# Comparison of the ATLAS and CMS Measurements of Entanglement in Top-Quark-Antiquark Pair Production

LHC TOP WG Meeting

Yoav Afik[1], on behalf of the ATLAS and CMS collaborations

[1]University of Chicago, Enrico Fermi Institute

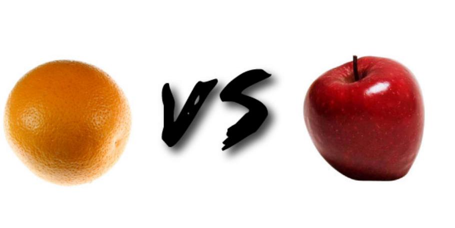
26.04.2024

# Overview

- Two recent measurements of top-quark pair entanglement:
  - ATLAS: 2311.07288, TOP 2023 talk.
  - CMS: CMS PAS TOP-23-001, Moriond EW 2024 talk.
- Both collaborations did things differently.
- Both collaborations reached the same conclusion: observation of entanglement between top-quark pairs.
- I will present the analysis by ATLAS, and a comparison between **ATLAS** and **CMS** results.
- Many thanks to Andy Jung (CMS) for valuable feedback.

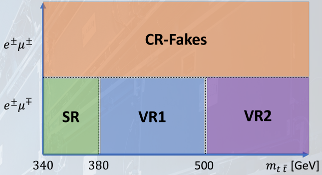
# Overview

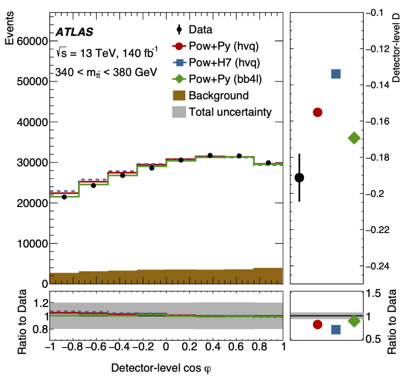
- Two recent measurements of top-quark pair entanglement:
  - ATLAS: 2311.07288, TOP 2023 talk.
  - CMS: CMS PAS TOP-23-001, Moriond EW 2024 talk.
- Both collaborations did things differently.
- Both collaborations reached the same conclusion: observation of entanglement between top-quark pairs.
- I will present the analysis by ATLAS, and a comparison between **ATLAS** and **CMS** results.
- Many thanks to Andy Jung (CMS) for valuable feedback.



# Analysis Strategy

- Dataset:
  - Full Run-2, 140 $\text{fb}^{-1}$.
  - CMS: 2016 data, 35.9 $\text{fb}^{-1}$.
- Analysis selection:
  - $e\mu$ with opposite charges.
    CMS: $e\mu$, $ee$, $\mu\mu$.
  - Single lepton triggers.
    CMS: Single+dilepton triggers.
  - $N_b \geq 1$ ($\sim 85\%$ $b$-tag efficiency).
- Regions are categorized by $m_{t\bar{t}}$.
  **Signal region:**
  $340 < m_{t\bar{t}} < 380$ **GeV.**
  **CMS: A signal region with**
  $345 < m_{t\bar{t}} < 400$ **GeV and**
  $\beta_{t\bar{t}} < 0.9$, **to enhance** $gg \to t\bar{t}$.



# Top Reconstruction

- Three methods:
  - 85%: Ellipse Method. Calculates two ellipses for $p_T^{\nu}$ and finds the intersections.
  - 5%: Neutrino Weighting.
  - 10%: Rudimentary pairing.
- CMS: Neutrino Weighting.
- The solution with the smallest $m_{t\bar{t}}$ is taken.

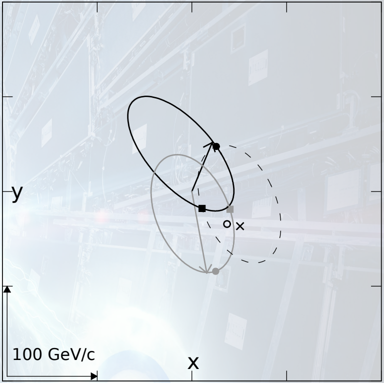
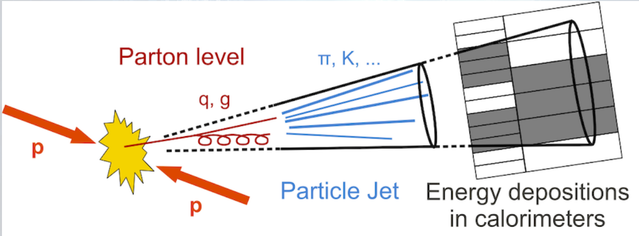



Figure: Constrain on neutrino momenta. Figure is from Nucl.Instrum.Meth.A 736 (2014) 169-178.

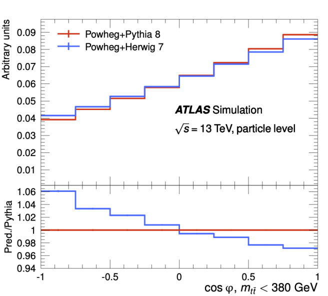
# Data Correction

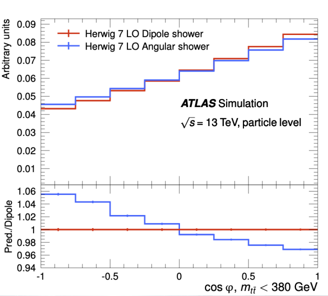
- **Particle-level fiducial regions are defined with similar selections.**
  **CMS: Result is reported at parton-level.**
- This is a key difference between both analyses.
  Why does ATLAS report the results at particle-level?
- **The difference between PowhegBox+Pythia and PowhegBox+Herwig is taken as a parton-shower uncertainty.**
  **CMS: PowhegBox+Herwig is not used as a parton-shower uncertainty, but as a different prediction.**



# Parton Shower Modeling

- Large difference between PowhegBox+Pythia 8.230 PowhegBox+Herwig 7.21, especially in the SR.
- A reason for an extensive scrutiny, to understand the difference.
- Comparison at particle-level.
- Main origin: the ordering of the shower.
- Observed both at detector and particle-level.
  → **Parton-level analysis: huge uncertainty.**
  → **Particle-level analysis: small uncertainty.**



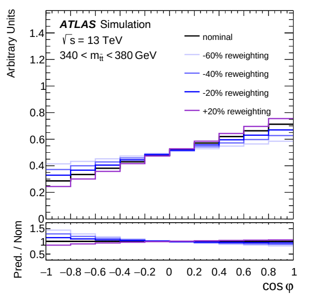
# Reweighting Method

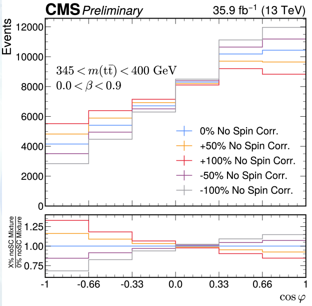
- To test the alternative hypotheses we must change $D$.
- Inherent in particle generators.
- **Each event is reweighted (at parton-level) taking into account $m_{t\bar{t}}$ to preserve linearity in $\cos\varphi$.**
- $D(m_{t\bar{t}})$ is calculated for each modeling systematic.
- The reweighting is done for all systematic uncertainties.

$$w = \frac{1 - D(m_{t\bar{t}}) \cdot \chi \cdot \cos\varphi}{1 - D(m_{t\bar{t}}) \cdot \cos\varphi}$$

$$\chi = 0.4, 0.6, 0.8, 1.2.$$

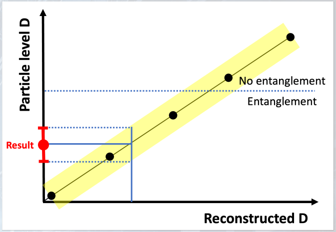
- **CMS: Mix samples with and without spin-correlations.**

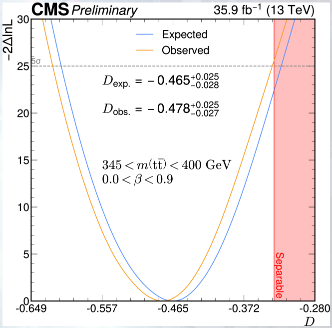


# Calibrating the Observable

- **Measure the particle-level value of $D$ using a calibration curve.**
- The curve is built from alternative sets of **reconstructed** $D$ and **particle-level** $D$, with variations of the parton-level $D$ value: -60%, -40%, -20%, SM, +20%.
- A first order polynomial is used to interpolate between the points.
- The data are corrected to the particle-level value of $D$.
- One curve for each systematic. The difference w.r.t. the nominal curve is the uncertainty.
- **CMS: Profile likelihood template fit.**



# Threshold Effects

- **NRQCD effects, i.e. toponium, are not used as an uncertainty.**
- Stress tests show that these effects can have an impact on the prediction, but a negligible impact on the measurement.

- Reweighted event-by-event to match the expected bump (red).
- Same, with larger cross-section account for the fact that a small fraction of the cross-section is not spin singlet (orange).
- A flat 5 GeV reweighting of the cross-section (purple).
- **The largest effect was an uncertainty of 0.5%.**

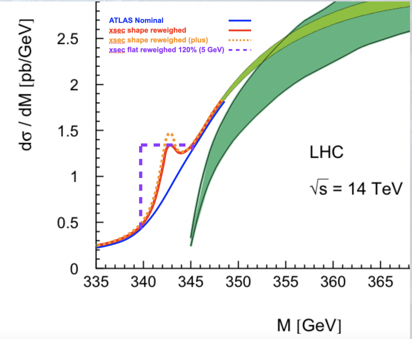
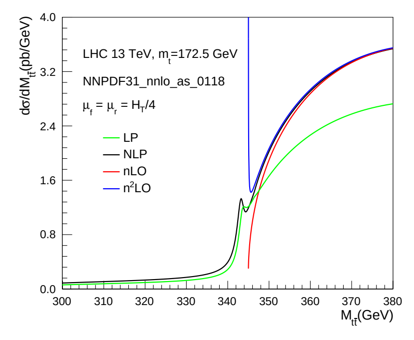
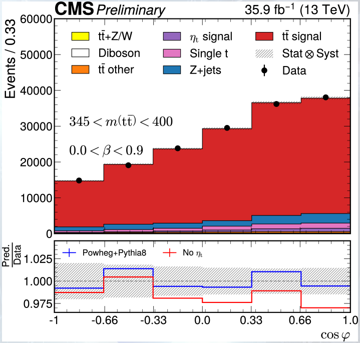



Figure: Figure is from Eur.Phys.J.C 60 (2009) 375-386.

# Threshold Effects

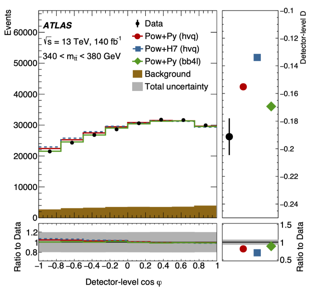
- **CMS: Toponium is considered on top of the signal. A flat uncertainty of 50% is applied, and a binding energy uncertainty of $\pm 0.5$ GeV is considered.**
- Left Figure is from JHEP 06 (2020) 158.

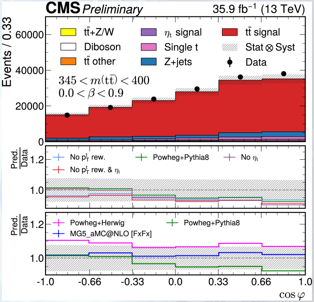


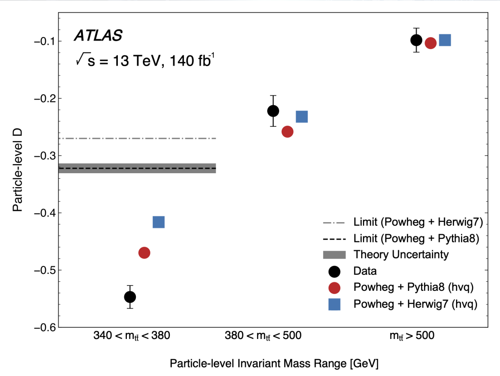
# Nominal and Alternative MC

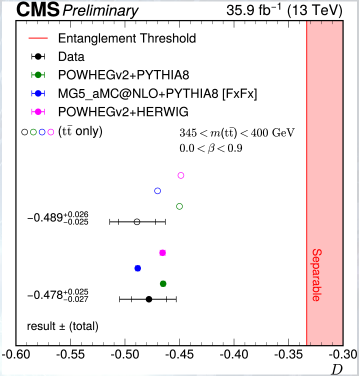
- **PowhegBox+Pythia as nominal, PowhegBox+Herwig and *bb4ℓ* as alternatives.**
- Caveat for *bb4ℓ*: it contains $t\bar{t} + tW$ with interference; we remove $tW$ from *bb4ℓ* to get '$t\bar{t}$'.
  $\rightarrow$ Therefore we don't add it in the result plot.
- **CMS: PowhegBox+Pythia as nominal, PowhegBox+Herwig and MG5_aMC@NLO(+MadSpin) [FxFx] as alternatives.**
- Toponium model with MG5_aMC@NLO(LO)+Pythia.



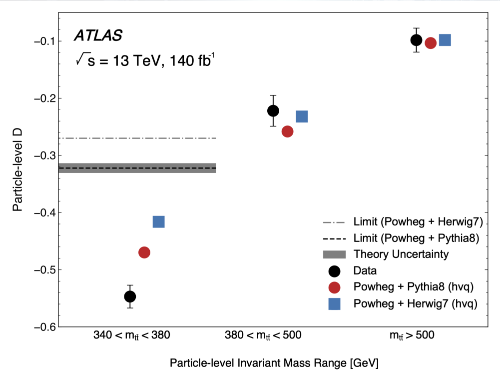
# Results

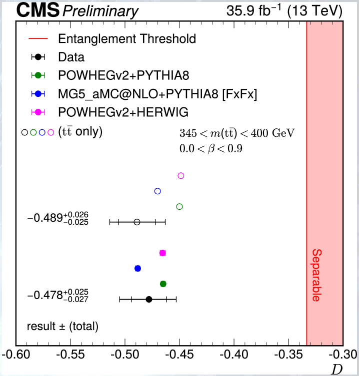



- No clear preference of a specific MC prediction.
- The limit of $D = -1/3$ is folded from parton to particle-level.
- **Entanglement is observed with a significance of more than $5\sigma$.**
  Observed: $D = -0.547 \pm 0.002$ [stat.] $\pm 0.021$ [syst.]
  Expected: $D = -0.470 \pm 0.002$ [stat.] $\pm 0.018$ [syst.]

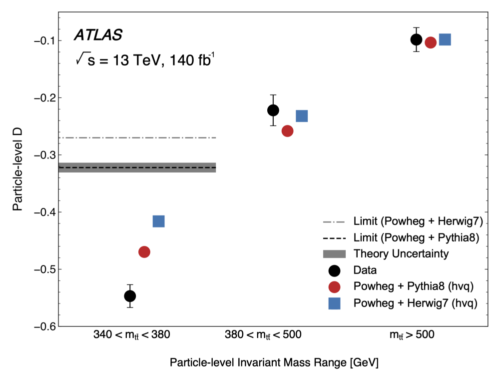
# Results

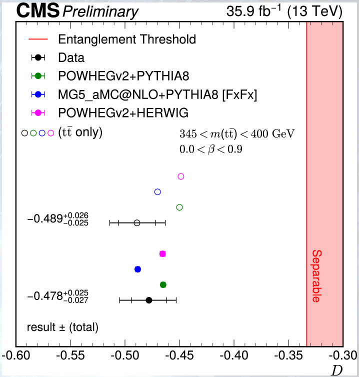



- No clear preference of a specific MC prediction.
- The limit of $D = -1/3$ is shown at parton-level.
- **Entanglement is observed with a significance of more than** $5\sigma$.
  Observed: $D = -0.478 \pm 0.017\ [\text{stat.}]^{+0.018}_{-0.021}\ [\text{syst.}]$
  Expected: $D = -0.465^{+0.016}_{-0.017}\ [\text{stat.}]^{+0.019}_{-0.022}\ [\text{syst.}]$

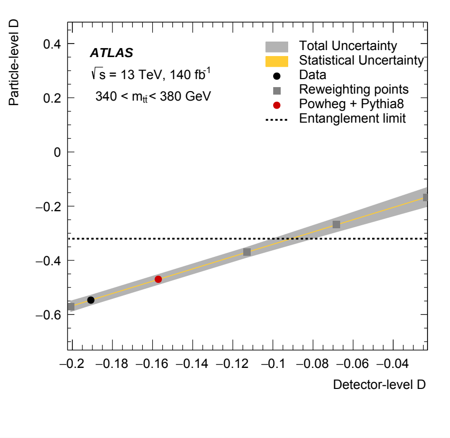
# Results




- Both are dominated by systematic uncertainty.
- Total [stat.] is an order of magnitude larger in the CMS analysis.
- Total [syst.] is similar between ATLAS & CMS, but different systematics are considered.

# Systematic Uncertainties




| Systematic source | $\Delta D_{\text{observed}}(D = -0.547)$ | $\Delta D$ (%) |
|---|---|---|
| Signal Modelling | 0.017 | 3.2 |
| Electron | 0.002 | 0.4 |
| Muon | 0.001 | 0.1 |
| Jets | 0.004 | 0.7 |
| $b$-tagging | 0.002 | 0.4 |
| Pileup | $< 0.001$ | $< 0.1$ |
| $E_T^{miss}$ | 0.002 | 0.3 |
| Backgrounds | 0.010 | 1.8 |
| Stat. | 0.002 | 0.3 |
| Syst. | 0.021 | 3.8 |
| Total | 0.021 | 3.8 |

Table: Systematic uncertainties for the **observed** $D$.

- The calibration curve for the SR and the uncertainties for the observed values are presented.

# Systematic Uncertainties

- Three categories:
  - Signal ($t\bar{t}$) modeling.
  - Background modeling.
  - Detector uncertainties.

| Systematic source | $\Delta D_{\text{expected}}(D = -0.470)$ | $\Delta D$ (%) |
|---|---|---|
| Signal Modelling | 0.015 | 3.2 |
| Electron | 0.002 | 0.4 |
| Muon | 0.001 | 0.1 |
| Jets | 0.004 | 0.8 |
| $b$-tagging | 0.002 | 0.4 |
| Pileup | $< 0.001$ | $< 0.1$ |
| $E_T^{miss}$ | 0.002 | 0.4 |
| Backgrounds | 0.009 | 1.8 |
| Stat. | 0.002 | 0.4 |
| Syst. | 0.018 | 3.9 |
| Total | 0.018 | 3.9 |

Table: Systematic uncertainties for the **expected** $D$.

- Signal ($t\bar{t}$) modeling breakdown:
  - Top decay (MadSpin): 1.6%
  - PDF (PDF4LHC): 1.2%
  - Recoil To Top: 1.1%
  - FSR: 1.1%
  - Scales ($\mu_R, \mu_F$): 1.1%
  - NNLO Reweighting: 1.1
  - pThard1 (`pThard = 1`): 0.8%
  - $m_t$ (172.5 $\pm$ 0.5 GeV): 0.7%
  - ISR: 0.2%
  - Parton Shower (Herwig): 0.2%
  - $h_{damp}$: 0.1%
- For each systematic, we extract a curve. The difference w.r.t. the nominal curve is the uncertainty.

# Systematic Uncertainties

| Systematic uncertainty source | Relative size (for SM $D$ value) |
|---|---|
| Top-quark decay | 1.6% |
| Parton distribution function | 1.2% |
| Recoil scheme | 1.1% |
| Final-state radiation | 1.1% |
| Scale uncertainties | 1.1% |
| NNLO QCD + NLO EW reweighting | 1.1% |
| pThard setting | 0.8% |
| Top-quark mass | 0.7% |
| Initial-state radiation | 0.2% |
| Parton shower and hadronization | 0.2% |
| $h_{damp}$ setting | 0.1% |

Table: **Dominant systematics in the ATLAS analysis. Relative uncertainty on $D$ of each component.**

| Source | Uncertainty $D$ |
|---|---|
| JES | 10.1% |
| Toponium normalization | 10.1% |
| Parton Shower (ISR) | 6.3% |
| Scale | 1.8% |
| Parton Shower (FSR) | 1.2% |
| JER | 0.9% |
| Z+jets shape | 0.8% |
| b quark fragmentation | 0.4% |
| $t\bar{t}$ normalization | 0.3% |
| PDF | 0.3% |

Figure: **Dominant systematics in the CMS analysis. Relative change in uncertainty when it is removed and the fit is repeated.**

- Dominant systematics are very different. CMS JES/Toponium normalization with ATLAS presentation: 2.3%.
- **This is NOT an apples-to-apples comparison!** There are major differences between both measurements.

# Summary of ATLAS Vs. CMS

| **Analysis Method** | **ATLAS** | **CMS** |
|---|---|---|
| Dataset | Full Run 2 (140.0 $fb^{-1}$) | 2016 (35.9 $fb^{-1}$) |
| $t\bar{t}$ decay | Di-lepton ($e\mu$) | Di-lepton ($e\mu/ee/\mu\mu$) |
| Main selections | $340 < M_{t\bar{t}} < 380$ GeV | $345 < M_{t\bar{t}} < 400$ GeV, $\beta_{t\bar{t}} < 0.9$ |
| $t\bar{t}$ reconstruction | Ellipse method | Neutrino weighting |
| Corrected to | Particle-level | Parton-level |
| Fit type | No fit, calibration curve | Template fit |
| Alternative hypothesis $D$ | Reweighing | Mixing samples with and without spin correlation |
| Threshold effects | Neglected | Considered |
| Dominant systematic | Top decay, PDF, Recoil, FSR, Scales, NNLO | JES, Toponium, ISR |
| Nominal MC | PowhegBox+Pythia | PowhegBox+Pythia |
| Alternative MC | PowhegBox+Herwig, *bb4ℓ* | PowhegBox+Herwig, MG5_aMC@NLO [FxFx] |
| Expected $D$ | $-0.470 \pm 0.002$ [stat.] $\pm 0.018$ [syst.] | $-0.465^{+0.016}_{-0.017}$ [stat.]$^{+0.019}_{-0.022}$ [syst.] |
| Observed $D$ | $-0.547 \pm 0.002$ [stat.] $\pm 0.021$ [syst.] | $-0.478 \pm 0.017$ [stat.]$^{+0.018}_{-0.021}$ [syst.] |
| Significance | $>> 5\sigma$ | $> 5\sigma$ |

Table: Main differences between the ATLAS and CMS analyses.

# Summary

- **Entanglement in top-quark pairs has been observed both by ATLAS and CMS with more than five standard deviations!**

# Summary

- **Entanglement in top-quark pairs has been observed both by ATLAS and CMS with more than five standard deviations!**
- These are the first measurements of entanglement between a pair of quarks, and at the highest energy scale ever.
- Entanglement in top-quark pairs has ignited the discussion of modeling next to the production threshold.
- The observable under study is sensitive to modeling:
  - Parton-shower (ATLAS).
  - Threshold effects (CMS).

  $\rightarrow$ More work is required to improve the prediction of mainstream generators for precision measurements.

  $\rightarrow\rightarrow$ The theory community is on it.

# Summary

- On a personal note, I would like to congratulate both collaborations for the great achievement! My (biased) perspective is that we started something new, special and extremely exciting.

# Summary

- On a personal note, I would like to congratulate both collaborations for the great achievement! My (biased) perspective is that we started something new, special and extremely exciting.
- **This is only the beginning of the journey!**

# Thank You

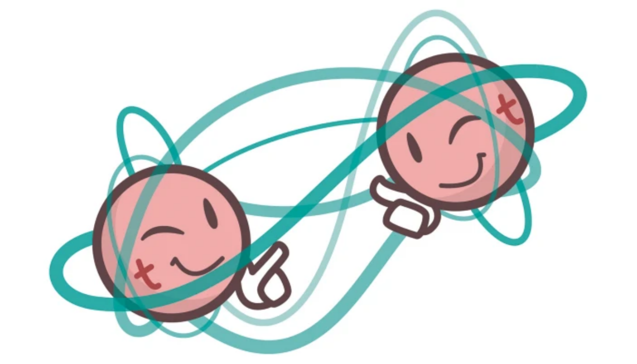



Figure: from **Nature Reviews Physics, Research Highlight, Editors' picks 2023: Entanglement between a pair of top quarks**.

# Backup Slides

## Backup

# Systematic Uncertainties

| Systematic source | $\Delta D_{\text{particle}}(D=-0.470)$ | $\Delta D$ (%) | $\Delta D_{\text{observed}}(D=-0.547)$ | $\Delta D$ (%) |
|---|---|---|---|---|
| Signal Modelling | 0.017 | 3.2 | 0.015 | 3.2 |
| Electron | 0.002 | 0.4 | 0.002 | 0.4 |
| Muon | 0.001 | 0.1 | 0.001 | 0.1 |
| Jets | 0.004 | 0.7 | 0.004 | 0.8 |
| $b$-tagging | 0.002 | 0.4 | 0.002 | 0.4 |
| Pileup | $< 0.001$ | $< 0.1$ | $< 0.001$ | $< 0.1$ |
| $E_T^{miss}$ | 0.002 | 0.3 | 0.002 | 0.4 |
| Backgrounds | 0.010 | 1.8 | 0.009 | 1.8 |
| Stat. | 0.002 | 0.3 | 0.002 | 0.4 |
| Syst. | 0.021 | 3.8 | 0.018 | 3.9 |
| Total | 0.021 | 3.8 | 0.018 | 3.9 |