A multidimensional study of SIDIS charged Kaon beam spin asymmetry over a wide range of kinematics

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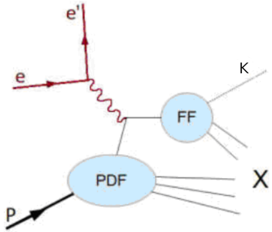
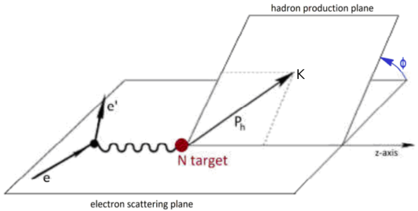
December 13, 2022

Physics motivation

- Kaon Sidis: $e^- p^+ \to e^- K^{\pm} X$
- polarised electron beam interacting with an un-polarised target:
- $d\sigma = d\sigma_0(1 + A_{UU}^{\cos\phi} \cos\phi + A_{UU}^{\cos 2\phi} \cos 2\phi + \lambda_e A_{LU}^{\sin\phi} \sin\phi)$
- $BSA = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-} = \frac{A_{LU}^{\sin\phi} \sin\phi}{1 + A_{UU}^{\cos\phi} \cos\phi + A_{UU}^{\cos 2\phi} \cos 2\phi}$





Process (left) and kinematics (right) of single kaon SIDIS

Physics motivation

- Previous experiments (CLAS and HERMES) showed that kaon signals generally follow the pion signals, but they have larger values
- With these measurements the s-quark can be accessed, but due to the low statistics the uncertainties are large and the kinematic bins are wide
- The high statistics on an extended kinematic range, which is available with the new CLAS12, enables a fully differential analysis for the first time

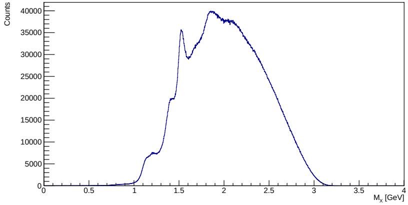
Particle ID and dataset

- Eventbuilder particle ID
- Fiducial cuts - can be found in the common RG-A analysis note
- Electron and hadron PID refinements:
  - PCAL minimum energy deposition
  - ECAL sampling fraction cut
  - z-vertex position cut
  - Cut on vertex difference
  - $|\chi^2_{PID}| < 3$
- Use machine learning for Kaon ID
- QA cuts
- Topology: at least one good electron and at least one good Kaon
- Combine in- and outbending 10.6 GeV (2018) and inbending 10.2 GeV (2019) RG-A datasets:
  - 5032-5419
  - 5422-5666
  - 6616-6783

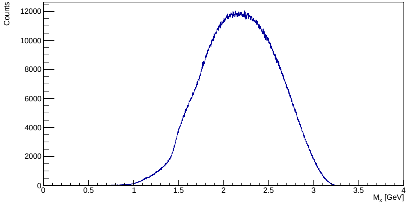
Kinematic cuts

- y $<$ 0.75 (minimal electron momentum of $\sim$2.65 GeV)
- 1.25 GeV $< p_K <$ 3 or 5 GeV
- Only use forward detector for Kaons:
  - $5^\circ < \theta_K < 35^\circ$
  - $5^\circ < \theta_e < 35^\circ$
- To select the deep inelastic scattering region:
  - W $>$ 2 GeV
  - $Q^2 > 1$ GeV^2
- To reject the kaons from the fragmentation region:
  - $x_F > 0$
  - 0.3 $<$ z $<$ 0.7
- To reduce the contamination from exclusive processes:
  - $M_X > 1.6$ GeV

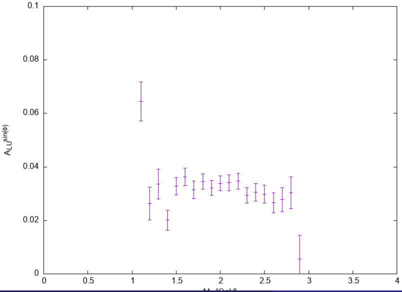
Missing mass

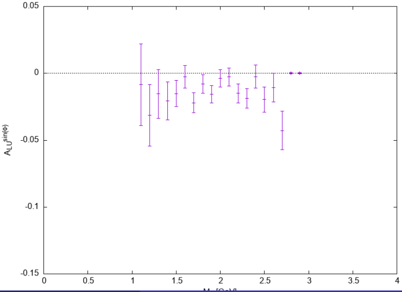


K^+



K^-





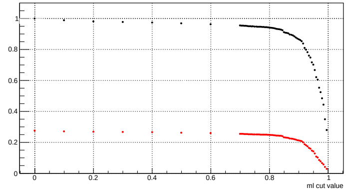
Machine learning

- Reduce pion contamination in the kaon sample
- The main goal is not to identify pions and kaons but to get a clean kaon sample with reasonable statistics
- Use most of the available detector information available:
  - EventBuilder PID
  - Momentum and β
  - Deposited energies in the 3 calorimeters
  - Calorimeter time information
  - Cluster moments and shower profiles
  - HTCC number of photoelectrons and time information
  - Energy depositions and time information in the 3 FTOF layers
- The results were cross-checked with an other MC samples and with the RICH

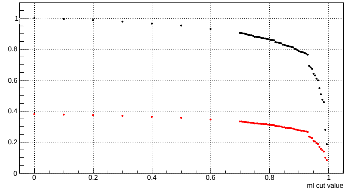
Method used for training

- Toolkit: Root TMVA
- Deep neural network
  - 3 hidden layers with 128 neurons per layer
  - Fully connected
  - tanh activation function, linear for the last neuron
- Training
  - Crossentropy loss function
  - Xavier weight initialisation
  - Optimizer: ADAM
  - Batch size: 30
  - Learning rate: 10^{-5}
  - The input variables are normalised
  - The same amount of π-s and Kaons are used during the training

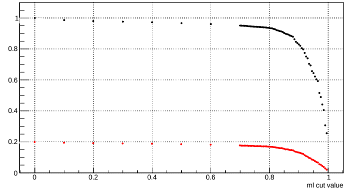
Contamination and machine learning



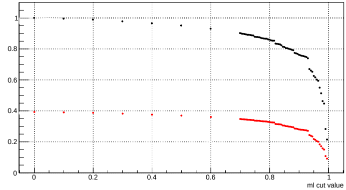
inbending, K^+



inbending, K^-



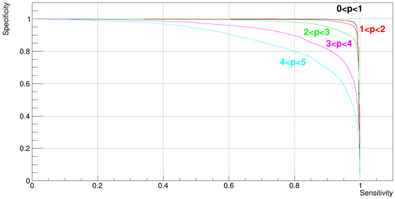
outbending, K^+



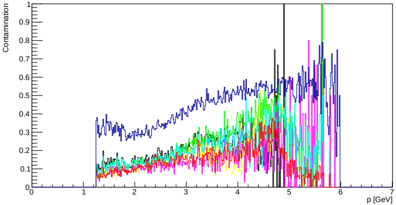
outbending, K^-

Red - Contamination, Black - Efficiency

Machine learning



ROC curves at different momenta ranges



Contamination obtained from simulated data

The resulting curve is red, when all variables are used during the training, yellow, when the EventBuilder PID and the χ^2_{PID} is not used, green, when the FTOF is not used, blue, when the calorimeter is not used, purple, when the HTCC is not used and black, when only the momentum and β is used. In the contamination plot the results with the EventBuilder PID are plotted in dark blue for comparison.

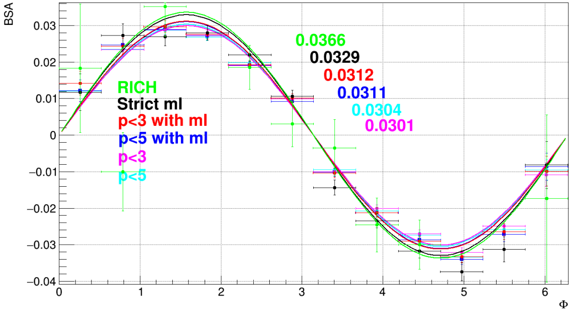
RICH-ML Correlation

RICH\EB	pion	Kaon
pion	104860	14454
Kaon	2372	11514

RICH\EB+ML	pion	Kaon
pion	119253	2040
Kaon	10001	4292

Correlation matrices of PID methods using kaons and pions in the RICH acceptance

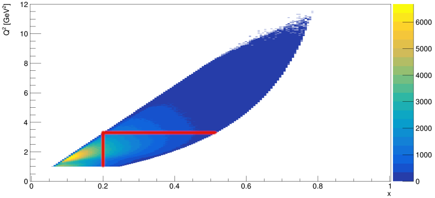
Integrated asymmetry



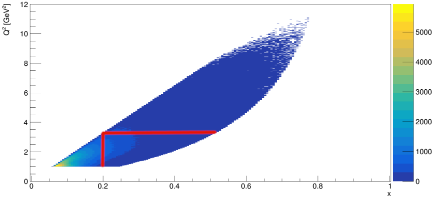
Integrated BSA values in bins of Φ together with the fitted $\sin\Phi$ functions for K^+ using different PID methods: turquoise-p$<$5 GeV, purple-p$<$3 GeV, blue-p$<$5 GeV and ml cut, red-p$<$3 GeV and ml cut, black-strict(0.99) ml cut, green-RICH (in order of decreasing pion contamination)

Multidimensional binning

- 3 bins on the $x - Q^2$-plane



K^+ with 3 bins



K^- with 3 bins

Bin borders on the Q^2-x_B-plane

Multidimensional binning

- 3 (K^+) or 2 (K^-) bins in P_T or x

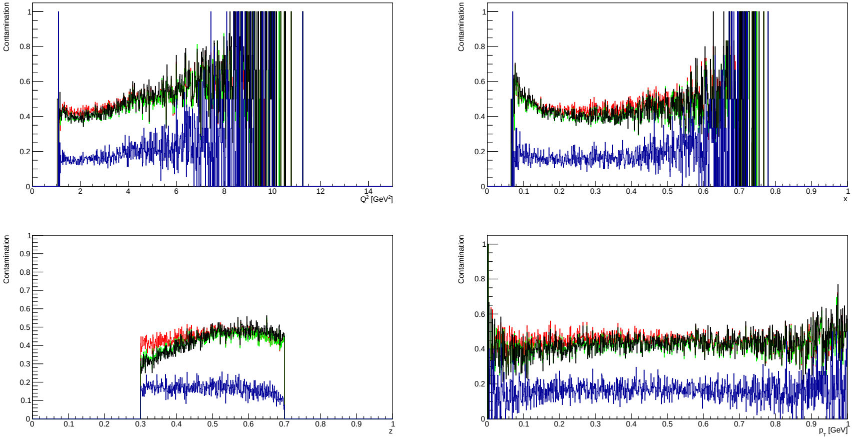
Bin number	P_T bin	x bin
1	$p_T < 0.33$ GeV	$z < 0.34$
2	0.33 GeV$< p_T < 0.66$	$0.34 < z < 0.52$
3	$p_T > 0.66$ GeV	$z > 0.52$

Bin number	P_T bin	x bin
1	$p_T < 0.5$ GeV	$z < 0.5$
2	$p_T > 0.5$ GeV	$z > 0.5$

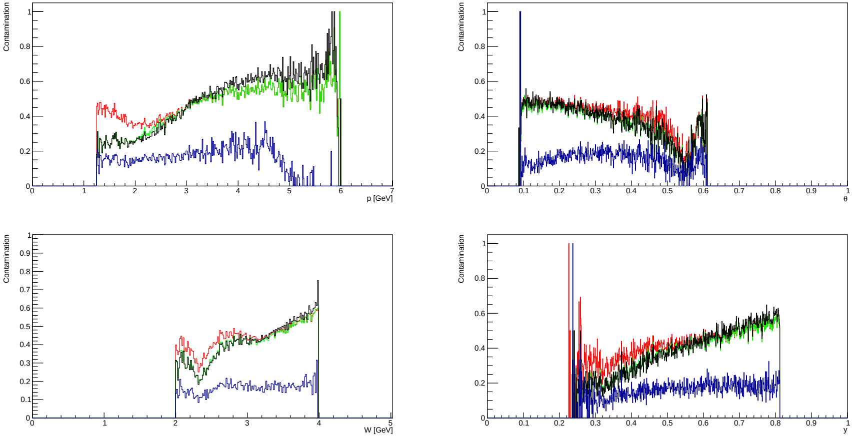
The binning for K^+ (top) and for K^- (bottom)

- 10 bins in the last dimension - x or P_T

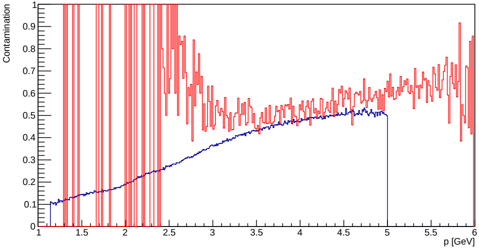
Pion contamination



Pion contamination



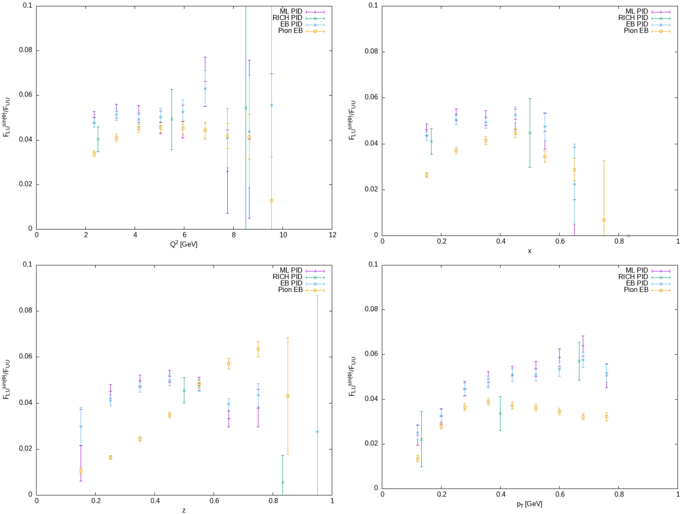
Pion contamination, subtraction



Comparison of the kaon-pion contamination obteined from MC (blue) and from RICH (red) as a function of momentum using positive Eventbuilder kaons

- The pion contamination is too high - The pion asymmetries should be subtracted
- Contamination in a given bin:
  $$\frac{1}{N_{in}^{rec}+N_{out}^{rec}+N_{2019}^{rec}}\left(\frac{N_{inmc}^{mcm\pi}}{N_{inmc}^{rec}}(N_{in}^{rec}+N_{2019}^{rec})+\frac{N_{outmc}^{mcm\pi}}{N_{outmc}^{rec}}N_{out}^{rec}\right)$$
- The asymmetry: $\frac{A_{meas}^{K}-CA_{meas}^{\pi}}{1-C}$

Pion contamination, subtraction



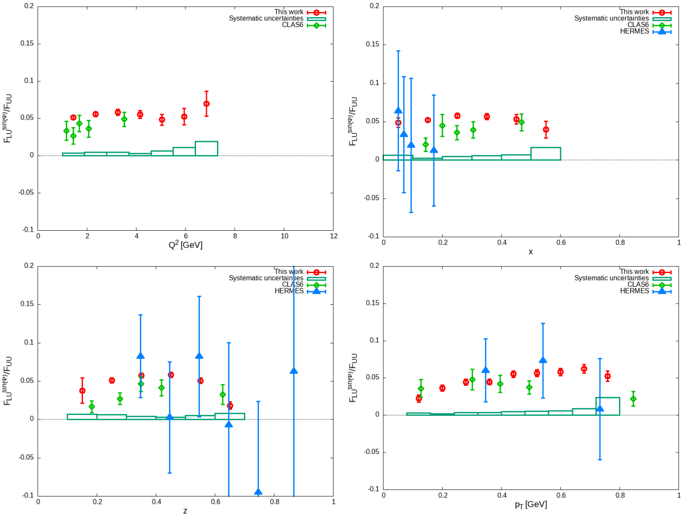
"Raw" $F_{LU}^{\sin\phi}/F_{UU}$ as a function of Q^2 (top left), x_B (top right), z (bottom left) and P_T (bottom right) for K$^+$ with different PIDs compared with π^+ results. The

Systematic uncertainties

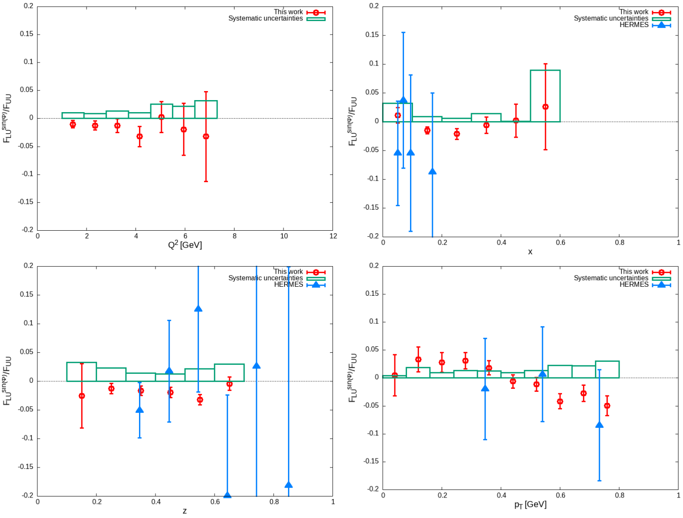
- Most of the sources are the same as for the pion SIDIS note
- All uncertainties are determined for every kinematic bin

- Uncertainty of the beam polarization
- Effect of the fiducial cuts
- Contamination of the electron and Kaon samples
- Contamination of the SIDIS sample
- Acceptance effects
- Effect of the extraction method and higher order moments
- Bin migration and resolution effects
- Radiative effects
- Effects of the pion subtraction

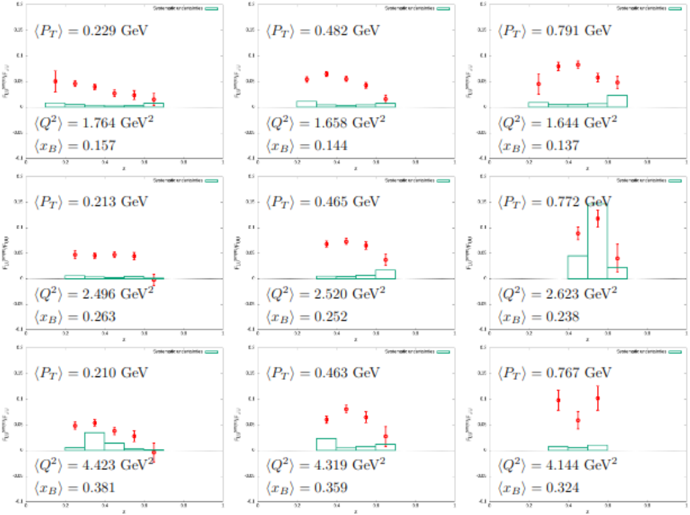
Final 1D results - K^+



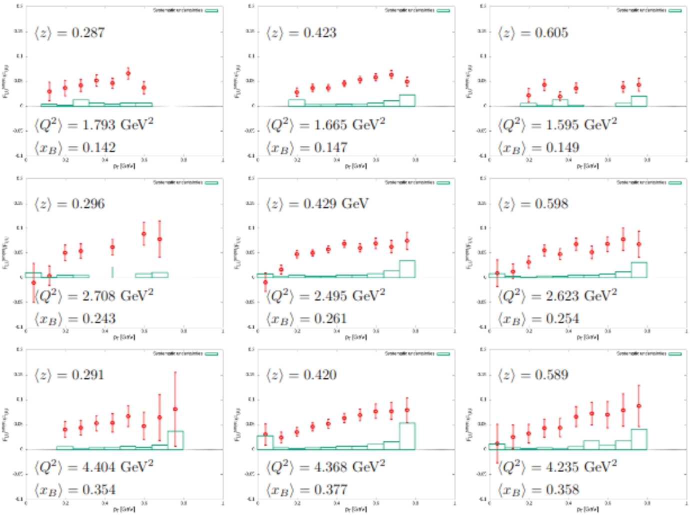
Final 1D results - K^-



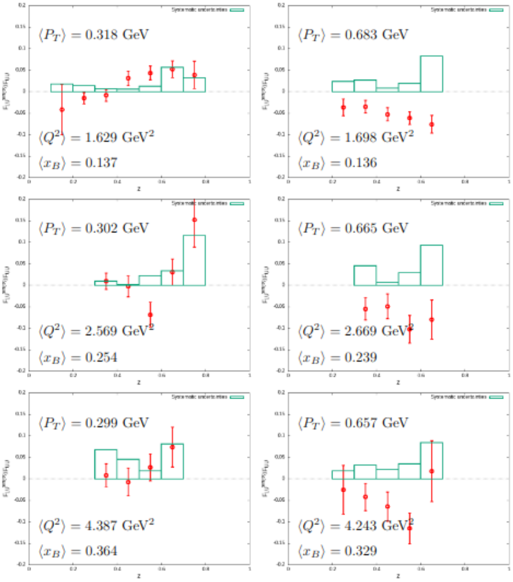
Final 4D results - K^+



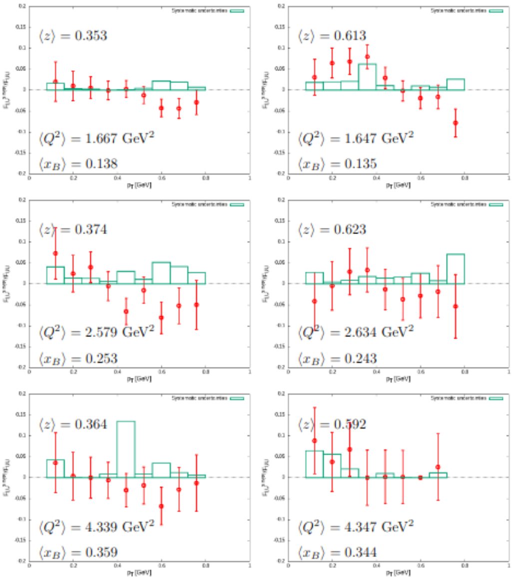
Final 4D results - K^+



Final 4D results - K^-



Final 4D results - K^-

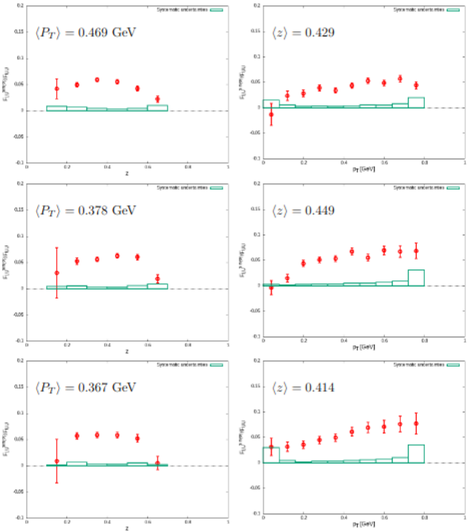


Conclusion

- The high statistics on an extended kinematic range, which is available with the new CLAS12, enables a fully differential analysis for the first time for charged kaons.
- The pion contamination is high, but it can be estimated and subtracted based on MC and ML.
- The contamination estimates should to be confirmed. (RICH)
- The results follow the pion asymmetries in general, but they are higher. In some cases they have a slightly different behavior.
- The results are in agreement with the previous measurements.
- The analysis review is currently ongoing.

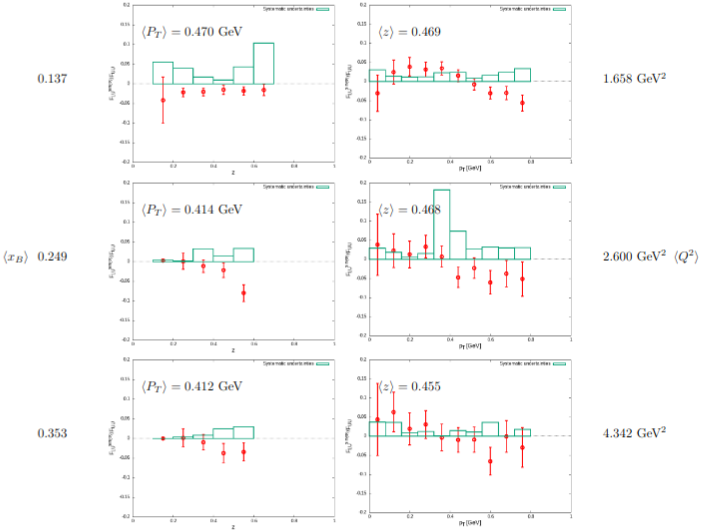
Backup

Final 3D results - K^+

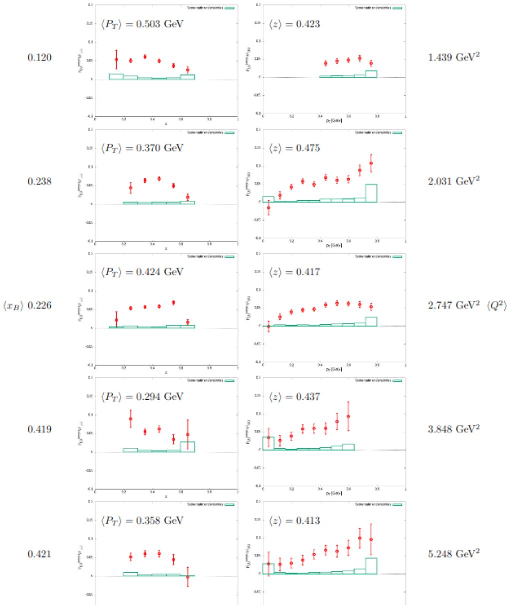


$\langle x_B \rangle$	$\langle Q^2 \rangle$
0.146	1.683 GeV^2
0.256	2.517 GeV^2
0.367	4.355 GeV^2

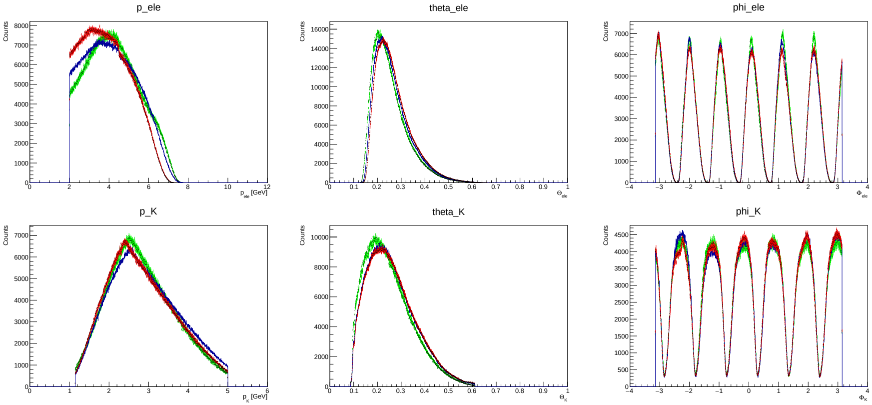
Final 3D results - K^-



Final 3D results - K^+

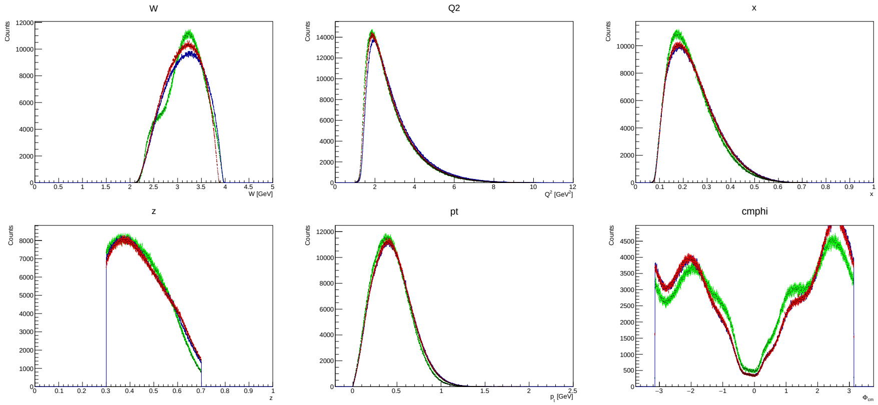


Comparison with MC - K$^+$ inbedning



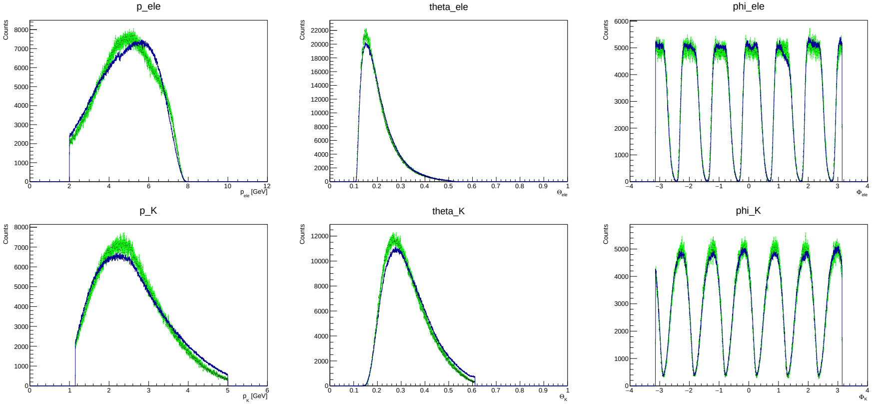
Comparison of the inbending simulated (green) and inbending experimental (blue-inbending, red-2019) distributions for the electron (up) and kaon (down) for the $e^- K^+ X$ sample

Comparison with MC - K^+ inbedning



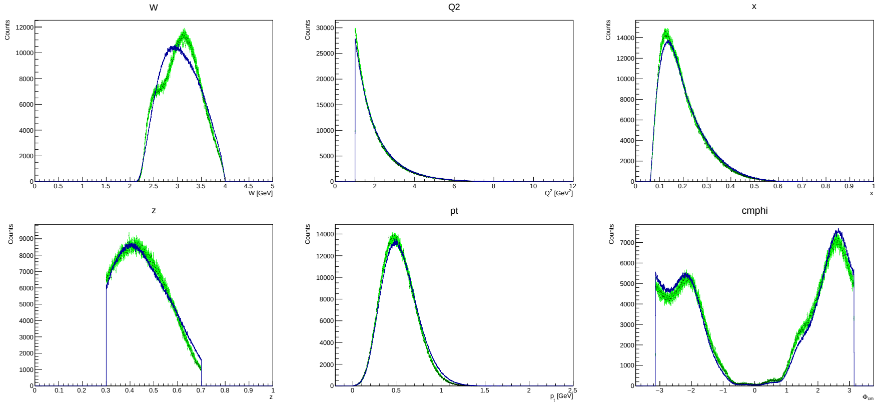
Comparison of the inbending simulated (green) and inbending experimental (blue-inbending, red-2019) kinematic distributions of W, Q^2, x_B, z, P_T and ϕ for the $e^- K^+ X$ sample

Comparison with MC - K^{+} outbedning



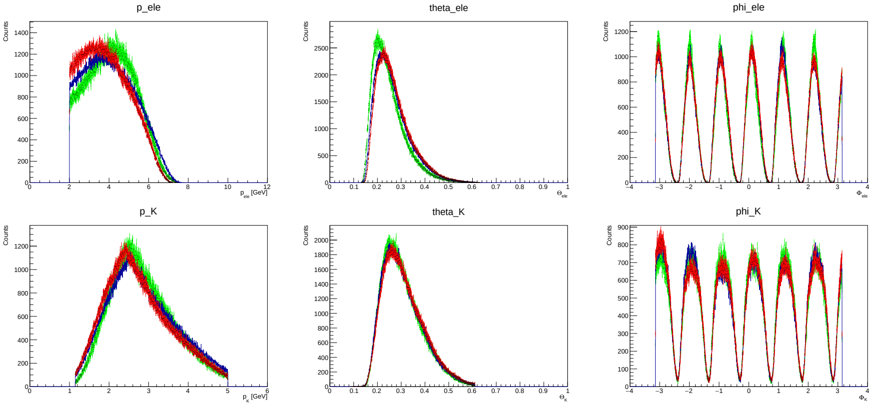
Comparison of the outbending simulated (green) and outbending experimental (blue) distributions for the electron (up) and kaon (down) for the $e^{-}K^{+}X$ sample

Comparison with MC - K^+ outbedning



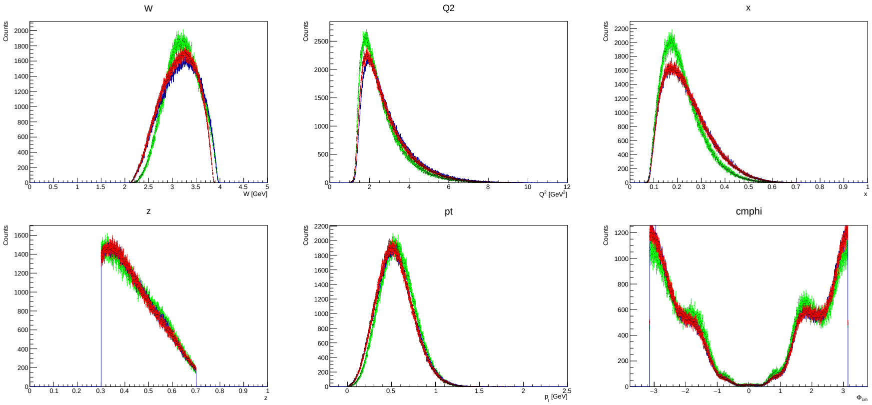
Comparison of the outbending simulated (green) and outbending experimental (blue) kinematic distributions of W, Q^2, x_B, z, P_T and ϕ for the $e^- K^+ X$ sample

Comparison with MC - K^- inbedning



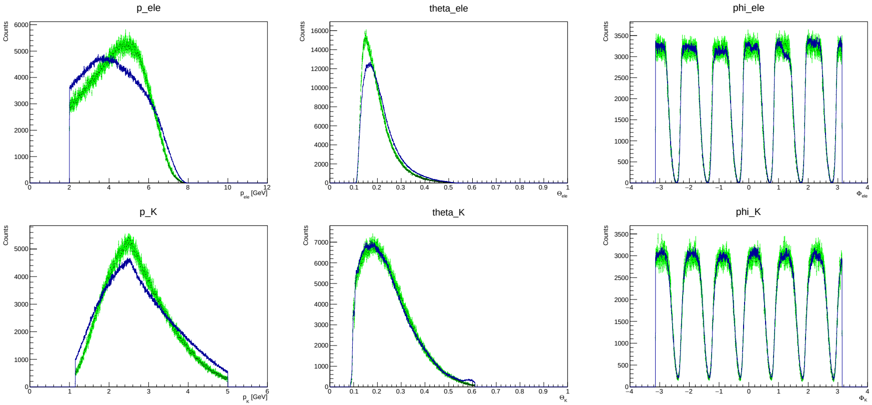
Comparison of the inbending simulated (green) and inbending experimental (blue-inbending, red-2019) distributions for the electron (up) and kaon (down) for the $e^- K^- X$ sample

Comparison with MC - K$^-$ inbedning



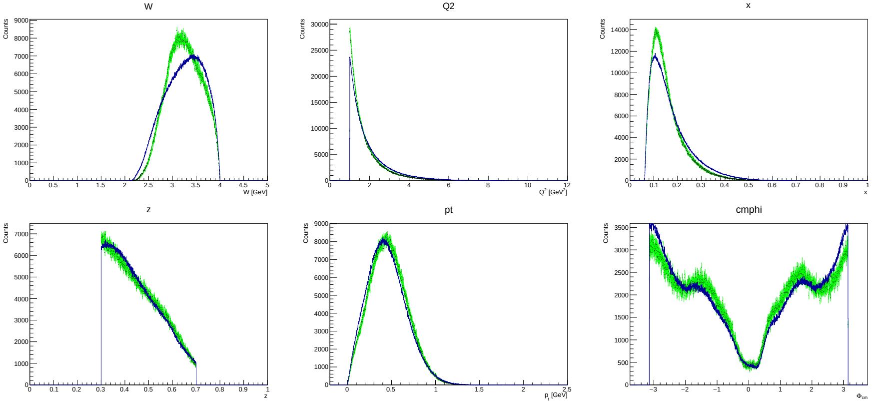
Comparison of the inbending simulated (green) and inbending experimental (blue-inbending, red-2019) kinematic distributions of W, Q^2, x_B, z, P_T and ϕ for the e^-K^-X sample

Comparison with MC - K^- outbedning



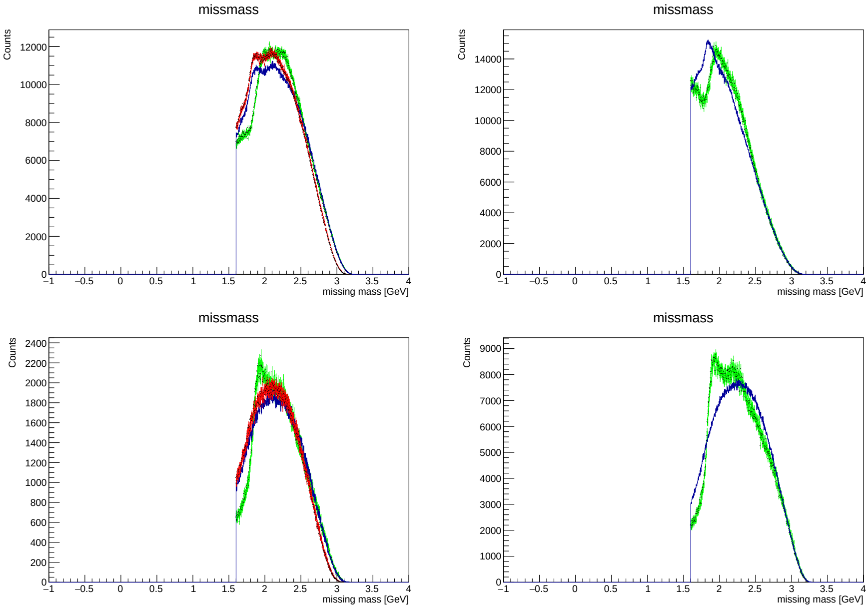
Comparison of the outbending simulated (green) and outbending experimental (blue) distributions for the electron (up) and kaon (down) for the $e^- K^- X$ sample

Comparison with MC - K^- outbedning

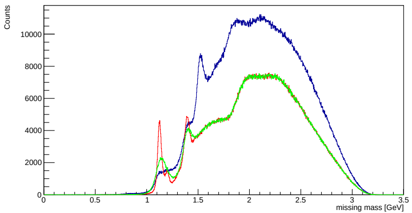


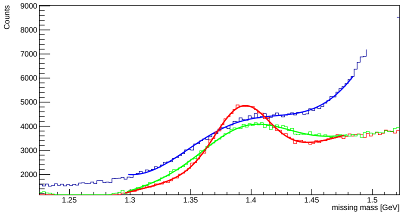
Comparison of the outbending simulated (green) and outbending experimental (blue) kinematic distributions of W, Q^2, x_B, z, P_T and ϕ for the e^-K^-X sample

Comparison with MC - K^+ inbedning



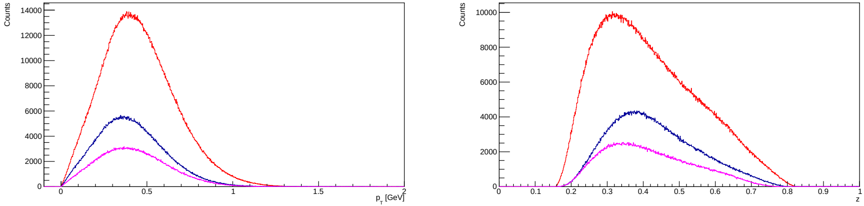
MC Smearing





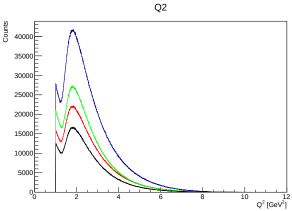
Comparison of the simulated with (green) and without the smearing (red) and experimental (blue) missing mass distributions in the inbending setting for the $e^- K^+ X$ sample on the whole missing mass range (left) and near the peak at 1.4 GeV (right)

Multidimensional binning - K^-

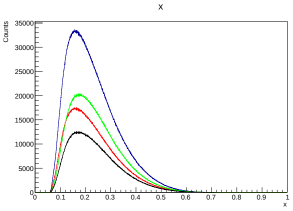


P_T (left) and z (right) distributions in different Q^2-x_B bins (red - bin 1, blue - bin 2, purple - bin 3) for the $e^- K^- X$ dataset with $\mathrm{p}_K < 5$ GeV cut

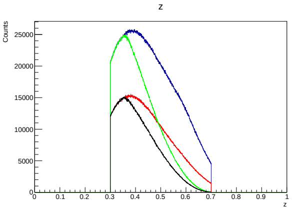
Kinematics - K^+



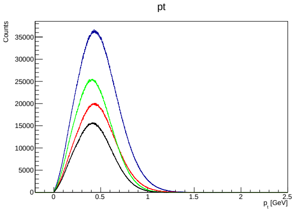
Q^2



x_B



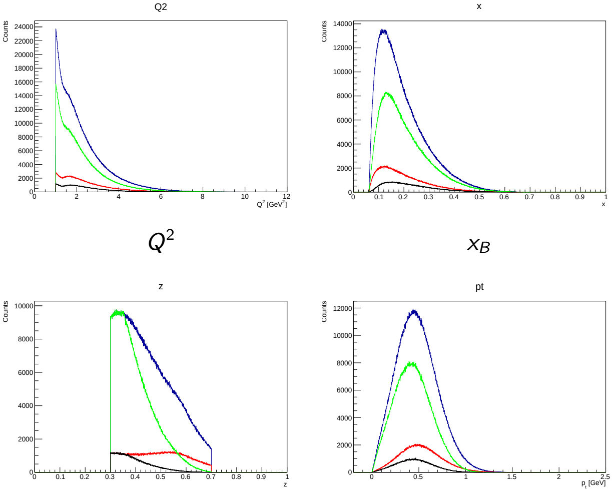
z



P_T

blue: $p_K < 5$ GeV, red: $p_K < 5$ GeV with ml, green: $p_K < 3$ GeV, black: $p_K < 3$

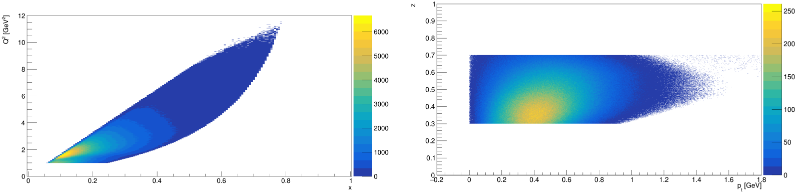
Kinematics - K^-



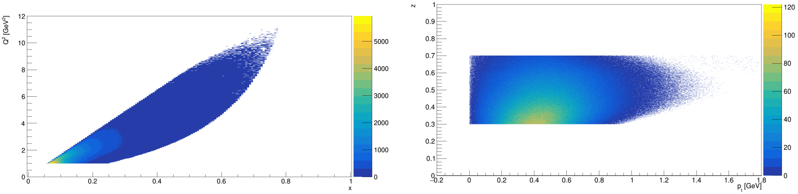
Q^2 $\qquad$ x_B

z $\qquad$ P_T

blue: $p_K < 5$ GeV, red: $p_K < 5$ GeV with ml, green: $p_K < 3$ GeV, black: $p_K < 3$

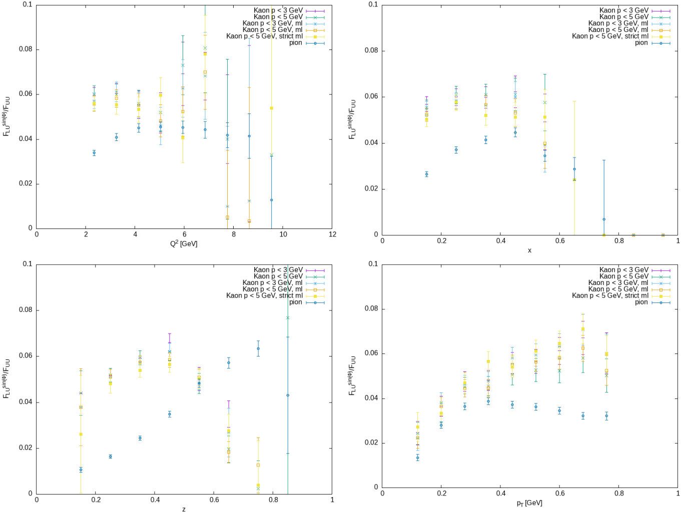


The correlations of Q^2-x_B (left) and P_T-z (right) for the $e^- K^+ X$ sample with $p_K < 5$ GeV cut

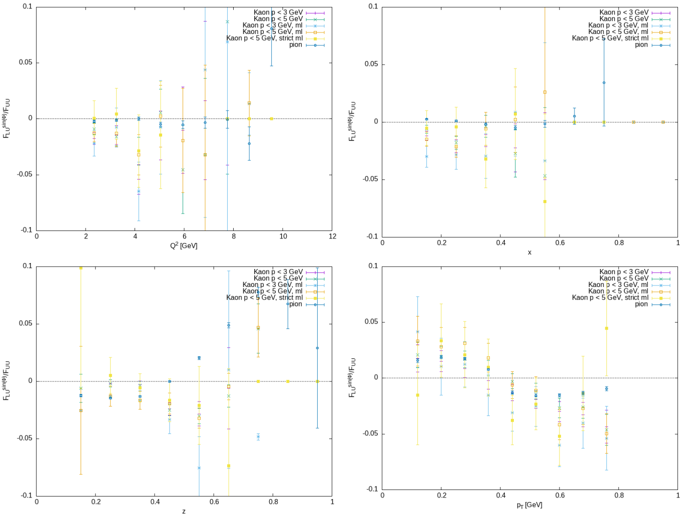


The correlations of Q^2-x_B (left) and P_T-z (right) for the $e^- K^- X$ sample with $p_K < 5$ GeV cut

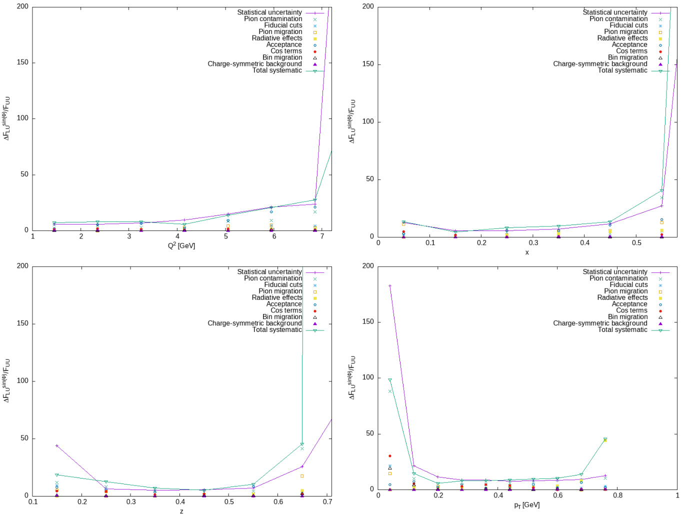
After pion subtraction - K^+



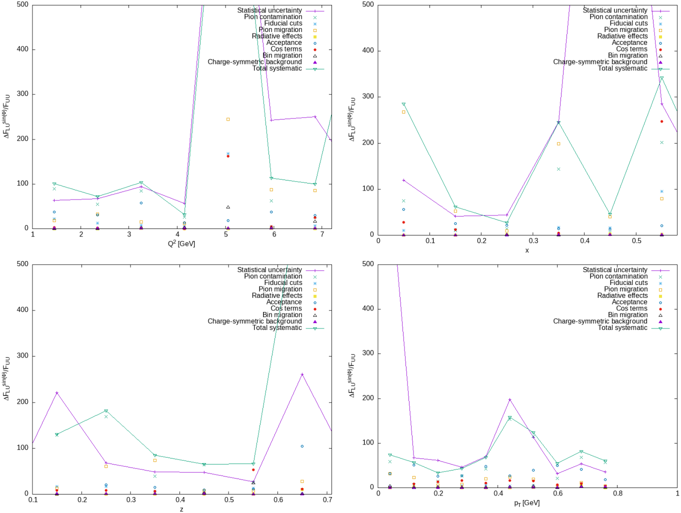
After pion subtraction - K^-



Systematic uncertainties - K^+

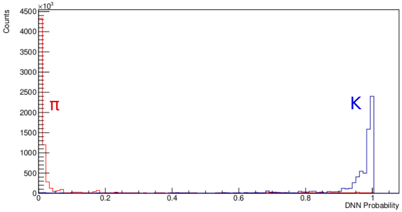


Systematic uncertainties - K^-

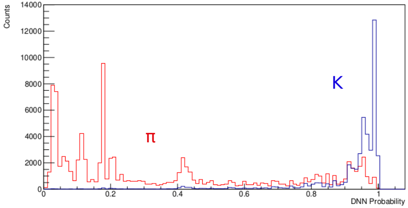


Return value

- The output from the neural network is a value between 0 and 1
- Red: mc π-s
- Blue: mc Kaons
- Cuts: 0.96 (standard) or 0.99 (strict)

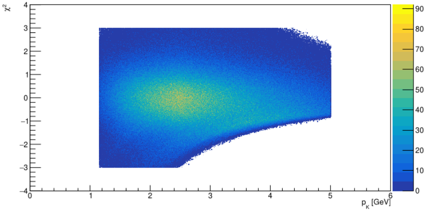


Whole p range

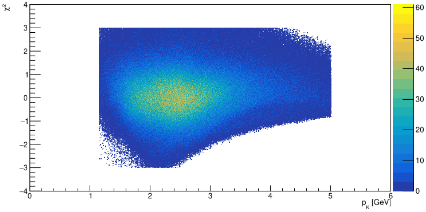


p $>$ 3 GeV

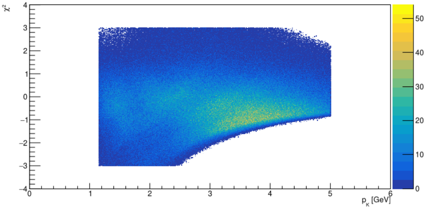
PID χ^2



Without machine learning



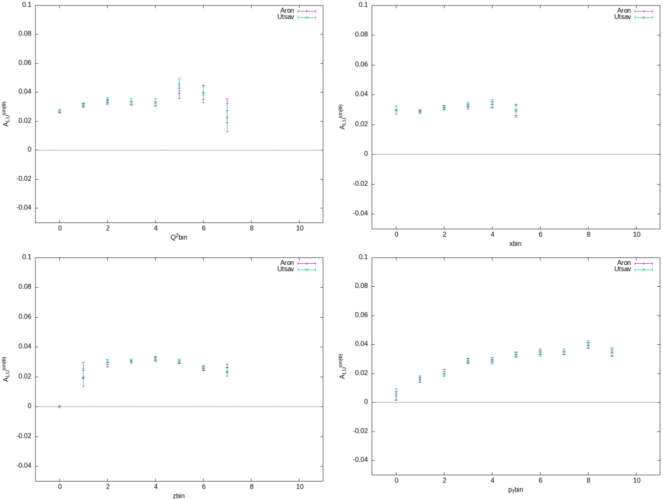
With machine learning



Difference - removed particles

Cross-checks - Utsav Shrestha

- Almost complete agreement in the number of particles, their kinematics, $N^{\pm}$ and BSA
- Minor A_{LU} differences - in bins which are removed from the results

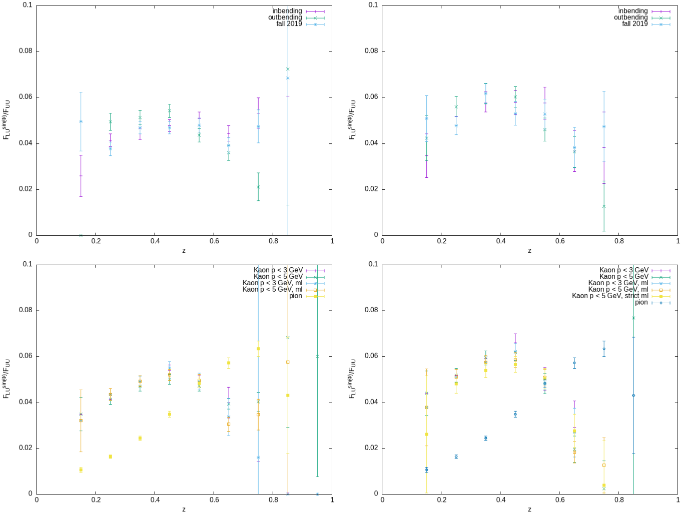


Multidimensional binning - Average uncertainty

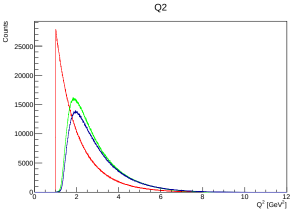
	Relative uncertainty		Absolute uncertainty	
Source	K^+	K^-	K^+	K^-
Statistical uncertainty	28.8%	123.7%	0.012	0.023
Pion contamination	11.5%	79.9%	0.005	0.015
Beam polarization	2.8%	3.2%	0.001	0.001
Fiducial cuts	8.5%	29.3%	0.003	0.006
Pion bin migration	5.3%	50.3%	0.002	0.009
Radiative effects	3.3%	1.1%	0.001	0.0002
Acceptance	3.5%	31.4%	0.001	0.006
Cos terms	5.4%	32%	0.002	0.006
Bin migration	1.8%	3.2%	0.001	0.001
Phi bin migration	1%	1%	0.0004	0.0001
Charge-symmetric bg.	0.2%	0.5%	0.0001	0.0002
Accidentals	1%	1%	0.0004	0.0001
Total systematic uncert.	21.6%	89.9%	0.009	0.017

Relative and absolute uncertainty from the different sources averaged over all bins

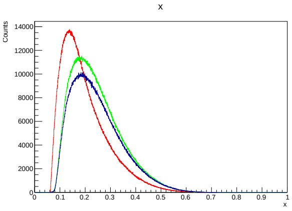
Before (left) and after (right) subtraction



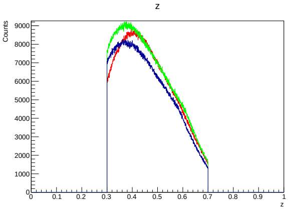
Comparison of different datasets - K^+



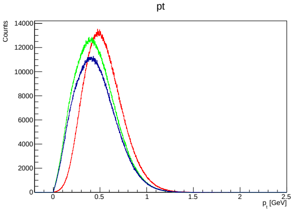
Q^2



x_B



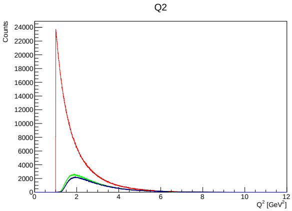
z



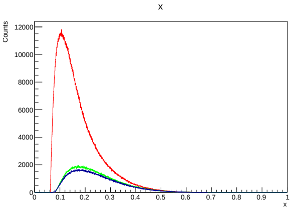
P_T

blue-inbending fall 2018, red-outbending fall 2018, green-inbending spring 2019

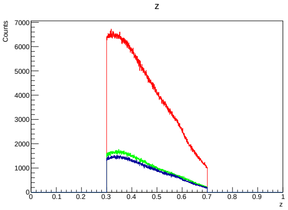
Comparison of different datasets - K^-



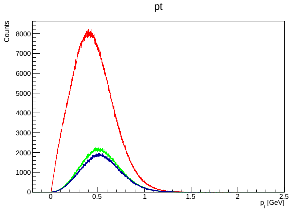
Q^2



x_B



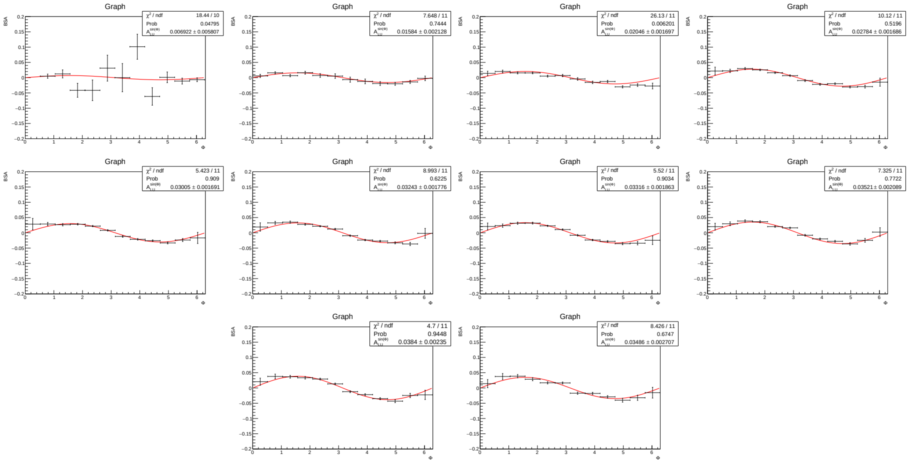
z



P_T

blue-inbending fall 2018, red-outbending fall 2018, green-inbending spring 2019

BSA fit examples



BSA in P_T bins in increasing order from top left to bottom right for the $e^- K^+ X$ dataset with $p_K < 5$ GeV cut