Top reconstruction in the dilepton channel for the top Yukawa extraction

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ATLAS EXPERIMENT

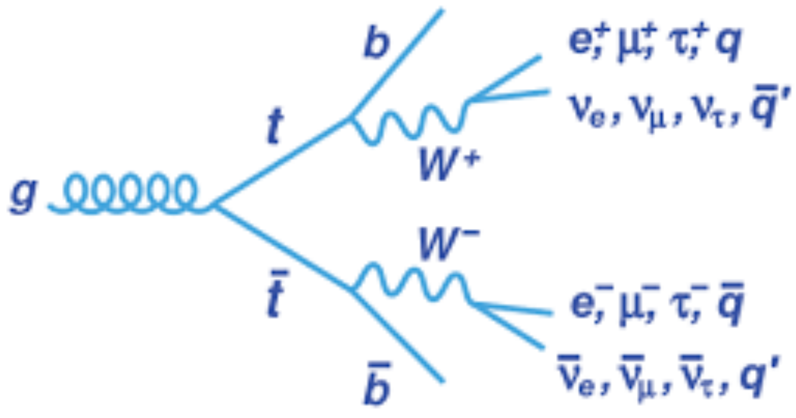
Yukawa coupling

- Yukawa coupling describes the strength of the interaction between the fundamental fermion fields and the Higgs field
- Fermion mass related to the strength of their Yukawa coupling
- Why are we interested in the Yukawa interaction?
  - Precision tests of the SM
  - Deviation from SM value could indicate new physics
  - Window into Higgs sector

Goal: Describe a study to include top quark kinematic reconstruction into a new analysis that will measure the top quark Yukawa coupling using ATLAS data

Top quark

- Top quark is the heaviest particle in the standard model
- Highest mass means it has the largest Yukawa coupling
- The top quark decays $t \to Wb$ ~ 100%
- b-quark forms a jet in the detector
- W boson can decay leptonically or hadronically
- This allows for three final states:
  - All hadronic
  - Lepton + jets
  - **Dilepton**



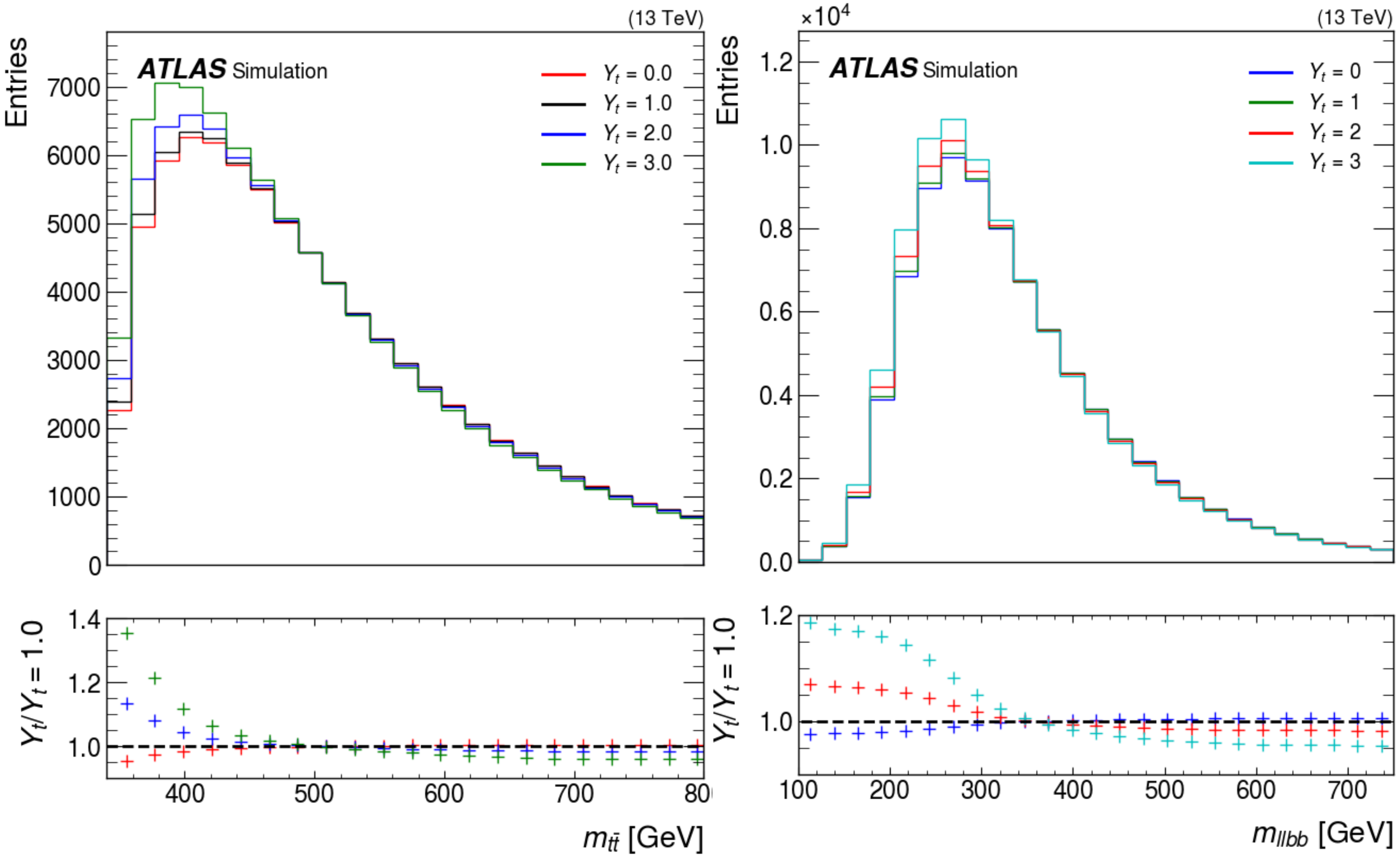
Possible decays of the $t\bar{t}$ system

Jet – a collimated spray of particles formed through hadronization of an isolated quark

Motivating top reconstruction

Kinematic reconstruction – reconstructing the kinematic properties of a decayed particle from its decay products

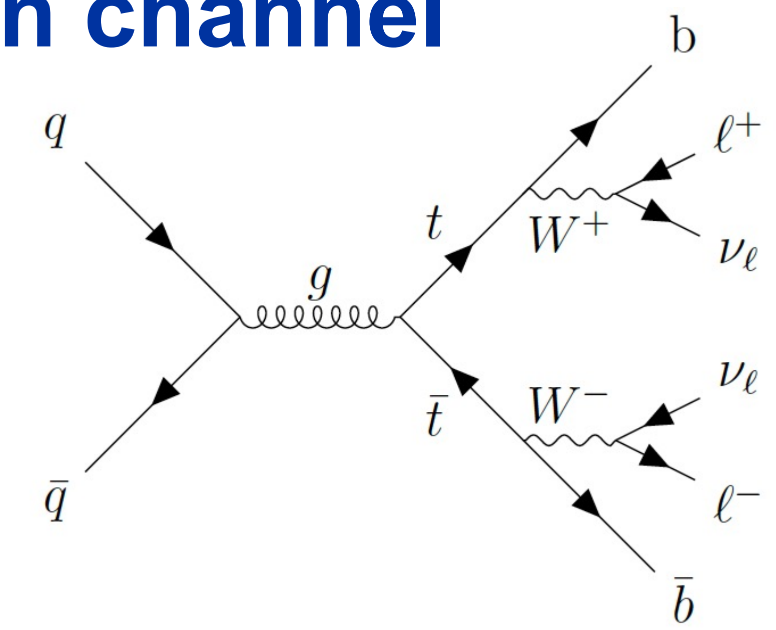
- Limiting factor of this analysis is the sensitivity of the kinematic distributions used
- Currently utilizing measured decay products of the top quark – m_{llbb}
- At truth level, m_{tt} is more sensitive than m_{llbb}



Cannot use the m_{tt} distribution without reconstructing the kinematics of the top quarks

Top reconstruction in the dilepton channel

- Dilepton final state contains:
  - 2 b-quarks
  - 2 leptons (e/μ)
  - 2 neutrinos
- In order to reconstruct the $t\bar{t}$ system, kinematics of all final state particles must be known
- Neutrinos can't be detected at ATLAS
- MET can be calculated for each event and attributed to the neutrinos
- Neutrino four vectors must be estimated to reconstruct the $t\bar{t}$ system



Feynman diagram of the $t\bar{t}$ dilepton final state

MET – Missing Transverse Momentum – the negative vector sum of the momentum in the transverse plane of all the physics objects in an event. Presence of MET can imply undetected particles.

Kinematic equations and constraints

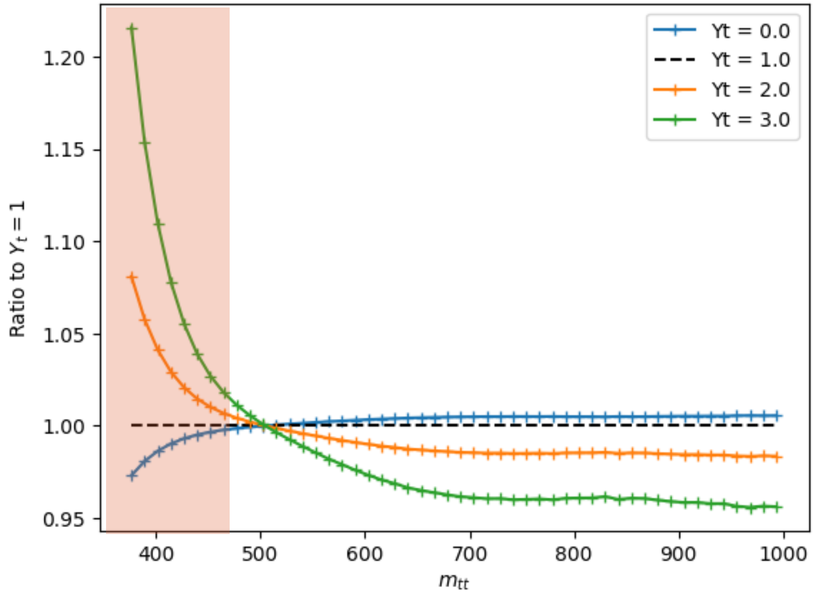
$$
\begin{aligned}
\not{E}_x &= p_{\nu_x} + p_{\bar{\nu}_x} \\
\not{E}_y &= p_{\nu_y} + p_{\bar{\nu}_y} \\
E_\nu^2 &= p_{\nu_x}^2 + p_{\nu_y}^2 + p_{\nu_z}^2 + m_\nu^2 \\
E_{\bar{\nu}}^2 &= p_{\bar{\nu}_x}^2 + p_{\bar{\nu}_y}^2 + p_{\bar{\nu}_z}^2 + m_{\bar{\nu}}^2 \\
m_{W^+}^2 &= (E_{\ell^+} + E_\nu)^2 - (p_{\ell_x^+} + p_{\nu_x})^2 \\
&\quad -(p_{\ell_y^+} + p_{\nu_y})^2 - (p_{\ell_z^+} + p_{\nu_z})^2 \\
m_{W^-}^2 &= (E_{\ell^-} + E_{\bar{\nu}})^2 - (p_{\ell_x^-} + p_{\bar{\nu}_x})^2 \\
&\quad -(p_{\ell_y^-} + p_{\bar{\nu}_y})^2 - (p_{\ell_z^-} + p_{\bar{\nu}_z})^2 \\
m_t^2 &= (E_b + E_{\ell^+} + E_\nu)^2 - (p_{b_x} + p_{\ell_x^+} + p_{\nu_x})^2 \\
&\quad -(p_{b_y} + p_{\ell_y^+} + p_{\nu_y})^2 - (p_{b_z} + p_{\ell_z^+} + p_{\nu_z})^2 \\
m_t^2 &= (E_{\bar{b}} + E_{\ell^-} + E_{\bar{\nu}})^2 - (p_{\bar{b}_x} + p_{\ell_x^-} + p_{\bar{\nu}_x})^2 \\
&\quad -(p_{\bar{b}_y} + p_{\ell_y^-} + p_{\bar{\nu}_y})^2 - (p_{\bar{b}_z} + p_{\ell_z^-} + p_{\bar{\nu}_z})^2
\end{aligned}
$$

Set of equations describing the kinematics of the $t\bar{t}$ system

- Equations cannot be solved analytically without imposing further constraints:
  - W boson masses fixed to 80 GeV
  - Mass of the top quarks fixed to 172.5 GeV
  - Assume that MET is attributed exclusively to the two neutrinos

Issues:

- m_{tt} distribution most sensitive to Y_t around the threshold region
- Threshold region is at $m_{tt} \backsimeq 2 \cdot m_t$
- At least one top quark must be off shell below threshold region
- Fixing top mass assumes that both top quarks in reconstruction are on shell



Ratio plot of m_{tt} for different Y_t values to SM Y_t

Solving and selecting solutions

Inputs per event:
Lepton four vectors
B-jet four vectors
MET, MET phi

Set neutrino eta to -5

Solve kinematic equations for all both possible combinations of b-quark and lepton pairs for specific neutrino eta

4 candidate solutions produced per lepton/b-jet combination

Apply weight to all candidate solutions

Is neutrino eta = 5?

No

Add 0.1 to neutrino eta

Yes

Select solution with highest weight

Outputs per event:
Two neutrino four vectors

$$\omega = \prod_{j=x,y} \exp\left(- \frac{(\not{E}_{T_{j,i}}^{\text{calc}} - \not{E}_{T_j}^{\text{obs}})^2}{2\sigma^2_{\not{E}^{\nu}_{T\,j}}} \right)$$

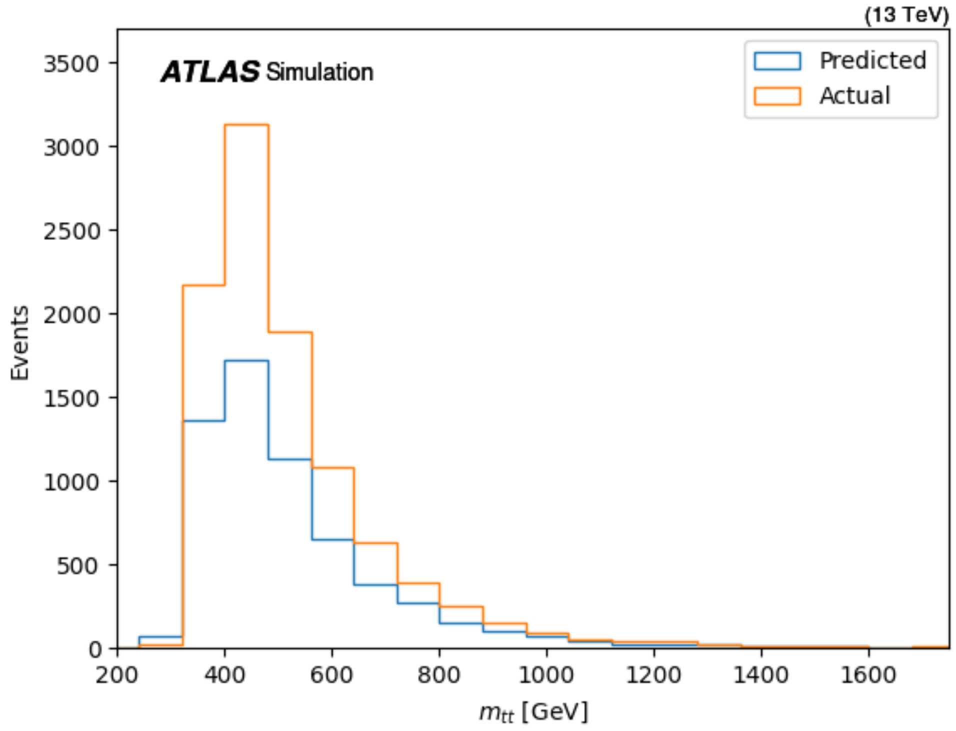
Equation used to weight candidate solutions

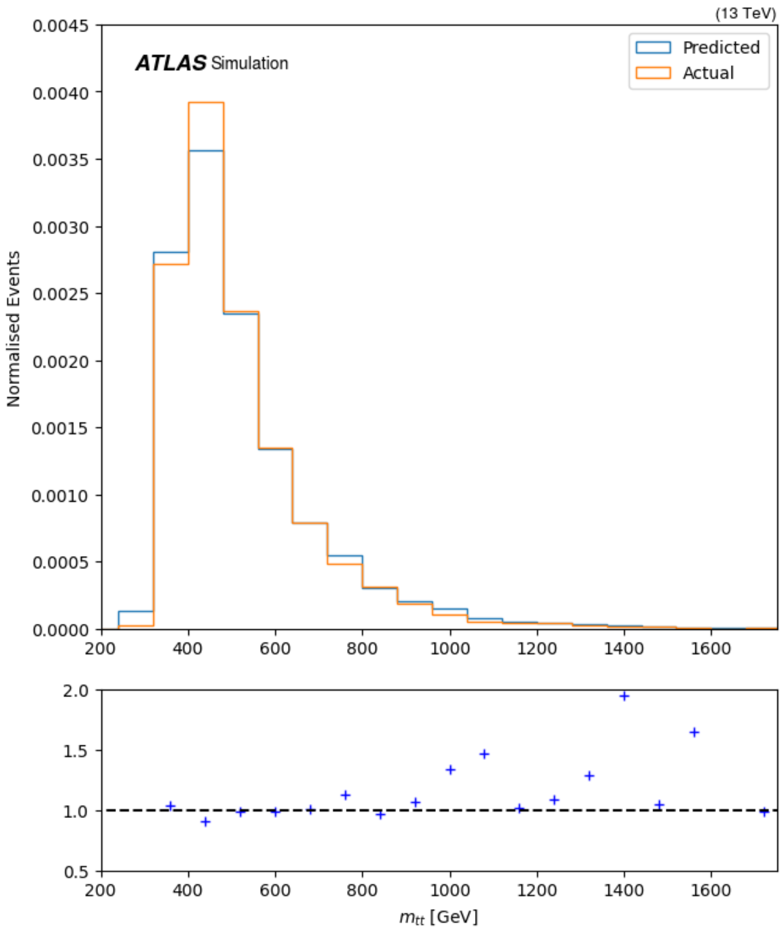
- The weighting function is a Gaussian that characterizes the level of agreement between the neutrino solutions and the MET

Initial results - distributions

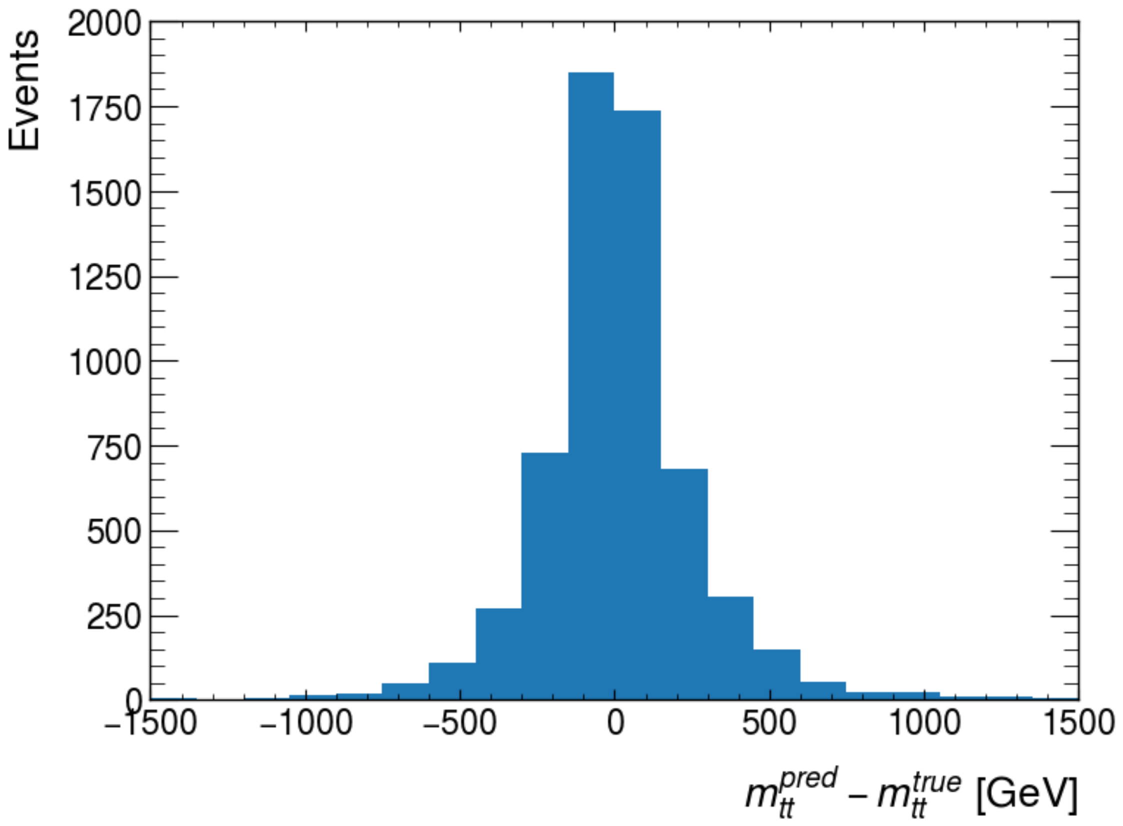
Efficiency – in this context, defined as the percentage of events where a solution to the kinematic equations was found, and neutrino four vectors have been created

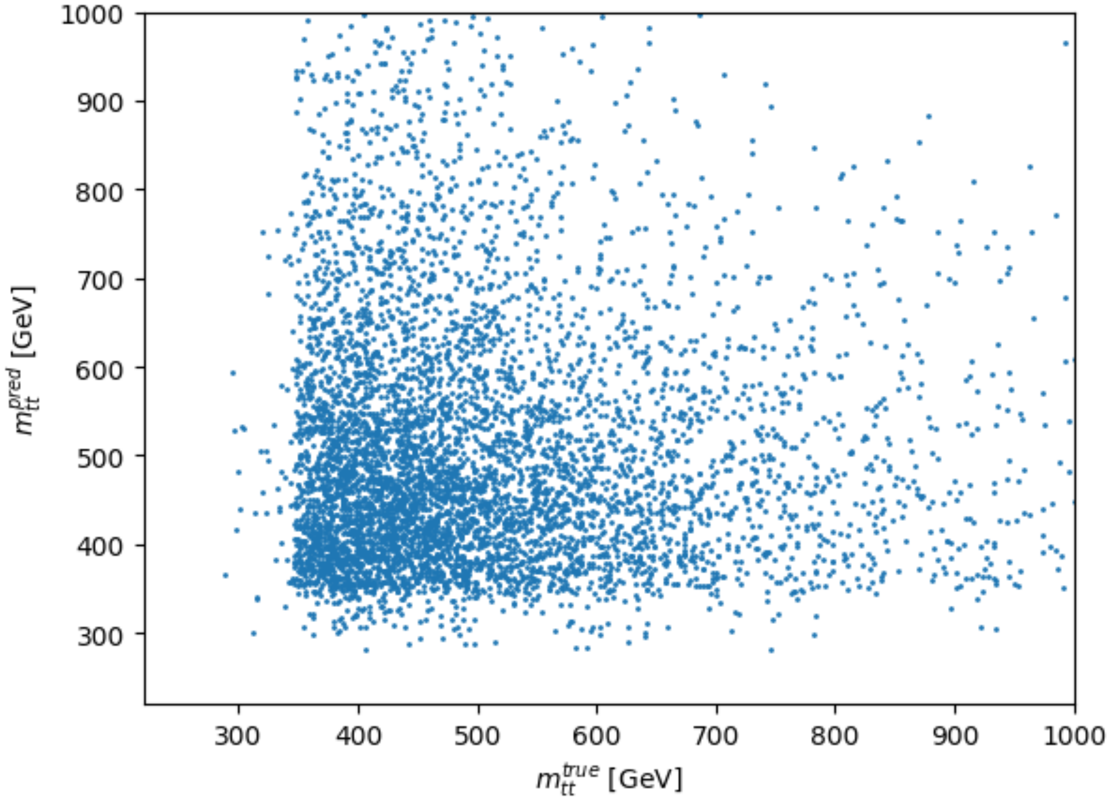
- Solution efficiency of 60.15%





Initial results – performance





Further work

Smearing:

- Purpose of smearing is to increase solution efficiency
- Attempt to solve kinematic equations 100 times
- For each attempt:
    - Lepton and b-jet energy randomly varied within detector resolution
    - W-boson mass varied according to Breit–Wigner distribution
- Solution calculated as weighted average of all solutions

Machine Learning

- Analytical solution attempted first to act as baseline for comparing machine learning techniques
- Test existing methods such as SPA-net
- Test range of different neural network architectures

Conclusion

- Dilepton channel used for Y_t extraction
- m_{tt} kinematic distribution is more sensitive at truth level to Y_t than other observables
- Cannot use m_{tt} distribution without top reconstruction
- Using analytical solution, solving $t\bar{t}$ system kinematic equations
- $t\bar{t}$ system under constrained, so additional constraints employed
- Output of algorithm can be used to construct m_{tt} kinematic distribution
- Construction efficiency currently too low to be used in this analysis, but further work will attempt to improve this

Thank you

Any questions?