Cross-Section Measurements of Top Quark Pair Production at ATLAS

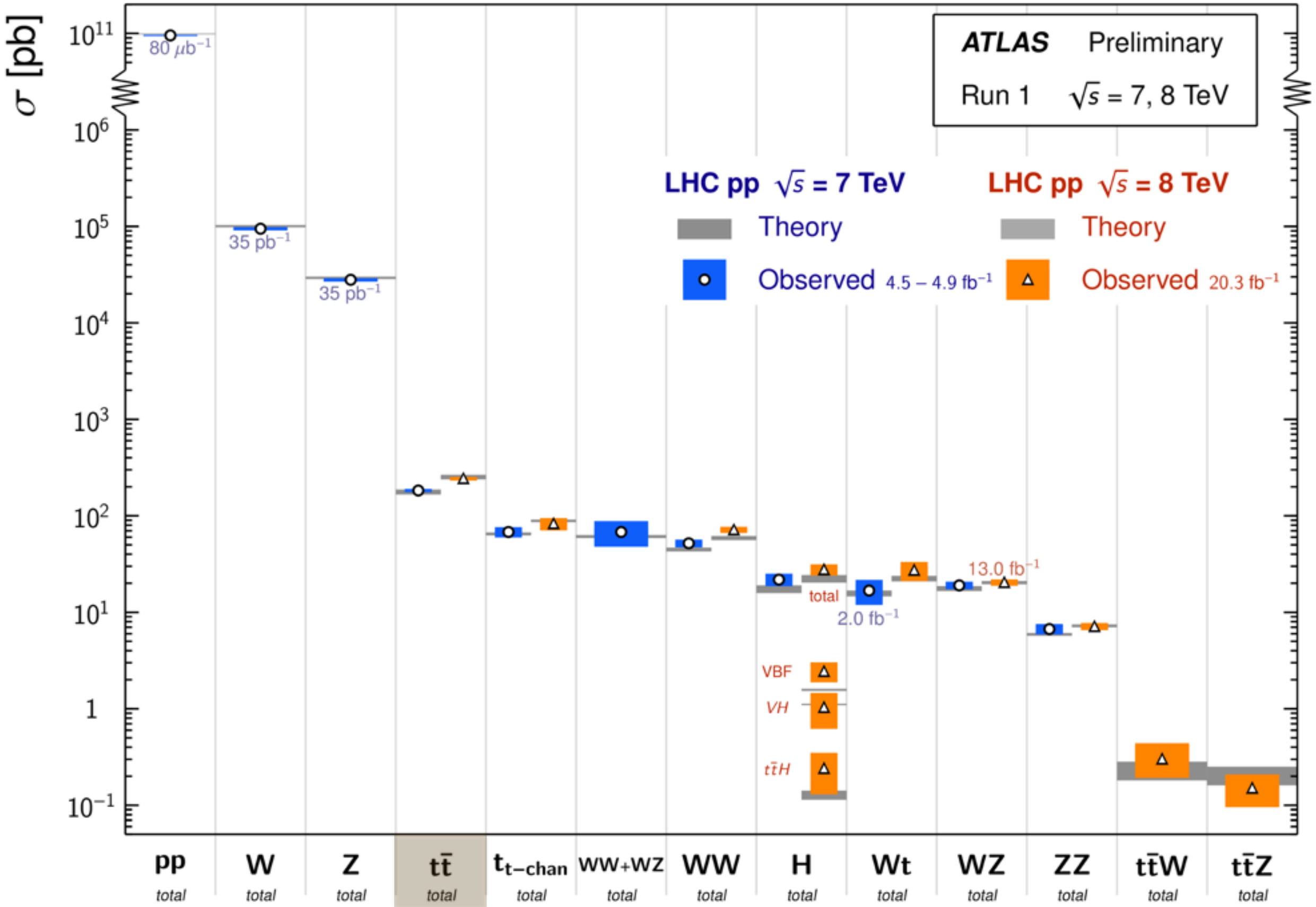
Tom Schwarz

on behalf of the ATLAS Collaboration

DPF 2015
August, 2015

Standard Model Total Production Cross Section Measurements

Status: March 2015



Standard Model Production Cross Section Measurements

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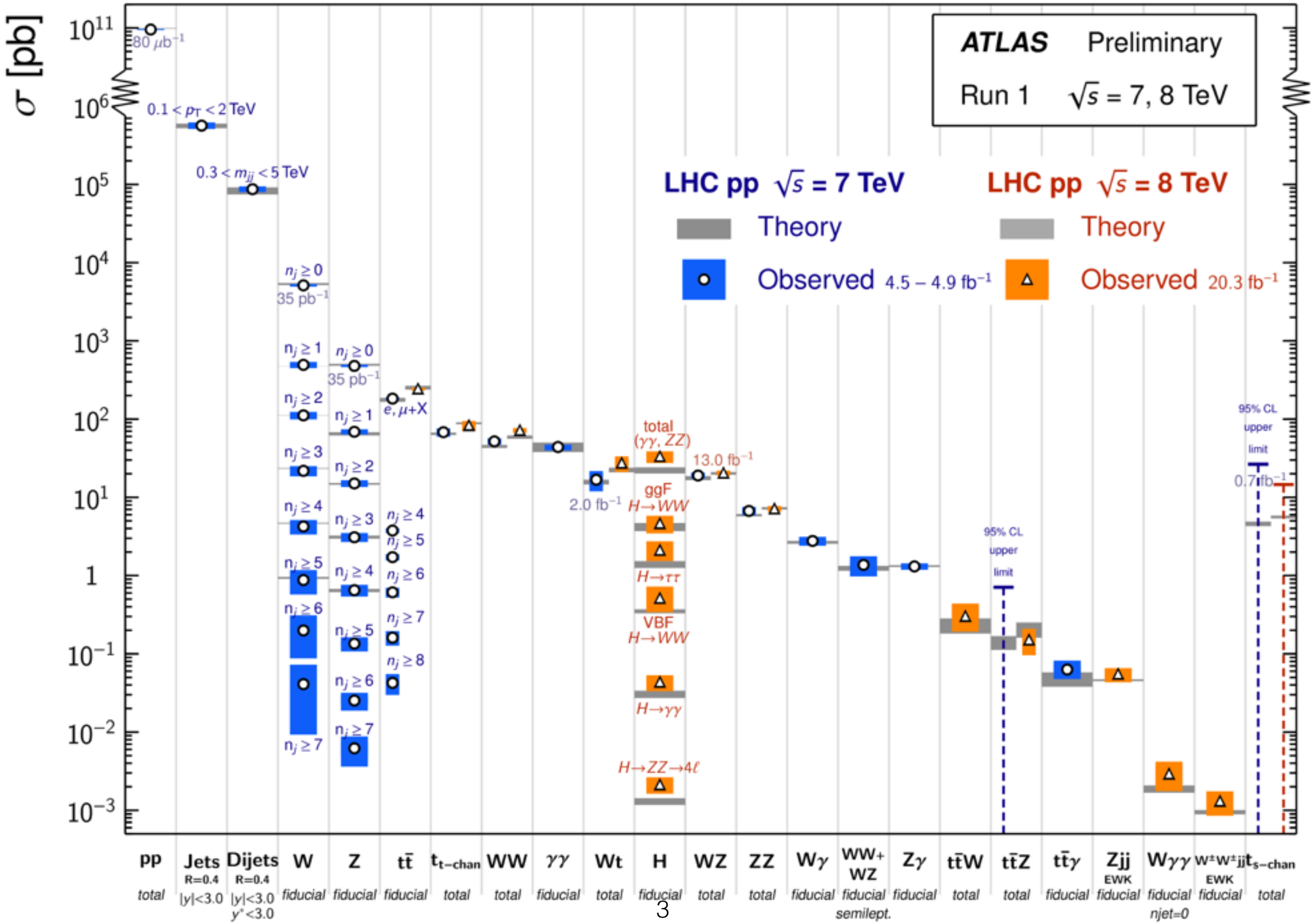
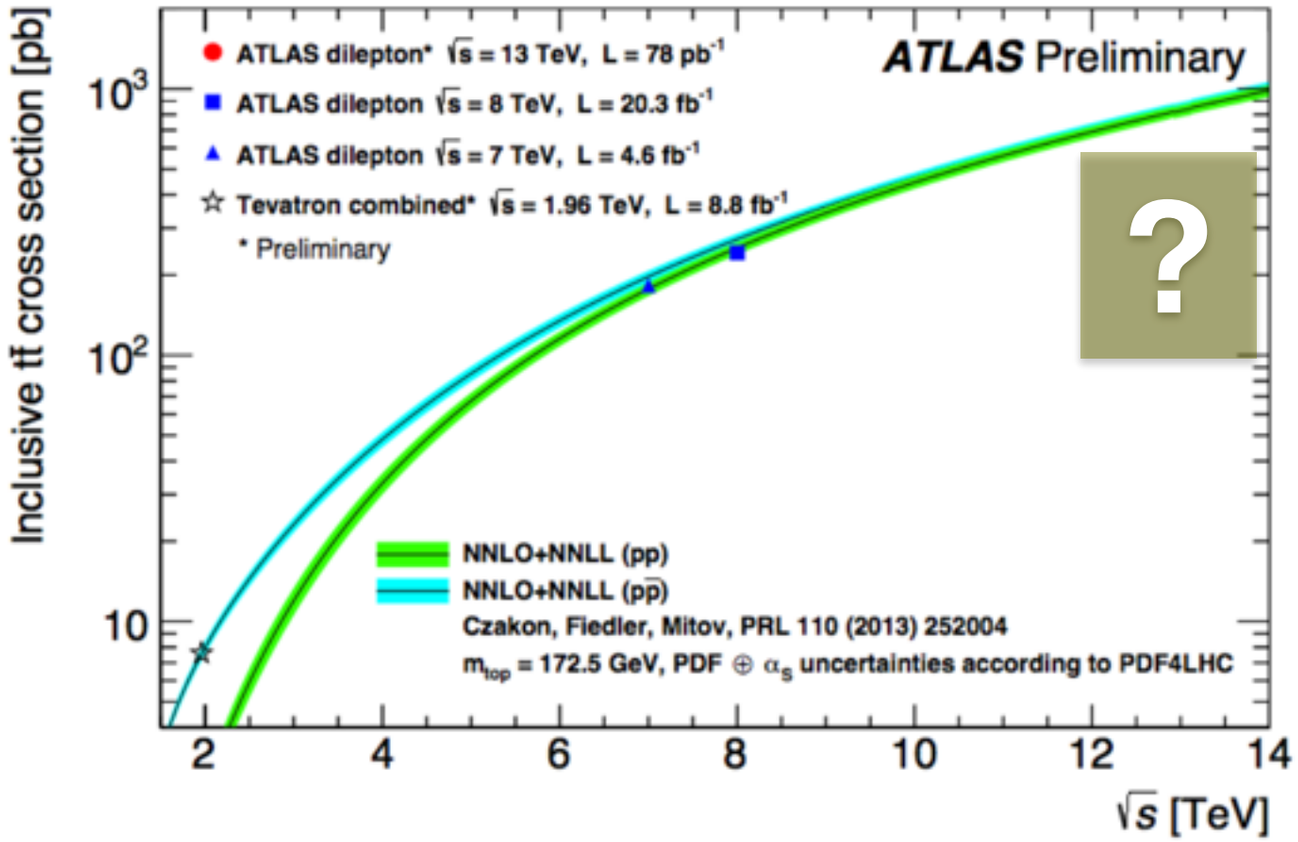
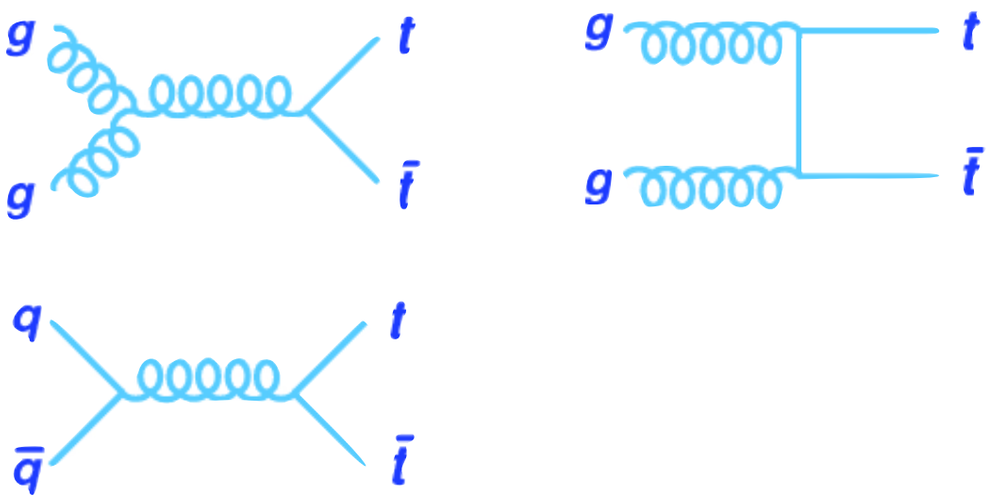


Top Quark Pair Production at the LHC

- First fundamental step in understanding top quark physics in a new energy regime
- Tests QCD predictions at NNLO and constrains PDF models
- Sensitive to new production mechanisms, and constrains the very important top quark background for other BSM and Higgs searches
- Top quark pair cross section increases 3.3x from 8 to 13 TeV





Full NNLO+NNLL calculation[1]

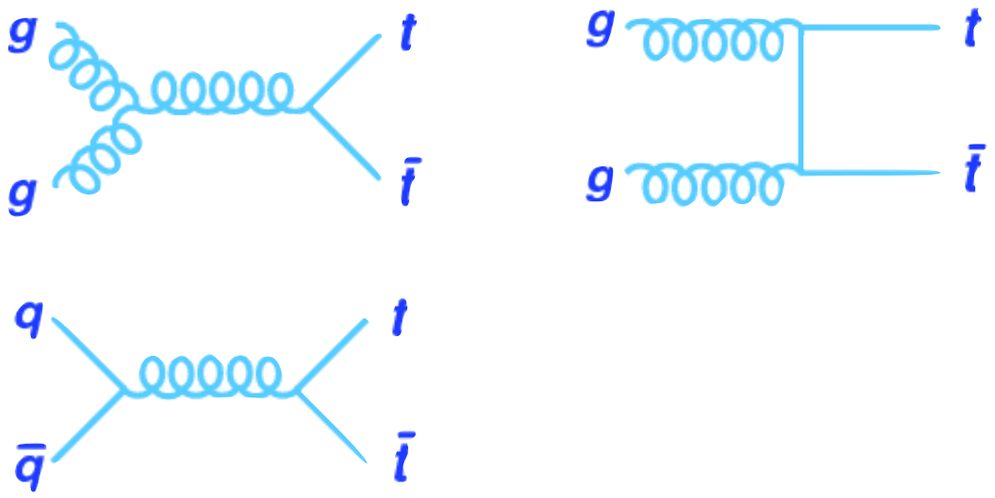
$\sqrt{s}$ [TeV]	$\sigma_{t\bar{t}}$(NNLO+NNLL)[2] [pb] (172.5 GeV)	Scale uncert. [pb]	PDF+α_s[3] uncert. [pb]	Mass uncert. [pb]
7	177.3	+4.6 -6.0	+9.0 -9.0	+5.4 -5.3
8	252.9	+6.4 -8.6	+11.7 -11.7	+7.6 -7.3
13	831.8	+19.8 -29.2	+35.1 -35.1	+23.2 -22.5

[1] https://twiki.cern.ch/twiki/bin/view/LHCPhysics/TtbarNNLO
[2] calculated using Top++(v2.0)
[3] calculated following PDF4LHC prescription

Production & Decay

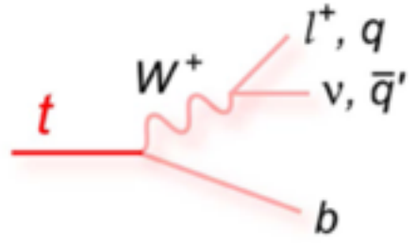
Production

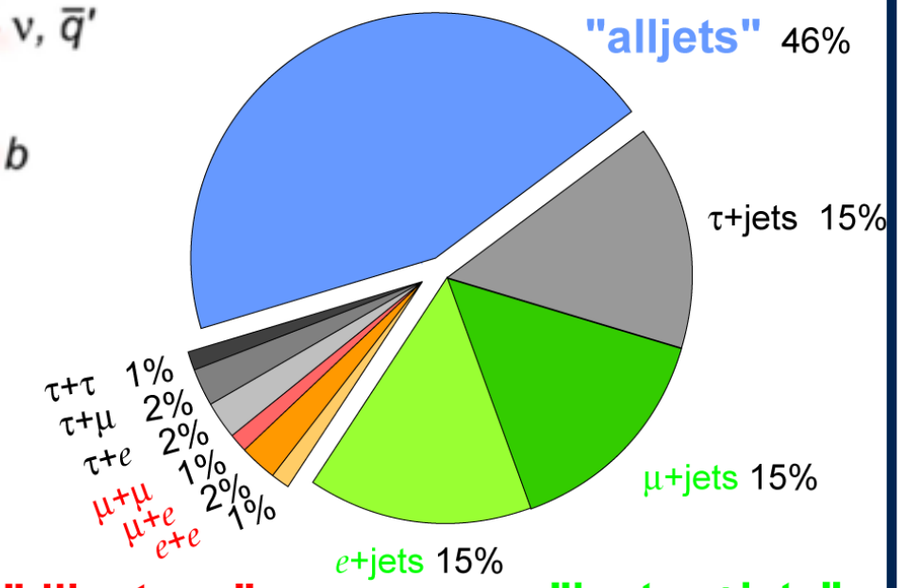
Produced in pairs, dominantly by gluon fusion followed by quark annihilation

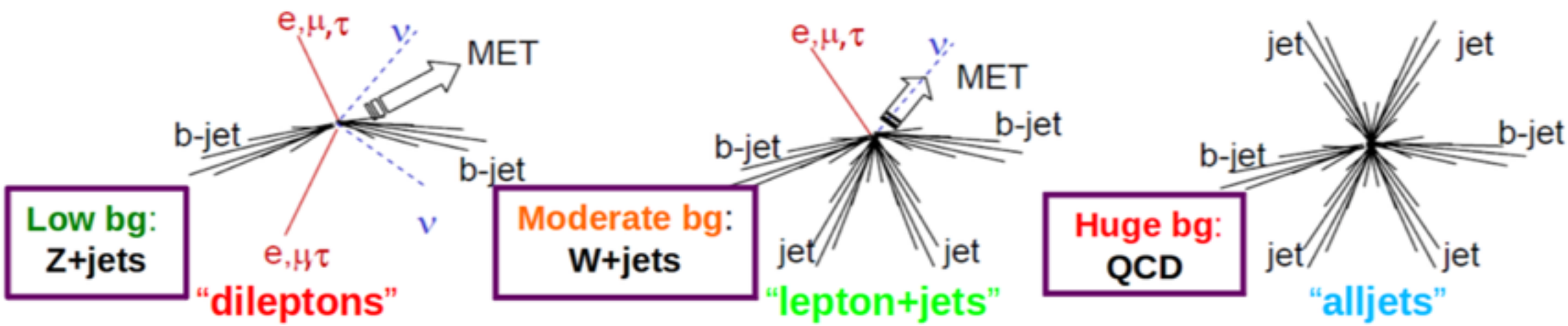


Decay

Nearly exclusive decay to Wb



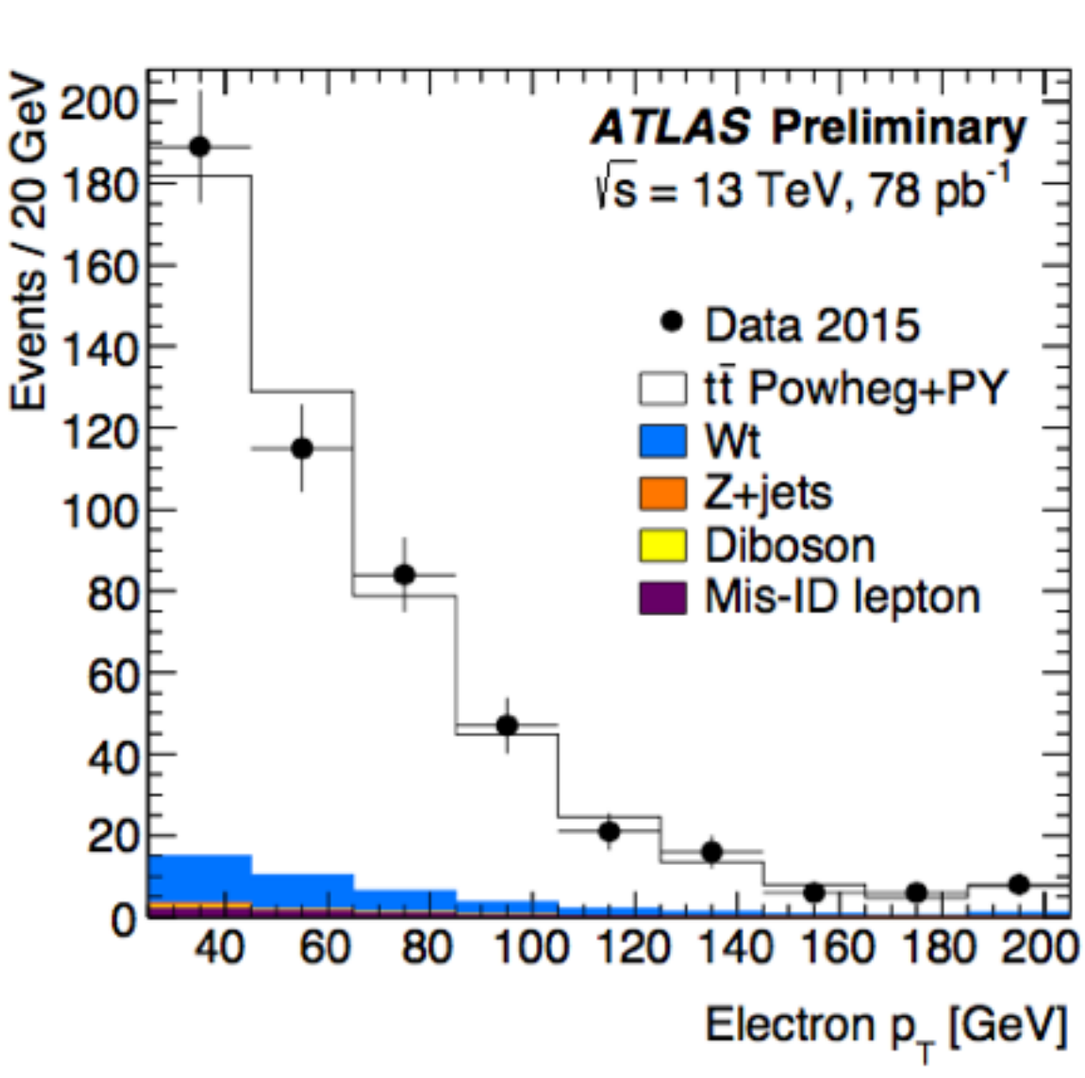


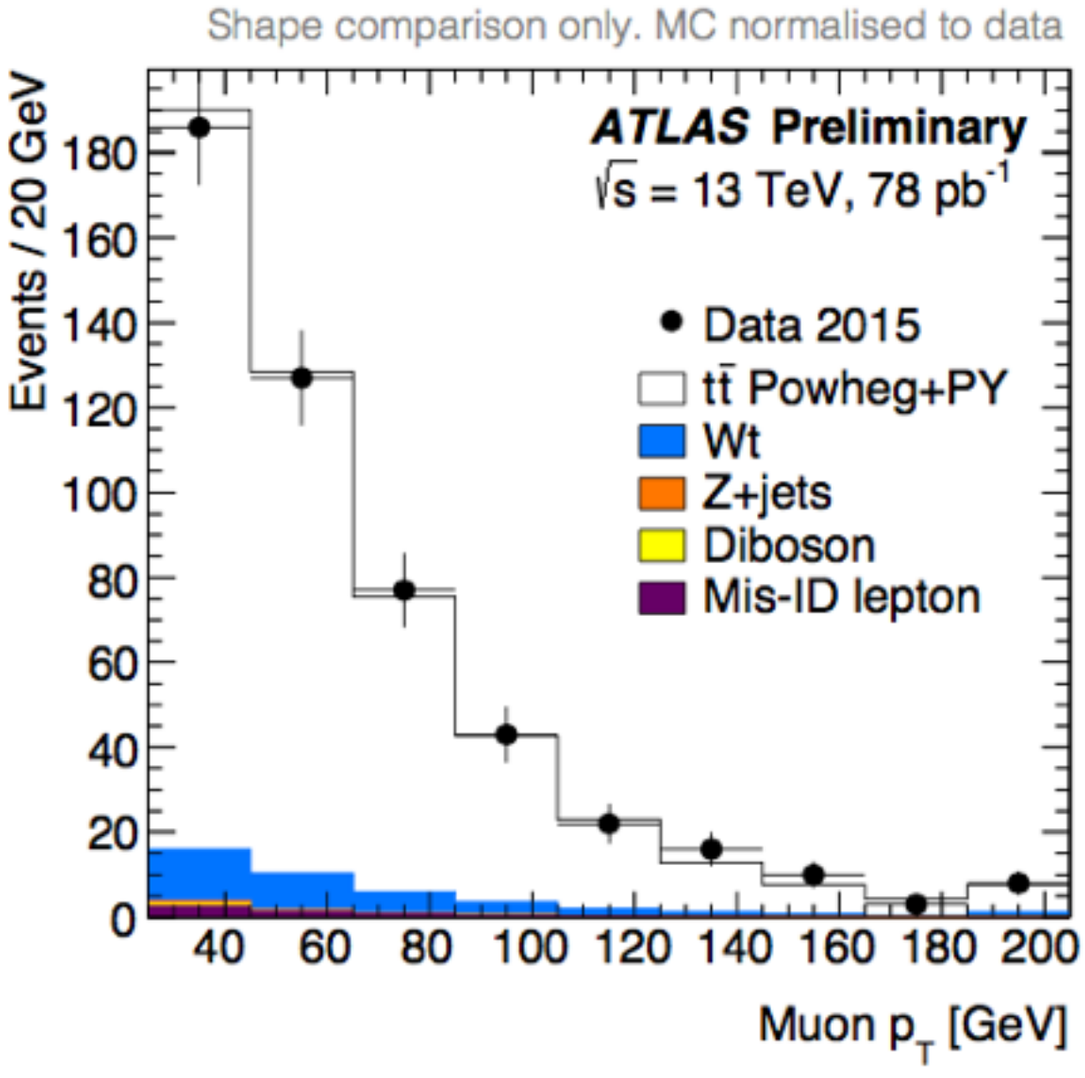


First $\sigma_{t\bar{t}}$ with ATLAS at 13 TeV

ATLAS-CONF-2015-033
$\sqrt{s}$ = 13 TeV L = 78 pb^{-1}

- <u>Cleanest channel:</u> tt ➜ (e + ν + b-jet) + (μ + ν + b-jet) = eμ + 2 b-jets + $E_{T,miss}$
- One electron and one muon with opposite charge and p_T > 25 GeV and at least one b-tagged jet with p_T > 25 GeV ➜ No $E_{T,miss}$ requirement which reduces systematics
  - ✳ *Jets calibrated using a simulation-based calibration scheme with in-situ corrections based on Run 1 data, cross-checked with early Run 2 data*





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Display of tt → eμ + 2 b-jets candidate event

ATLAS EXPERIMENT

Run: 267638
Event: 193690558
2015-06-13 23:52:26 CEST

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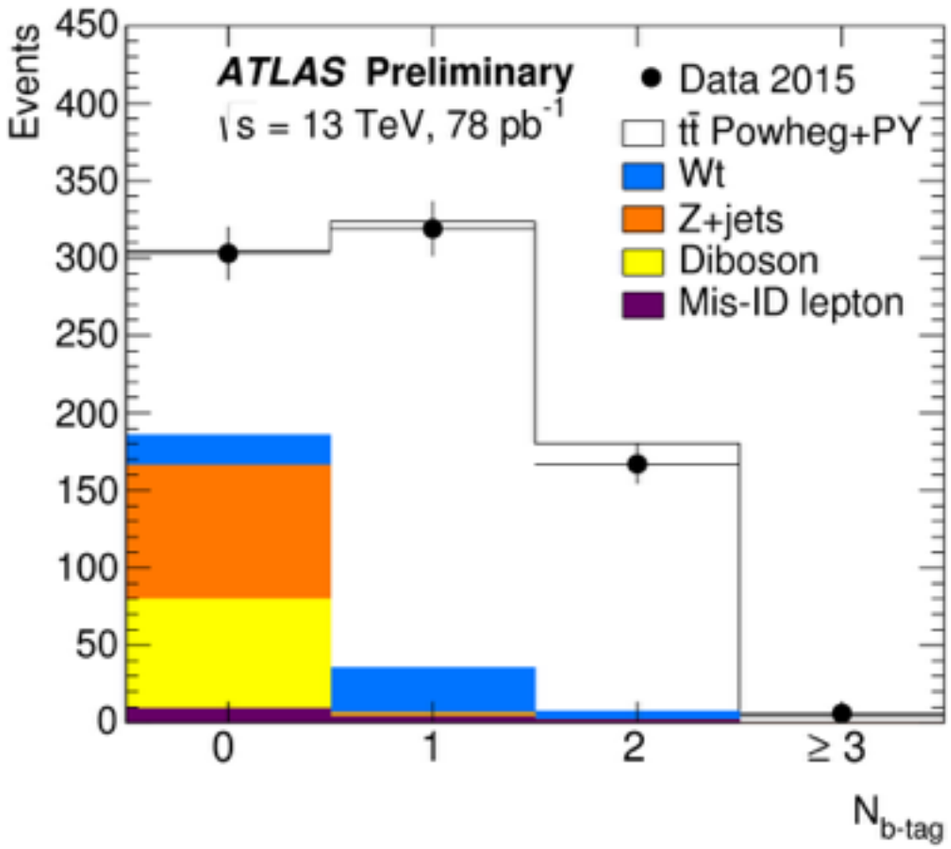
L	Luminosity of the data sample
$N_{1(2)}$	Number of selected events with 1(2) b-tags
$N_{1(2)}^{bkg}$	Number of background events with 1(2) b-tags
$\varepsilon_{e\mu}$	tt ➜ eμ selection efficiency and acceptance (~0.9%)
ε_b	Probability to b-tag q from t ➜ Wq
$C_b = \varepsilon_{bb} / \varepsilon_b^2$	Tagging correlation coefficient (1.005 +/- 0.006 from MC)

Event counts	N_1	N_2
Data	319	167
Wt single top	29.0 ± 3.8	5.6 ± 2.0
Dibosons	1.1 ± 0.2	0.0 ± 0.0
$Z(\rightarrow \tau\tau \rightarrow e\mu)$+jets	1.3 ± 0.7	0.1 ± 0.1
Misidentified leptons	6.0 ± 3.9	2.8 ± 2.9
Total background	37.3 ± 5.5	8.5 ± 3.5



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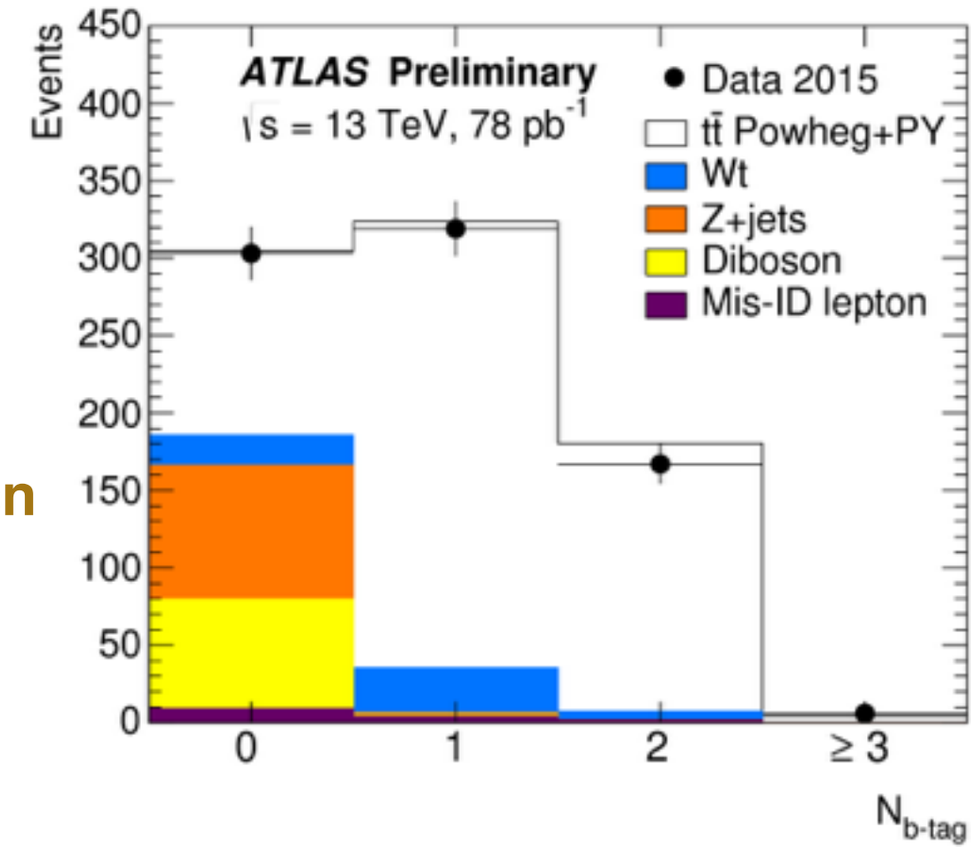
MC prediction



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- 'Misidentified leptons' consist of events with one real and one misidentified lepton
- Estimated from a combination of data and simulation
- Same-sign events with one or two b-tags are dominated by events with mis-identified leptons, with rates equivalent to those in OS samples
- $N_{1(2)}$mis-id predicted by subtracting the number of predicted prompt same-sign events from those in data and multiplying by the OS/SS ratio (from simulation)

Component	OS 1b	SS 1b	(OS/SS) R_1
Prompt	-	0.93 ± 0.06	-
Misidentified	4.03 ± 0.11	2.75 ± 0.10	1.47 ± 0.04
Total expectation	-	3.68 ± 0.11	-
Data	-	5	-

MC Simulation

$N_1^{\text{mis-id}} = (5 - 0.93) \cdot 1.47 = 6.0$

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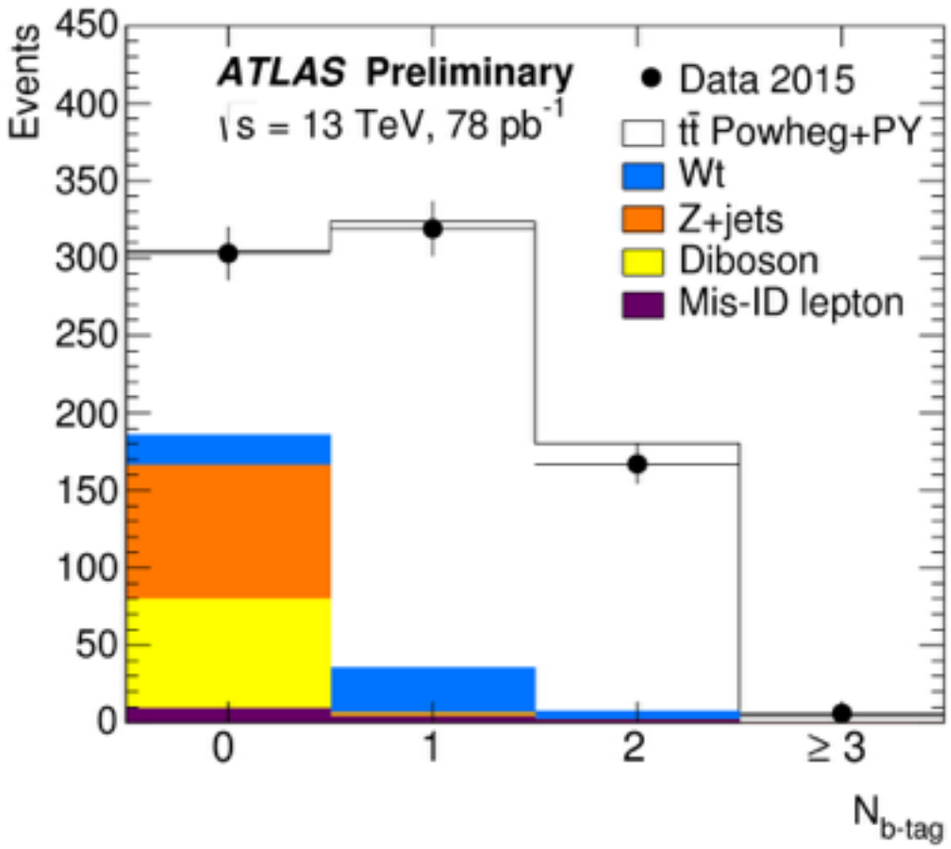

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Component	OS 1b	SS 1b	(OS/SS) R_1	OS 2b	SS 2b	(OS/SS) R_2
Prompt	-	0.93 ± 0.06	-	-	0.44 ± 0.04	-
Misidentified	4.03 ± 0.11	2.75 ± 0.10	1.47 ± 0.04	1.75 ± 0.07	0.98 ± 0.05	1.79 ± 0.07
Total expectation	-	3.68 ± 0.11	-	-	1.42 ± 0.07	-
Data	-	5	-	-	2	-

$N_2^{\text{mis-id}} = (2 - 0.44) \cdot 1.79 = 2.8$

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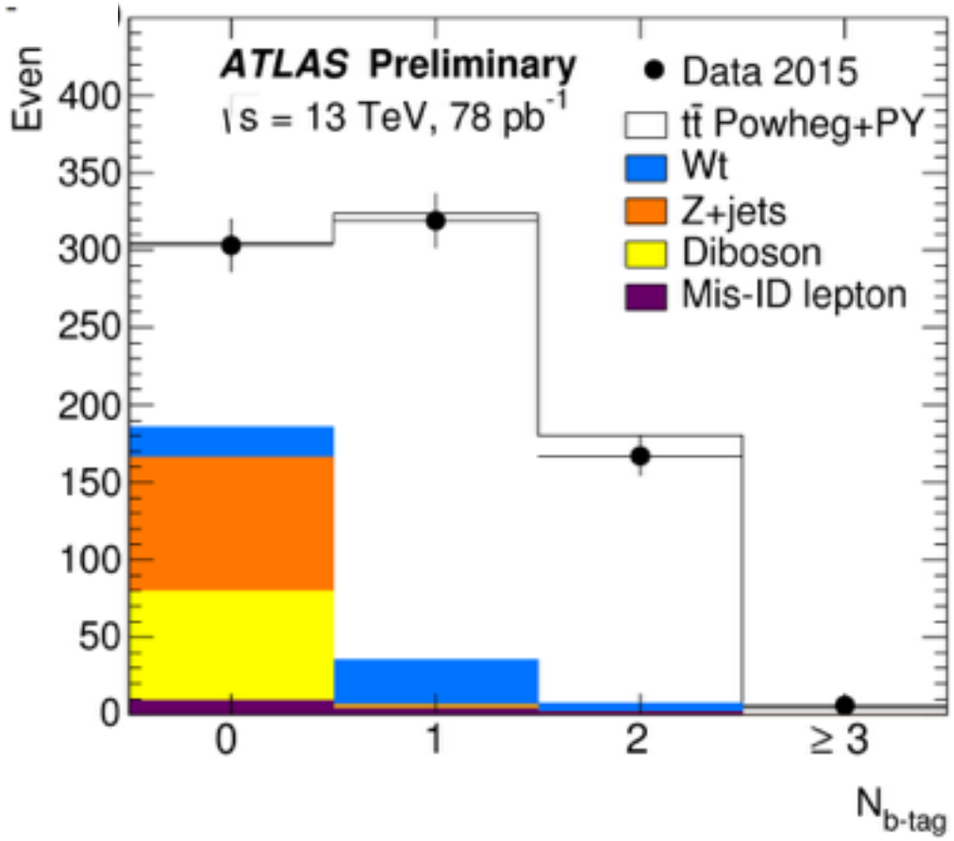

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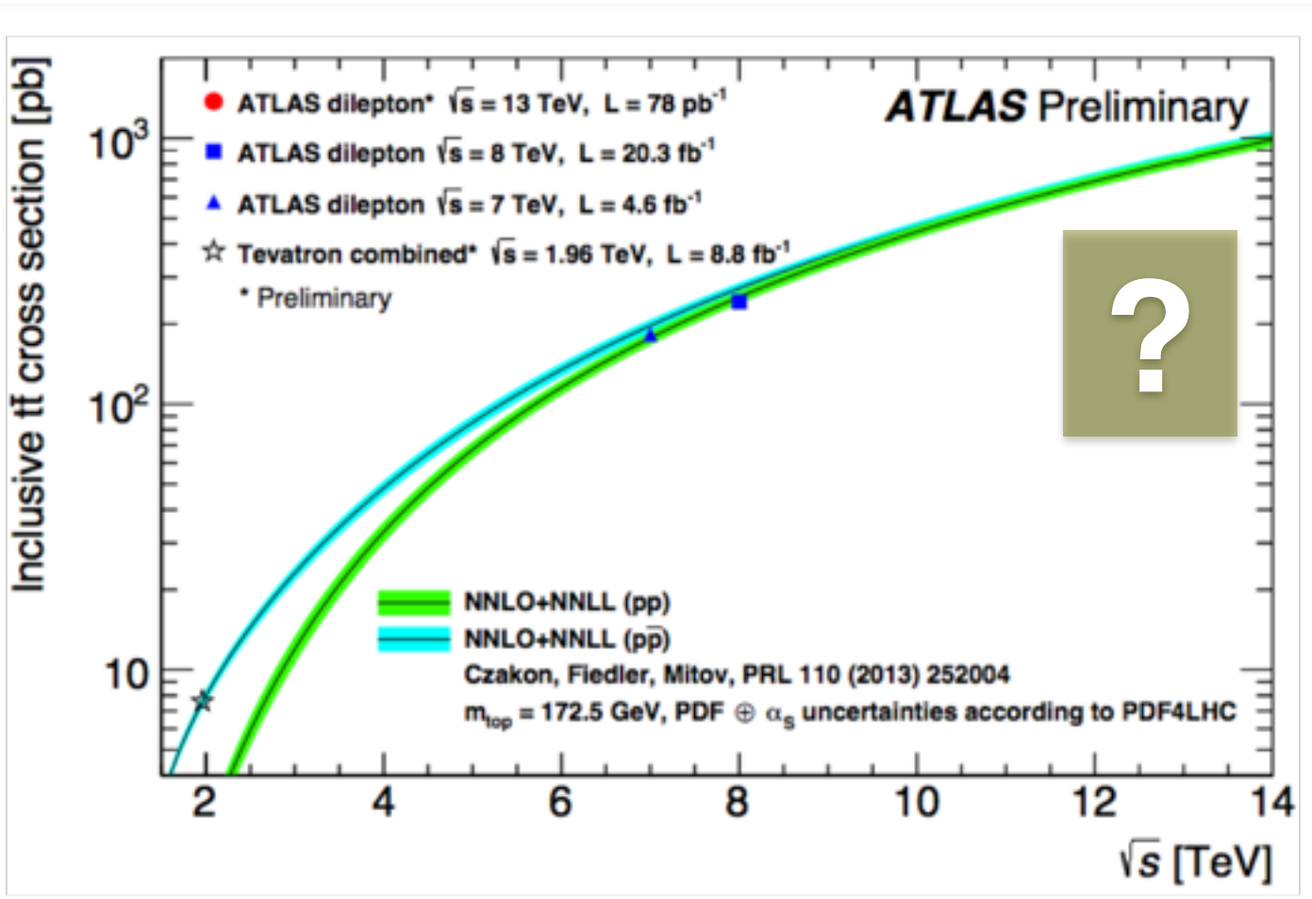

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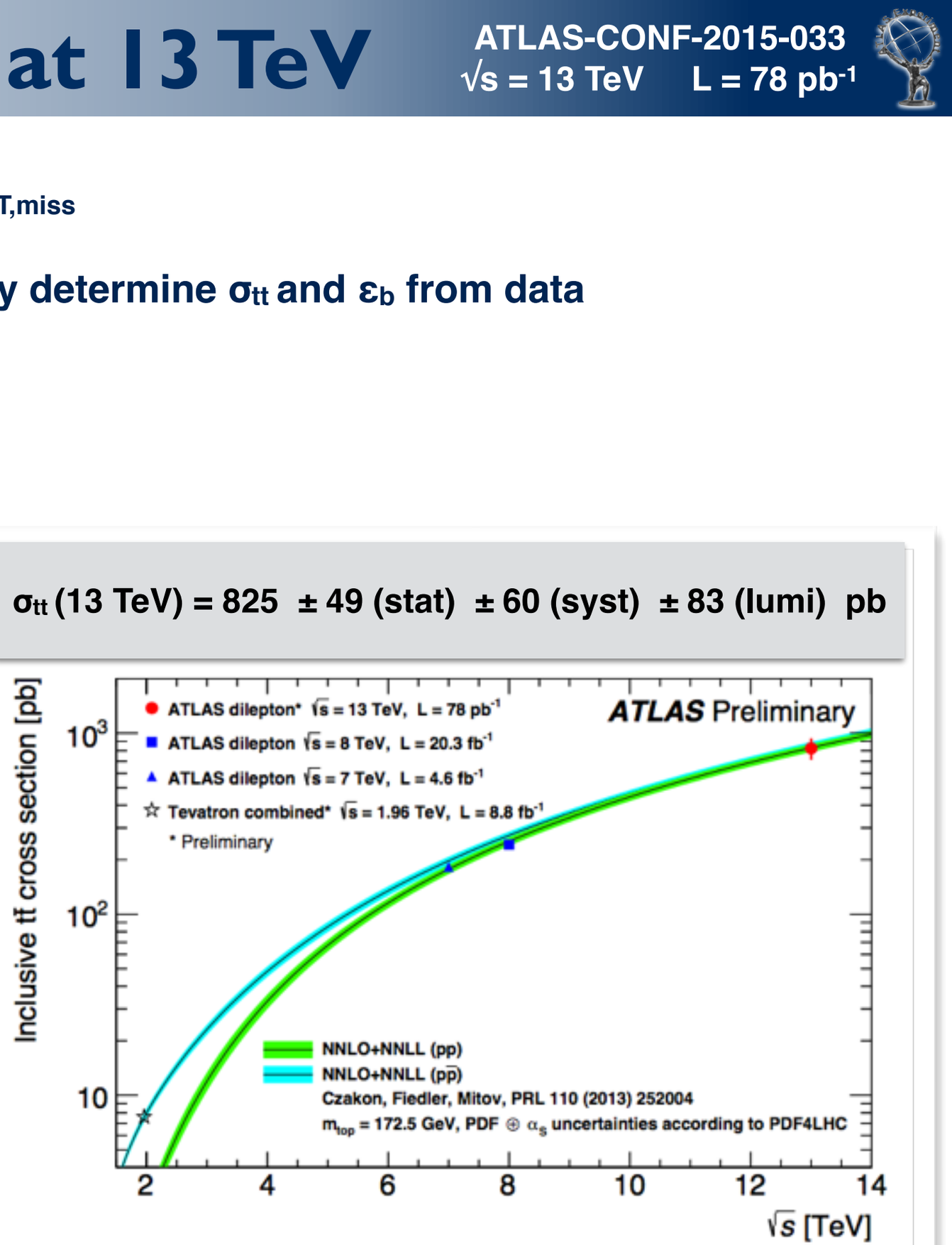
σ_{tt} (13 TeV) = 825 ± 49 (stat) ± 60 (syst) ± 83 (lumi) pb



First $\sigma_{t\bar{t}}$ with ATLAS at 13 TeV

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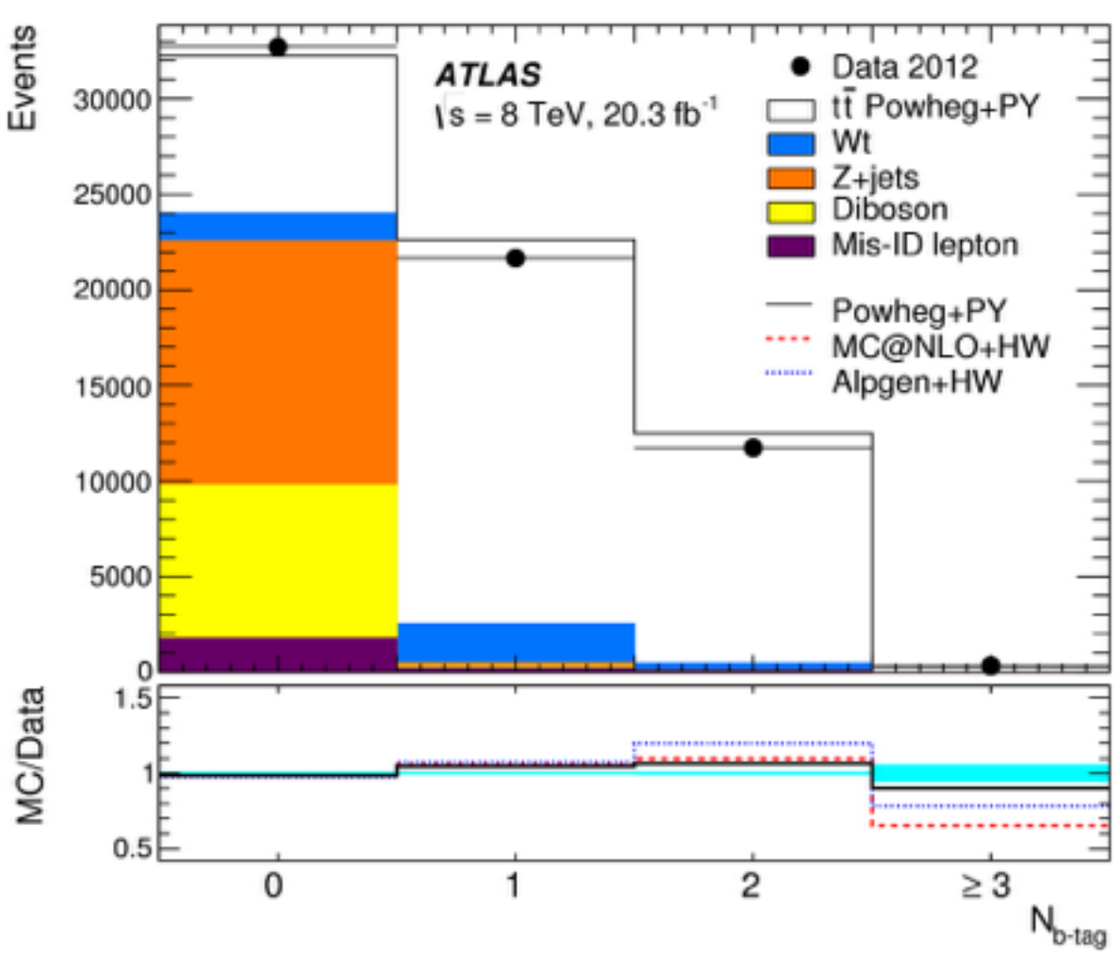
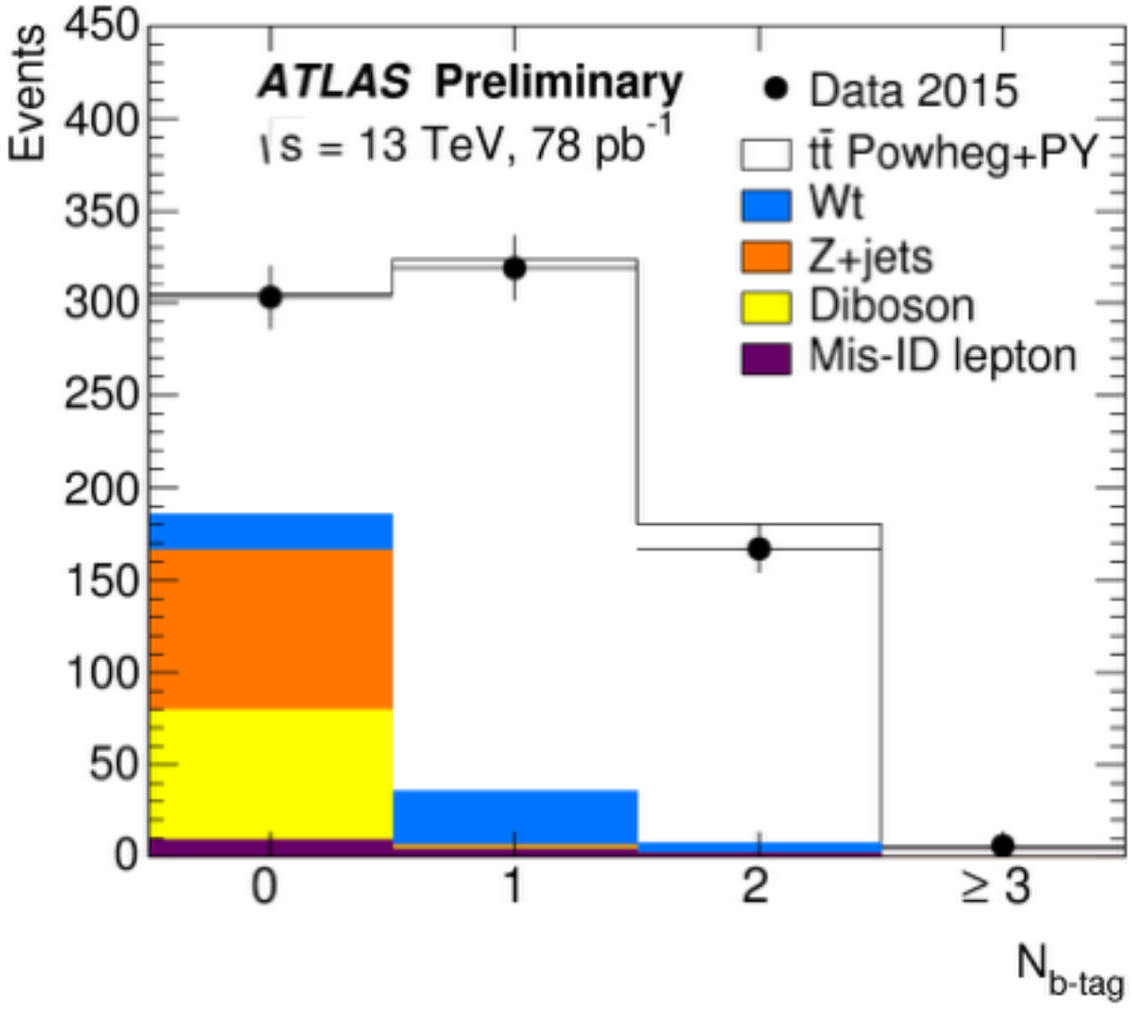
13 TeV Result has 14% relative uncertainty compared to 4.3% at 8 TeV

σ_{tt} (8 TeV) = 242.4 ± 10 pb

EPJC 74 (2014) 3109
$\sqrt{s}$ = 8 TeV L = 20 fb^{-1}

σ_{tt} (13 TeV) = 825 ± 49 (stat) ± 60 (syst) ± 83 (lumi) pb





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σ_{tt}[SM] (13 TeV) = 832^{+40}_{-46} pb (at NNLO + NNLL accuracy, m_t = 172.5 GeV, Top++ 2.0)

Uncertainty	$\Delta\epsilon_{e\mu}/\epsilon_{e\mu}$ (%)	$\Delta C_b/C_b$ (%)	$\Delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}}$ (%)
Data statistics			6.0
$t\bar{t}$ NLO modelling	1.9	-0.3	2.2
$t\bar{t}$ hadronisation	-4.0	0.5	4.5
Initial/final state radiation	-1.1	0.1	1.2
Parton distribution functions	1.3	-	1.4
Single-top generator*	-	-	0.5
Single-top/$t\bar{t}$ interference*	-	-	0.1
Single-top Wt cross-section	-	-	0.5
Diboson modelling*	-	-	0.1
Diboson cross-sections	-	-	0.0
Z+jets extrapolation	-	-	0.2
Electron energy scale/resolution	0.2	0.0	0.2
Electron identification	3.6	0.0	4.0
Electron isolation	1.0	-	1.1
Muon momentum scale/resolution	0.0	0.0	0.1
Muon identification	1.1	0.0	1.2
Muon isolation	1.0	-	1.1
Lepton trigger	1.3	0.0	1.3
Jet energy scale	-0.3	0.0	0.3
Jet energy resolution	-0.1	0.0	0.1
b-tagging	-	0.1	0.3
Misidentified leptons	-	-	1.3
Analysis systematics	6.4	0.6	7.3
Integrated luminosity	-	-	10.0
Total uncertainty	6.4	0.6	13.7

➡ *Large Pythia8 / Herwig++ parton shower effect, to be further studied*

➡ *will improve with more data*

➡ *will improve with Van der Meer Luminosity Scan*

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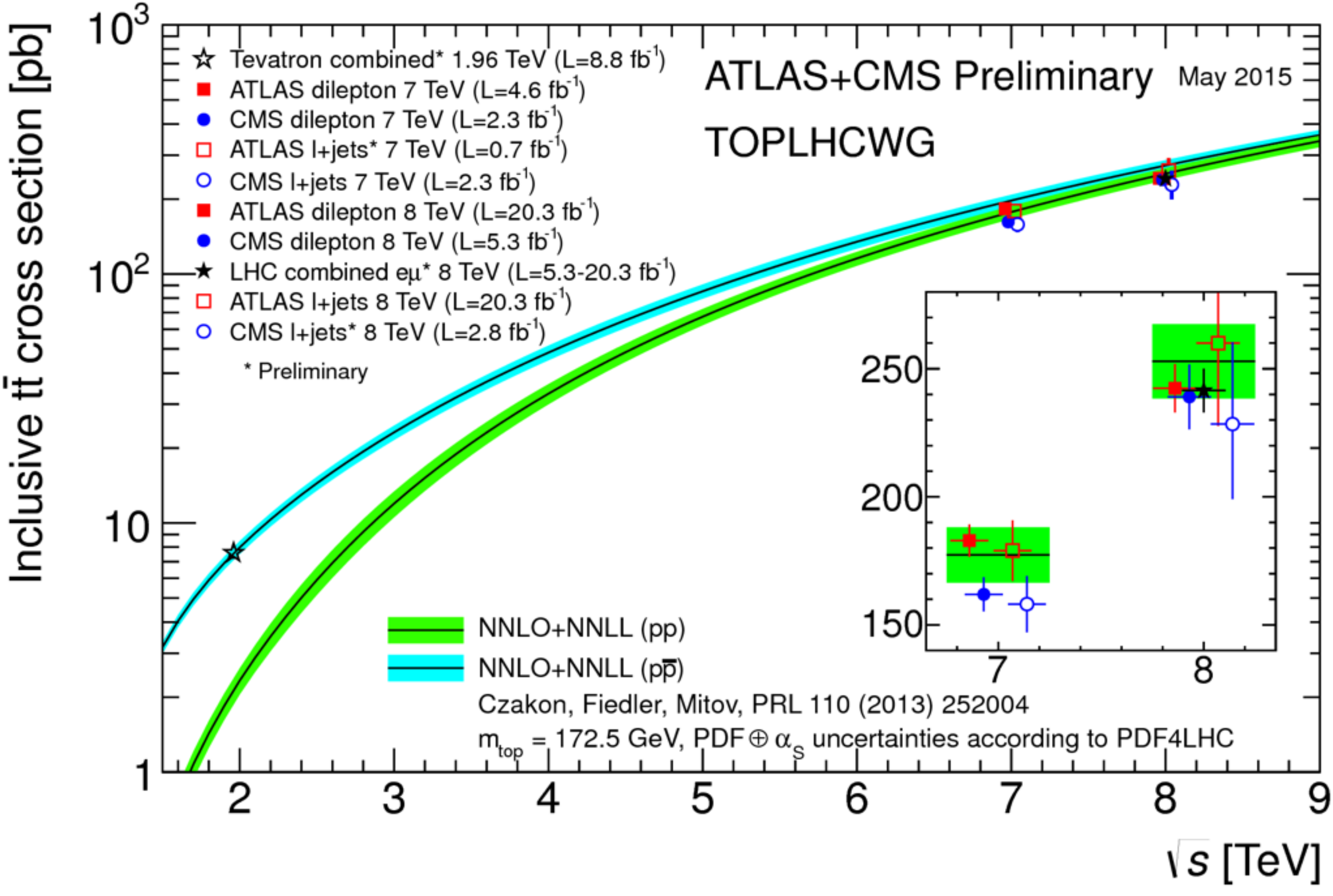
ε_b	Probability to b-tag q from t ➜ Wq
$C_b = \varepsilon_{bb} / \varepsilon_b^2$	Tagging correlation coefficient (1.005 +/- 0.006 from MC)

$$\varepsilon_b = 0.527 \pm 0.026\ (stat) \pm 0.006\ (syst)$$

In good agreement with simulation ➜ 0.543


ATLAS+CMS Preliminary May 2015
TOPLHCWG
Tevatron combined* 1.96 TeV (L=8.8 fb-1)
ATLAS dilepton 7 TeV (L=4.6 fb-1)
CMS dilepton 7 TeV (L=2.3 fb-1)
ATLAS l+jets* 7 TeV (L=0.7 fb-1)
CMS l+jets 7 TeV (L=2.3 fb-1)
ATLAS dilepton 8 TeV (L=20.3 fb-1)
CMS dilepton 8 TeV (L=5.3 fb-1)
LHC combined eμ* 8 TeV (L=5.3-20.3 fb-1)
ATLAS l+jets 8 TeV (L=20.3 fb-1)
CMS l+jets* 8 TeV (L=2.8 fb-1)
* Preliminary
NNLO+NNLL (pp)
NNLO+NNLL (pp̄)
Czakon, Fiedler, Mitov, PRL 110 (2013) 252004
mtop = 172.5 GeV, PDF ⊕ αS uncertainties according to PDF4LHC
Inclusive tt̄ cross section [pb]
√s [TeV]

Differential Cross-Sections

- **Inclusive measurements for all energies (so far) agree with the SM, but what about the shape of differential distributions?**

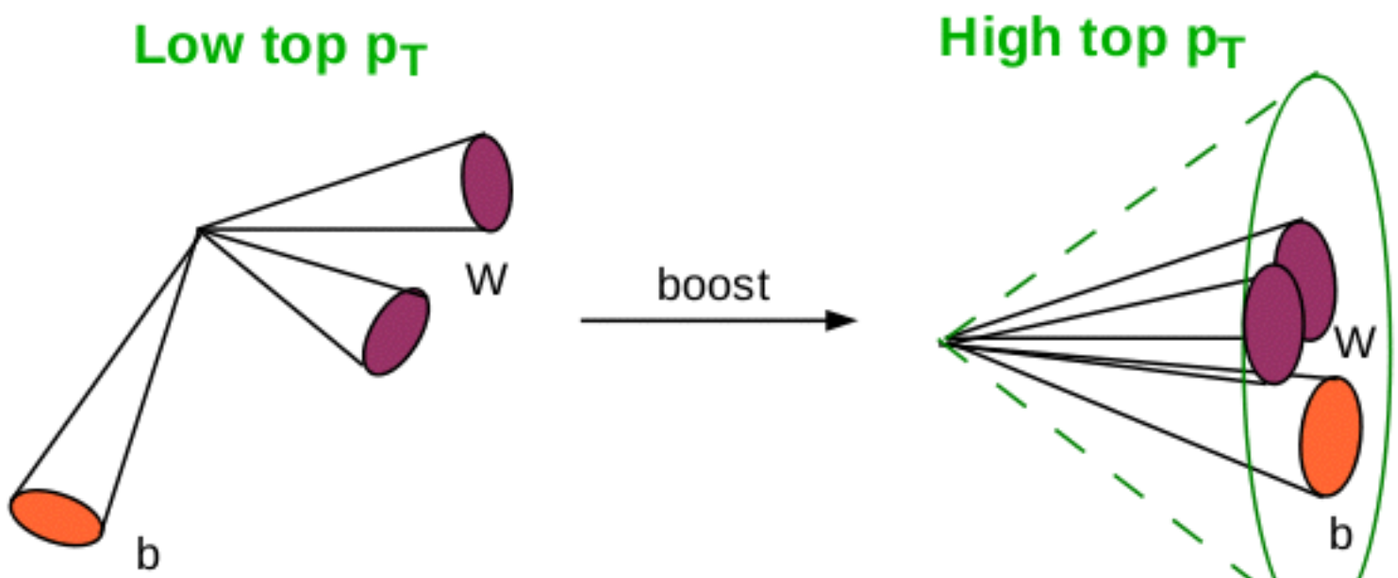
- **Requires the reconstruction of top kinematics ➜ two strategies…**

Resolved

- **Optimized for top quarks with $p_T < 300$ GeV**
- **Decay products are well separated and can be reconstructed individually**
- **Top kinematics determined from reconstructed decay products**

Boosted

- **Optimized for top quarks with $p_T > 300$ GeV**
- **Decay products are not isolated**
- **Hadronically decaying top quark is reconstructed as a single large radius jet**



Differential Cross-Sections

- **Inclusive measurements for all energies (so far) agree with the SM, but what about the shape of differential distributions?**

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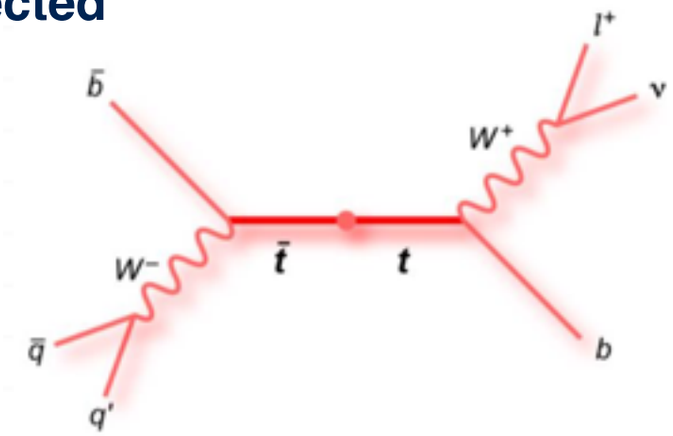
Resolved

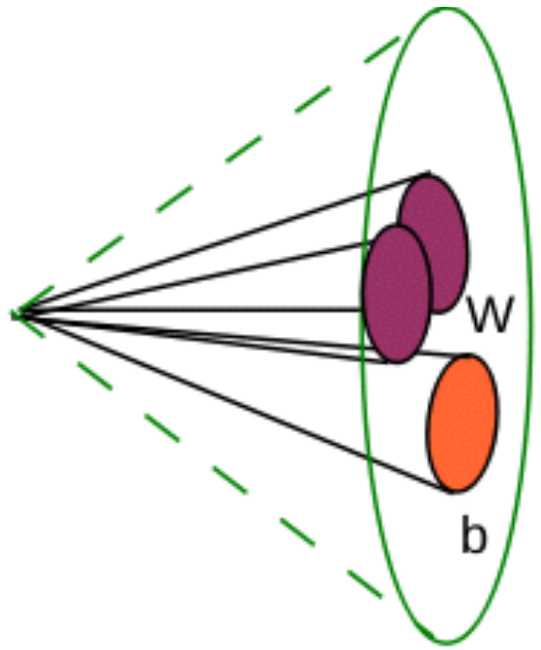
- **Likelihood-based reconstruction, matching jets to partons in a top pair event**
- **Observables (4 or 5 jets, lepton, $E_{T,miss}$) fed to likelihood and permutation w/ max likelihood is selected**



$$
\begin{aligned}
\mathcal{L} \;=\; & \mathcal{B}\left(\widetilde{E}_{p,1}, \widetilde{E}_{p,2} | m_W, \Gamma_W\right) \cdot \mathcal{B}\left(\widetilde{E}_l, \widetilde{E}_\nu | m_W, \Gamma_W\right) \cdot \\
& \cdot \; \mathcal{B}\left(\widetilde{E}_{p,1}, \widetilde{E}_{p,2}, \widetilde{E}_{p,3} | m_t, \Gamma_t\right) \cdot \mathcal{B}\left(\widetilde{E}_l, \widetilde{E}_\nu, \widetilde{E}_{p,4} | m_t, \Gamma_t\right) \cdot \\
& \cdot \; \mathcal{W}\left(\widehat{E}_x^{miss} | \tilde{p}_{x,\nu}\right) \cdot \mathcal{W}\left(\widehat{E}_y^{miss} | \tilde{p}_{y,\nu}\right) \cdot \mathcal{W}\left(\widehat{E}_{lep} | \widetilde{E}_{lep}\right) \cdot \\
& \cdot \; \prod_{i=1}^{4} \mathcal{W}\left(\widehat{E}_{jet,i} | \widetilde{E}_{p,i}\right) \cdot P\left(b \text{ tag} \mid \text{quark}\right),
\end{aligned}
$$

Boosted

- **Hadronically decaying top quark is reconstructed as a single large radius jet**
- **Leading Anti-kt R=1.0 jet after trimming:**
  - **p_T > 300 GeV**
  - **m > 100 GeV**
  - **$\sqrt{d_{12}}$ > 40 GeV**
  - **Some ΔR isolation requirements**

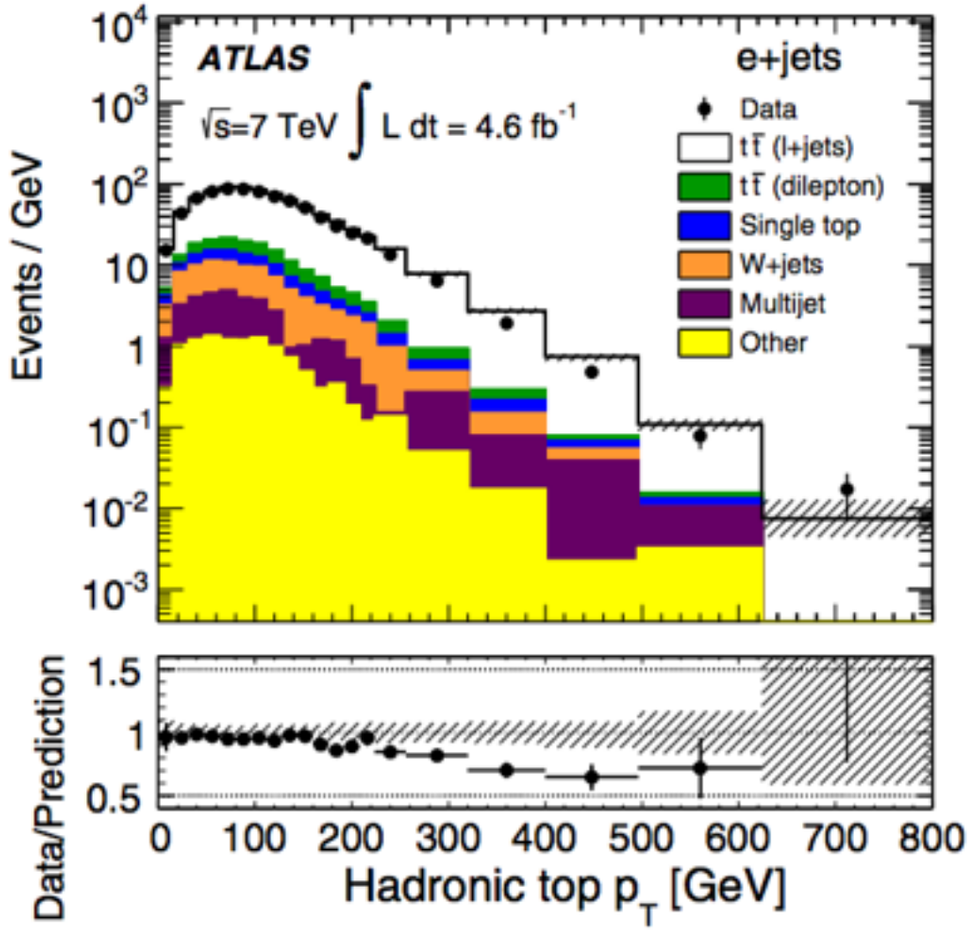


Differential Cross-Sections

The detector-level spectra are connected to the 'parton level' cross section σ_j by

$$N_i = \sum_j M_{ij} \cdot \varepsilon_j \cdot \sigma_j \cdot \beta \cdot L + B_i$$

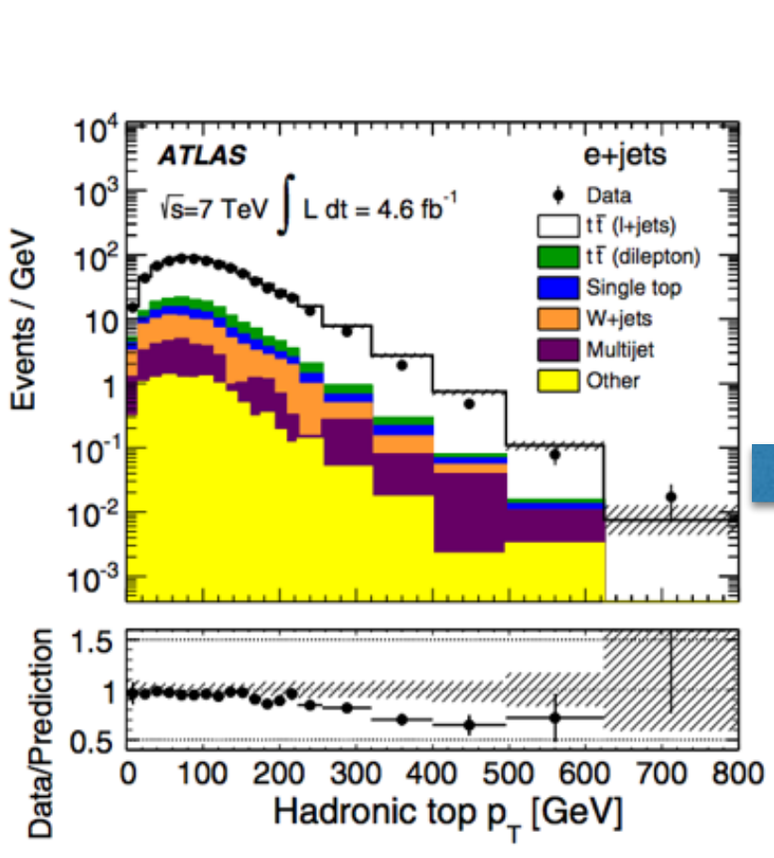
- N_i **is the number of observed data events in bin i**
- L **is the luminosity**
- B_i **is the number of background events in bin i**
- β **is the branching ratio**
- M_{ij} **is the 'migration matrix'**
- ε_j **is the efficiency of the selection**

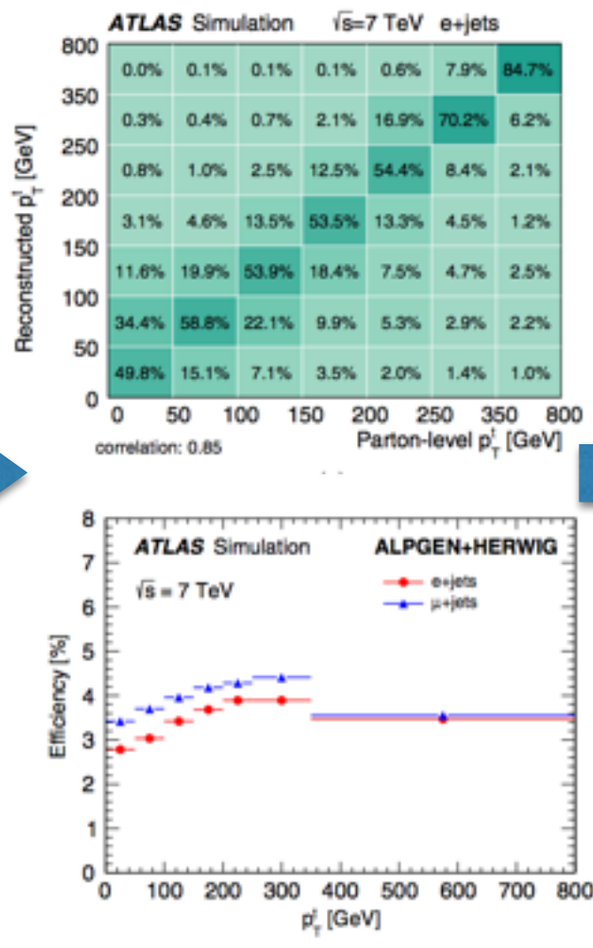


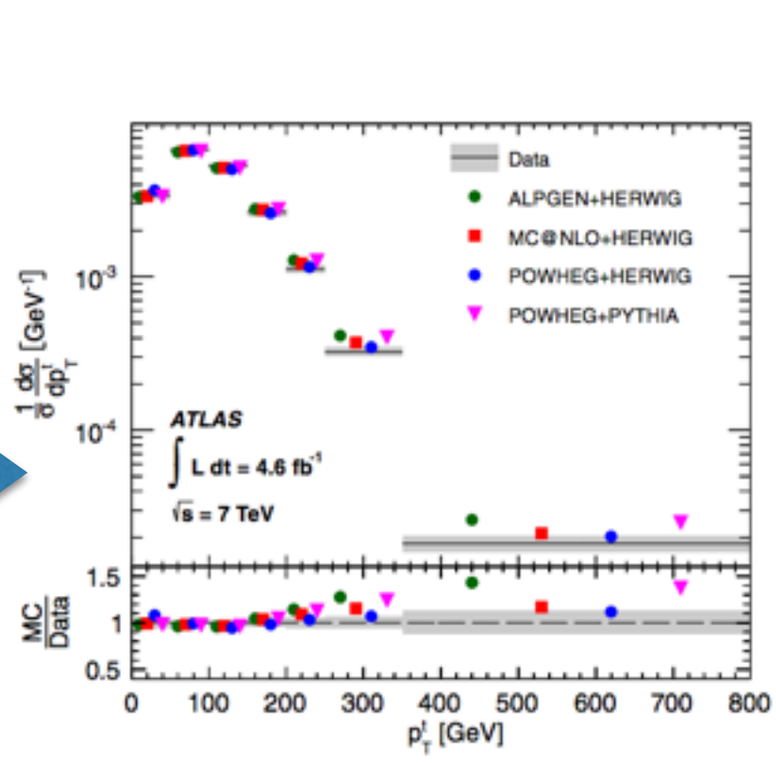
Resolved Differential

PHYS REV D90 072004
$\sqrt{s}$ = 7 TeV L = 4.6 fb^{-1}

- Measuring $1/\sigma\, d\sigma/dX$ for several kinematics: X = m_{tt} $p_{T,tt}$ $p_{T,t}$ $|y_{tt}|$
- Relative measurements more precise than absolute as cancellation of correlated systematics
- Lepton+Jets channel is reconstructed by kinematic likelihood fit
- parton level measurement extracted by unfolding and applying acceptance corrections



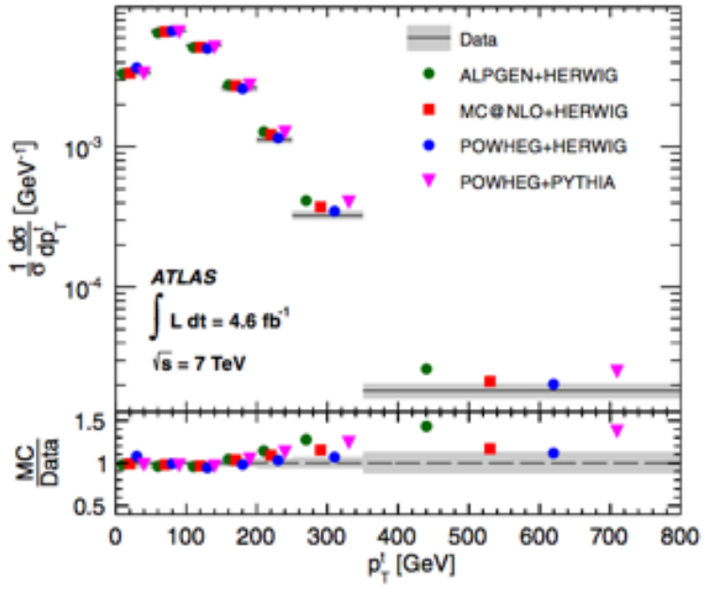


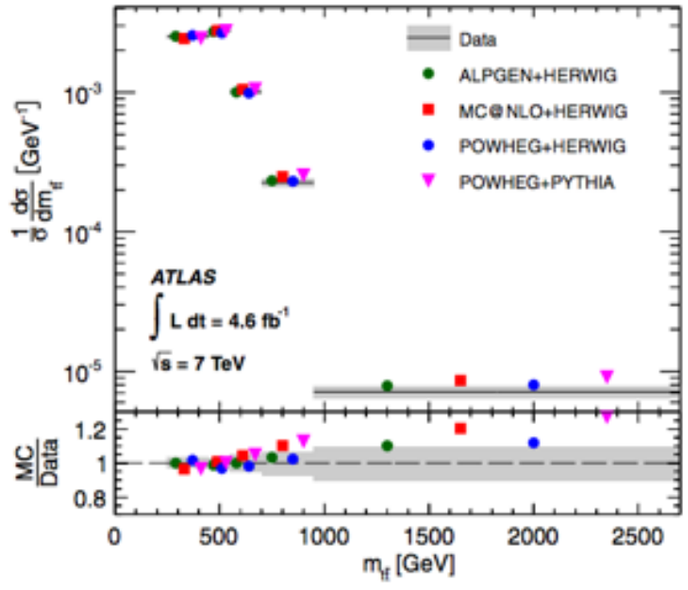


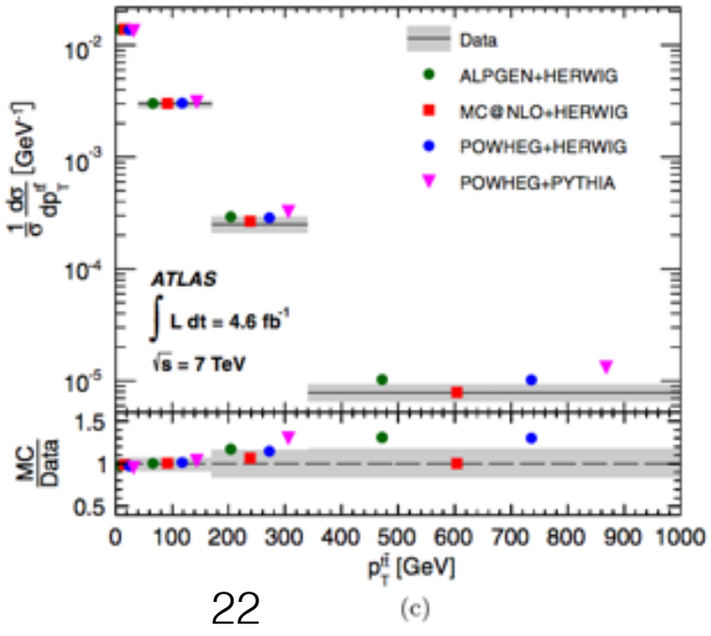
Resolved Differential

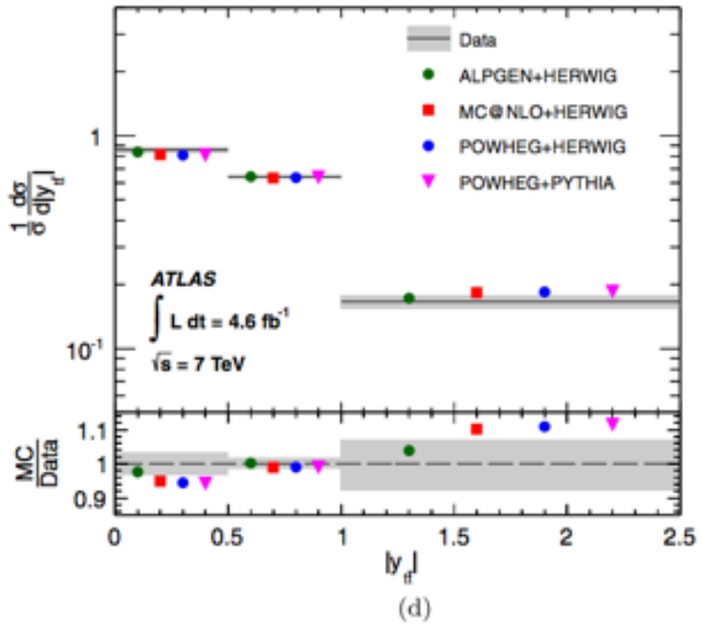
PHYS REV D90 072004
$\sqrt{s}$ = 7 TeV L = 4.6 fb^{-1}

- Comparison to MC generators Alpgen, Powheg, and MC@NLO interfaced with Herwig+Jimmy and Powheg+Pythis
- General trend of data being softer in $p_{T,t}$ above 200 GeV
- All four MC generators well describe the shape of m_{tt} and $P_{T,tt}$
- Alpgen gives the best prediction of $|y_{tt}|$
- Main Uncertainties:
  - ➡ $p_{T,t}$ & m_{tt}: JES, generator, b-tag
  - ➡ $p_{T,tt}$: IFSR, generator, PS, JER
  - ➡ $|y_{tt}|$: generator and PS







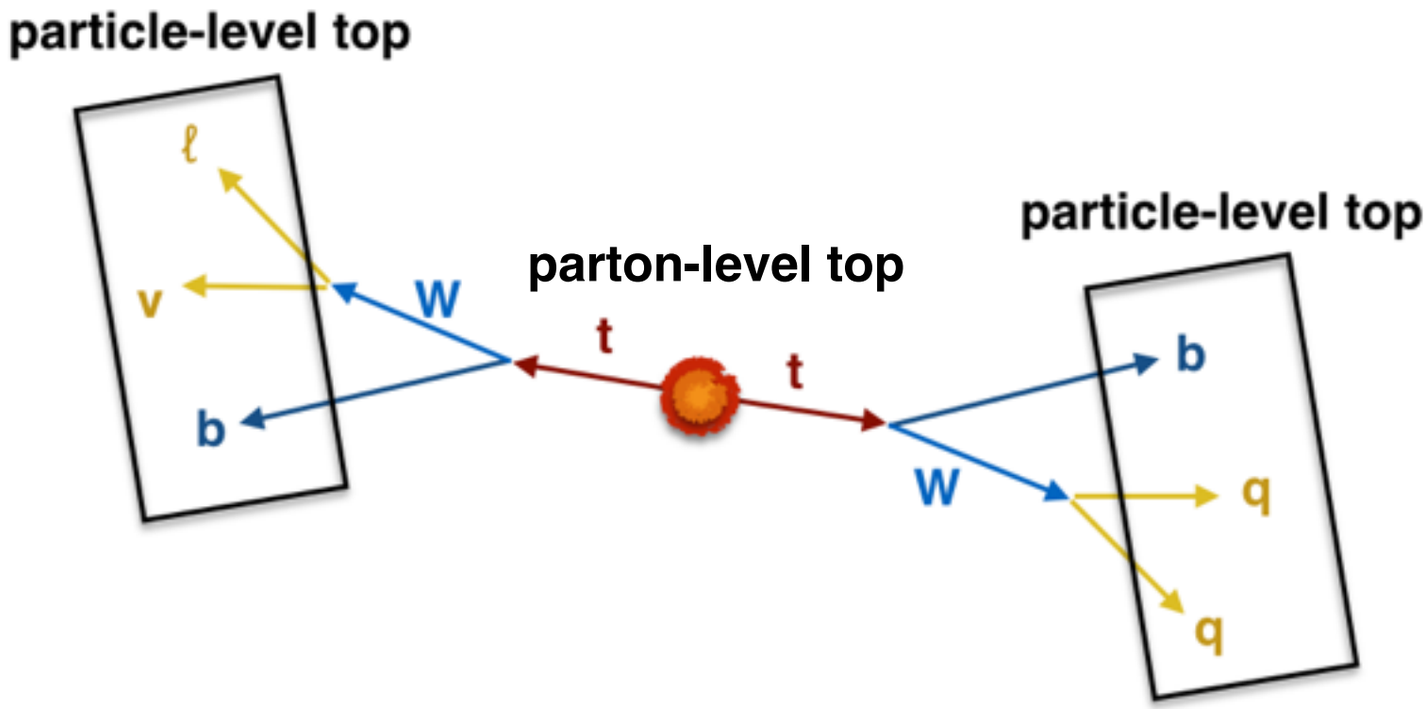


‘Parton-level’ top

Top quark approximately after final state radiation and before decay

‘Particle-level’ top (or pseudo-top)

Observable constructed from stable particles directly related to the top quark

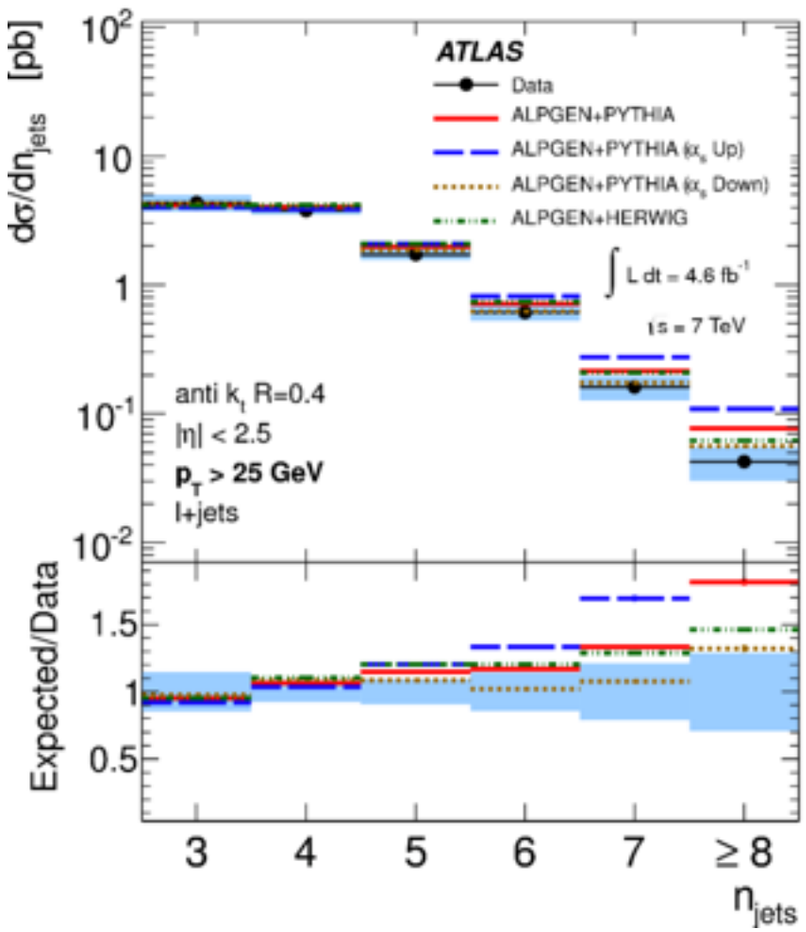


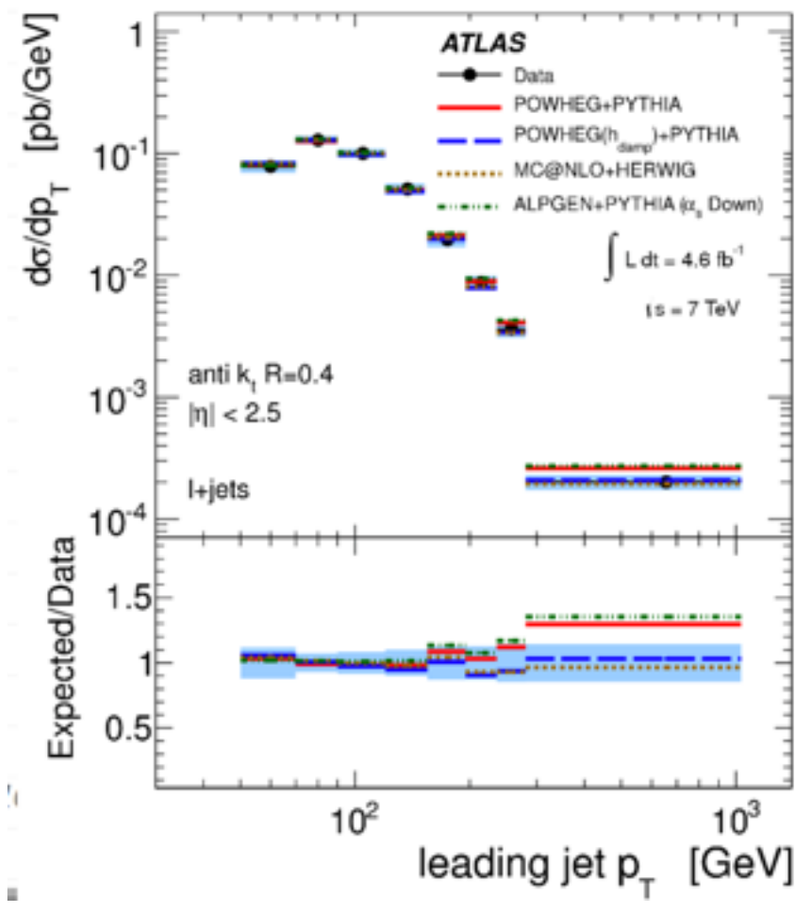
- **Leptons and jets are defined using particles with mean lifetime > 3×10^{-11}**
- **Includes prompt leptons not generated by the decay of a hadron and leptons coming from the decay of a tau**
- **Leptons are ‘dressed’ with photons within R < 0.1 of the lepton**
- **Jets reconstructed from stable particles except for selected electrons, muons, and neutrinos using anti-kt R=0.4**
- **Missing energy is the vector sum of the neutrinos four-momenta**
- **Events are ‘selected’ at particle level by applying same requirements to the ‘reco-level’ objects**

Resolved Differential

JHEP 01(2015) 020
$\sqrt{s}$ = 7 TeV L = 4.6 fb^{-1}

- Study 'particle-level' differential measurements of tt+jets
- $d\sigma/dN_{jets}$ sensitive to hard emissions in QCD bremsstrahlung processes
- $d\sigma/dp_{T,jet}$ sensitive to modeling of higher-order QCD effects in MC
- Limited by systematic uncertainties: background modeling ($n_{jet} < 4$) and jet energy scale ($n_{jets} \geq 4$)

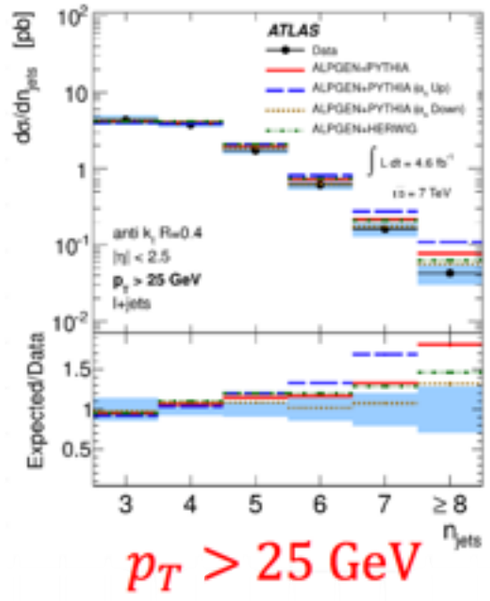


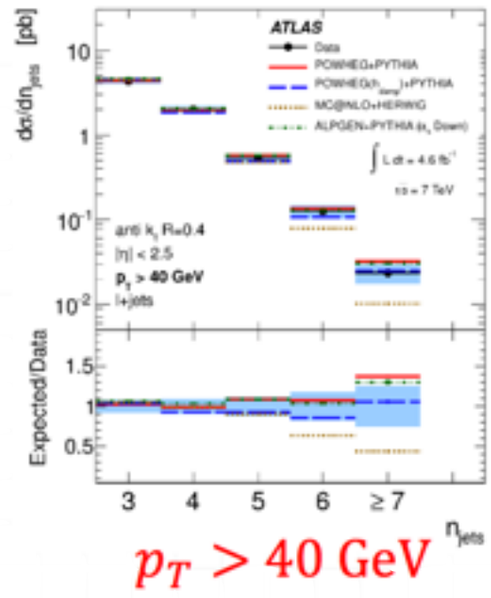


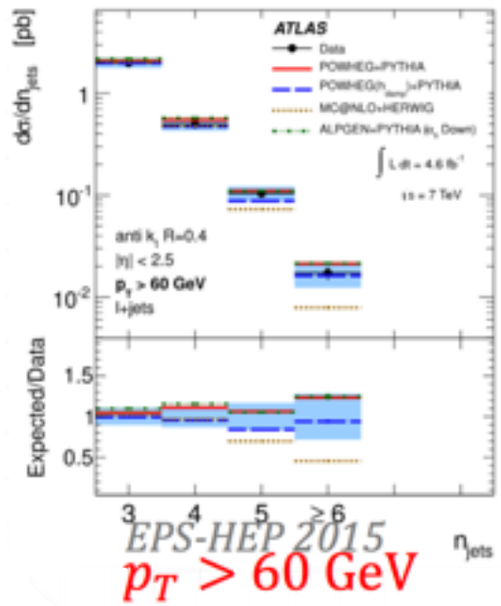
Jet multiplicity in tt final states

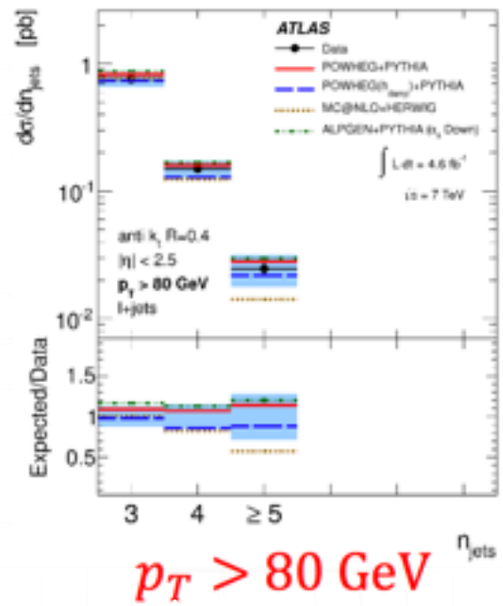
JHEP 01(2015) 020
$\sqrt{s}$ = 7 TeV L = 4.6 fb^{-1}

- Useful to constrain models of initial and final state radiation
- Test of perturbative QCD
- Single lepton channel with four p_T thresholds (25, 40, 60 and 80 GeV)
- Results are corrected to particle level through all detector effects
- MC@NLO modeling predicts a lower jet multiplicity spectrum and softer jets
- Alpgen+Herwig or Pythia and Powheg + Pythia are consistent with data





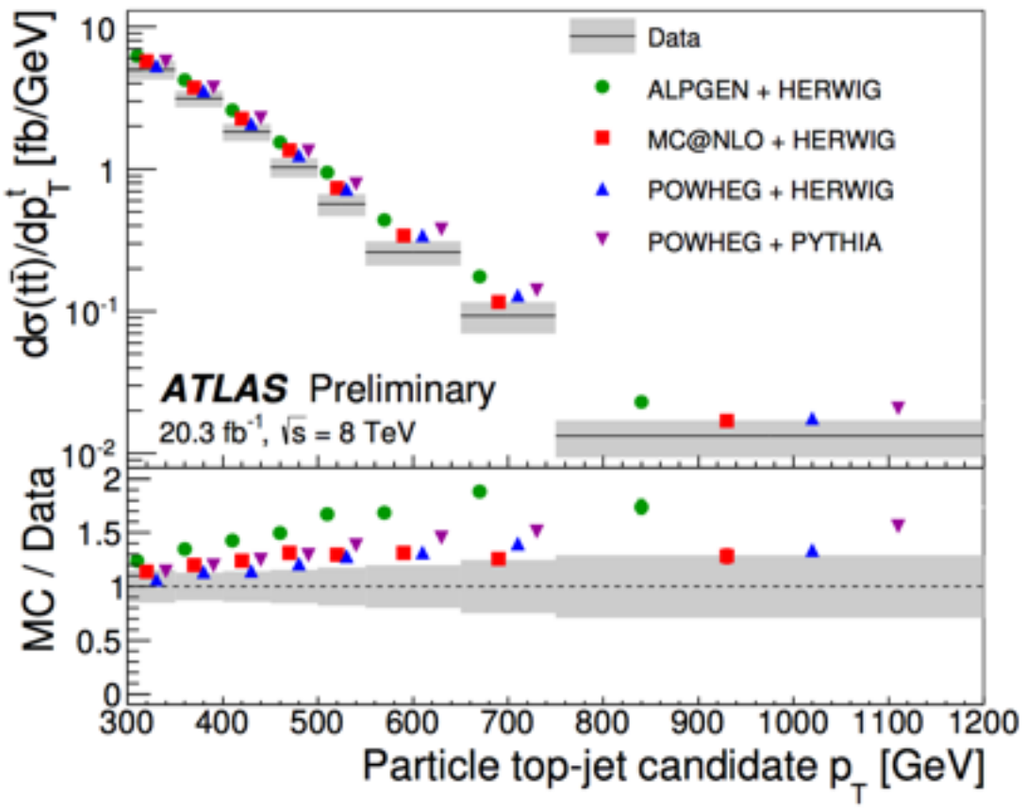


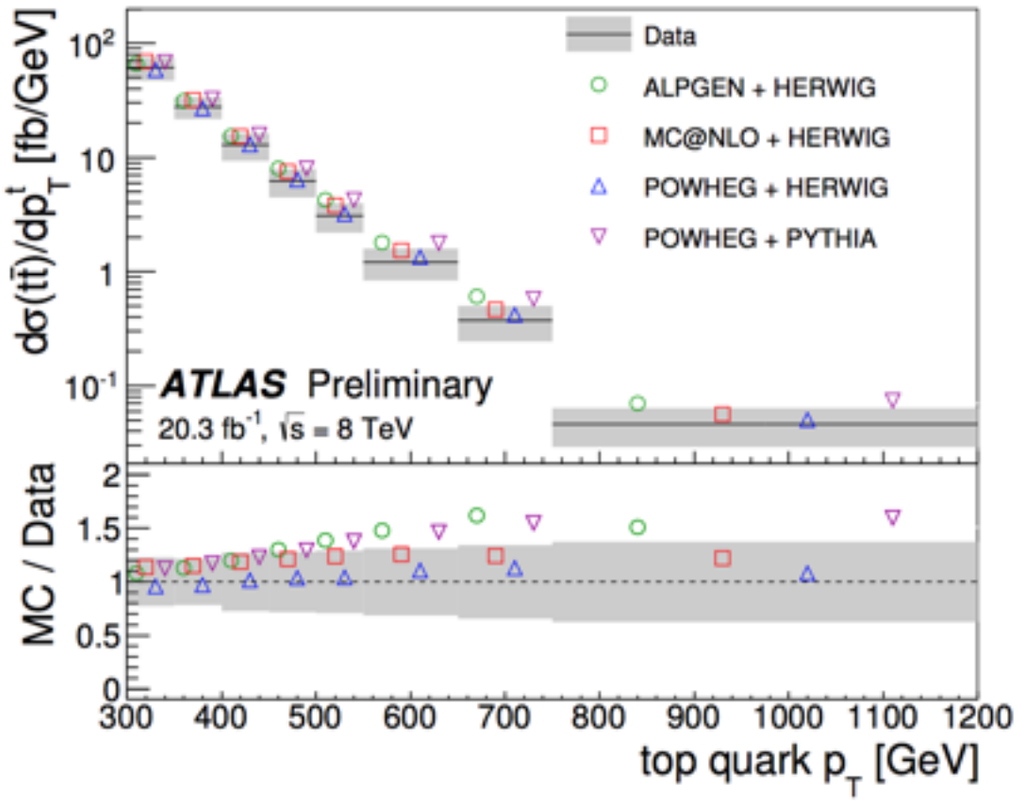


Boosted Differential

ATLAS-CONF-2014-057
$\sqrt{s}$ = 8 TeV L = 20 fb^{-1}

- First measurement of $d\sigma/dp_T$ for high-p_T (boosted) top quarks
- Require high-p_T lepton + additional jets ➜ boosted Hadronic top with single large R-jet p_T > 300 GeV
- Fiducial (pseudo-tops) and parton level measurements performed ➜ extrapolation to particle level affected by an increased signal modeling systematics
- Large-R jet energy scale dominates uncertainties



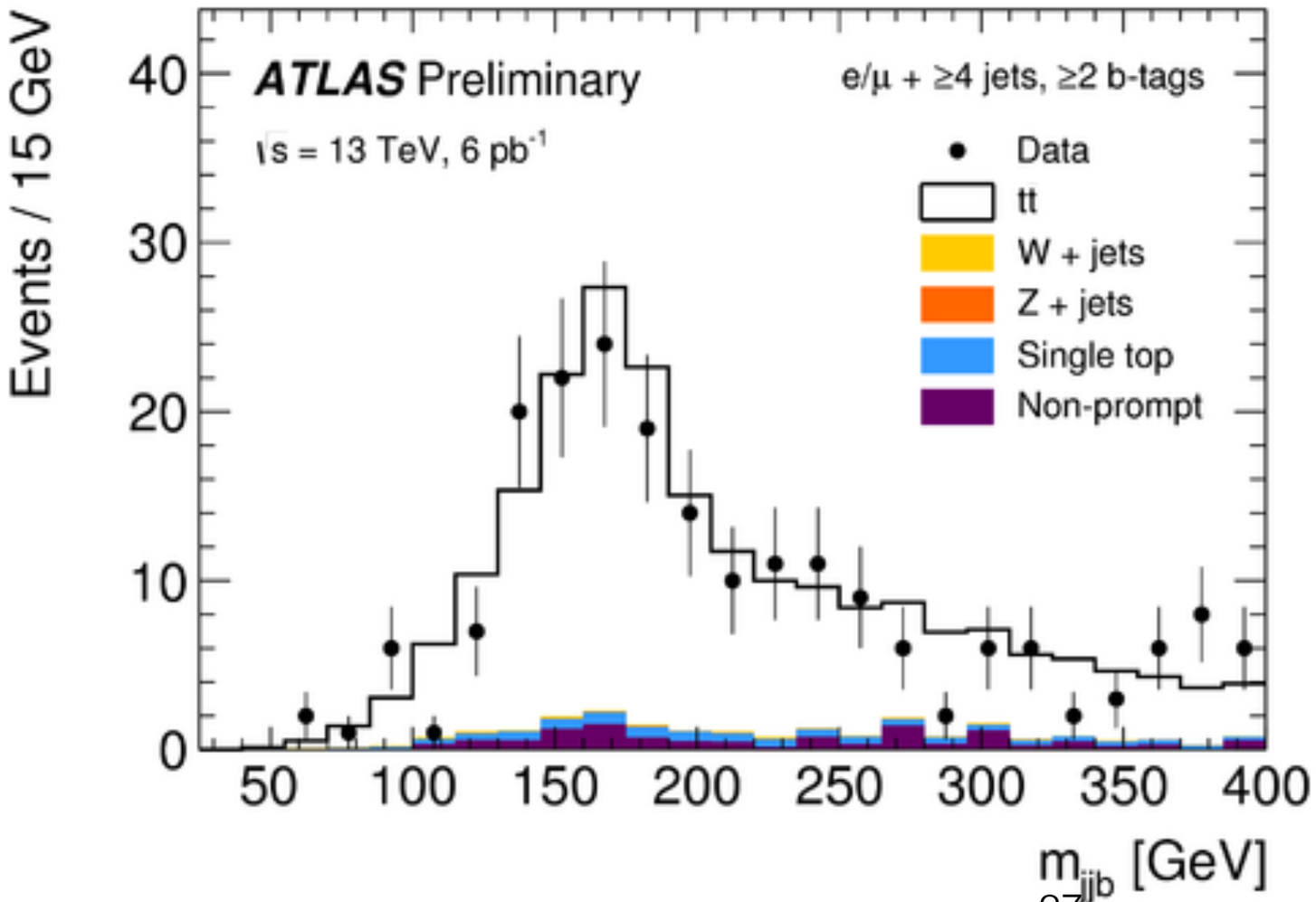


Data generally lower then predictions and worse at high P_T (behavior seen in resolved analyses)

13 TeV Top Quark Eye-Candy

ATLAS-PHYS-PUB-2015-017
$\sqrt{s}$ = 13 TeV L = 6 pb^{-1}

- Kinematic distributions enriched in top quark events
- Data collected by ATLAS on June 13th and 14th
- Single high-p_T lepton (e/μ) and dilepton (ee/μμ/eμ) candidate events
- Background and tt are normalized to SM predictions and scaled to the data
- Corrections for jets derived using MC simulations which describe changes in detector and data taking conditions from 2012 to 2015 ➜ x-checked with Run 2 data



b-jet that has largest ΔR with lepton is combined with the two highest p_T un-tagged jets

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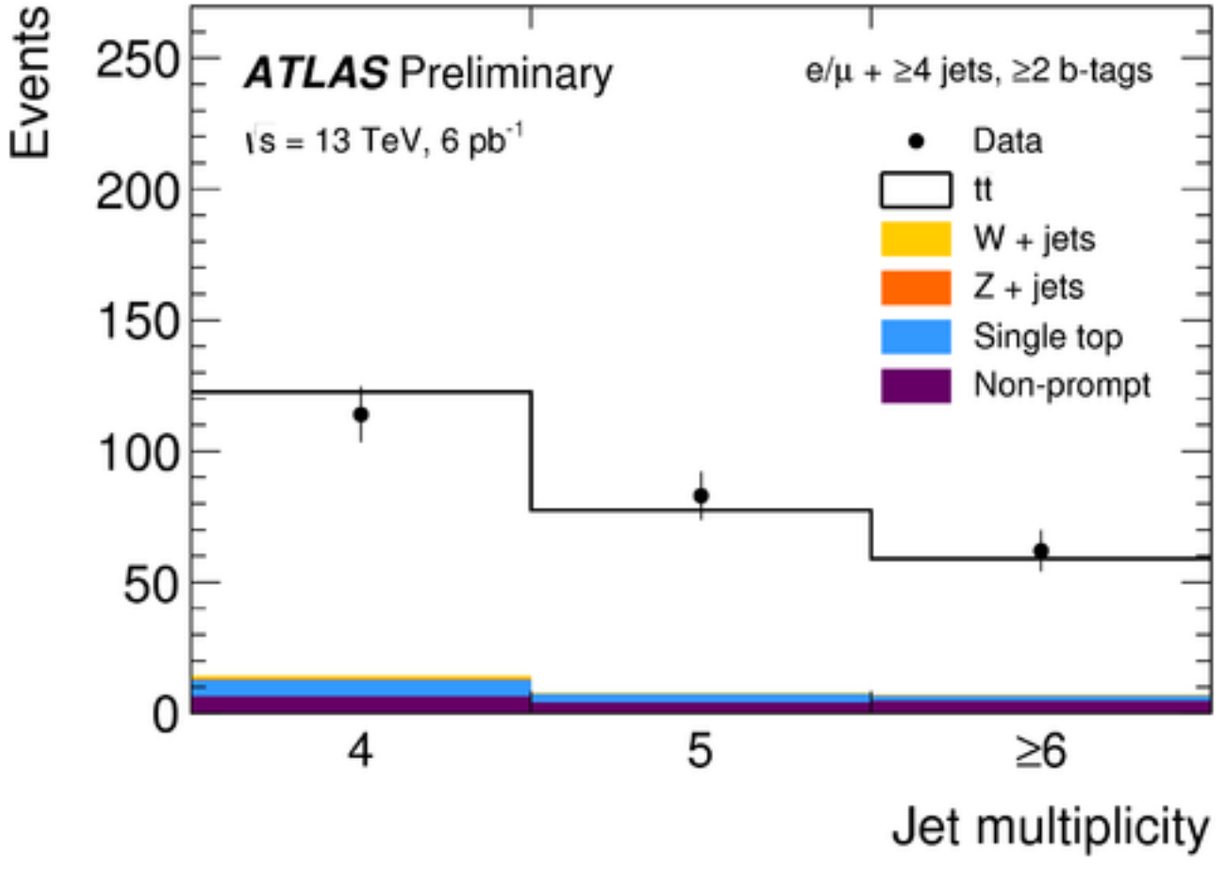

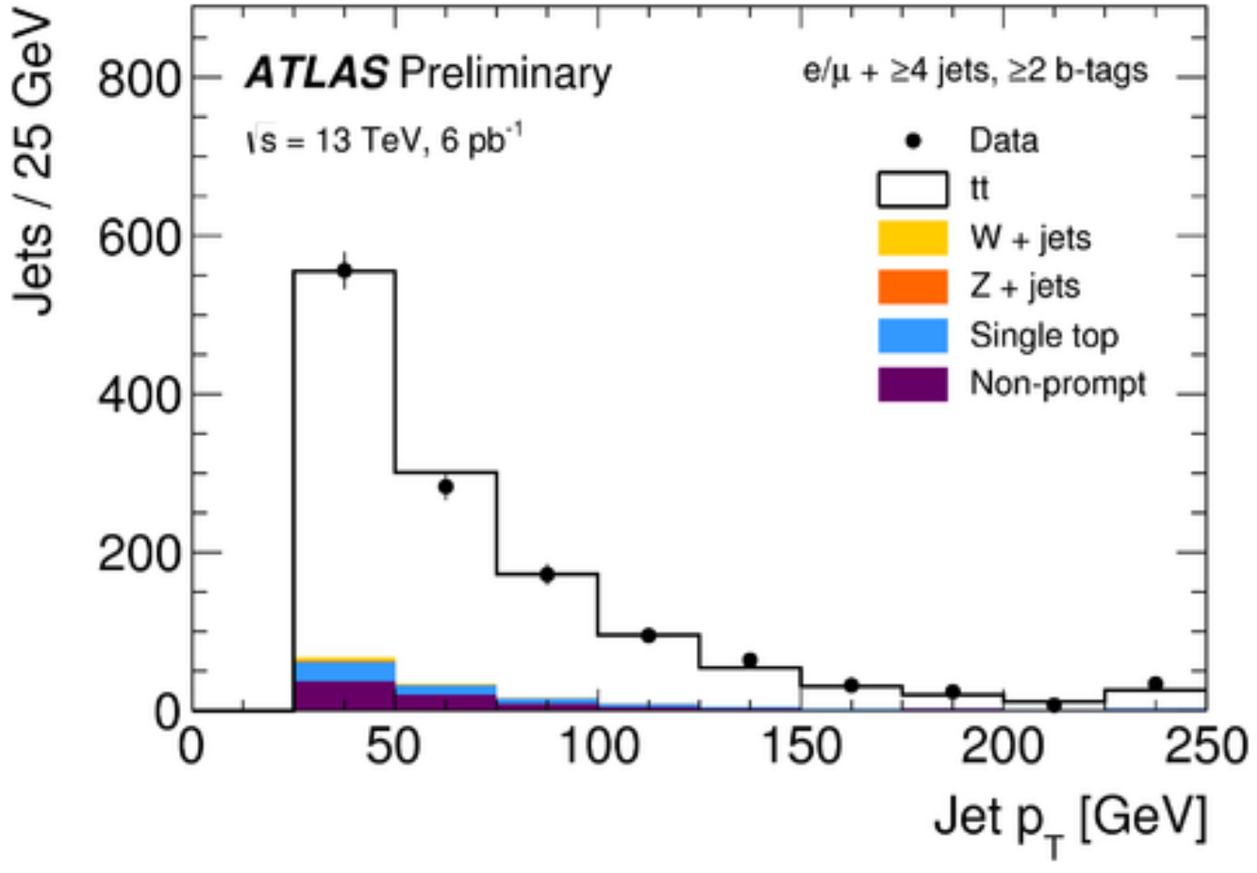

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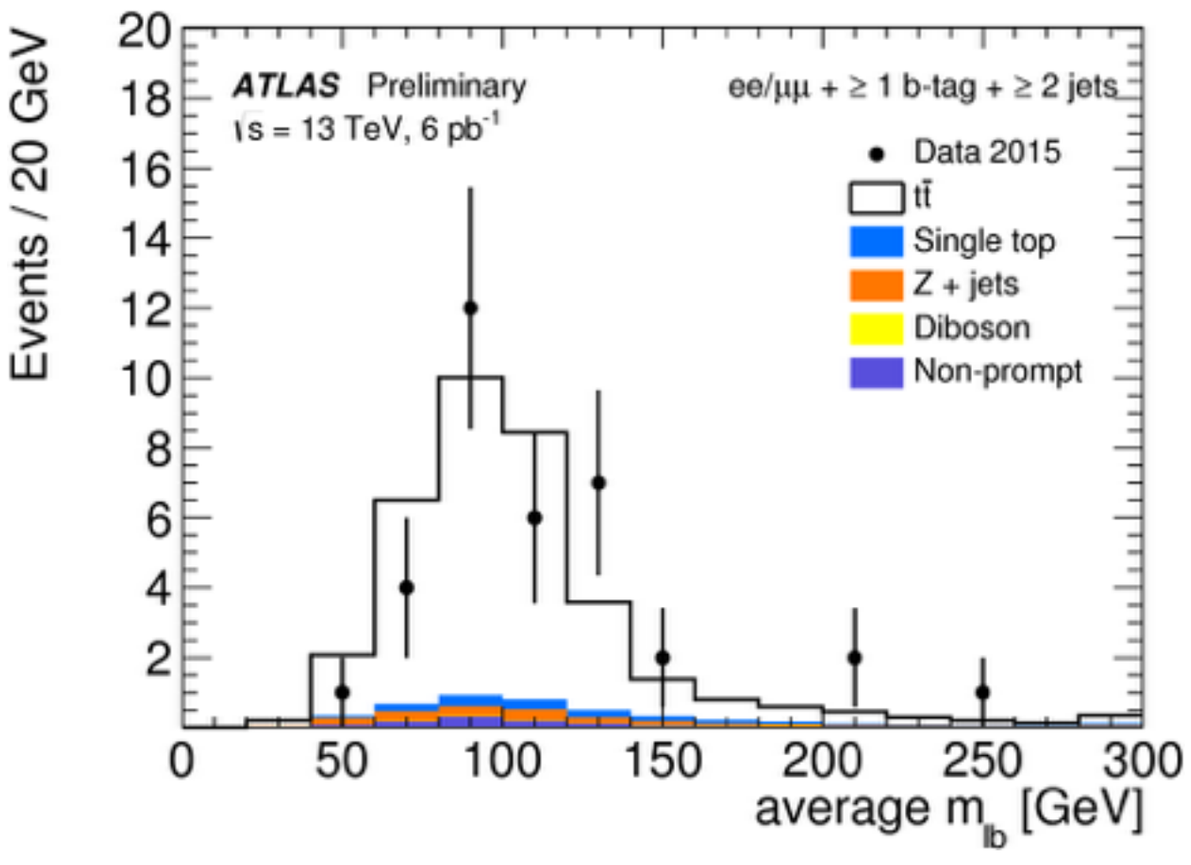

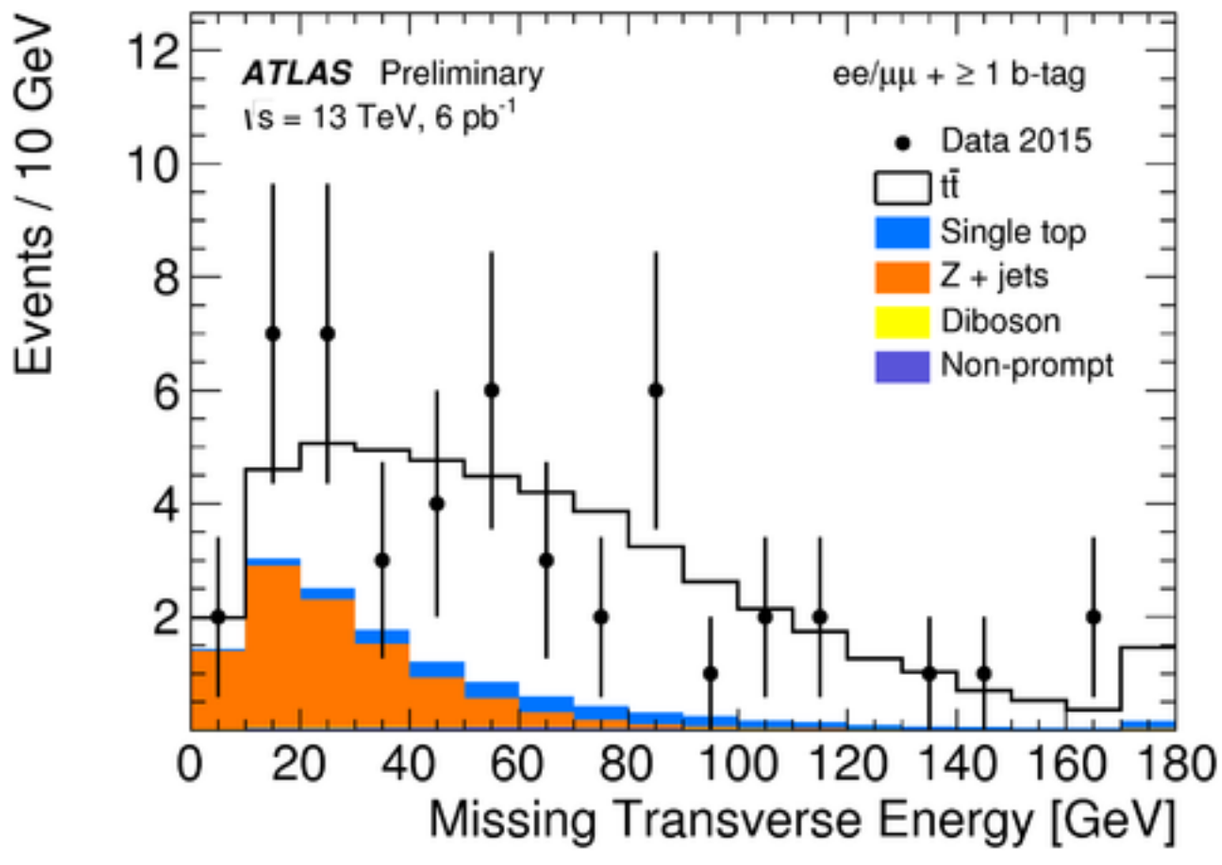

Summary

- **Entered the 13 TeV era!!!**
- **Inclusive Cross-Sections measured across 7, 8 (4% accuracy) and now 13 TeV (14% accuracy)**
- **Differential cross-sections performed with great precision at parton and particle level for resolved and boosted topologies**
- **Needless to say the SM is still working just fine ➜ but will it hold up against higher statistics…. ?**