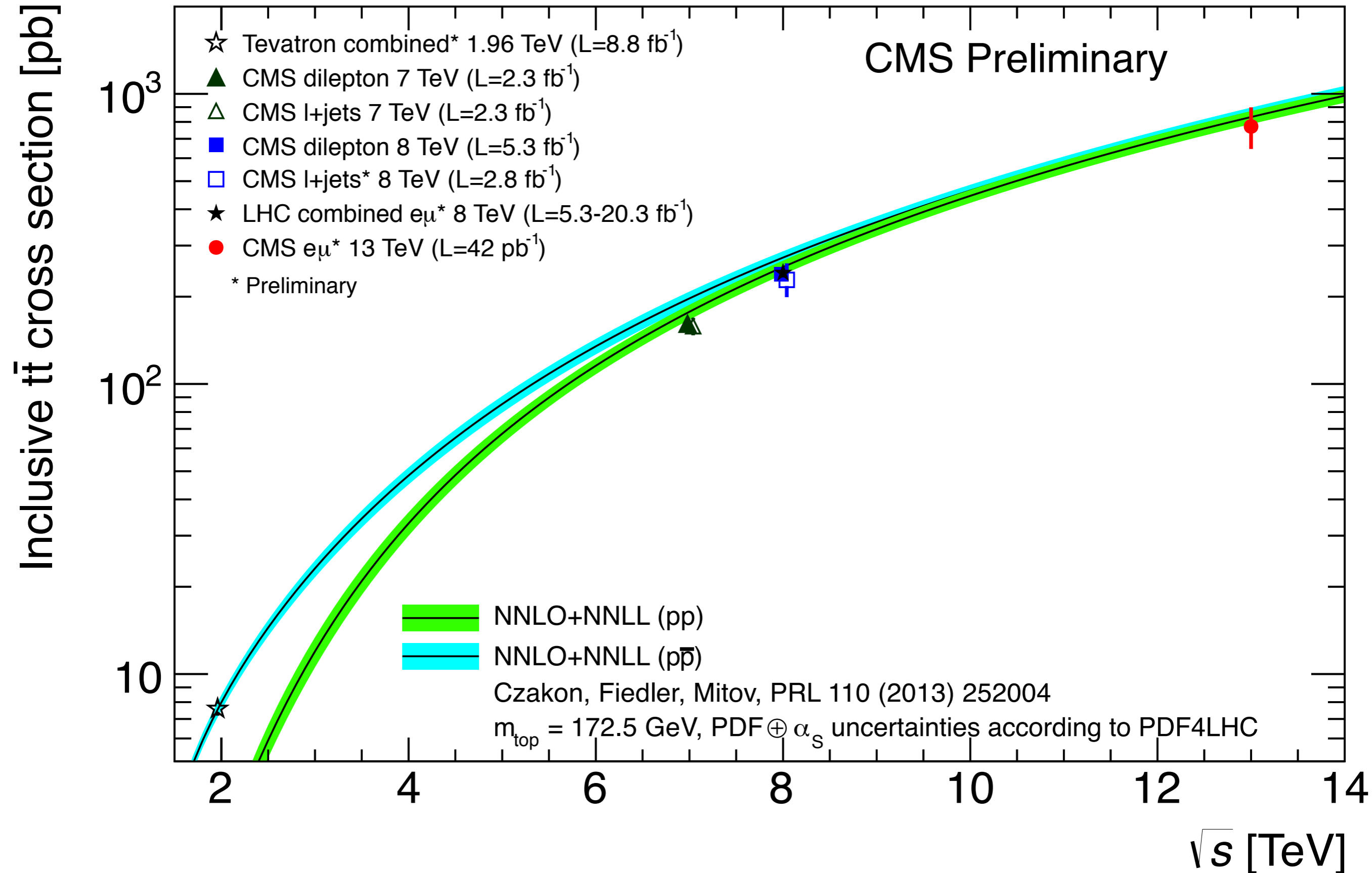
# ATLAS summary plot

Inclusive  $t\bar{t}$  cross section [pb]

**ATLAS Preliminary**



# CMS summary plot





## Why?

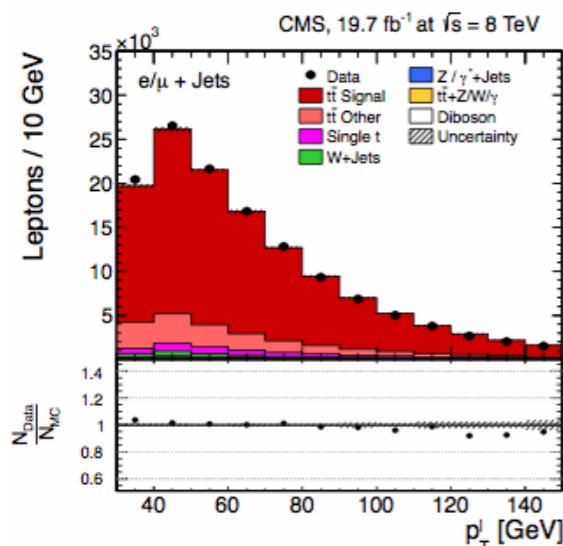
- detailed test of pQCD
- constrain PDF and some MC parameters
- background for Higgs, rare processes and many BSM searches

## General analysis strategy

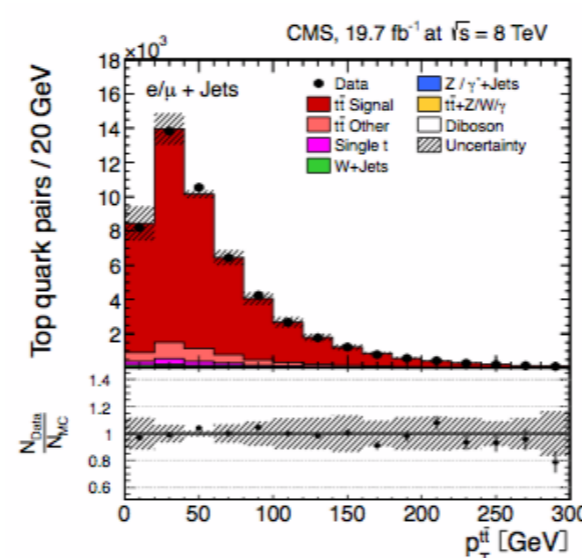
- tight event selection  $\rightarrow$  pure  $t\bar{t}$  sample
- $t\bar{t}$  system / top quark kinematic reconstruction
- background subtraction
- corrections: detector acceptance, resolution  $\rightarrow$  unfolding
- compare to theory predictions at parton or particle level

$$\frac{1}{\sigma} \frac{d\sigma_i}{dX} = \frac{1}{\sigma} \frac{\text{unfold}(s_i^X - b_i^X)}{\Delta_i^X \cdot \int \mathcal{L} dt}$$

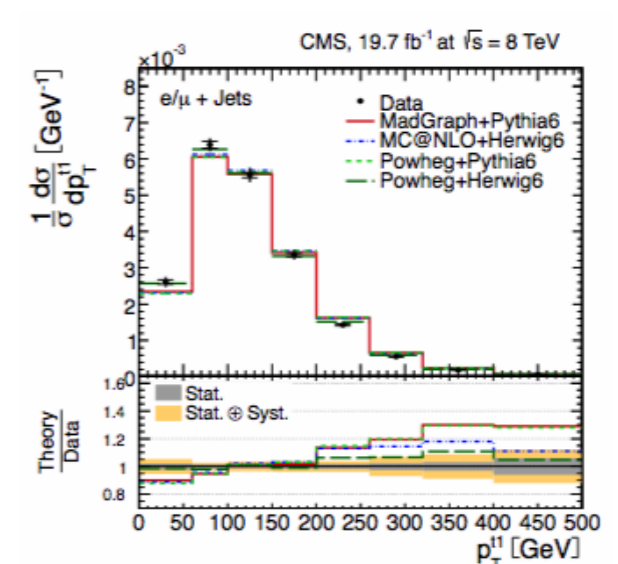
### Object Reconstruction



### Top Kinematic Reconstruction



### Theory Comparison



# $t\bar{t}$ differential: 8 TeV results

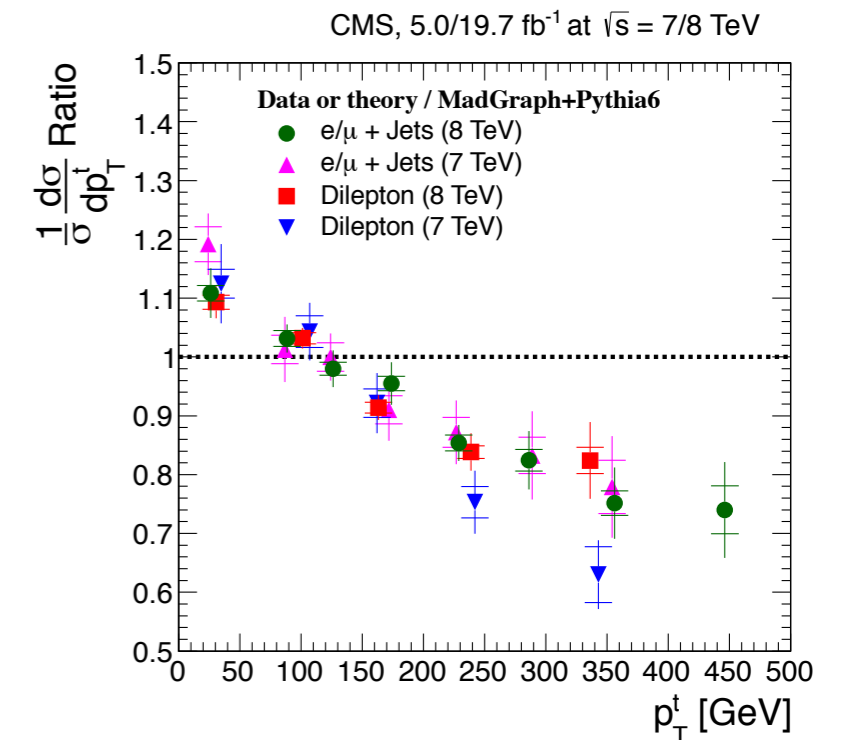
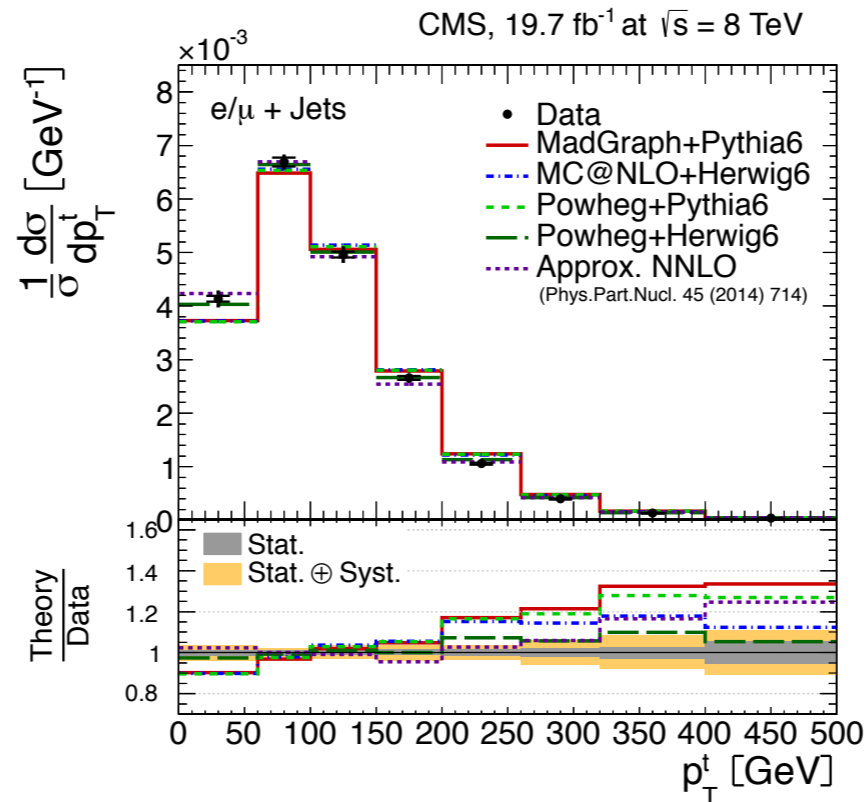
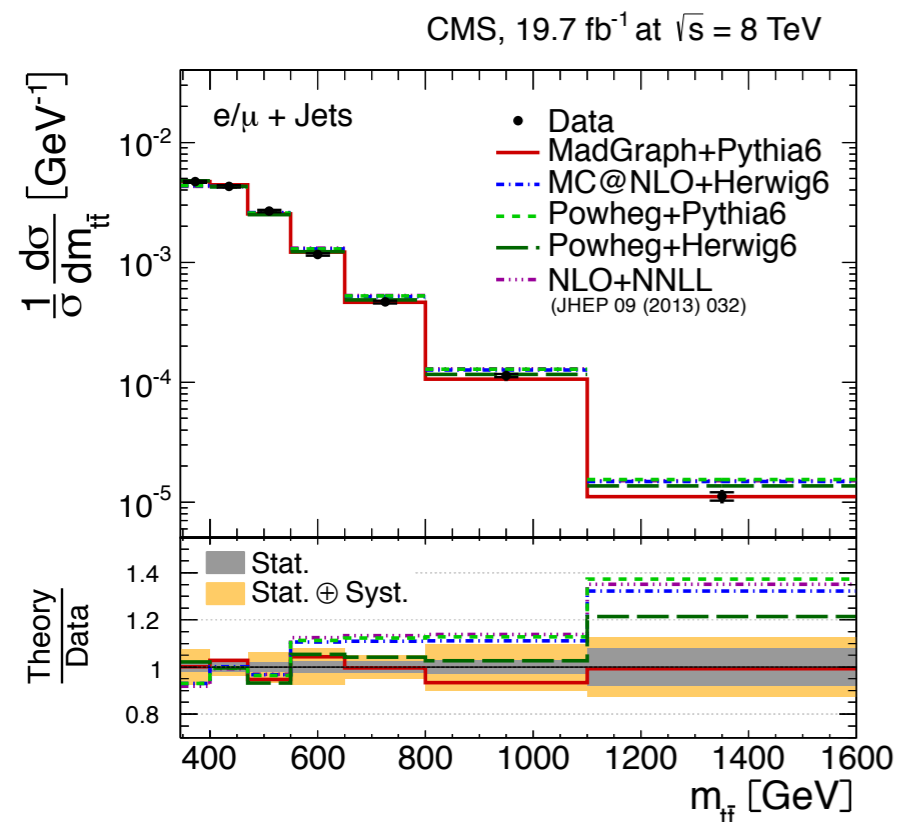
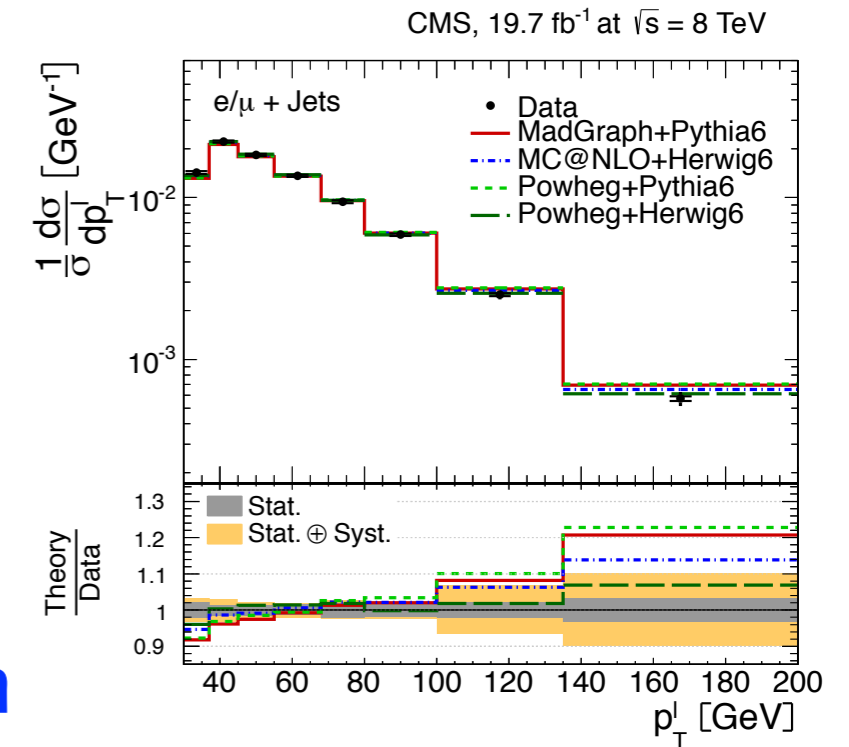
## Many observables studied in $t\bar{t}$ ( $\ell$ +jets, dil.)

- **directly measured quantities of decay products**
  - ▶ kinematics of leptons, b-jets in fiducial phase space
  - ▶ compared with MC simulations
- **reconstructed quantities (top and  $t\bar{t}$  system) unfolded at parton level**
  - ▶ determined in full phase space
  - ▶ compared with MC and calculations



[arXiv:1505.04480](https://arxiv.org/abs/1505.04480)  
 submitted to EPJC

## $p_T(t)$ measured to be softer than expectation



# $t\bar{t}$ differential: particle level top

## Use well-defined top definition at particle level<sup>1</sup>

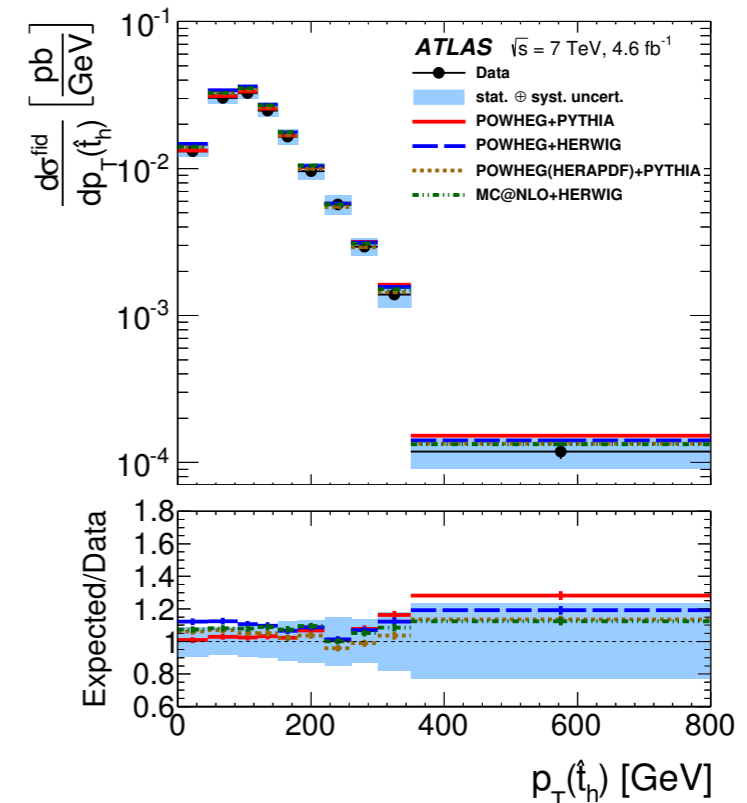
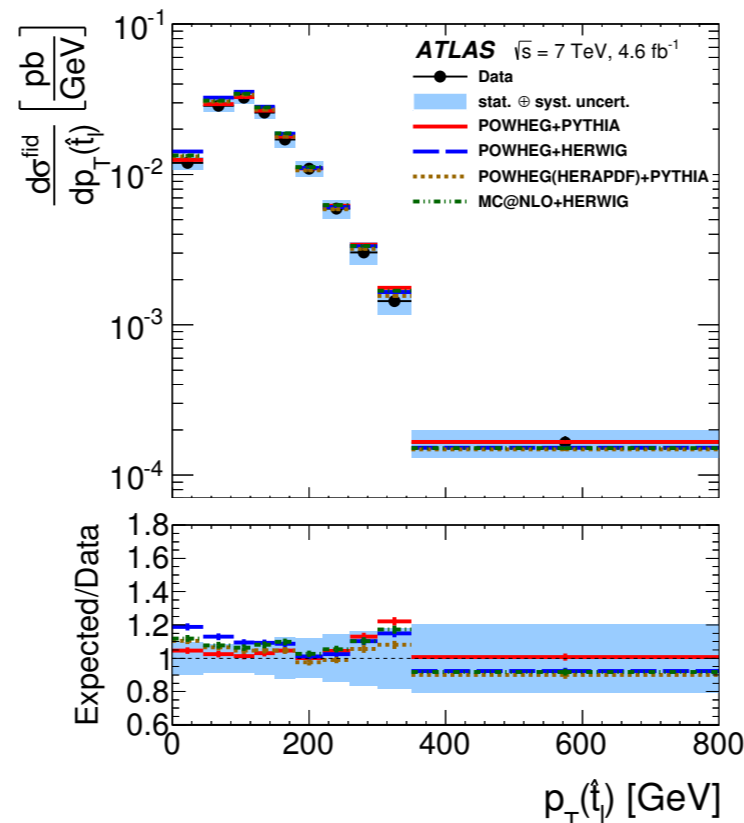
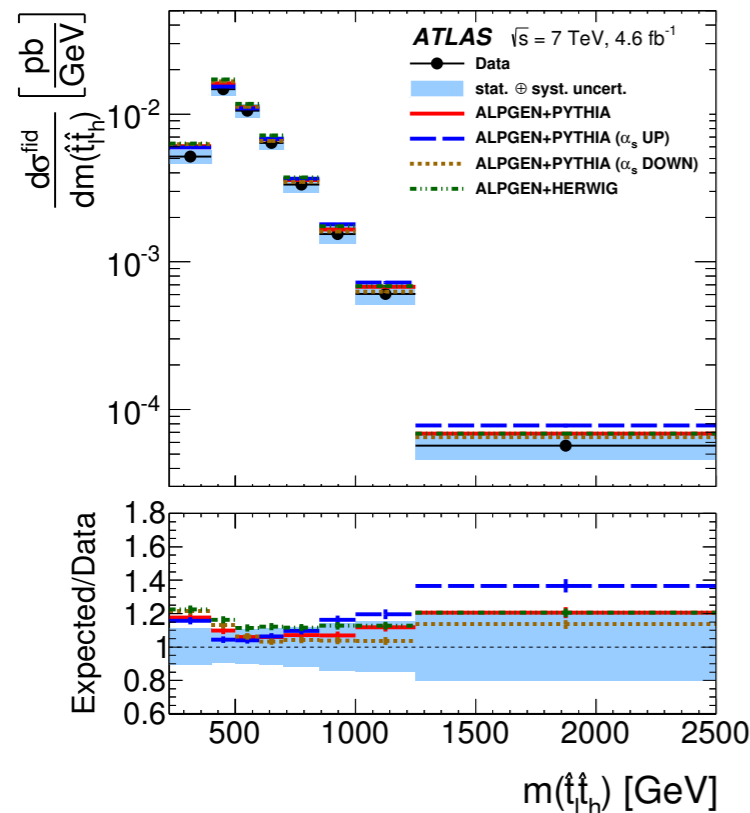
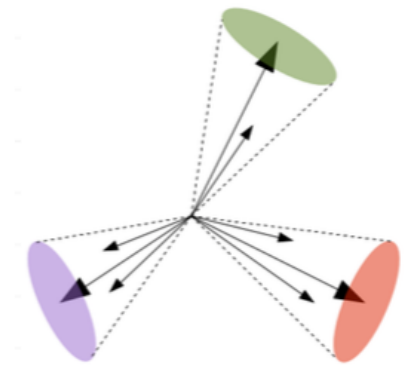


JHEP06 (2015) 100

- fully fiducial, differential measurement
- top-quark proxy constructed from stable particles/detector-level observables

## Cut based analysis in $\ell$ +jets channel

- data generally well described by models
- discrepancy at low  $m_{t\bar{t}}$  observed
- main uncertainties:  $b$ -tagging, JES and JER



<sup>1</sup>TOPLHCWG recommendations at <https://twiki.cern.ch/twiki/bin/view/LHCPhysics/ParticleLevelTopDefinitions>

For  $p_T(t) > 300$  GeV enter boosted regime

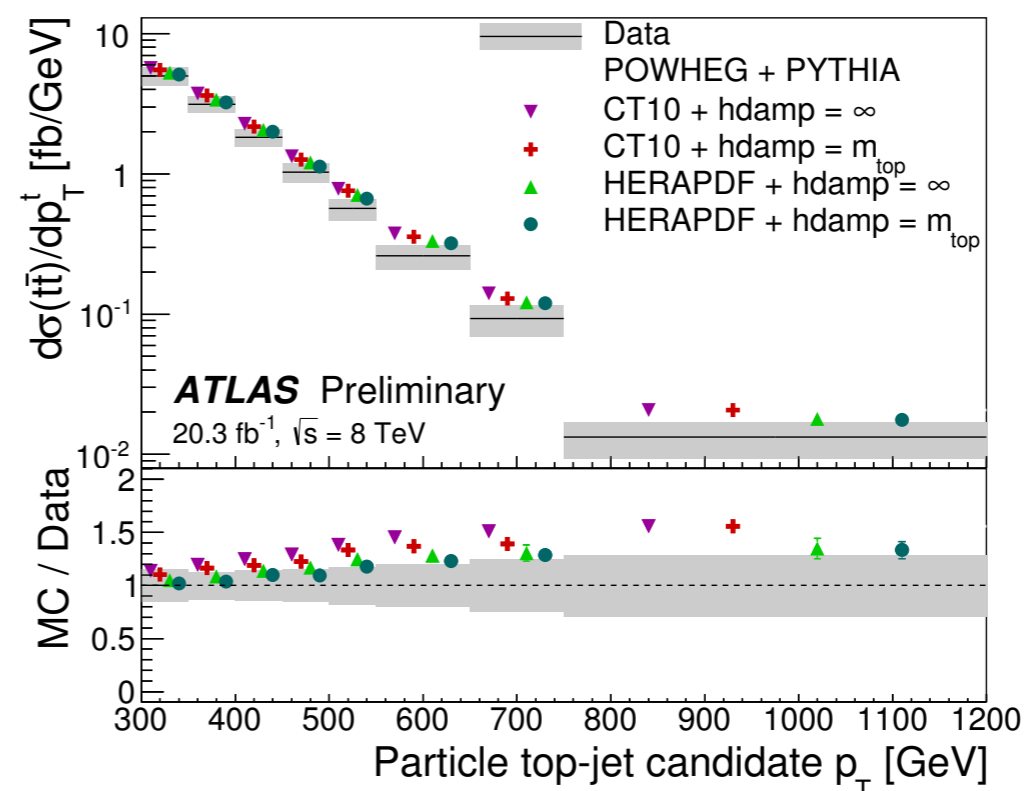
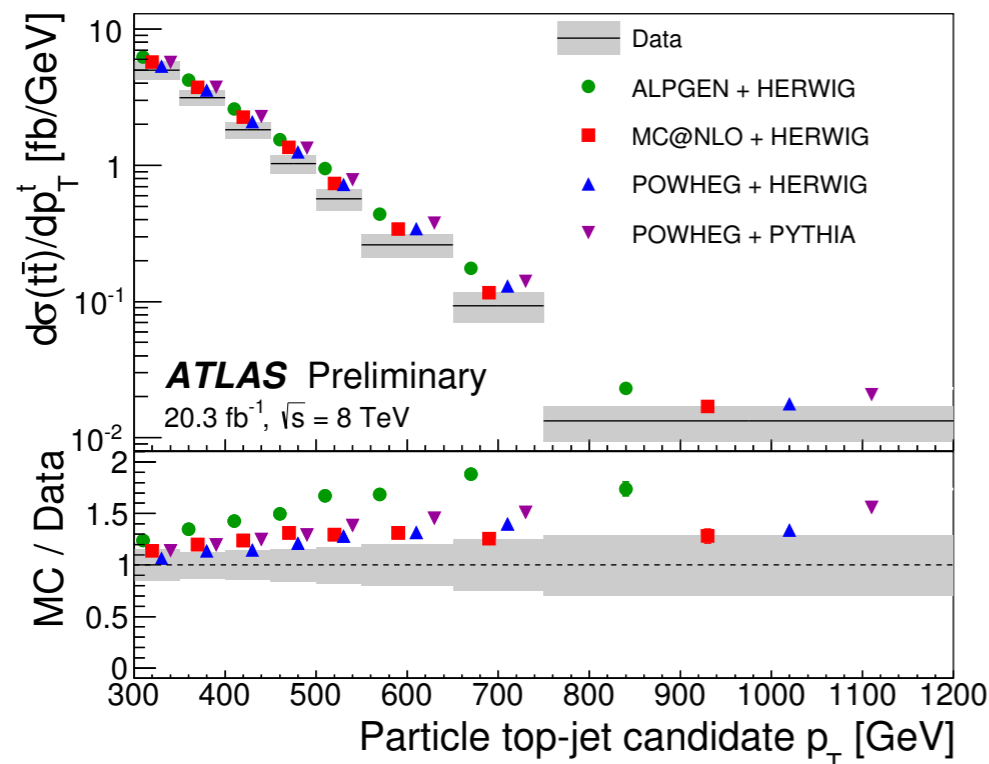
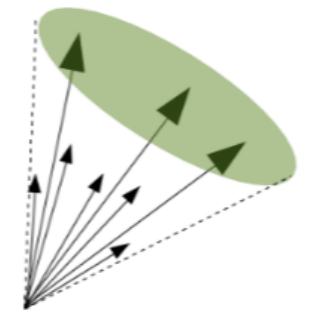
- merging of jets, dedicated reconstruction, single large-R jet

Fiducial, particle and parton level differential measurements

- main uncertainty: large-R jet energy scale (signal modeling)

Measured  $\sigma$  lower than predictions

- discrepancy increases with  $p_T(t)$
- compared with several generators



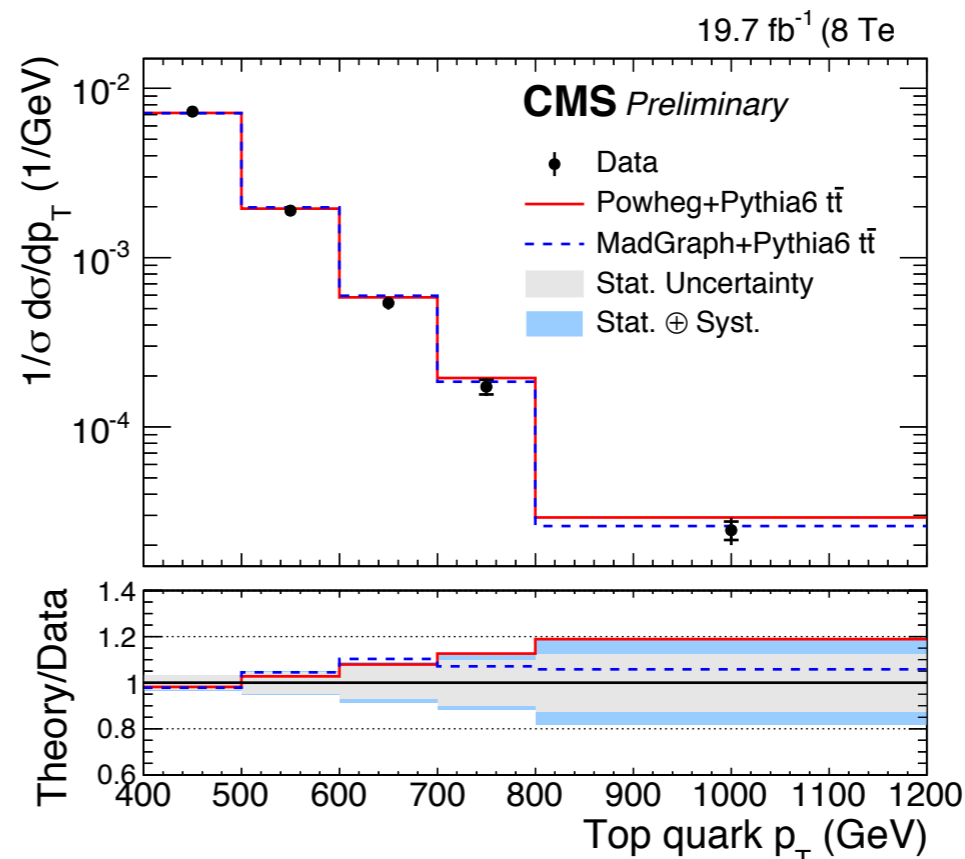
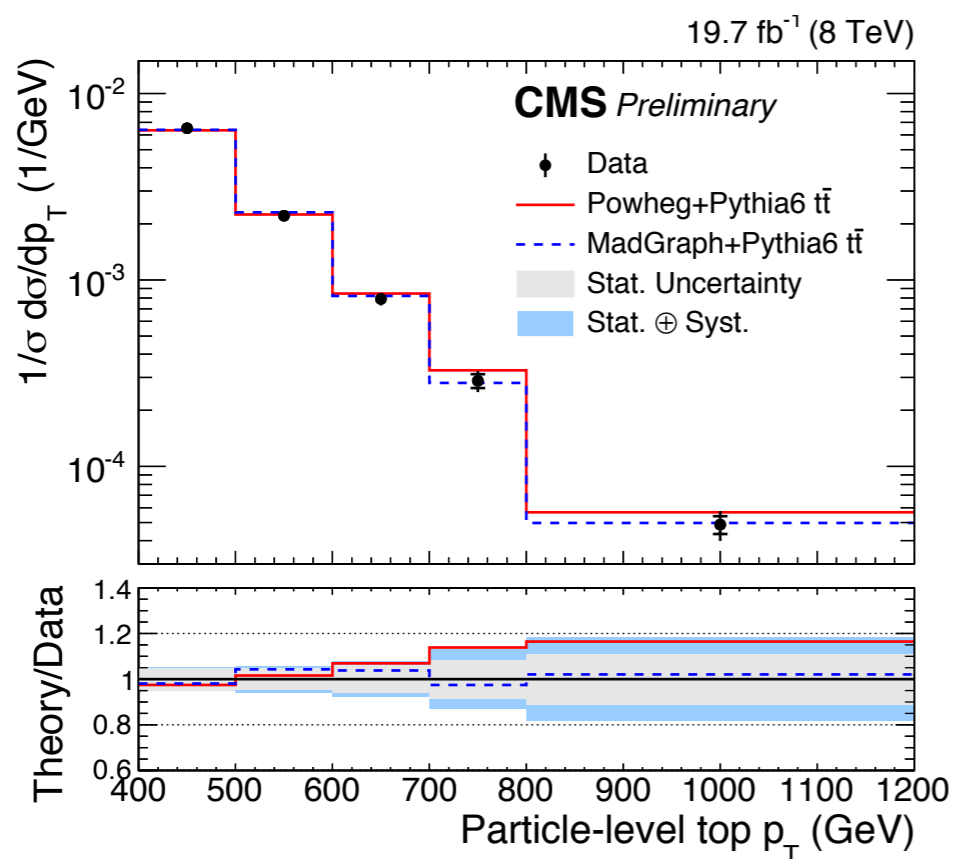
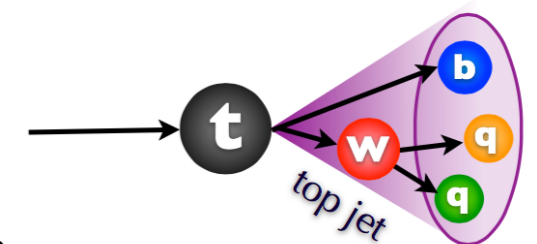
## Measure inclusive $\sigma_{t\bar{t}}$ for $p_T(t) > 400$ GeV

- $\sigma_{t\bar{t}}$  (particle-level) =  $1.28 \pm 0.09_{\text{stat+syst}} \pm 0.10_{\text{PDF}} \pm 0.09_{Q^2} \pm 0.03_{\text{lumi}}$  pb
- $\sigma_{t\bar{t}}$  (parton-level) =  $1.44 \pm 0.10_{\text{stat+syst}} \pm 0.13_{\text{PDF}} \pm 0.15_{Q^2} \pm 0.04_{\text{lumi}}$  pb

Powheg MC predicts 1.49 pb (particle), 1.67 pb (parton level)

## Differential measurements in $p_T(t)$

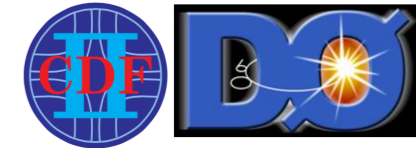
- normalised, shape comparison only



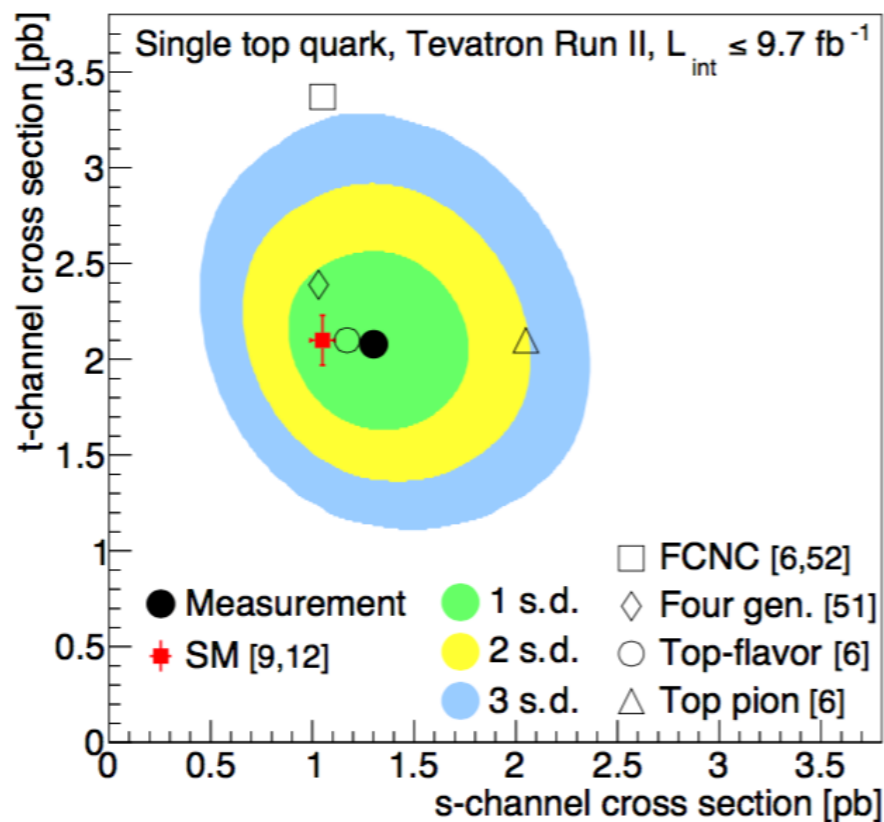
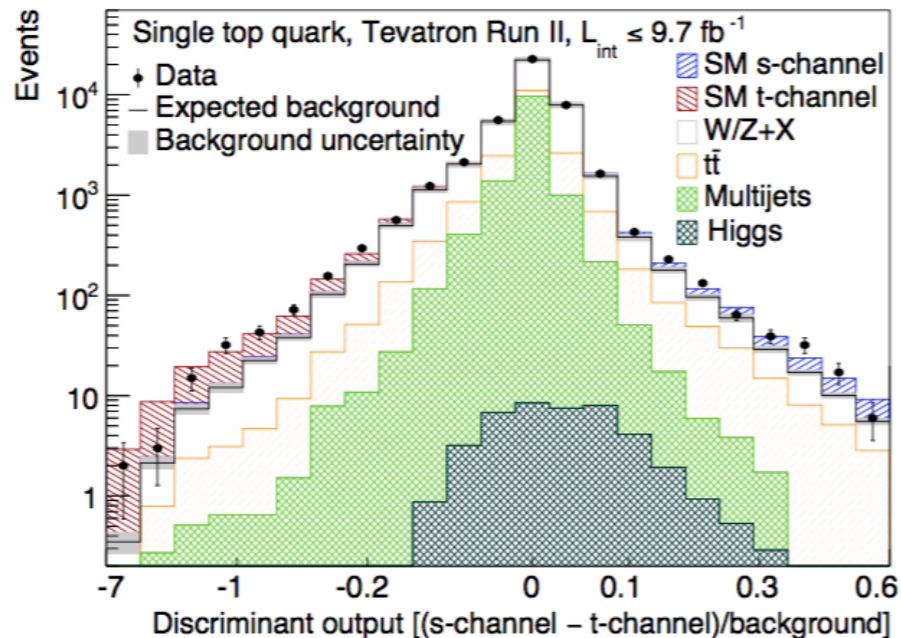
Generators predict harder distribution than measured

# Single top at Tevatron

## CDF and D0 combination of $\sigma_{t+s}$ VS $\sigma_t$

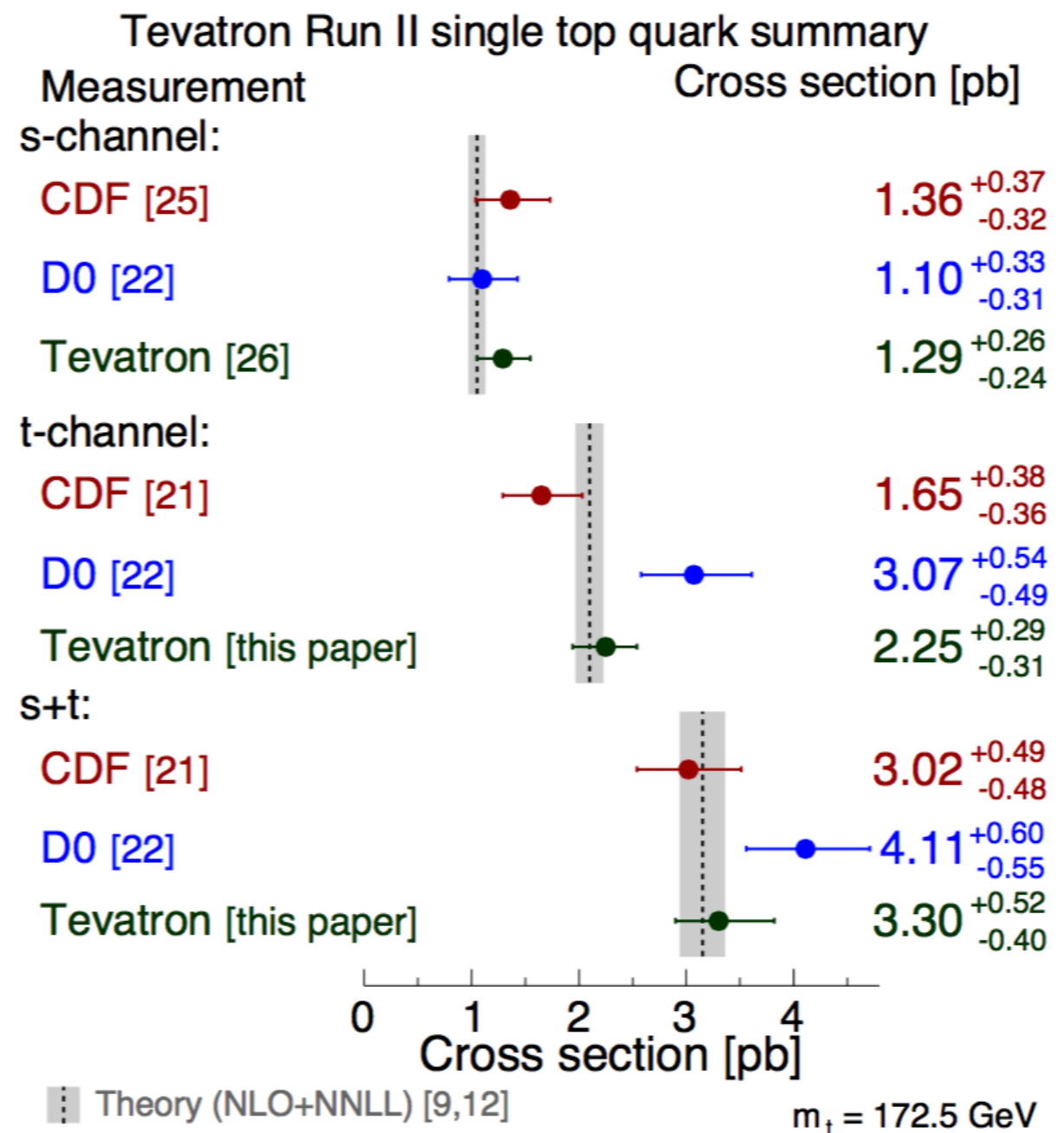


- following previous combinations, s-channel (observed at  $6.3 \sigma$ )

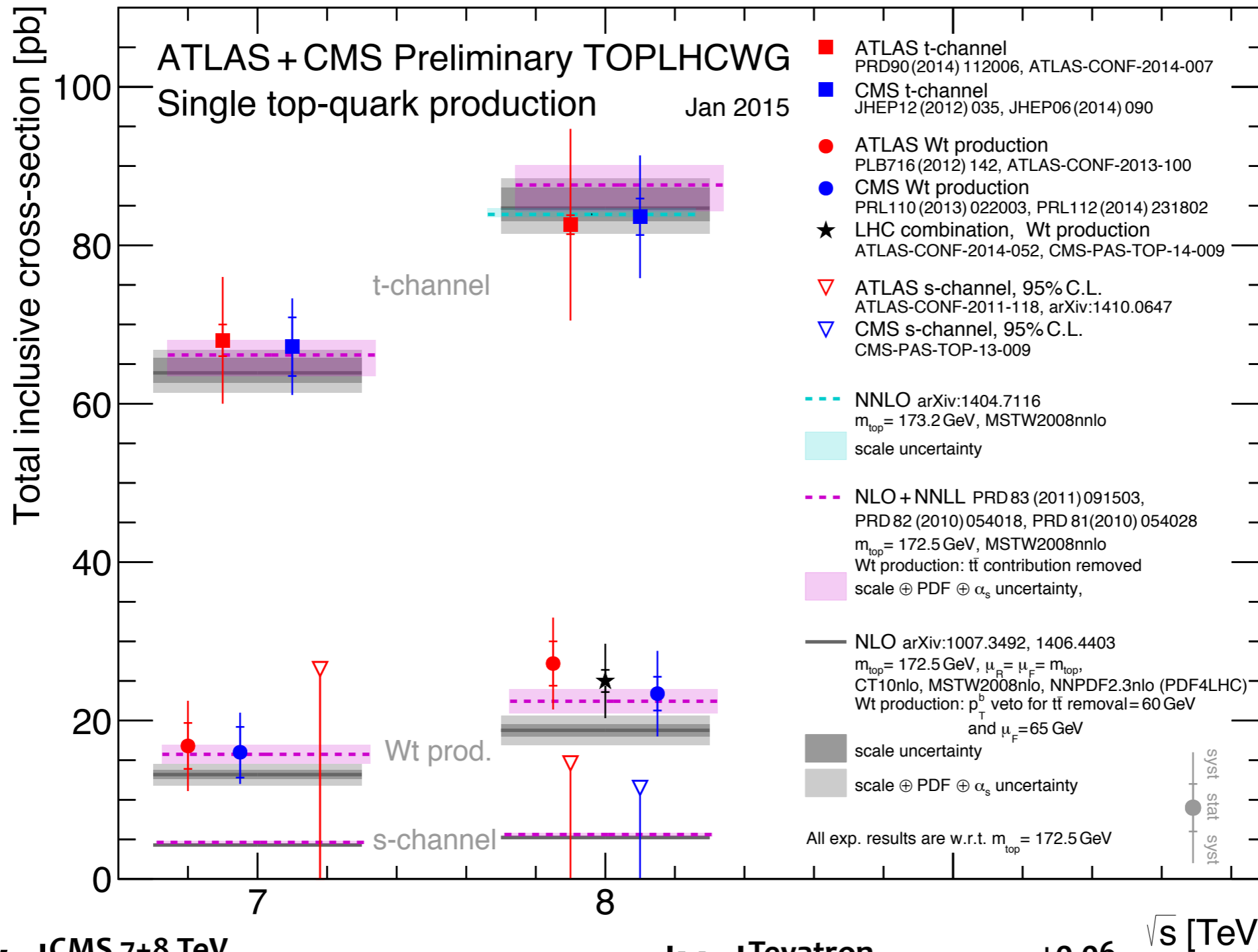


- adding s- and t-channel discriminants

[arXiv:1503.05027](https://arxiv.org/abs/1503.05027)



# Single top at LHC



$$|V_{tb}|_{t\text{-channel}}^{\text{CMS 7+8 TeV}} = 1.00 \pm 0.04$$

$$|V_{tb}|_{s+t\text{-channel}}^{\text{Tevatron}} = 1.02^{+0.06}_{-0.05}$$

$$|V_{tb}|_{Wt\text{-channel}}^{\text{LHC 8 TeV}} = 1.06 \pm 0.11$$

in good agreement with  $|V_{tb}|_{\text{global SM fit}} = 0.99914 \pm 0.00005$  Chin. Phys. C38 (2014) 1

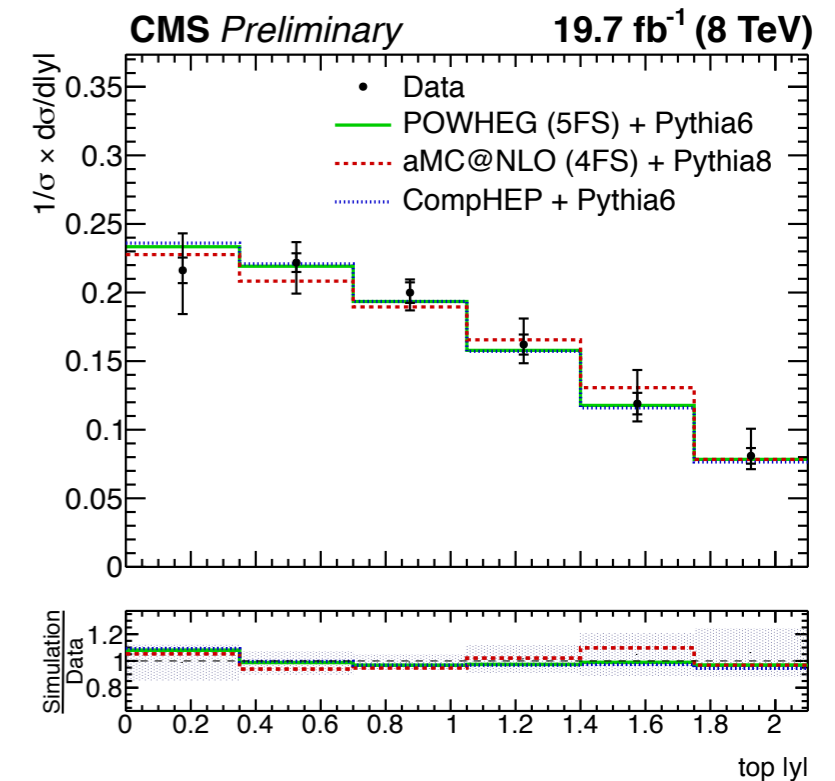
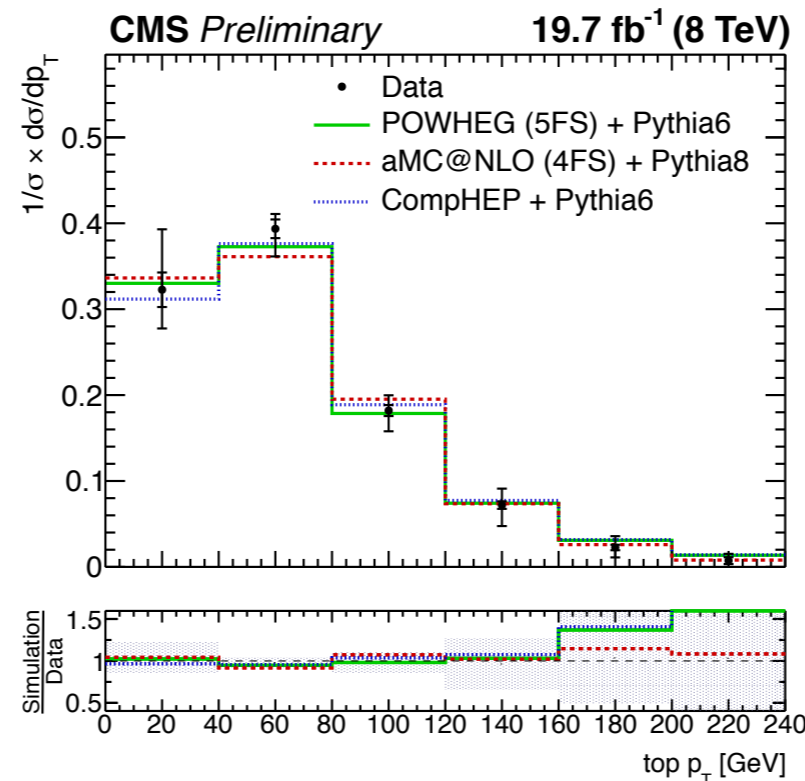
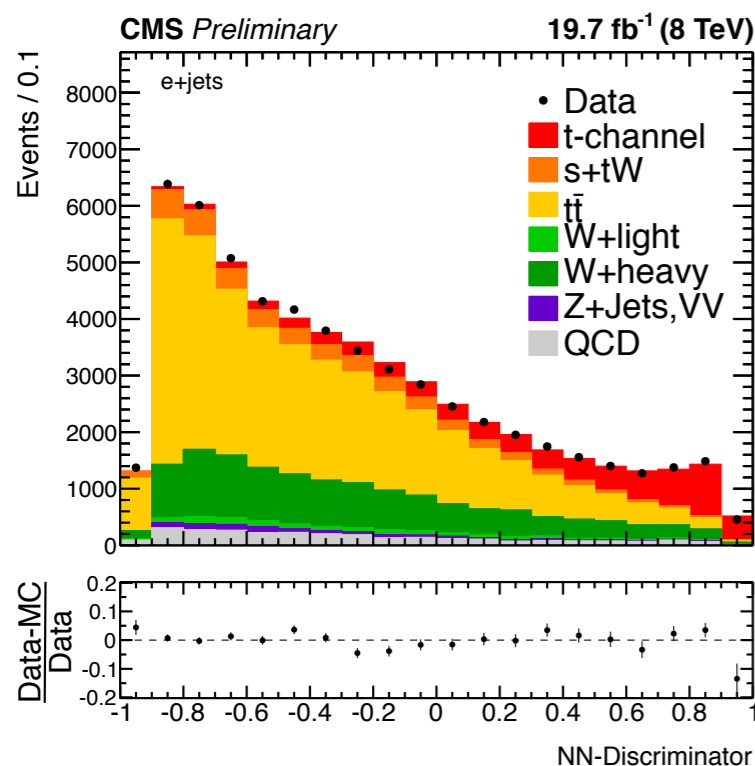
## Measurement of single top t-channel firmly established

- inclusive and fiducial cross-section at 7 and 8 TeV
- large dataset allows for differential measurements (7 TeV)
- helps validate theory predictions and MC generators at NLO

## Differential cross-section vs $p_T$ and $|y|$ of top quark at 8 TeV

- employ NN discriminator with variables like  $\eta(\text{jet})$  or  $m_{\ell\nu b}$
- cut on NN to enhance signal
- unfolded distributions show good agreement with generators

CMS PAS TOP-14-004





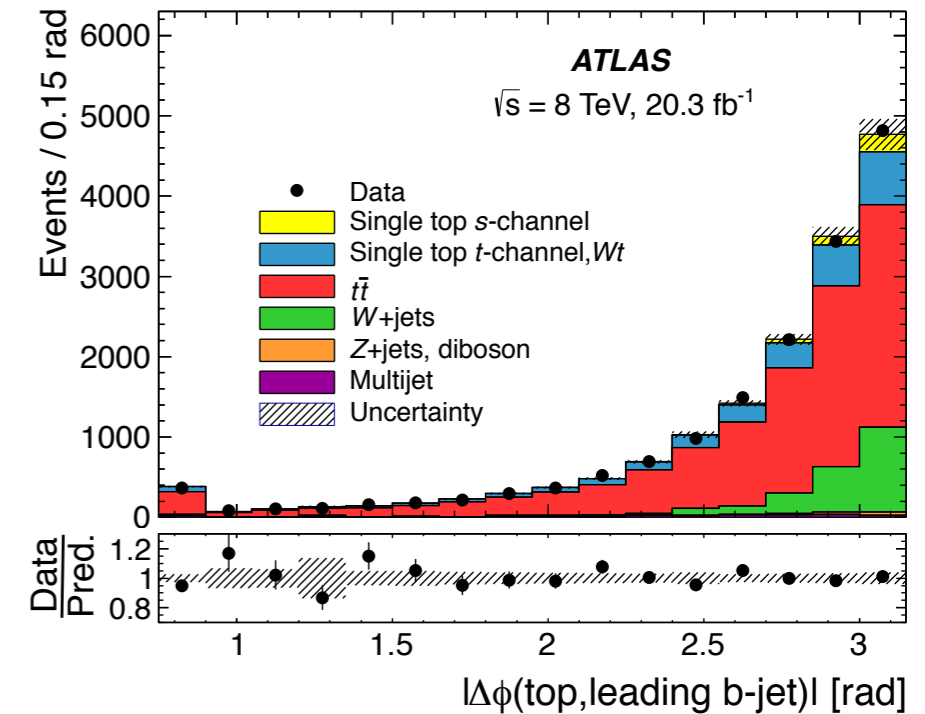
## Very low rate in $pp$ collisions

- expect  $\sigma(\text{s-channel}) = 5.61 \pm 0.22 \text{ pb}$

PRD 81 (2010) 054028

## Analysis

- $|\Delta\varphi(t,b)|$  is the most discriminating variable
- use BDT to increase sensitivity
- ML fit to extract signal cross-section

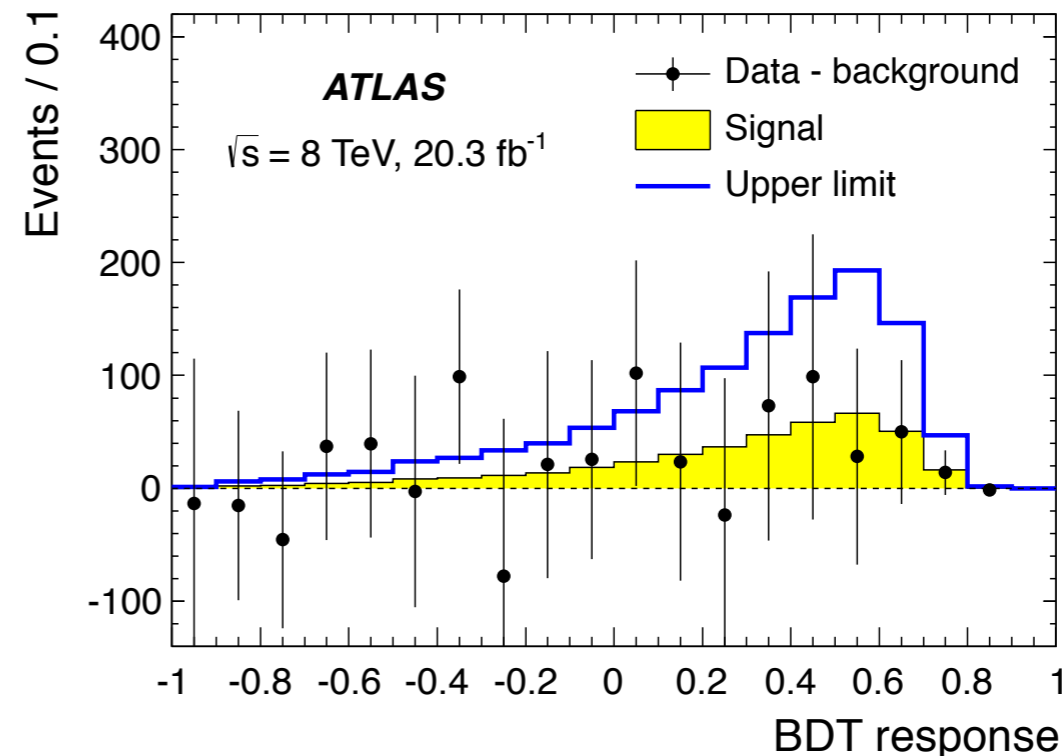


## Result

- $\sigma(\text{s-channel}) = 5.0 \pm 4.3 \text{ pb}$
- $< 14.6 \text{ pb @ 95\% C.L.}$
- significance  $1.3 \sigma$  ( $1.4 \sigma$  expect.)

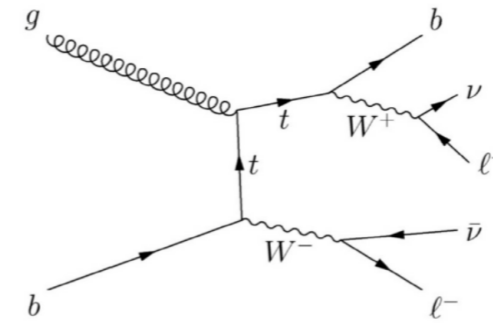
## Uncertainties

- $E_T^{\text{miss}}$ , JES, statistical

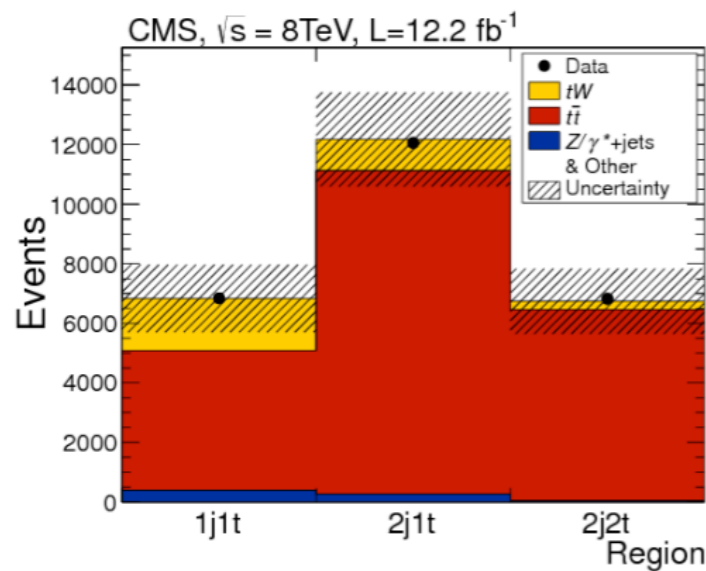


## LHC measurements

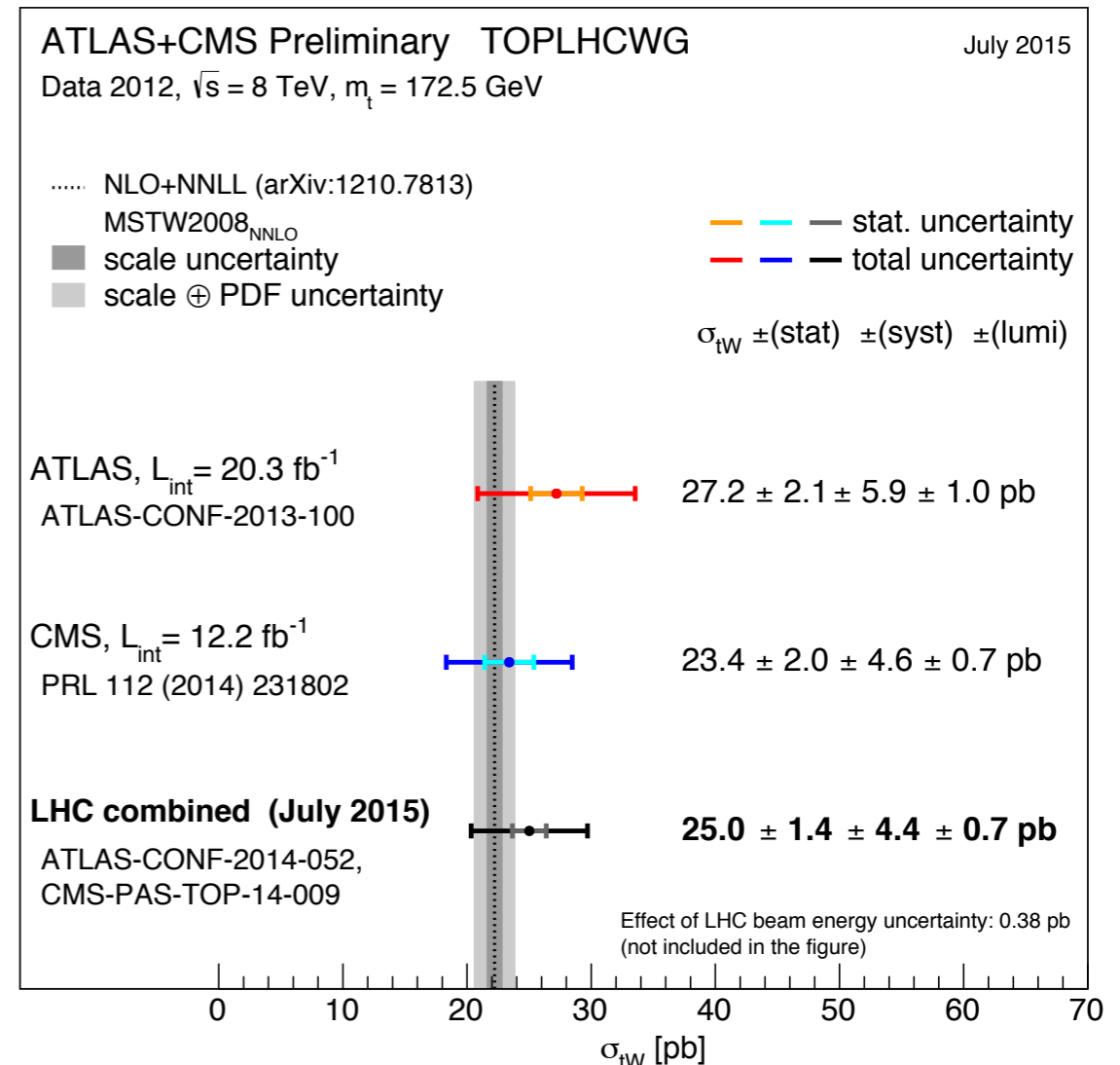
- exploit dilepton signature + 1 or 2 jets
- use BDT for S/B separation
- Powheg+Pythia generator with DR scheme



**ATLAS-CONF-2014-052**  
**CMS PAS TOP-14-009**

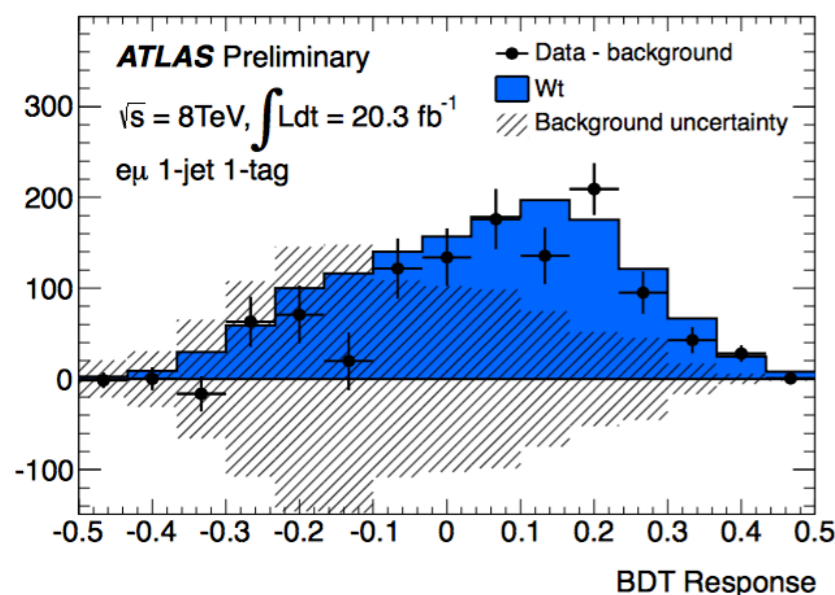


**all dilepton channels  
partial dataset  
22% uncertainty**



**eμ only  
full dataset  
23% uncertainty**

**Combination: 19% uncertainty**  
**dominated by ME/PS matching and scales**

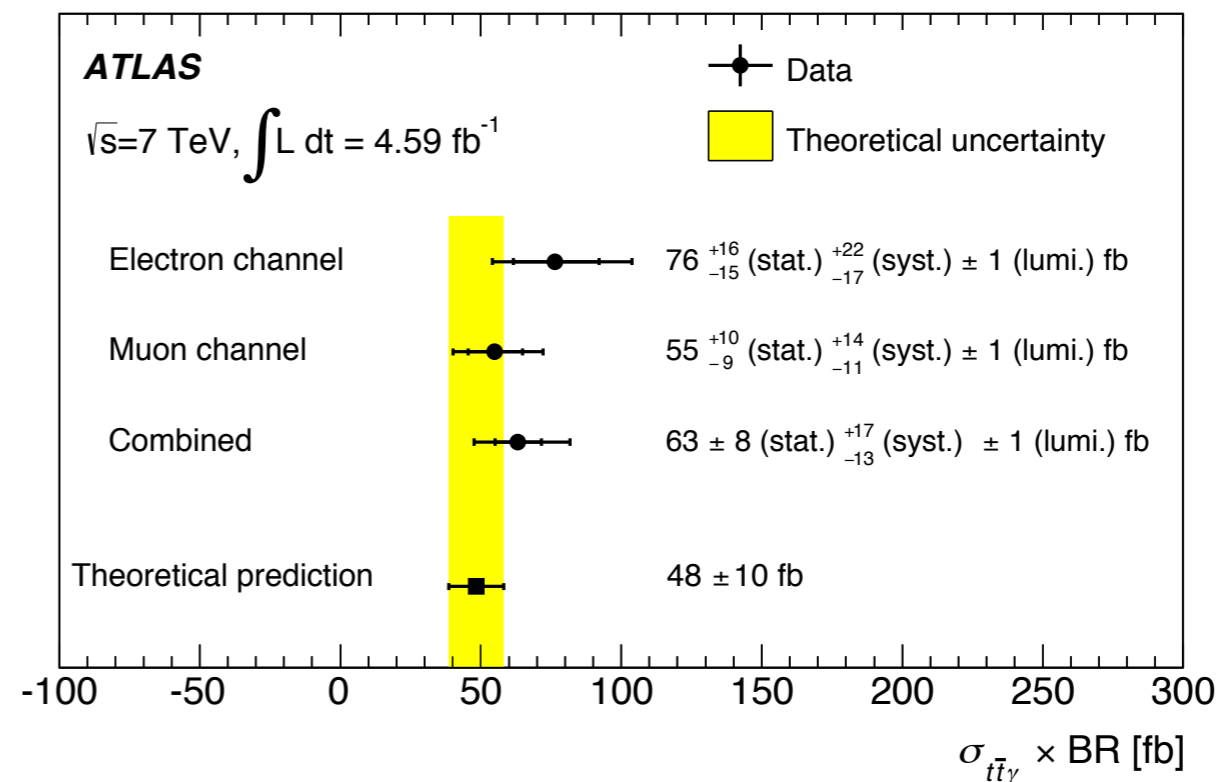
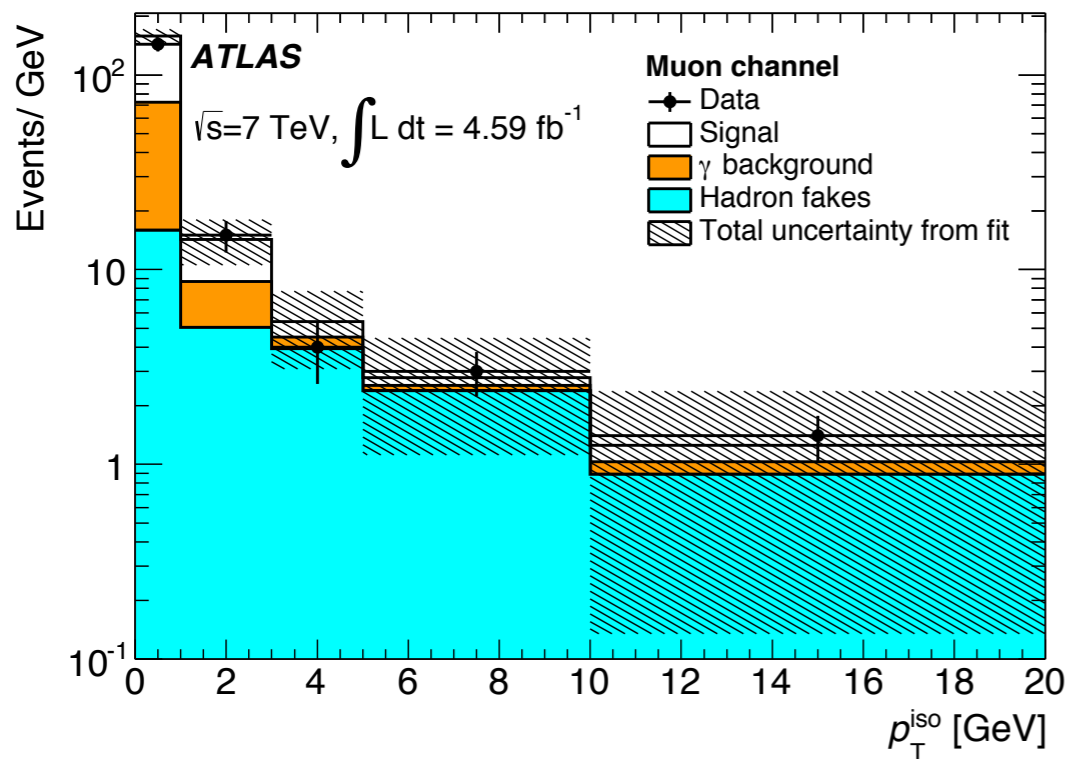


## Observation in 7 TeV data

- sensitive to  $t\gamma$  coupling and to anomalous  $t^* \rightarrow t\gamma$

## Fiducial cross section measurement at particle level

- with generator cuts  $p_T(\gamma) > 20$  GeV and  $\Delta R(\gamma, \ell) > 0.7$
- template fit to photon isolation variable in  $\ell + \text{jets} + \gamma$  channel
- suppress misidentified  $\gamma$  from  $Z \rightarrow ee$ :  $|m_{e\gamma} - m_Z| > 5$  GeV

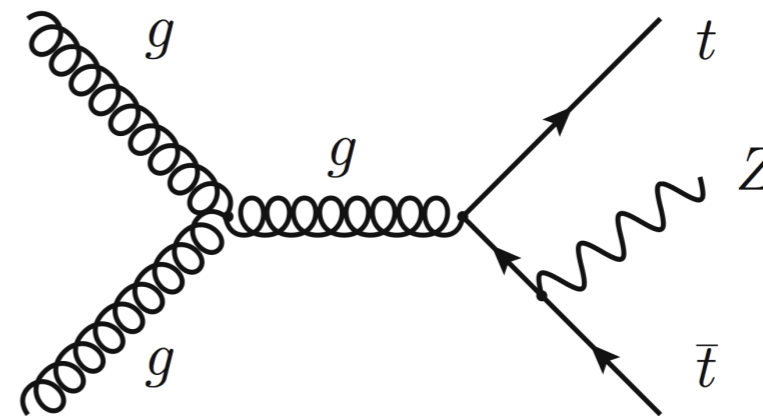
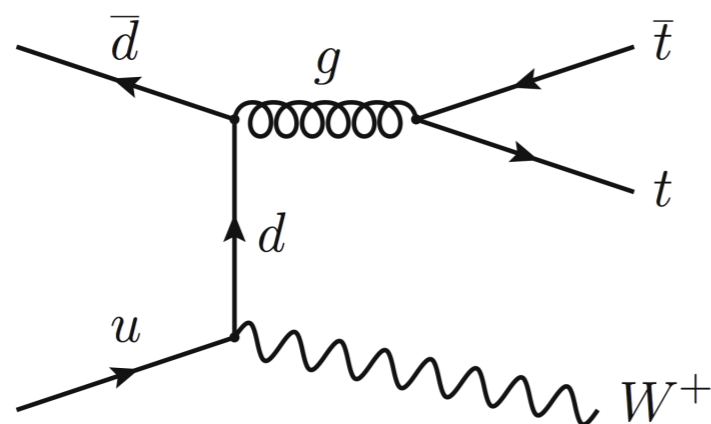


- jet energy scale and  $b$ -tagging efficiency are main systematics

## Null hypothesis excluded at $5.3 \sigma$

## Couplings of top quark to Z are largely unexplored

- can probe EWSB
- $t\bar{t}W$  and  $t\bar{t}Z$  backgrounds to new physics searches and  $t\bar{t}H$

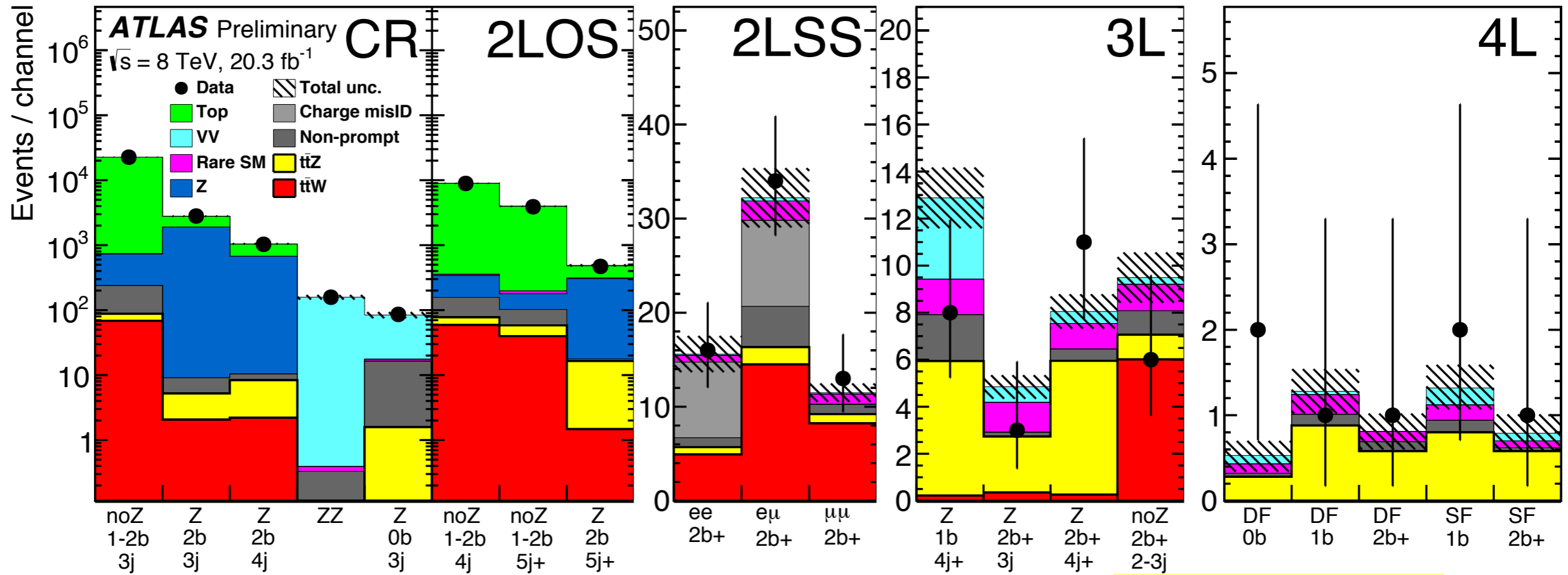


## Four signal regions: 2 $l$ OS, 2 $l$ SS, 3 $l$ , 4 $l$

- extract  $t\bar{t}W$  and  $t\bar{t}Z$  simultaneously in a binned profile likelihood fit
- increase sensitivity by splitting channels according to
  - ▶ number of jets and  $b$ -jets
  - ▶ relative lepton flavour (Z or not-Z like),  $m_{\ell\ell}$
  - ▶  $E_T^{\text{miss}}$  or  $H_T$
- profile likelihood technique, statistical uncertainty dominates

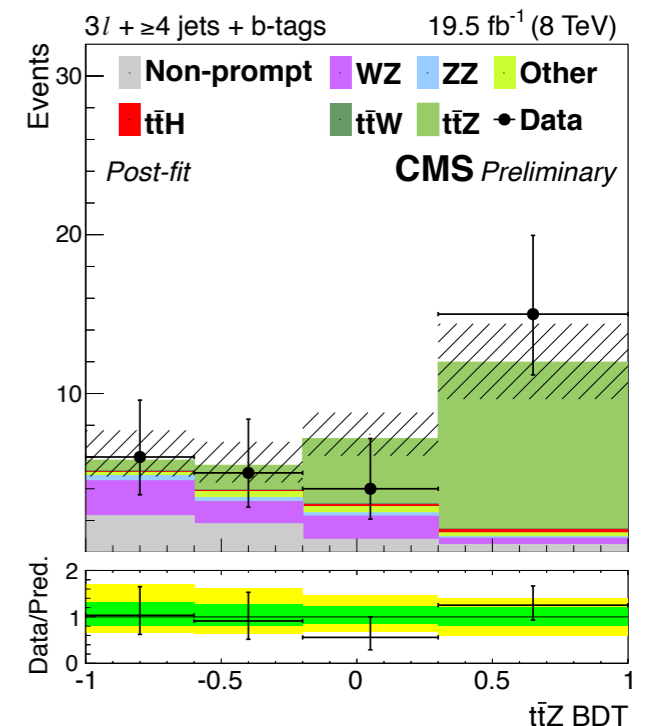
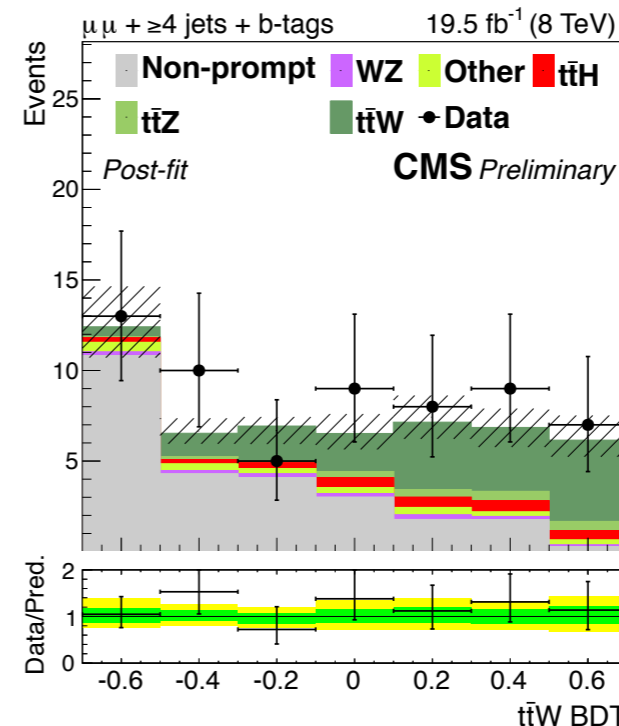
# $t\bar{t}+Z$ and $t\bar{t}+W$ fit to data

ATLAS-CONF-2015-032

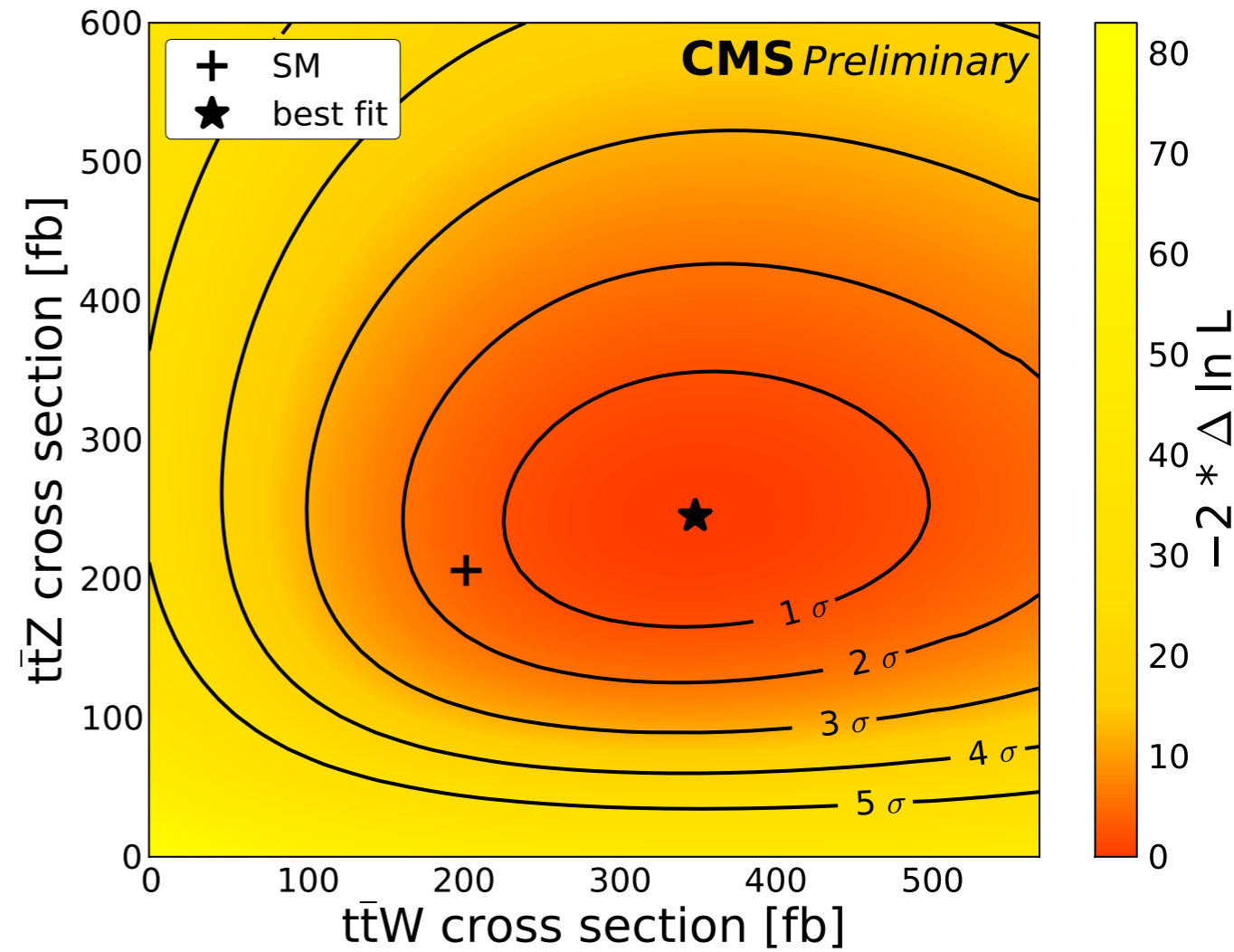
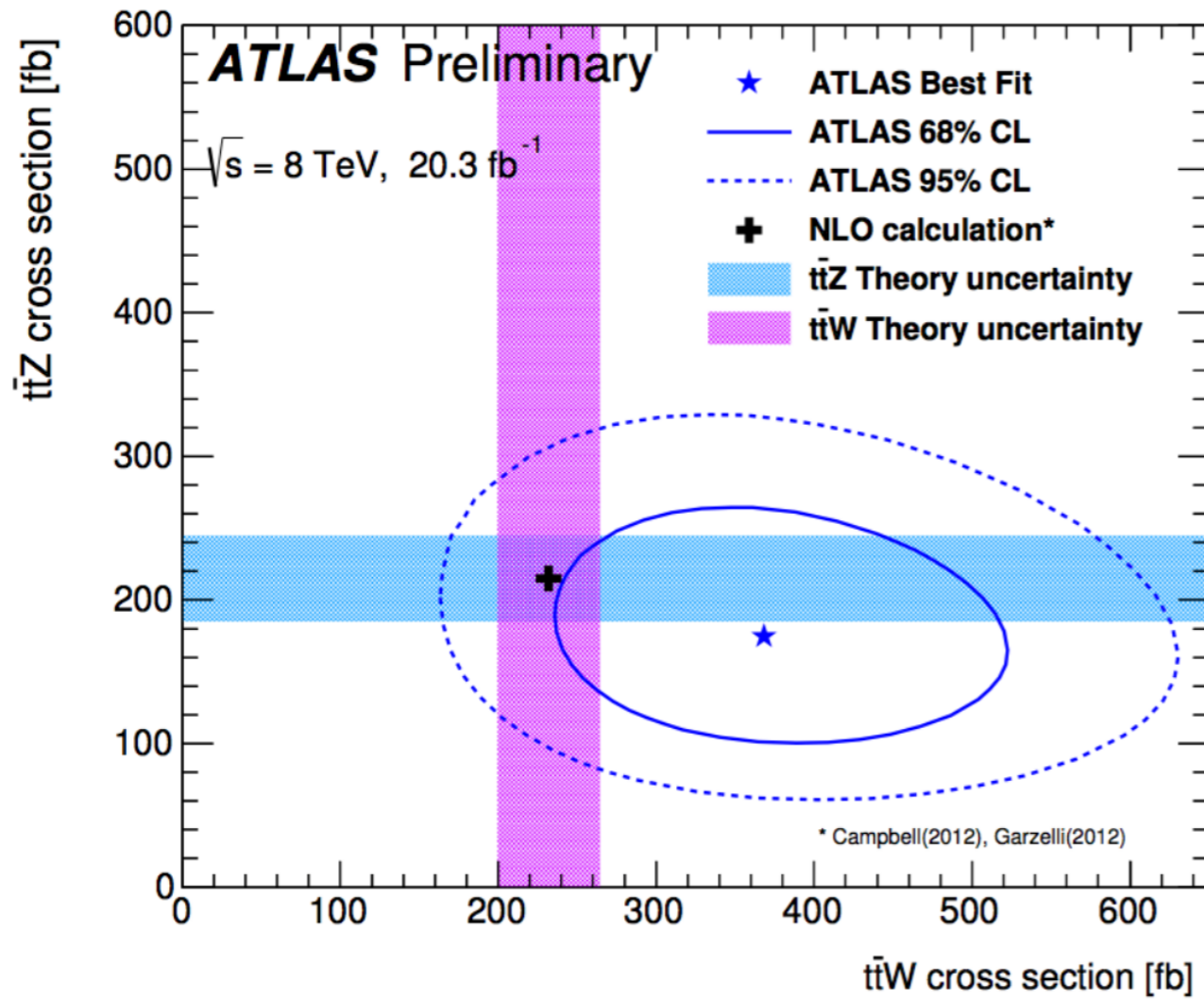


CMS PAS TOP-14-021

- additionally attempt full (partial)  $t\bar{t}W/Z$  reconstruction
  - ▶ match reconstructed objects to  $W, Z, t\bar{t}$
  - ▶ combine into linear discriminant
  - ▶ choose best permutation
- combine information into BDT →
  - ▶ using kinematic quantities



# $t\bar{t}+Z$ and $t\bar{t}+W$ results



Channel	$t\bar{t}W$ significance		$t\bar{t}Z$ significance	
	Expected	Observed	Expected	Observed
$2\ell OS$	0.4	0.1	1.4	1.1
$2\ell SS$	2.8	5.0	-	-
$3\ell$	1.4	1.0	3.7	3.3
$4\ell$	-	-	2.0	2.4
Combined	3.2	5.0	4.5	4.2

$t\bar{t}W$	Significance	
	Expected	Observed
Channels		
SS	3.4	4.9
$3\ell$	1.0	1.0
SS + $3\ell$	3.5	4.8

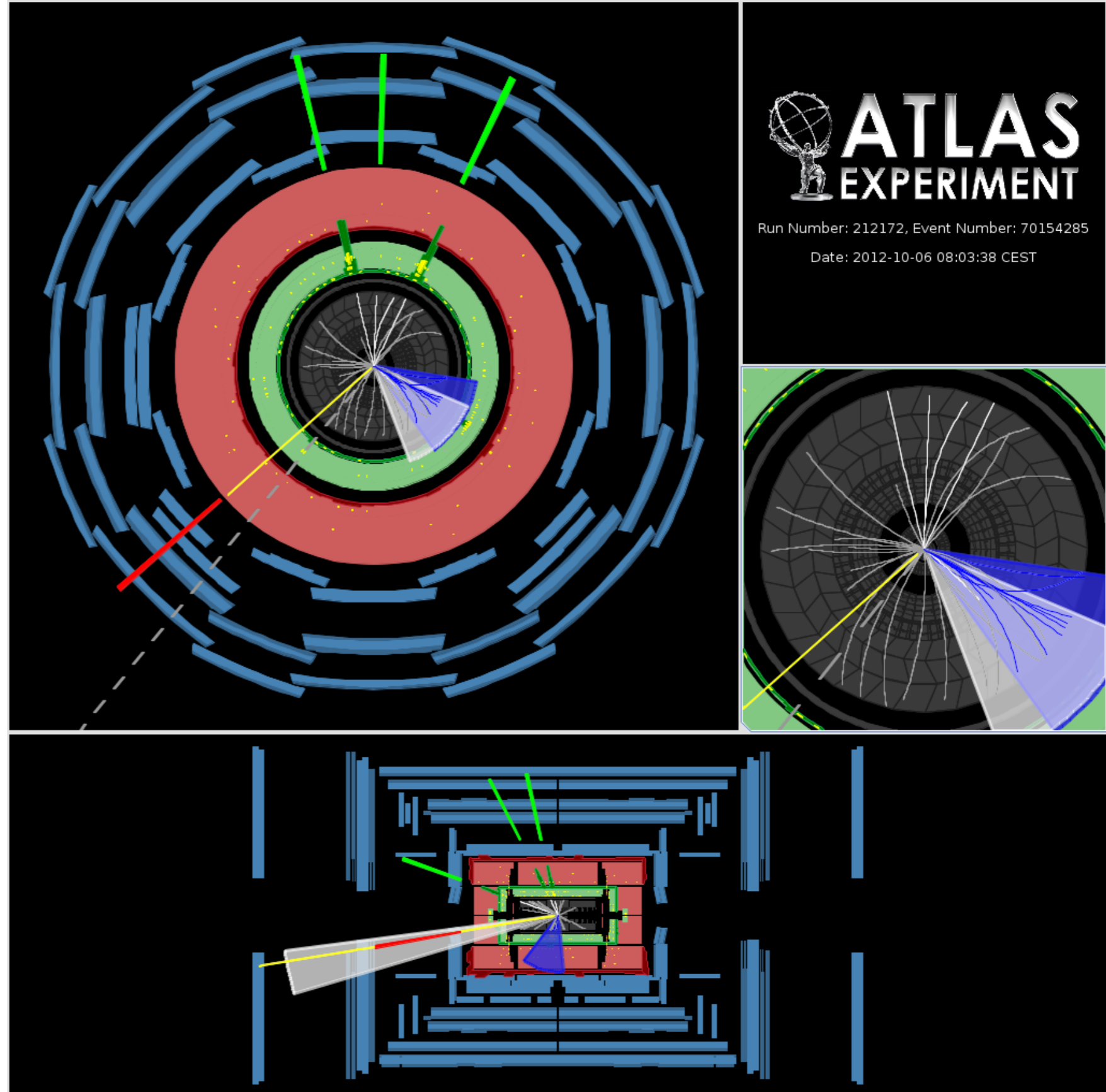
$t\bar{t}Z$	Significance	
	Expected	Observed
Channels		
OS	1.8	2.1
$3\ell$	4.6	5.1
$4\ell$	2.7	3.4
OS + $3\ell$ + $4\ell$	5.7	6.4

→ associated  $t\bar{t}+W$  and  $t\bar{t}+Z$  production established

# $t\bar{t}+Z$ event display

## $t\bar{t}Z$ candidate

- 4 leptons:  $\mu^- e_1^+ e_2^- e_3^+$
- $m(e_2 e_3) = 94 \text{ GeV}$
- 2 jets  $p_T > 50 \text{ GeV}$
- both  $b$ -tagged
- $E_T^{\text{miss}} = 57 \text{ GeV}$





PLB 746 (2015) 132

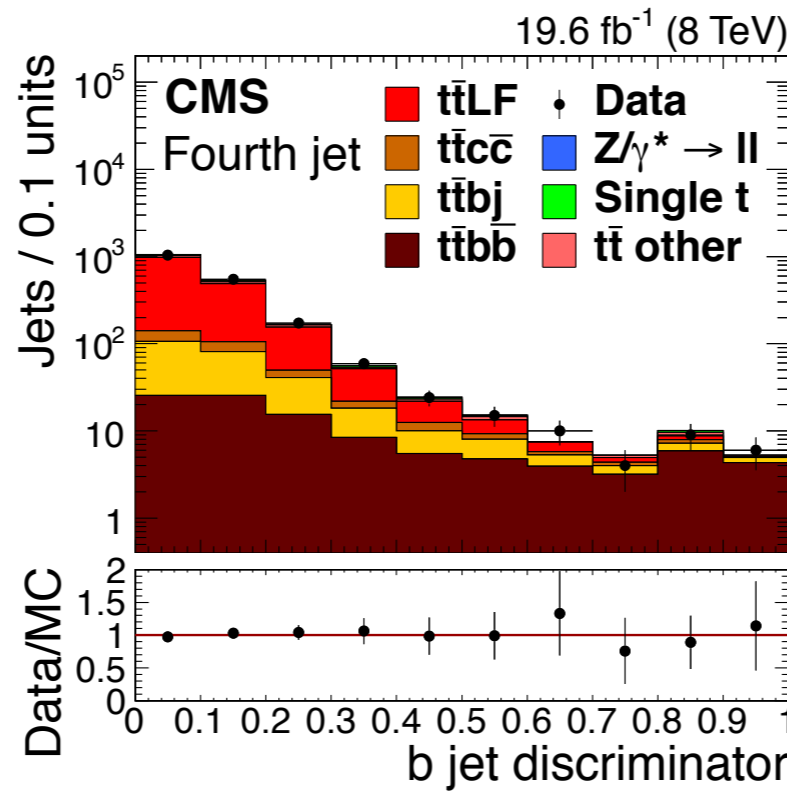
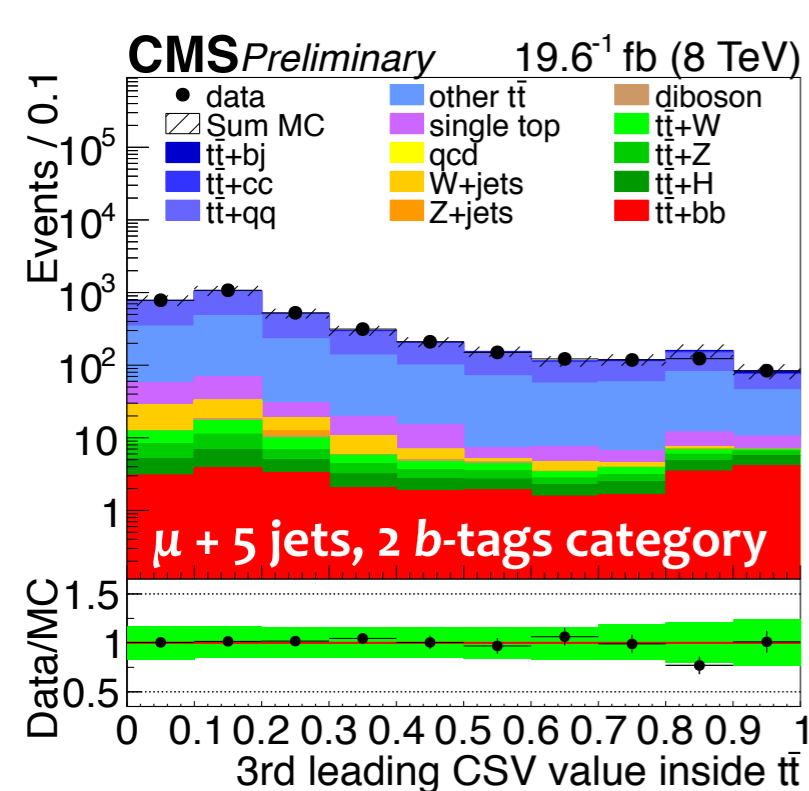
CMS PAS TOP-13-016

## Interest

- irreducible background to  $t\bar{t}H(\rightarrow b\bar{b})$
- test of NLO QCD calculation

## Measurements in dilepton and $\ell$ +jets channels

- fit to combined information of  $b$ -jet discriminator of jets beyond 2  $b$ -tags
- several categories in  $\ell$ +jets
- jet flavour at gen. level defined by
  - ▶ leading quark flavour (parton) or presence of  $B$  hadron (particle)



$$\frac{\sigma_{t\bar{t}b\bar{b}}}{\sigma_{t\bar{t}jj}}(\text{NLO}) = (1.09^{+0.43}_{-0.14})\%$$

*JHEP 07 (2014) 135*

$$\frac{\sigma_{t\bar{t}b\bar{b}}}{\sigma_{t\bar{t}jj}}(\text{dil.}) = (2.2 \pm 0.3_{\text{stat.}} \pm 0.5_{\text{syst.}})\%$$

$$\frac{\sigma_{t\bar{t}b\bar{b}}}{\sigma_{t\bar{t}jj}}(\ell + \text{jets, parton}) = (1.17 \pm 0.40)\%$$

$$\frac{\sigma_{t\bar{t}jj}}{\sigma_{t\bar{t}b\bar{b}}}(\ell + \text{jets, particle}) = (1.51 \pm 0.49)\%$$



## Detailed $t\bar{t}b(b)$ study

- cut-based and fit-based analyses for  $t\bar{t}+bb$  in dil. channel
- fiducial measurements of  $t\bar{t}+b$  in  $\ell$ +jets and dil. channels
- ratio  $t\bar{t}bb/t\bar{t}jj$  determined to be  $R = (1.30 \pm 0.33_{\text{stat}} \pm 0.28_{\text{syst}}) \%$

available soon

NEW FOR THIS CONFERENCE  
LEPTON PHOTON 2015

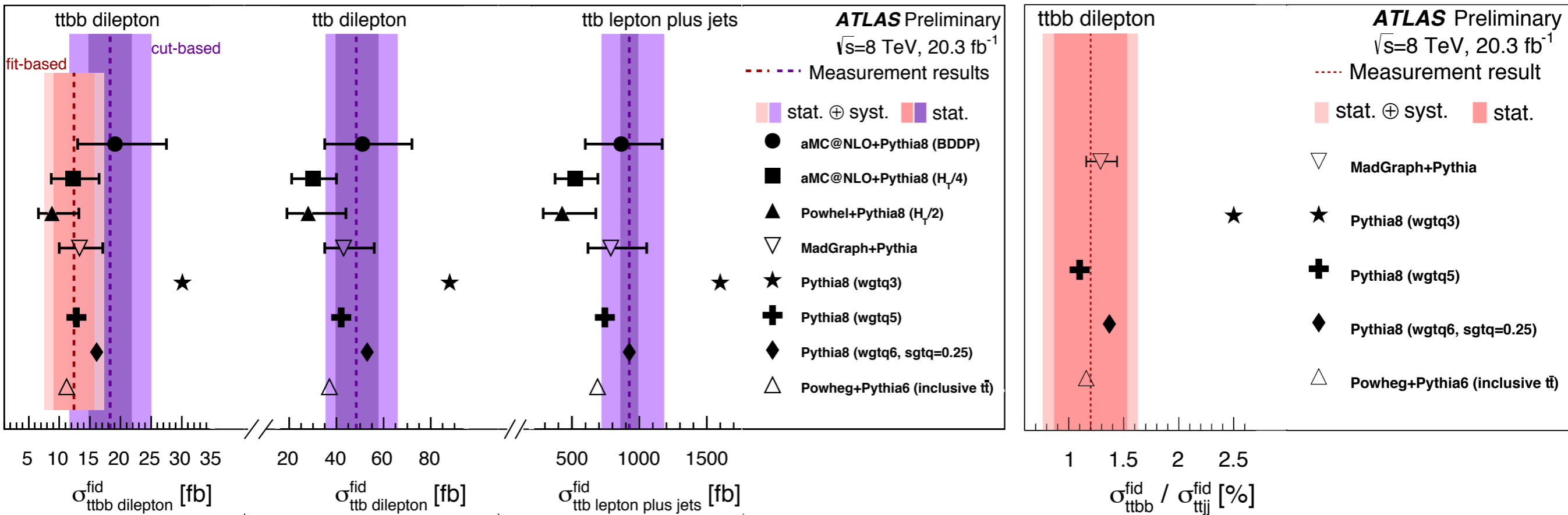


## Additionally checked

- subtract  $t\bar{t}V/H$  and compare to QCD-only predictions
- compare with different  $g \rightarrow b\bar{b}$  splitting models

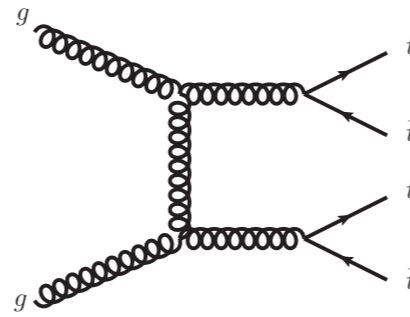
$$\frac{\sigma_{t\bar{t}b\bar{b}}}{\sigma_{t\bar{t}jj}}(\text{NLO}) = (1.09^{+0.43}_{-0.14})\%$$

JHEP 07 (2014) 135



## At 8 TeV $\sigma_{t\bar{t}t\bar{t}} \sim 1$ fb

- main background is  $t\bar{t}$ +jets



## Searches

- Dedicated CMS  $\ell + \geq 6$  jets,  $\geq 2$   $b$ -tags, large  $H_T$
- Two ATLAS searches targeting several exotic final states
  - ▶  $\ell$ +jets and same-sign  $2\ell$

## Strategies

- use BDT classifier with top content, event activity and  $b$ -jet content

## Limits at 95% C.L. in fb

Experiment	Channel	Expected	Observed
CMS	$\ell$ +jets	$32 \pm 17$	32
ATLAS	same sign $2\ell$	27	70
ATLAS	$\ell$ +jets	32	23



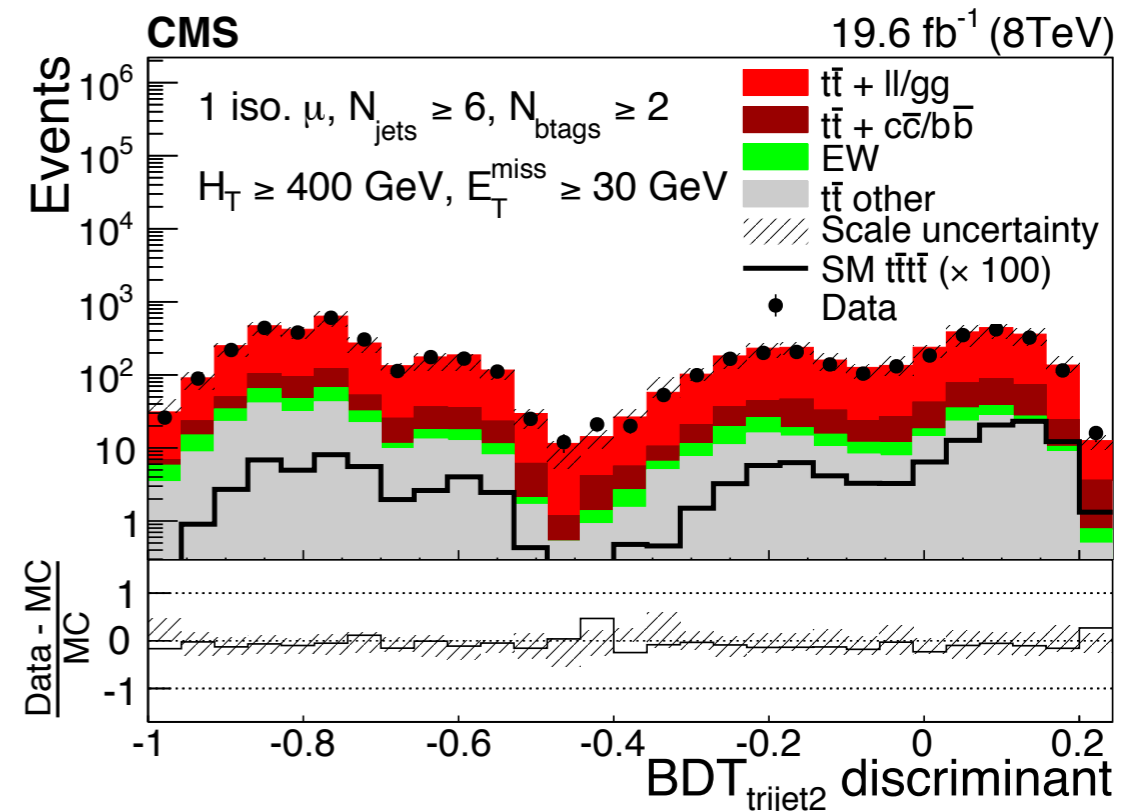
JHEP11 (2014) 154



arXiv:1504.04605  
submitted to JHEP



arXiv:1505.04306  
accepted for JHEP



## Top quark production studies provide stringent tests of pQCD

### $t\bar{t}$ production

- inclusive cross-section measured with 4% accuracy, first 13 TeV analysis
- differential: resolved vs. boosted, parton vs. particle level, central vs. forward
- $t\bar{t}$  modelling important for Higgs and searches
- ✓ SM predictions in general in good agreement with data

### Single top production

- $t$ -channel large enough to investigate properties
- $Wt$  channel observed (LHC) and  $s$ -channel observed (Tevatron)
- ✓ again SM holds remarkably well

### Associated production

- $t\bar{t}$ +heavy flavour important for  $tH$  coupling
- first look at  $t\gamma$  and  $tZ$  couplings → important for Run-2