

Exclusive ϕ electroproduction with CLAS12 (RGA)

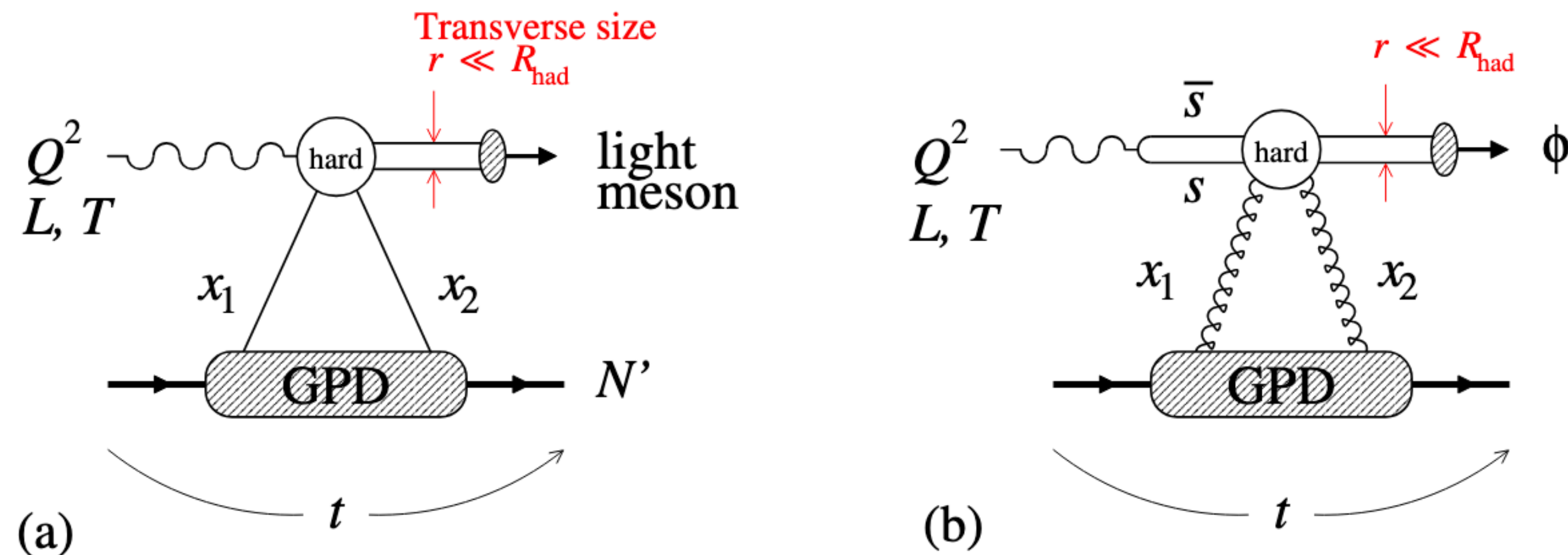
CLAS Collaboration Meeting

P. Chatagnon, V.D. Burkert, L. Elouadrhiri, F.X. Girod, R. Milner,
K. Neupane, M. Ronayette, **Bhawani Singh**, and Y. Wang

Thursday, November 20, 2025

Clean Probe For Gluonic Structure of Nucleon

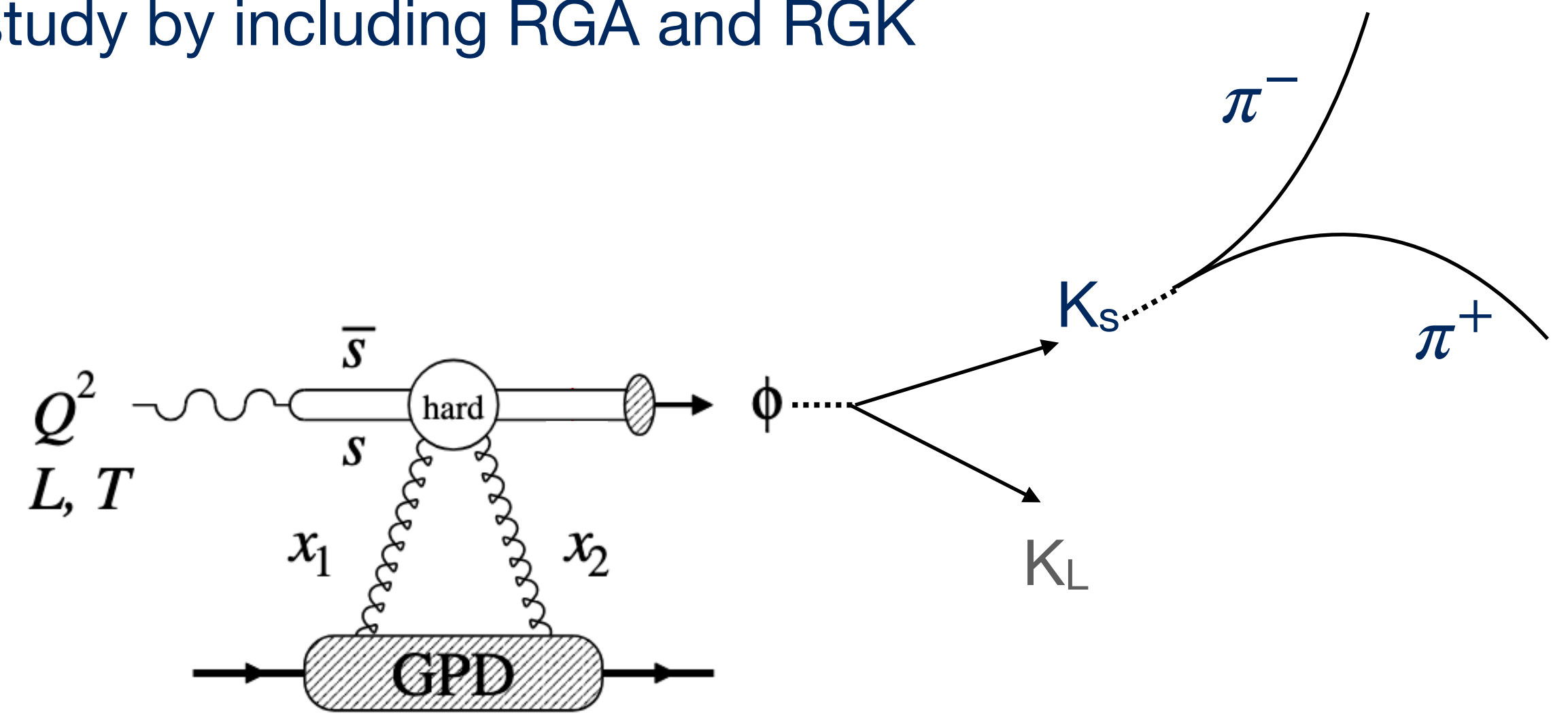
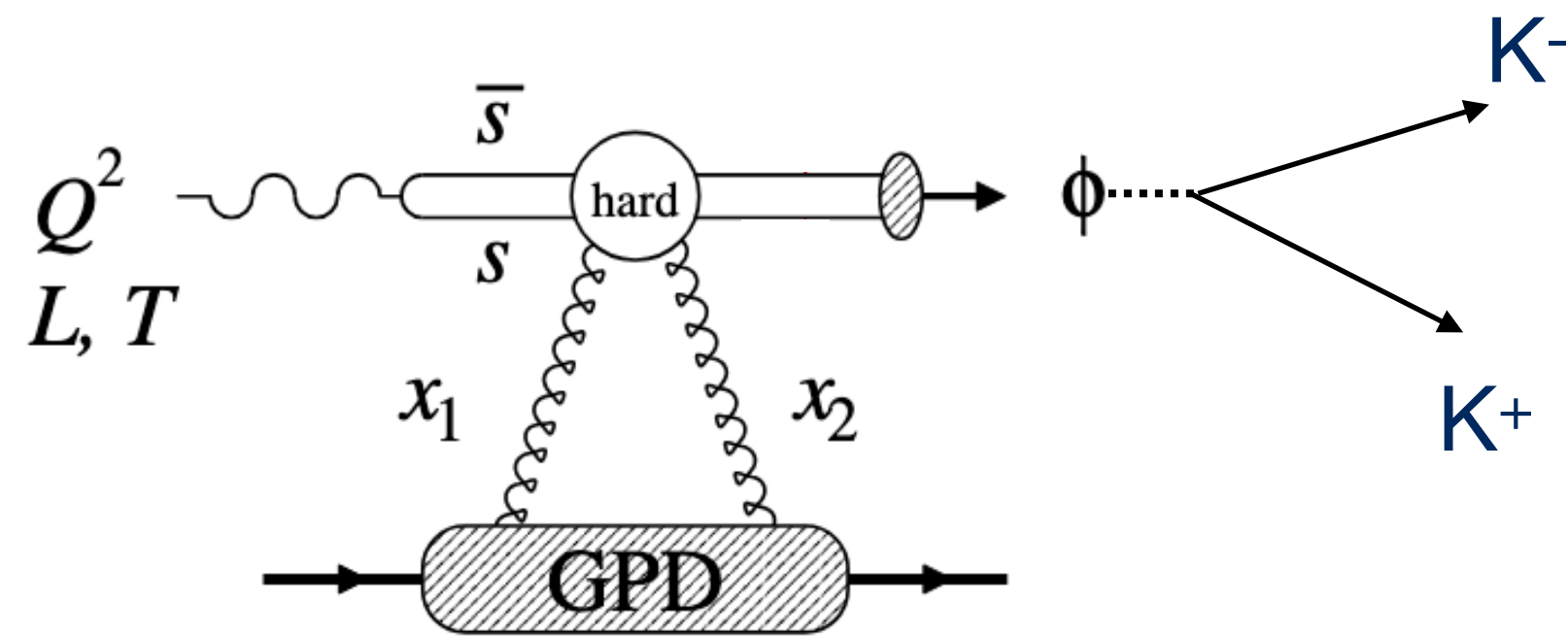
- ϕ meson a **pure $s\bar{s}$ state**, so its coupling to light quarks (u,d) is suppressed (by OZI rule)
- CLAS12 covers much **wider kinematics region** in W from 2–5 GeV, Q^2 from 1–12 GeV²
- Access to the gluon GPD even at low energy due to its flavor content $s\bar{s}$



- Q^2 scaling of ϕ 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 ➔ **gluonic radius** of the proton
- Search for **near-threshold effects** linked to intrinsic $s\bar{s}$ pairs

Analysis strategies: two decay channels

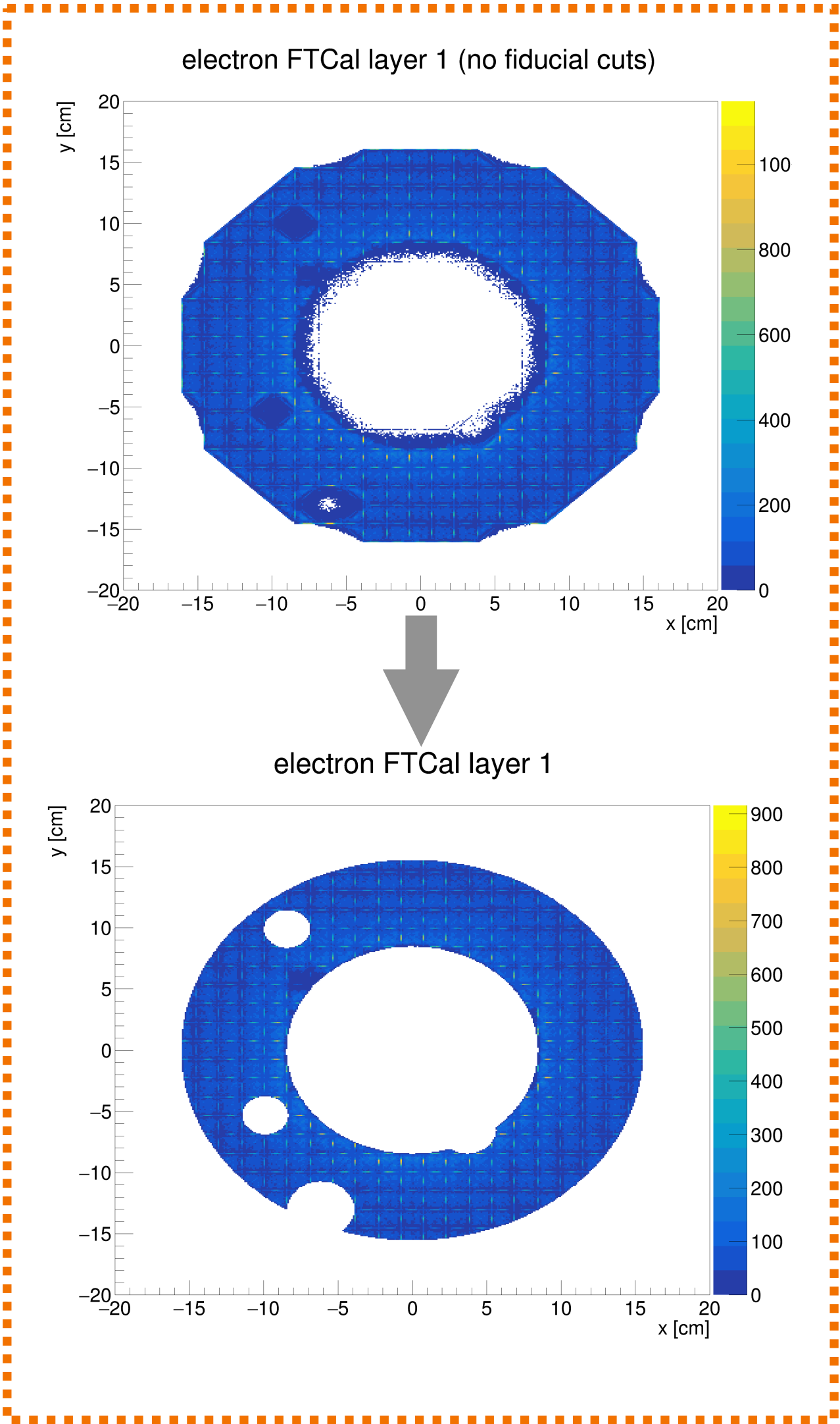
- Two channels
 - 1. $ep \rightarrow e'p'K^+K^-$ (BR: $\sim 49.2\%$)
 - 2. $ep \rightarrow e'p'K_S K_L$ (BR: $\sim 34\%$) (further limits the acceptance due to $K_S \rightarrow \pi^+ \pi^-$)
 - Beam energy (6.5-10.6 GeV) dependent production study by including RGA and RGK



Mathieu and Pierre!

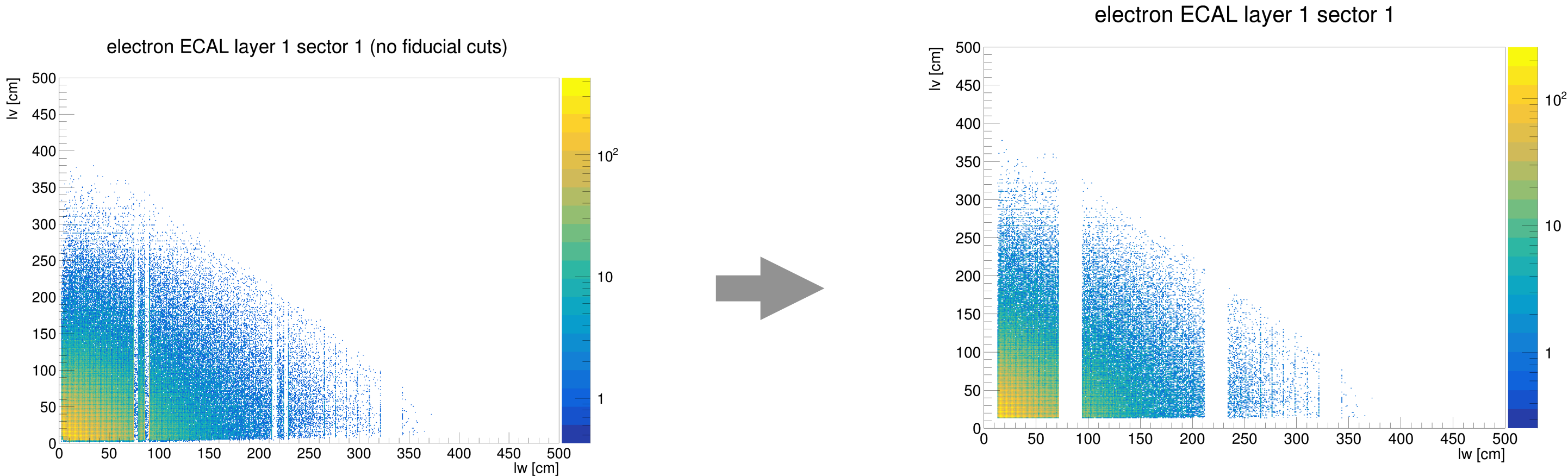
Fiducial volume for electron and hadrons

- **FT**, **FD**, and CVT regions with possible reconstruction inefficiencies are removed.



Circular regions (details in common RGA analysis note)

Region	Radius (cm)	Center (x,y) cm
1(inner circle)	8.50	(0,0)
2(outer circle)	15.0-100	(0,0)
3	1.6	(-8.42, 9.89)
4	1.6	(-9.89, -5.33)
5	2.3	(-6.15, -13.0)
6	2.0	(3.7, -6.5)



Edge (lv, lu, and lw) cuts (all sectors!), PCAL, ECAL_{in} and ECAL_{out}

Fiducial volume for electron and hadrons

- FT, **FD**, and **CVT** regions with possible reconstruction inefficiencies are removed.

Electron protons and Kaons are removed from the DC regions with new pass 2 Edge variables

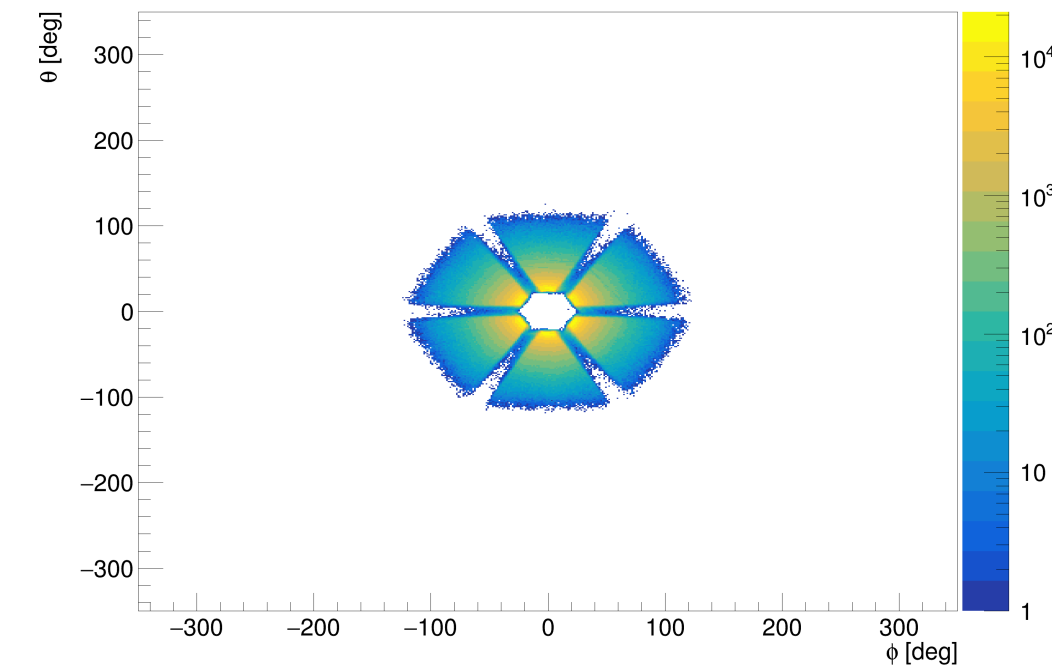
—e:

$R1 > 3\text{cm}$, $R2 > 3\text{cm}$, and $R3 > 10\text{ cm}$

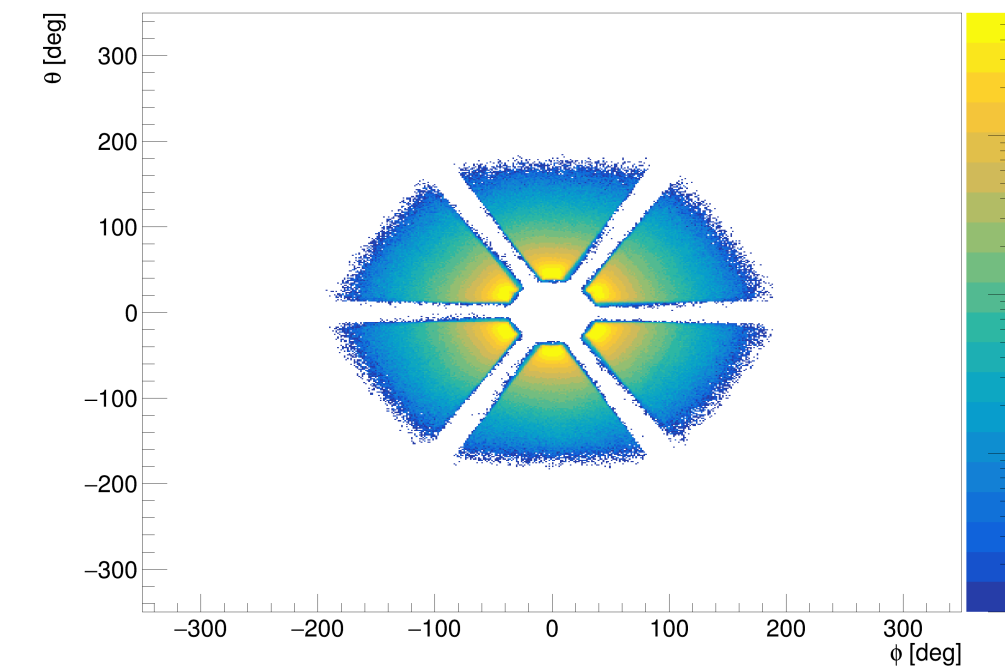
—Hadrons:

$R1 > 3\text{cm}$, $R2 > 3\text{cm}$, and $R3 > 7\text{ cm}$

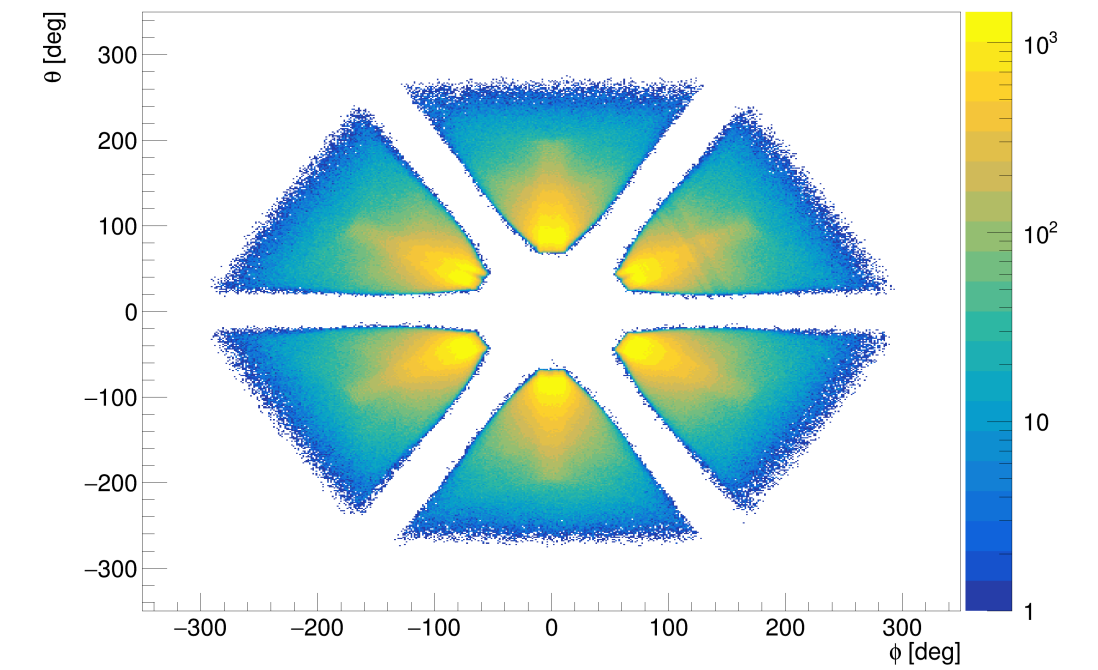
electron DC layer 6 (no fiducial cuts)



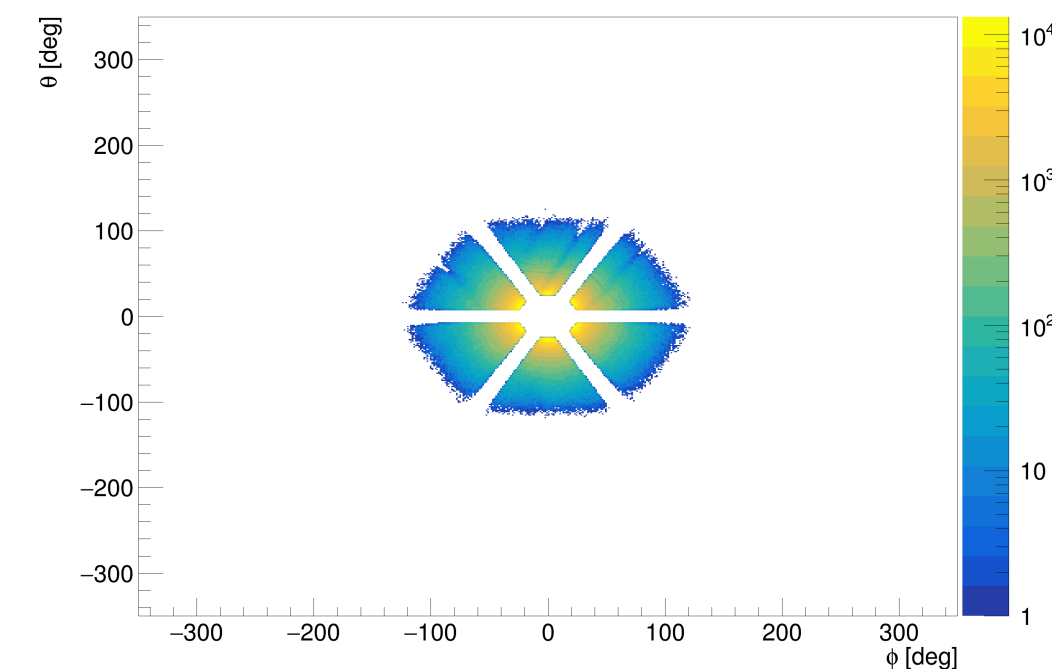
electron DC layer 18 (no fiducial cuts)



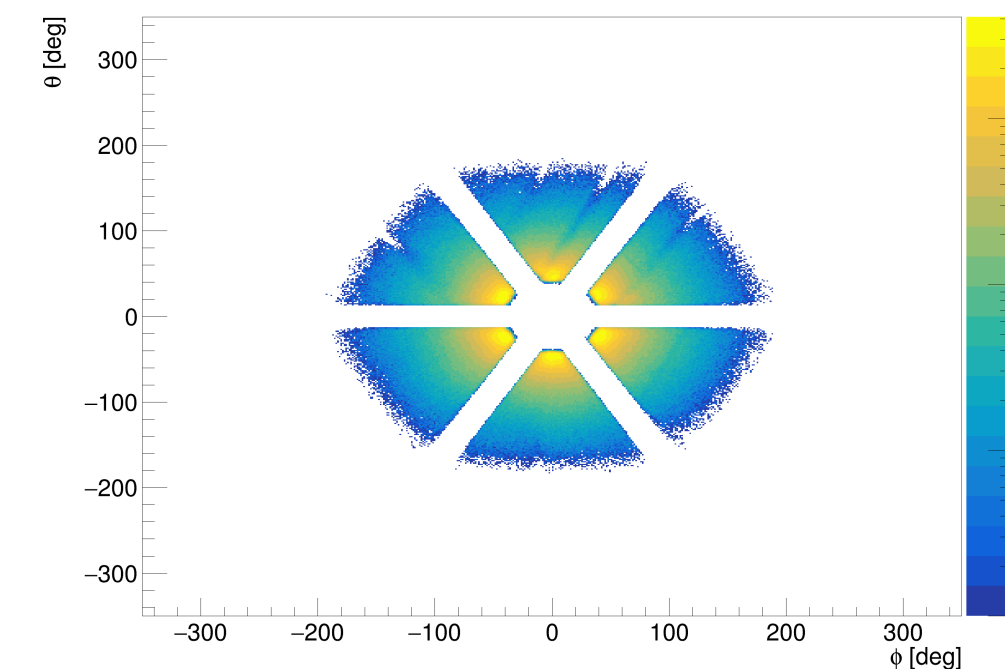
electron DC layer 36 (no fiducial cuts)



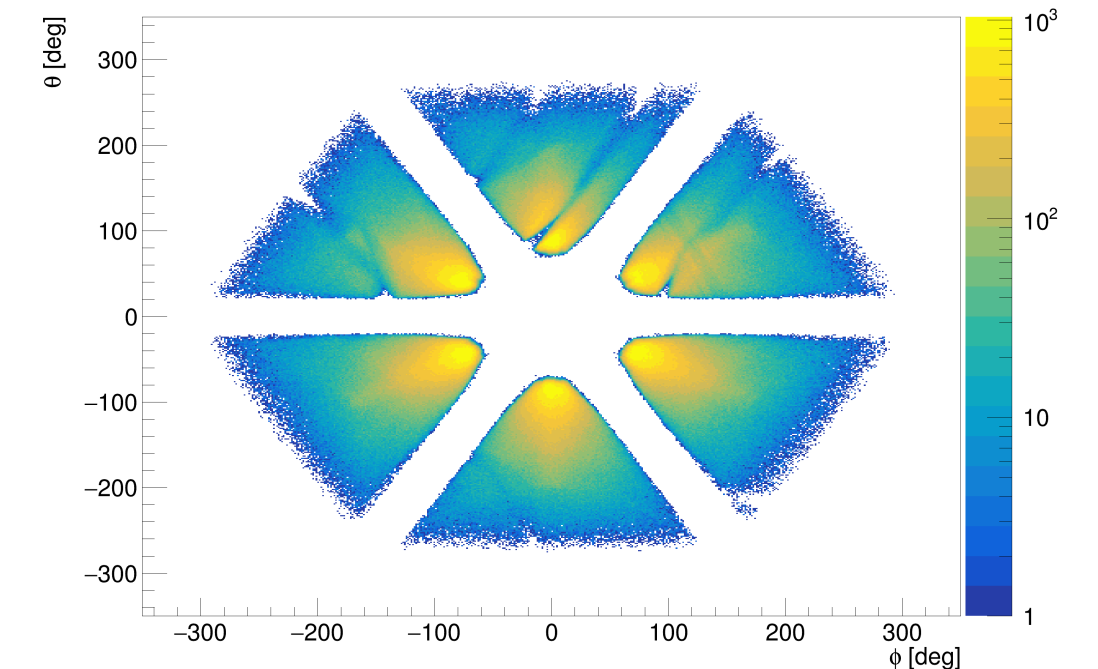
electron DC layer 6



electron DC layer 18



electron DC layer 36



- CVT regions layer 1, 3, 5, 7, and 12 also have respective fiducial cuts are employed.
- Sampling fraction cuts for electron, and energy loss corrections for proton are applied.
- QADB cuts to select the physics run/events

Particle Kinematics

- DVKpKm wagon: pass2 datasets but all $K^+ K^-$
- No RICH detector for Kaons
- Particle selections with Event Builder

$p_e > 1.5$ GeV in FD

Proton (2212)

$p_p > .3$ GeV in CD

$p_p > .42$ GeV in FD

$$\theta_p < 64^\circ$$

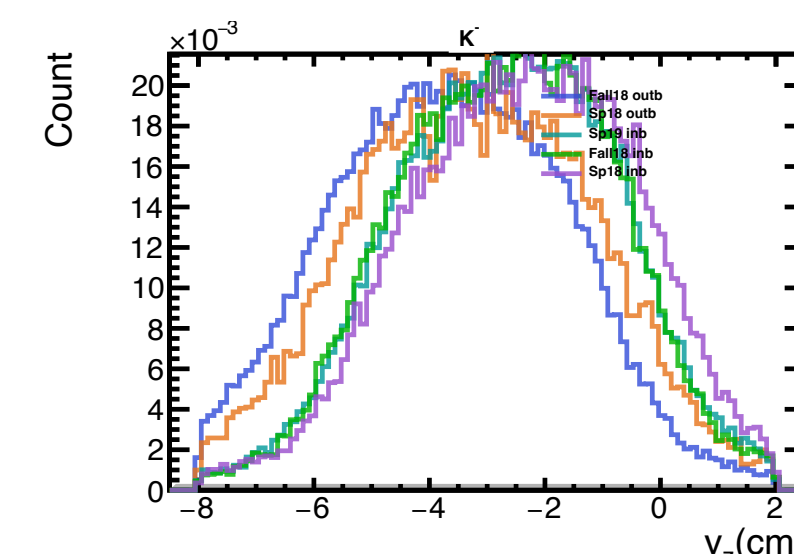
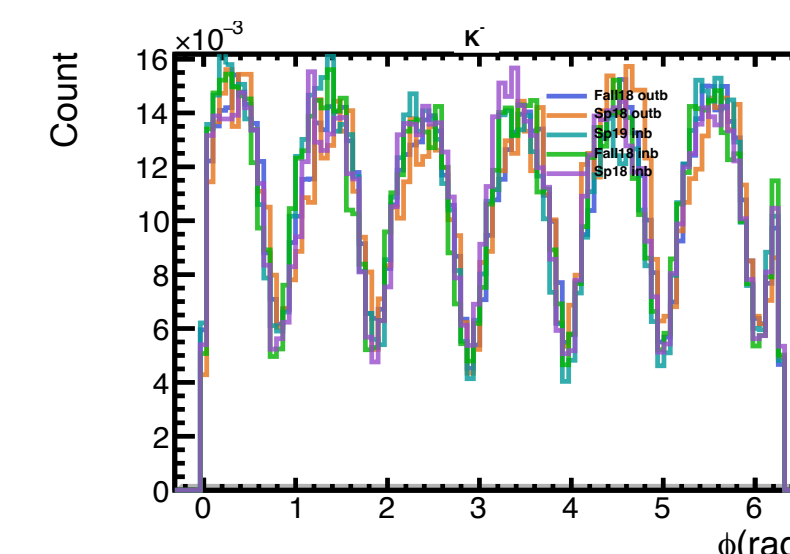
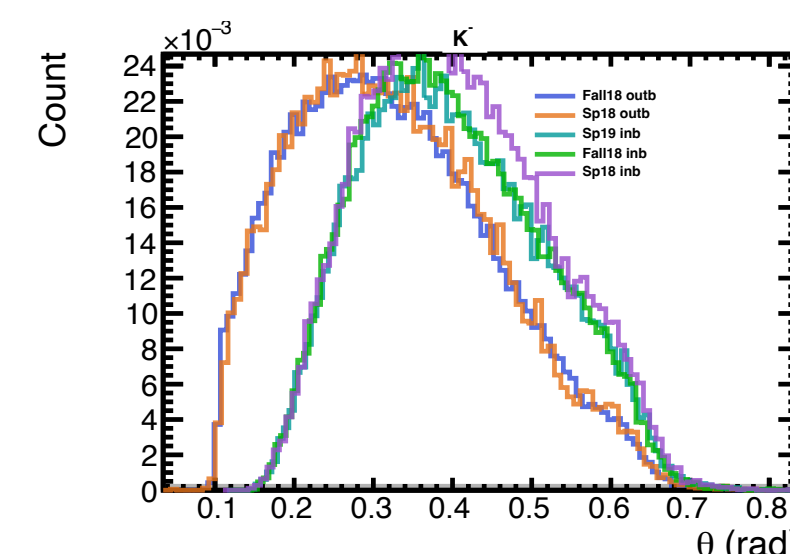
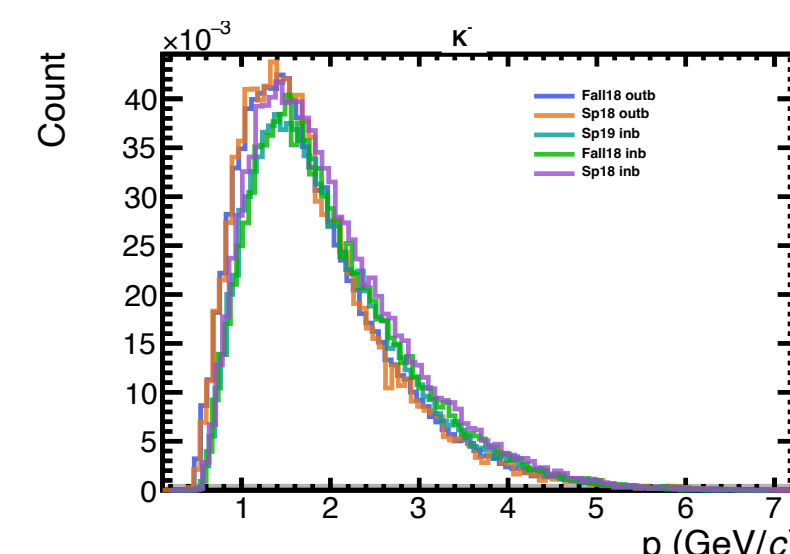
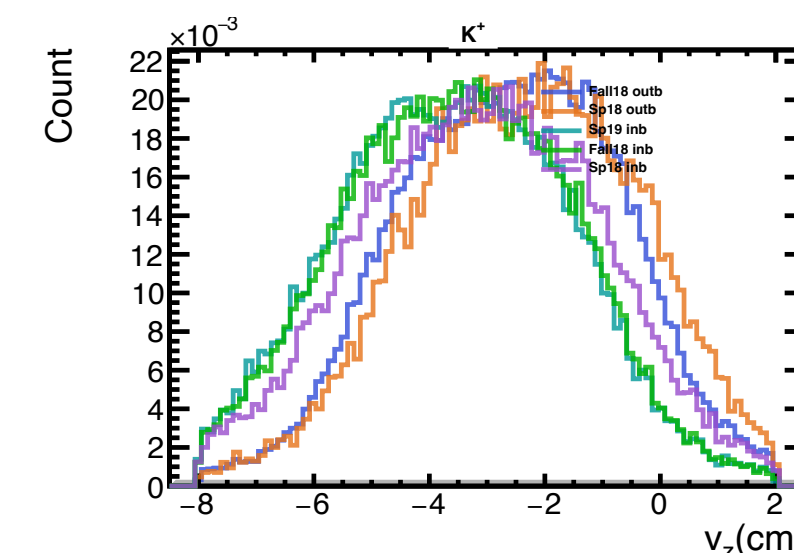
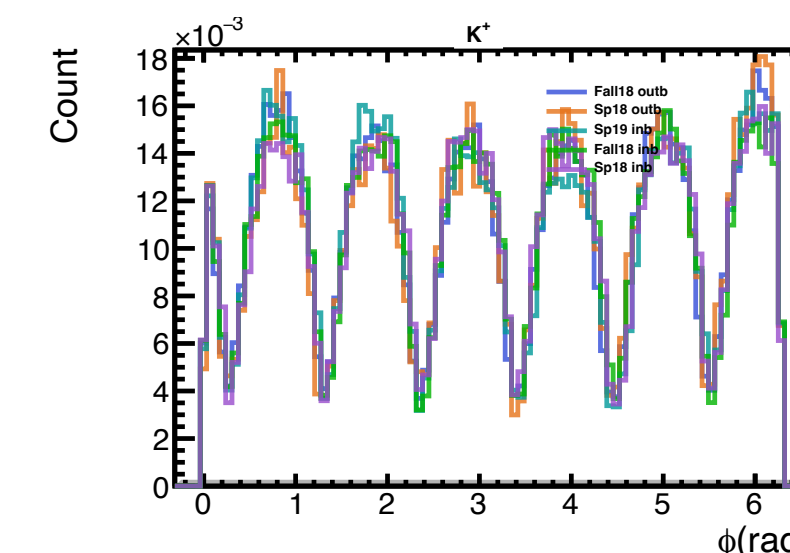
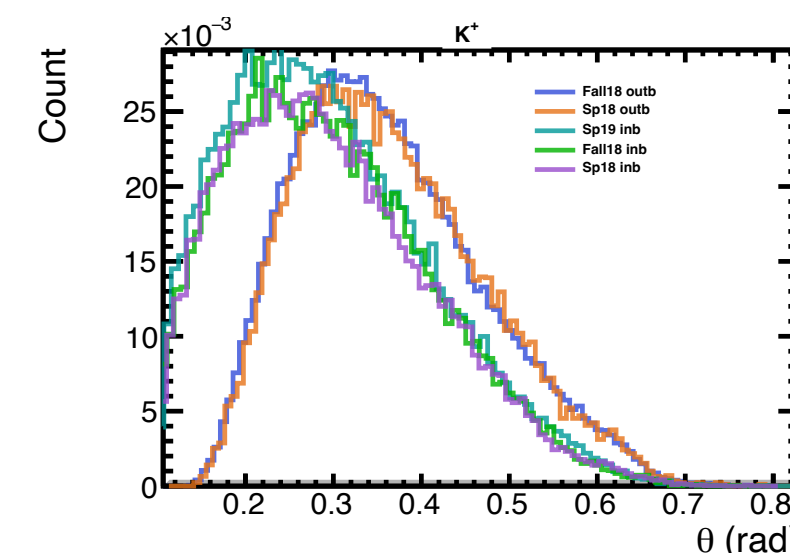
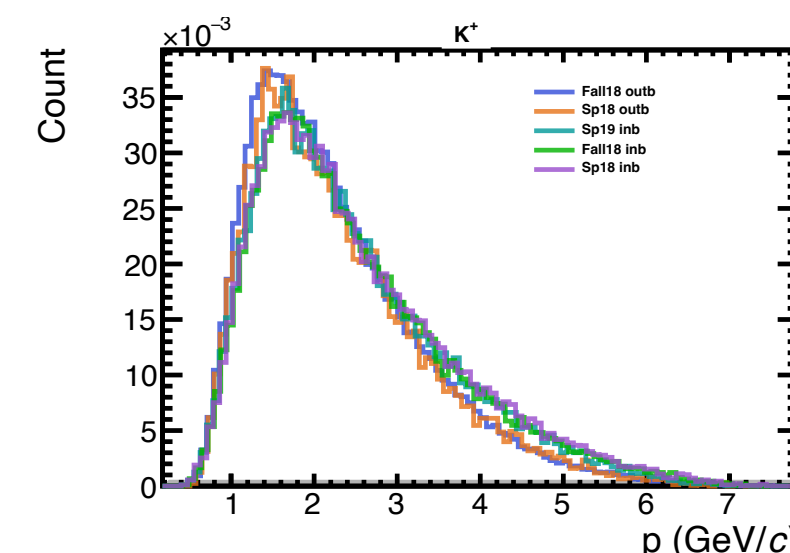
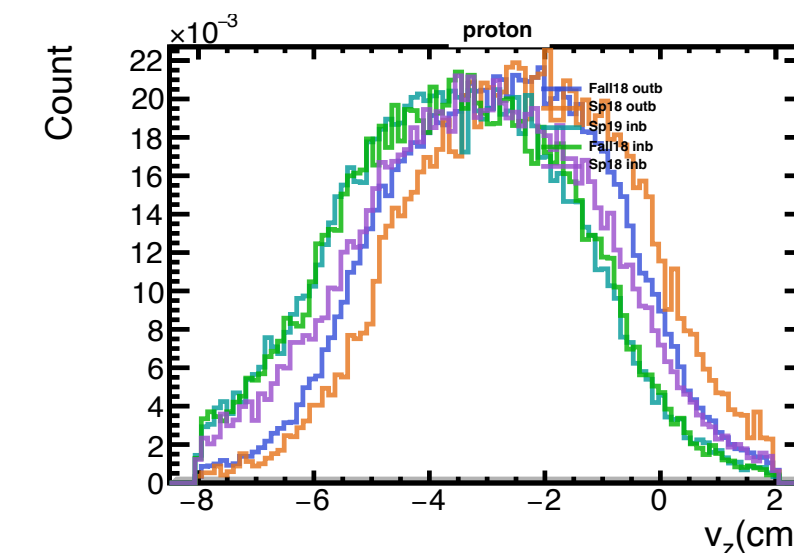
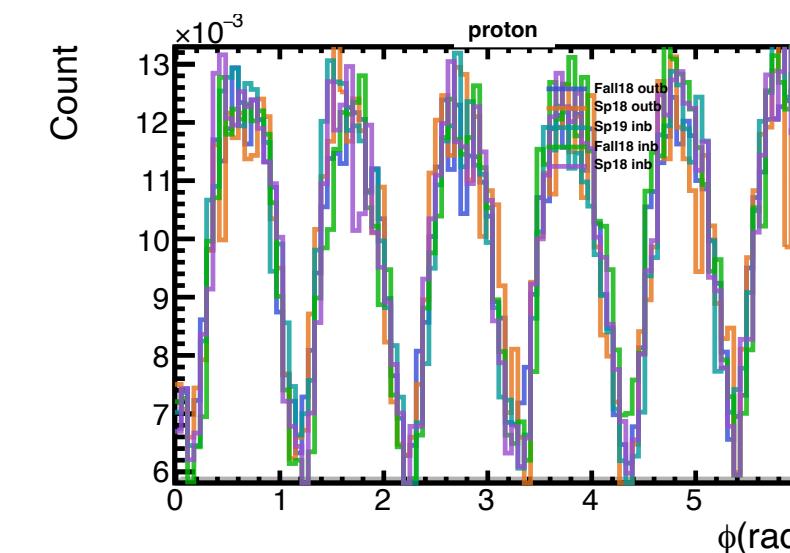
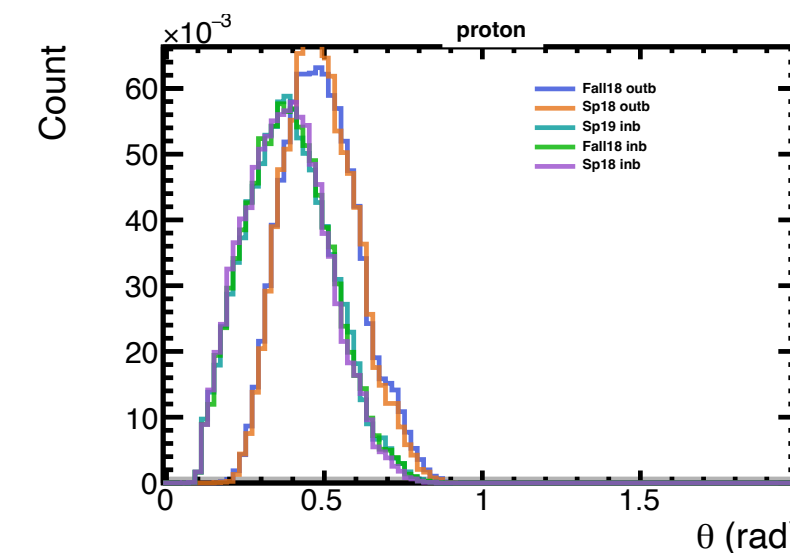
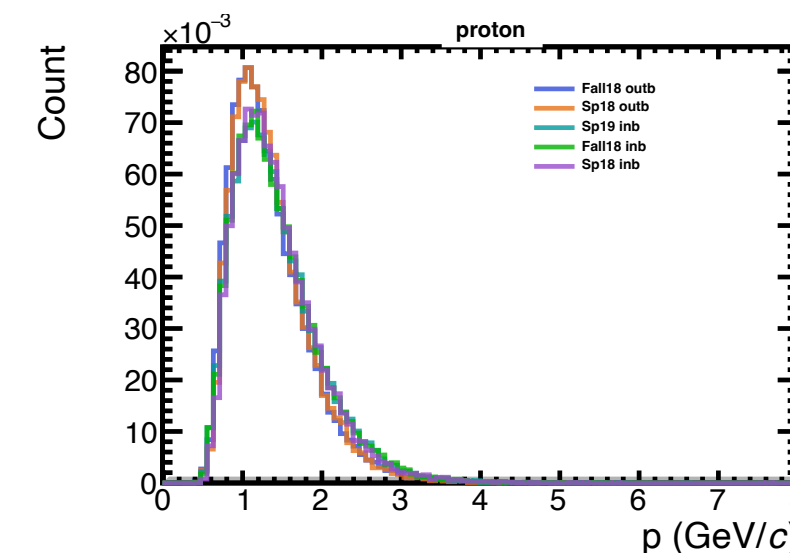
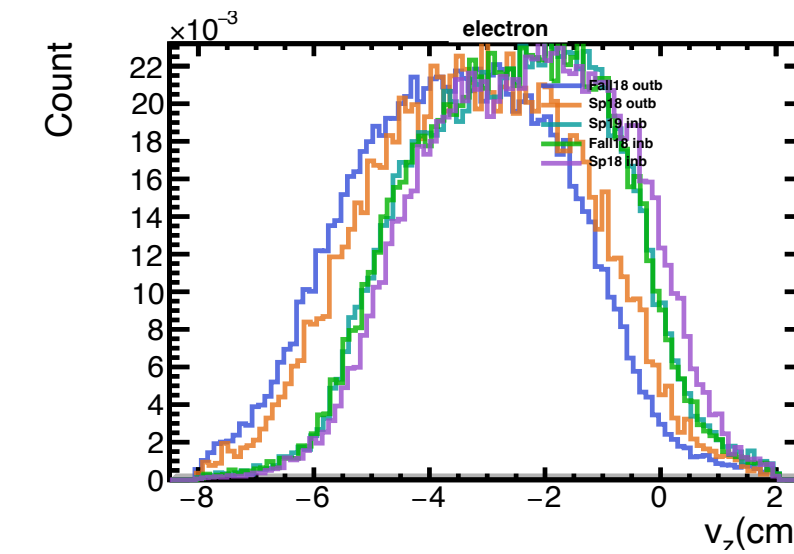
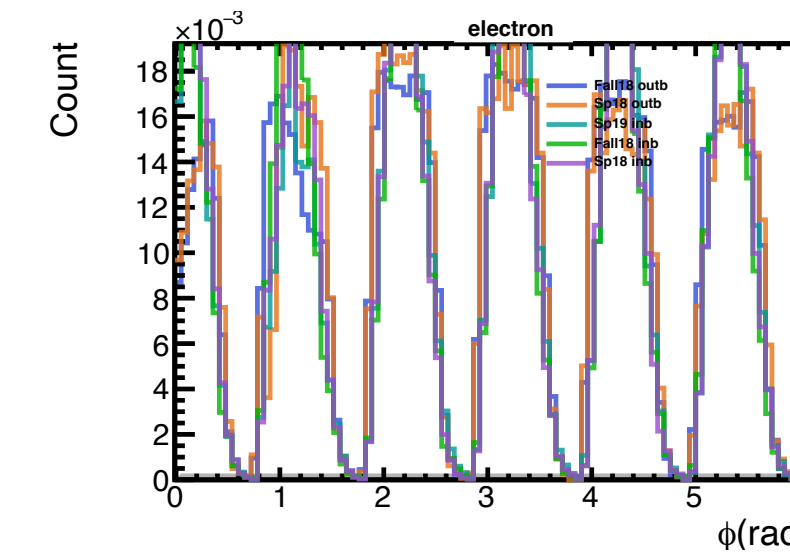
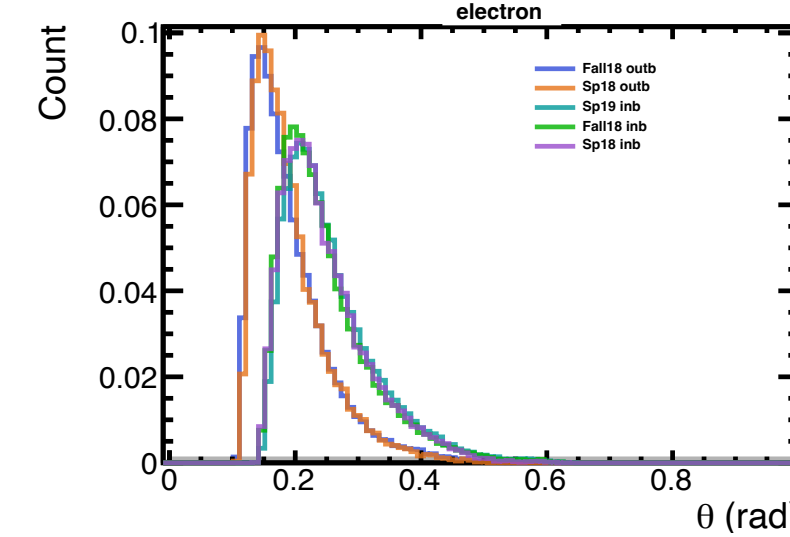
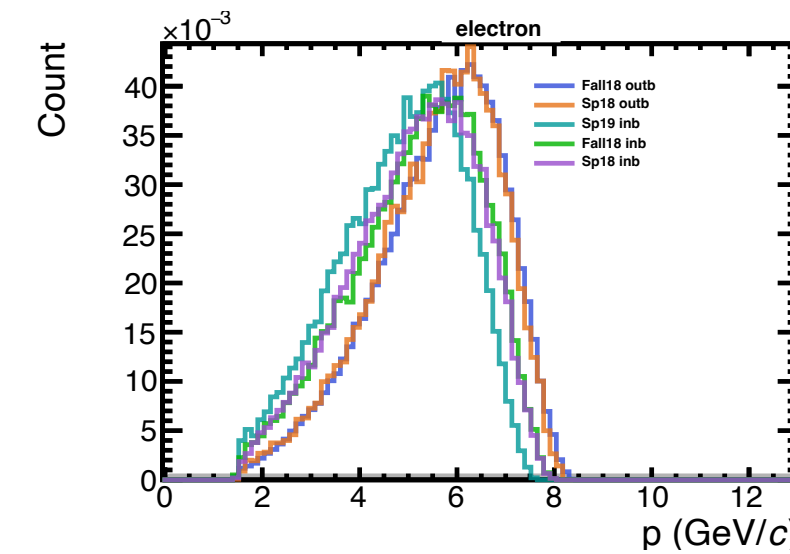
Kaons (± 321)

$0.2 < p_K < 7.5$ GeV in FD

Vertex for all particles

$$-8\text{cm} < v_z < 2\text{ cm}$$

— **Fall18 outb**
— **Sp18 outb**
— **Sp19 inb**
— **Fall18 inb**
— **Sp18 inb**

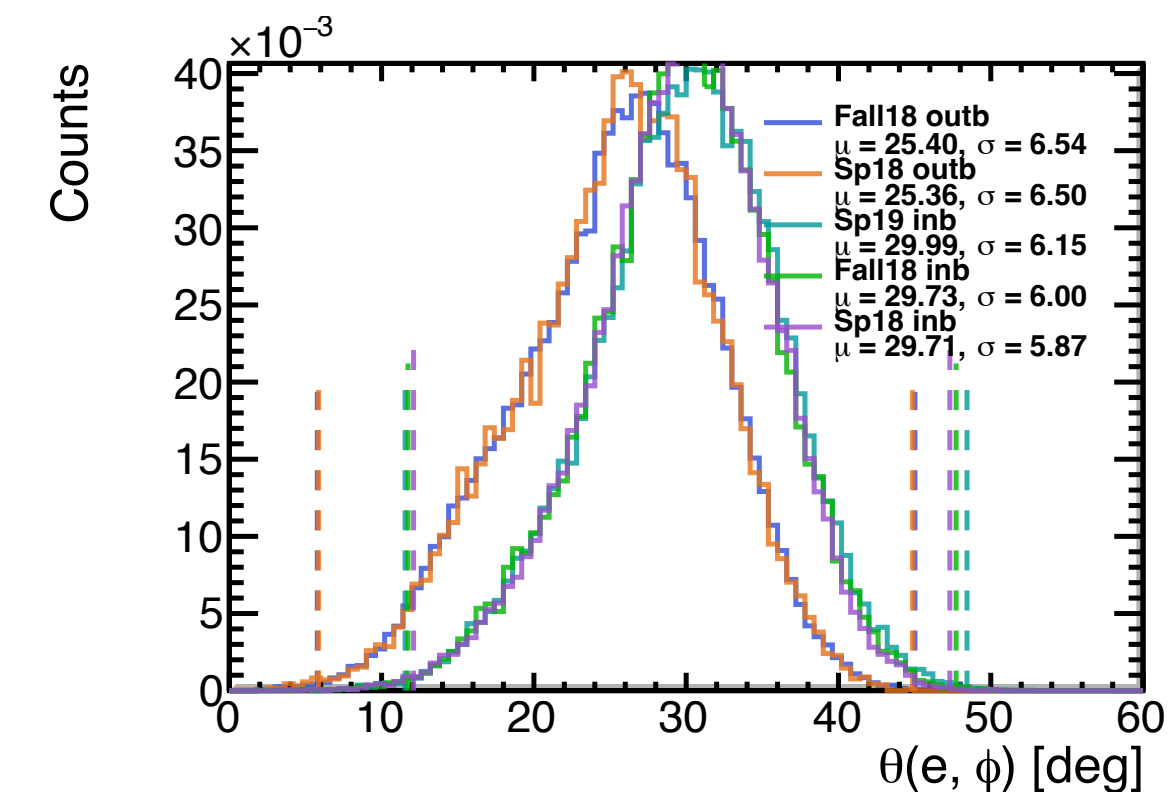
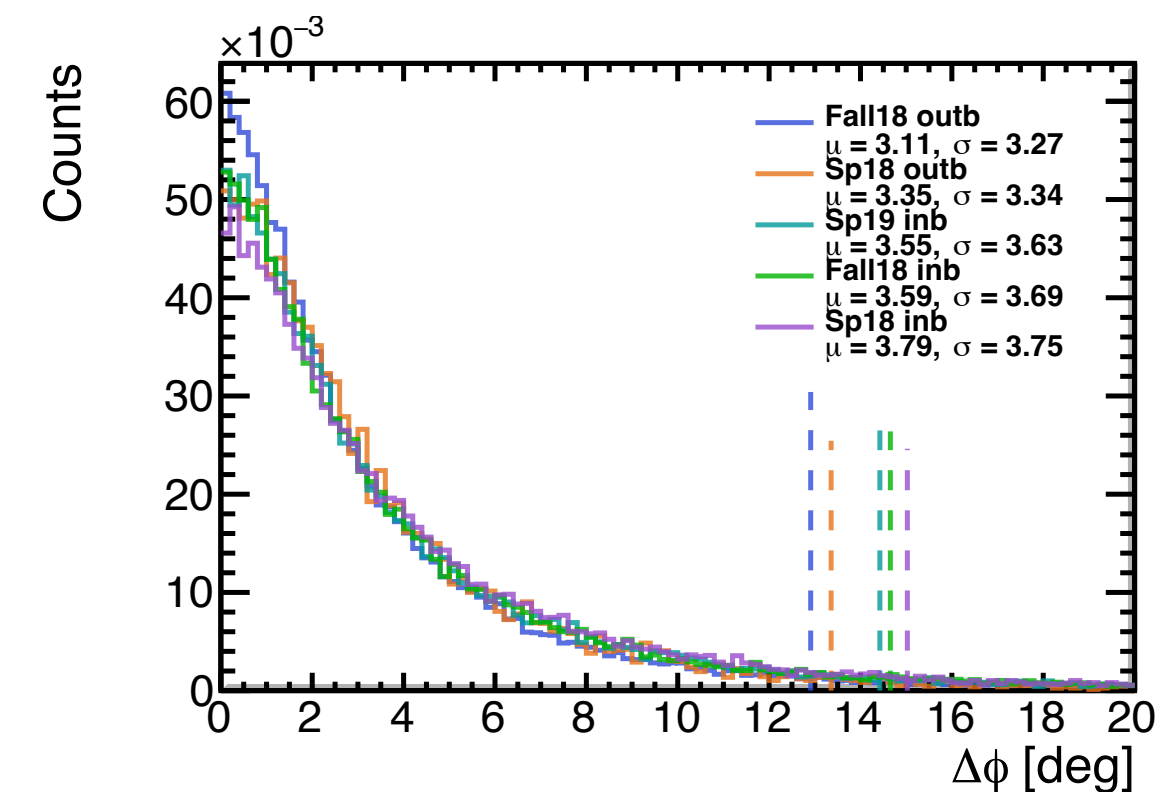
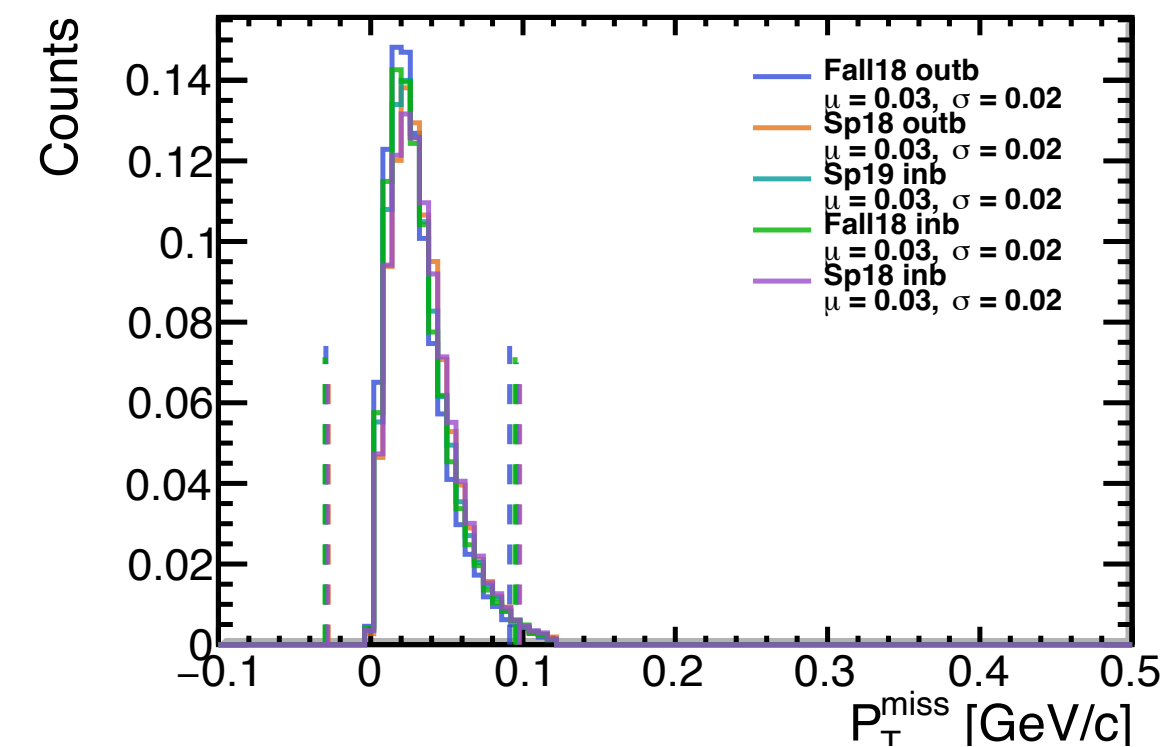
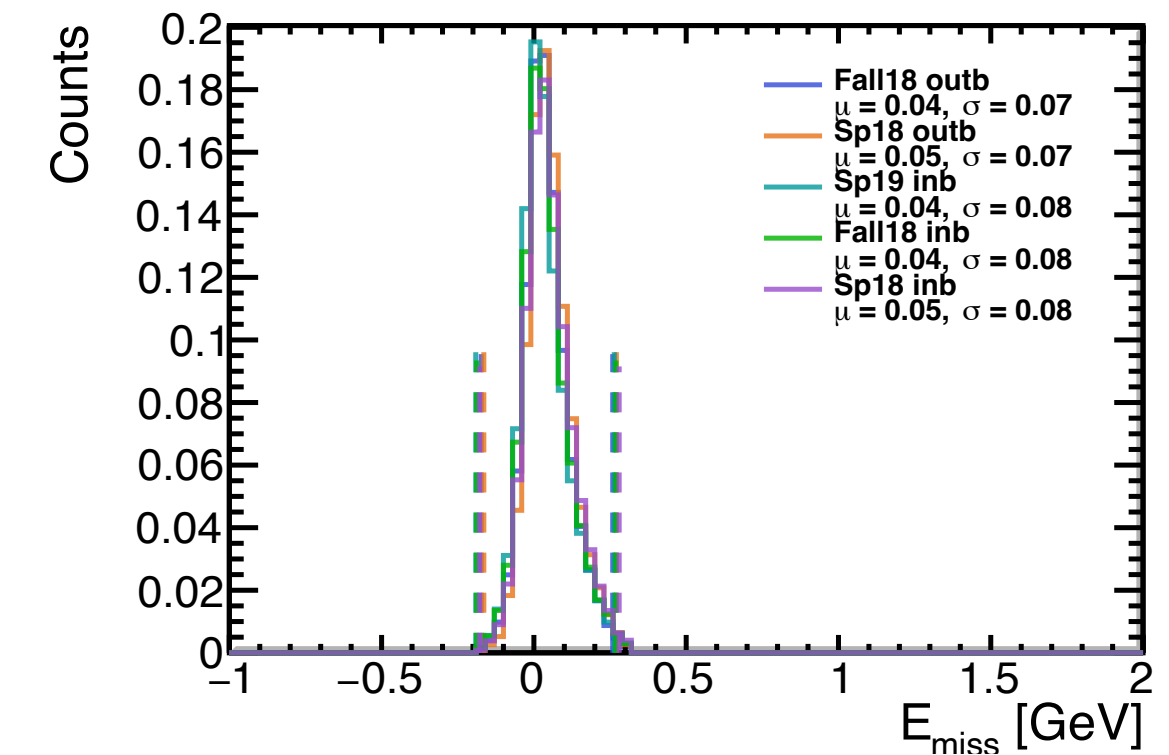
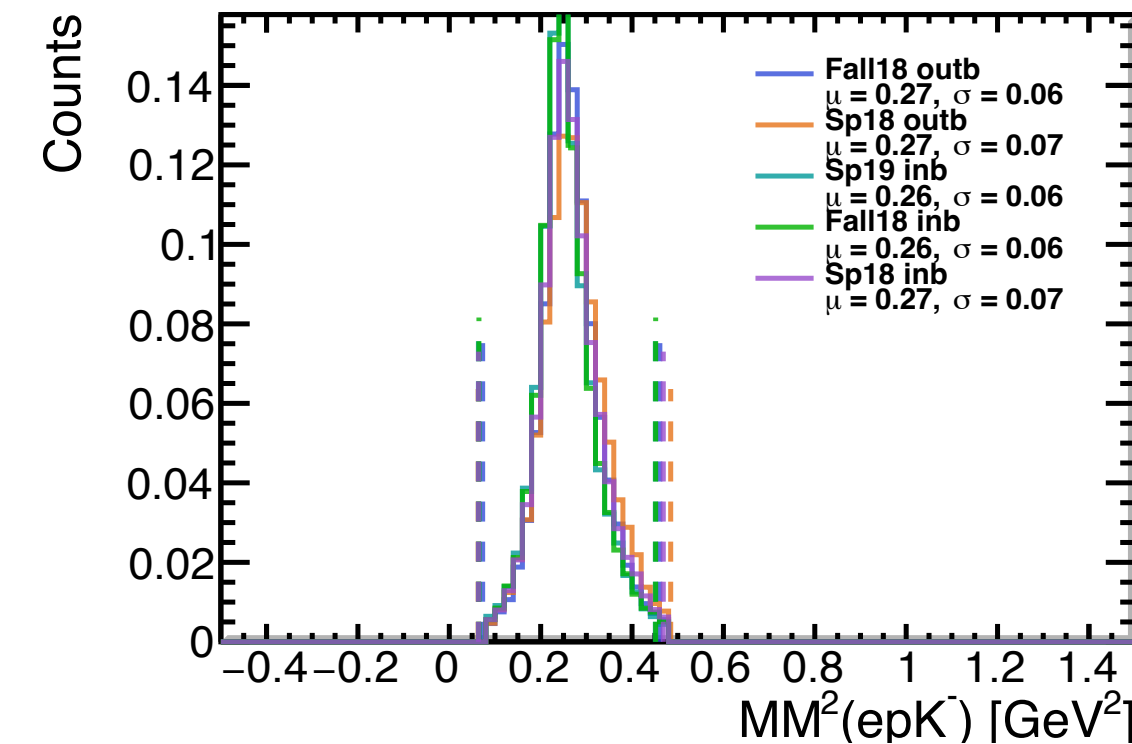
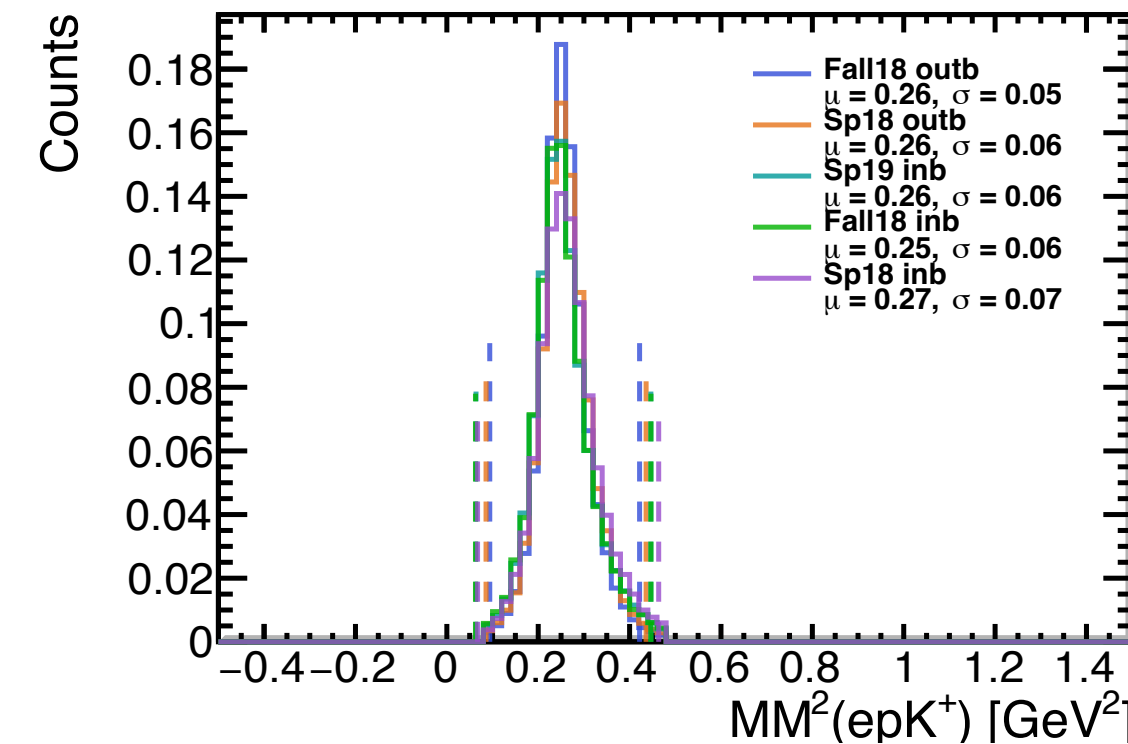
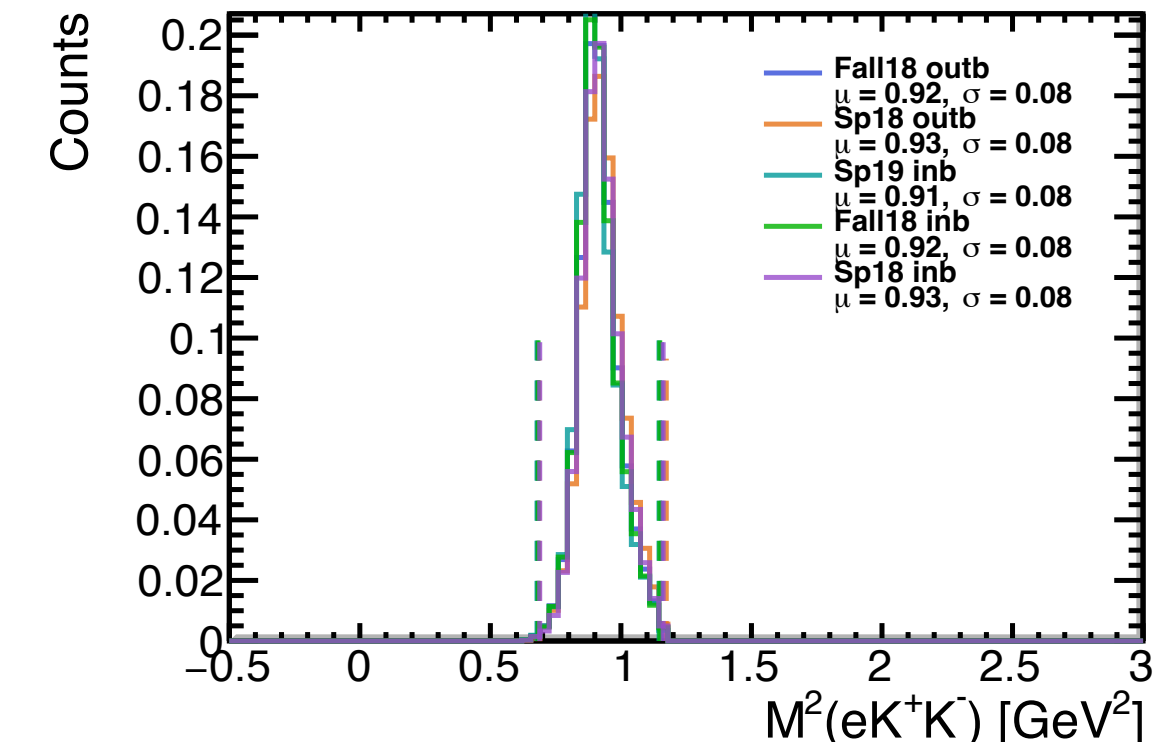
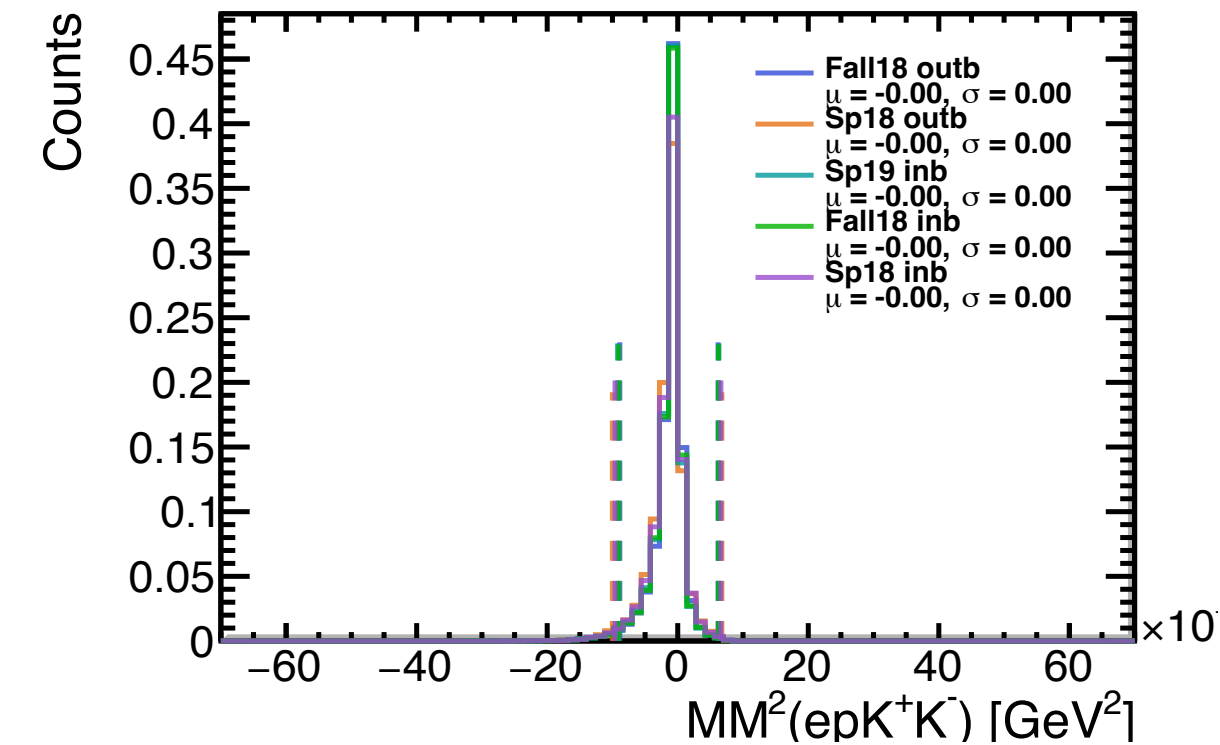
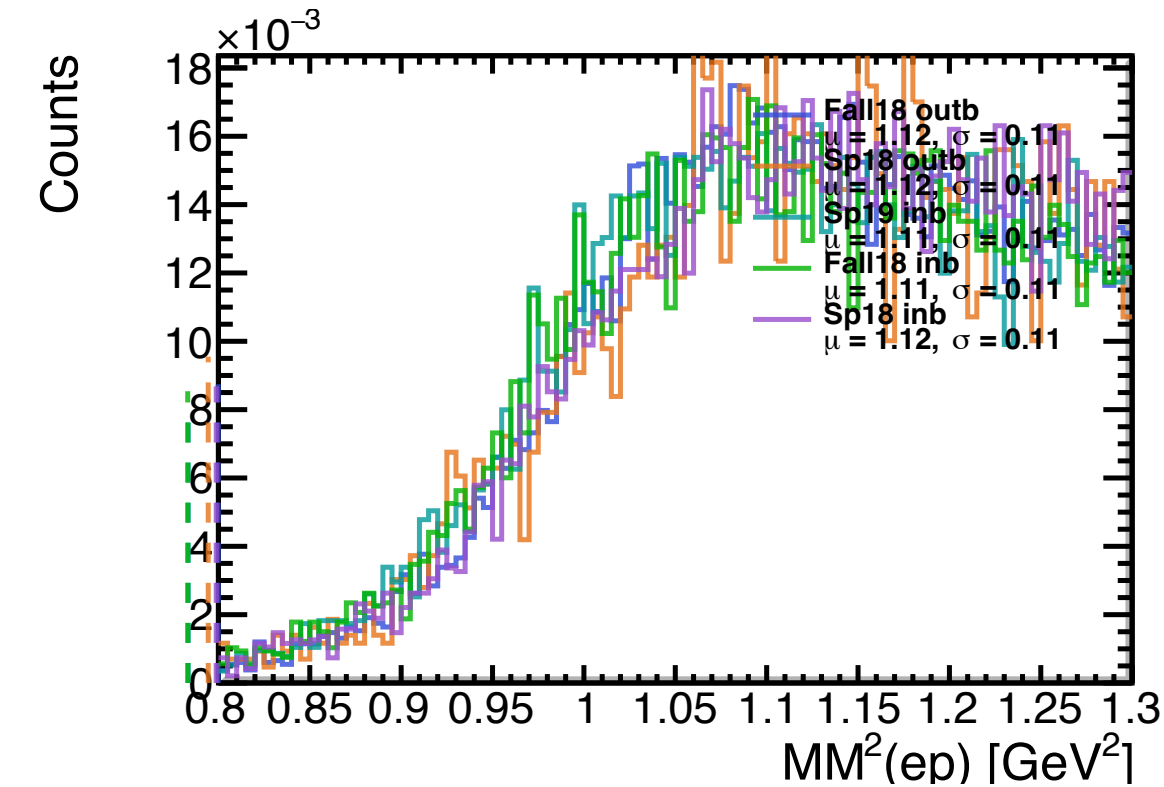


Exclusivity variables

- Both Proton and Kaons in FD
- Exclusivity variables are prior to phi mass peak cut

- Exclusivity cuts

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

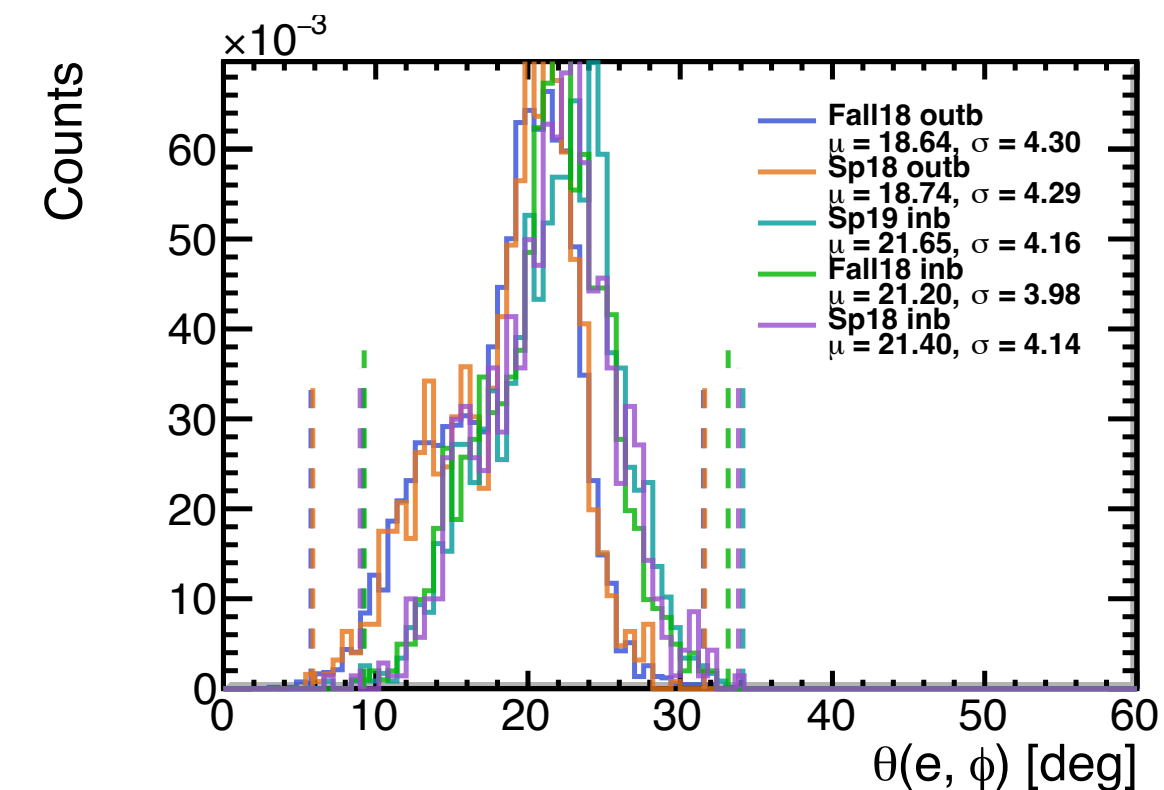
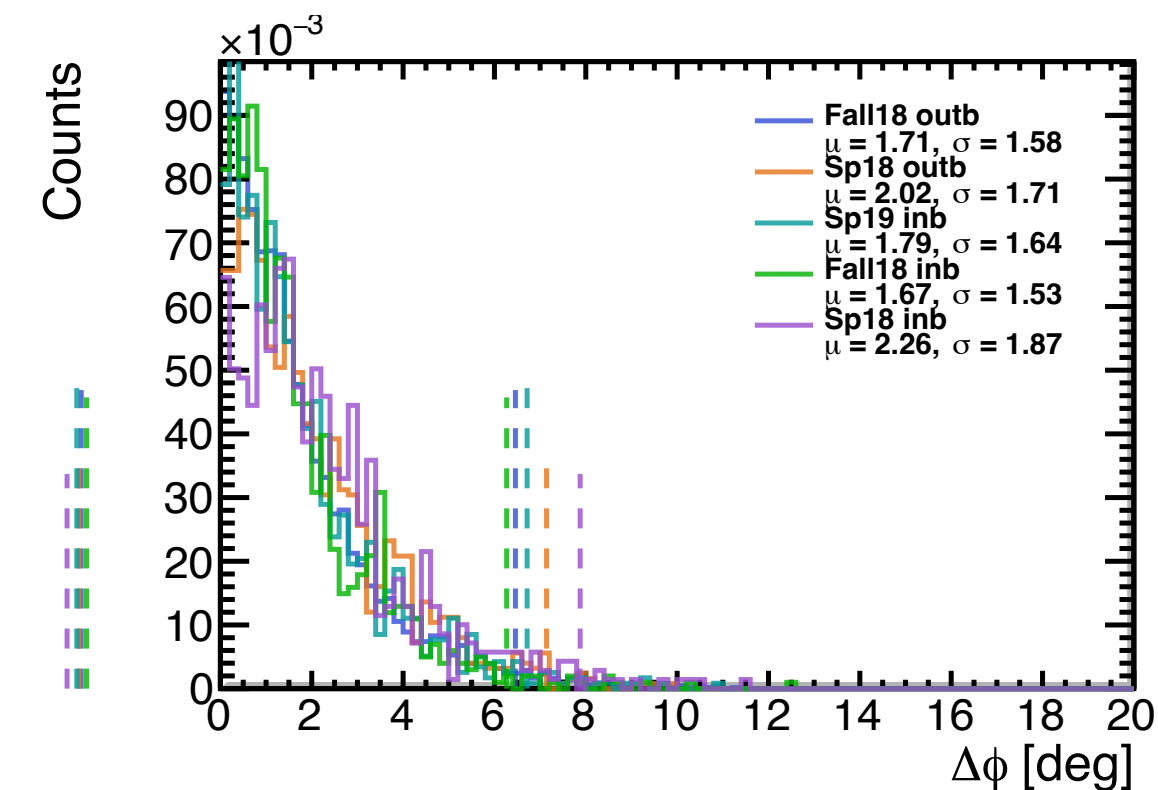
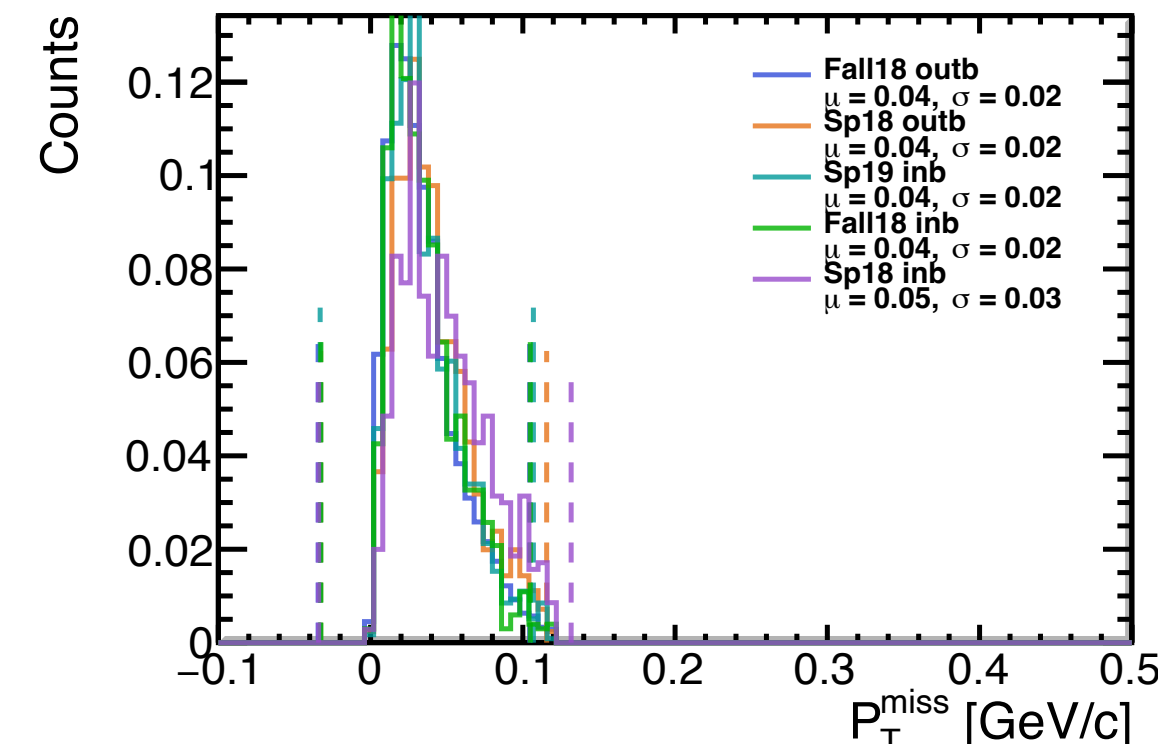
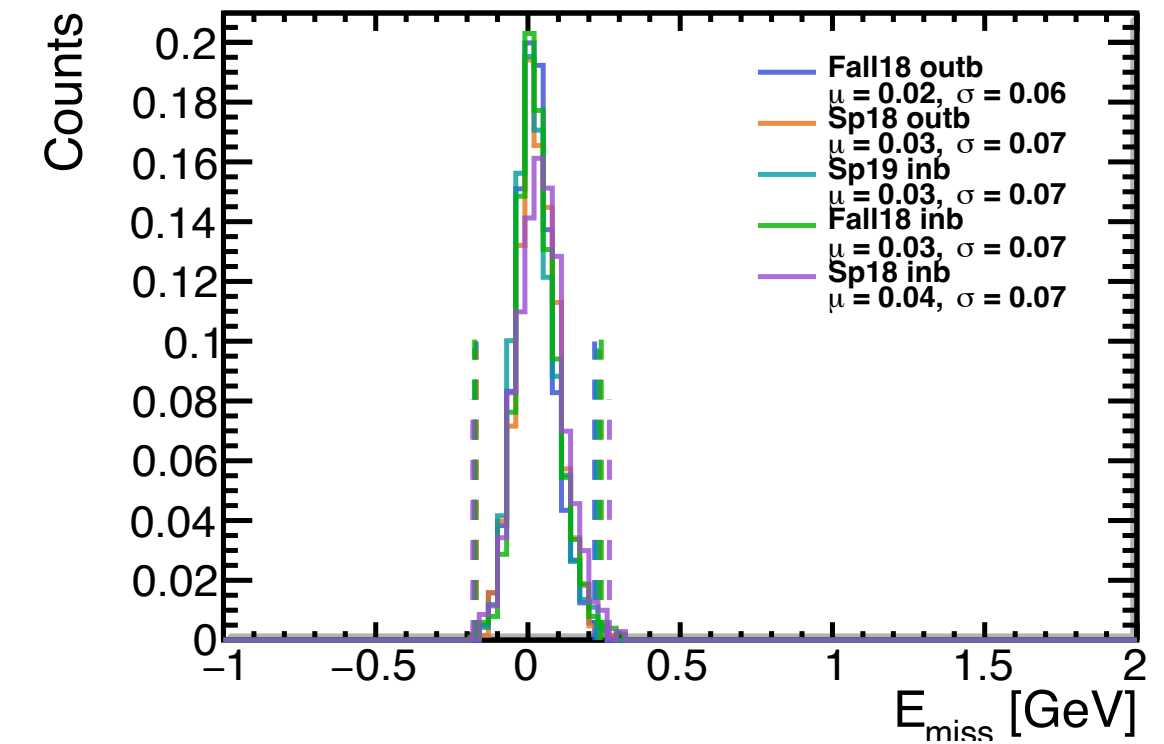
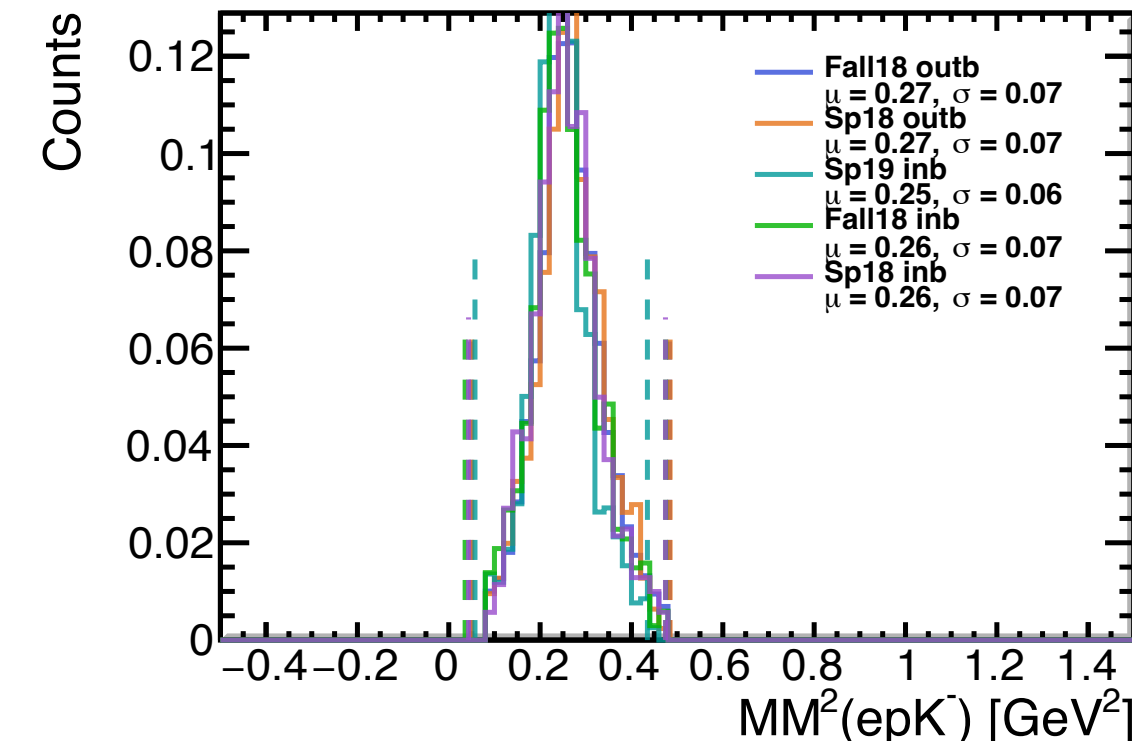
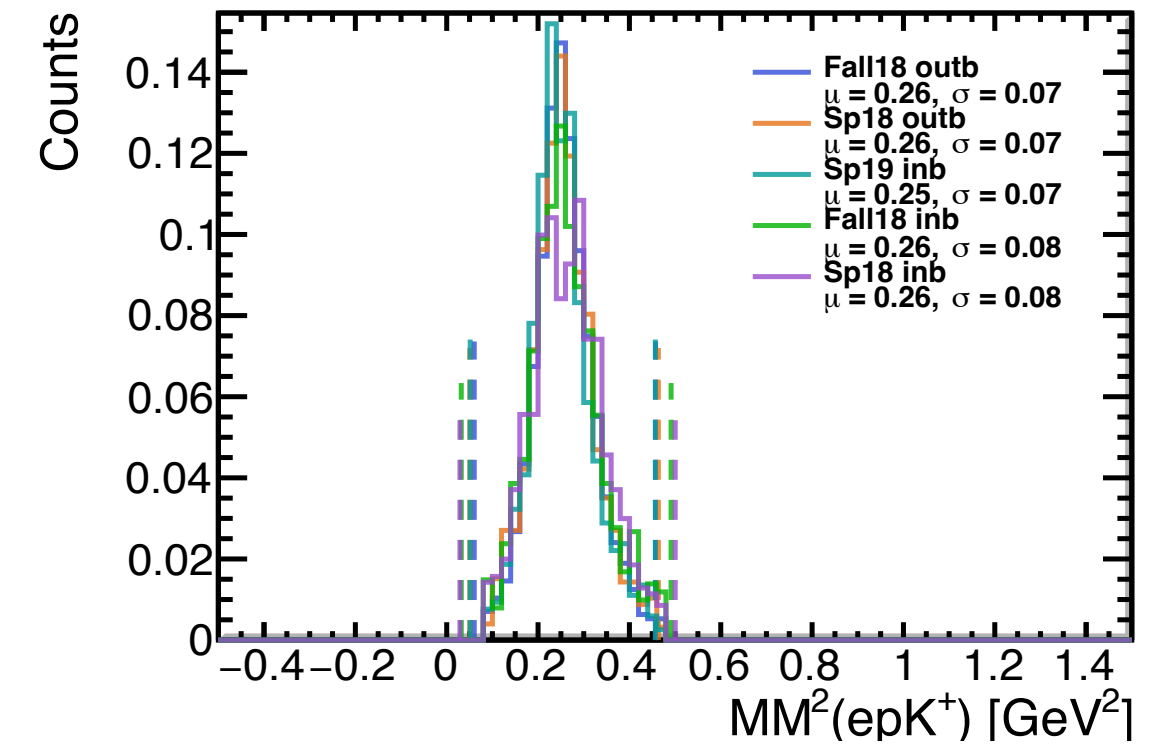
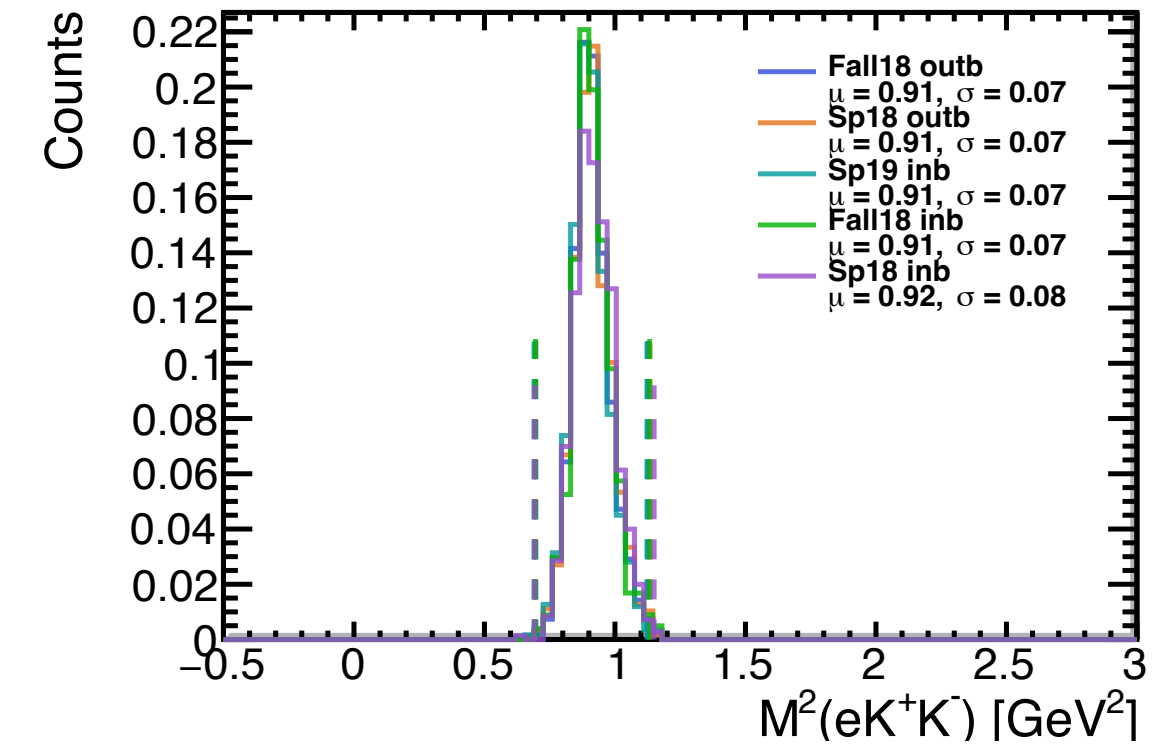
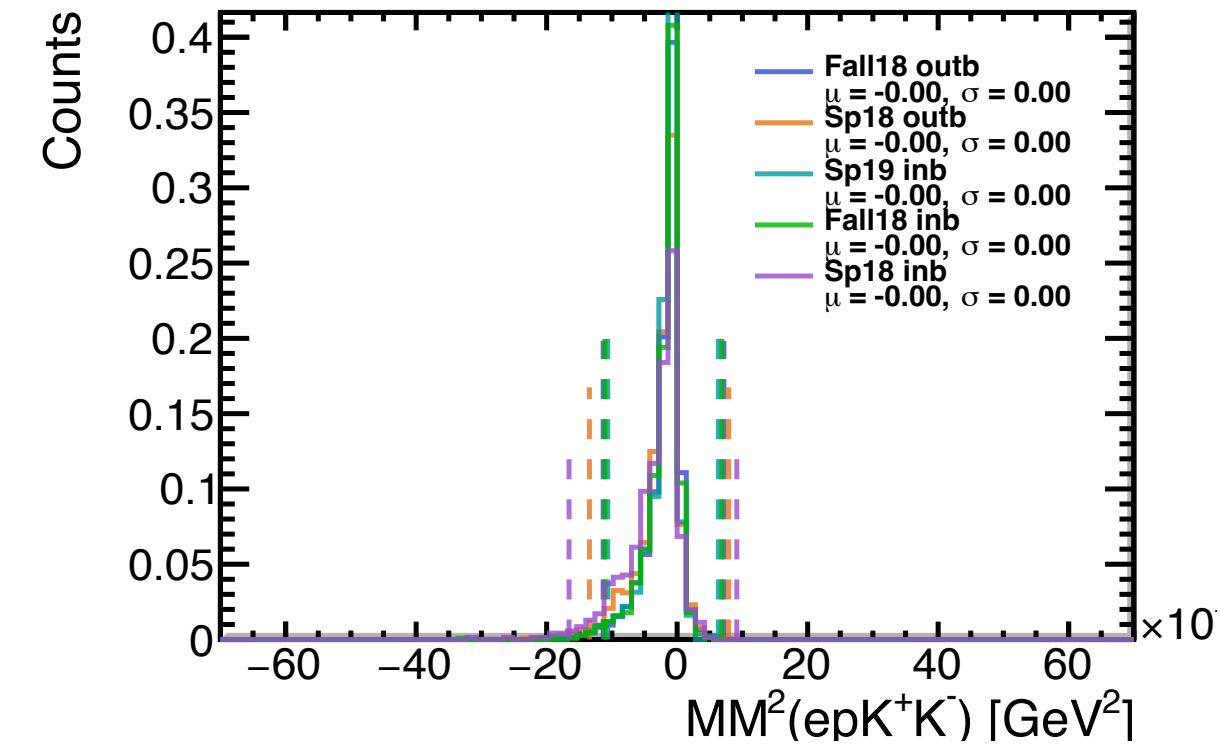
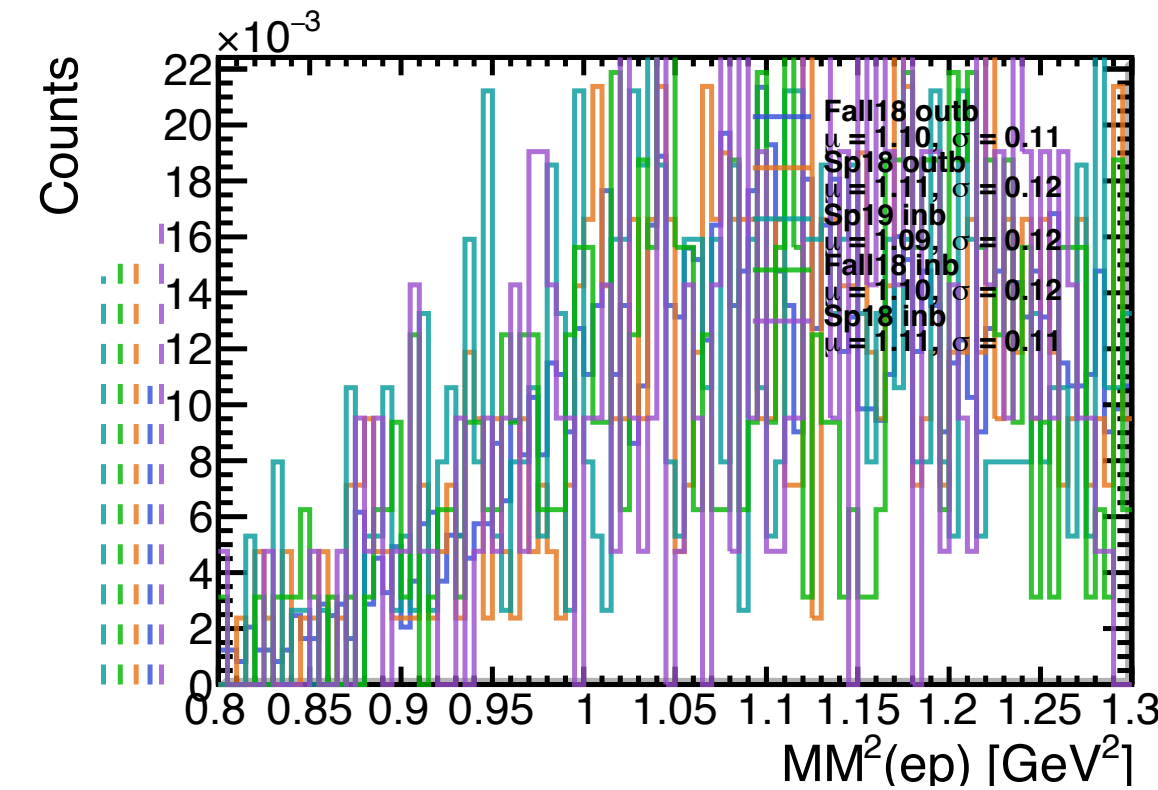


Exclusivity variables

- Proton in CD and Kaons in FD (less stat)
- Exclusivity variables are prior to phi mass peak cut

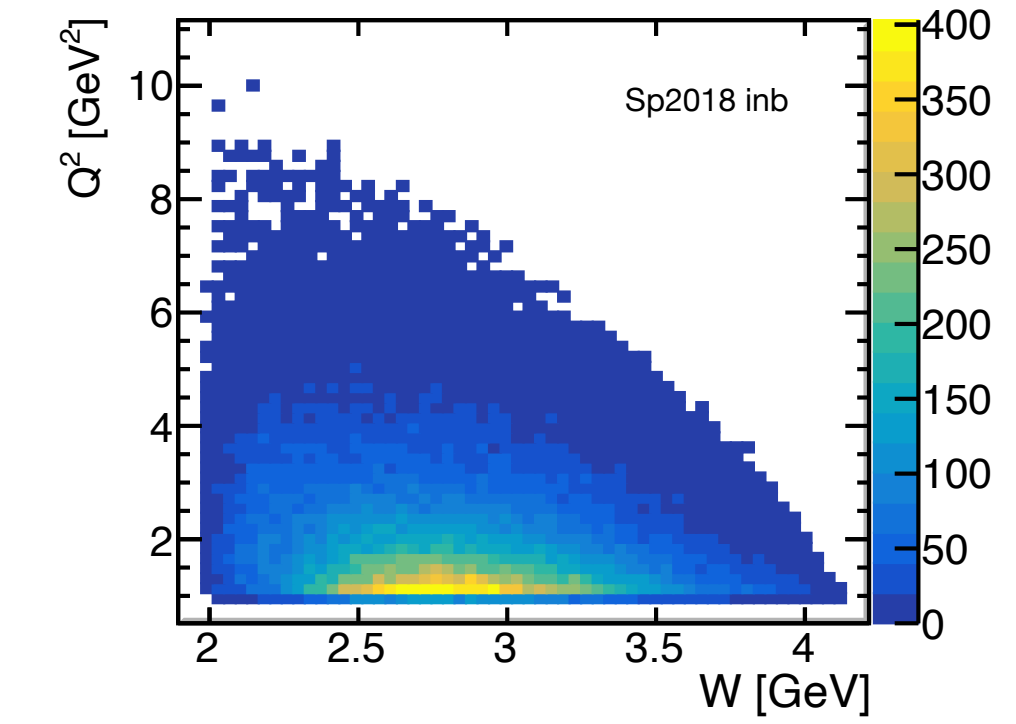
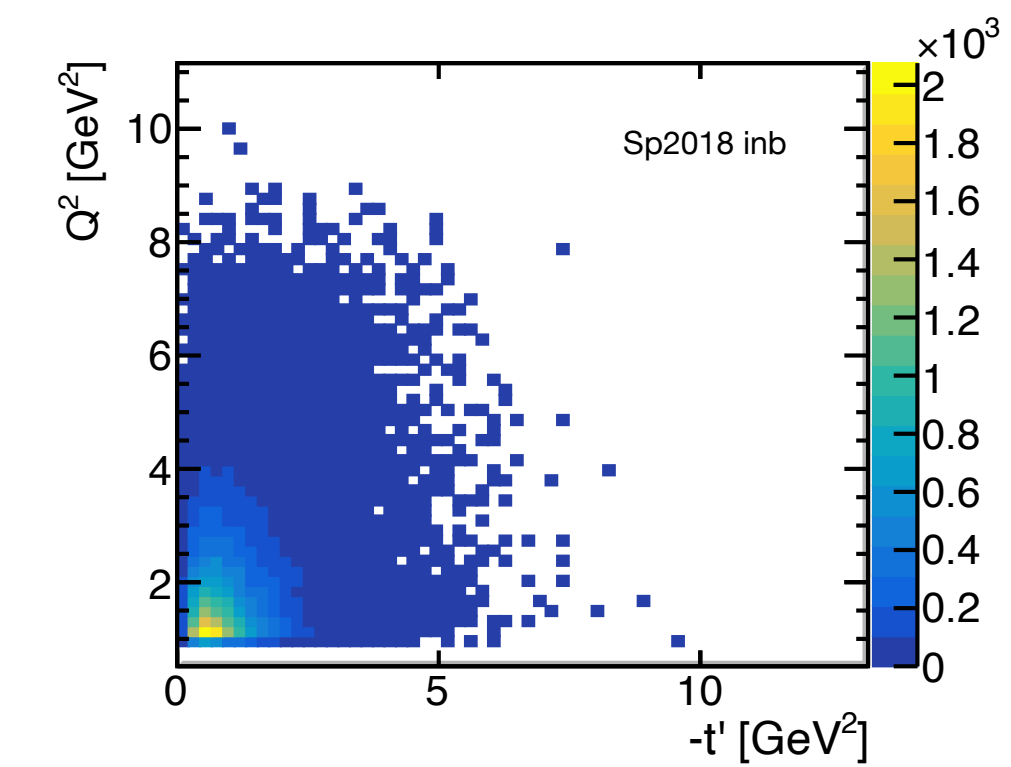
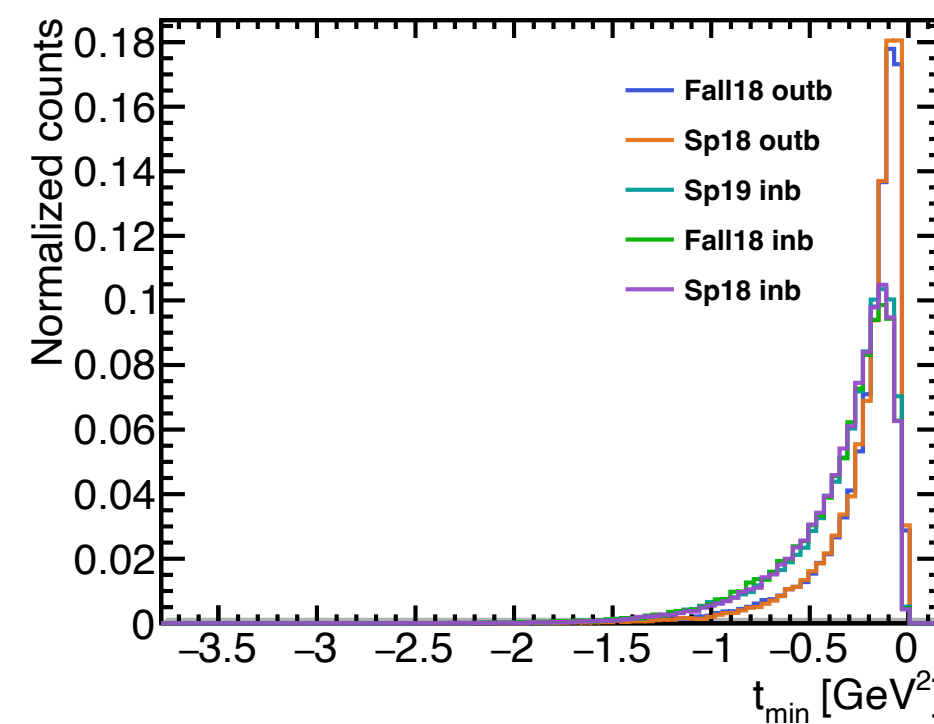
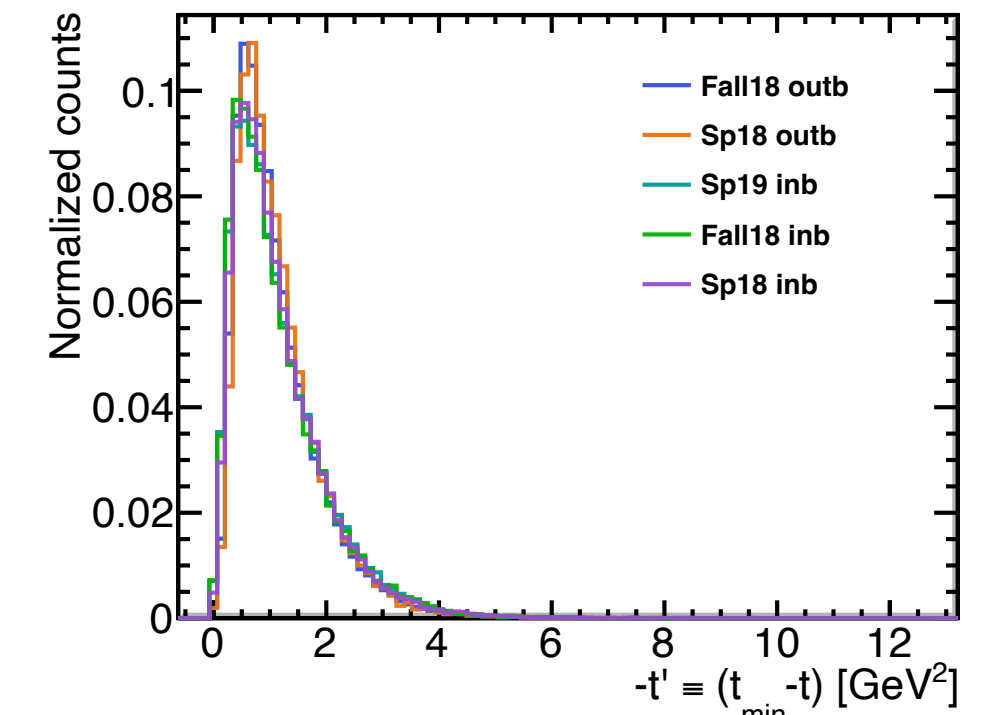
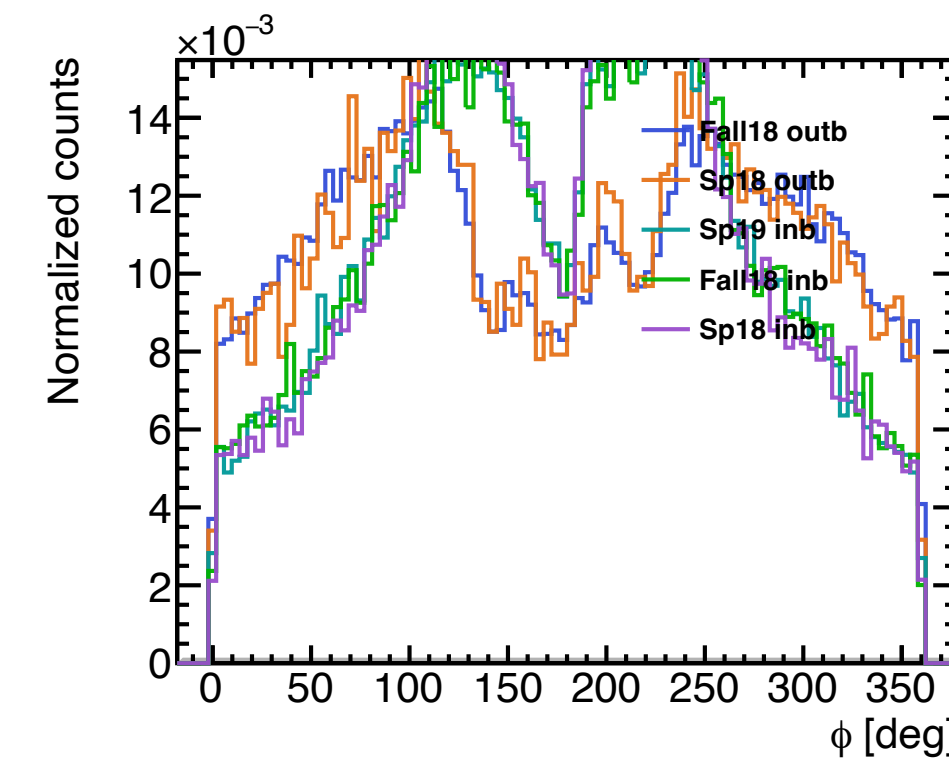
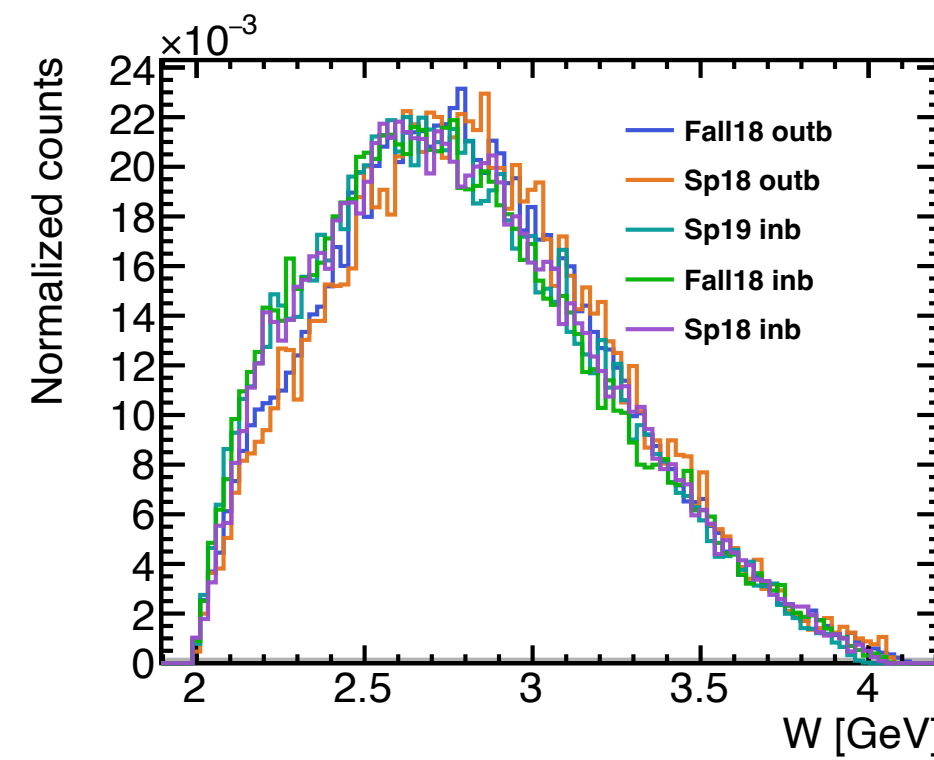
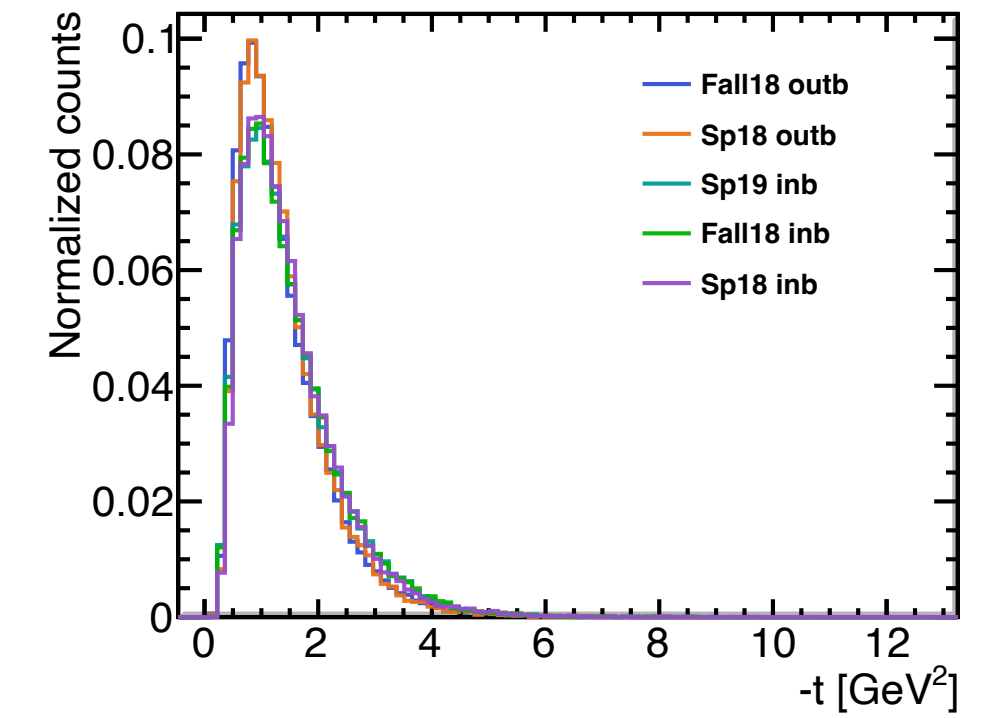
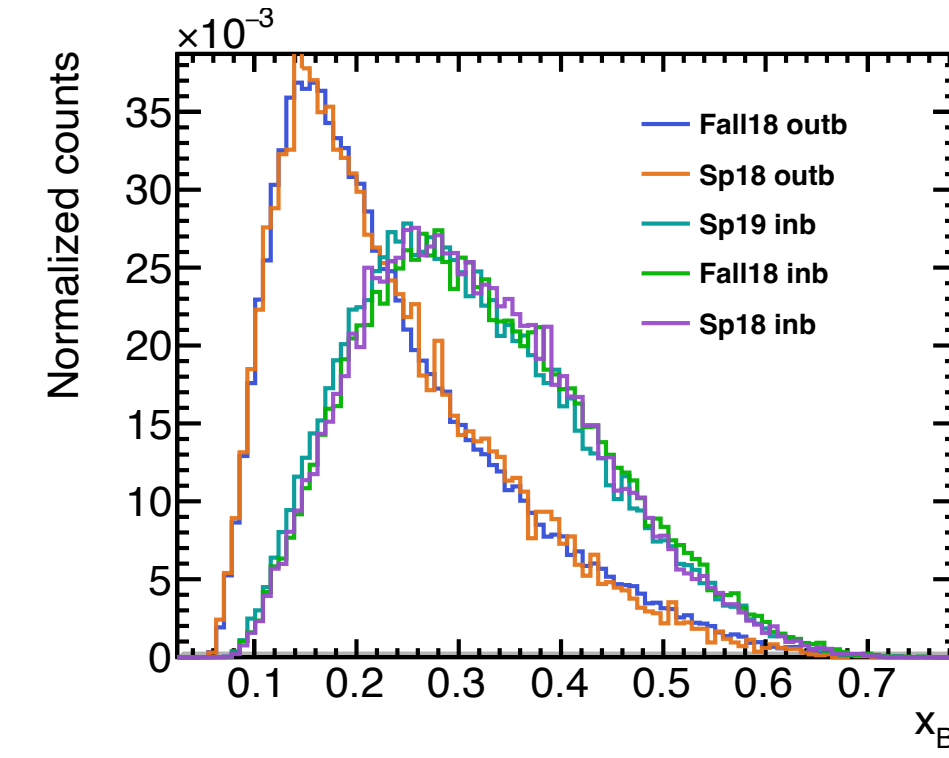
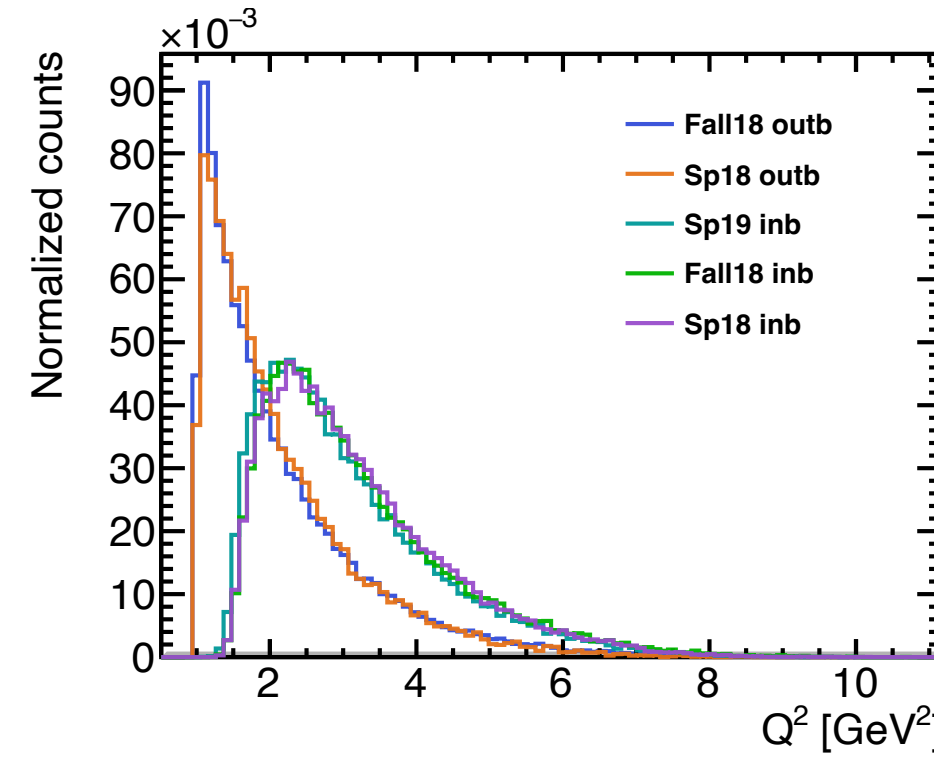
- Exclusivity cuts

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



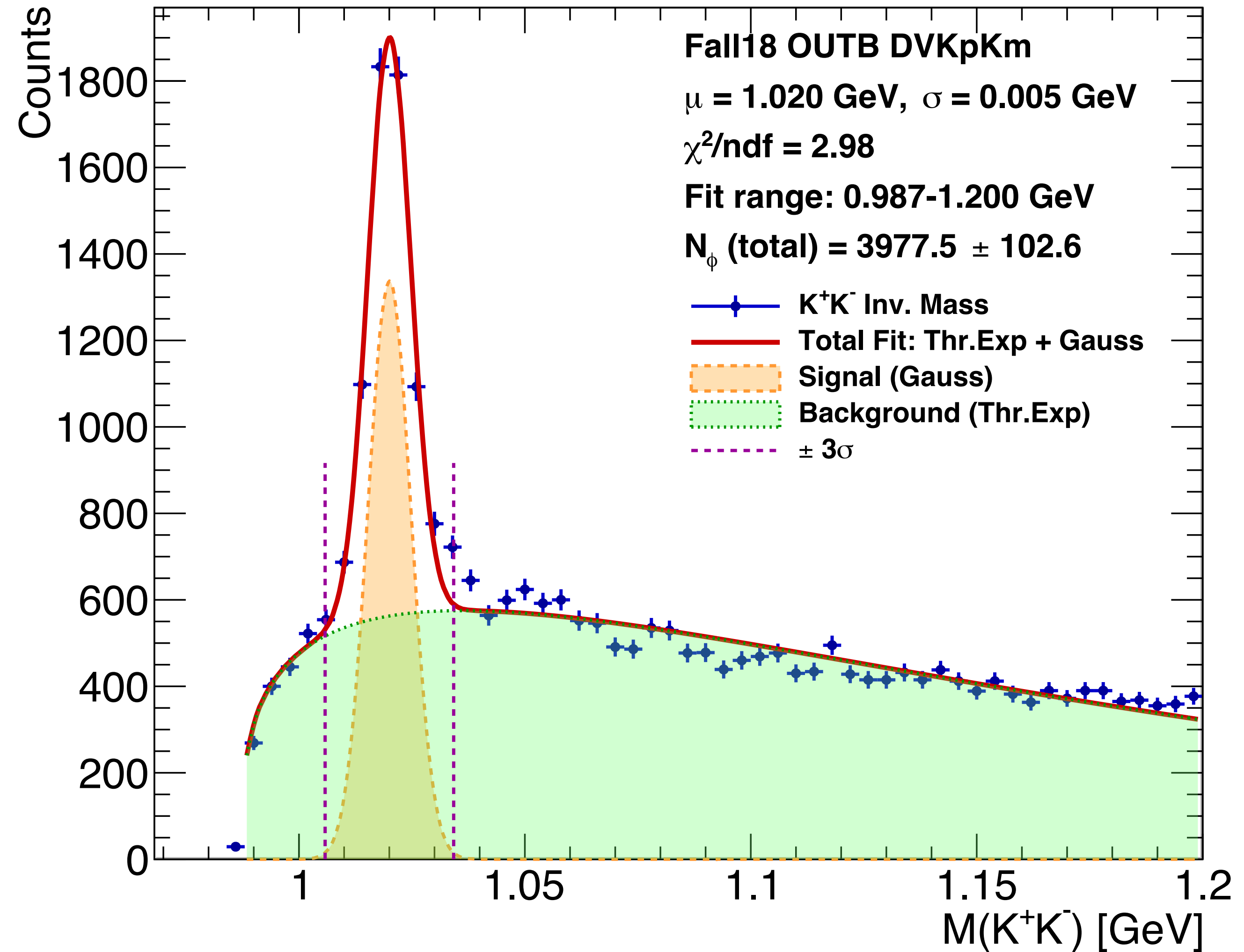
DVEP Kinematic variables

- After selecting e, p, and Kaons
- Fiducial cuts, exclusivity cuts
- Energy loss correction for proton
- $W > 2.0$ GeV
- $Q^2 > 1$ GeV²
- $p_e > 1.5$ GeV
- $p_p > 0.3$ / 0.4 (inb and outb)



K⁺K⁻ Invariant Mass Distributions

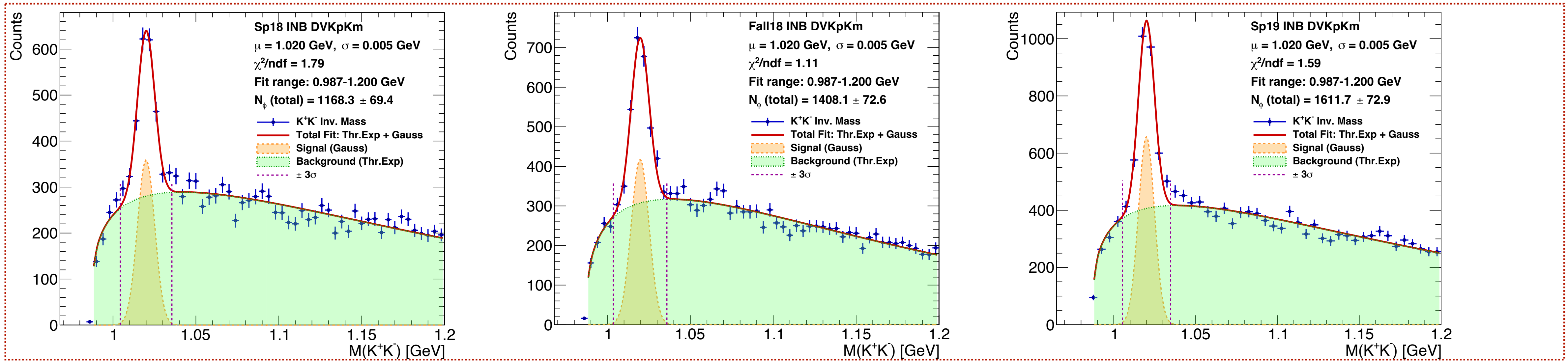
- ϕ meson via the invariant mass peak at ~ 1.019 GeV of K^+K^- in $ep \rightarrow epK^+K^-$
- Fully exclusive selection: ~ 4000 candidates from fall 2018 outb
- Signal: Gaussian distribution
- Background: Exponential+polynomial 3rd order
- Extracted yield as integral of the Gaussian function



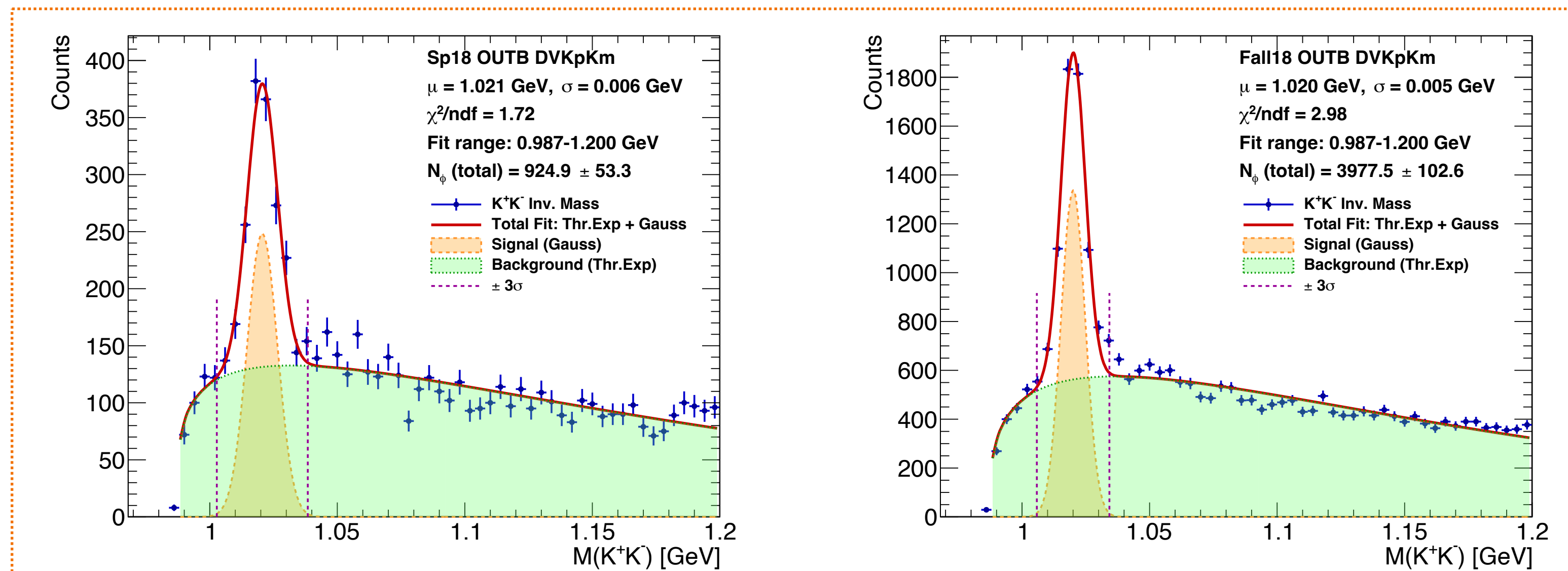
All phi K⁺K⁻ Invariant Mass all periods of RGA

- Phi peak at ~1020 MeV, cross-section analysis: $\pm 3\sigma$ cut around the the peak, total ~8000 candidates

Inb

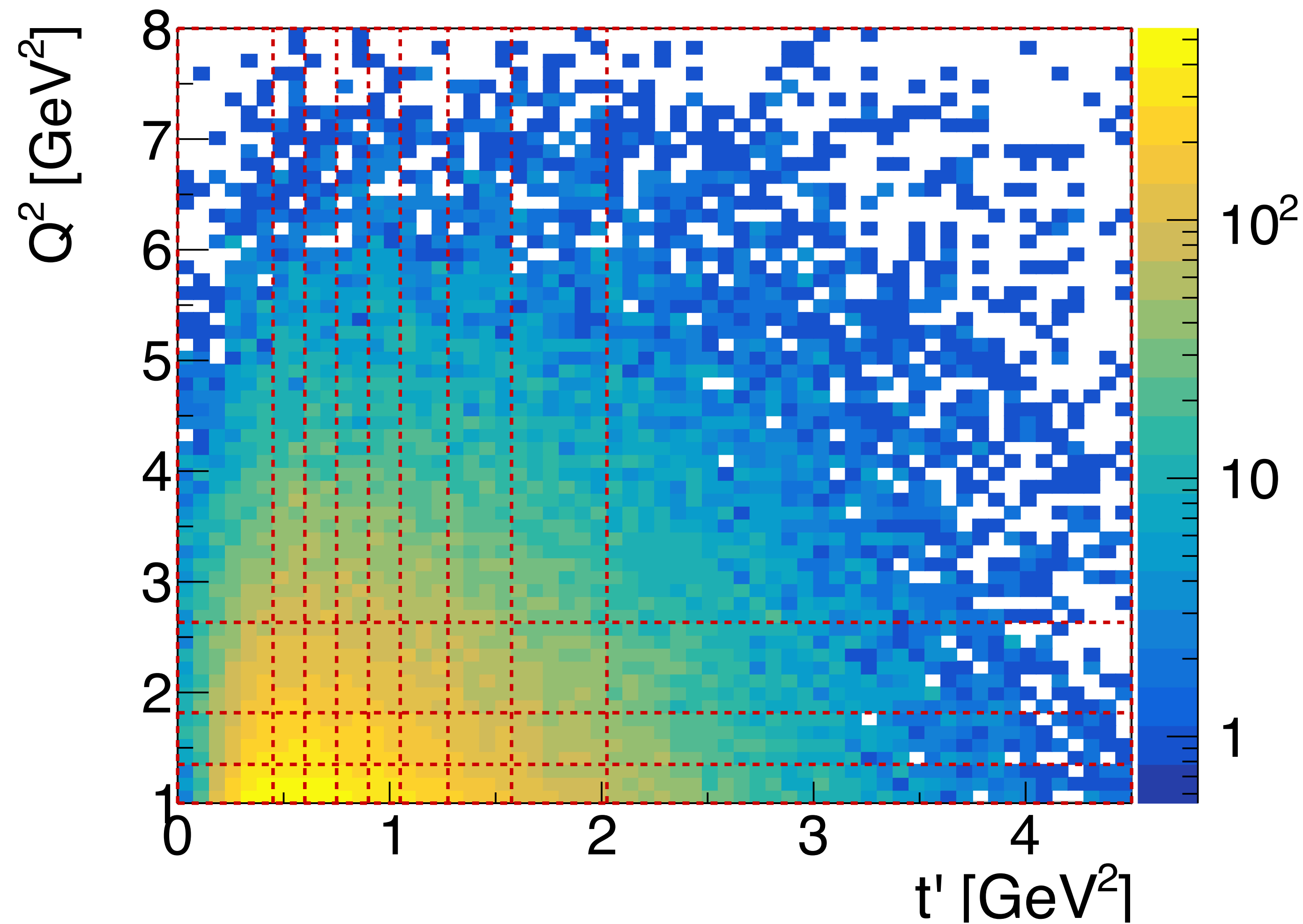


Out



Extraction of cross-section

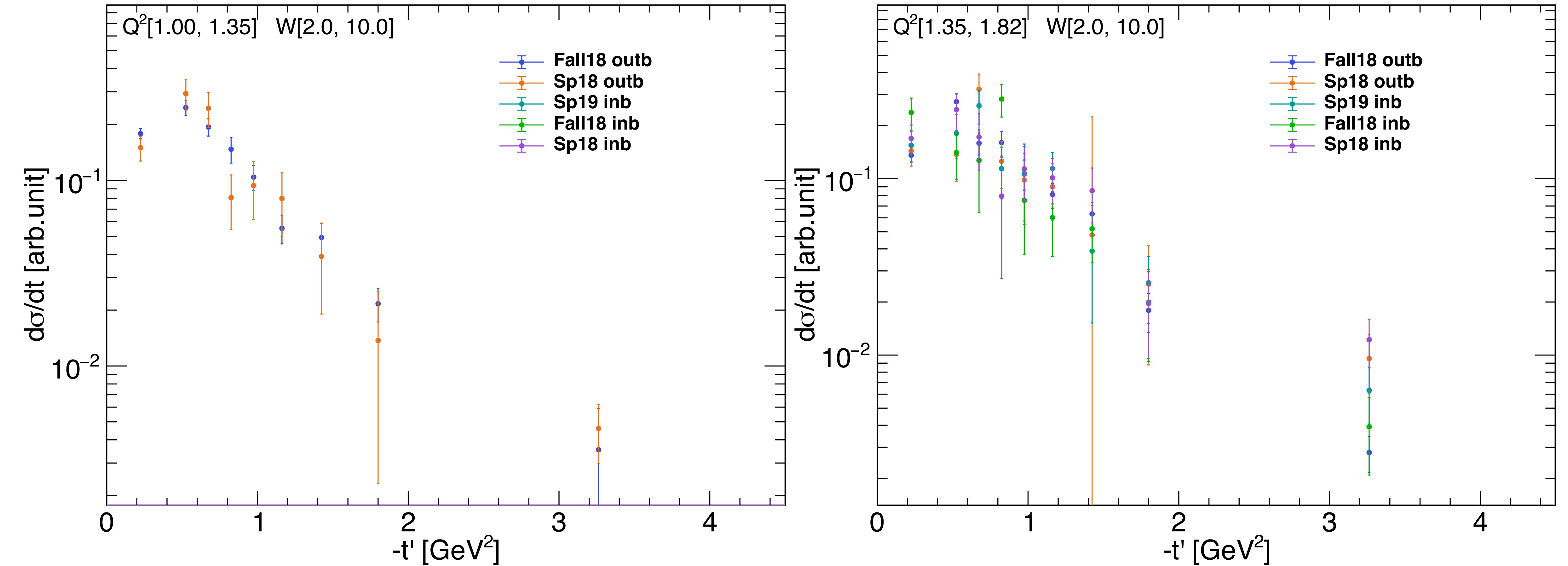
- Divide the sample total sample with equal statistics in each Q^2 and t' bin
- Currently bins 4 Q^2 and 8 t'
- In each $-t'$ bin used a $InvM_{K^+K^-}$ distribution to extract the counts of ϕ



t' bin edge (GeV ²)	[0,0.45]	[0.45, .6]	[.6,.75]	[.75,.90]	[.90,1.05]	[1.05,1.27]	[1.27,2.02]	[2.2,4.5]
Q ² bin edge (GeV ²)	[1.0,1.35]	[1.35,1.81]	[1.81,2.63]	[2.63,8.0]				

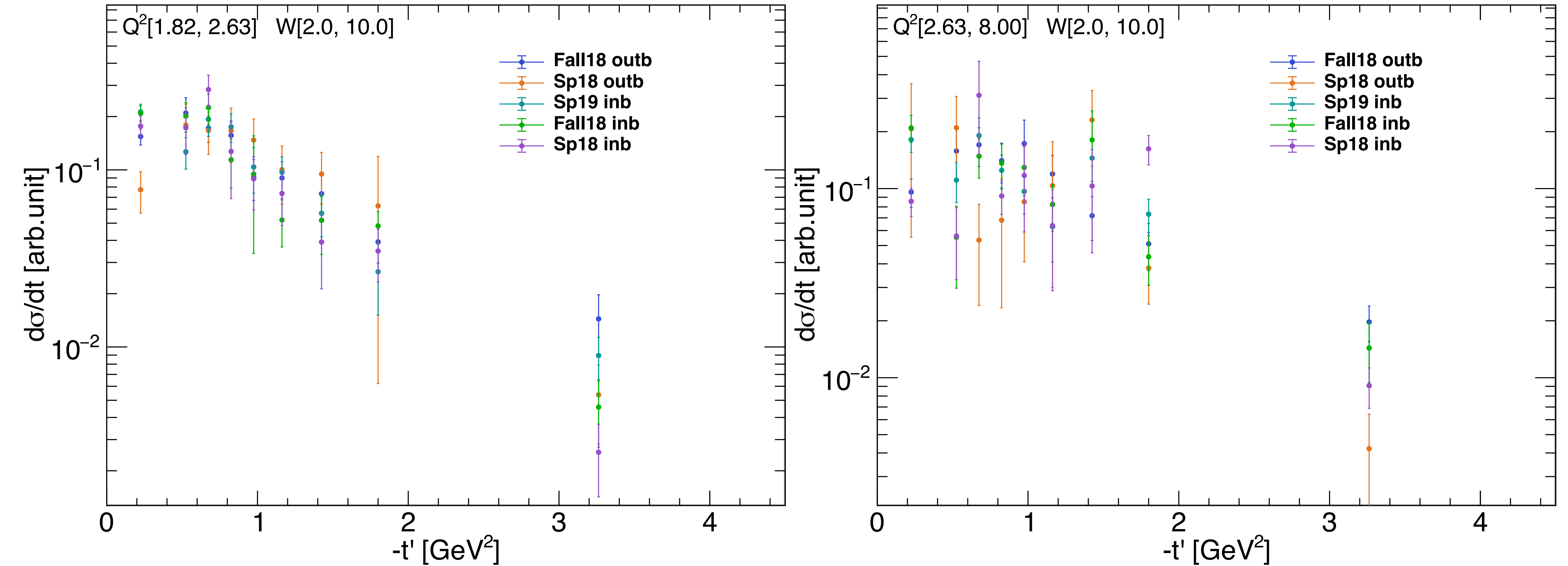
Normalized (total counts) yield from all periods

- In bins of Q^2 vs $-t$



Normalized (to integral) yield from all periods

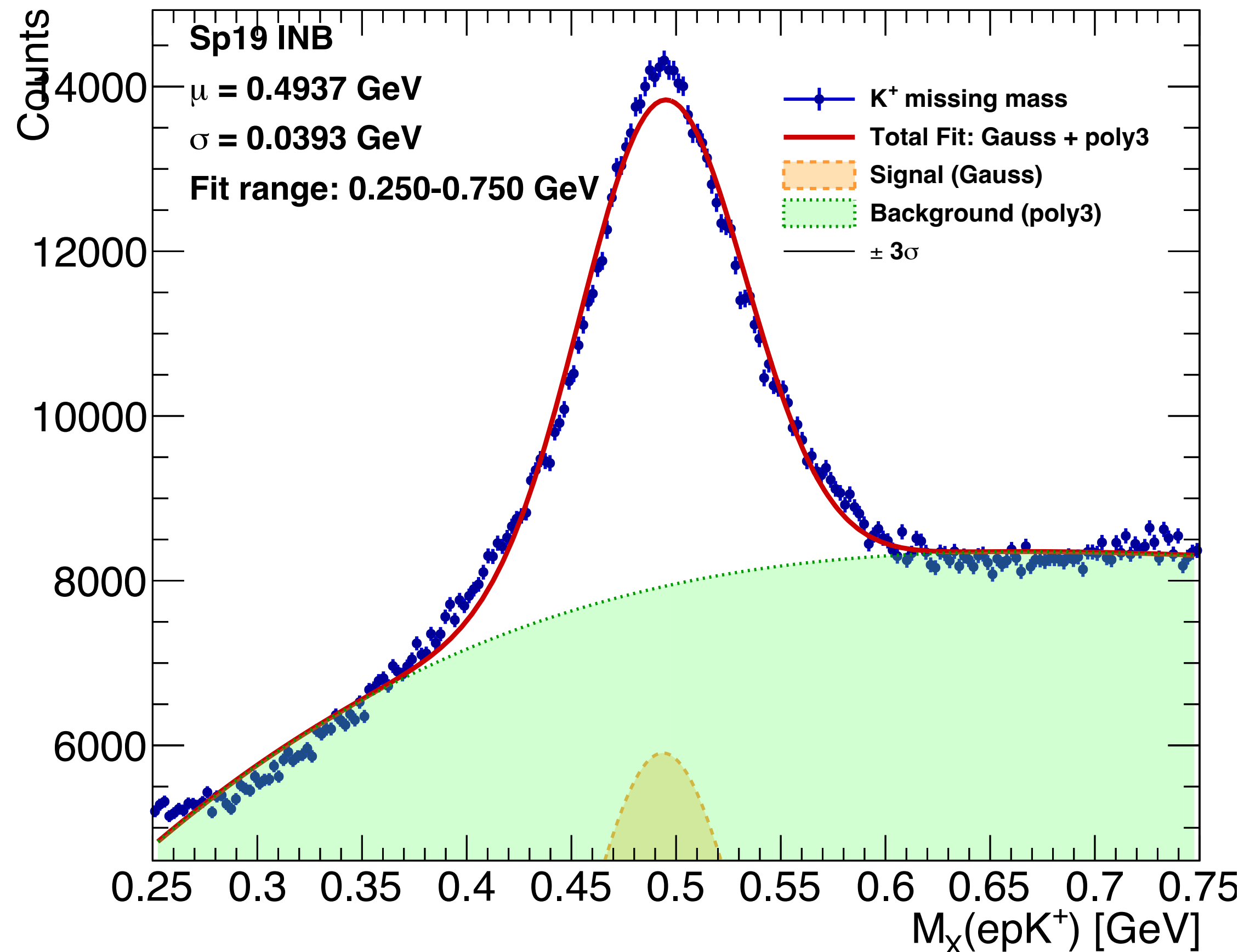
- In bins of Q^2 vs $-t$



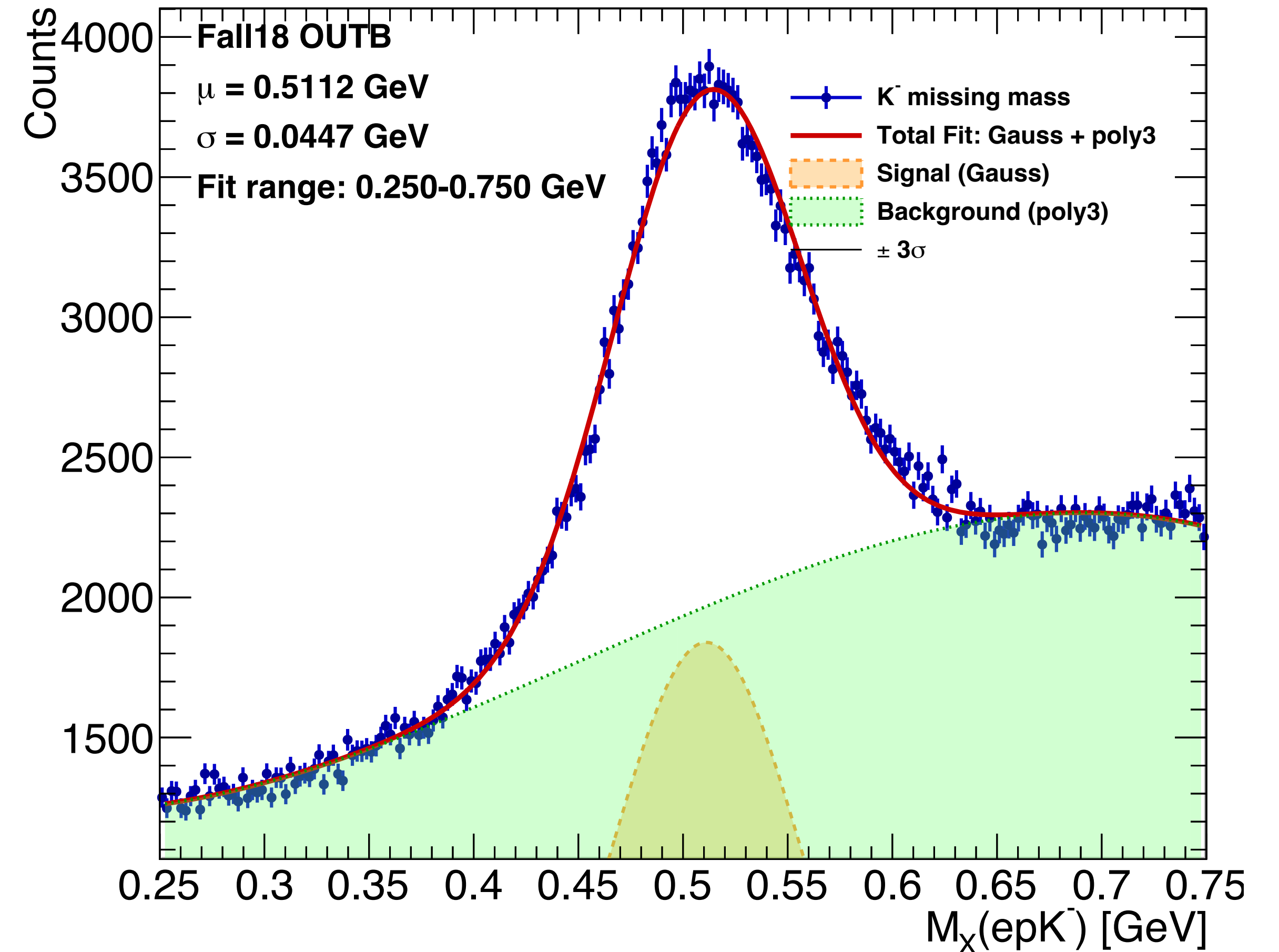
Missing mass analysis

- Reconstruct the missing K^- peak at ~ 493 MeV: $\pm 3\sigma$ cut around the the peak

K^- peak for $ep \rightarrow epK^+(K^-)$



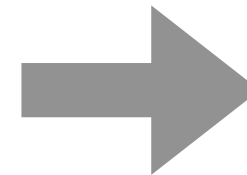
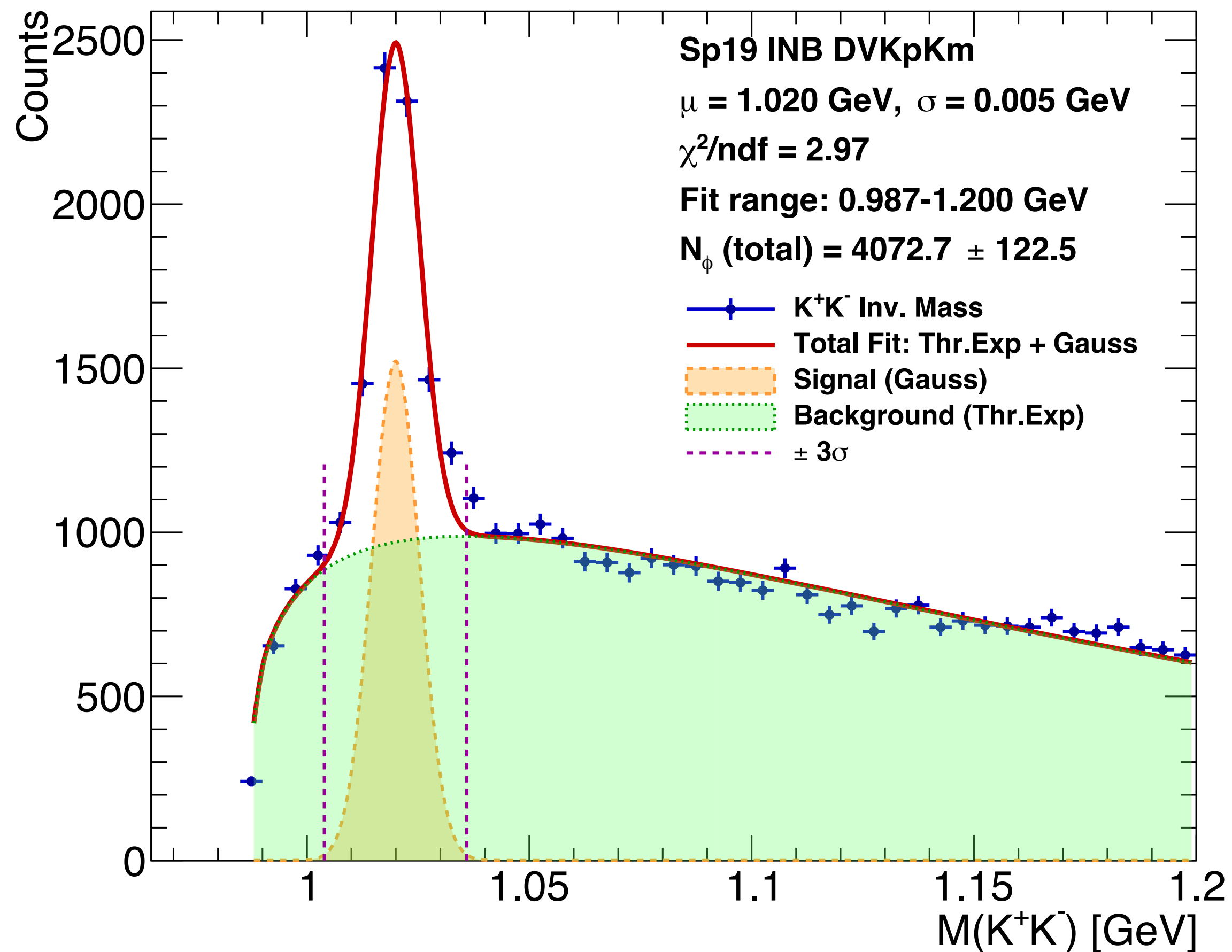
K^+ peak for $ep \rightarrow epK^-(K^+)$



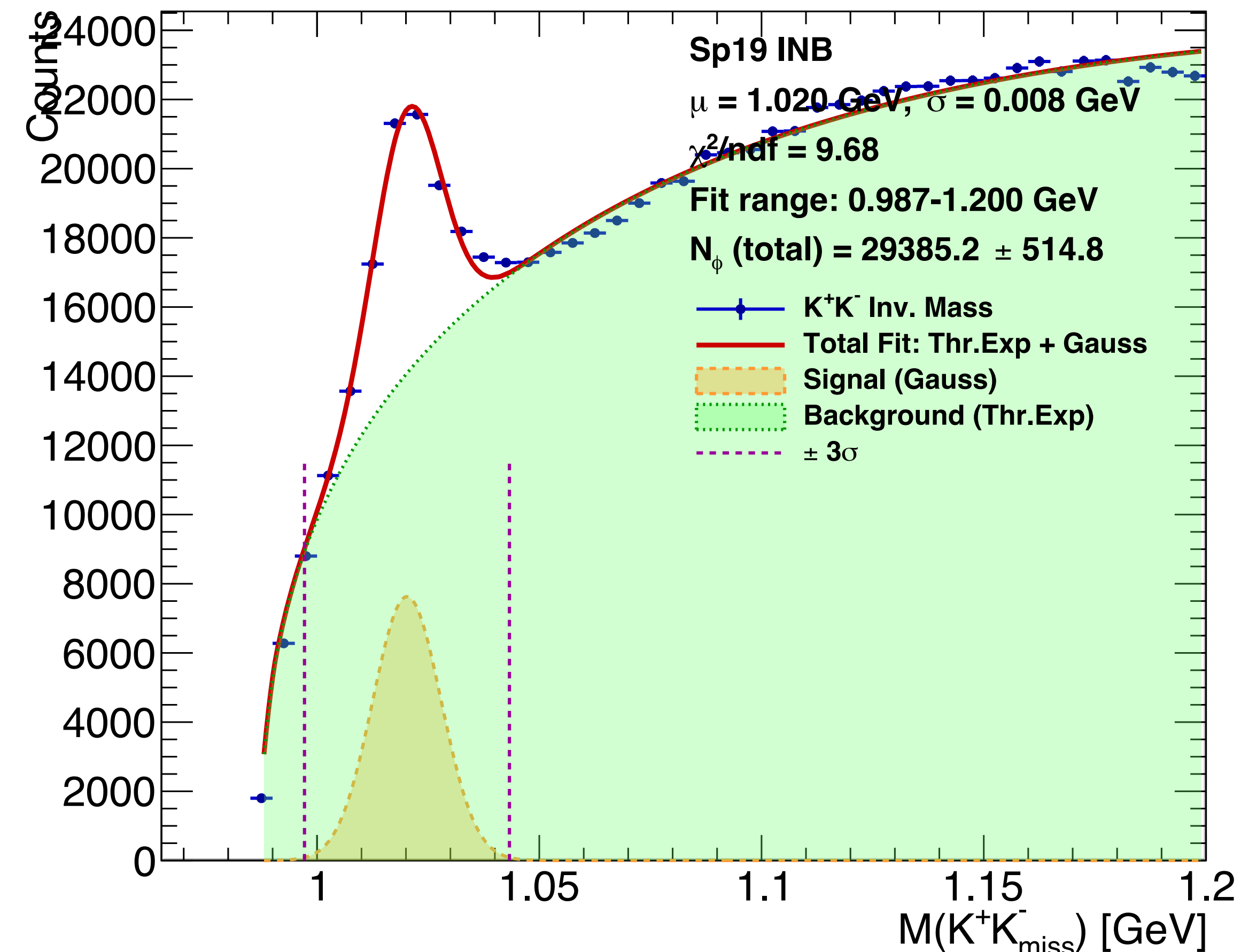
Missing mass analysis (sp19, Inb) $ep \rightarrow epK^+(K^-)$

- Reconstructed ϕ using the missing K candidate peak at ~ 1.019 GeV: $\pm 3\sigma$ cut around the the peak

$ep \rightarrow epK^+K^-$: 4K candidates, resolution: 4.7 MeV

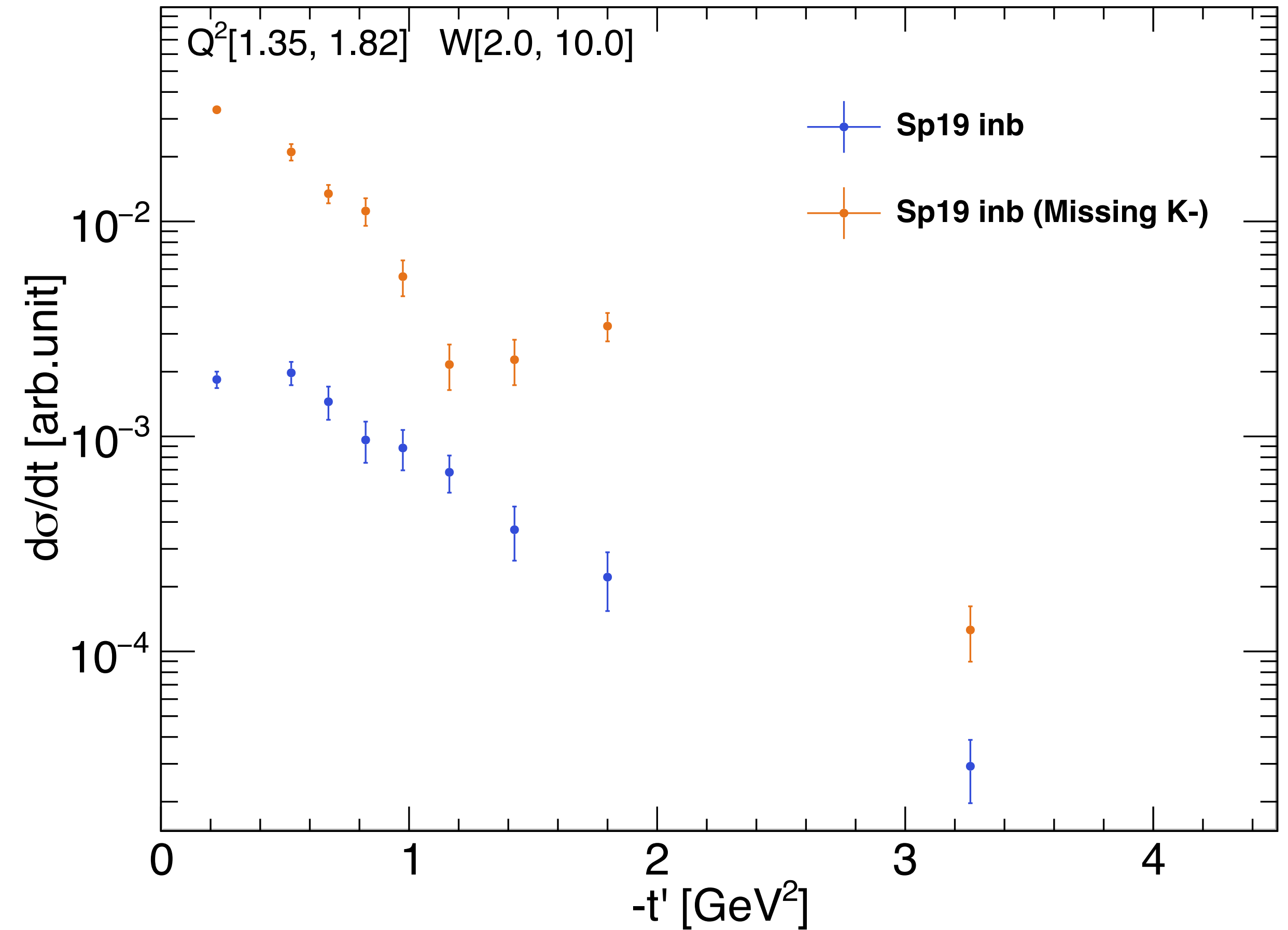
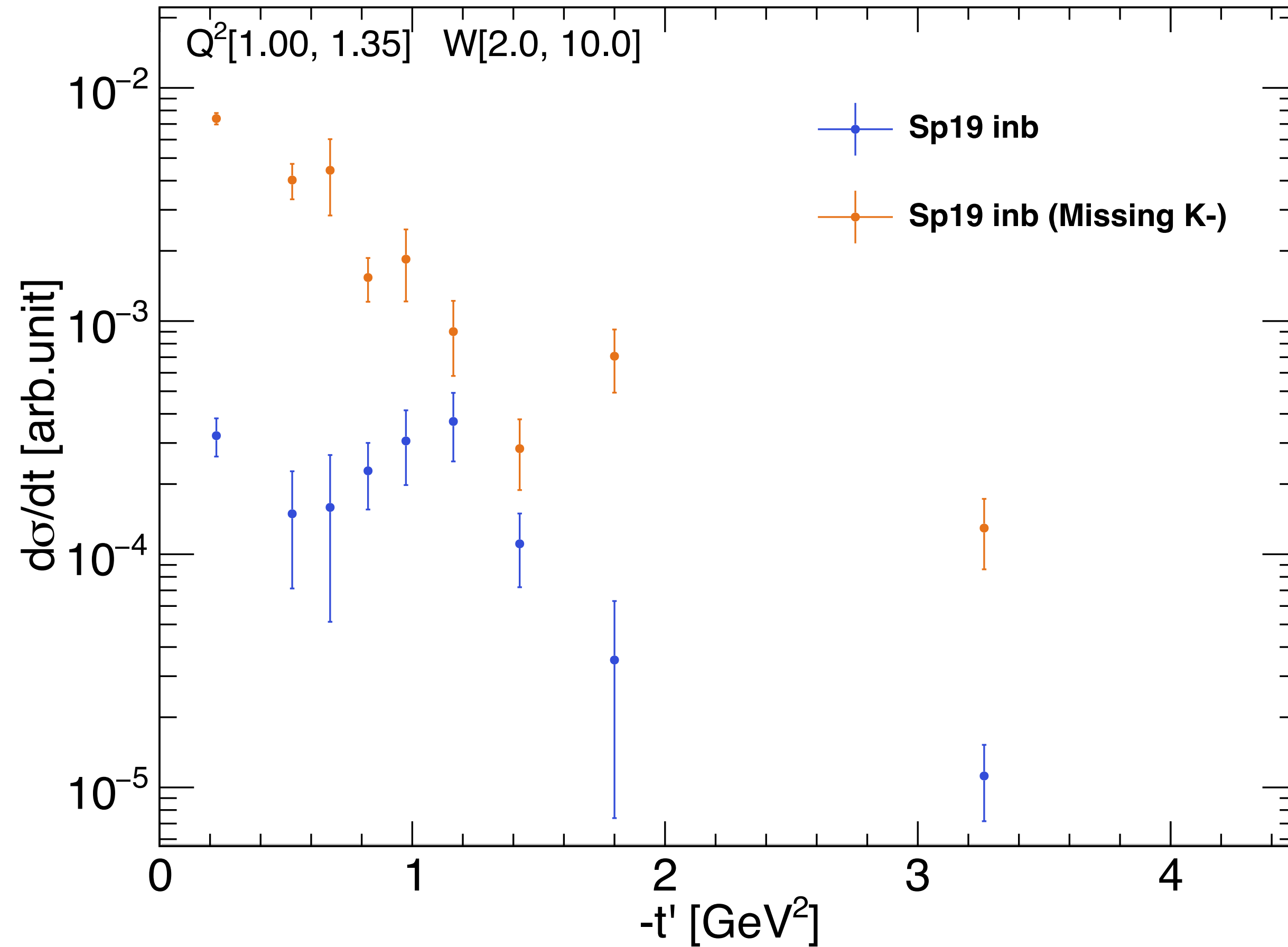


$ep \rightarrow epK^+(K^-)$: 30K candidates, resolution: 7.8 MeV



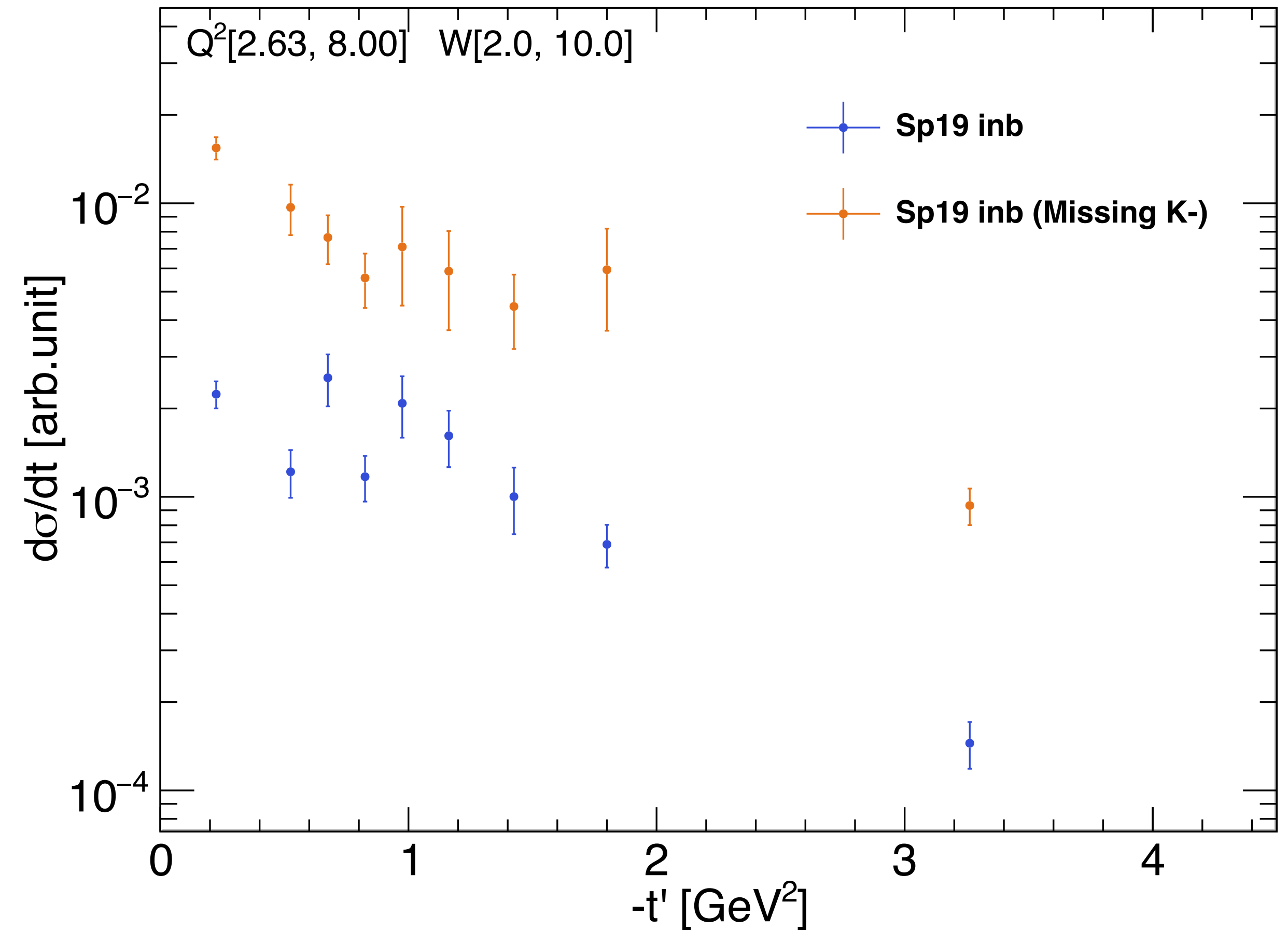
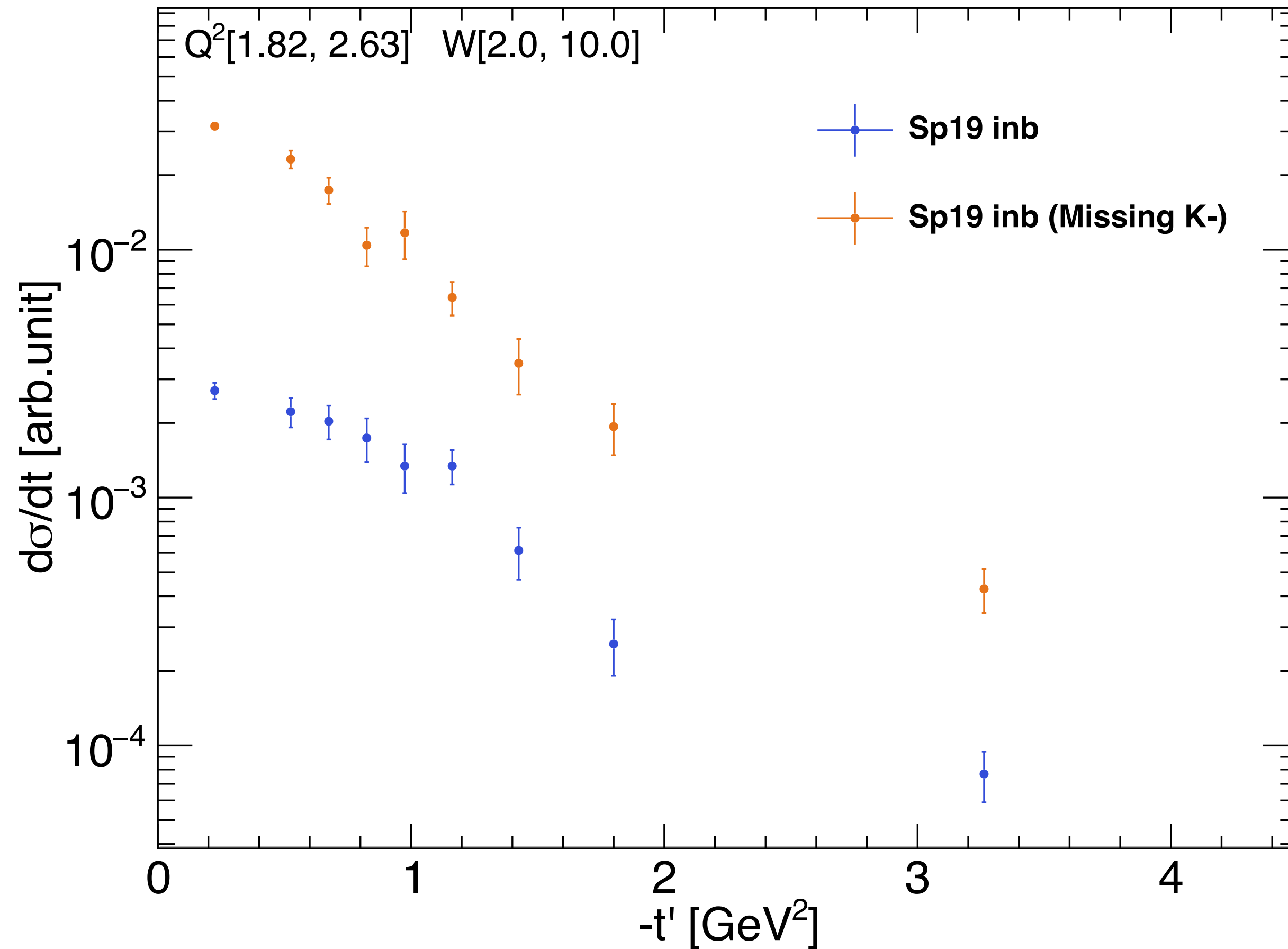
Cross-section (raw)

- Kaon reconstruction efficiency effect visible (**no efficiency and acceptance corrections applied!**)
- Better statistics at smaller $-t'$



Cross-section (raw)

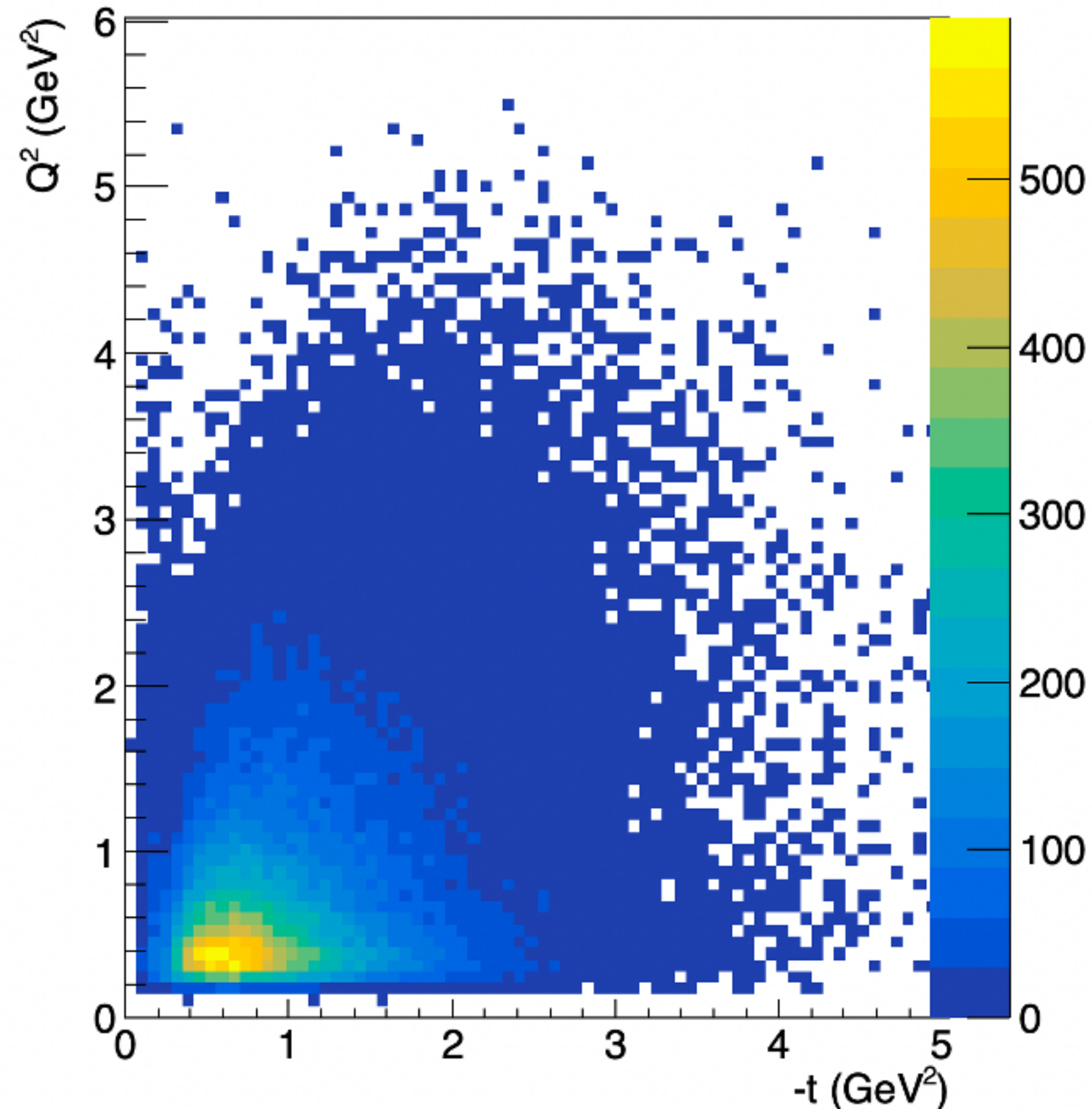
- Kaon reconstruction efficiency effect visible (**no efficiency and acceptance corrections applied!**)
- Better statistics at smaller $-t'$



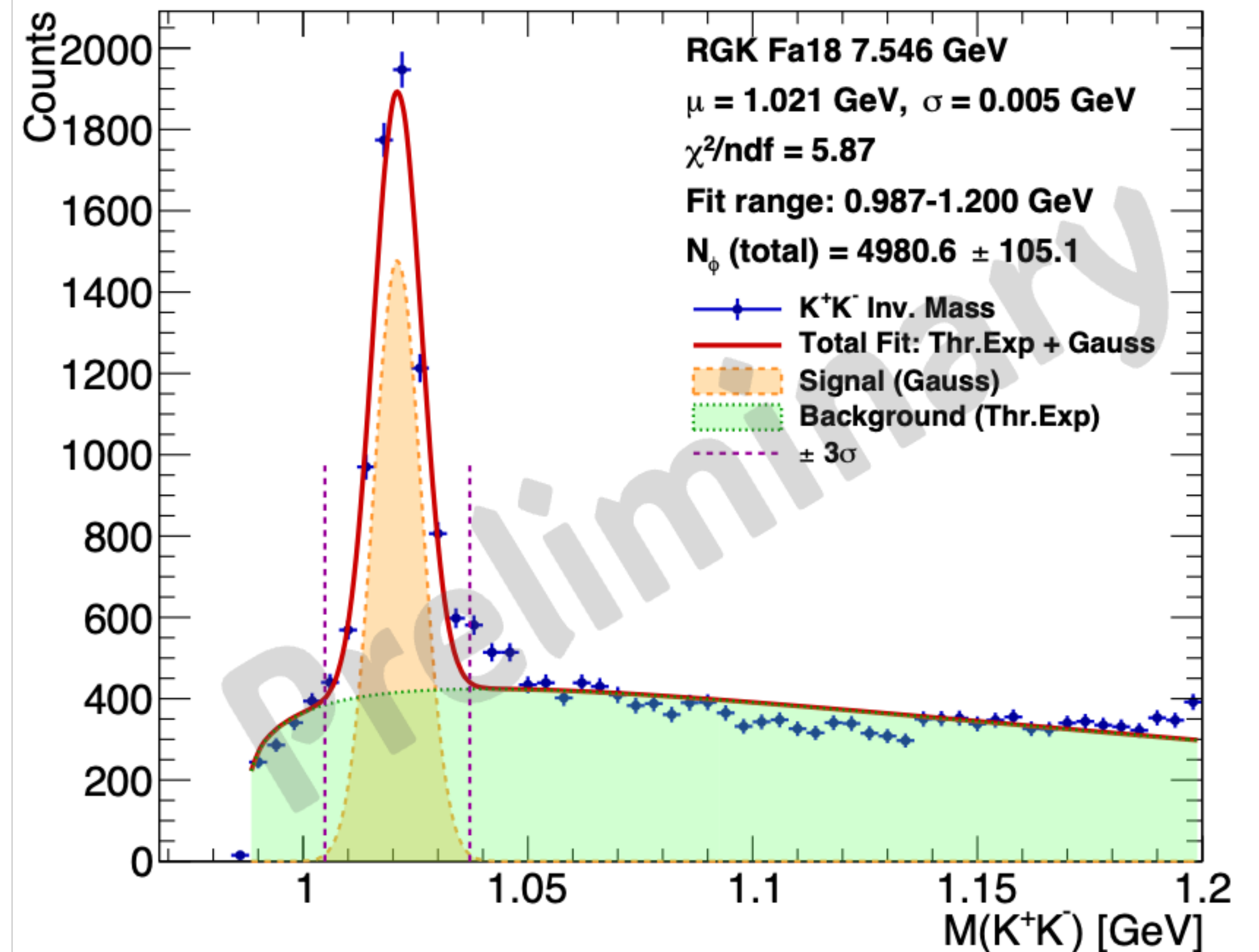
Sneak peak: RGK Fall 2018 Outbending (pass2) (K. Neupane)

- Charge Decay Channel : $ep \rightarrow e'p'\phi \rightarrow e'p'K^+K^-$ (Exclusive Topology)
- Exp. data:** RGK, beam energy 7.546 GeV ~ 4980 ϕ candidates with full exclusive topology (135 runs)

Q^2 vs $-t$ Distribution

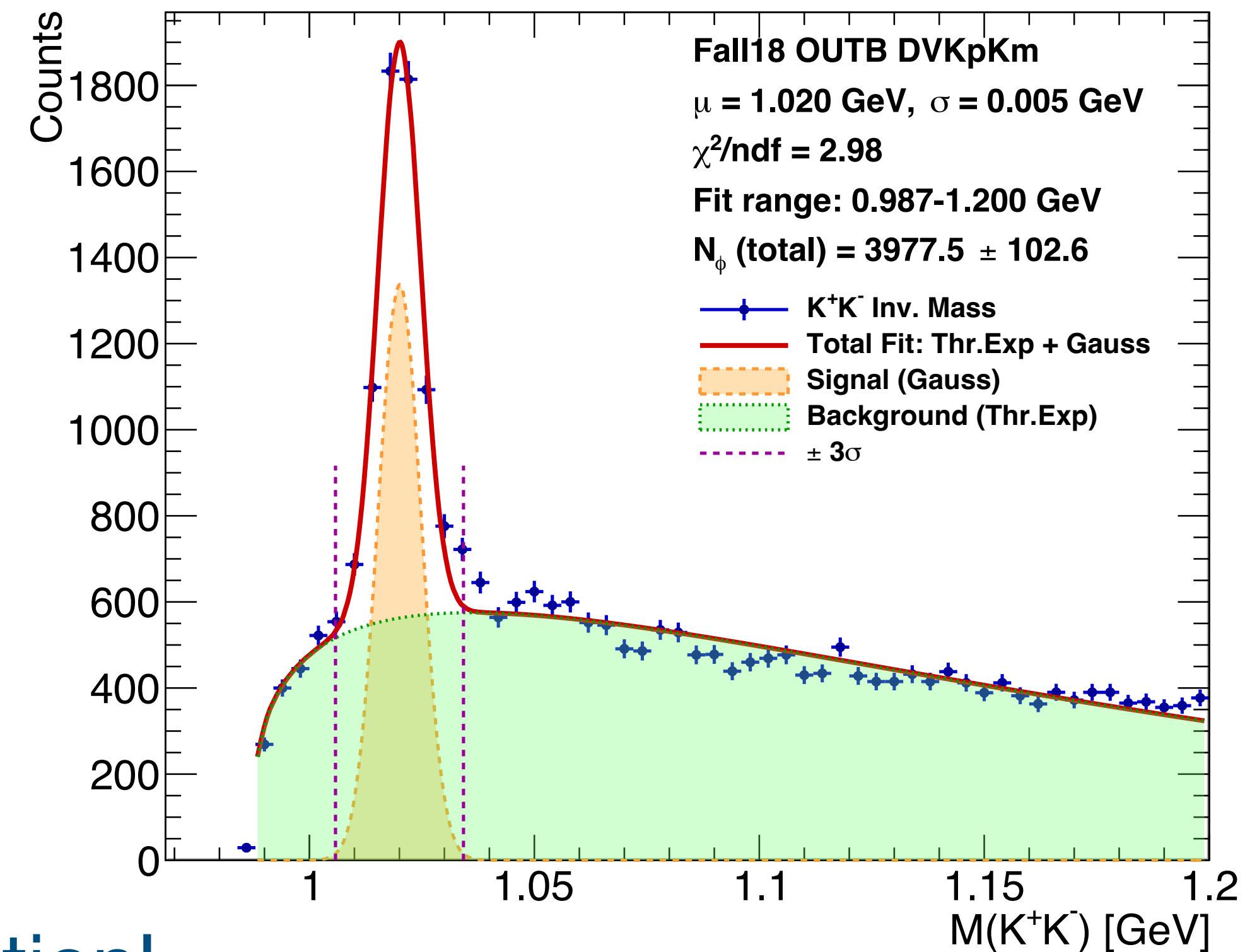


ϕ - Inv mass Distribution



Summary

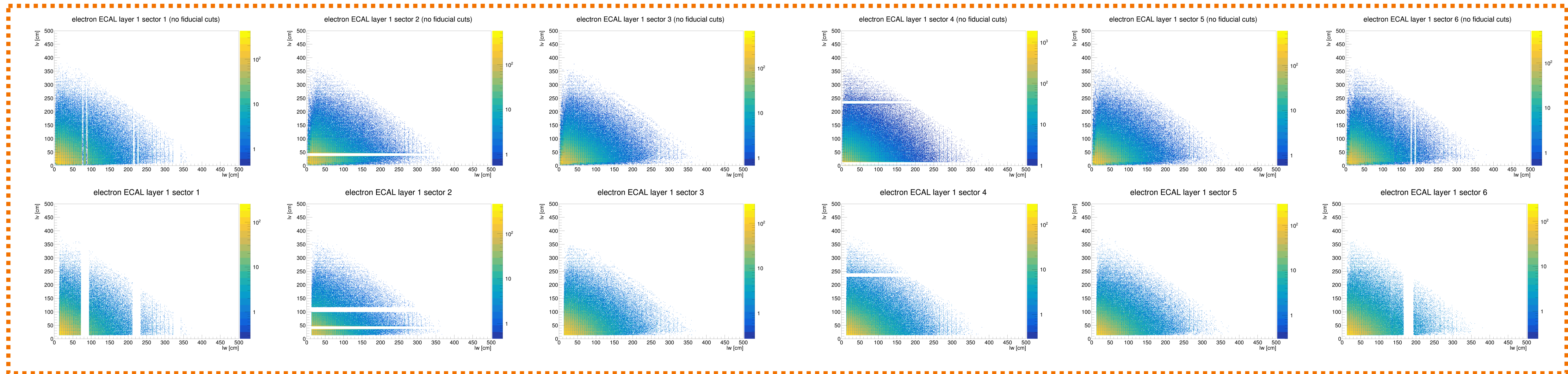
- So far..
 - First look at the exclusive ϕ meson production combining all data set from RGA 10.6 GeV
 - Finalized the fiducial cuts, SF cuts, as well momentum correction for proton
 - Established missing mass analysis
 - QADB for all periods for spring 19, fall 18, and spring 18 outbending
- Long journey ahead...
 - Development of reliable **event generator**
 - Establish **Kaon pid** at large momentum
 - Acceptance and efficiency corrections!
 - **Charge neutral** channel as well data from RGK!



Thank you for your attention!

Fiducial volume for electron and hadrons

- FT, **FD**, and CVT regions with possible reconstruction inefficiencies are removed.



Excluded PCAL cuts for electron

Edge cuts (all sectors): lw: 0.0–13.5, lv: 0.0–13.5cm

Sector 1: lw: 72–94.5cm, 211.5–234cm

Sector 2: lv: 99–117.5cm

Sector 3: lv: 346.5–378cm

Sector 4: lv: 0–13.5cm, 229.5–243cm

Sector 6: lw: 166.5–193.5cm

Similarly for EC_{in}

Sector 1 lv: 67.5cm — 94.5cm

Sector 4 lw: 0.0cm — 23.5cm

Sector 5 lv: 0.0cm — 23.5cm

Sector 6 lv: 0.0cm — 23.5cm

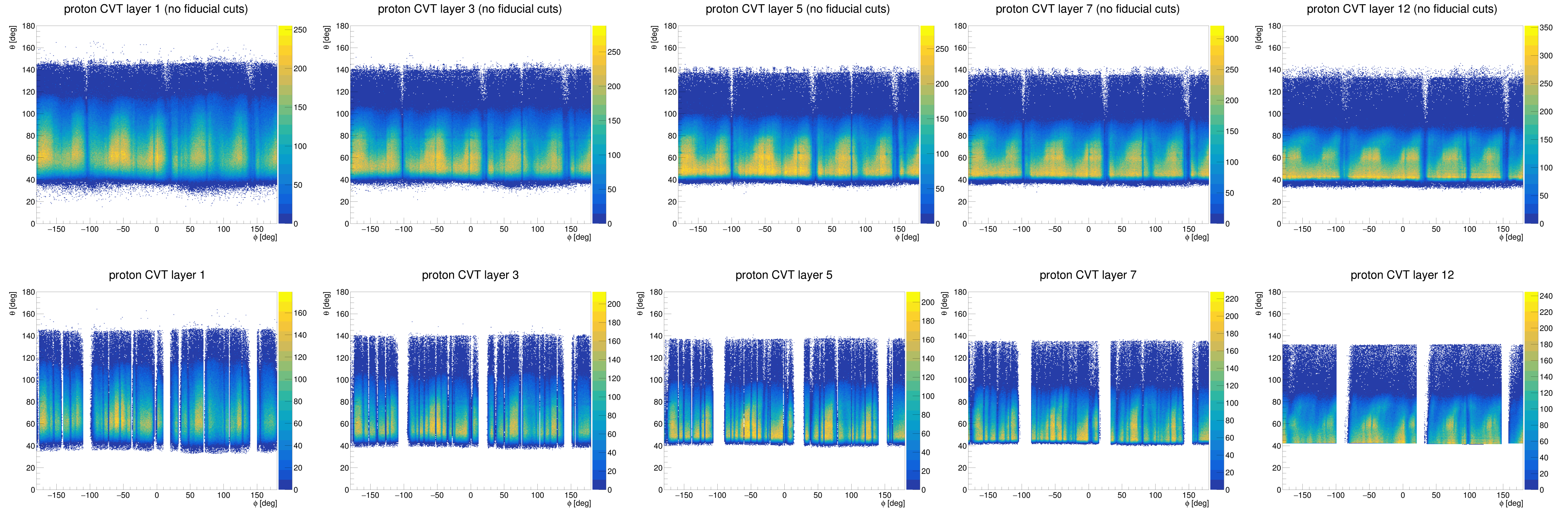
Similarly for EC_{out}

Sector 1 lv: 0.0cm → 40.5cm

Sector 5 lw: 193.5cm → 216.0cm

Fiducial volume for electron and hadrons

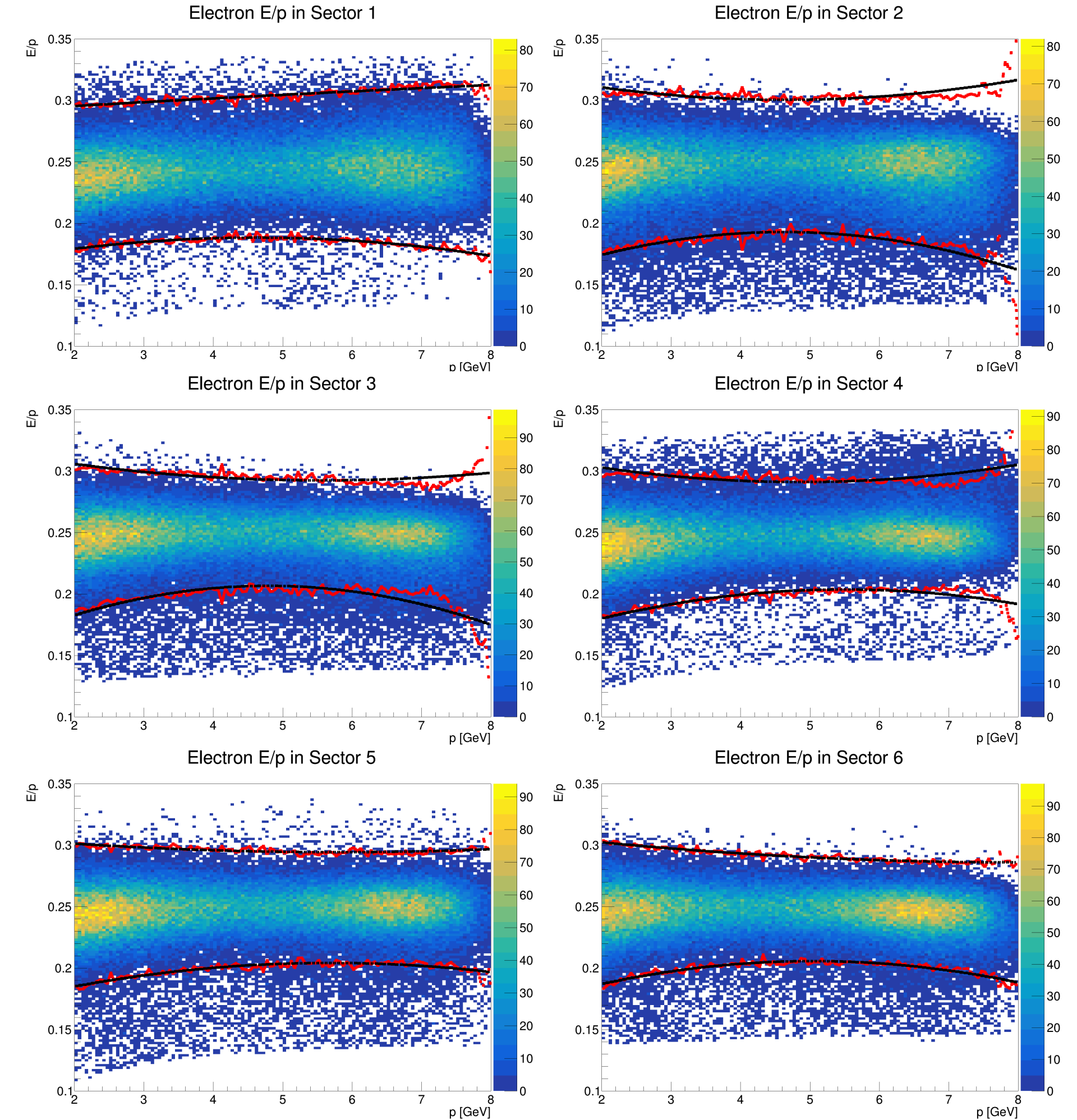
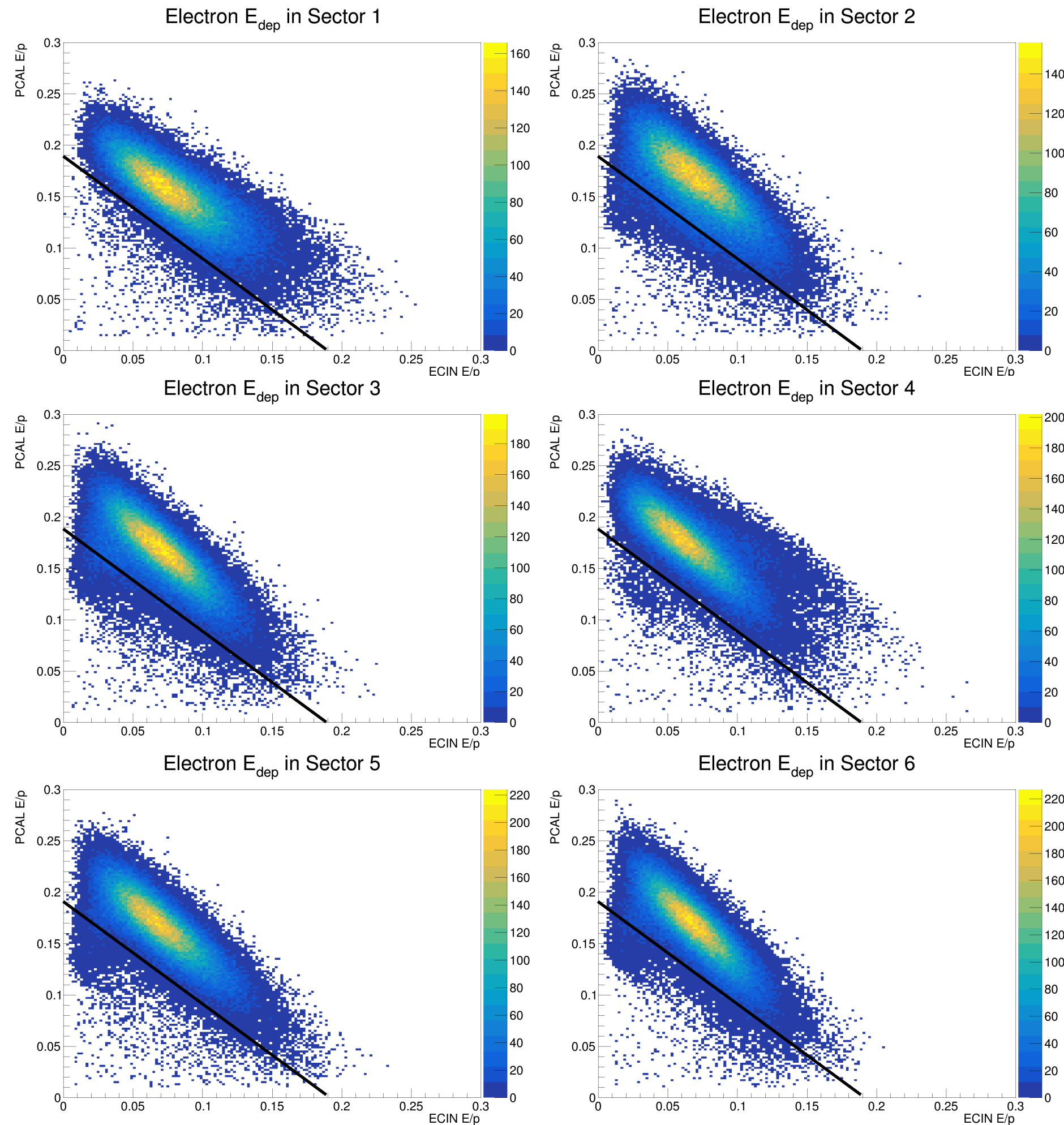
- FT, FD, and **CVT** regions with possible reconstruction inefficiencies are removed.



- CVT regions for χ^2/NDF is non-flat below the edge variable **Fiducial cuts for the layer 1, 3, 5, 7, and 12)**
- Sampling fraction cuts for electron, and energy loss corrections for proton are applied.**
- QADB cuts to select the good run/events**

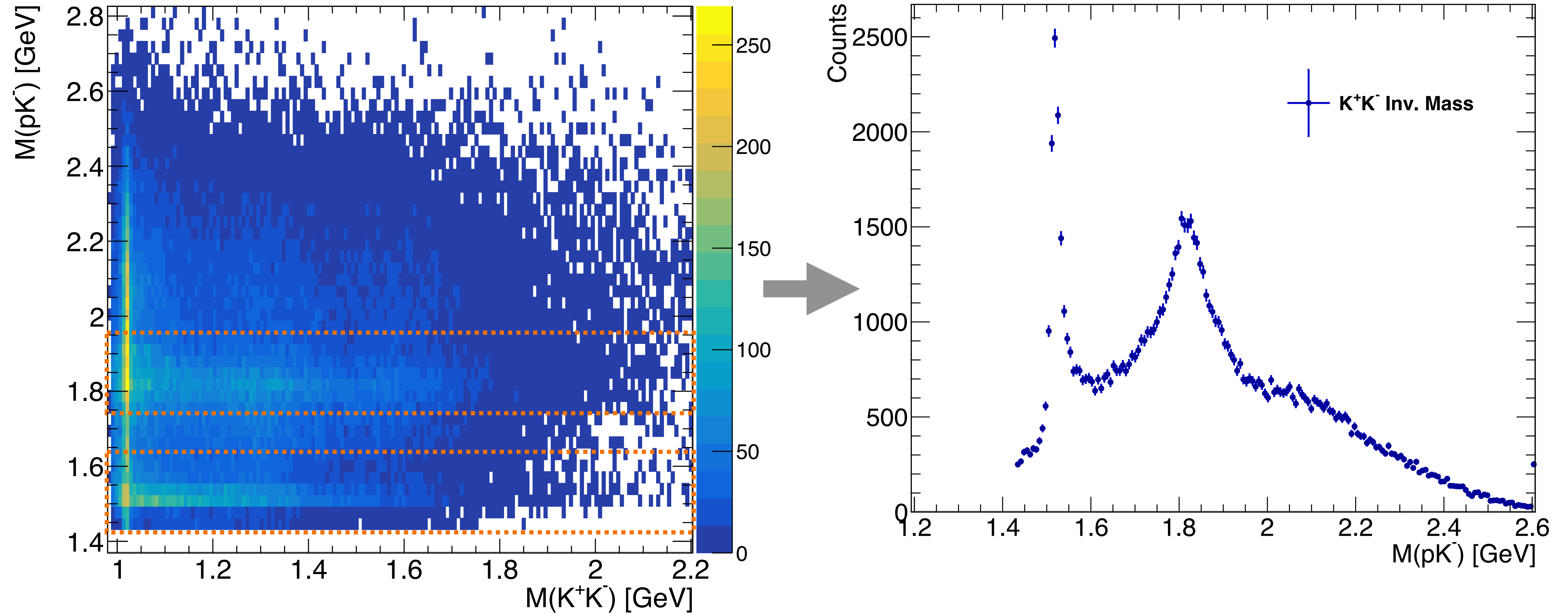
Electron sampling fraction (spring 2018 inb)

- To reduce the contamination in the electron sample we enforce ± 3 sigma cuts on E/P distributions and PCAL E/p vs ECin E/p diagonals cuts to separate possible pi- contaminations



Background under the signal

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



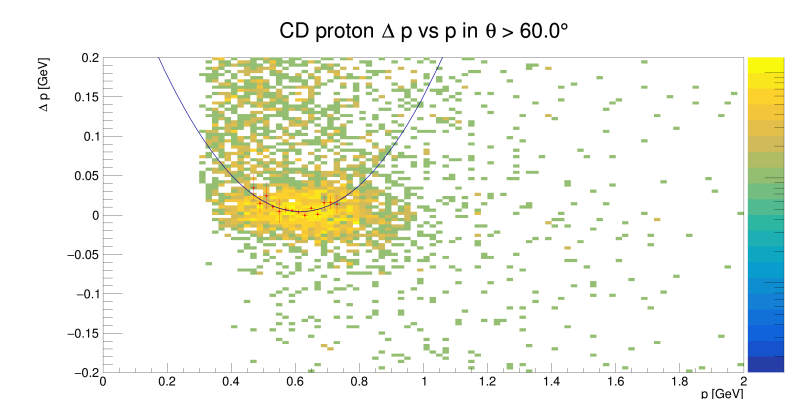
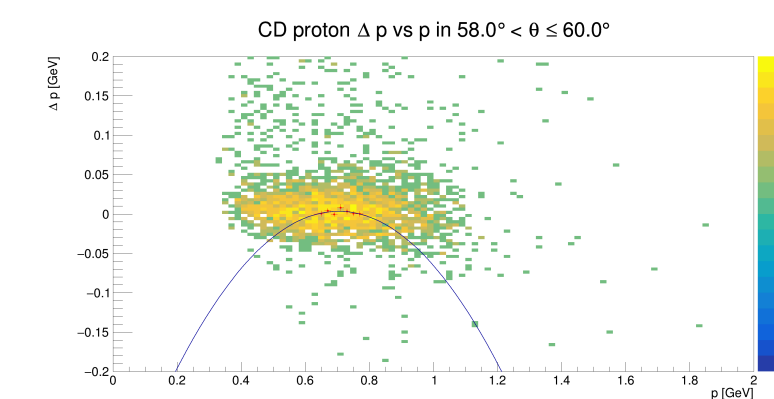
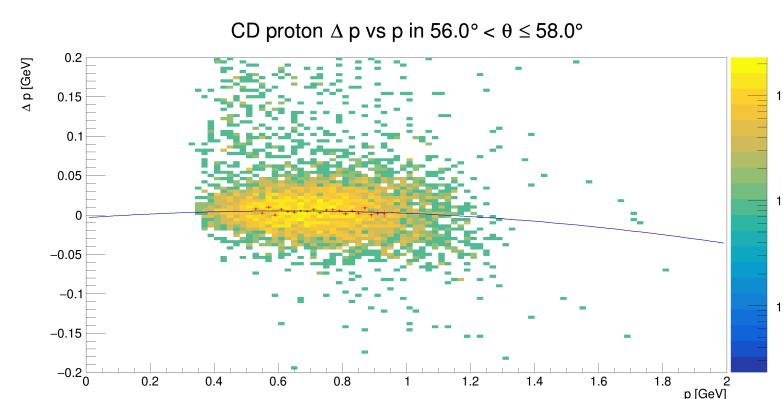
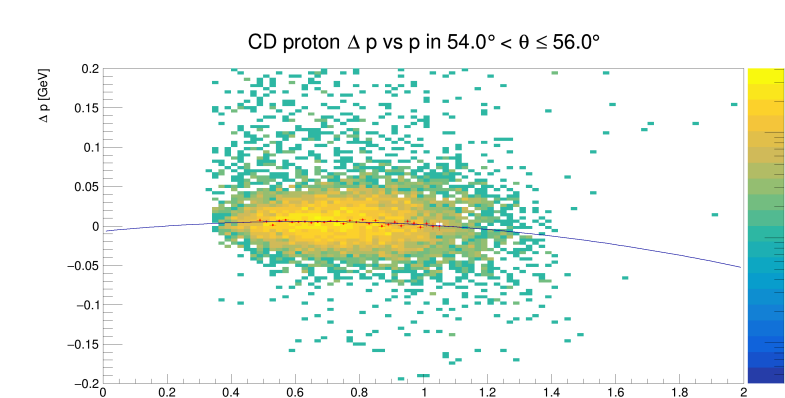
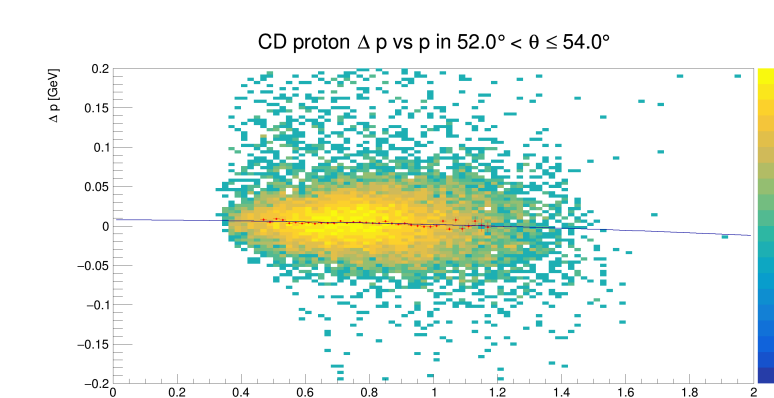
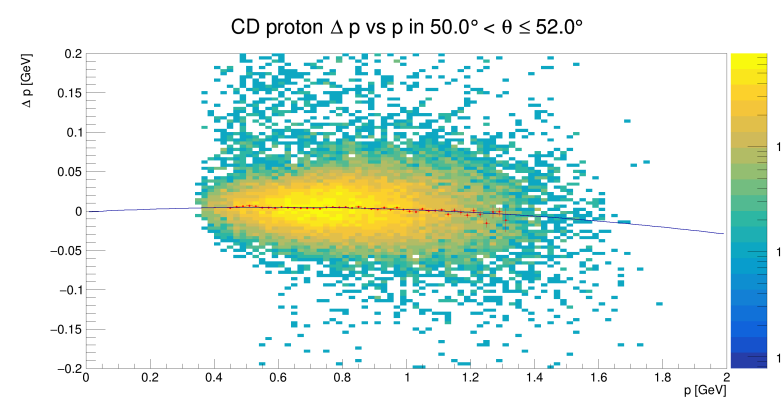
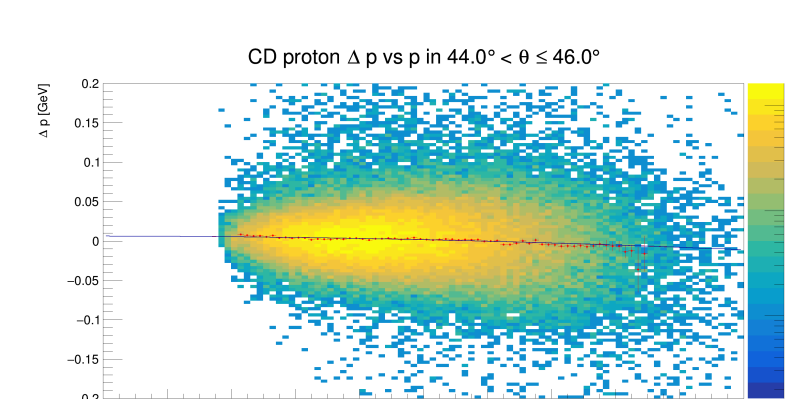
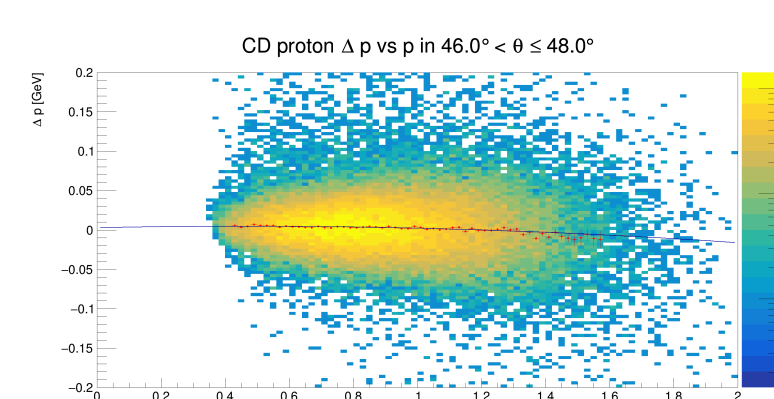
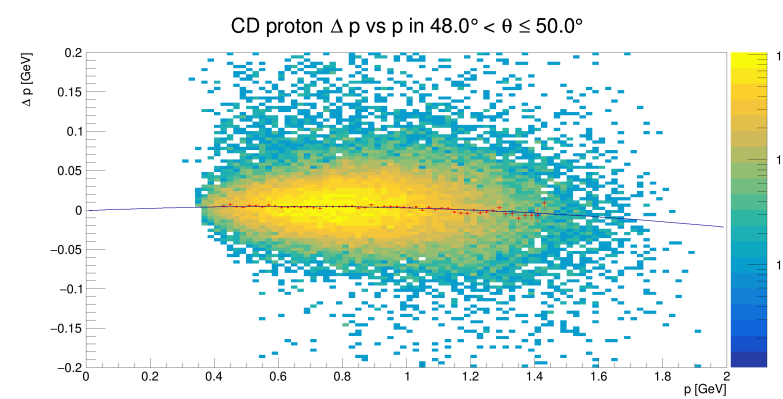
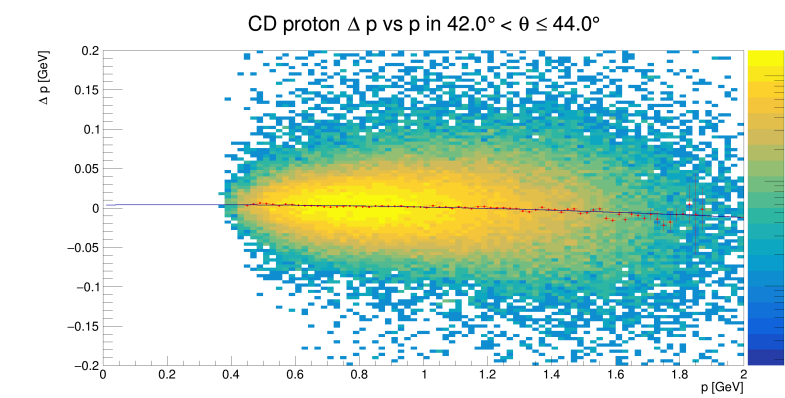
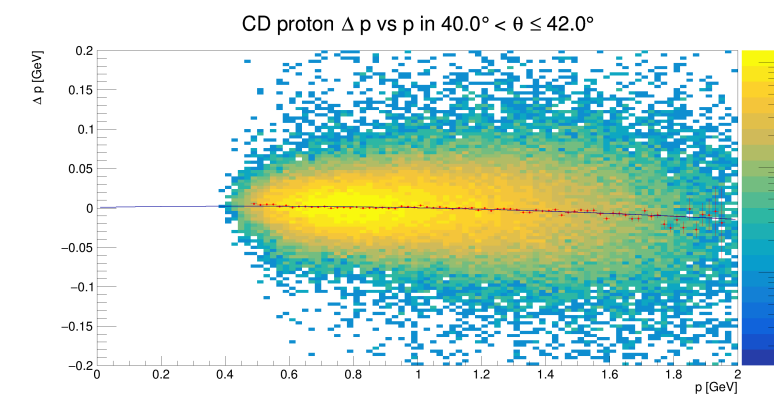
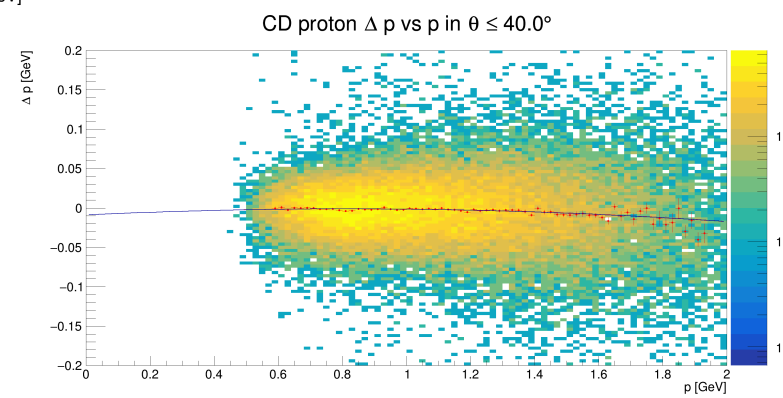
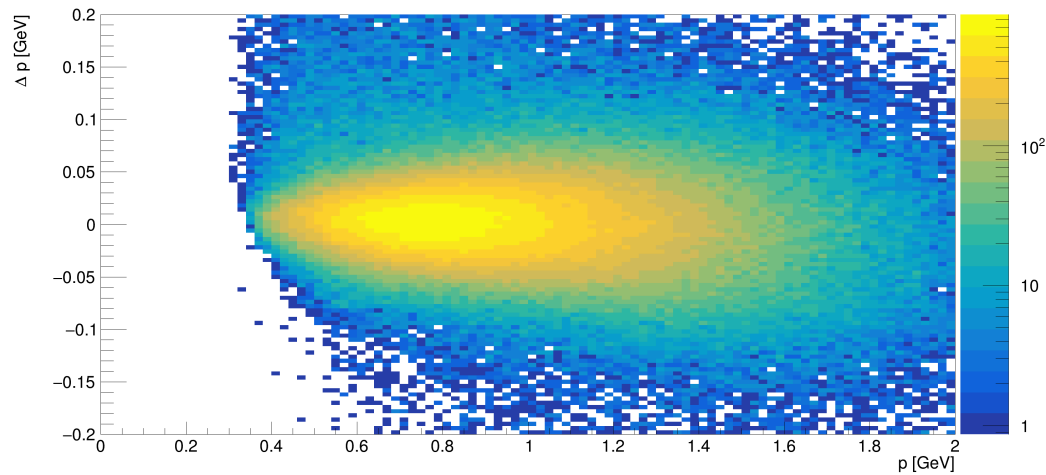
Energy loss corrections RGA (spring 2018 inb)

- Here spring 2018 (Fall 2018, spring 2019 T. Hayward see slides:)

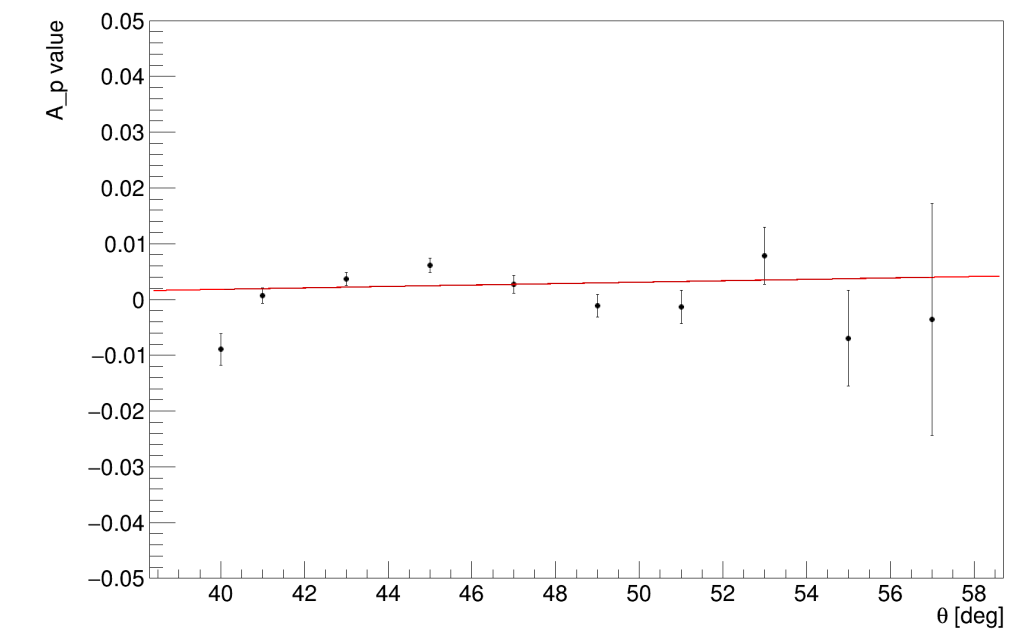
$$\Delta p = A + B \cdot p + C \cdot p^2$$

**CD
Proton**

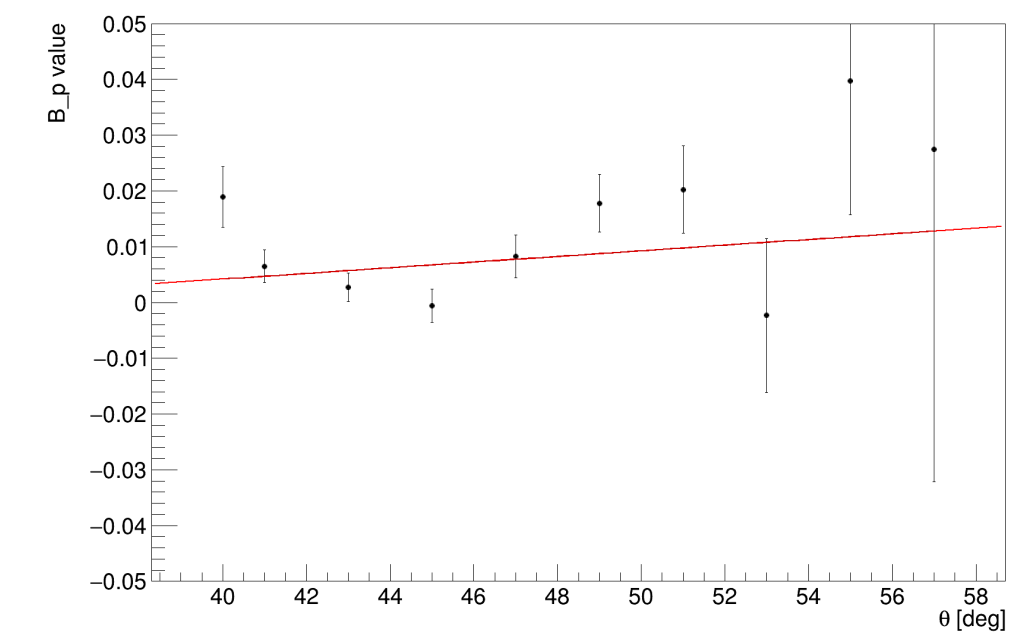
CD proton Δp vs p



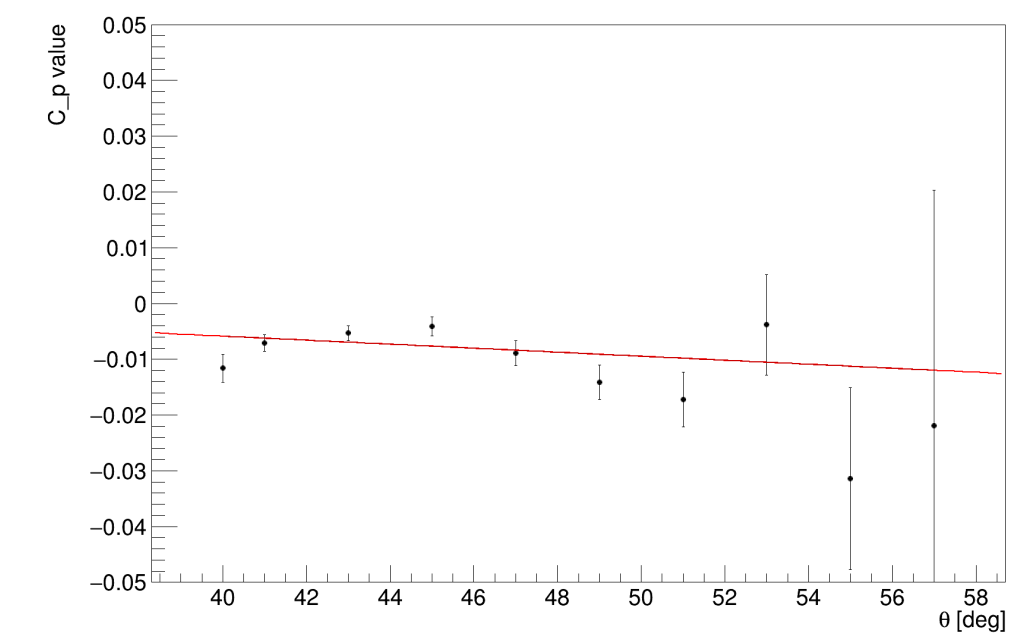
proton_CD: A_p vs θ



proton_CD: B_p vs θ



proton_CD: C_p vs θ

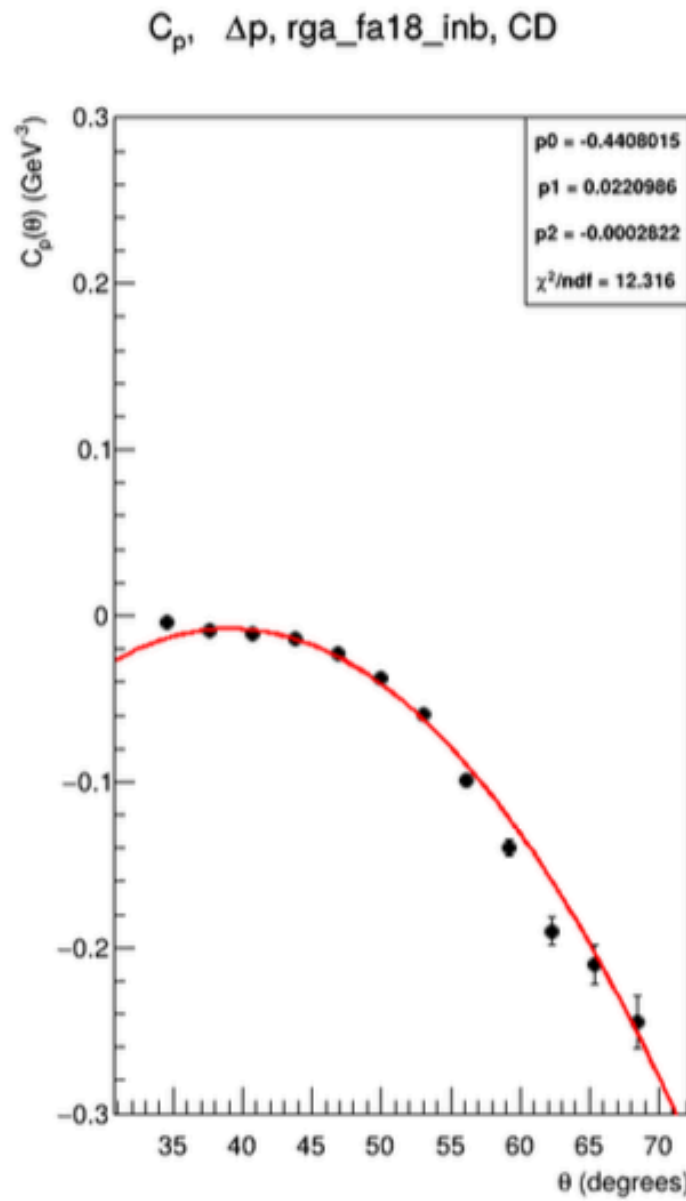
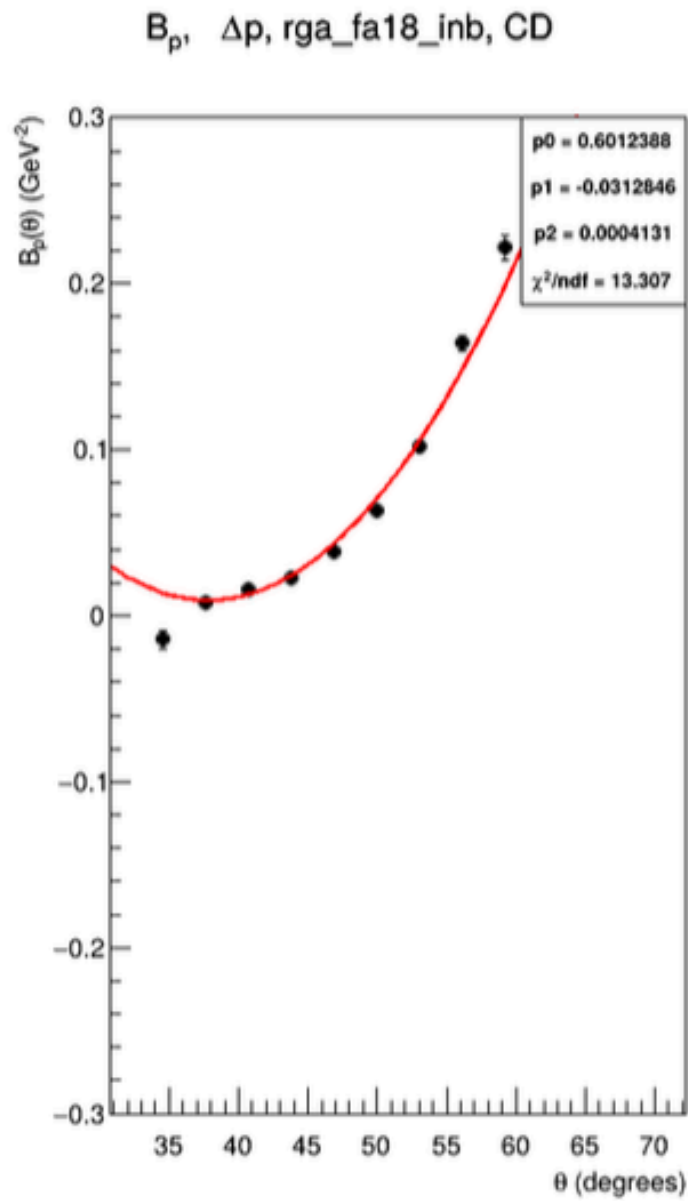
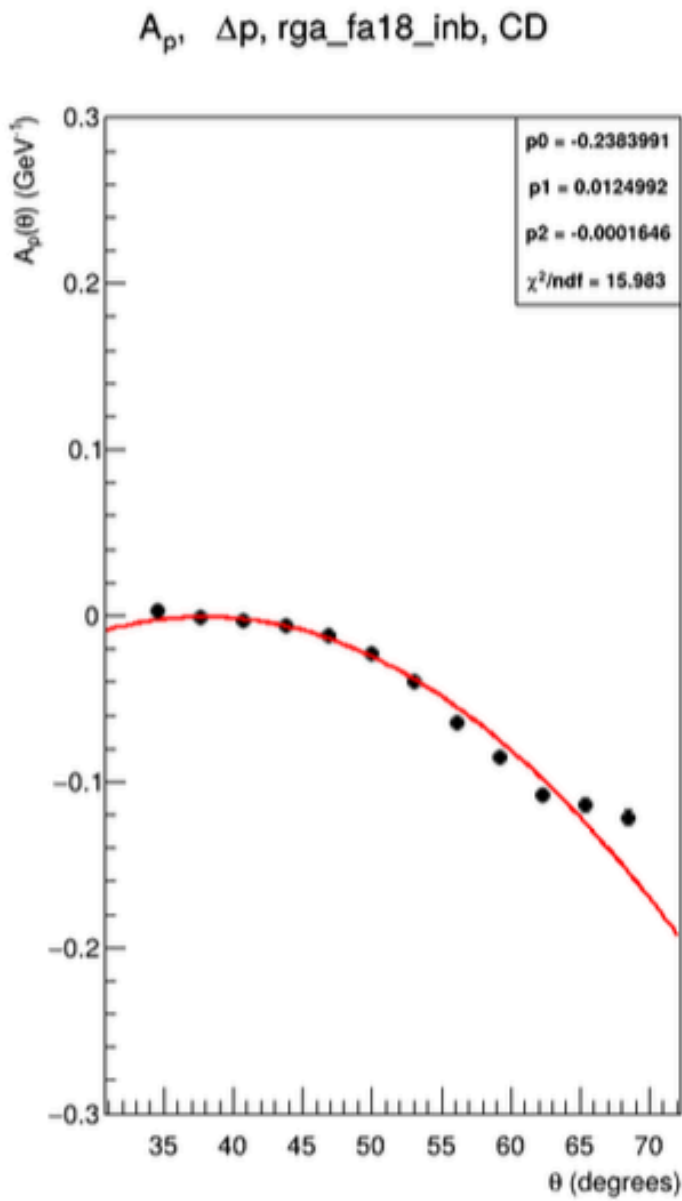
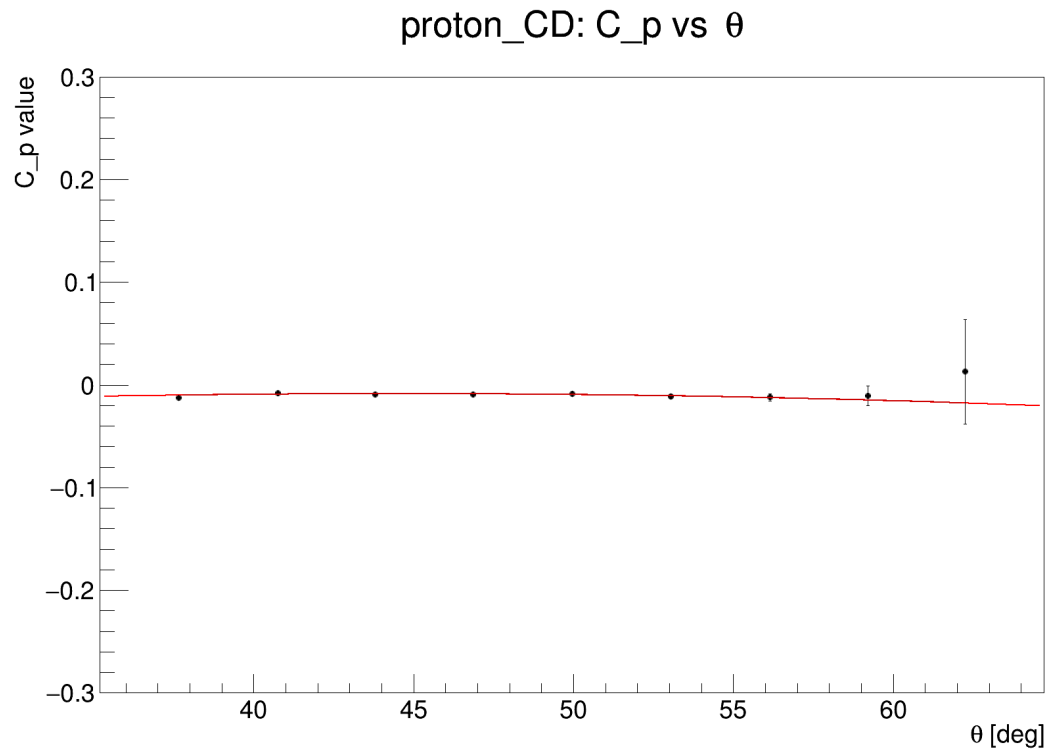
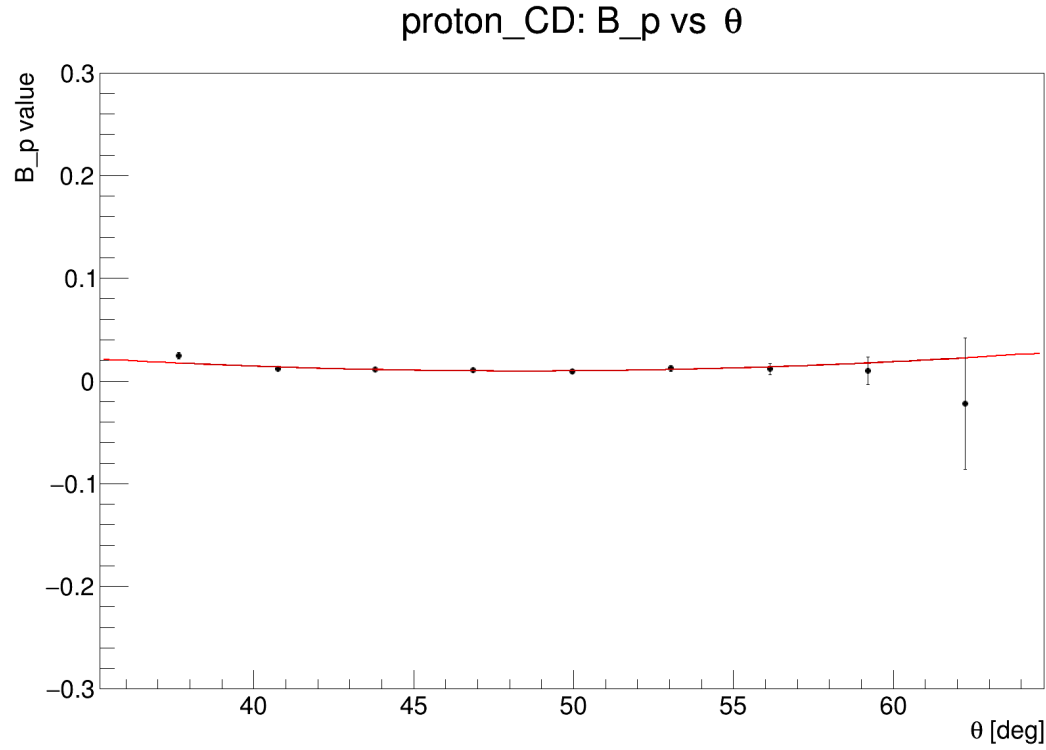
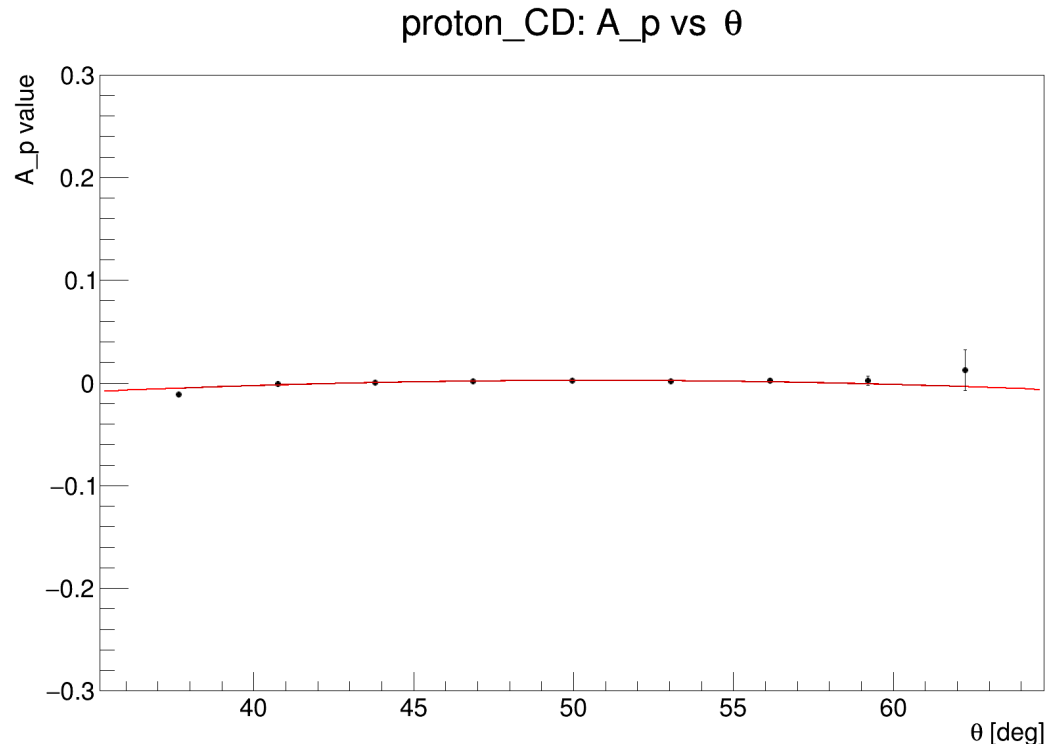


Benchmark: Fall2018_inb proton energy loss correction

CD

From Timothy

$$p \rightarrow p + A_p^{\text{CD}}(\theta) + B_p^{\text{CD}}(\theta)p + C_p^{\text{CD}}(\theta)p^2$$

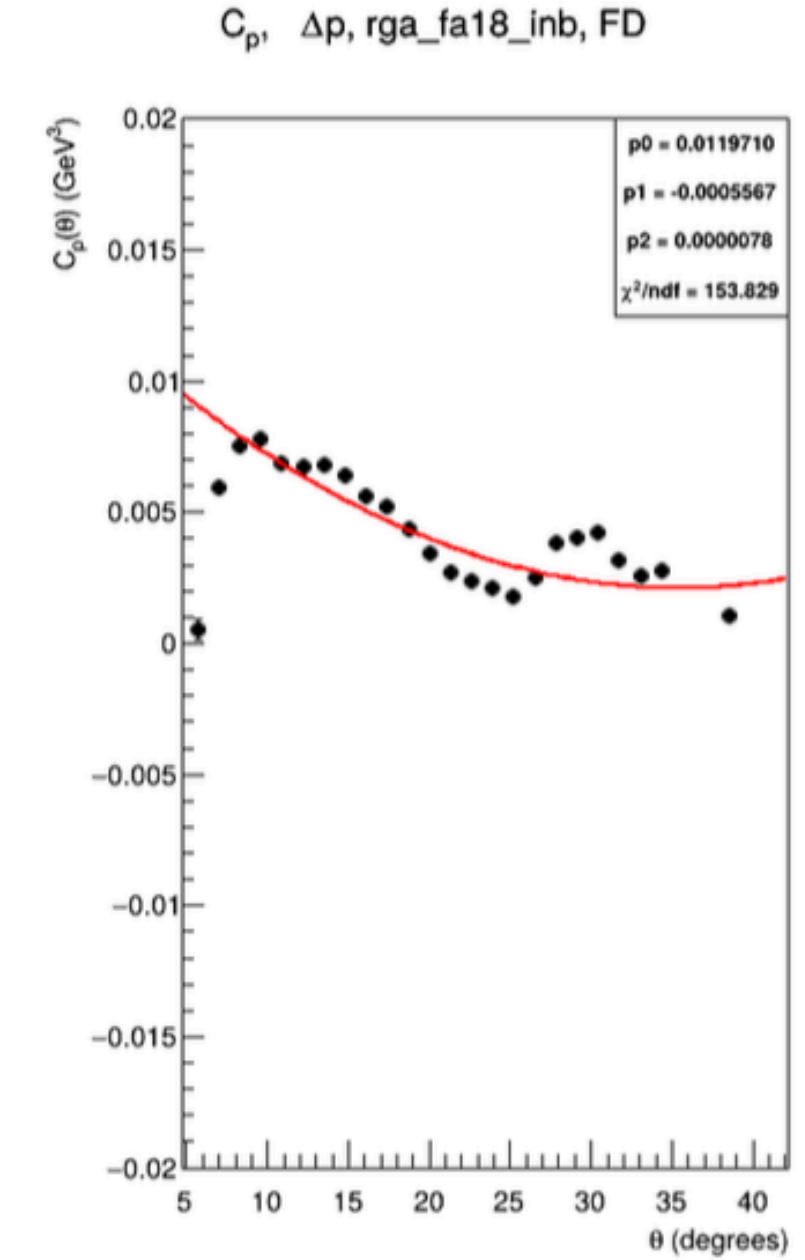
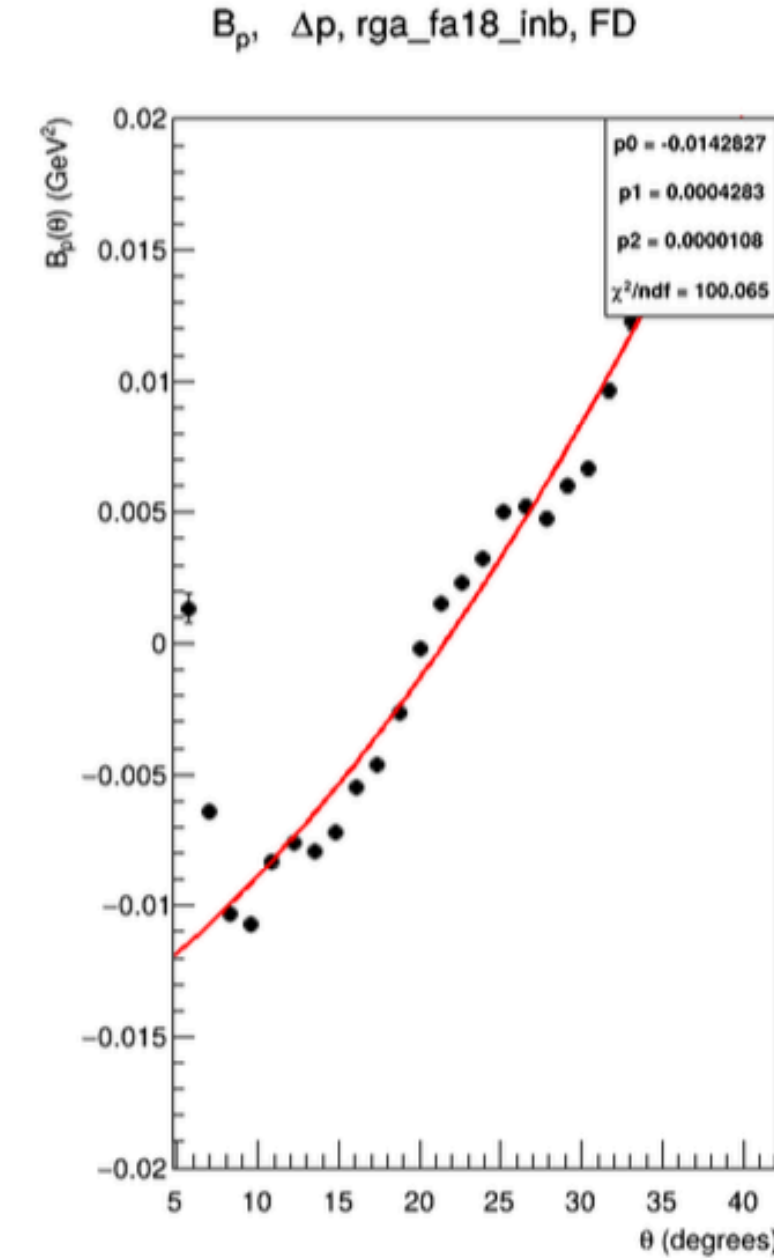
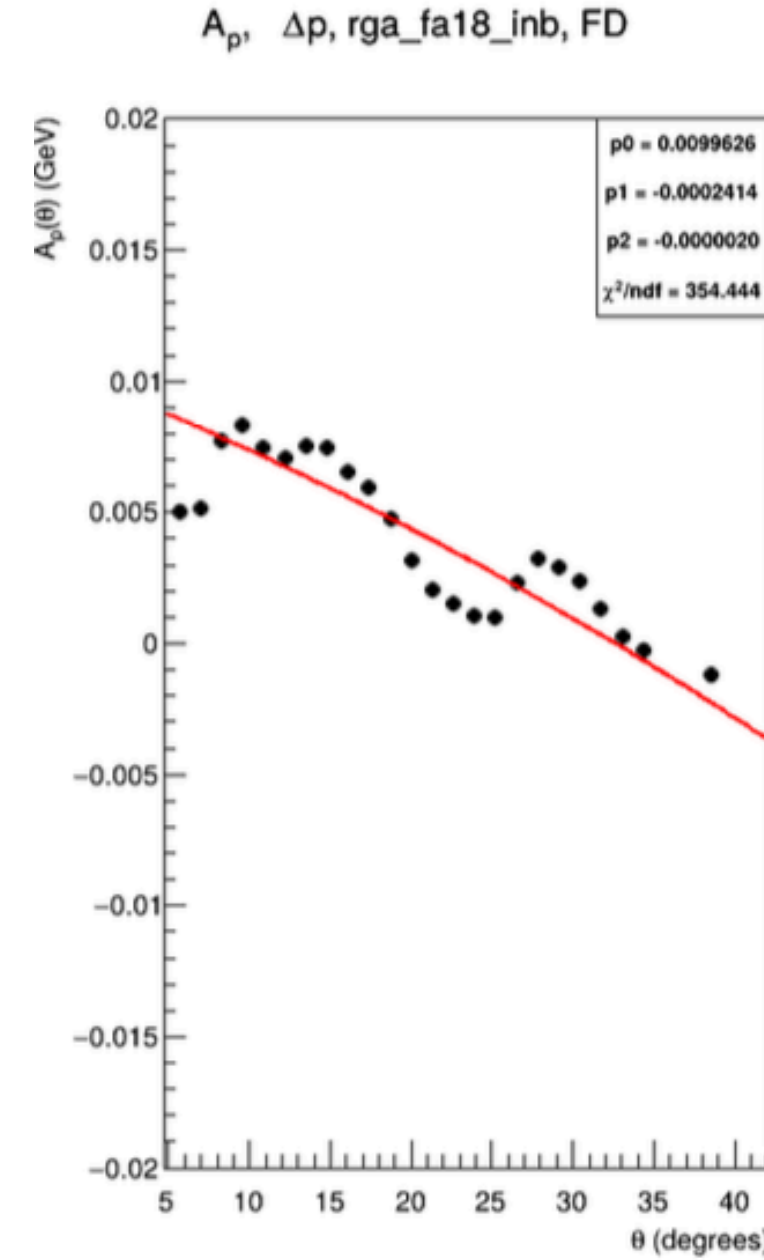
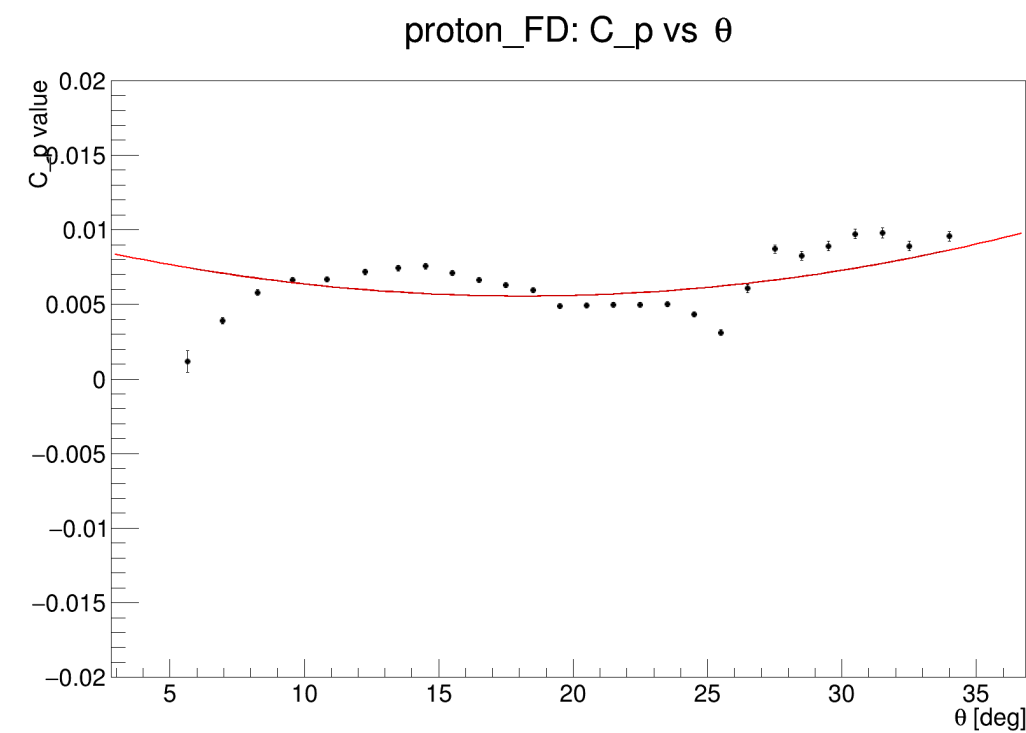
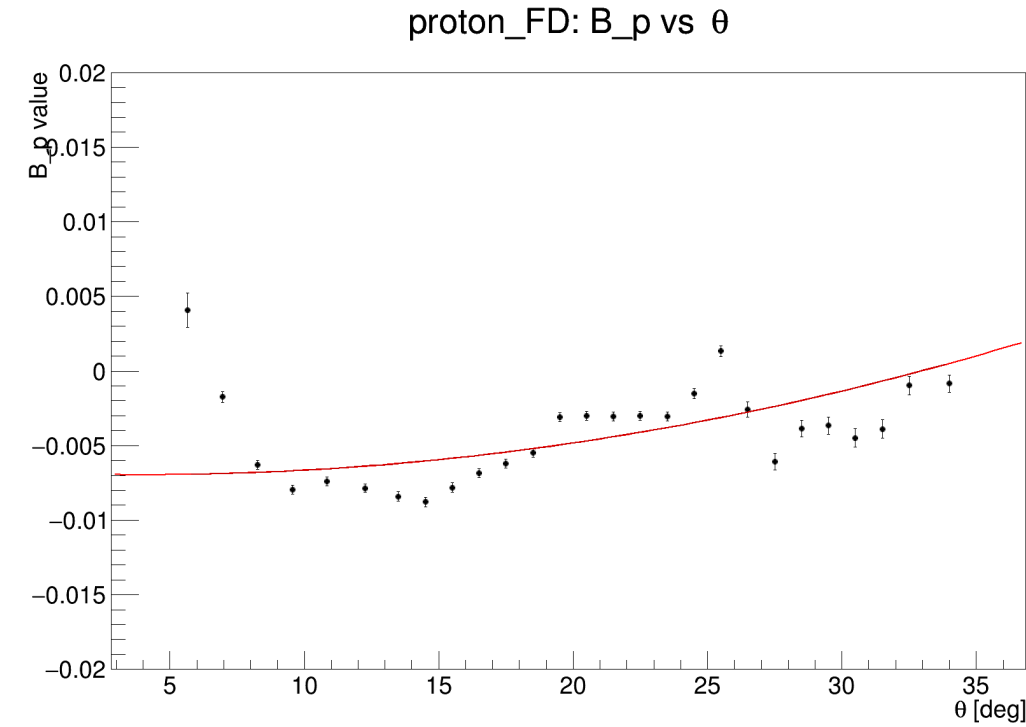
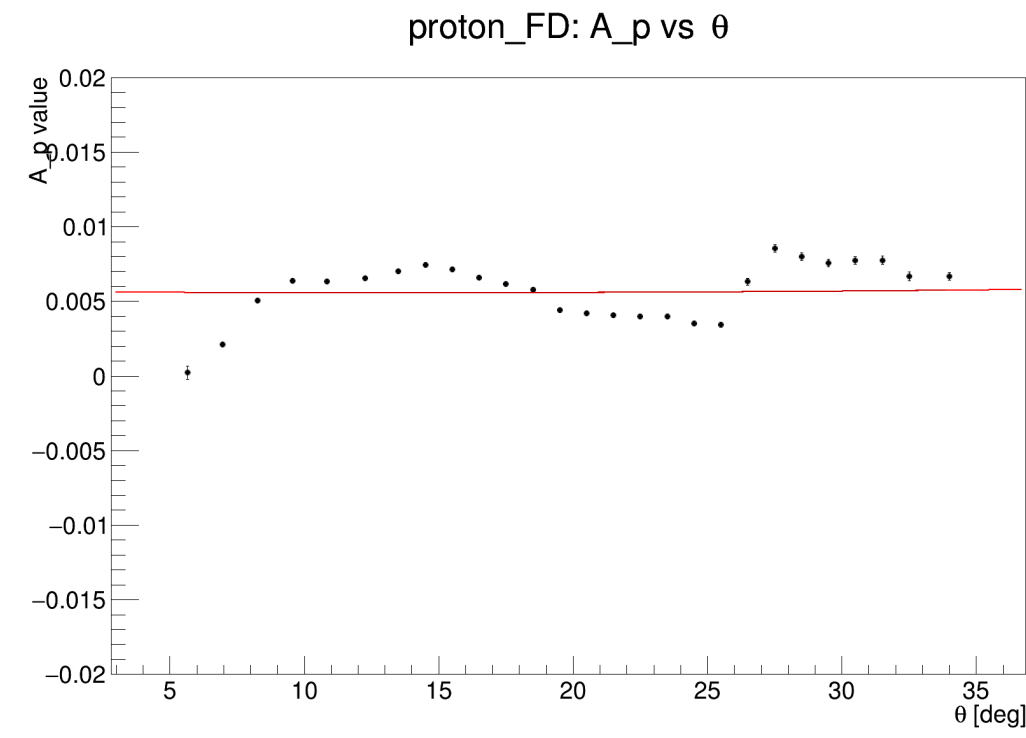


Benchmark: Fall2018_inb proton energy loss correction

FD

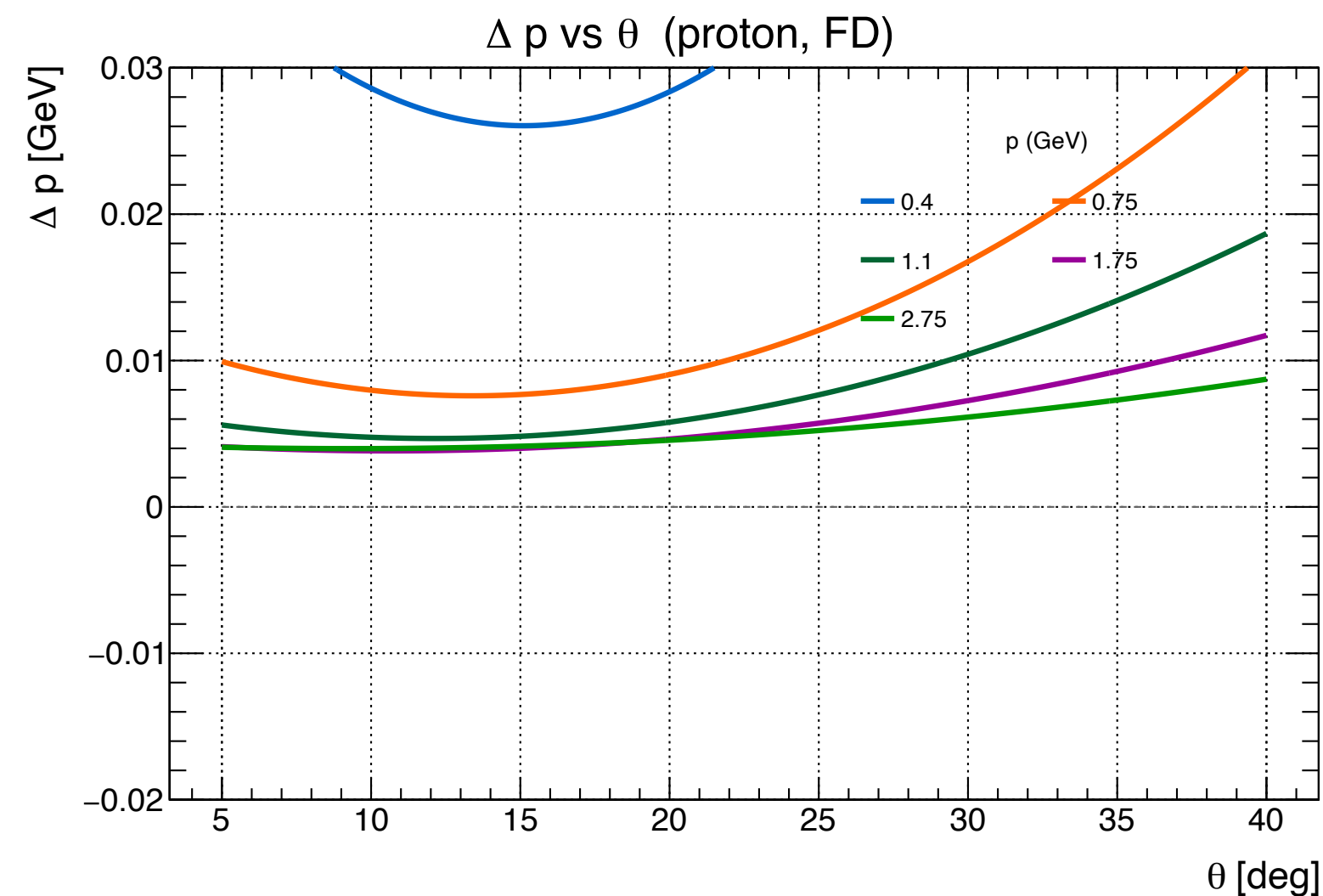
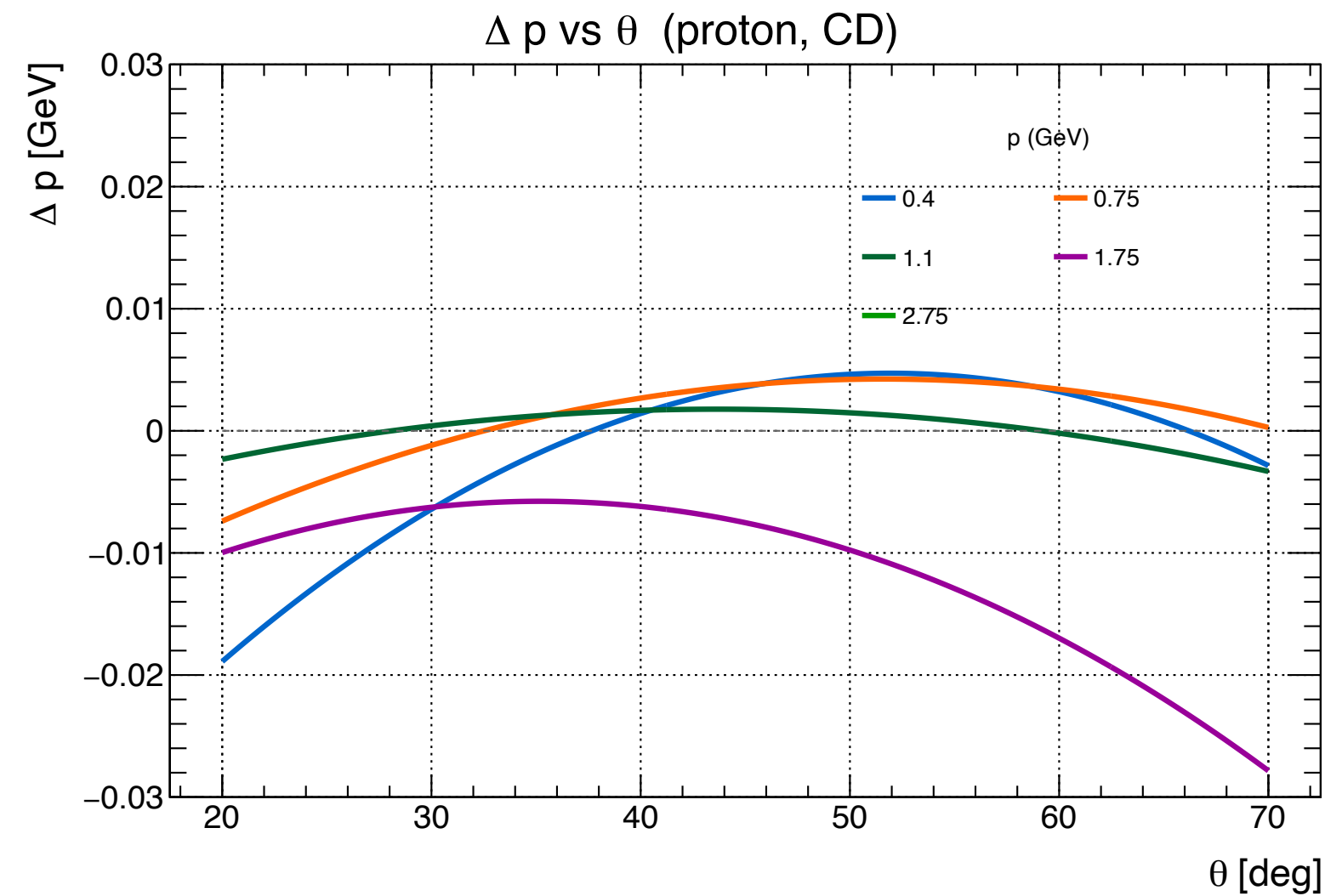
From Timothy

$$p \rightarrow p + A_p^{\text{FD}}(\theta) + B_p^{\text{FD}}(\theta)/p + C_p^{\text{FD}}(\theta)/p^2$$



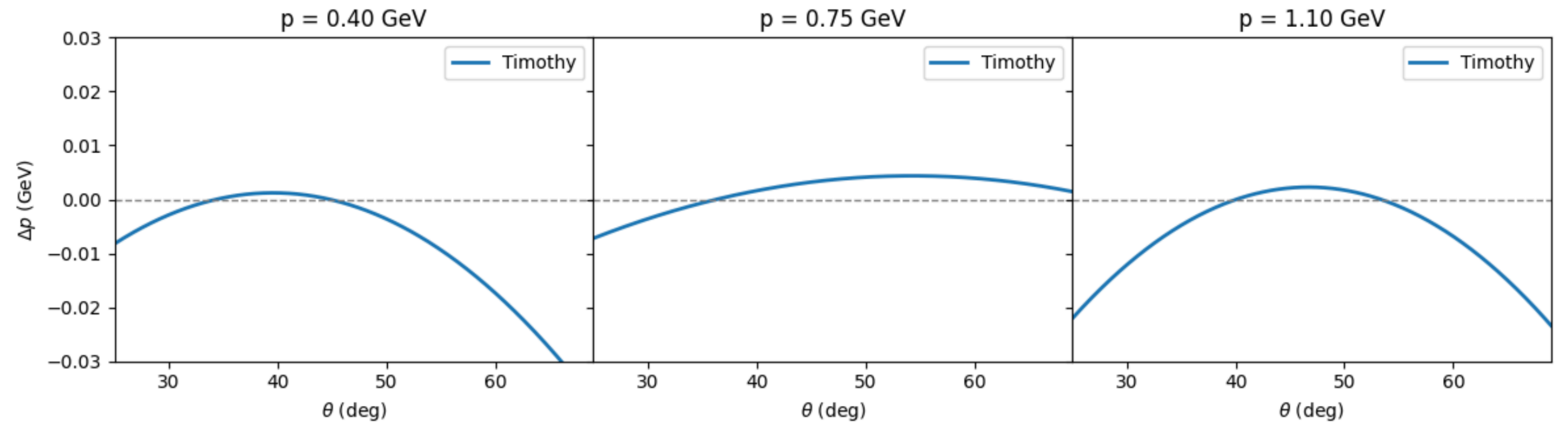
Corrections as function of theta (inb fall 2018)

- Final corrections for different momenta

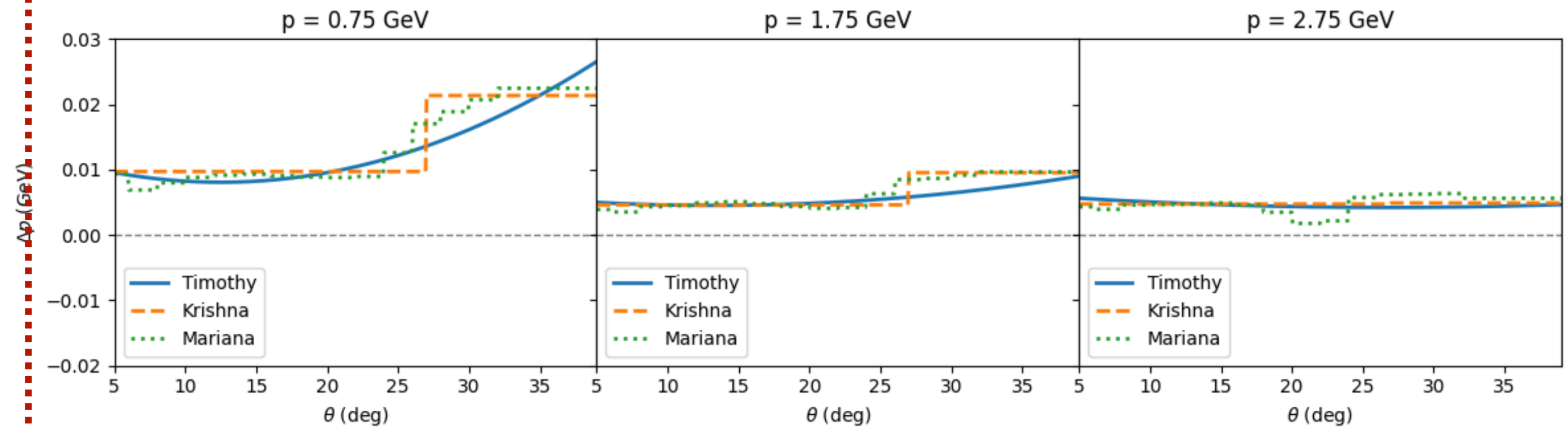


From Timothy

Central Detector Energy Loss Corrections

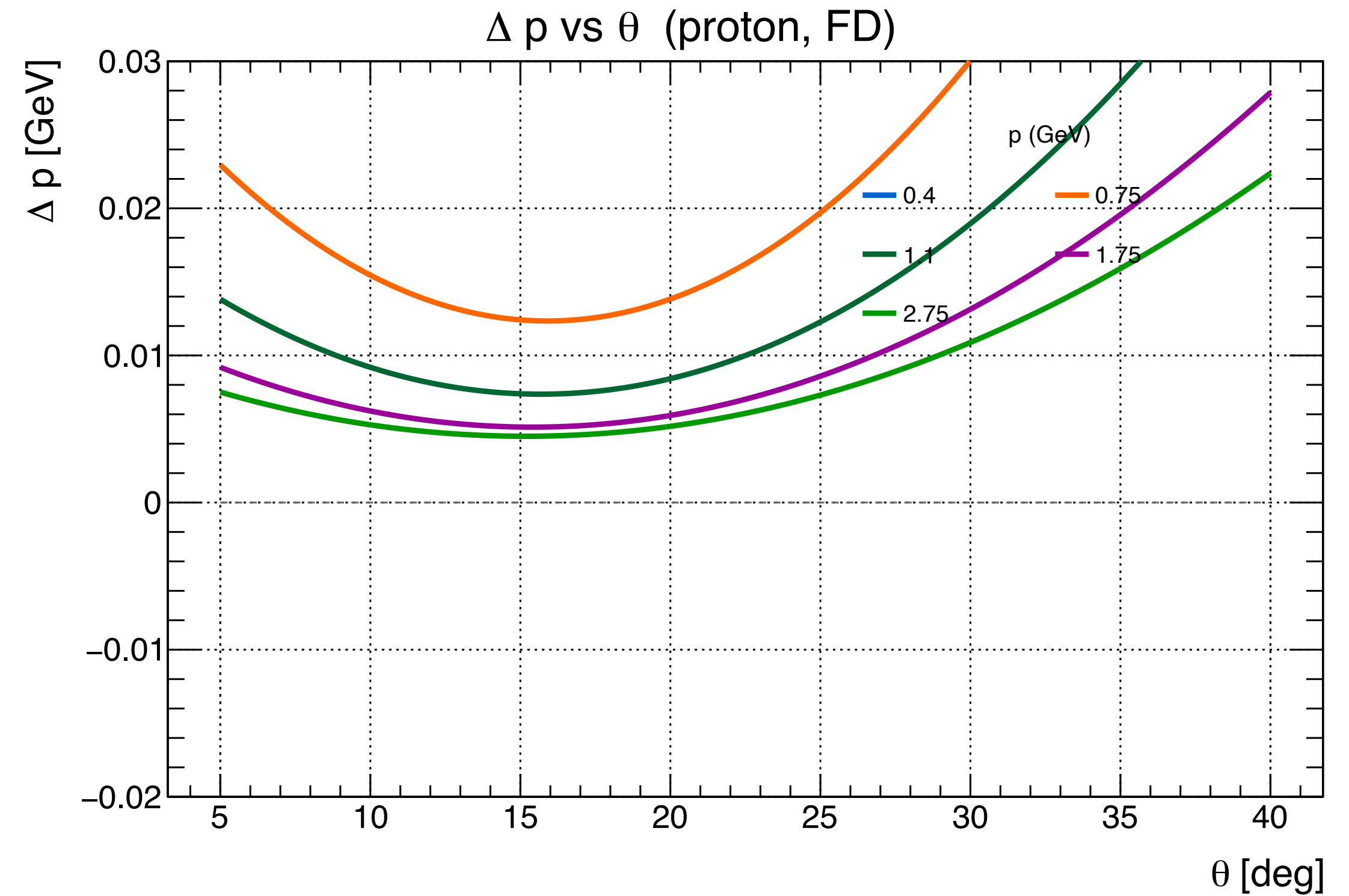
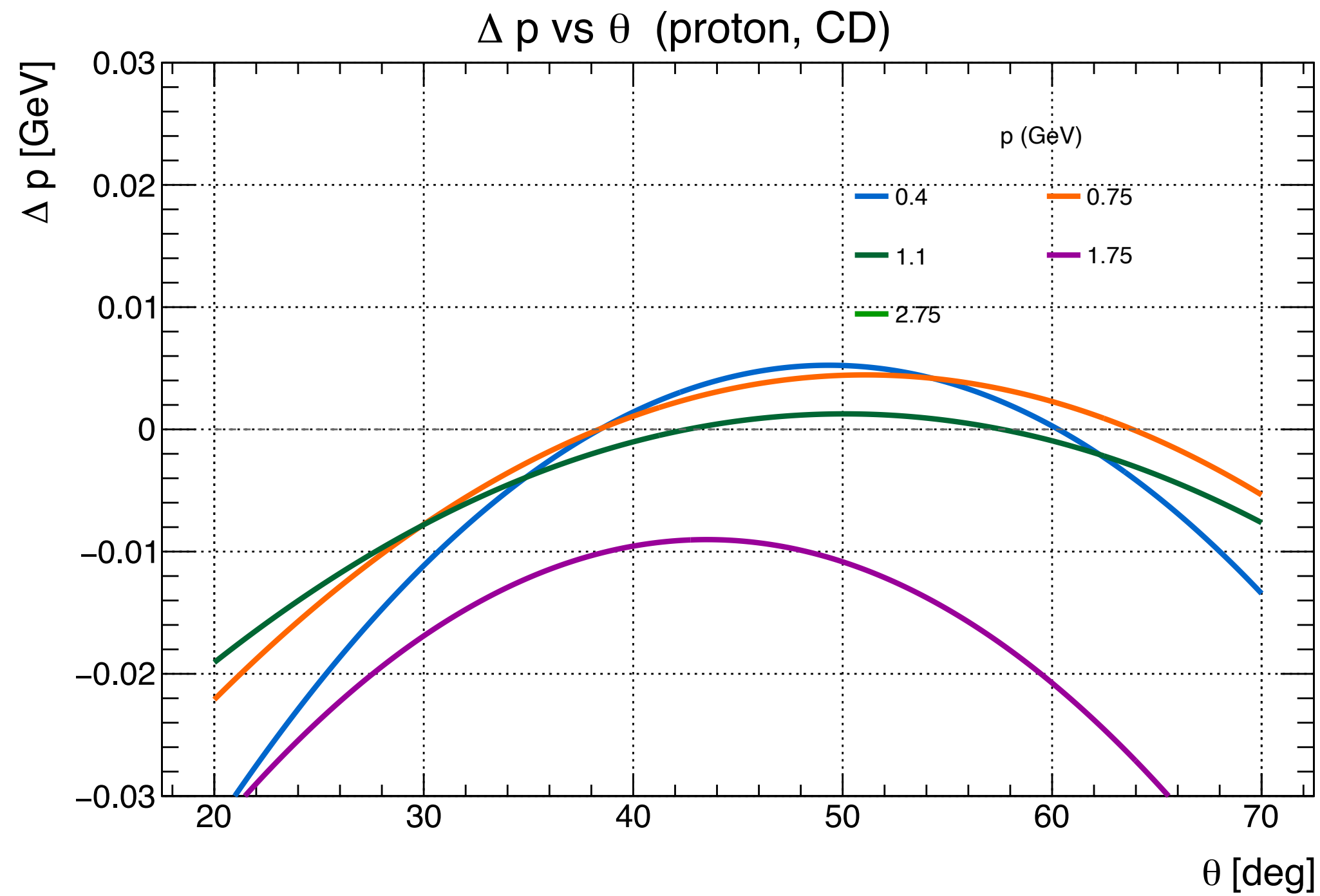


Forward Detector Energy Loss Corrections



Corrections as function of theta (inb sp2018)

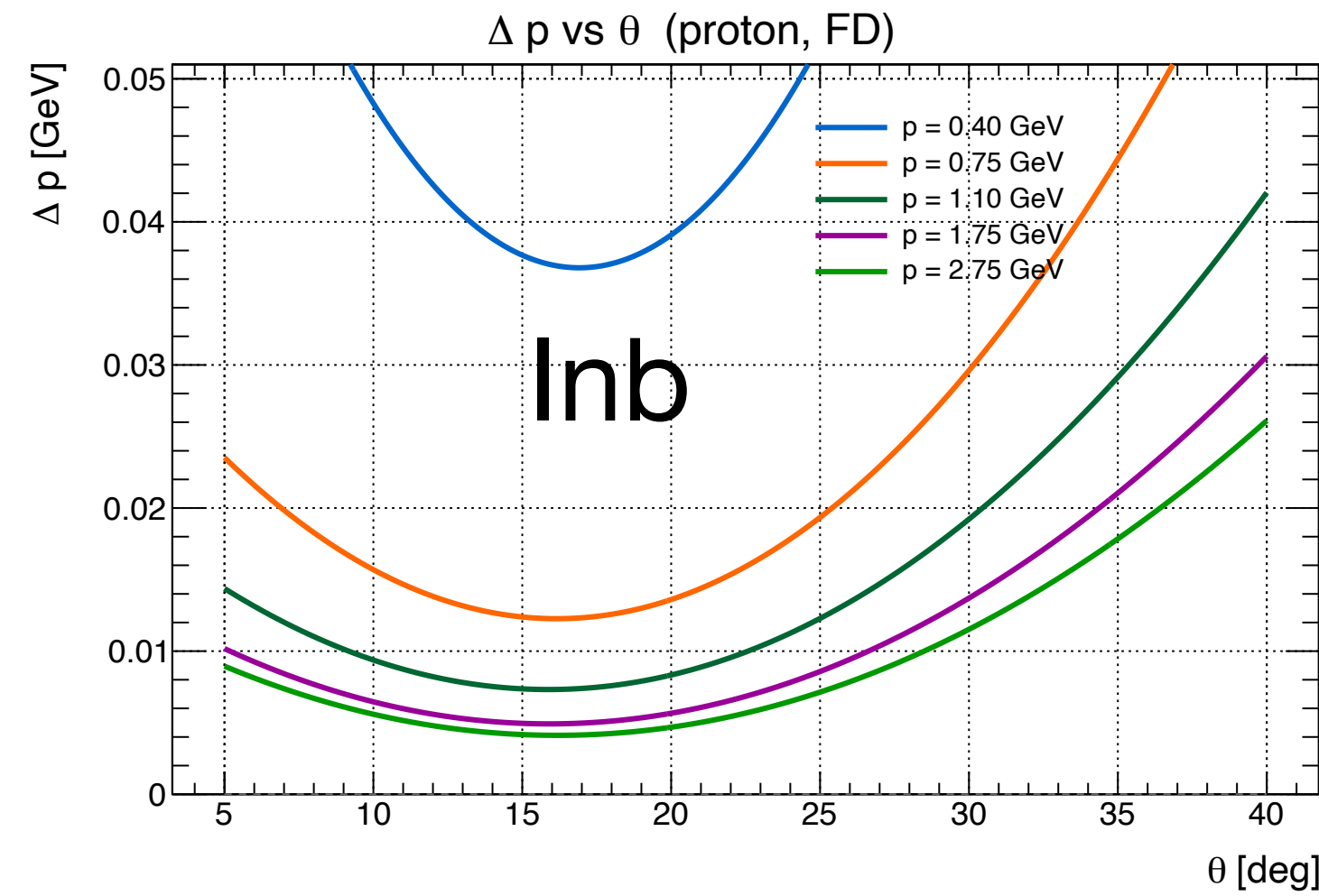
- Final corrections for different momenta



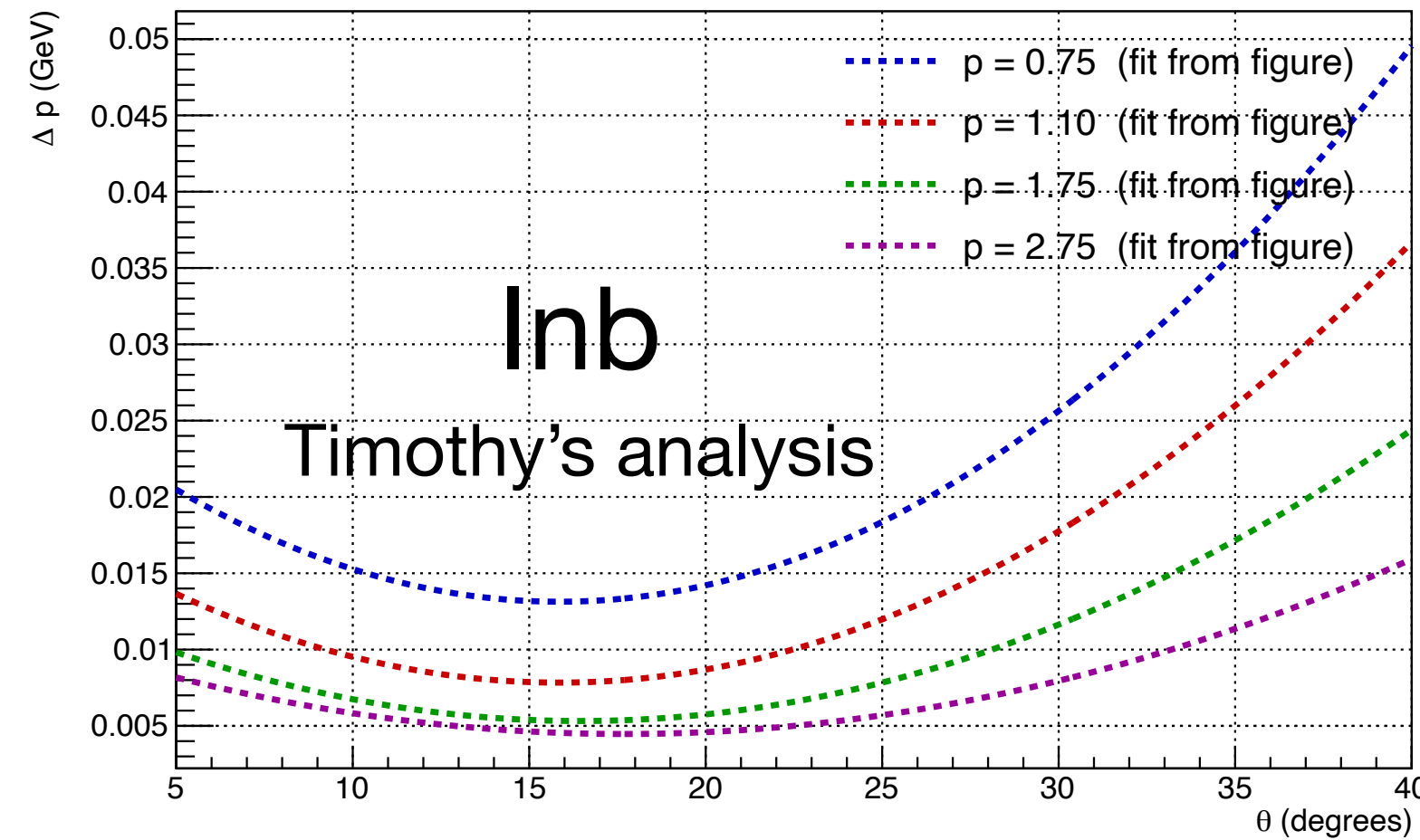
Corrections as function of theta (inb and outb sp2018)

- Final corrections for different momenta

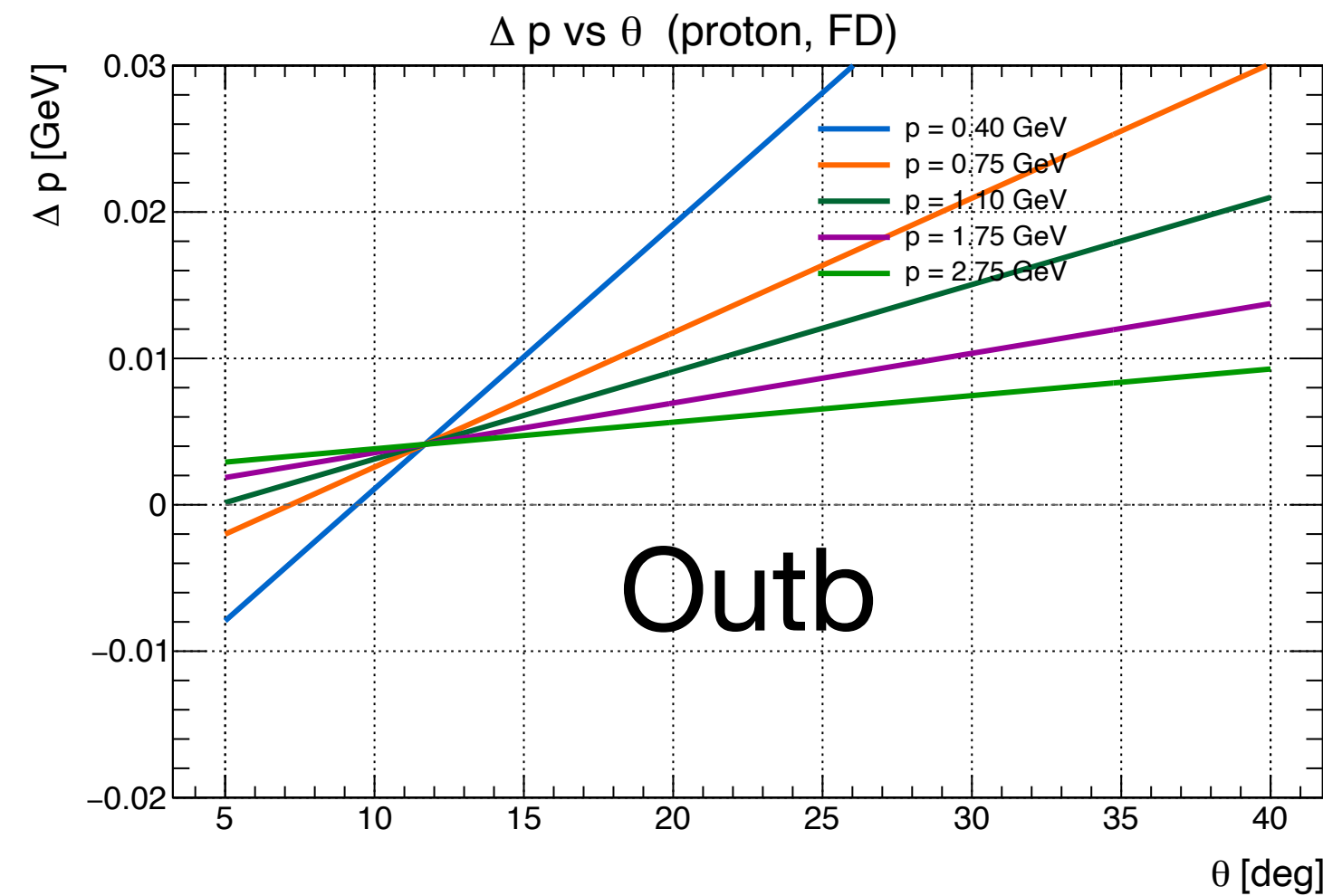
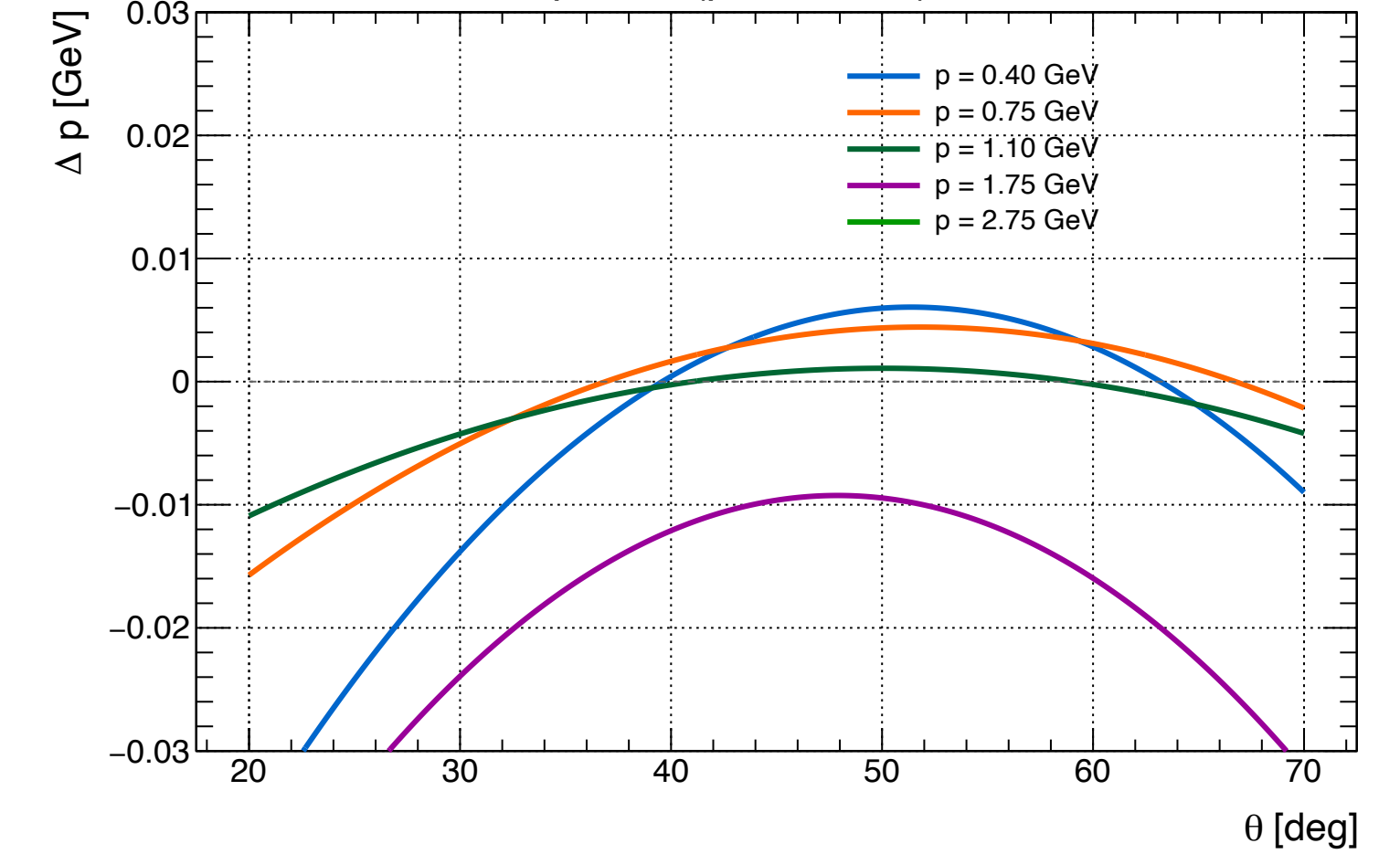
Inb



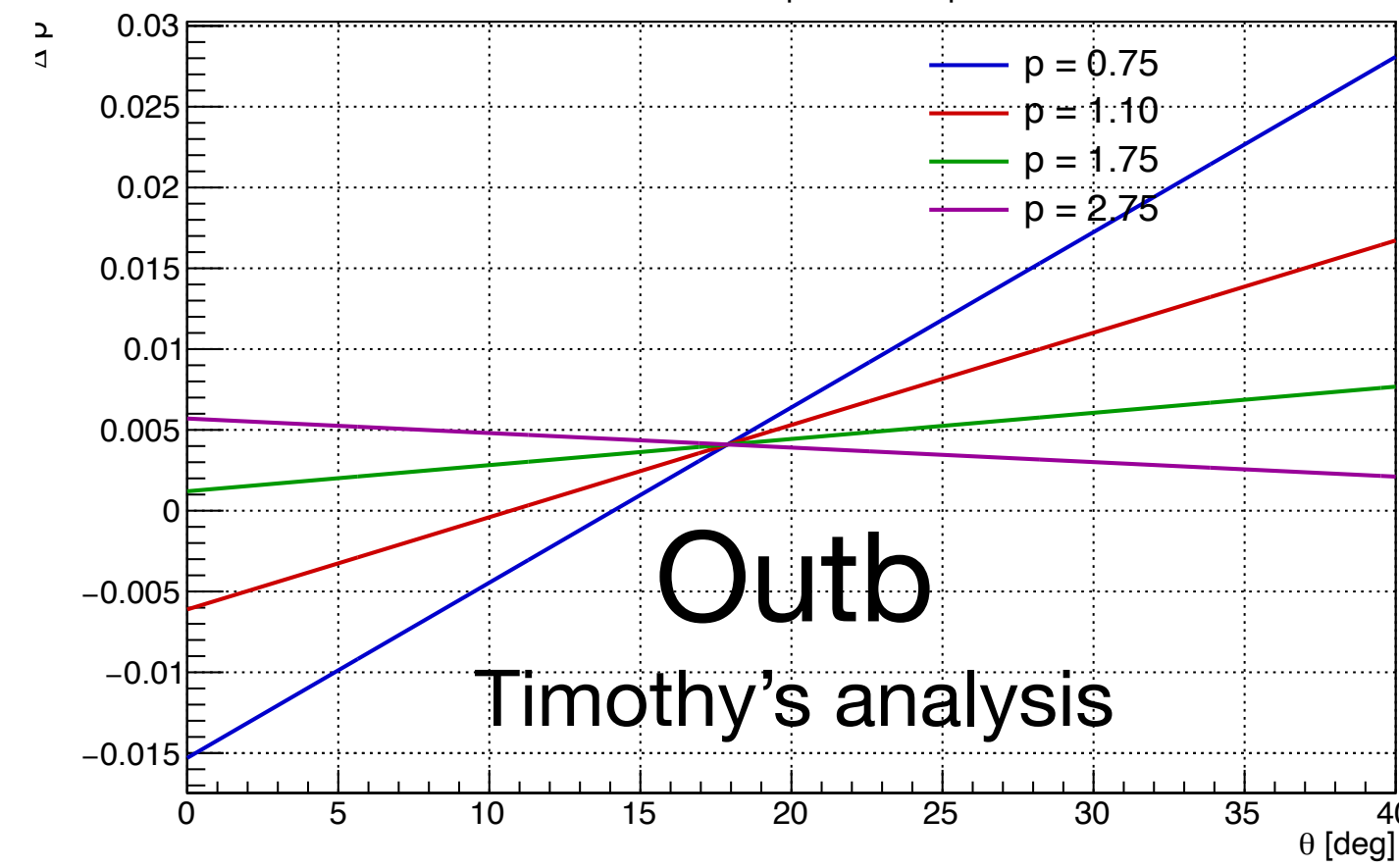
$\Delta p(\theta, p)$ FD, sp2018 inb)



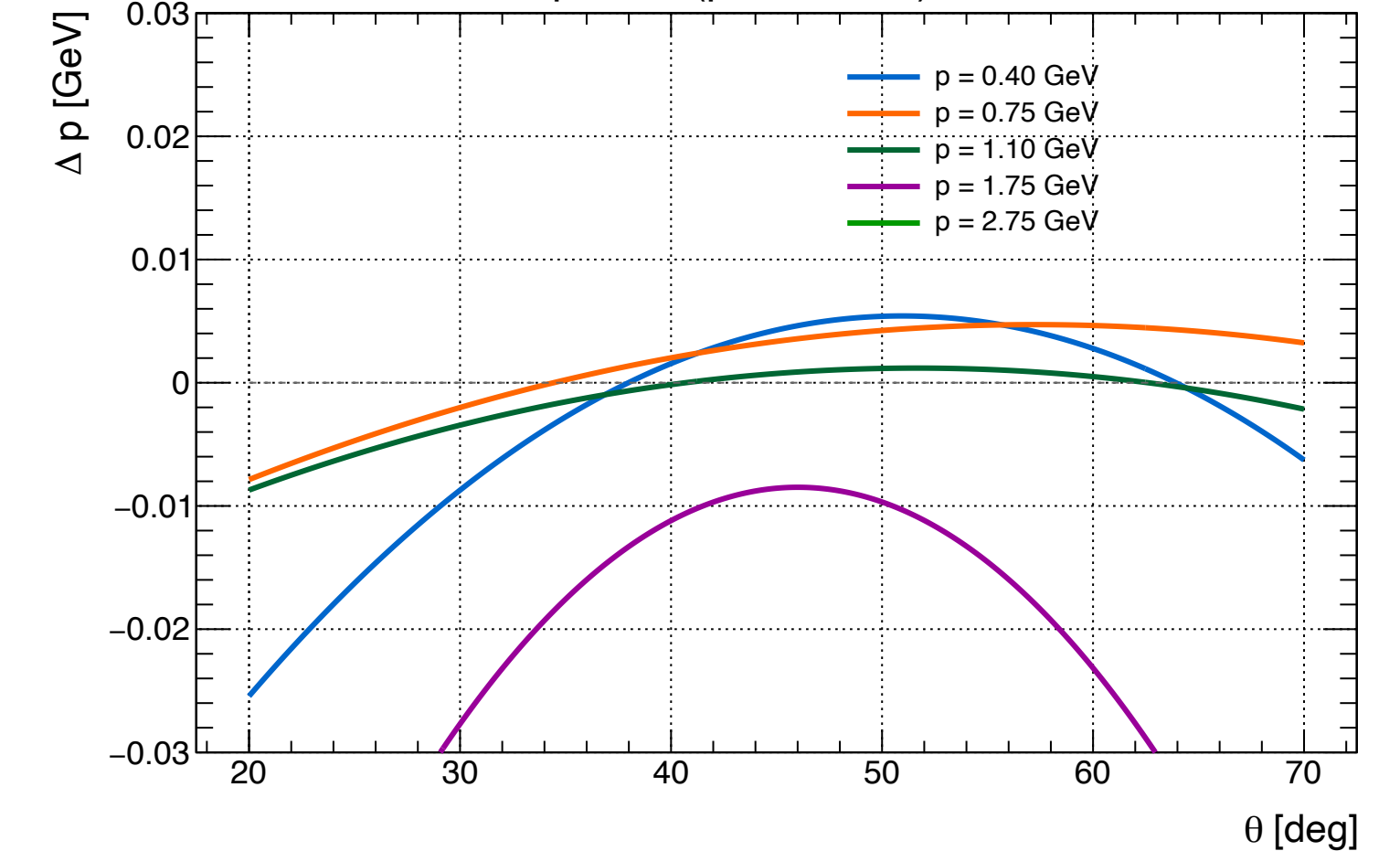
Δp vs θ (proton, CD)



$\Delta p(\theta, p) = A_p(\theta) + B_p(\theta)/p$

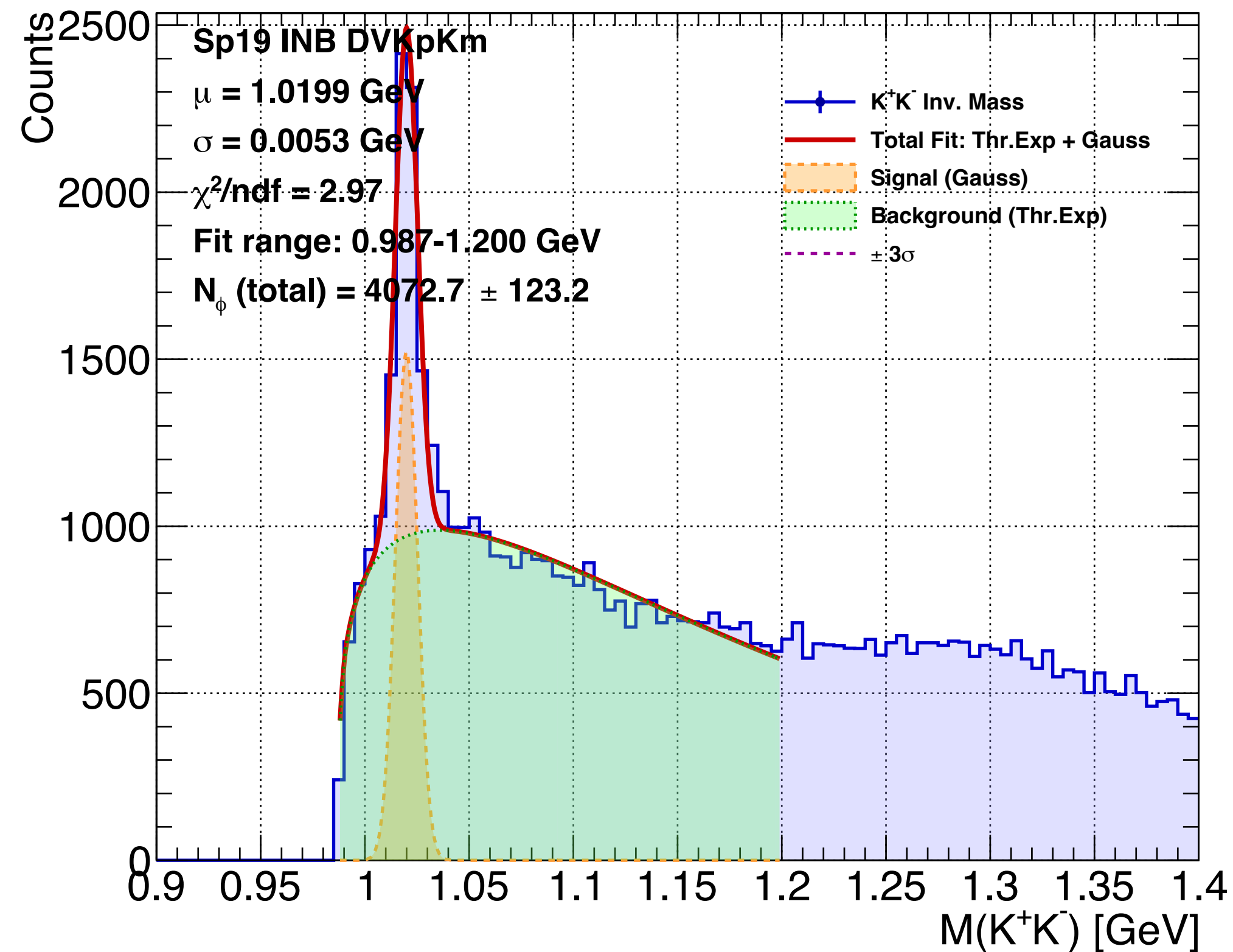


Δp vs θ (proton, CD)

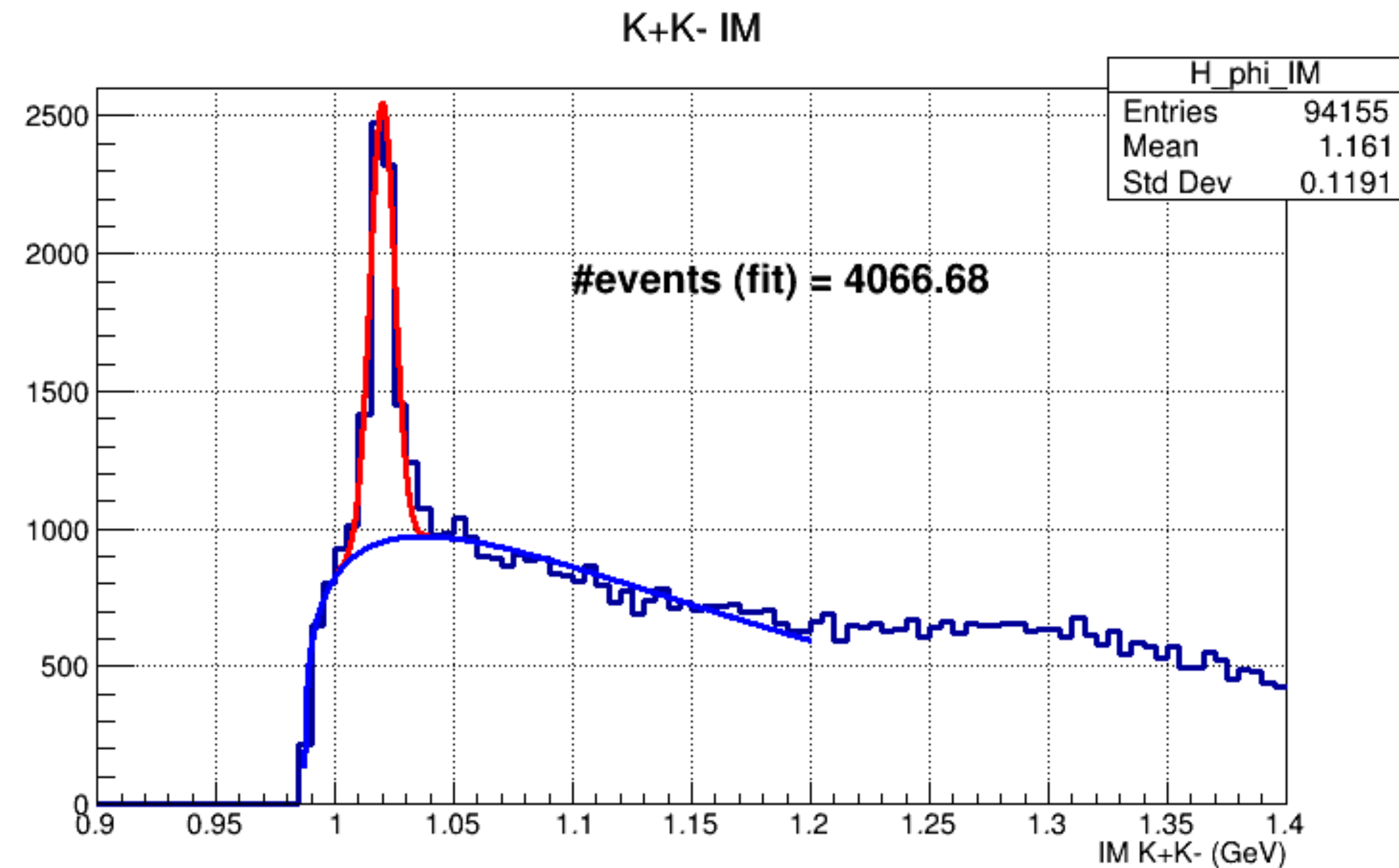


Comparison with FX codes

Spring 2019: 4072 $\pm$ 123 candidates



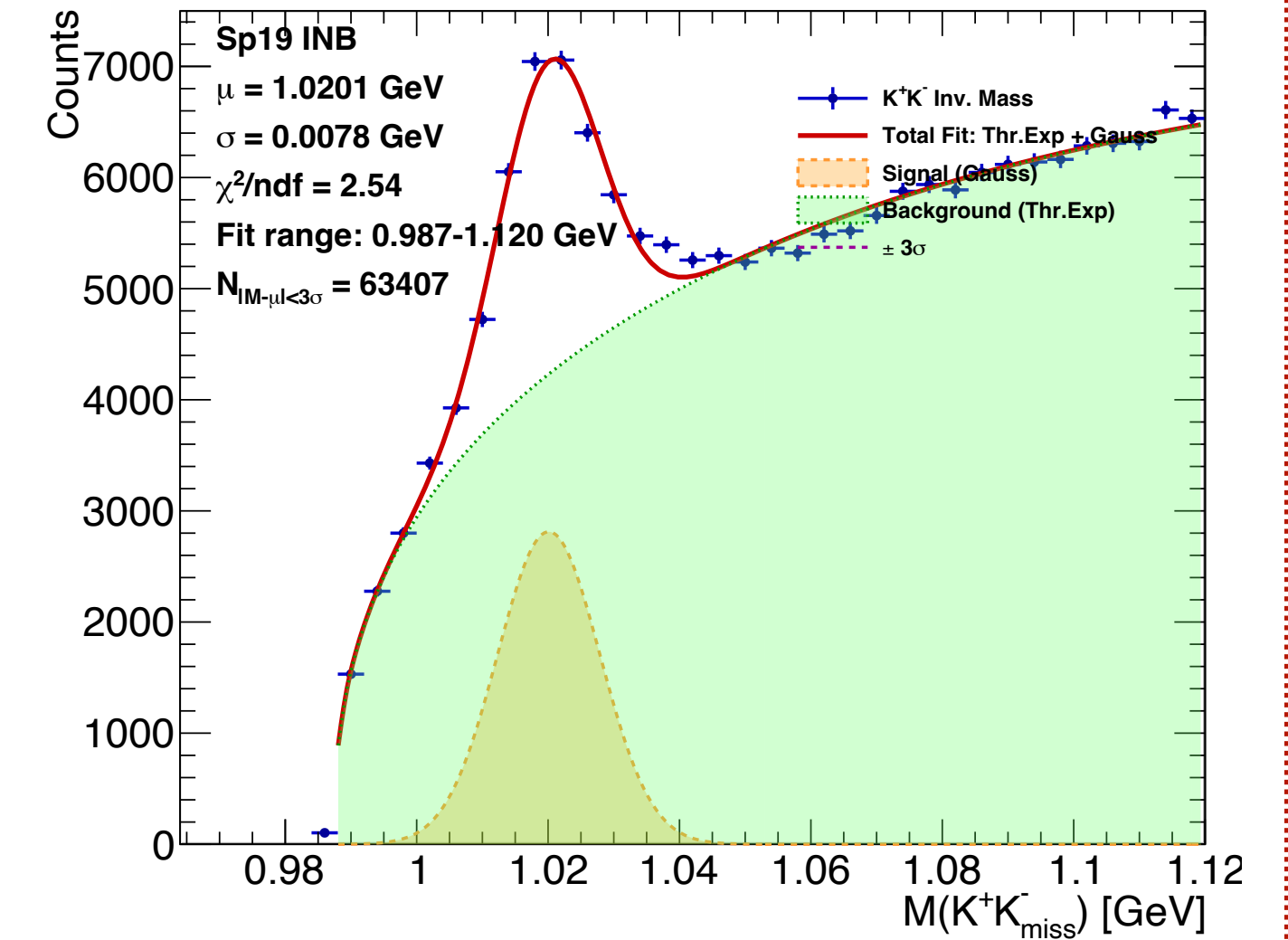
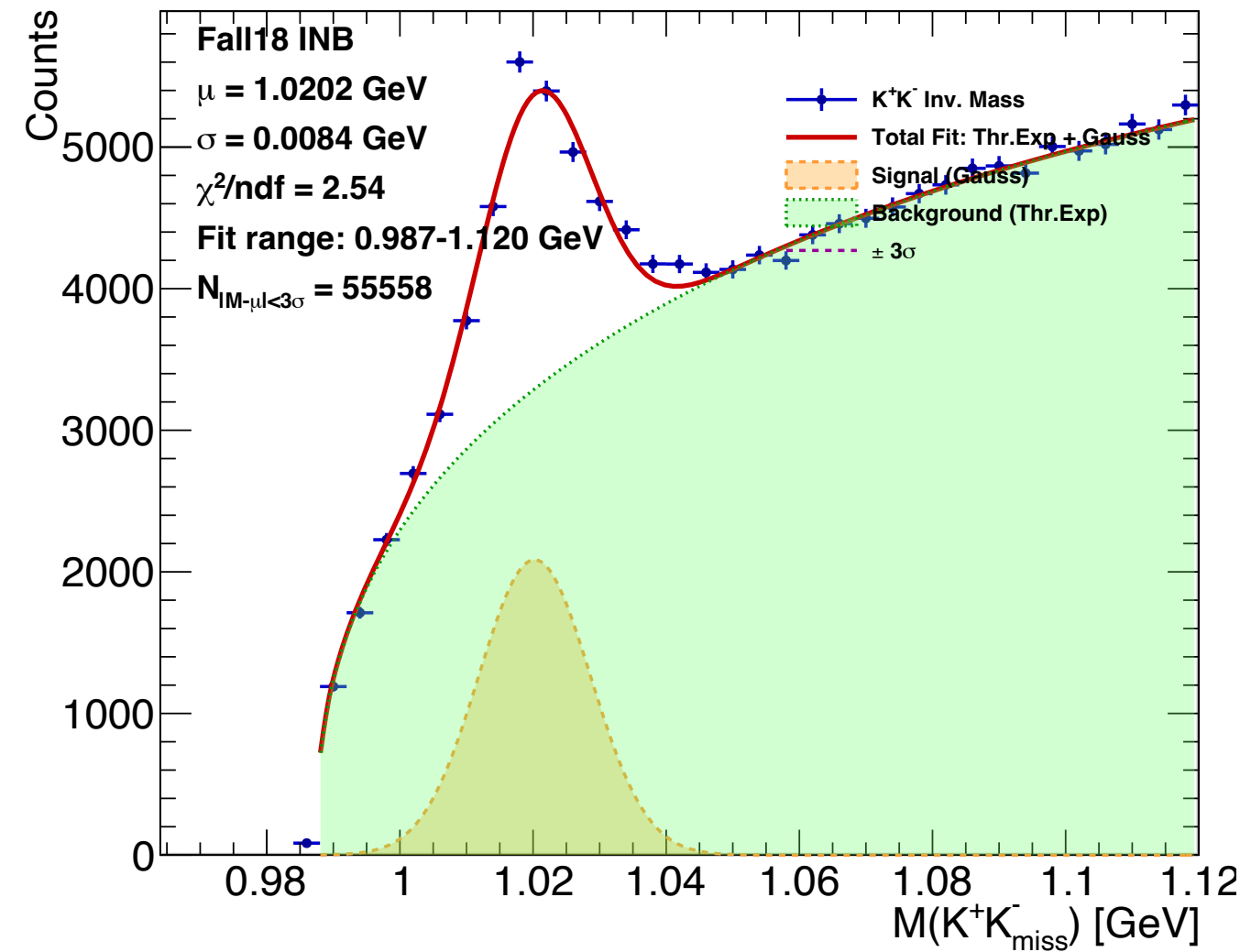
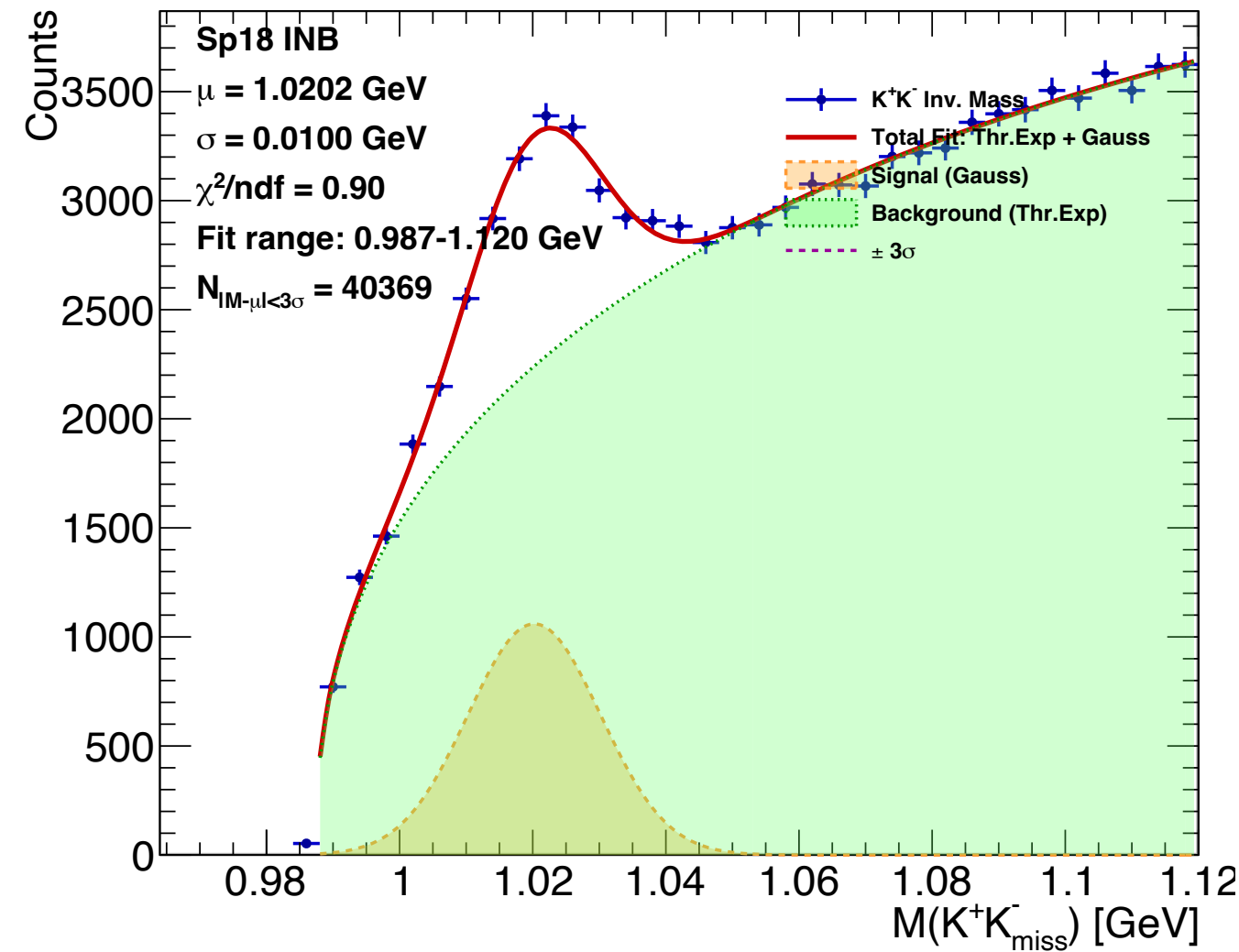
Spring 2019: 4066 candidates



All phi K⁺K⁻ Invariant Mass all periods of RGA

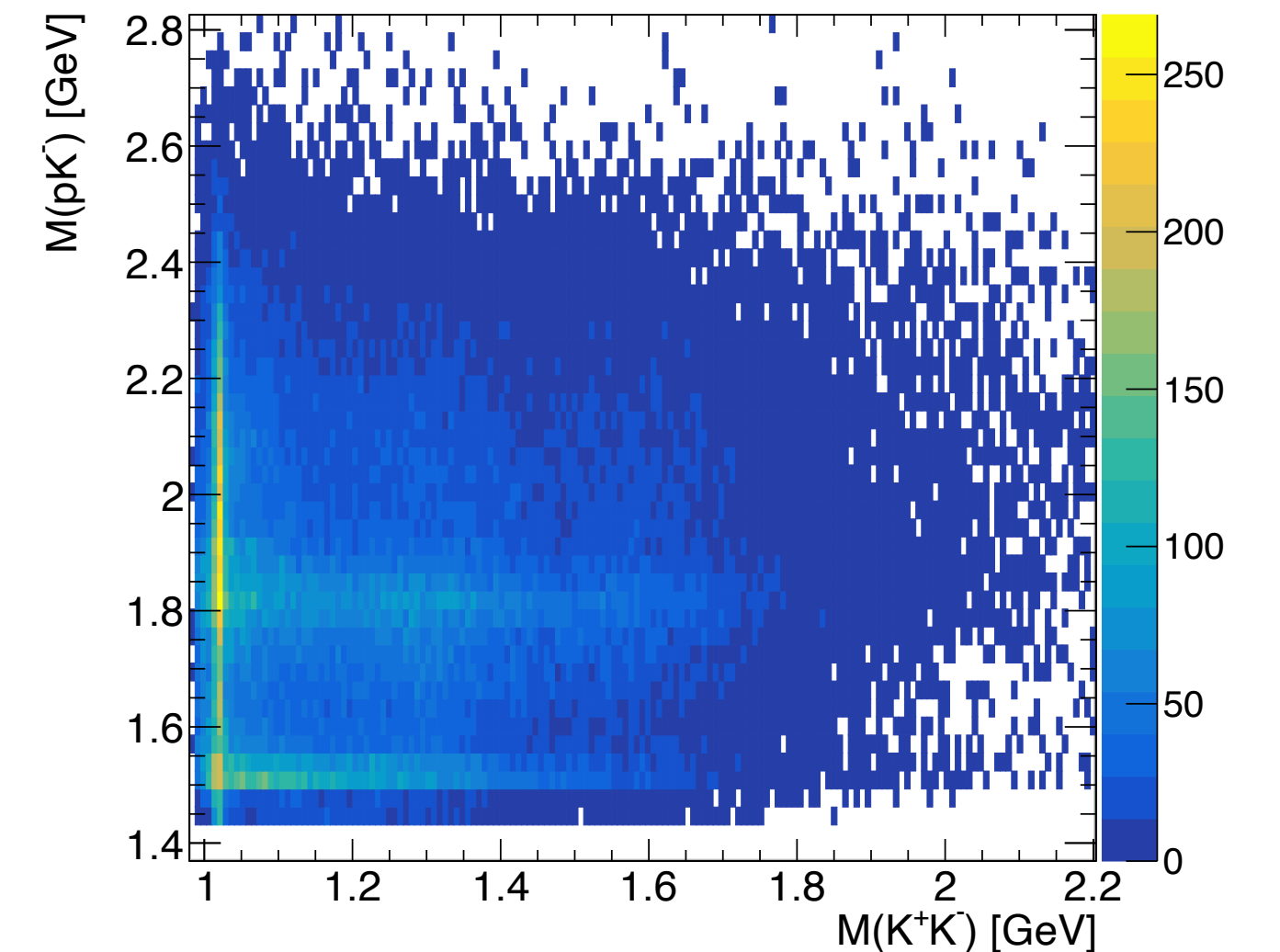
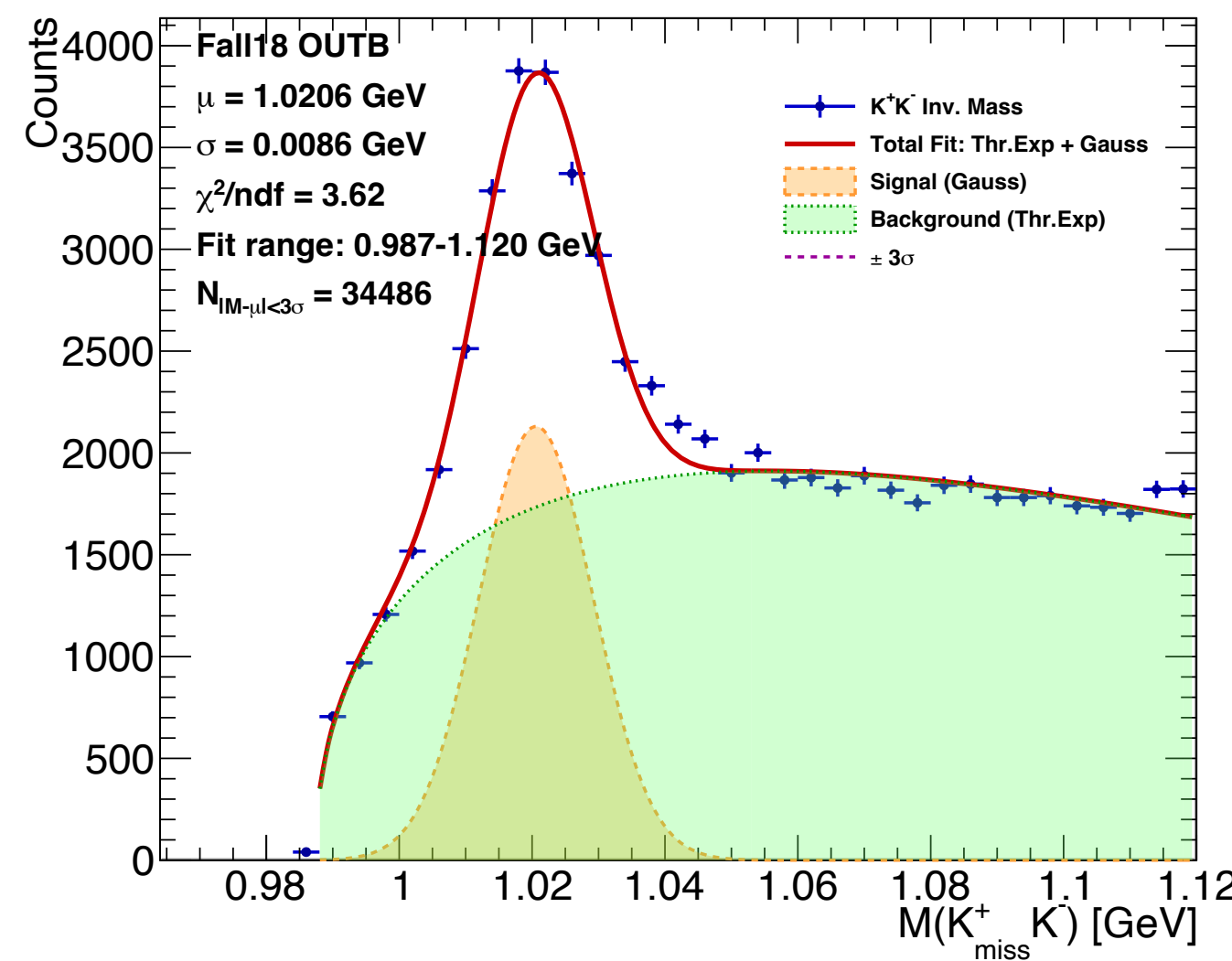
- Phi peak at ~1020 MeV, cross-section analysis: $\pm 3\sigma$ cut around the the peak

Inb



Out

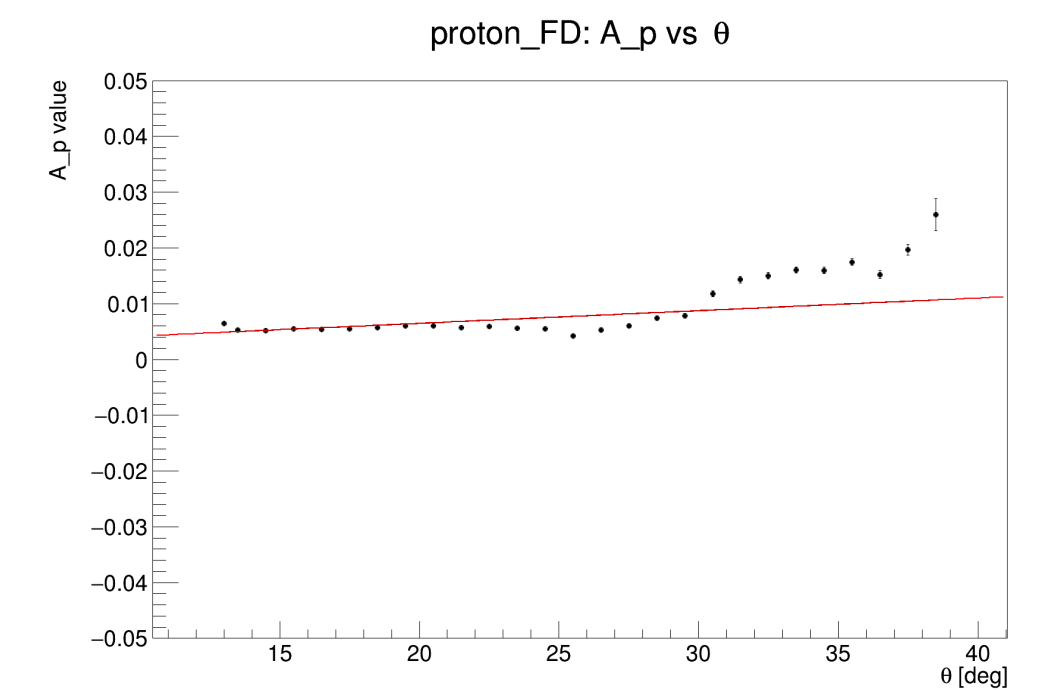
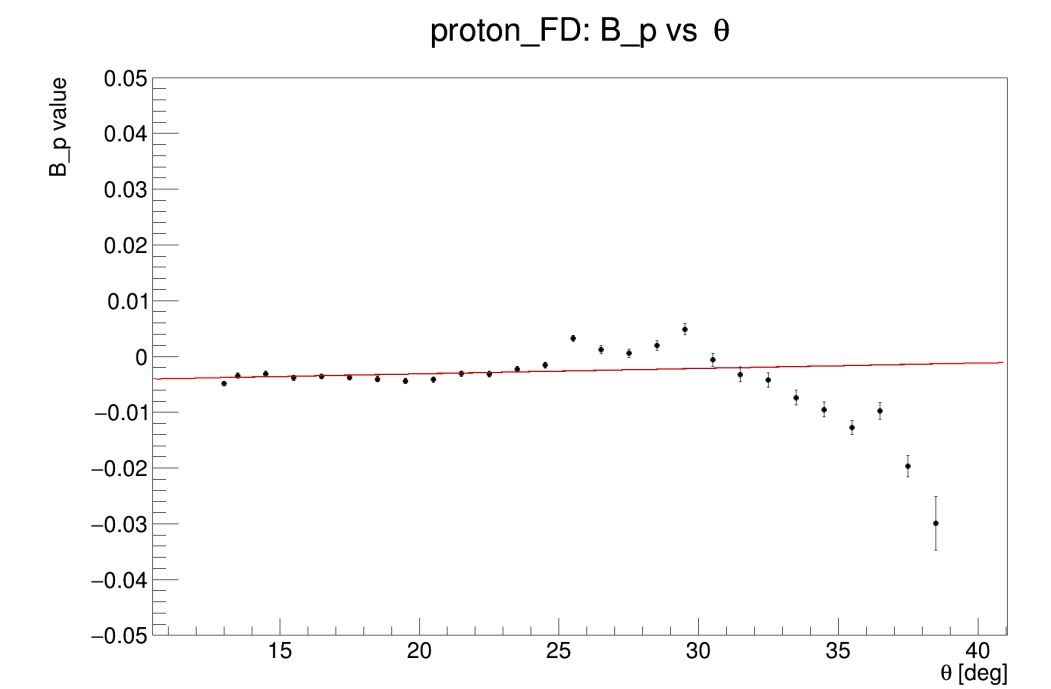
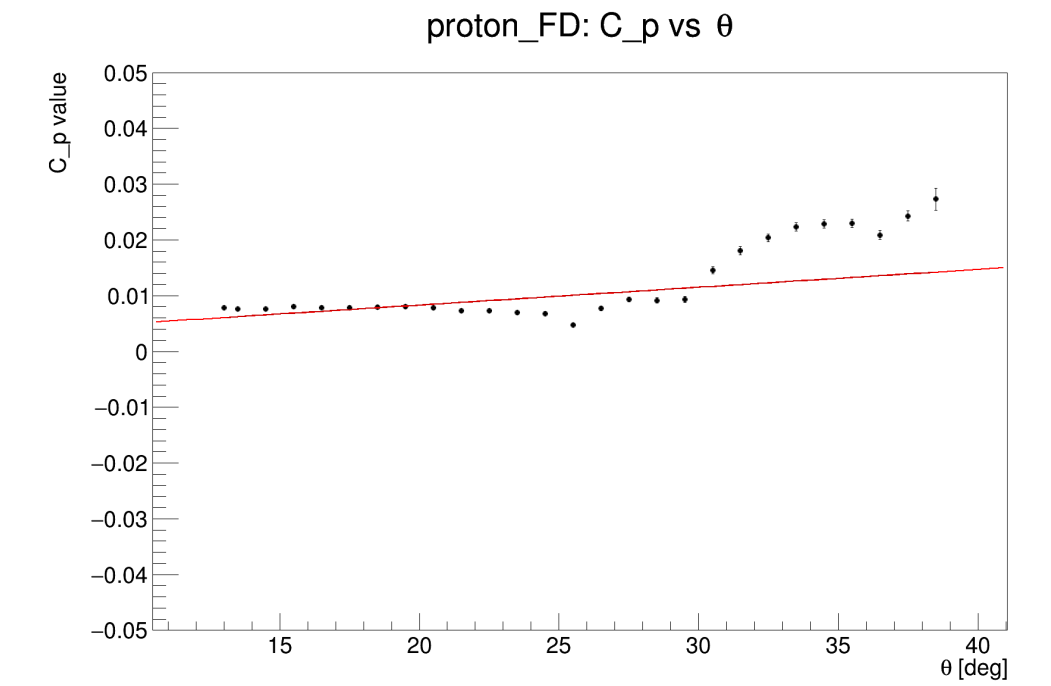
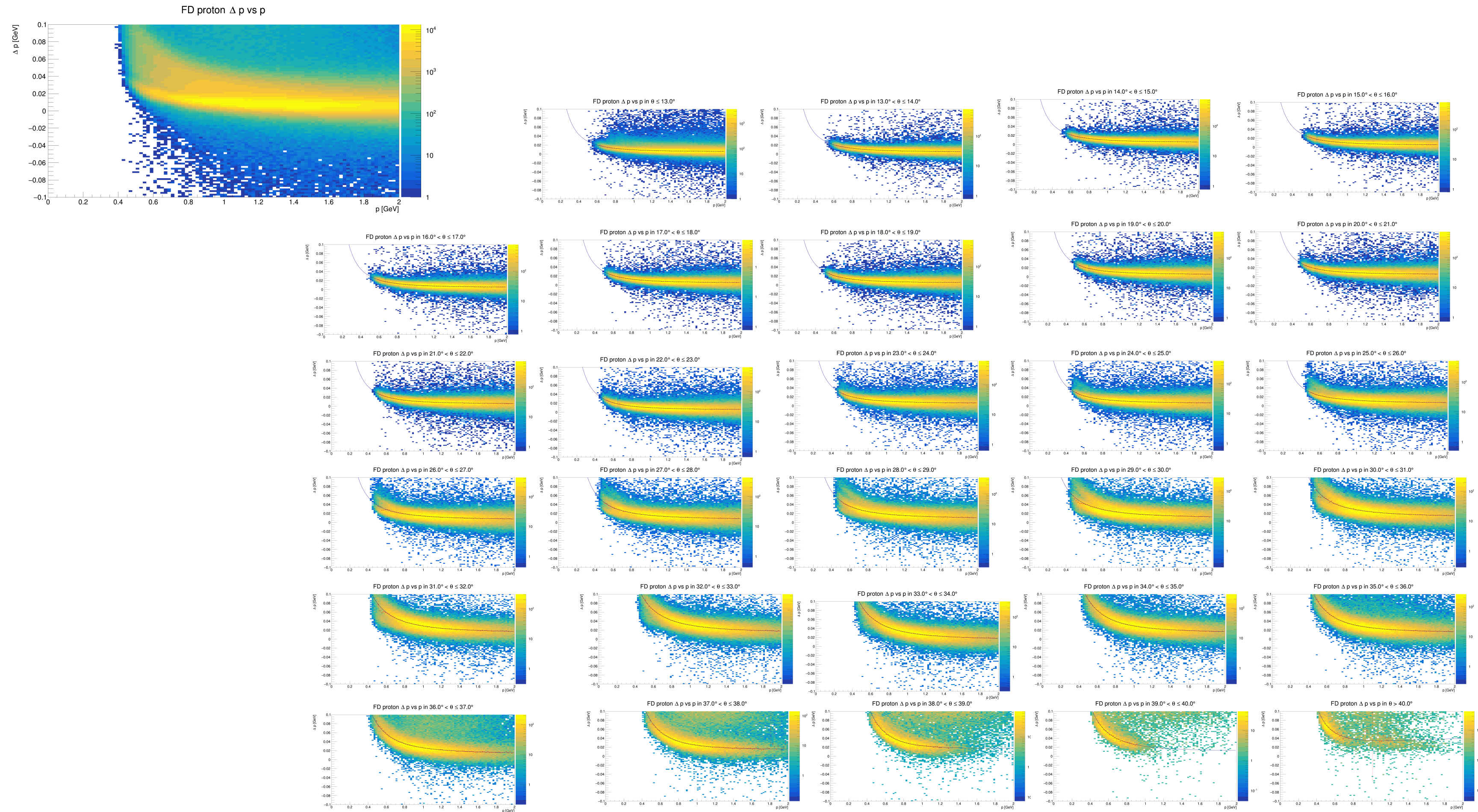
Sp18 in progress



Energy Loss Correction: RGA Spring2018 inb

FD
Proton

$$\Delta p = A + B/p + C/p^2$$



Energy Loss Correction: RGA Spring2018 inb

CD Proton $\Delta p = A + B \cdot p + C \cdot p^2$

