Exploring Toponium Formation at the LHC

Aminul Hossain

Supervisor: Dr. James Keaveney

Hossain, Keaveney, Fuks, arXiv:25XX.YYYY, (In preparation)

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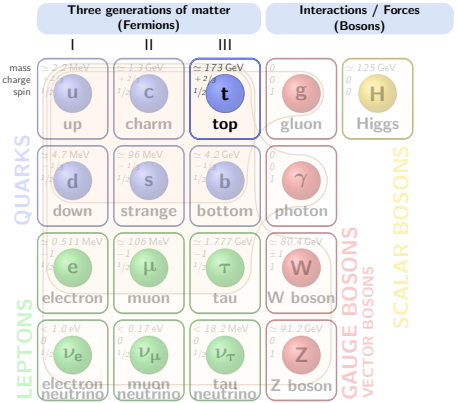
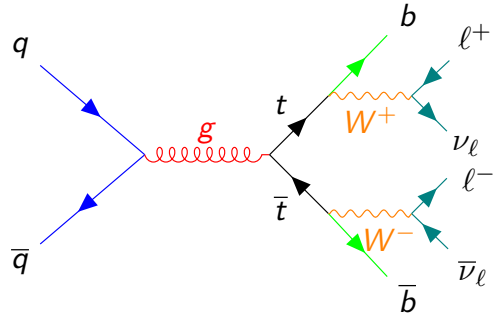
Why is the Top Quark Interesting?

- **The Top quark**:
  - 3rd generation fermion with mass ∼173 GeV
  - ∼40× heavier than bottom quark
  - Mass comparable to gold atom nucleus!
- **Special properties from its mass**:
  - Decays before hadronization ($\tau \sim 5 \times 10^{-25}$ s)
  - Width $\Gamma_t \approx 1.35$ GeV (SM NLO)
  - Largest Yukawa coupling ($y_t \approx 1$)
- **BSM physics portal**:
  - Sensitive probe for new physics at high energy scales



Top Quark Production and Decay

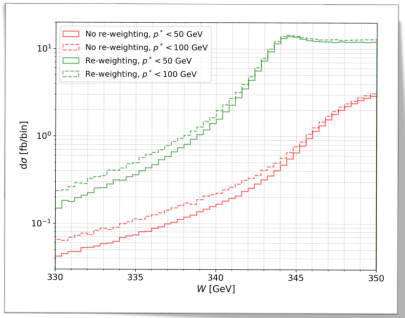
- **Production mechanisms**:
  - Dominant: $gg \to t\bar{t}$ (90% at LHC)
  - $q\bar{q} \to t\bar{t}$ (10% at LHC)
  - Near threshold ($q^2 \sim 2m_t$), tops emerge slowly — allowing study of non-relativistic QCD effects, (arXiv:hep-ph/9711391).
- **Dilepton channel advantage**:
  - Dilepton channel has low backgrounds
  - Access to precise angular observables based on the kinematics of two leptons.



Feynman diagram for $t\bar{t}$ with dilepton final state.

What is Toponium? — Physical Motivation

- **Physical Motivation:**
  - **Quasi-bound state** of $t\bar{t}$ with mass $\sim 2m_t$
  - Unlike lighter quarkonia, the **short top quark lifetime** prevents true bound-state formation.
  - At threshold, gluon exchange can lead to temporary resonance-like states.
- **Toponium Modelling:**
  - Fuks et al. (arXiv:2411.18962) models toponium signals using NRQCD
  - $t\bar{t}$ decay produces characteristic angular distributions due to spin correlations between the top and anti-top quarks

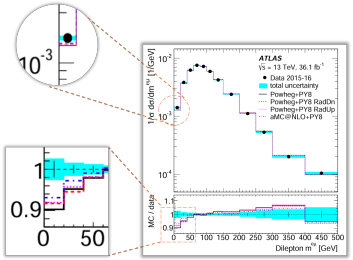


Invariant mass ($W = m_{t\bar{t}}$) of a color-singlet top-antitop system with/without Green's function re-weighting (arXiv:2411.18962).

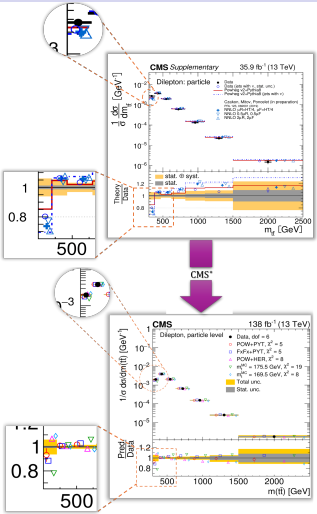
Discrepancies in Kinematic Observables Near Threshold

- **Explains ATLAS/CMS discrepancies in**
  - $m_{t\bar{t}}$ distribution - arXiv:1811.06625v2
  - $m^{e\mu}$ distribution - arXiv:1910.08819
  - $\Delta\phi(l\bar{l})$ distribution - arXiv:1910.08819
  - $\Delta\phi^{e\mu} m^{e\mu}$ distribution - arXiv:1811.06625

  and many other



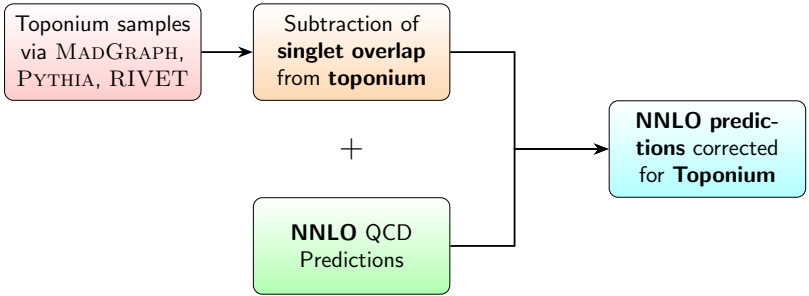
Invariant dilepton mass ($m^{e\mu}$)



Particle level $m_{t\bar{t}}$

Outline

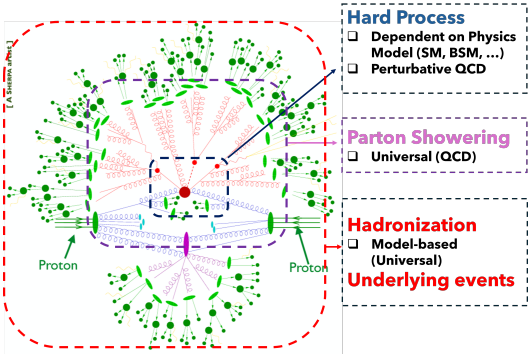
- **Modelling Strategy:** Incorporating Toponium into Differential Distributions



- **Results:** Kinematic Observables Sensitive to Toponium Effects

MadGraph, Pythia and RIVET (arXiv:1101.2599)

- **MadGraph:**
  - **Event generation**: Feynman diagrams, amplitudes, MC integration
- **Pythia:**
  - Handles parton showering, hadronization, underlying event modelling
- **RIVET** (**Not a generator**):
  - **Analysis toolkit that:**
    - Extracts observables from MC events
    - Compares to experimental data

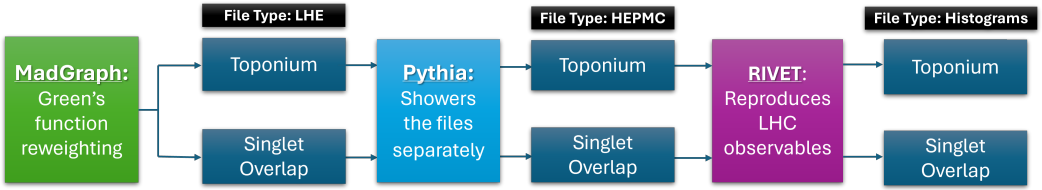


Key Distinction

RIVET **analyzes** events (from MadGraph/Pythia) but does not generate or modify physics content.

Extracting Toponium Samples

- **Overview:** The diagram below outlines the full pipeline for generating and analyzing toponium-enhanced $t\bar{t}$ events:

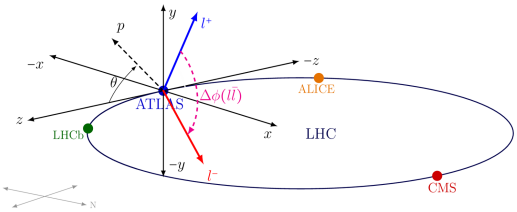


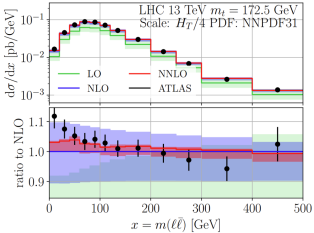
Workflow from MadGraph (Green's function re-weighting) to Pythia showering and RIVET analysis, producing histogram observables for both Toponium and Singlet overlap.

Next-to-Next-to-Leading Order (NNLO) Predictions

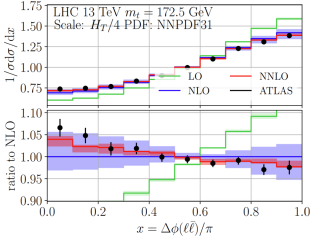
- **NNLO QCD predictions:**
  - Provides the **most precise calculation** for $t\bar{t}$ production
  - Includes higher-order corrections that significantly **reduce theoretical uncertainties**
  - Can be **validated** against **ATLAS/CMS** data
  - Is available at both **parton** and **particle** levels

- Publicly available through the **Centre for Precision Studies in Particle Physics Working Group**





Cambridge - arXiv:2008.11133



Cambridge - arXiv:2008.11133

NNLO + Toponium

- Toponium correction defined as:

$$\boxed{\eta_t = \text{Toponium} - \text{Singlet Overlap}}$$

- This correction is added to the absolute NNLO differential distributions:

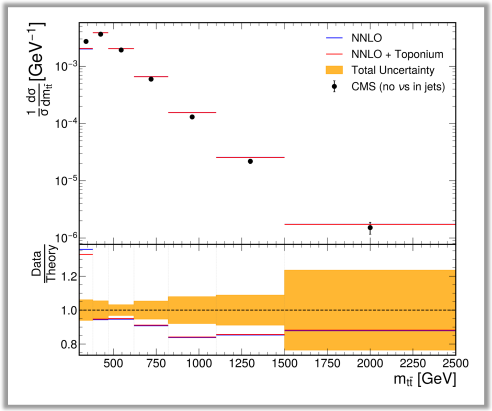
$$\boxed{\left.\frac{d\sigma}{dX}\right|_{\text{NNLO}+\eta_t} = \left.\frac{d\sigma}{dX}\right|_{\text{NNLO}} + \left.\frac{d\sigma}{dX}\right|_{\eta_t}}_{X \equiv m_{t\bar{t}}, m^{e\mu}, \ldots}$$

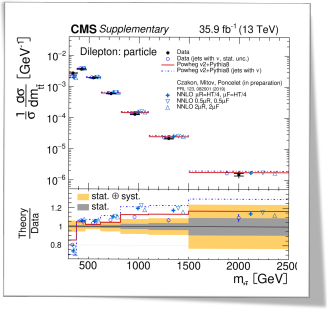
- Compared against differential distributions measured by **ATLAS** and **CMS**
- Observables include:
  - both single-differential distributions — $m_{t\bar{t}}$, $m^{e\mu}$, and $\Delta\phi(\ell\bar{\ell})$ — as well as the double-differential distribution $\Delta\phi^{e\mu}$ $m^{e\mu}$
- Distributions are normalized to unit area to analyze shape effects from the toponium contribution.

RESULTS

Particle level $m^*_{t\bar{t}}$

- Enhancement in the threshold region due to toponium

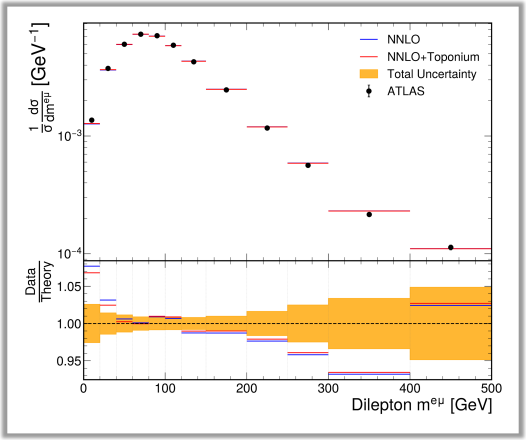




Normalised differential cross section as a function of $m_{t\bar{t}}$ - (**No ν's in jets**) → arXiv:1811.06625

Particle level $m^{e\mu}$

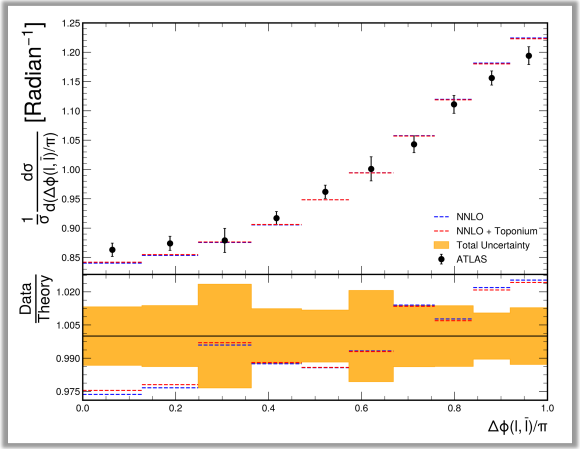
- An enhancement is observed due to toponium correction across the first few bins



Normalised differential cross-sections as a function of $m^{e\mu}$ → arXiv:1910.08819

Particle level $\Delta\phi(l\bar{l})$

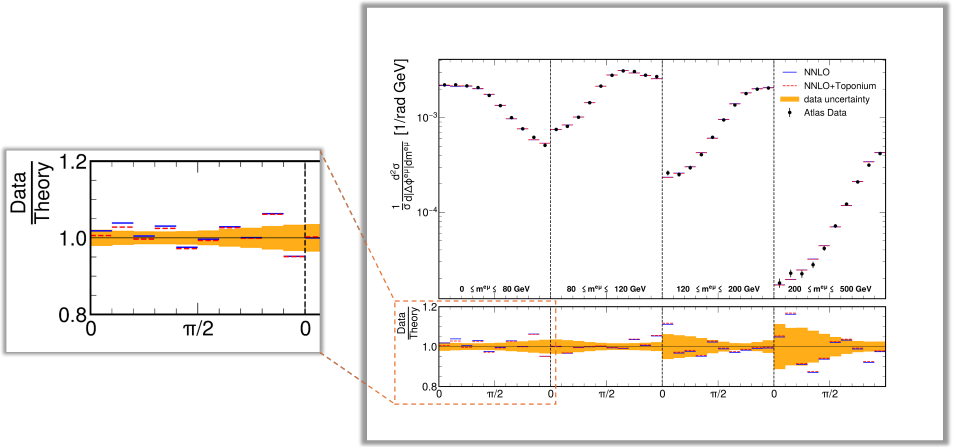
- A mild enhancement is observed in the first few bins due to toponium



Normalised differential cross-sections as functions of $\Delta\phi(l\bar{l})$ → arXiv:1910.08819

Particle level $\Delta\phi^{e\mu}$ $m^{e\mu}$

- Enhancement due to toponium is observed in the first few bins



Normalised double-differential cross-sections as a function of $\Delta\phi^{e\mu}$ and $m^{e\mu}$ → arXiv:1910.08819

Summary

- Toponium, a quasi-bound $t\bar{t}$ state, may explain discrepancies observed in the threshold region.
- We implemented a dedicated Monte Carlo model that incorporates color-singlet toponium corrections via Green's function re-weighting in MadGraph+Pythia, using RIVET to extract observables.
- This approach isolates toponium effects, avoids double counting, and allows consistent combination with NNLO QCD predictions.
- The resulting NNLO+Toponium predictions show enhancements in key observables: $m_{t\bar{t}}$, $m^{e\mu}$, $\Delta\phi(\ell\bar{\ell})$ and $\Delta\phi^{e\mu}\, m^{e\mu}$.
- Observed shape effects suggest toponium could account for discrepancies within ATLAS and CMS results.

Thank You

Thanks for your time!

Questions or comments?

Simulating Toponium in MadGraph and Pythia (arXiv:2411.18962)

Goal

Model non-perturbative QCD effects in $t\bar{t}$ production near threshold (toponium) using Green's function re-weighting in MadGraph + parton showering in Pythia.

Methodology

- Generate color-singlet -$t\bar{t} \to bW^+ \bar{b}W^- \to \ell^+\nu\,\ell^-\bar{\nu}$ - events near threshold in MadGraph
- Reweight matrix elements:

$$|\mathcal{M}|^2 \to |\mathcal{M}|^2 \left| \frac{\widetilde{G}(E, p^*)}{\widetilde{G}_0(E, p^*)} \right|^2 \tag{1}$$

  - $\tilde{G}(E, p^*)$ - Non-relativistic Green's function with QCD potential
  - $\tilde{G}_0(E, p^*)$ - Free Green's function (Breit-Wigner)

Simulating Toponium in MadGraph and Pythia (arXiv:2411.18962)

Methodology (continued)

- Green's function re-weighting is applied within the Fortran code generated by MadGraph.
- Pythia is used to:
  - Shower color-singlet events
  - Inject a fictitious Z' resonance to preserve the invariant mass of the toponium system during showering
- The output HEPMC event files contain both the toponium contribution and a singlet overlap sample, which are then analysed using RIVET.
- RIVET applies the appropriate analysis cuts corresponding to specific ATLAS or CMS measurements on both the toponium and singlet overlap.
- The final output consists of histograms for various kinematic observables, generated separately for the toponium and singlet components.