



# Exclusive $\phi$ electroproduction off the proton at 6.5-10.6 GeV (Run Groups A & K)

## CLAS Collaboration Meeting

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**Jefferson Lab**

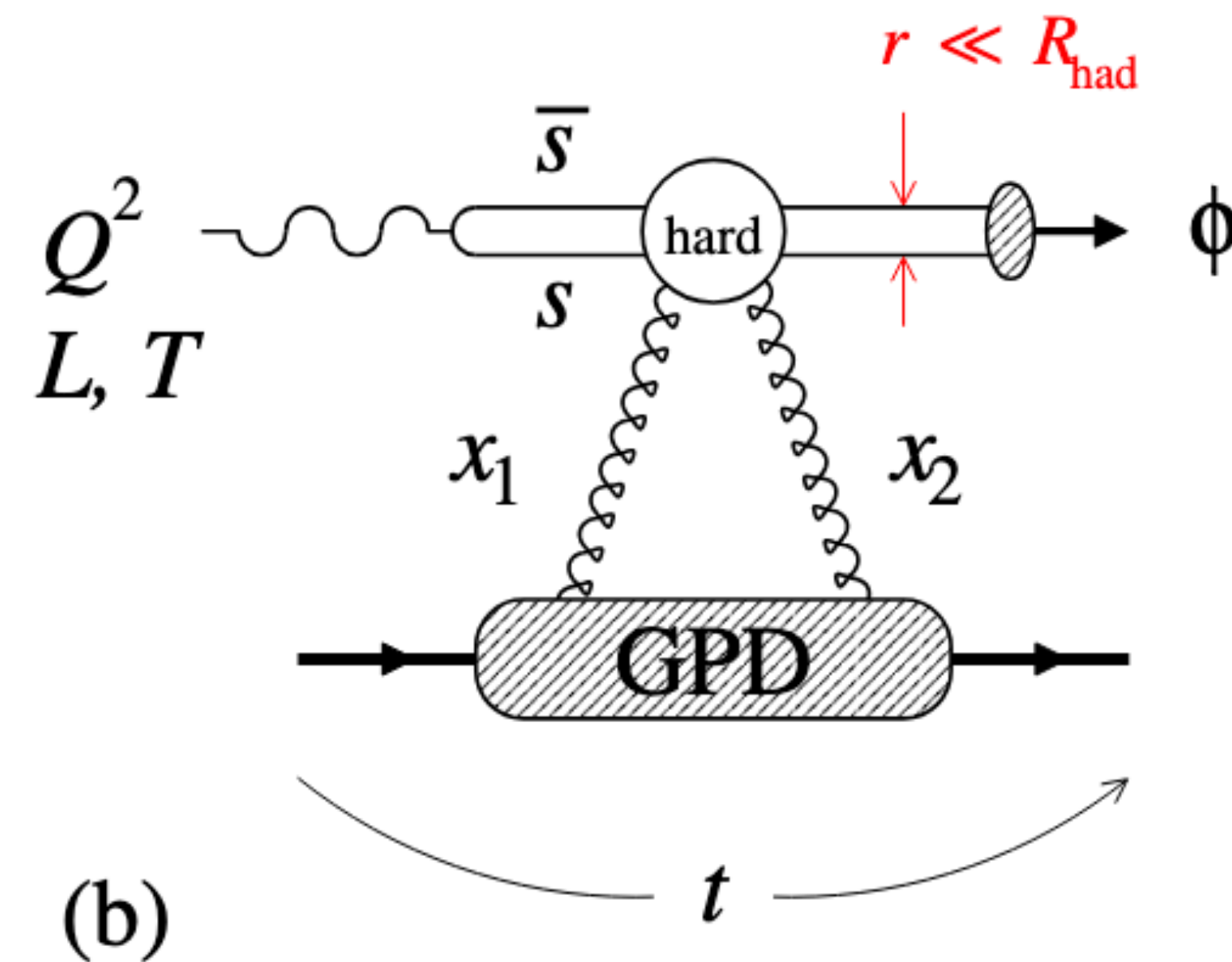
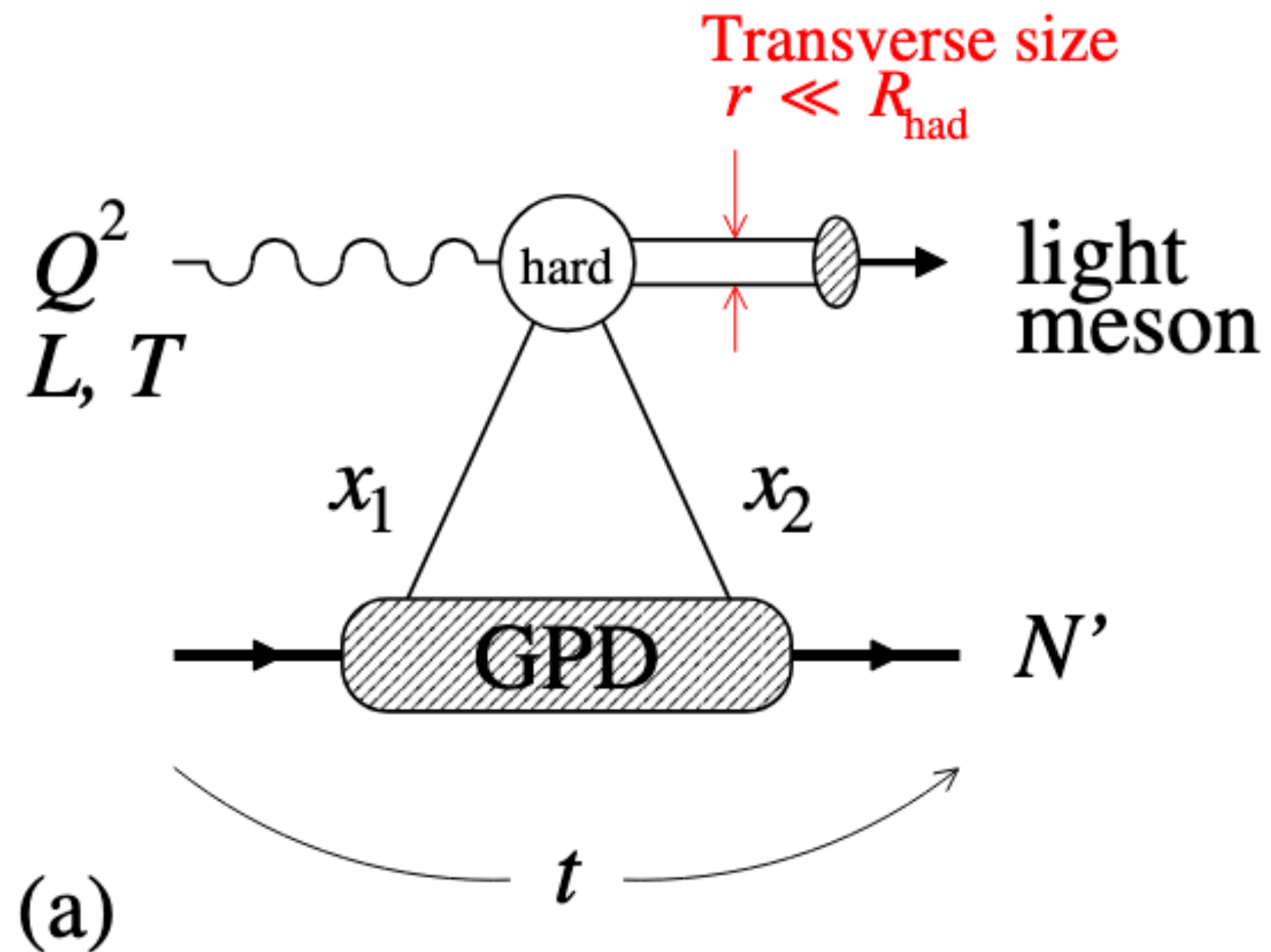
Tuesday, June 30, 2026

\* Y. Wang, H. Avakian, V.D. Burkert, L. Elouadrhiri, D. Glazier, F.X. Girod, Y. Li, R. Milner, I. Korover, K. Neupane, V. Kubarovsky, and P. Moran

✉ [singh@jlab.org](mailto:singh@jlab.org)

# Clean Probe For Gluonic Structure of Nucleon

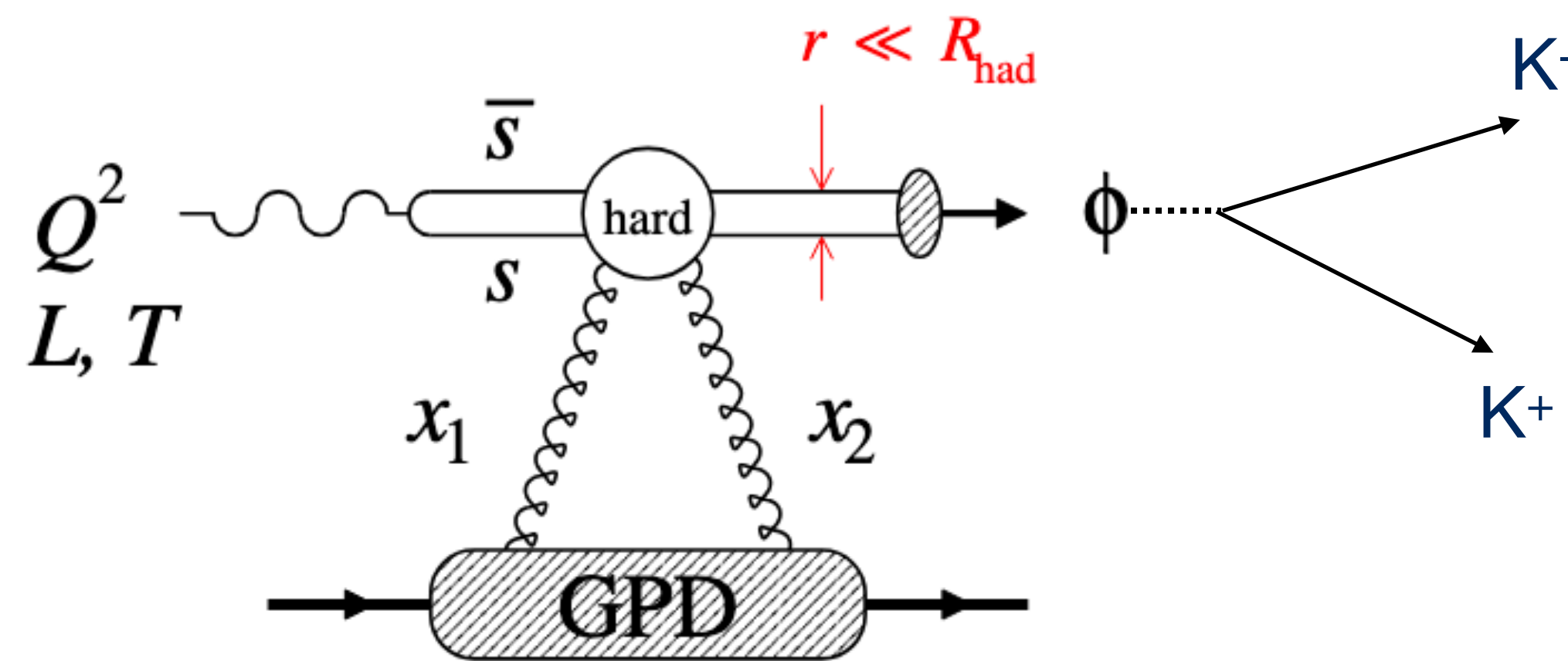
- $\phi$  meson is a **pure  $s\bar{s}$  state**, its coupling to light quarks (u,d) is suppressed (by OZI rule)
- Access to the gluon GPD even at low energy due to its flavor content  $s\bar{s}$



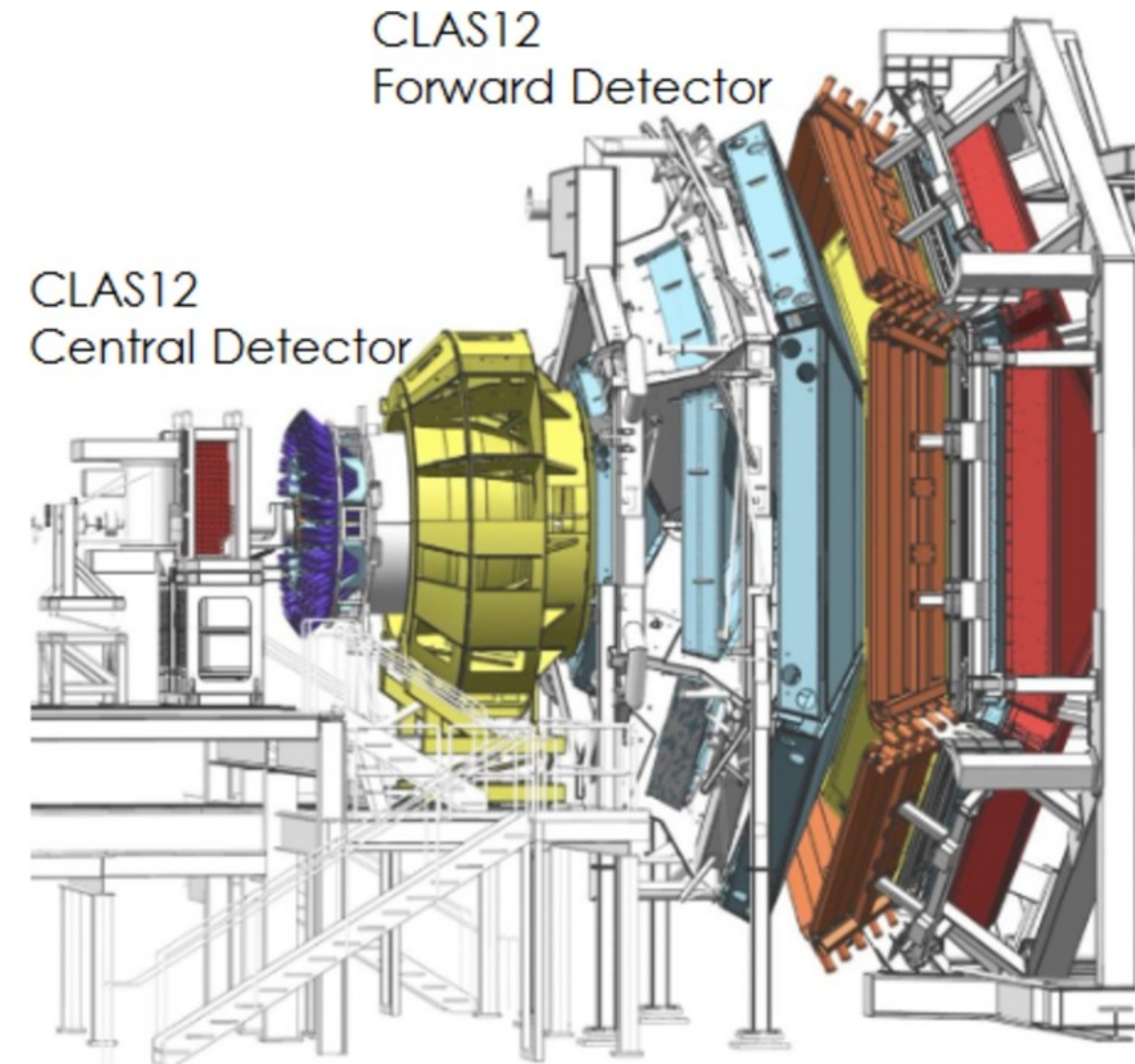
- $Q^2$  scaling of  $\phi$  production cross section: opens doors to test **QCD factorization** ( $\sigma_L \sim 1/Q^6$ ,  $\sigma_L/\sigma_T \sim Q^2$ )
- Change of  $|t|$ -dependence with  $Q^2 \rightarrow$  **gluonic radius** of the proton

# Exclusive $\phi$ production with proton target

- Beam energy 6.5, 7.5, and 10.6 GeV dependent production from data sets collection during **2018-19**
- Analysis strategy: select charged decay daughters  $e p \rightarrow e' p' K^+ K^-$  (branching ratio:  $\sim 49.2\%$ )



- **Forward Detector (FD)** covers the range of polar angles from 5 to 35 degrees segmented into 6 sectors in azimuthal angle
- **Central Detector (CD)** covers the range of polar angles from 35 to 125 degrees
- Electron is selected in only FD while protons and kaons are selected in both CD and FD

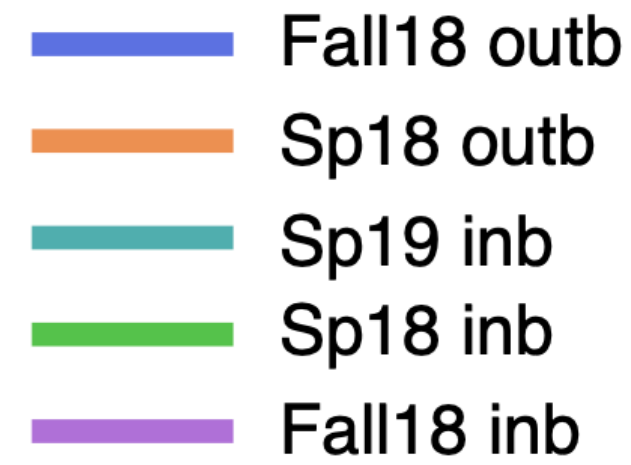


R. Tyson et al, Comp. Phys. Com., 290, 108783, (2023)

# Particle Kinematics (exclusive reaction) for RGA

- **Datasets** from Run group A (10.6 & 10.2 GeV beam)
- Torus -1 (inbending) Spring & Fall 2018, and Spring 2019

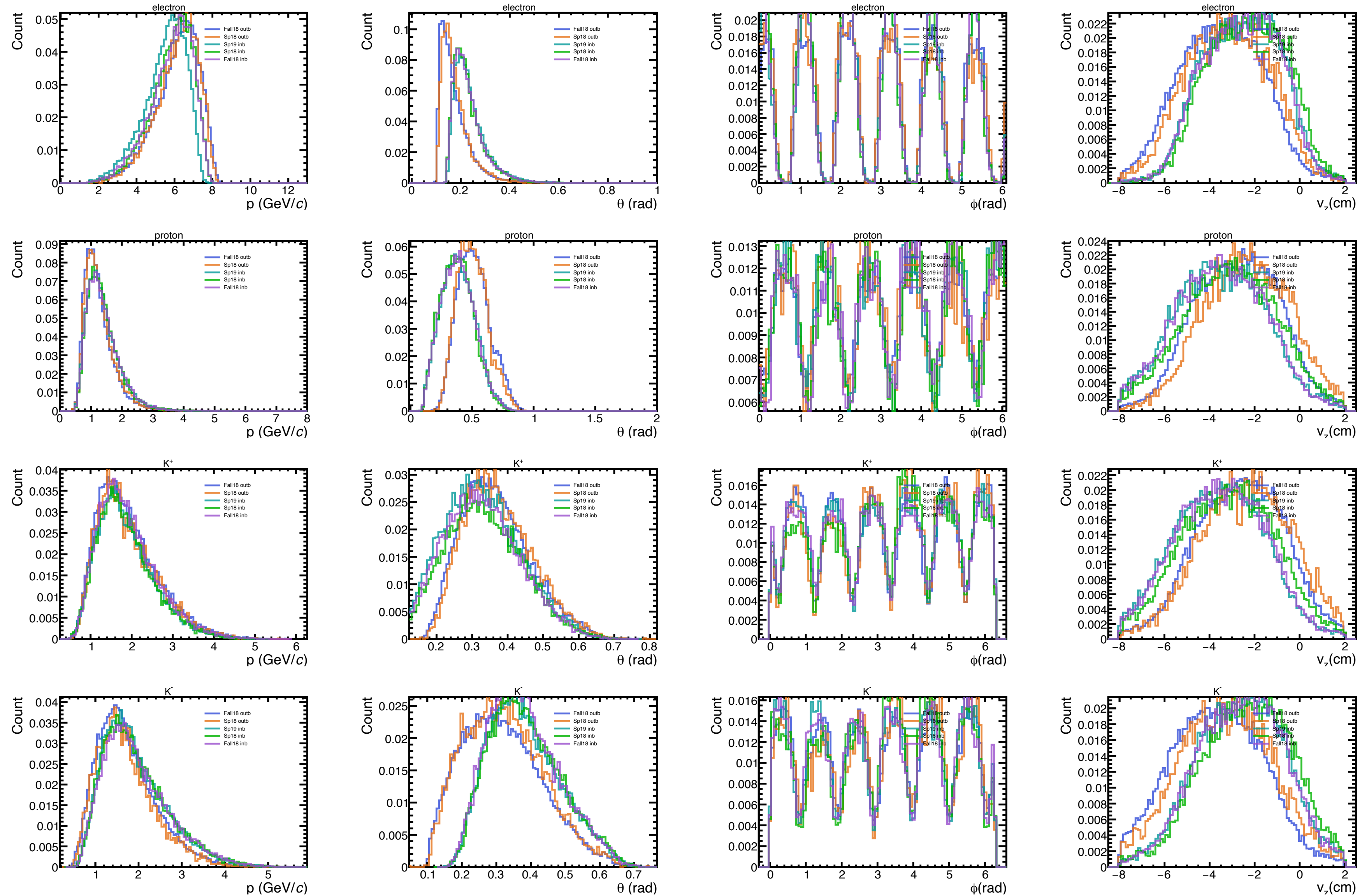
- Torus+1 (outbending) Spring & Fall 2018



- Minimum cuts

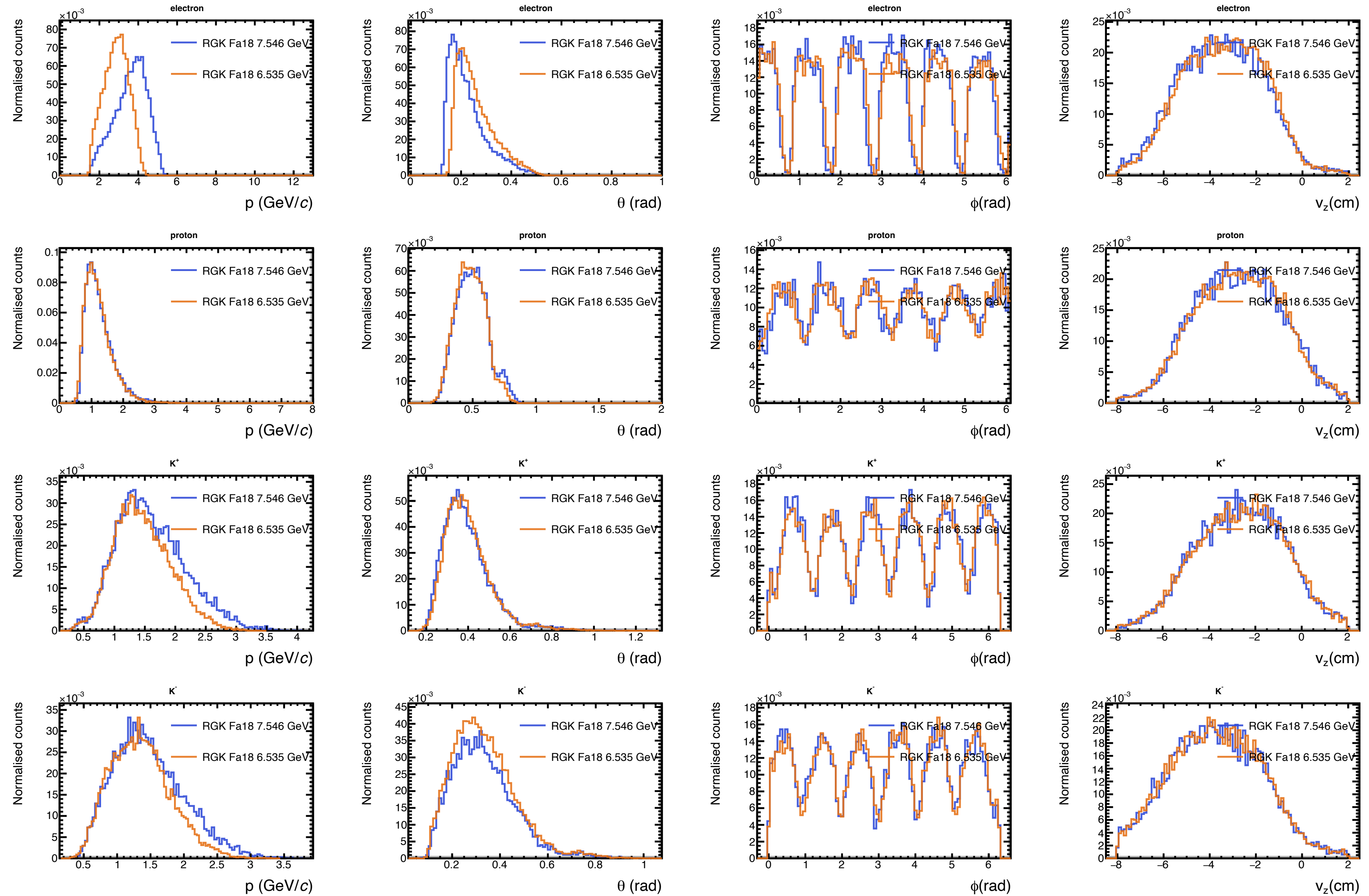
$p_e > 1.5$  GeV in FD  
 $p_p > .4$  GeV in FD and CD

$0.2 < K_p < 7.5$  GeV in FD  
 Vertex for all particles  
 $-8\text{cm} < v_z < 2\text{ cm}$



# Particle Kinematics (exclusive reaction) for RGK

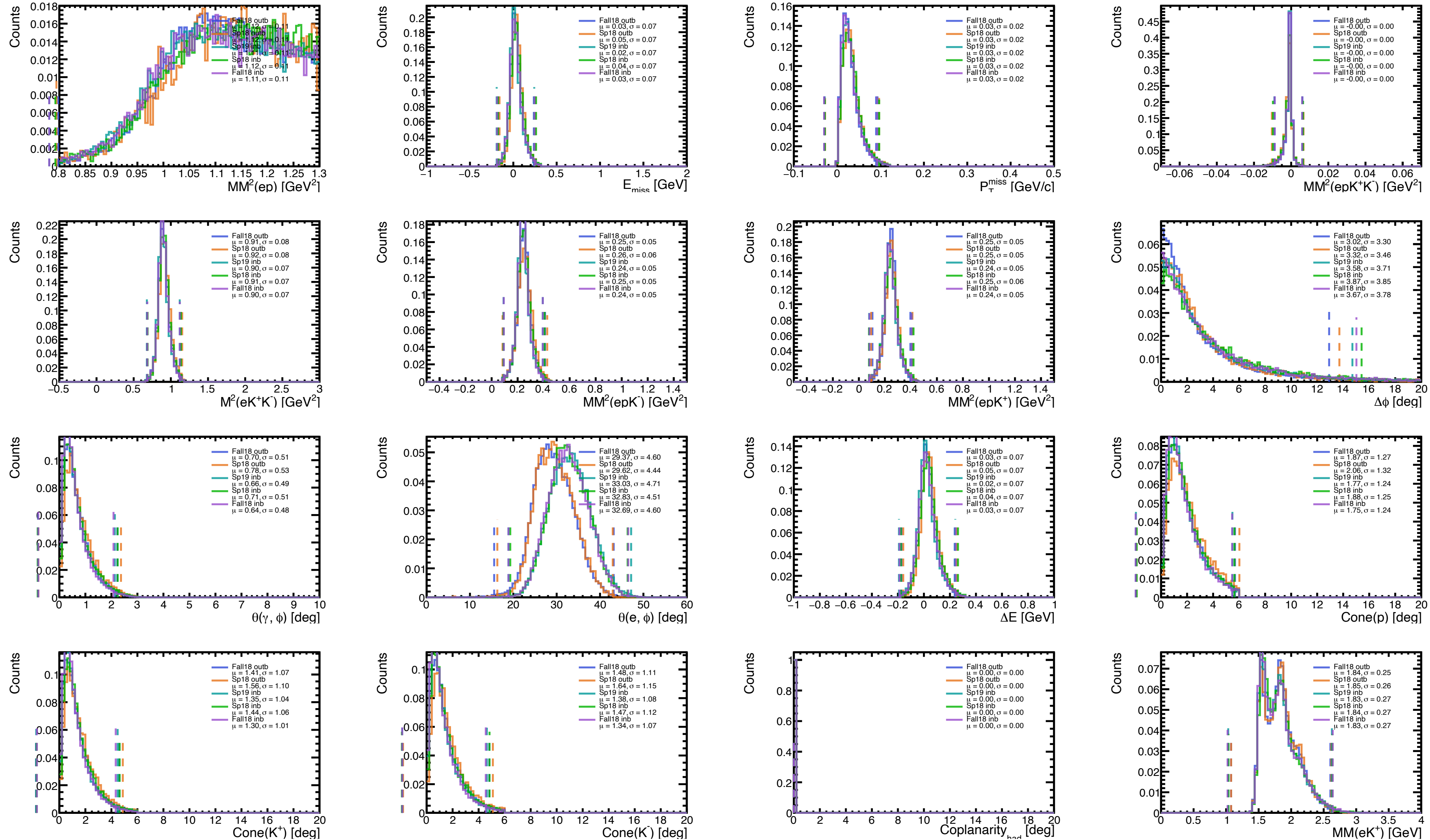
- Fall 2018 6.5 and 7.5 GeV
- Electron momentum differs from each other due to the beam energies
- Same effects observed for Kaon momenta



# Exclusivity cuts for further refinements

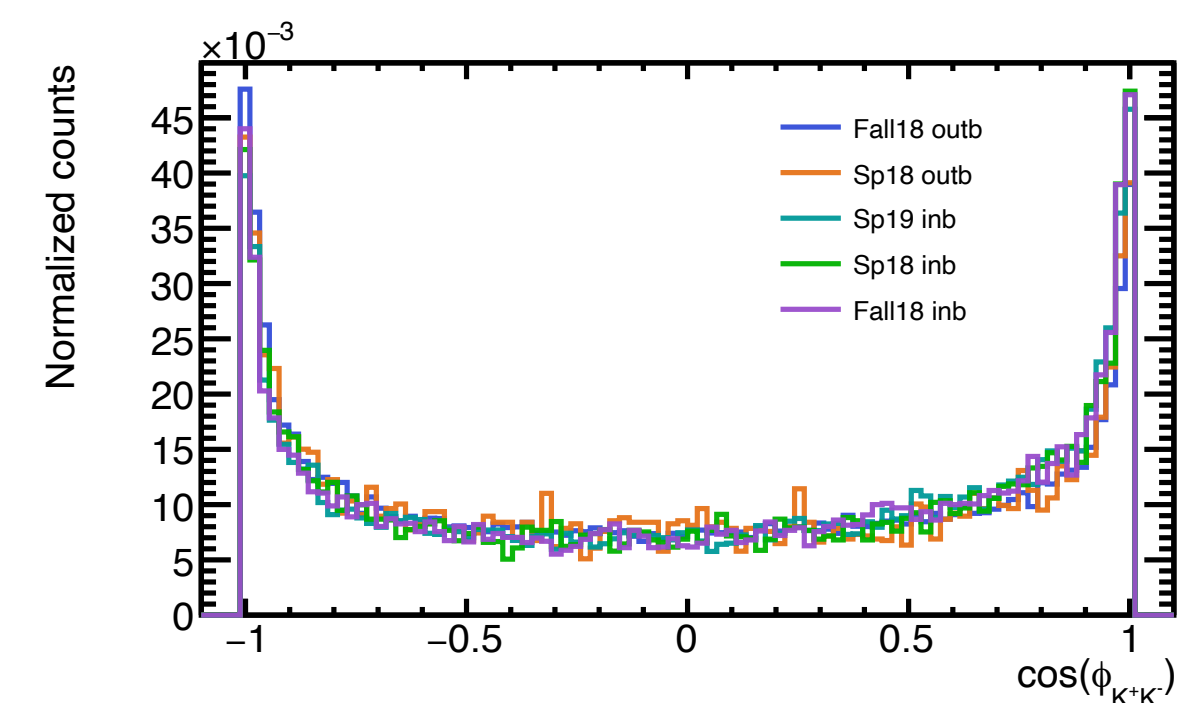
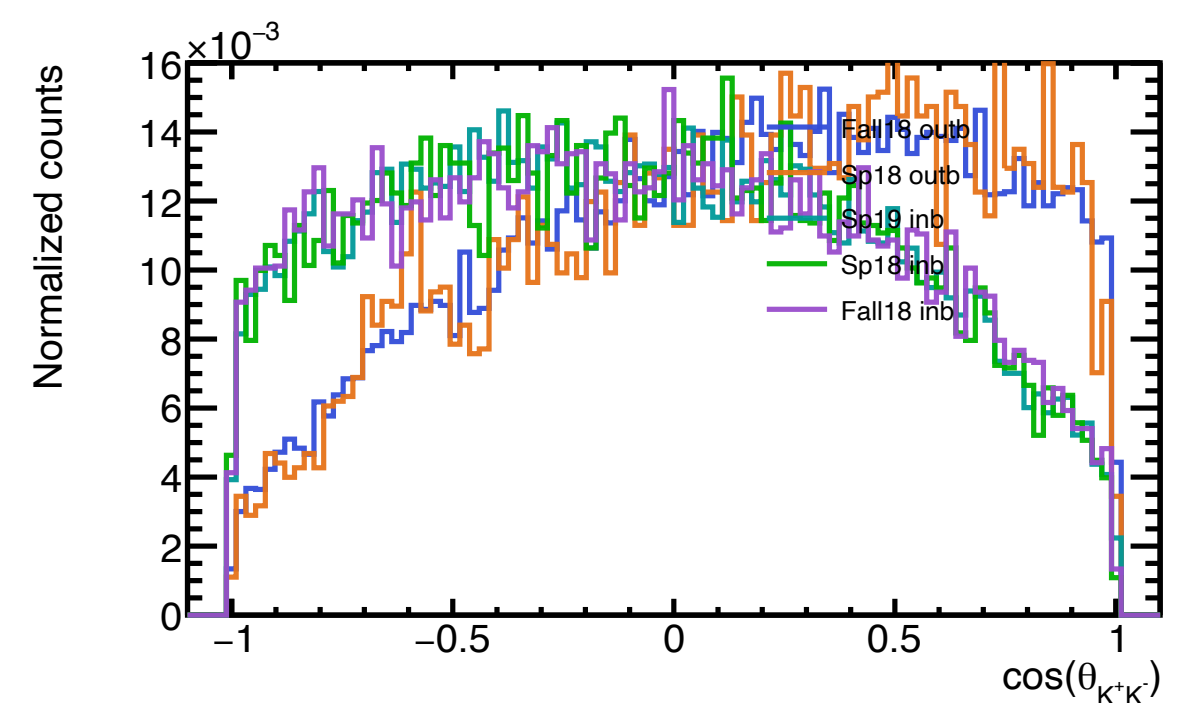
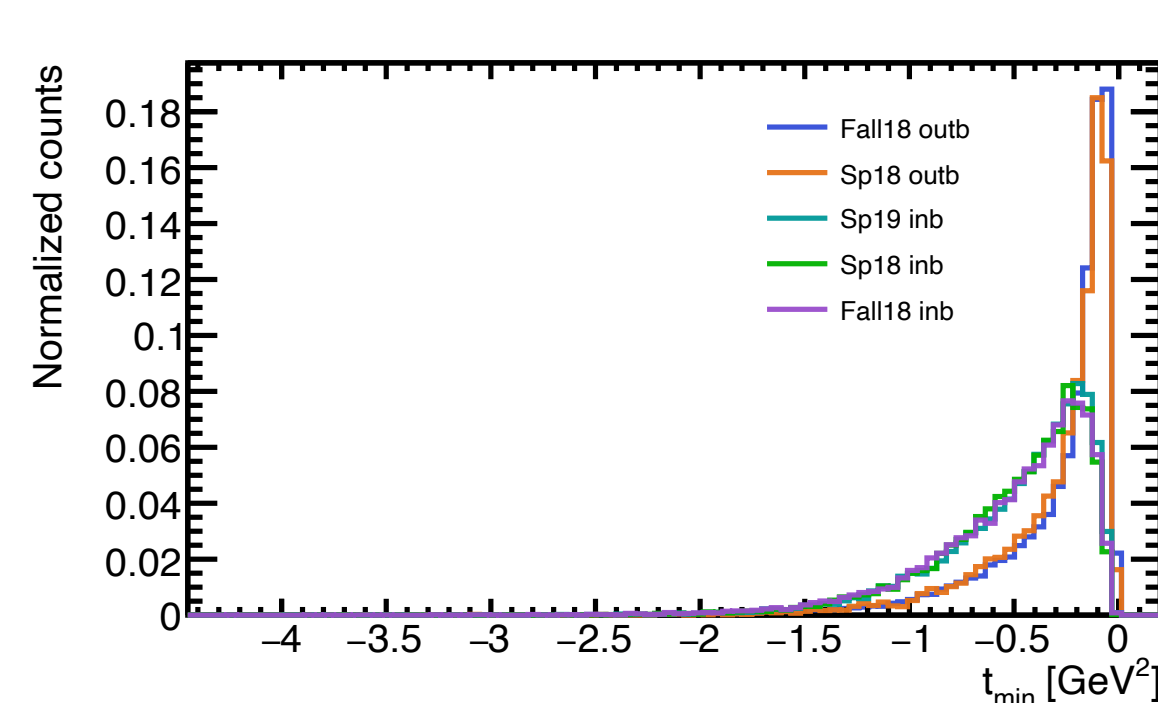
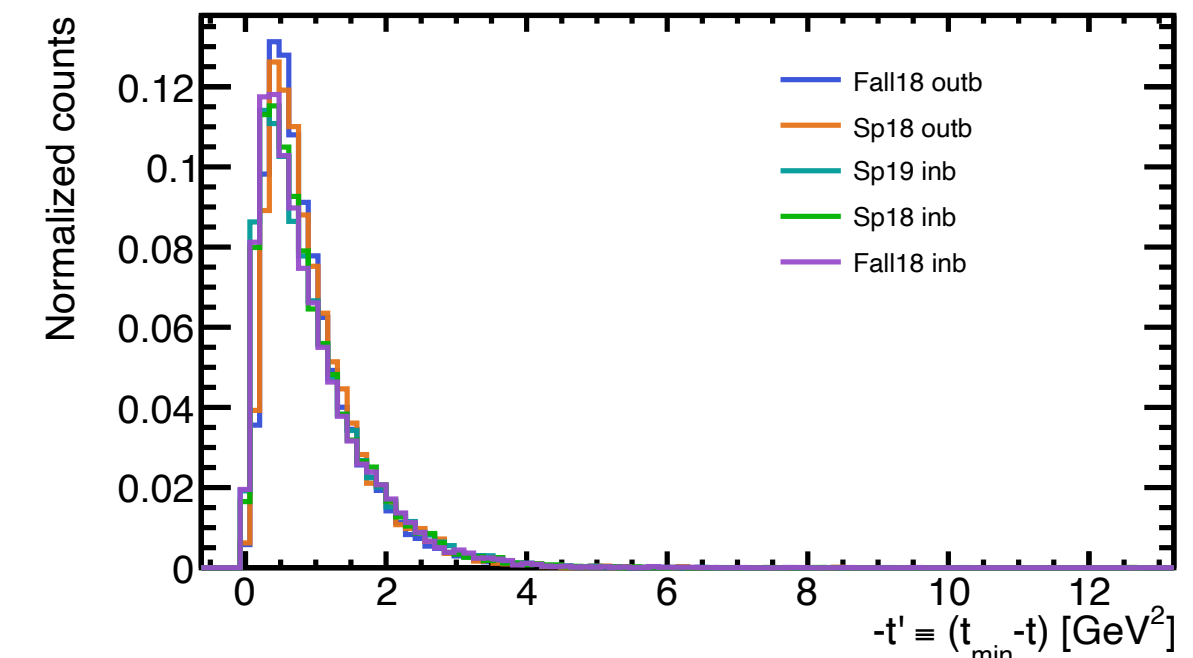
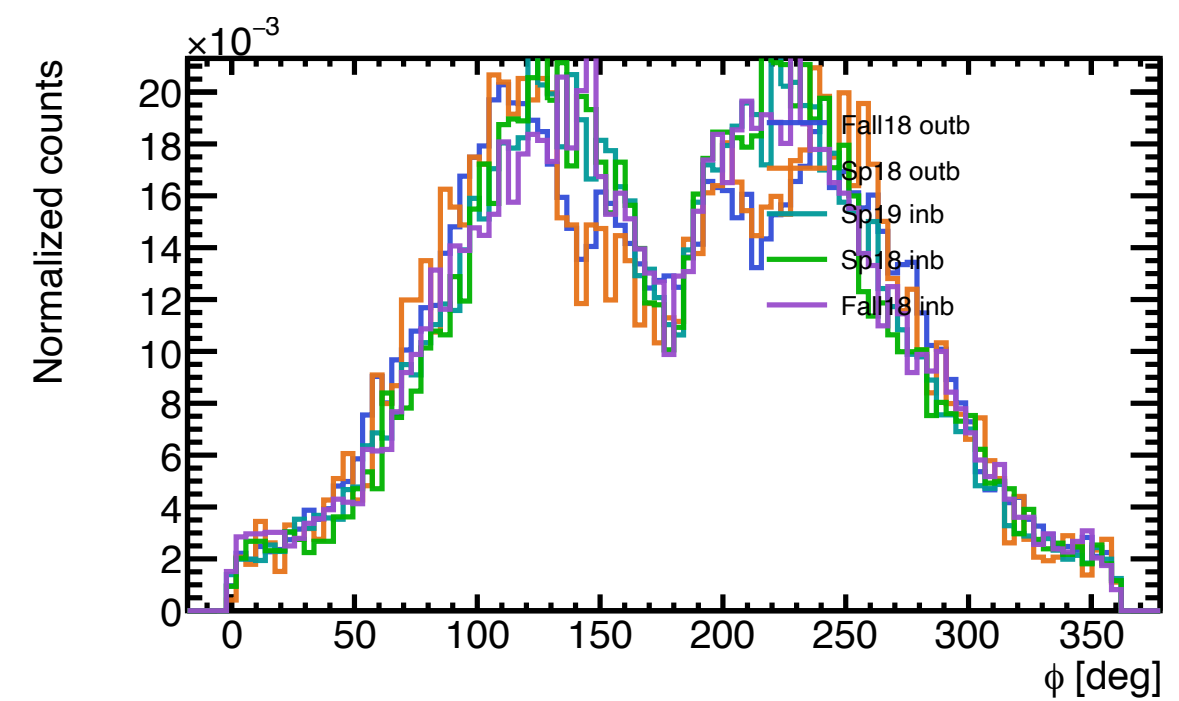
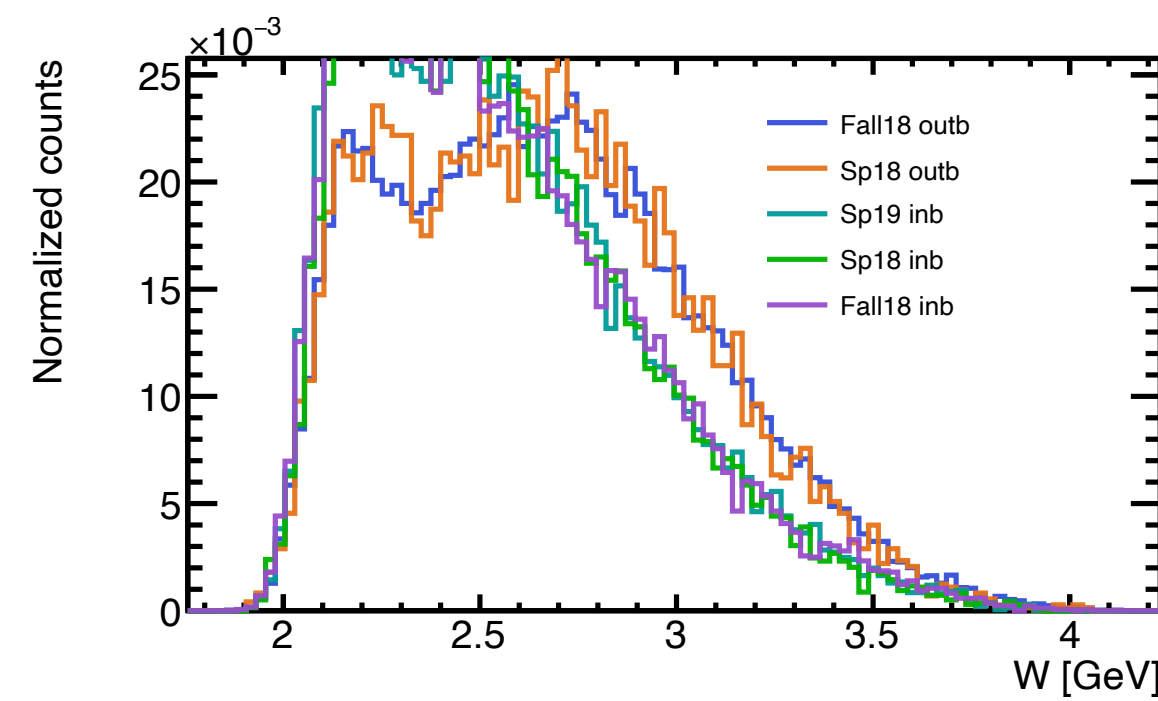
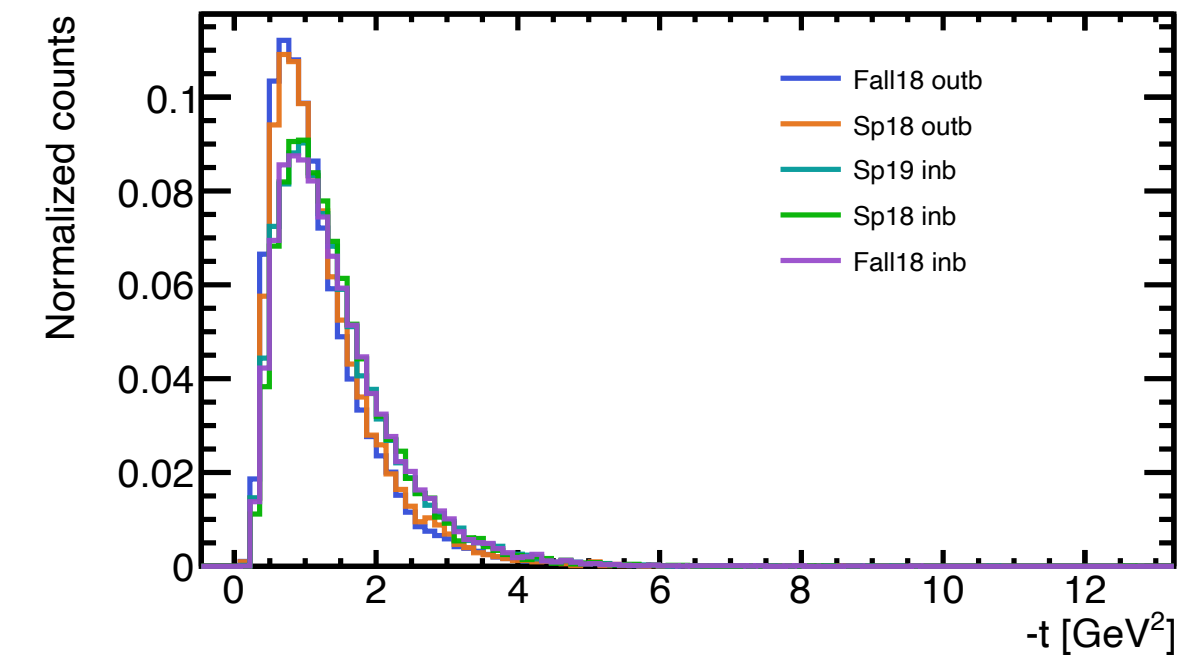
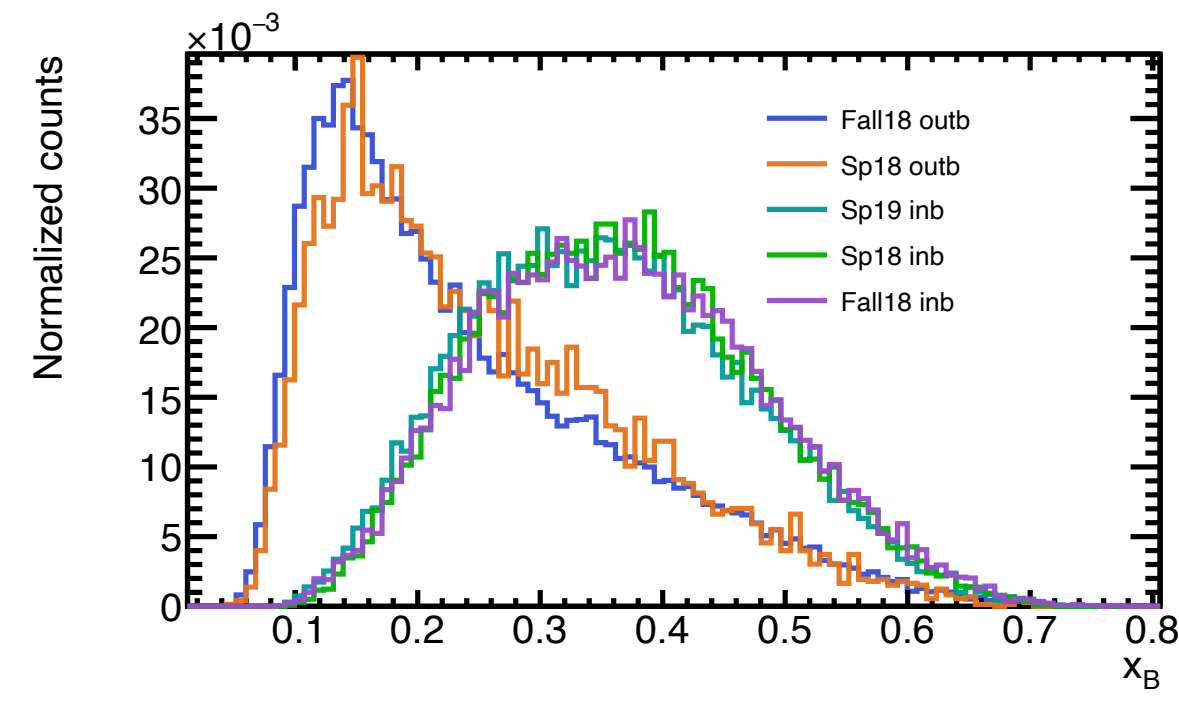
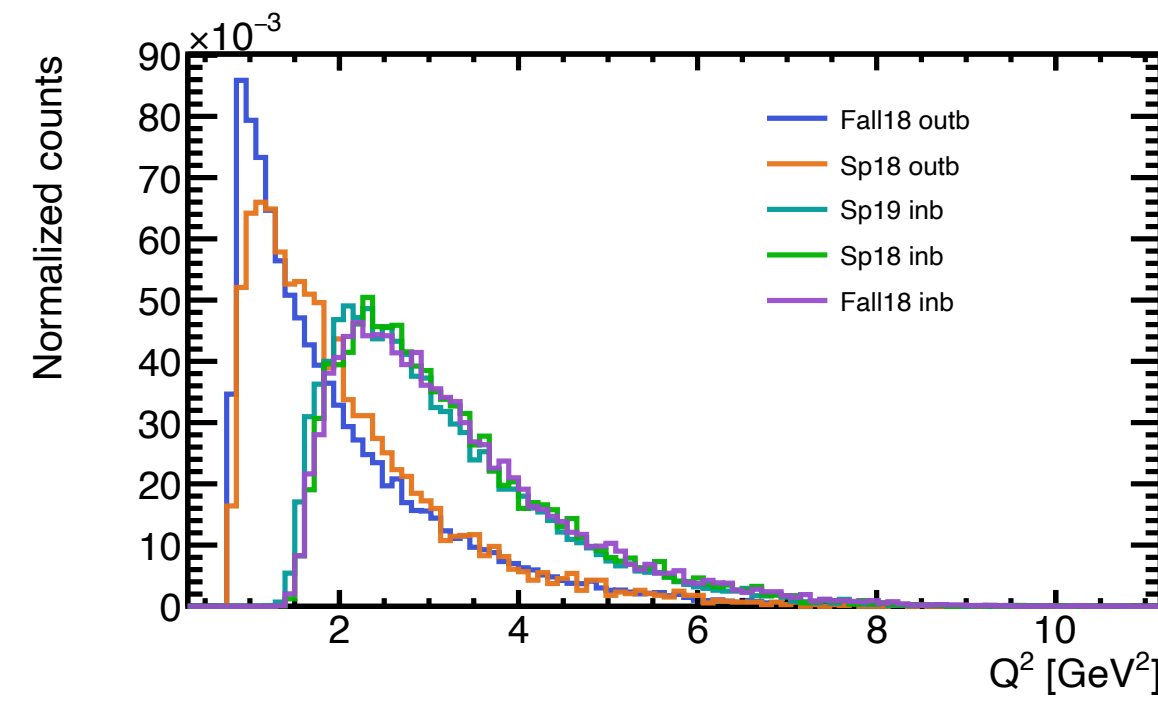
- Exclusivity variables are prior to phi mass peak cut
- Exclusivity cuts

$E_{\text{miss}} \in [-0.0075, 0.32] \text{ GeV}$   
 $P_{T\text{miss}} < 0.12 \text{ GeV}$   
 $M_{x^2}(\text{eK}^+\text{K}^-) \in [0.64, 1.1664] \text{ GeV}^2$   
 $M_{x^2}(\text{epK}^+\text{K}^-) < 0.0075 \text{ GeV}^2$   
 $M_{x^2}(\text{epK}^-) \in [0.08, 0.48] \text{ GeV}^2$   
 $M_{x^2}(\text{epK}^+) \in [0.08, 0.48] \text{ GeV}^2$   
 cone angles  $K_p/K_m/p < 6 \text{ deg}$   
 coplanarity  $< 15 \text{ degrees}$



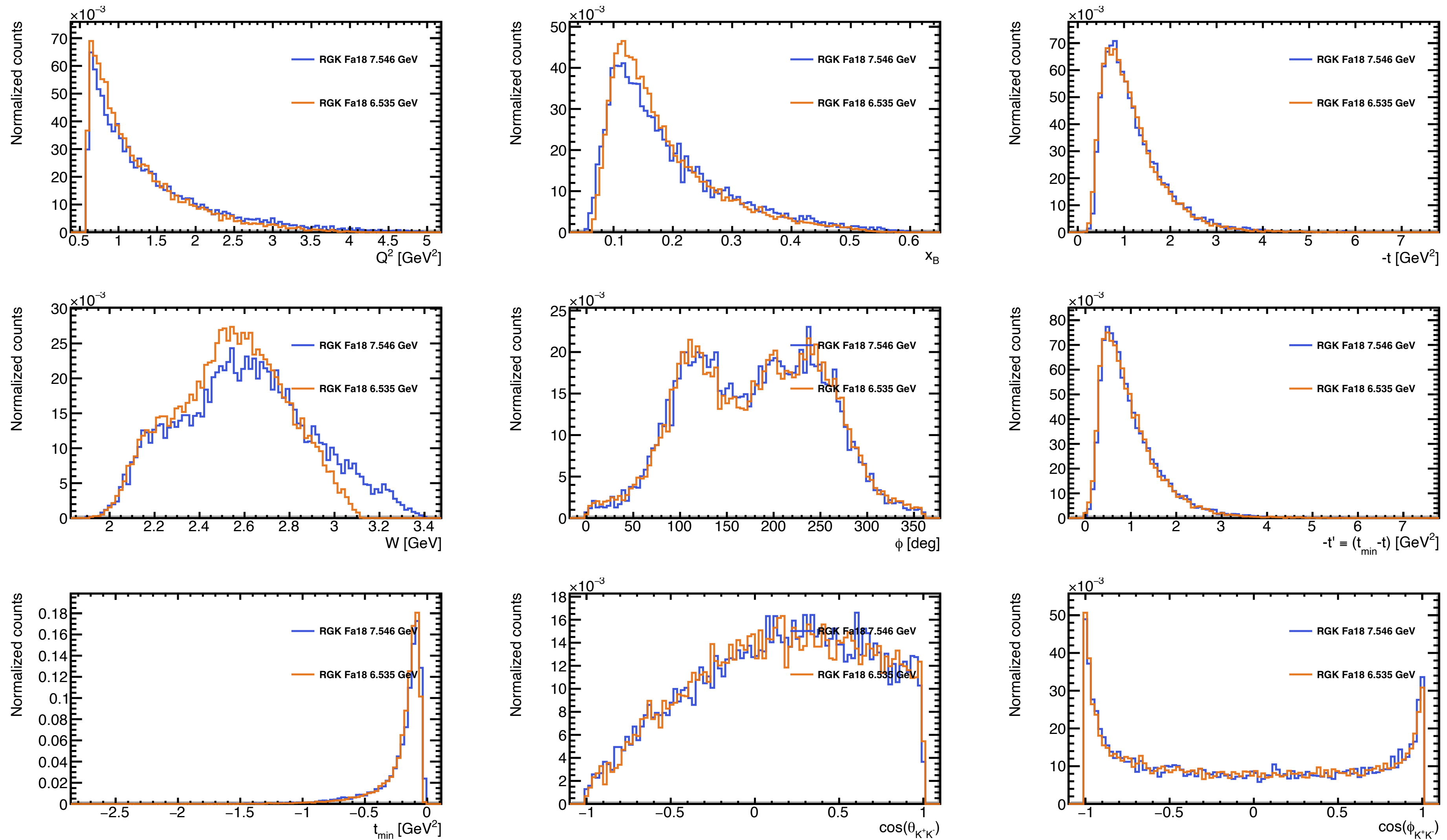
# DVEP Kinematic variables: RGA

- $W > 1.8 \text{ GeV}$  and  $Q^2 > 1.0 \text{ GeV}^2$



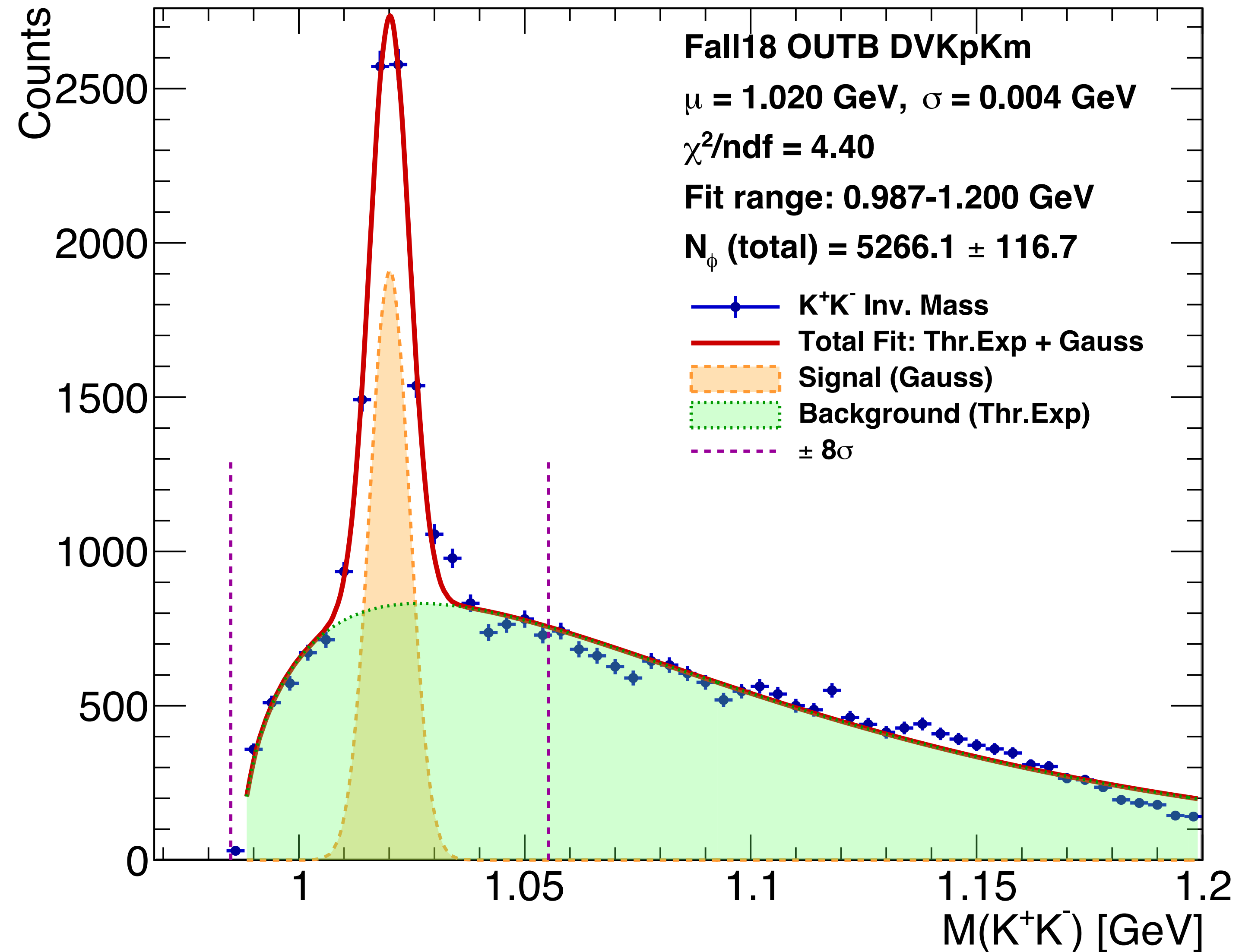
# DVEP Kinematics: RGK

- $W$  distribution becomes slightly smaller for 6.5 GeV data but overall they look comparable and similar to RGA



# K<sup>+</sup>K<sup>-</sup> Invariant Mass Distributions

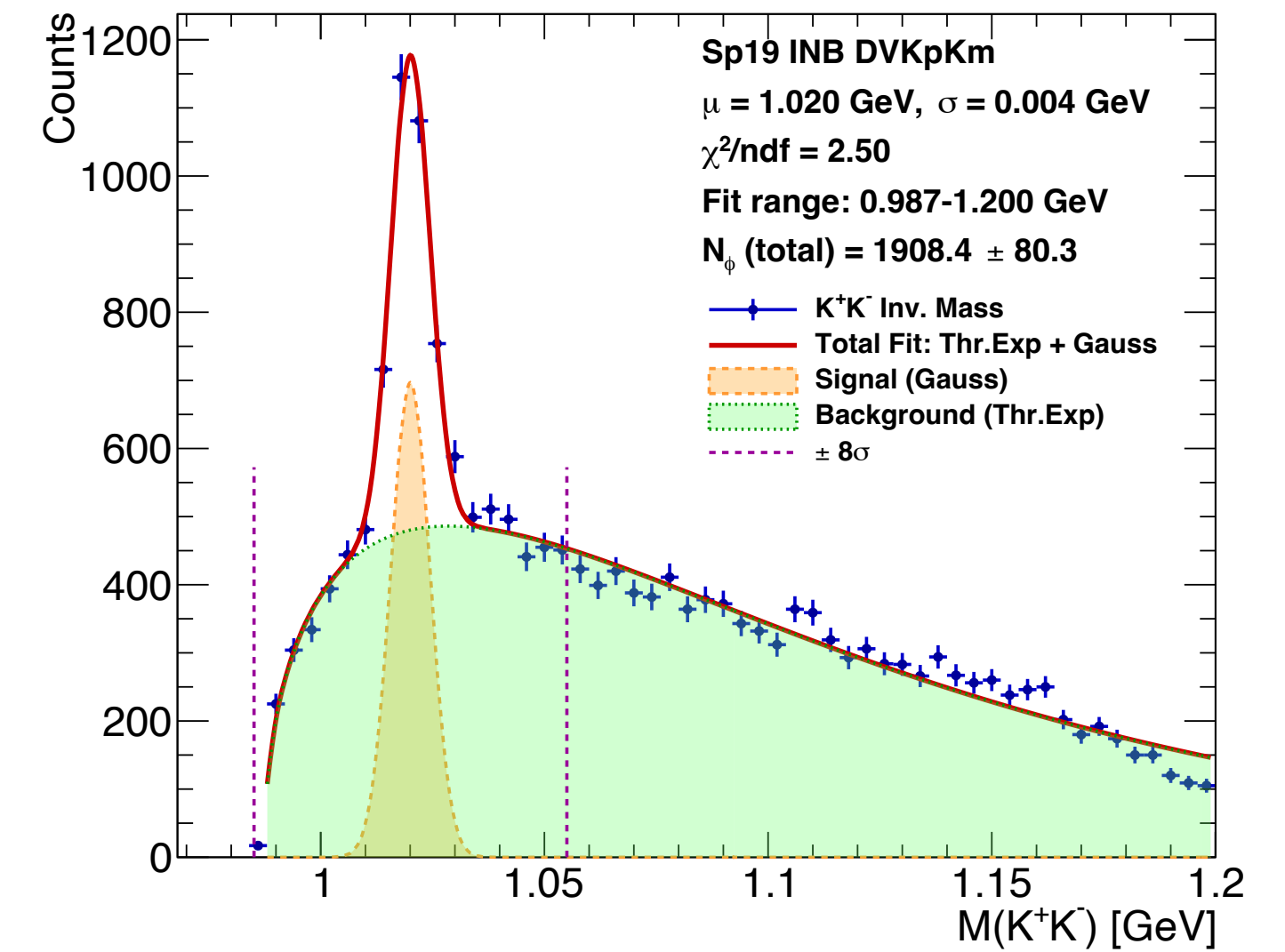
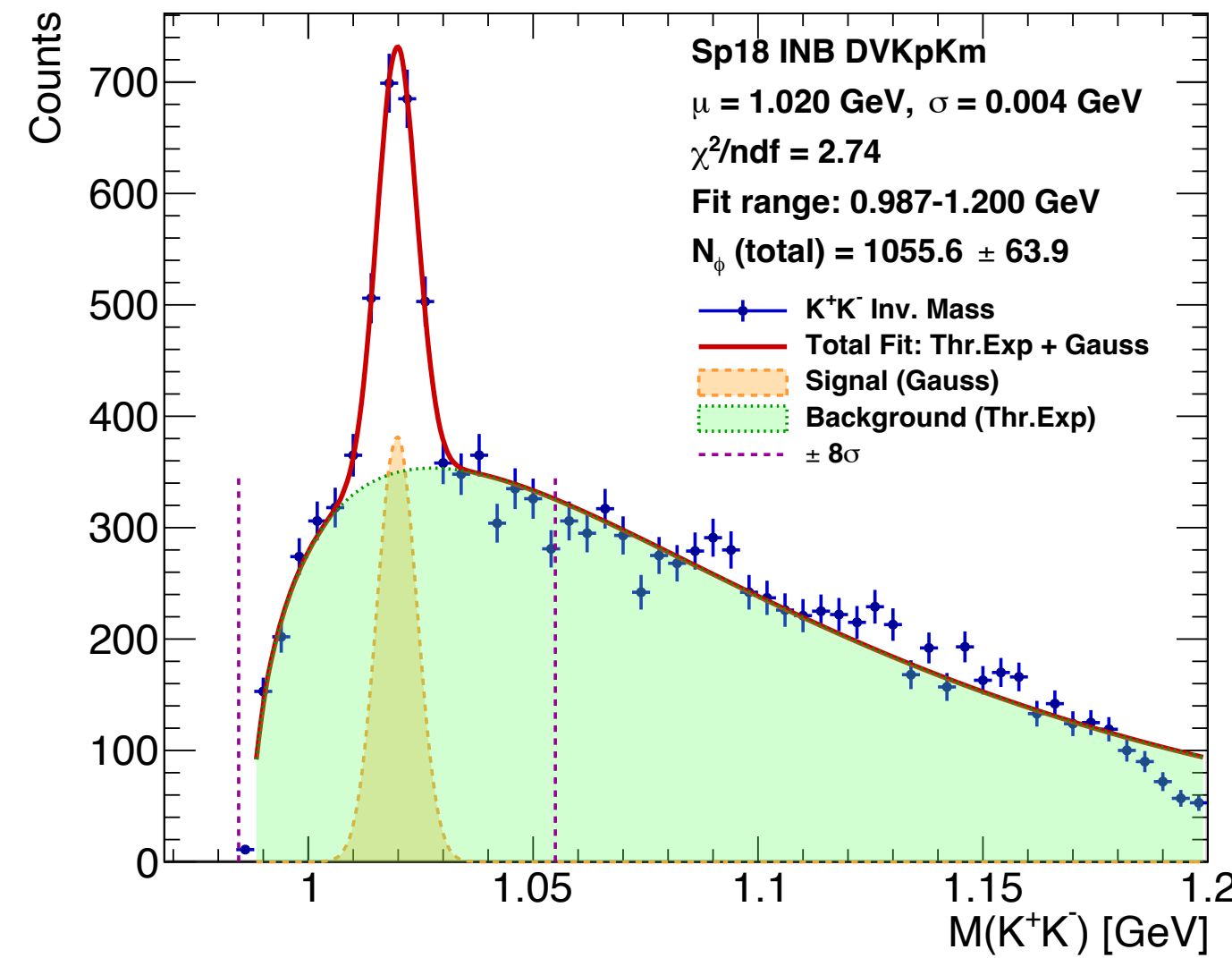
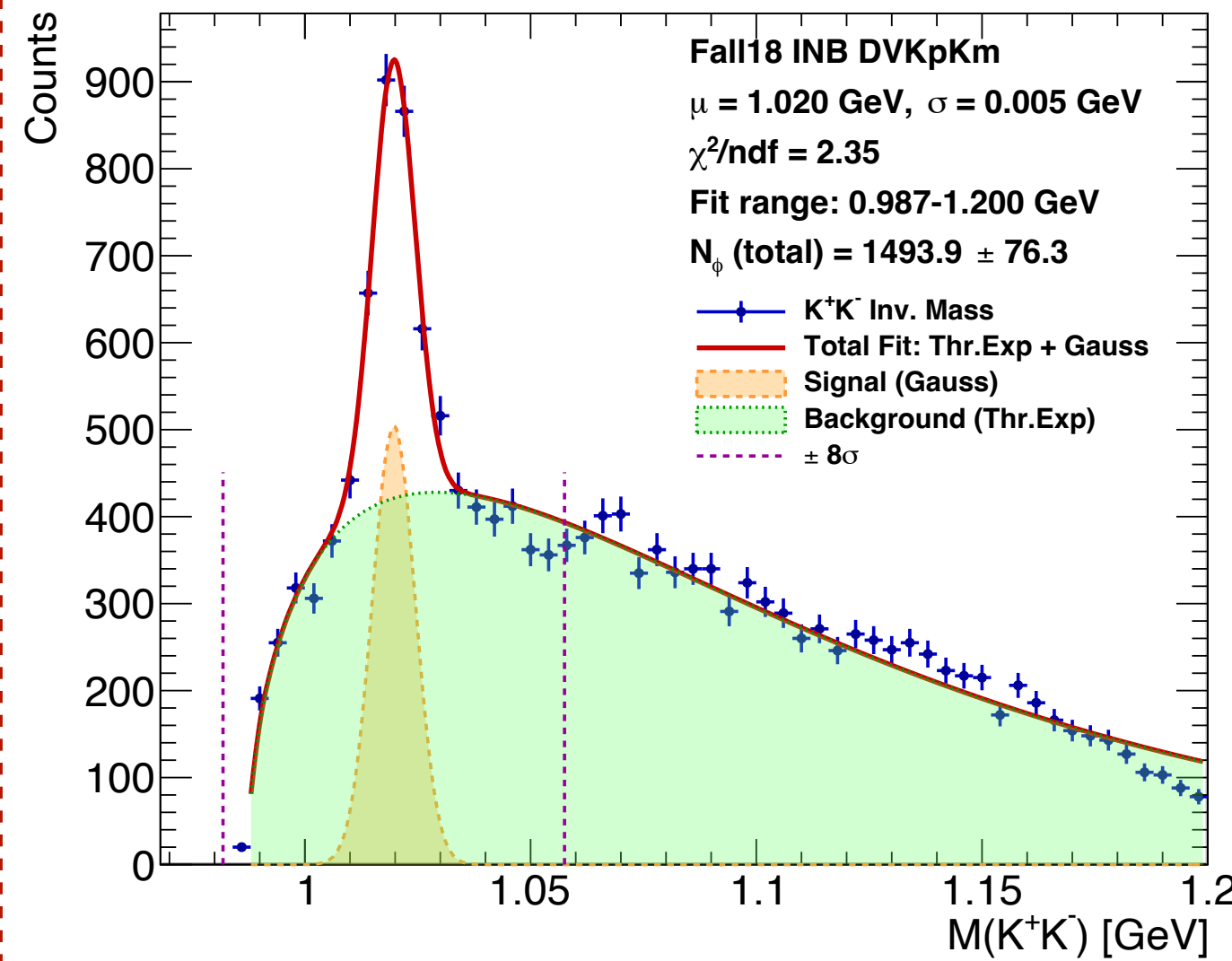
- $\phi$  candidate counts from the invariant mass peak at  $\sim 1.019$  GeV of  $K^+K^-$  in  $ep \rightarrow epK^+K^-$
- Signal: Gaussian distribution
- Background: threshold exponential function
- Extracted yield as integral of the Gaussian function
- Exclusive selection:  **$\sim 5200$**  candidates from fall 2018 outb alone



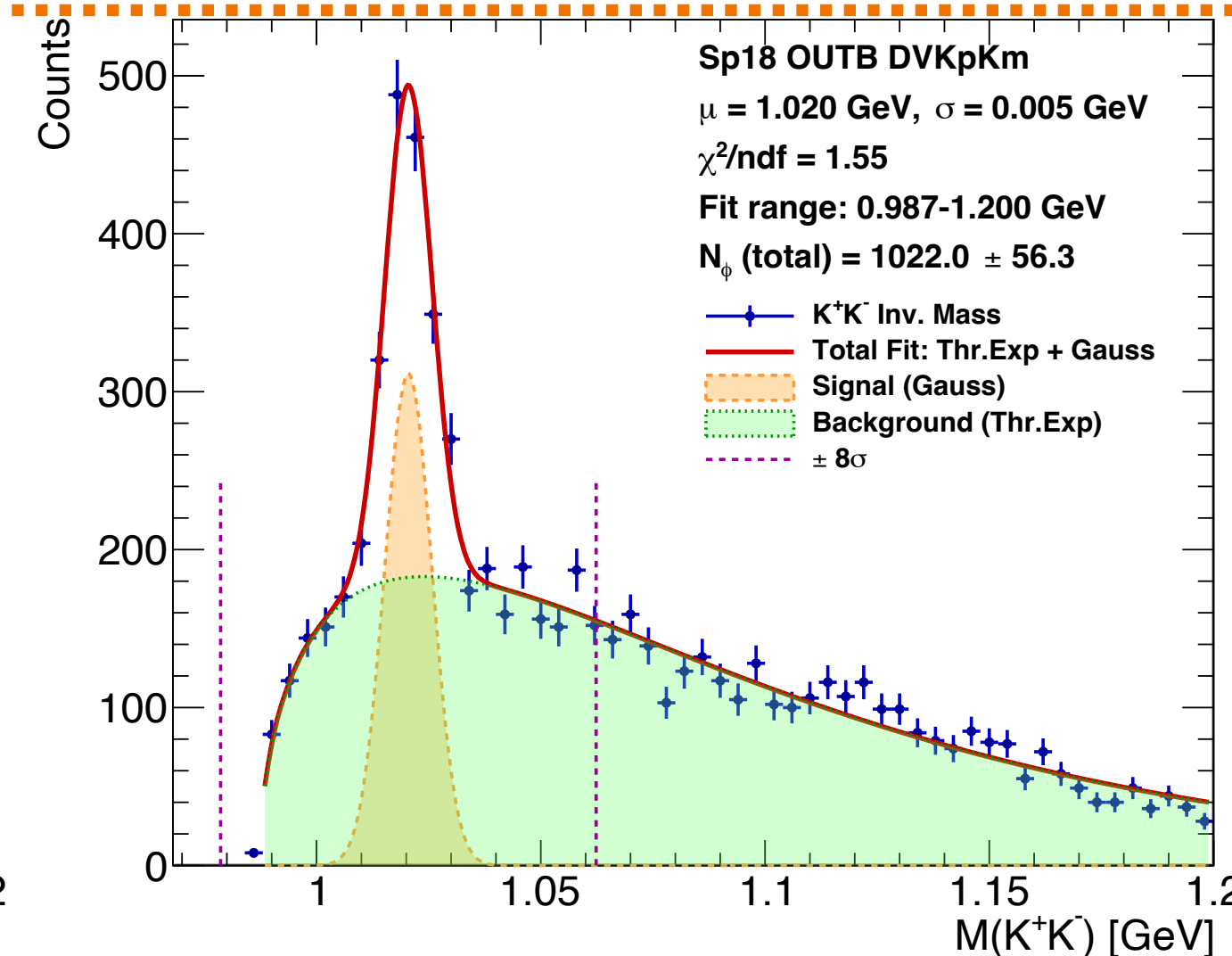
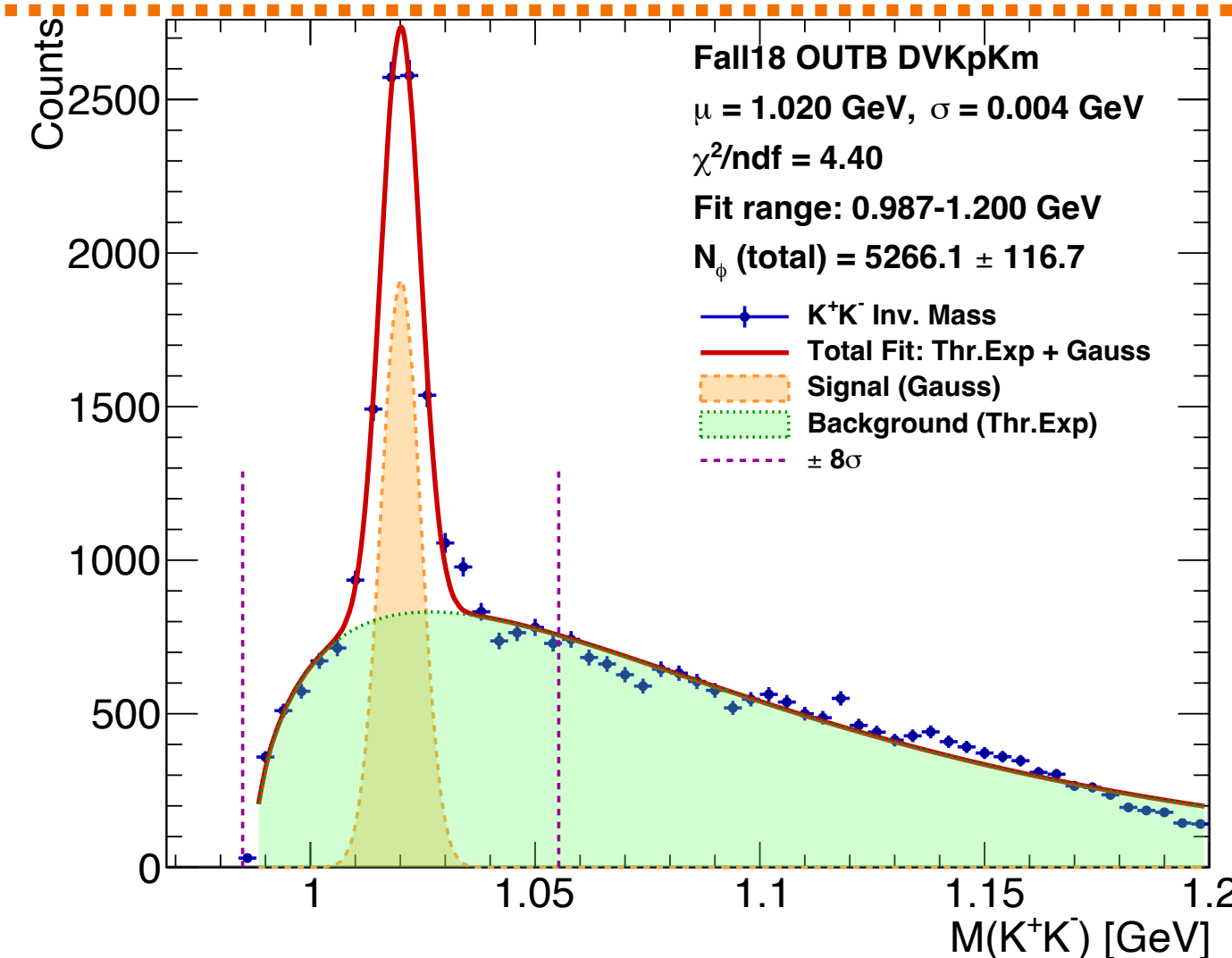
# All phi K<sup>+</sup>K<sup>-</sup> Invariant Mass all periods of 2018-19 run

- $\phi$  peak at  $\sim 1020$  MeV, total  $\sim 10000$  candidates from 2018-19 Run group A datasets

Inb

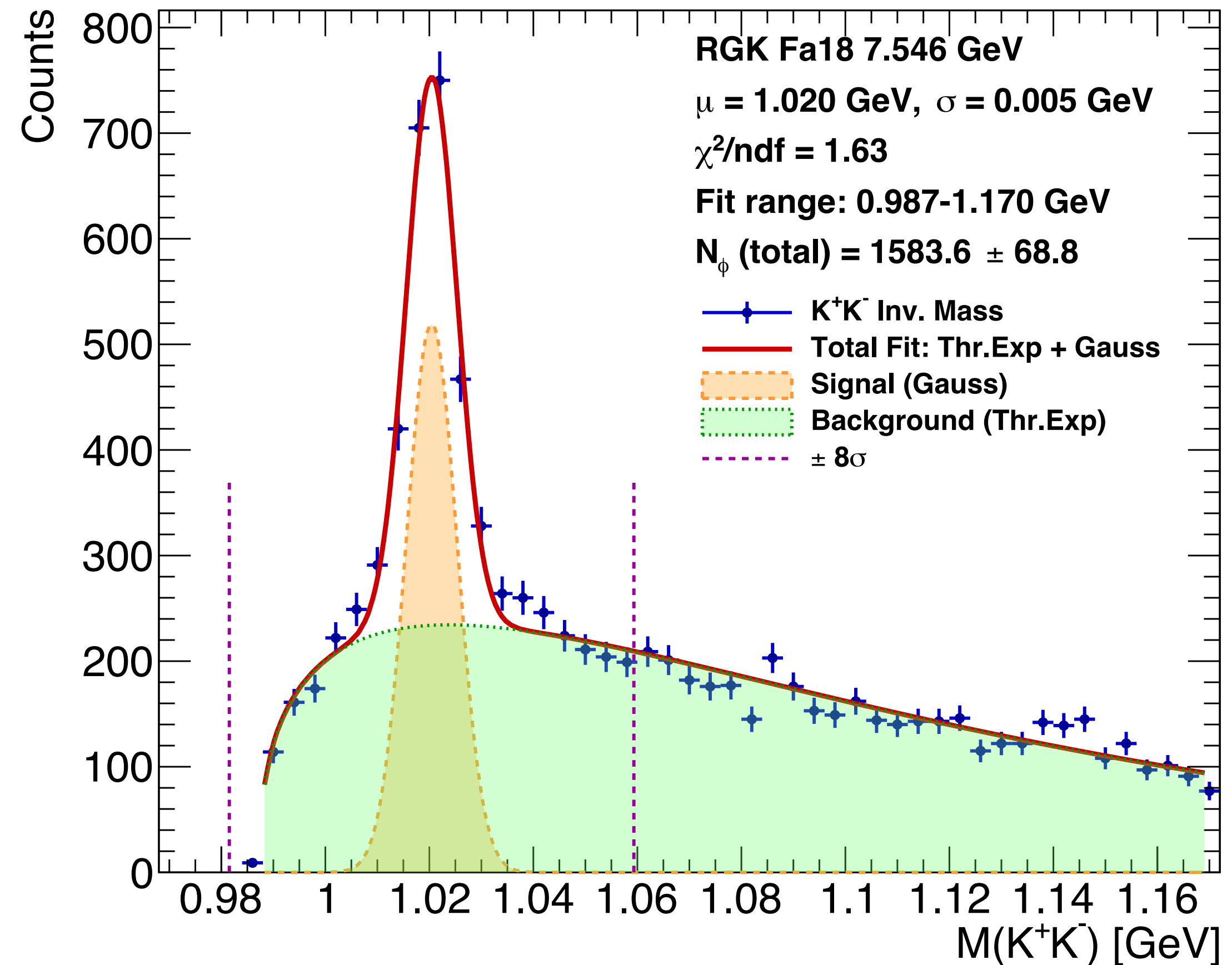
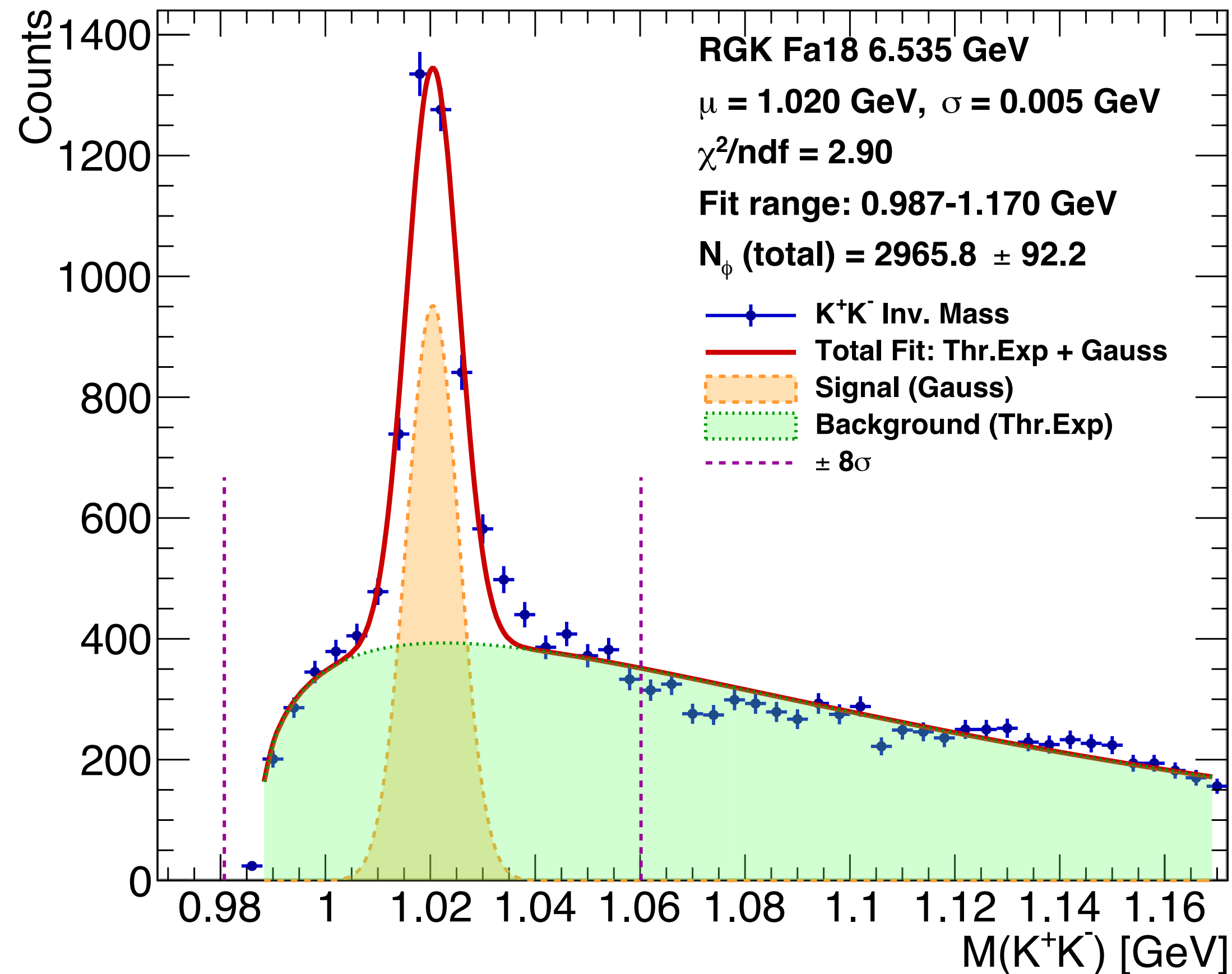


Outb



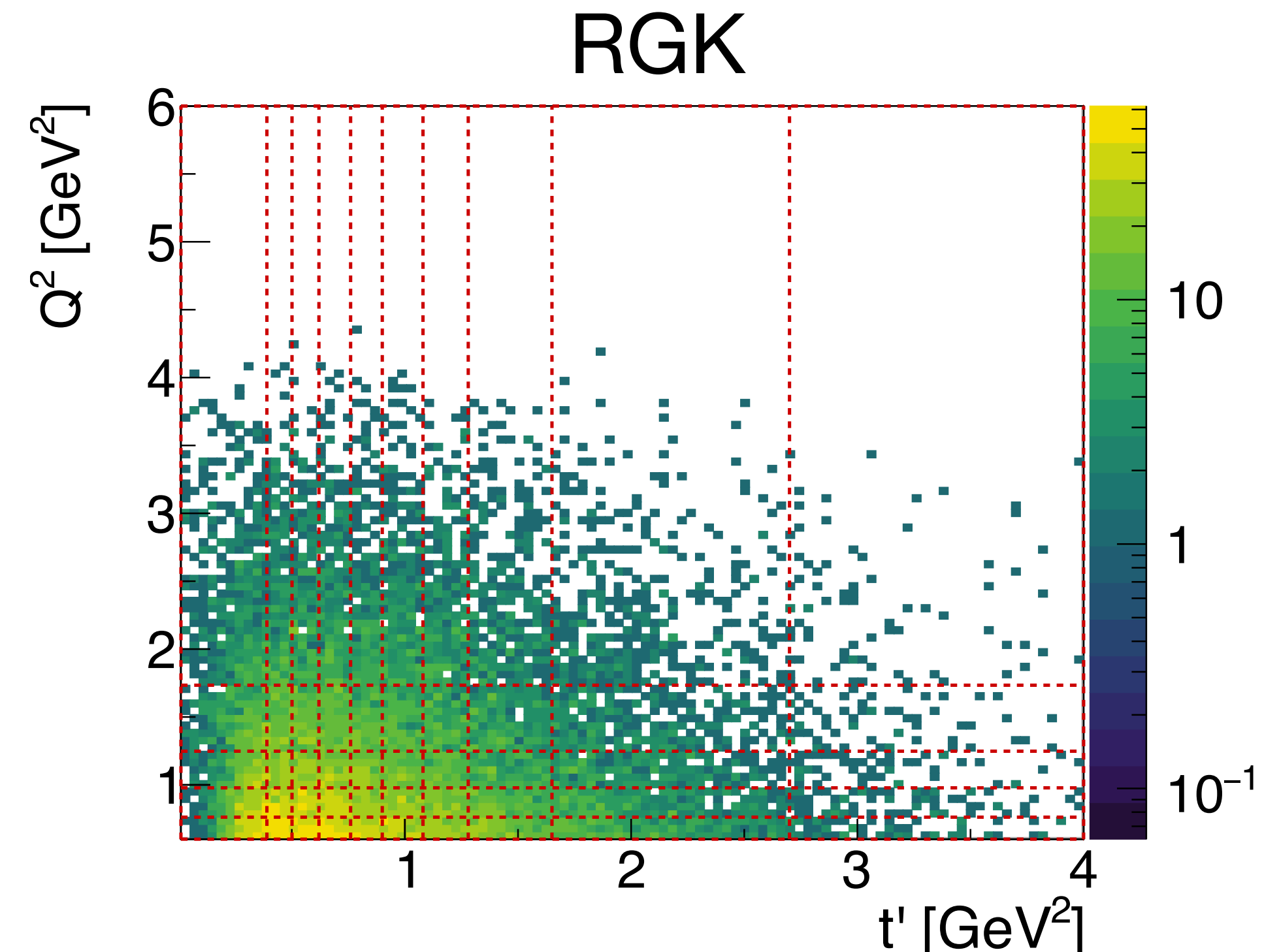
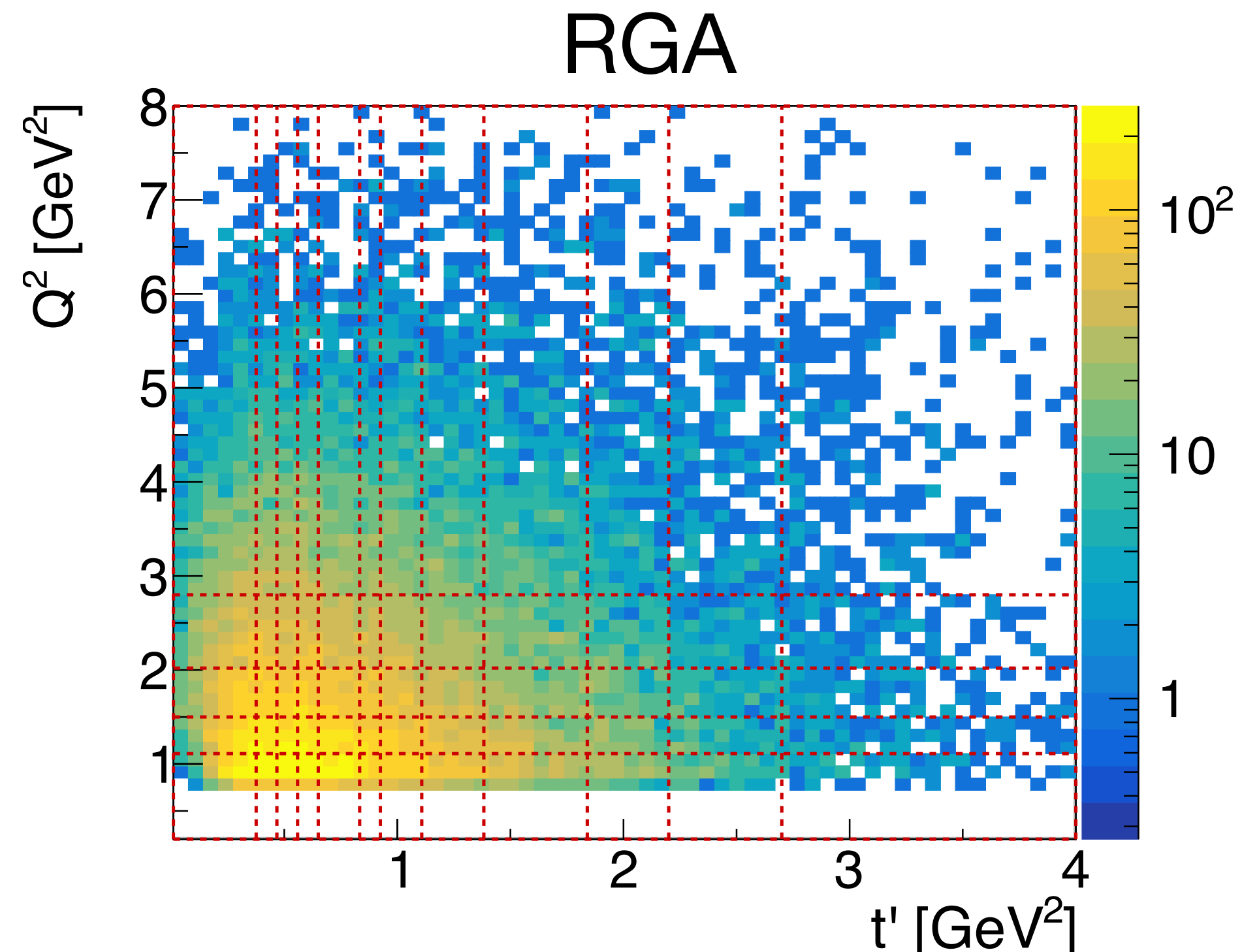
# RGK, Full DSTs analysis

- 6.5 and 7.5 GeV fall 2018 data,  $Q^2 > 0.6 \text{ GeV}^2$ , after all fiducial cuts and sampling fraction cuts for electron, energy loss correction for proton, 3 sigma exclusivity cuts
- Statistics 3K (6.535 GeV) and 1.5K (7.546 GeV)



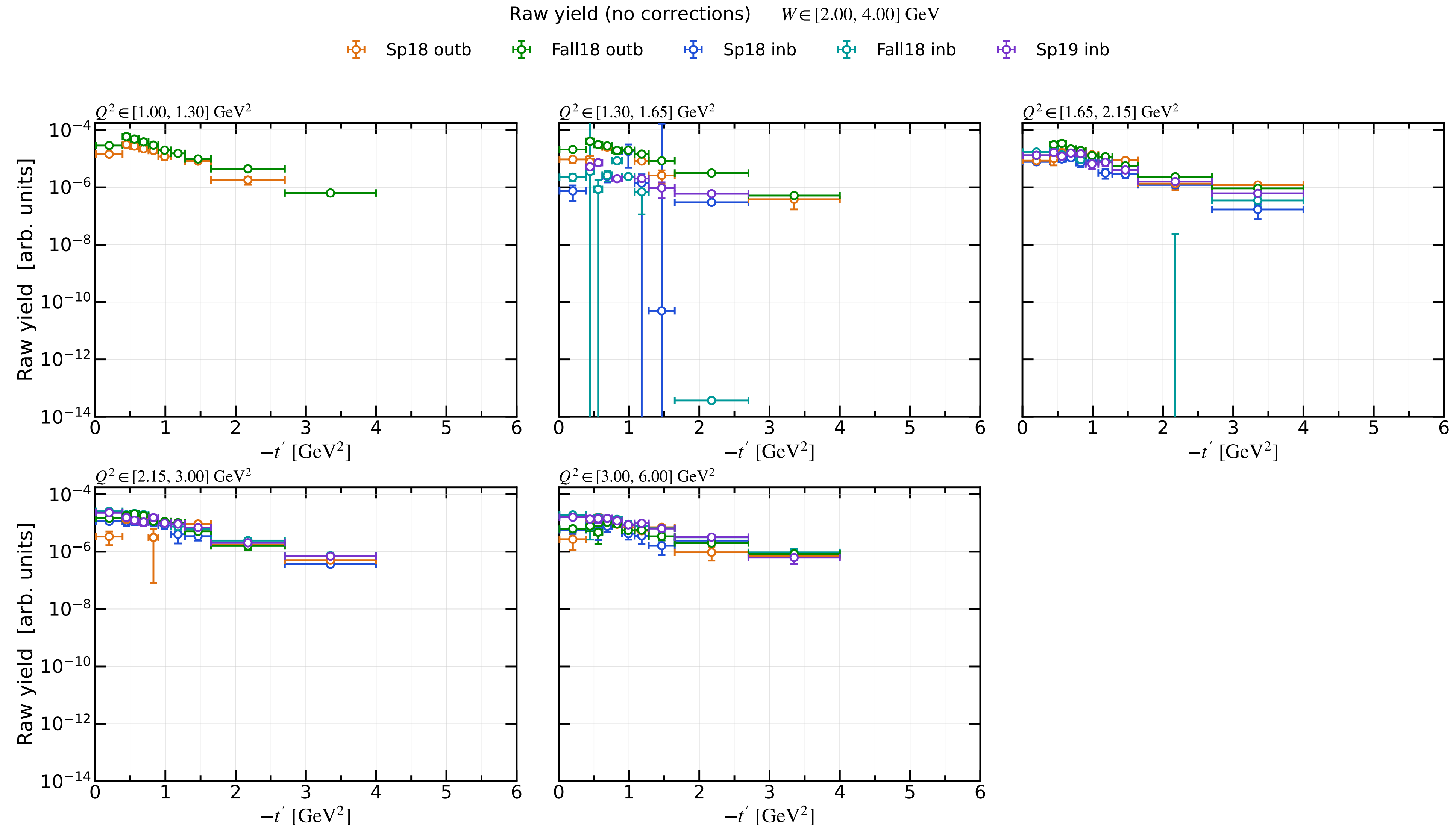
# Extraction of cross-section: RGA and RGK binning

- Divide the total sample with equal statistics in each  $Q^2$  and  $t'$  bin
- Currently **5**  $Q^2$  and **12**  $t'$  bins
- In each  $t'$  bin, we used a  $InvM_{K+K^-}$  distribution to extract the counts of  $\phi$



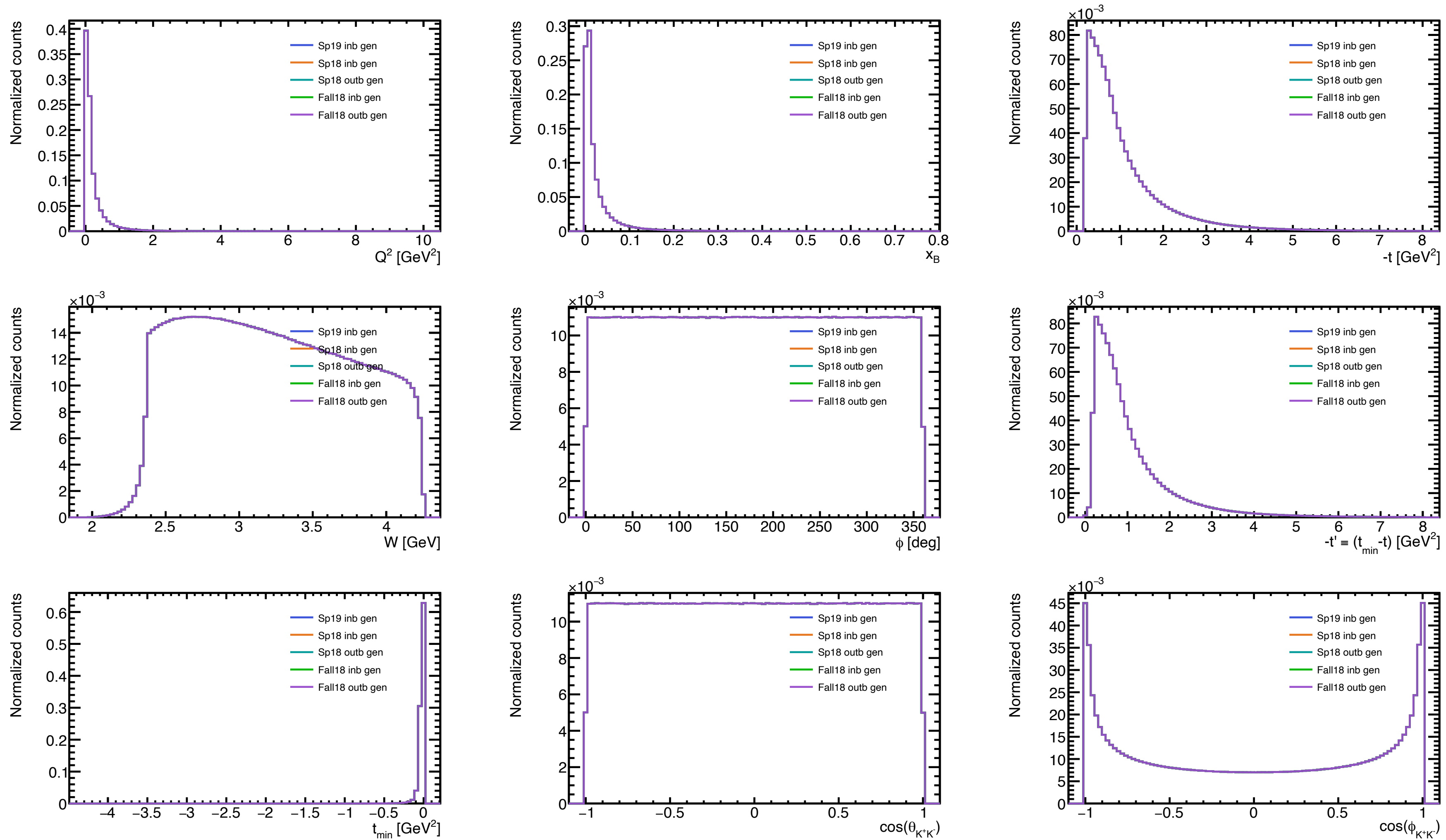
# The raw yields RGA

- Without the efficiency corrections!



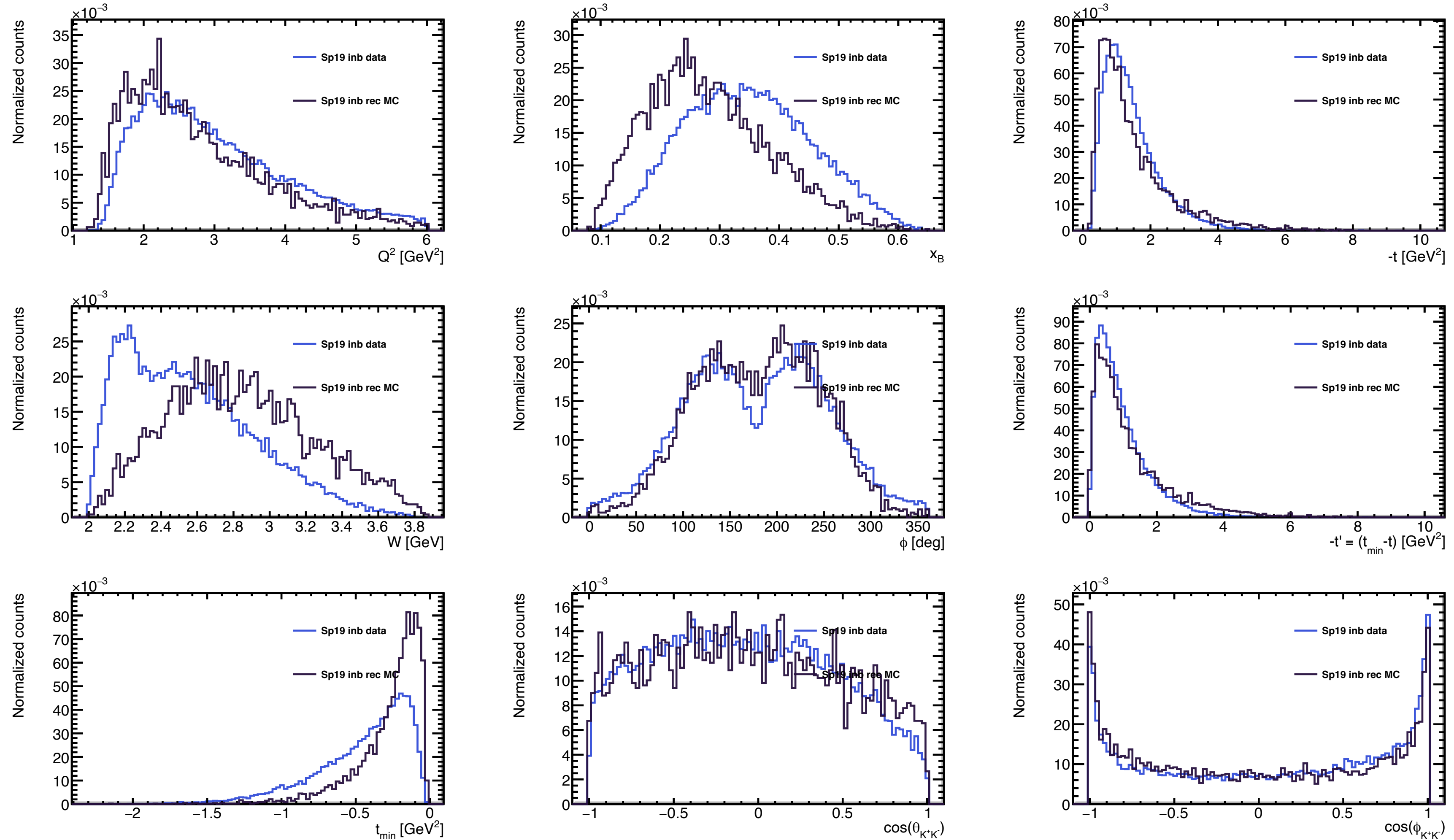
# Acceptance Effects within CLAS12

- Simulations based on the Argonne  $\phi$  Event Generator tuned to Clas 6 data and  $\phi$  event decay in rest mass is considered as isotropic (flat distribution)



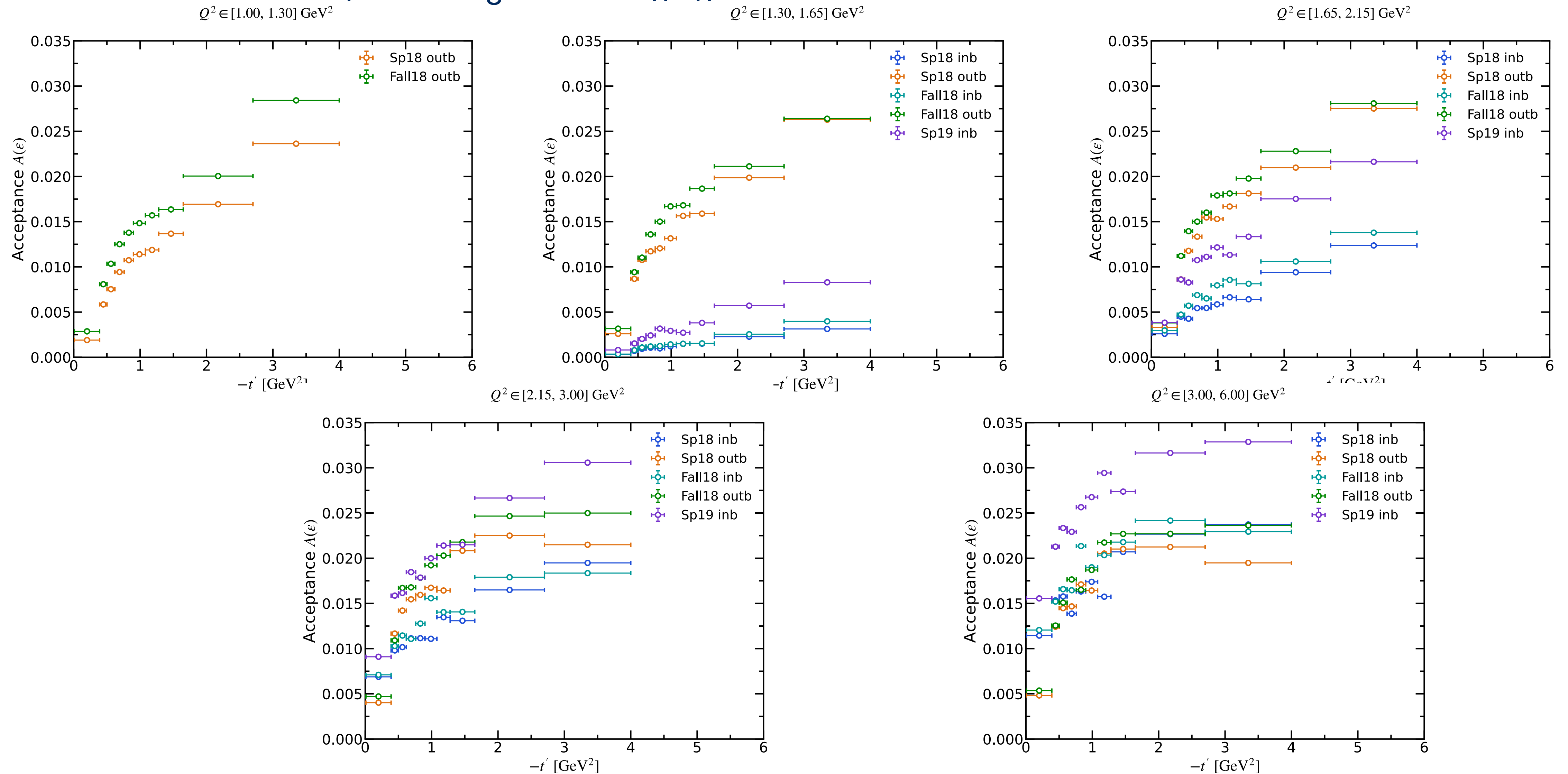
# Simulation vs Data

- Simulations based on the Argonne  $\phi$  Event Generator tuned to Clas 6 data and  $\phi$  event decay in rest mass is considered as isotropic (flat distribution)



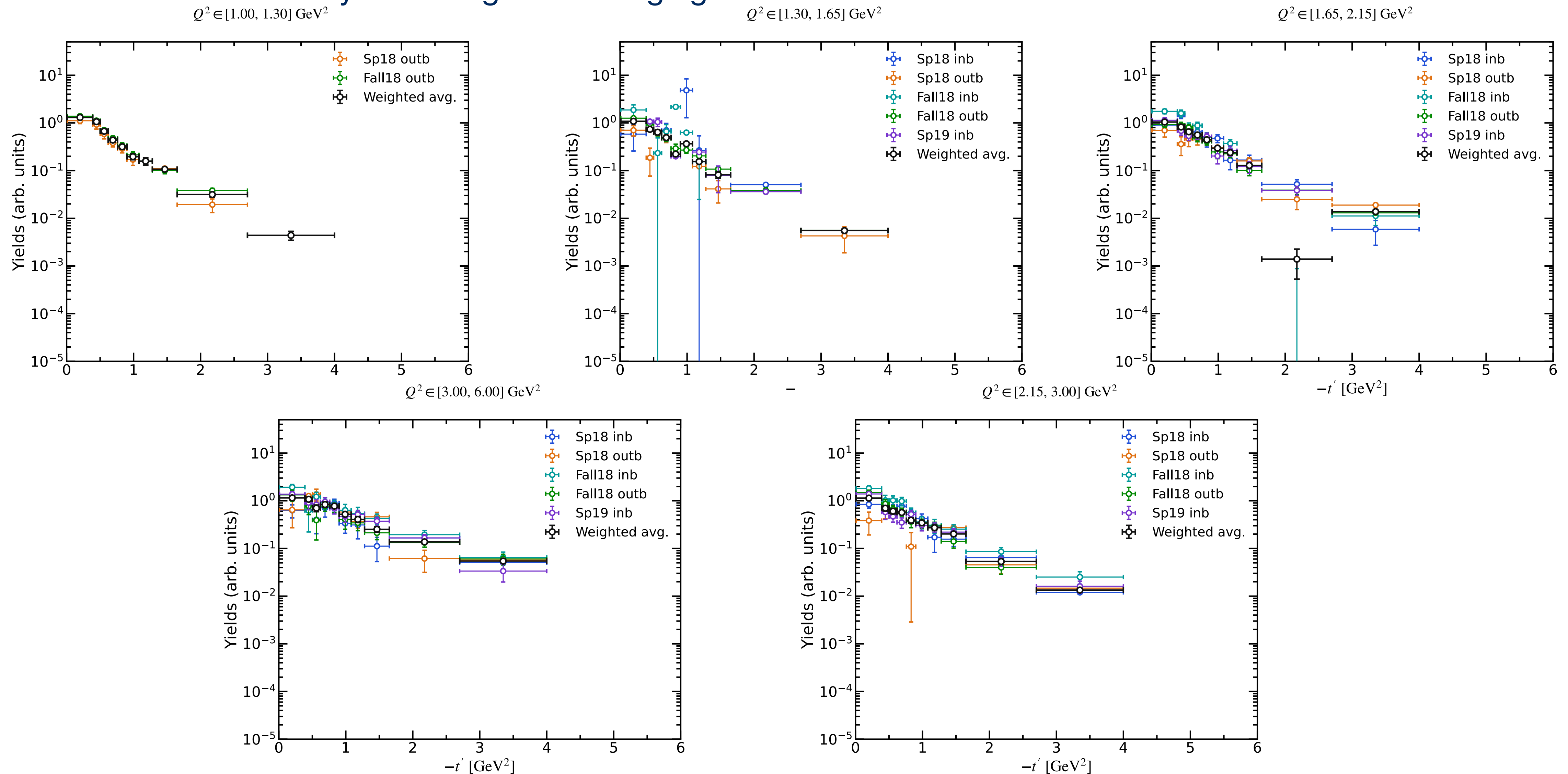
# Detector acceptance effects RGA

- Without the efficiency for background merging corrections!

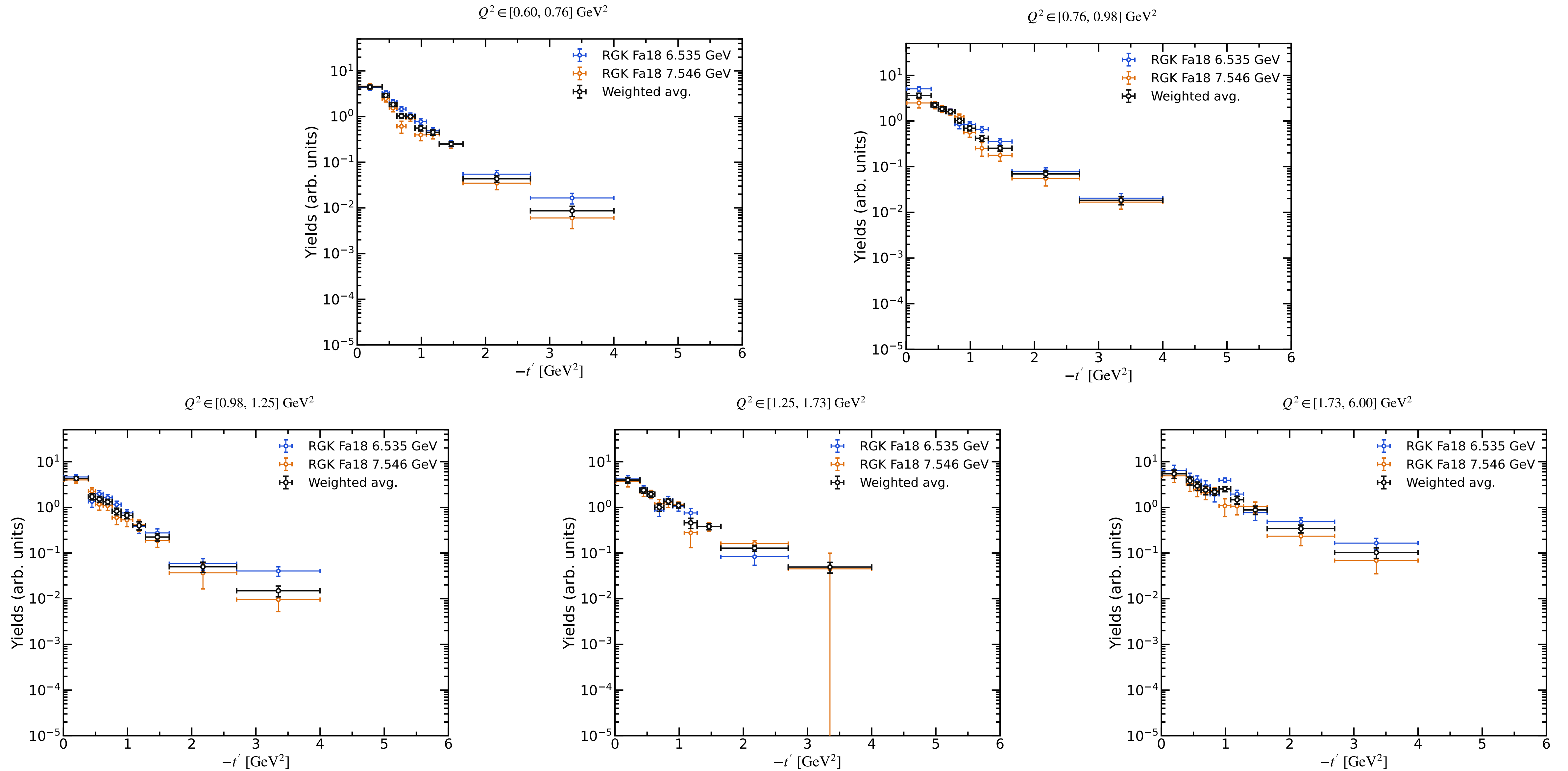


# Final reduced cross-sections RGA

- Without the efficiency for background merging corrections!

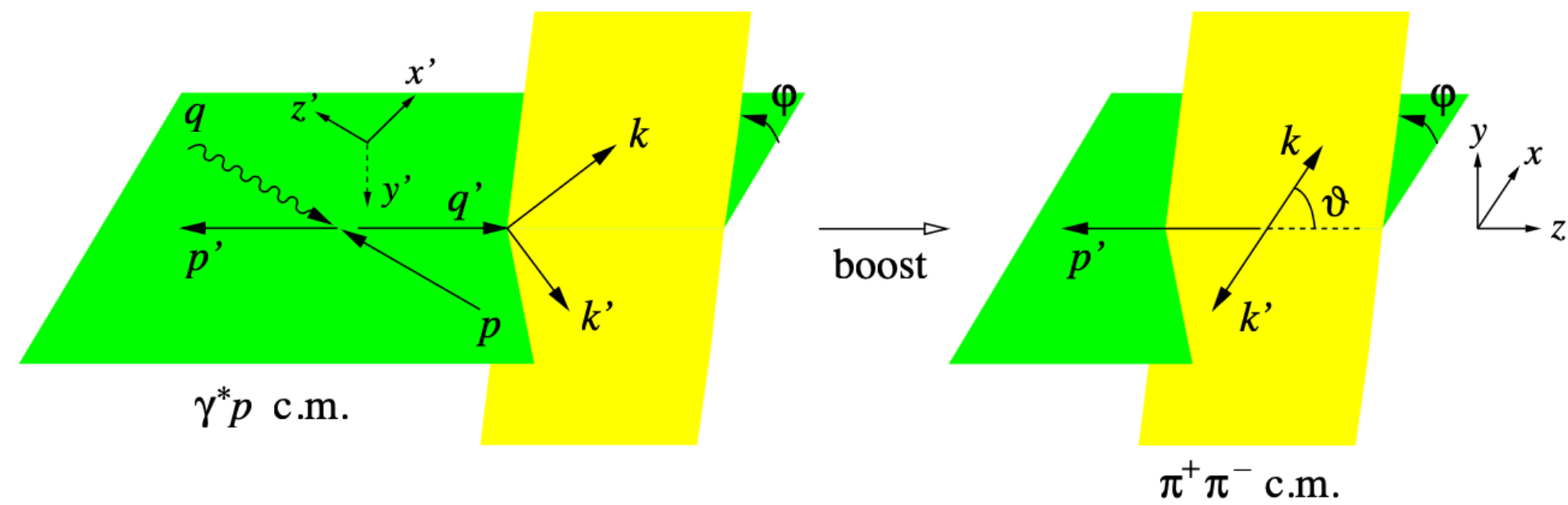


# RGK Efficiency corrected cross-sections

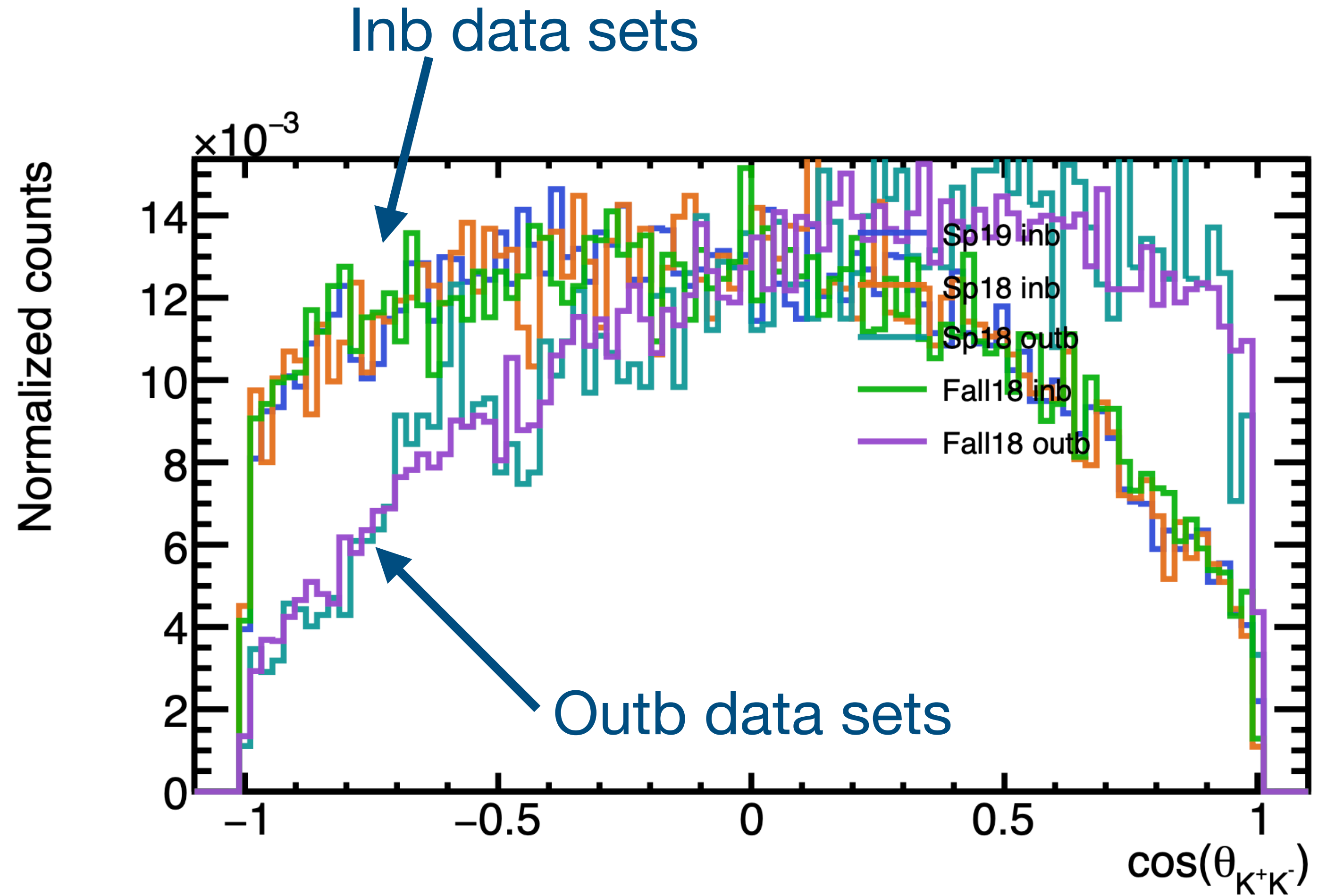


# $\phi$ -decay and acceptance within CLAS12

- Vector meson with spin 1 possible decay is expected to be a non-flat distribution



Markus Diehl JHEP09(2007)064



# Total cross-section from normalized SDMEs

- A generic cross-section depends on both SDMEs and the  $\sigma_L$  and  $\sigma_T$

$$[\sigma_T(Q^2, x_B, t) + \epsilon\sigma_L(Q^2, x_B, t)] W(SDME(Q^2, x_B, t), \cos\theta, \Phi, \phi)$$

- Schilling-Wolf form

$$W(\cos\theta, \phi, \Phi; \epsilon, P_\ell; \{r_{ij}^\alpha\}) = W_{UU} + P_\ell W_{LU}$$

with 23 SDMEs as free parameters:

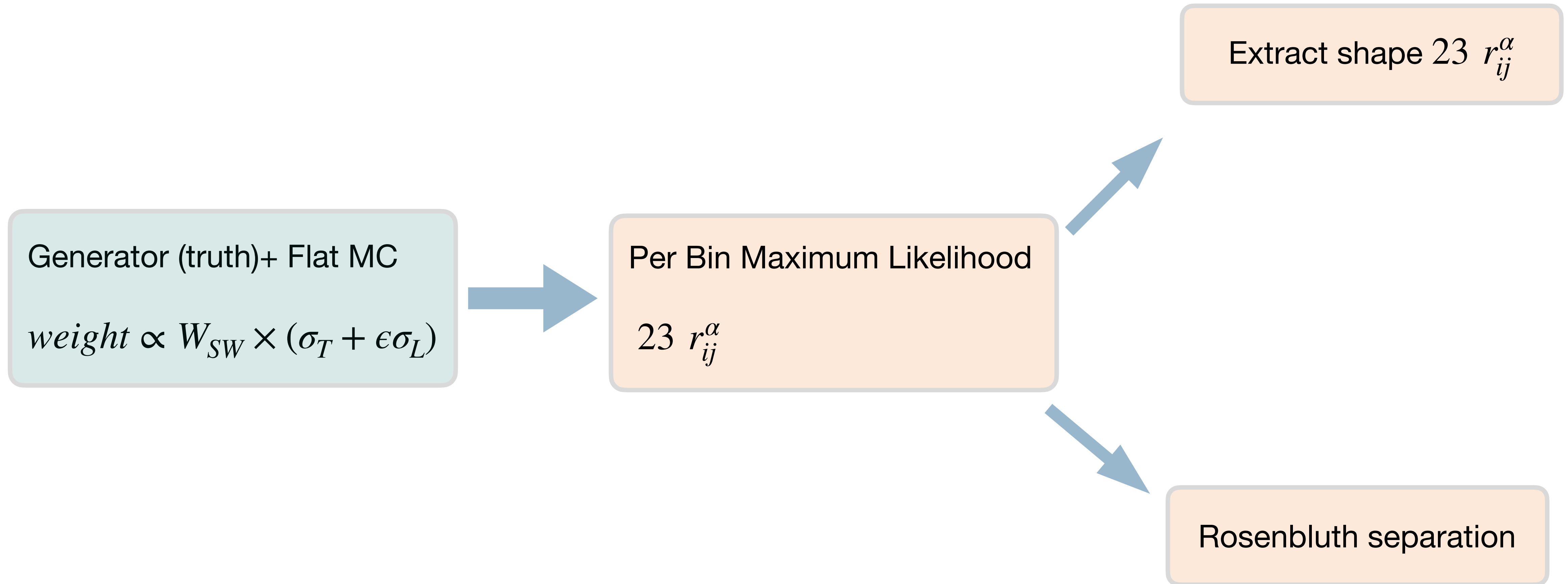
- $W_{UU}$  (15 unpolarised-beam SDMEs):  $r_{00}^{04}, \text{Re}r_{10}^{04}, r_{1,-1}^{04}$  ( $\alpha = 0 + 4$ );  $r_{11}^1, r_{00}^1, \text{Re}r_{10}^1, r_{1,-1}^1$  ( $\alpha = 1$ );  $\text{Im}r_{10}^2, \text{Im}r_{1,-1}^2$  ( $\alpha = 2$ );  $r_{11}^5, r_{00}^5, \text{Re}r_{10}^5, r_{1,-1}^5$  ( $\alpha = 5$ );  $\text{Im}r_{10}^6, \text{Im}r_{1,-1}^6$  ( $\alpha = 6$ ).
- $W_{LU}$  (8 polarised-beam SDMEs):  $\text{Im}r_{10}^3, \text{Im}r_{1,-1}^3$  ( $\alpha = 3$ );  $\text{Im}r_{10}^7, \text{Im}r_{1,-1}^7$  ( $\alpha = 7$ );  $r_{11}^8, r_{00}^8, \text{Re}r_{10}^8, r_{1,-1}^8$  ( $\alpha = 8$ ).
- M. Diehl (JHEP 09 (2007) 064)

$$2\pi \frac{d\sigma}{dt d\Phi} = \frac{d\sigma_T}{dt} + \epsilon \frac{d\sigma_L}{dt} + \epsilon \cos 2\Phi \frac{d\sigma_{TT}}{dt} + \sqrt{2\epsilon(1+\epsilon)} \cos \Phi \frac{d\sigma_{LT}}{dt} + h_\ell \sqrt{2\epsilon(1-\epsilon)} \sin \Phi \frac{d\sigma_{LT'}}{dt},$$

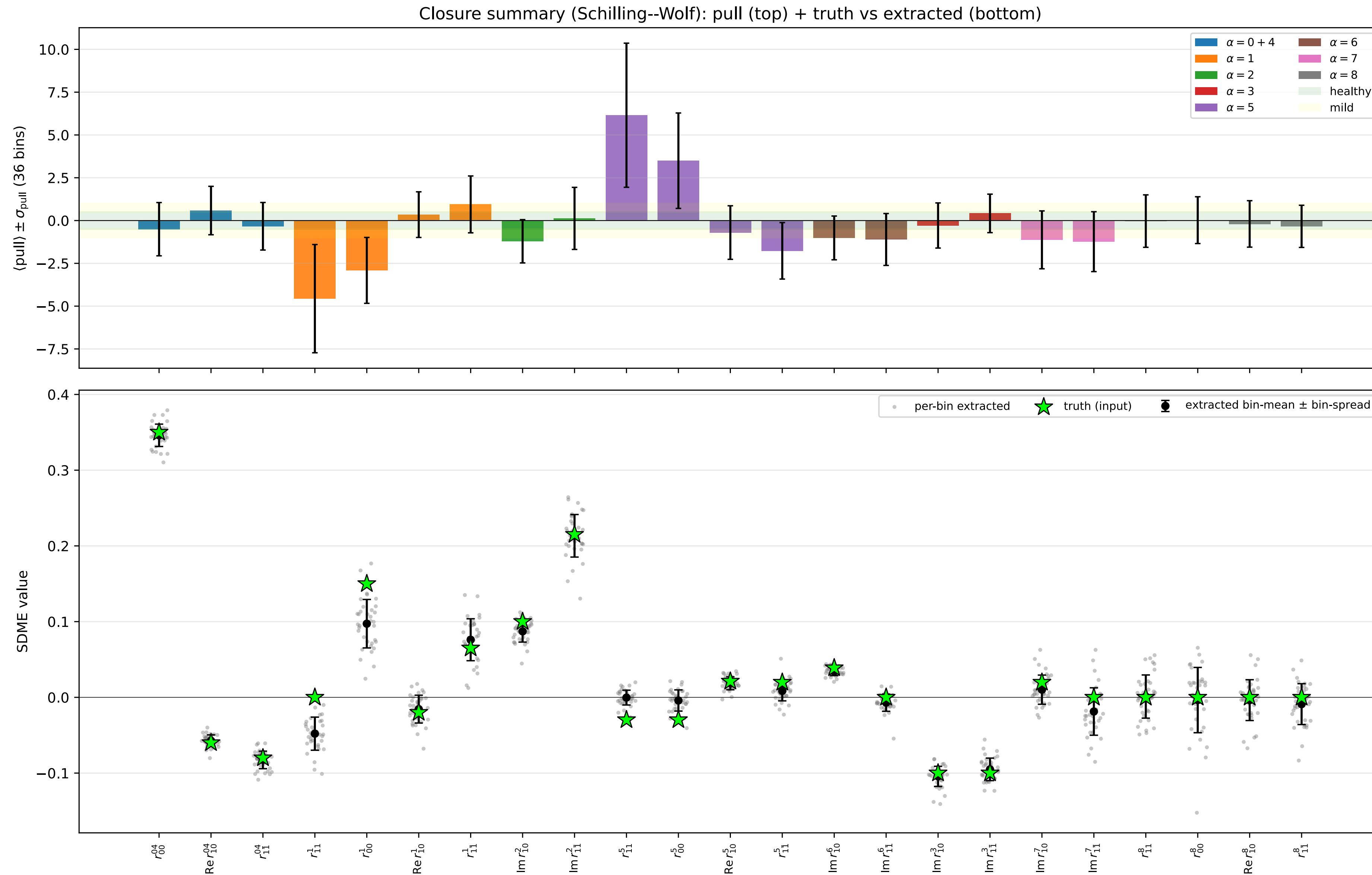
$$\rho_{\mu\mu', \lambda\lambda'}^{\nu\nu'} = \frac{1}{N_T + \epsilon N_L} \sum_{\sigma} T_{\mu\lambda}^{\nu\sigma} (T_{\mu'\lambda'}^{\nu'\sigma})^*,$$

# Closure test: to check if the fit works

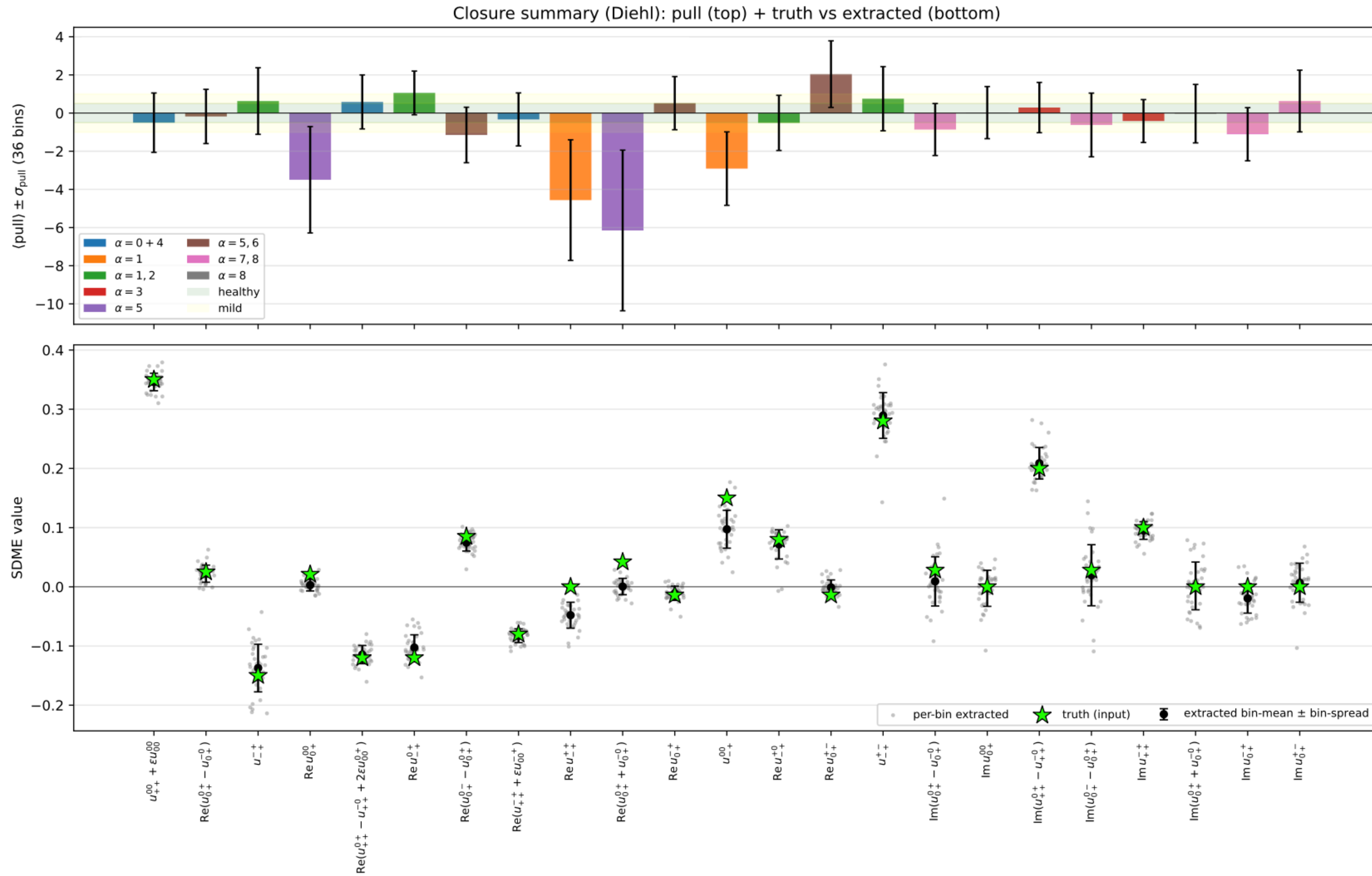
- Events at the generator level only!



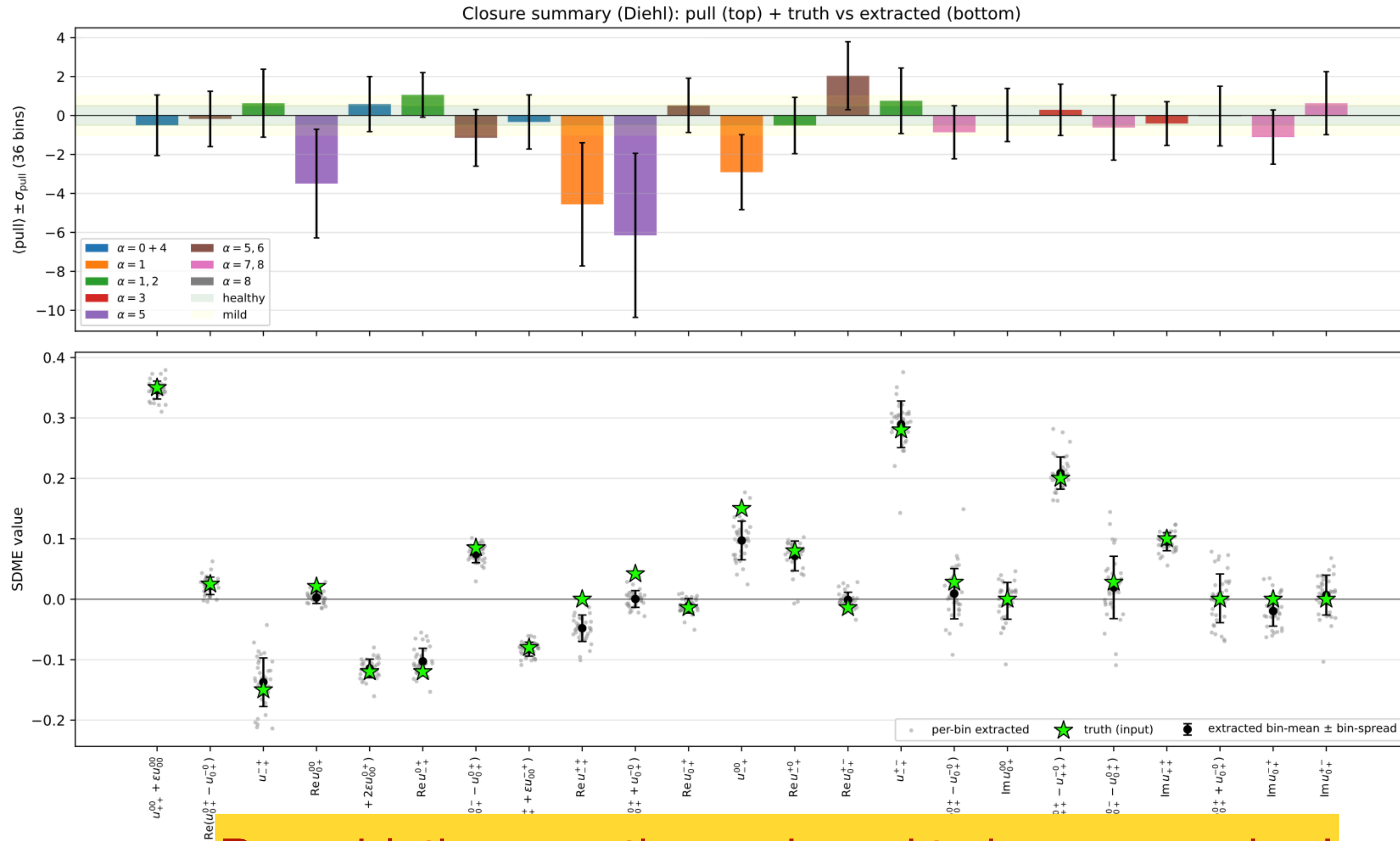
# Extracted SDMEs (sims only): S+W notation



# Extracted SDMEs (sims only): Diehl's notation



# Extracted SDMEs (sims only): Diehl's notation



Rosenbluth separation and need to know  $\sigma_L$  and  $\sigma_T$ !

# Diehl's unnormalized SDME and Rosenbluth Separation

- A generic cross-section depends on both SDMEs and the  $\sigma_L$  and  $\sigma_T$

$$[\sigma_T(Q^2, x_B, t) + \epsilon\sigma_L(Q^2, x_B, t)] W(SDME(Q^2, x_B, t), \cos\theta, \Phi, \phi)$$

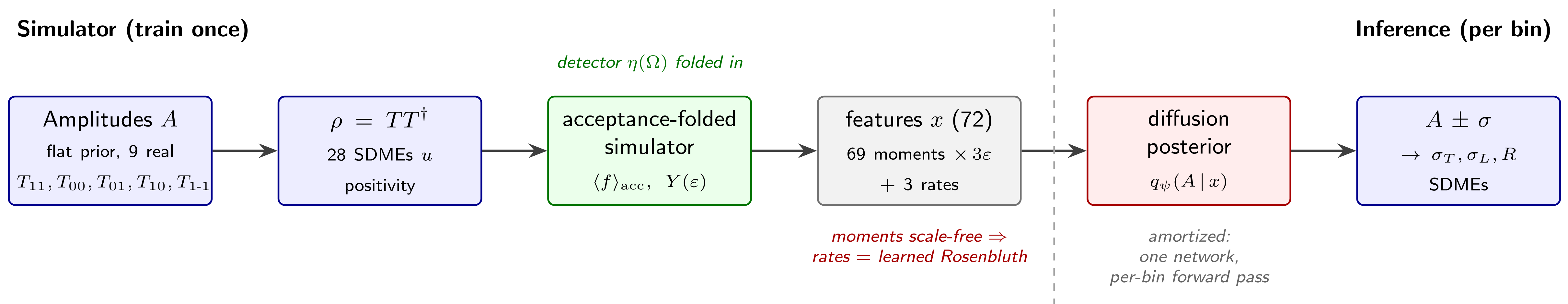
- We can absorb the  $\sigma_L$  and  $\sigma_T$  into the normalization of the W distribution

$$W_{\text{unnorm}}(\Omega; \epsilon) = (\sigma_T + \epsilon\sigma_L) W_{\text{SW}}(\Omega; \{r_{ij}^\alpha\}, \epsilon), \quad \int W_{\text{unnorm}} d\Omega = \sigma_T + \epsilon\sigma_L.$$

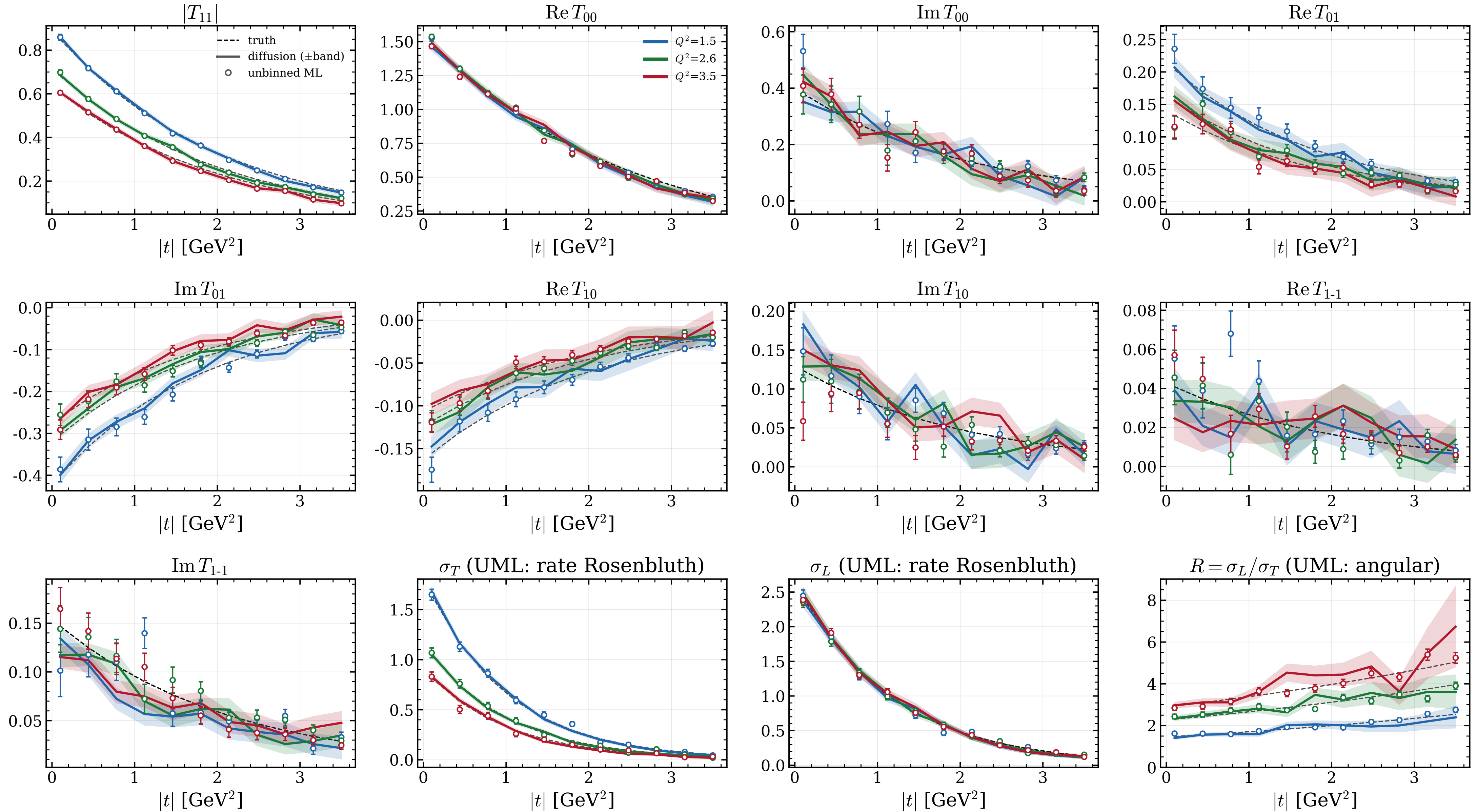
- Advantage is we don't need separate modeled functions for  $\sigma_L$  and  $\sigma_T$  but calculate from the form of Helicity amplitude/SDMEs
- Here: Each ( $Q^2, t'$ ) bin is fit with the 28 unnormalized  $u^{\nu\nu'}_{\mu\mu'}$ , including the trace parameters that carry the cross sections:
- $\sigma_T = 2u_{++}^{++} + u_{++}^{00}$ ,  $\sigma_L = 2u_{00}^{++} + u_{00}^{00}$ . 25 independent physical degrees of freedom
- Three are tied by the natural-parity / symmetry relations Diehl uses (e.g.  $u^{+- - -} = u^{++ ++}$ ). So eventually only independent dof: 25 (unnormalized) vs 23 (normalized)
- The 2 extra independent dof (25 vs 23) are exactly the absolute L/T scale that SW throws away — carried by  $u^{++ ++}/u^{++ 00}$  and the L-partners. No assumption of the **SCHC** —> **try functions ( $Q^2, t, W$ )**

# Work flow for extraction

- **A conditional diffusion model:**  $q_\psi(u | x)$  — the third neural route, twin of the normalizing-flow NPE.
- Different engine: iterative denoising instead of one invertible map (no Jacobian constraint  $\Rightarrow$  flexible, correlated posteriors).

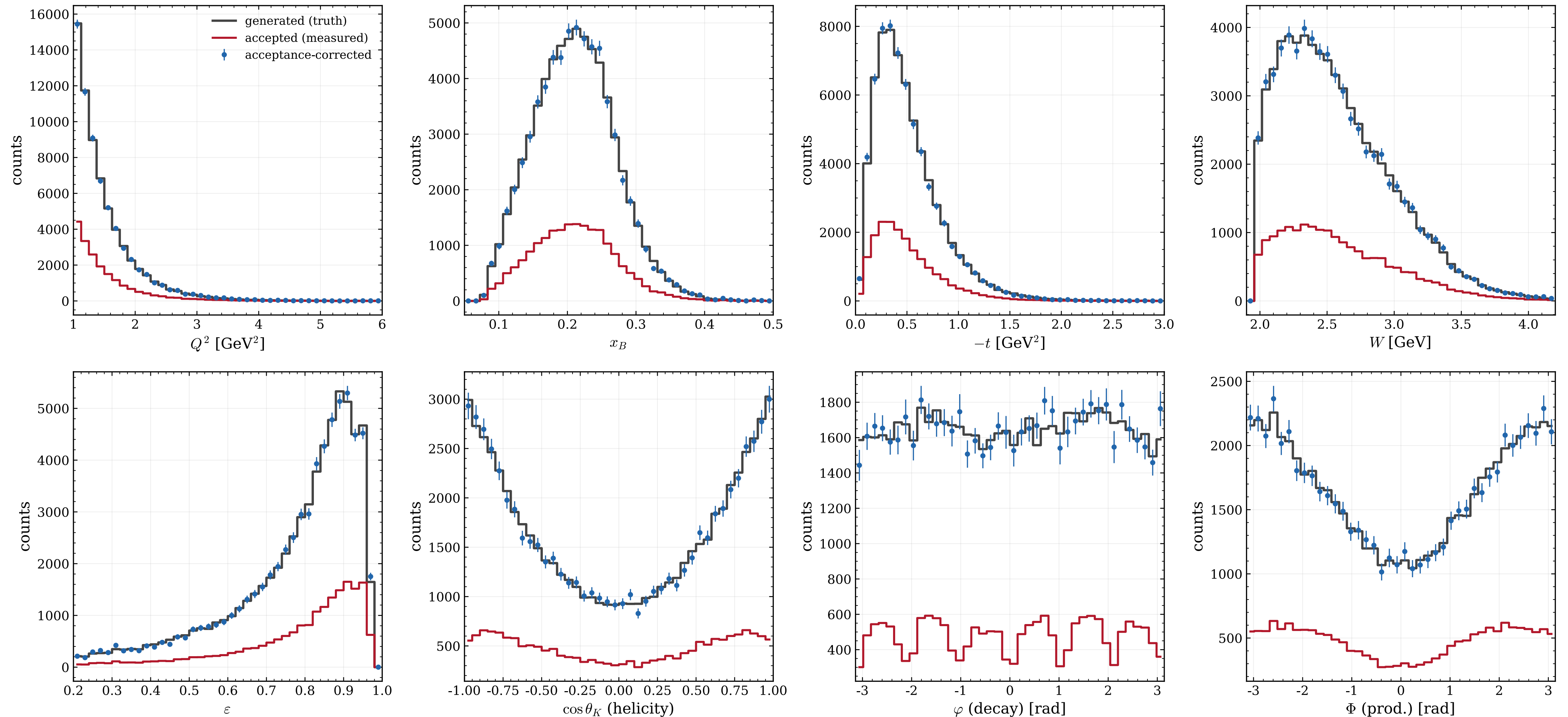


# Extracted amplitudes



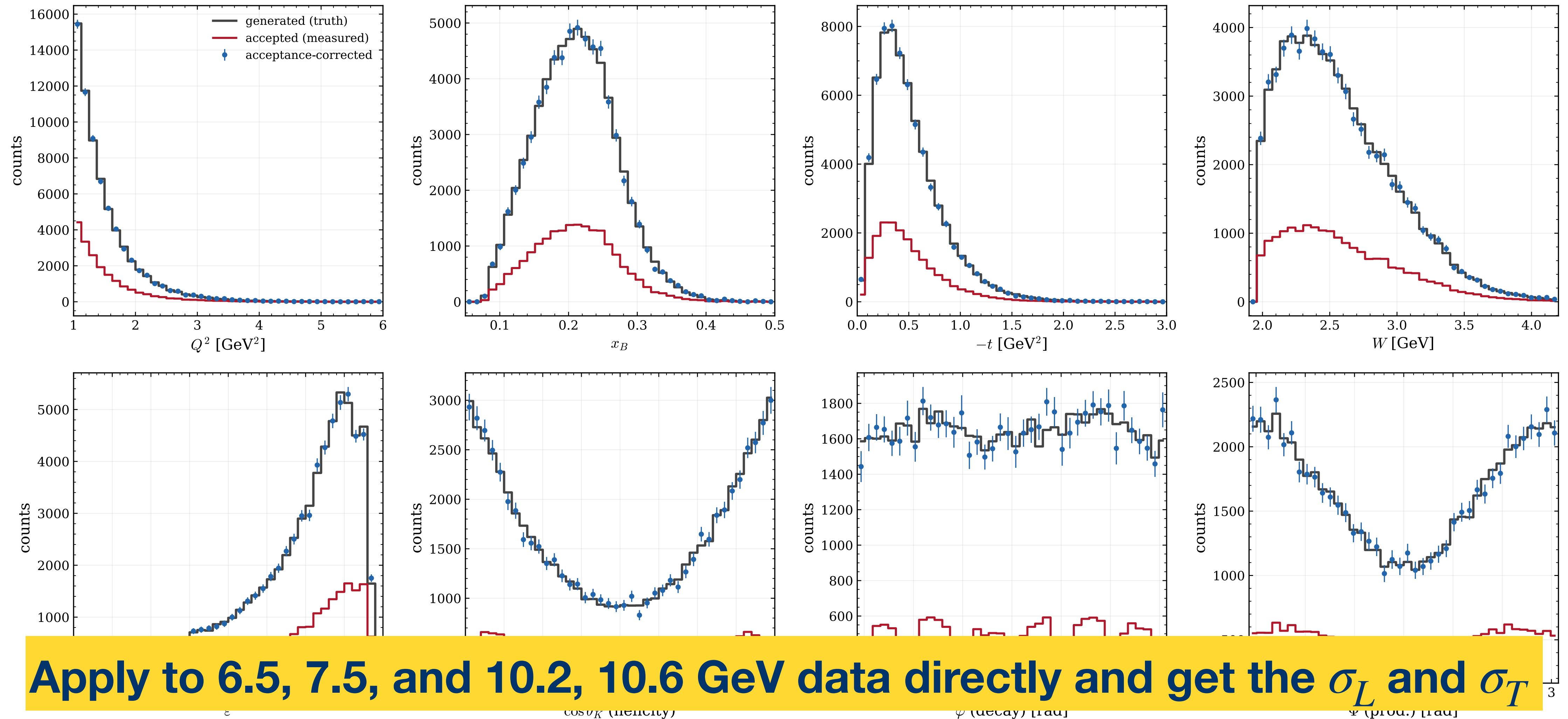
# Acceptance correction to the data

- Once we extract the amplitudes we can apply inverse correction to the data and get proper acceptance corrected cross-section from the measurements



# Acceptance correction to the data

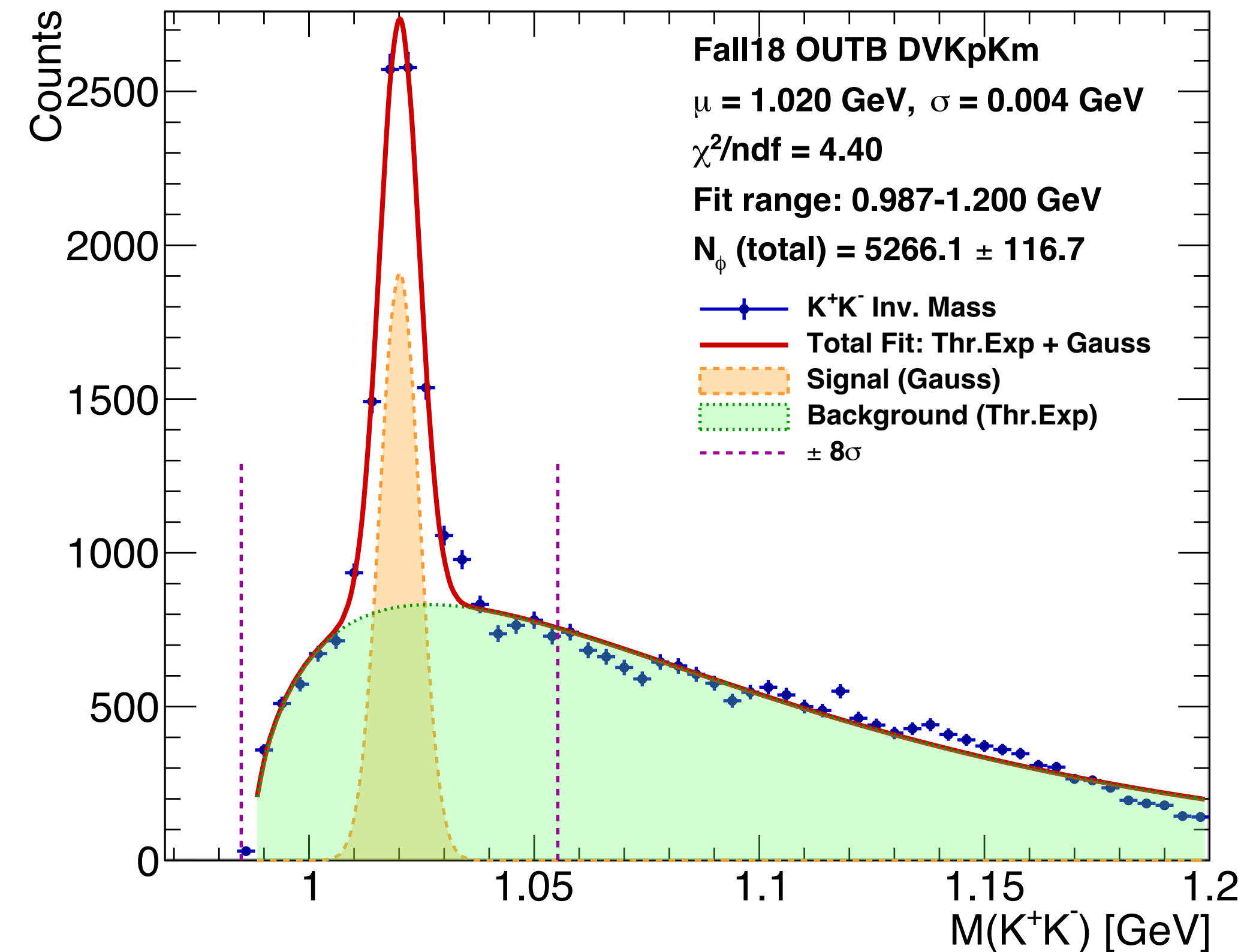
- Once we extract the amplitudes we can apply inverse correction to the data and get proper acceptance corrected cross-section from the measurements



**Apply to 6.5, 7.5, and 10.2, 10.6 GeV data directly and get the  $\sigma_L$  and  $\sigma_T$**

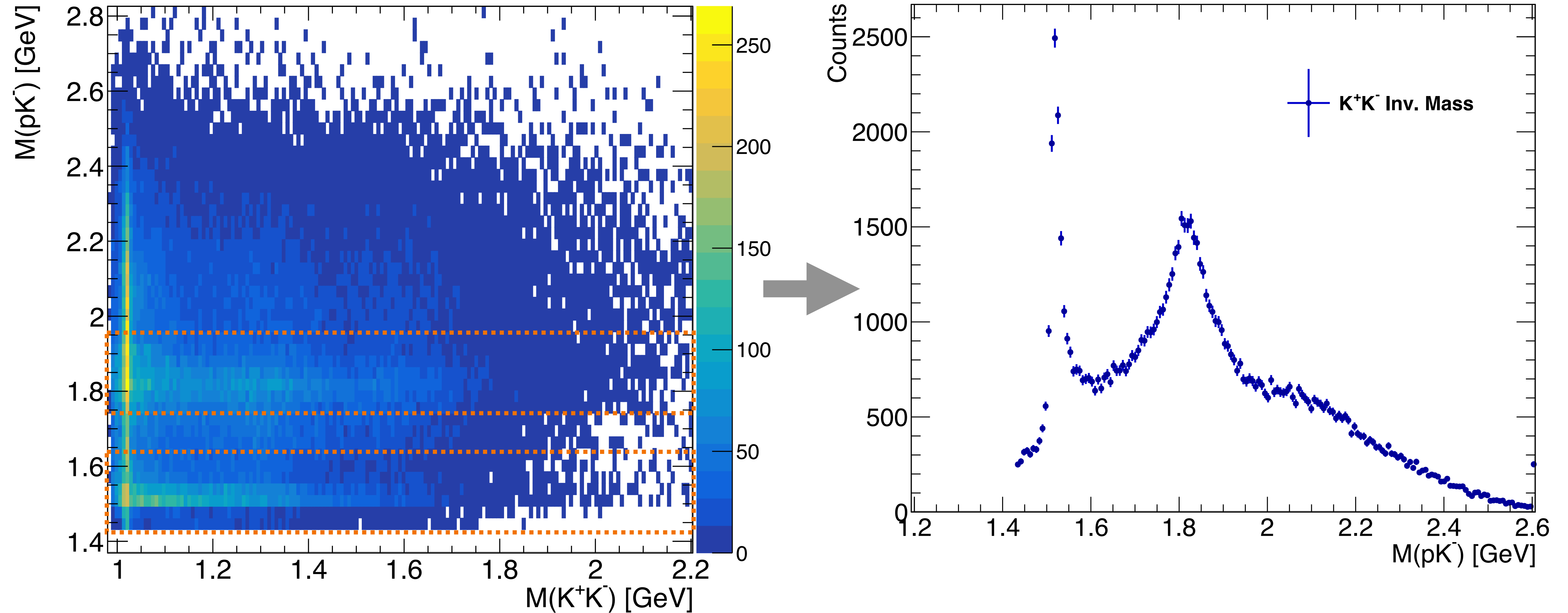
# Summary

- So far
  - First look at the exclusive  $\phi$  meson production combining all data set from RGA and RGK 6.5, 7.5, and 10.2-10.6 GeV
  - We raw yields corrected for flat angles event generators
  - Radiative correction in progress
- Next steps
  - Development of realistic **event generator with SDMEs**
  - Systematics on **acceptance** and efficiency corrections!
  - **More data from 8.4 GeV!**
- Apply
  - **Calculations to better interpretation of the measurement-> gluon structure and strangeness in proton**



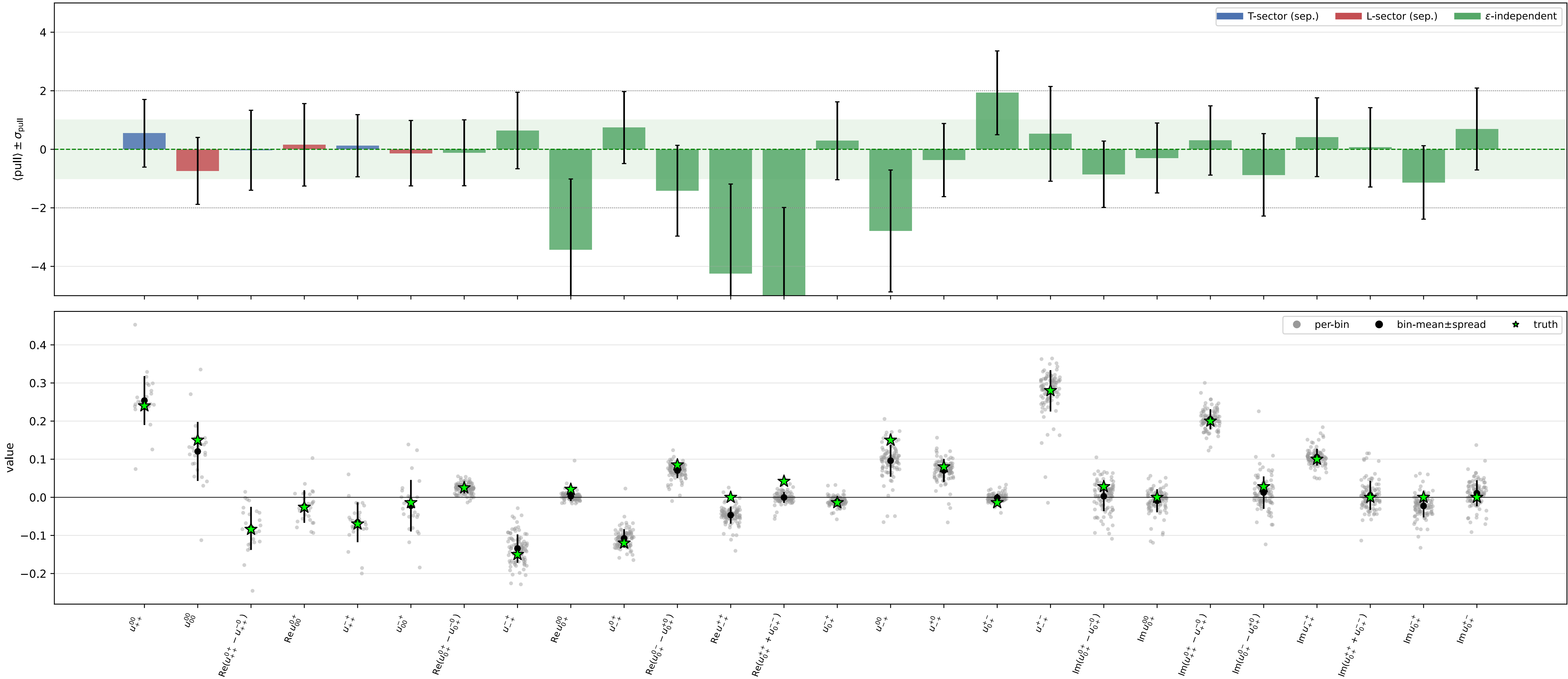
# Background under the signal

- Production of  $\Lambda^*(1520,1830)$  can lead to contamination in the phi DVMP channel



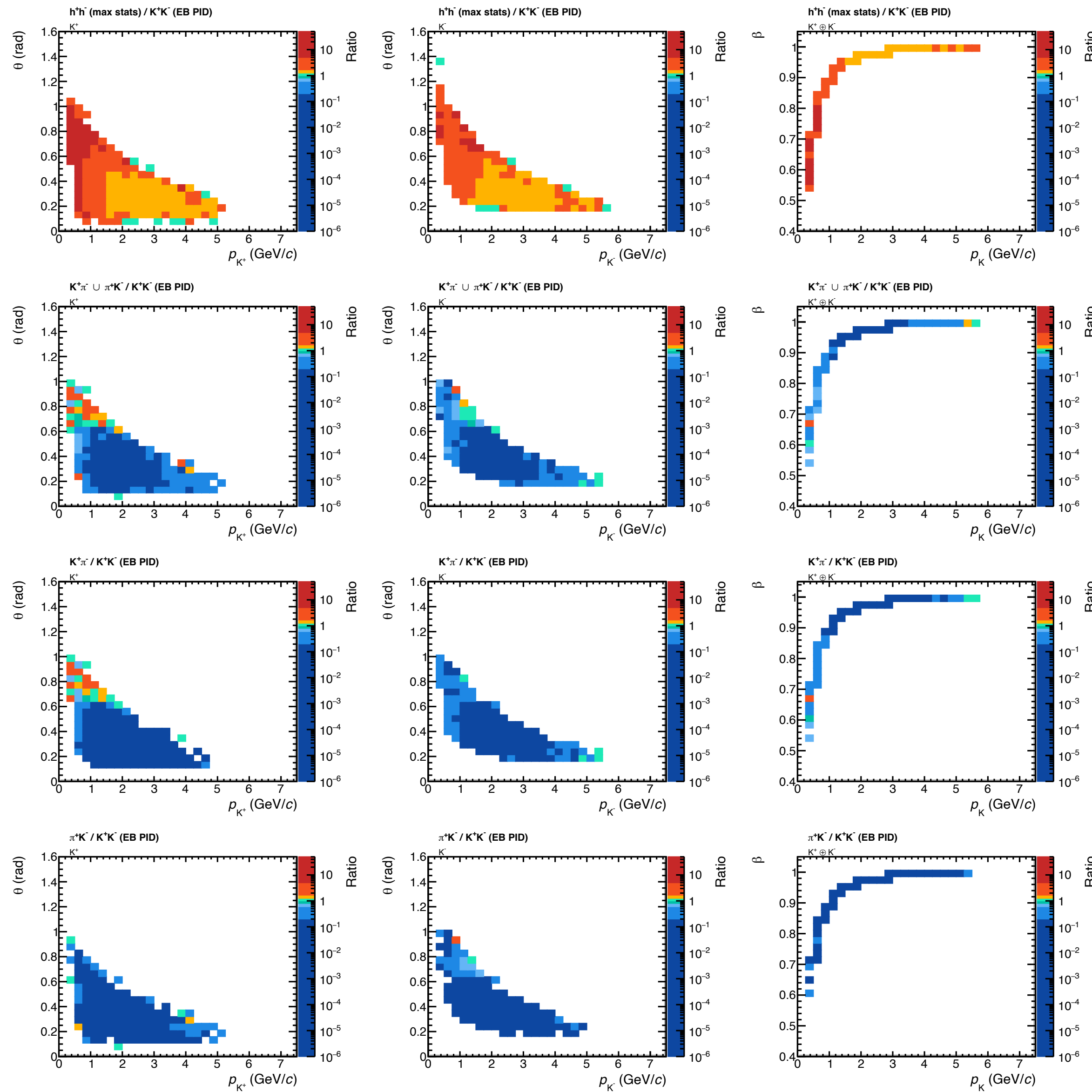
# L-T separation in each $(Q^2, t)$ : Diehl's notation

- L-T separated in each kinematics bin, extracted intercepts and slopes using 6.5, 7.5, and 10.6 GeV beam energies

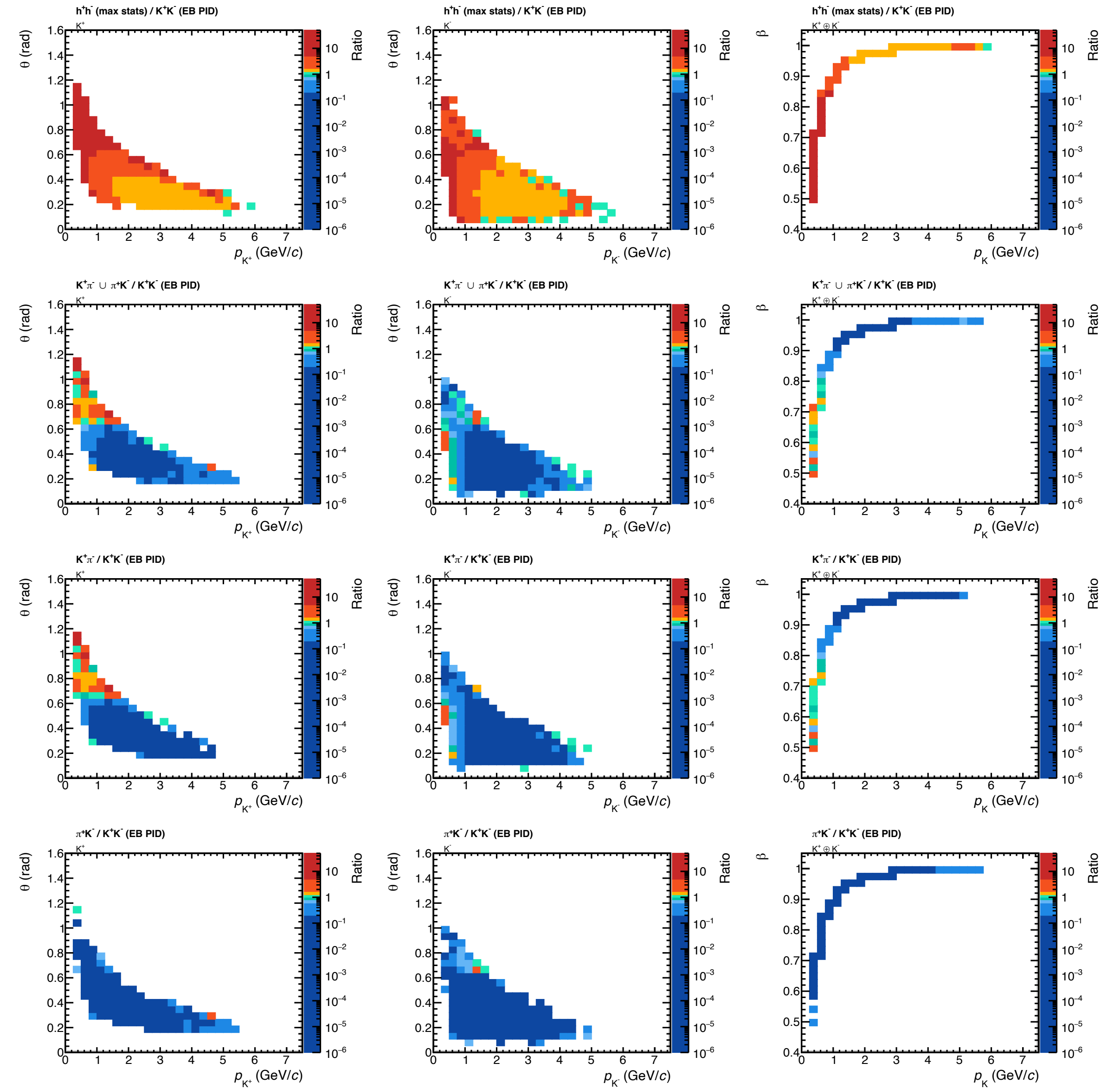


# Pion Contamination

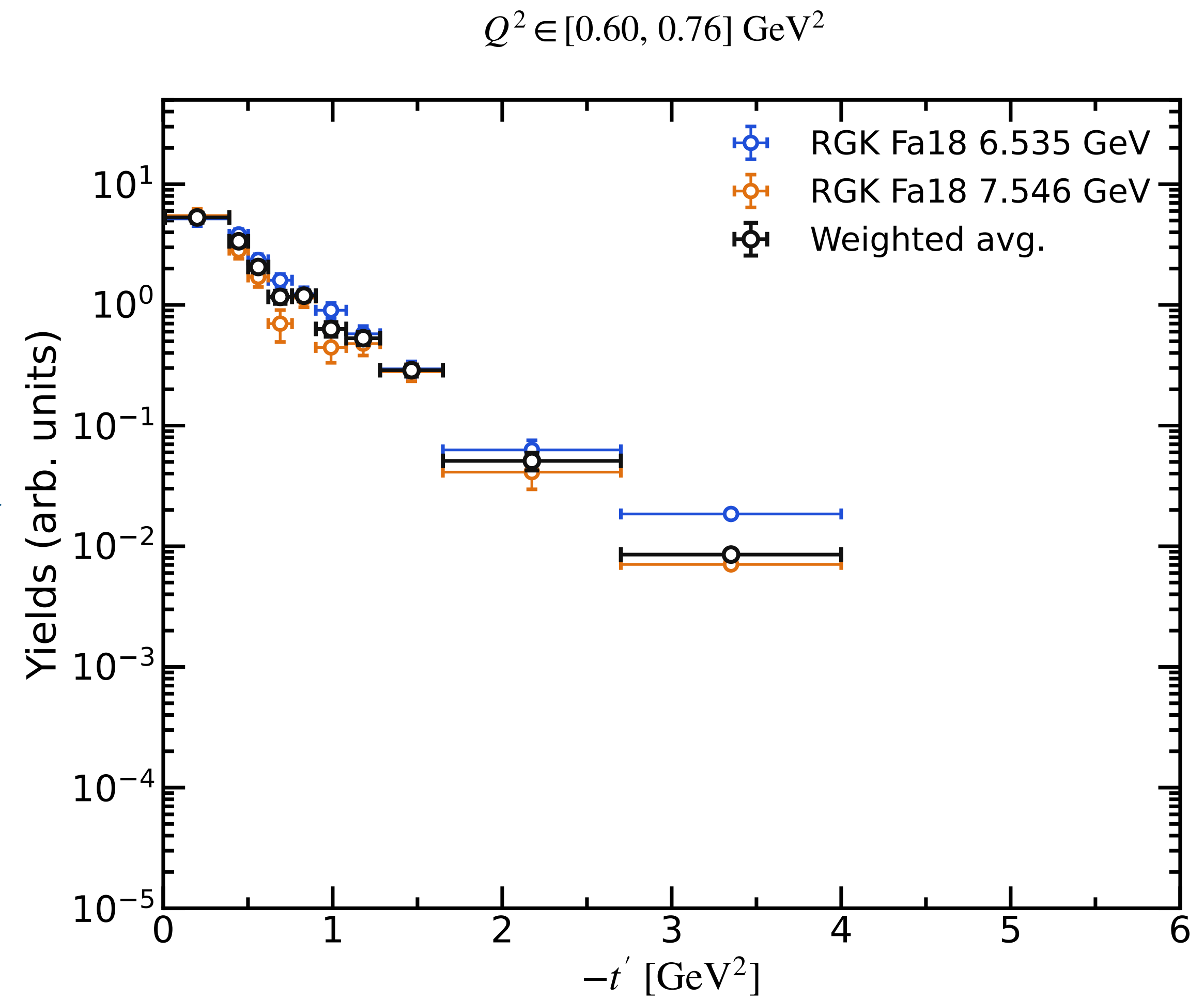
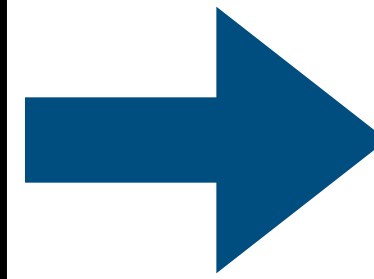
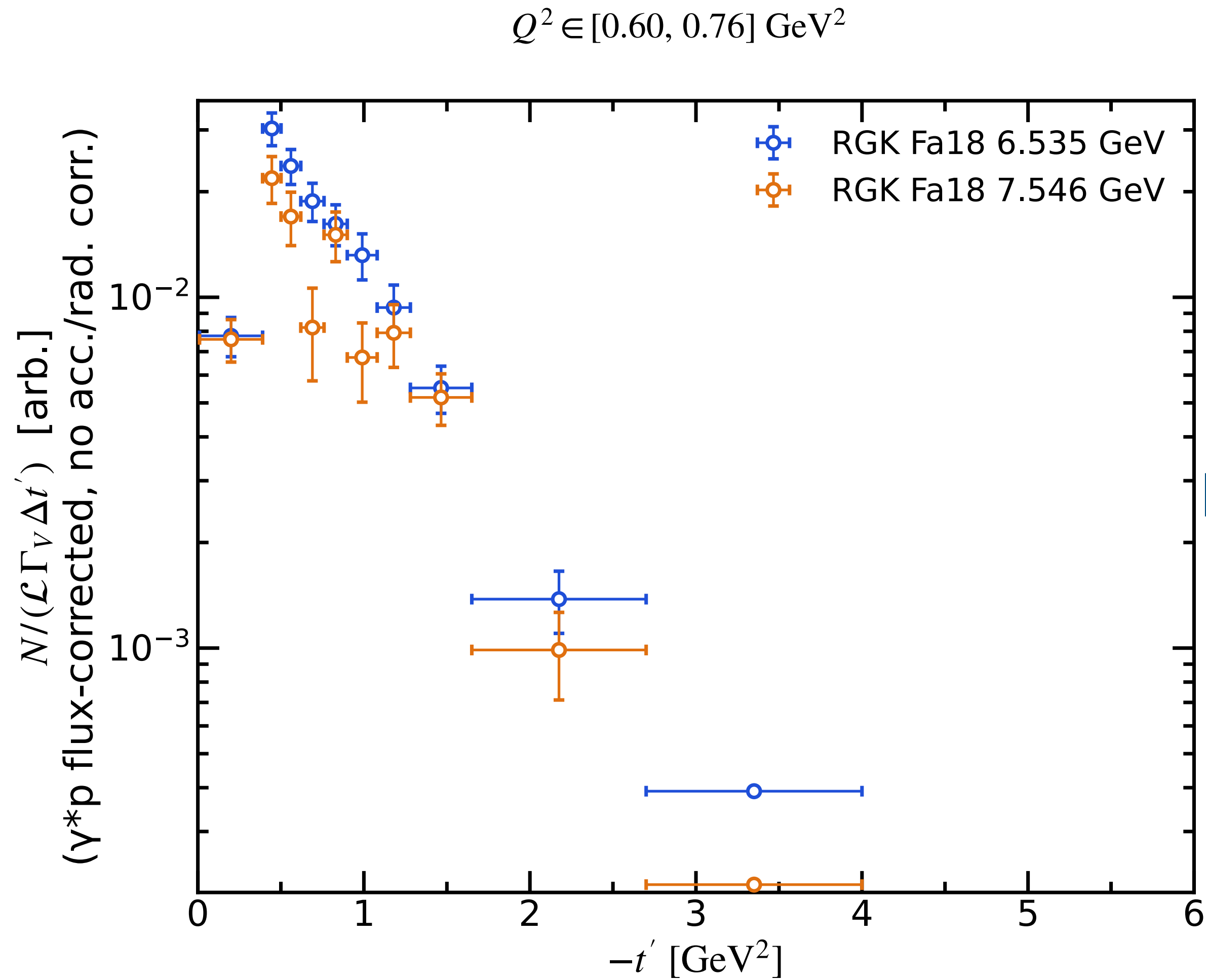
Yield Ratio: Fall18 INB



Yield Ratio: Fall18 OUTB

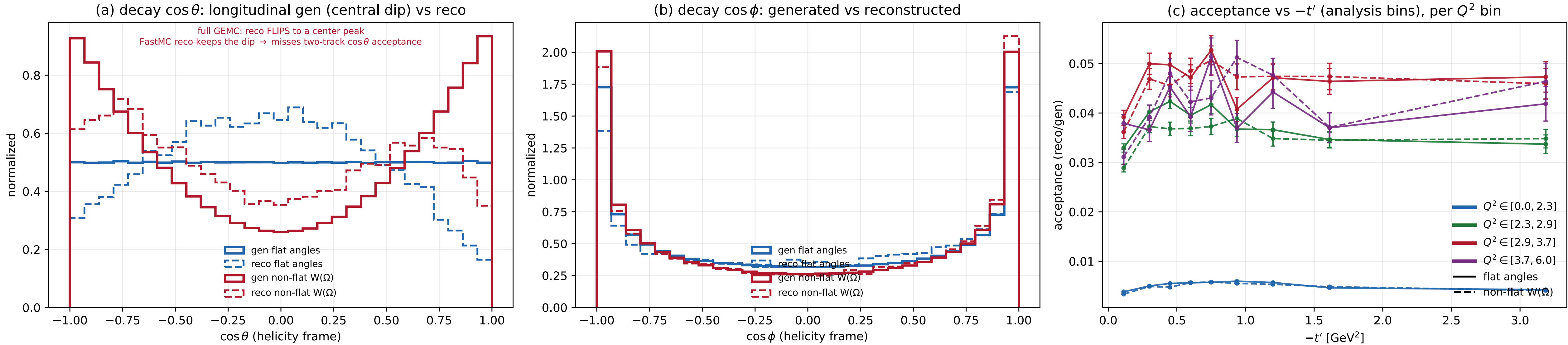


# Impact of acceptance correction



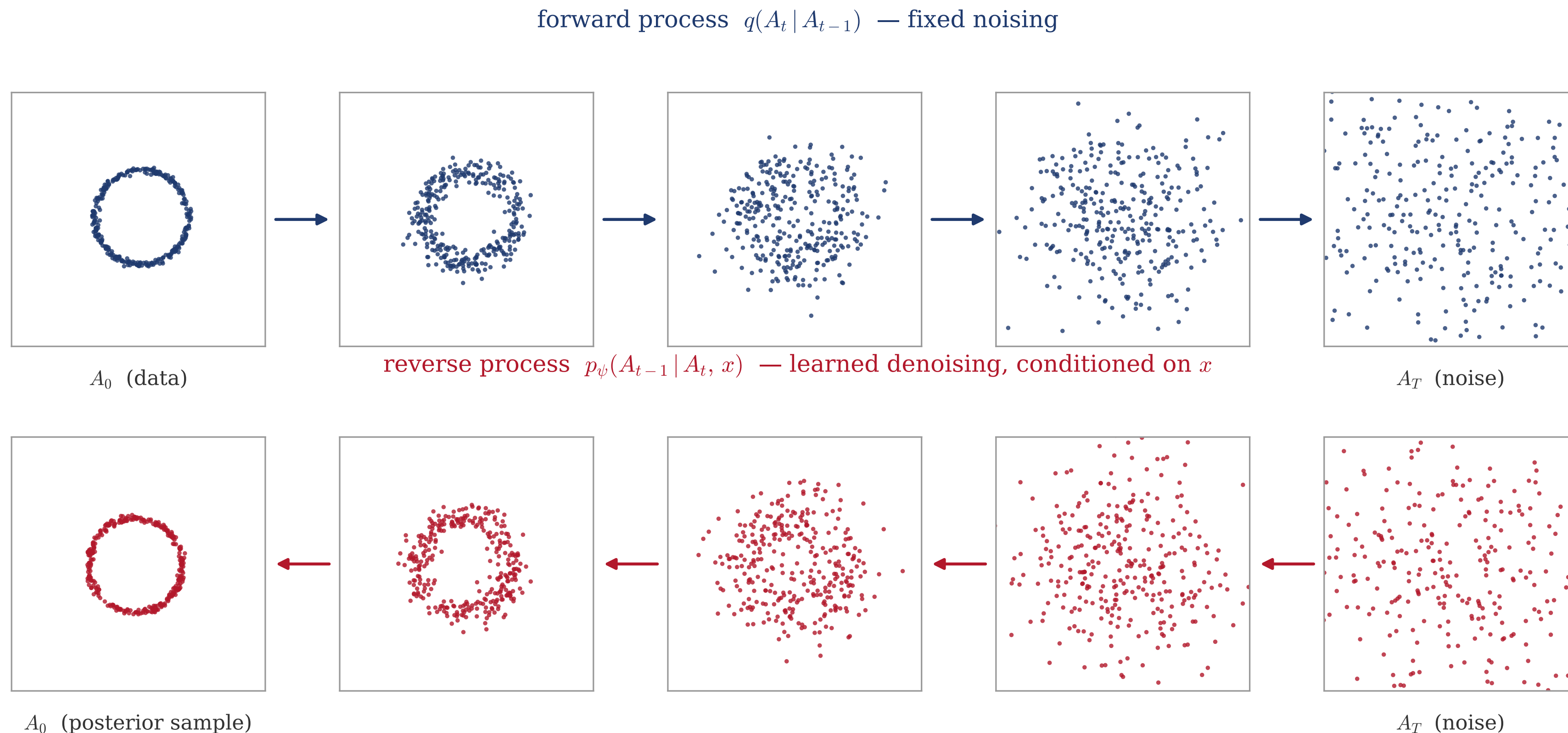
# Acceptance impacted by the SDMEs

- Non-flat decay angle affects the acceptance of the cross-section for vector meson



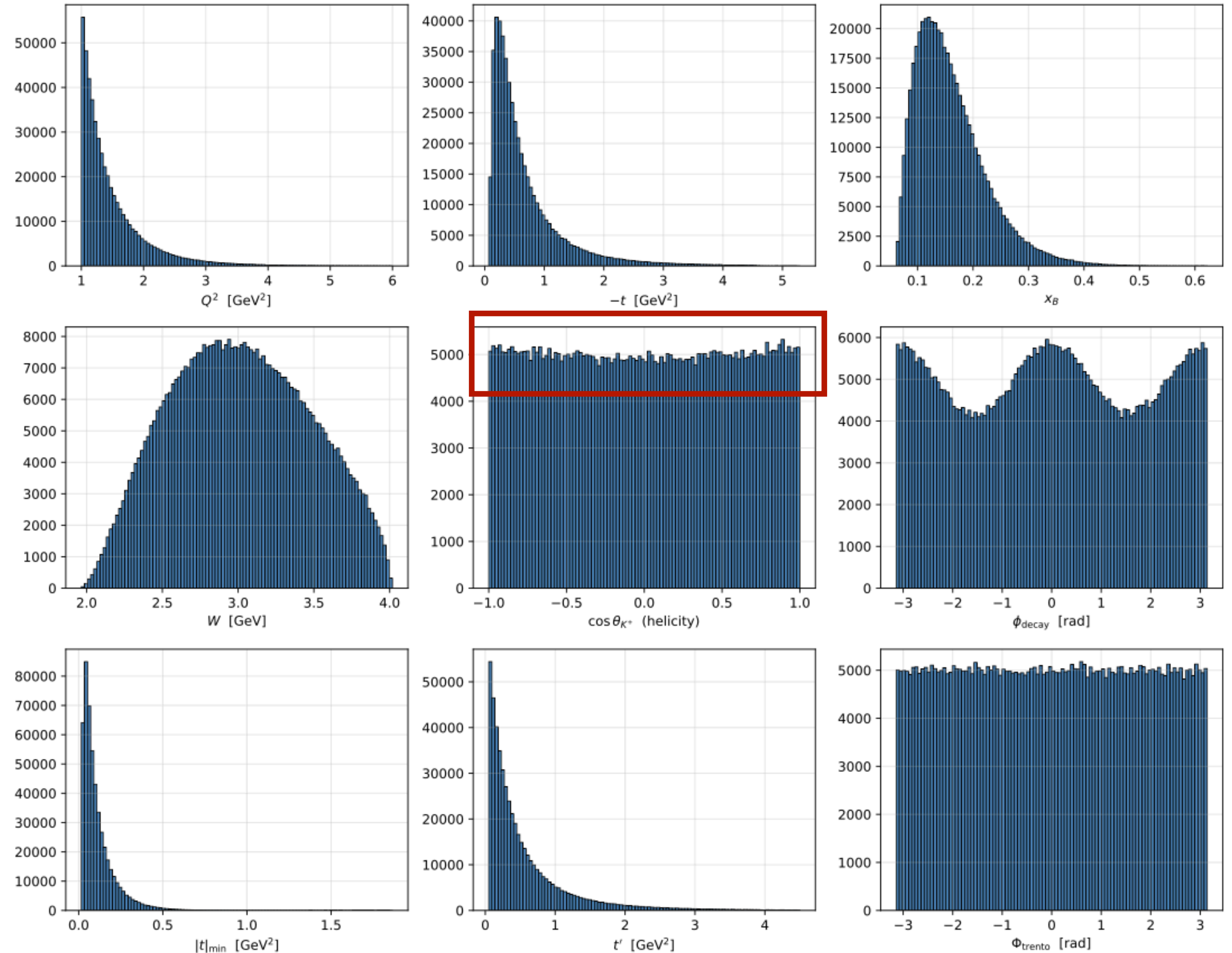
# The problem and how diffusion model can help

- From those angles we want 23/25 numbers — the SDMEs — that describe the  $\phi$ 's spin state
- Going SDMEs  $\rightarrow$  data is easy: we have the formula.
- Going data  $\rightarrow$  SDMEs is the hard INVERSE problem! A diffusion model is a tool that learns this inverse — and gives honest error bars.



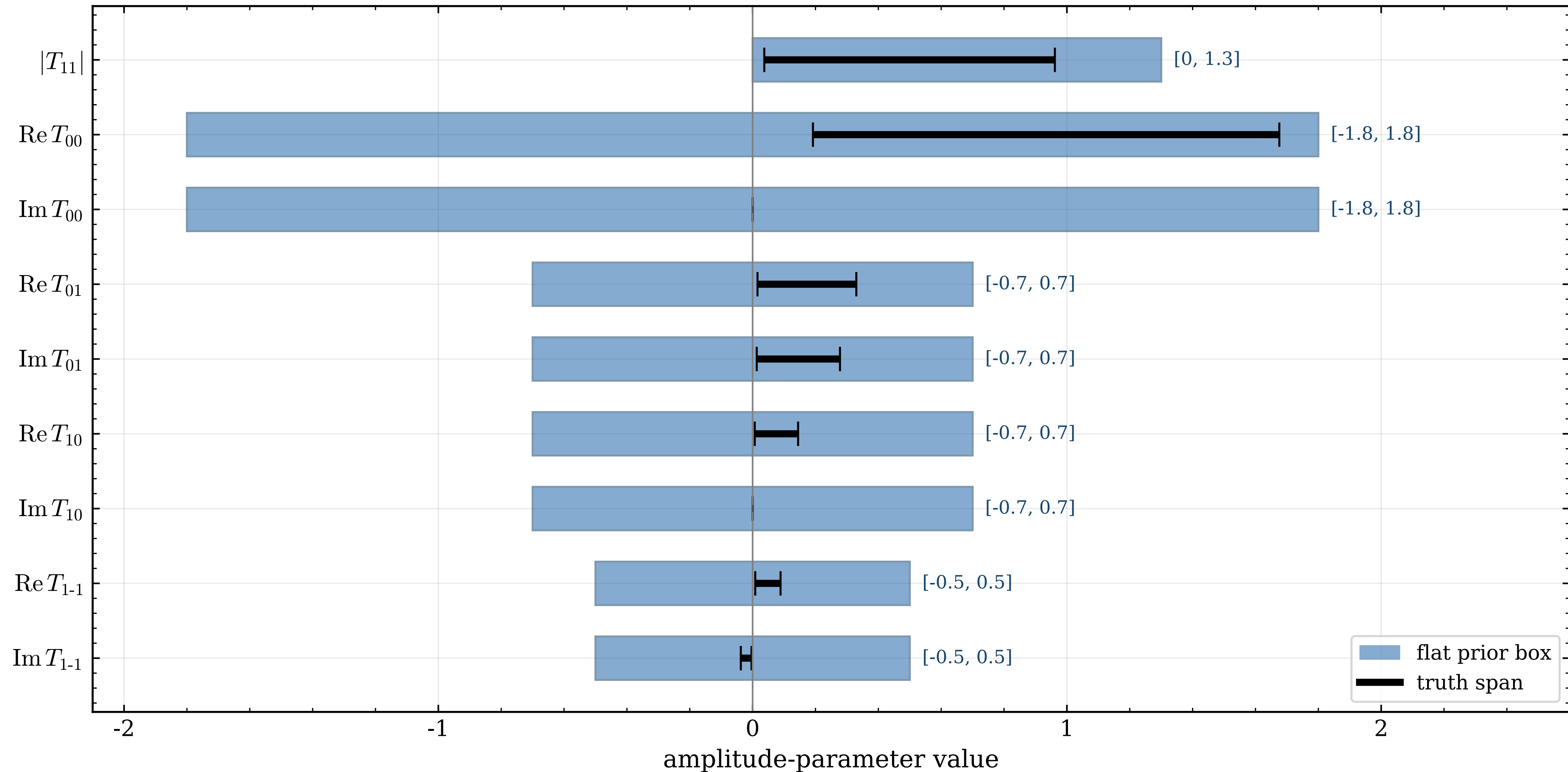
# DVEP kinematics with Heuristic SDMEs

- Take 10.6 GeV CLAS12 setup
- Tried **5**  $Q^2$  and **12**  $t'$  bins, similar to data
- 500K events
- Generator is tuned to 6 GeV CLAS data of  $\phi$ -meson, Event Generator describes the  $Q^2$  and  $t$ , modulations are accounted by Heuristic SDMEs



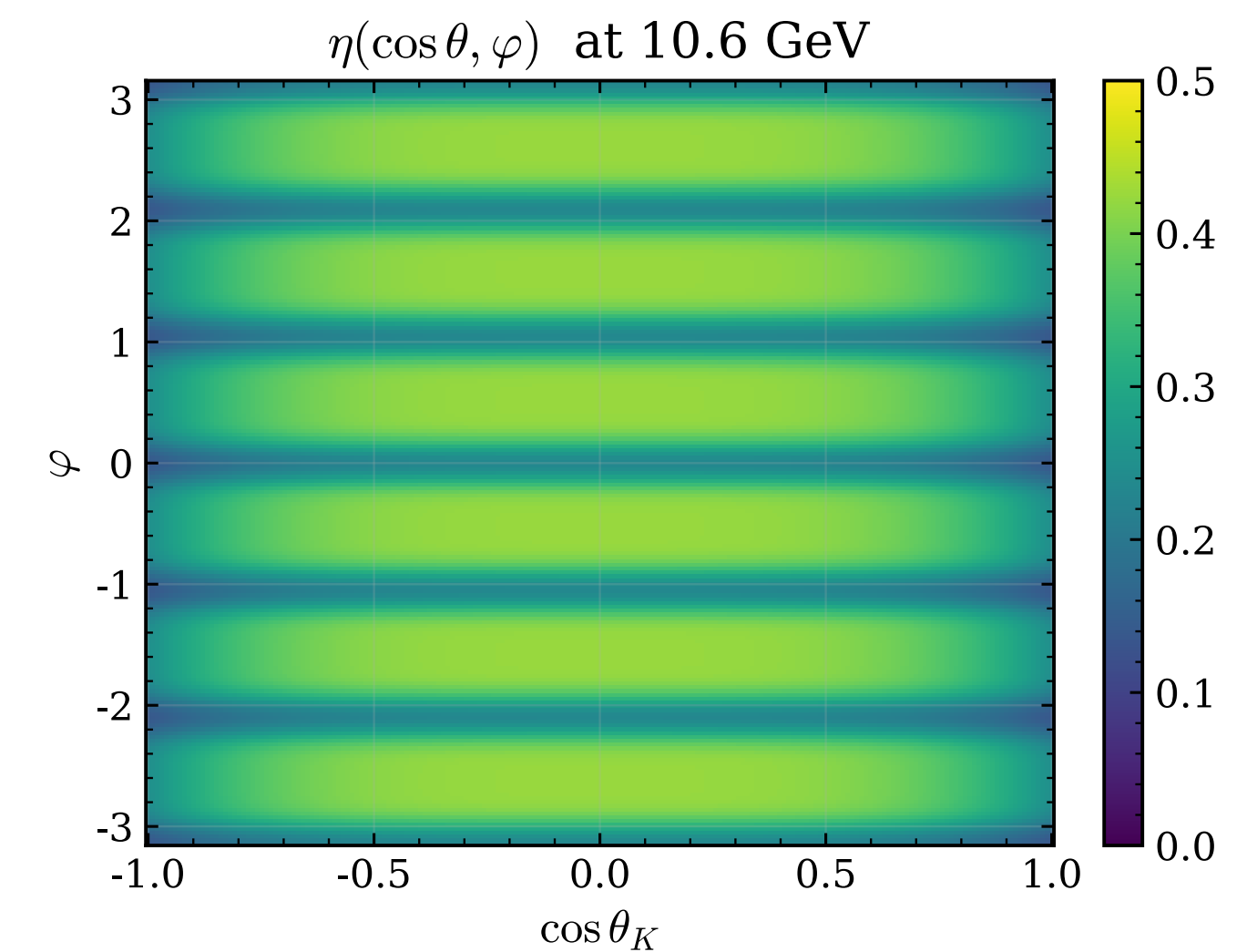
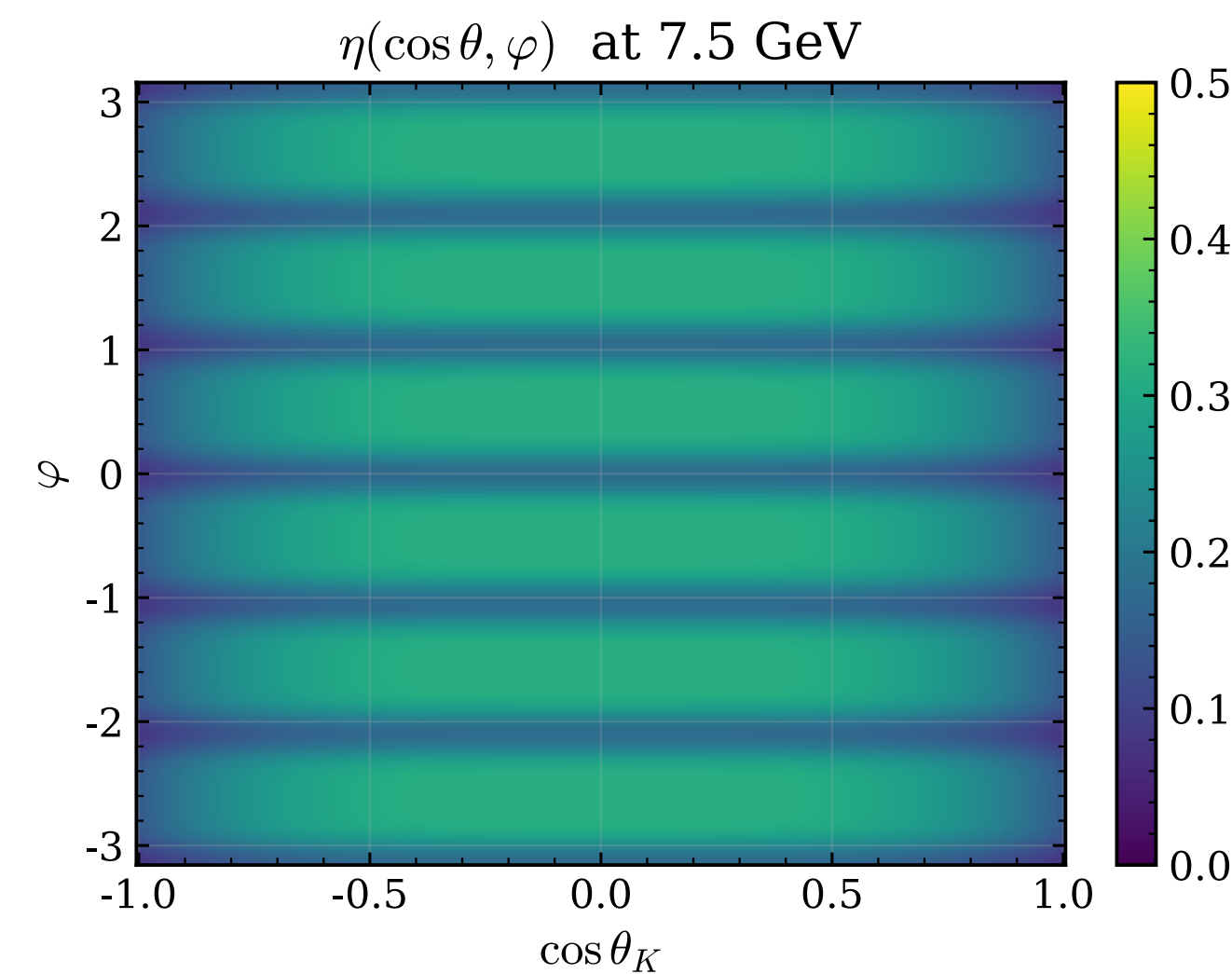
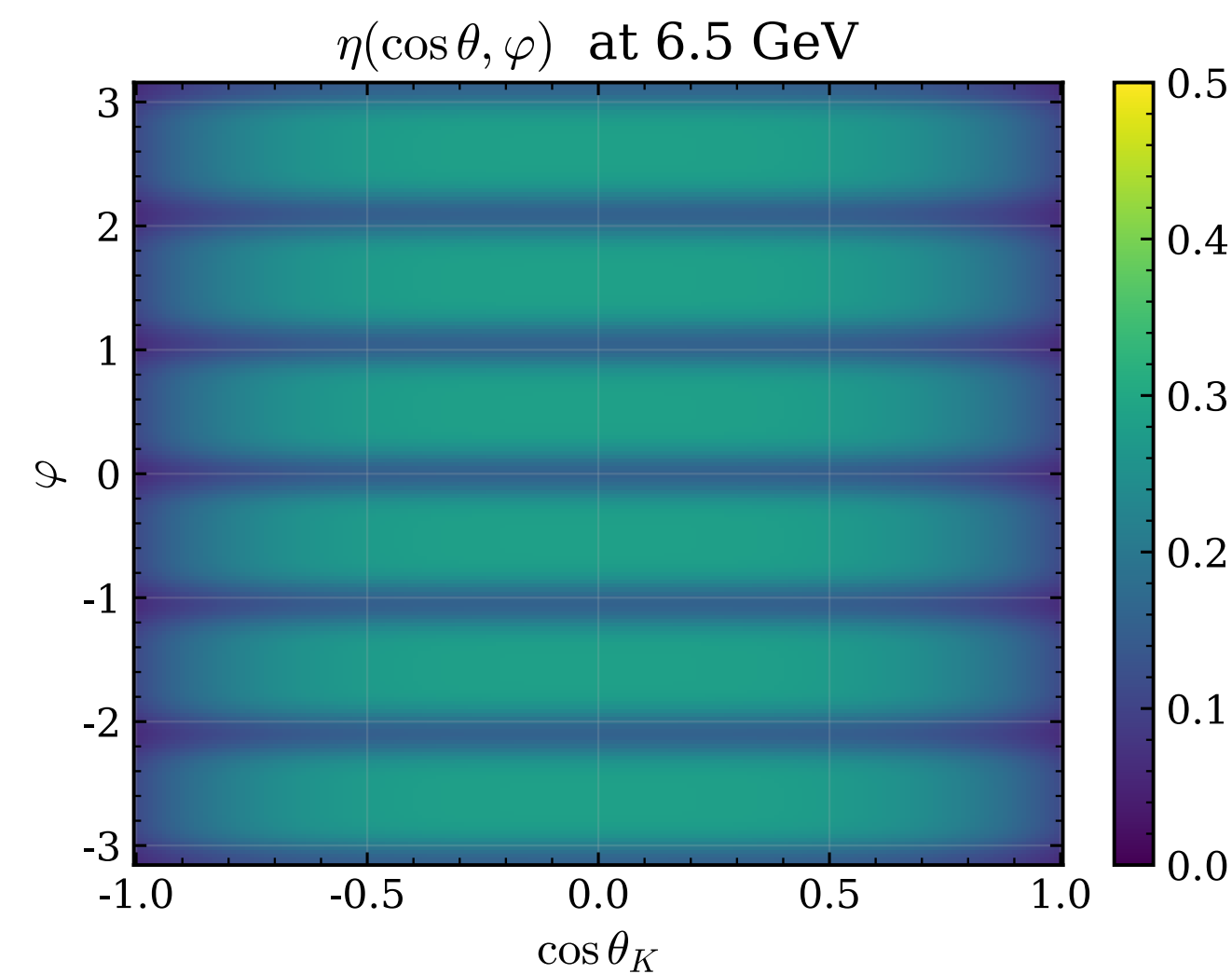
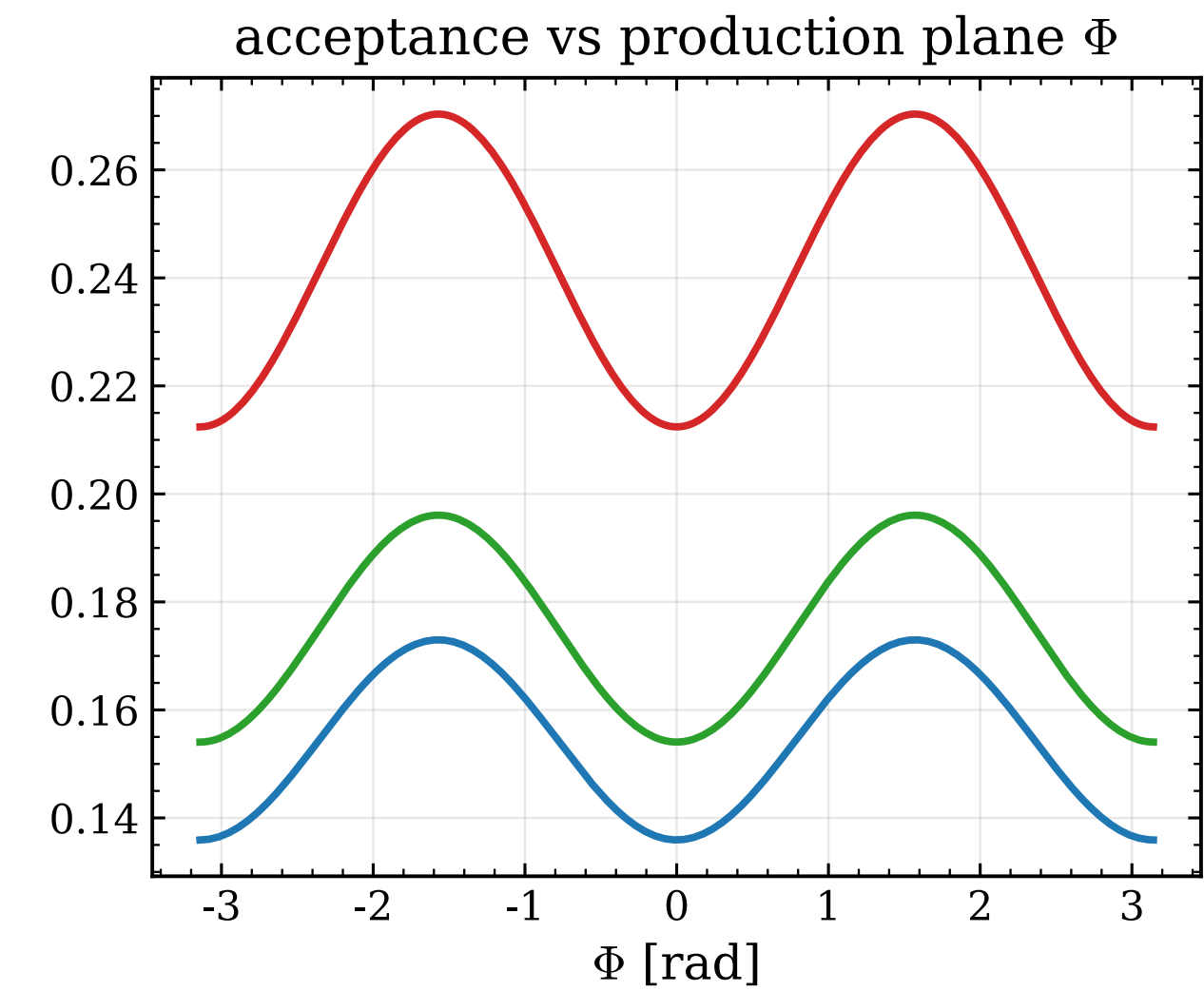
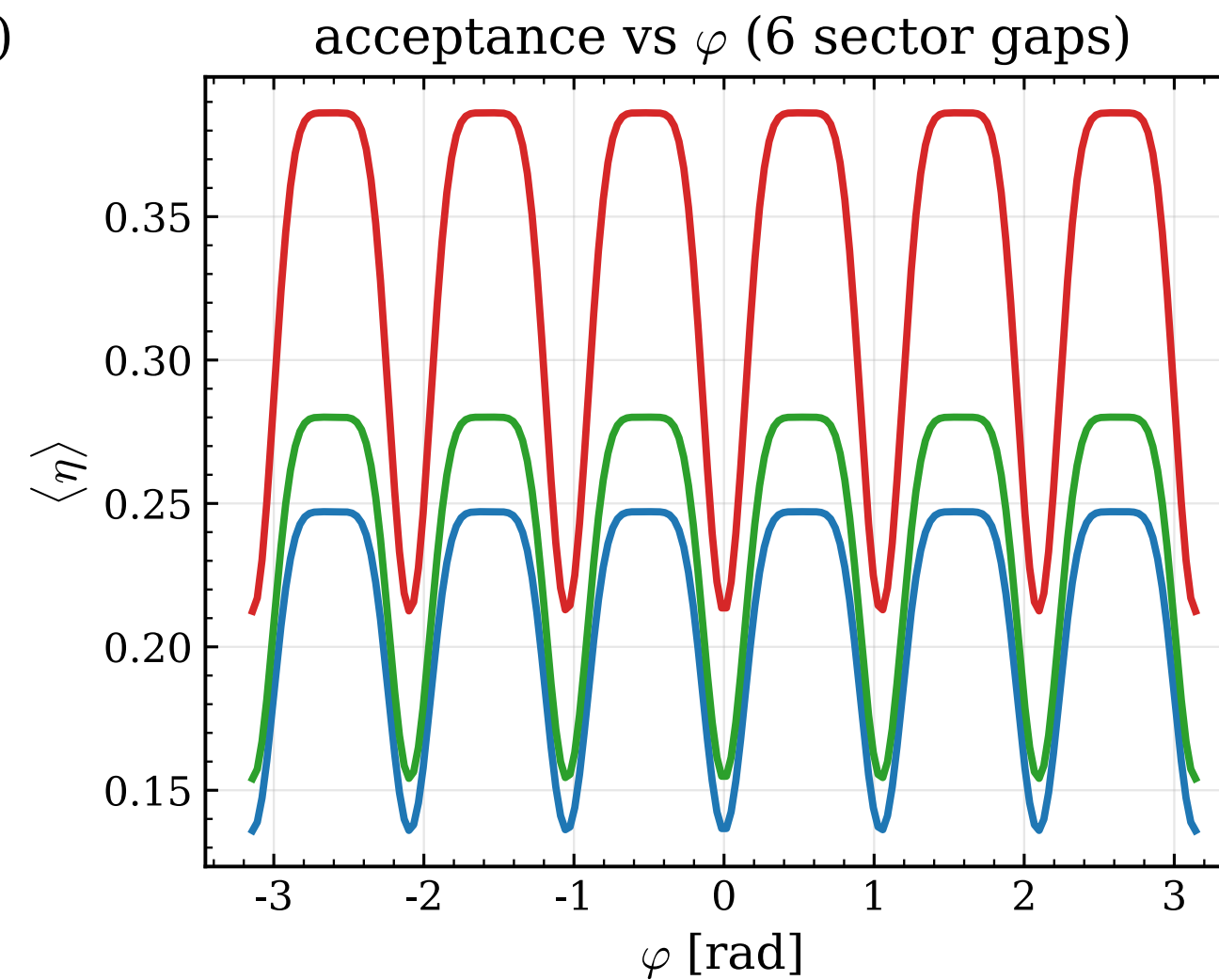
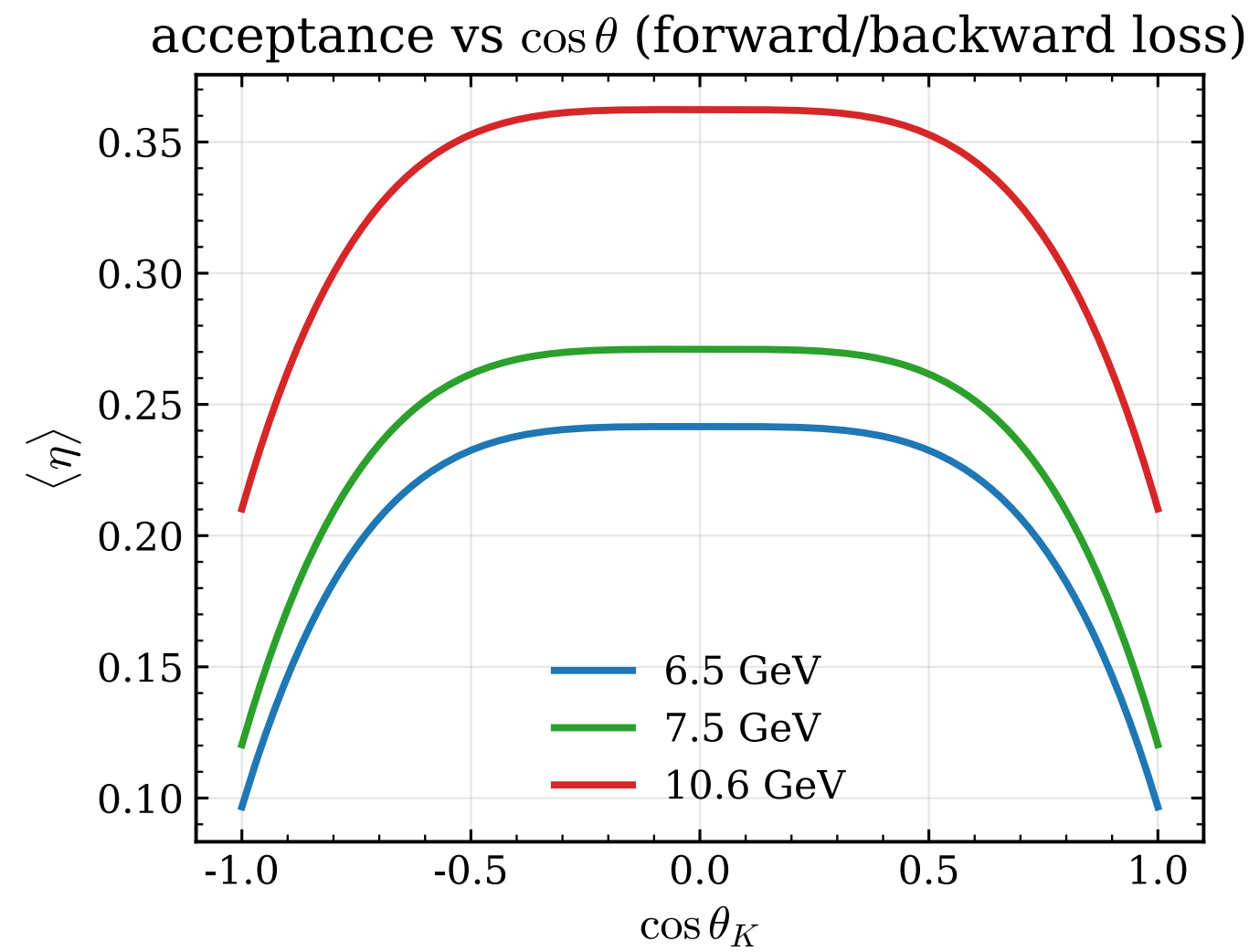
# Training with uniform distributions

- The model does not know if there is any kinematics dependencies of the amplitudes



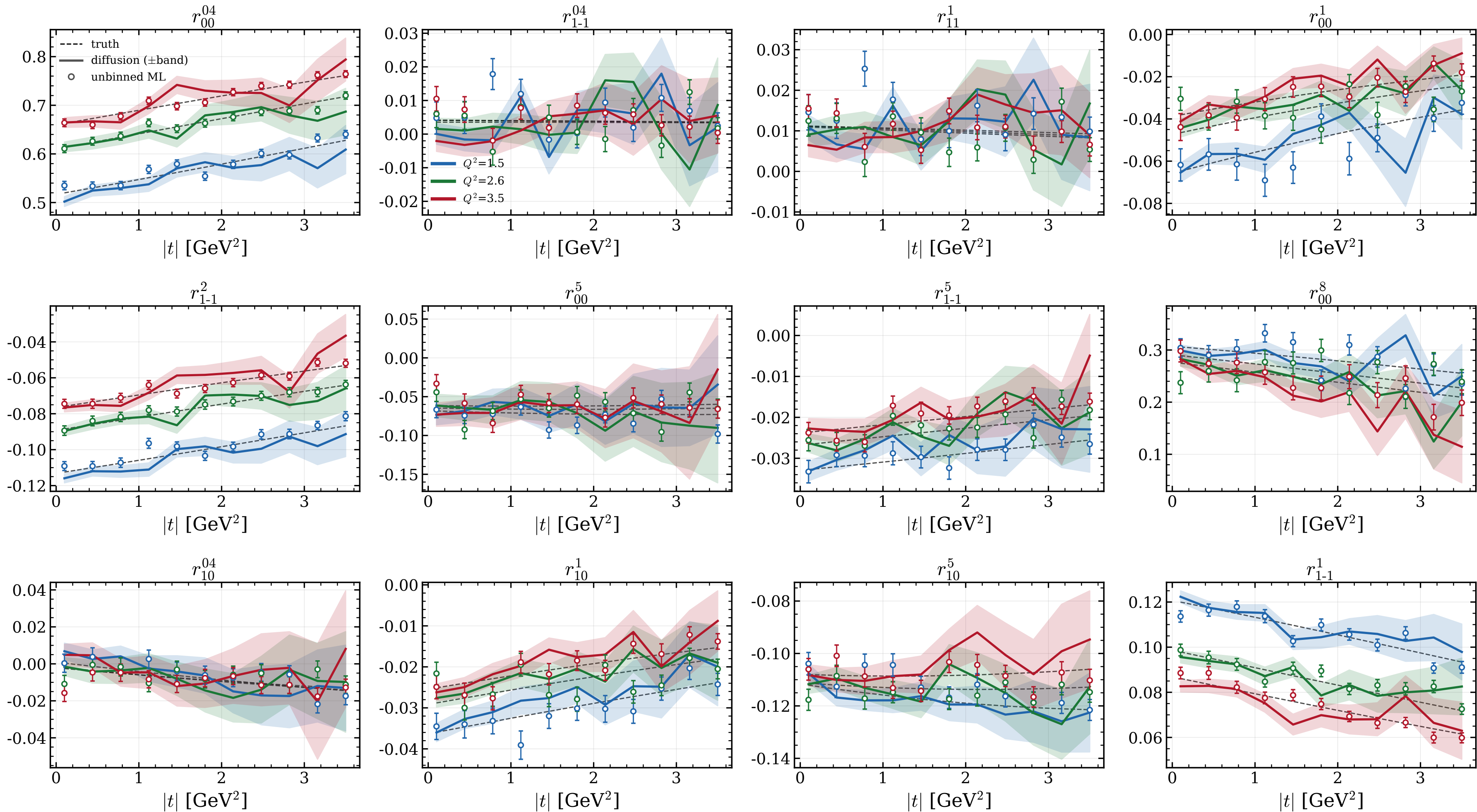
# Any acceptance model – agnostic approach

- For method paper: toy detector acceptance model



# Converted into the SDMEs

- Once we have the amplitudes we can always get the SDMEs



# More energies: path to LT separation

Closure-sim DVEP kinematics across RGA+RGK energies (normalised, merged 36-bin TreeData)

