Top quark production measurements at ATLAS

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On behalf of the ATLAS Collaboration
Top quark physics

Top quark basics:
- Mass: $173.34 \pm 0.27 \pm 0.71$ GeV (arXiv:1403.4427, Tevatron-LHC combination)
- Decays: charged current weak decays in $t \rightarrow Wb$

Why study top quark physics?
- Yukawa coupling with the Higgs $\sim 1 \rightarrow$ Important role in the EWSB
- Life-time shorter than hadronization time
  $\rightarrow$ Unique possibility to study a 'bare' quark
- Precise tests of the Standard Model and verification of pQCD
- Privileged window to search for new physics
  - Cross section measurements needed to improve top quark MC modelling, especially when used as a background for BSM processes

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Top quark cross section measurements

- $t\bar{t}$: inclusive and differential
- Single top inclusive
Production mechanisms at LHC
- Gluon-gluon fusion (~85% @ 7 TeV)
- Quark-antiquark annihilation

Decays
- $t \rightarrow Wb(~100\%)$
  - $W \rightarrow l\nu_l \sim 33\%$
  - $W \rightarrow q\bar{q}' \sim 66\%$

Top pair final states
- "alljets" 44%
- $\tau + \text{jets} 15\%$
- $\mu + \text{jets} 15\%$
- e + jets 15%
- "Lepton + jets"
**Top quark pair inclusive cross section: summary**

$$\sigma(t\bar{t}) @ \sqrt{s} = 7 \text{ TeV}$$  
$$\sigma(t\bar{t}) @ \sqrt{s} = 8 \text{ TeV}$$

Good agreement of all measurements with SM predictions

Experimental uncertainties already comparable with theoretical ones

Dilepton $e\mu$ measurement is the most precise measurement to date

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**Table and Graphs:**

<table>
<thead>
<tr>
<th>Region</th>
<th>$\sigma([t\bar{t}])$ @ $\sqrt{s} = 7$ TeV</th>
<th>$\sigma([t\bar{t}])$ @ $\sqrt{s} = 8$ TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATLAS, dilepton (+)</td>
<td>179 ± 4 ± 9 ± 7 pb</td>
<td>260 ± 1 ± 20 ± 8 pb</td>
</tr>
<tr>
<td>ATLAS, all jets (+)</td>
<td>167 ± 18 ± 78 ± 6 pb</td>
<td>228 ± 9 ± 20 ± 10 pb</td>
</tr>
<tr>
<td>ATLAS combined</td>
<td>177 ± 3 ± 3 ± 7 pb</td>
<td>257 ± 3 ± 24 ± 7 pb</td>
</tr>
<tr>
<td>CMS, dilepton (+)</td>
<td>164 ± 3 ± 12 ± 7 pb</td>
<td>195 ± 2 ± 3 ± 7 pb</td>
</tr>
<tr>
<td>CMS, all jets (+)</td>
<td>156 ± 20 ± 40 ± 8 pb</td>
<td>187 ± 13 ± 20 ± 7 pb</td>
</tr>
<tr>
<td>CMS combined</td>
<td>166 ± 2 ± 11 ± 8 pb</td>
<td>242.4 ± 1.7 ± 5.5 ± 7.5 pb</td>
</tr>
<tr>
<td>LHC combined (Sep 2012)</td>
<td>173 ± 2 ± 8 ± 6 pb</td>
<td></td>
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</tbody>
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**Graphs:**

- Dilepton $e\mu$ measurement is the most precise measurement to date

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**Links:**

**$t\bar{t}$ inclusive cross section $e\mu$ channel**

**EPJC 74 (2014) 3109**

$\sqrt{s} = 7$ TeV, $L = 4.6$ fb$^{-1}$

$\sqrt{s} = 8$ TeV, $L = 20.3$ fb$^{-1}$

Simultaneous fit of the $t\bar{t}$ production cross section (total and fiducial) and the $b$-jet reconstruction and tagging efficiency in 1 and 2 $b$-tag samples

- Correlation between the $b$-tag probabilities of the 2 jets taken in account
- Significant reduction of major systematics
- Dominating systs: beam energy, integrate lumi, $t\bar{t}$ modelling
- Fiducial phase space: $1e$ and $1\mu$ ($p_T > 25$GeV, $|\eta| < 2.5$)

**Total cross section [pb]**

7 TeV: $\sigma_{tt} = 182.9 \pm 7.1$ (±3.9%)

8 TeV: $\sigma_{tt} = 242.4 \pm 10$ (±4.3%)

**NNLO+NNLL predictions**

(M. Czakon and A. Mitov, Comp. Phys. Comm. 182 2930 (2014))

7 TeV: $\sigma_{tt}^{th} = 177.3 \pm 9.0^{+4.6}_{-6.0}$ (±5.1%±2.6%)

8 TeV: $\sigma_{tt}^{th} = 252.9$ pb $\pm 11.7^{+6.4}_{-8.6}$ (±4.6%±2.5%)

**Fiducial cross section [pb]**

7 TeV: $\sigma_{tt} = 2.615 \pm 0.082$ (±3.8%)

8 TeV: $\sigma_{tt} = 3.448$ pb $\pm 0.14$ (±4.1%)
Strong dependence of NNLO $\sigma_{tt}$ on $m_t$

- Also $\sigma_{tt}^{\text{meas}}$ shows (weak) dependence on $m_t$
- Extraction of top pole mass via the maximization of a Bayesian likelihood function

Constraints on stop pair production

- $R$-parity conserving SUSY extension of SM with $\tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$ (BR = 100%)
- Fit $\sigma_{\tilde{t}_1\tilde{t}_2}$ to the $\sigma_{tt}^{\text{meas}} - \sigma_{tt}^{\text{th}}$ difference
- 95% CL exclusion of stop with $m_t < m_{\tilde{t}_1} < 177$ GeV

$\bar{t}t$ inclusive cross section $e\mu$ channel

EPJC 74 (2014) 3109

Fits to $\sigma_{tt}$ and $m_{\tilde{t}_1}$
Top quark pairs differential cross section measurements in ATLAS

Total $\sigma_{t\bar{t}}$ measurements show very good agreement with the SM

- New physics phenomena can still affect the shape of $\sigma_{t\bar{t}}$

Top reconstruction strategies

### ‘Resolved’ topology
- Optimized for low-$p_T$ (< 300 GeV) top quarks
- Top-quark decay products are well separated and can be reconstructed individually
- Top-antitop kinematic evaluated from the reconstructed decay products

### ‘Boosted’ topology
- Optimized for high-$p_T$ (> 300 GeV) top quarks
- Top quark decay products are not isolated
- Hadronically decaying top quark is reconstructed in a single large radius jet
Top-antitop relative differential cross section \(\frac{1}{\sigma} \frac{d\sigma}{dX}\) where \(X = m_{t\bar{t}}, p_T, t, |y_{t\bar{t}}|\) and \(p_T, t\) are reconstructed via a kinematic likelihood fit

Relative measurement more precise than the absolute \(\rightarrow\) cancellation of correlated systematics

Events selected in the lepton (e/\(\mu\)) + jets channel

Parton t and \(\bar{t}\) reconstructed via a kinematic likelihood fit

Final parton level measurement extracted via unfolding procedure and extrapolated to the total phase space

Electron and muon channel combination via the Asymmetric Iterative BLUE (AIB)

Main uncertainty (top \(p_T\)): \(t\bar{t}\) modelling, JES, b-tag

Reco spectrum

Resolution & efficiency corrections

Parton level measurement
$t\bar{t}$ differential cross section

JHEP 06 (2015) 100

$\sqrt{s} = 7$ TeV, $L = 4.6$ fb$^{-1}$

- Top-antitop differential cross section \( \frac{d\sigma}{dX} \) where \( X = m_{t\bar{t}}, p_{T,t\bar{t}}, |y_{t\bar{t}}|, p_{T,t} \) and |\(y_t| |

- *Fiducial* measurement: limited to the actual «visible» phase space

- Pseudo top (\(\hat{t}\)) observables built from stable final state objects

- Cut-based analysis in the \(l(e/\mu)+\)jets channel

- Main uncertainties: \(b\)-tag, JES and IFSR

- General trend of data being softer in \(p_{T,t}\) above 200 GeV

- Same behavior is observed by the parton level analysis
$t\bar{t}$ differential cross section

boosted tops

First measurement $\frac{d\sigma}{dp_{T,t}}$ for high-$p_T$ (boosted) top quarks

Semi-leptonic ($e/\mu$) channel with $p_T(t_{\text{had}}) > 300$ GeV

Boosted hadronic top defined as a single large-$R$ jet

Fiducial (particle pseudo tops) and total (parton tops) phase space measurements

Measured $\sigma$ in general lower than predictions

Discrepancy tends to increase at high $p_T$

In agreement with the behavior observed in resolved analyses

Main uncertainties:

- Large-$R$ jet energy scale
- Extrapolation to parton level affected by an increased signal modelling systematics
Single top quark cross section

Cross section summary @ Run I

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/TOP/

Measurements at 7 and 8 TeV:
- Cross section for $t$ and $Wt$ channels
  - $|V_{tb}|$ extraction
  - Differential cross sections in the $t$ channel
- Upper limit for the $s$ channel
- Top/antitop $t$-channel ratio ($R_t$)

$$R_t = \frac{\sigma_t}{\sigma_{\bar{t}}$$

EPS-HEP 2015

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Single top $t$-channel cross section

- A multivariate Neural Network (NN) discriminant trained with the 14 most-sensitive variables
- Contributions from signal and background evaluated via MC (data driven for Multijet bkg in the $\mu$ channel)
- Lepton + 2 jets channel, 1 $b$-tag
- $\sigma_{t\text{-chan}}$ extracted via a maximum-likelihood fit of the NN output in the data
- Fiducial and total phase space measurements

$$\sigma_{t\text{-chan}}^{\text{fiducial}}(\sqrt{s} = 8 \text{ TeV}) = 3.4 \pm 0.48 \text{ pb (±14%)}$$
Main uncertainties: JES and signal modelling

$$\sigma_{t\text{-chan}}^{\text{total}}(\sqrt{s} = 8 \text{ TeV}) = 82.6 \pm 12.1 \text{ pb (±15%)}$$
(extrapolated via MG5_aMC@NLO)
Additional uncertainty: PDF

$$\sigma_{t\text{-chan}}^{\text{th}}(\sqrt{s} = 8 \text{ TeV}) = 87.8^{+3.4}_{-1.9} \text{ pb (±3.9%)}$$
N. Kidonakis, Phys. Rev. D 83 (2011) 091503

$\sqrt{s} = 8 \text{ TeV}, L = 20.3 \text{ fb}^{-1}$
Single top/antitop t-chan ratio

\[ R_t = \frac{\sigma_t}{\sigma_{\bar{t}}} \]

- Very sensitive to the ratio of the PDF of the valence quark in the high \( x \) regime
- Smaller uncertainties because of error cancelations
- Sensitive to new physics effects
- Same analysis technique used in the \( \sigma_{tchan} \) measurement at 8 TeV

\[ \sqrt{s} = 7 \text{ TeV}, \; L = 4.6 \text{ fb}^{-1} \]

The measurement is in agreement with the predictions from different PDF sets and is dominated by statistical and systematic (MC statistics and PDF) uncertainties.
**Single top $Wt$-channel cross section**

1. Hard to separate from $t\bar{t}$, interference at NLO
2. Event selected requiring $1e, 1\mu, 1/2$jet, $1b$-tag, $E_T^{miss}$
3. Multivariate analysis based on Boosted Decision Tree (BDT) employed to increase the discrimination power
   - BDT trained using $Wt$ as signal and $t\bar{t}$ as background
   - BDT discriminants built separately for 1 and 2 jet samples
4. Most discriminating variable: $p_T^{sys}(lep1, lep2, E_T^{miss}, jet1)$
5. Maximum likelihood fit to the BDT output to extract the signal cross section

**ATLAS-CONF-2013-100**

$\sqrt{s} = 8$ TeV, $L = 20.3$ fb$^{-1}$

$\sigma_{Wt}(\sqrt{s} = 8$ TeV$) = 27.2 \pm 5.8$ pb ($\pm 21\%$) (observed $4.2\sigma$, expected $4.0\sigma$)

Main systematics: $b$-tagging, JES, generator uncertainties

$\sigma_{Wt}^{th}(\sqrt{s} = 8$ TeV$) = 22.4 \pm 1.5$ pb($\pm 6.7\%$)

Single top $s$-channel search

- Low rate in $pp$ collisions (was dominant at Tevatron)
- Event selected requiring 1l, 2b-tag, $E_T^{miss}$
- Multivariate analysis based on Boosted Decision Tree (BDT) employed to increase the discrimination power
- Most discriminating variable: $|\Delta\phi(t, b)|$
- Maximum likelihood fit to the BDT output to extract the signal cross section

$\sqrt{s} = 8$ TeV, $L = 20.3$ fb$^{-1}$

$\sigma_{s-chan}(\sqrt{s} = 8$ TeV$) = 5.0 \pm 4.3$ pb (±86%)

(1.3$\sigma$, expected 1.4$\sigma$)

Upper limit: 14.6 pb @ 95%CL

Main uncertainties: $E_T^{miss}$ and jet energy scale, data & MC statistics

$\sigma_{s-chan}^{th}(\sqrt{s} = 8$ TeV$) = 5.61 \pm 0.22$ pb (±3.9%)

Data collected by the ATLAS detector on the 13th and 14th of June 2015 at $\sqrt{s} = 13$ TeV

Monte Carlo predictions have been scaled to match the normalisation of the data

Single lepton ($e/\mu$) and dilepton ($ee/\mu\mu/e\mu$) channel
Event Kinematic Distributions in Top-Quark Enriched Samples

Within the limited statistics, the shape of the kinematic distributions appear well modeled.

ATL-PHYS-PUB-2015-017
Summary

- Top quark measurements have provided stringent tests of SM
- Top quark pair production
  - Inclusive cross-section measured with 4% accuracy
  - Top quark pole mass and stop exclusion from inclusive cross section measurements
  - Differential cross sections: resolved and boosted topologies, parton and particle level
  - SM predictions in general good agreement with data
- Single top production
  - Wt-channel rediscovered, s-channel limits set
  - t-channel dataset large enough to investigate single top properties
  - In general, SM has held up remarkably well
- Stay tuned for new results with data in Run II at 13 TeV
  - Higher statistics will improve all analyses
  - Higher energy means greater reach for searches
Backup
Cross section measurements

$\sigma_{t\bar{t}}$:
• can put constraints on SM parameters
• current statistics allow the study of differential spectra

$\sigma_t$:
• Sensitive to electroweak physics involving $Wtb$ vertex
• Sensitive to the pdf of the valence quarks
Common object definitions

- Details can vary among the different analyses

- Jets:
  - Reconstructed from topological clusters using the anti-kt algorithm ($R = 0.4$)
  - $p_T > 25$ GeV, $|\eta| < 2.5$

- B-tagging via a Neural network based algorithm (MV1) with average efficiency of 70% and light jet rejection factor ~140

- Electrons:
  - EM cluster with track matched
  - Isolation in tracker and calorimeter
  - $E_T > 25$ GeV, $|\eta| < 1.37$ or $1.52 < |\eta| < 2.47$

- Muons:
  - Tracks in inner detector and muon spectrometer
  - Isolation in tracker and calorimeter
  - $p_T > 20$ GeV, $|\eta| < 2.5$

- Missing transverse energy
  - Vector sum of energy deposits in calorimeters, with corrections based on the associated reconstructed object
Top quark pairs differential cross section measurements in ATLAS

Definition of the object “top-quark”

‘Parton-level’ top:
- the 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

Leptonic pseudo-top

Hadronic pseudo-top

Leptonic parton top

Hadronic parton top

Lepton

W

b

t
Reconstruction of the $tt$ system via kinematic likelihood fit

- The $tt$ system reconstruction is performed through a kinematic fit using a maximum likelihood approach.

\[ L = B\left(\tilde{E}_{p,1}, \tilde{E}_{p,2}|m_{W}, \Gamma_{W}\right) \cdot B\left(\tilde{E}_{l, \tilde{E}_{\nu}}|m_{W}, \Gamma_{W}\right) \cdot \\
\cdot B\left(\tilde{E}_{p,1}, \tilde{E}_{p,2}, \tilde{E}_{p,3}|m_{t}, \Gamma_{t}\right) \cdot B\left(\tilde{E}_{l, \tilde{E}_{\nu}, \tilde{E}_{p,4}}|m_{t}, \Gamma_{t}\right) \cdot \\
\cdot \mathcal{W}\left( E_{x}^{miss} | \vec{p}_{x, \nu}\right) \cdot \mathcal{W}\left( E_{y}^{miss} | \vec{p}_{y, \nu}\right) \cdot \mathcal{W}\left( E_{lep} | \vec{E}_{lep}\right) \cdot \\
\cdot \prod_{i=1}^{4} \mathcal{W}\left( E_{jet,i} | \tilde{E}_{p,i}\right) \cdot P(\text{b tag | quark}), \]

- The likelihood assesses the compatibility of the event with a typical $ttbar$ pair.
- The algorithm is fed with the 4 or 5 reconstructed highest-$pt$ jets (and their b-tag info), the lepton and the $E_{T}^{miss}$.
- The output is the permutation of the four jets, lepton and $E_{T}^{miss}$ that maximizes the likelihood.
From the detector-level spectra to the cross section measurement

The ‘detector-level’ spectra are linked to the ‘parton level’ cross section $\sigma_j$ via

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

Where

- $N_i$ is the number of observed data events in the bin $j$.
- $L$ is the luminosity.
- $B_i$ is the number of background events in the bin $i$.
- $\beta$ is the branching ratio.
- $M_{ij}$ is the ‘migration matrix’.
- $\epsilon_j$ is the efficiency of the selection.
Electron and muon channel combination via the Asymmetric Iterative BLUE (AIB)

Main uncertainties:
- $p_{T,t}$, $m_{t\bar{t}}$: JES, generator $b$-tag;
- $p_{T,t\bar{t}}$: IFSR, generator, PS, JER
- $|y_{t\bar{t}}|$: generator and PS

Comparison to MC generators: Alpgen, Powheg and MC@NLO interfaced with Herwig+Jimmy and Powheg+Pythia

- General trend of data being softer in $p_{T,t}$ above 200 GeV
- All four MC generators describe well the shape of $m_{t\bar{t}}$ and $p_{T,t\bar{t}}$
- Alpgen gives the best prediction of the $|y_{t\bar{t}}|$
Results: comparison with NLO calculations

NLO prediction based on MCFM with different PDF sets

Uncertainty: scale (fixed) and PDF
- A small discrepancy between data and all predictions is observed in $p_T,t$ at higher $p_T$
- Overall better agreement with HERAPDF1.5
- Poor constraining power for $p_T,t\bar{t}$ (LO observable)
Results: comparison with approximate NNLO calculations

NLO+NNLL prediction for $p_{T,t}$ (N. Kidonakis, Phys. Rev. D82 (2010) 114030), for $m_{t\bar{t}}$ (V. Ahrens et al., JHEP 1016 (2010) 097) and for $p_{T,t\bar{t}}$ (Hua Xing Zhu et al., Phys. Rev. Lett. 110 (2013) 082001) with the MSTW2008NNLO PDF

Theory uncertainty from the fixed scale variations and, only for $p_{T,t}$, from the alternate dynamic scale $\mu = \sqrt{m_t^2 + p_{T,t}^2}$

- As in the NLO calculation, the $p_{T,t}$ spectrum in data seems softer
- Opposite trend appears for $p_{T,t\bar{t}}$ spectrum
- The $m_{t\bar{t}}$ spectrum is not well described by the NLO+NNLL prediction
“Particle level” object definitions and selection

- Details can vary among the different analyses
- Leptons and jets are defined using particles with a mean lifetime \( \tau > 3 \times 10^{-11} \) s
- Prompt leptons (e/mu/nu) *not* generated by the decay of a hadron as well as leptons coming from the decay of a tau
- The electron and muon four-momenta are calculated after the addition of any photon four-momenta, not originating from hadron decay that are found \( \Delta R < 0.1 \) with respect to the lepton direction ("dressed" leptons)
- Jets:
  - Reconstructed from all stable particles except for the selected electrons, muons and neutrinos, using the anti-kt algorithm \( (R = 0.4) \)
- ‘b-tagging’:
  - The presence of one or more b-hadrons with \( p_T > 5 \) GeV associated to a jet defines it as a b-jet.
- Missing transverse energy
  - Vector sum the neutrinos four-momenta
- Events are “selected” at particle level by applying, to the particle level objects, the same requirements applied to the “reco level” objects
Pseudo-Top reconstruction

1) Reconstruct neutrino 4-momentum applying W mass constraint

2) Reconstruct W from lepton and neutrino

3) Select two highest $p_T$ b-jets

4) Reconstruct leptonic top from W and closest b-jet

5) Reconstruct W from two hardest light jets

6) Reconstruct hadronic top from W and other b jet

The pseudo-tops reconstruction is identical at reco and particle level with the exclusion of the neutrino that at particle level is taken from truth
Particle level measurement of \( \frac{d\sigma_{tt}}{dN_{jets}} \) (with different cuts on \( p_{T,\text{jet}} \)) and \( \frac{d\sigma_{tt}}{dp_{T,\text{jet}}} \)

Limited by systematic uncertainties: background modelling (for \( n_{jets} < 4 \)) and jet energy scale (\( n_{jets} \geq 4 \))

\( \frac{d\sigma_{tt}}{dN_{jets}} \): sensitive to hard emissions in QCD bremsstrahlung processes.

\( \frac{d\sigma_{tt}}{dp_{T,\text{jet}}} \): sensitive to the modelling of higher-order QCD effects in MC

\[ \sqrt{s} = 7 \text{ TeV}, \int Ldt = 4.6 \text{ fb}^{-1} \]
Jet multiplicity in top–anti-top final states

- Useful to constrain models of initial and final state radiation (ISR/FSR)
- Provides a test of perturbative QCD
- Single-lepton channel
  - Four jet $p_T$ thresholds: (25, 40, 60, and 80 GeV)
- Results are corrected for all detector effects through unfolding
  - Reconstructed level $\rightarrow$ particle level
- Measurement is limited by systematic uncertainties,
  - background modelling (at lower jet multiplicities)
  - jet energy scale (at higher jet multiplicities)
Jet multiplicity in top–anti-top final states

- MC@NLO modelling predicts a lower jet multiplicity spectrum and softer jets
- Predictions from ALPGEN + HERWIG or PYTHIA and POWHEG + PYTHIA are consistent with the data
Events selected in a high purity ($O_{NN} > 0.8$) region

- Allows the measurement of differential distributions

Differential cross section as a function of $p_T(t/\bar{t})$ and $|y(t/\bar{t})|$:

- Reconstructed spectra corrected to parton level via unfolding procedures

General good agreement with NLO predictions


$\sqrt{s} = 7$ TeV, $\int L \, dt = 4.6 \, \text{fb}^{-1}$
A direct determination of $V_{tb}$ can be extracted from the cross-sections measurements ($t$- and $Wt$-channel)

Two general assumptions
1. $W - t - b$ interaction is left-handed
2. top quark production and decay through $|V_{ts}|$ and $|V_{td}|$ are negligible

$|V_{tb}|$ is extracted by the ratio

$$|V_{tb}| = \frac{\sigma_{exp}}{\sigma_{th}}$$

Where, for the SM, $f = 1$
Top quarks are being produced at 13 TeV as we speak!
Event Kinematic Distributions in Top-Quark Enriched Samples

Data collected by the ATLAS detector on the 13th and 14th of June 2015 at $\sqrt{s} = 13$ TeV

Monte Carlo predictions have been scaled to match the normalisation of the data

Single lepton ($e/\mu$) and dilepton ($ee/\mu\mu/e\mu$) channel

Within the limited statistics, the shape of the kinematic distributions appear well modeled

Plots to be approved for EPS