$t\bar{t}$ + heavy flavor production at the LHC

Tae Jeong Kim (Hanyang University)

on behalf of the ATLAS and CMS collaborations

Rencontres du Vietnam 30th Anniversary:

Windows on the Universe

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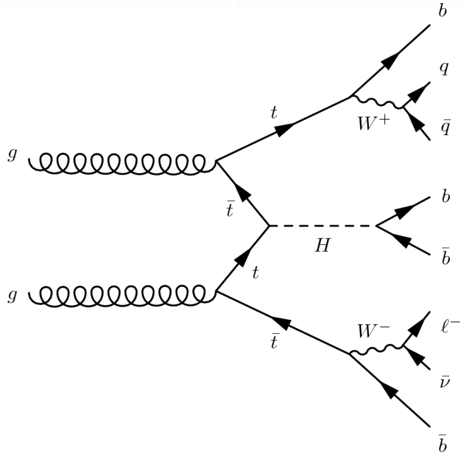
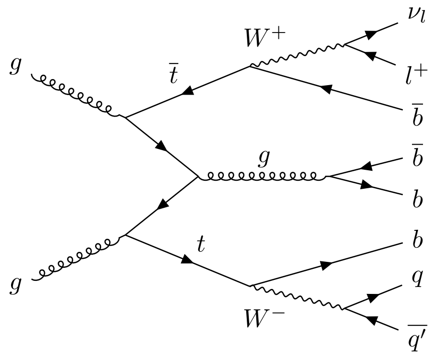
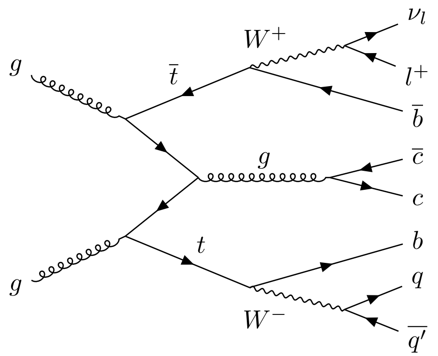
Introduction

- After the Higgs boson discovery, the consistency check with the H boson was the highest priority
- Confirmation with the couplings of a top quark and a bottom quark (third-generation) is only possible by measuring $t\bar{t}H(b\bar{b})$
- Understading the $t\bar{t}b\bar{b}$ process is a prerequistite to discovery
- In addition, the charm jets in the $t\bar{t}c\bar{c}$ can also be misidentified as b jets
- The measurements of cross-sections of the $t\bar{t}$+heavy flavor (HF) process are essential yet challenging objectives
  - Poor Higgs mass resolution
  - Huge combinatorics
  - b jets can come from top quark, gluon decay, H boson or another boson







Theoretical predictions

- Calculations of $t\bar{t}b\bar{b}$ by matching Matrix Element to Parton Shower were performed at NLO in QCD within the 5 Flavor Scheme (5FS)
- Full NLO QCD corrections for $t\bar{t}b\bar{b}$ production including off-shell of top quark are available
- 4 Flavor Scheme (4FS) $t\bar{t}b\bar{b}$ prediction is also available (b quark not part of the proton PDF)
- NLO QCD prediction for the $t\bar{t}b\bar{b}$ with one additional jet is also available

- However, they suffer from large factorization and renormalization uncertainties due to the presence of two very different scales (top quark mass and b quark mass)
- Therefore, precise measurements can also provide a good test of the NLO QCD theory itself

Measurements of $t\bar{t}$ + heavy flavor process

- ATLAS measurements
  - 7 TeV, dilepton, Phys. Rev. D 2014, 89, 072012 [A1]
  - 8 TeV, dilepton, lepton + jets, Eur. Phys. J. C 2016, 76, 11 [A2]
  - 13 TeV, dilepton, lepton + jets, J. High Energy Phys. 04, 2019, 46 [A3]
- CMS measurements
  - 8 TeV, dilepton, Eur. Phys. J. C 2016, 76, 379 [C1]
  - 8 TeV, dilepton, Phys. Lett. B 2015, 746, 132-153 [C2]
  - 13 TeV, dilepton, Phys. Lett. B 2018, 776, 355-378 [C3]
  - 13 TeV, lepton + jets, J. High Energy Phys. 07, 2020, 125[C4]
  - 13 TeV, all hadronic, Phys. Lett. B 2020, 803, 135285 [C5]
  - 13 TeV, dilepton, $t\bar{t}c\bar{c}$, Phys. Lett. B 2021, 820, 136565 [C6]
  - 13 TeV, differential measurement, CMS-PAS-TOP-22-009 [C7]

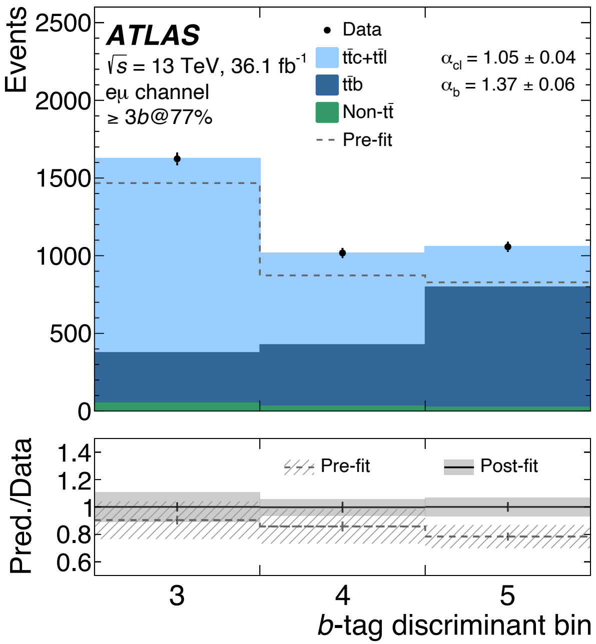
Phase space definition

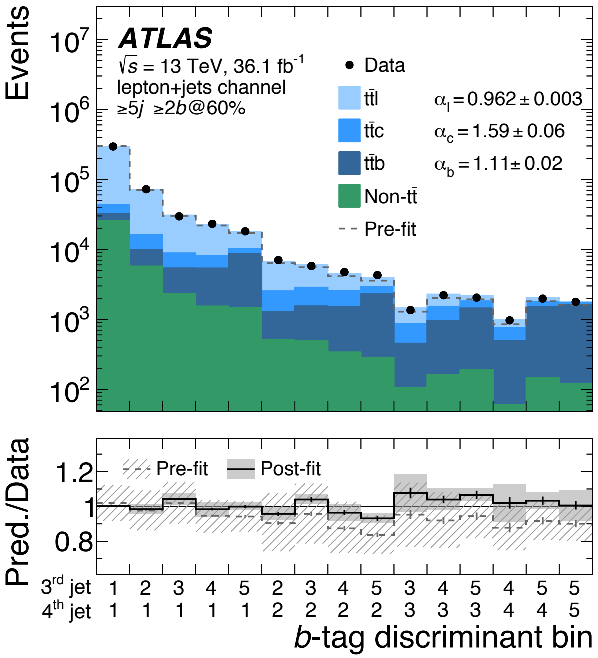
- Full phase space
  - Not requiring any cuts on the decay products from top quarks
- Visible phase space
  - Same as the selection at the reconstruction level
  - Reduce systematic uncertainty on the MC dependency

Phase space	Process	ATLAS	CMS
Full	$t\bar{t}b\bar{b}$		$\geq 2b$ not from top [C1-C4]
	$t\bar{t}c\bar{c}$		$\geq 2c$ not from top [C6]
Visible	$t\bar{t}b\bar{b}$ (di-lepton)	$\geq 3(4)$b [A1-A3]	≥ 4b [C1-C4]
	$t\bar{t}b\bar{b}$ (semi-lepton)	$\geq 5(6)$j, $\geq 3(4)$b [A2-A3]	$\geq 5(6)$j, $\geq 3(4)$b [C4,C7]
	$t\bar{t}b\bar{b}$ (semi-lepton)		$\geq 6(7)$j, $\geq 3(4)$b, ≥ 3l [C7]
	$t\bar{t}b\bar{b}$(hadronic)		≥ 8j, ≥ 4b [C5]
	$t\bar{t}c\bar{c}$(di-lepton)		≥ 2b, ≥ 2c [C6]

$t\bar{t}b\bar{b}$ cross section measurement (dilepton, lepton + jets)

For $e\mu$ channel,third-highest b-tagging discriminat-ranked jet



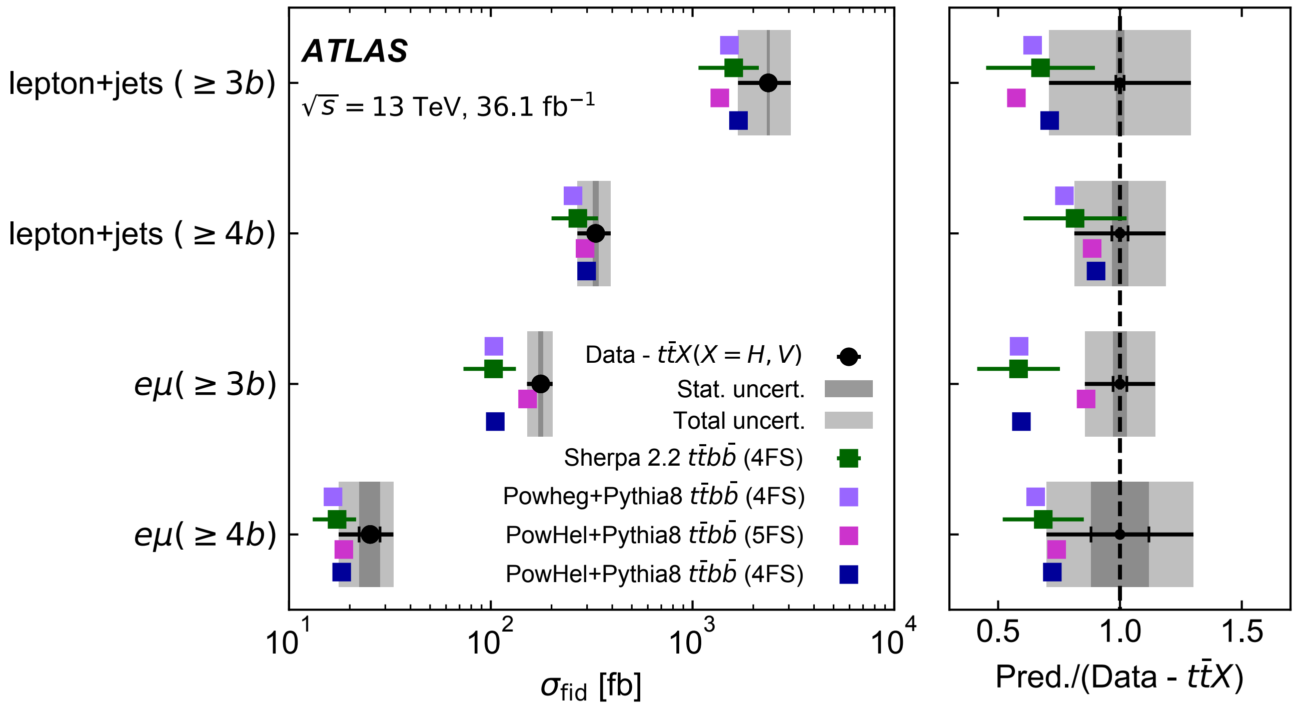


For lepton + jets channel, two-dimensional templates from third and fourth b-tagging discriminant-ranked jets are flattened into one dimension

- The cross-section measurements were performed in the $e\mu$ channel within at least 3 b jet and in lepton + jets within at least 3(4) b jet
- To extract the $t\bar{t}$+heavy flavor, a binned maximum likelihood fit is used on the b-tagging discriminant
  - Three templates of $t\bar{t}b$, $t\bar{t}c$ and $t\bar{t}l$

$t\bar{t}b\bar{b}$ cross section measurement (dilepton, lepton + jets)

- To facilitate the comparison with the theory $t\bar{t}b\bar{b}$ cross-section, the $t\bar{t}H$ and $t\bar{t}V$ contributions are subtracted from the measured cross-section
- The measurement in the $e\mu$ channel with at least three b jets tends to be more precise than the lepton + jets with at least four b jets
- Observed that generally predictions are lower than the measurements



$t\bar{t}b\bar{b}$ cross section measurement (dilepton, lepton + jets)

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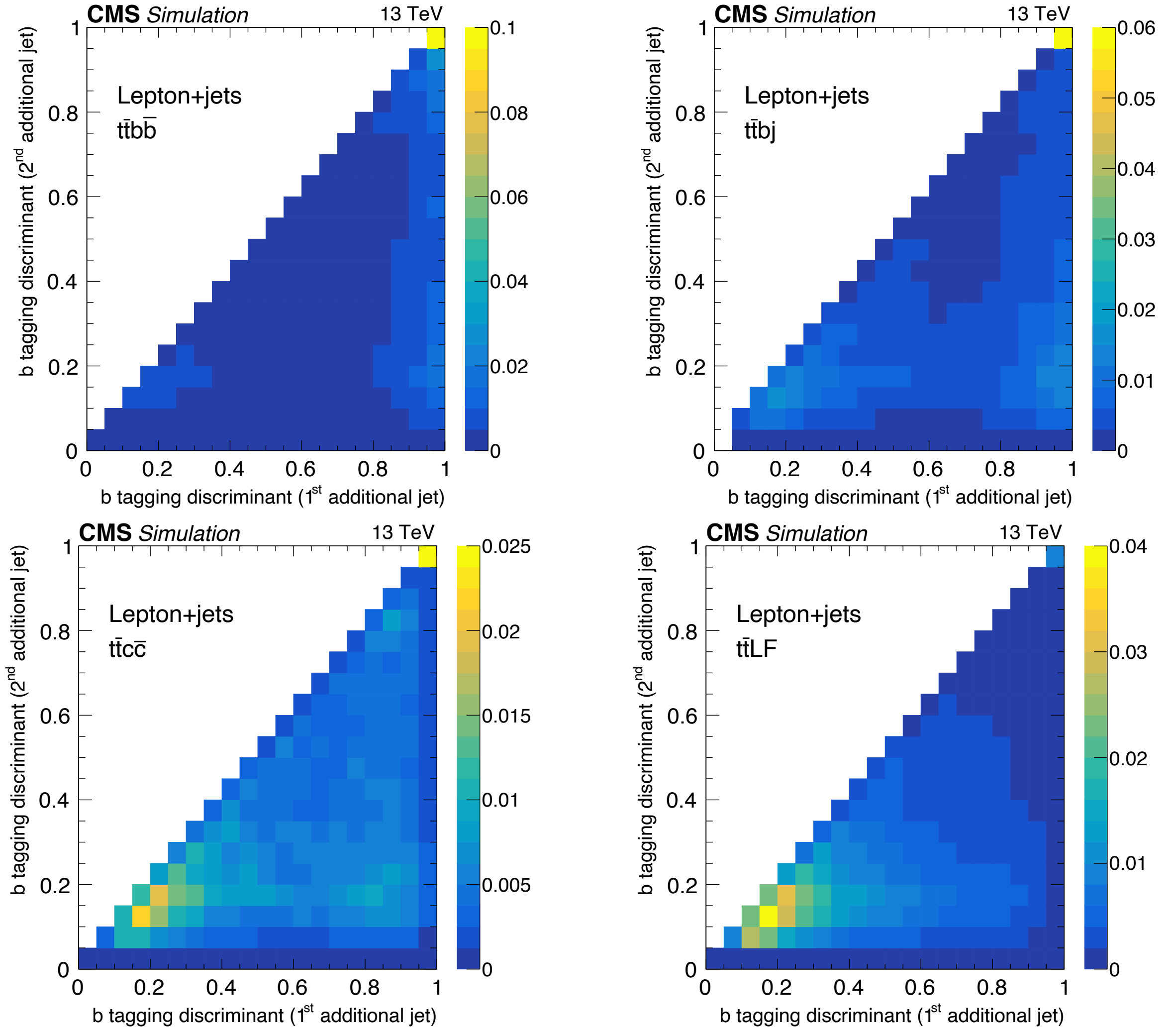
- In dilepton channel, the third and fourth b-tagged jets are treated as additional two b jets
- In the lepton + jets, there are more combinatorics
  - kinematic reconstruction was used to remove jets from top quarks
  - Then the first and second b-tagged jets are used
- Fitting to 2D distribution of two additional b-tagged jets to extract $t\bar{t}b\bar{b}$ contribution



$t\bar{t}b\bar{b}$ cross section measurement (dilepton, lepton + jets)

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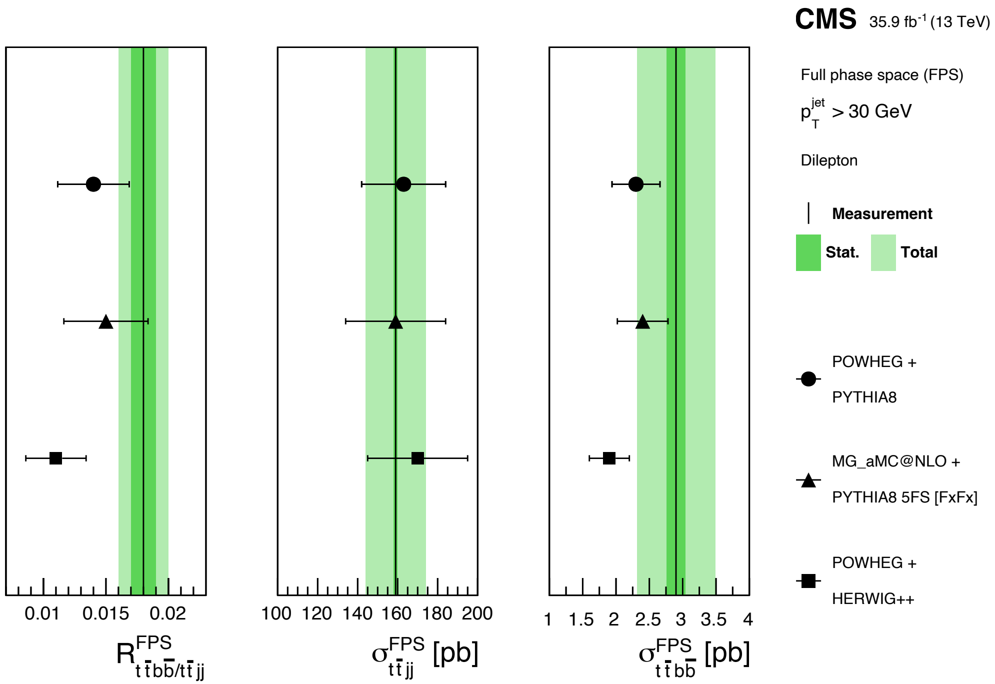
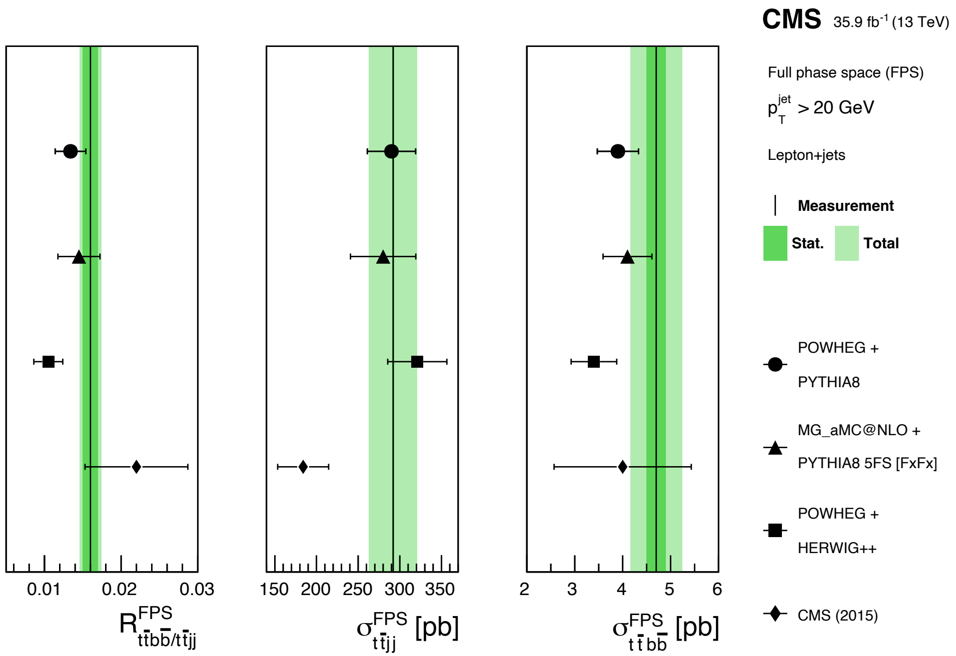
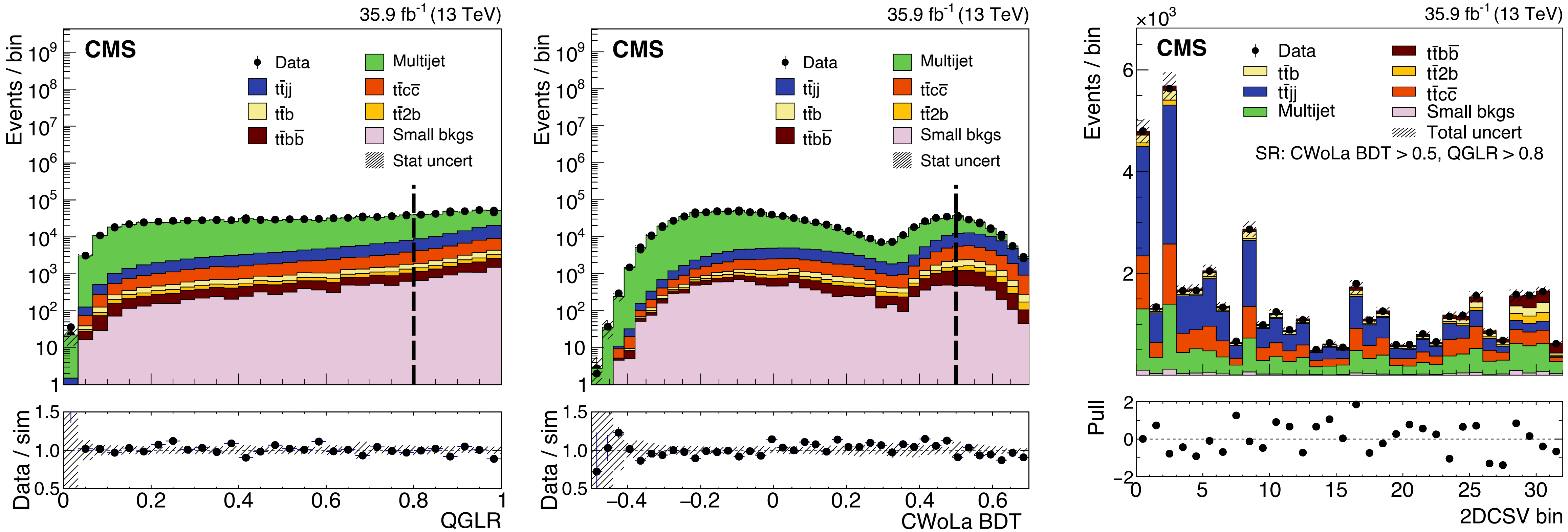




- $t\bar{t}b\bar{b}$ in full phase space
  - Corrected by the acceptance and branching ratio
  - Facilitate the comparison with other decay channels and theory predictions
- For both channels (dilepton, lepton + jets), several MC predictions are lower than measured values but consistent within the uncertainty

$t\bar{t}b\bar{b}$ cross section measurement (hadronic channel)

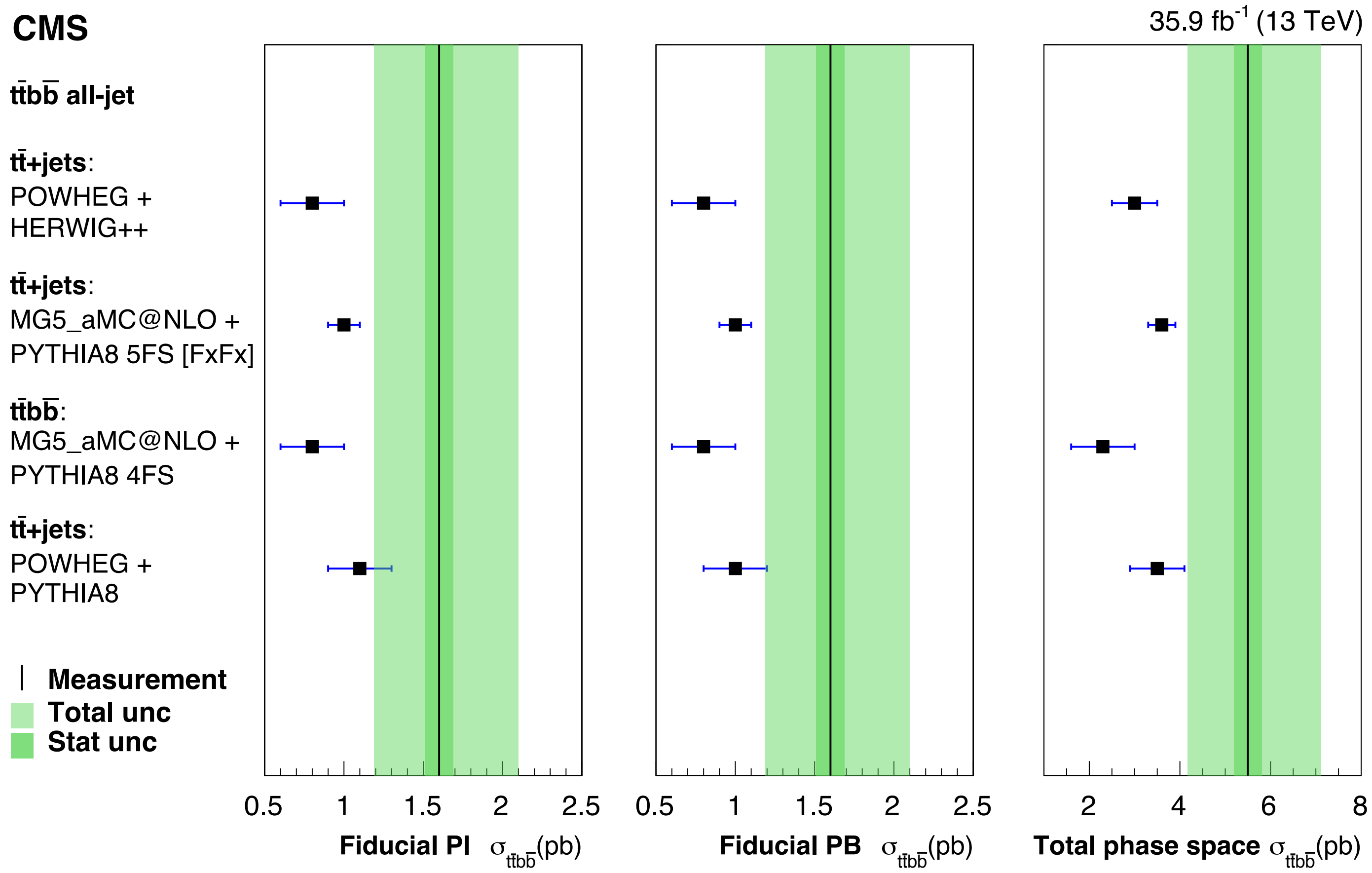


- Main background is QCD
- Quark-gluon discriminant and additionally unsupervised learning to remove QCD
- For $t\bar{t}b\bar{b}$ extraction, 2D distribution of the b-tag output from two additional b-tag jets is used

PLB 2020, 803, 135285

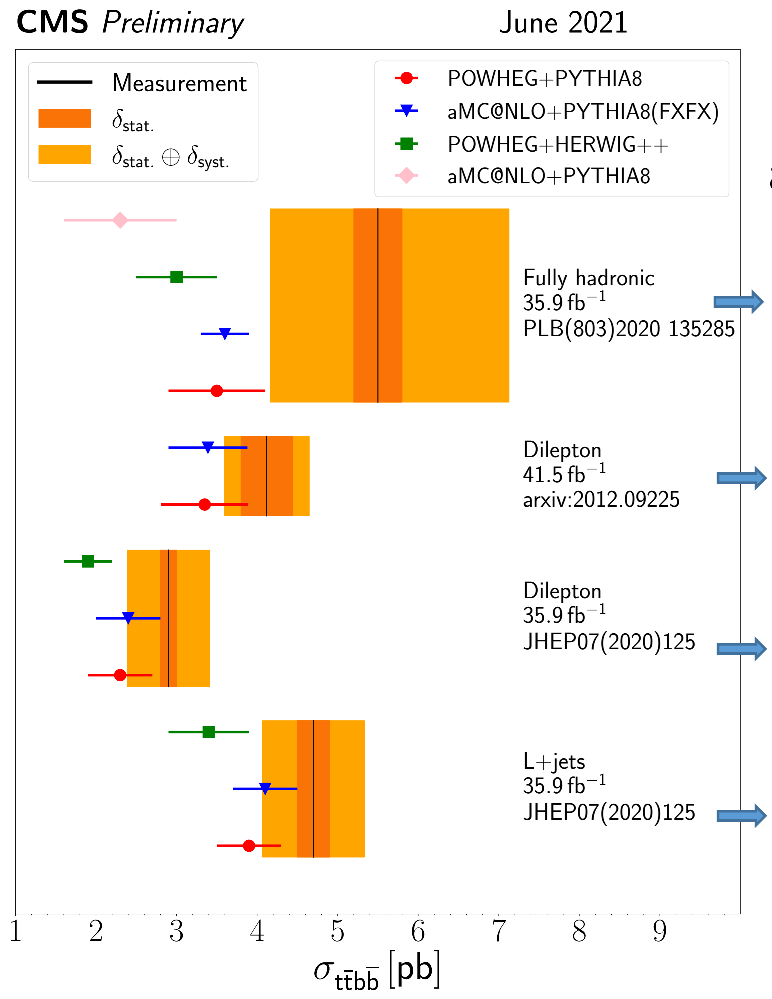
$t\bar{t}b\bar{b}$ cross section measurement (hadronic channel)

- Parton independent
  - Use information after the hadronization
- Parton Based definition
  - Use the parton level information after the radiation emission.
- Total phase space definition
  - Correct the acceptance and branching ratio



$t\bar{t}b\bar{b}$ measurement in full phase space (summary)

- Comparison between the measured values in the full phase space and various theoretical predictions
- Systematically the theoretical predictions are lower than the measurement in all channels



Requirement on the additional b-jets

- $p_T > 20$ GeV, $|\eta| < 2.5$
- $p_T > 20$ GeV, $|\eta| < 2.4$
- $p_T > 30$ GeV, $|\eta| < 2.4$
- $p_T > 20$ GeV, $|\eta| < 2.5$

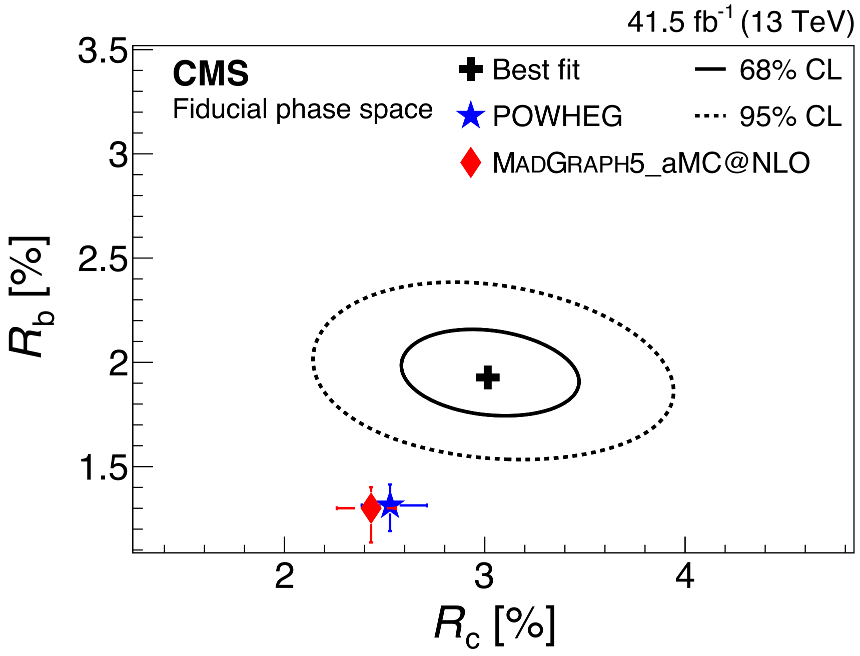
Measurements of $t\bar{t}c\bar{c}$

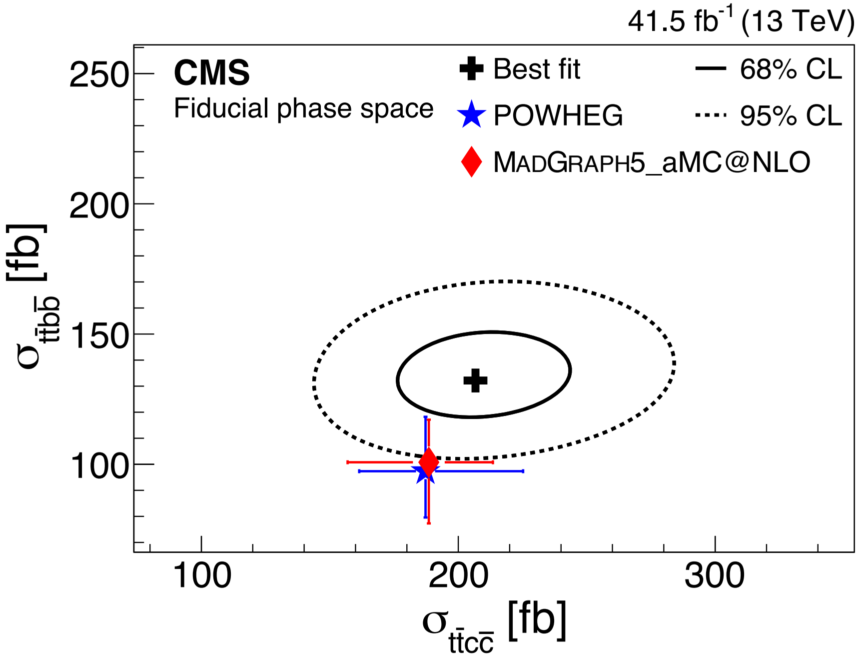
PLB 2021, 820, 136565

- The $t\bar{t}c\bar{c}$ process is measured by CMS for the first time
- It is challenging as the experimental signature of a b-jet is very similar to a c-jet
- To separate the heavy flavor processes, the NN is trained using c-tagging and kinematic information of the first and second additional jets
- Derive two discriminants to extract the $t\bar{t}b\bar{b}(c\bar{c})$ cross-sections and their ratios $R_{b(c)}$ to $t\bar{t}jj$

$$\Delta_b^c = \frac{P(\mathrm{t\bar{t}c\bar{c}})}{P(\mathrm{t\bar{t}c\bar{c}}) + P(\mathrm{t\bar{t}b\bar{b}})},$$

$$\Delta_L^c = \frac{P(\mathrm{t\bar{t}c\bar{c}})}{P(\mathrm{t\bar{t}c\bar{c}}) + P(\mathrm{t\bar{t}ll})}.$$





Differential cross section measurement

- Differentail cross sections could give us the hints to identify variables where the difference (visible in the inclusive measurement) becomes larger
- Unfolded to the generator level removing the detector effect
- Not trivial to define the additional b jets in the $t\bar{t}b\bar{b}$ process as we have b jets from top quark or any other bosons.
- Identifications of additional b jets
  - Two b jets with the highest p_T
  - Two b jets with the smallest angle
  - Two b jets not from a top quark using simulation chain
- With the first two definitions (highest p_T and smallest angle), we can remove the systematic uncertainty on theory dependence

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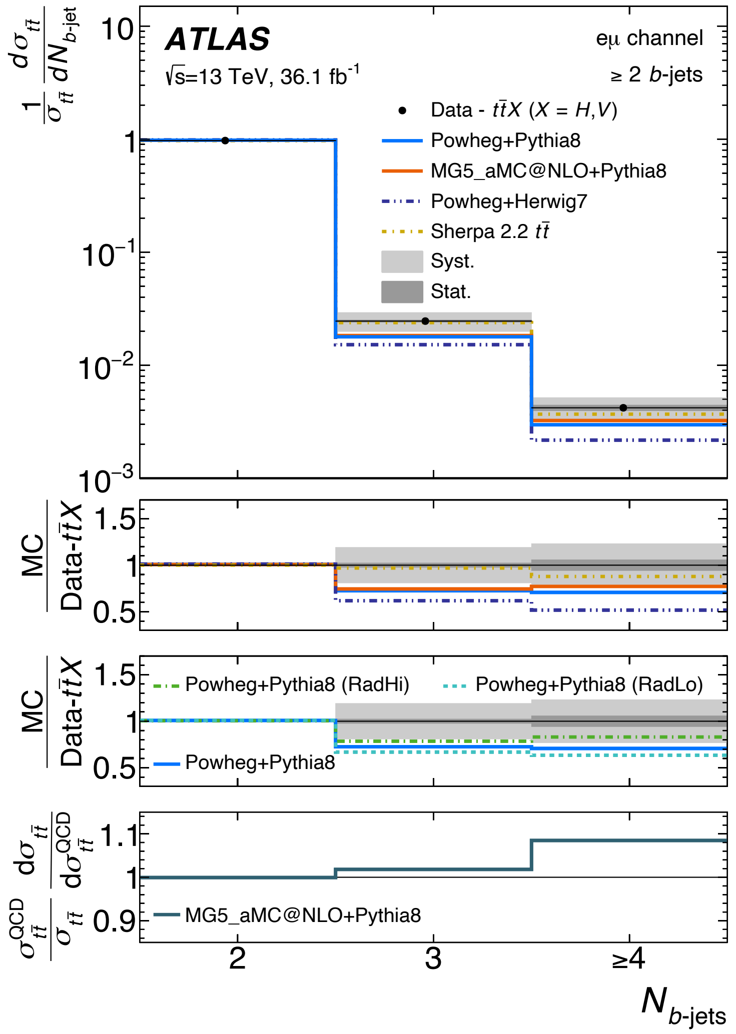
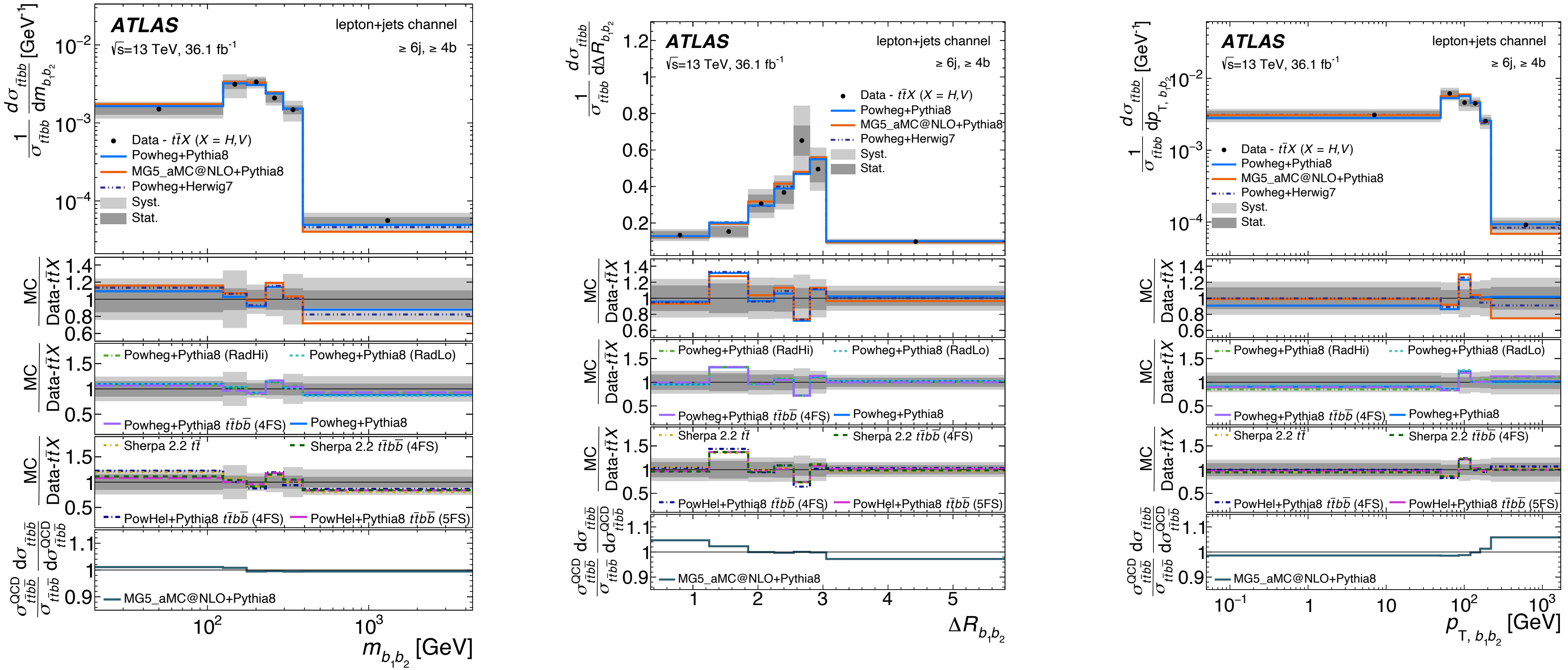
Differential Cross Section measurement (ATLAS)

- Normalized cross sections as a function of the b jet multiplicity
- All predictions relying on the parton shower generation of jets for high multiplicities are lower compared to the measurements
- The b jet production by the parton shower is not optimal in these processes



Differential Cross Section measurement (ATLAS)



- $t\bar{t}+H$ and $t\bar{t}+V$ are subtracted from the measurement
- Two b jets are selected with the highest p_T

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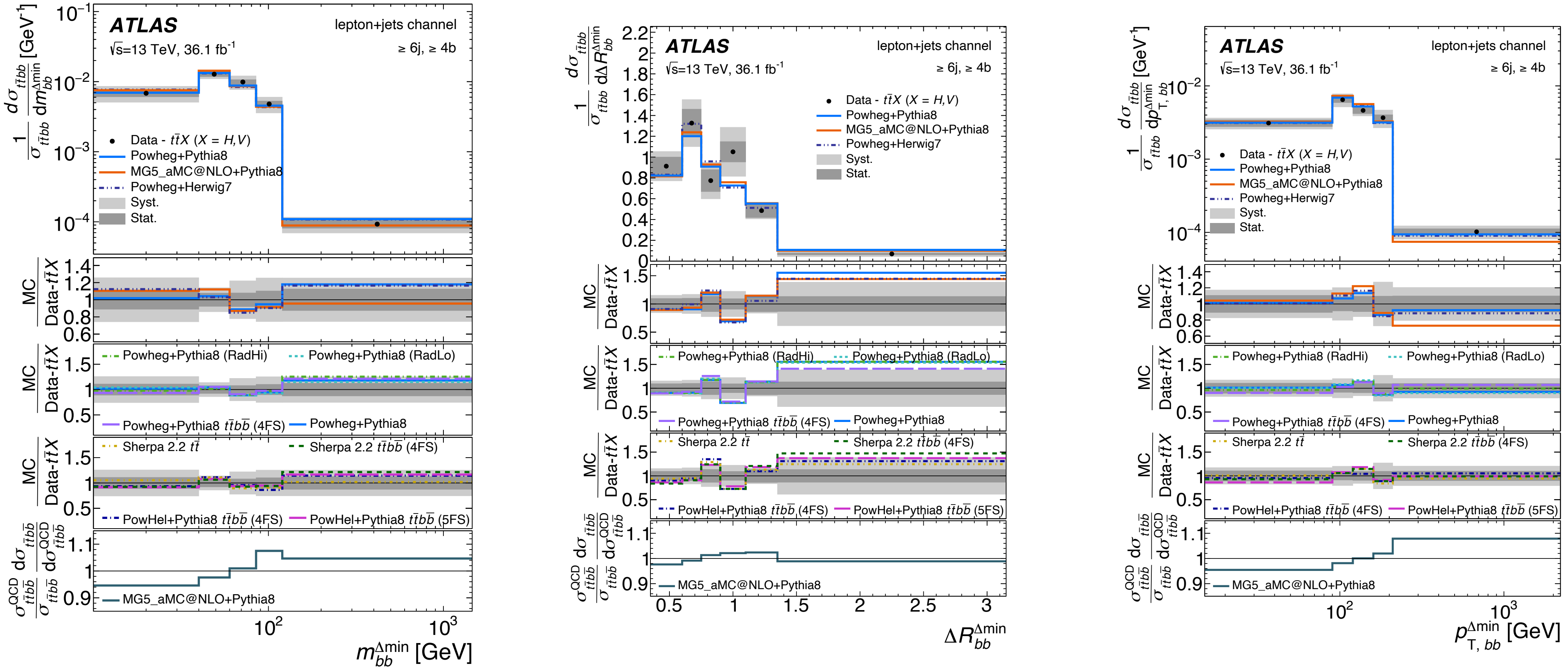
Differential Cross Section measurement (ATLAS)

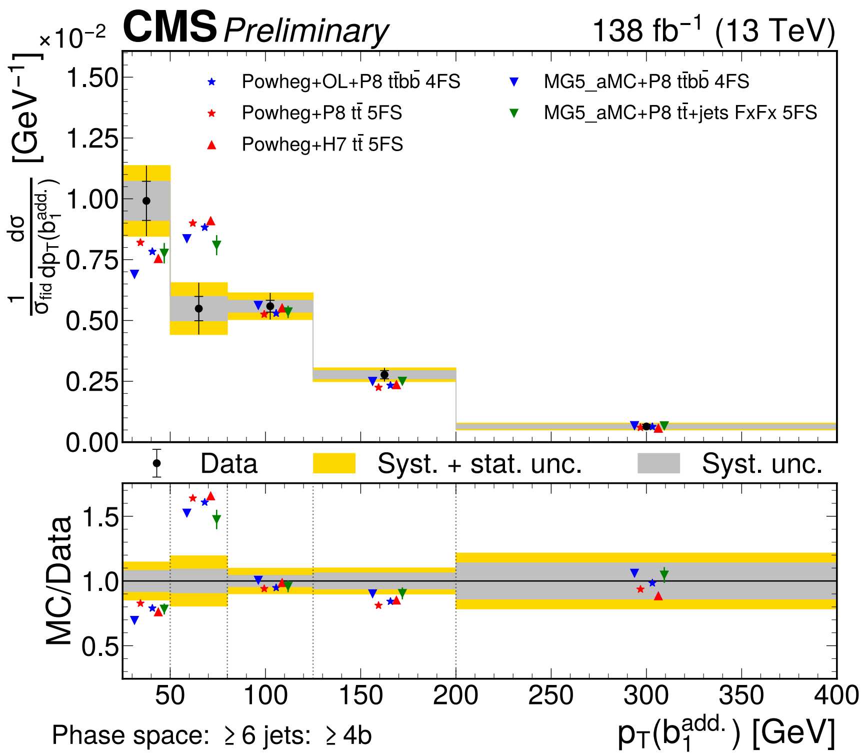


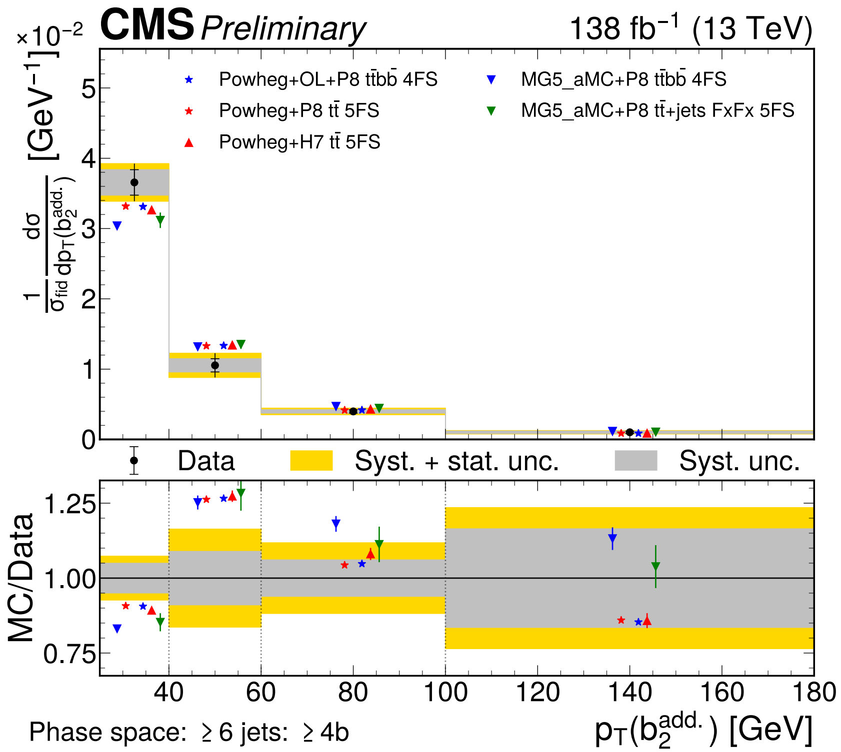
- Two b jets are selected with the smallest angular separation
- Measured differential cross sections are in general consistent with theory predictions within its large systematic uncertainty

Differential Cross Section measurement (CMS)

NEW

CMS-PAS-TOP-22-009



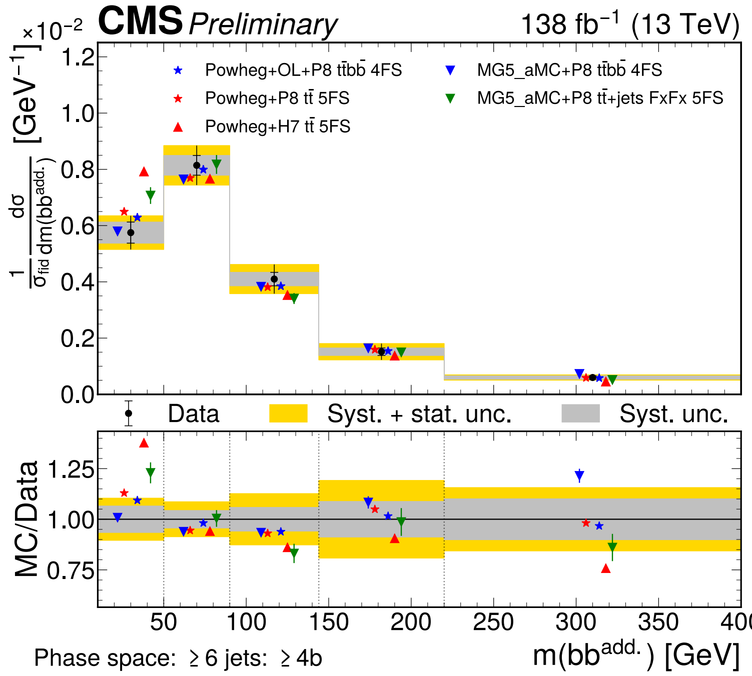


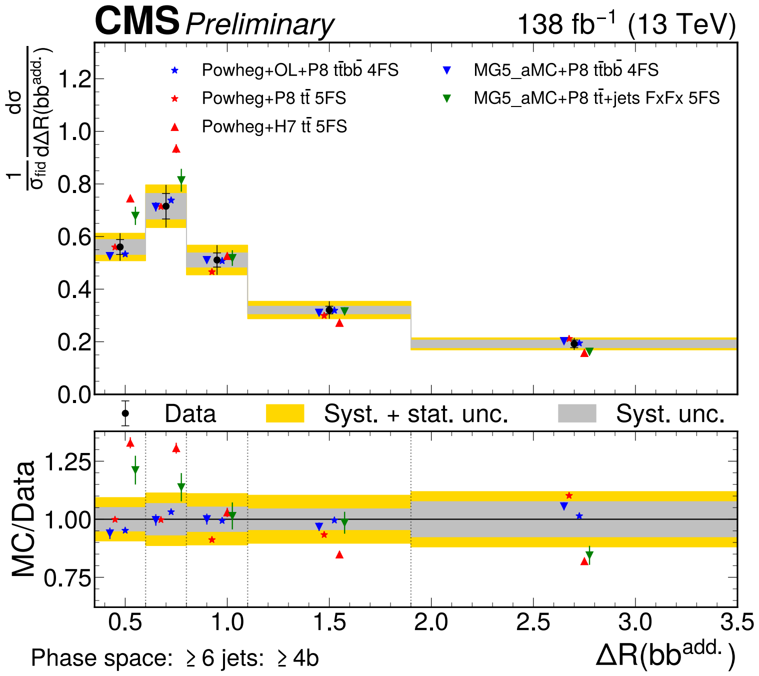
- DNN is used to find the correct pair of b jets not from top quarks
  - Accuracy of DNN correctly assigning two additional b jets is around 49%
- Two sets of input variables
  - jet-specific input: $p_T, \eta, \Delta R$ and mass with lepton, etc.
  - global event information: p_T sum of four candidate b jets, $\Delta\eta$ and mass of dijet, etc.

Differential Cross Section measurement (CMS)

NEW

CMS-PAS-TOP-22-009





- HERWIG tends to produce two additional b jets with smaller angles than the measured values

Conclusion

- Generally, we observed that the data are under-estimated by the predictions in $t\bar{t}$ +HF measurement
- The discrepancy between data and MC could be from the fact that the signal samples are modeled only at NLO in QCD
- A large fraction of Run-2 data yet to be analyzed
- We expect twice more data in Run 3 and more in HL-LHC
  - More data can enable more data-driven techniques and reduce systematic uncertainties
  - Use smaller bin width to enable hints about potential discrepancies shown in the inclusive measurement
- Should make use of the effective field theory (EFT) approach for possible new physics search
  - To interpret the results in the context of physics beyond the standard model, the EFT approach is of interest as a model-independent approach
  - Differential measurements may be crucial in this approach as the presence of the SMEFT operators can modify the kinematics in the standard model processes