



Angular Analysis of the $B^0 \rightarrow K^{*0} (892) \mu^+ \mu^-$ Decay Channel Using Data from CMS Experiment at $\sqrt{s} = 13.6$ TeV

Rare Decays Meeting

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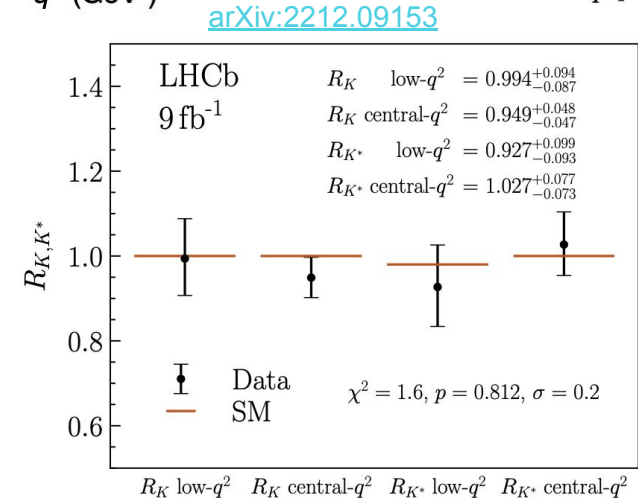
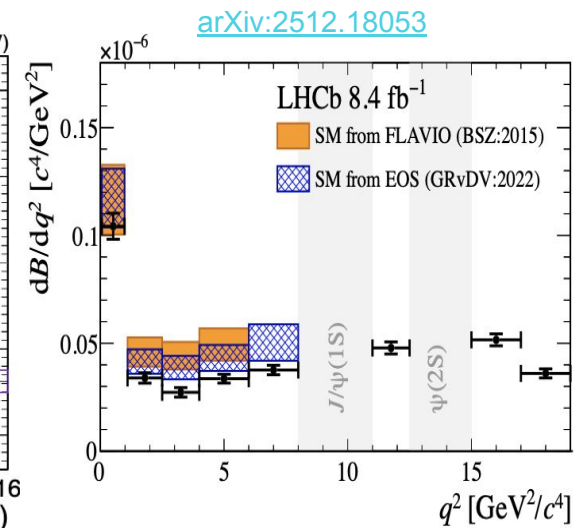
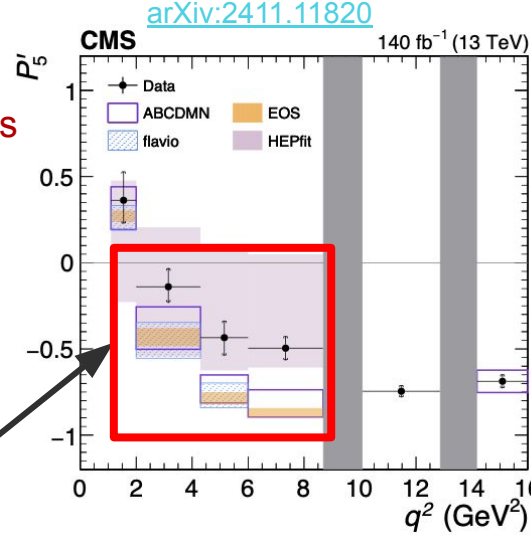
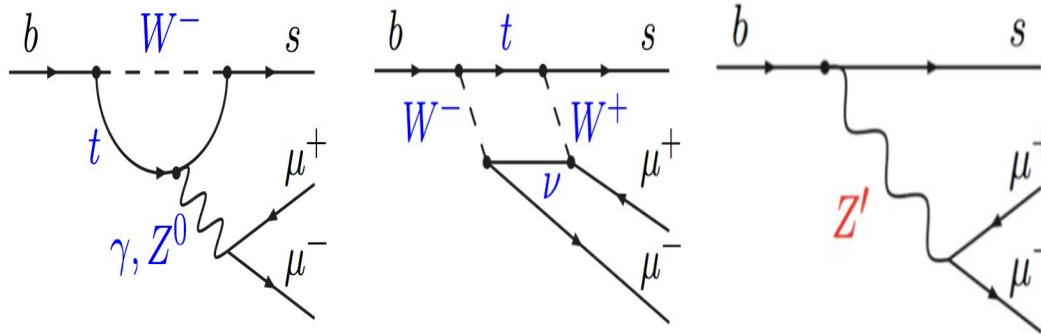
Flavour Anomalies $b \rightarrow s \ell^+ \ell^-$

FCNC process in SM -- $\text{BF} \lesssim 10^{-6}$

- ❑ Highly sensitive to **New Physics**
- ❑ (indirect tests of NP @TeV)
 - SUSY
 - Lepto Quarks
 - Heavy gauge bosons

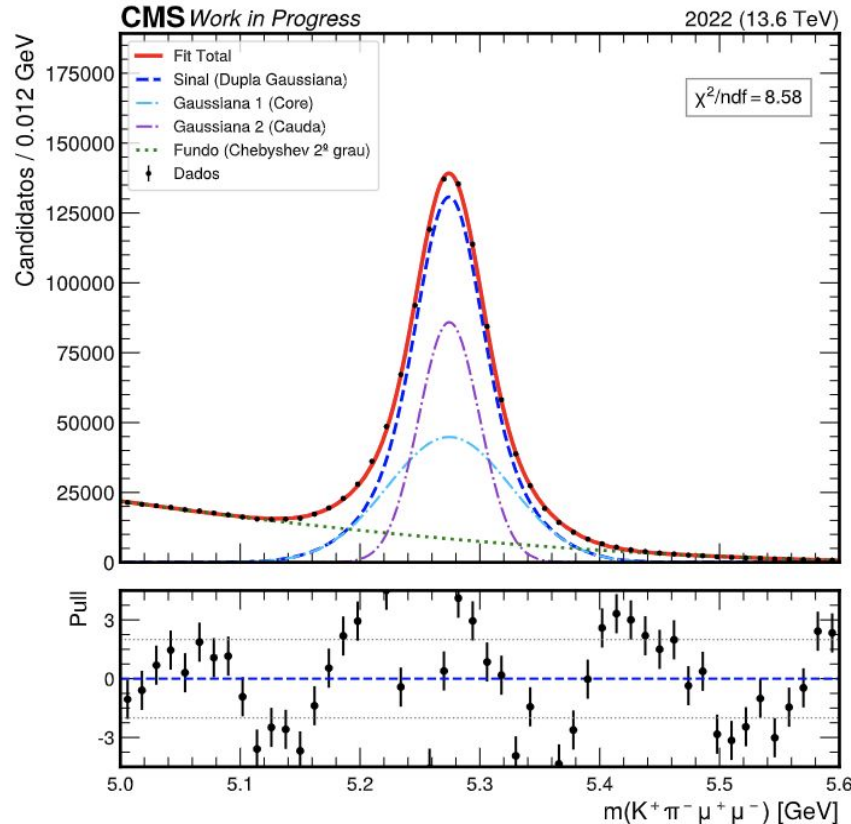
From Feynman Diagrams to the exp. observables:

- ❑ Lepton Flavour Universality test
- ❑ Differential Decay Rate
- ❑ **Angular Observables**



MC Correction: Reweighting Procedure

To compare the data with MC we use the resonant like J/ψ and ψ(2s) channels to take advantage of the higher statistics of these events.



- To ensure a proper comparison with the MC, we applied the **sPlot technique** to the **collision data**, which allows for the **statistical subtraction of the background**.
- The **invariant mass of the final system was used as the discriminating variable** in the fit to calculate the statistical weights (**sWeights**).

$$w_n(x_i) = \frac{\sum_{j=1}^{N_s+N_b} \mathbf{V}_{nj} f_j(x_i)}{\sum_{j=1}^{N_s+N_b} N_j f_j(x_i)}$$

- $f_j(x_i)$ is the PDF value of component j for event i .
- N_j is the number of events of component j obtained in the fit.
- $\mathbf{V}_{nj}$ is the **inverse covariance matrix** of the yields obtained in the likelihood fit.

MC Correction: Reweighting Procedure

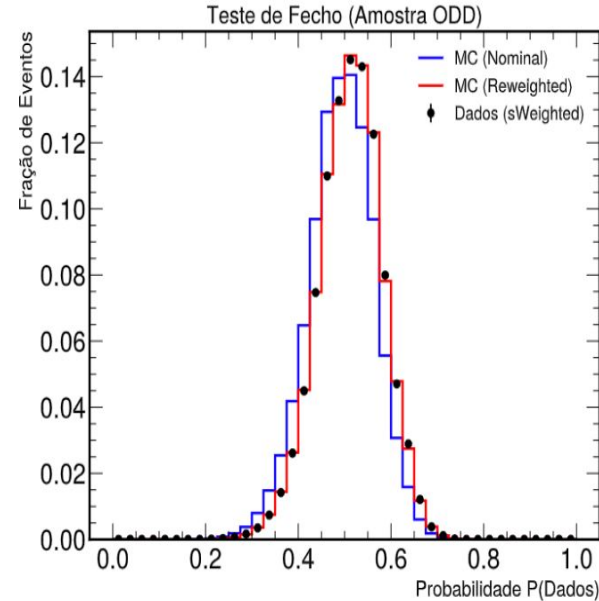
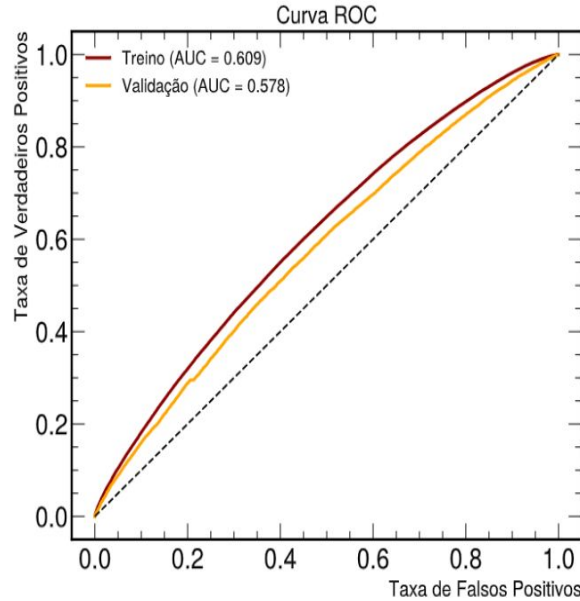
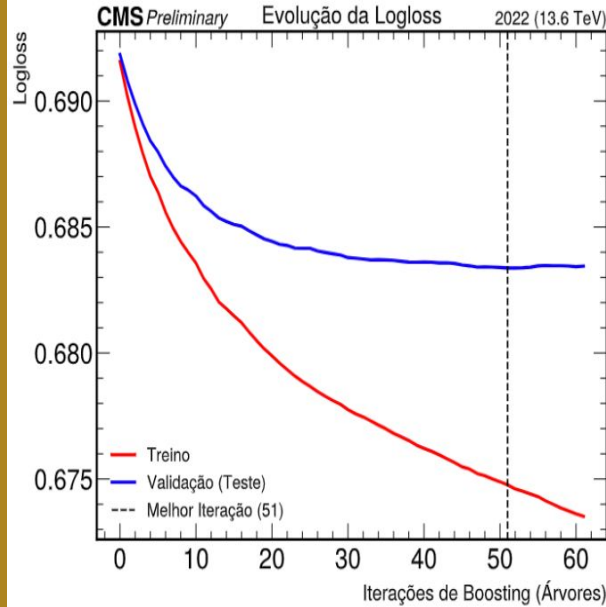
A reweighting technique using the XGBoost Classifier is employed to address discrepancies between data and MC simulation. The classifier is trained to distinguish between data and MC signal distributions, providing event probabilities for both. The ratio of these probabilities approximates the density ratio for reweighting.

$$w(x) = \frac{f_{data}(x)}{f_{MC}(x)} \sim \frac{p_{data}(x)}{p_{MC}(x)}$$

Variable	Description
$p_T(\mu_1)$ [GeV]	p_T of the leading muon
$p_T(\mu_2)$ [GeV]	p_T of the subleading muon
$p_T(trk_1)$ [GeV]	p_T of the leading track
$p_T(trk_2)$ [GeV]	p_T of the subleading track
$\eta(B^0)$	pseudorapidity of the B^0
$\cos \alpha_{2D}$	cosine of the pointing angle between the B^0 momentum and the distance vector from the beamspot to the B^0 vertex, in the transverse plane
DCA (trk_1)	transverse impact parameter of the leading track wrt the beamspot
DCA (trk_2)	transverse impact parameter of the subleading track wrt the beamspot

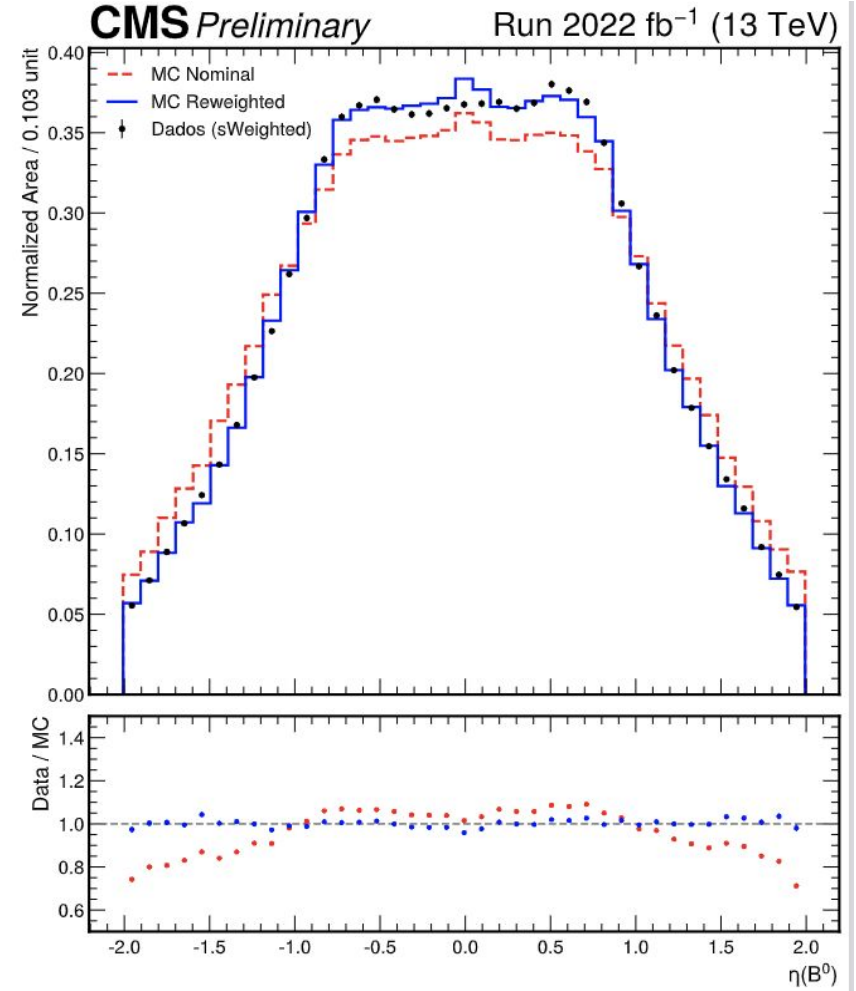
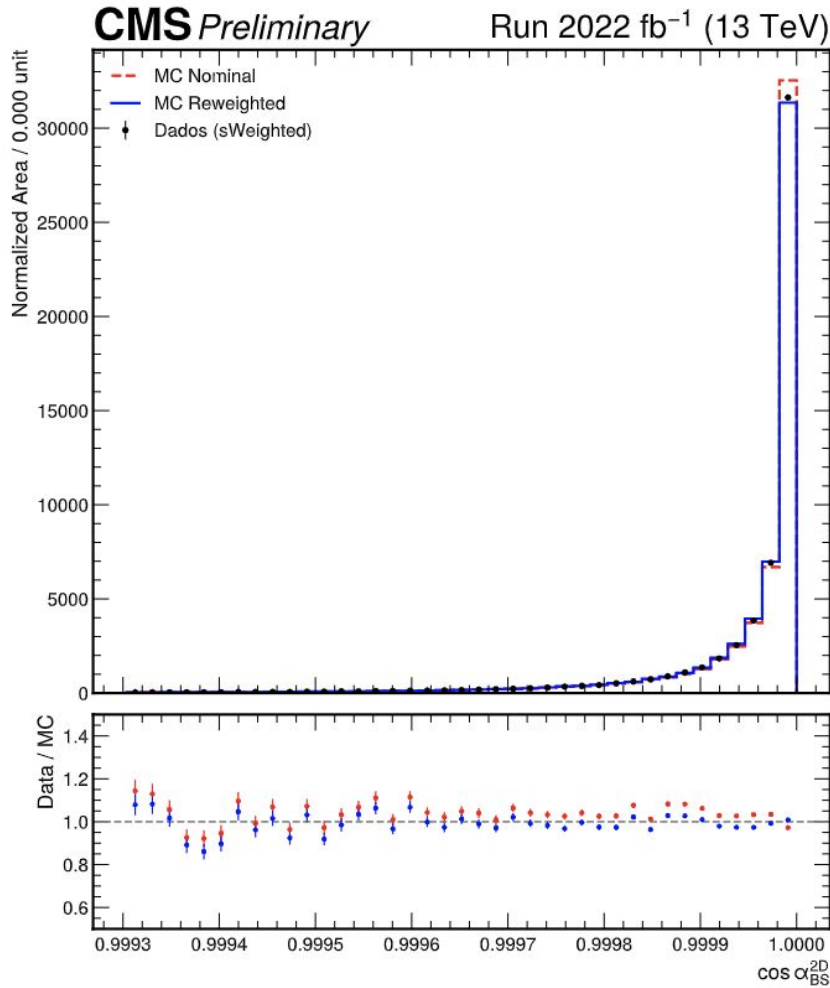
Hyperparameter	Value	Description
objective	'multi:softprob'	Multiclass probability objective function.
num_class	2	Number of target classes.
eval_metric	'mlogloss'	Evaluation metric (multiclass log loss).
learning_rate	0.1	Learning rate (step size shrinkage) to prevent overfitting.
max_depth	7	Maximum depth of the decision trees.
n_estimators	500	Number of boosting rounds (trees to build).
early_stopping_rounds	10	Validation rounds with no improvement to trigger early stopping.
random_state	42	Random seed for reproducibility.
n_jobs	-1	Number of parallel threads used to run XGBoost (all available).

MC Correction: Reweighting Procedure

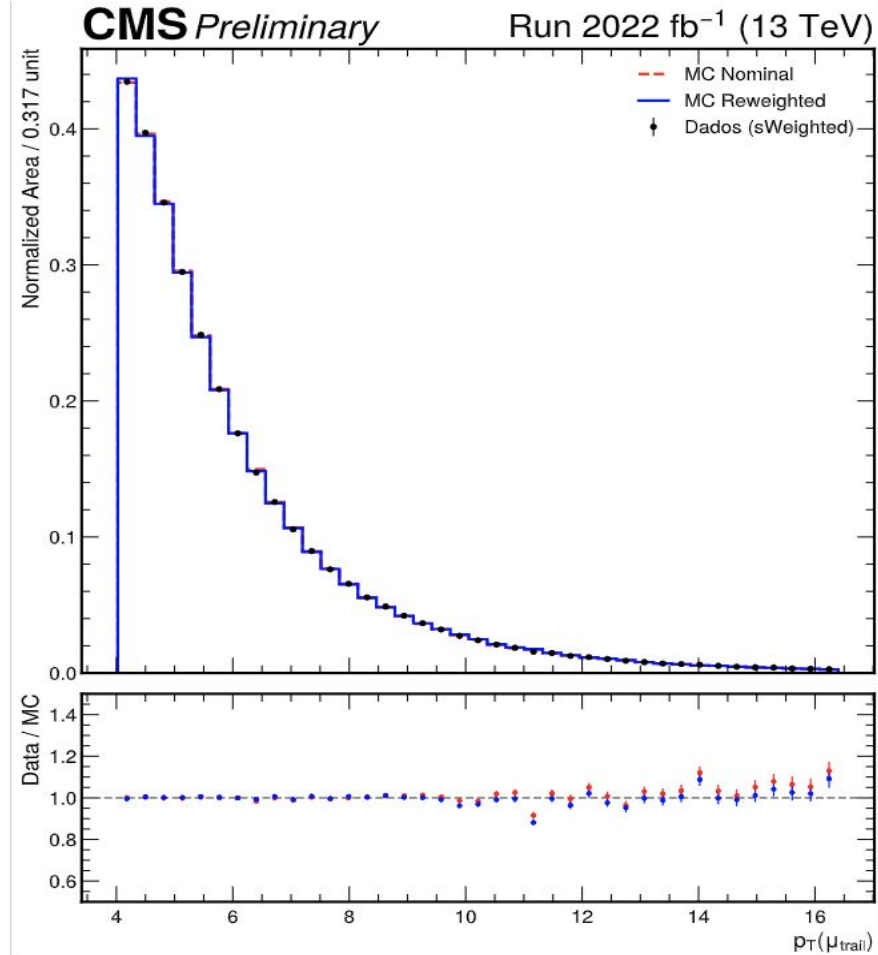
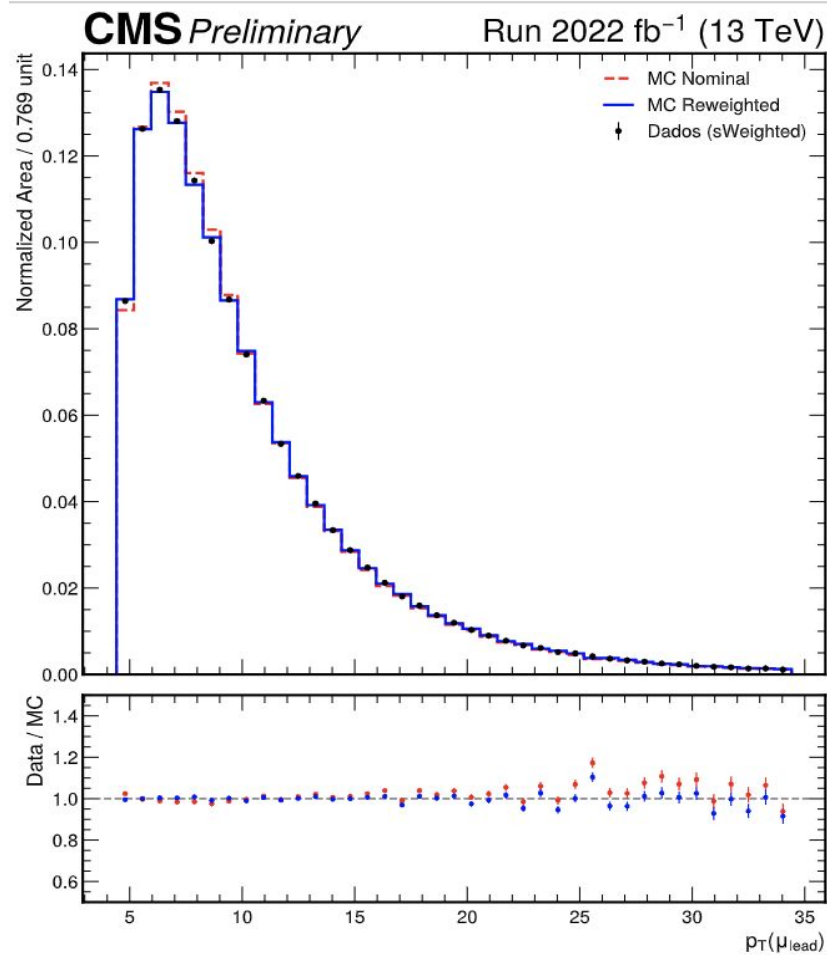


- ❑ In these plots, we can see that both the LogLoss and the ROC AUC score exhibit the expected behavior for a successful reweighting procedure.
- ❑ The AUC is close to 0.6, and the BDT probability output is heavily centered around 0.5.

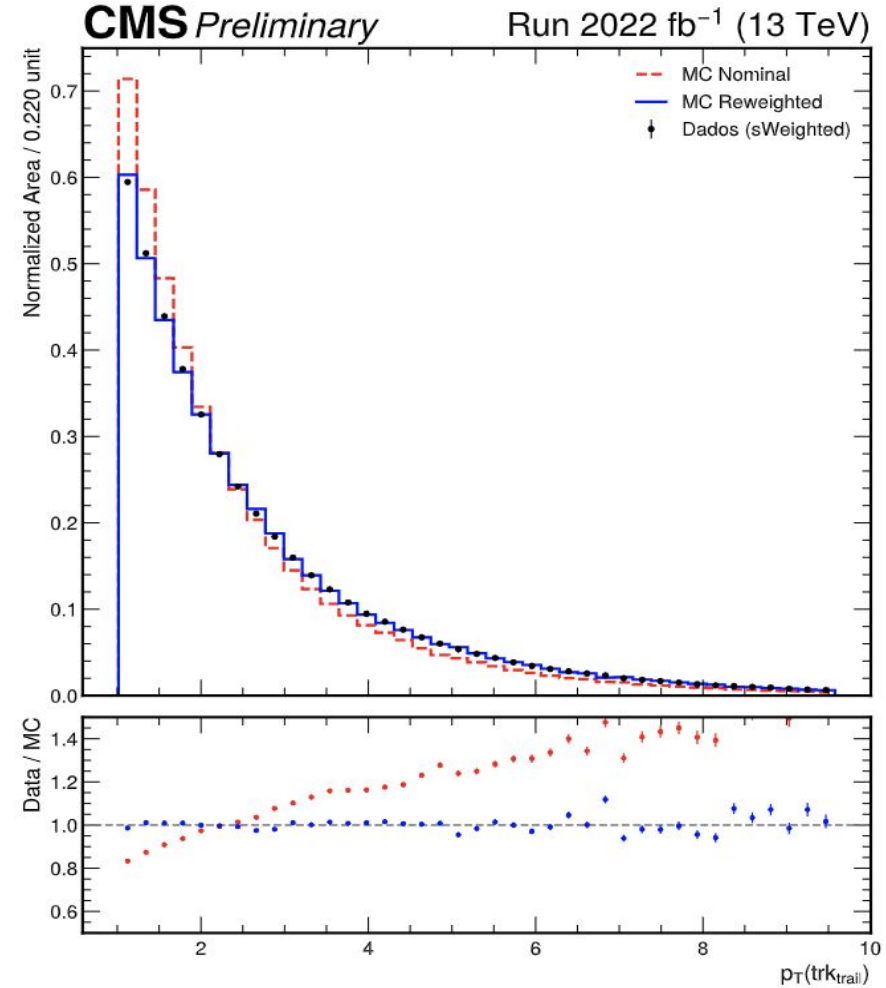
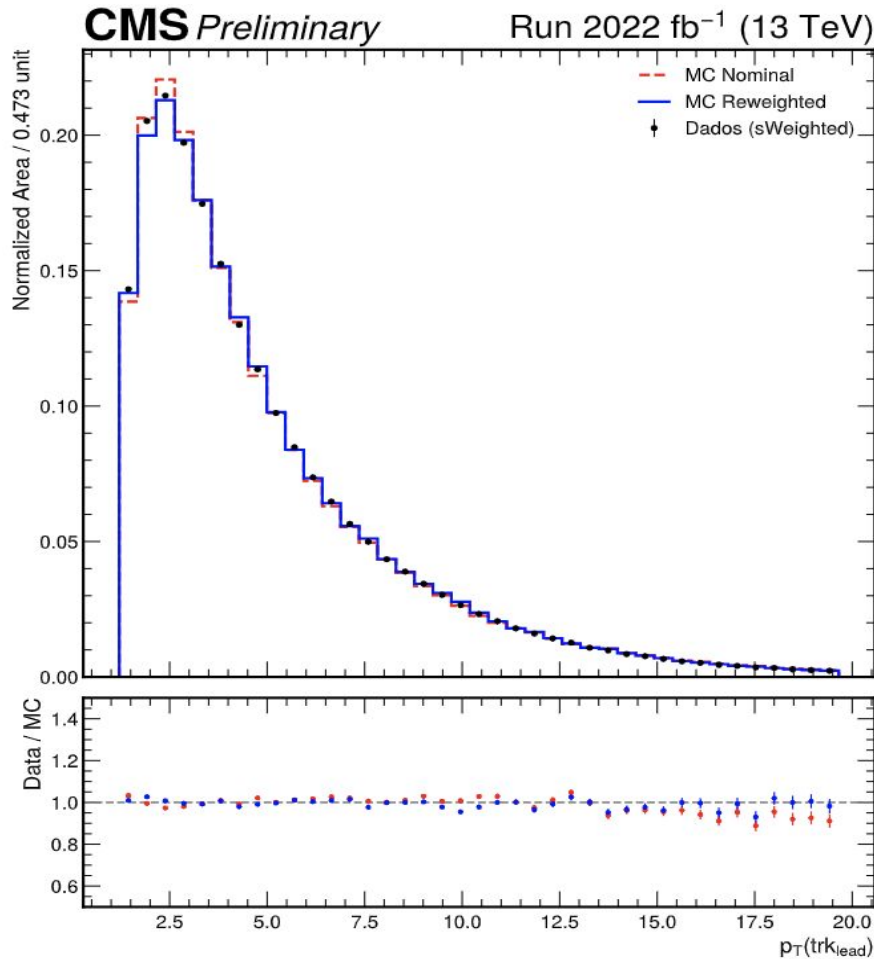
MC Correction: Reweighting Procedure



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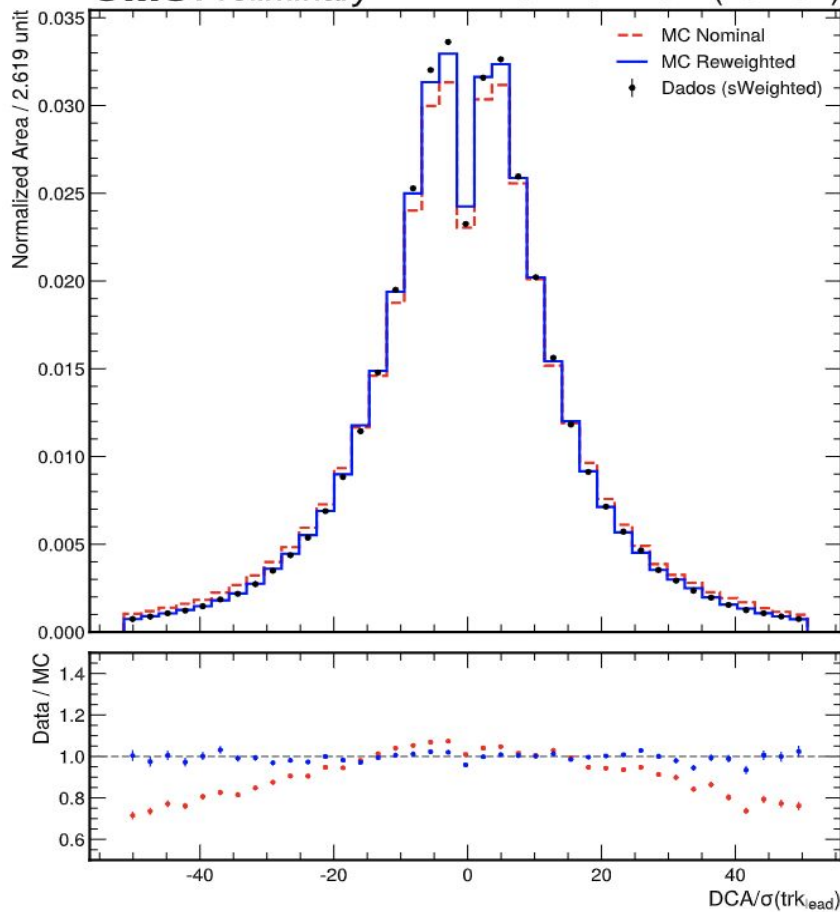


MC Correction: Reweighting Procedure



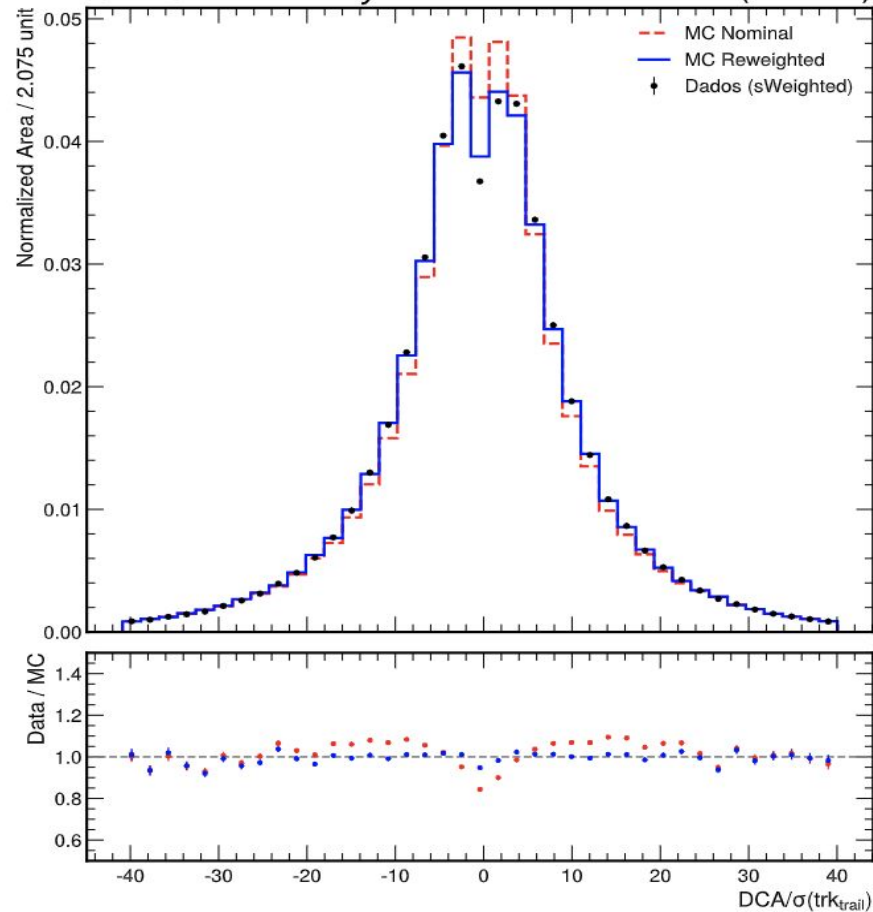
CMS Preliminary

Run 2022 fb⁻¹ (13 TeV)



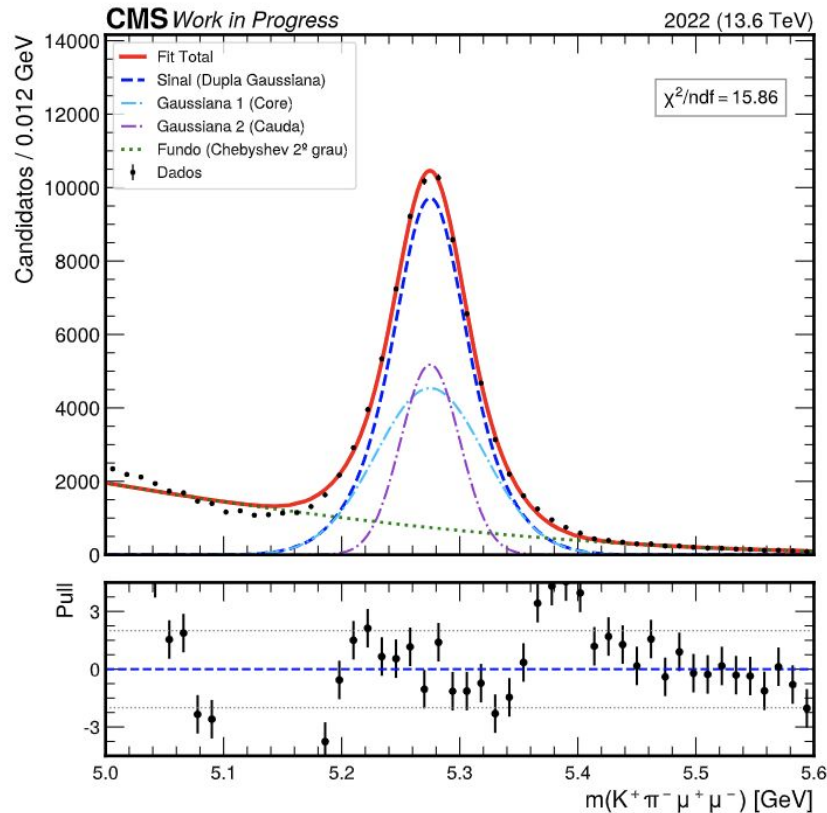
CMS Preliminary

Run 2022 fb⁻¹ (13 TeV)



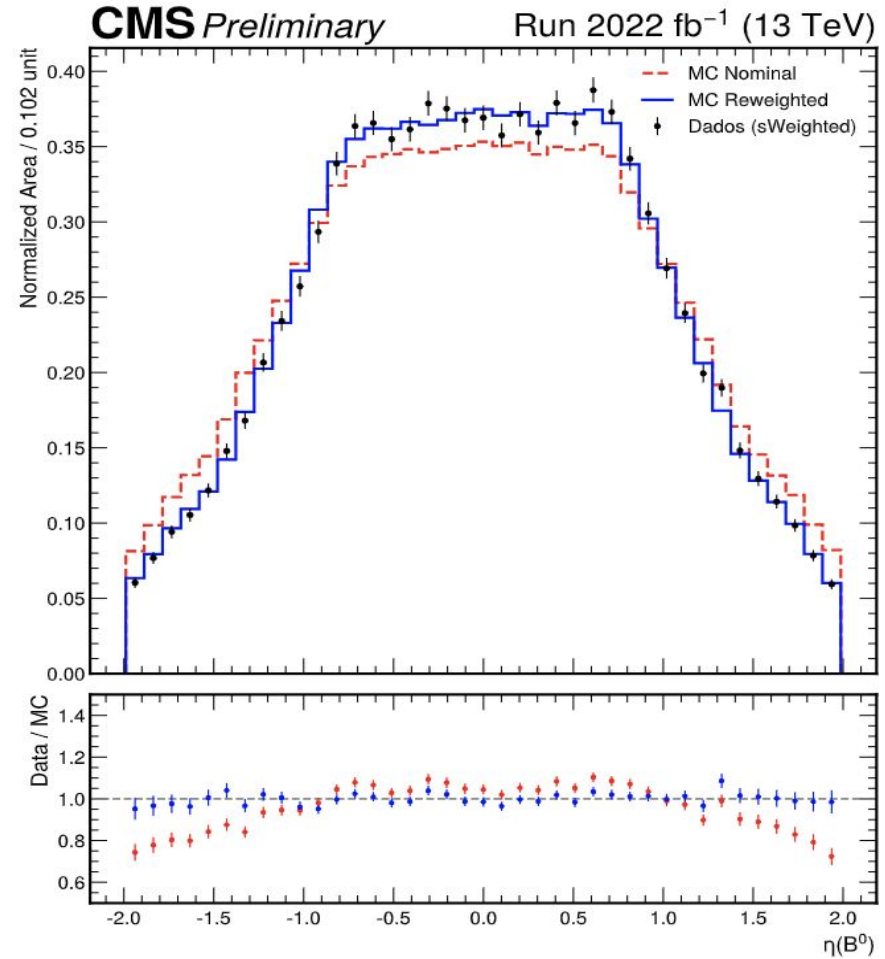
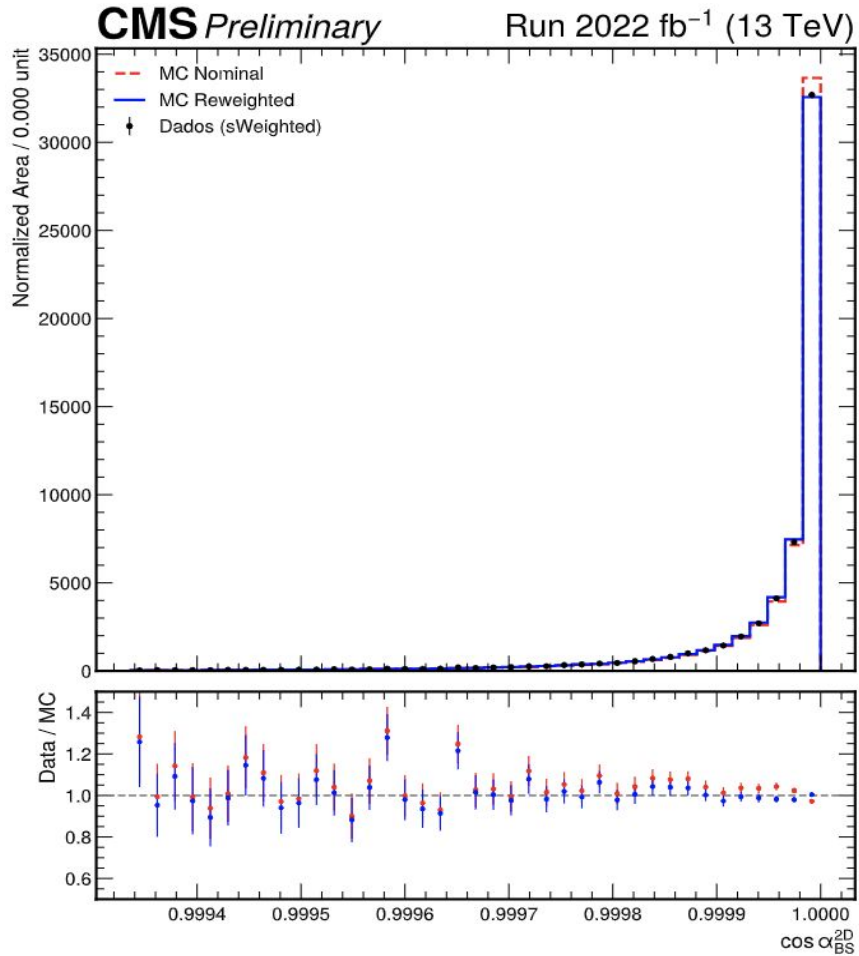
MC Correction: Closure Procedure

In order to test the model trained in the J/ψ channel we will use this trained model in the $\psi(2S)$ channel as a closure test to check if the model is really correcting the simulation properly.

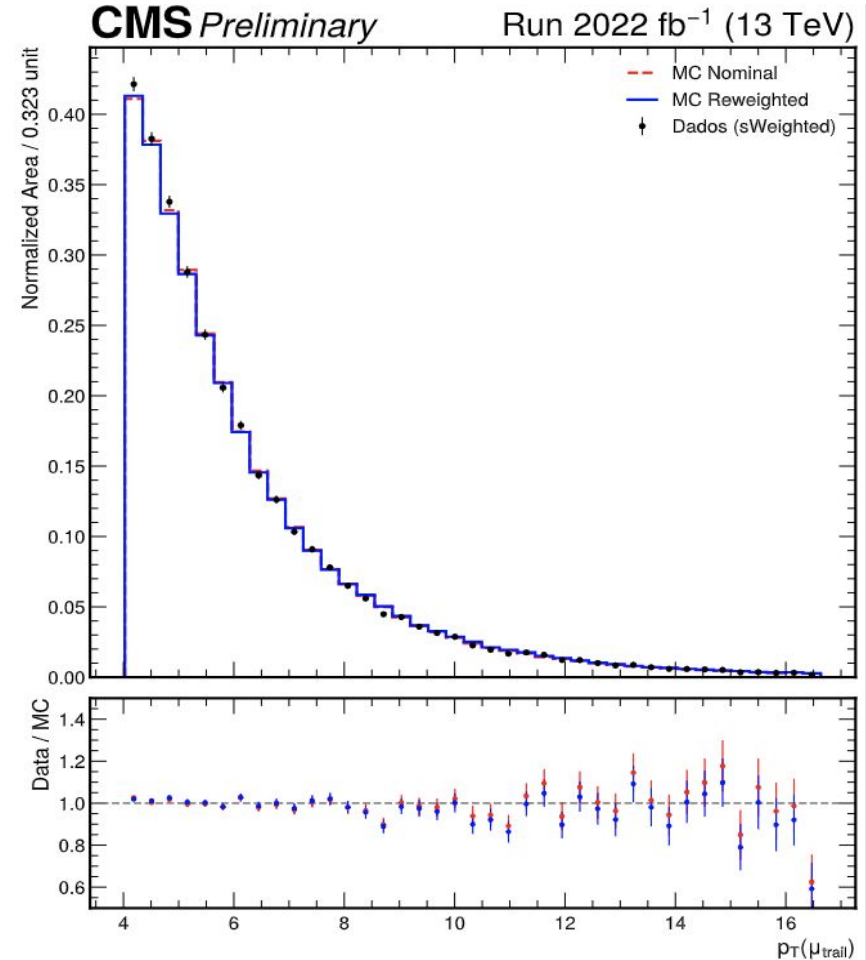
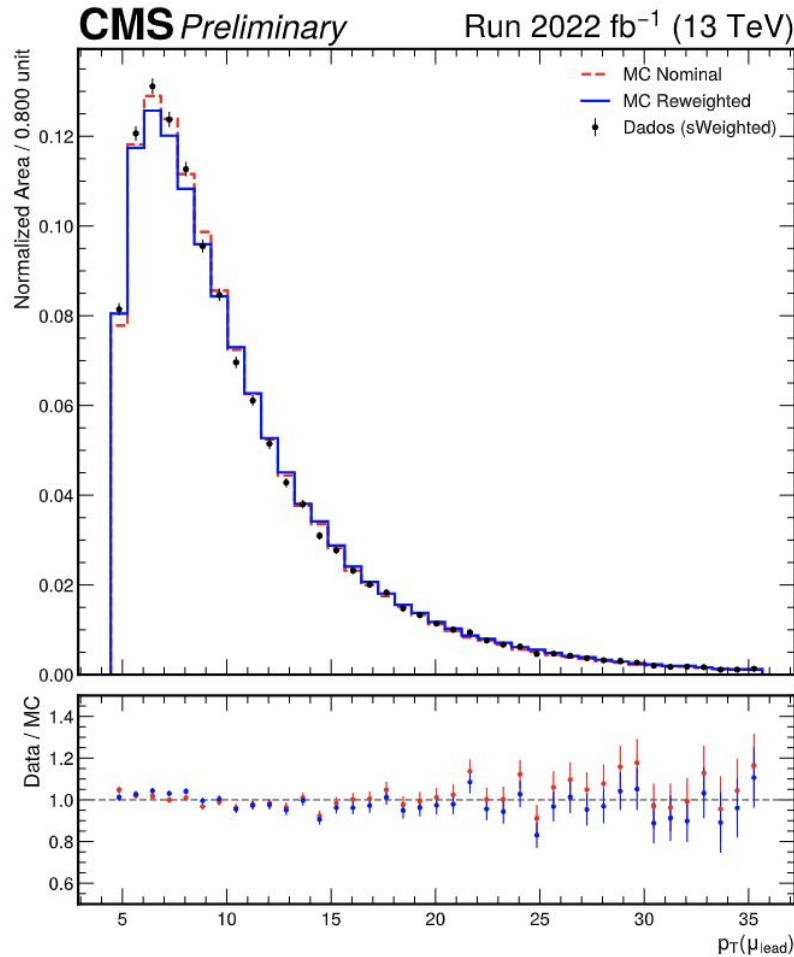


- ❑ Application of the weights generated by the BDT (trained on the J/ψ) directly to the $B^0 \rightarrow \psi(2S)K^{*0}$ control channel sample.
- ❑ Use of the **sPlot technique on the data** to isolate the pure kinematics of the $\psi(2S)$ decay.
- ❑ With the weights produced by the BDT model we compare to the data as seen in the next slides:
- ❑ the **fit range is still preliminary** and will be adapted to reduce the contamination from partially-reconstructed background

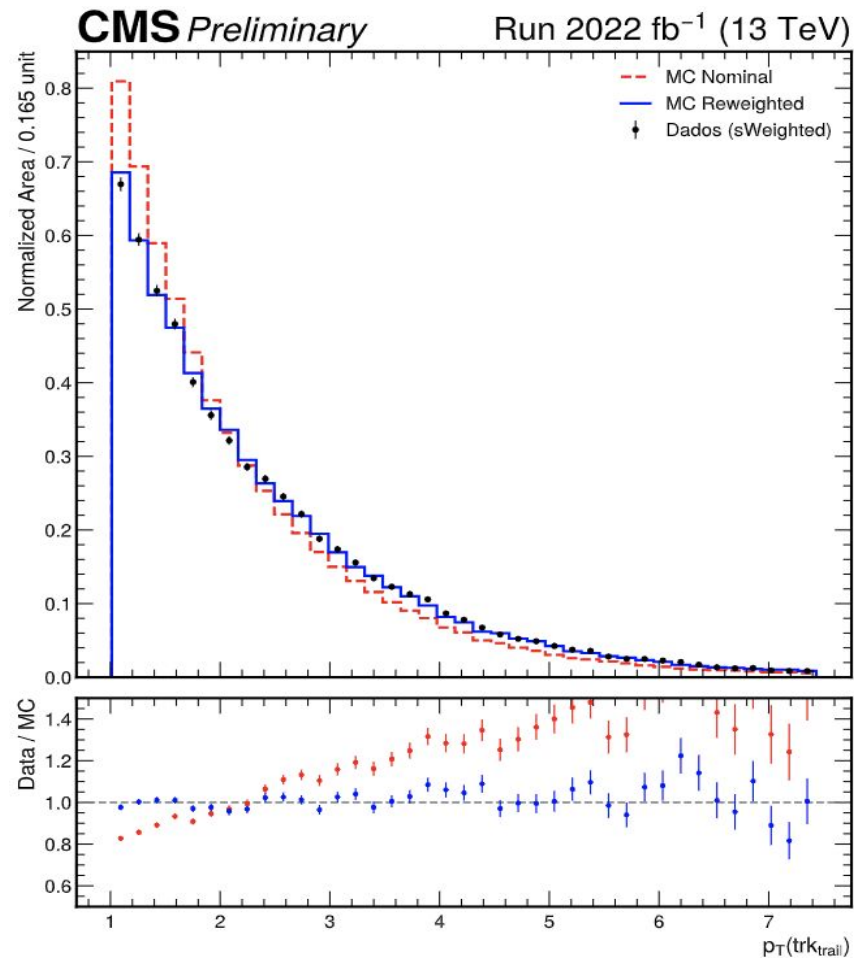
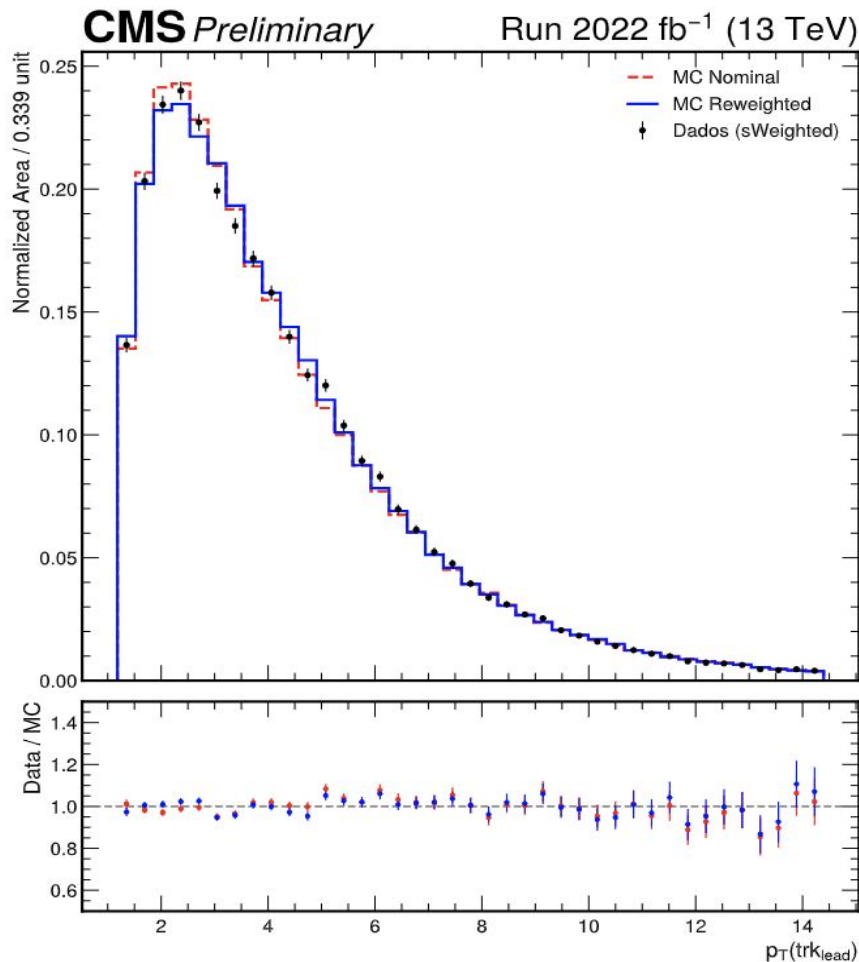
MC Correction: Closure Procedure



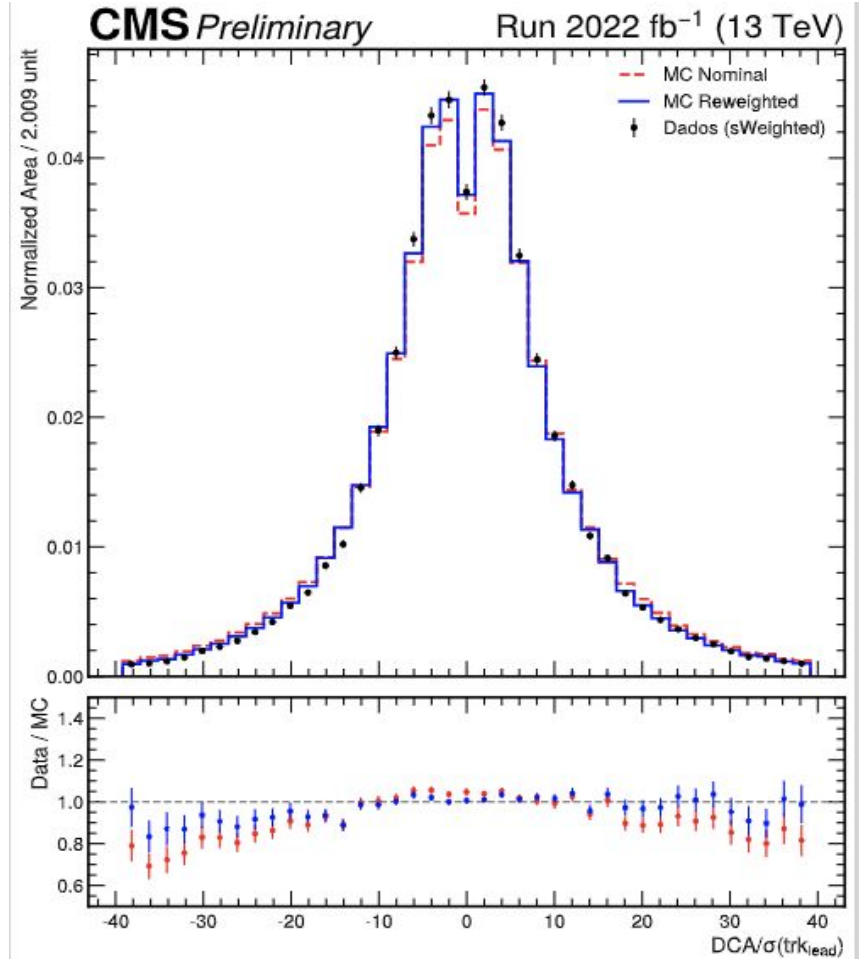
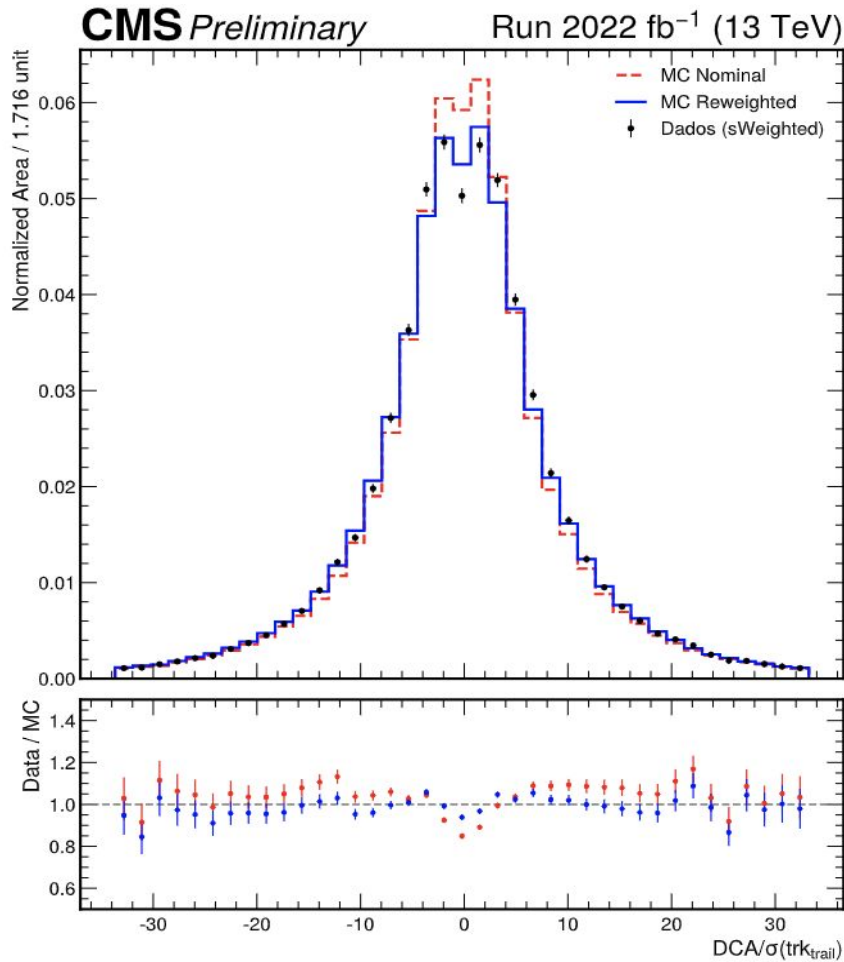
MC Correction: Closure Procedure



MC Correction: Closure Procedure



MC Correction: Closure Procedure



Feed-Through from resonant channels

Run 2

The value of Δm is tuned independently for the three dimuon mass regions: below the J/ψ (bin 3), between the J/ψ and the $\psi(2S)$ (bin 5), and above the $\psi(2S)$ (bin 7) [for the binning definition, see Tab. 1]. The optimisation criteria is the reduction of the feed-through from the control channels to a negligible level, below X% of the total background on data within the mass window defined by $|m(K^\pm \pi^\mp \mu^+ \mu^-) - m_{B_0}^{PDG}| < 0.28 \text{ GeV}$, where X is defined as:

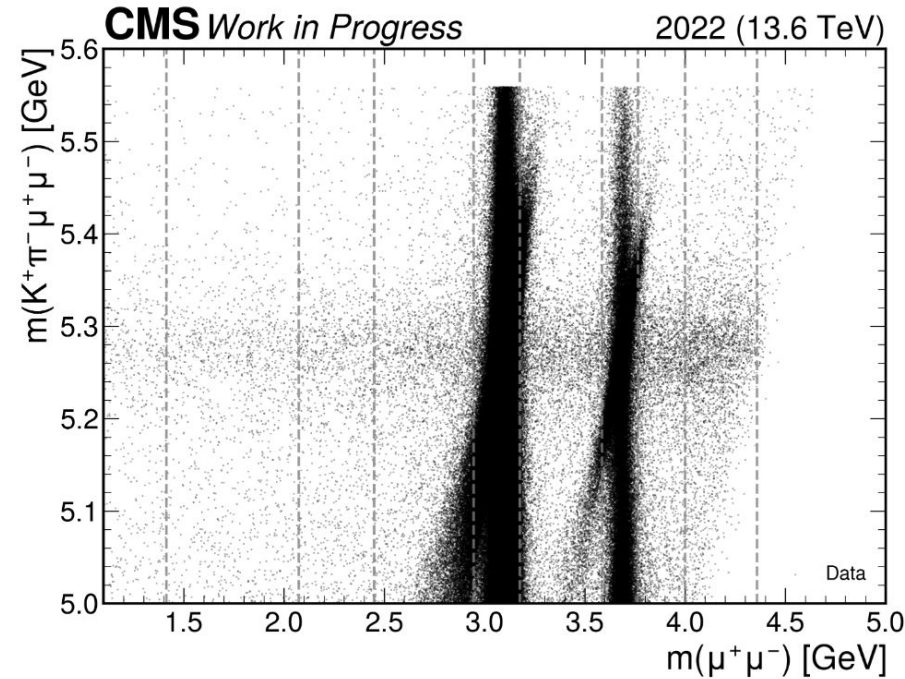
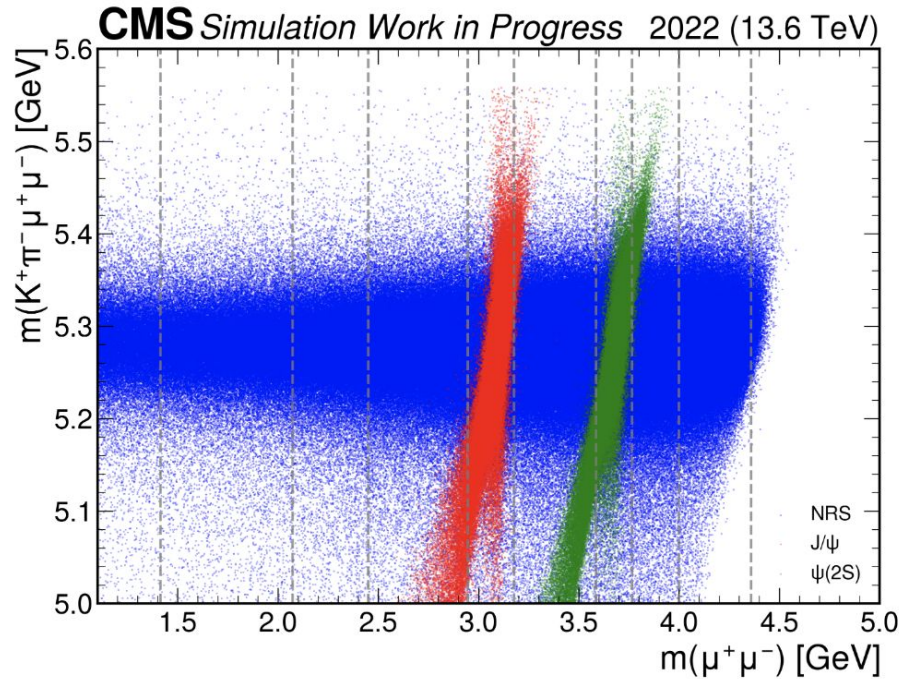
- 5% for each of the two resonant channels for bin 3 and 5,
- 1% for the sum of the two channels for bin 7.

The background from the control channels (B_{peak}) and the overall background (B_{tot}) are evaluated as:

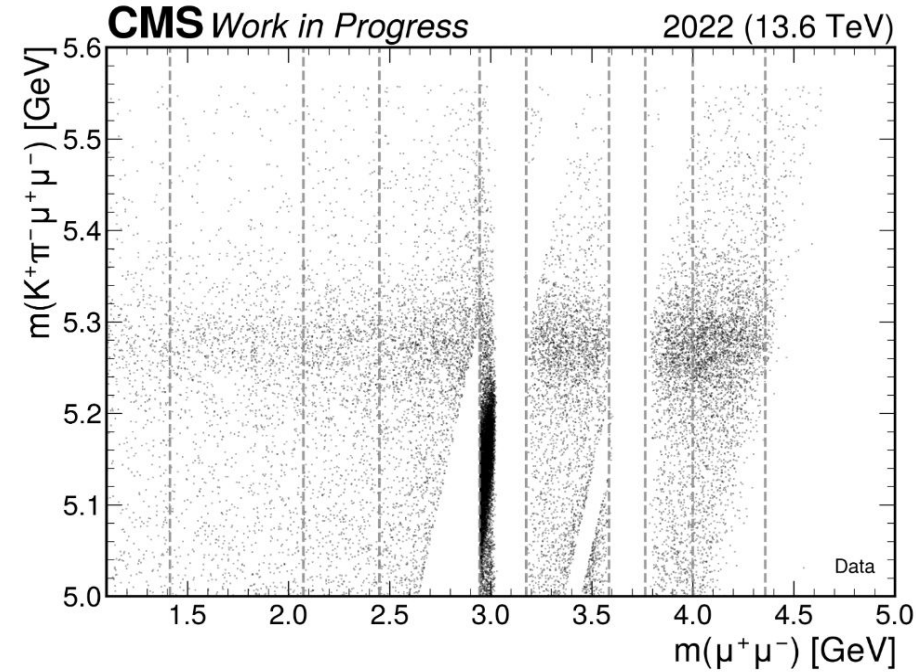
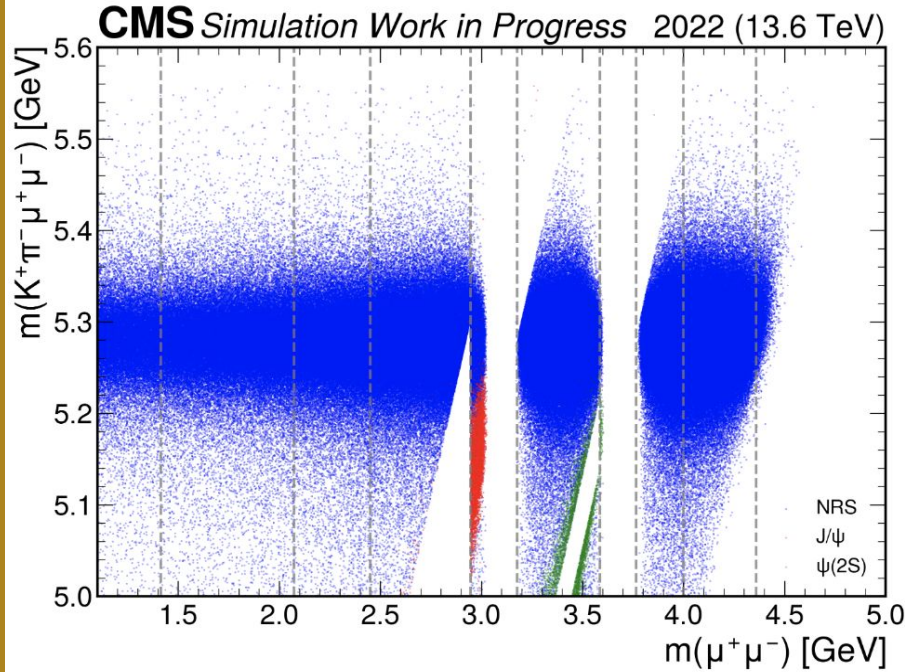
- B_{peak} : number of feed-through events from the control channel simulations;
- B_{tot} : number of events in the data minus the number of events from signal (non-resonant) simulation.

Simulated events are truth matched and their number is rescaled by the ratio between data and simulation integrated luminosities, multiplied by the correction factor mentioned in Sec. 4.1.3. The distributions of $|(m(K\pi\mu\mu) - m_{B_0}^{PDG}) - (m(\mu\mu) - m_\psi^{PDG})|$ for signal and control channel simulations in bin 3, 5 and 7 are shown in Fig. 19.

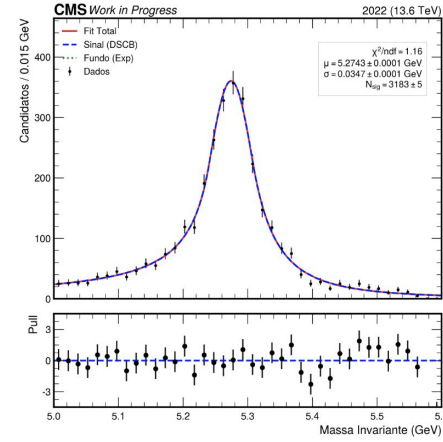
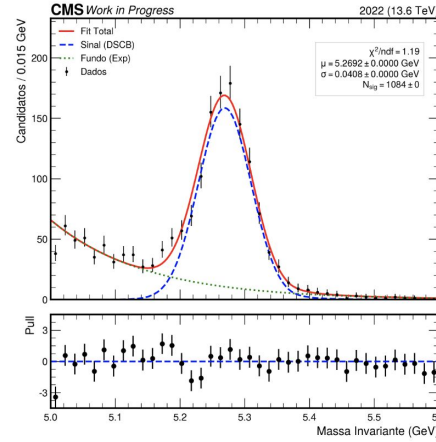
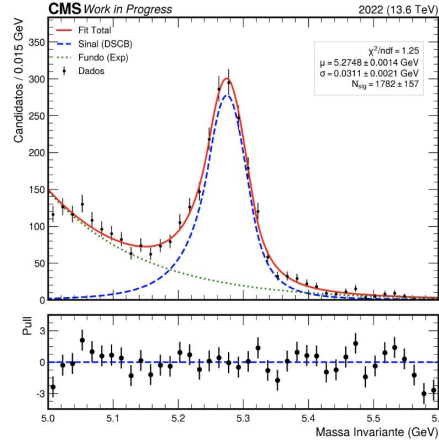
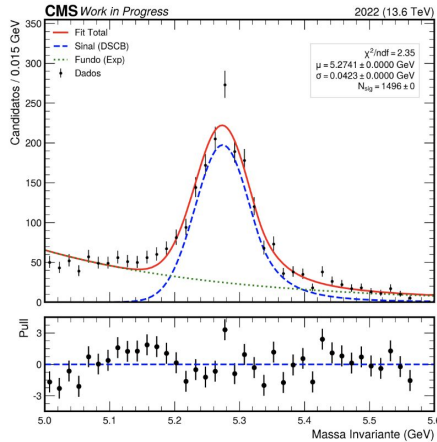
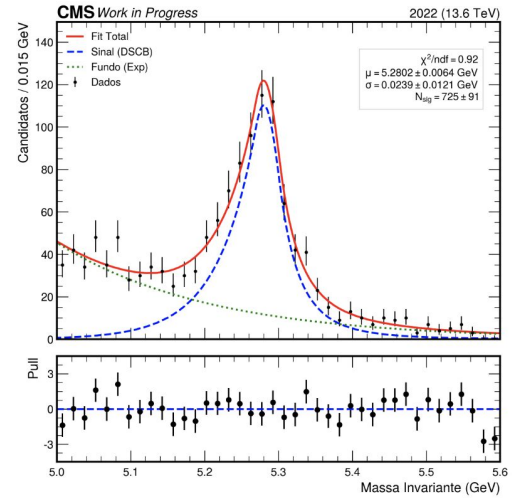
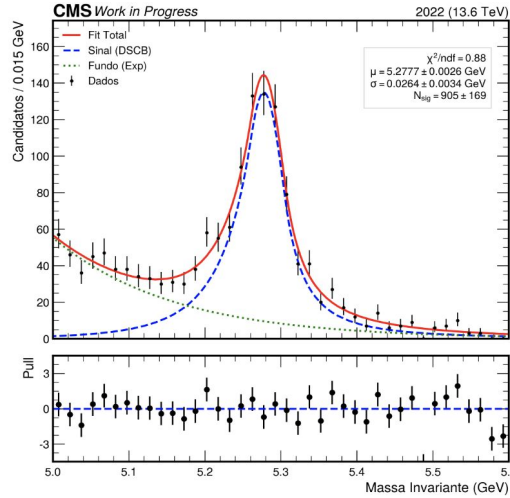
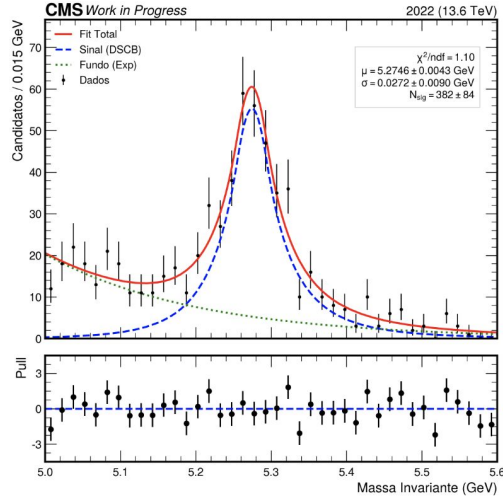
Feed-Through from resonant channels



Feed-Through from resonant channels

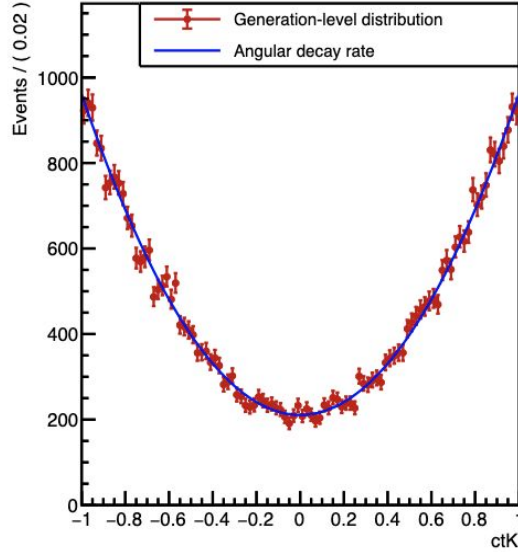


Feed-Through from resonant channels

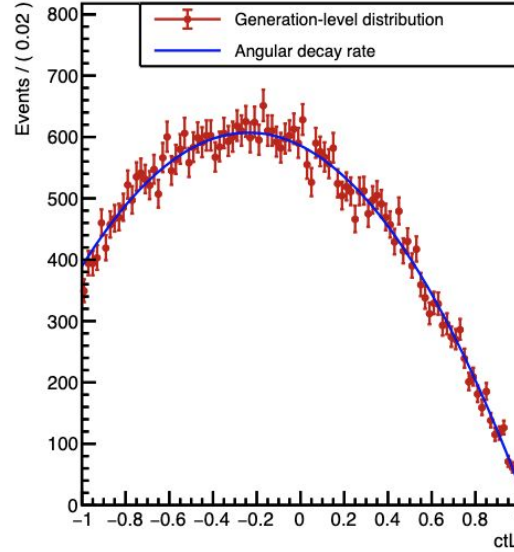


UML-Fit at Generator Level

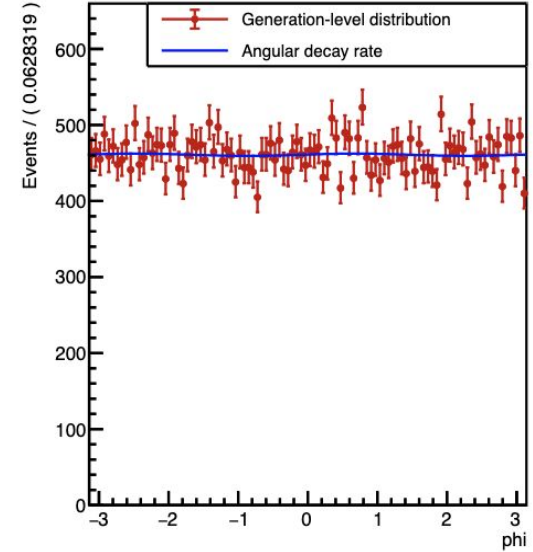
Fit to generation-level distributions (q2-bin 0 odd)



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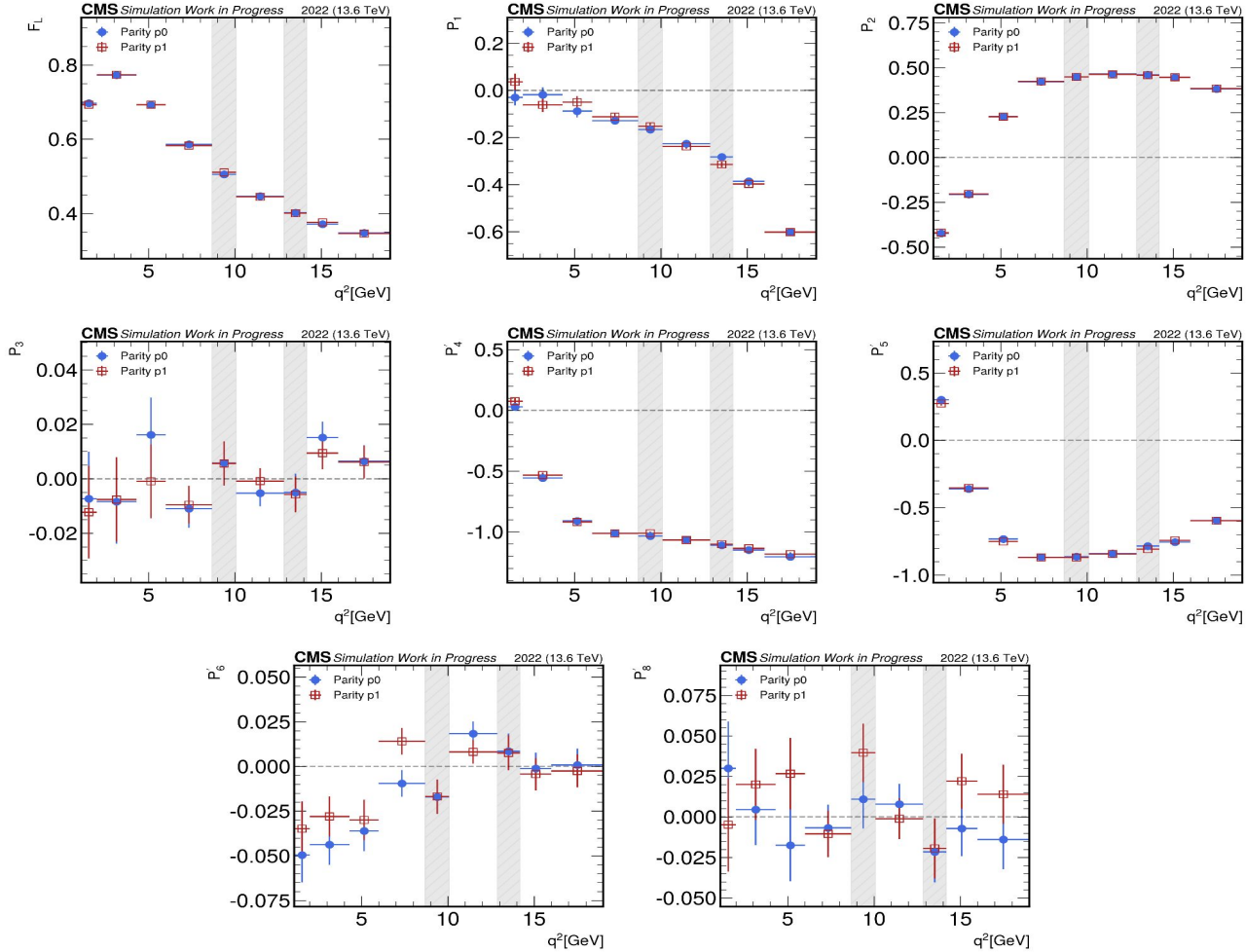


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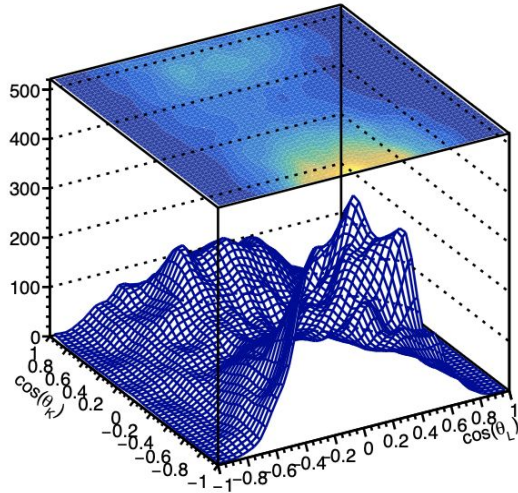
$$\begin{aligned} \text{pdf}(m, \cos \theta_K, \cos \theta_l, \phi) = & Y_S \left[S^C(m) S^a(\cos \theta_K, \cos \theta_l, \phi) \epsilon^C(\cos \theta_K, \cos \theta_l, \phi) \right. \\ & + R \cdot S^M(m) S^a(-\cos \theta_K, -\cos \theta_l, -\phi) \epsilon^M(\cos \theta_K, \cos \theta_l, \phi) \left. \right] \\ & + Y_B B^m(m) B^a(\cos \theta_K, \cos \theta_l, \phi) \end{aligned}$$

UML-Fit at Generator Level

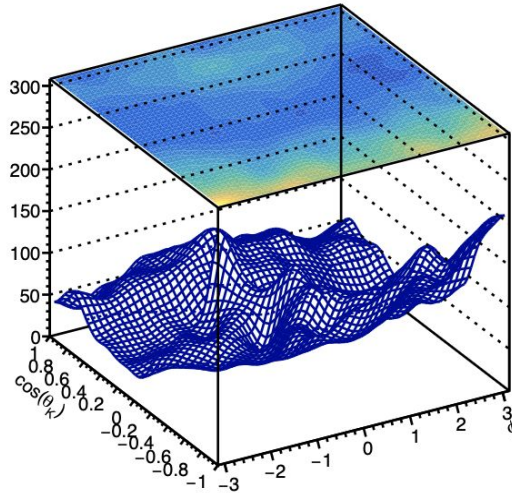


Efficiencies using KDE Method

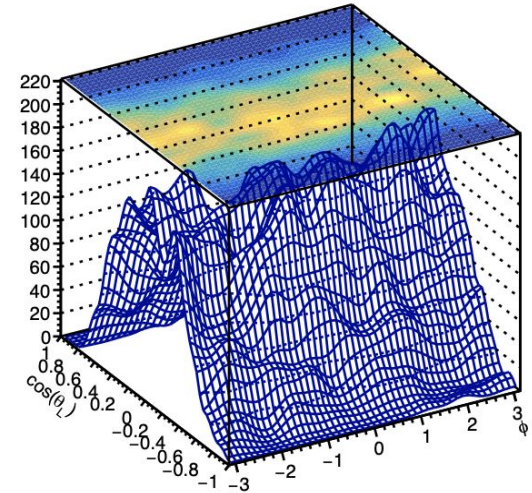
Selected correct-tag distribution - q2 bin 0 (even) w0-0.50_w1-0.50_w2-0.50_50_50



Selected correct-tag distribution - q2 bin 0 (even) w0-0.50_w1-0.50_w2-0.50_50_50

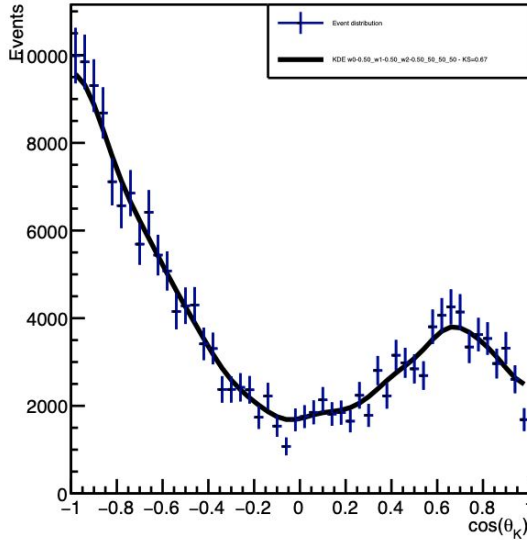


Selected correct-tag distribution - q2 bin 0 (even) w0-0.50_w1-0.50_w2-0.50_50_50

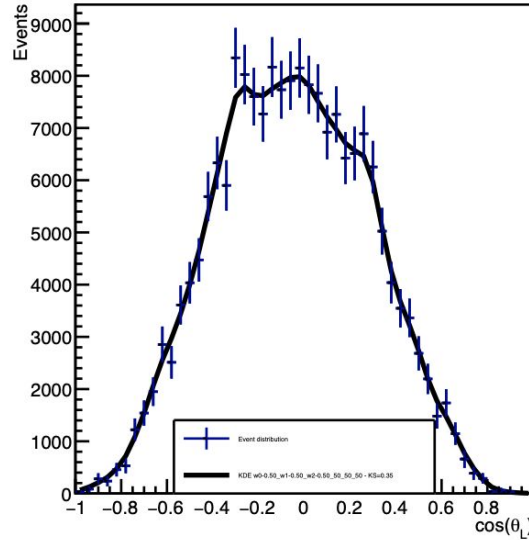


Efficiencies using KDE Method

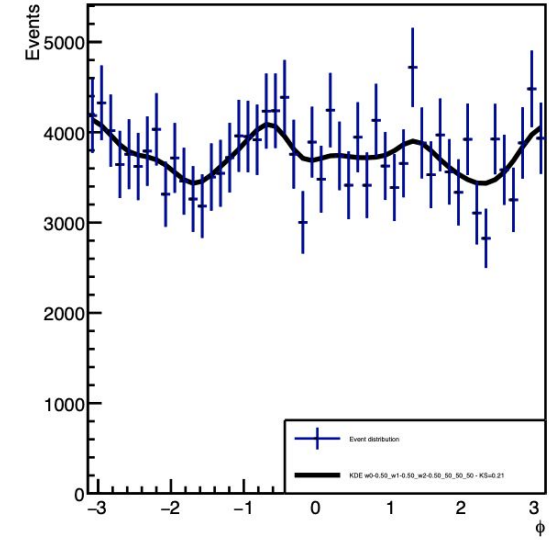
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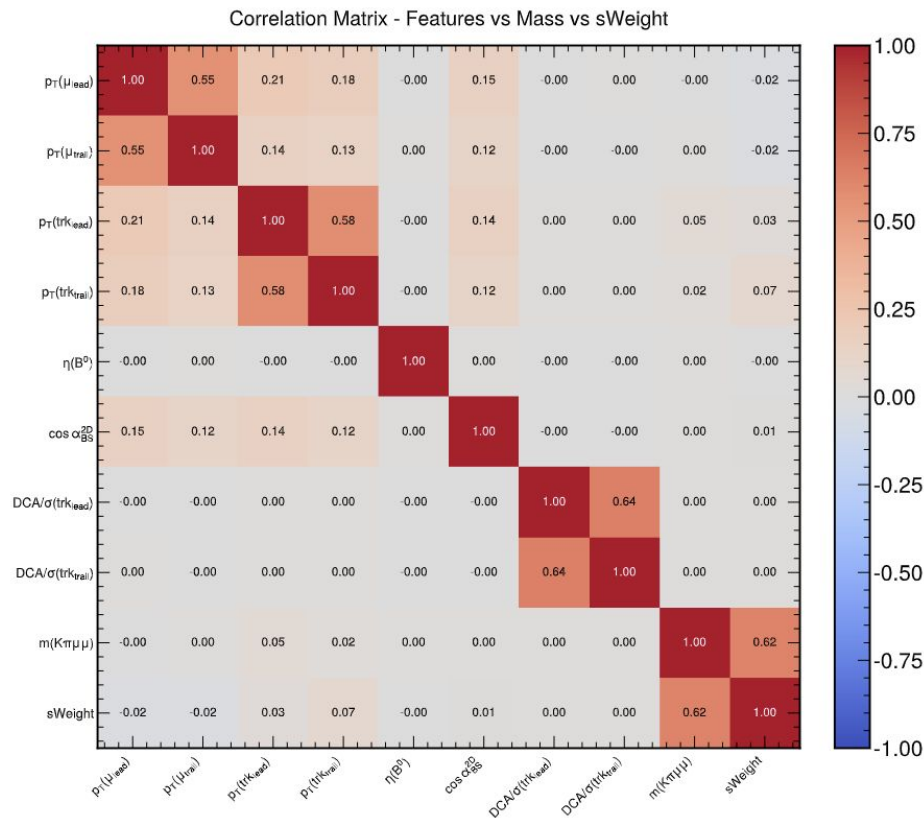
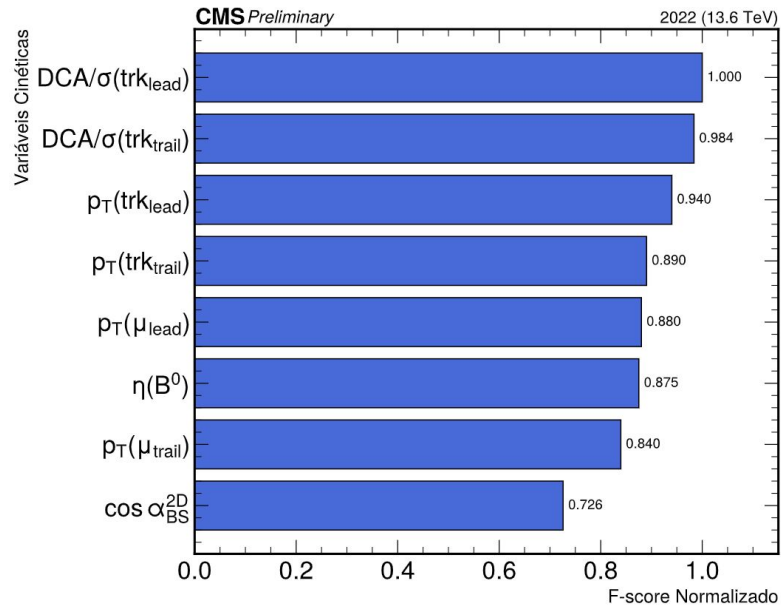


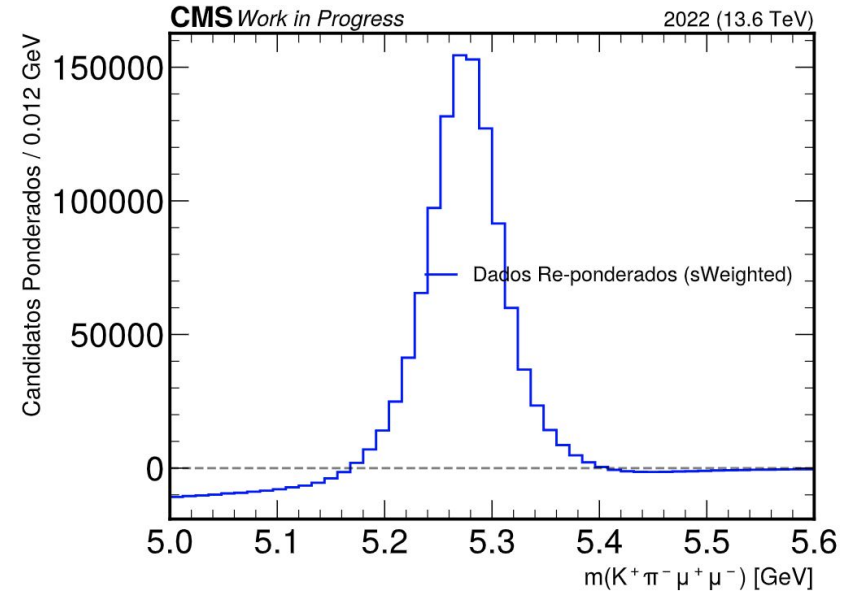
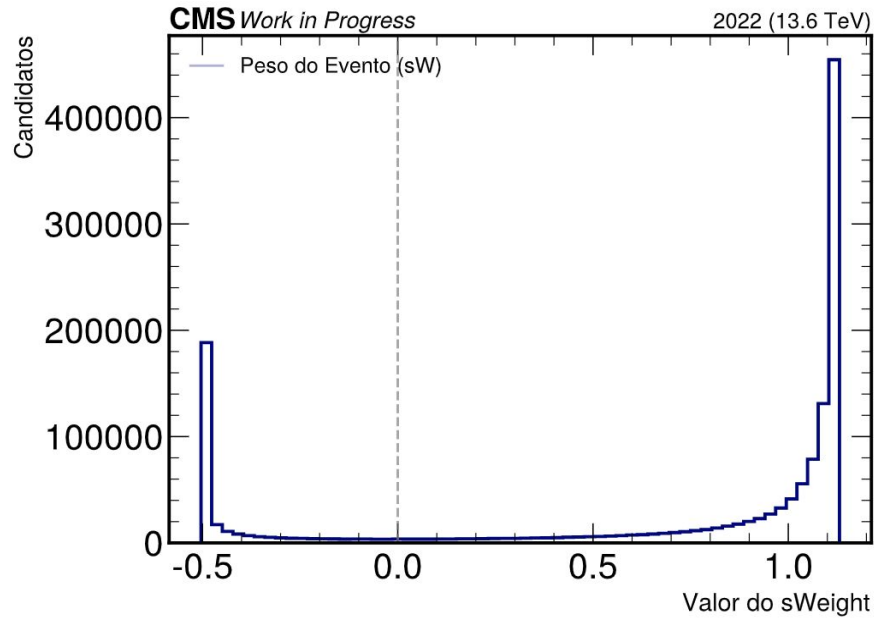
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 & + R \cdot S^M(m) S^a(-\cos \theta_K, -\cos \theta_l, -\phi) \epsilon^M(\cos \theta_K, \cos \theta_l, \phi) \\
 & \left. + Y_B B^m(m) B^a(\cos \theta_K, \cos \theta_l, \phi) \right]
 \end{aligned}$$



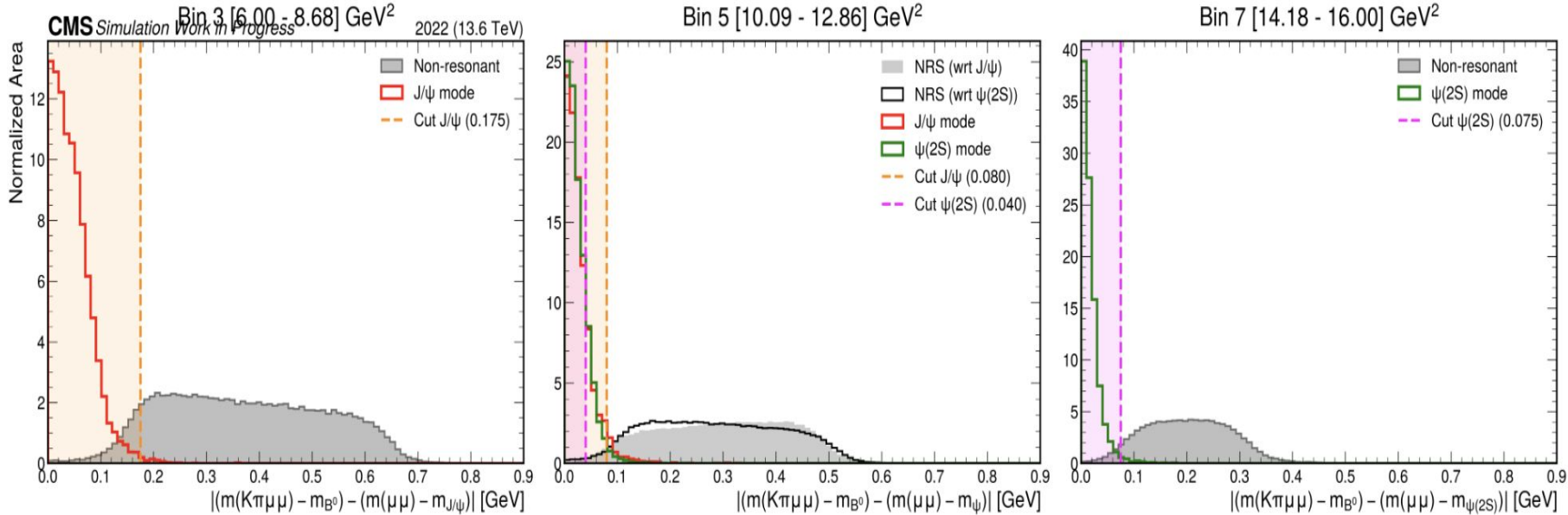
Backup Slides

Backup



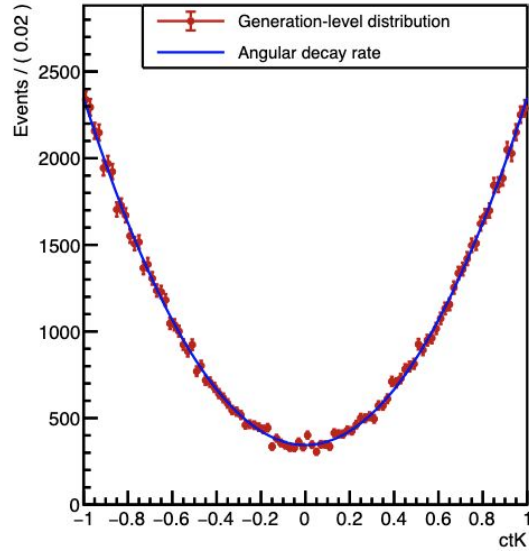


Feed-Through from resonant channels

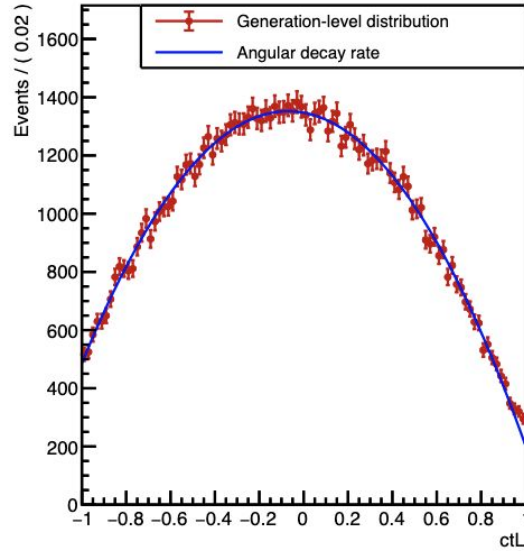


UML-Fit at Generator Level

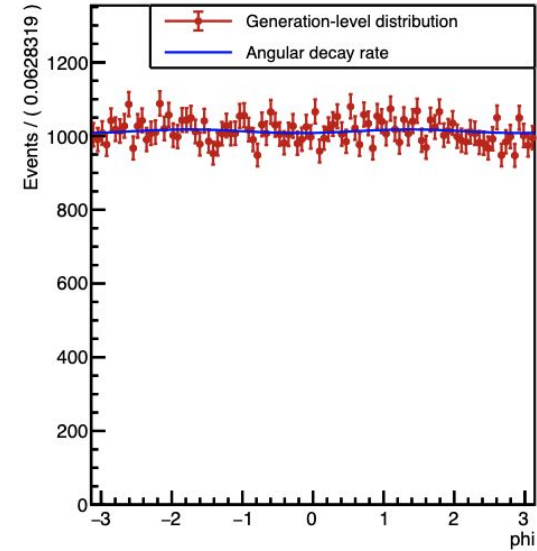
Fit to generation-level distributions (q2-bin 1 odd)



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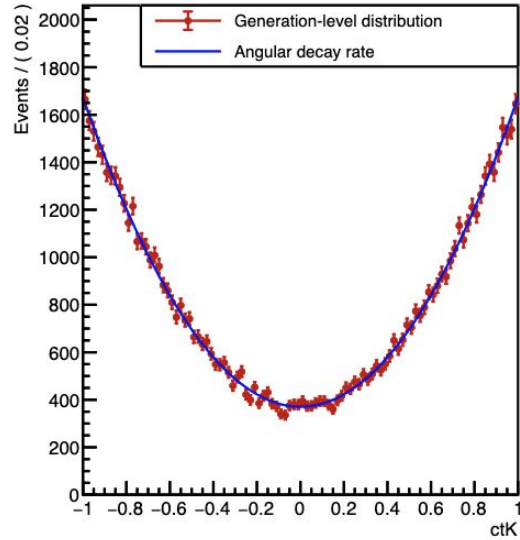


Fit to generation-level distributions (q2-bin 1 odd)

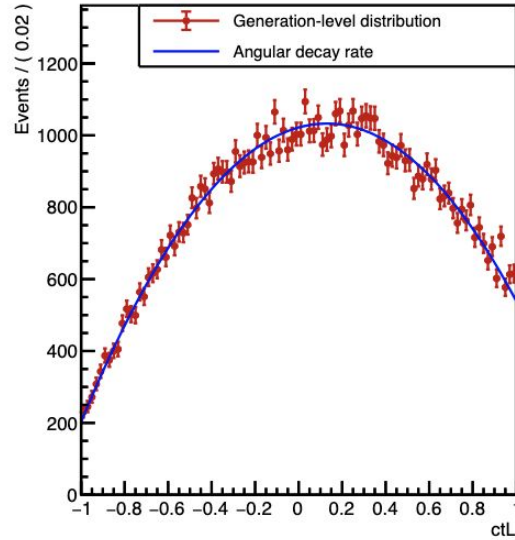


UML-Fit at Generator Level

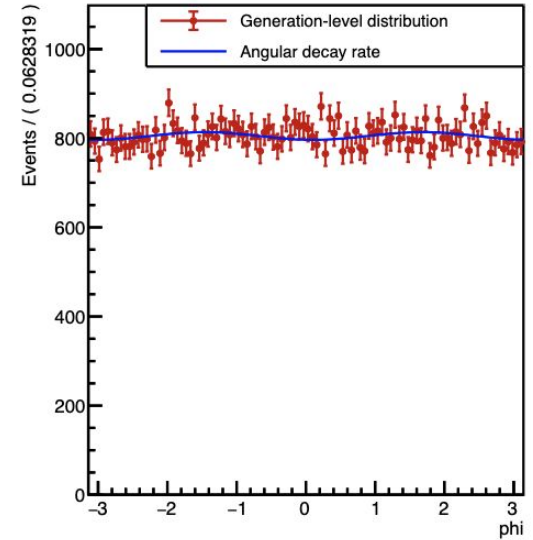
Fit to generation-level distributions (q2-bin 2 odd)



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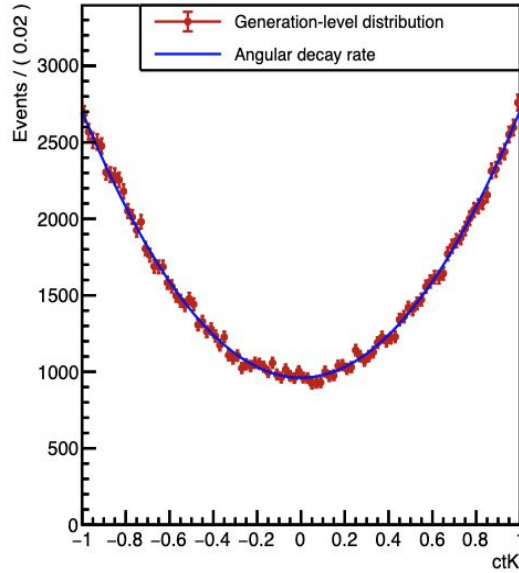


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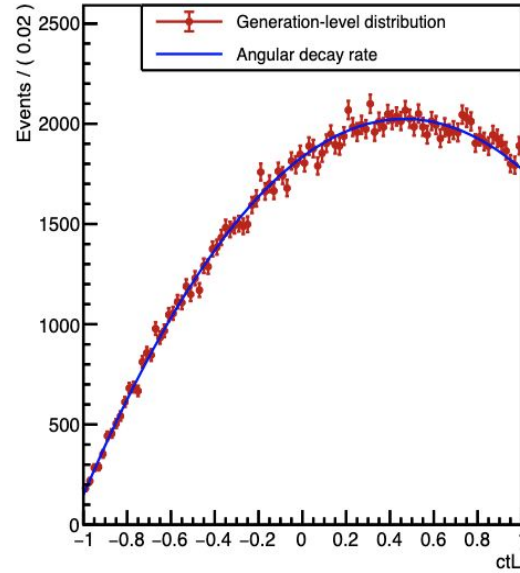


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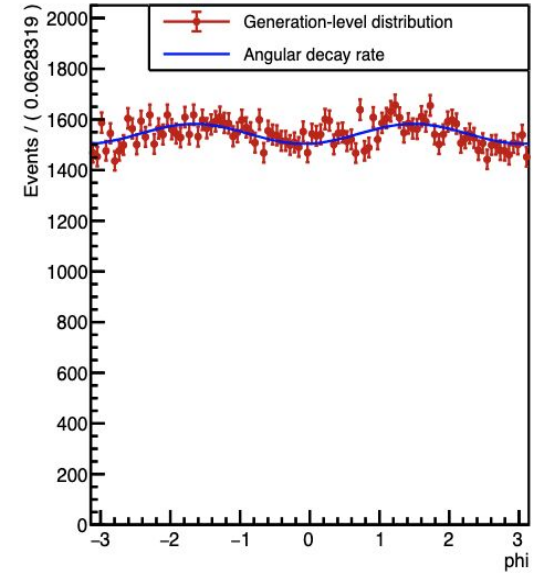
Fit to generation-level distributions (q2-bin 3 odd)



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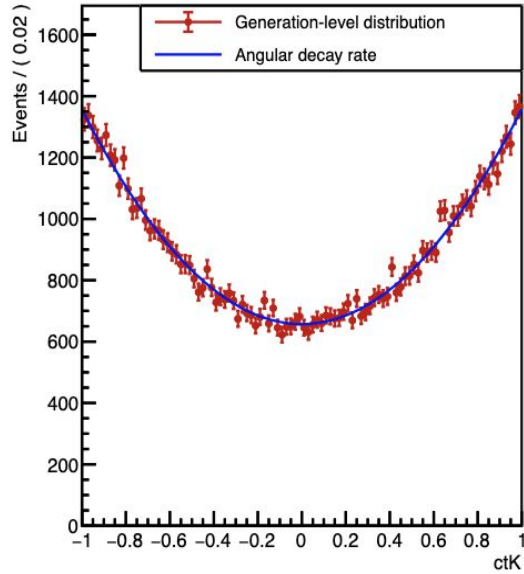


Fit to generation-level distributions (q2-bin 3 odd)

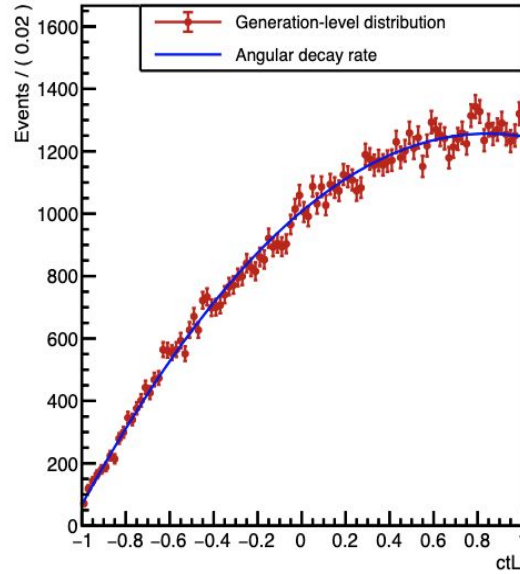


UML-Fit at Generator Level

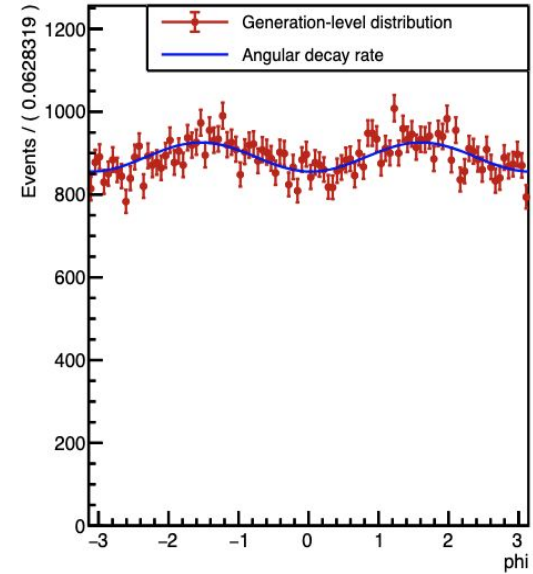
Fit to generation-level distributions (q2-bin 4 odd)



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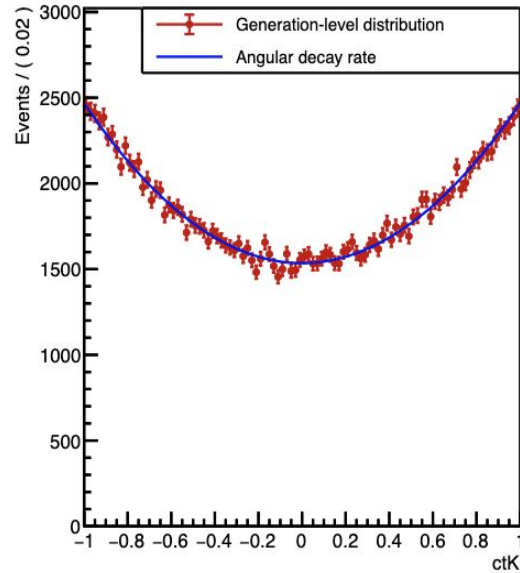


Fit to generation-level distributions (q2-bin 4 odd)

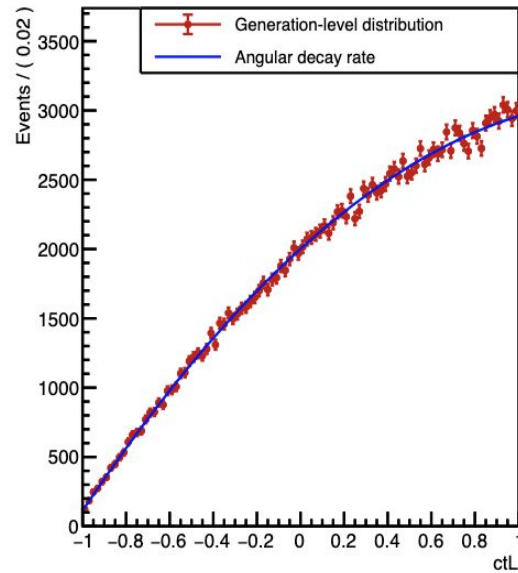


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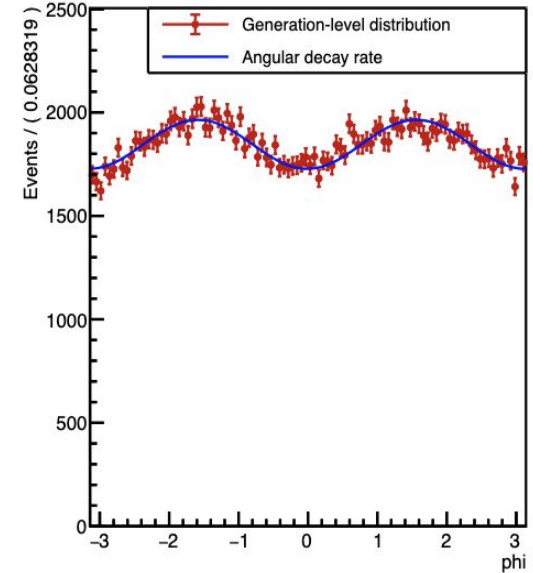
Fit to generation-level distributions (q2-bin 5 odd)



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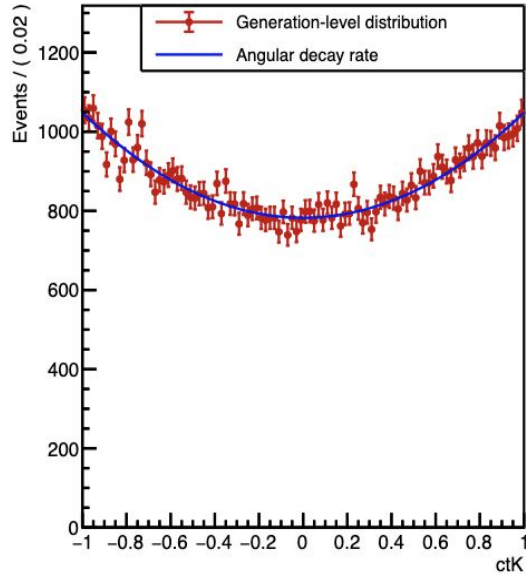


Fit to generation-level distributions (q2-bin 5 odd)

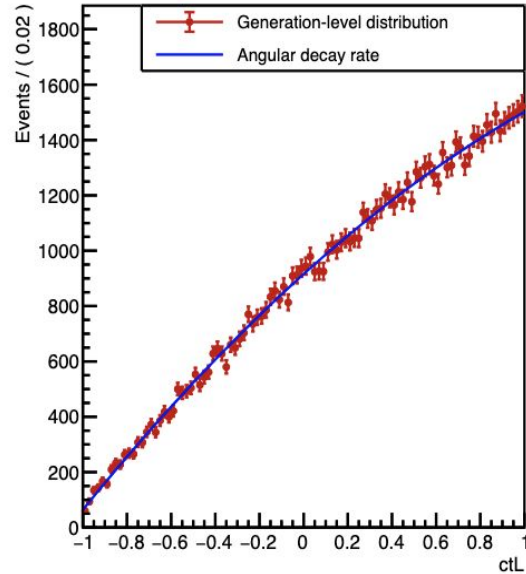


UML-Fit at Generator Level

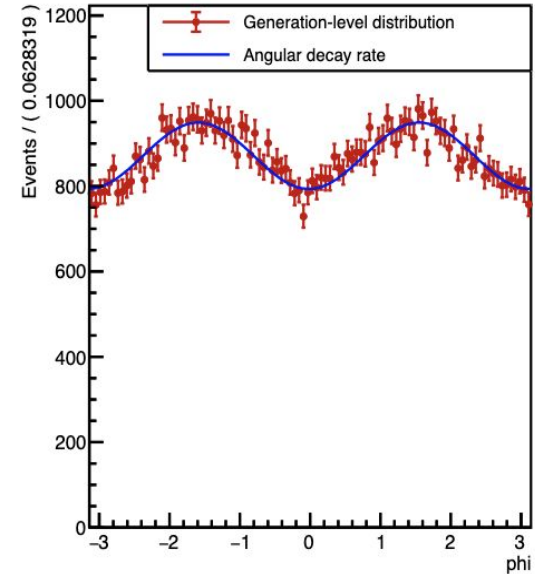
Fit to generation-level distributions (q2-bin 6 odd)



Fit to generation-level distributions (q2-bin 6 odd)

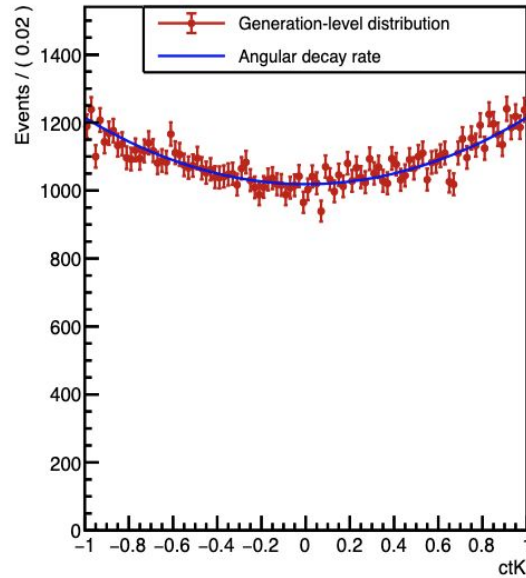


Fit to generation-level distributions (q2-bin 6 odd)

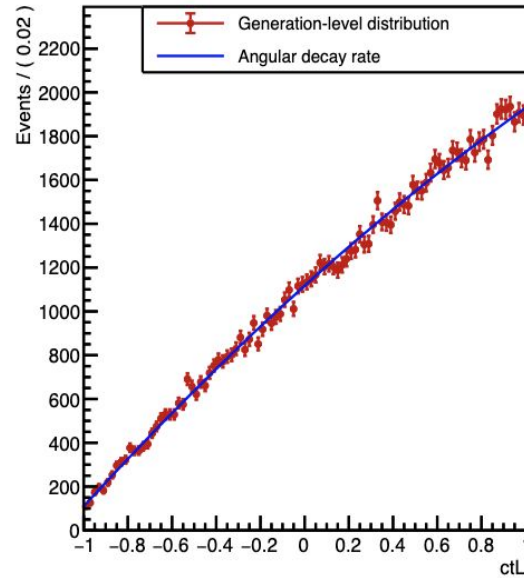


UML-Fit at Generator Level

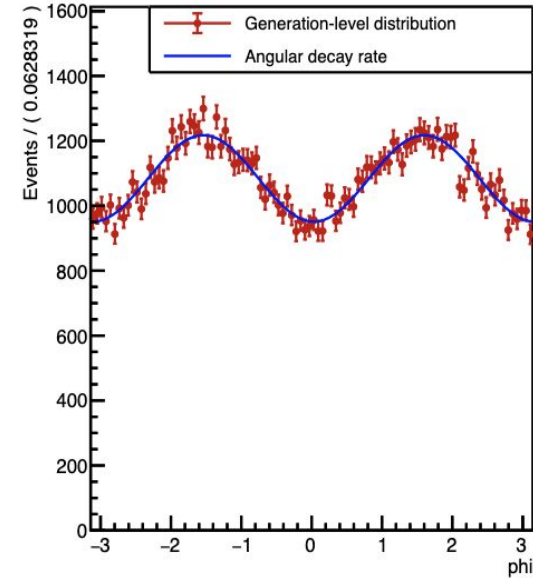
Fit to generation-level distributions (q2-bin 7 odd)



Fit to generation-level distributions (q2-bin 7 odd)

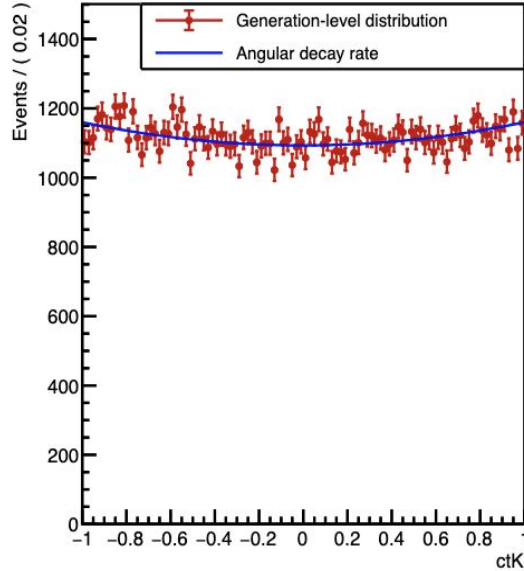


Fit to generation-level distributions (q2-bin 7 odd)

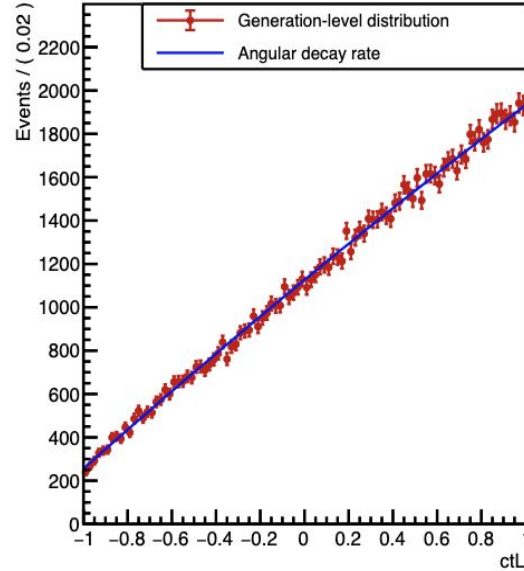


UML-Fit at Generator Level

Fit to generation-level distributions (q2-bin 8 odd)



Fit to generation-level distributions (q2-bin 8 odd)



Fit to generation-level distributions (q2-bin 8 odd)

