Top quark Production

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Physics in Collision, University of Warwick,
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Outline: focus on recent measurements

- Top quark pair production cross sections from Tevatron and LHC

    - Total inclusive

    - Differential

    - tt+bb

- Associated Production of top quarks with a boson

    - except for Higgs (see Higgs talk)

- Single top quark production from Tevatron and LHC

Some results are shown here for the first time (or very very recent)!

8 TeV results use the full dataset (~20 fb^{-1})!
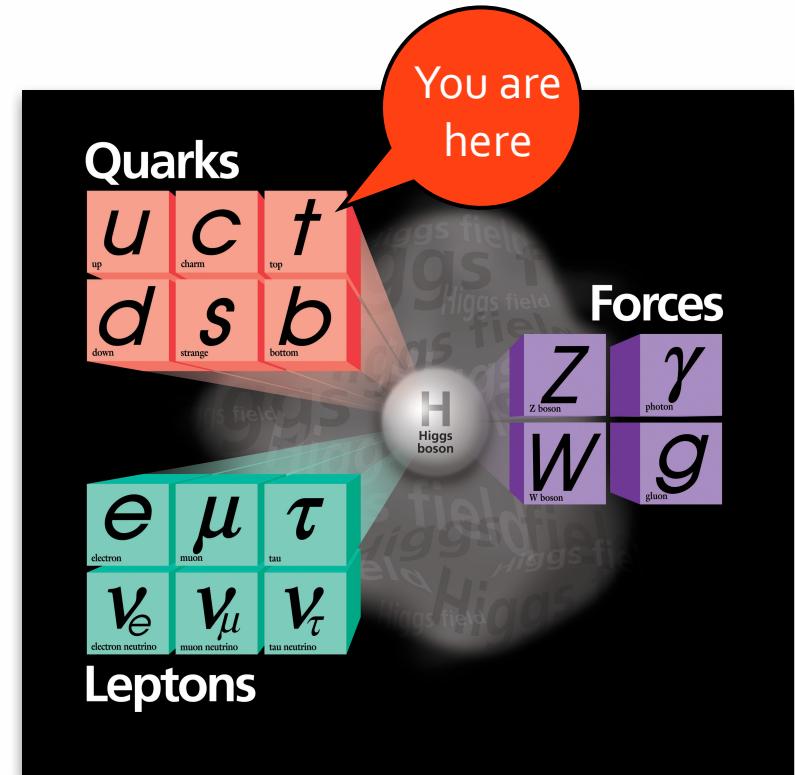
Top quark is so heavy!

- May be not a normal quark…

- Top decays before it feels non-perturbative strong interaction

- LHC is a top quark factory: at 13 TeV about 2 tops every second!

- Studying top production is crucial to the LHC programme:

  - Detailed measurements of QCD, EWK

  - Probe couplings to Higgs, W, Z, γ

  - 3rd generation models within BSM

 - Significant background to searches and Higgs
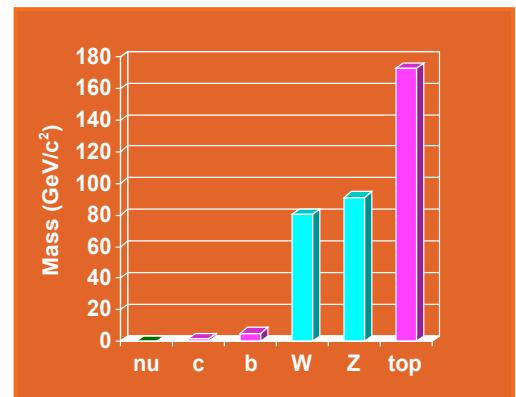
How the top quark decays

$t\bar{t}$ decay modes
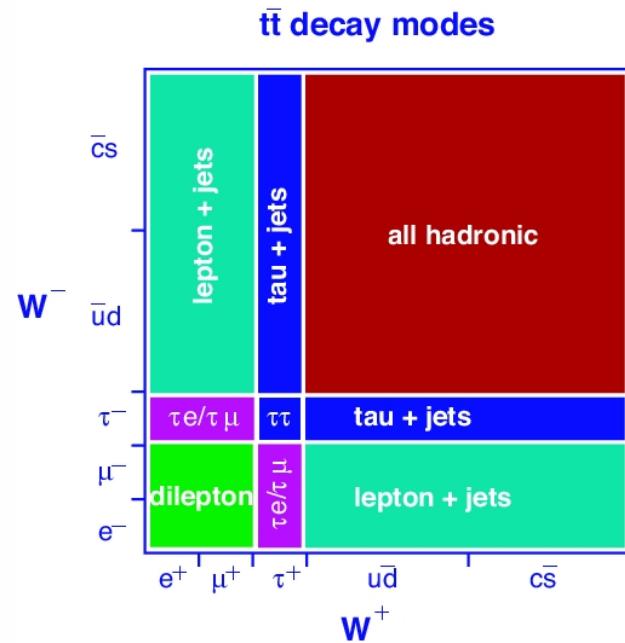
(not inc. τ)	BR	background
dilepton	~5%	low
lepton + jets	~30%	moderate
all hadronic	~44%	high

Jets

b-jets

Leptons

E_T^{missing}
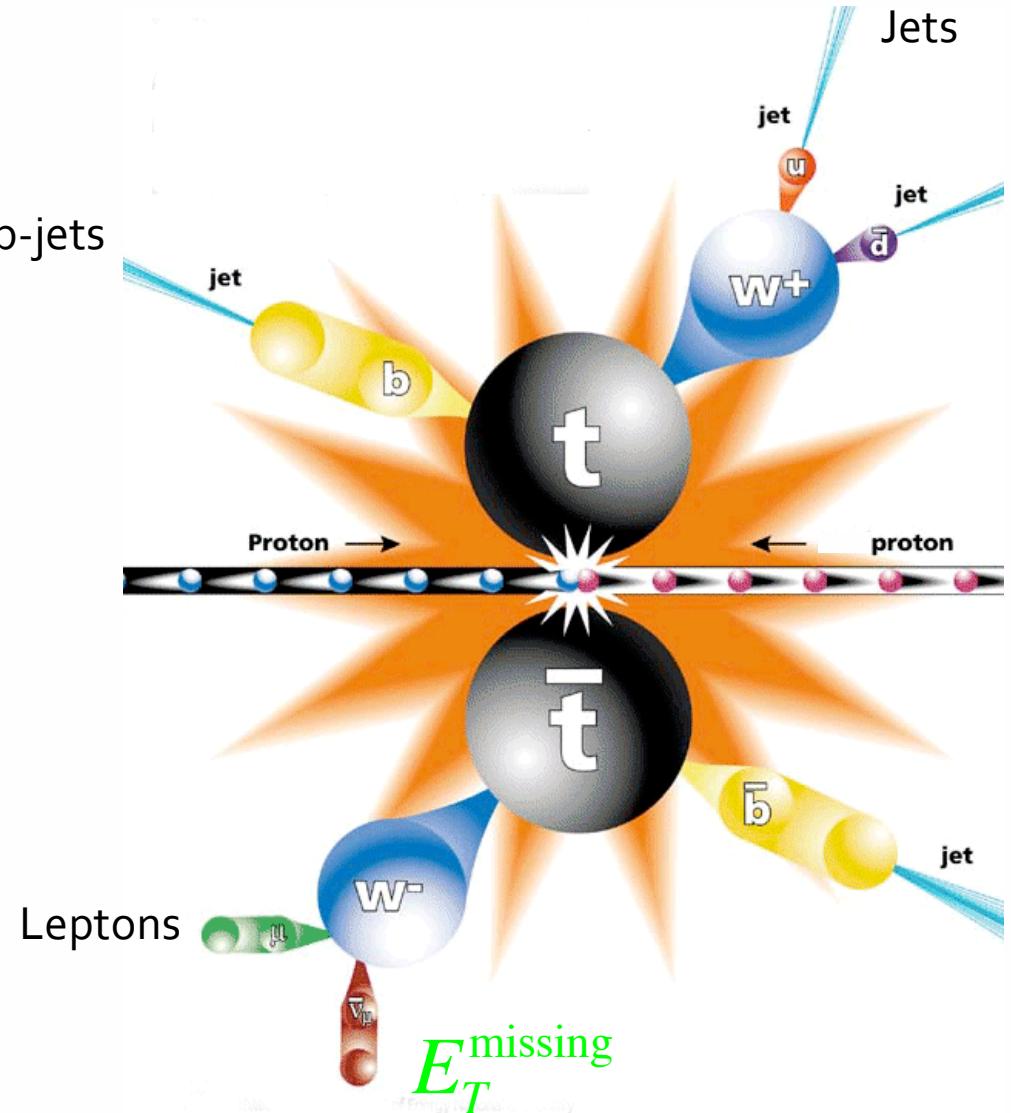
Top anti-top quark total inclusive cross sections

Top anti-top quark production
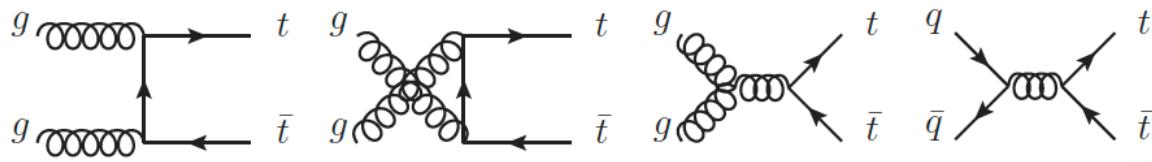
1303.6254

$$\hat{s} = x_i \sqrt{s} \cdot x_j \sqrt{s} \geq (2m_t)^2$$

$$x_i \approx \frac{2m_t}{\sqrt{s}}$$

H1 and ZEUS HERA I+II PDF Fit

xg (× 0.05) $Q^2 = 10000$ GeV^2 March 2011

HERAPDF1.5 NNLO (prel.)
exp. uncert.
model uncert.
parametrization uncert.

xS (× 0.05)

xu_v

xd_v

HERAPDF Structure Function Working Group

Scale variation

LHC 8 TeV; m_{top}=173.3 GeV; A=0
MSTW2008 LO; NLO; NNLO

Fixed Order
NLO+res
NNLO+res
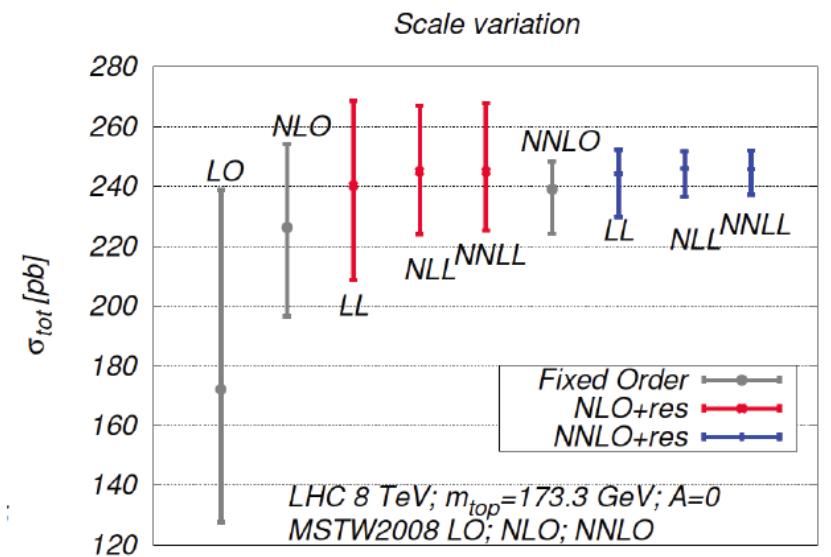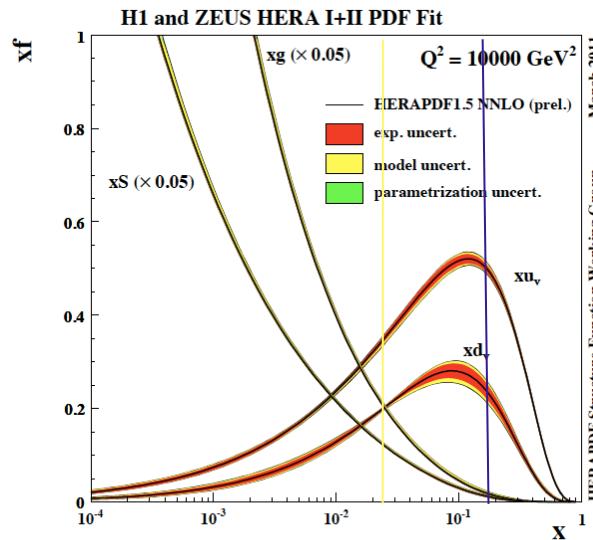
NNLO+NNLL   1303.6254

	x	qq vs gg	cross section	± scales	± pdf
Tev 1.96 TeV	0.18	90% vs 10%	7.164 pb	~2%	~2%
LHC 7 TeV	0.048	15% vs 85%	172.0 pb	~3%	~3%
LHC 8 TeV	0.043	12% vs 88%	245.8 pb	~3%	~2.5%
LHC 14 TeV	0.025	10% vs 90%	953.6 pb	~3%	~2%

m_t=173.3 GeV, MSTW2008nnlo68cl

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tt inclusive cross section at 1.96 TeV

Physics

- l+jets: fit the topological MVA distribution
  - 30 variables for each lepton type and number of jet bins into a BDTG
- dilepton: fit the b-tag MVA distribution

$$\sigma = 7.73 \pm 0.13 \text{ (stat.)} \pm 0.55 \text{ (syst.) pb}$$ 7.3%

Tevatron Run II

CDF dilepton	7.09 ± 0.83 $\pm 0.49 \pm 0.67$	8.8 fb^{-1}
CDF ANN lepton+jets	7.82 ± 0.56 $\pm 0.38 \pm 0.41$	4.6 fb^{-1}
CDF SVX lepton+jets	7.32 ± 0.71 $\pm 0.36 \pm 0.61$	4.6 fb^{-1}
CDF all-jets	7.21 ± 1.28 $\pm 0.50 \pm 1.18$	2.9 fb^{-1}
CDF combined	7.63 ± 0.50 $\pm 0.31 \pm 0.39$	
DØ dilepton	7.36 ± 0.85	5.4 fb^{-1}
DØ lepton+jets	7.90 ± 0.74	5.3 fb^{-1}
DØ combined	7.56 ± 0.59 $\pm 0.20 \pm 0.56$	
Tevatron combined	7.60 ± 0.41 $\pm 0.20 \pm 0.36$	5.4%
$m_t = 172.5$ GeV		

$p\bar{p} \rightarrow t\bar{t}$ cross section (pb) at $\sqrt{s}=1.96$ TeV

DØ, L=9.7 fb^{-1}

$\sigma_{t\bar{t}}$ (pb)

Top quark pole mass (GeV)

- Measured $\sigma(p\bar{p} \rightarrow t\bar{t}+X)$
- Measured dependence of σ
- NNLO+NNLL

tt inclusive cross section at 7 and 8 TeV

- eμ channel with full integrated luminosity
- binned likelihood fit to 12 distributions, including nuisance parameters for systematics
- obtain fiducial cross section, pole top mass, stop quark limit

$$R_{tt} = 1.41 \pm 0.06 \quad (R_{tt}^{nnlo} = \sigma_8 / \sigma_7 = 1.430 \pm 0.006)$$

least energetic additional non b-tagged jet

tt total inclusive cross section at 7 TeV

**ATLAS+CMS Preliminary**   **LHC*top*WG** $\sigma_{t\bar{t}}$ summary, $\sqrt{s}$ = 7 TeV   Sep 2015

NNLO+NNLL PRL 110 (2013) 252004, PDF4LHC
m_{top} = 172.5 GeV

scale uncertainty

scale $\oplus$ PDF $\oplus$ α_S uncertainty

total stat

$\sigma_{t\bar{t}}$ ±(stat) ±(syst) ±(lumi)

Measurement	Value	Lumi
ATLAS, l+jets	$179 \pm 4 \pm 9 \pm 7$ pb	L_{int}=0.7 fb⁻¹
ATLAS, dilepton (*)	$173 \pm 6\,^{+14}_{-11}\,^{+8}_{-7}$ pb	L_{int}=0.7 fb⁻¹
ATLAS, all jets (*)	$167 \pm 18 \pm 78 \pm 6$ pb	L_{int}=1.0 fb⁻¹
ATLAS combined	$\mathbf{177 \pm 3\,^{+8}_{-7} \pm 7}$ **pb**	L_{int}=0.7-1.0 fb⁻¹
CMS, l+jets (*)	$164 \pm 3 \pm 12 \pm 7$ pb	L_{int}=0.8-1.1 fb⁻¹
CMS, dilepton (*)	$170 \pm 4 \pm 16 \pm 8$ pb	L_{int}=1.1 fb⁻¹
CMS, $\tau_{had}+\mu$ (*)	$149 \pm 24 \pm 26 \pm 9$ pb	L_{int}=1.1 fb⁻¹
CMS, all jets (*)	$136 \pm 20 \pm 40 \pm 8$ pb	L_{int}=1.1 fb⁻¹
CMS combined	$\mathbf{166 \pm 2 \pm 11 \pm 8}$ **pb**	L_{int}=0.8-1.1 fb⁻¹
LHC combined (Sep 2012)	$\mathbf{173 \pm 2 \pm 8 \pm 6}$ **pb**	L_{int}=0.7-1.1 fb⁻¹
ATLAS, l+jets, b→X$\mu\nu$	$165 \pm 2 \pm 17 \pm 3$ pb	L_{int}=4.7 fb⁻¹
ATLAS, dilepton eμ, b-tag	$182.9 \pm 3.1 \pm 4.2 \pm 3.6$ pb	L_{int}=4.6 fb⁻¹
ATLAS, dilepton eμ, N_{jets}-E_T^{miss}	$181.2 \pm 2.8\,^{+9.7}_{-9.5} \pm 3.3$ pb	L_{int}=4.6 fb⁻¹
ATLAS, τ_{had}+jets	$194 \pm 18 \pm 46$ pb	L_{int}=1.7 fb⁻¹
ATLAS, all jets	$168 \pm 12\,^{+60}_{-57} \pm 7$ pb	L_{int}=4.7 fb⁻¹
ATLAS, τ_{had}+l	$183 \pm 9 \pm 23 \pm 3$ pb	L_{int}=4.6 fb⁻¹
CMS, l+jets	$158 \pm 2 \pm 10 \pm 4$ pb	L_{int}=2.2-2.3 fb⁻¹
CMS, dilepton eμ	$174.5 \pm 2.1\,^{+4.5}_{-4.0} \pm 3.8$ pb	L_{int}=5.0 fb⁻¹
CMS, τ_{had}+l	$143 \pm 14 \pm 22 \pm 3$ pb	L_{int}=2.2 fb⁻¹
CMS, τ_{had}+jets	$152 \pm 12 \pm 32 \pm 3$ pb	L_{int}=3.9 fb⁻¹
CMS, all jets	$139 \pm 10 \pm 26 \pm 3$ pb	L_{int}=3.5 fb⁻¹

(*) Superseded by results shown below the line

Effect of LHC beam energy uncertainty: 3.3 pb
(not included in the figure)

$\sigma_{t\bar{t}}$ [pb]

3.5%

3.6%

tt total inclusive cross section at 8 TeV

ATLAS+CMS Preliminary **LHC top WG** $\sigma_{t\bar{t}}$ summary, $\sqrt{s}$ = 8 TeV   Sep 2015

.... NNLO+NNLL PRL 110 (2013) 252004, PDF4LHC
m_{top} = 172.5 GeV
  scale uncertainty
  scale ⊕ PDF ⊕ α_S uncertainty

total stat

$\sigma_{t\bar{t}}$ ±(stat) ±(syst) ±(lumi)

ATLAS, lepton+jets
PRD 91 (2015) 112013, L_{int}=20.3 fb^{-1}
$260 \pm 1 \, ^{+22}_{-23} \pm 8$ pb

CMS prel., lepton+jets
CMS-PAS TOP-12-006, L_{int}=2.8 fb^{-1}
$228 \pm 9 \, ^{+29}_{-26} \pm 10$ pb

CMS, lepton+τ_h
PLB 739 (2014) 23, L_{int}=19.6 fb^{-1}
$257 \pm 3 \pm 24 \pm 7$ pb

ATLAS, dilepton eμ
EPJ C74 (2014) 3109, L_{int}=20.3 fb^{-1}
$242.4 \pm 1.7 \pm 5.5 \pm 7.5$ pb

3.9%

CMS, dilepton (ee, $\mu\mu$, eμ)
JHEP 02 (2014) 024, L_{int}=5.3 fb^{-1}
$239.0 \pm 2.1 \pm 11.3 \pm 6.2$ pb

LHC combined eμ (Sep 2014)
ATLAS-CONF-2014-053, CMS-PAS TOP-14-016,
L_{int}=5.3-20.3 fb^{-1}
$241.5 \pm 1.4 \pm 5.7 \pm 6.2$ pb

3.5%

CMS prel., dilepton eμ
CMS-PAS TOP-13-004, L_{int}=19.7 fb^{-1}
$245.6 \pm 1.3 \, ^{+6.6}_{-5.5} \pm 6.5$ pb

3.8%

CMS, all jets
CMS TOP-14-018, L_{int}=18.4 fb^{-1}
$275.6 \pm 6.1 \pm 37.8 \pm 7.2$ pb

Effect of LHC beam energy uncertainty: 4.2 pb
(not included in the figure)

100 150 200 250 300 350 400

$\sigma_{t\bar{t}}$ [pb]

tops at 13 TeV!

proton-proton collisions at
13 TeV centre-of-mass energy

Run: 266919
Event: 19982211
2015-06-04 00:21:24

ATLAS EXPERIMENT

tt inclusive cross section at 13 TeV

ATLAS

ATLAS-CONF-2015-033

78 pb^{-1}

lep p$_T$ > 25GeV

jet p$_T$ > 25GeV

1 and 2 b-tags

(70% eff, 440 light jet rejection)

main background: tW single top

$$e^{\pm}\mu^{\mp}$$

CMS

CMS PAS TOP-15-003

42 pb^{-1}

lep p$_T$ > 20GeV

jet p$_T$ > 30GeV

≥ 2jets

main background:tW single top

and Non-W/Z leptons

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tt total inclusive cross section at 13 TeV

ATLAS+CMS Preliminary   **LHC top WG** $\sigma_{t\bar{t}}$ summary, $\sqrt{s}$ = 13 TeV   Sep 2015

....   NNLO+NNLL PRL 110 (2013) 252004, PDF4LHC
m_{top} = 172.5 GeV
scale uncertainty
scale $\oplus$ PDF $\oplus$ α_S uncertainty

total   stat

$\sigma_{t\bar{t}}$ ±(stat) ±(syst) ±(lumi)

ATLAS, dilepton eμ *   829 ± 50 ± 56 ± 83 pb
ATLAS-CONF-2015-049 L_{int}=78 pb⁻¹

ATLAS, dilepton ee/μμ *   749 ± 57 ± 79 ± 74 pb
ATLAS-CONF-2015-049 L_{int}=85 pb⁻¹

ATLAS, l+jets *   817 ± 13 ± 103 ± 88 pb
ATLAS-CONF-2015-049 L_{int}=85 pb⁻¹

CMS, dilepton eμ *   772 ± 60 ± 62 ± 93 pb
CMS-PAS TOP-15-003 L_{int}=42 pb⁻¹

CMS, l+jets *   836 ± 27 ± 84 ± 100 pb
CMS-PAS TOP-15-005 L_{int}=42 pb⁻¹

* Preliminary

$\sigma_{t\bar{t}}$ [pb]

13.5%

15.3%

16.7%

16.4%

15.9%

ATLAS Preliminary
13 TeV, 78 - 85 pb⁻¹

data ± total uncertainty
data ± stat. uncertainty
▲   **ABM12LHC**
▼   **CT10nnlo**
■   **NNPDF3.0**
●   **MMHT14nnlo68CL**
(NNLO QCD, inner uncert.: PDF only)

$\sigma_{t\bar{t}}^{tot}$ / σ_{Z}^{tot}

σ (NNLO+NNLL) = 832^{+40}_{-46} (PDF, α_s, scales) pb

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tt inclusive cross section at 13 TeV

tt production in the forward region!

- Enhancement of qq and qg relative to gg tt production (charge asymmetry)
- Constrain gluon PDF at large x

- Muon $p_T > 25$ GeV, also included in a jet (j_μ), jet (anti-kt R=0.5) 50 GeV $< p_T < 100$ GeV, Secondary Vertex b-tagger, $p_T(j_\mu+j) > 20$ GeV (dijet suppression)

- Dominant backgrounds: W+b, Z+b, bb

- W+b contributions from template fits to $p_T(\mu)/p_T(j_\mu)$ 1505.04051

- Fiducial cross sections obtained

$2 < \eta < 5$
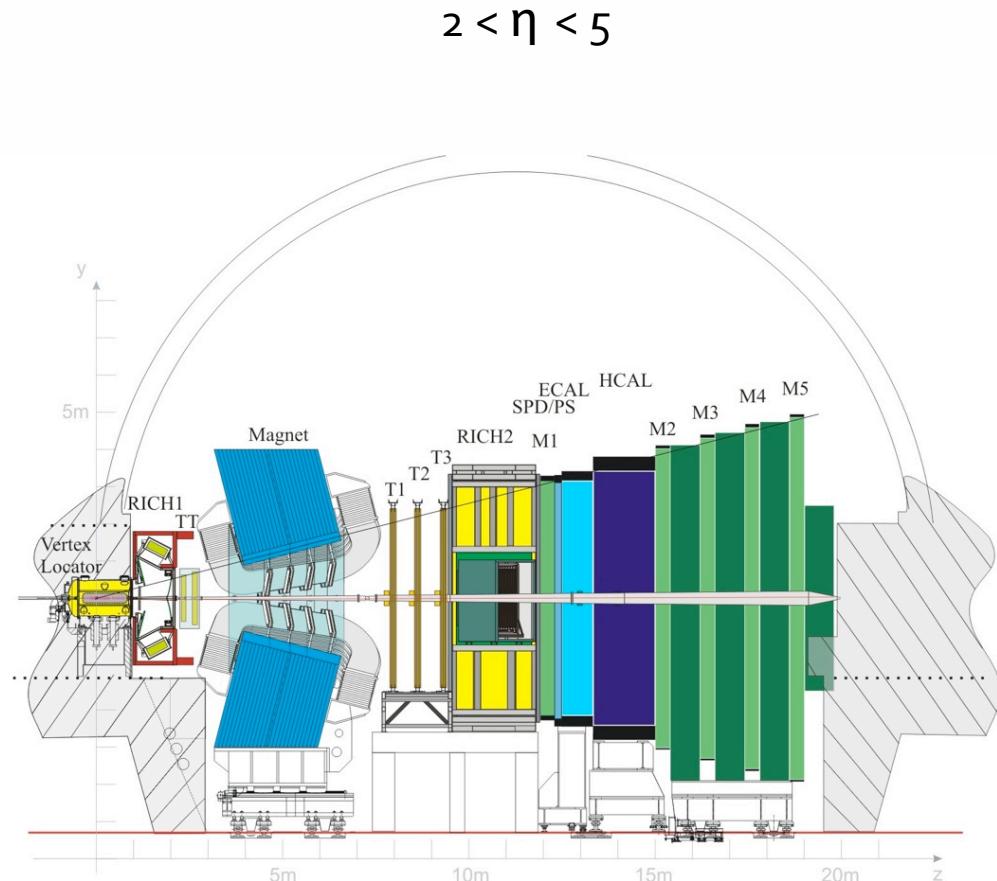
tt production in the forward region!
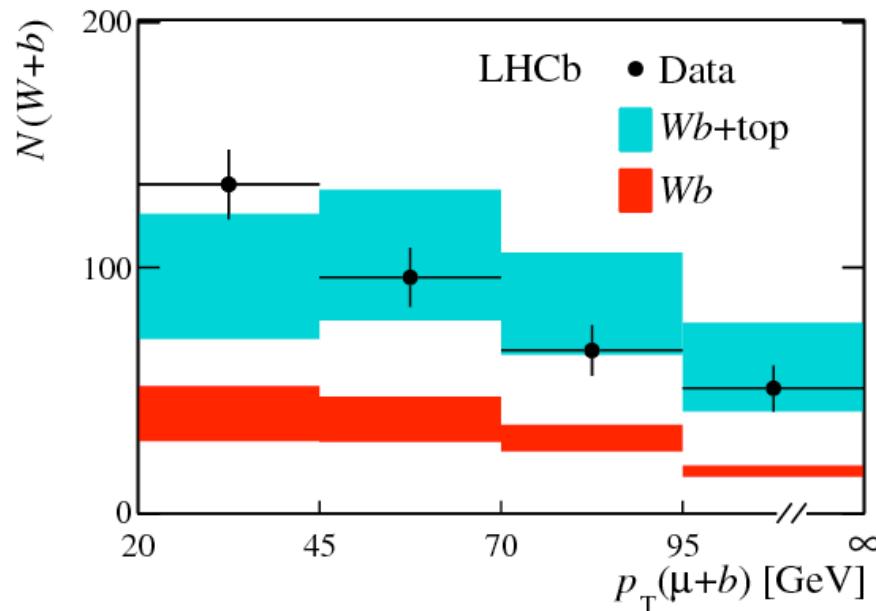
$$\sigma_{\text{fiducial}} \text{ [7 TeV]} = 239 \pm 53 \text{ (stat.)} \pm 38 \text{ (syst.) fb}$$

27%

$$\sigma_{\text{fiducial}} \text{ [8 TeV]} = 289 \pm 43 \text{ (stat.)} \pm 46 \text{ (syst.) fb}$$

22%

$$\sigma_{\text{NLO(MCFM)}} \text{ [7 TeV]} = 180^{+51}_{-41} \text{ fb}$$

$$\sigma_{\text{NLO(MCFM)}} \text{ [8 TeV]} = 312^{+83}_{-68} \text{ fb}$$

7 TeV: 1.0 fb^{-1}
8 TeV: 2.0 fb^{-1}

Top anti-top differential cross-sections

From experiment…

Jets

b-jets

Leptons

E_T^{missing}

... to theory...

QED bremsstrahlung

Hadronisation

Parton Showering

FSR: Final State Radiation

Hard scatter

PDF: Parton Distribution Function

Multiple Parton Interaction Underlying Event

ISR: Initial State Radiation
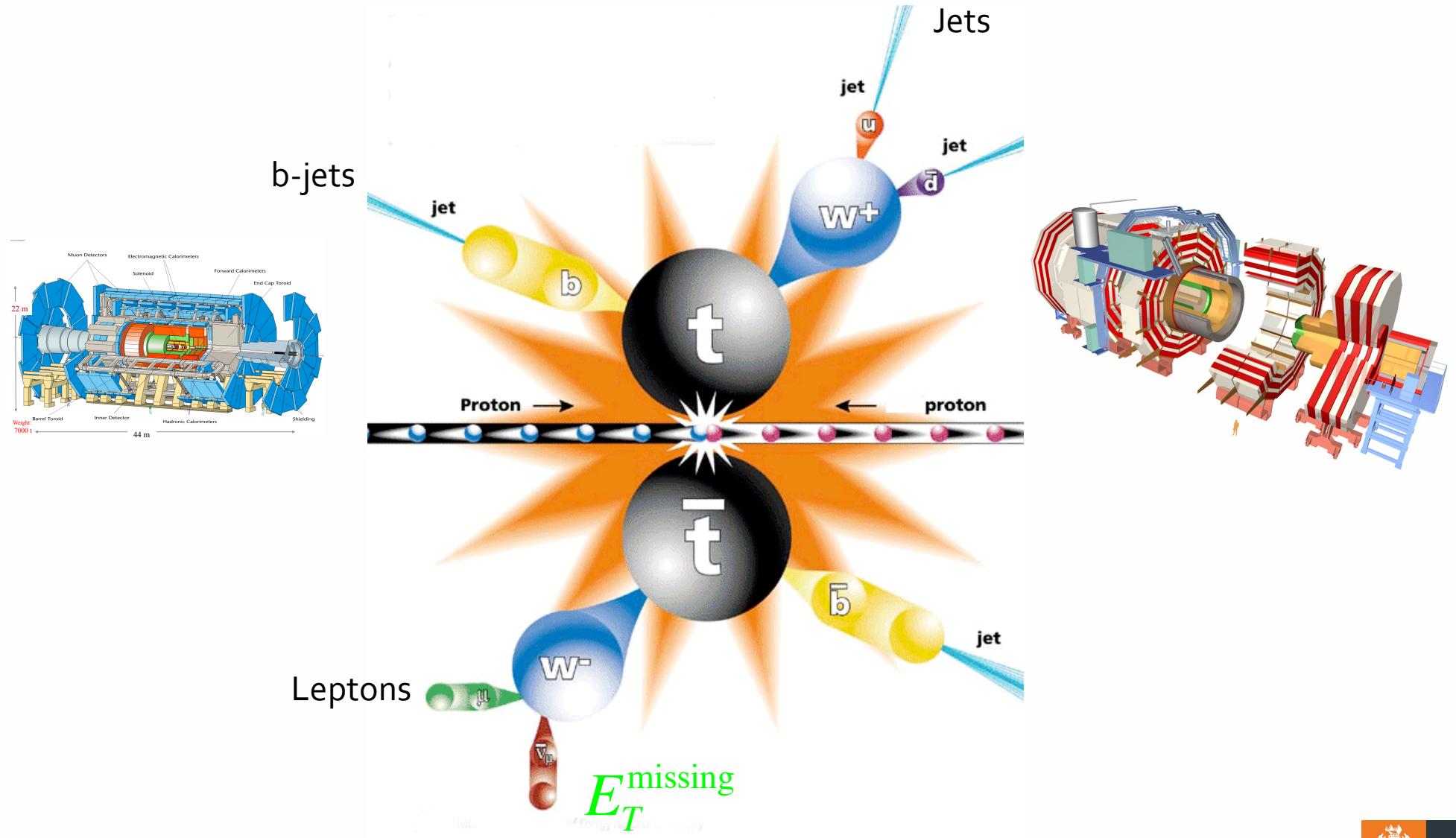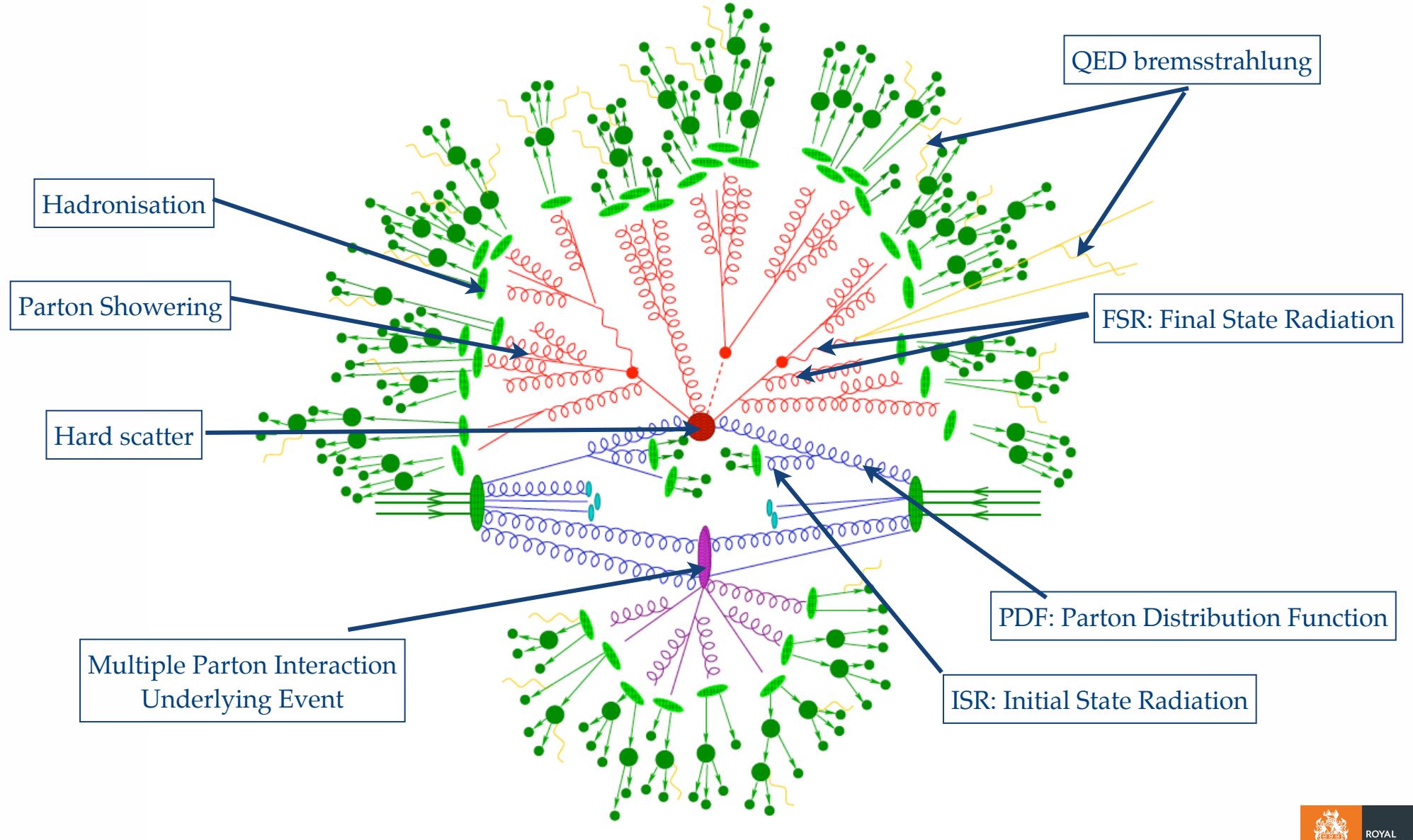
... connecting the two:

detector to parton unfolding

Theory

parton-level
full phase space

Experiment

detector-level
fiducial phase space

parton to particle

detector to particle unfolding

Monte Carlo

particle-level
HepData

Theorists can use data with
new models
Ensures longevity of results

Fiducial measurements reduce
uncertainties due to extrapolations
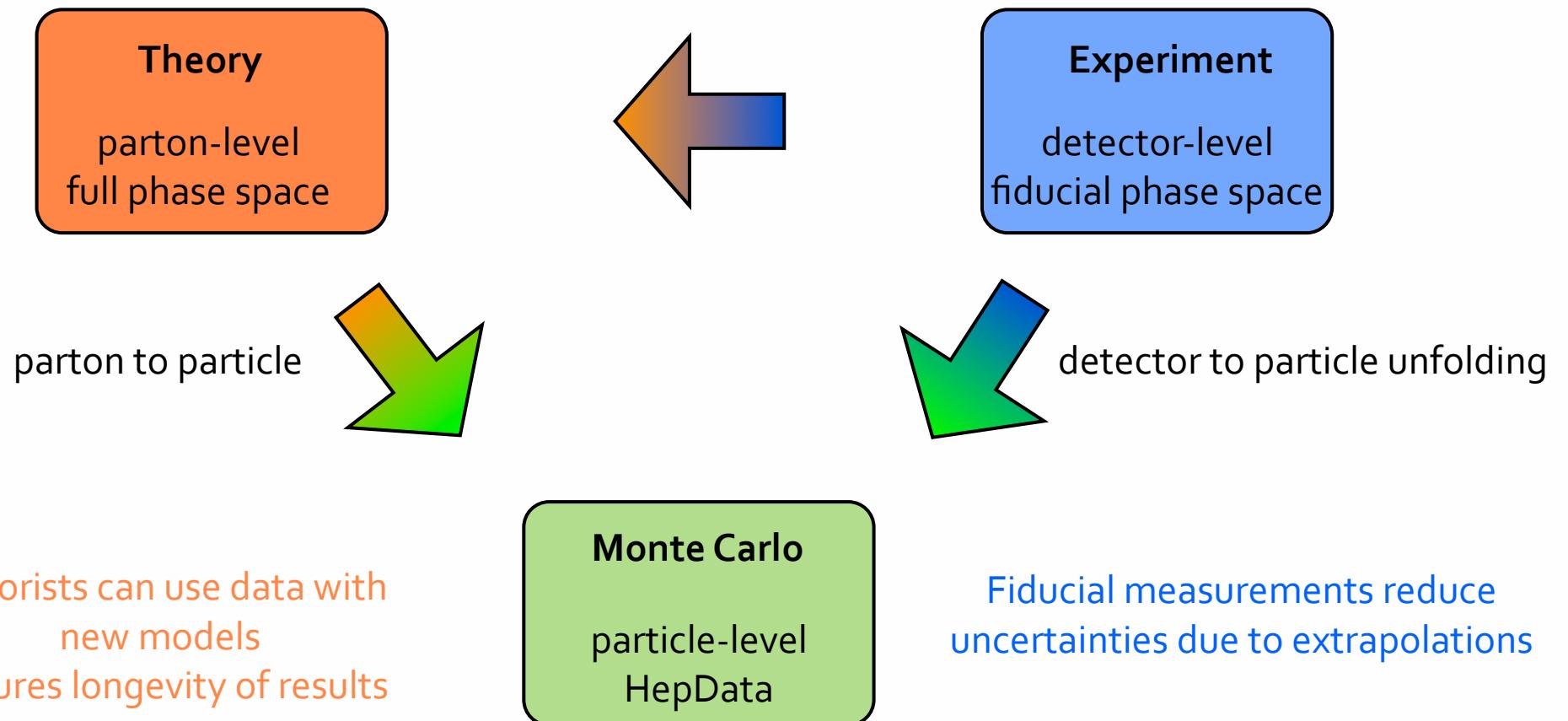
Particle-level objects

ATLAS and CMS differ in detailed definitions

Charged leptons (not from hadrons) are dressed with the energy from nearby photons
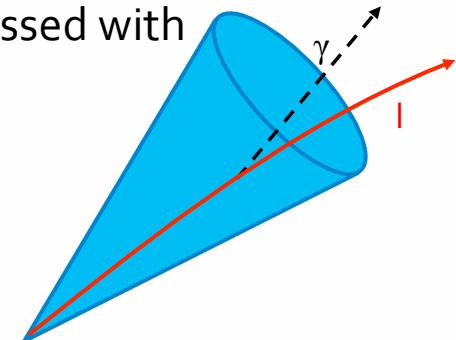
Jets are clustered from stable MC particles using anti-kt algorithm
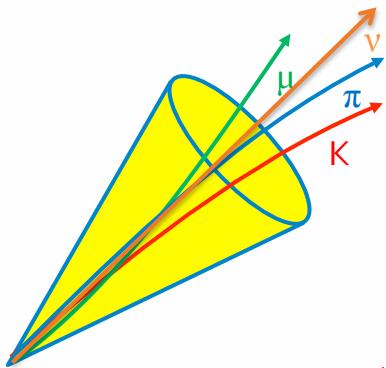
ETMiss calculated from the sum of all other neutrinos
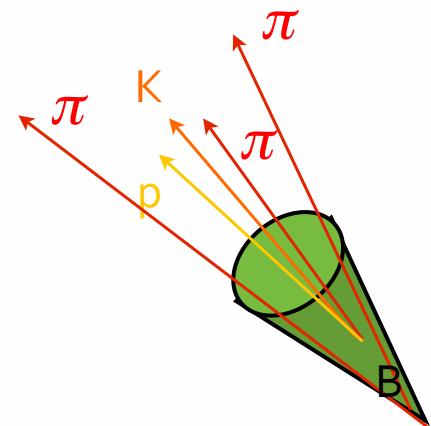
b-jets defined by a jet containing a b-quark hadron

Differential tt cross section at 8 TeV

ATLAS

TOPQ-2015-06

lepton+jets

lep p_T > 25GeV

≥ 4 jets p_T > 25GeV

≥ 2 b-jets

main backgrounds: tW single top and W+jets

Pseudo-top reconstruction
Fiducial particle-level results
and Parton full phase space results
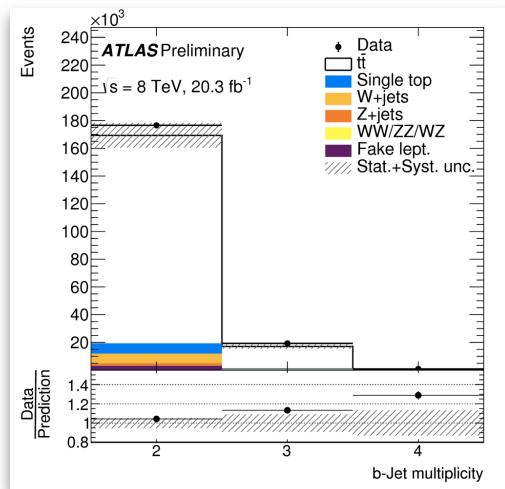
CMS

1505.04480

lepton+jets and (dilepton)

1 (2)lep p_T > 33 GeV

≥ 4 (2) jets p_T > 30GeV

≥ 2 (1) b-jets

main backgrounds: other tt and single top

Performant kinematic fitting
Fiducial results for detector-level variables
parton full phase space results for nominal variables
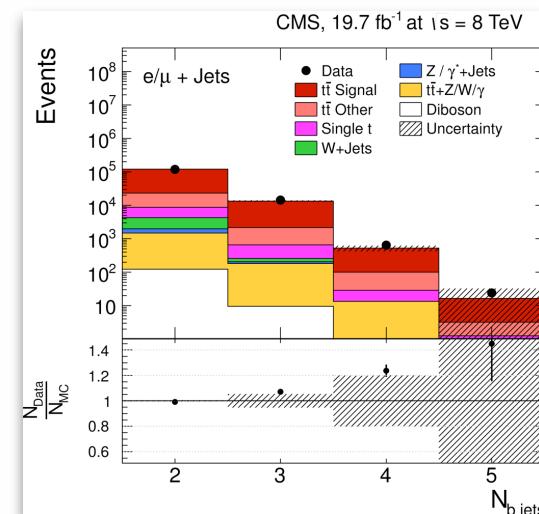
Differential tt cross section at 8 TeV

- same binning between ATLAS and CMS for full phase space (to help with comparisons and discussions within LHC Top WG)
- top p_T simulations still show a harder spectrum than the data (Madgraph is worse for both ATLAS and CMS)
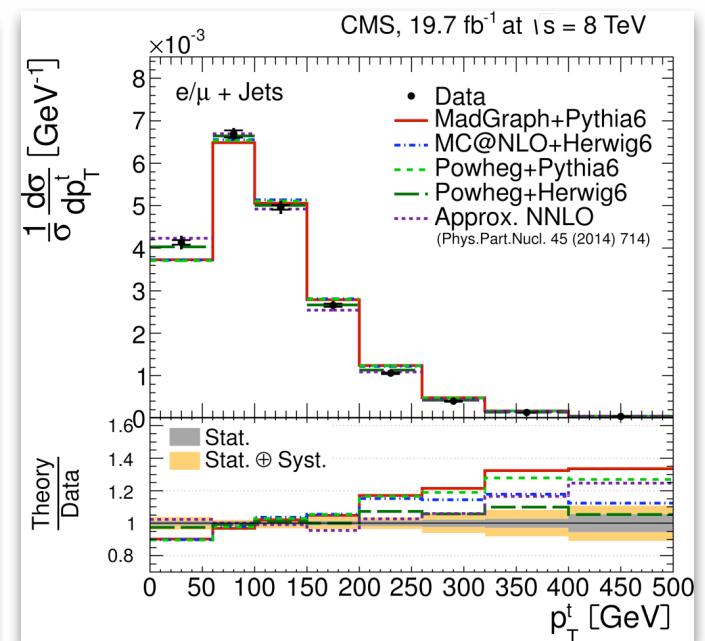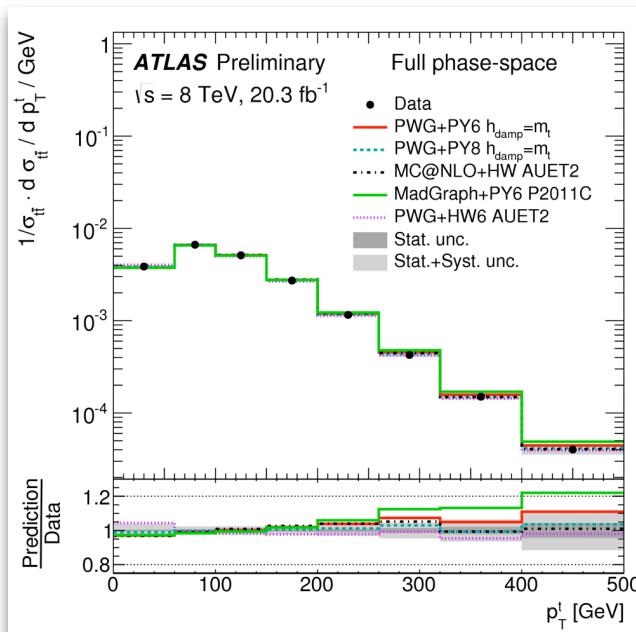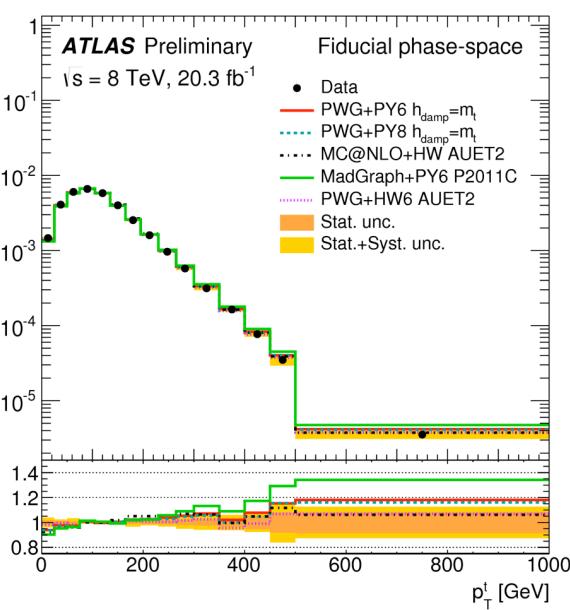
TOPQ-2015-06

1505.04480

variables: top: p_T, y
tt: p_T, y, m, $\Delta\Phi$
QCD-like (tt): p_{out}, y_{boost}, χ, H_T, R_{Wt}

variables: lepton and b: p_T, η
bb: p_T, m
top: p_T, y, p_T*, p_{T1}, p_{T2}
tt: pt, y, m, $\Delta\Phi$

Differential tt cross section at 8 TeV
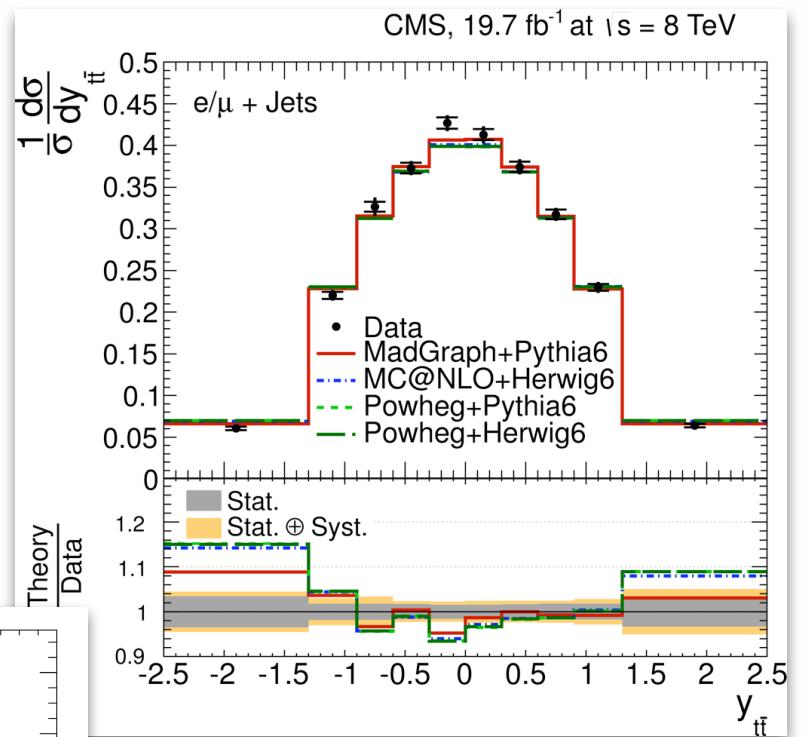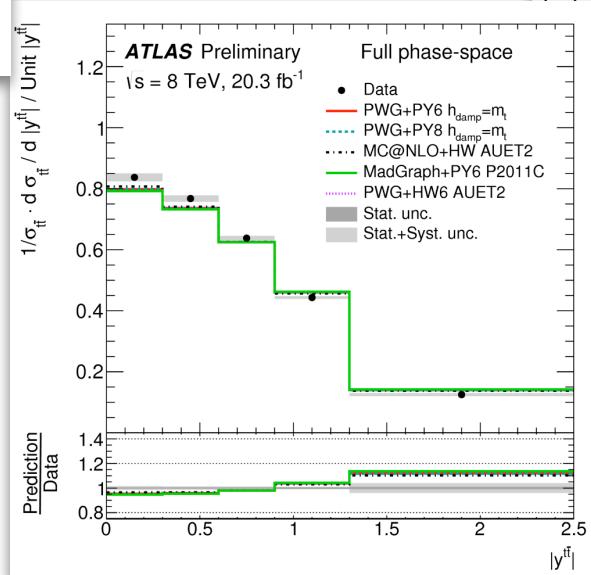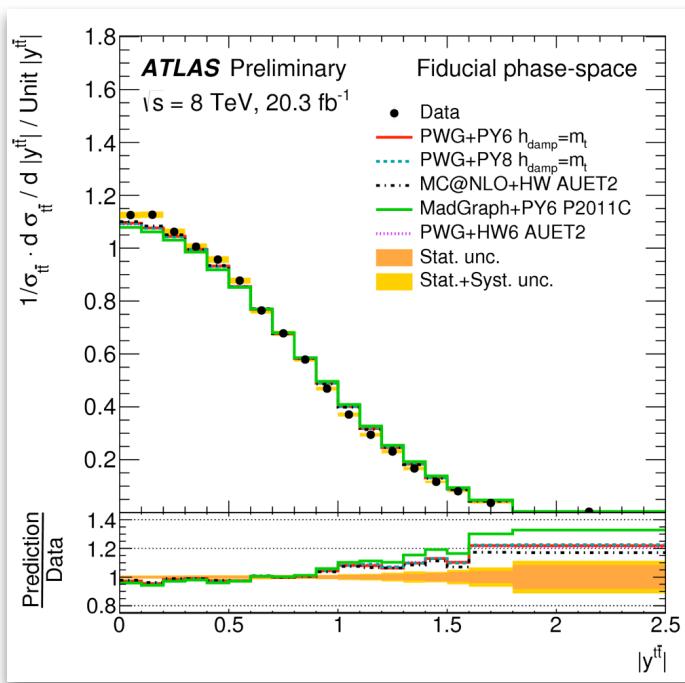
TOPQ-2015-06

1505.04480

Differential tt cross section at 8 TeV
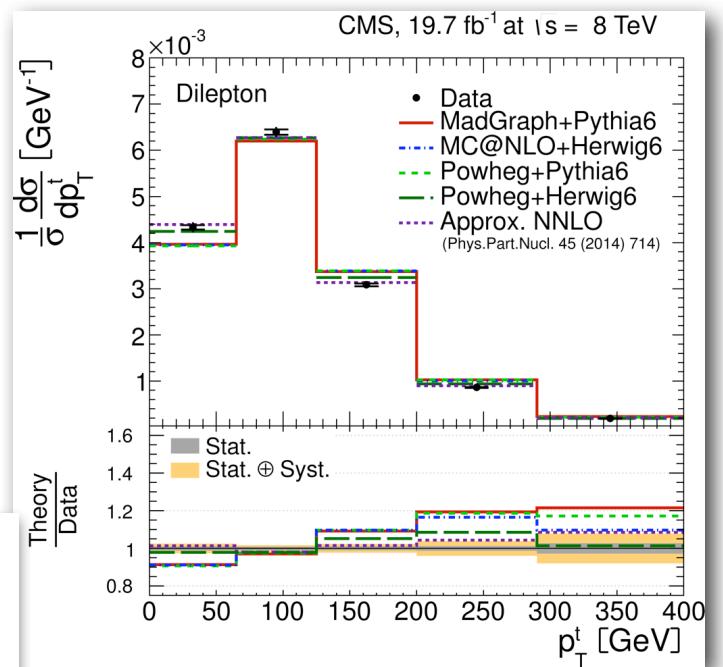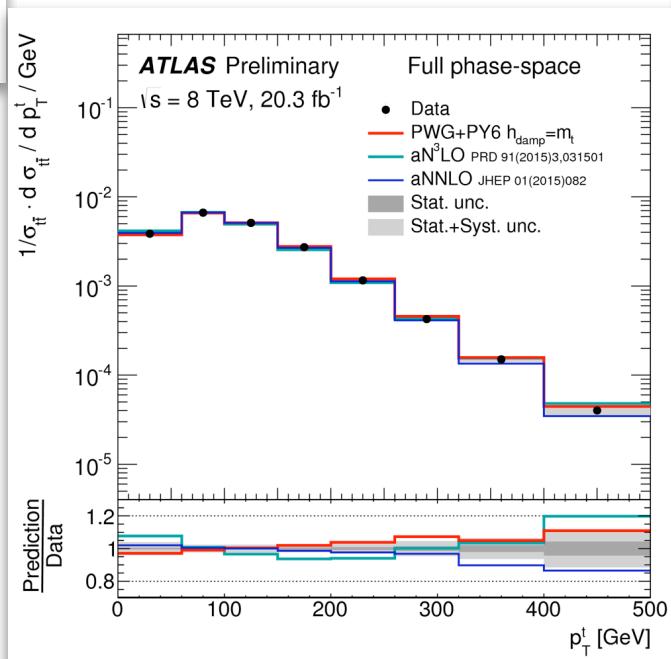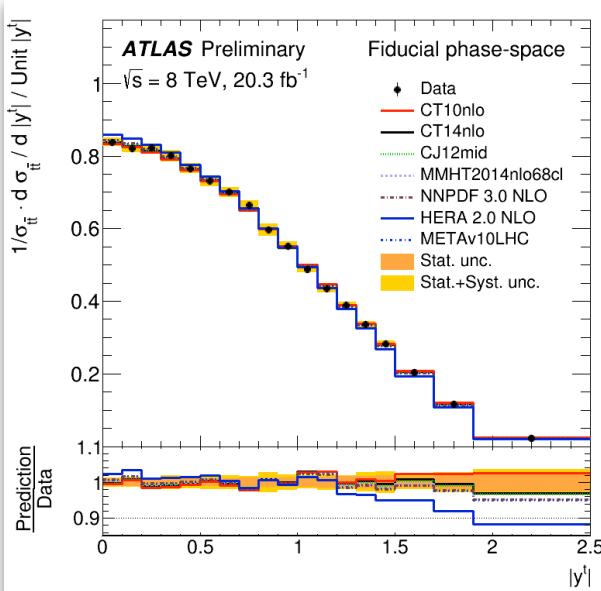
TOPQ-2015-06

1505.04480

Differential tt cross section at 13 TeV

- Similar object selection as 13 TeV inclusive analysis and same top reconstruction and unfolding method as 8 TeV analysis
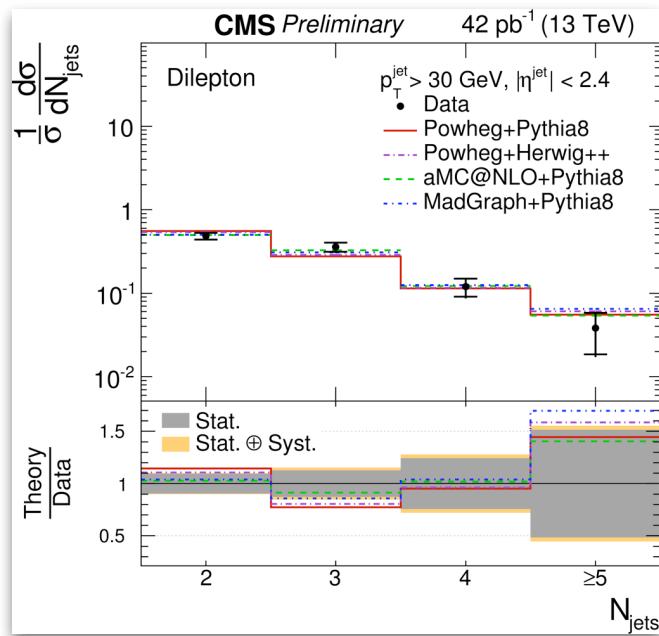
particle level fiducial phase space
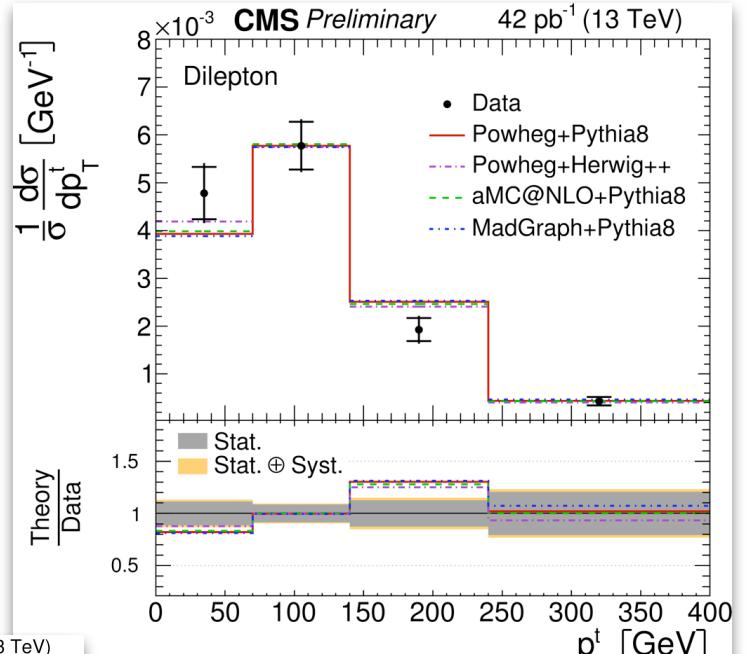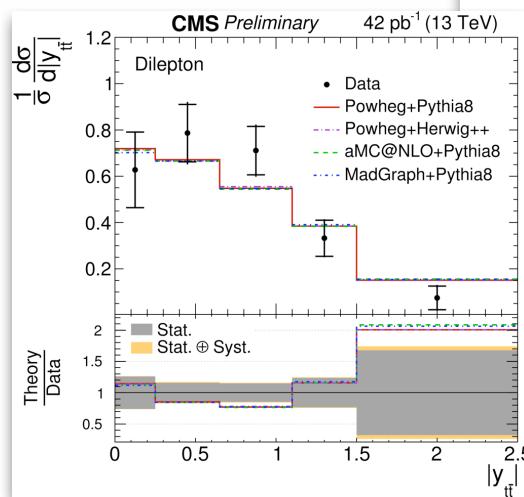
variables: Njets
top: p_T, y
tt: p_T, y, m

Differential tt cross section at 13 TeV
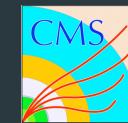
- lepton+jets selection
- top reconstruction using highest likelihood permutation: 49% correct
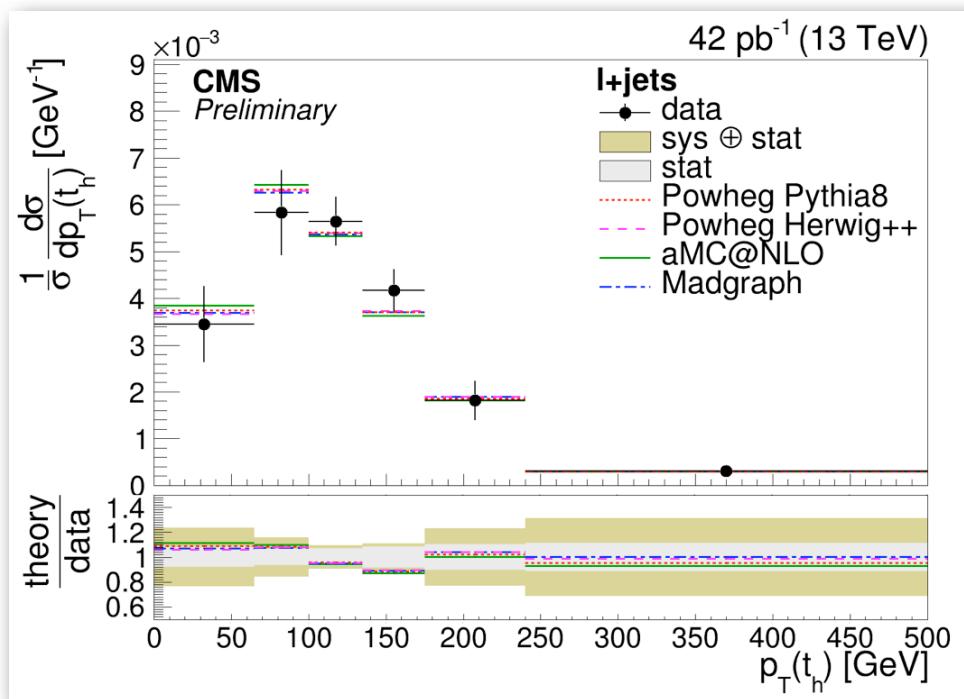
variables: Njets
top: $p_T(l,h)$, $y(l,h)$
tt: p_T, y, m
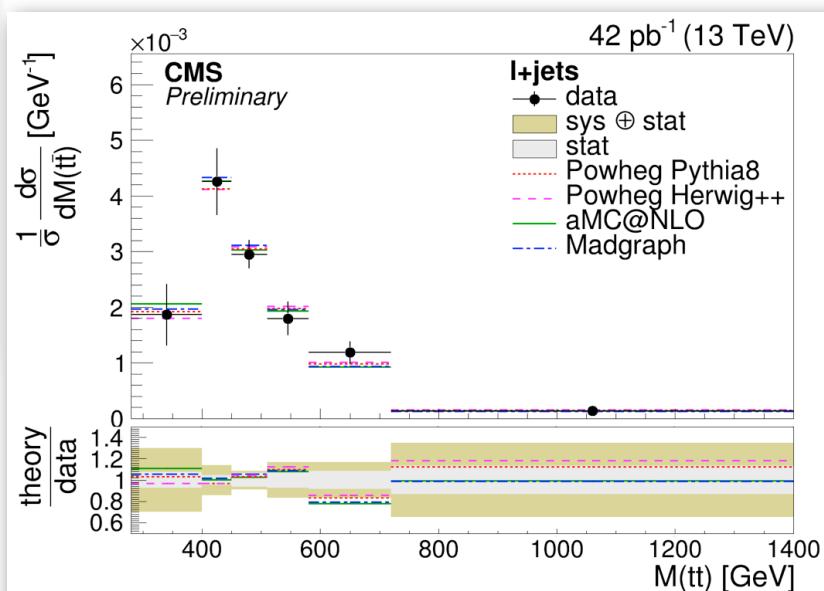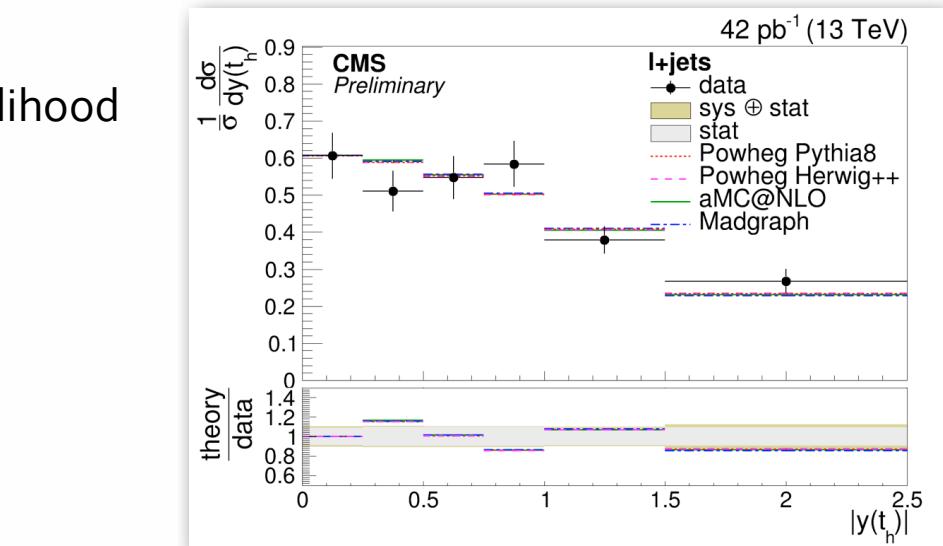
Boosted tops at 13 TeV!

A boosted top quark has high p_T (~>400 GeV) and its decay products are collimated into a large R~1.0 jet
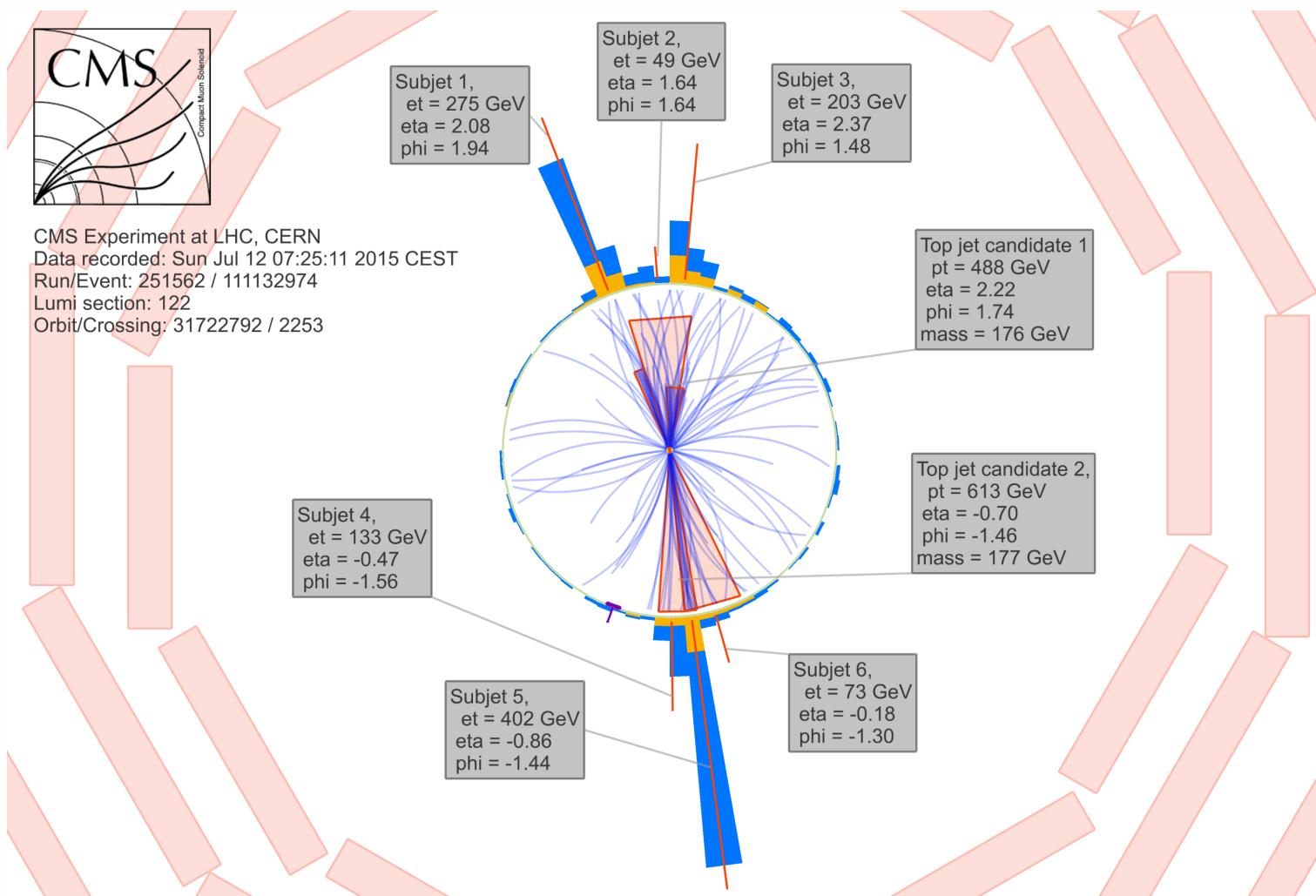
tt differential cross section using boosted tops at 8 TeV

ATLAS

TOPQ-2014-15

lepton+jets

lep p_T > 25GeV

≥ 1 anti-kt R=0.4 jet p_T > 25GeV

(same hem. as lepton)

anti-kt R=1.0, trimmed, m>100GeV

hadronic top p_T > 300 GeV

main backgrounds: tt dil, W+jets, single top

Fiducial particle-level results
and Parton full phase space results
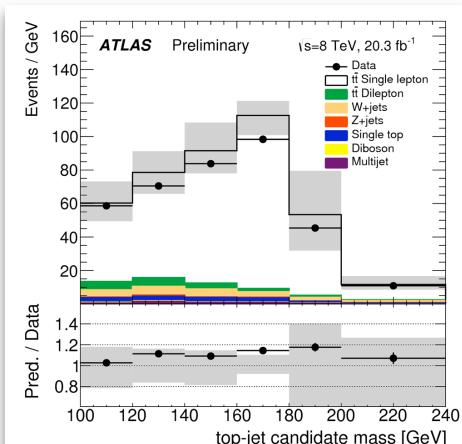
CMS

CMS PAS TOP-14-012

lepton+jets

e (mu) p_T > 45(35) GeV and |eta|<2.1 (2.5)

≥ 1 anti-kt R=0.5 jet p_T > 30GeV

(same hem as lepton)

Cambridge-Aachen R=0.8, TopTagged

hadronic top p_T > 400 GeV

main backgrounds: single top and W+jets

background enriched: 0t, 1t+0b, signal: 1t+1b
Fiducial particle-level and parton full phase space for top p_T
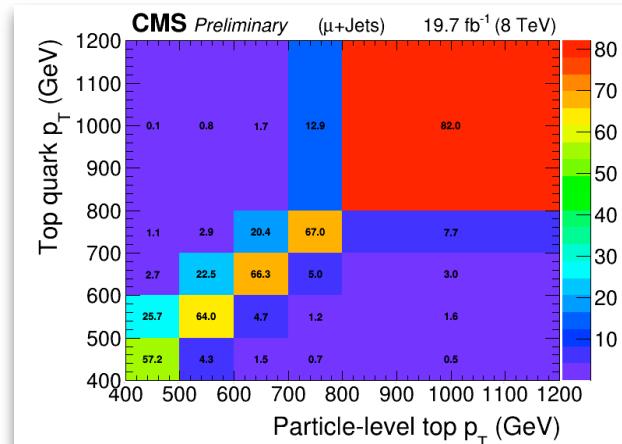
tt differential cross section using boosted tops at 8 TeV

TOPQ-2014-15

CMS PAS TOP-14-012
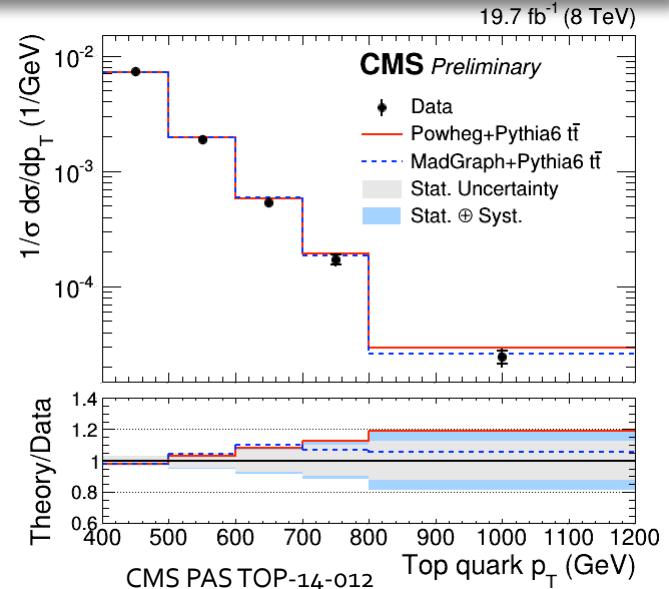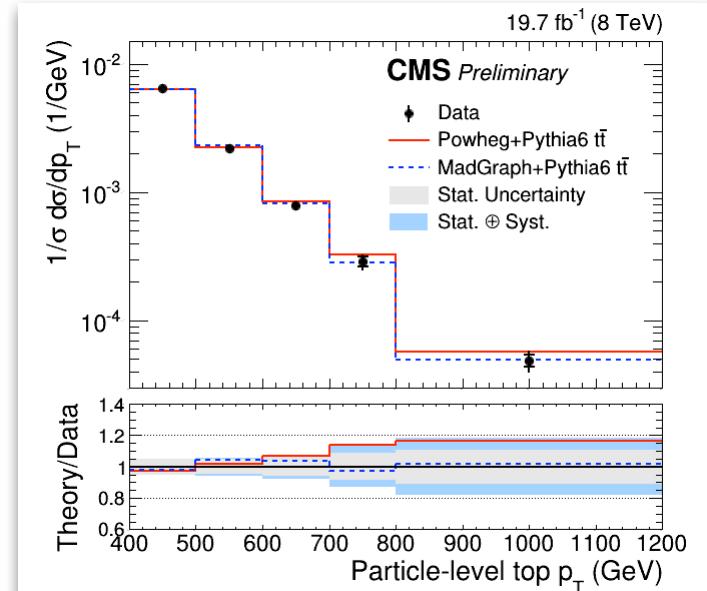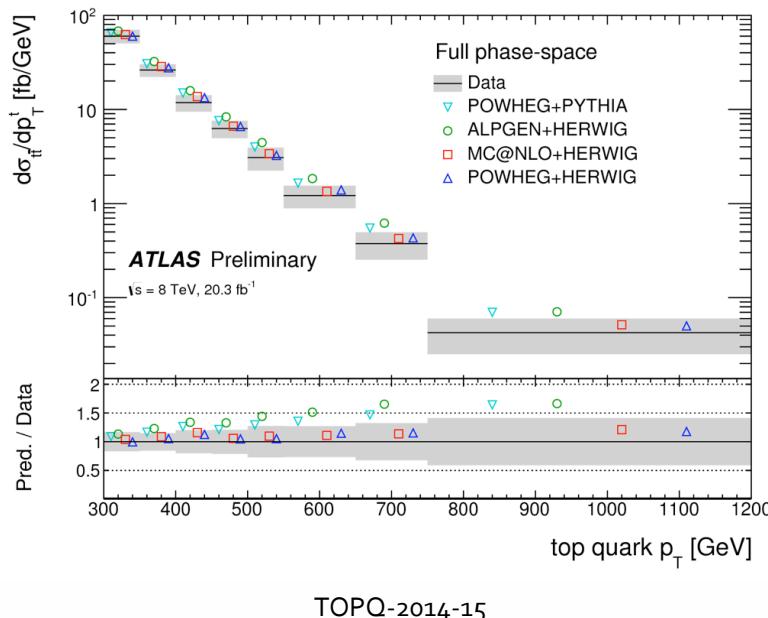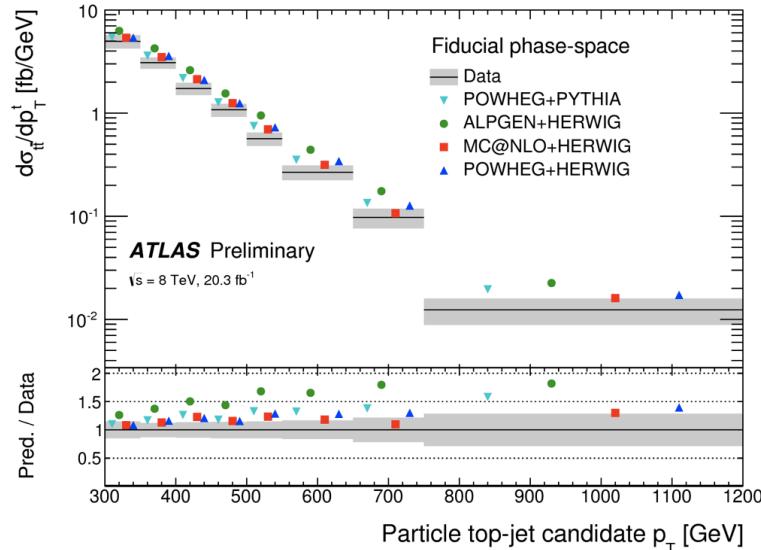
tt differential cross section using boosted tops at 8 TeV
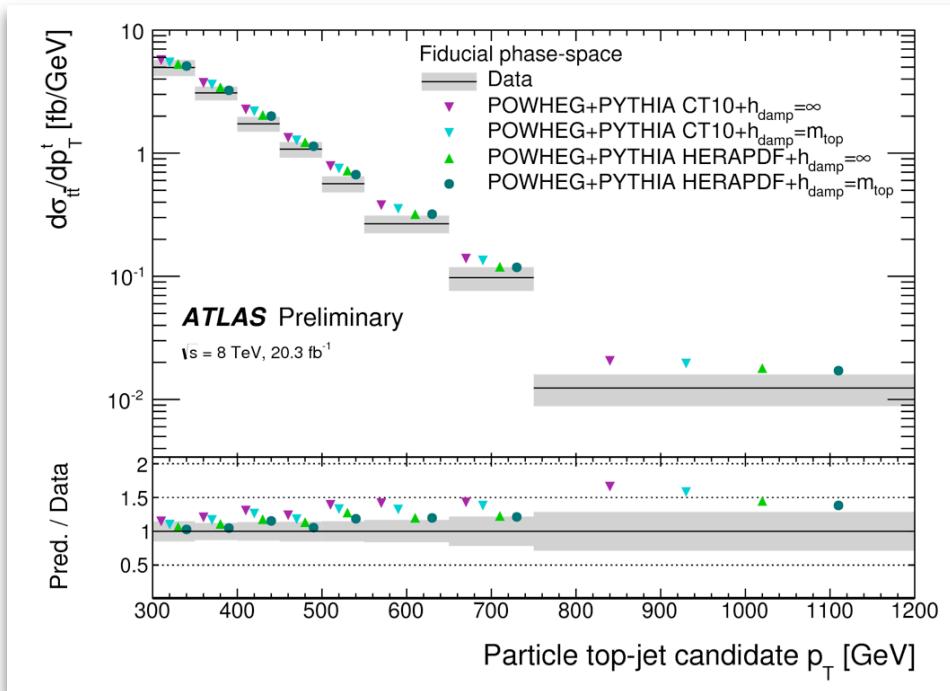
TOPQ-2014-15

Particle level

$\sigma(p_T^{top} > 400 \text{ GeV}) = 1.28 \pm 0.09 \text{ (stat.+syst.)} \pm 0.10 \text{ (PDF)} \pm 0.09 \text{ (Q}^2\text{)} \pm 0.03 \text{ (lumi.) pb}$

POWHEG: 1.49 pb

Parton level

$\sigma(p_T^{top} > 400 \text{ GeV}) = 1.44 \pm 0.10 \text{ (stat.+syst.)} \pm 0.13 \text{ (PDF)} \pm 0.15 \text{ (Q}^2\text{)} \pm 0.04 \text{ (lumi.) pb}$

POWHEG: 1.67 pb

14% difference
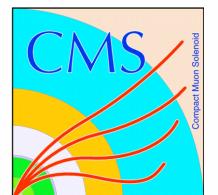
CMS PAS TOP-14-012

tt + bb cross sections

tt+b jets cross sections at 8 TeV

G. Bevilacqua and M. Worek, 1403.2046

- Additional b-jets can come from hard scatter (tt + N partons from the NLO generator) or from parton shower (Pythia, Herwig)

- Current such pQCD fixed-order calculations at NLO suffer from significant uncertainties from missing higher-order terms

- irreducible background to ttH(->bb)!

- Measurements are done using particle-level and fiducial phase space

tt+b jet(s) cross sections at 8 TeV

ATLAS EXPERIMENT
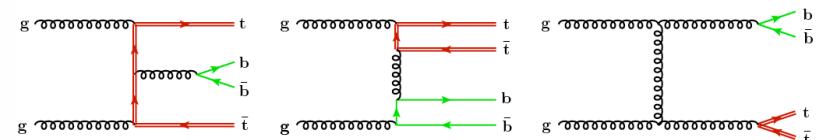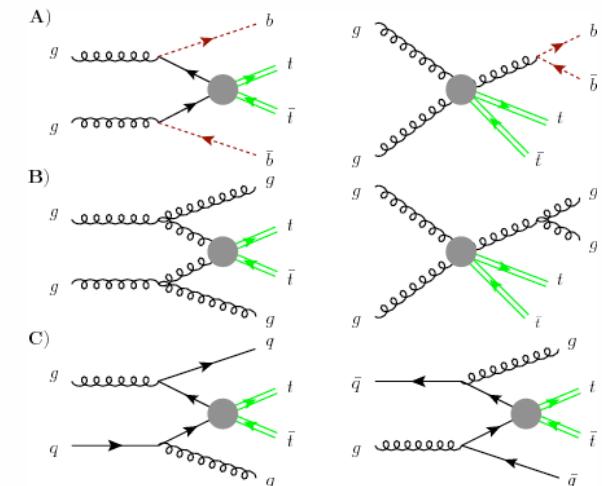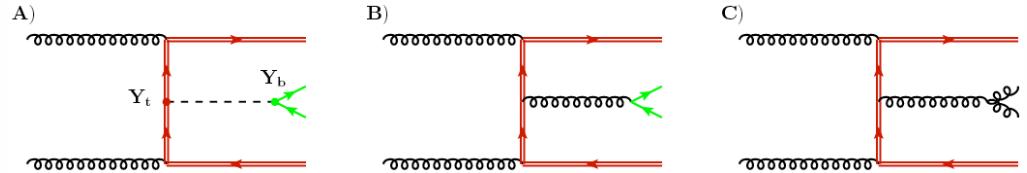
Physics

Measurement Strategy

lepton+jets and dilepton (eμ) tt+b

lepton p_T > 25 GeV

jets p_T > 20 GeV: ≥ 5 l+jets, ≥ 3 dil

≥ 3 b-jets

Profile likelihood template fit to b-tag MVA discriminant of the jet with the 3rd highest b-tag weight ↕
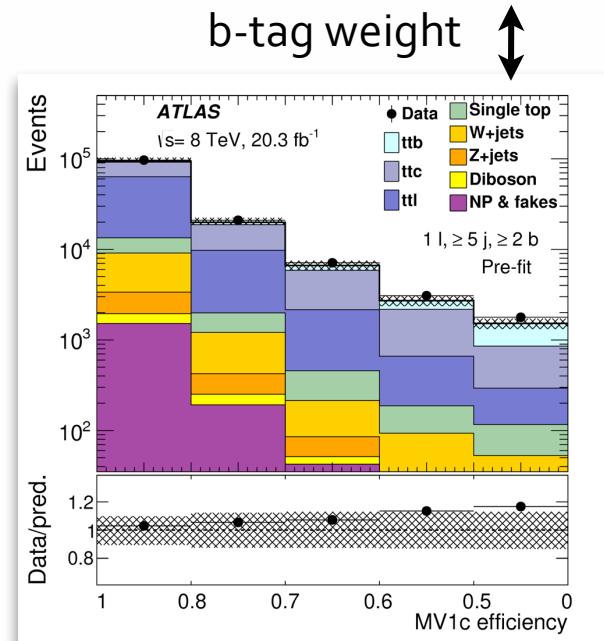
dilepton tt+bb (cut based)

2 leptons p_T > 25 GeV

jets p_T > 20 GeV: ≥ 4

≥ 4 b-jets

ttbb = 68% of selection ↔
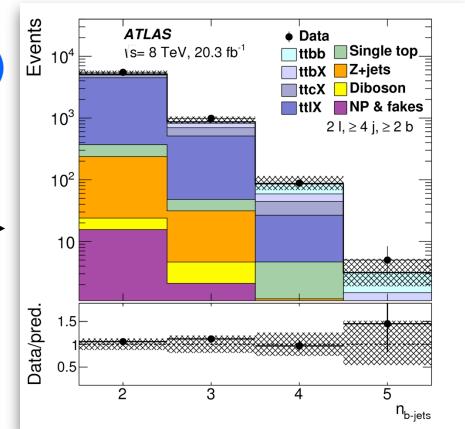
dilepton tt+bb (fit based)

2 leptons p_T > 25 GeV

jets p_T > 20 GeV: ≥ 4

≥ 2 b-jets

Template Fit for ttbb, ttbX, ttc, ttlX ↔

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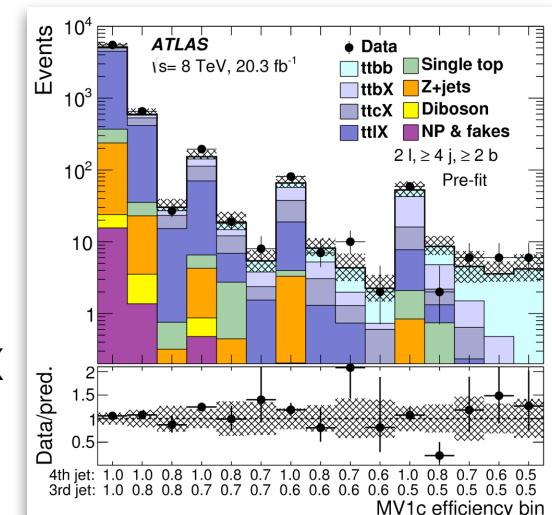
tt+b jet(s) cross sections at 8 TeV
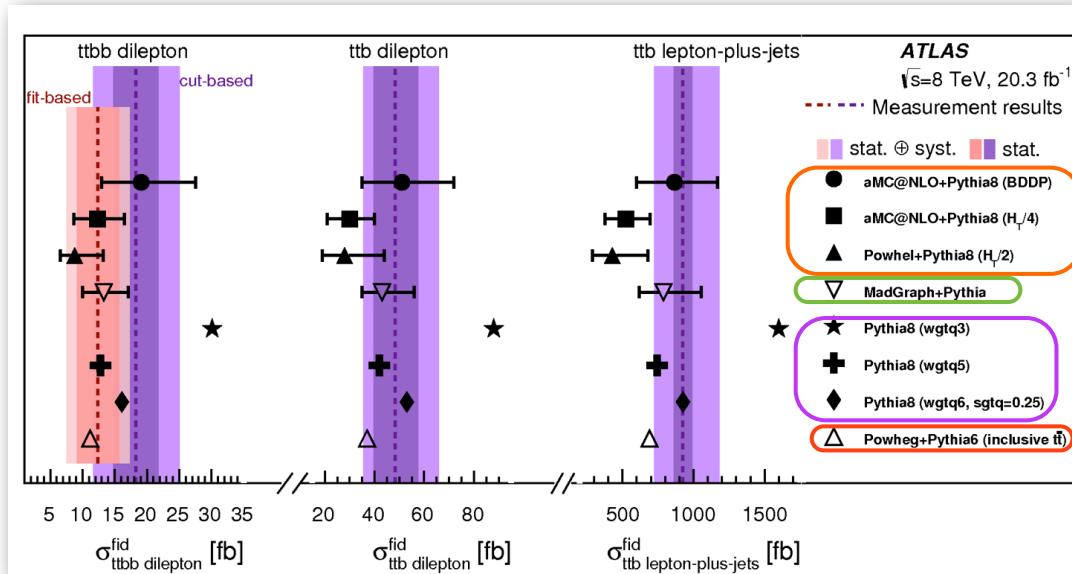
tt+bb@NLO

tt+bb@LO+PS

tt+bb from PS with different splittings

tt+b@NLO, tt+bb from PS

$$\sigma_{\text{fid, lepton+jets}} = 950 \pm 70 \text{ (stat.)} \, ^{+240}_{-190} \text{ (syst.) fb}$$

26%

$$\sigma_{\text{fid.}} = 720 \text{ fb}$$

PowhegBox+Py6
Helac(ttH)
MadGraph5(ttV)
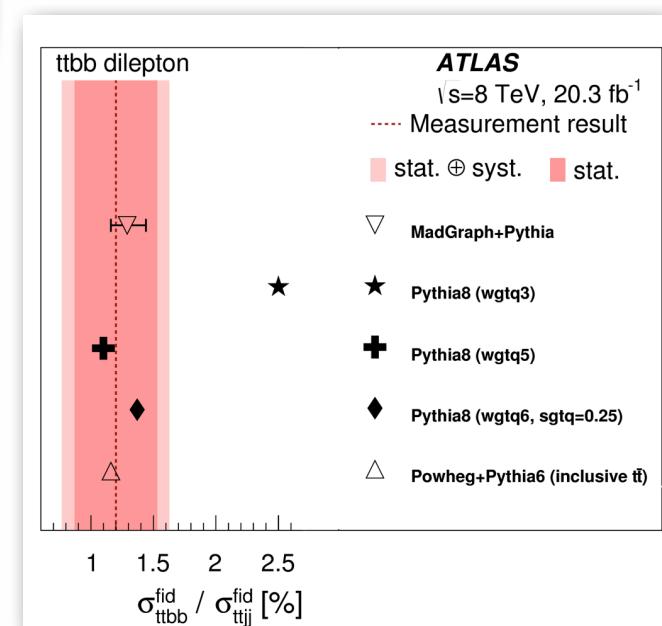
tt+b jet(s) cross sections at 8 TeV
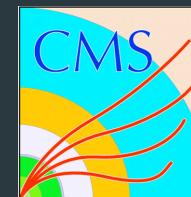
- lepton+jets:
  - lepton p_T > 30 GeV
  - ≥ 4 jets with p_T > 50 GeV
  - ≥ 2 b-jets (CSVM at 70%)

- Reconstruction of top pairs:
  - 1. kinematic fit
  - 2. separation of correct vs wrong combinations using BDTG
  - 3. use b-tag information
- correct assignment:
  - ttjj: 78% (N_j=4)
  - ttbb: 75% (N_j=4)

- Get cross section from 13 template fits for each number of jet category and lepton category

	$\sigma(ttbb)$	$\sigma(ttjj)$	$\sigma(ttbb)/\sigma(ttjj)$
fiducial	271 fb ± 40%	23.1 pb ± 16%	0.012 ± 34%
Madgraph+Pythia	174 fb ± 28%	24.3 pb ± 20%	0.007 ± 10%
NLO (1403.2046)	229 fb $^{+18\%}_{-24\%}$	21.0 pb $^{+15\%}_{-13\%}$	0.011 $^{+39\%}_{-13\%}$

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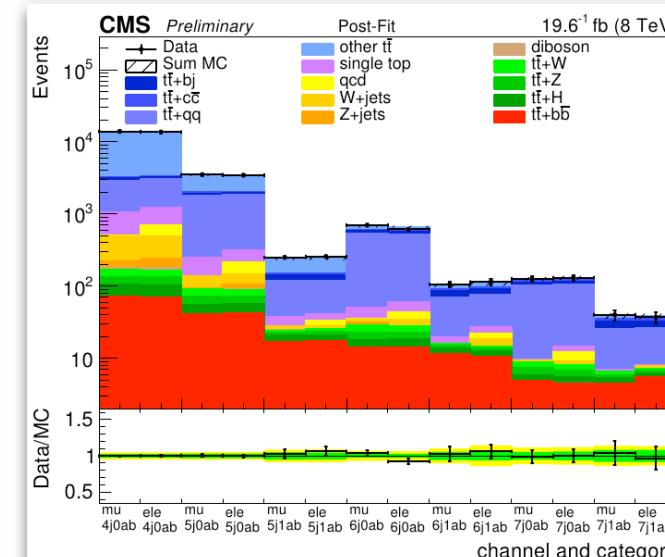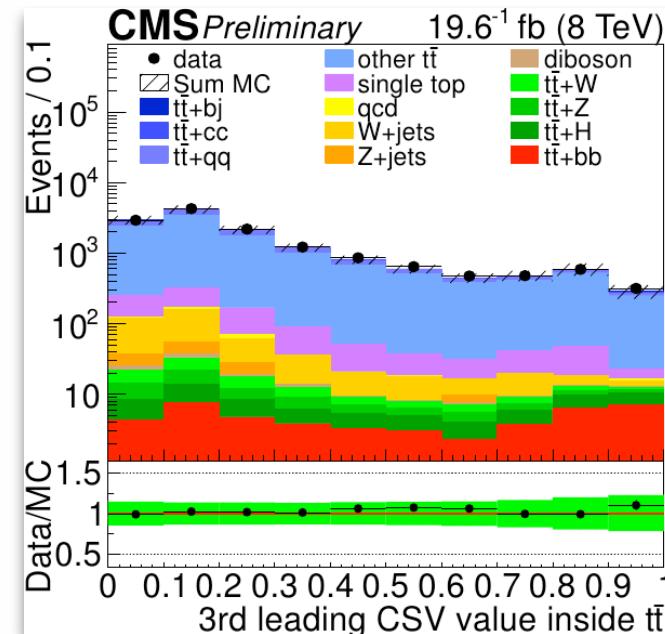
ttW, ttZ cross sections

ttW, ttZ cross sections at 8 TeV

- top-Z couplings never measured and modified from SM in extensions like Technicolour or scenarios with a strongly coupled Higgs sector

- ttZ, ttγ, ttH: direct couplings to bosons

- ttW: source of SS dilepton events: signatures of many BSM models

- ttZ and ttW: modified by additional dimension-six operators in the Lagrangian

- ttZ at 7 TeV by CMS: twice the SM value (large uncertainties)

- 2 OS leptons: ttZ (CMS), ttZ and ttW (ATLAS)
- 2 SS leptons: ttW
- 3 leptons: ttZ and ttW
- 4 leptons: ttZ
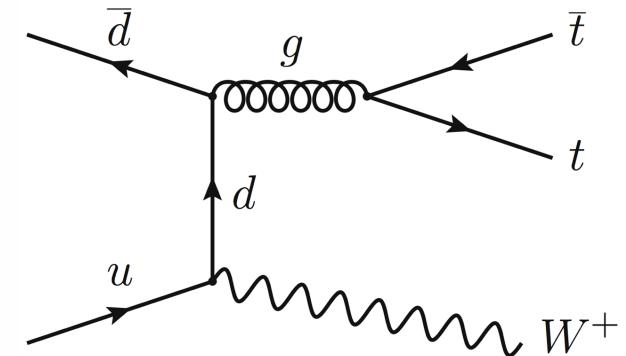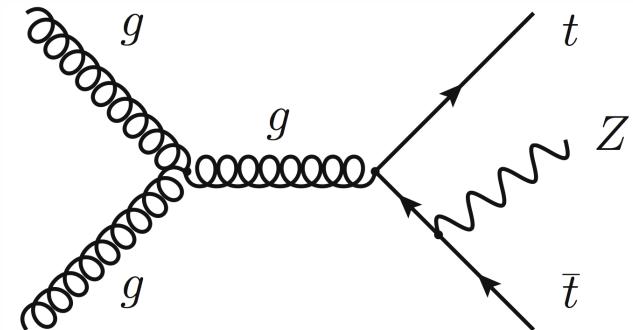
ttW, ttZ cross sections at 8 TeV

- 5 mutually exclusive signal channels: at least 1 lepton $p_T > 20$ GeV, additional leptons $p_T > 10$ GeV:
- In some channels: control regions for the backgrounds
- After selections: background dominated
- Use full reconstruction, and use linear discriminant to match the tt system
  - for tt L+J with 4 jets (from tt) correct assignment: 75%

- Match scores and other reconstructions variables into BDT
- Cross sections extracted from binned likelihood functions
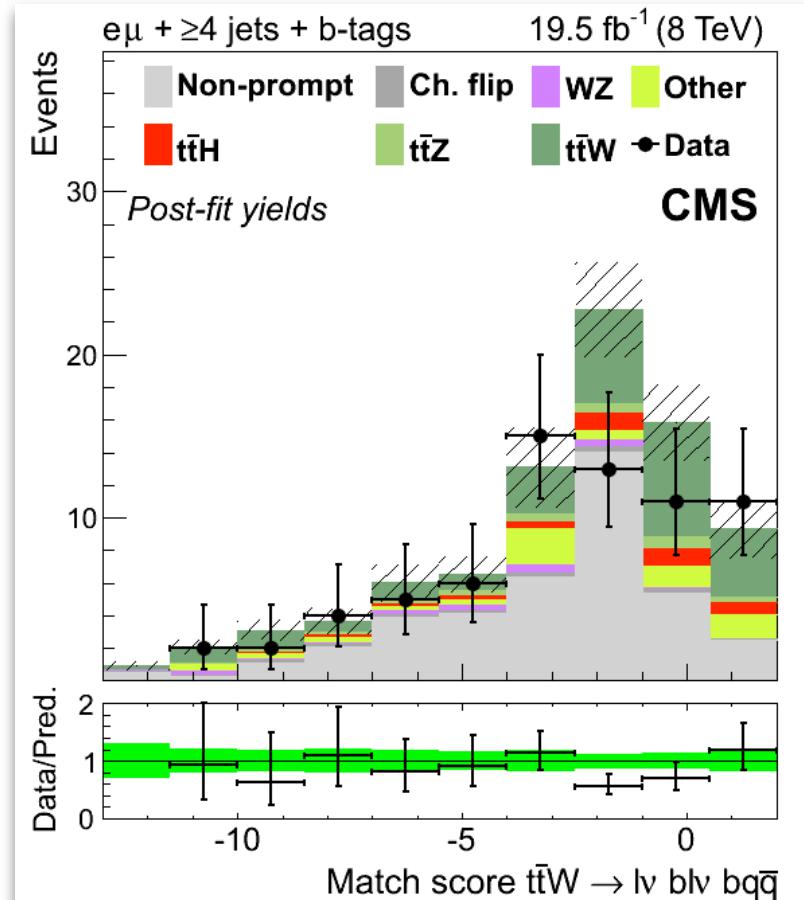
ttW, ttZ cross sections at 8 TeV
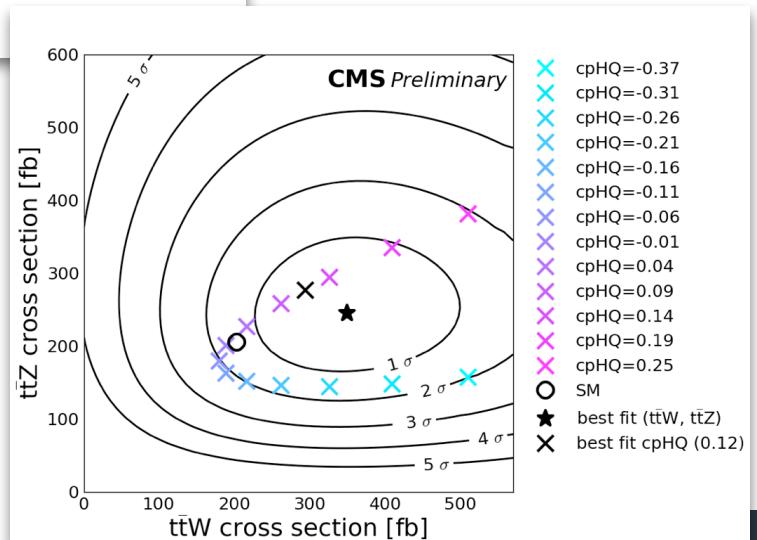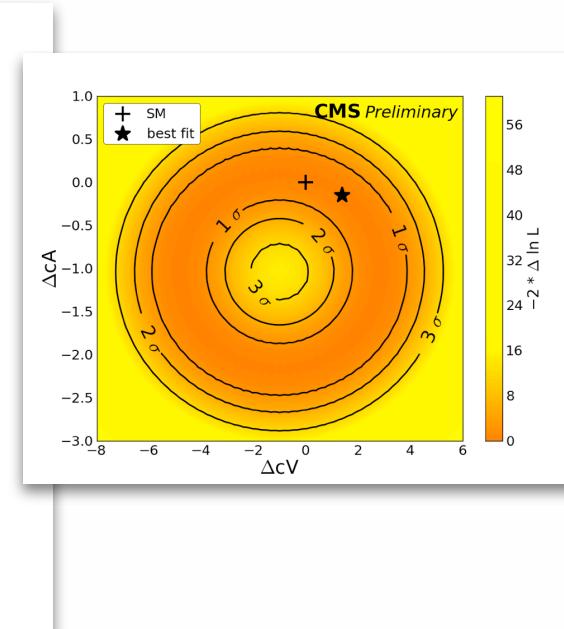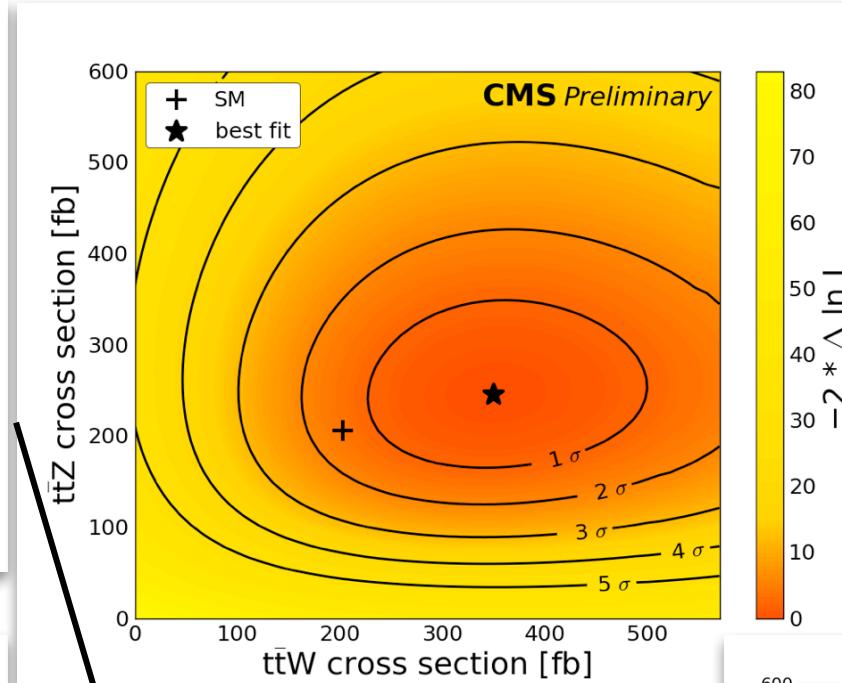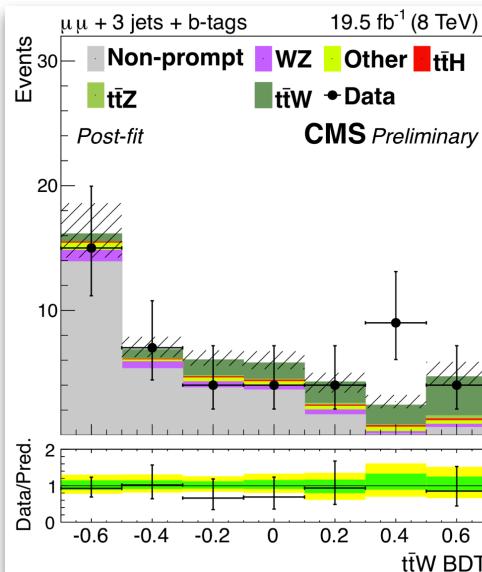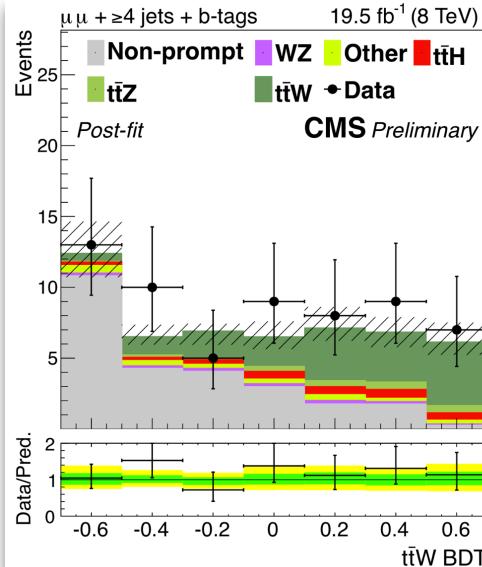
source of slight excess in ttW, consistent with CMS ttH excess (1408.1682)

ttW, ttZ cross sections at 8 TeV
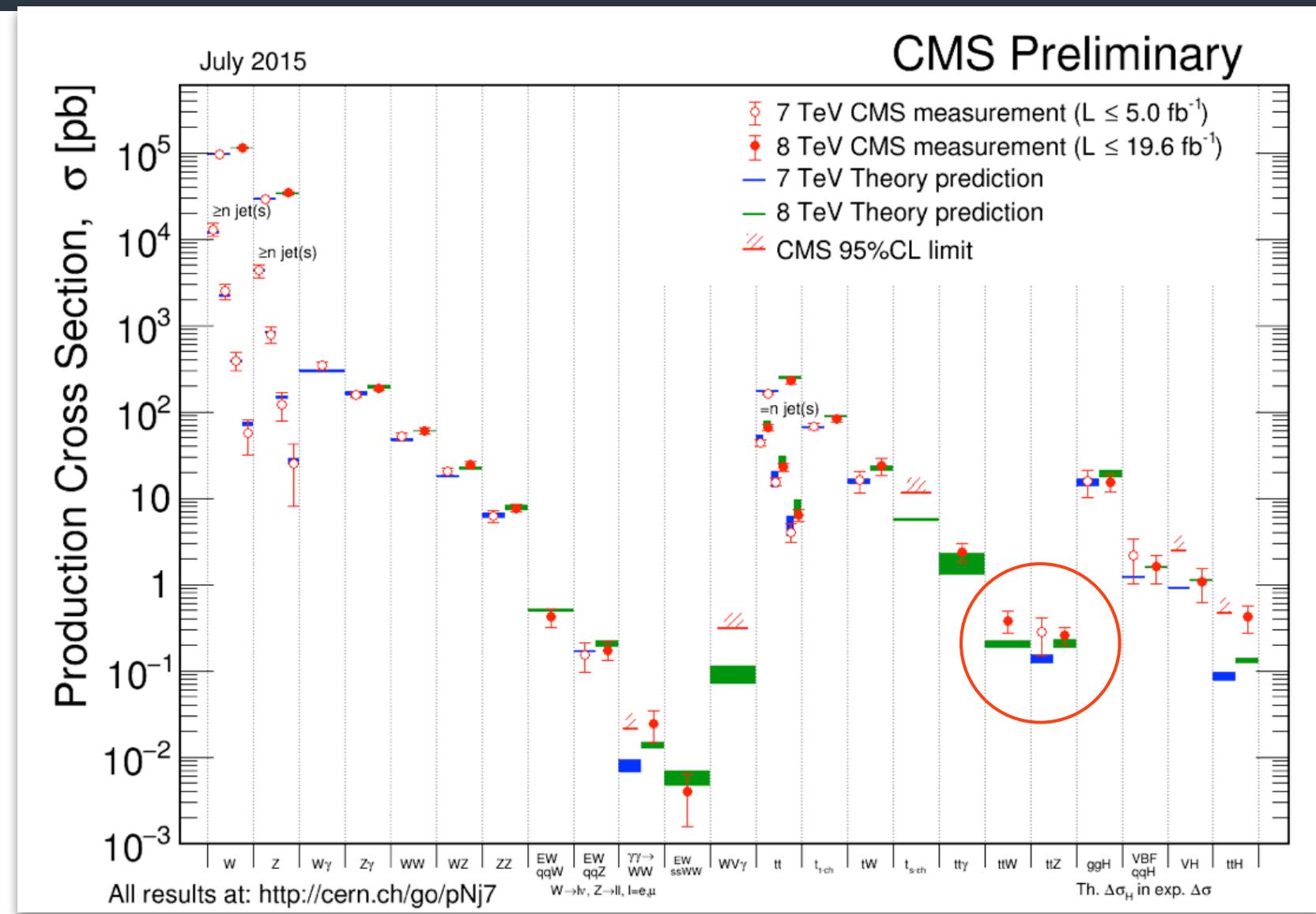
# ttW, ttZ cross sections at 8 TeV

- 15 signal regions and 5 control regions, at least 1 lepton p_T> 20 GeV, additional leptons p_T>15 or 7 GeV

- 2 OS leptons: NN used to separate ttW and ttZ
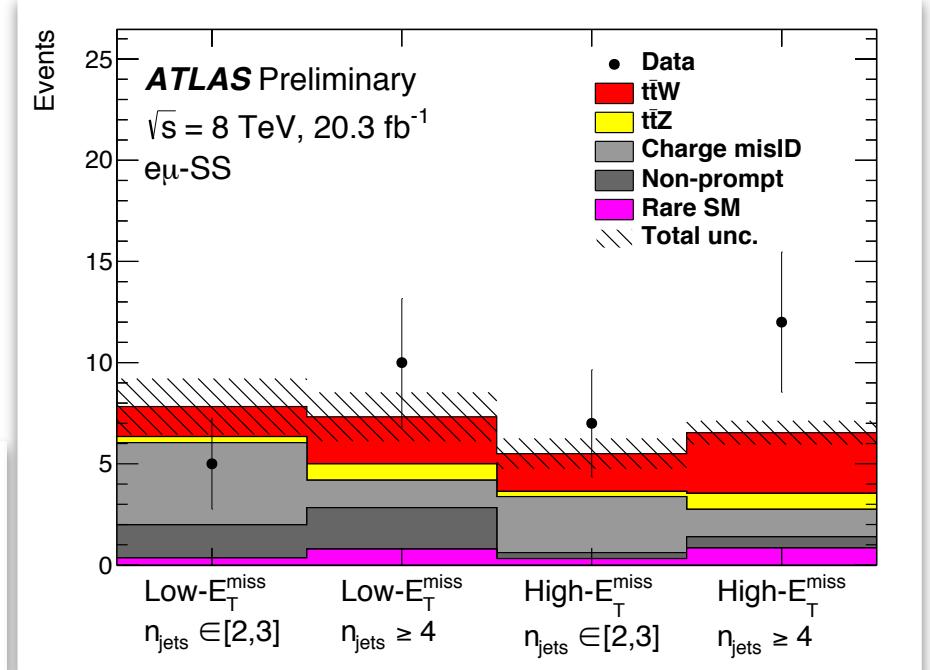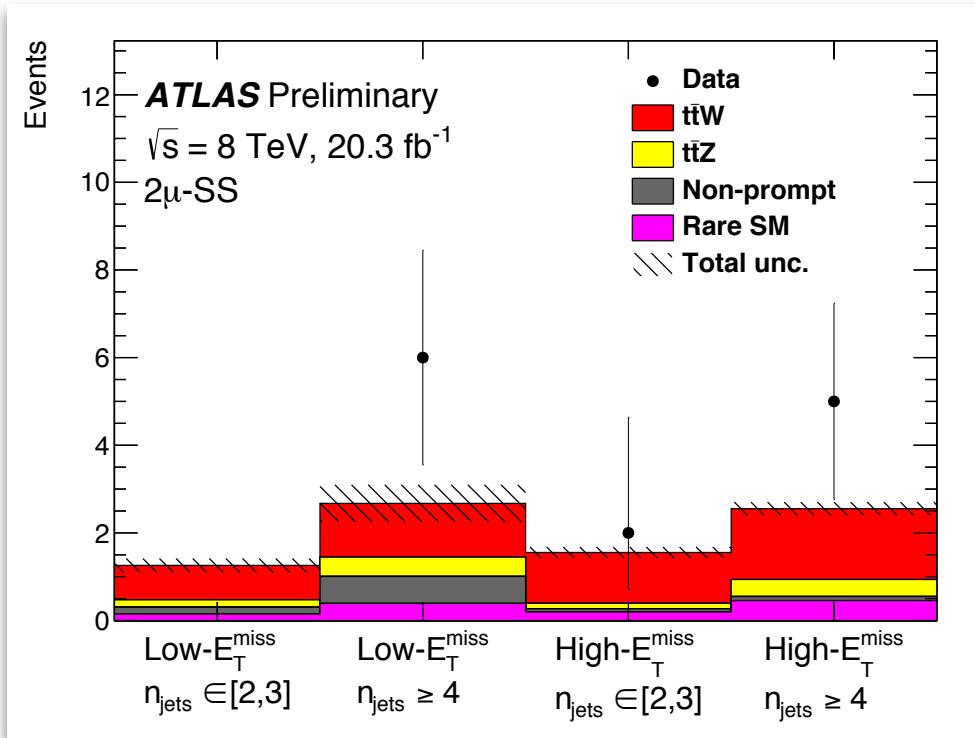
- Profile likelihood fit over all 20 bins simultaneously

ttW, ttZ cross sections at 8 TeV
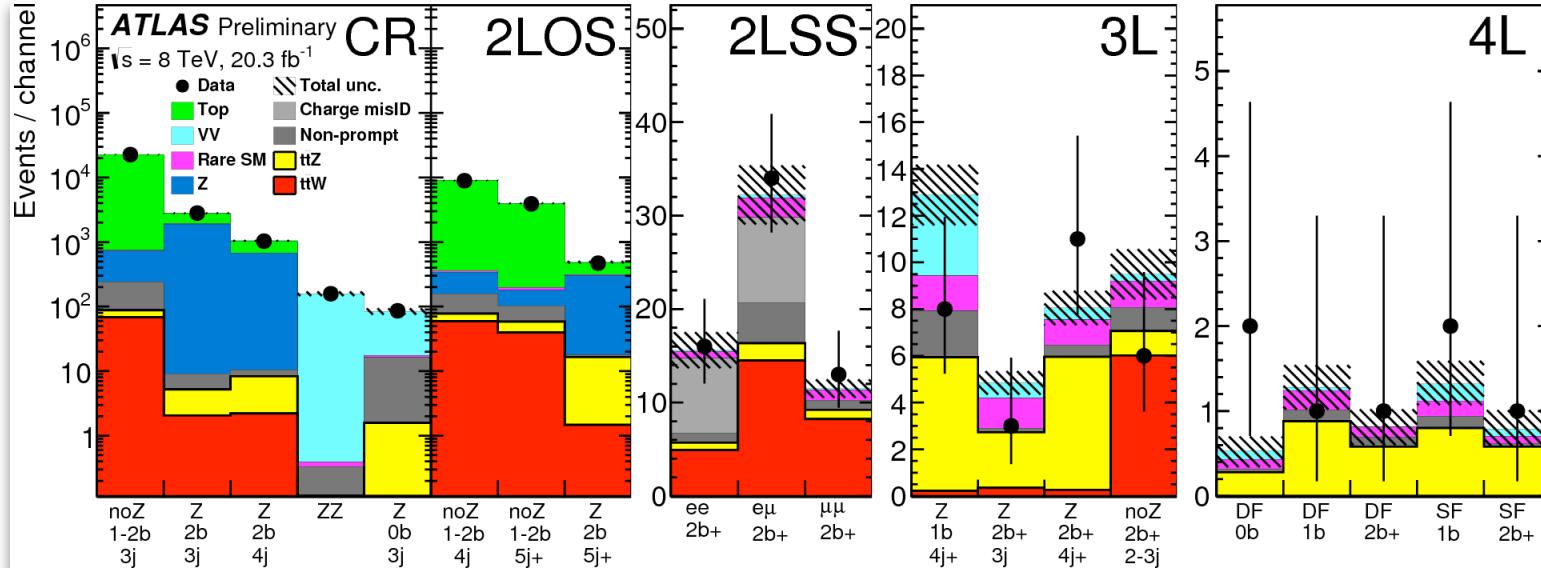
The observed (expected) significance of ttW is 5.0σ (3.2σ) and of ttZ is 4.2σ (4.5σ)
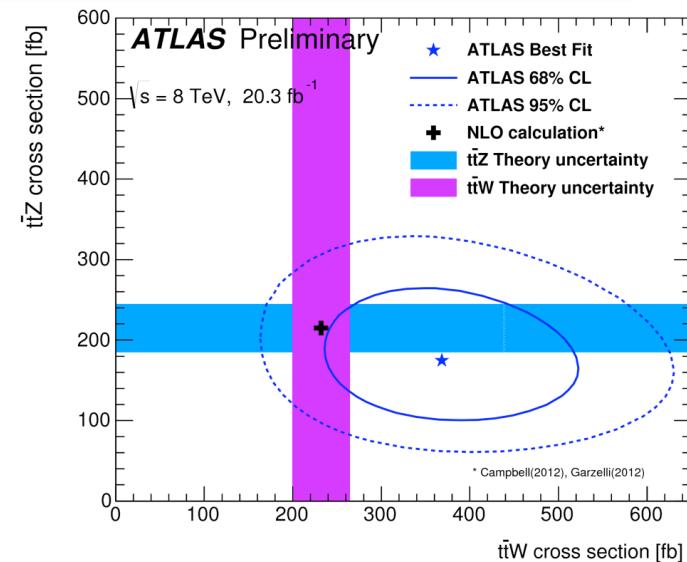
single top quark production

Single top production

1lep, 2j: 1b, 1forward jet
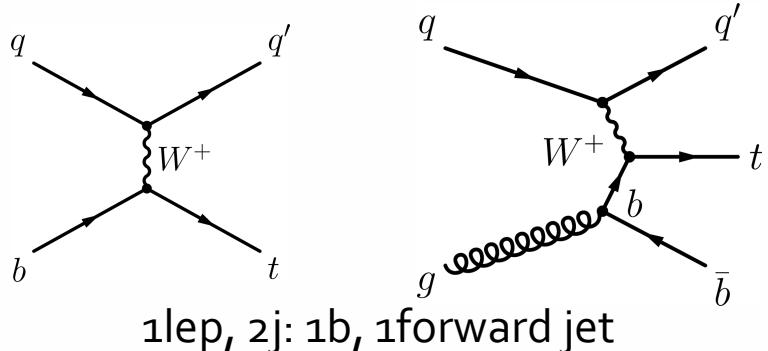
t-channel
FCNC
b quark PDF

1.96 TeV: 2.1 pb
8 TeV: 87.8 ± 3.4 pb   ~40

2lep, 1j: 1b
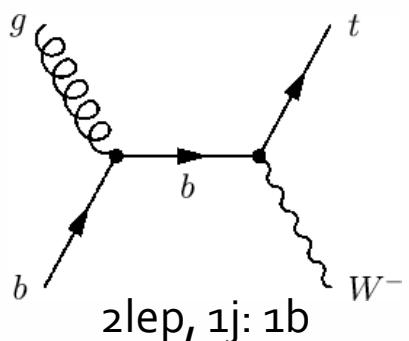
Wt channel | 1.96 TeV: 0.25 pb   ~100
8 TeV: 22.4 ± 1.5 pb
New resonances, anomalous couplings

1lep, 2j: 2b
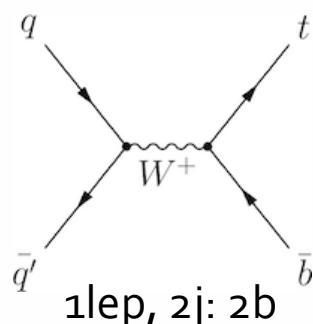
s-channel
New resonances

1.96 TeV: 1.1 pb   ~5
8 TeV: 5.6 ± 0.2 pb

Measurement of $|V_{tb}|$

Single top production at the Tevatron

Tevatron Run II Preliminary single top quark summary

Measurement — Cross section [pb]

s-channel:

CDF
PRL 112, 231805 (2014) — $1.36^{+0.37}_{-0.32}$

D0
PLB 726, 656 (2013) — $1.10^{+0.33}_{-0.31}$

Tevatron
PRL 112, 231803 (2014) — $1.29^{+0.26}_{-0.24}$ 20%, 6.3σ

t-channel:

CDF
CDF-CONF-11033 (2014) — $1.65^{+0.38}_{-0.36}$

D0
PLB 726, 656 (2013) — $3.07^{+0.54}_{-0.49}$

Tevatron — $2.25^{+0.29}_{-0.31}$ 14%

s+t:

CDF
CDF-CONF-11033 (2014) — $3.02^{+0.49}_{-0.48}$

D0
PLB 726, 656 (2013) — $4.11^{+0.60}_{-0.55}$

Tevatron — $3.30^{+0.52}_{-0.40}$

Cross section [pb]

Theory (NLO+NNLL)
PRD81 054028 (2010), PRD83 091503 (2011) $m_t = 172.5$ GeV

1503.05027

t-channel single top at 8 TeV

- One electron (muon) with p_T > 30 GeV (26 GeV)
- jet p_T > 40 GeV
- $E_T$miss > 45 GeV ($m_T(W)$ > 50 GeV)
- signal: 2j1t, W+jets: 2jot, tt: 3j2t

tW single top at 8 TeV

ATLAS EXPERIMENT

Physics
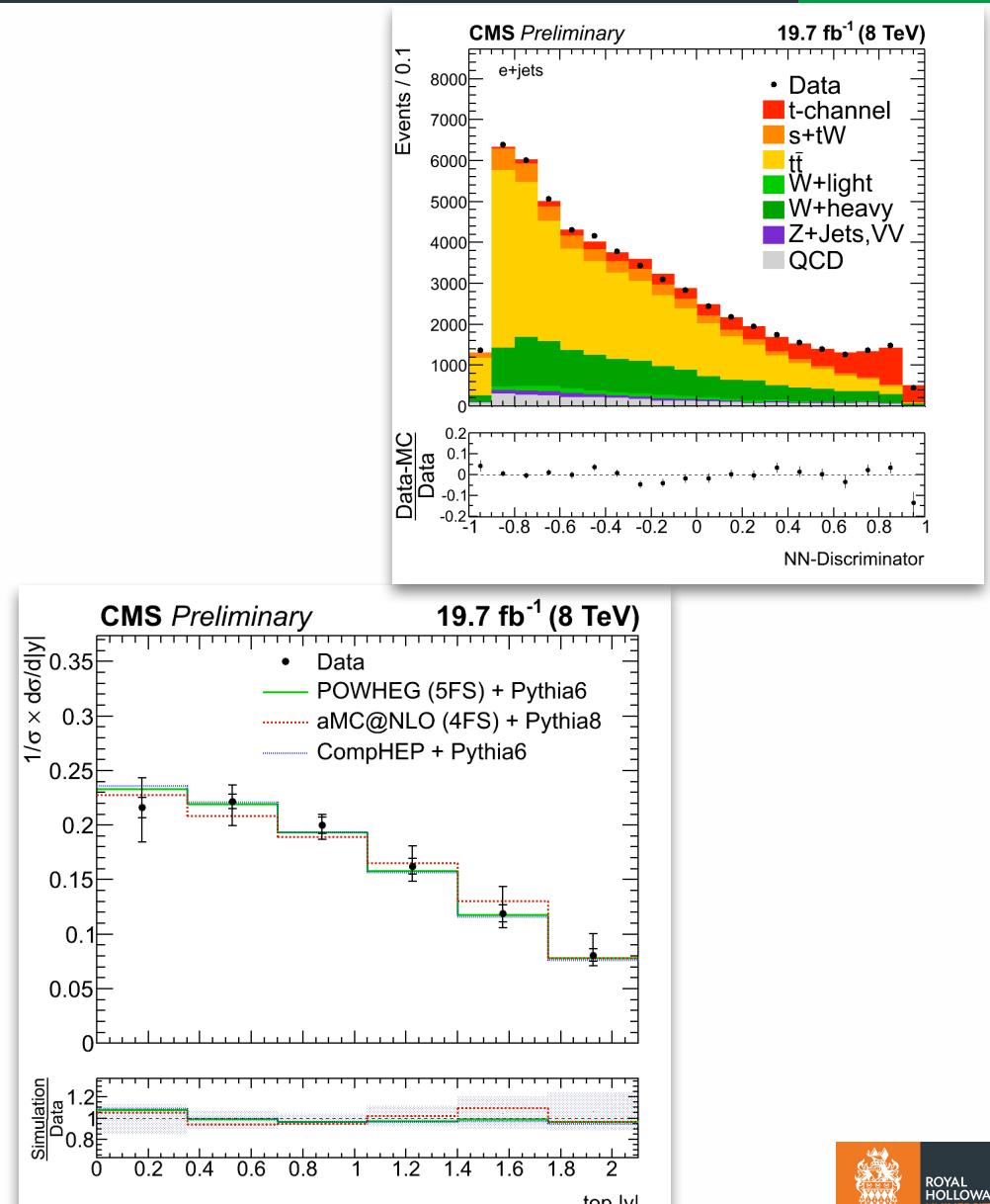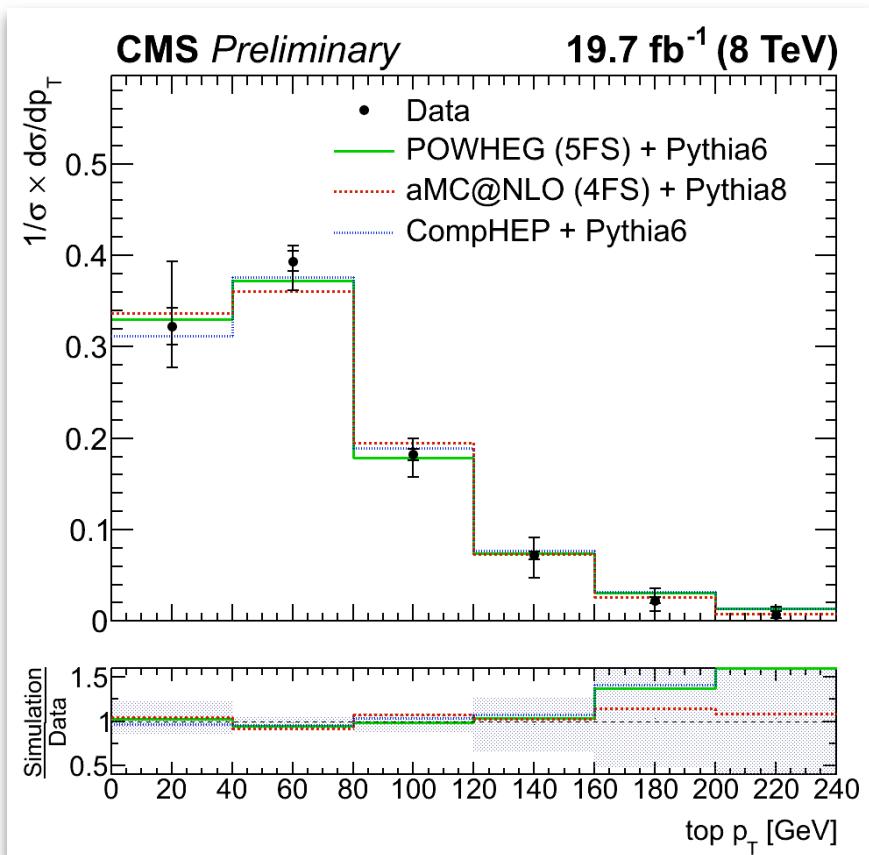
- Dilepton selection with 1 or 2 b-jets (tt control)
- BDT to separate from tt
- Fiducial cross section to compare with NLO

$$\sigma_{tW} = 23.0 \pm 1.3 \text{ (stat.)} \, ^{+3.2}_{-3.5} \text{ (syst.)} \pm 1.1 \text{ (lumi.) pb}$$

16% 7.7σ

BREAKING NEWS

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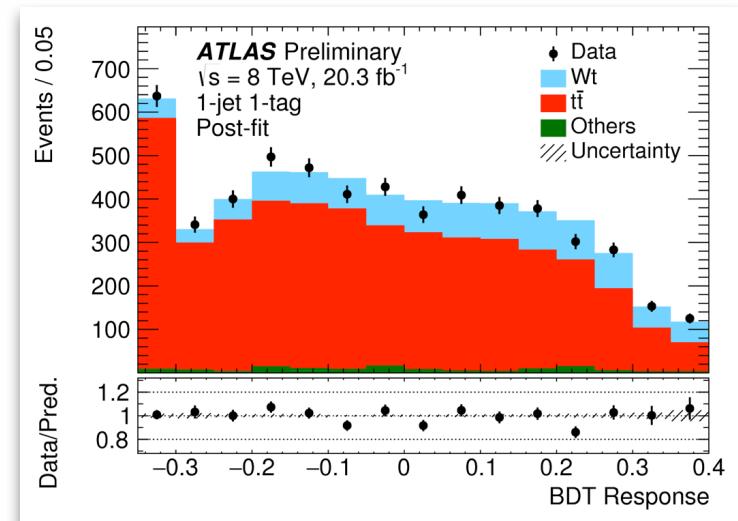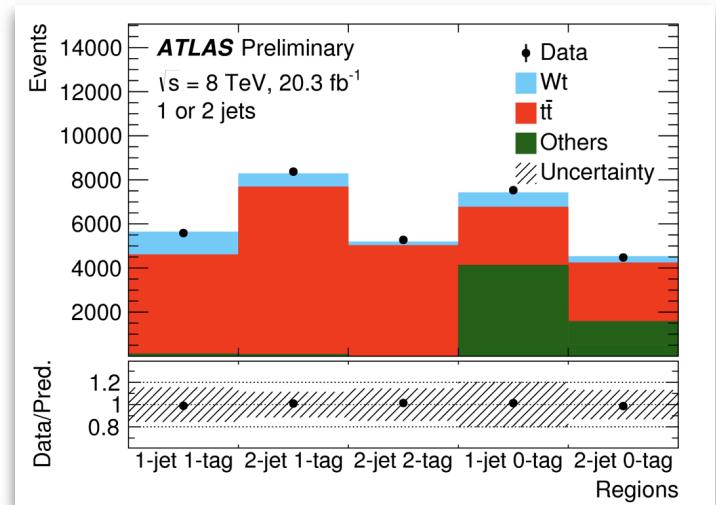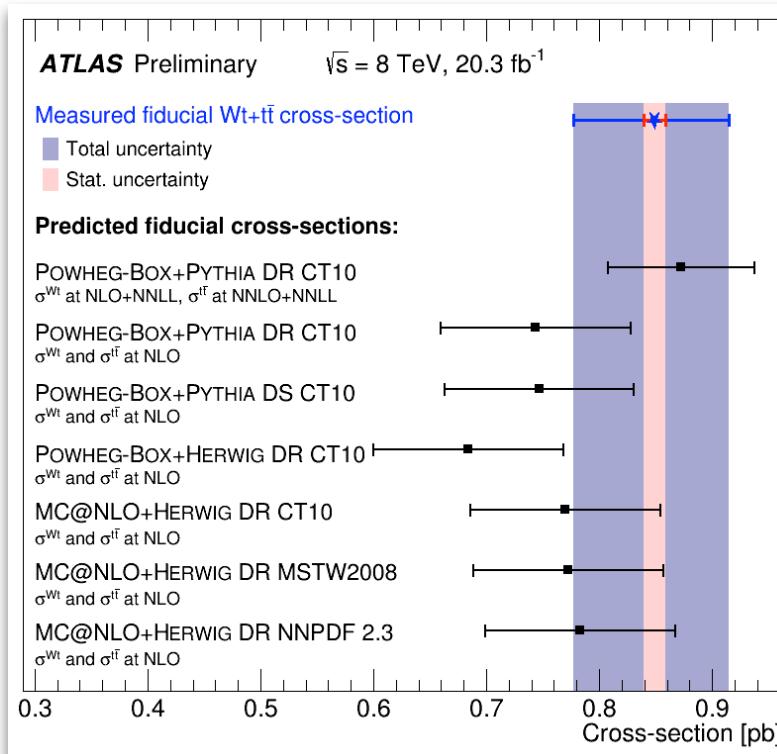
Combination for tW single top at 8 TeV

18.7%
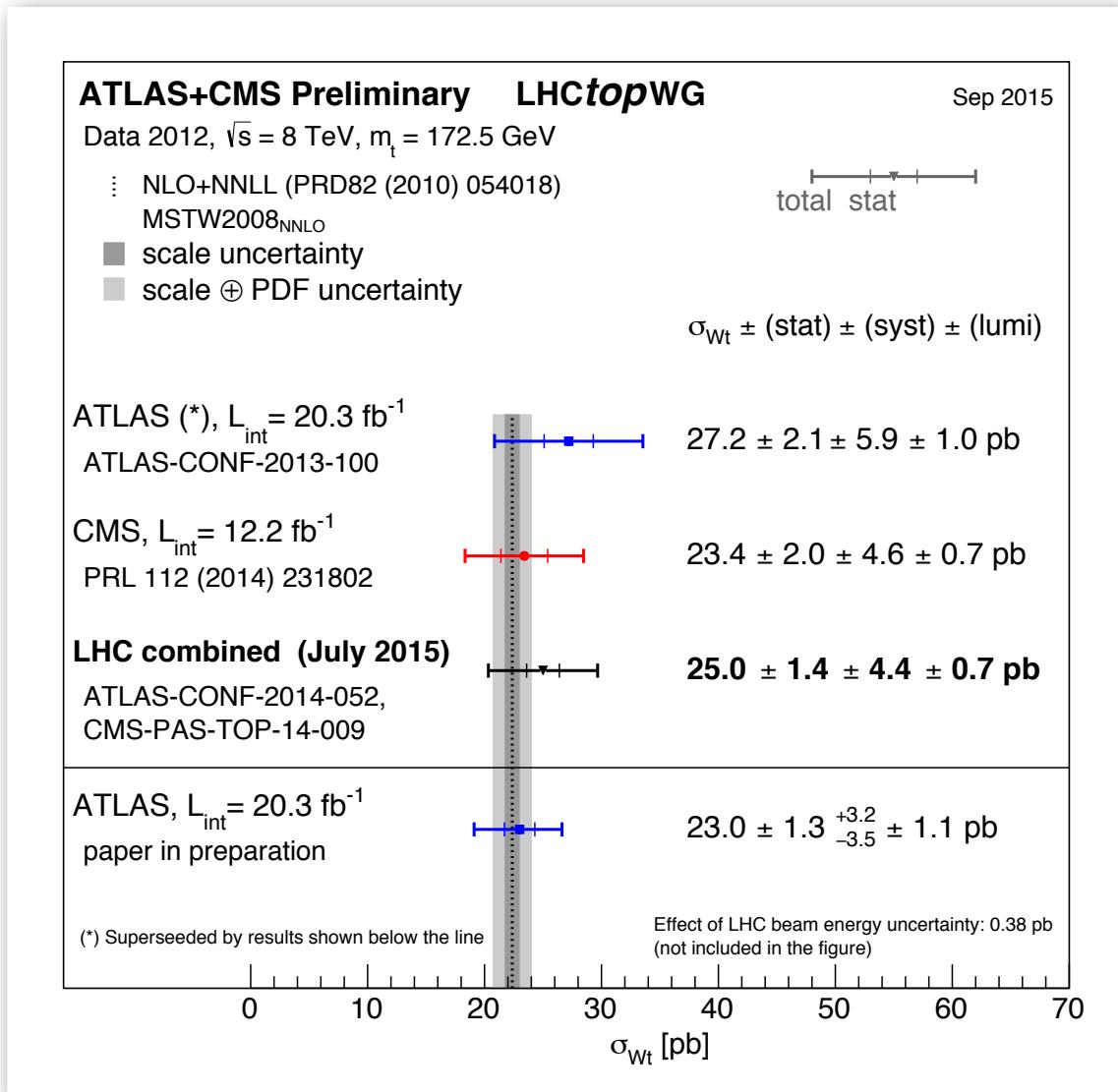
s-channel single top quark at 8 TeV

- Lepton+jets selection with 2 b-jets and large E_TMiss
- Build Matrix Element discriminant for each selected event
  - s-channel vs t-channel, tt, W+jets
- Template fit in signal and control regions

$$\sigma_s = 4.8 \pm 1.1 \,(\text{stat.})\,^{+2.2}_{-2.0}\,(\text{syst.+lumi.})\,\text{pb} \qquad 49\%$$

Observed (expected) significance: 3.2σ (3.9σ)
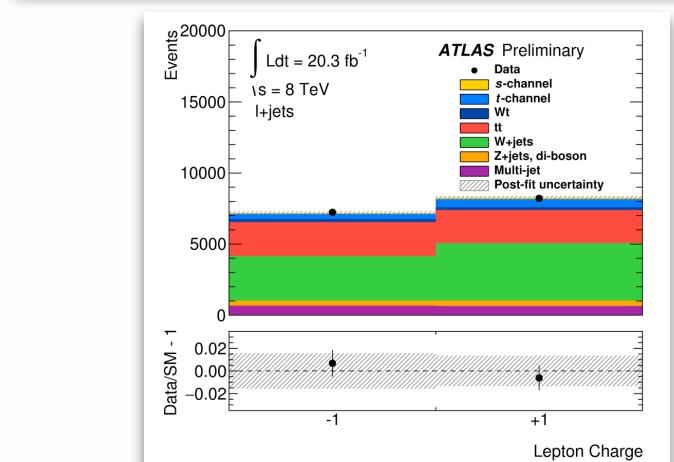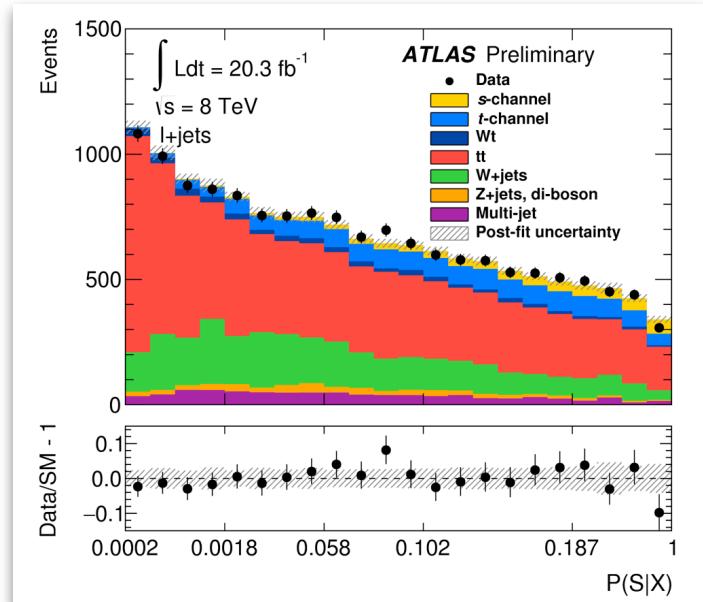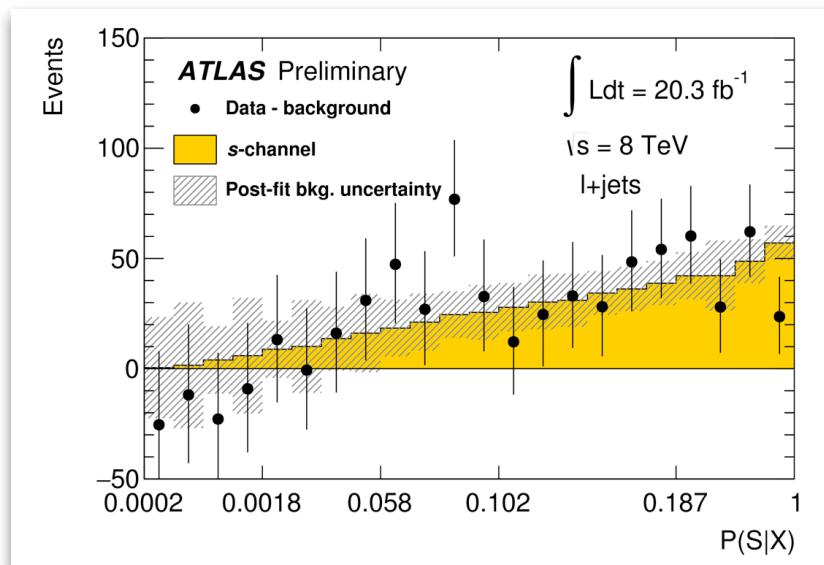
First evidence of single-top s-channel production at the LHC!

single-top quark at the LHC
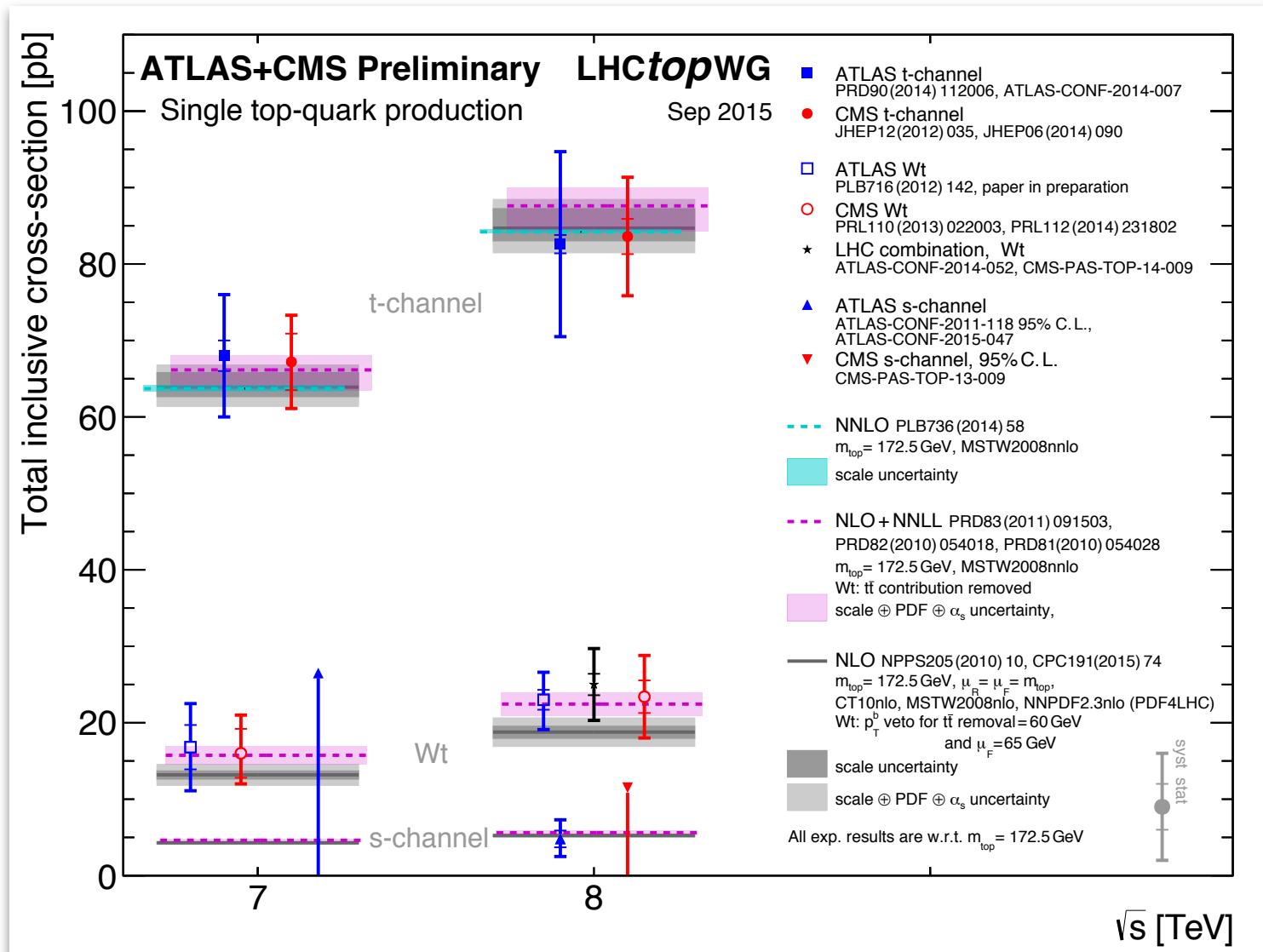
Extracting |Vtb|
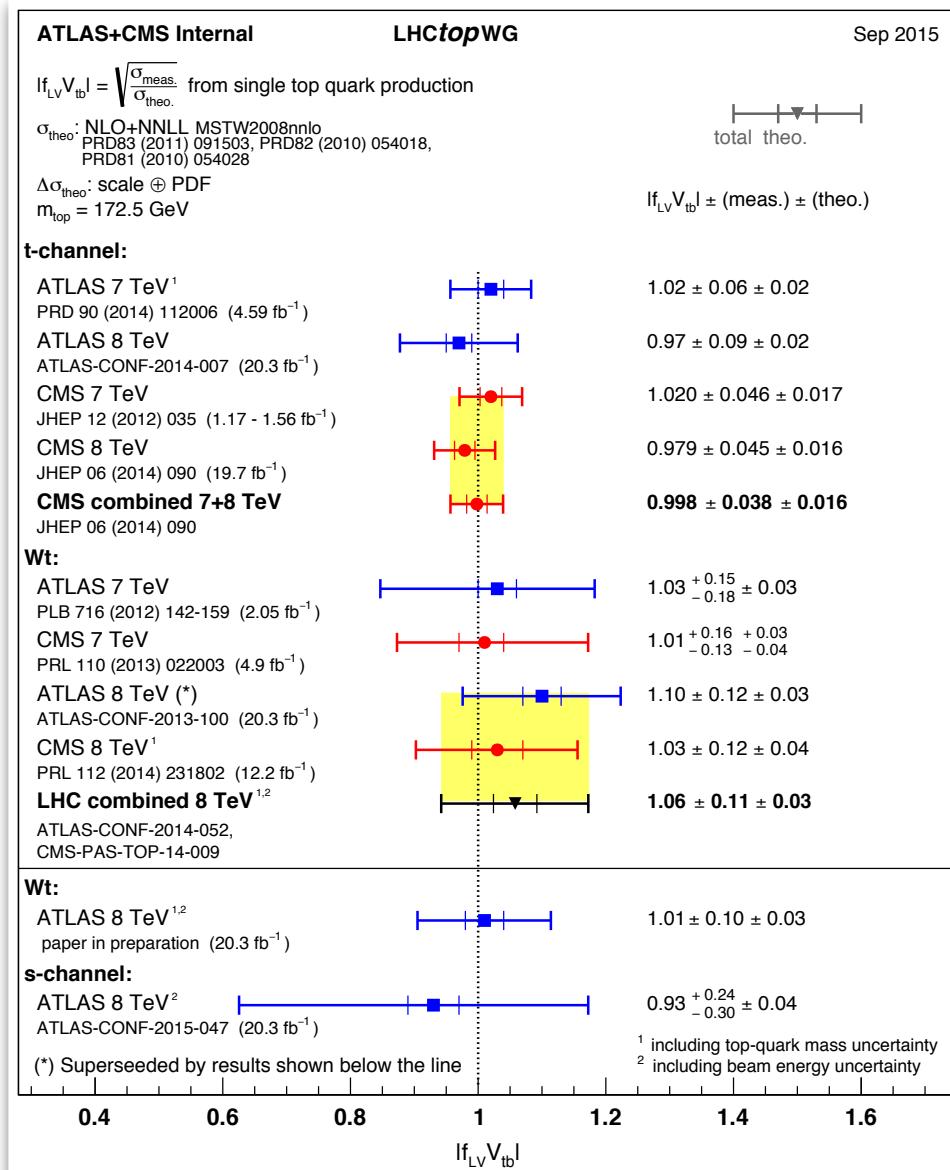
4.1%

The top quark is 20 years old!

Precision measurements

inclusive and differential theory calculations

Discovery

FERMILAB-PUB-95/022-E
CDF/PUB/TOP/PUBLIC/3040

Observation of Top Quark Production in $\bar{p}p$ Collisions
with the CDF Detector at Fermilab

Abstract

We establish the existence of the top quark using a 67 pb^{-1} data sample of $\bar{p}p$ collisions at $\sqrt{s} = 1.8$ TeV collected with the Collider Detector at Fermilab (CDF). Employing techniques similar to those we previously published, we observe a signal consistent with $t\bar{t}$ decay to $WWb\bar{b}$, but inconsistent with the background prediction by 4.8σ. Additional evidence for the top quark is provided by a peak in the reconstructed mass distribution. We measure the top quark mass to be $176 \pm 8(\text{stat.}) \pm 10(\text{sys.})$ GeV/c^2, and the $t\bar{t}$ production cross section to be $6.8^{+3.6}_{-2.4}$ pb.

1995 ⟶ 2015

~50% ⟶ 3.5%!

(8 TeV LHC combination)

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The top quark is 20 years old!

Discovery

Precision measurements
inclusive and differential
theory calculations

Analysis techniques
jet substructure
fiducial measurements
Matrix Element, MVA

New physics window
tt and single top
ttV
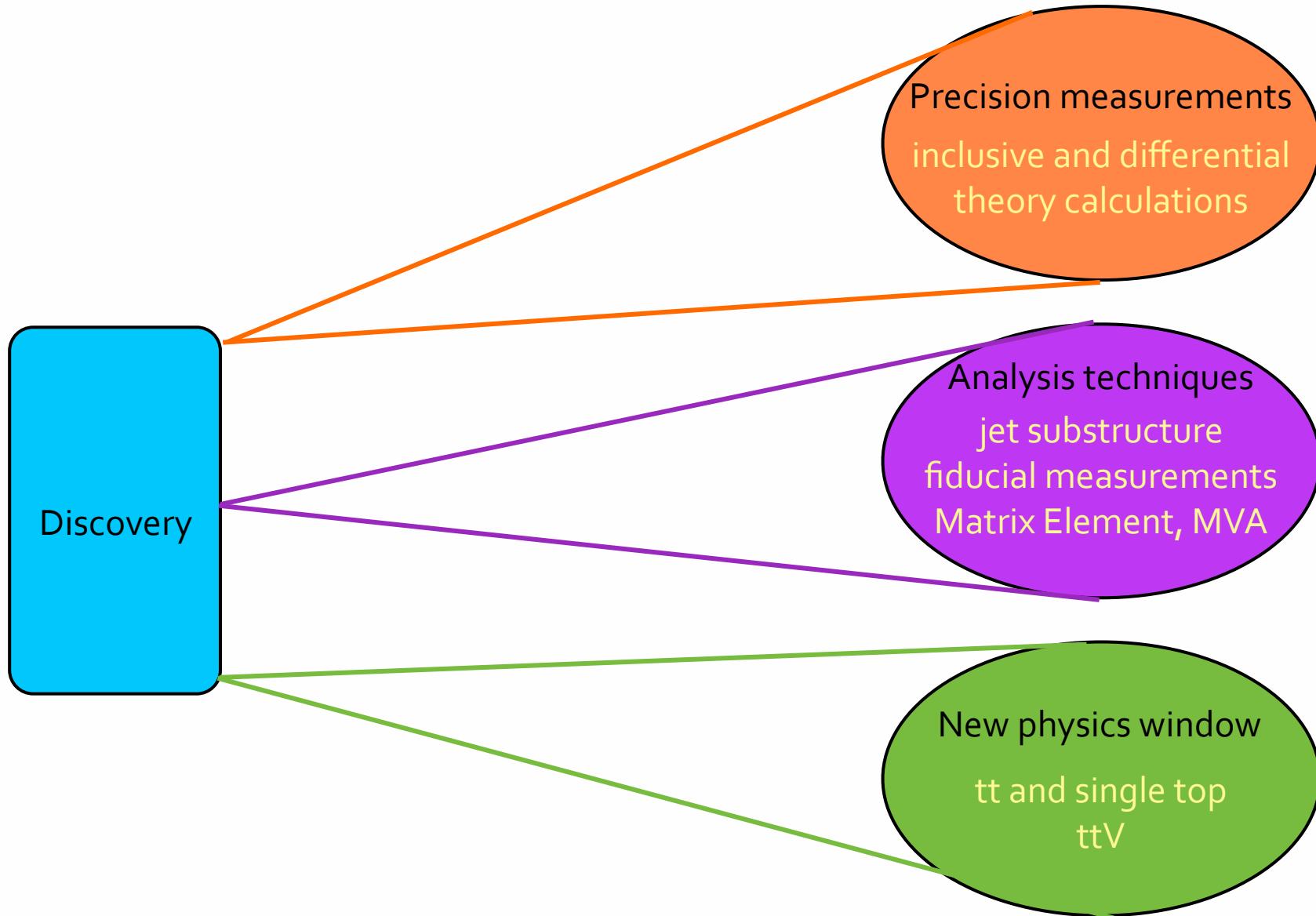
backups

13 TeV systematics

Uncertainty	$\Delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}}$ (%)
Data statistics	7.6
$t\bar{t}$ NLO modelling	2.6
$t\bar{t}$ hadronisation	7.9
Initial/final state radiation	1.5
PDF	3.7
Single-top Wt cross-section	0.6
Single-top interference	<0.05
Diboson cross-section	0.4
Z+jets $\to ee/\mu\mu$ modelling	1.5
Z+jets $\to \tau\tau$ modelling	0.1
Electron energy scale	0.3
Electron energy resolution	0.2
Electron identification	3.6
Electron trigger	0.2
Electron isolation	1.0
Muon momentum scale	0.1
Muon momentum resolution	1.1
Muon identification	0.8
Muon trigger	0.6
Muon isolation	1.0
Jet energy scale	1.2
Jet energy resolution	0.2
b-tagging efficiency	0.8
Missing transverse momentum	0.3
NP & fakes	1.5
Analysis systematic	11
Integrated luminosity	10
Total uncertainty	16

Table 4: Summary of the statistical, systematic and total uncertainties on the $t\bar{t}$ production cross-section $\sigma_{t\bar{t}}$ in the same flavour dilepton channel.

Uncertainty	$\Delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}}$ (%)
Data statistics	1.5
$t\bar{t}$ NLO modelling	0.6
$t\bar{t}$ hadronisation	4.1
Initial/final state radiation	1.9
PDF	0.7
Single top cross-section	0.3
Diboson cross-sections	0.2
Z+jets cross-section	1.0
W+jets method statistics	1.7
W+jets modelling	1.0
Electron energy scale/resolution	0.1
Electron identification	2.1
Electron isolation	0.4
Electron trigger	2.8
Muon momentum scale/resolution	0.1
Muon identification	0.2
Muon isolation	0.3
Muon trigger	1.2
$E_{\mathrm{T}}^{\mathrm{miss}}$ scale/resolution	0.4
Jet energy scale	$+10$ -8
Jet energy resolution	0.6
b-tagging	4.1
NP & fakes	1.8
Analysis systematics	$+13$ -11
Integrated luminosity	$+11$ -9
Total uncertainty	$+17$ -14

Table 5: Summary of the statistical, systematic and total uncertainties on the $t\bar{t}$ production cross-section $\sigma_{t\bar{t}}$ measured in the lepton-plus-jets channel.

13 TeV systematics

Table 1: Overview on uncertainties in the total inclusive cross section measureme:

source	inclusive cross section [%]
statistical uncertainty	3.2
b tagging	5.1
jet energy scale	3.5
jet energy resolution	3.4
lepton selection	3.0
E_T^{miss} (non jet)	< 0.1
pileup	1.2
background	1.6
PDF	4.7
factorization scale	< 0.1
renormalization scale	< 0.1
NLO generator	2.0
POWHEG + PYTHIA8 vs. HERWIG++	3.4
total systematic uncertainty (no luminosity)	10.0
luminosity	12
total uncertainty	15.6

Source	$\Delta\sigma_{t\bar{t}}$ (pb)	$\Delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}}$ (%)
Data statistics	60	7.7
Trigger efficiencies	39	5.0
Lepton efficiencies	33	4.3
Lepton energy scale	< 1	≤ 0.1
Jet energy scale	20	2.6
Jet energy resolution	< 1	≤ 0.1
Pileup	2.8	0.4
Scale (μ_F and μ_R)	1.5	0.2
$t\bar{t}$ NLO generator	15	1.9
$t\bar{t}$ hadronization	14	1.8
PDF	12	1.5
Single top quark	14	1.8
VV (V = W or Z)	3.5	0.5
Drell–Yan	3.9	0.5
Non-W/Z leptons	8	1.0
Total systematic (no integrated luminosity)	62	8.0
Integrated luminosity	93	12
Total	126	16.4

Differential variables

the central scattering region. The angle between the two top quarks quarks has been found to be sensitive to non-resonant contributions due to hypothetical new particles exchanged in the t-channel [7]. The rapidities of the two top quarks produced in the hard scattering process in the pp center of mass frame are denoted by $y_{t,1}$ and $y_{t,2}$, while their rapidities in the $t\bar{t}$ center of mass frame are $y^\star = \frac{1}{2}(y_{t,1} - y_{t,2})$ and $-y^\star$. The longitudinal motion of the $t\bar{t}$ system in the pp frame is described by the rapidity boost $y^{t\bar{t}}_{\mathrm{boost}} = \frac{1}{2}[y_{t,1} + y_{t,2}]$ and the scattering angle $\chi_{t\bar{t}} = e^{2|y^\star|}$. In particular, many signals due to processes not included in the Standard Model are predicted to peak at low values of $\chi_{t\bar{t}}$[7].

The following observables have been measured:

- The absolute value of the azimuthal angle between the two top quarks ($\Delta\phi_{t\bar{t}}$);

- the absolute value of the out-of-plane momentum ($|p^{t\bar{t}}_{\mathrm{out}}|$), *i.e.* the projection of top-quark three-momentum onto the direction perpendicular to a plane defined by the other top quark and the beam axis (z) in the laboratory frame

$$\left|p^{t\bar{t}}_{\mathrm{out}}\right| = \left|\vec{p}_{t,\mathrm{had}} \cdot \frac{\vec{p}_{t,\mathrm{lep}} \times \hat{z}}{|\vec{p}_{t,\mathrm{lep}} \times \hat{z}|}\right| ; \qquad (3)$$

- the scalar sum ($H^{t\bar{t}}_{\mathrm{T}}$) of the transverse momenta of the two top quarks

$$H^{t\bar{t}}_{\mathrm{T}} = p^{t,\mathrm{had}}_{\mathrm{T}} + p^{t,\mathrm{lep}}_{\mathrm{T}} ; \qquad (4)$$

- the longitudinal boost of the $t\bar{t}$ system with respect to the center-of-mass of the colliding protons ($y^{t\bar{t}}_{\mathrm{boost}}$);

- the scattering angle between the two top quarks ($\chi_{t\bar{t}}$);

- and the ratio of the transverse momenta of the hadronic W boson and the top quark from which it originates (R_{Wt})

$$R_{Wt} = p^{W}_{\mathrm{T}}/p^{t,\mathrm{had}}_{\mathrm{T}} . \qquad (5)$$

Differential tt cross section at 7 TeV

- ·lepton+jets, 4.6fb^{-1}, ≥ 2 b-jets, E_TMiss>30 GeV, M_T(W)> 35GeV
- ·"pseudo-top": reconstruction algorithm only uses detector-level objects
  - ·leptonic top: lepton + E_TMiss (use W mass for p_z) + b-jet closest in DR to lepton
  - ·hadronic top: 2 highest p_T jets + remaining b-jet
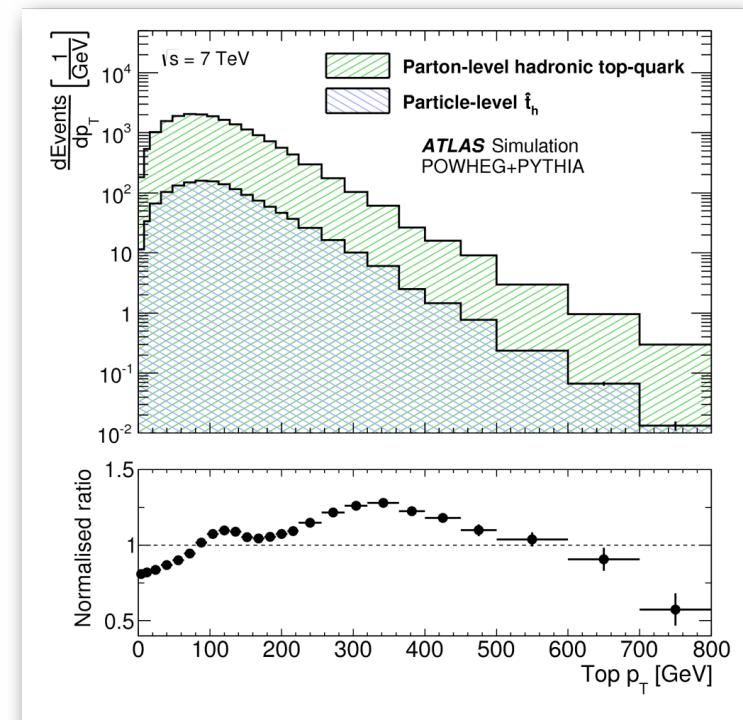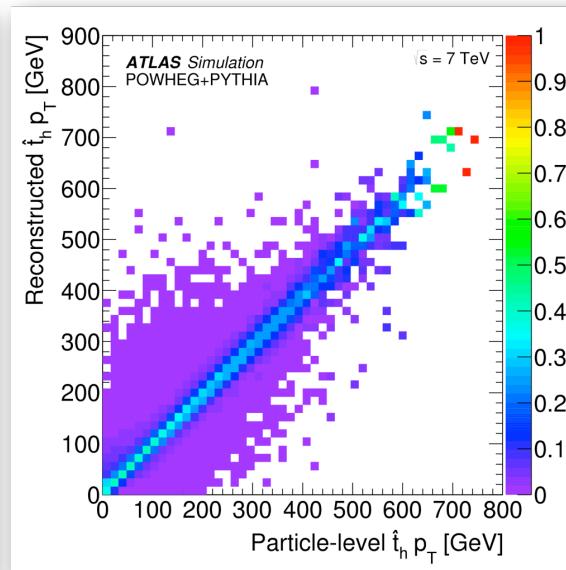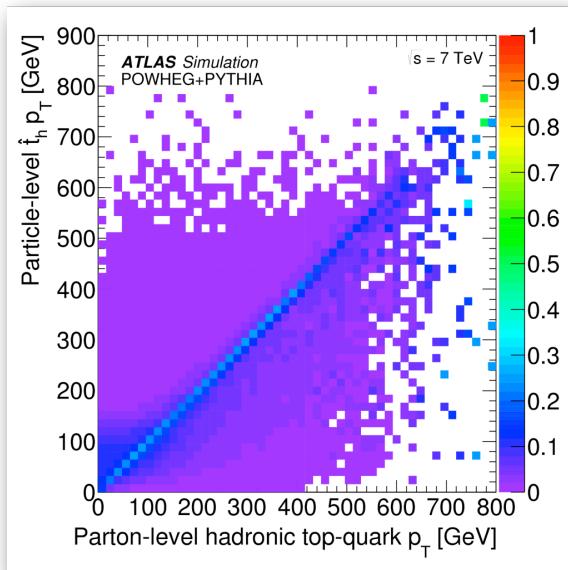
# Differential tt cross section at 7 TeV

Top p_T: models indicate a harder p_T than data: possibly because of CTEQ6L1 PDF?

Parton shower and radiation comparison
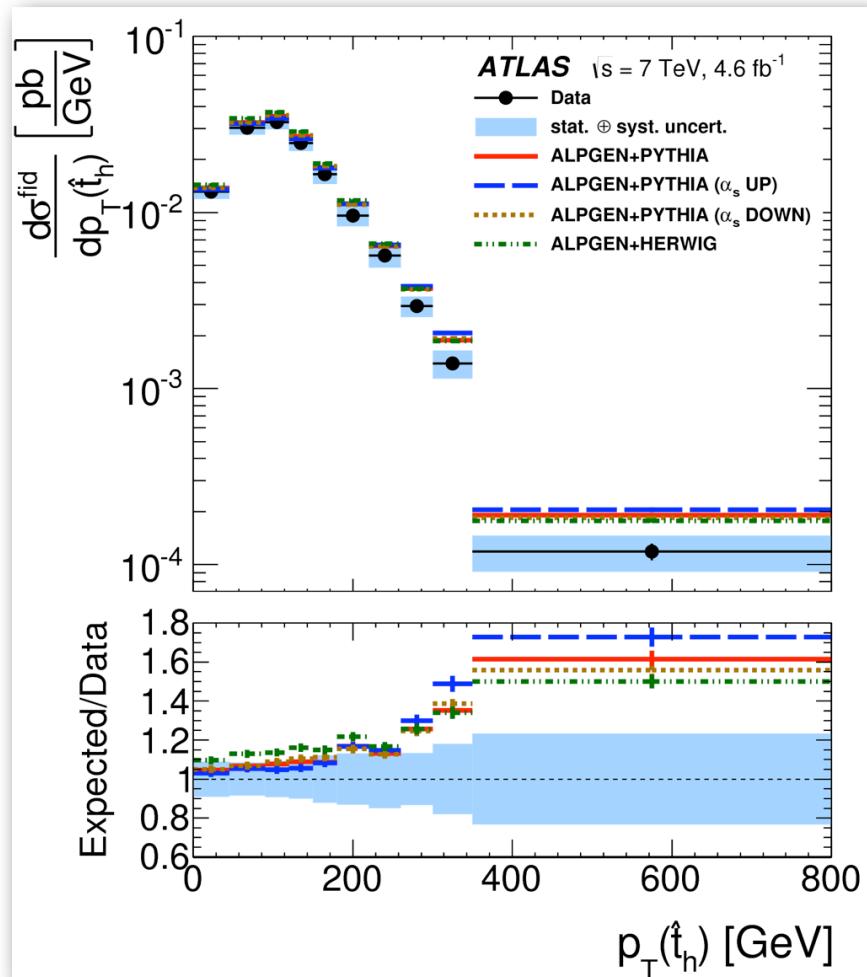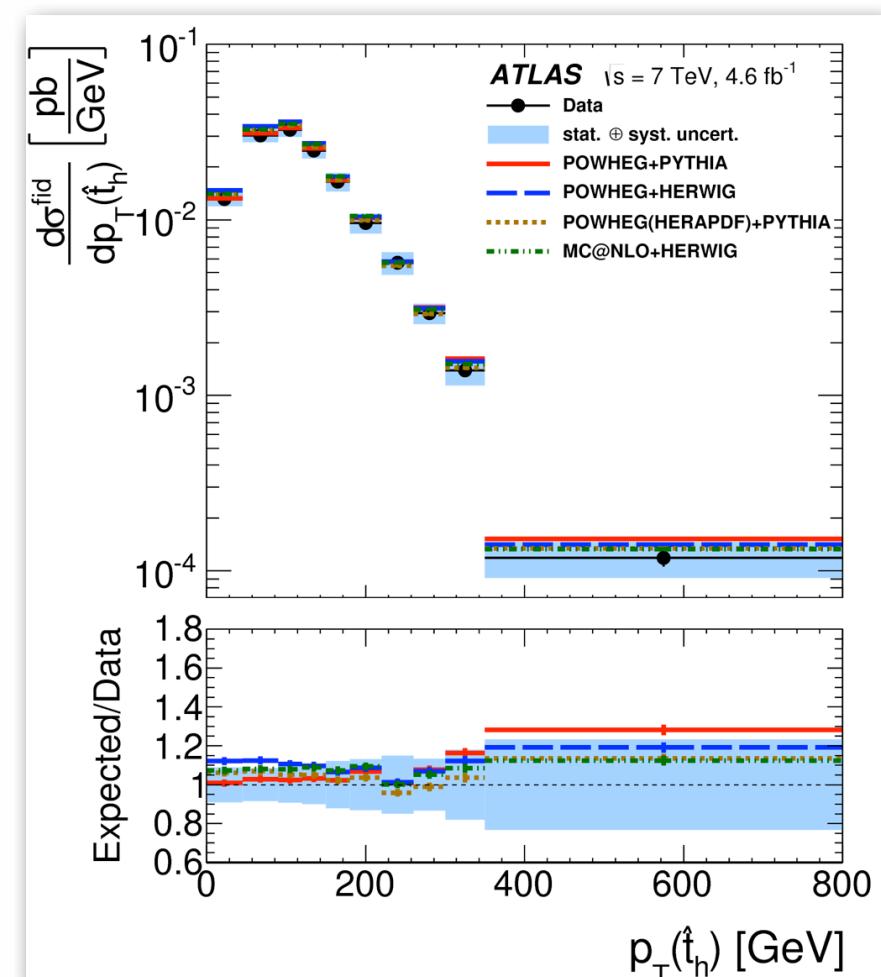
generator and PDF comparison

list of variables

1502.05923

differential tt cross section at 7 TeV

- tt pT very sensitive to additional radiation and highlights the different hard-gluon emission models
- MC@NLO prediction lower due to the softer 5th jet pt compared to other generators
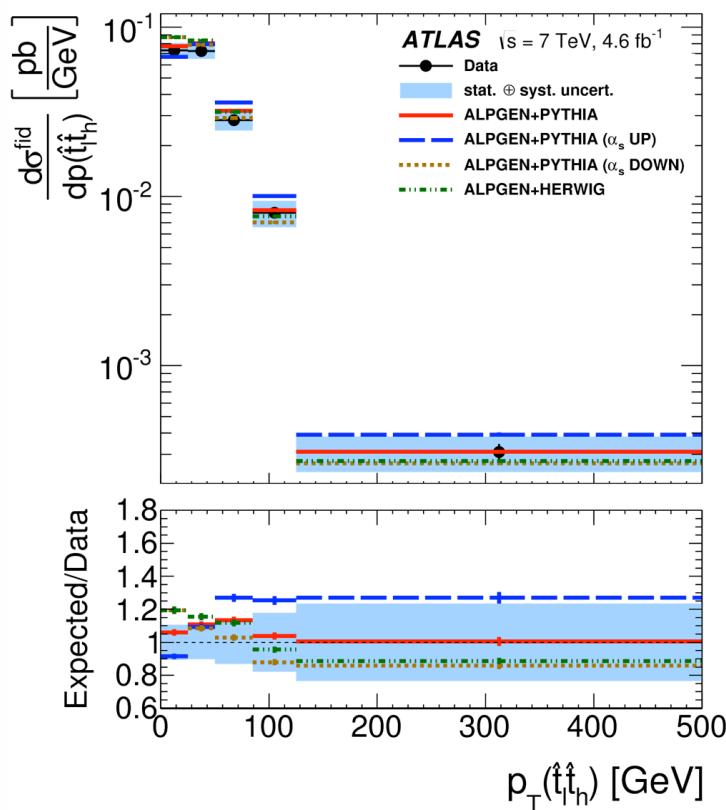
Parton shower and radiation comparison
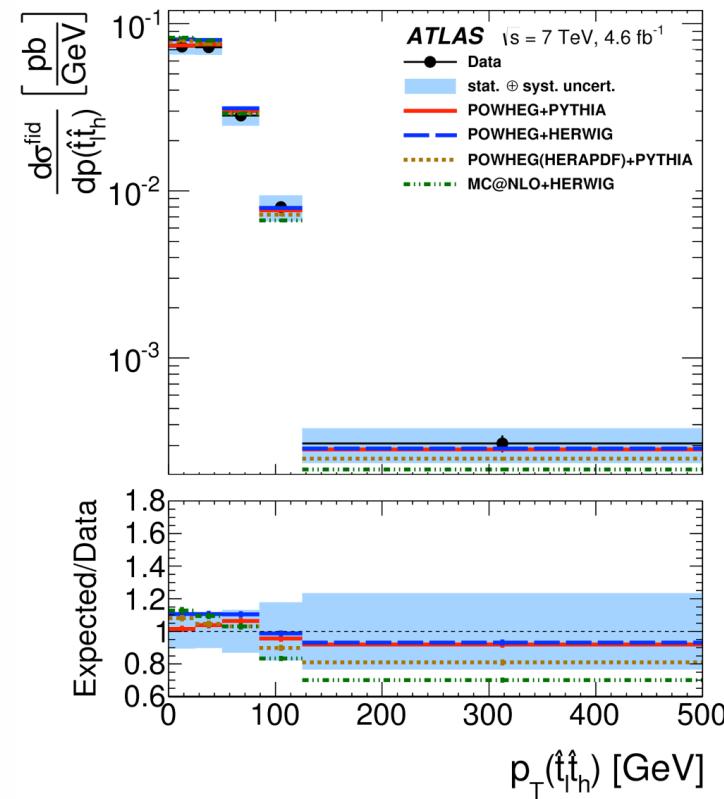
generator and PDF comparison

- CMS: preliminary luminosity scale and its uncertainty from x-y beam-beam scans