Top quark differential cross-section measurement with the ATLAS detector

Matteo Scornajenghi
on behalf of The ATLAS Collaboration

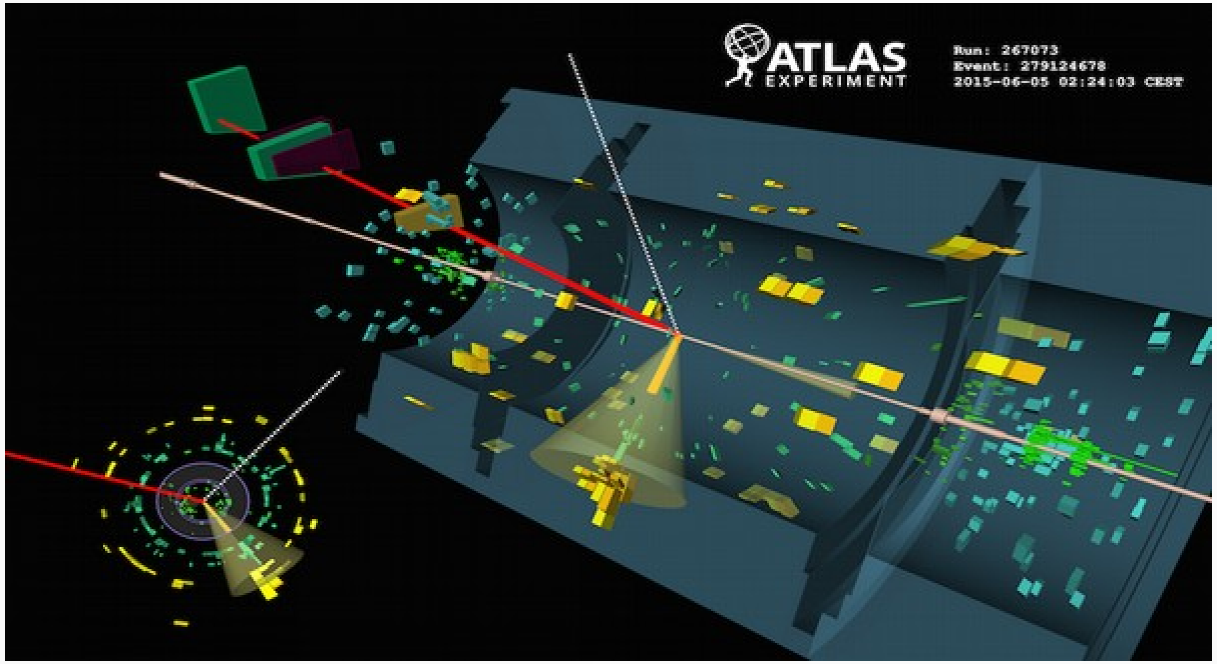
XXIV Cracow EPIPHANY Conference on Advances in Heavy Flavour Physics
9-12 January 2018

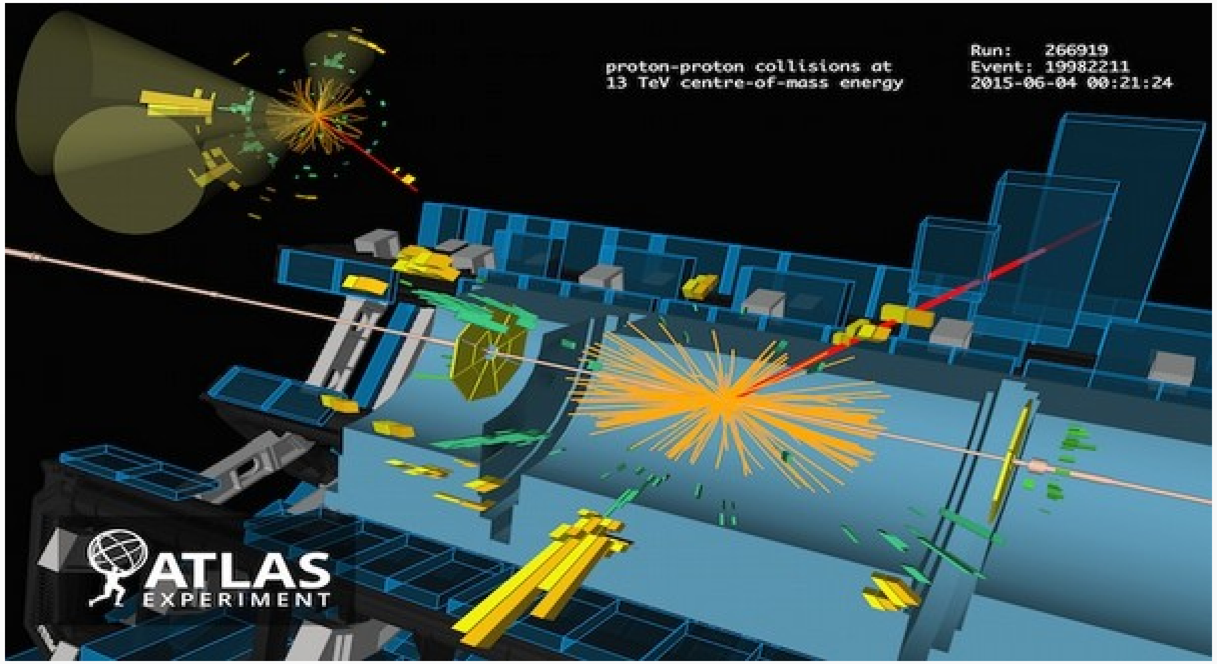
UNIVERSITÀ DELLA CALABRIA

Outline

- The importance of being top
- Recent ATLAS differential cross-section measurements
  - Single top t-channel
  - Single top in association of a W boson
  - Top-antitop pair production
- Summary

[Ref.]

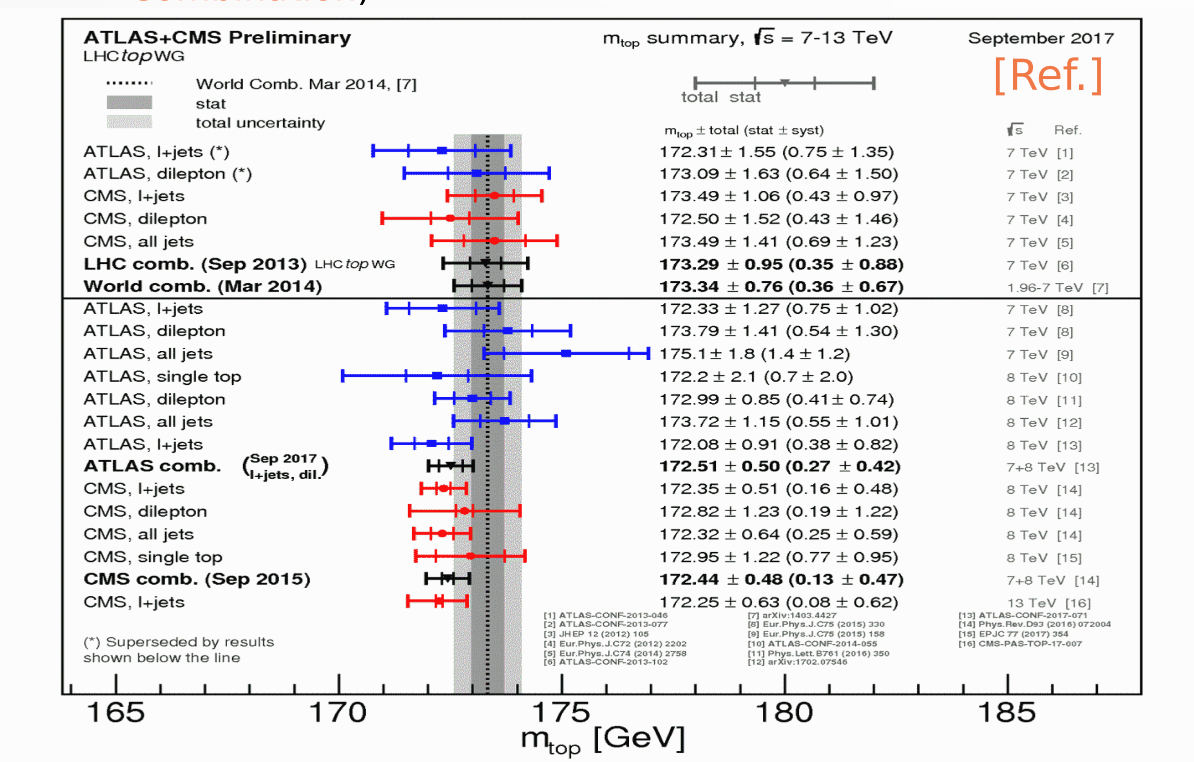




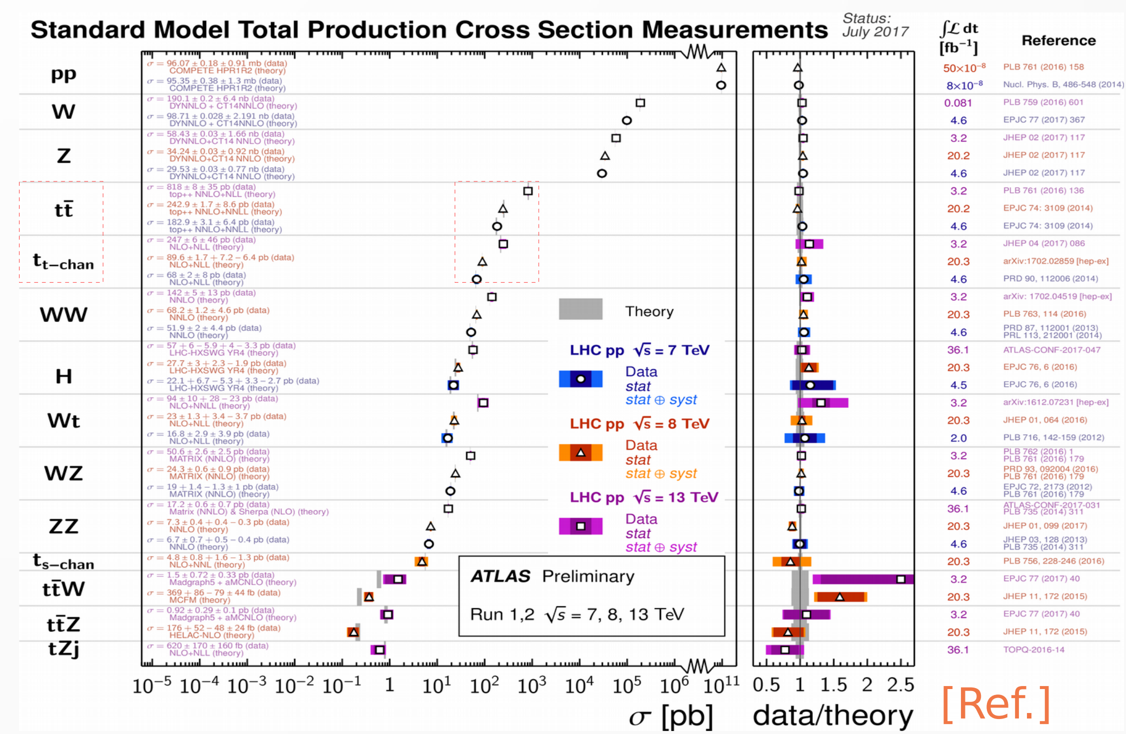
Event displays recorded by ATLAS on June 2015, with LHC stable beams at √s=13 TeV, for a t-channel single top-quark (left) and $t\bar{t}$ (right) production candidates.

The importance of being top

- The most massive particle of the Standard Model
  - m_{top}=173.24±0.27(stat)±0.71(syst) GeV (2014 world combination)
- The only quark decaying before hadronizing
  - Unique opportunity to study the properties of a *free* quark
  - t→Wb BR~1
    - $|f_{LV}V_{tb}|$=1.02±0.08(meas)±0.04(theo) (ATLAS, CMS→ Combination)



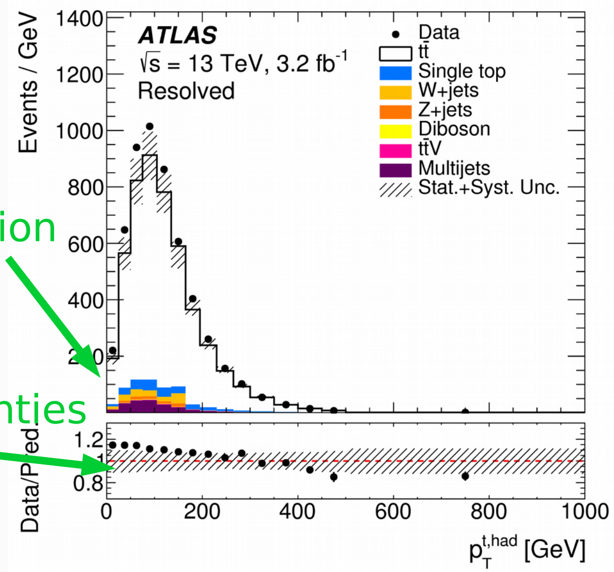
- Very large production cross-section at the LHC
- Top Yukawa coupling close to 1
  - Likely to have a primary role in EW Symmetry Breaking mechanism
- Main background in many BSM searches
- dσ($t\bar{t}$) inputs can put strong constraints over gluon PDF

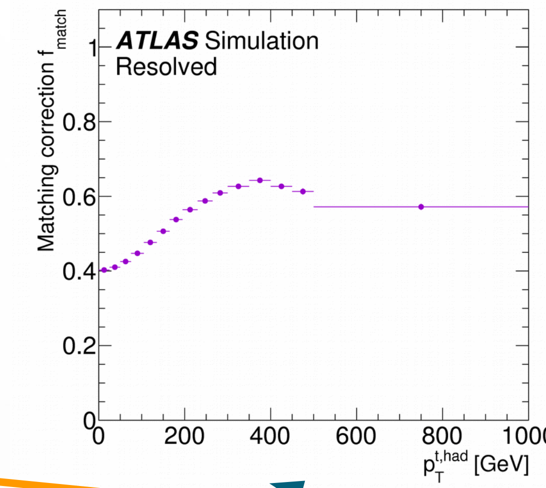


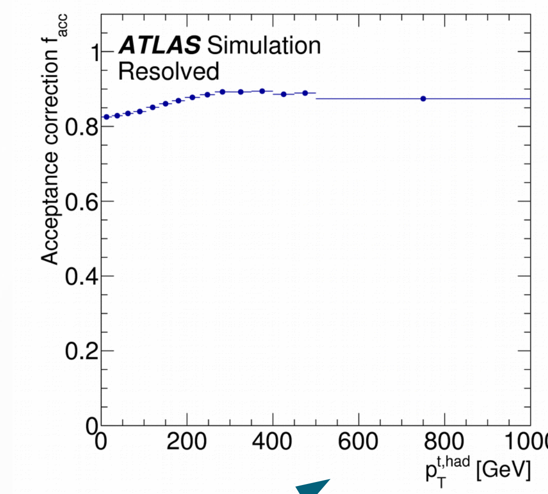
Don't count your spectra before they're unfolded

Background estimation

Statistical and systematic uncertainties



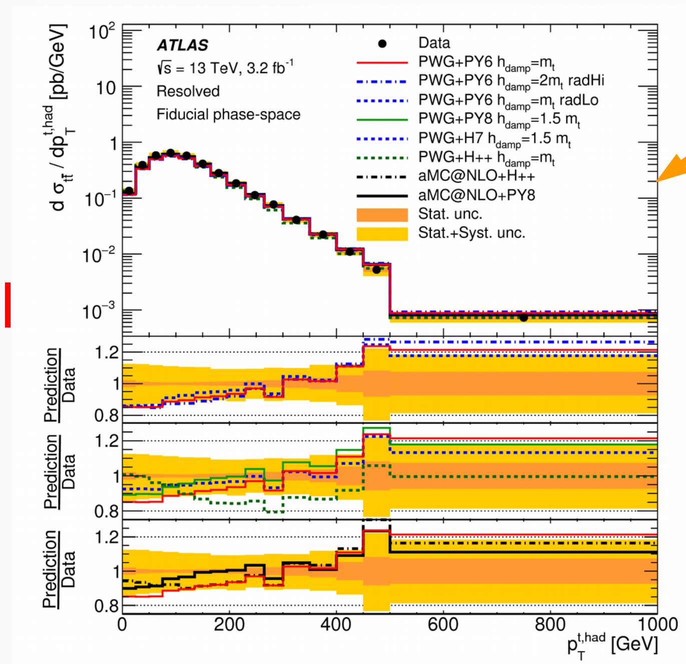


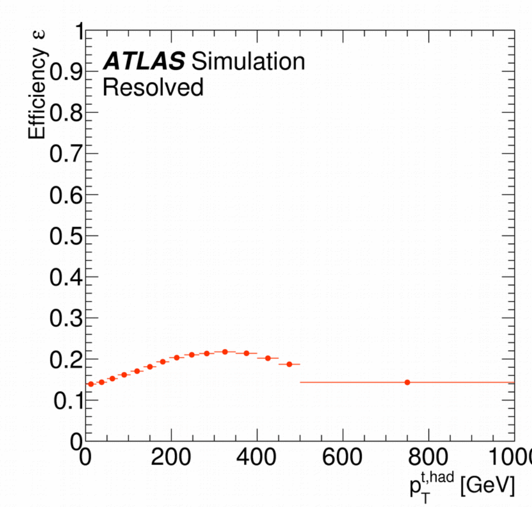


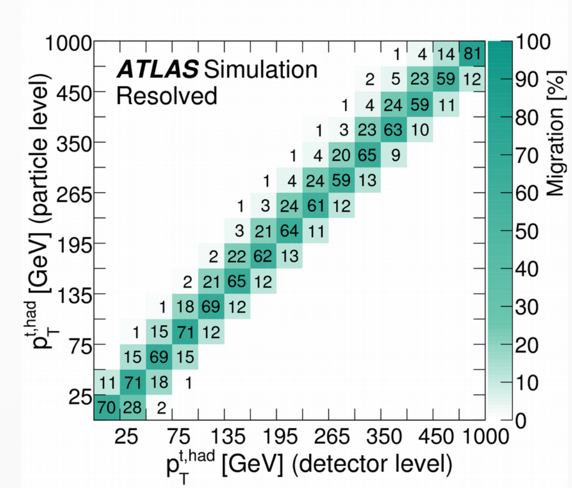
Reco level

Particle level

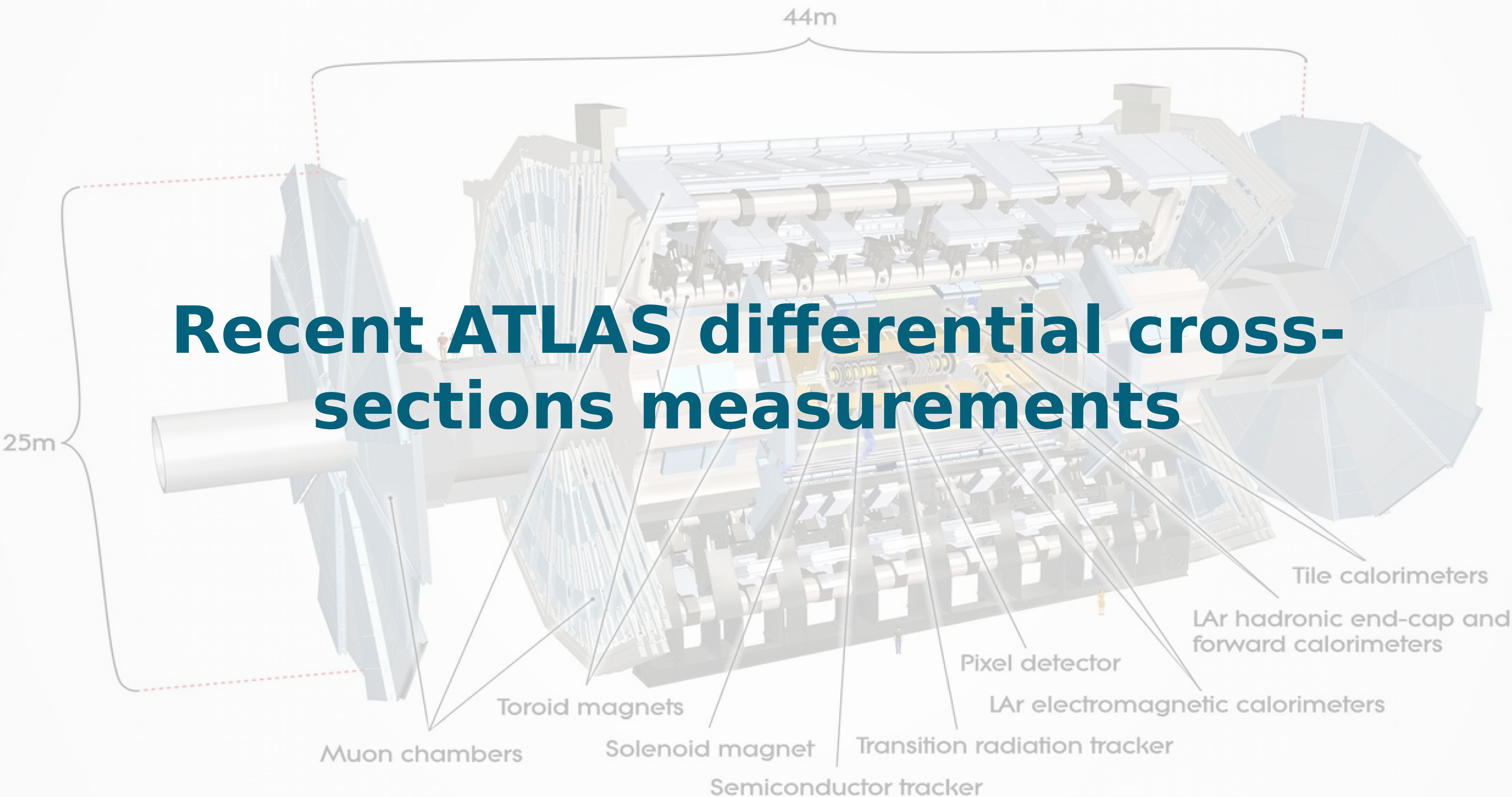
$$\frac{\mathrm{d}\sigma^{\mathrm{fid}}}{\mathrm{d}X^i} \equiv \frac{1}{\mathcal{L}\cdot\Delta X^i}\cdot\frac{1}{\epsilon^i}\cdot\sum_j \mathcal{M}^{-1}_{ij}\cdot f^j_{\mathrm{match}}\cdot f^j_{\mathrm{acc}}\cdot\left(N^j_{\mathrm{reco}}-N^j_{\mathrm{bg}}\right)$$





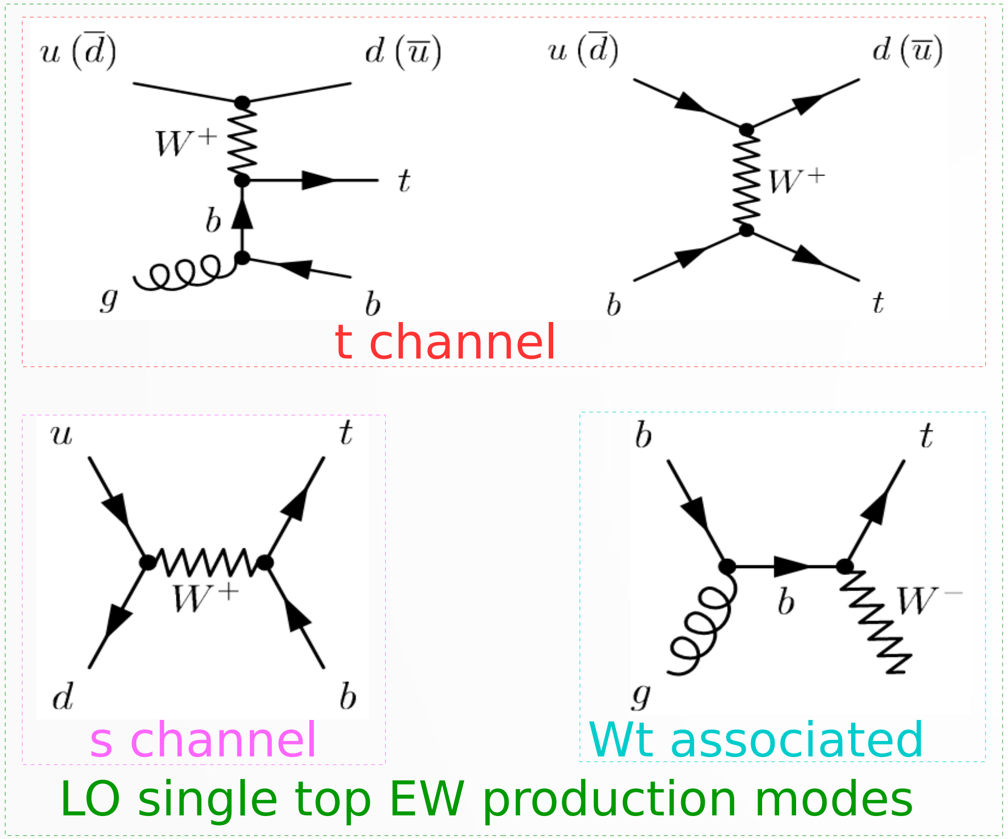


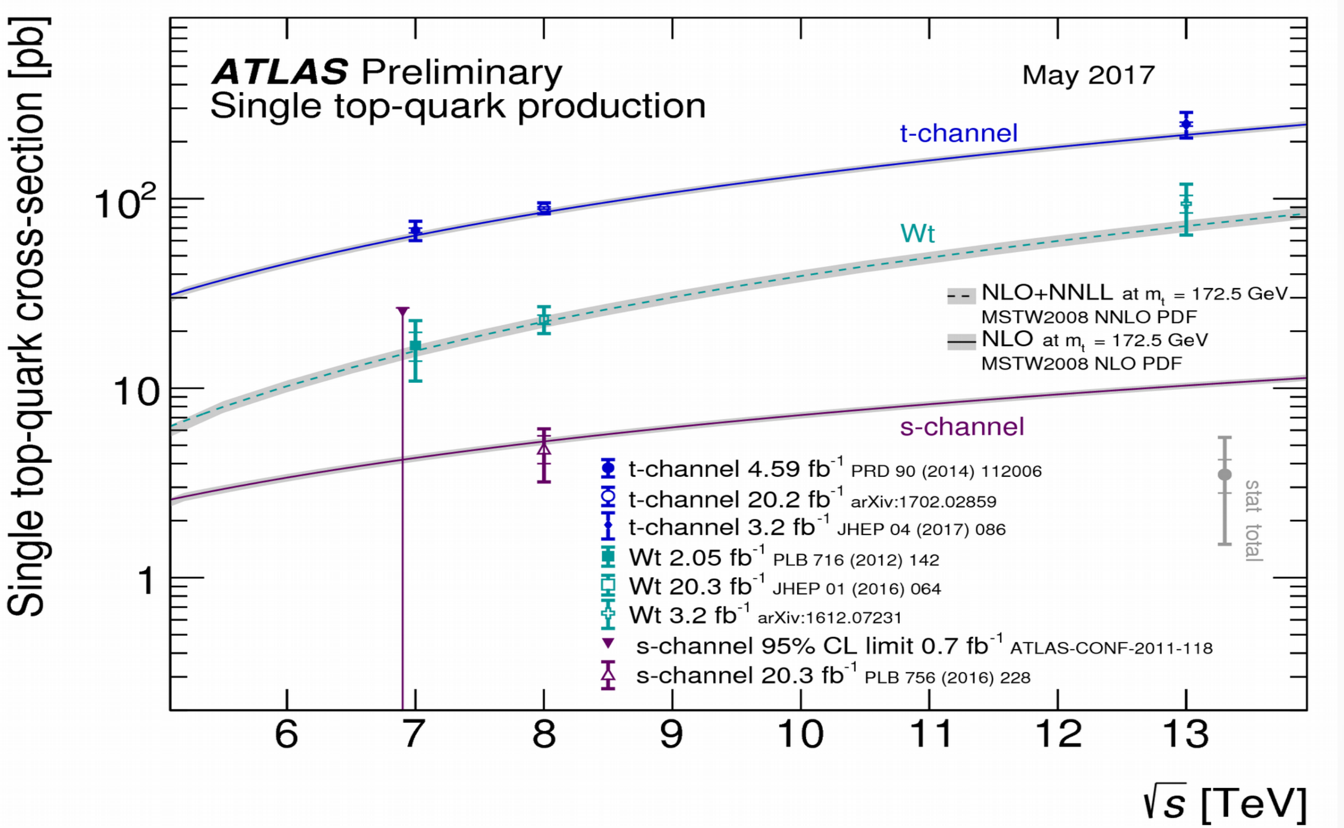
Recent ATLAS differential cross-sections measurements



Single top differential cross-section measurements

[Ref.]





- Sensitivity to u, d and b quark PDF
- Insight of the Wtb interaction → CKM V_{tb} element

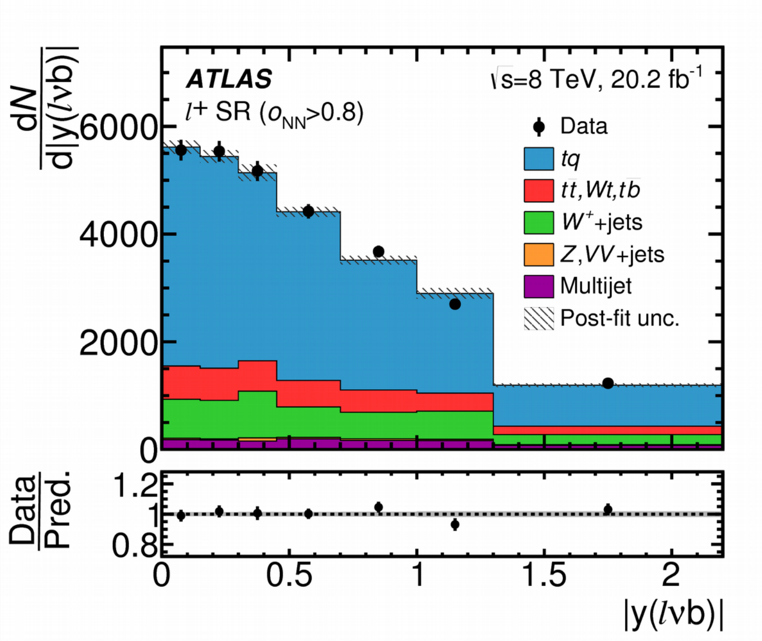
- Latest ATLAS results at 8 TeV
  - σ(t-ch)=89.6±1.2(stat)±6.6(syst) pb
  - σ(Wt)=23.0±1.3(stat)±3.4(syst) ±1.1(lumi) pb
  - σ(s-ch)=4.8±0.8(stat)±1.5(syst) pb
- Latest ATLAS results at 13 TeV
  - σ(t-ch)=247±6(stat)±45(syst) ±5(lumi) pb
  - σ(Wt)=94±10(stat)±25(syst) ±2(lumi) pb

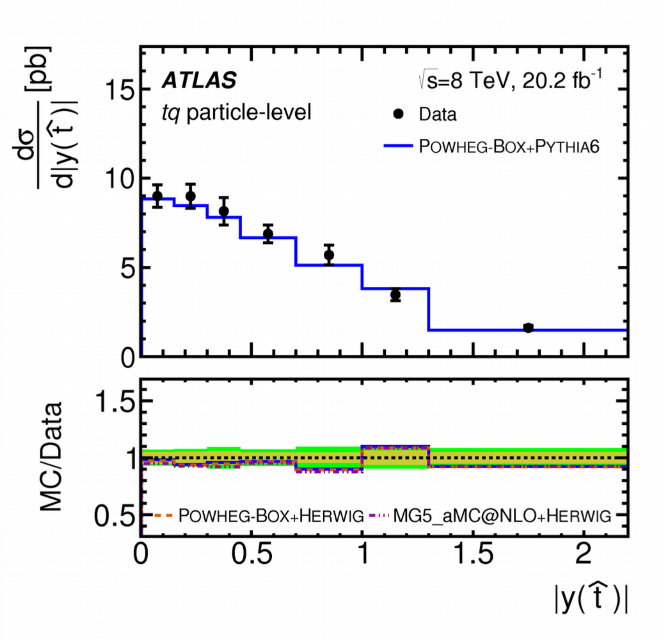
Fiducial, total and differential cross-section measurements of t-channel single top-quark production in pp collisions at 8 TeV using data collected by the ATLAS detector

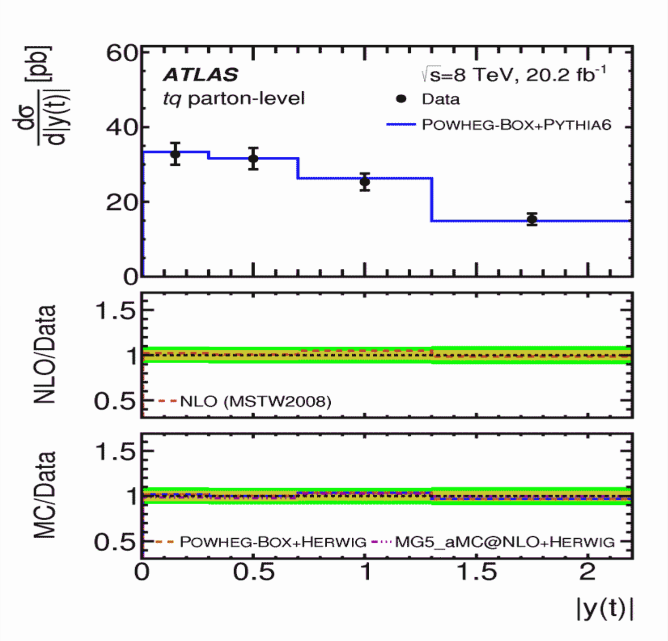
Eur. Phys. J. C 77 (2017) 531

- L=20.2 fb^{-1}, √s=8 TeV
- tj→Wbj→νμ(e)bj process
- Inclusive measurements in backup
- Data-driven multi-jet background estimation through E^T_{miss} fit
- O_{NN} discriminant for W+jets and $t\bar{t}$ background
- Pseudo-top reconstruction (see backup)
- Unfolding to particle and parton level

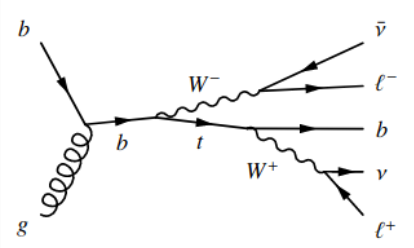
Event selection
Single lepton trigger
Exactly 2 jets, 1 b-tagged 50%WP
E^T_{miss}>30 GeV
ΔR=0.15 trigger matched lepton
m_T(lν)>50 GeV
m(lb)<160 GeV
O_{NN}>0.8



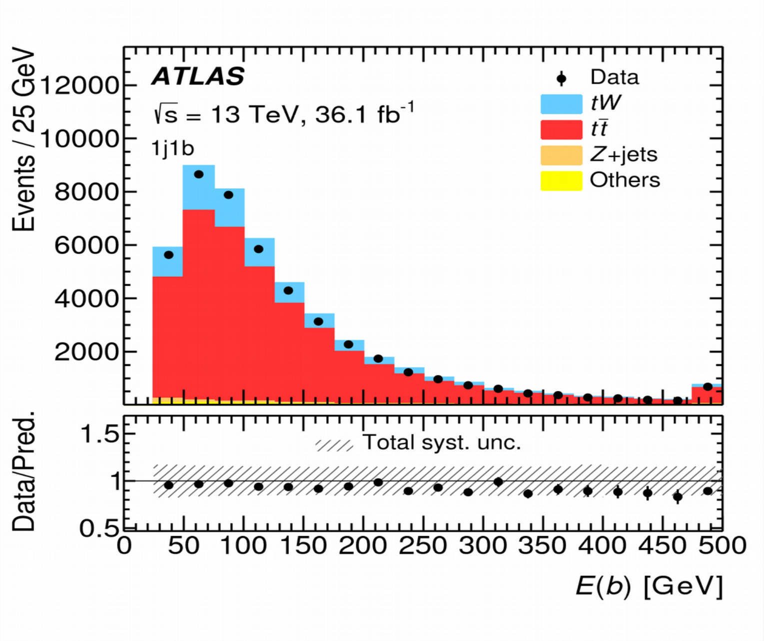


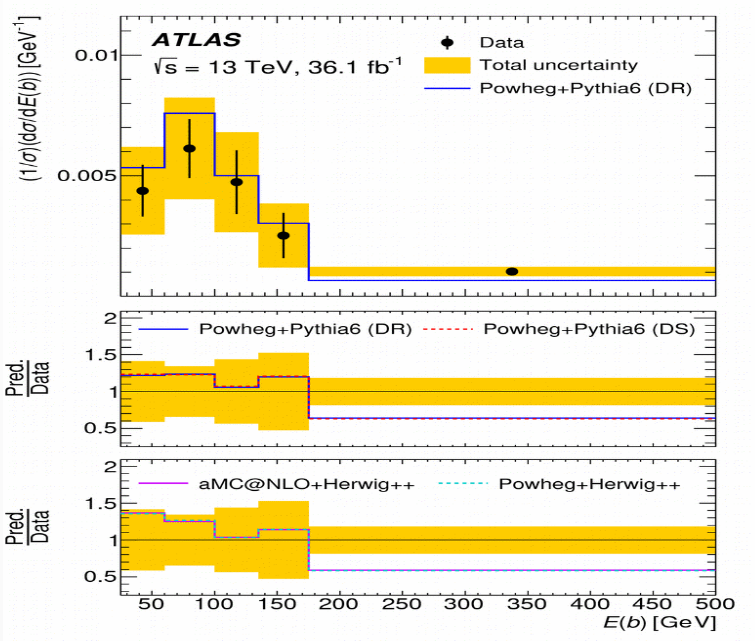


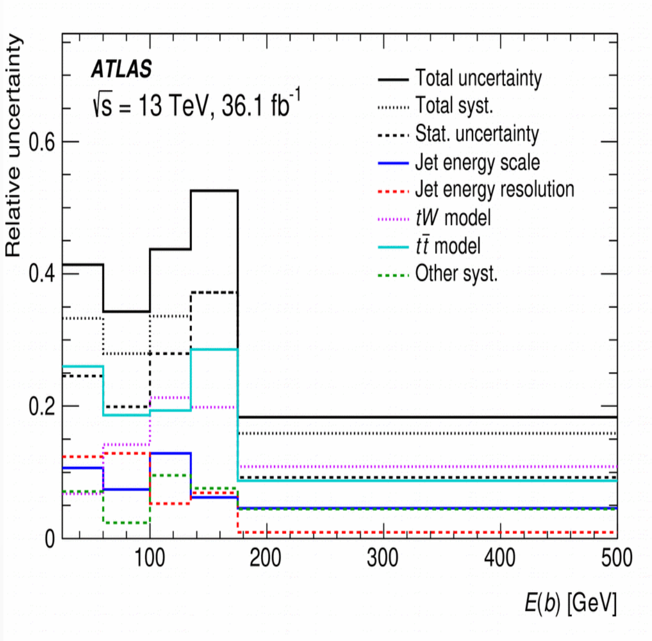
- L=36.1 fb^{-1}, $\sqrt{s}$=13 TeV
- $tW \to \nu\bar{\nu}l^{+}l^{-}$ process
  - Channel with less W+jets contamination
- BDT discriminant for $t\bar{t}$ background (see backup)
- No top reconstruction, kinematic properties of tW production presented
- Unfolding to particle level



Event selection
Single lepton trigger
Exactly 2 jets, 1 b-tagged 77%WP
2 opposite sign e, μ pair p_T>25 GeV
ΔR_μ=0.1 ΔR_e=0.07 trigger matched lepton
m(ll) and E_T^{miss} cut lepton flavours dependant
m(ll)>101 GeV && E_T^{miss}>20 GeV
BDT>0.3

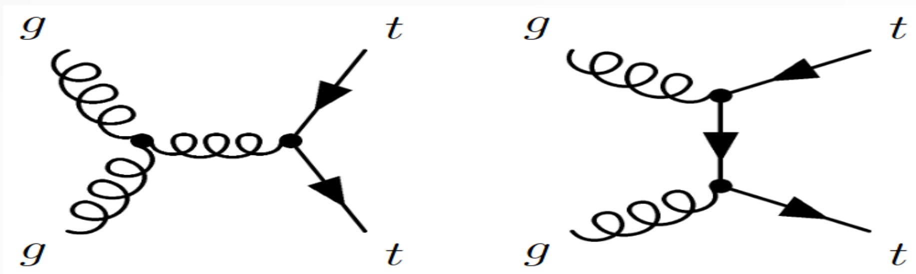




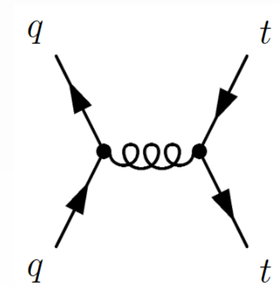


Top pair differential cross-section measurements

[Ref.]

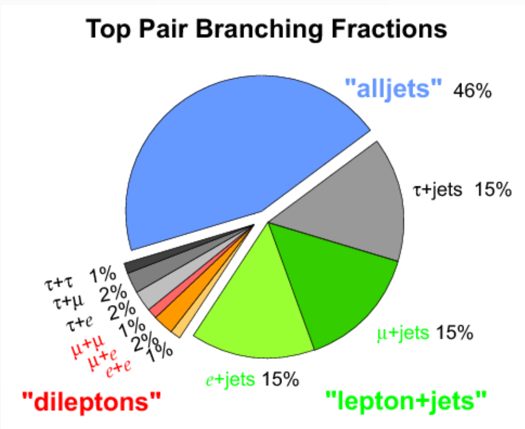


Gluon fusion~90% at 13 TeV

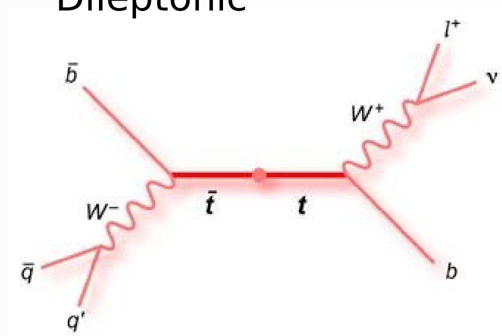


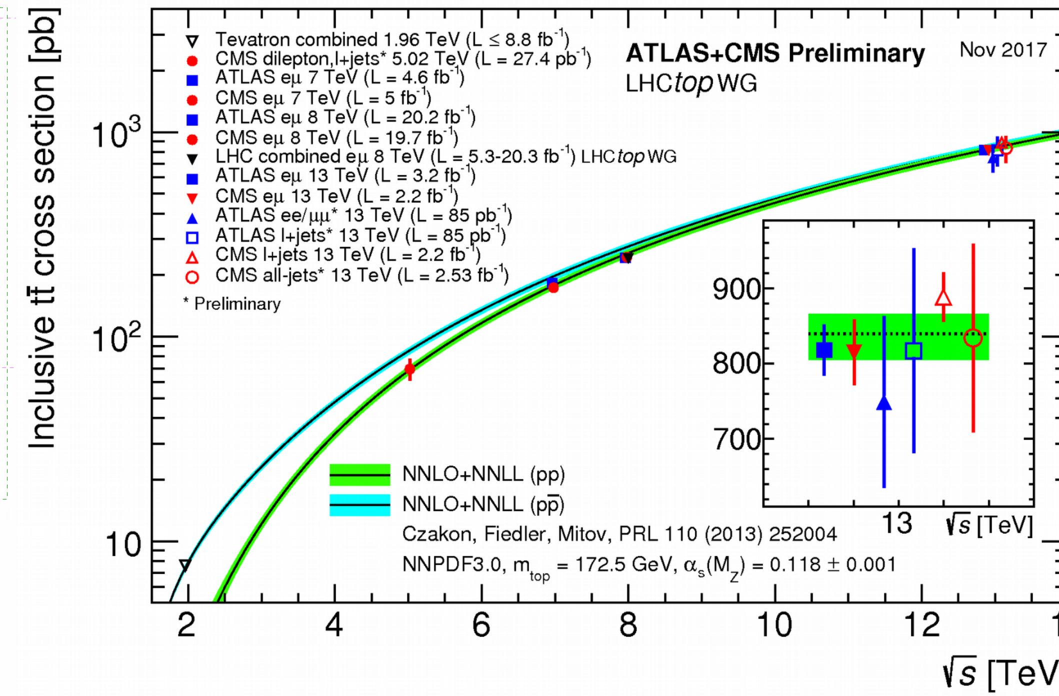
q fusion

LO top pair production modes



- Analysis channels based on W decay modes
  - Full hadronic
  - Lepton + jets
  - Dileptonic

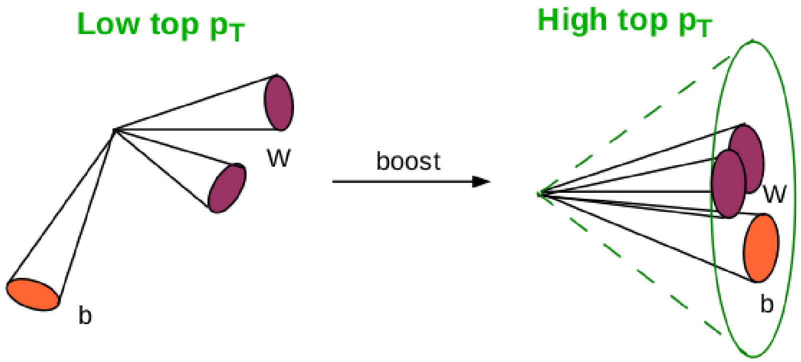


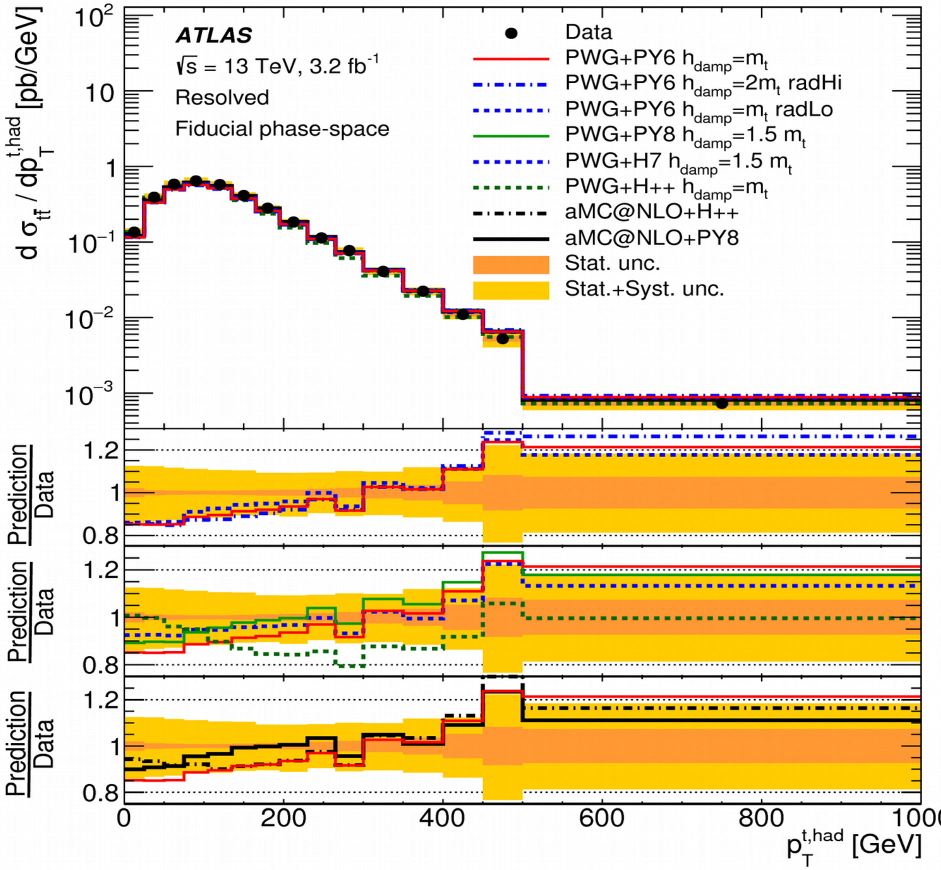


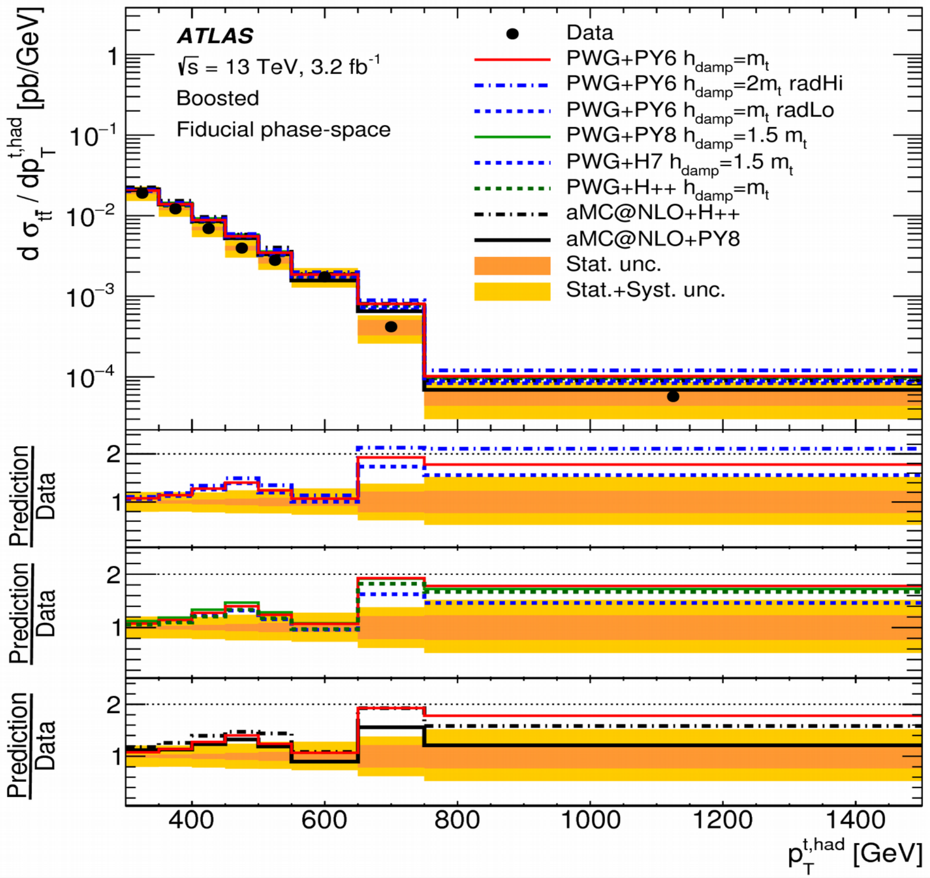
- Sensitivity to gluon PDF
- Precise test of pQCD
- Monte Carlo fine tuning

- L=3.2 fb-1, √s=13 TeV
- l+jets resolved and boosted regimes
- Regime dependant event selection (see backup)
- Data-driven techniques for W+jets and fake leptons backgrounds

- Top reconstruction
  - Resolved: pseudo-top algorithm
  - Boosted: large-R and b-tagged jet system
- Unfolding to particle level

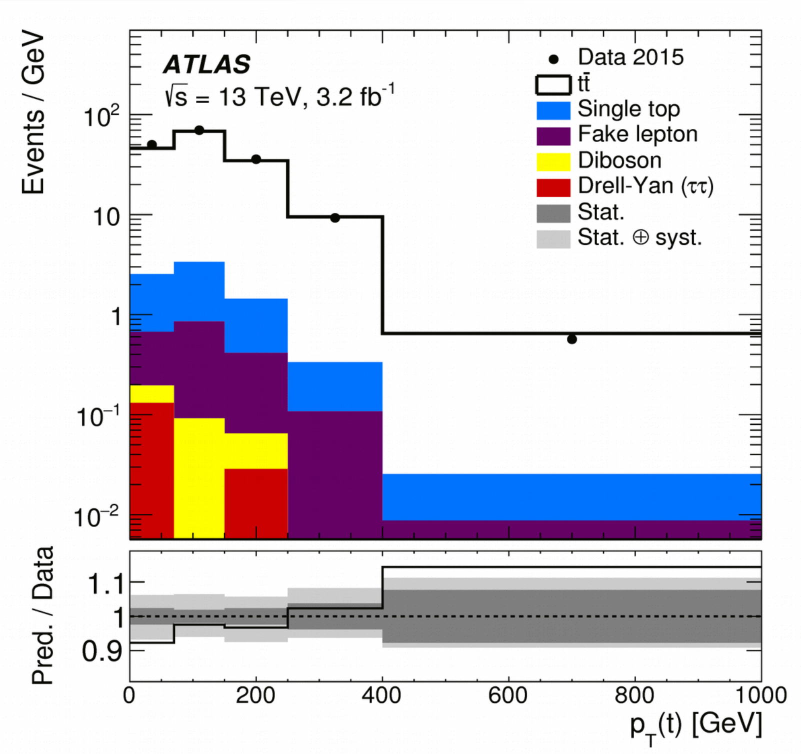


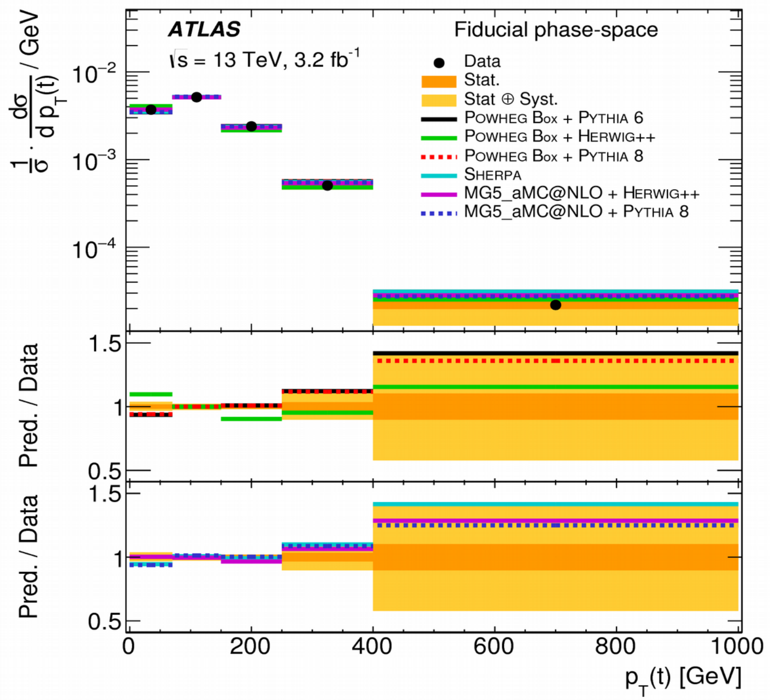


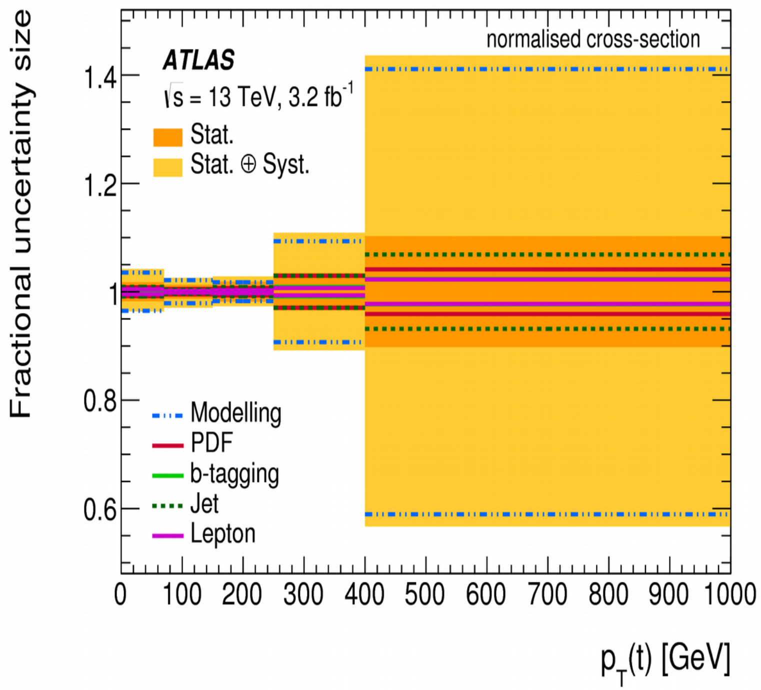


- L=3.2 fb-1, √s=13 TeV
- Dilepton channel
- Monte Carlo based background estimation
- Top reconstruction through Neutrino Weighting (see backup)
- Unfolding to particle level

Event selection
Single lepton trigger
At least 2 jets, 1 b-tagged 77%WP
2 opposite sign leptons p_T>25 GeV







Measurements of tt differential cross-sections in the all-hadronic channel with the ATLAS detector using highly boosted top quarks in pp collisions at √s = 13 TeV
ATLAS-CONF-2016-100

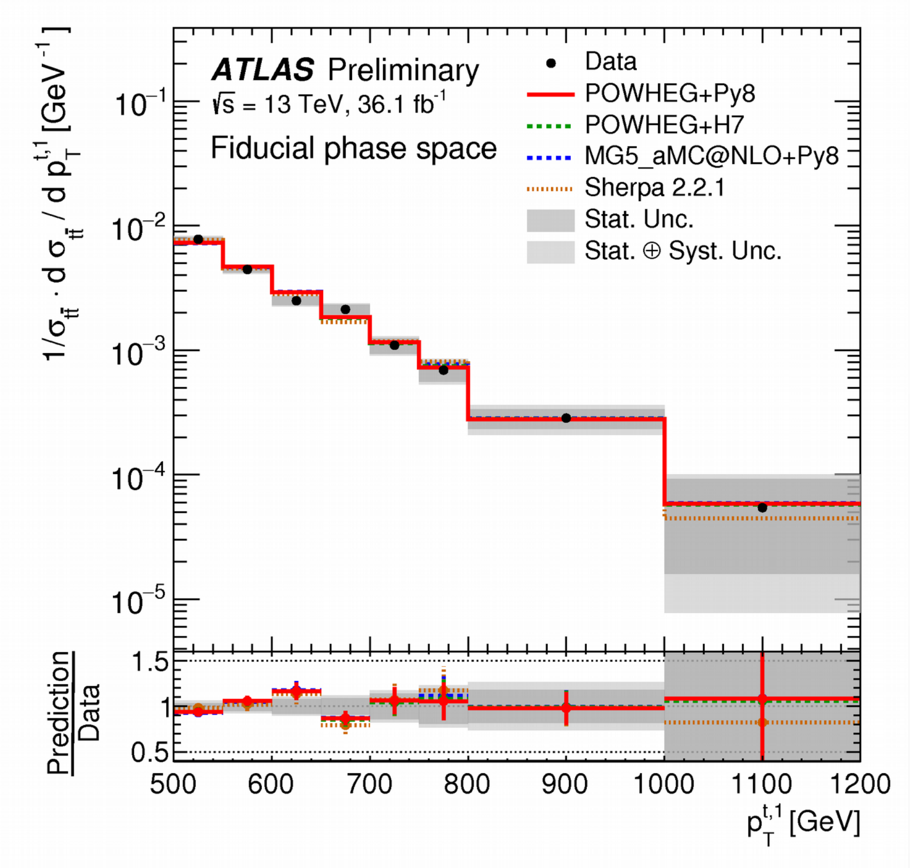
- L=14.7 fb^{-1}, √s=13 TeV
- Di-boosted regime
- Data-driven ABCD method multi-jet background estimation
- Large-R and b-jet system as reconstructed top
- Unfolding to particle level

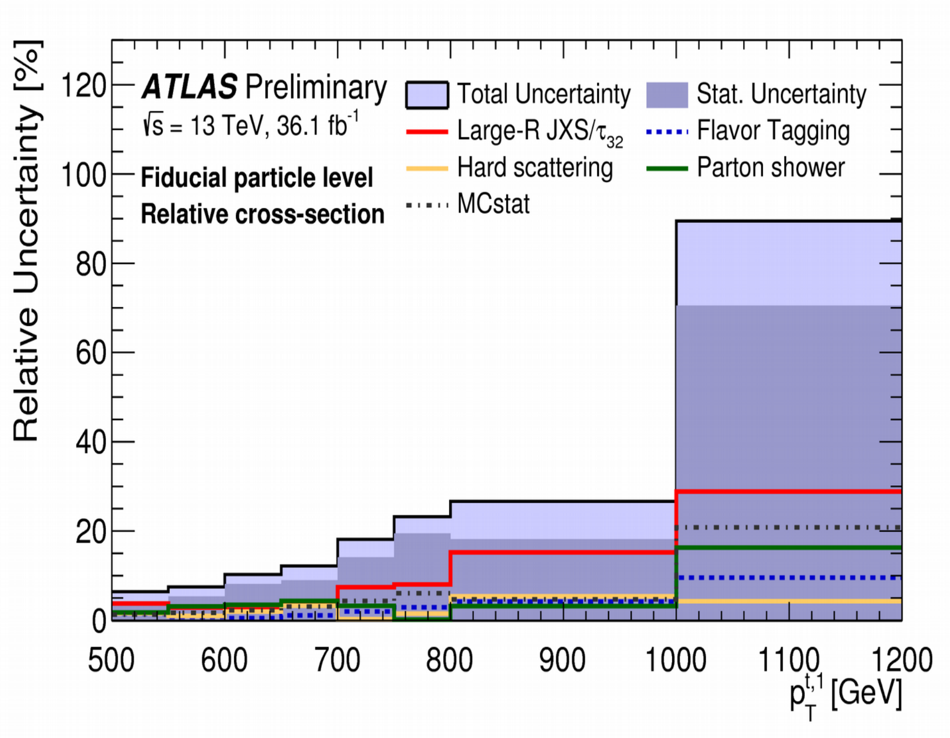
Event selection
No lepton
Exactly 2 high-pT (500, 350 GeV) large-R (ΔR=1) jets
Exactly 2 small-R (ΔR=0.4) 70% WP b-tagged jets
ΔR<1 between top-tagged large-R and b-jets

	0 t	1 t	2 t
0 b	A	D	G
1 b	B	E	H
2 b	C	F	S

$$S_{bg} = \frac{1}{2}\left(\frac{G}{A} + \frac{H}{B}\right) \times C$$

- Regions are defined by the number of b and top-tagged jets





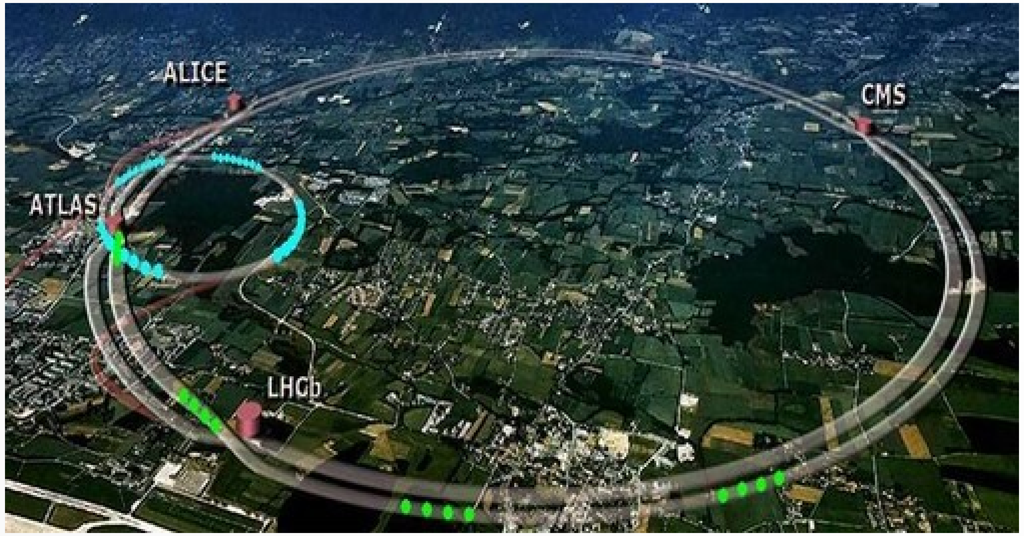
Summary

- Top sector physics plays a key role in pQCD tests, PDF constraints, Monte Carlo tuning, BSM searches
- Presented latest top differential cross-section measurements with the ATLAS detector
  - Many more available from the TopPublicResults web site
  - Measurement show very good agreement with respect to the Standard Model
- Although different reconstruction techniques (pseudo-top, neutrino weighting, top tagging) are used, results from different $t\bar{t}$ channels are consistent
  - Boosted techniques allow to explore very high-p_T phase-space regions
- Measurements with full 2015+2016 and 2017 data in preparations

Thanks for your attention

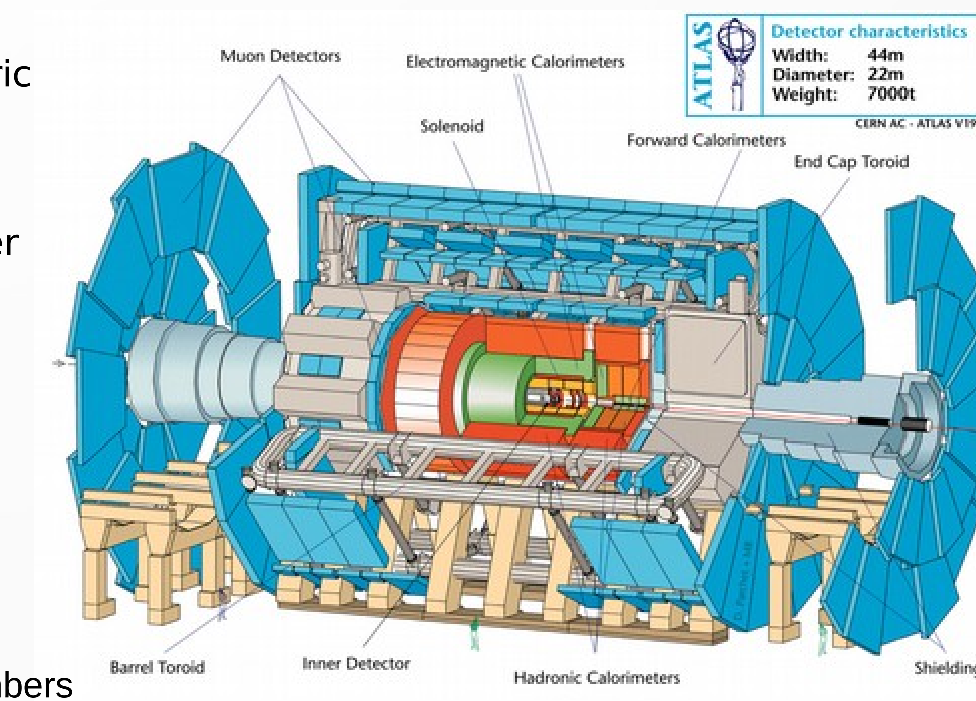
Backup

The ATLAS Detector at the LHC



- World's largest and most powerful particle accelerator
- Operating since November 2009
- 27 km ring of superconducting magnets and accelerating structures
- Accelerates 2 beams of high-energy particles in separate beam pipes
- 4 major experiments (ATLAS, CMS, ALICE, LHCb) placed at the 4 collision points

- ATLAS (A Toroidal Large ApparatuS) is a general-purpose detector with cylindric simmetry. It is made of different layers:
  - Inner detector (tracker)
    - Pixel detector, Semiconductor Tracker (SCT), Transition Radiation Tracker (TRT)
  - Calorimeters:
    - Liquid Argon (LAr) electromagnetic calorimeter ($|\eta|<3.2$)
    - Hadronic Tile Calorimeter ($|\eta|<1.7$)
    - LAr hadronic calorimeter ($1.5<|\eta|<3.2$)
    - LAr High Density Forward Calorimeter (FCAL) ($3.1<|\eta|<4.9$)
  - Muon spectrometer
    - Thin-gap chambers (TGC), Cathode Strip chambers (CSC), Resistive-plate chambers (RPC), Monitored drift tubes (MDT)



Analysis general strategy

- Trigger, object and event selection
  - Topology dependant, aim to maximize Signal over Background ratio
- Definition of spectra to be measured
  - $t\bar{t}$, t, $\bar{t}$, final state related observables
- Background estimation
  - Monte Carlo predictions or data-driven methods
- Systematic uncertainties evaluation
  - Signal modelling, background modelling, detector response, PDF, luminosity...
- Unfolding to particle and/or parton level
  - Technique to account for detector efficiencies, limited acceptance, hadronization, parton shower...
  - Master formula
    - $$\frac{d\sigma^{unfolded}}{dX^i} = \frac{1}{Lumi \cdot \Delta X^i} \cdot f^i_{efficiency} \cdot \sum_j M^{-1}_{ij} \cdot f^i_{acceptance} \cdot \left(N^i_{reco} - N^i_{background}\right)$$

Pseudo-top reconstruction

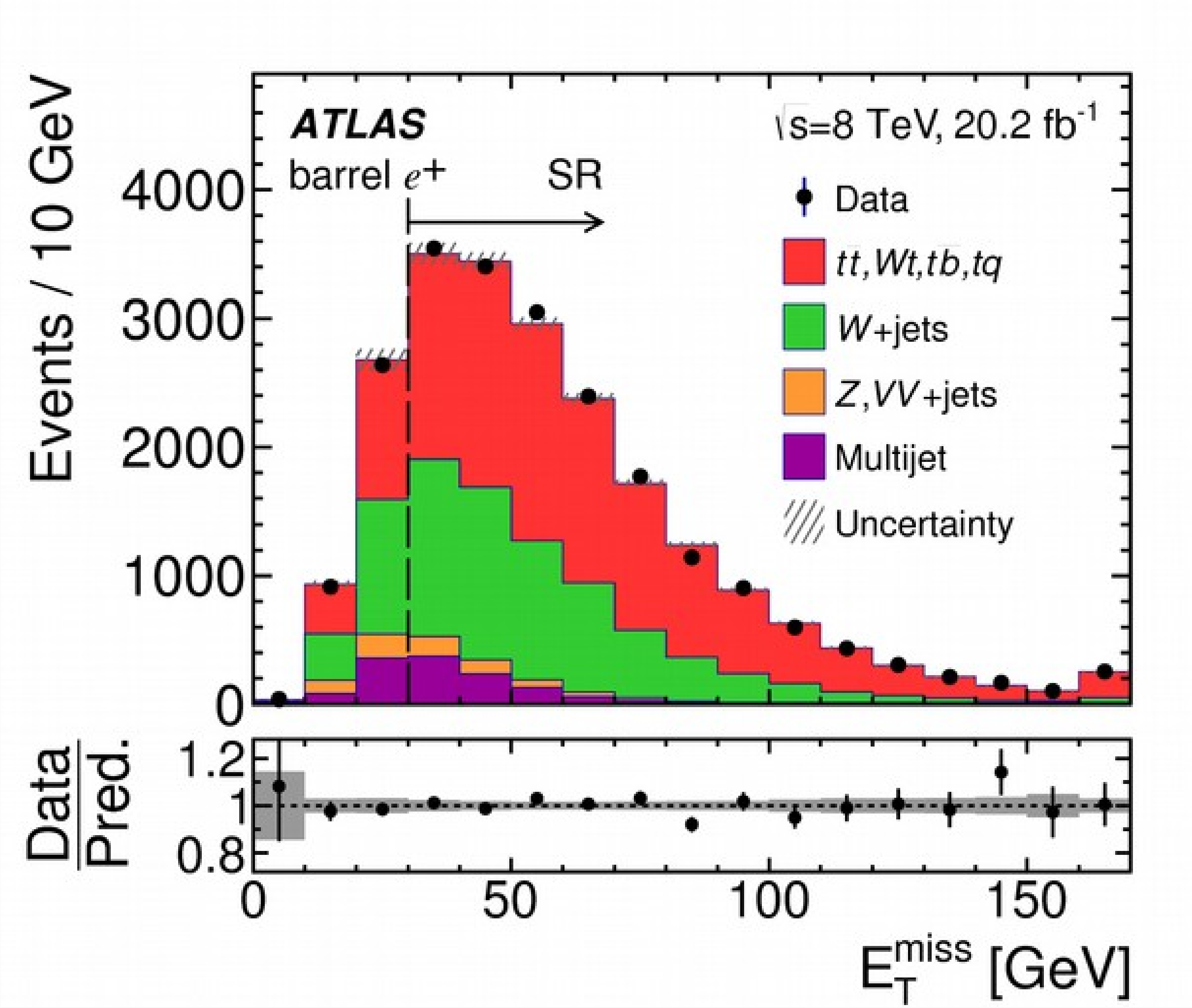
- Kinematic reconstruction of top four-vector from final state objects
- Leptonic top
  - p_z component of neutrino four-momentum is evaluated by constraining the invariant mass of the E_T^{miss}, b-tagged jet, lepton and ΔR closest jet to be m_W=80.399 GeV and solving the associated quadratic equation
    - 2 real solutions
      - Solution with smaller $|p_z|$ taken
    - 2 imaginary solutions
      - Imaginary part dropped

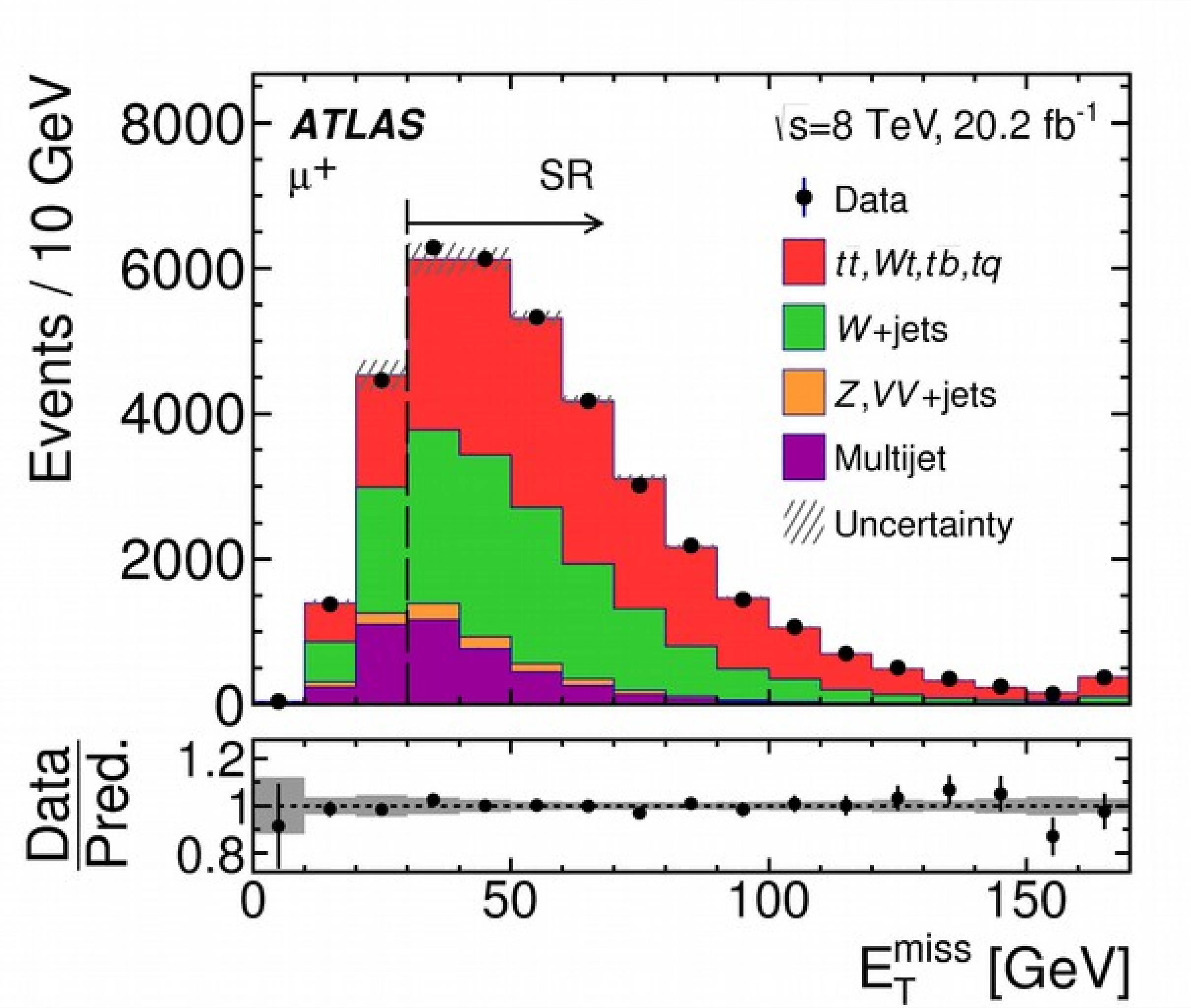
        or
      - Netruino four-momentum smeared
  - Top is reconstructed from ν, l, b-jet and jet
- Hadronic top
  - Top is reconstructed from b-jet and 2 leading p_T jets

Neutrino Weighting

- Kinematic reconstruction of $t\bar{t}$ system in dilepton channel
- System is underconstrained
  - Set m_W=80.399 GeV, m_t in [168;178] GeV (1 GeV step) and (η_ν^1, η_ν^2) in [-5;5] (0.2 step), jet p_T smeared by $0.1 \cdot p_T$ (20 times)
- For each configuration, try to reconstruct $t\bar{t}$ system
- If solution is found, evaluate weight
  - $$w = \exp\left(\frac{-(E_{miss,x}^{reco} - E_{miss,x}^{calculated})^2}{2\sigma_x^2}\right) \cdot \exp\left(\frac{-(E_{miss,y}^{reco} - E_{miss,y}^{calculated})^2}{2\sigma_y^2}\right)$$
- Take solution with maximum weight

Multijet background fit



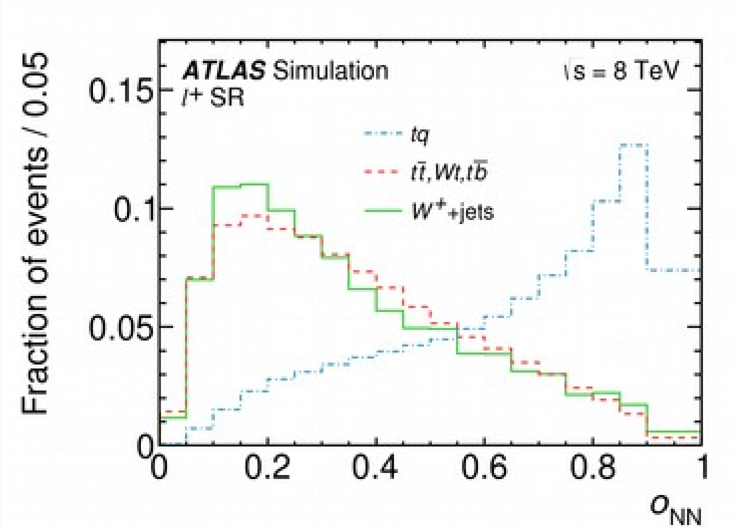


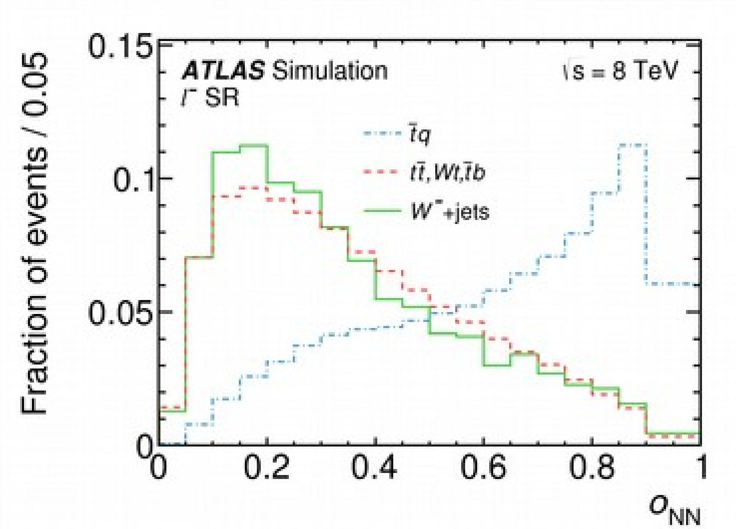
Input to NN

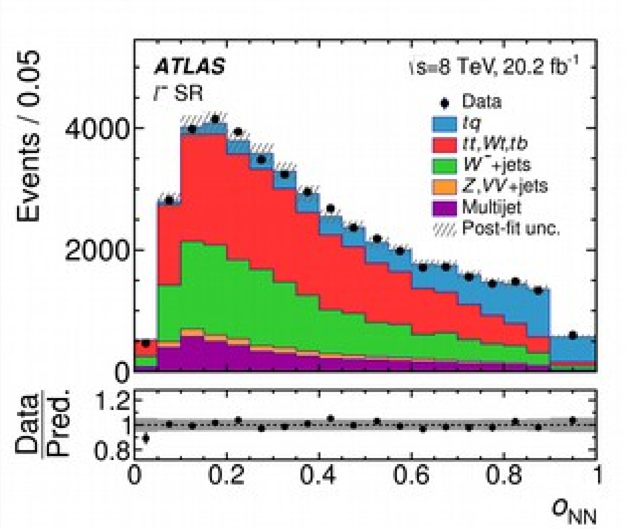
Variable symbol	Definition
$m(jb)$	The invariant mass of the untagged jet (j) and the b-tagged jet (b).
$\|\eta(j)\|$	The absolute value of the pseudorapidity of the untagged jet.
$m(\ell\nu b)$	The invariant mass of the reconstructed top quark.
$m_{\mathrm{T}}(\ell E_{\mathrm{T}}^{\mathrm{miss}})$	The transverse mass of the lepton–$E_{\mathrm{T}}^{\mathrm{miss}}$ system, as defined in Eq. (**??**).
$\|\Delta\eta(\ell\nu, b)\|$	The absolute value of $\Delta\eta$ between the reconstructed W boson and the b-tagged jet.
$m(\ell b)$	The invariant mass of the charged lepton (ℓ) and the b-tagged jet.
$\cos\theta^*(\ell, j)$	The cosine of the angle, θ^*, between the charged lepton and the untagged jet in the rest frame of the reconstructed top quark.

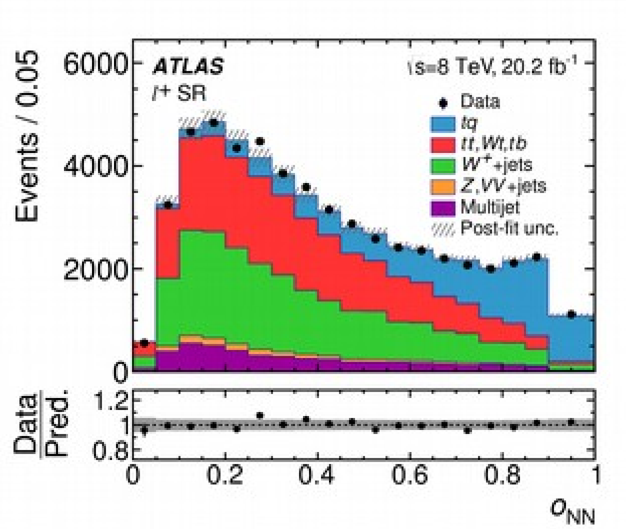
$$m_{\mathrm{T}}\left(\ell E_{\mathrm{T}}^{\mathrm{miss}}\right) = \sqrt{2 p_{\mathrm{T}}(\ell) \cdot E_{\mathrm{T}}^{\mathrm{miss}} \left[1 - \cos\left(\Delta\phi\left(\ell, E_{\mathrm{T}}^{\mathrm{miss}}\right)\right)\right]}, \quad (2)$$

NN discriminant









Inclusive measurements

$$\begin{aligned}\sigma_{\text{fid}}(tq) &= 9.78 \pm 0.16\,(\text{stat.}) \pm 0.52\,(\text{syst.})\\ &\quad \pm 0.19\,(\text{lumi.})\text{ pb}\\ &= 9.78 \pm 0.57\text{ pb}\end{aligned}$$

$$\begin{aligned}\sigma_{\text{fid}}(\bar{t}q) &= 5.77 \pm 0.14\,(\text{stat.}) \pm 0.41\,(\text{syst.})\\ &\quad \pm 0.11\,(\text{lumi.})\text{ pb}\\ &= 5.77 \pm 0.45\text{ pb.}\end{aligned}$$

$$\begin{aligned}\sigma_{\text{tot}}(\bar{t}q) &= 32.9 \pm 0.8\,(\text{stat.}) \pm 2.3\,(\text{exp.})\,^{+1.4}_{-0.8}\,(\text{scale})\\ &\quad \pm 0.3\,(\text{PDF})\\ &\quad \pm\,^{+0.7}_{-0.6}\,(\text{NLO-matching method})\\ &\quad \pm 0.6\,(\text{parton shower}) \pm 0.6\,(\text{lumi.})\text{ pb}\\ &= 32.9^{+3.0}_{-2.7}\text{ pb.}\end{aligned}$$

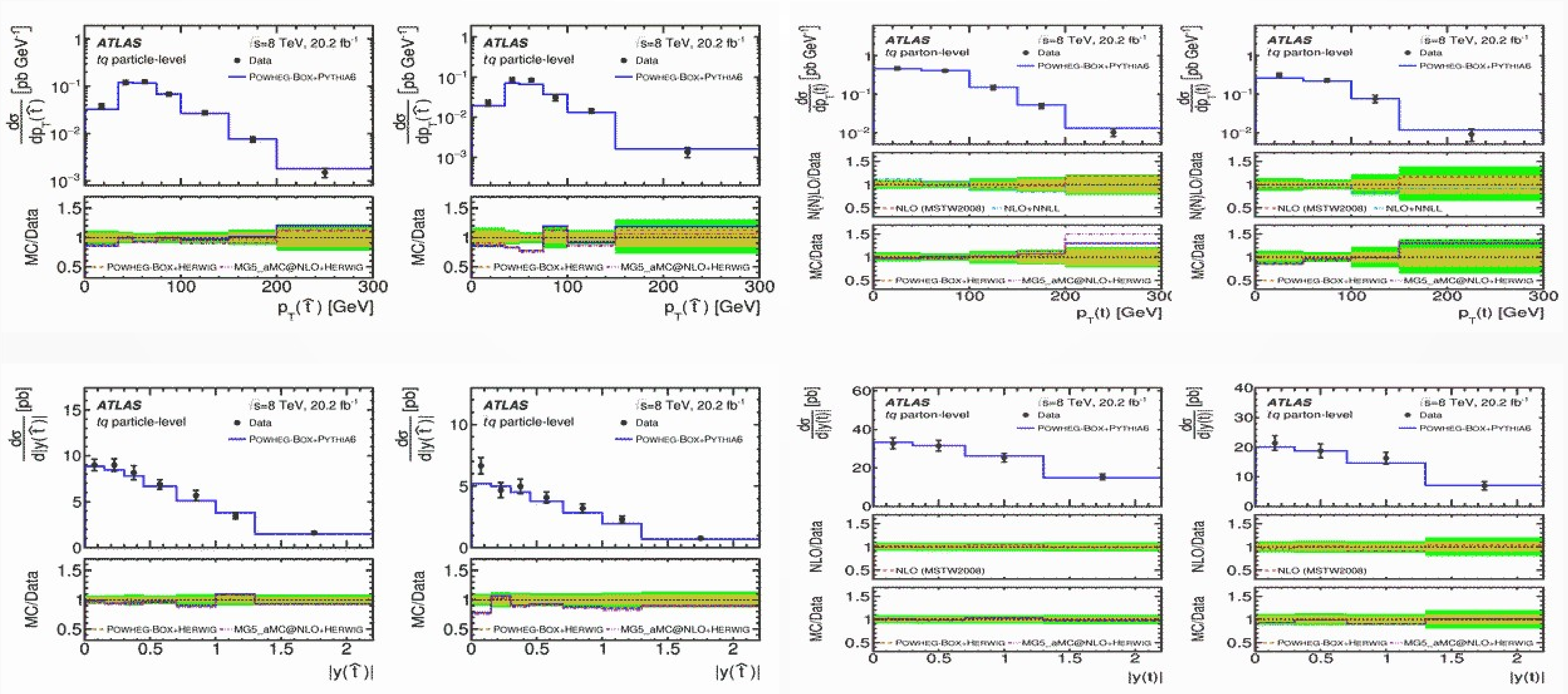
$$\begin{aligned}\sigma_{\text{tot}}(tq) &= 56.7 \pm 0.9\,(\text{stat.}) \pm 2.7\,(\text{exp.})\,^{+2.7}_{-1.7}\,(\text{scale})\\ &\quad \pm 0.4\,(\text{PDF}) \pm 1.0\,(\text{NLO-matching method})\\ &\quad \pm 1.1\,(\text{parton shower}) \pm 1.1\,(\text{lumi.})\text{ pb}\\ &= 56.7^{+4.3}_{-3.8}\text{ pb}\end{aligned}$$

$$\begin{aligned}\sigma_{\text{tot}}(tq + \bar{t}q) &= 89.6 \pm 1.2\,(\text{stat.}) \pm 5.1\,(\text{exp.})\,^{+4.1}_{-2.5}\,(\text{scale})\\ &\quad \pm 0.7\,(\text{PDF})\\ &\quad \pm\,^{+1.7}_{-1.6}\,(\text{NLO-matching method})\\ &\quad \pm 1.6\,(\text{parton shower}) \pm 1.7\,(\text{lumi.})\text{ pb}\\ &= 89.6^{+7.1}_{-6.3}\text{ pb.}\end{aligned}$$

$$\begin{aligned}f_{\text{LV}} \cdot |V_{tb}| &= 1.029 \pm 0.007\,(\text{stat.})\\ &\quad \pm 0.029\,(\text{exp.})\,^{+0.023}_{-0.014}\,(\text{scale}) \pm 0.004\,(\text{PDF})\\ &\quad \pm 0.010\,(\text{NLO-matching method})\\ &\quad \pm 0.009\,(\text{parton shower}) \pm 0.010\,(\text{lumi.})\\ &\quad \pm 0.005\,(m_t) \pm 0.024\,(\text{theor.})\\ &= 1.029 \pm 0.048.\end{aligned}$$

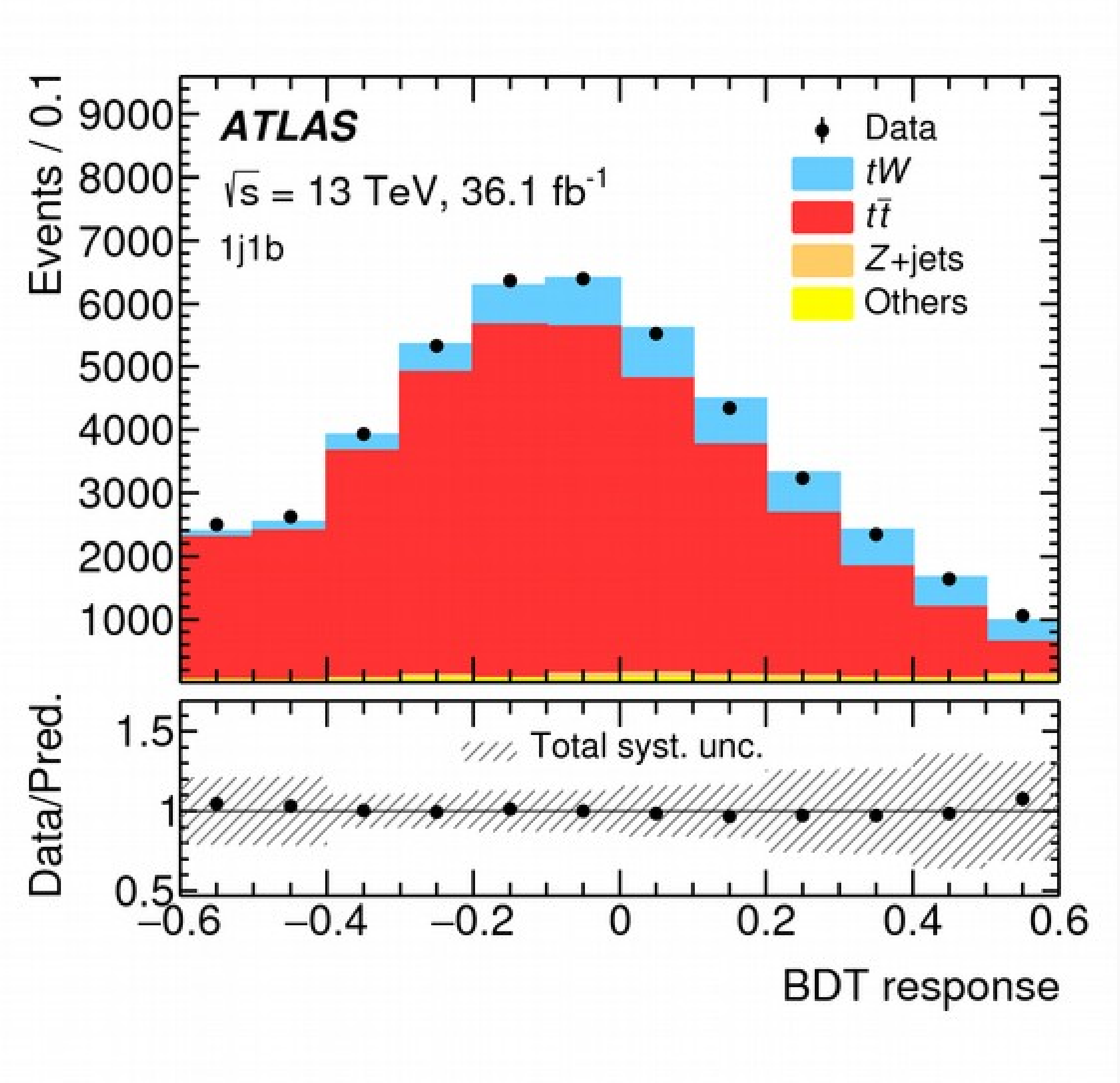
$$\begin{aligned}R_t &= \frac{\sigma_{\text{tot}}(tq)}{\sigma_{\text{tot}}(\bar{t}q)} = 1.72 \pm 0.05\,(\text{stat.}) \pm 0.07\,(\text{exp.})\\ &= 1.72 \pm 0.09.\end{aligned}$$

Unfolded spectra

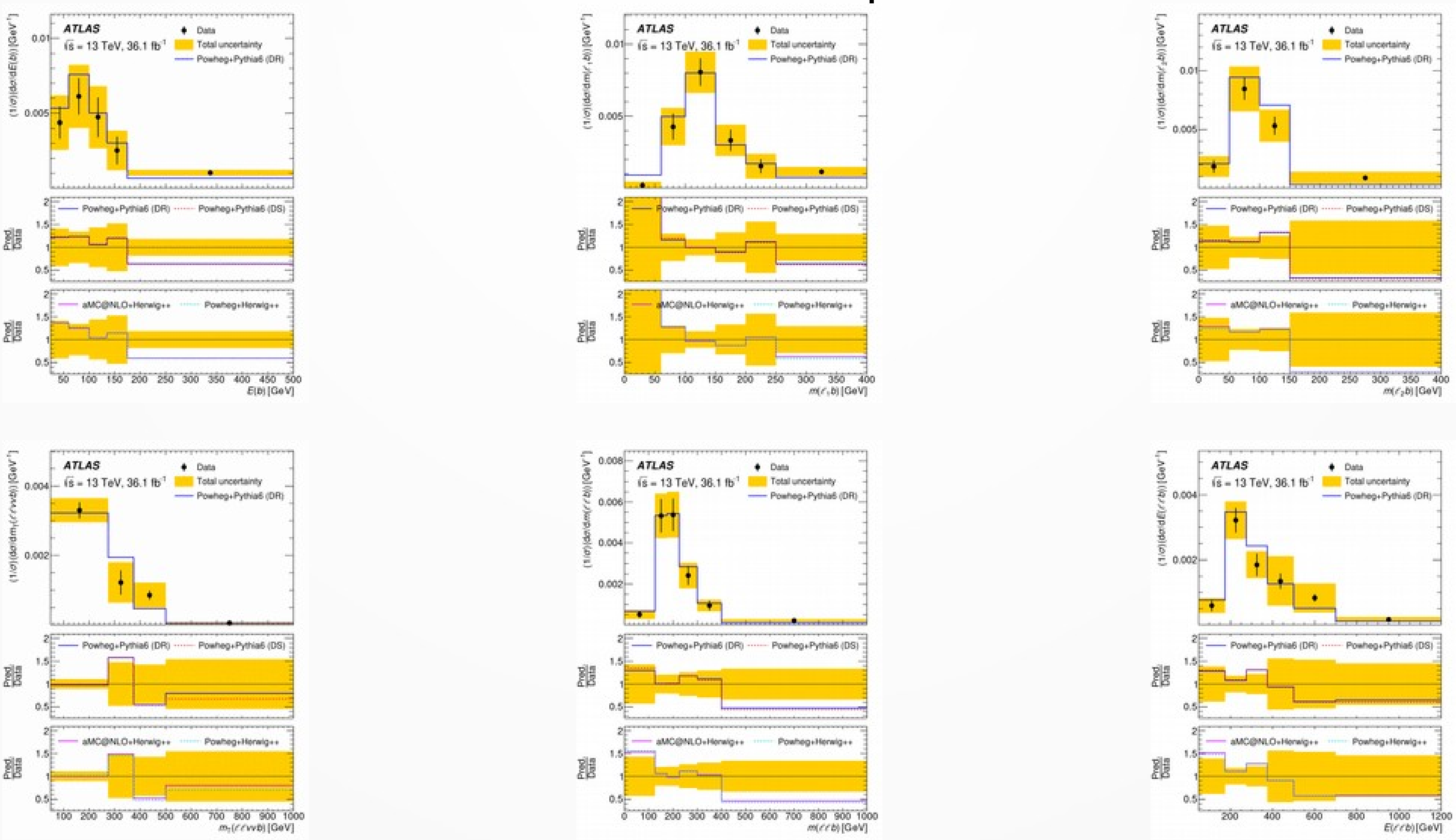


BDT

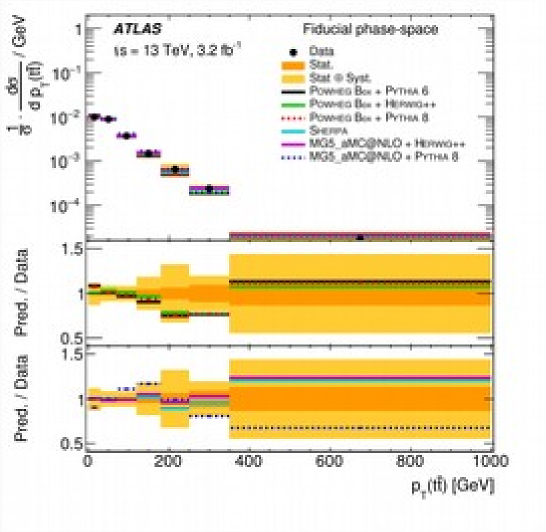
Variable	$S\ [10^{-2}]$
$p_{\mathrm{T}}(\ell_1\ell_2 E_{\mathrm{T}}^{\mathrm{miss}} b)$	4.1
$\Delta p_{\mathrm{T}}(\ell_1\ell_2 b, E_{\mathrm{T}}^{\mathrm{miss}})$	2.5
$\sum E_{\mathrm{T}}$	2.3
$\eta(\ell_1\ell_2 E_{\mathrm{T}}^{\mathrm{miss}} b)$	1.3
$\Delta p_{\mathrm{T}}(\ell_1\ell_2, E_{\mathrm{T}}^{\mathrm{miss}})$	1.1
$p_{\mathrm{T}}(\ell_1\ell_2 b)$	1.0
$C(\ell_1\ell_2)$	0.9
$m(\ell_2, b)$	0.2
$m(\ell_1, b)$	0.1
BDT response	8.1

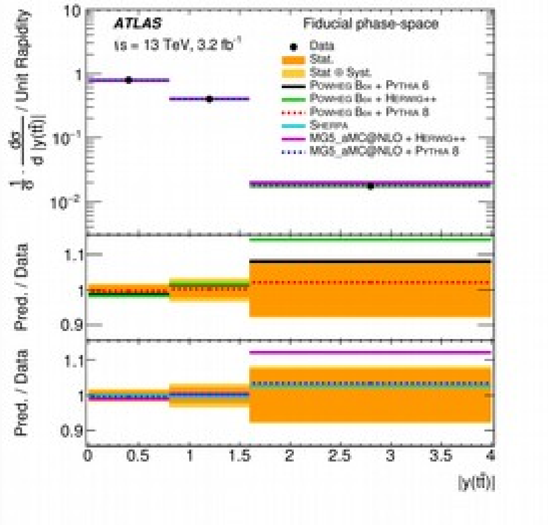


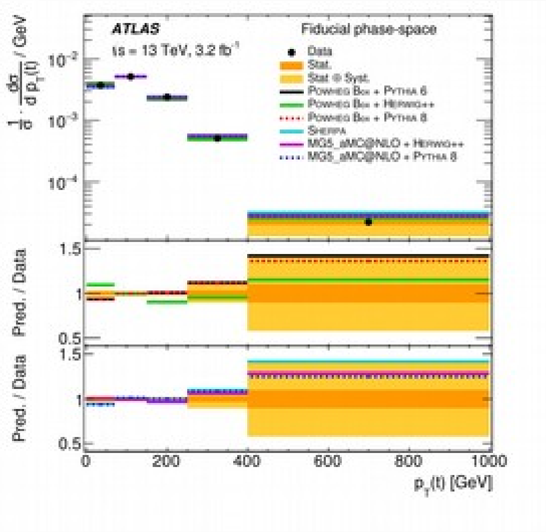
Unfolded spectra

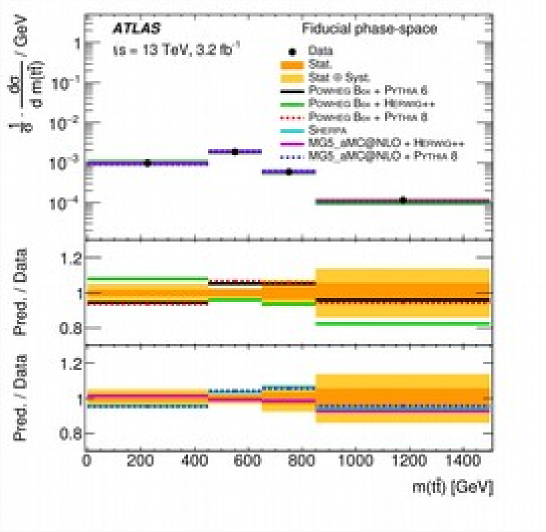


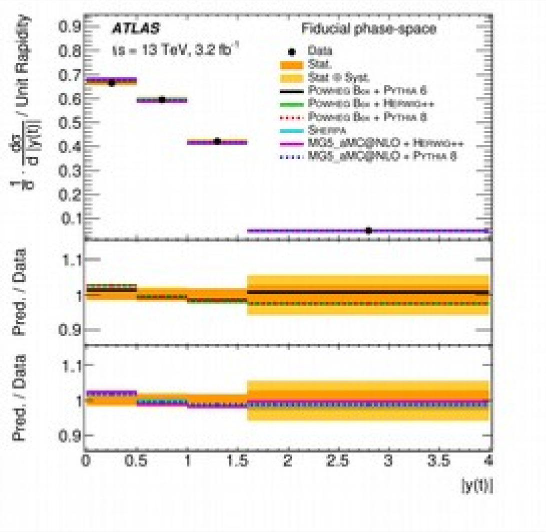
Unfolded spectra



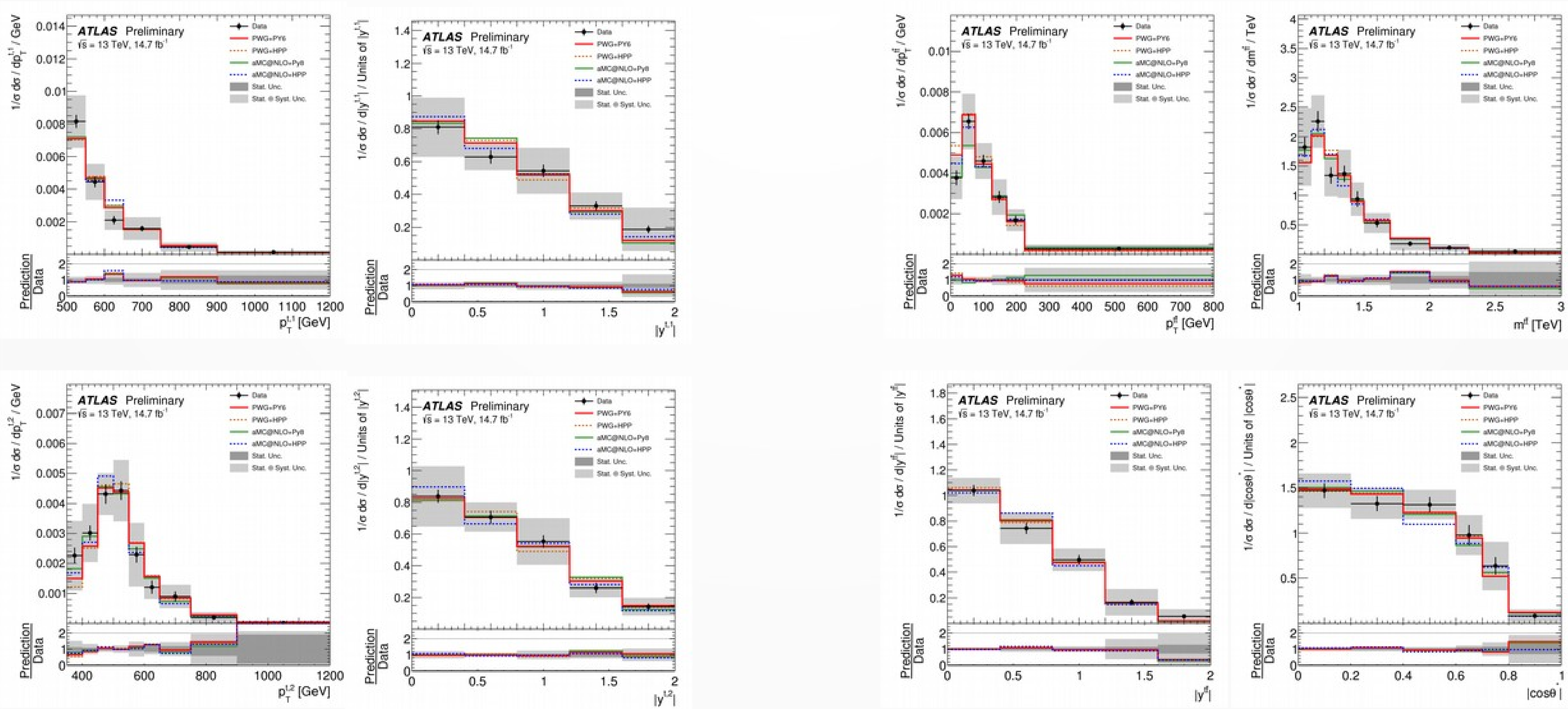




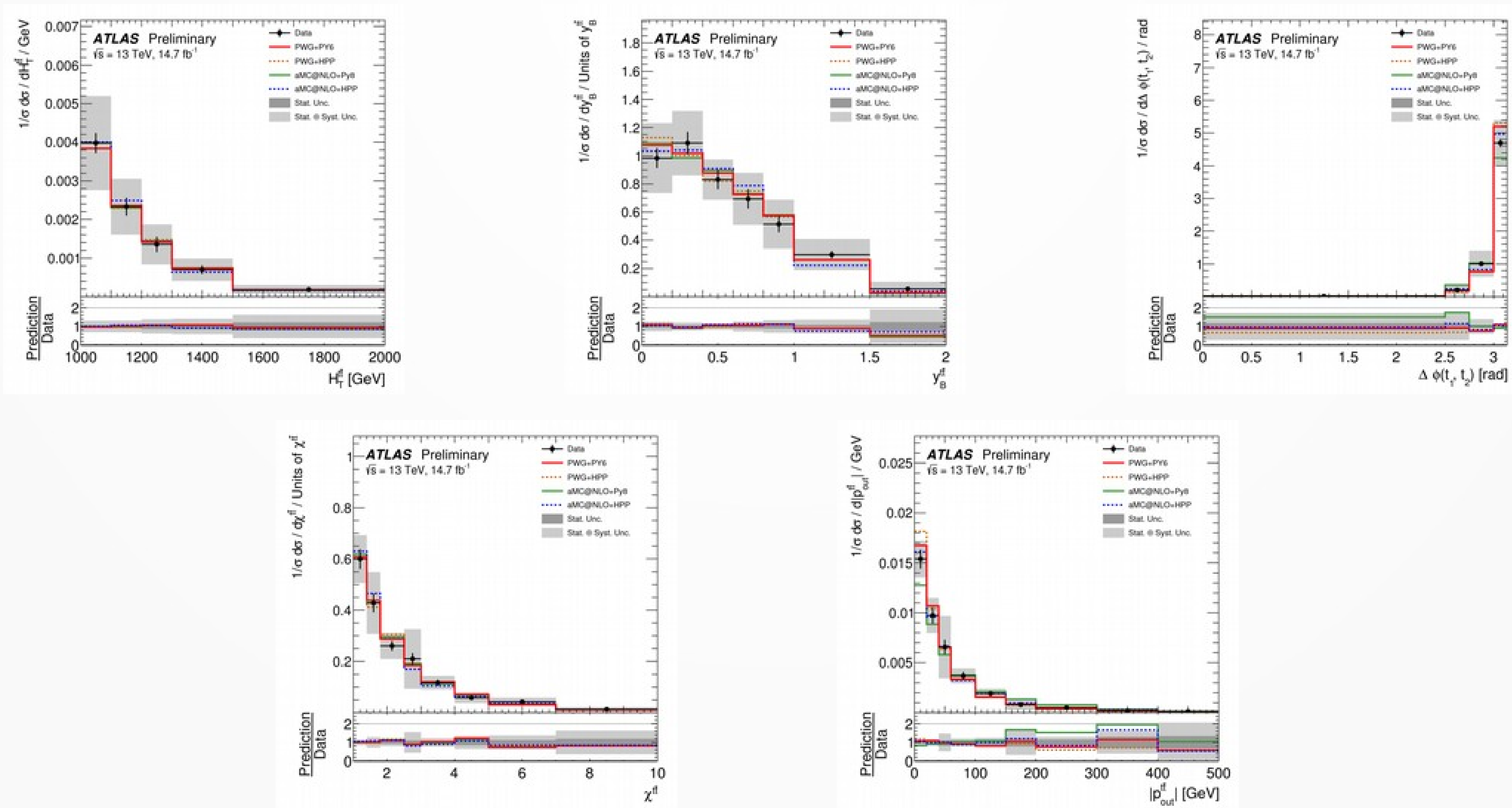




Unfolded spectra



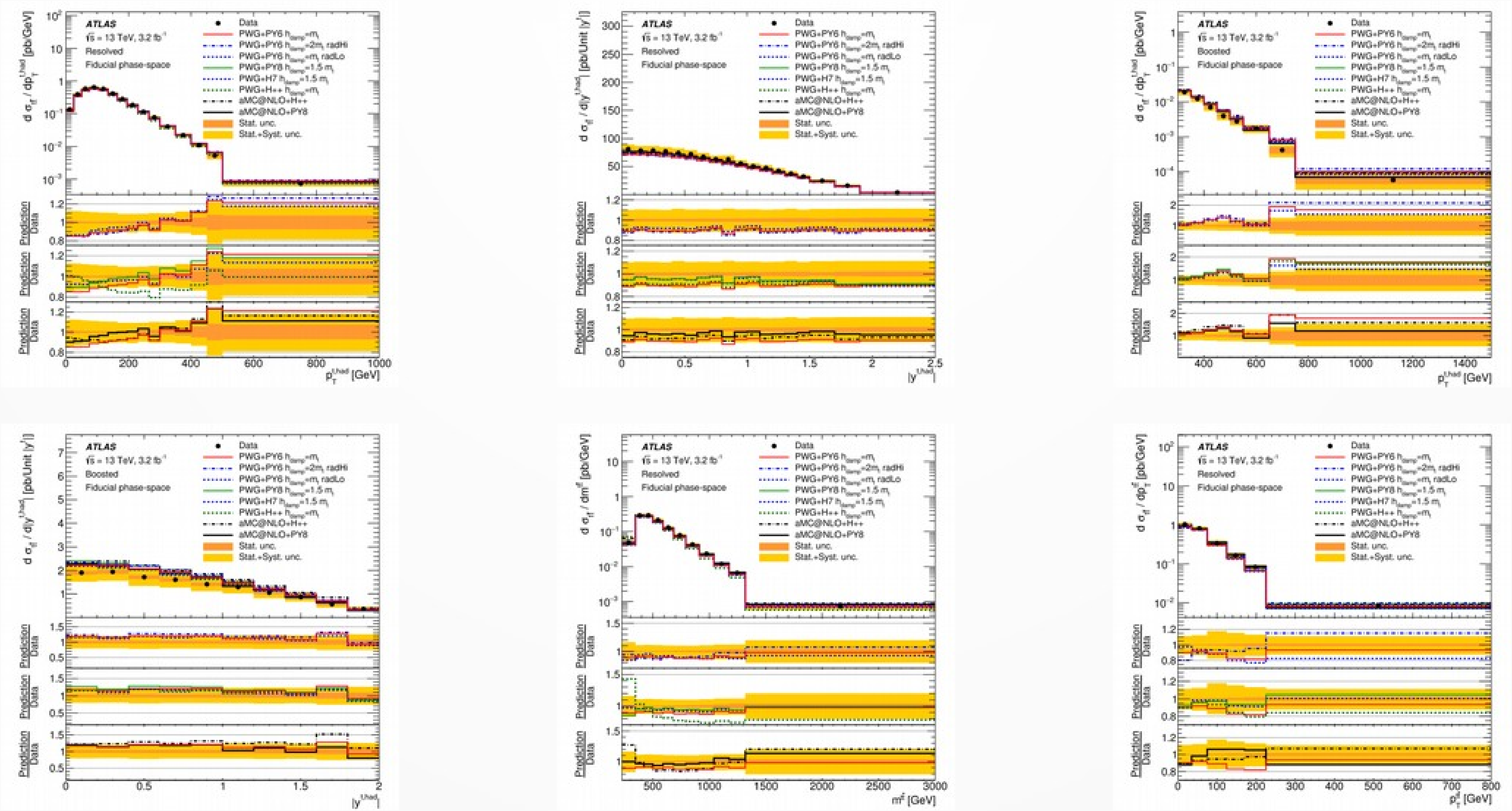
Unfolded spectra



Event Selection

Level	Detector		Particle
Topology	Resolved	Boosted	
Leptons	$\|d_0\|/\sigma(d_0) < 5$ and $\|z_0 \sin\theta\| < 0.5$ mm Track and calorimeter isolation $\|\eta\| < 1.37$ or $1.52 < \|\eta\| < 2.47$ (e), $\|\eta\| < 2.5$ (μ) E_T (e), p_T (μ) > 25 GeV		$\|\eta\| < 2.5$ $p_T > 25$ GeV
Small-R jets	$\|\eta\| < 2.5$ $p_T > 25$ GeV JVT cut (if $p_T < 60$ GeV and $\|\eta\| < 2.4$)		$\|\eta\| < 2.5$ $p_T > 25$ GeV
Num. of small-R jets	≥ 4 jets	≥ 1 jet	Same as detector level
E_T^{miss}, m_T^W		$E_T^{miss} > 20$ GeV, $E_T^{miss} + m_T^W > 60$ GeV	Same as detector level
Leptonic top	Kinematic top-quark reconstruction for detector and particle level	At least one small-R jet with $\Delta R(\ell$, small-R jet$) < 2.0$	
Hadronic top	Kinematic top-quark reconstruction for detector and particle level	The leading-p_T trimmed large-R jet has: $\|\eta\| < 2.0$, 300 GeV $< p_T <$ 1500 GeV, $m > 50$ GeV, Top-tagging at 80% efficiency ΔR(large-R jet, small-R jet associated with lepton) > 1.5, $\Delta\phi(\ell$, large-R jet$) > 1.0$	**Boosted:** $\|\eta\| < 2.0$ $300 < p_T < 1500$ GeV Top-tagging: $m > 100$ GeV, $\tau_{32} < 0.75$
b-tagging	At least 2 b-tagged jets	At least one of: 1) the leading-p_T small-R jet with $\Delta R(\ell$, small-R jet$) < 2.0$ is b-tagged 2) at least one small-R jet with ΔR(large-R jet, small-R jet$) < 1.0$ is b-tagged	Ghost-matched b-hadron

Unfolded spectra



Unfolded spectra