I - Machine-Learning quantum entanglement with top quark pair production at the LHC

---Exploring dilepton ttbar reconstruction methods

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Based on ongoing work in collaboration with
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Why top quark pair production?

- Growing interest in observing entanglement and violation of Bell's inequality at the LHC.
- Top quark pair productions are good candidate because they decay before de-correlation and that the lepton from two-step decay is highly correlated with Top spin.

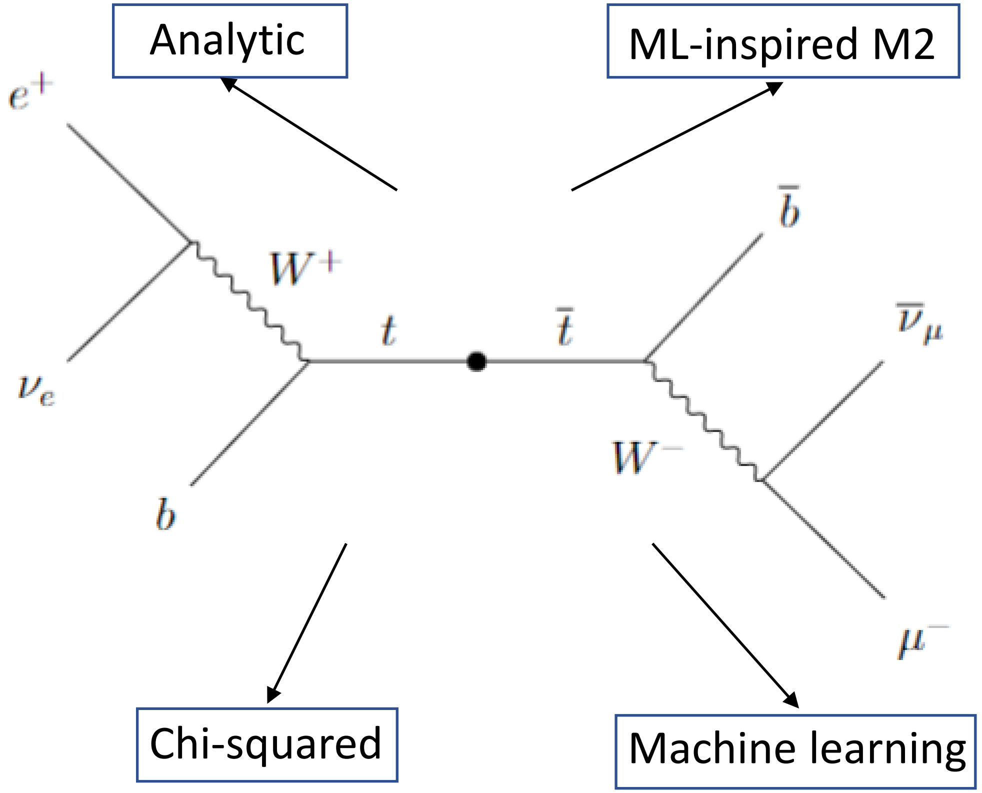
$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\chi} = \frac{1+\alpha\cos\chi}{2} = \begin{cases} +1.0 & l^+ \text{ or } \bar{d} \\ -0.31 & \nu \text{ or } u \\ -0.41 & b \end{cases}$$

1001.3422 Mahlon, Parke

- χ is the angle between the decay product and top quark spin axis in the top quark rest frame.
- To obtain optimal basis for spin-correlation study, we need to reconstruct top quarks in dileptonic ttbar events.

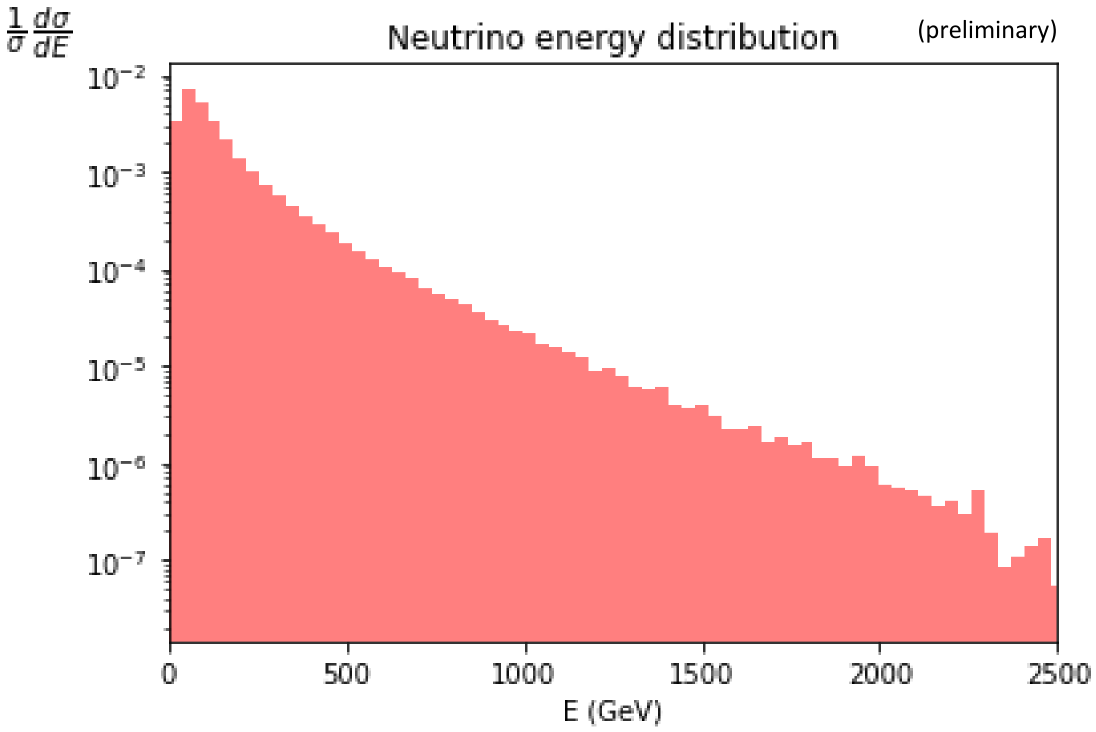
Top quark reconstruction

- To maximally exclude backgrounds, we study events with different flavored lepton final states.
- We need to find the neutrino momentum and the correct b quark and lepton pairing given all the visible momentum.
- We will compare the performance of different reconstruction methods cross different statistics.
- Event generation using MG5, Pythia and Delphes.



Analytic reconstruction

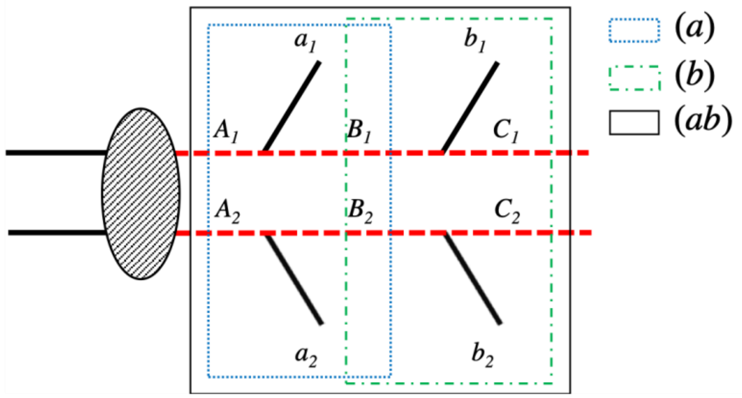
- Based on the four on-shell conditions.
- Involves solving quartic polynomial with potential multiple real solutions.
- We compute weighted solution based on neutrino energy distribution.
- Does not consider widths of Top and W masses. Reconstructed mass distribution is not optimal.



0603011 Sonnenschein

ML-inspired M2 reconstruction

- Generalization of MT2, which allows additional mass constraints.
- Obtain neutrino momentum from minimization.
- Reconstructed mass distribution of the non-constrained mass is not optimal.
- Accuracy of combinatorial assignment is not great, we used neural network to resolve combinatorics instead.



$$M_{2CW}^{(b\ell)} \equiv \min_{\vec{q}_1,\vec{q}_2} \{\max [M_{P_1}(\vec{q}_1,\tilde{m}),\ M_{P_2}(\vec{q}_2,\tilde{m})]\}$$
$$\vec{q}_{1T} + \vec{q}_{2T} = \not{\vec{P}}_T$$
$$M_{P_1} = M_{P_2}$$
$$M_{R_1}^2 = M_{R_2}^2 = m_W^2$$

$$M_{2Ct}^{(\ell)} \equiv \min_{\vec{q}_1,\vec{q}_2} \{\max [M_{P_1}(\vec{q}_1,\tilde{m}),\ M_{P_2}(\vec{q}_2,\tilde{m})]\}$$
$$\vec{q}_{1T} + \vec{q}_{2T} = \not{\vec{P}}_T$$
$$M_{P_1} = M_{P_2}$$
$$M_{R_1}^2 = M_{R_2}^2 = m_t^2$$

1703.06887, Kim, Matchev, Moortgat, Pape

Chi-squared reconstruction

- Minimized over chi-squared statistic.
- Uses explicit mass information

$$\chi^2 \equiv \min_{\not{p}_T = p_{\nu T} + p_{\bar{\nu} T}} \Big[\frac{(m_{bl^+\nu} - m_t)^2}{\sigma_t^2} + \frac{(m_{l^+\nu} - m_W)^2}{\sigma_W^2} + \frac{(m_{\bar{b}l^-\bar{\nu}} - m_t)^2}{\sigma_t^2} + \frac{(m_{l^-\bar{\nu}} - m_W)^2}{\sigma_W^2} + \frac{(|pT_t| - |pT_{\bar{t}}|)^2}{\sigma_{pT}^2} \Big]$$

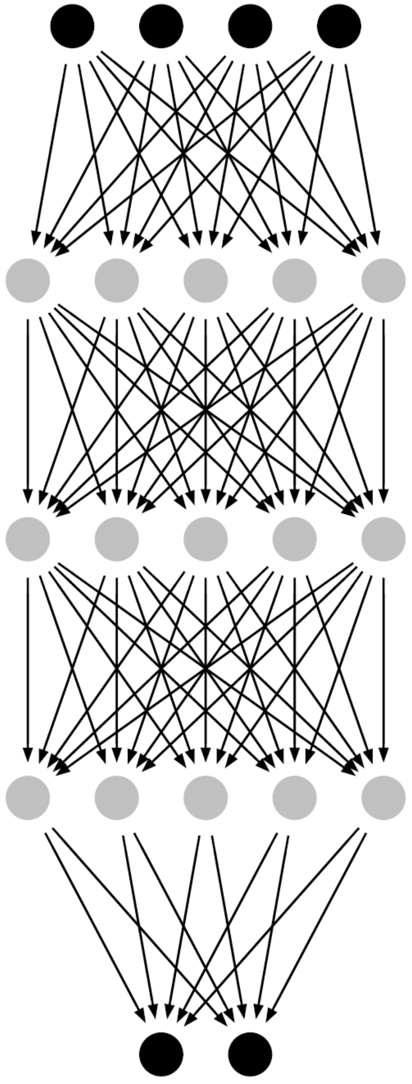
- Resolves combinatorics by choosing the combination with a smaller chi-squared value.
- More hyperparameters are used compared to other methods.
- Cannot generalize to other mass configurations.

Machine learning reconstruction

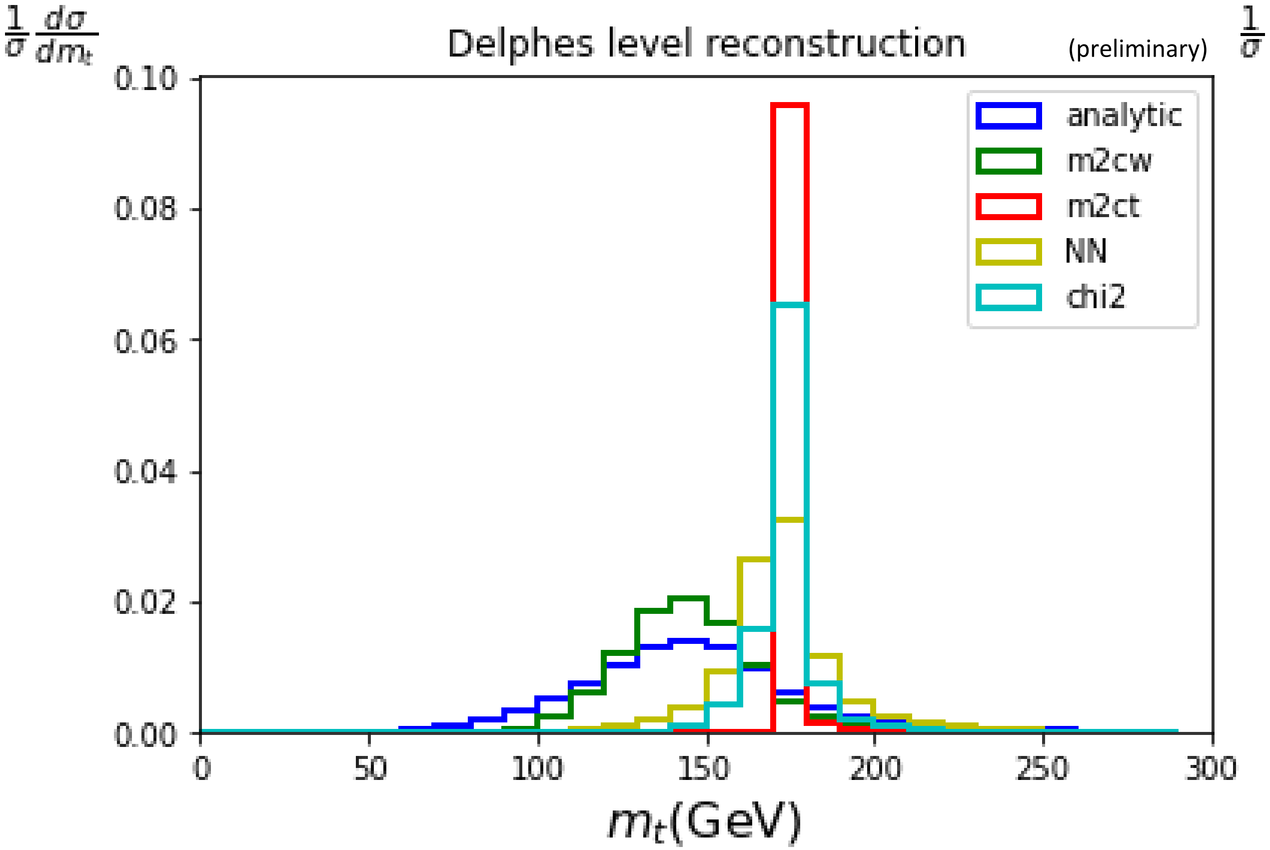
- Fully connected DNN trained on parton level data.
- Uses mean squared loss of neutrino momentum.
- Adds additional mean squared loss of Top and W masses, as inspired from the chi-squared method.

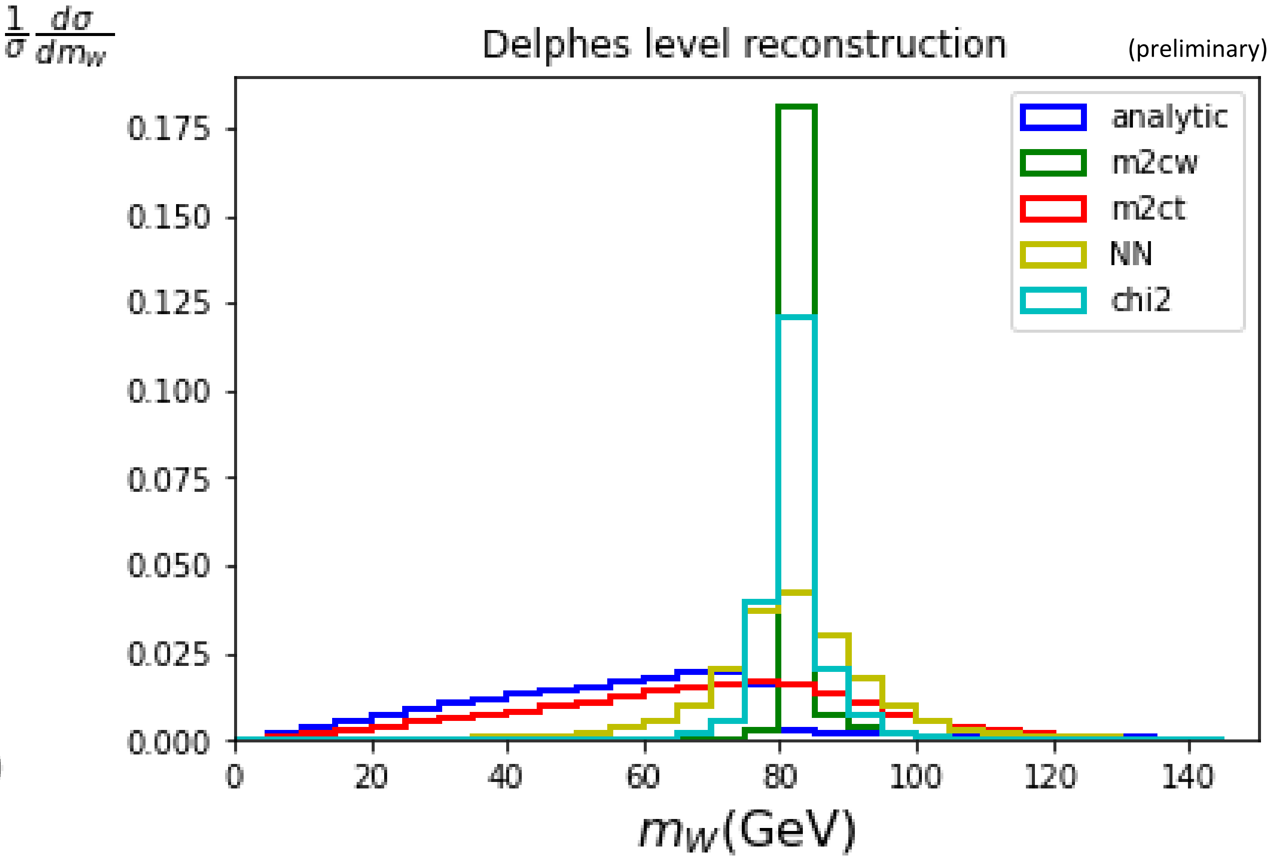
$$L = \sum_{i=1}^{6}(\hat{p}_i - p_i)^2 + \lambda_1\left[(\hat{m}_t - m_t)^2 + (\hat{m}_{\bar{t}} - m_t)^2\right] + \lambda_2\left[(\hat{m}_{W^+} - m_W)^2 + (\hat{m}_{W^-} - m_W)^2\right]$$

- A separate network resolves combinatorial assignment of b quark and leptons.

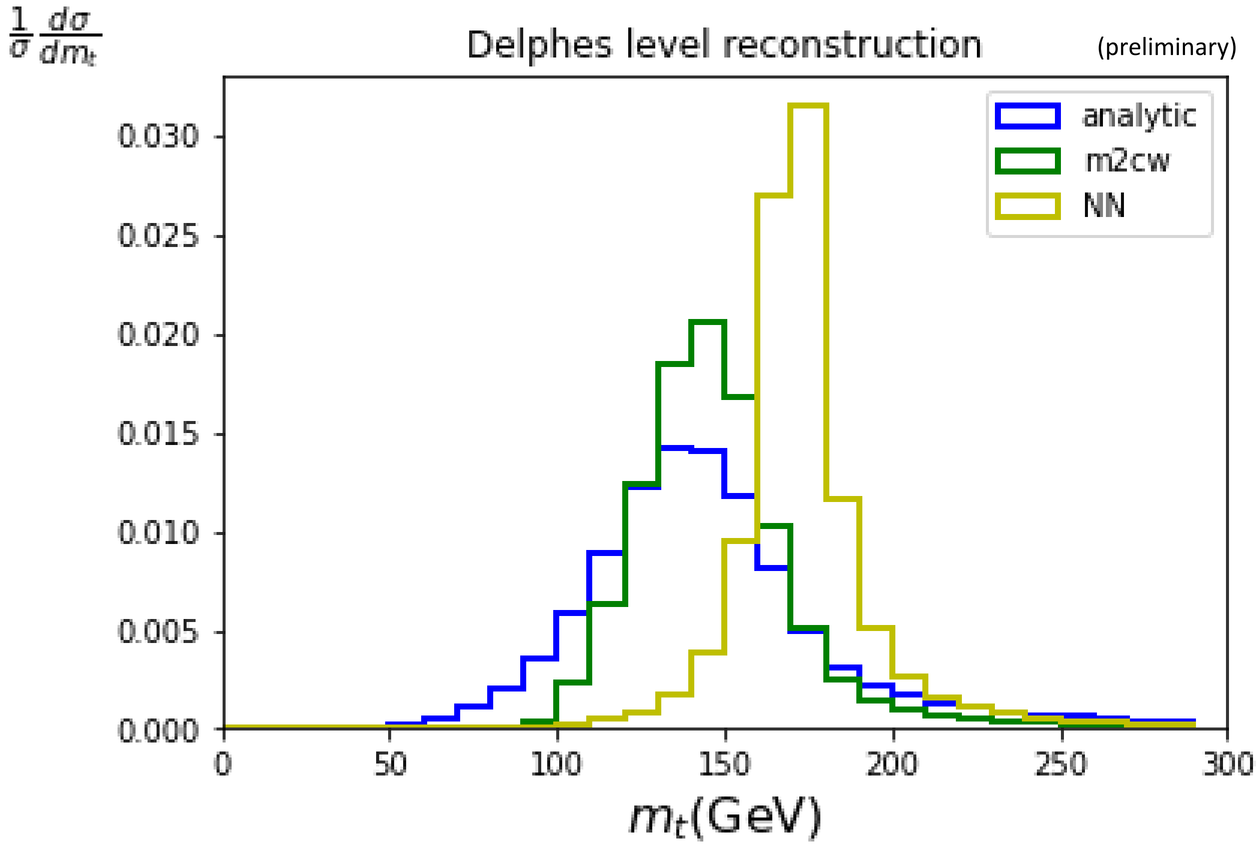


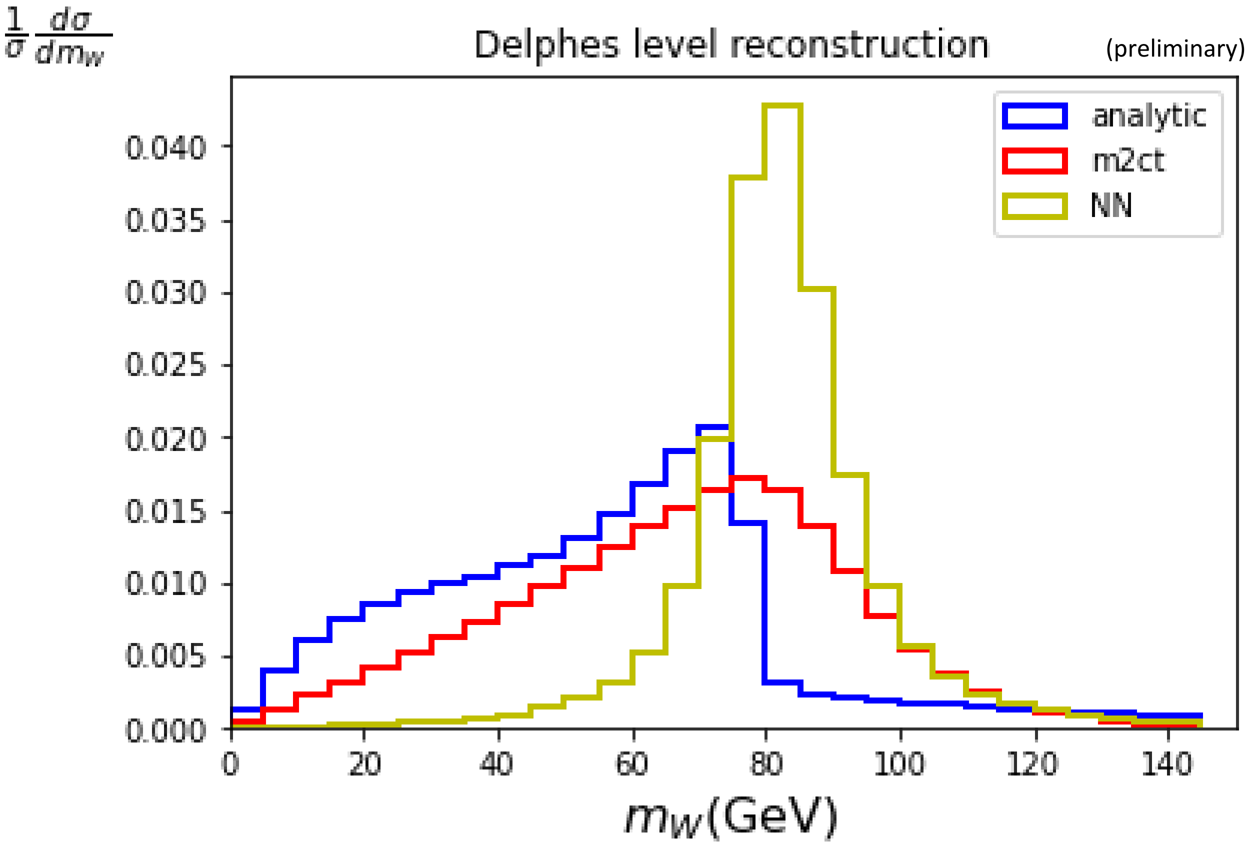
Comparisons

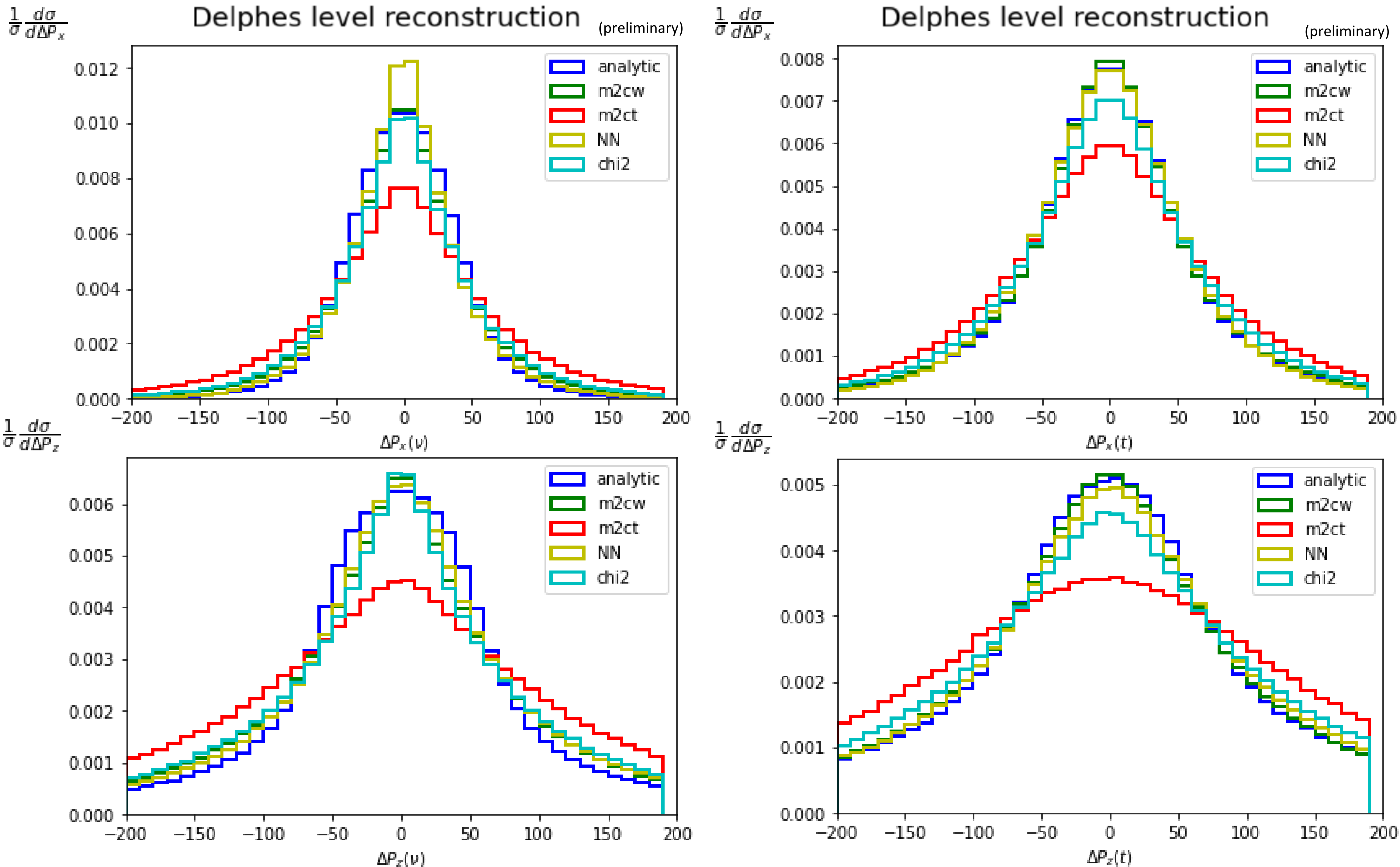




Comparisons

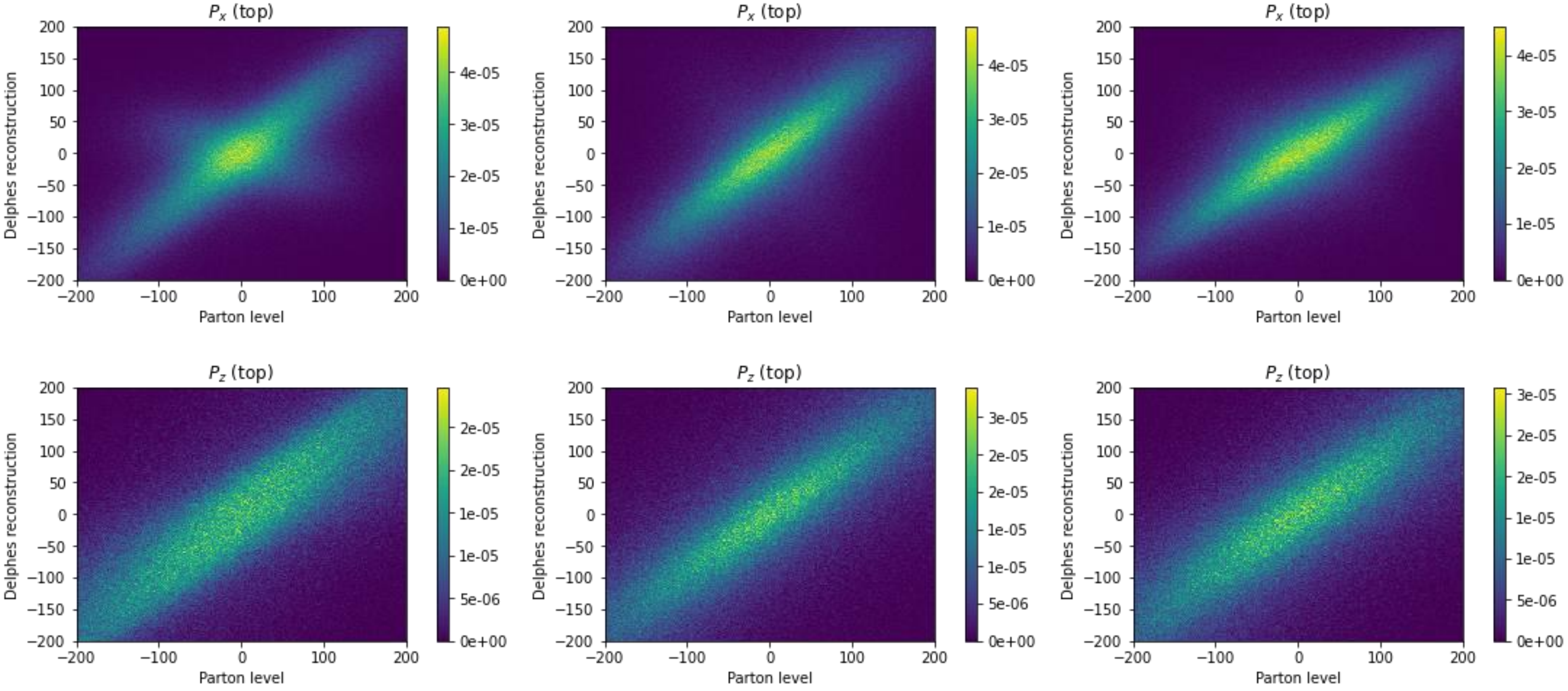






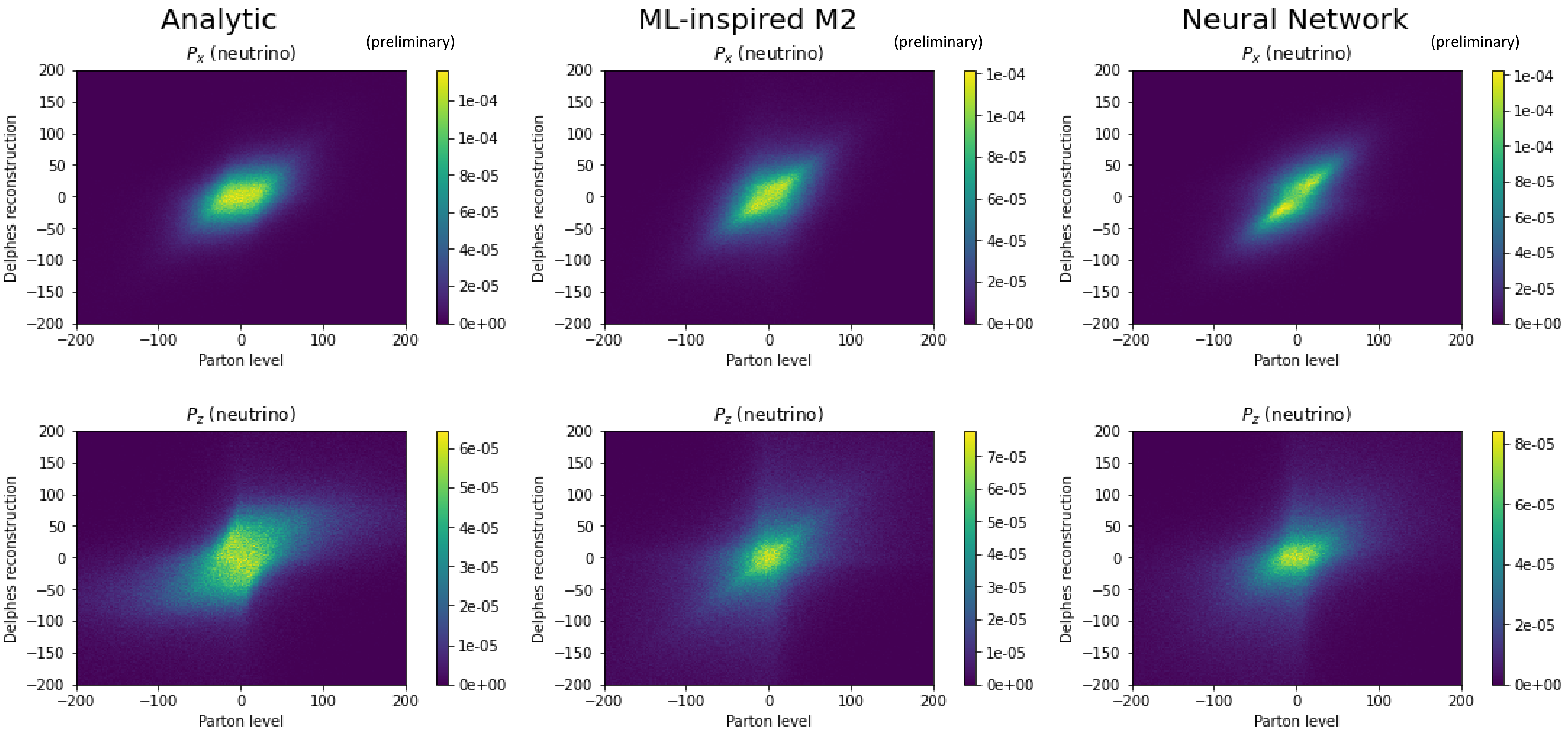
Delphes level reconstruction
(preliminary)
$\frac{1}{\sigma}\frac{d\sigma}{d\Delta P_x}$
$\Delta P_x(\nu)$
$\frac{1}{\sigma}\frac{d\sigma}{d\Delta P_x}$
$\Delta P_x(t)$
$\frac{1}{\sigma}\frac{d\sigma}{d\Delta P_z}$
$\Delta P_z(\nu)$
$\frac{1}{\sigma}\frac{d\sigma}{d\Delta P_z}$
$\Delta P_z(t)$
analytic
m2cw
m2ct
NN
chi2

Analytic (preliminary) | ML-inspired M2 (preliminary) | Neural Network (preliminary)



Summary

- Top quark reconstruction is important to study spin correlation.
- The reconstruction performance can be evaluated on several different metrics.
- We should choose the reconstruction method that best fits our purpose.
- The next talk will cover more on the performance of these reconstruction methods on spin correlation/entanglement of top quarks.

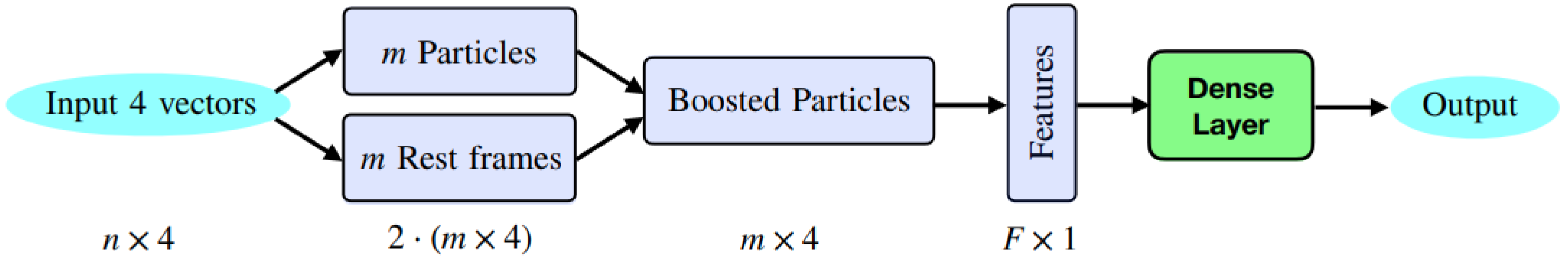


Analytic
ML-inspired M2
Neural Network
(preliminary)
(preliminary)
(preliminary)
P_x (neutrino)
P_x (neutrino)
P_x (neutrino)
P_z (neutrino)
P_z (neutrino)
P_z (neutrino)
Delphes reconstruction
Parton level

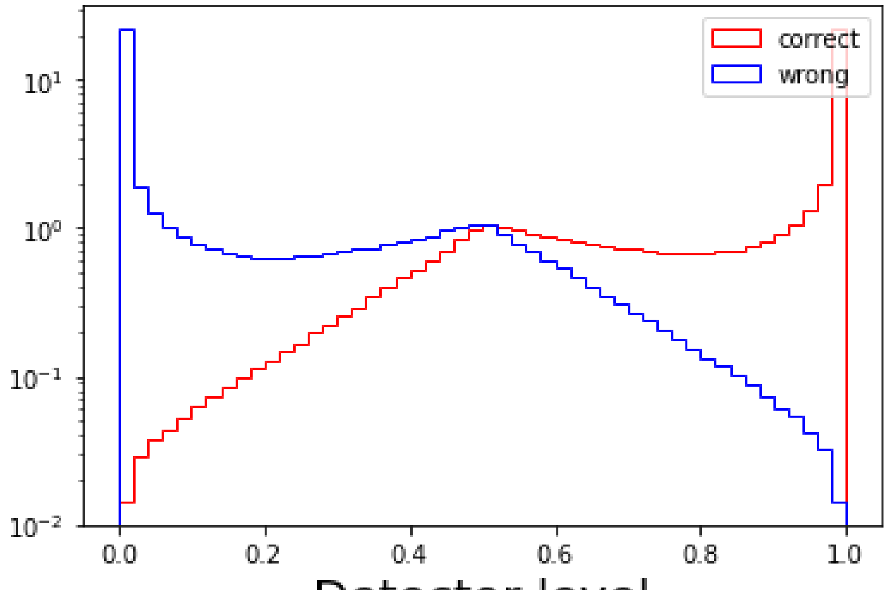
Combinatorial Classification: Lorentz Boosted Network

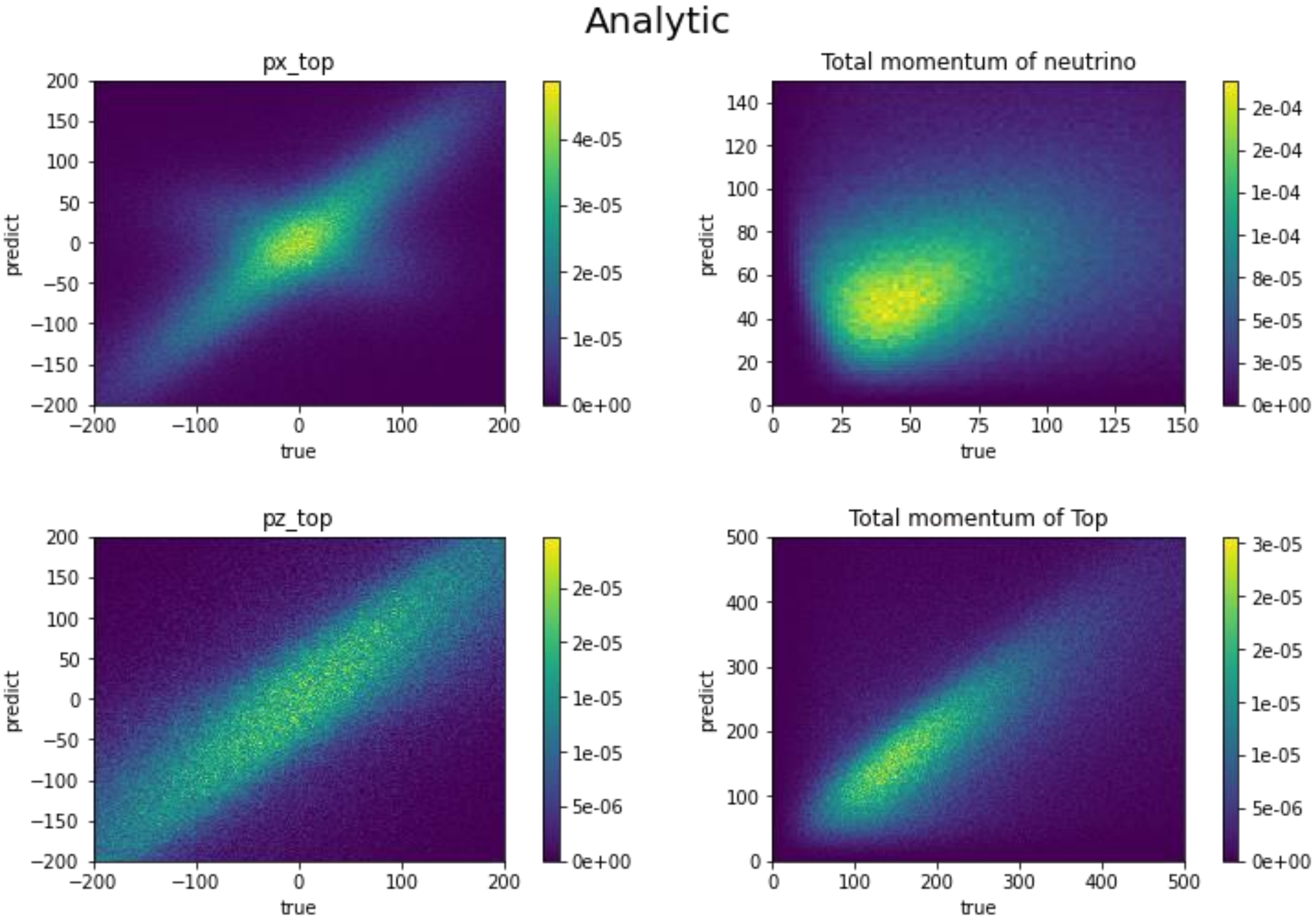
- Motivated by particle kinematics in the rest frames of various particle combinations.
- Form linear combinations of input momentums and boosts into rest frames.
- Output features of the boosted particles.
- We used the network structure studied in our previous work.

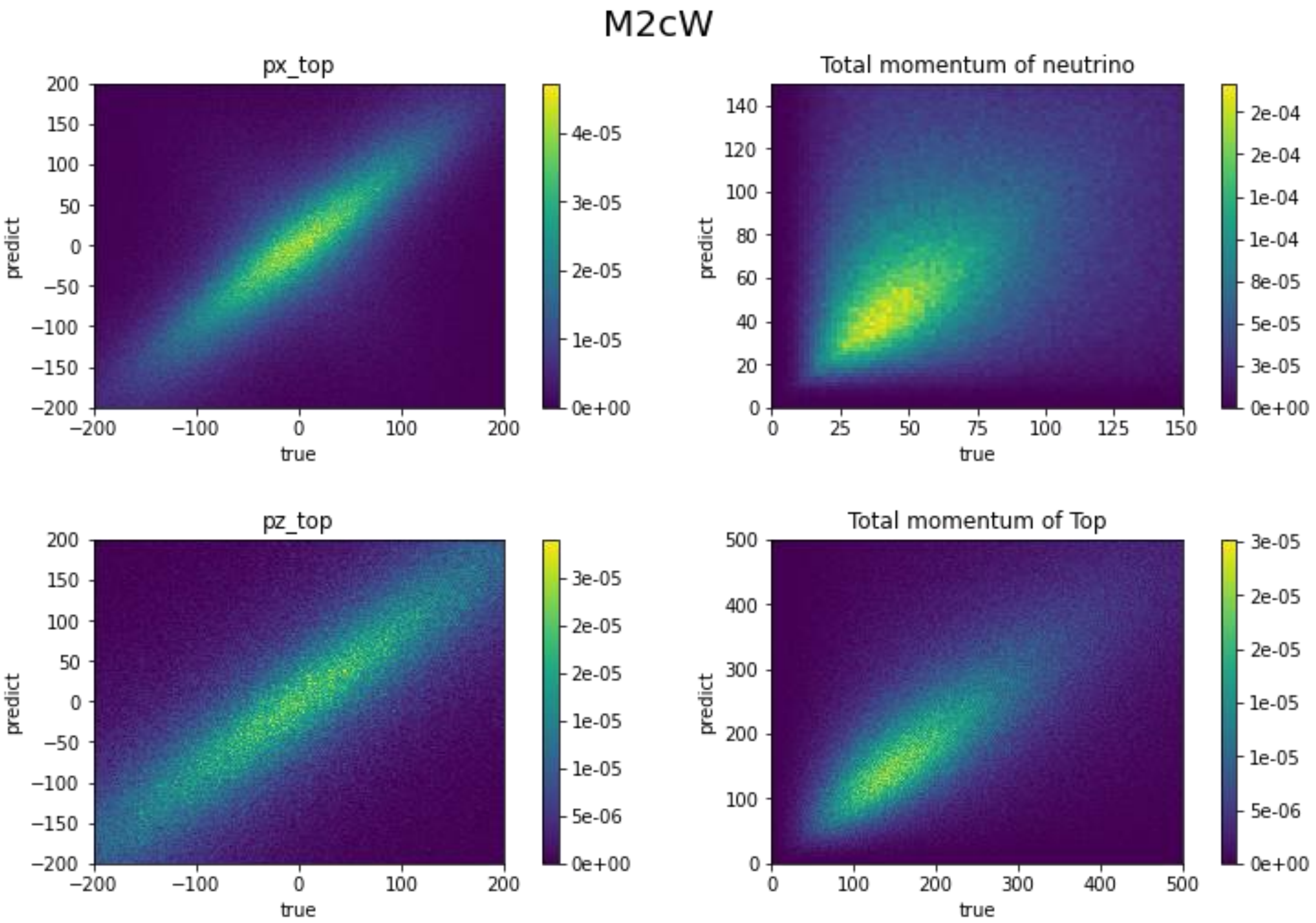
2202.05849 Alhazmi, Dong, Huang, Kim, Kong, Shih



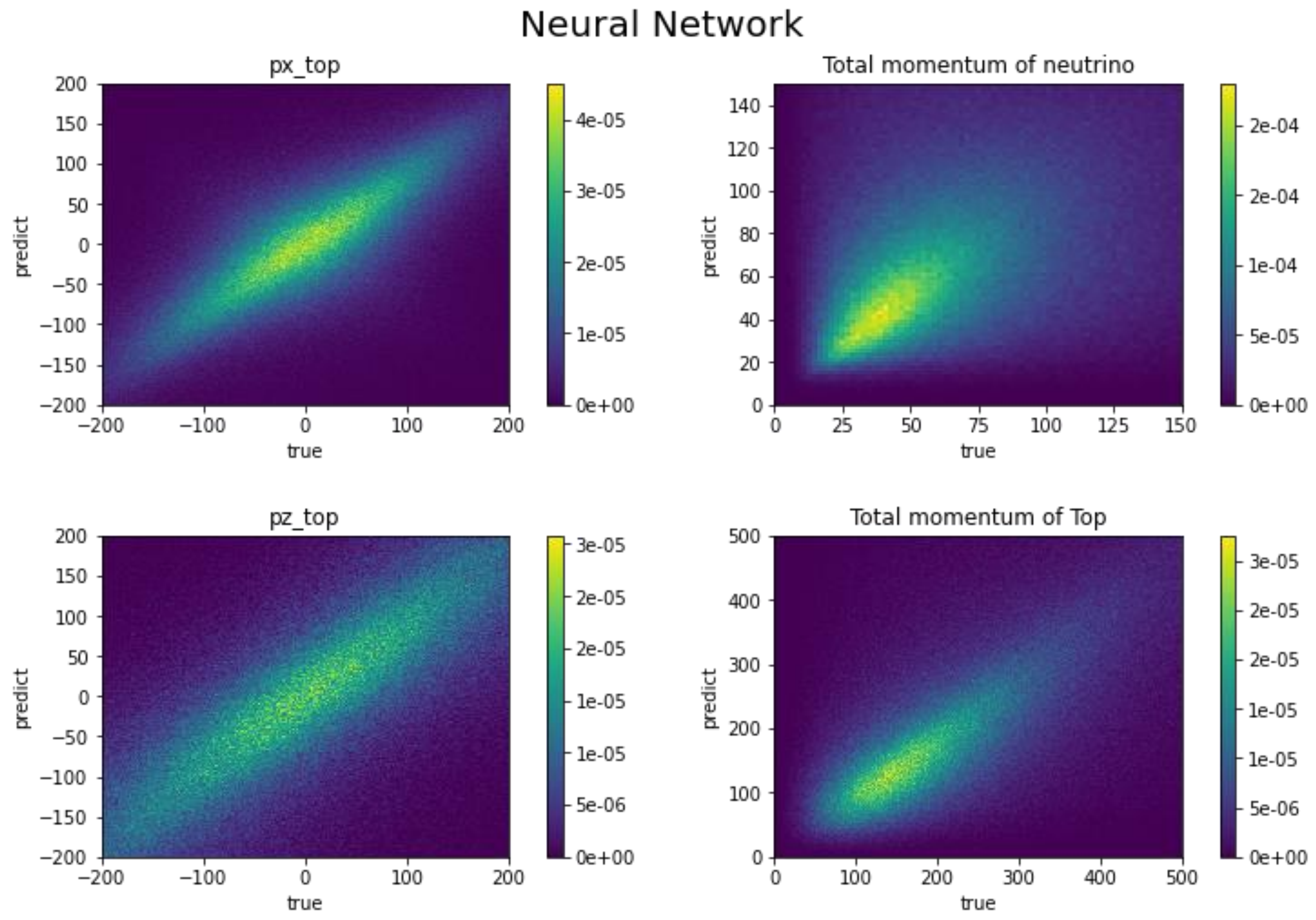
1812.09722 Erdmann, Geiser, Rath, Rieger

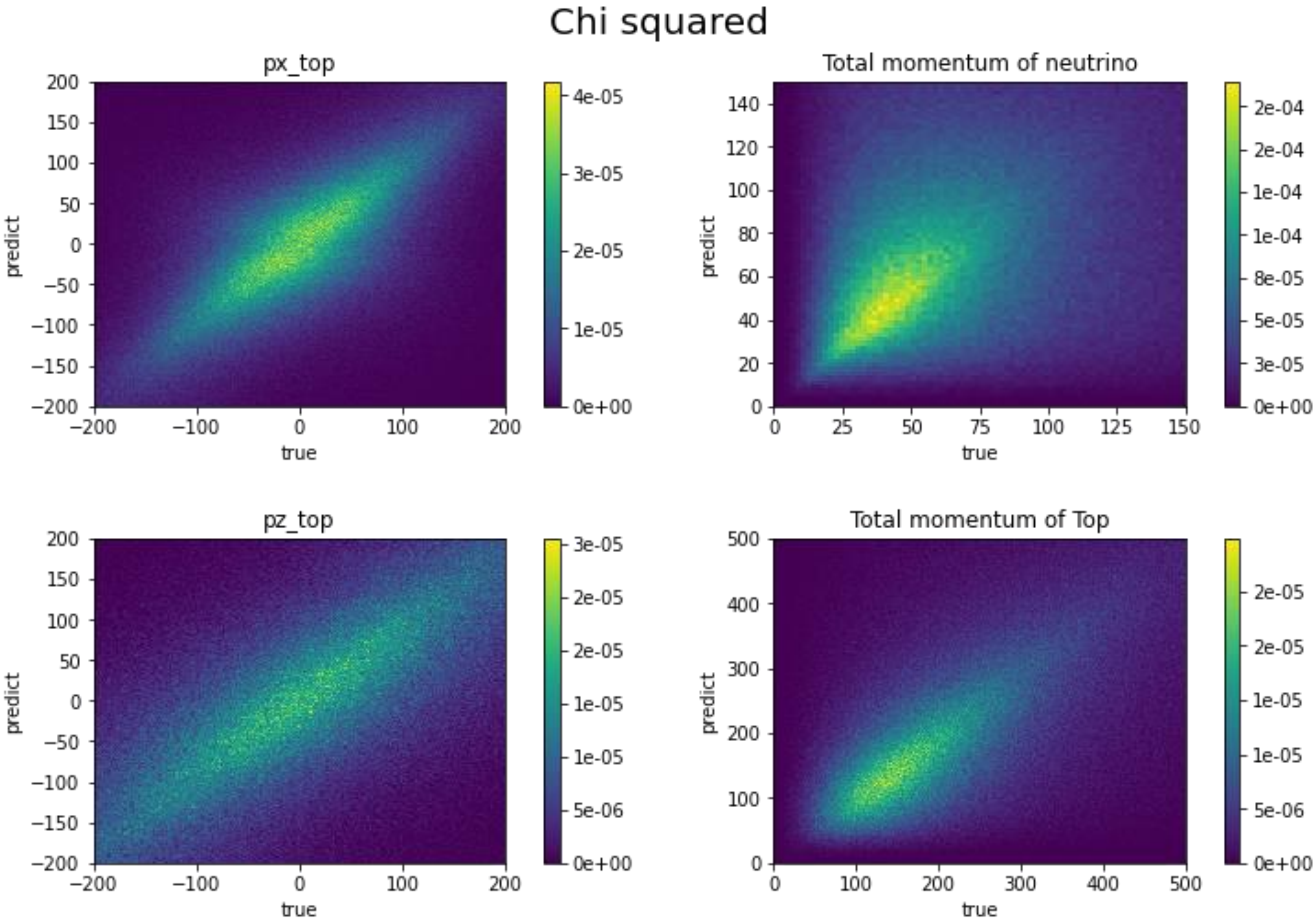



Analytic
px_top
Total momentum of neutrino
pz_top
Total momentum of Top
predict
true
4e-05
3e-05
2e-05
1e-05
0e+00
2e-04
2e-04
1e-04
1e-04
8e-05
5e-05
3e-05
0e+00
2e-05
2e-05
1e-05
1e-05
5e-06
0e+00
3e-05
2e-05
2e-05
1e-05
1e-05
5e-06
0e+00



M2cW
px_top
Total momentum of neutrino
pz_top
Total momentum of Top
predict
true


Neural Network
px_top
Total momentum of neutrino
pz_top
Total momentum of Top
predict
true


Chi squared
px_top
Total momentum of neutrino
pz_top
Total momentum of Top
predict
true
4e-05
3e-05
2e-05
1e-05
0e+00
2e-04
2e-04
1e-04
1e-04
8e-05
5e-05
3e-05
0e+00
3e-05
2e-05
2e-05
1e-05
1e-05
5e-06
0e+00
2e-05
2e-05
1e-05
1e-05
5e-06
0e+00