Search for CP violation in charm baryon decays

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Goal of this analysis

- Complementary search for CP violation in the baryon sector.
- Important aspect to understand baryon asymmetry in the universe.
- Measure ΔA_{CP} (Λ_c) with $\Lambda_c \to pKK$ and $\Lambda_c \to p\pi\pi$ decays.
- Previous measurement is statistically limited [10.1007/JHEP03(2018)]

$$\Delta A_{CP} = A_{CP}(pK^-K^+) - A_{CP}(p\pi^-\pi+) = (0.30 \pm 0.91_{stat} \pm 0.61_{syst})\,\%\,.$$

Strategy of the analysis

- Goal: measure ΔA_{CP} as $\Delta A_{CP} = A_{CP}(pKK) - A_{CP}(p\pi\pi)$.

- A_{CP} defined as $A_{CP} = \dfrac{\Gamma(\Lambda_c^+ \to f) - \Gamma(\Lambda_c^- \to \bar{f})}{\Gamma(\Lambda_c^+ \to f) + \Gamma(\Lambda_c^- \to \bar{f})}$ can be measured from $A_{raw} = \dfrac{N(\Lambda_c^+) - N(\Lambda_c^-)}{N(\Lambda_c^+) + N(\Lambda_c^-)}$

- A_{raw} measured from a simultaneous fit for both decay channels.

$$A_{raw}(phh) = A_{CP}(phh) + A_P(\Lambda_c) + A_D(p) + A_{L0}(phh) - A_D(h1) + A_D(h2).$$

$$\Delta A_{CP} = A_{CP}(pKK) - A_{CP}(p\pi\pi) = A_{raw}(pKK) - A_{raw}(p\pi\pi) - A_P^{KK}(\Lambda_c) + A_P^{\pi\pi}(\Lambda_c) - A_D^{KK}(p) + A_D^{\pi\pi}(p) -$$
$$- A_{L0}^{KK} + A_{L0}^{\pi\pi} + A_D(K^-) - A_D(K^+) + A_D(\pi^-) - A_D(\pi^+).$$

- Selection: cut based approach + BDT.
- Use two independent samples based on trigger configuration: TISnotTOS and TOS. →
- Reweight the kinematic distributions of Λ_c and of the proton in the $p\pi\pi$ sample on the pKK

  →cancellation of A_P^{hh}, A_D^{hh} *and* A_{L0}^{hh}.

Trigger Independent of Signal(TIS):

Candidates do not contribute to trigger decision

Trigger On Signal(TOS):

Candidates have triggered the event

Strategy of the analysis

- Use Cabibbo-favoured decay $\Lambda_c \to pK\pi$ is employed to estimate the detection asymmetries $A_D(hh) = -A_D(h^-) + A_D(h^+)$.
- A_{raw} can be expressed as

$$A_{raw}(pK\pi) = A_P(\Lambda_c) + A_D(p) - A_D(K^-) + A_D(\pi^+).$$

- Reweight the kinematic of the positive kaon, and the negative kaon.
- Assuming the same kinematics for the other particles

$$A_D(KK) = A_{raw}^{K^-} - A_{raw}^{K^+},$$

  and similarly for pions.

- Combine the measurement performed in each year of, magnet polarity and trigger configuration through a weighted average,

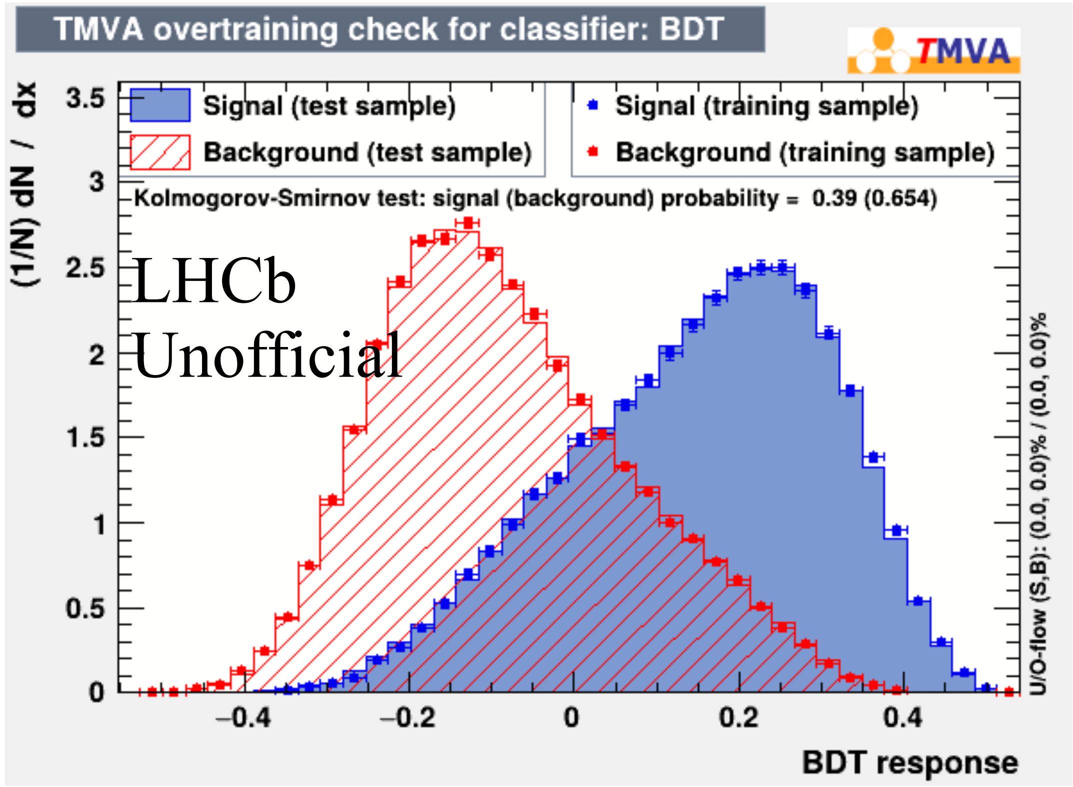
$$\Delta A_{CP} = \frac{1}{\sum_i (1/\sigma_i^2)} \sum_i \left(\frac{1}{(1/\sigma_i^2)} \Delta A_{CP}(i) \right).$$

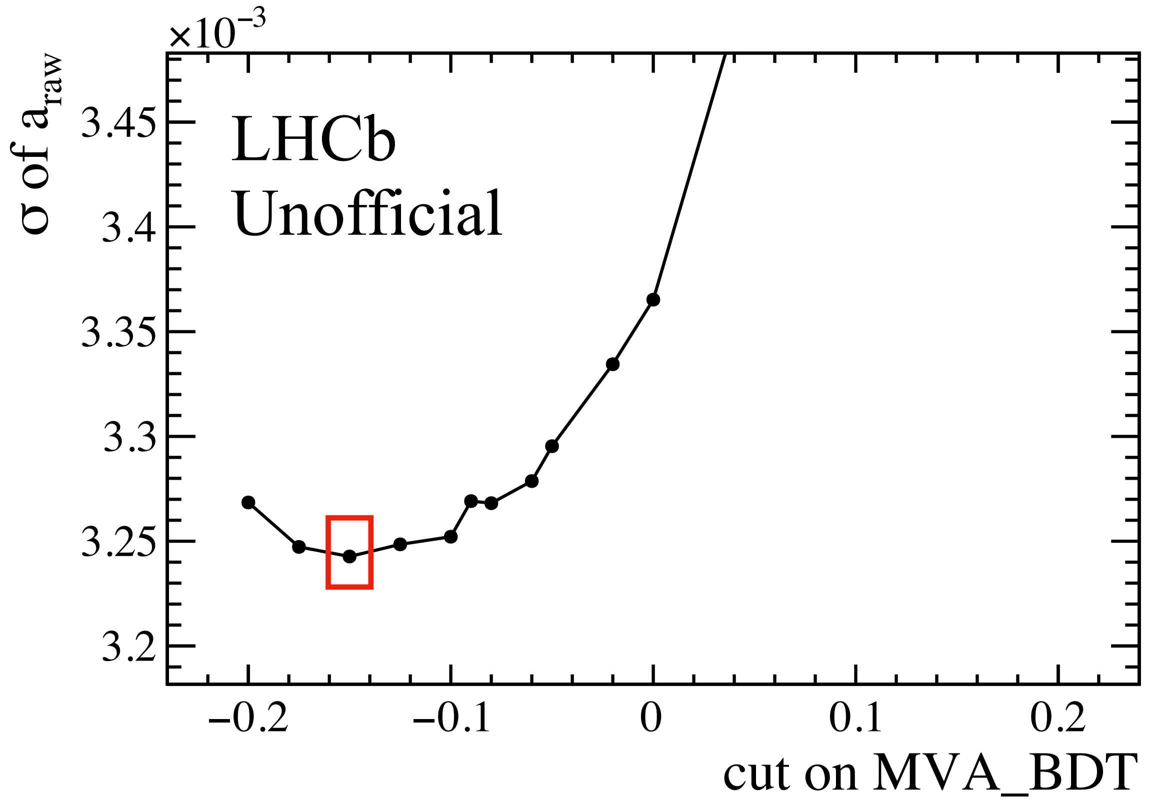
- Raw asymmetries are blinded with different blind string for pKK and $p\pi\pi$.

BDT selection

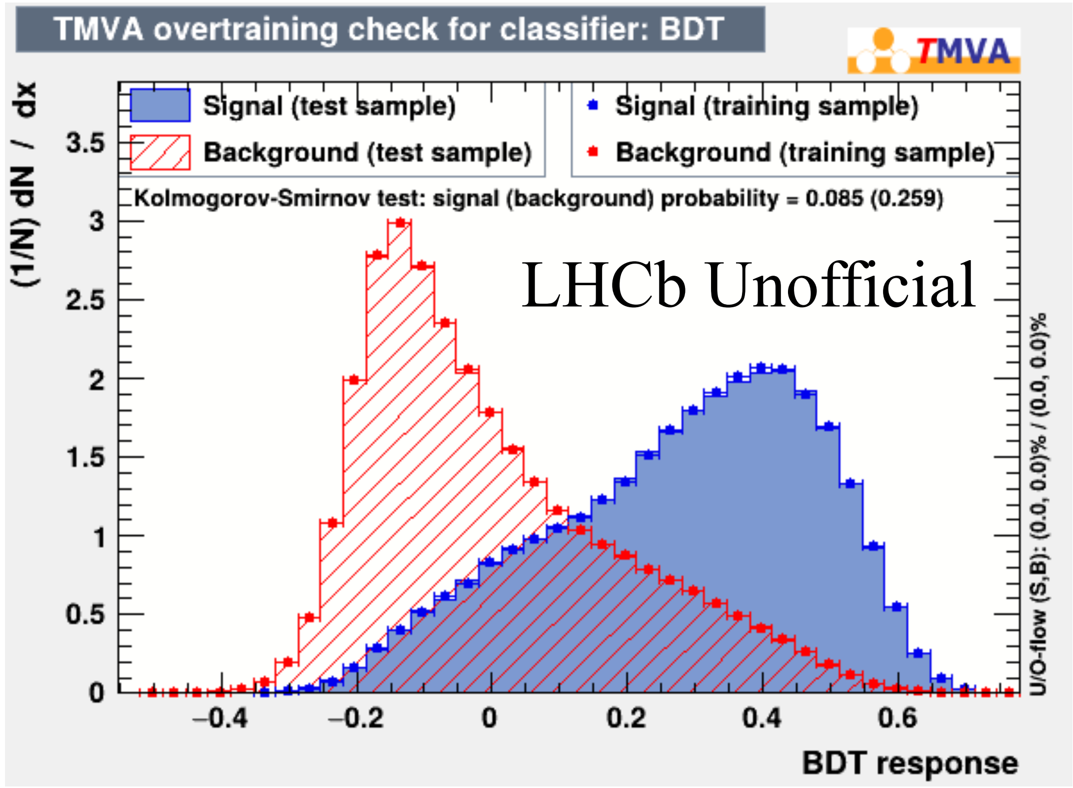
- Each sub-sample is trained and classified independently.
- Similar set of input variables between $p\pi\pi$ and pKK to avoid introducing additional asymmetries.
- sWeighted background and signal variables for training phase.
- BDT optimization performed with toys generated from the test sample.
- BDT cut chosen to minimize the error on the asymmetry.

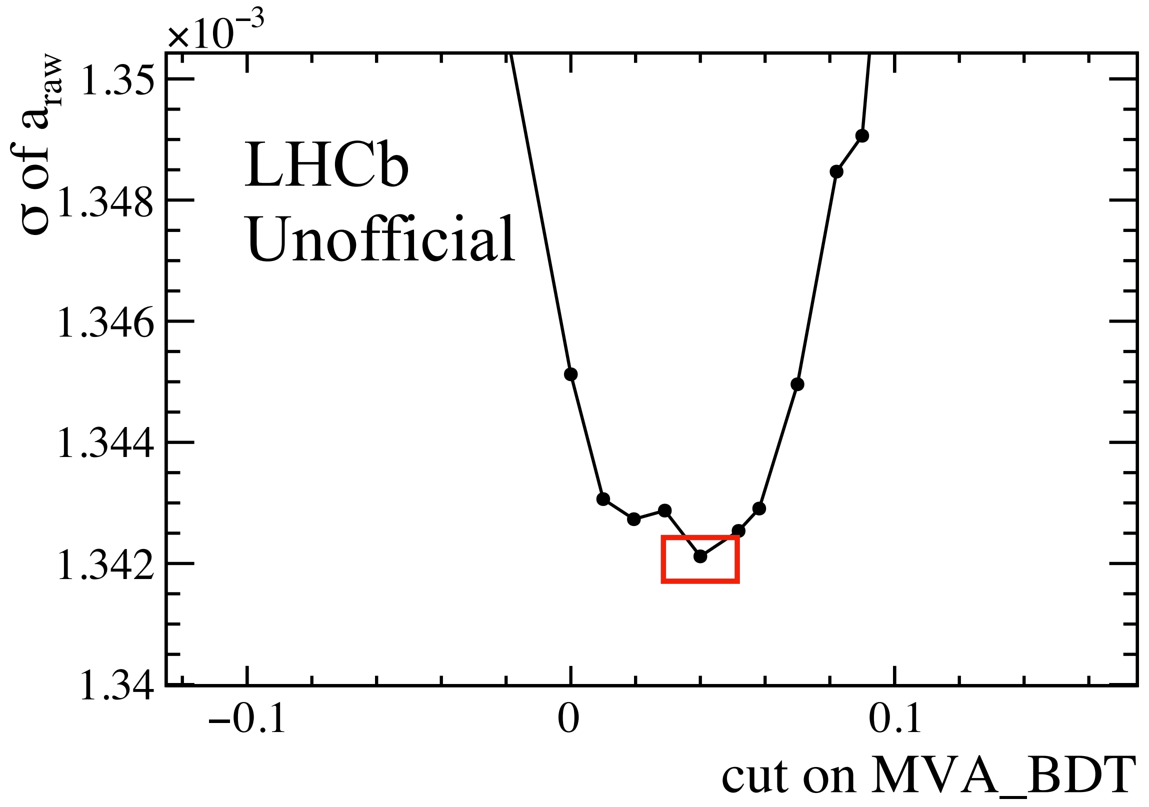
pKK





$p\pi\pi$





Input variables for pKK

Variable in BDT
$\chi^2_{IP}(\Lambda_c)$
$p_T(\Lambda_c)$
$\phi(\Lambda_c)$
$p_T(p)$
$p_T(K^+)$
$p_T(K^-)$
$\eta(\Lambda_c)$
$IP(p)$
$IP(K^+)$
$IP(K^-)$
$\chi^2_{\text{ENDVERTEX}}(\Lambda_c)$
$DIRA(\Lambda_c)$
ProbNNghost(p)
ProbNNghost$(K^+)\cdot$ ProbNNghost(K^-)

Input variables for ppipi

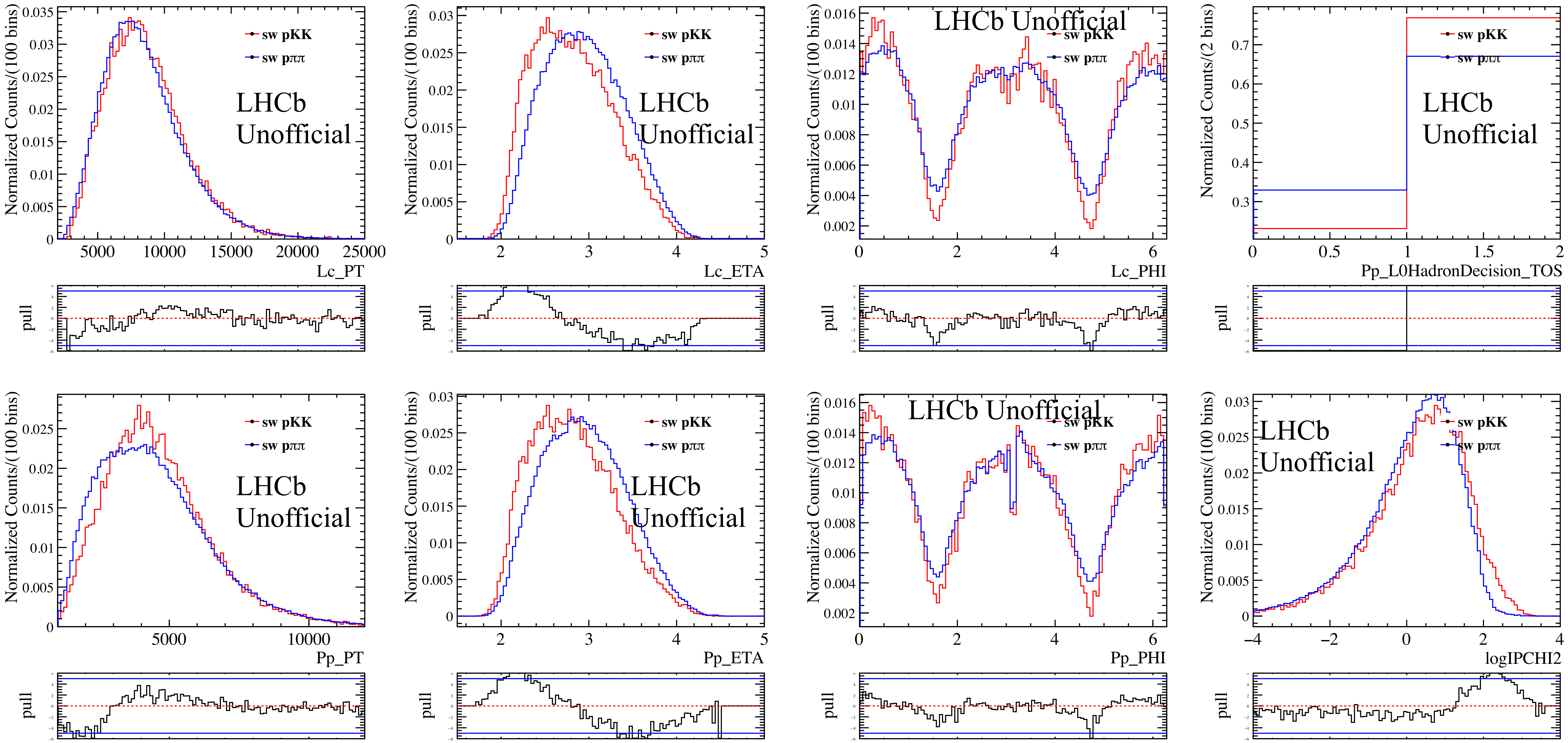
Variable in BDT
$\chi^2_{IP}(\Lambda_c)$
$p_T(\Lambda_c)$
$\phi(\Lambda_c)$
$p_T(p)$
$p_T(\pi^+)$
$p_T(\pi^-)$
$\eta(\Lambda_c)$
$IP(p)$
$IP(\pi^+)$
$IP(\pi^-)$
$\chi^2_{\text{ENDVERTEX}}(\Lambda_c)$
DIRA(Λ_c)
ProbNNghost(p)
ProbNNghost$(\pi^+)\cdot$ ProbNNghost(π^-)

Re-weighting

To cancel $A_P(\Lambda_c), A_D(p)$ *and* A_{L0}, the kinematic distributions of Λ_c and proton are re-weighted with an iterative method starting from s-weighted distributions.

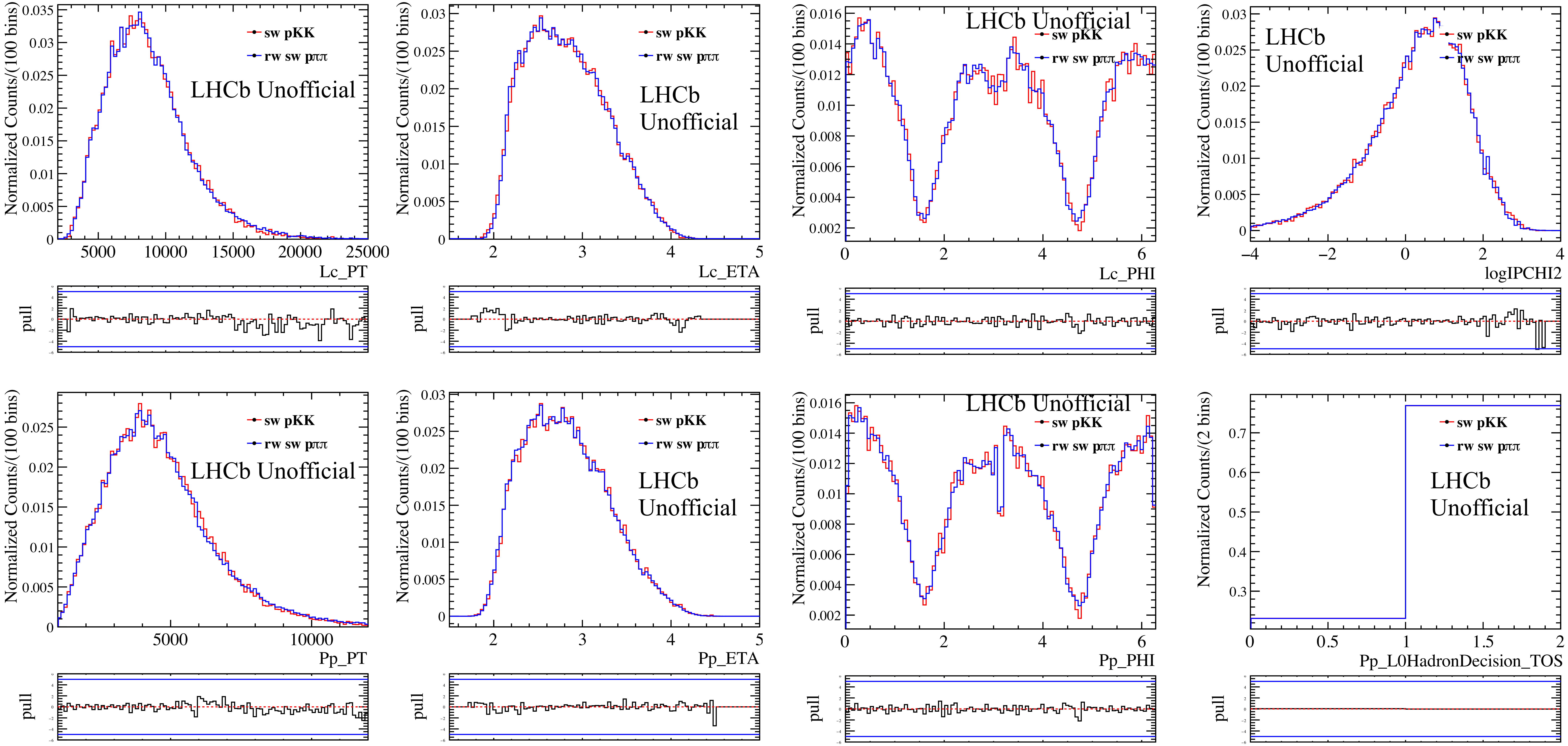
In order we 1-D re-weight:

- $p_T(\Lambda_c)$,
- $\eta(\Lambda_c)$,
- $\phi(\Lambda_c)$,
- $p_T(p)$,
- $\eta(p)$,
- $\phi(p)$,
- Pp_L0HadronDecision_TOS,
- $\log(\chi^2_{IP}(\Lambda_c))$.



Example of 18 MagDown TOS.

Re-weighting



Example of 18 MagDown TOS after the 100th iteration.

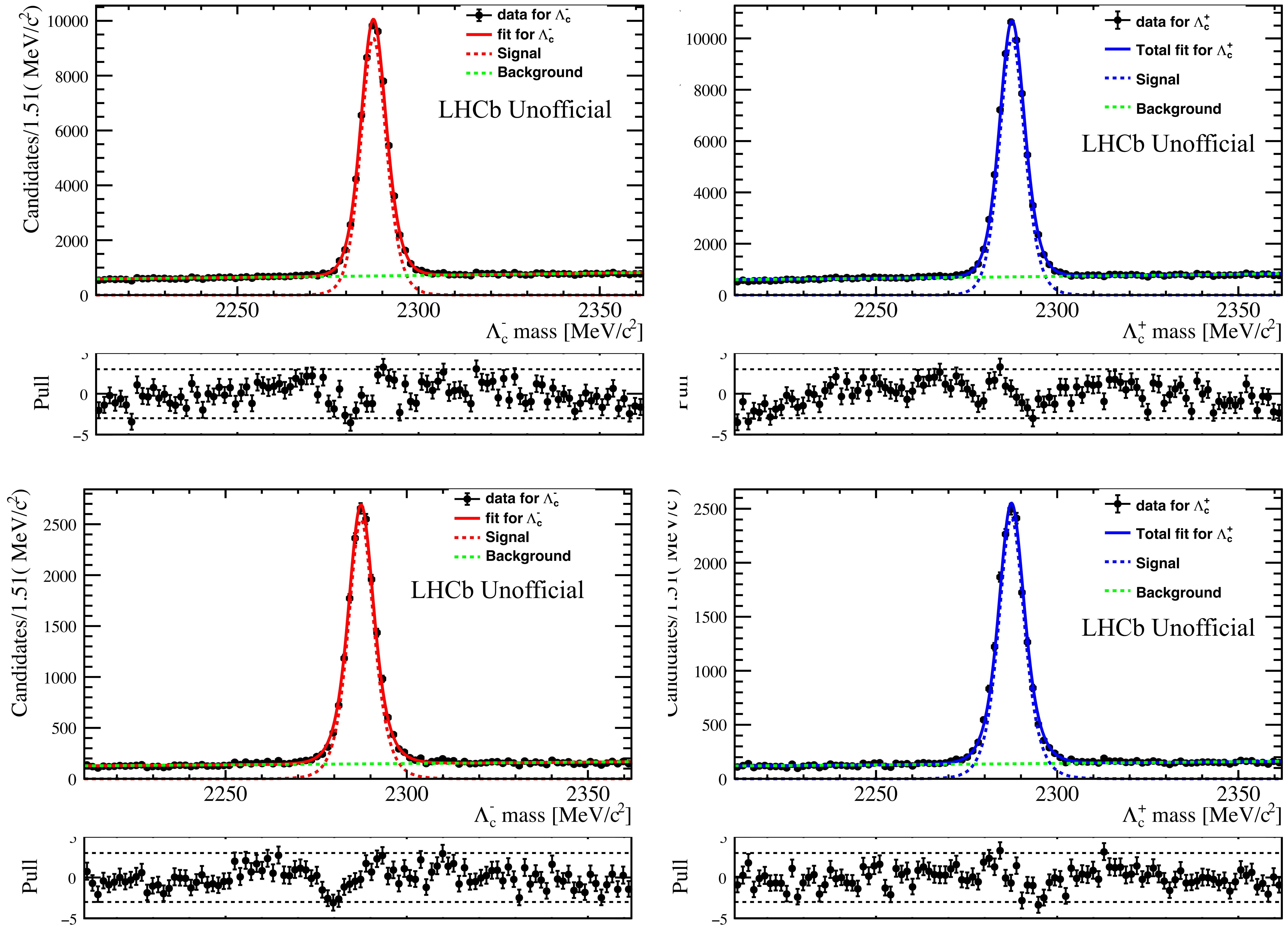
Invariant Mass Fits

Fit performed independently in each subsample.

Fit model for pKK:

Johnson(sig) + Exp.(bkg).

TISnotTOS 18 md



TOS 18 md

Negative charged Λ_c

Positive charged Λ_c

Invariant Mass Fits

Fit model for $p\pi\pi$:

TISnotTOS:

Johnson(sig) + Exp.(bkg).

TOS:

Johnson(sig) + Exp.(bkg) + Gauss.(mis-id)

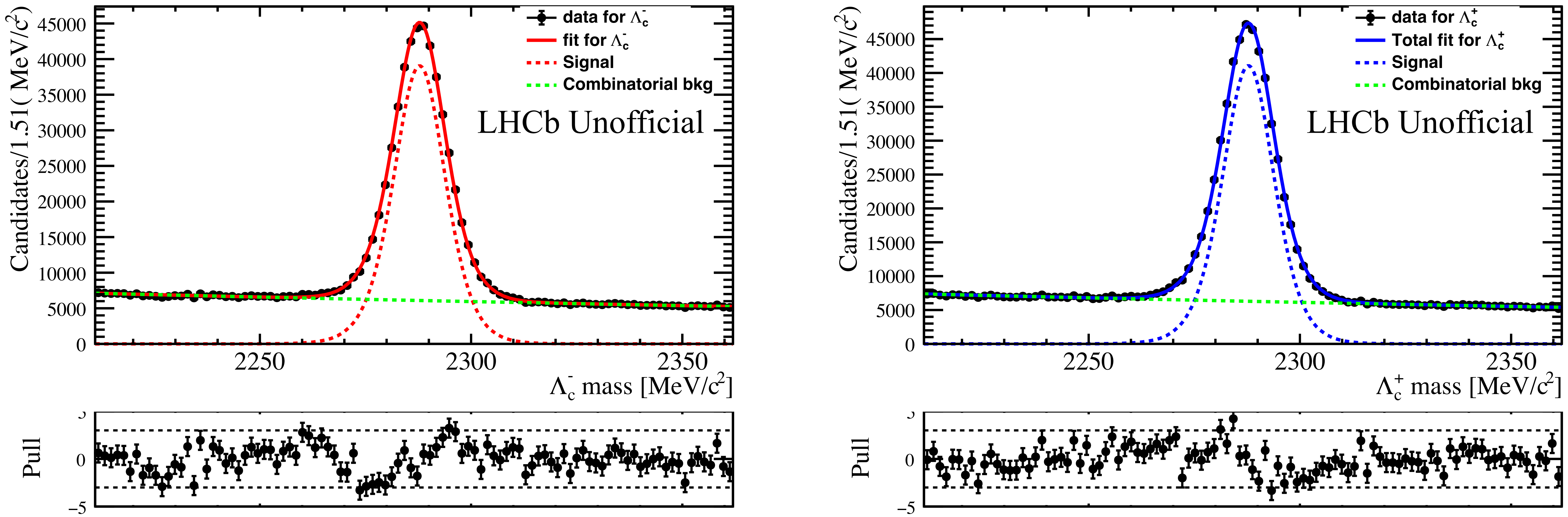
Tail from mis-id events from $pK\pi$.

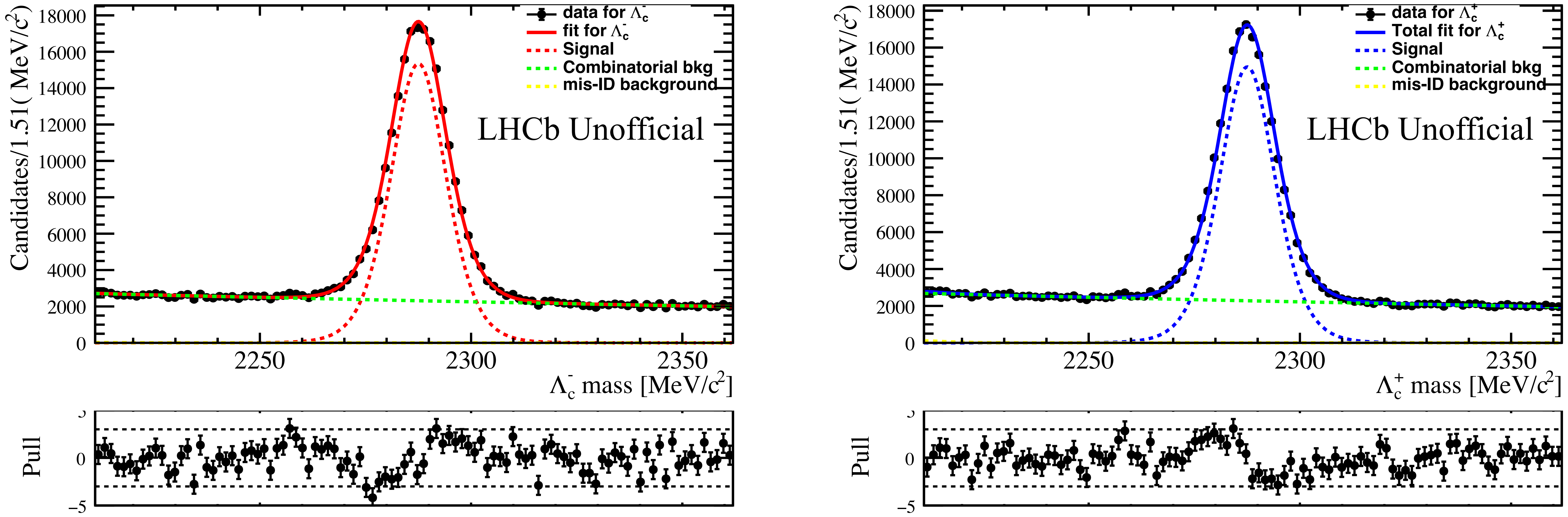
Added a gaussian to model the tail with parameters extracted from MC.

Negative charged Λ_c

Positive charged Λ_c

TISnotTOS 18 md





TOS 18 md

Invariant Mass Fits

Fit performed independently in each subsample.

Fit model for $pK\pi$:

2DSCB(sig) + Exp.(bkg).

Crystal Ball parameters n and alpha extracted from MC and constrained in 5σ range.

Total signal yields:

8×10^5 pKK.

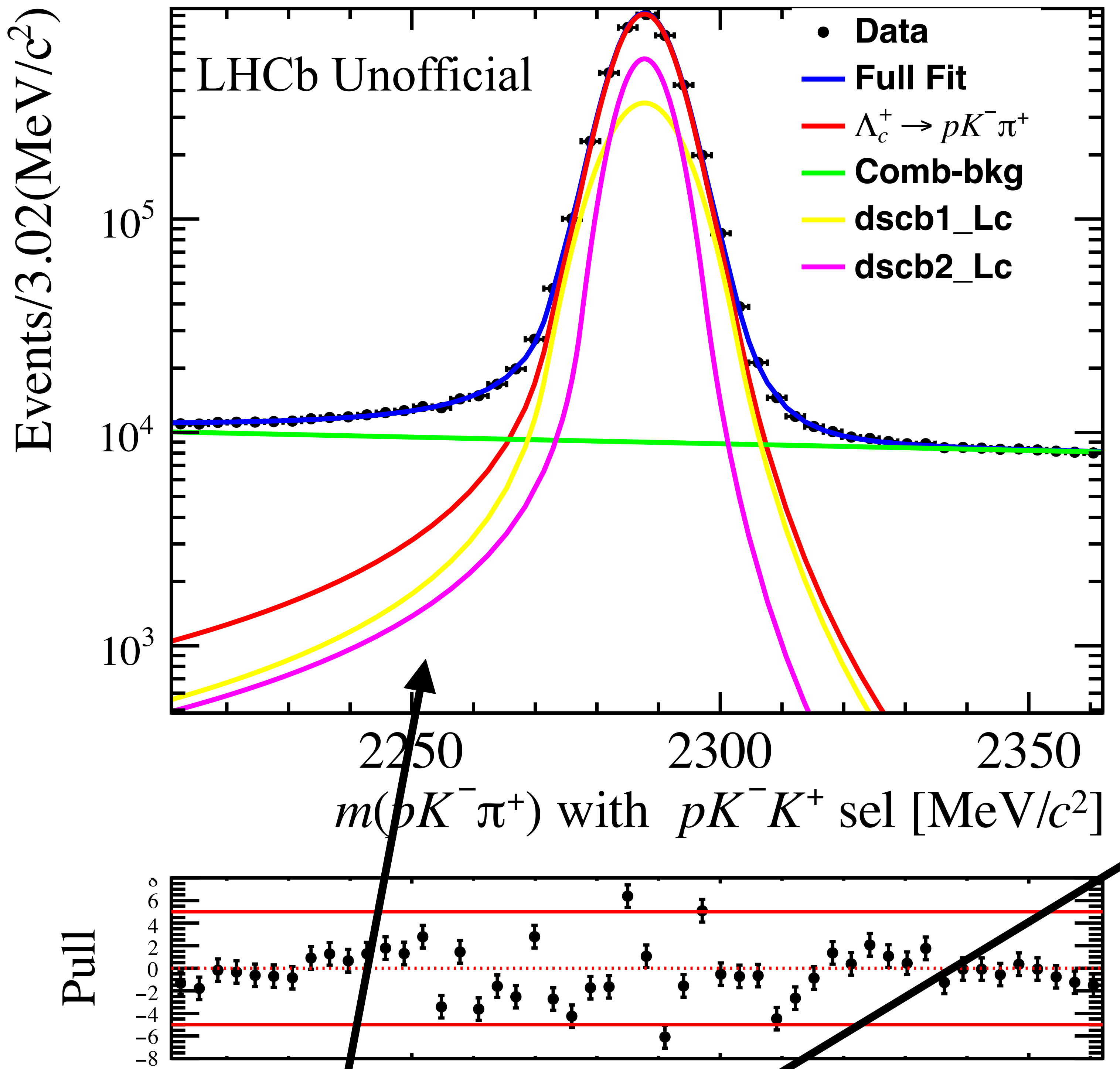
6.5×10^6 $p\pi\pi$.

2.6×10^7 $pK\pi$ with pKK selection.

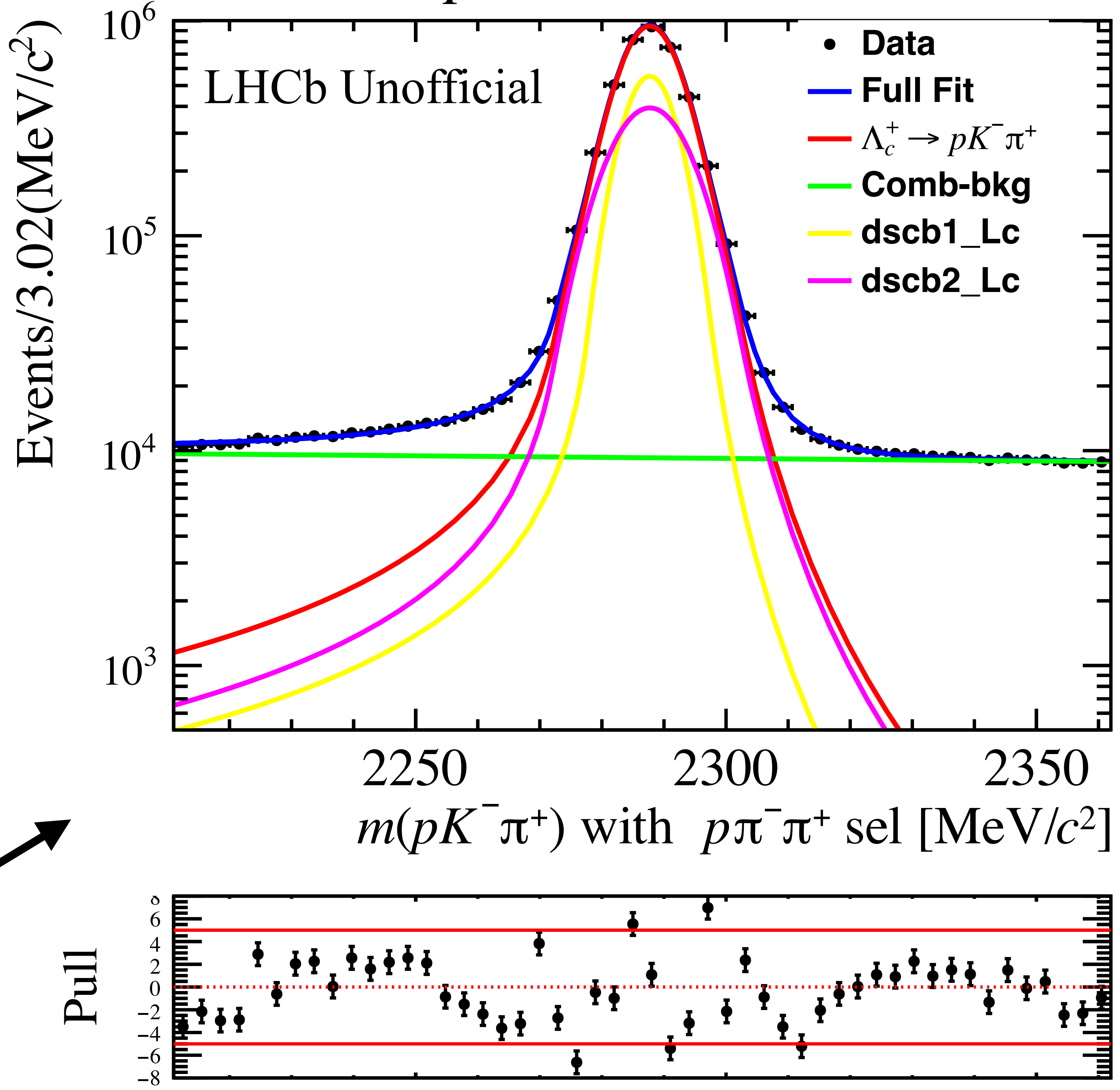
2.8×10^7 $pK\pi$ with $p\pi\pi$ selection.

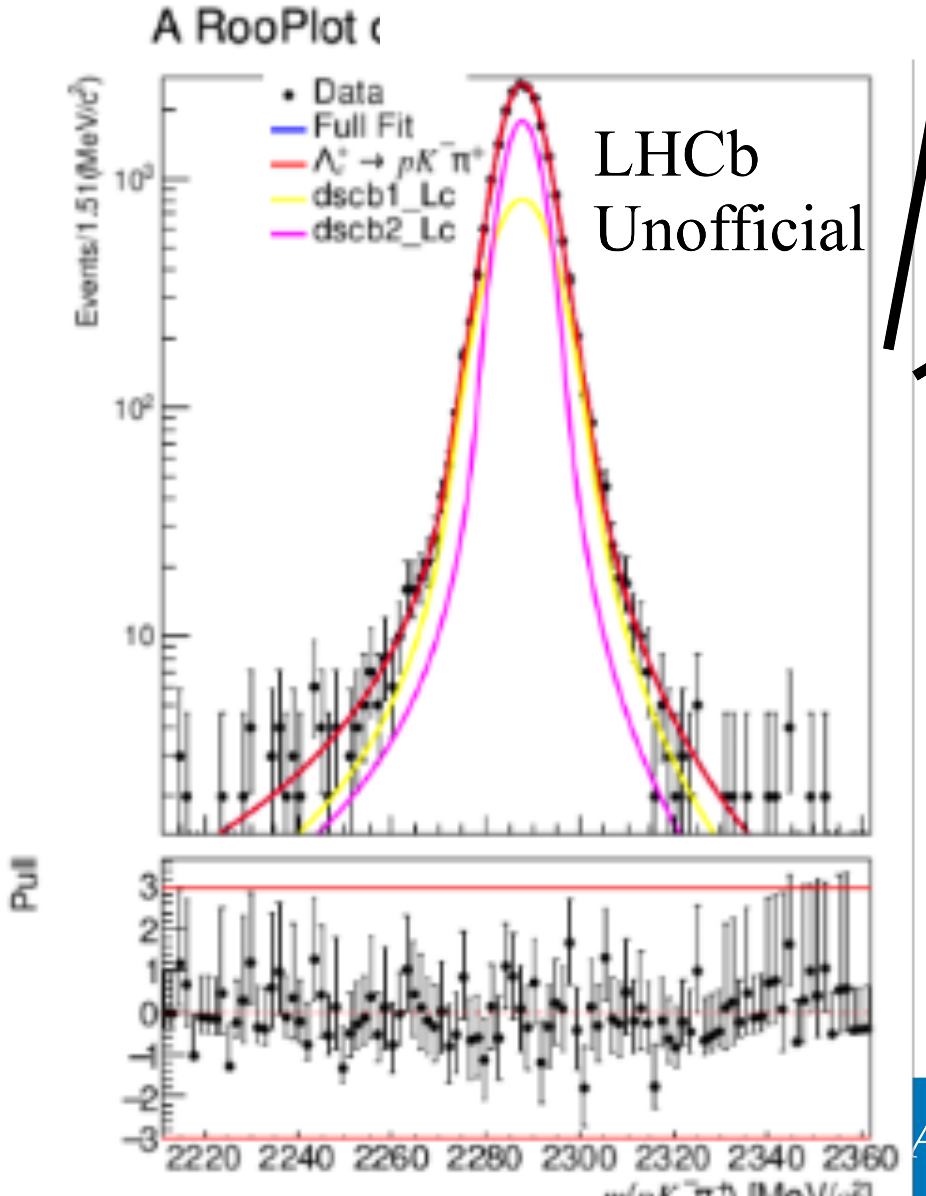
TISnotTOS

pKK selection



$p\pi\pi$ selection





MC

Detection asymmetry extraction

After the reweighting of $\Lambda_c^+ \rightarrow pK\pi$ to $\Lambda_c^+ \rightarrow phh$ the detection asymmetries are extracted.

This data-driven technique allows us to estimate the detection asymmetries with a higher precision with respect to the statical uncertainty of the ΔA_{CP}.

This method has also been validated earlier with an alternative method of estimation that employed detection asymmetry measured in [10.1016/j.physletb.2018.10.039].

TIS

Year	$A_D^{MagDown}(KK)[\%]$	$A_D^{MagUp}(KK)[\%]$
16	0.030 ± 0.031	0.002 ± 0.032
17	0.005 ± 0.021	-0.021 ± 0.022
18	0.030 ± 0.021	-0.010 ± 0.020

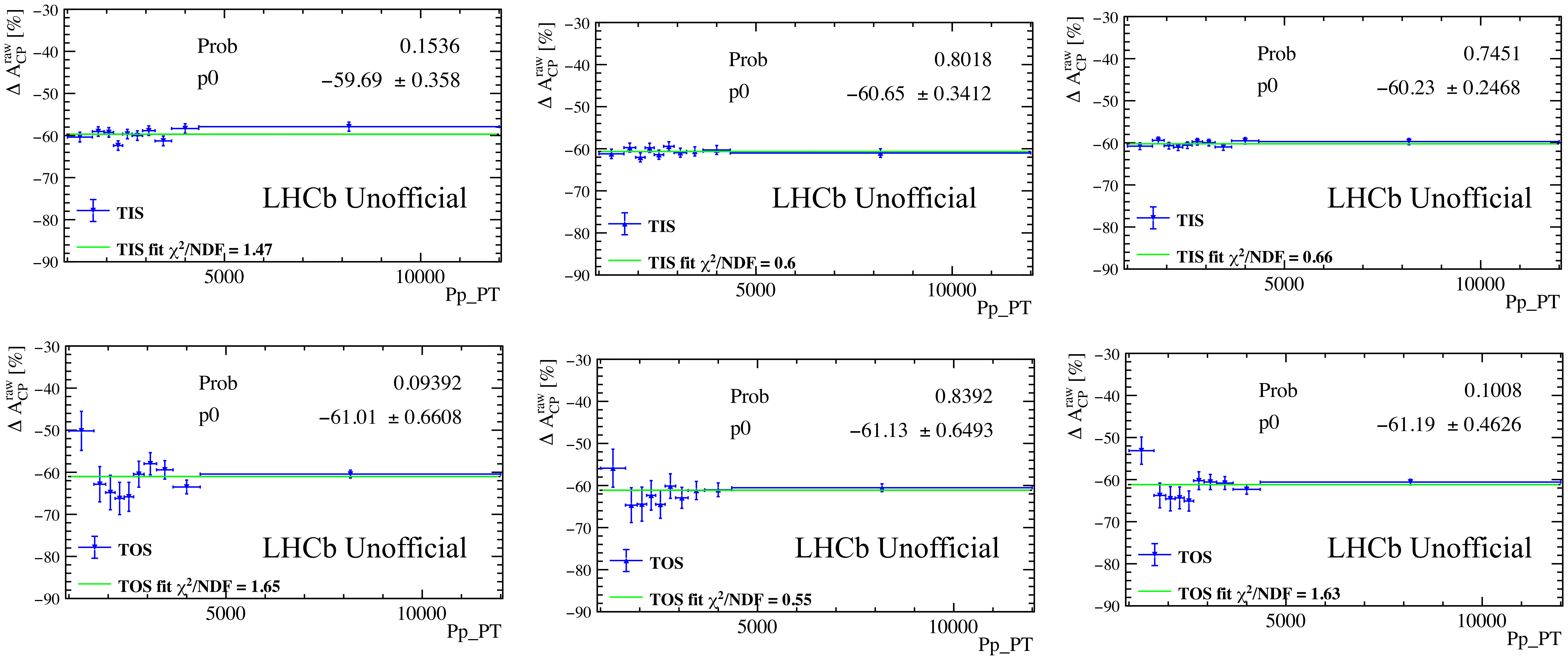
Year	$A_D^{MagDown}(\pi\pi)[\%]$	$A_D^{MagUp}(\pi\pi)[\%]$
16	-0.070 ± 0.035	0.021 ± 0.036
17	-0.058 ± 0.025	0.023 ± 0.025
18	-0.066 ± 0.024	0.030 ± 0.022

TOS

Year	$A_D^{MagDown}(KK)[\%]$	$A_D^{MagUp}(KK)[\%]$
16	-0.061 ± 0.063	-0.097 ± 0.068
17	-0.013 ± 0.41	-0.067 ± 0.043
18	-0.069 ± 0.043	-0.078 ± 0.040

Year	$A_D^{MagDown}(\pi\pi)[\%]$	$A_D^{MagUp}(\pi\pi)[\%]$
16	0.081 ± 0.079	-0.021 ± 0.083
17	0.078 ± 0.042	0.049 ± 0.046
18	0.131 ± 0.045	0.053 ± 0.046

ΔA_{CP}^{raw} Dependence on kinematics



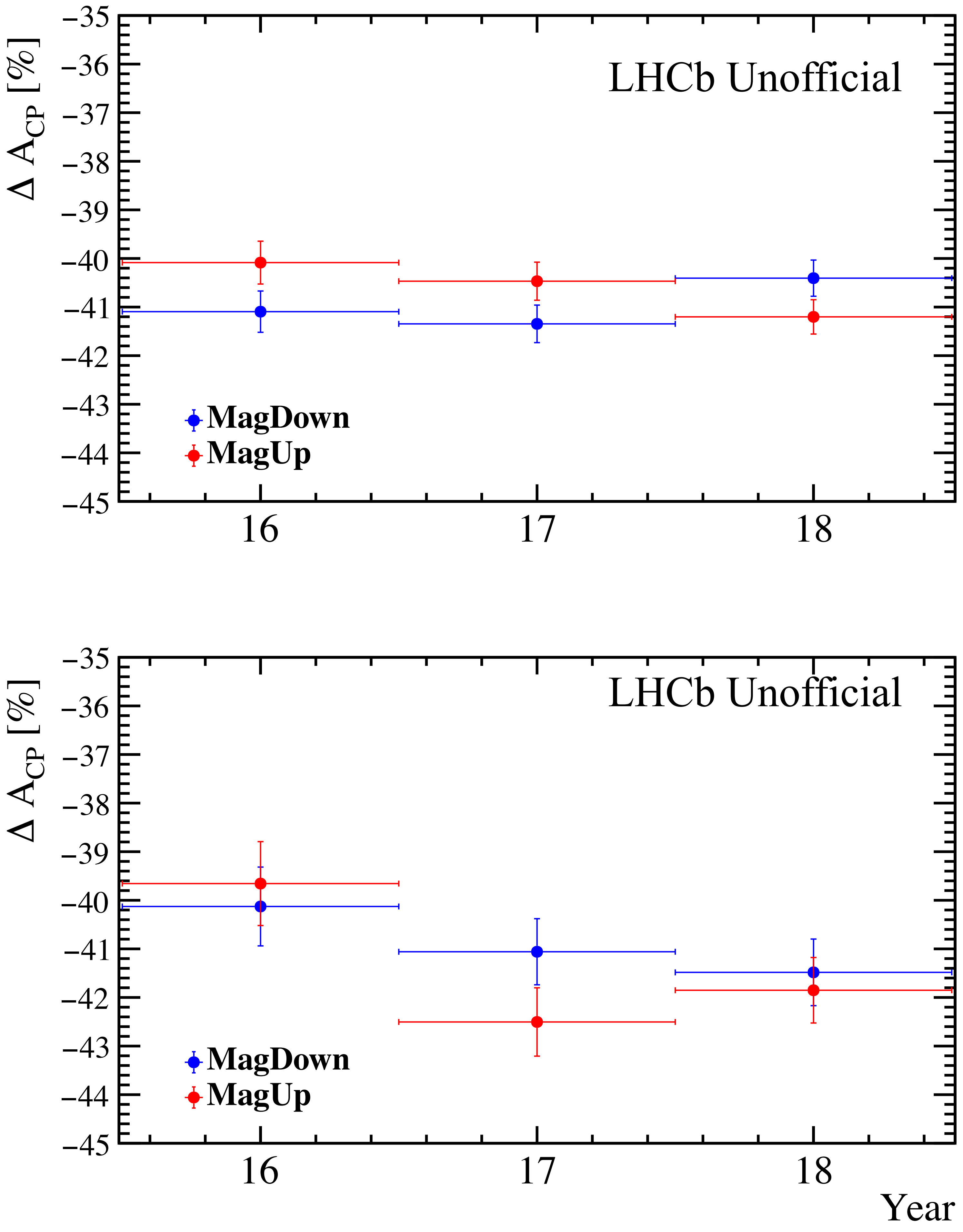
TISnotTOS

TOS

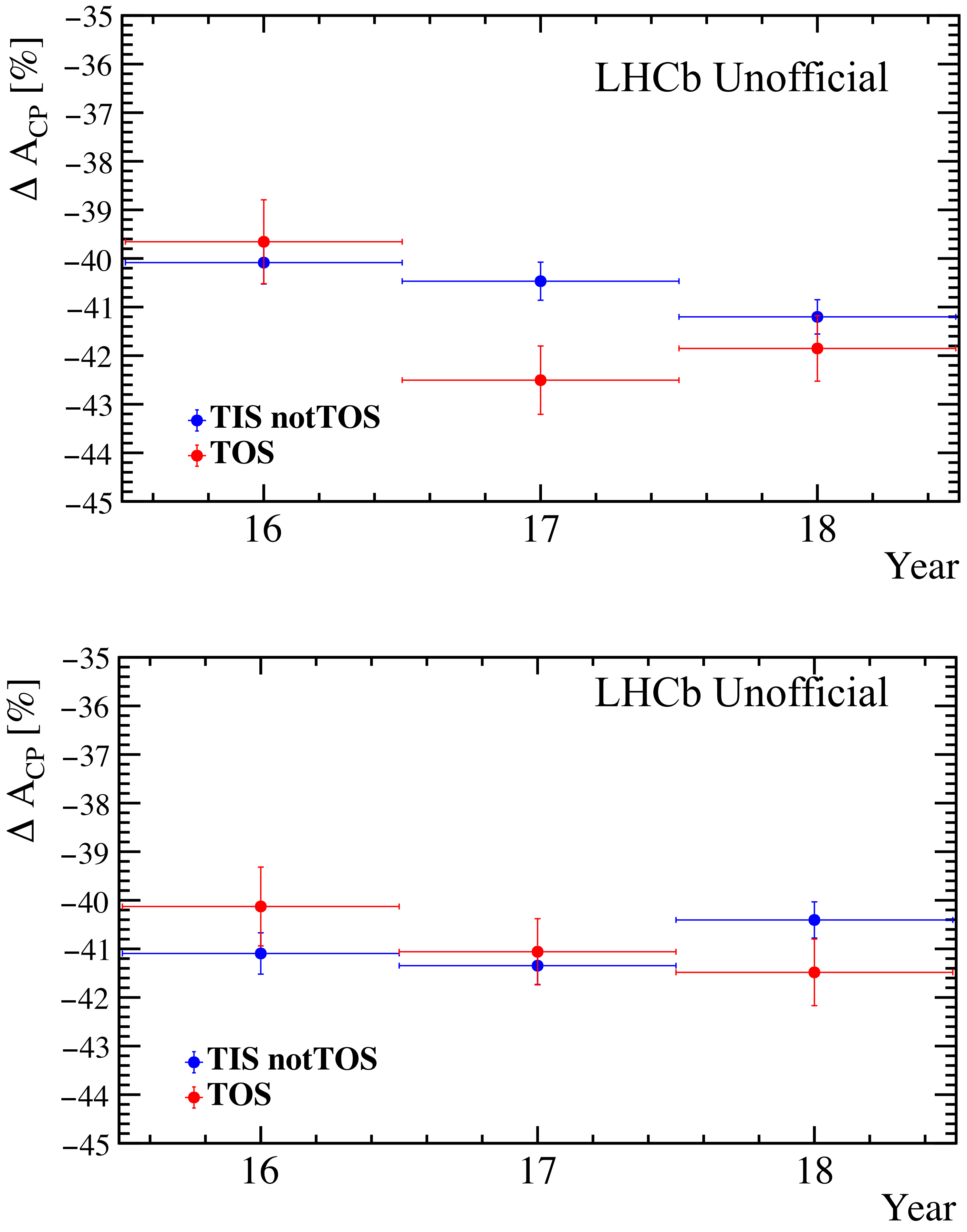
MagDown MagUp MagAverage

- TISnotTOS and TOS sample are binned differently due to different distribution of transverse momentum.
- The distribution are fitted with a pol0.
- No dependency on p_T of proton.
- No dependency seen also as a function of $\eta(p), \phi(p), p_T(\Lambda_c), \eta(\Lambda_c), \phi(\Lambda_c)$.

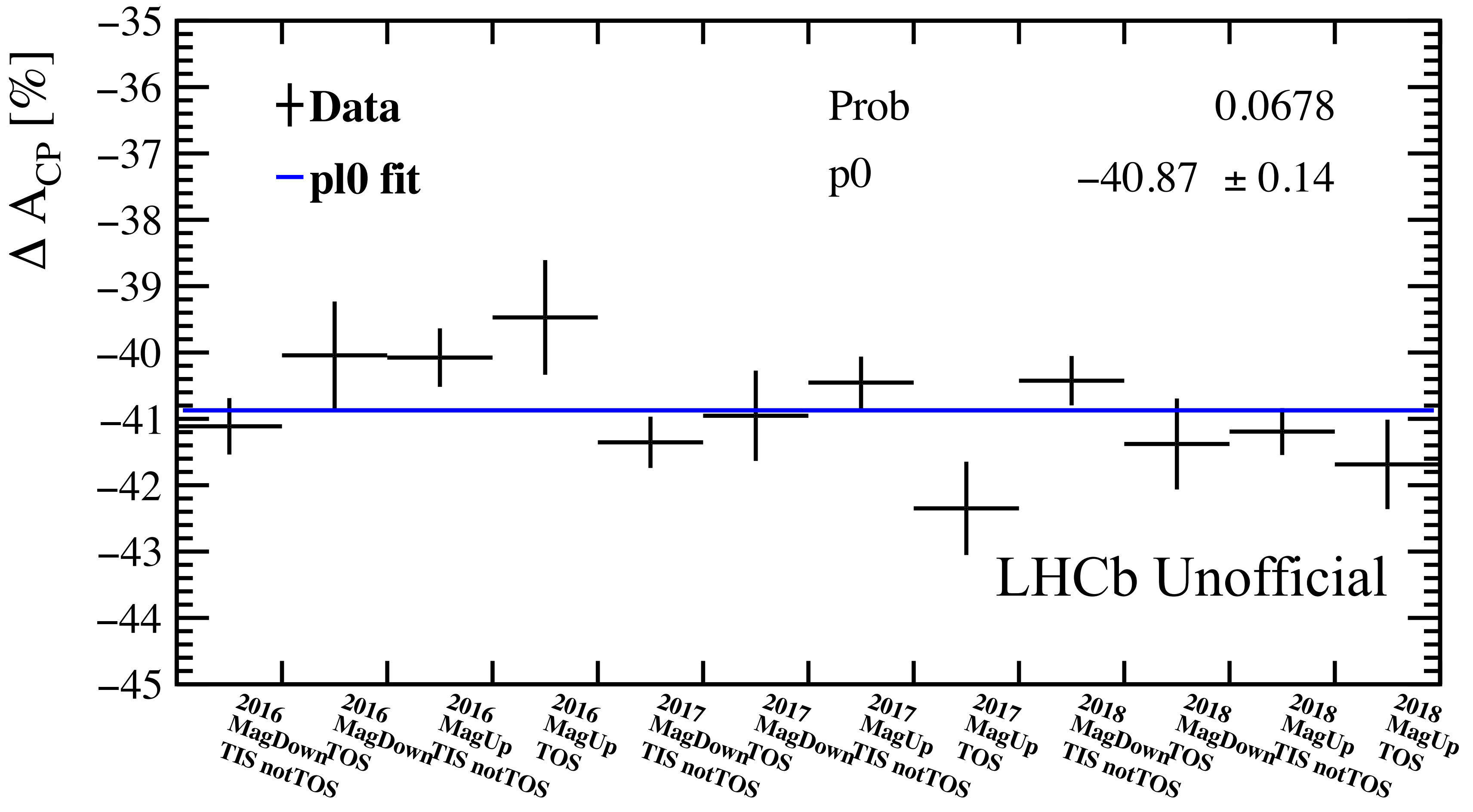
ΔA_{CP} Blinded



Magnet Comparison



Trigger Comparison



All sub-samples comparison

All sub-samples combination

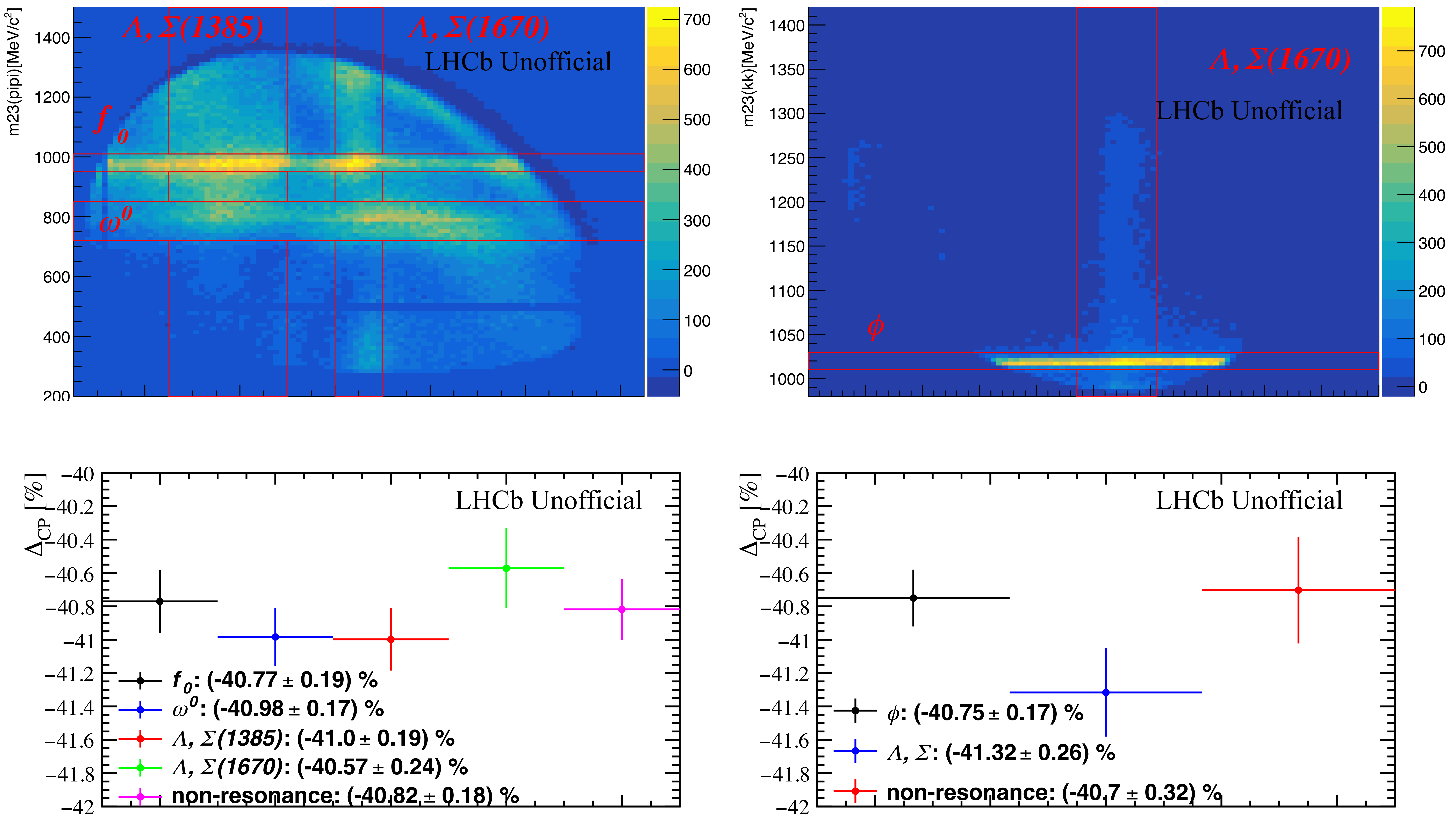
$$\Delta A_{CP} = (-40.87 \pm 0.14 \pm 0.08)\,\%$$

- All subsamples are compatible with each other.

ΔA_{CP} in Dalitz bins

- Analysis also performed in bins of the Dalitz plot to account for possible enhancement of the CP asymmetry
- Bins have been chosen around resonances present in the decay channel i.e. $\Lambda, \Sigma(1670)$ and ϕ in the pKK channel and $f_0, \omega_0, \Lambda, \Sigma(1385)$ and $\Lambda, \Sigma(1670)$ om $p\pi\pi$ channel
- ΔA_{CP} is the measured after performing the fits in each bin of both decays
- No dependance has been observed

$\Lambda_c^+ \to p\pi\pi$ $\Lambda_c^+ \to pKK$



Systematic uncertainties

Main sources of systematic uncertainties studied:

- Fit model:
  - Fits performed with different signal model i.e. a double sided Crystal Ball function
- Variables correlation
  - Possible correlation between reweighting variables is not accounted for in 1D reweighting so an alternative 2D reweighting is also performed
- Secondary Λ_c^+
  - Possible contamination of secondary produced Λ_c^+ studied with a stricter $IP(\Lambda_c^+)$
- Residual detection asymmetry
  - Residual detection asymmetry due to the kaon of $\Lambda_c^+ \to pK\pi$ that is not completely cancelled in $A_D(\pi\pi)$

Source	Section	Uncertainty[%]
Fit model	9.1	0.02
variables Correlation	9.2	0.07
Secondary Λ_c^+	9.3	0.003
Residual detection asymmetry	9.4	0.002
Total	9.5	0.08

Conclusions

- Measurement of ΔA_{CP} using prompt decays with Run 2 data.
- Analysis strategy settled.
- Selection, re-weighting and fit model finalized.
- Detection asymmetries measured with the final selection.
- Systematic uncertainties studies performed.
- Blind value: $\Delta A_{CP} = (-40.87 \pm 0.14 \pm 0.08)\,\%$
- Analysis is starting Working Group review soon

Backup

Preselection: Overlap Cut

- If two hadrons overlap in the same HCAL cluster →irreducible correlation, not eliminated with by re-weighting.

- Veto this "overlap" events

1 → Proton

2 → Negative hadron

3 → Positive hadron

$$\Delta x_{12} = \|x_1 - x_2\|, \Delta y_{12} = \|y_1 - y_2\|$$

$$\Delta x_{12}\ AND\ \Delta y_{12},\ OR\ \Delta x_{13}\ AND\ \Delta y_{13},\ OR\ \Delta x_{23}\ AND\ \Delta y_{23} > 262\ mm \text{ for the inner region of the HCAL.}$$

$$\Delta x_{12}\ AND\ \Delta y_{12},\ OR\ \Delta x_{13}\ AND\ \Delta y_{13},\ OR\ \Delta x_{23}\ AND\ \Delta y_{23} > 524\ mm \text{ for the outer region of the HCAL.}$$

This ensures a proper compatibility between years, magnet polarities and between TOS and TISnotTOS sample.

Preselection

Rectangular cuts on PID, IP of the Λ_c, angle θ, and fiducial cuts.

For $p\pi\pi$ additional cuts are applied to exclude non-CPV decay modes, i.e. with Λ and K_S^0 resonances.

Veto on $p\pi\pi$:

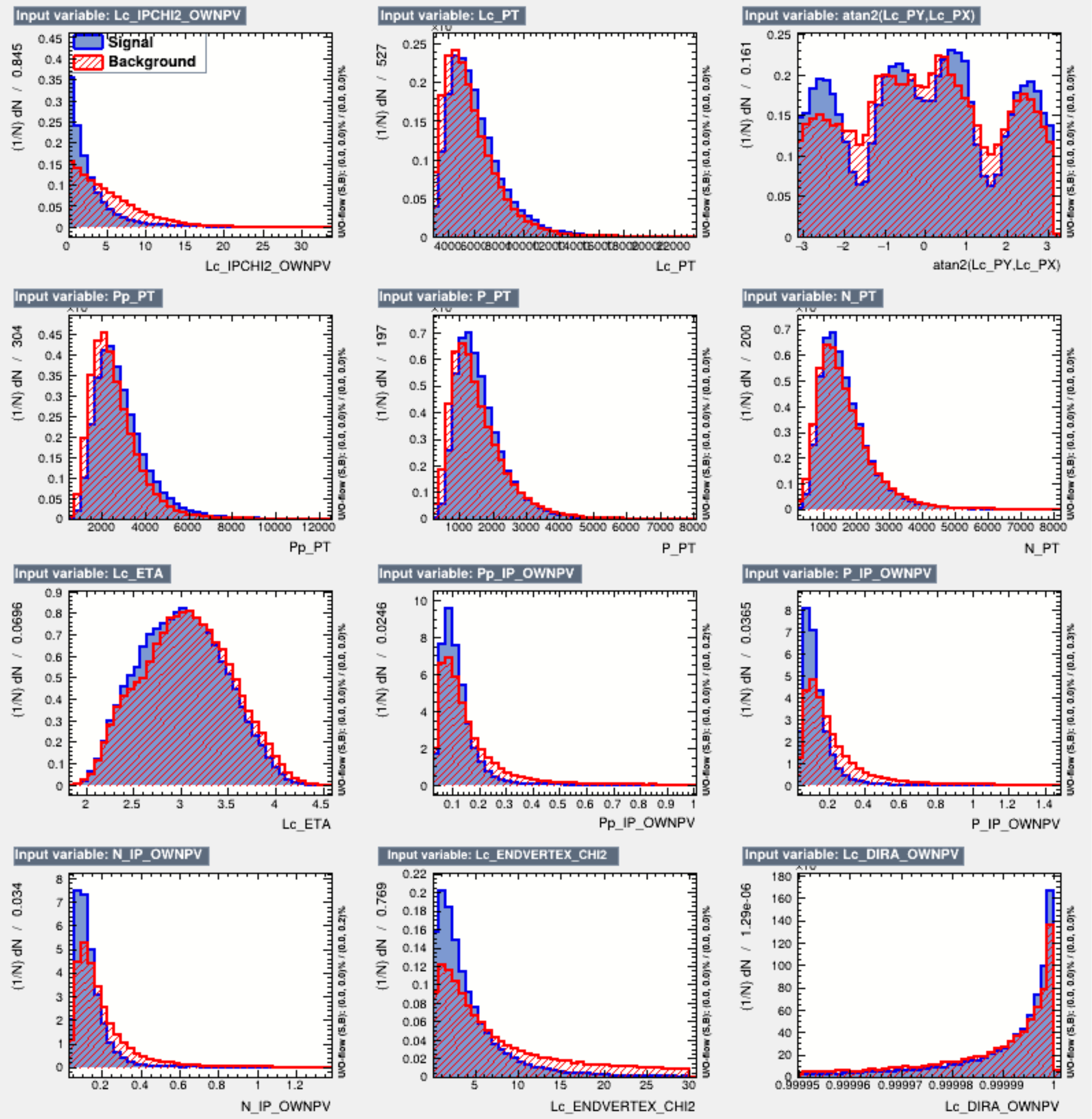
$485\ MeV < m(p\pi) < 510\ MeV$

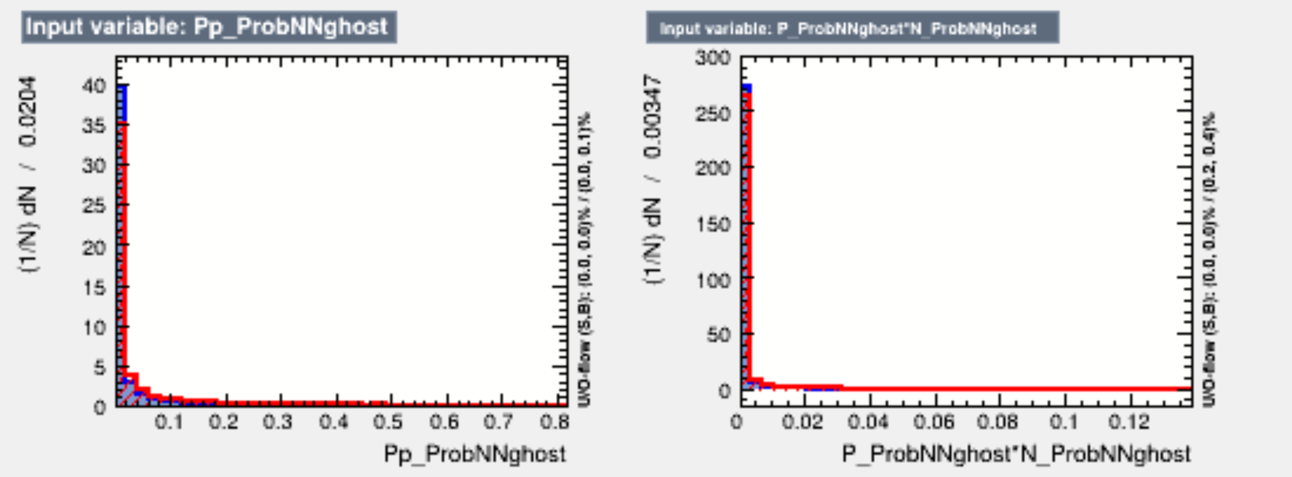
$1110\ MeV < m(\pi\pi) < 1120\ MeV$

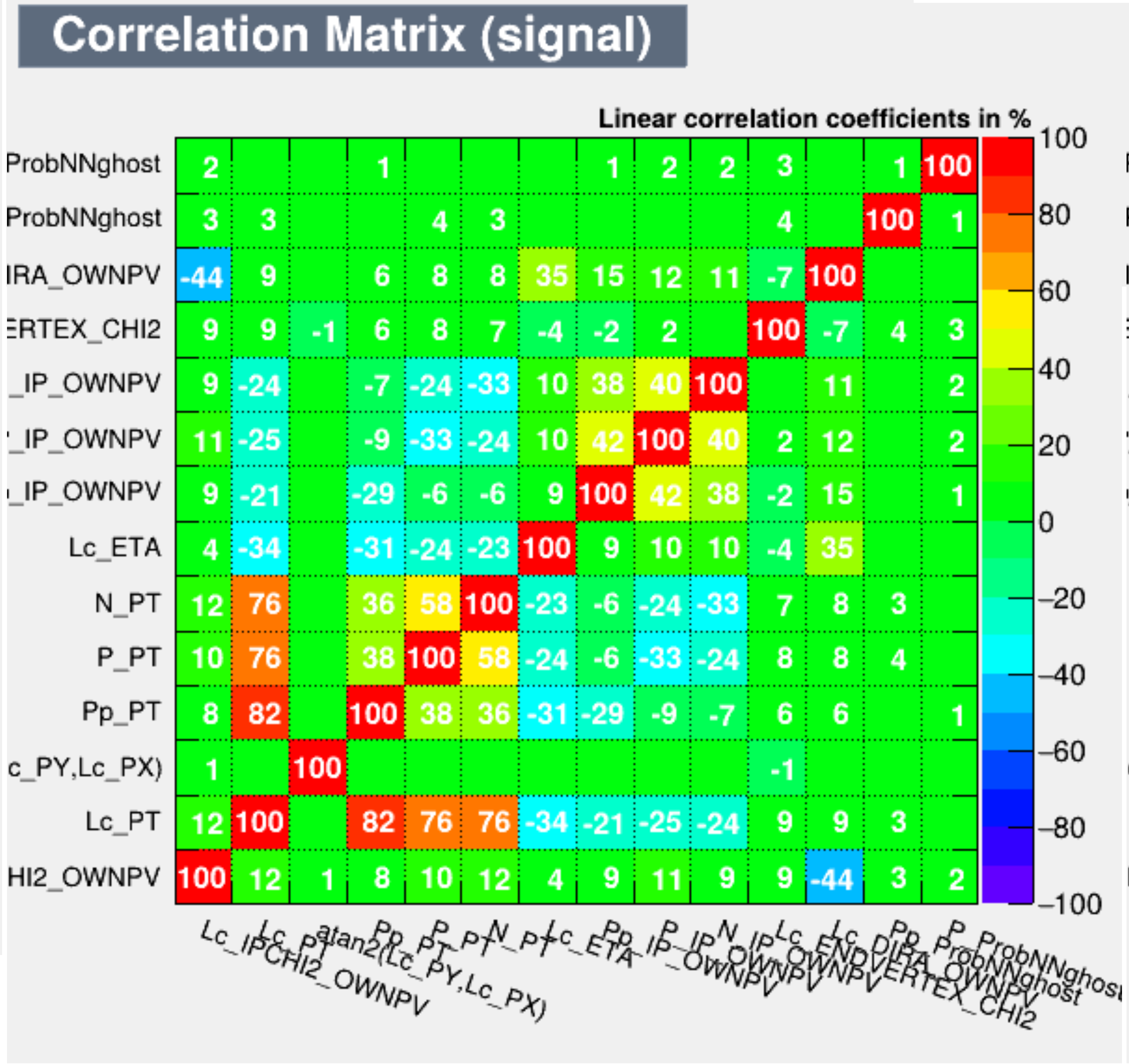
Variable	Cut
Pp_ProbNNp	> 0.85
$IP(\Lambda_c^+)$	< 0.05 mm
Km_ProbNNk	> 0.6
Kp_ProbNNk	> 0.6
Open angle θ	$\theta_{PKm} > 0.0008$
	$\theta_{PKp} > 0.0008$
	$\theta_{KmKp} > 0.0008$
Fiducial cut 1	$\lVert PX(h) \rVert \leq 0.317(PZ(h) - 2000\text{MeV/c})$
Fiducial cut 2	$\lVert PY(h)/PZ(h) \rVert > 0.02$
	$\cup \lVert PX(h) \rVert < (418 - 0.01397 * PZ(h))$
	$\cup \lVert PX(h) \rVert > (497 + 0.01605 * PZ(h))$
HCAL Veto	$(\text{Pp\_L0Calo\_HCAL\_region} == 1)\cap$
	$((\Delta x_{12} < 262 \text{ mm} \cap \Delta y_{12} < 262 \text{ mm})\cup$
	$(\Delta x_{13} < 262 \text{ mm} \cap \Delta y_{13} < 262 \text{ mm})\cup$
	$(\Delta x_{23} < 262 \text{ mm} \cap \Delta y_{23} < 262 \text{ mm}))$
HCAL Veto	$(\text{Pp\_L0Calo\_HCAL\_region} == 0)\cap$
	$((\Delta x_{12} < 524 \text{ mm} \cap \Delta y_{12} < 524 \text{ mm})\cup$
	$(\Delta x_{13} < 524 \text{ mm} \cap \Delta y_{13} < 524 \text{ mm})\cup$
	$(\Delta x_{23} < 524 \text{ mm} \cap \Delta y_{23} < 524 \text{ mm}))$

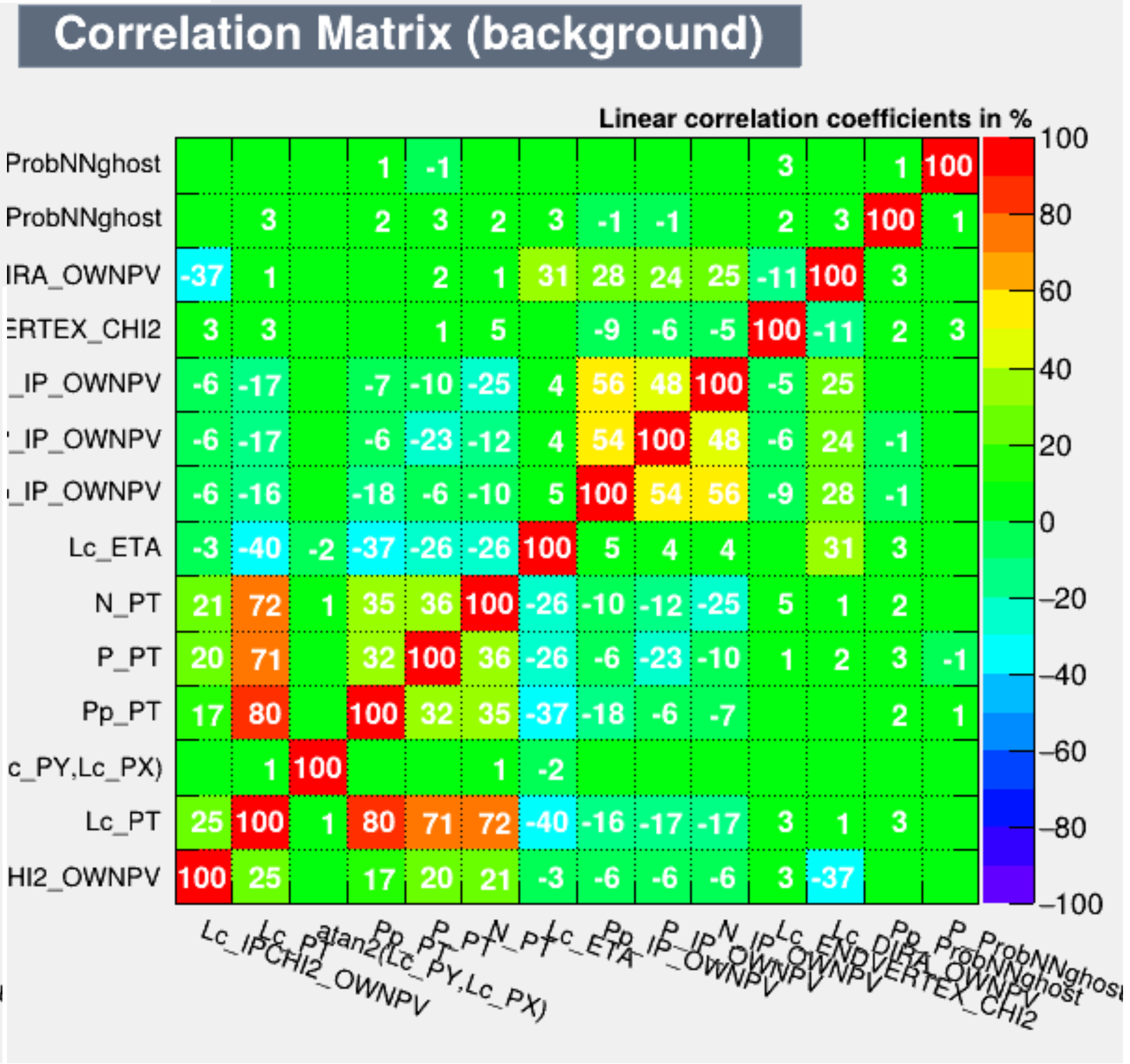
BDT variables

Input variables distribution and correlation matrix for 18 md TISnotTOS for *pKK* channel.





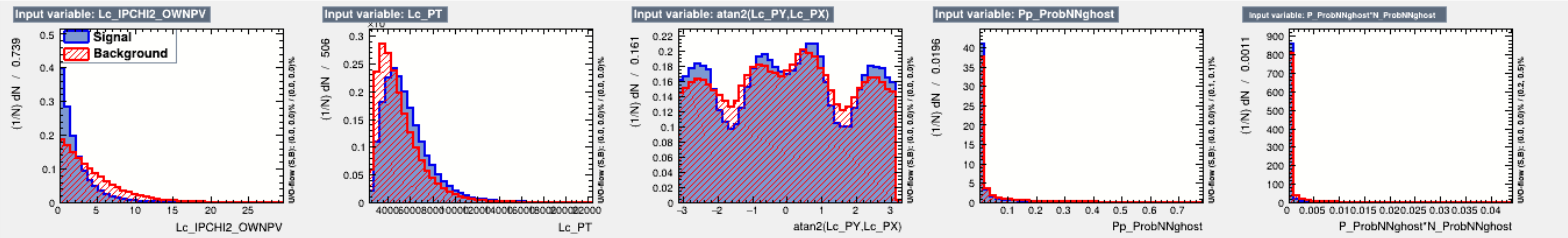


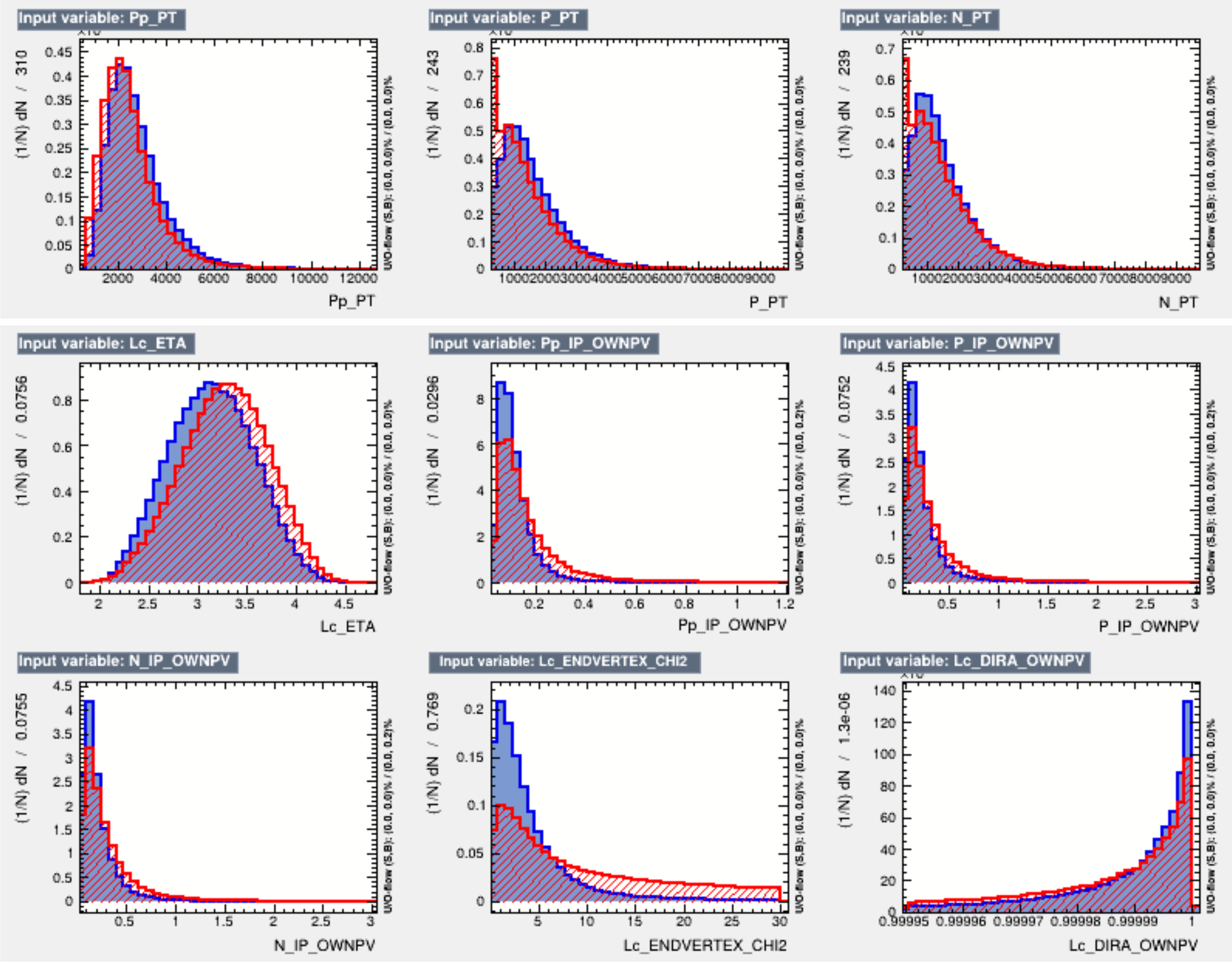


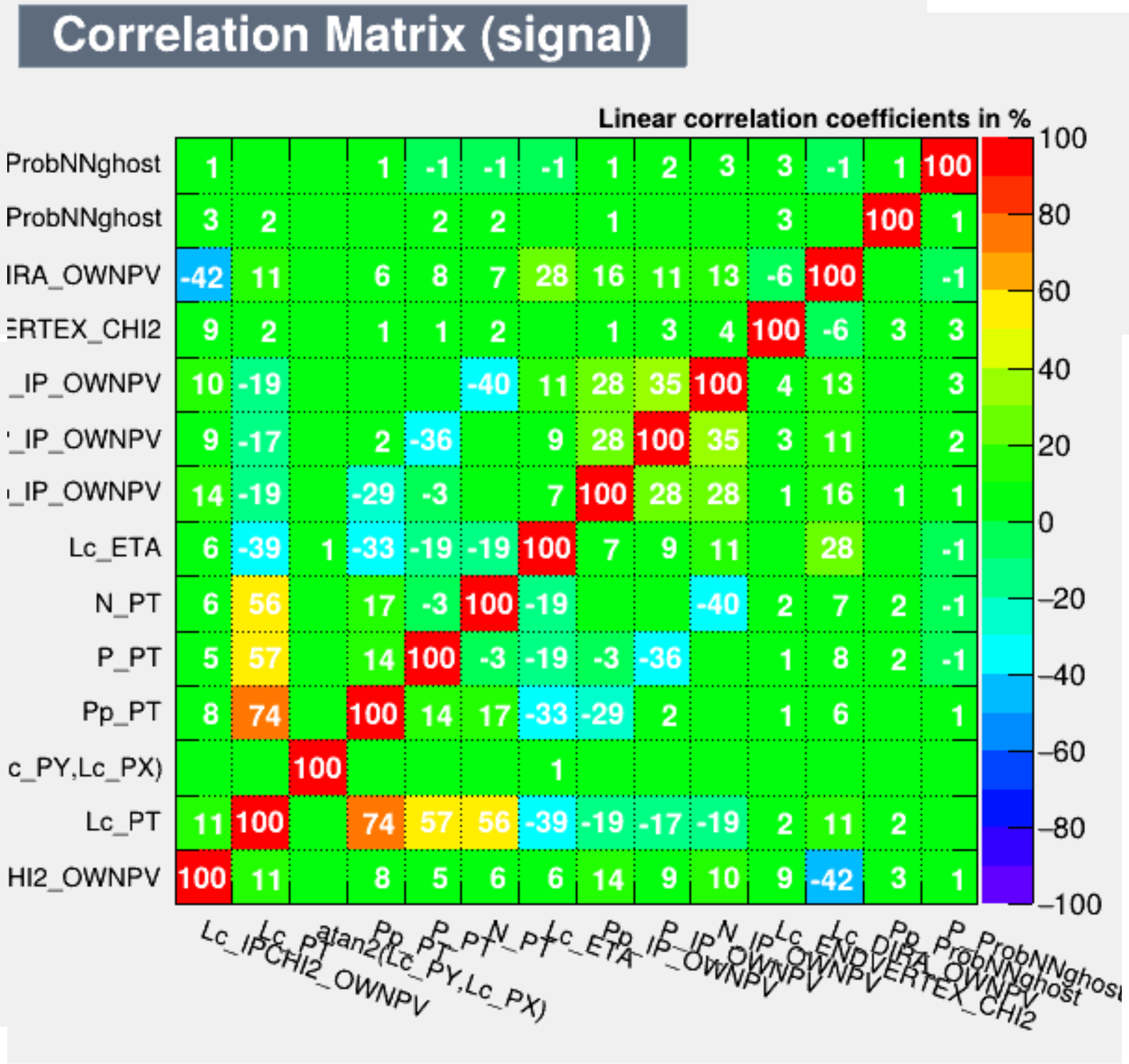
No variables used as input in the training have very high correlation.

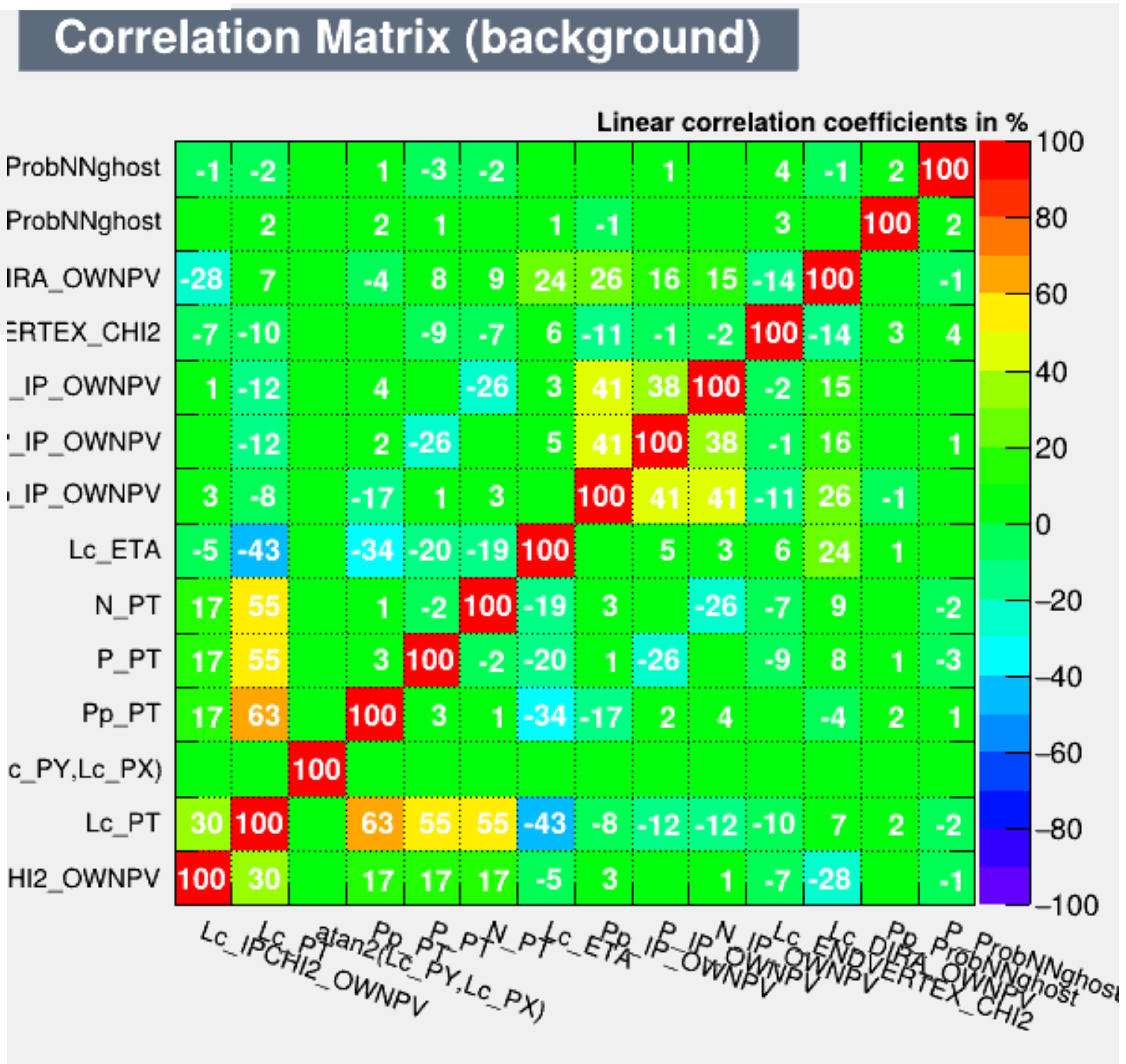
BDT variables

Input variables distribution and correlation matrix for 18 md TISnotTOS for $p\pi\pi$ channel.







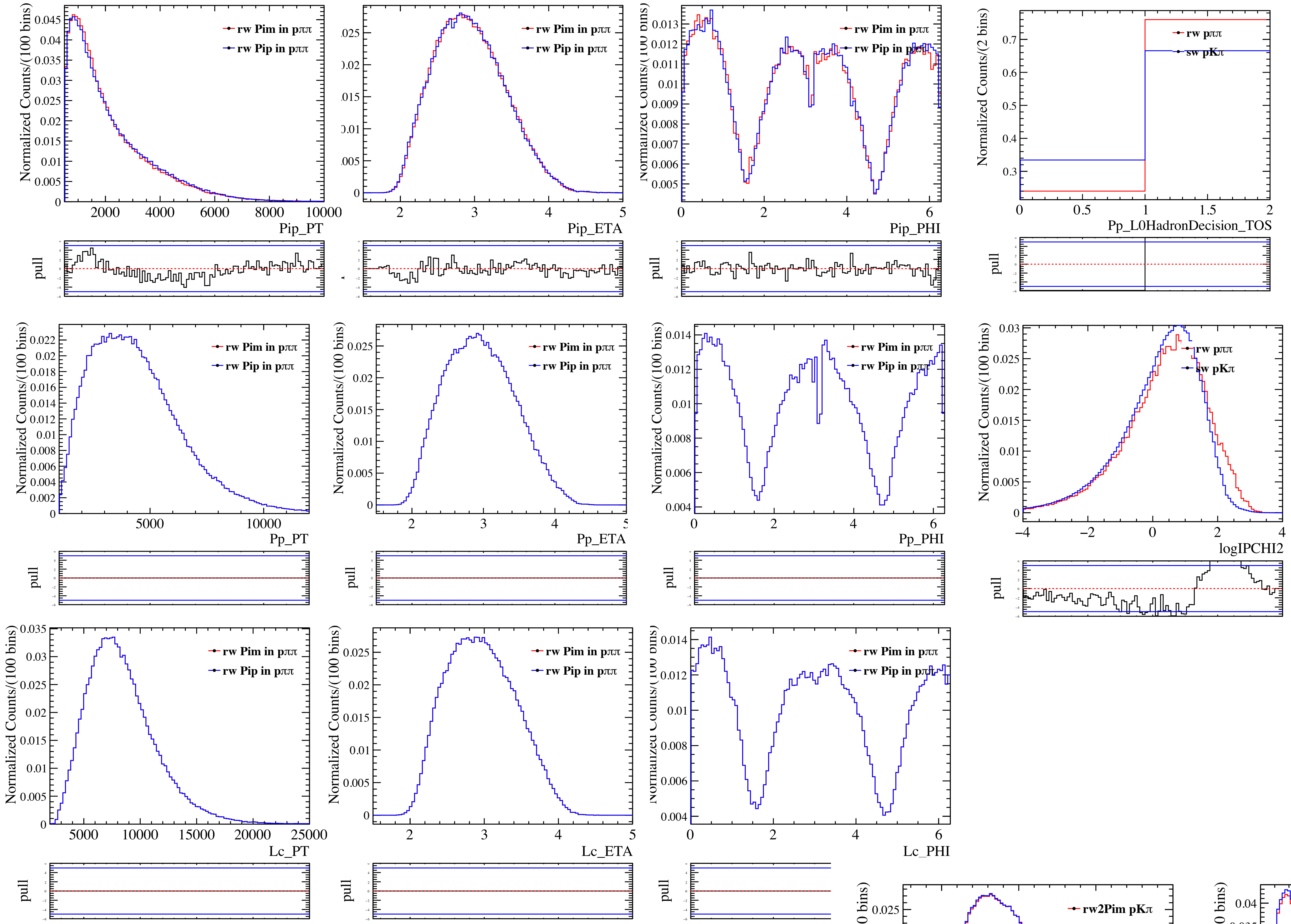


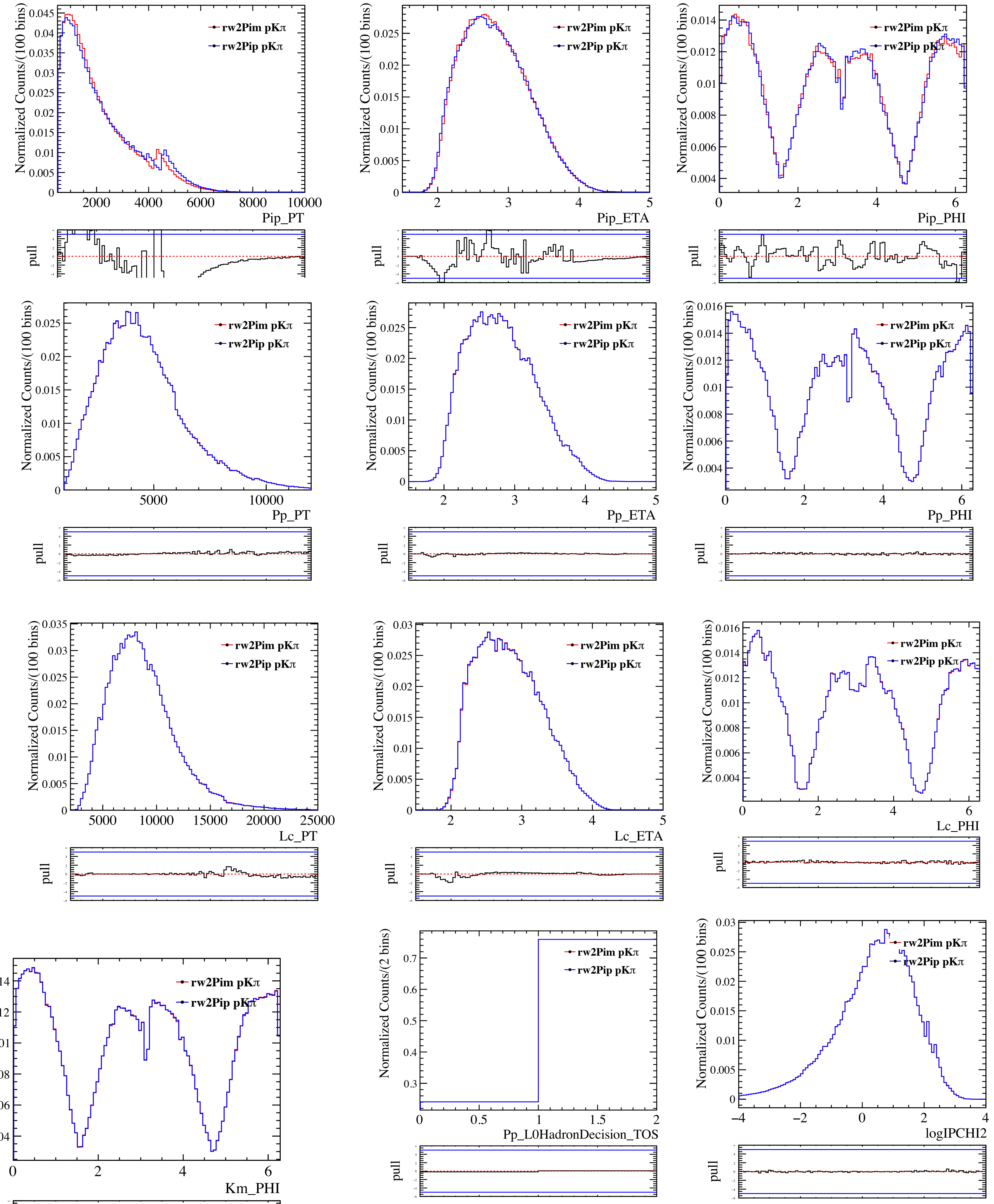
No variables used as input in the training have very high correlation.

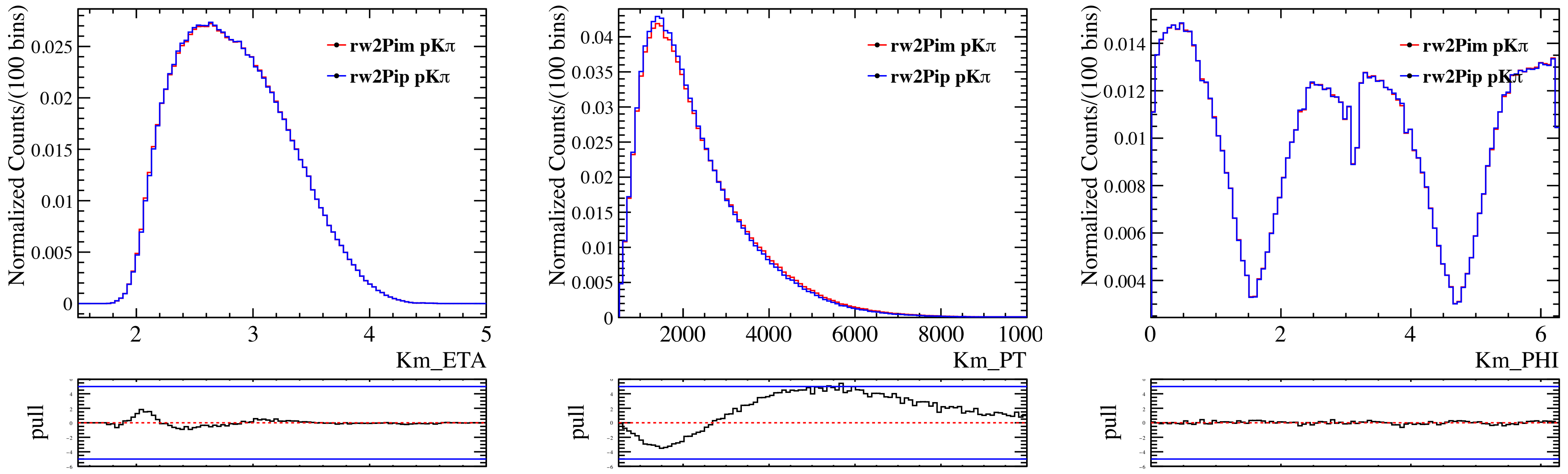
Detection asymmetry extraction $A_D(\pi\pi)$

The 18 MagDown TOS has been shown as an example.

Re-weighting the kinematic of the kaon on both π^+ *and* π^- with 1-D iterative method on $p_T(\pi), \eta(\pi), \phi(\pi), p_T(\Lambda_c), \eta(\Lambda_c), \phi(\Lambda_c), p_T(p), \eta(p), \phi(p), \log(\chi^2_{IP}(\Lambda_c), (TOS\ fraction)$.



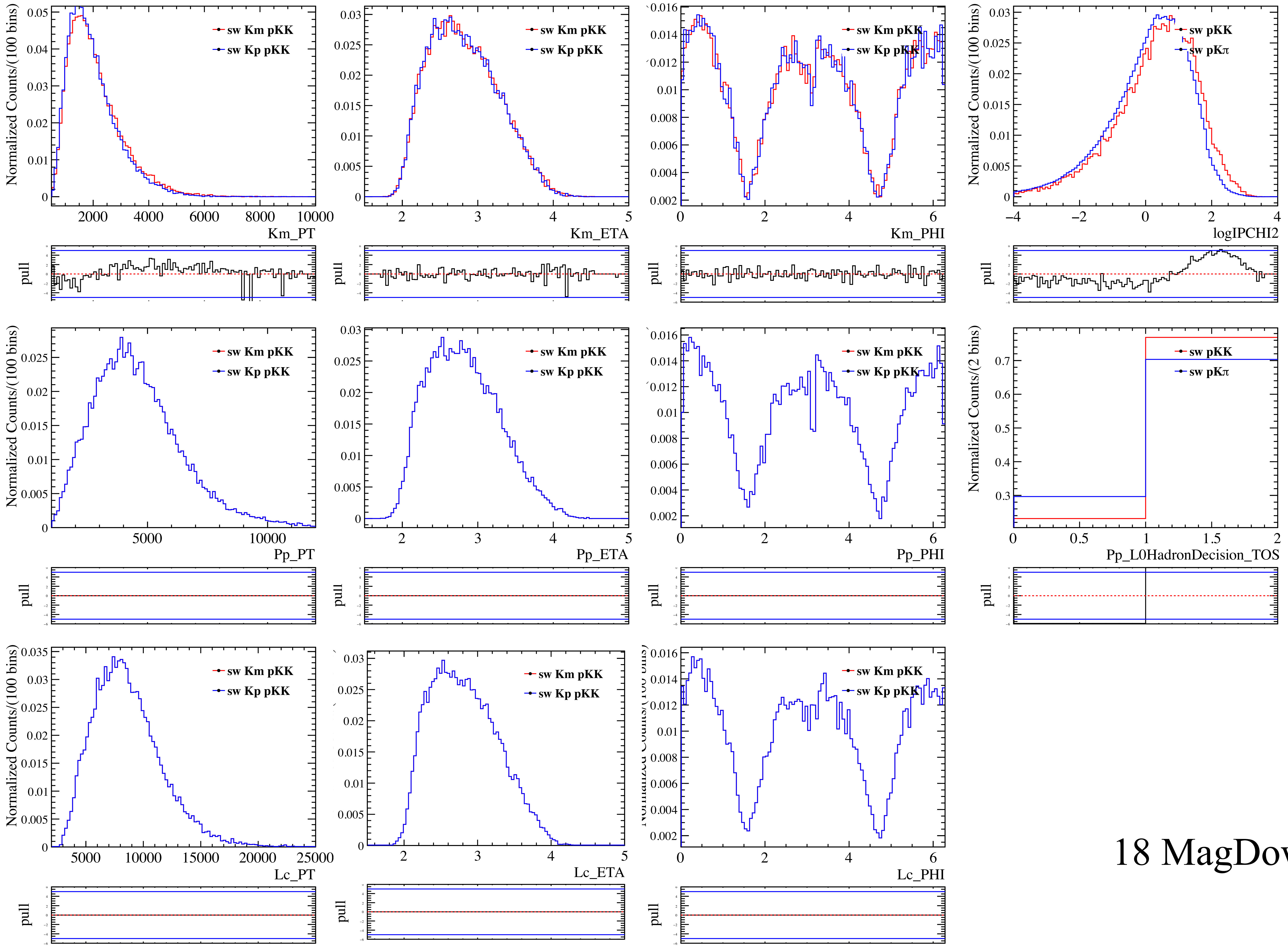




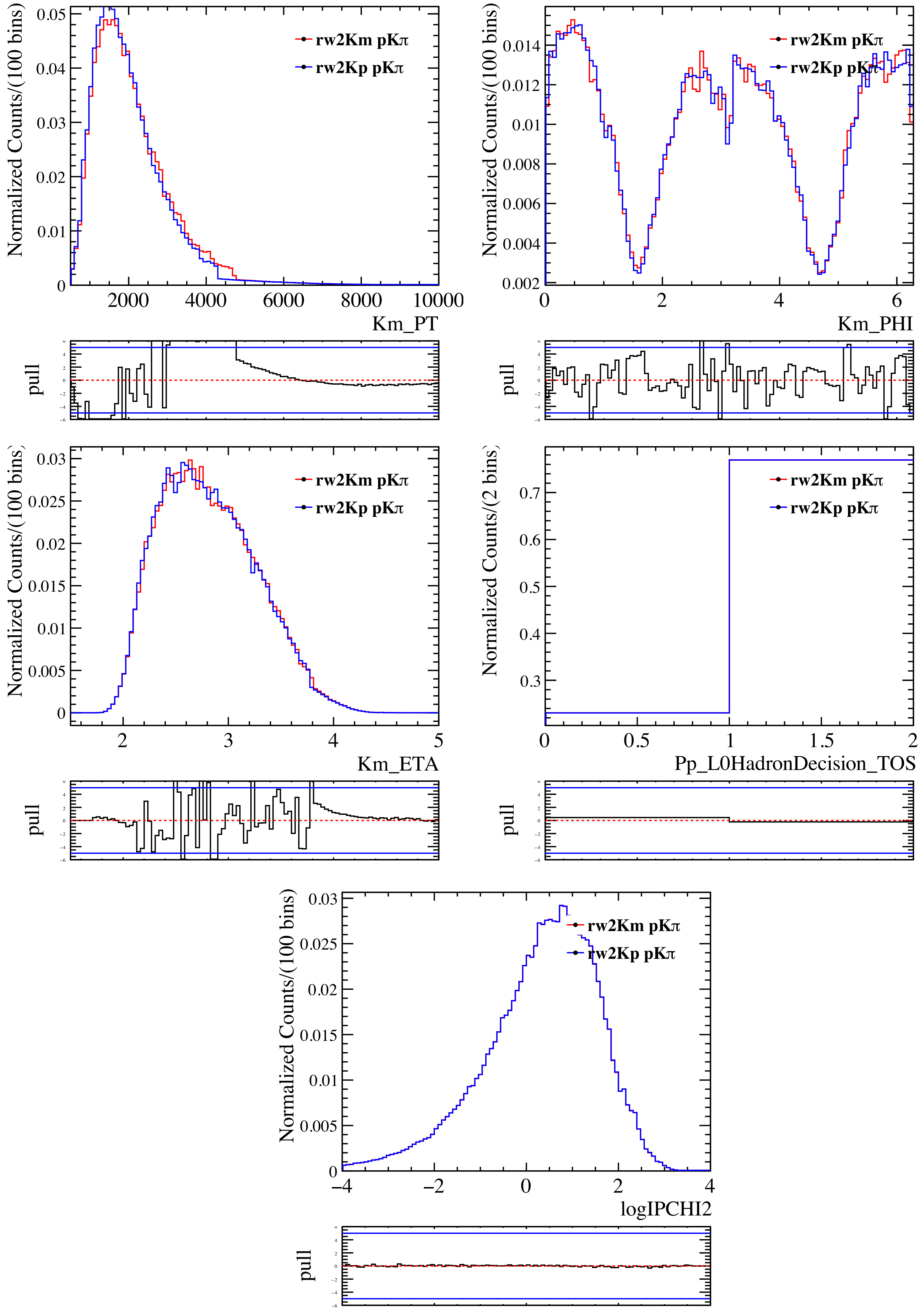
Similar procedure for $p\pi\pi$ shown in backup.

Detection asymmetry extraction $A_D(KK)$

Re-weighting the kinematic of the kaon on both K^+ *and* K^- with 1-D iterative method on $p_T(K), \eta(K), \phi(K), \log(\chi^2_{IP}(\Lambda_c), (TOS\ fraction)$.



18 MagDown TOS

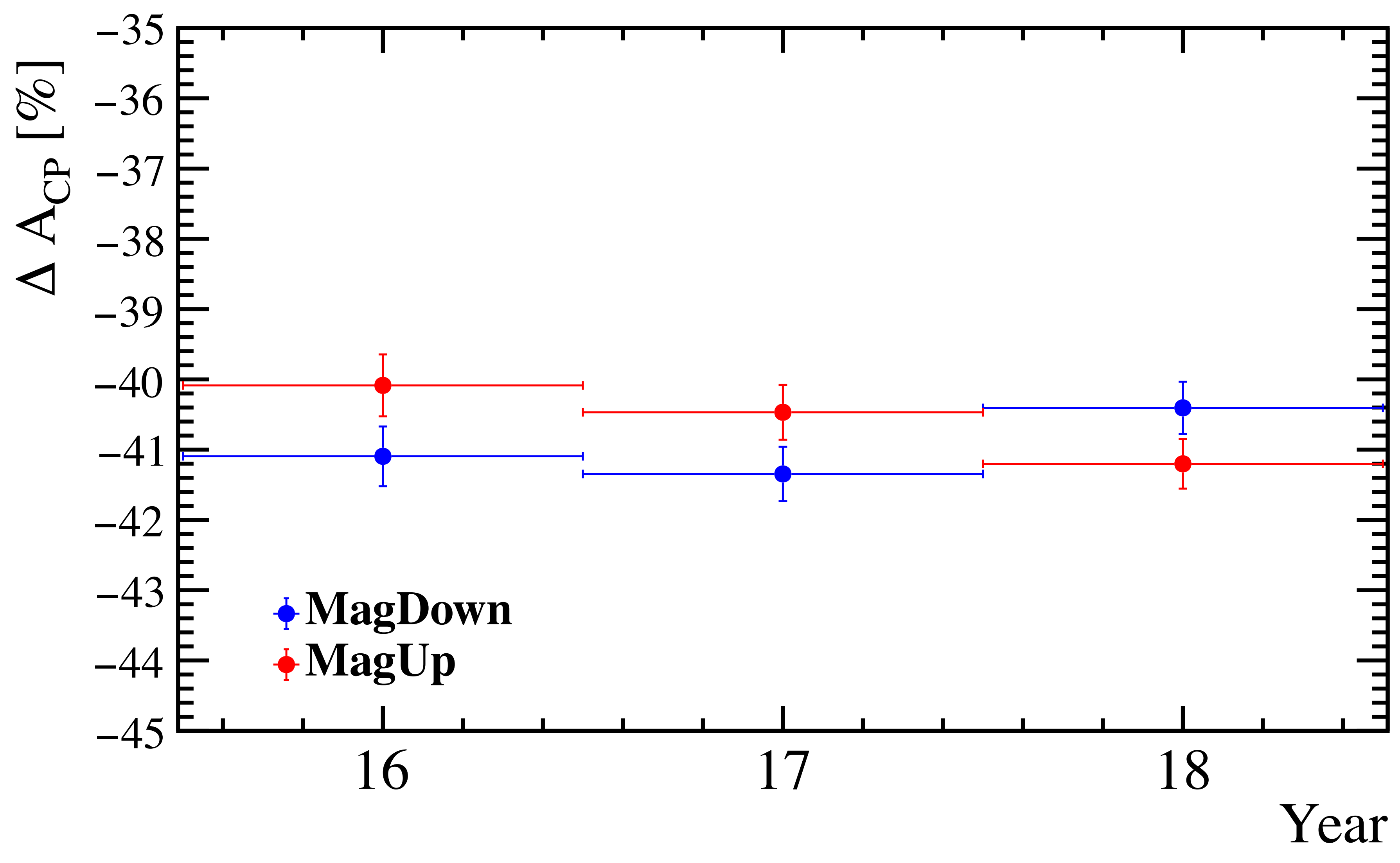


ΔA_{CP} Blinded

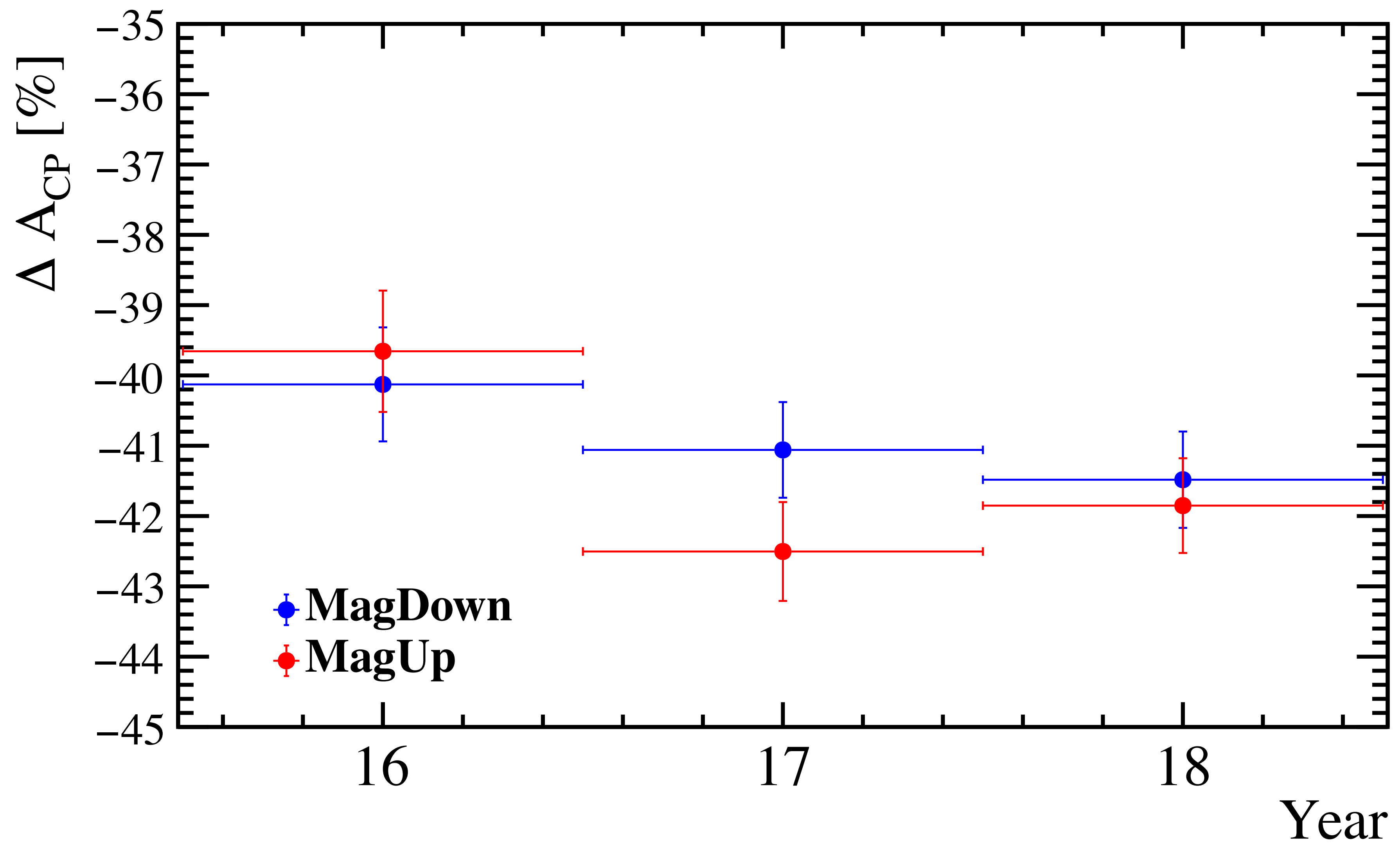
Sample	ΔA_{CP}^{raw}[%]	$A_D(K_1K_2)$[%]	$A_D(\pi_1\pi_2)$[%]	ΔA_{CP}[%]
16 Down TIS	-41.01 ± 0.42	0.030 ± 0.031	-0.070 ± 0.035	-41.11 ± 0.43
16 Down TOS	-40.18 ± 0.81	-0.061 ± 0.063	0.081 ± 0.079	-40.04 ± 0.81
16 Up TIS	-40.10 ± 0.44	0.002 ± 0.032	0.021 ± 0.036	-40.08 ± 0.44
16 Up TOS	-39.55 ± 0.86	-0.097 ± 0.068	-0.021 ± 0.083	-39.47 ± 0.86
17 Down TIS	-41.29 ± 0.38	0.005 ± 0.021	-0.058 ± 0.025	-41.35 ± 0.39
17 Down TOS	-41.05 ± 0.68	-0.013 ± 0.041	0.078 ± 0.042	-40.95 ± 0.68
17 Up TIS	-40.50 ± 0.39	-0.021 ± 0.022	0.023 ± 0.025	-40.45 ± 0.39
17 Up TOS	-42.46 ± 0.70	-0.067 ± 0.043	0.049 ± 0.046	-42.35 ± 0.70
18 Down TIS	-40.33 ± 0.37	0.030 ± 0.021	-0.066 ± 0.024	-40.42 ± 0.37
18 Down TOS	-41.58 ± 0.68	-0.069 ± 0.043	0.131 ± 0.045	-41.38 ± 0.69
18 Up TIS	-41.23 ± 0.35	-0.010 ± 0.020	0.030 ± 0.022	-41.19 ± 0.35
18 Up TOS	-41.82 ± 0.67	-0.078 ± 0.040	0.053 ± 0.046	-41.69 ± 0.67

Combination of all sub-samples: $\Delta A_{CP} = (-40.87 \pm 0.14)\,\%$

ΔA_{CP} Blinded



TISnotTOS

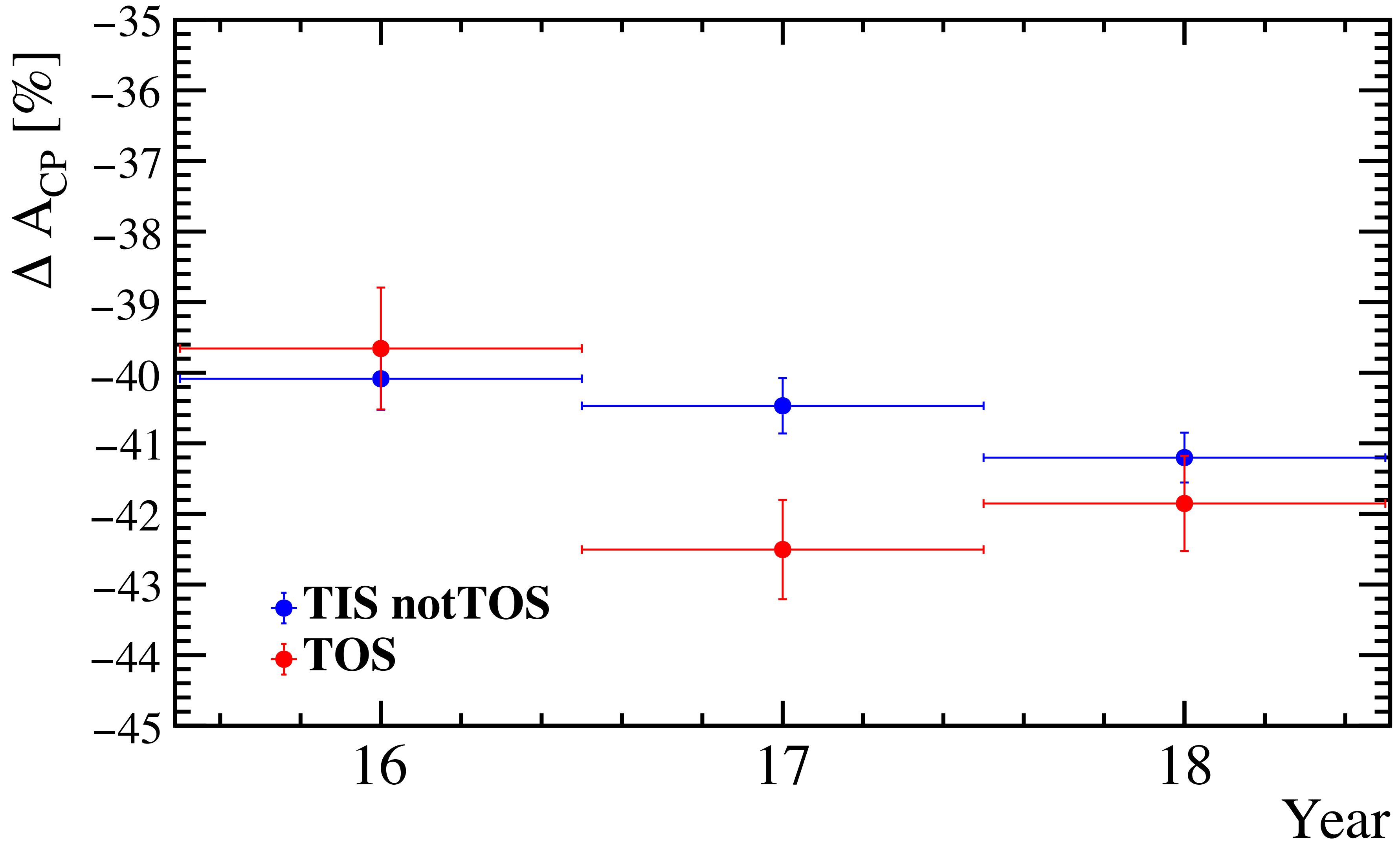


TOS

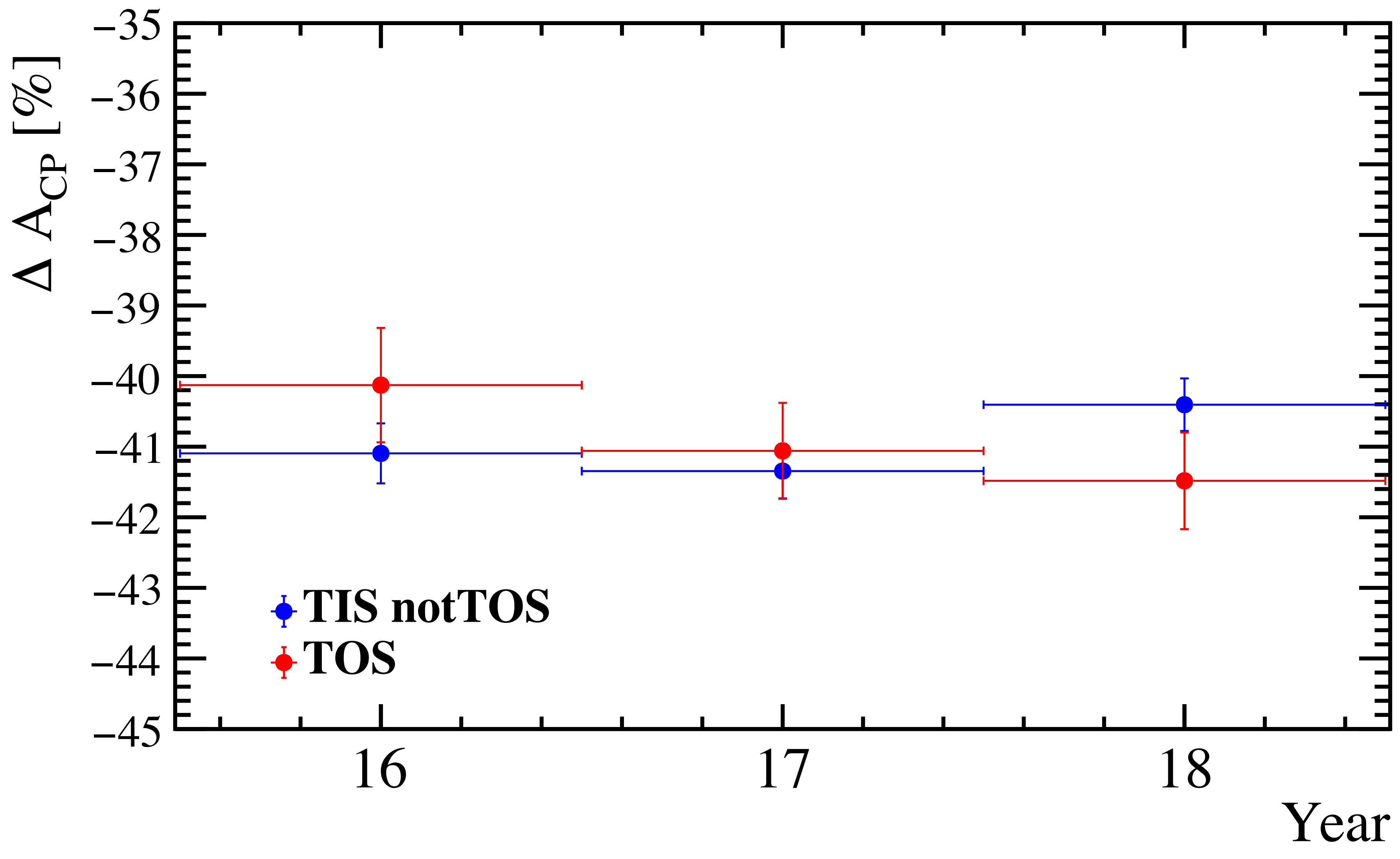
Sample	$\Delta A_{CP}^{MagDown}$[%]	ΔA_{CP}^{MagUp}[%]	*Difference* [σ]
TISnotTOS 16	-41.11 ± 0.43	-40.08 ± 0.44	-1.67
TISnotTOS 17	-41.35 ± 0.39	-40.45 ± 0.39	-1.63
TISnotTOS 18	-40.42 ± 0.37	-41.19 ± 0.35	1.51
TOS 16	-40.04 ± 0.81	-39.47 ± 0.86	-0.48
TOS 17	-40.95 ± 0.68	-42.35 ± 0.70	1.43
TOS 18	-41.38 ± 0.69	-41.69 ± 0.67	0.32

Each sub-sample is compatible with each other between different magnet polarities.

ΔA_{CP} Blinded



MagUp



MagDown

Sample	$\Delta A_{CP}^{TISnotTOS}$[%]	ΔA_{CP}^{TOS}[%]	*Difference* [σ]
Down 16	-41.11 ± 0.43	-40.04 ± 0.81	-1.17
Down 17	-41.35 ± 0.39	-40.95 ± 0.68	-0.51
Down 18	-40.42 ± 0.37	-41.38 ± 0.69	1.23
Up 16	-40.08 ± 0.44	-39.47 ± 0.86	-0.63
Up 17	-40.45 ± 0.39	-42.35 ± 0.70	2.37
Up 18	-41.19 ± 0.35	-41.69 ± 0.67	0.66

Each sub-sample is compatible with each other between different triggers configuration.

Systematic studies: Fit model

- Setting a single Double-Side Crystal Ball function as the signal model could describe the data well, but give different yields with respect to our model (single Johnson function).
- To study this systematic, data are fitted with a DSCB with only the σ parameter independent between charges.
- The combinatorial background and the mis-ID background in $p\pi\pi$ TOS samples are not changed.
- Applying the same blinding and detection asymmetries as the nominal, the blinded delta asymmetry results with DSCB fits are measured in all sub-samples and combined as a weighted sum.
- The absolute difference between combined delta asymmetry is assigned as a systematic uncertainty.

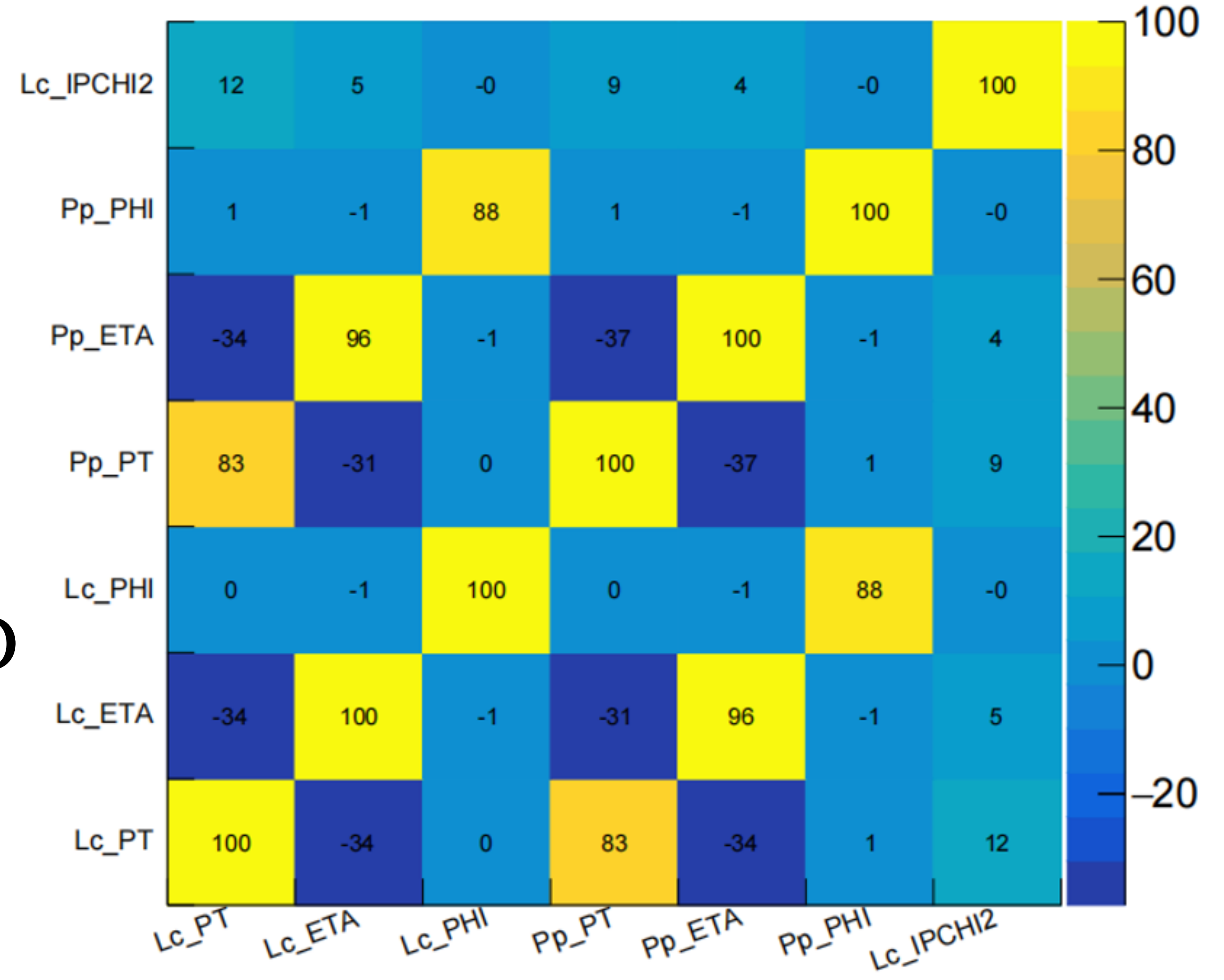
18 Mag Down pKK TOS

18 Mag Down $p\pi\pi$ TOS

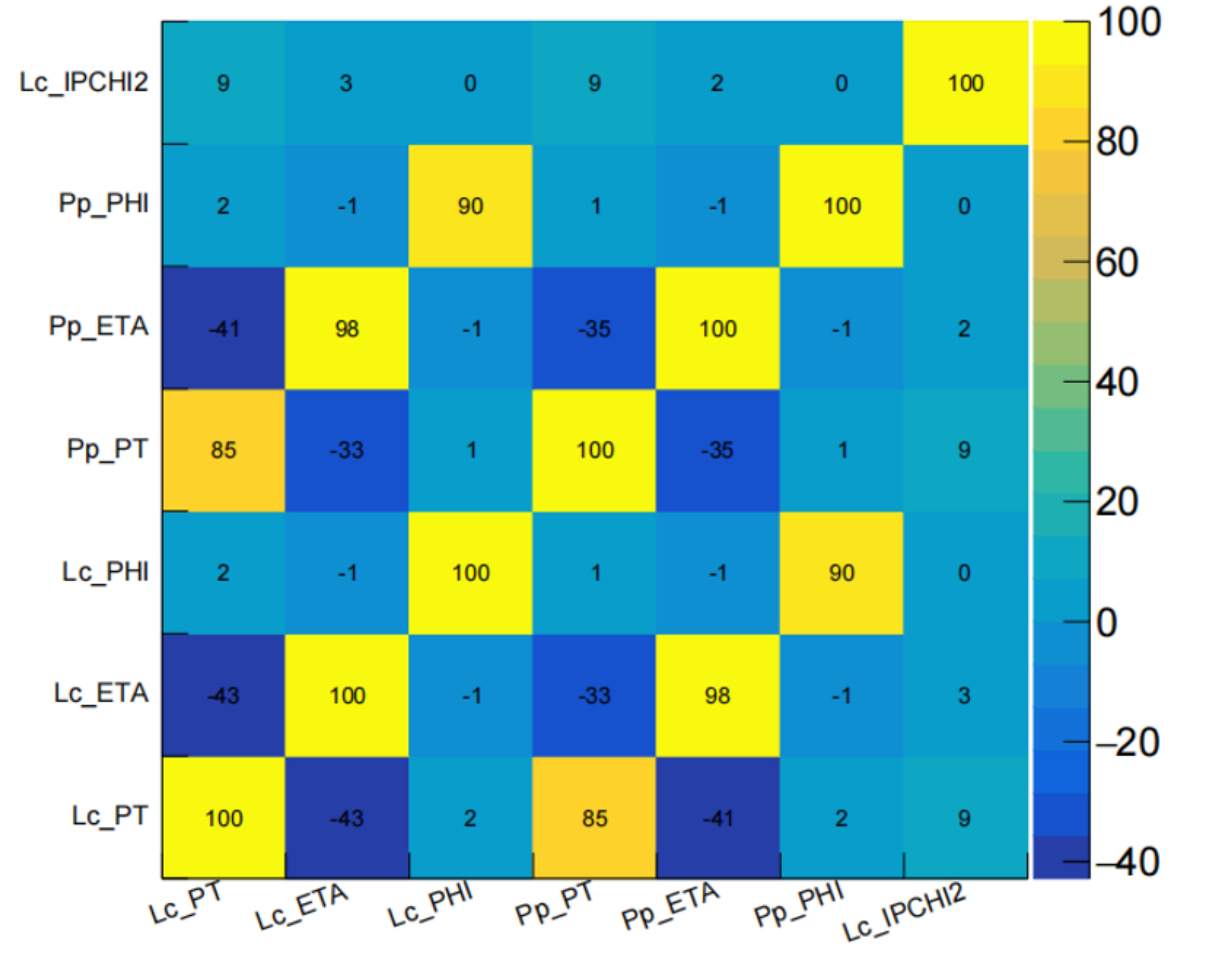
Systematic studies: Re-weighting procedure

- The correlation between the re-weighting variables (following plot) might have effect on the measurements, which was not considered in the 1D iteration re-weighting.
- In that case, the 2D iteration re-weighting method is introduced, with the same logic as the 1D re-weighting
- The combination of variables on which the re-weighing is iterated is:

  [Lc_PT, Lc_ETA] , [Lc_PT, Pp_PT] , [Lc_PT, Pp_ETA] , [Lc_ETA, Pp_PT] , [Lc_ETA, Pp_ETA] , [Lc_PHI, Pp_ETA] , [Pp_PT, Pp_ETA]
- The Pp_TOS distributions in pK^-K^+ and $p\pi^-\pi^+$ are not consistent after aboves steps.
- One step Pp_TOS weighting is applied then.
- The blinded delta asymmetry results are measured in all sub-samples and combined as a weighted sum.
- The absolute difference between combined delta asymmetry is signed as a systematic uncertainty.



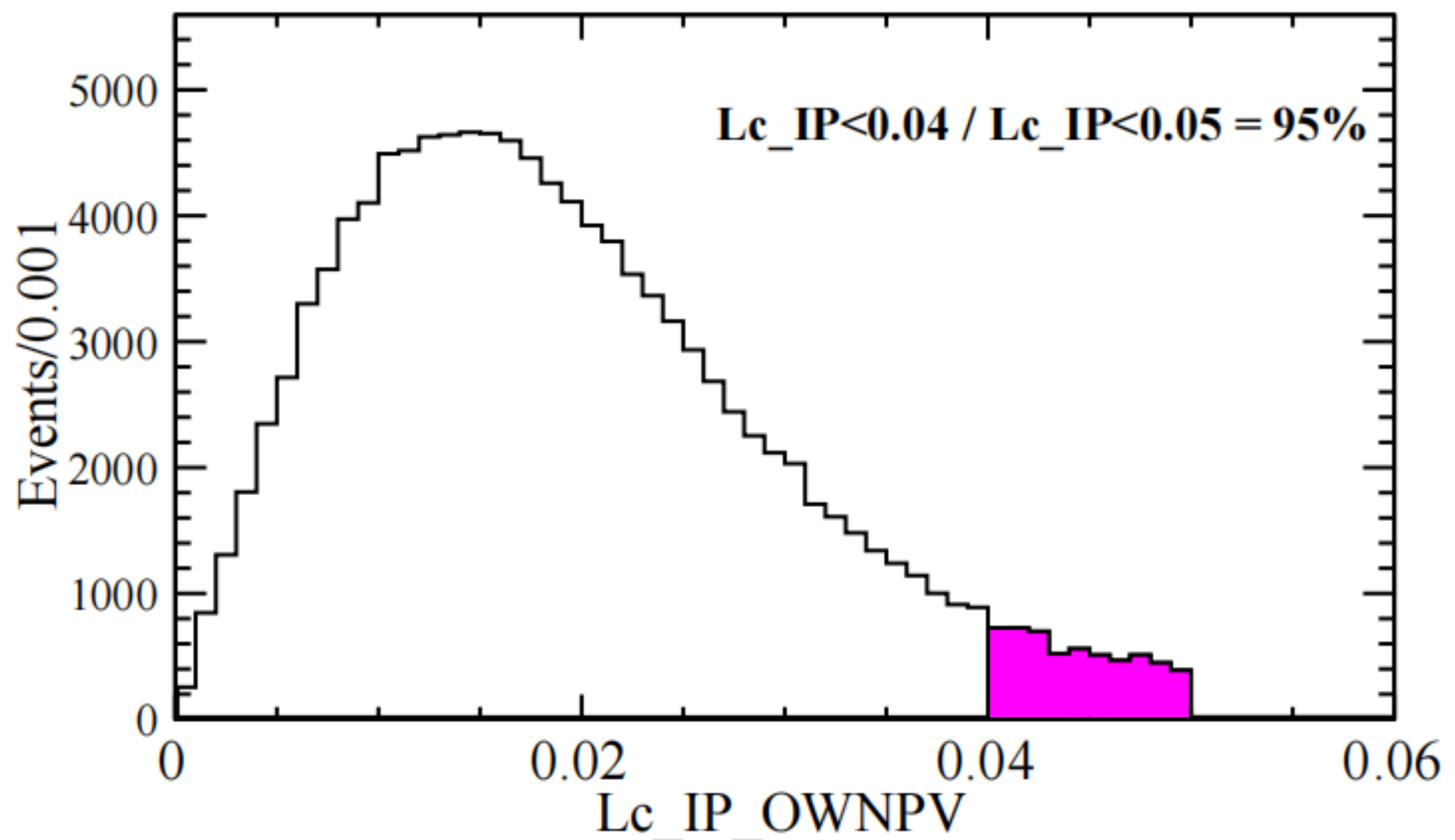
18 Mag Down pKK TIS



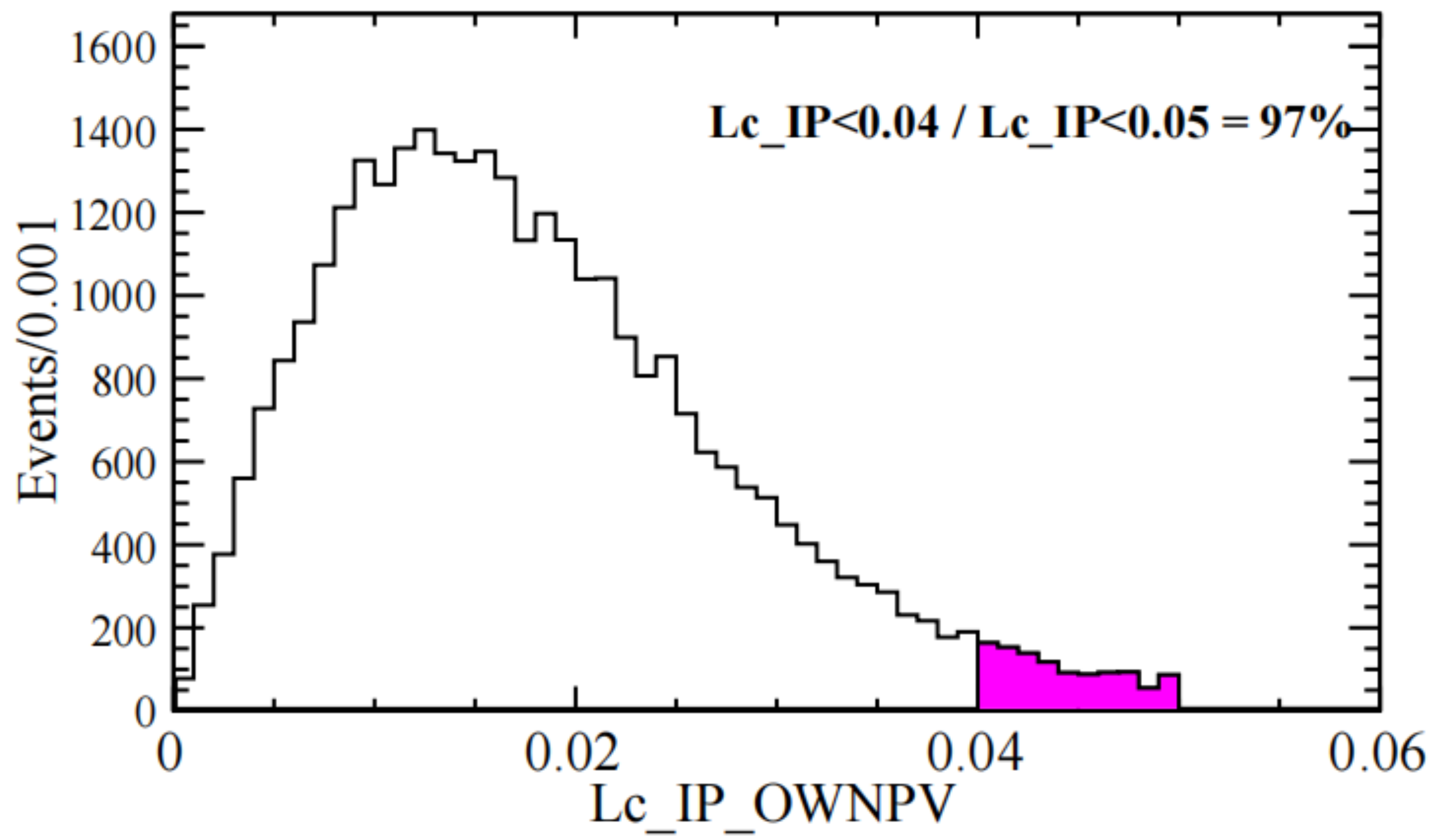
18 Mag Down pKK TOS

Systematic studies: Secondary produced Λ_c

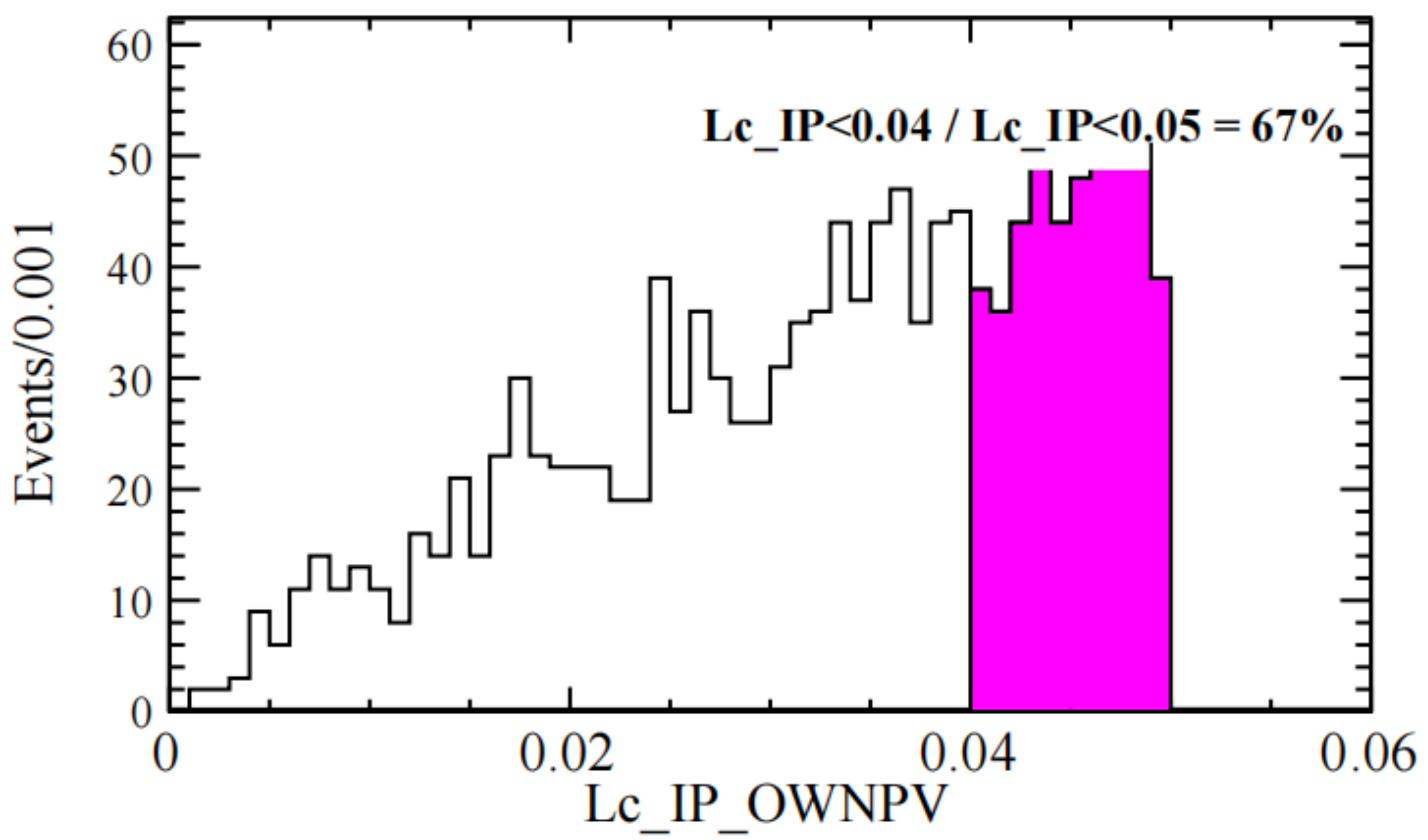
- The secondary produced Λ_c^+ might contribute to a different delta asymmetry.
- A stricter Lc_IP cut is applied to study this effect: Lc_IP_OWNPV<0.04
- This indicates a different secondary Λ_c^+ contamination ratio.
- The mass fit, blinding and detection asymmetry methods employed in the full sample are also applied on the datasets with the new IP cut.
- The blinded delta asymmetry results are measured in all sub-samples and combined as a weighted sum.
- The absolute difference between combined delta asymmetry is assigned as a systematic uncertainty.



18 Mag Down *pKK* TIS



18 Mag Down *pKK* TOS



18 Mag Down *pKK* Secondaries produced

Systematic studies: Residual asymmetry in $A_D(\pi\pi)$

- The re-weighting of $pK\pi$ to $p\pi\pi$ does not completely remove all differences between the Kaon kinematics.
- So we can re-write $\Delta A^{K\pi}_{raw} = -A_D(\pi^-) + A_D(\pi^+) + \left[-A_D^{\pi^-}(K^-) + A_D^{\pi^+}(K^+)\right] = A_D(\pi\pi) + A_{residual}$
- The residual asymmetry can be estimated by the detection asymmetry table quoted from LHCb-ANA-2018-002.

$$A_{residual} = (-1)\cdot\left[\frac{1}{N_{\pi^-}}\sum_i A^D_{i,\pi^-}(K^-) - \frac{1}{N_{\pi^+}}\sum_i A^D_{i,\pi^+}(K^-)\right]$$

The absolute value of the combined residual asymmetry as $\sigma_{\Delta A_{CP}} = \sqrt{1/\sum_i (1/\sigma_i^2)}$ is assigned as a systematic uncertainty.

Independent systematic uncertainties → sum in quadrature.

Source	Section	Uncertainty[%]
Fit model	9.1	0.02
variables Correlation	9.2	0.07
Secondary Λ_c^+	9.3	0.003
Residual detection asymmetry	9.4	0.002
Total	9.5	0.08