Update on inclusive $K^{\pm}$ production in p+p@4.5 GeV

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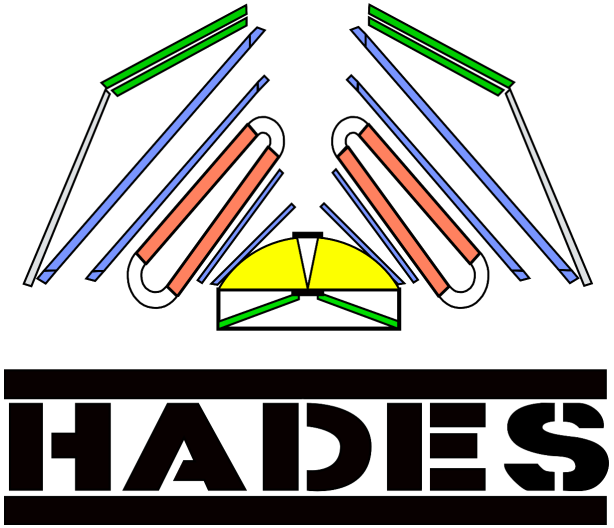
23.06.2026



Motivation

Feb22 p+p@4.5 GeV : $\sqrt{s} \approx 3.46$ GeV

- K^+ associated production comfortably allowed

$$pp \rightarrow p \Lambda K^+$$

$$\sqrt{s_{K^+}^{\text{thr}}} = m_p + m_\Lambda + m_{K^+} \approx 1.58\,\text{GeV}$$

- K^- production moderately above threshold

$$pp \rightarrow pp K^+ K^-$$

$$\sqrt{s_{K^-}^{\text{thr}}} = 2m_p + 2m_{K^\pm} \approx 2.5\,\text{GeV}$$

- Expect reasonably good statistics (for K^+)
- Still somewhat near-threshold
  - Expect significantly different yields for $K^\pm$

Project Goals

- **Inclusive analysis of $K^\pm$ production**
  - Transverse mass spectra
  - Rapidity distribution
  - Total production yield
  - Systematic uncertainty estimation
  - …
- **Comparison to transport / Pythia**
  - **…**

Pre-Selection : Overview

	Data	Simulation	
Statistic	Gen4 Full Target Day 33 - 65 /lustre/hades/user/croy/ EventList_p4500p_Gen4_target.list	SMASH Gen4 “Standard” /lustre/hades/dstsim/feb22/p4500p/smash/ smash_standard	
Event Selection	PT2 ∩ (-130 < z_{Vertex} < -110)	-	
Track Sorter	HParticleTrackSorter::selectHadrons kIsBestRKSorter , kIsHadronSorter		
TrackSelection	kIsUsed ∩ !(AtAnyMdcEdge)		
	Standard / Open	**Medium**	**Tight**
	$\chi^2_{RK} < 400$ MetaQa < 3	$\chi^2_{RK} < 300$ MetaQa < 2.5	$\chi^2_{RK} < 200$ MetaQa < 2 nLayer ≥ 23

Table 1: DataQA parameter summary

Pre-Selection : Events

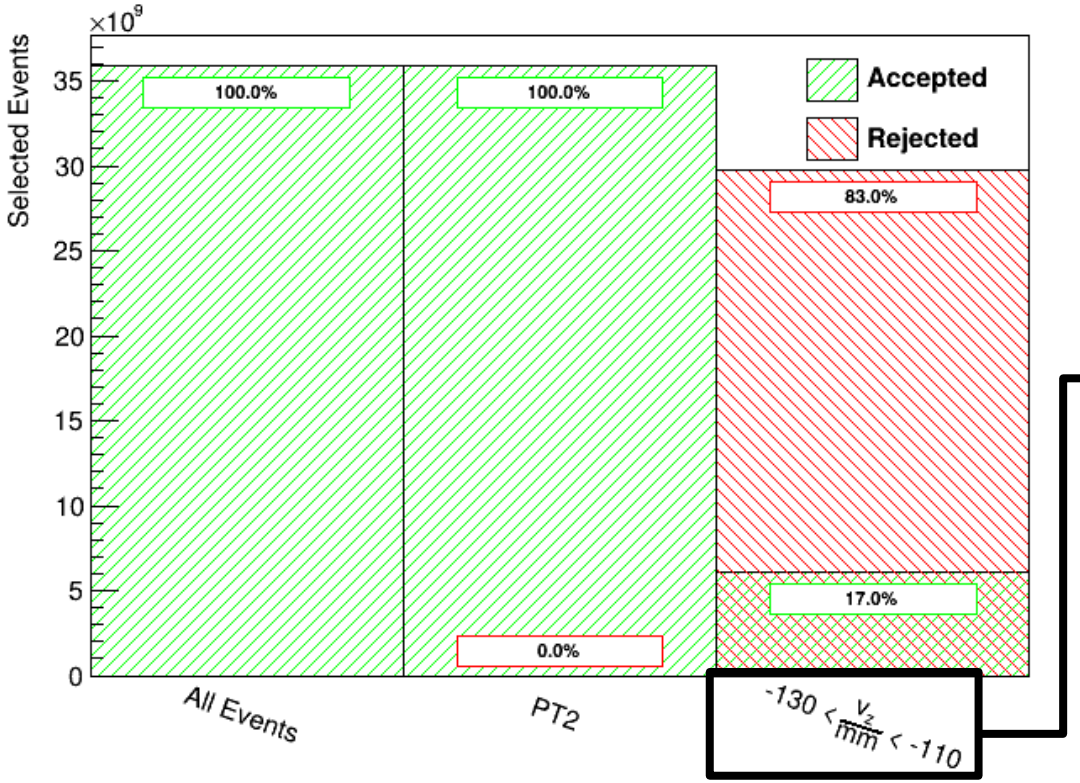


Figure 1: Illustration of the event selection procedure

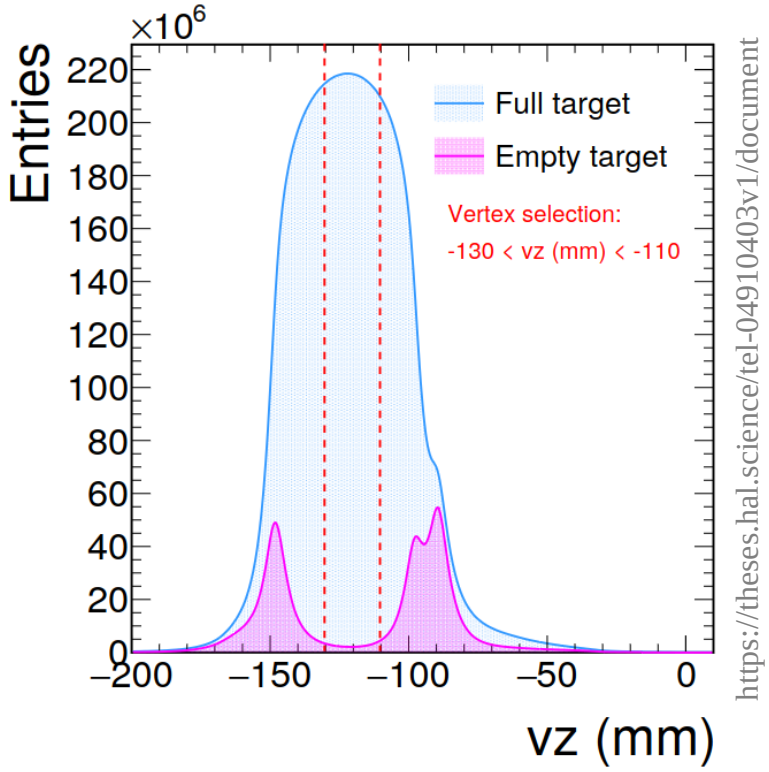


Figure 2: Z-component of primary vertex. Cut parameters obtained by Rayane.

Pre-Selection : $\langle -dE/dx \rangle_{MDC}$ Constrains

- Pre-select particle candidates via mass cut for $p, \pi^{\pm}$

$\pi^{\pm}$	[0, 500] MeV/c
p	[740, 1140] MeV/c

Table 3: Mass selection windows.

- Fit projections with modified (logarithmic) asymmetric gaussian + extrapolate

$$f(x) = A \cdot \begin{cases} \exp\left(-\frac{[\ln(x)-\mu]^2}{2\sigma_1^2}\right) & \ln(x) \leq \mu \\ \exp\left(-\frac{[\ln(x)-\mu]^2}{2\sigma_2^2}\right) & \ln(x) > \mu \end{cases}$$

- Construct $n\sigma_{1,2}$-selection region around μ to suppress abundant particles to enhance $K^{\pm}$ signal

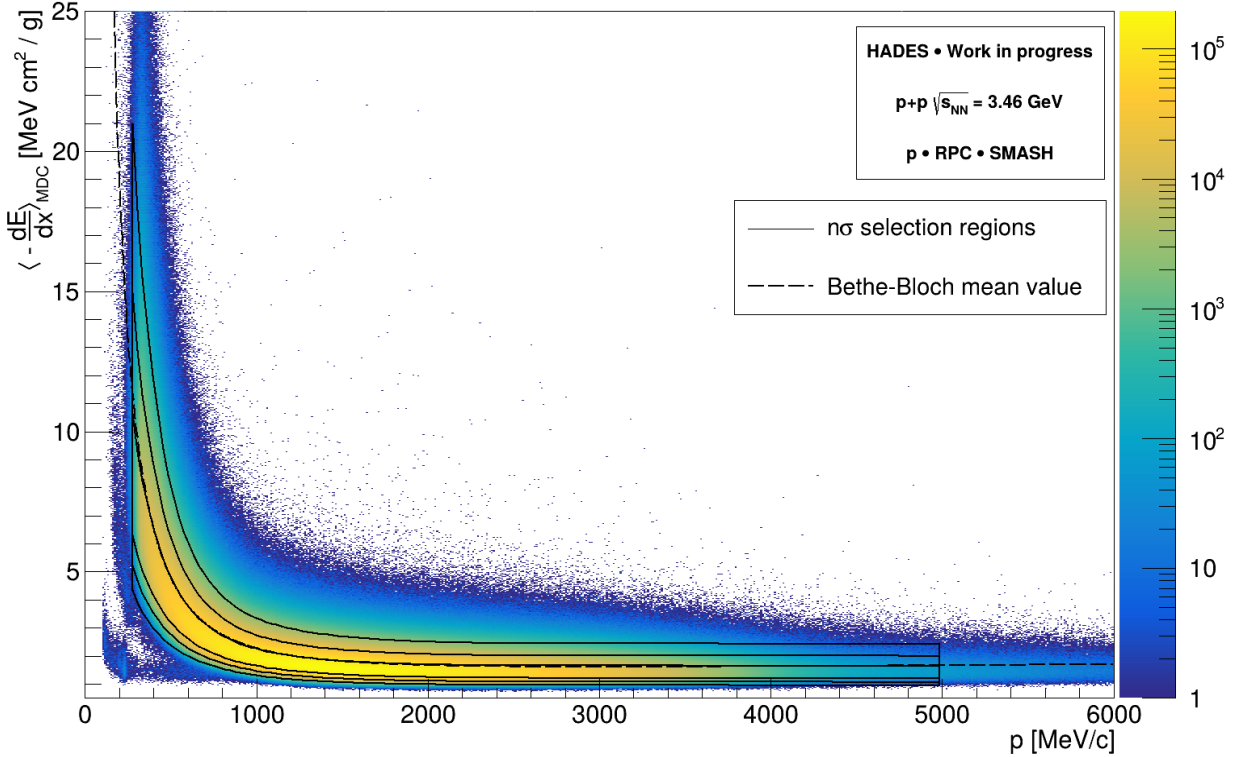


Figure 4: Specific energy loss vs. momentum over charge for proton candidates from SMASH within RPC acceptance with selection region

Ex. :<-dE/dx>$_{MDC}$ of K^+ candidates - RPC

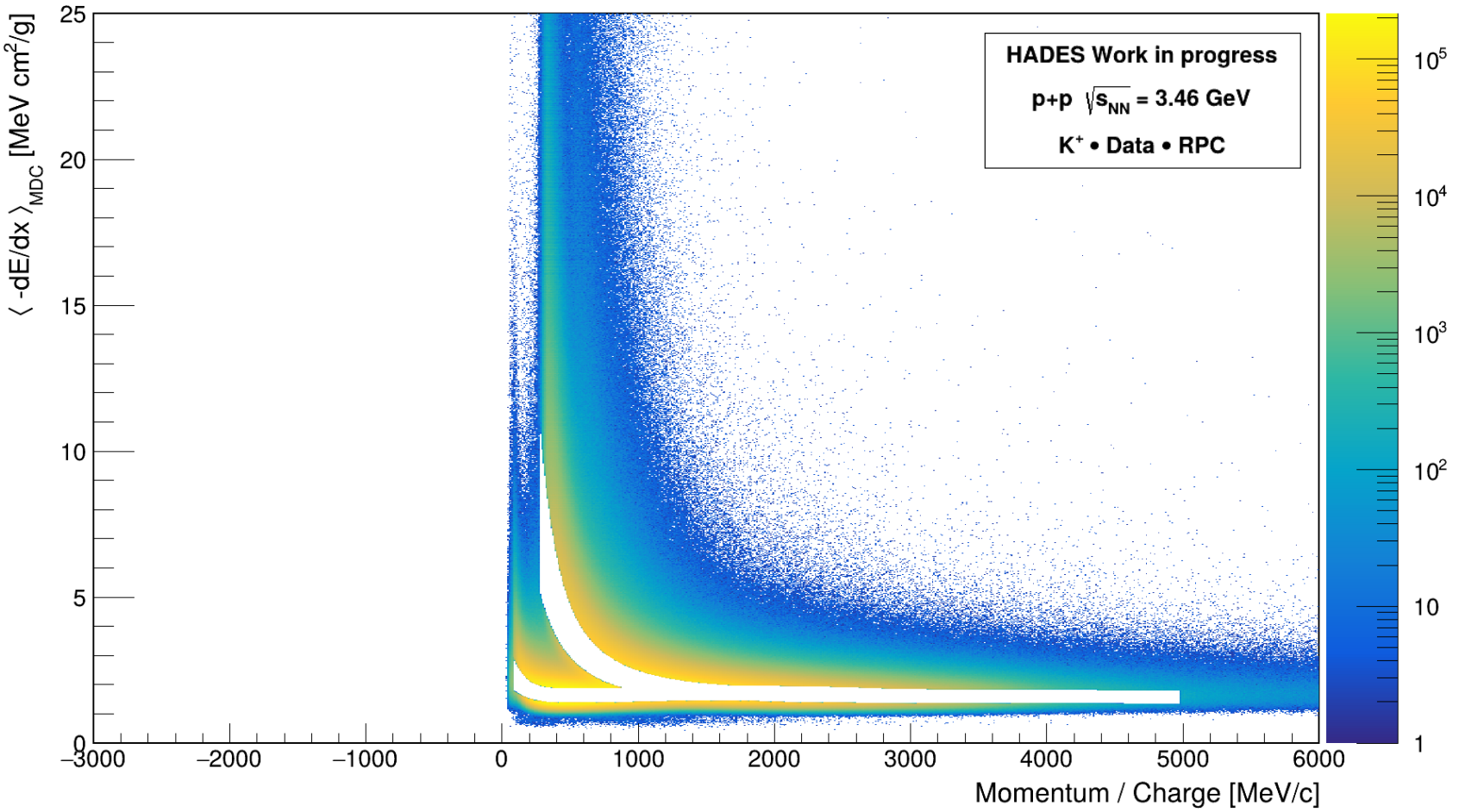


Figure 5: Specific energy loss vs. momentum over charge for K^+ candidates from within RPC acceptance with 1σ-exclusion cuts for p, π^+ applied.

Multi-Differential Analysis of $K^{\pm}$

	K^+	K^-
χ^2_{RK} (dflt) MetaQa (dflt) nLayer (dflt)	< 400 < 3 -	< 200 < 2 ≥ 23
Pre-selection dE/dx	p, π^+ (1σ excl.)	π^- (1σ excl.)
p_t-range binning	[0, 800] MeV/c 40 bins	[0, 800] MeV/c 20 bins
y-range binning	[-2.05, 2.95] 40 bins	[-2.1, 2.9] 20 bins
m^2-range binning	[0.04, 0.64] $(GeV/c^2)^2$ * 300 bins	

Table 2: Analysis details

* $(m_{K^{\pm}})^2 \approx (493\,MeV/c^2)^2 \approx 0.244\,(GeV/c^2)^2$

Signal Extraction

- Combines cubic spline interpolation [1] with iterative fitting procedure
- Deduct background to obtain signal estimate
- Fit signal estimate with asymmetric gaussian
- Integrate full spectrum within $2\sigma_{1,2}$-range, deduct integrated background to obtain yield

$$B = \int_{\mu-2\sigma_1}^{\mu+2\sigma_2} \left(\frac{\mathrm{d}N}{\mathrm{d}m^2}\right)_{\text{Back}} (p_t, y)\,\mathrm{d}m^2$$

$$S = \int_{\mu-2\sigma_1}^{\mu+2\sigma_2} \left(\frac{\mathrm{d}N}{\mathrm{d}m^2}\right)_{\text{All}} (p_t, y)\,\mathrm{d}m^2 - B$$

[1] https://indico.gsi.de/event/17507/contributions/72724/attachments/44289/62424/HADES_SimAna_DeuteronEmission.pdf

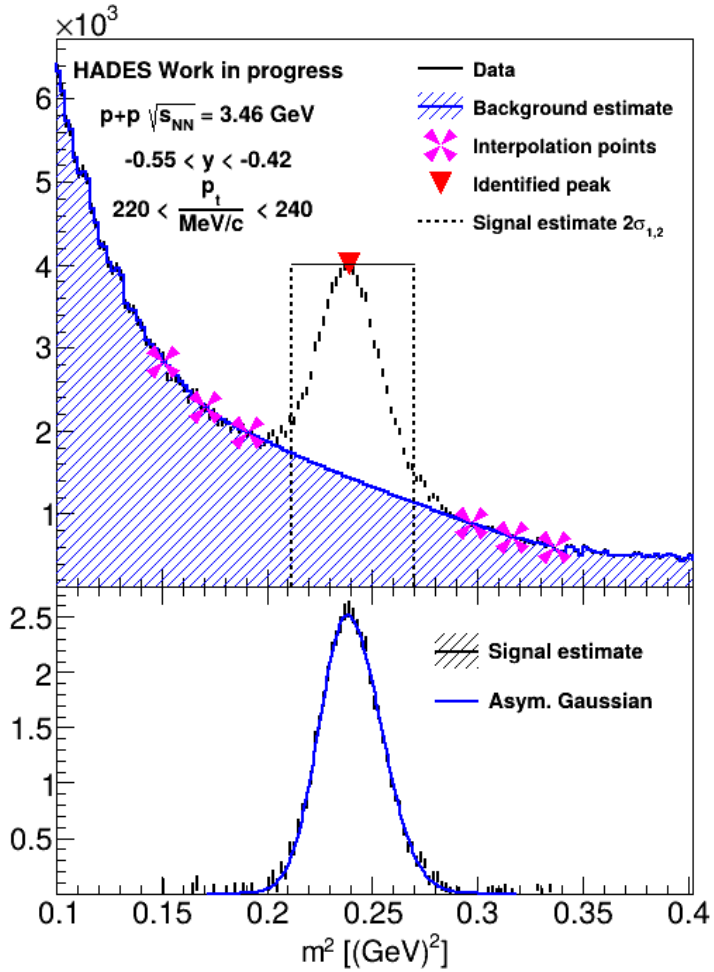


Figure 6: Interpolated mass histogram of K^+ candidates

Signal Extraction : Simulation vs. Data

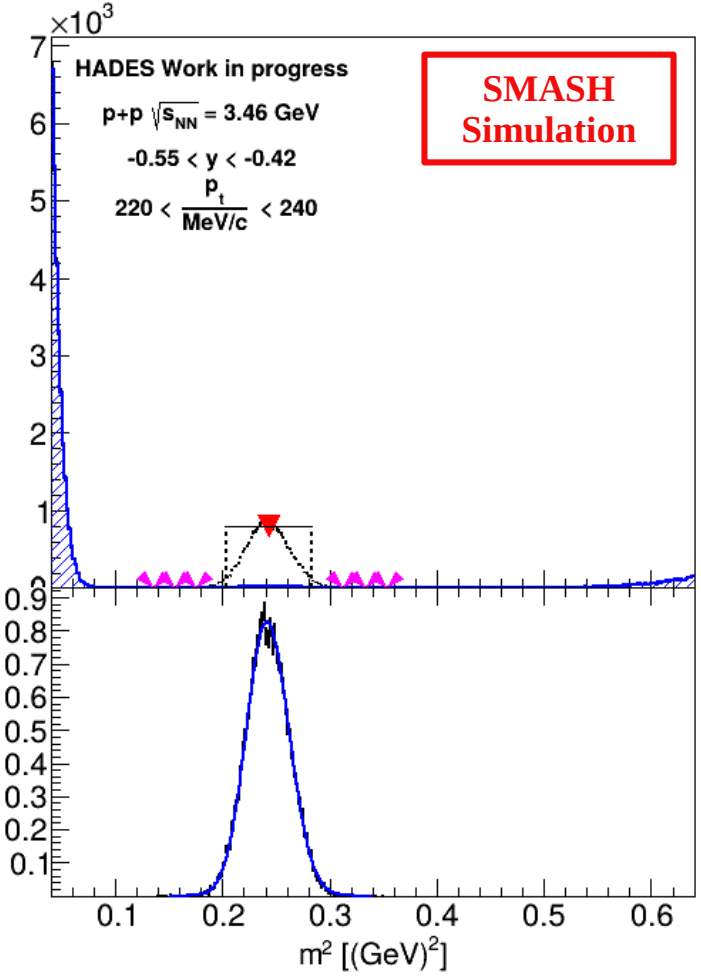


Figure 8: Interpolated mass histogram of K^+ candidates from SMASH simulation.

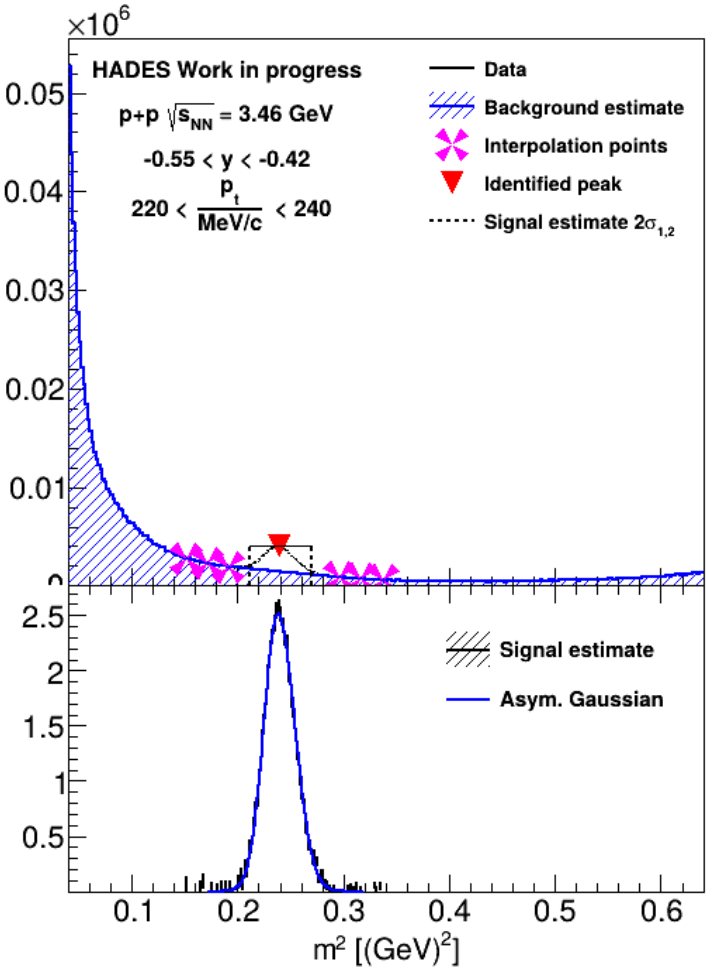


Figure 7: Interpolated mass histogram of K^+ candidates from real data.

Signal Extraction : Simulation vs. Data

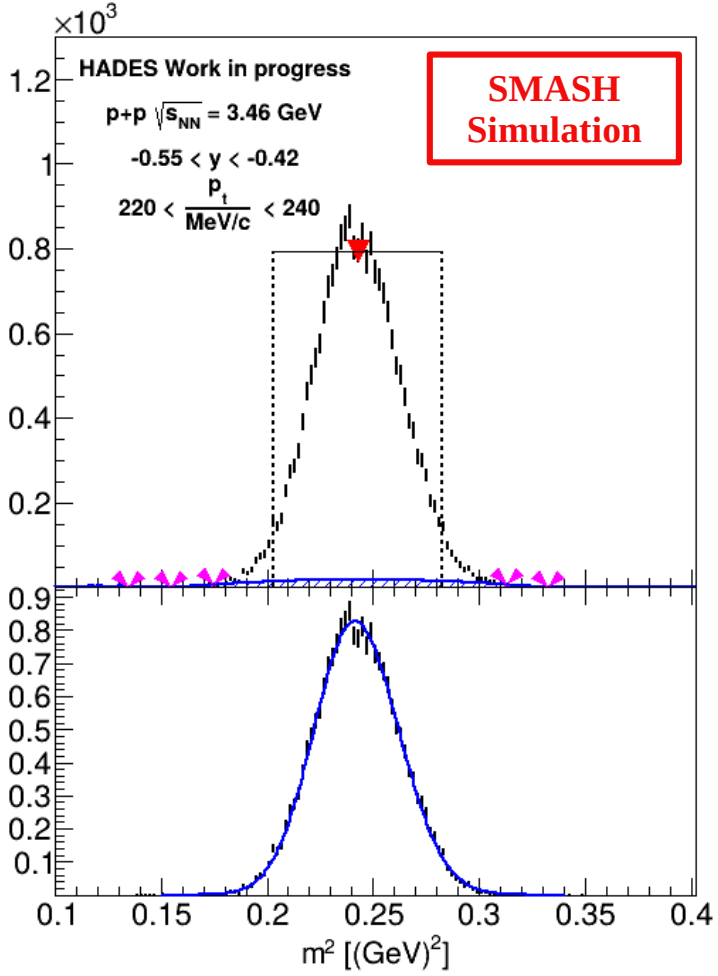


Figure 10: Interpolated mass histogram of K^+ candidates from SMASH simulation.

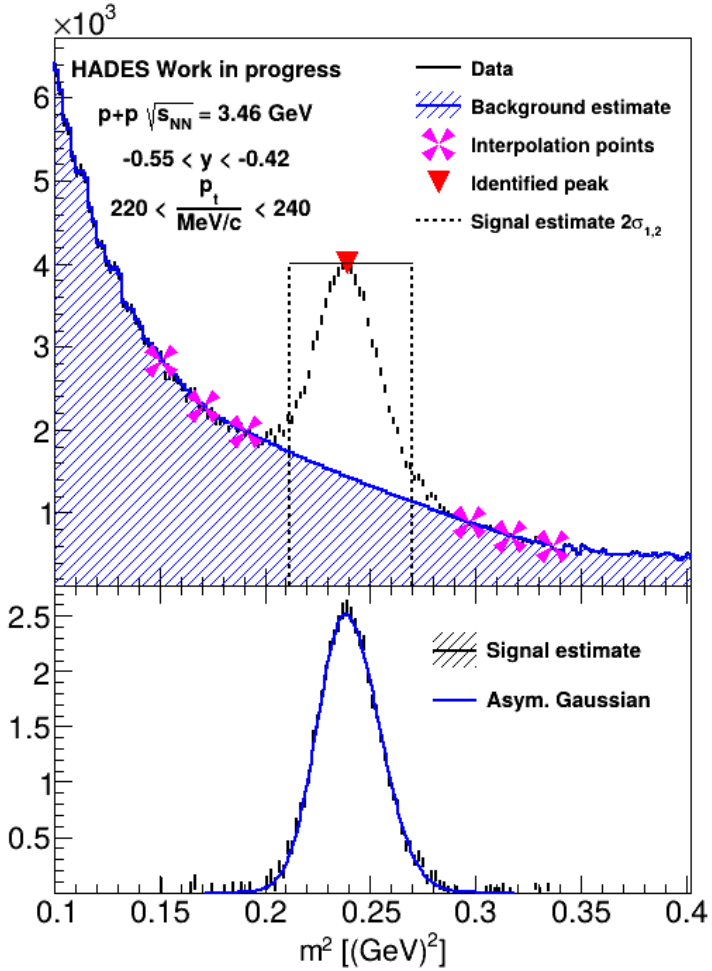


Figure 9: Interpolated mass histogram of K^+ candidates from real data.

Signal Extraction : Rejection Criteria

Reason	Rejected if ...	Comment
Insufficient statistics	$\int \left(\frac{dN}{dm^2}\right)_{\text{All}} (p_t, y)\, dm^2 < 1000$	
Signal dominance	$\left[S/B\right](p_t, y) < 0.15$	$B = \int_{\mu-2\sigma_1}^{\mu+2\sigma_2} \left(\frac{\mathrm{d}N}{\mathrm{d}m^2}\right)_{\text{Back}} (p_t, y)\, \mathrm{d}m^2$ $S = \int_{\mu-2\sigma_1}^{\mu+2\sigma_2} \left(\frac{\mathrm{d}N}{\mathrm{d}m^2}\right)_{\text{All}} (p_t, y)\, \mathrm{d}m^2 - B$
Statistical error	$\left[(\Delta S)/S\right](p_t, y) > 0.2$	(ΔS) : Statistical error in a bin. Applied individually to raw as well as corrected and normalized yields.
Missing $K^{\pm}$ peak	No valid peak within $[0.224, 0.264]\,(\text{GeV}/c^2)^2$	$(m_{K^{\pm}})^2 \approx 0.244\,(\text{GeV}/c^2)^2$
Interpolation / fitting error		Use class-based error status
Insufficient simulation	$[S^{\text{Rec}}_{\text{Sim}}/N^{\text{Gen}}_{\text{Sim}}](p_t, y) \notin [0.1, 1]$	$N^{\text{Gen}}_{\text{Sim}}$: generated particles from SMASH
Correction error	$\text{IsNaN}(S^{\text{Corr}}) \vee \text{!isFinite}(S^{\text{Corr}}) \vee$ $\text{isNaN}(\Delta S^{\text{Corr}}) \vee \text{!isFinite}(\Delta S^{\text{Corr}})$	$S^{\text{Corr}}(\Delta S^{\text{Corr}})$: Corrected and normalized yield (statistical error)

Table 4: Differential mass spectra rejection criteria.

Signal Extraction : Rejection Criteria

Reason	Rejected if ...
Insufficient statistics	$\int \left(\frac{dN}{dm^2}\right)_{\text{All}} (p_t, y)\, dm^2 < 1000$
Signal dominance	$\left[S/B\right](p_t, y) < 0.15$
Statistical error	$\left[(\Delta S)/S\right](p_t, y) > 0.2$
Missing $K^{\pm}$ peak	No valid peak within $[0.224, 0.264]\ (\text{GeV}/c^2)^2$
Interpolation / fitting error	
Insufficient simulation	$[S^{\text{Rec}}_{\text{Sim}}/N^{\text{Gen}}_{\text{Sim}}](p_t, y) \notin [0.1, 1]$
Correction error	$\text{IsNaN}(S^{\text{Corr}}) \vee \text{!isFinite}(S^{\text{Corr}}) \vee$ $\text{isNaN}(\Delta S^{\text{Corr}}) \vee \text{!isFinite}(\Delta S^{\text{Corr}})$

- **“Statistics”**
- **“Signal extraction”**
- **“Simulation”**

K^+ : Raw Yields

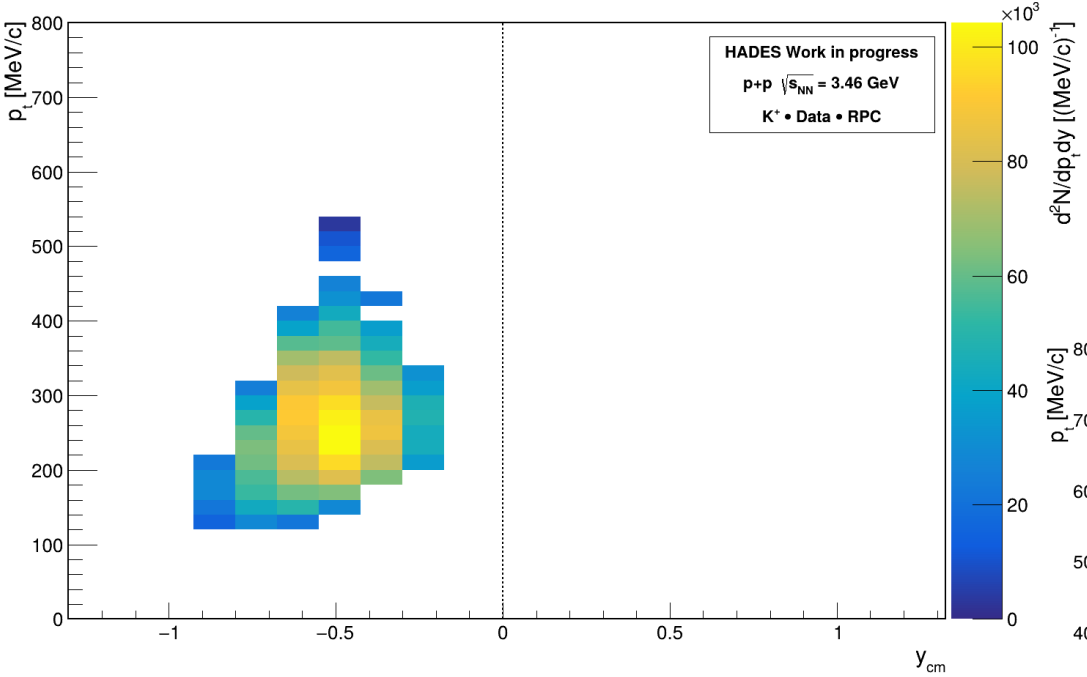
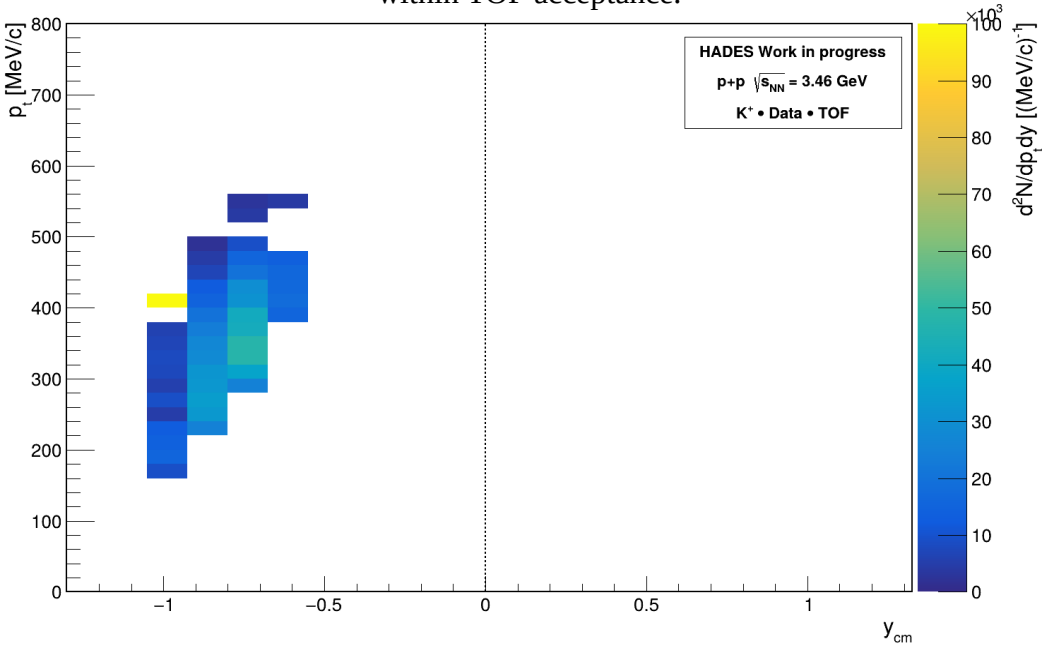
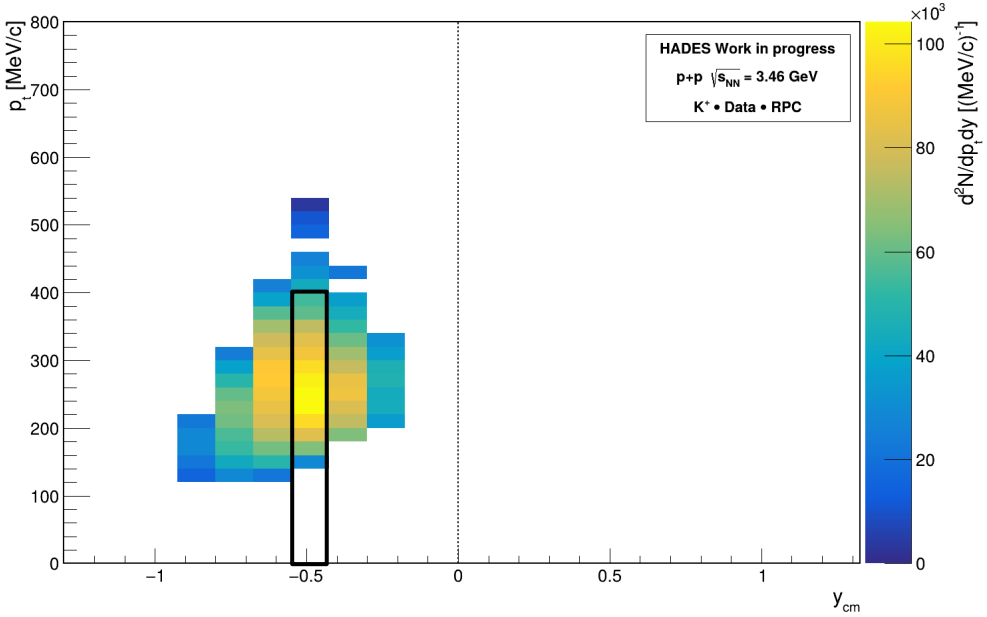


Figure 11: Reconstructed momentum-space distribution of K^+ measured within RPC acceptance.

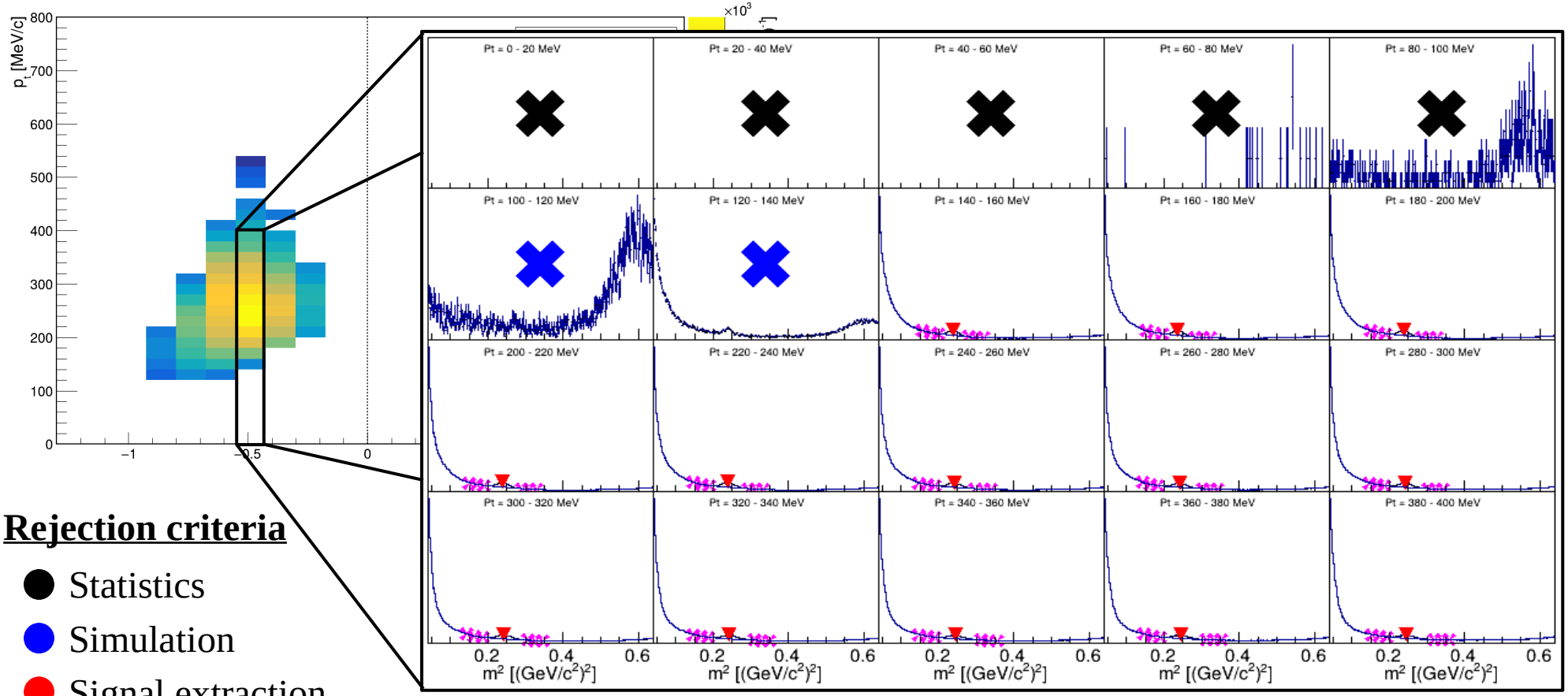
Figure 12: Reconstructed momentum-space distribution of K^+ measured within TOF acceptance.



K^+ : Raw Yields


HADES Work in progress
p+p $\sqrt{s_{NN}}$ = 3.46 GeV
K^+ • Data • RPC
p_t [MeV/c]
y_{cm}
$d^2N/dp_t dy$ [(MeV/c)$^{-1}$]
×10^3

K^+ : Raw Yields

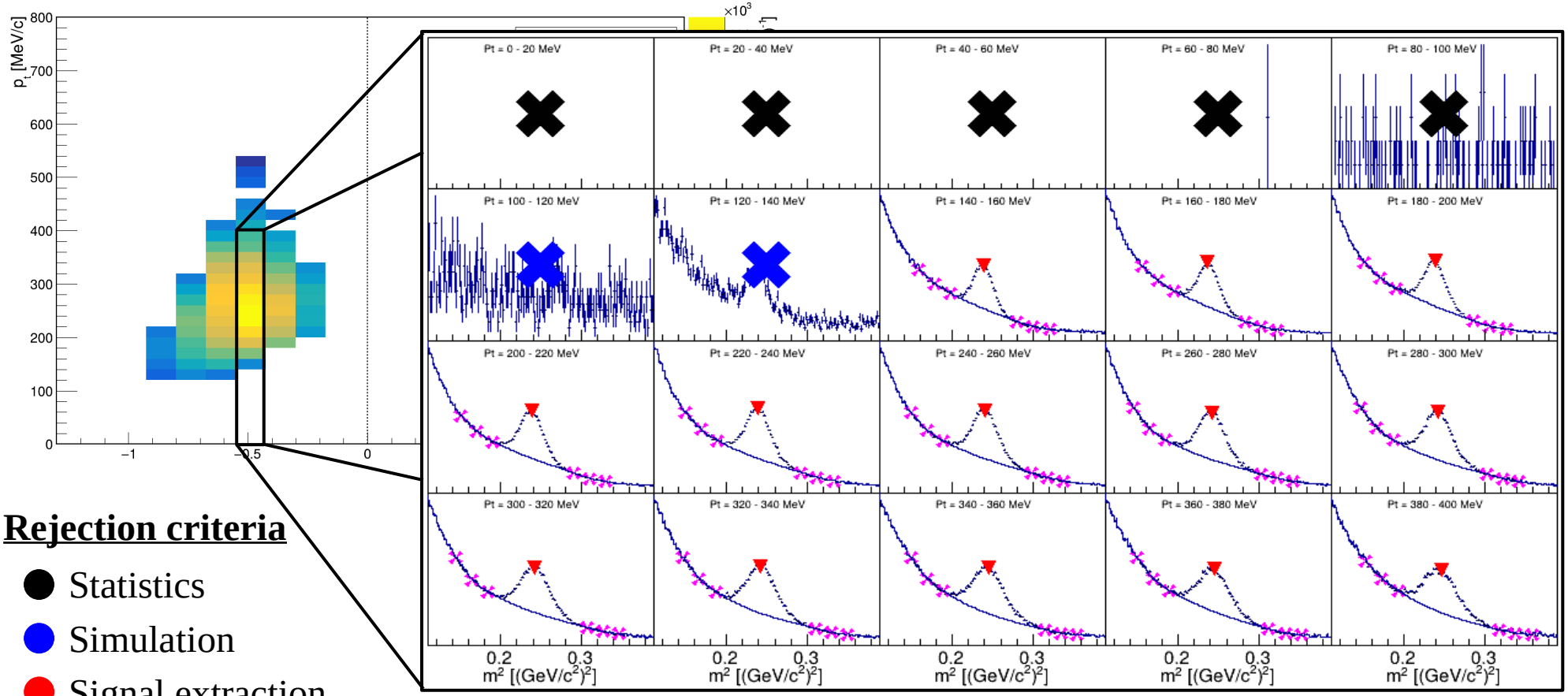


Rejection criteria

- Statistics
- Simulation
- Signal extraction

Figure 13: Differential mass spectra of K^+ candidates measured by the RPC detector.

K^+ : Raw Yields

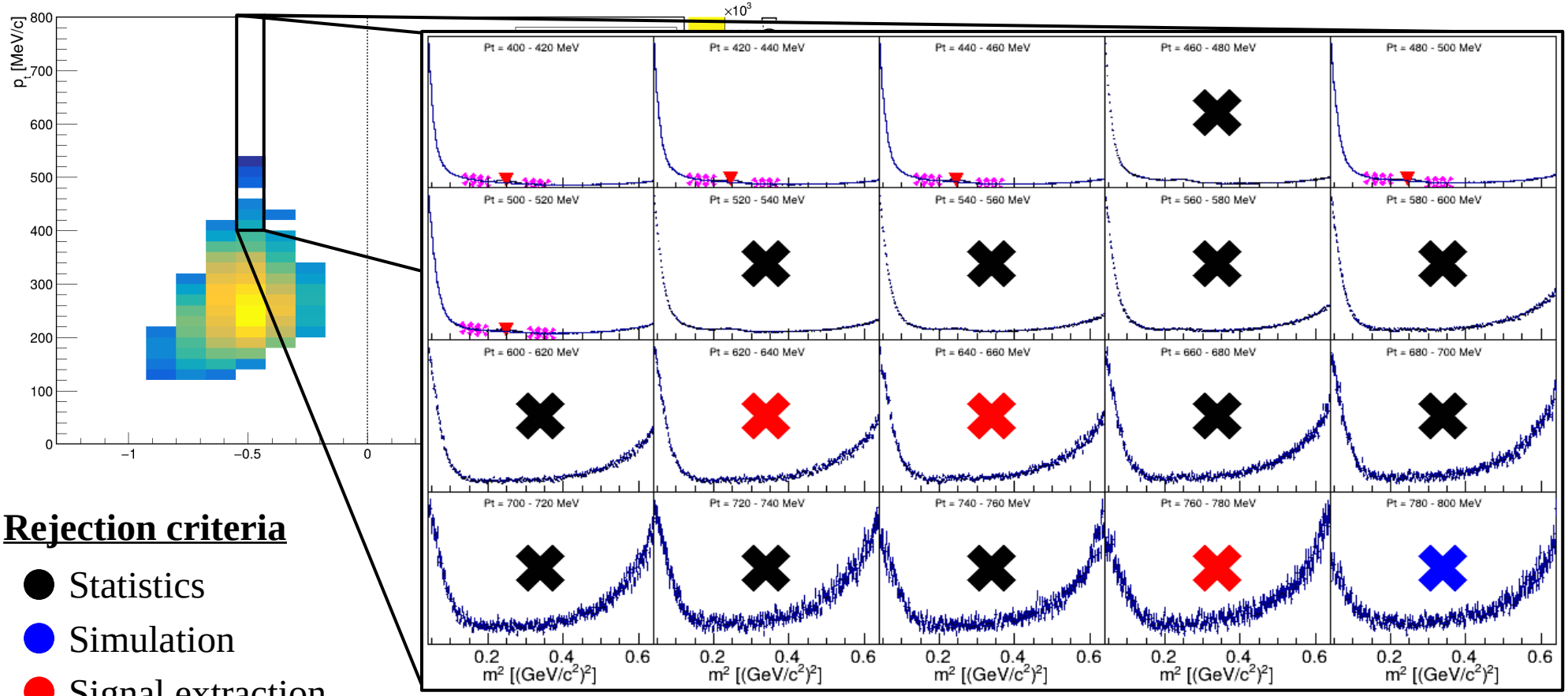


Rejection criteria

- Statistics
- Simulation
- Signal extraction

Figure 14: Differential mass spectra of K^+ candidates measured by the RPC detector.

K^+ : Raw Yields

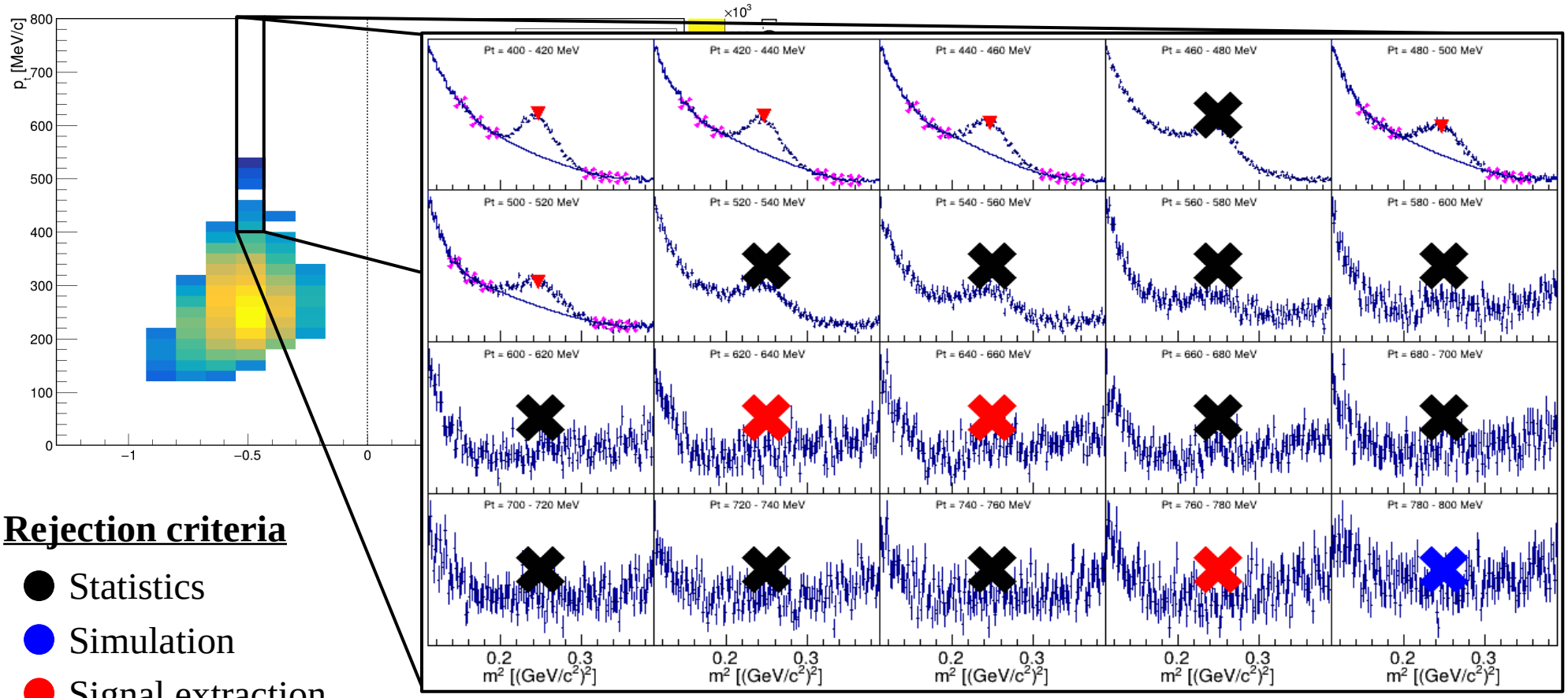


Rejection criteria

- Statistics
- Simulation
- Signal extraction

Figure 15: Differential mass spectra of K^+ candidates measured by the RPC detector.

K^+ : Raw Yields

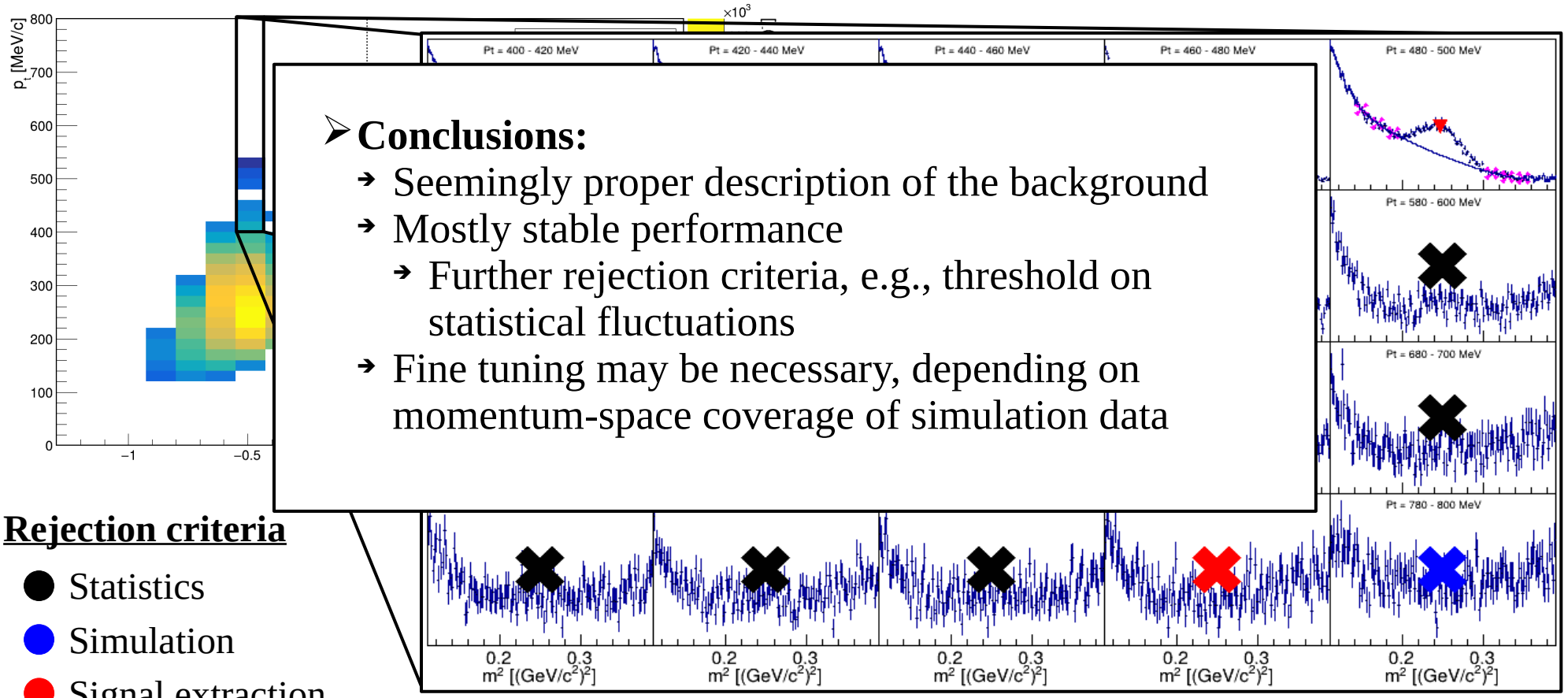


Rejection criteria

- Statistics
- Simulation
- Signal extraction

Figure 16: Differential mass spectra of K^+ candidates measured by the RPC detector.

K^+ : Raw Yields



Conclusions:

- Seemingly proper description of the background
- Mostly stable performance
  - Further rejection criteria, e.g., threshold on statistical fluctuations
- Fine tuning may be necessary, depending on momentum-space coverage of simulation data

Rejection criteria

- Statistics
- Simulation
- Signal extraction

Figure 16: Differential mass spectra of K^+ candidates measured by the RPC detector.

K^+ : Raw Yields : SMASH

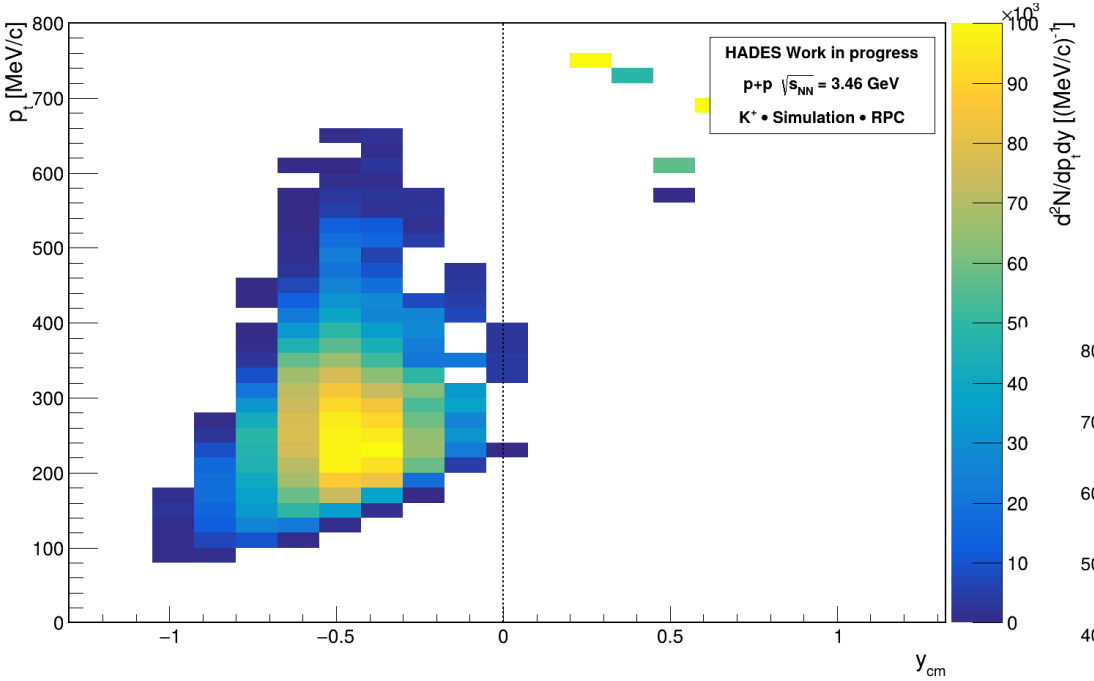
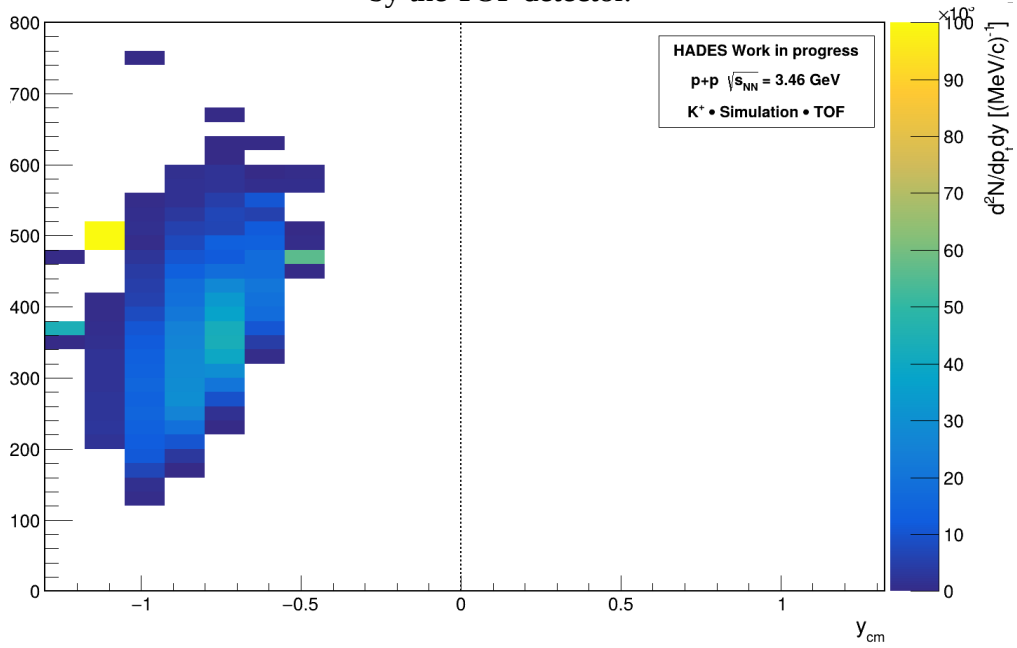
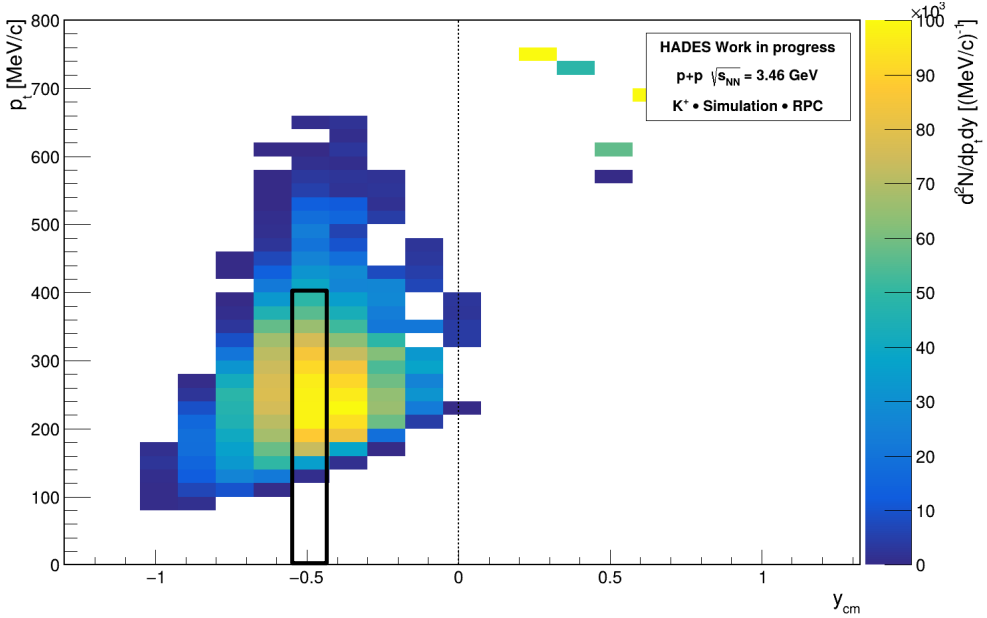


Figure 17: Reconstructed momentum-space distribution of K^+ measured by the RPC detector.

Figure 18: Reconstructed momentum-space distribution of K^+ measured by the TOF detector.



K^+ : Raw Yields : SMASH



K^+ : Raw Yields : SMASH

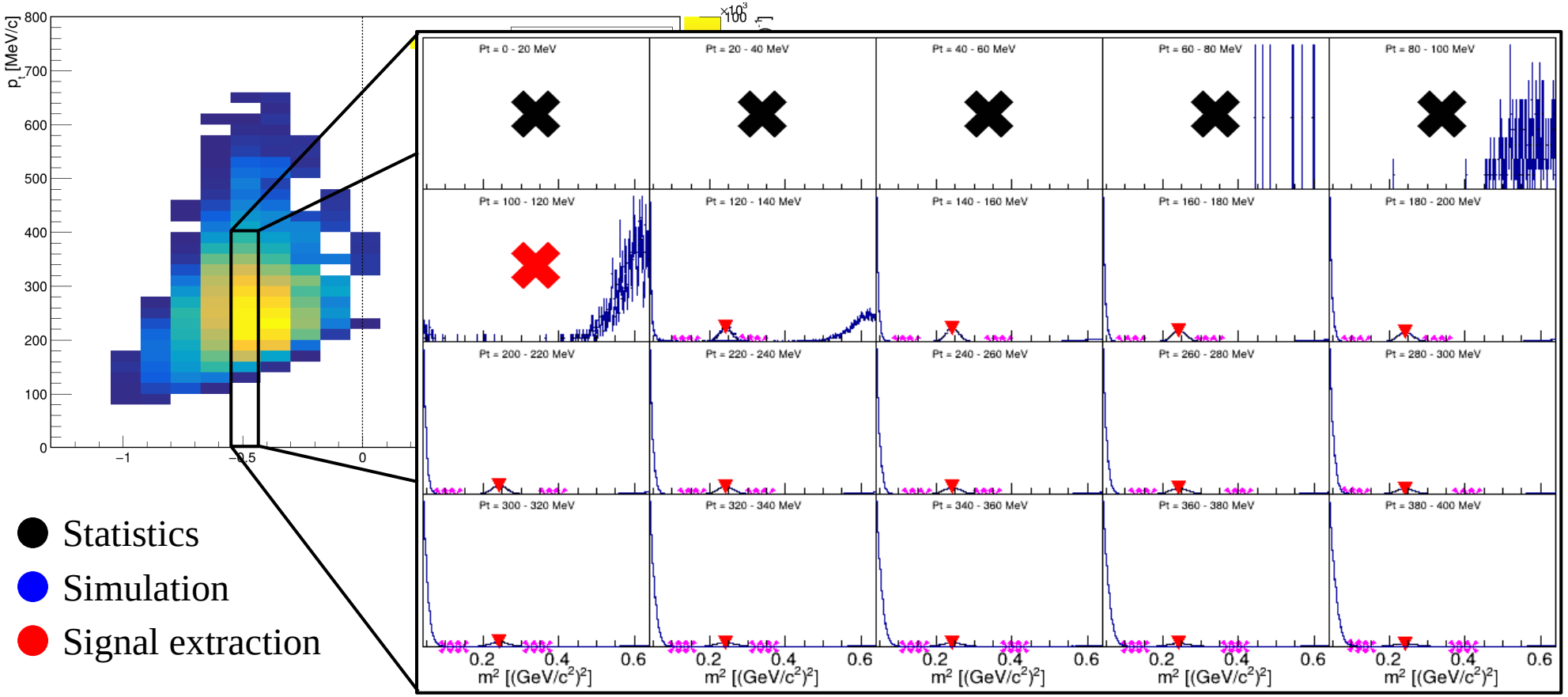


Figure 19: Differential mass spectra of K^+ candidates measured by the RPC detector.

K^+ : Raw Yields : SMASH

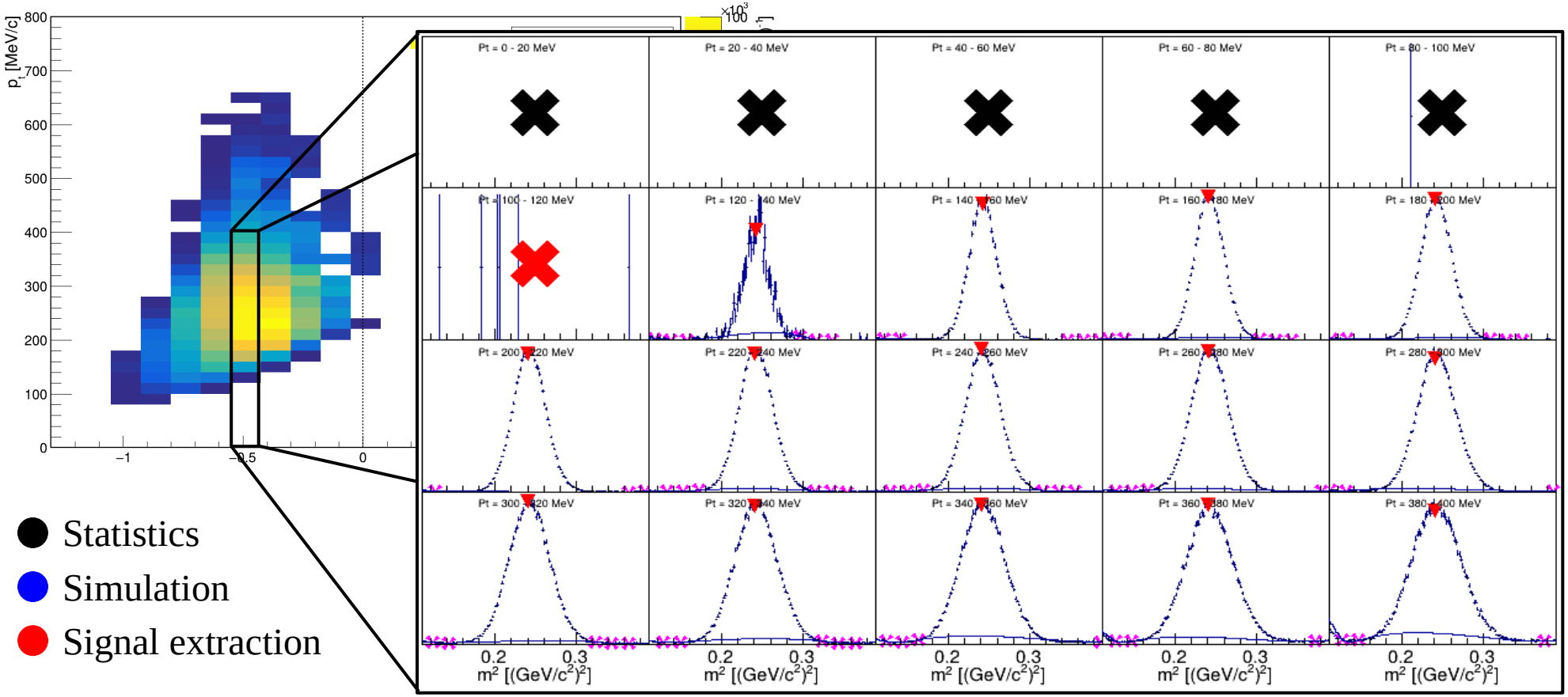


Figure 20: Differential mass spectra of K^+ candidates measured by the RPC detector.

K^+ : Raw Yields : SMASH

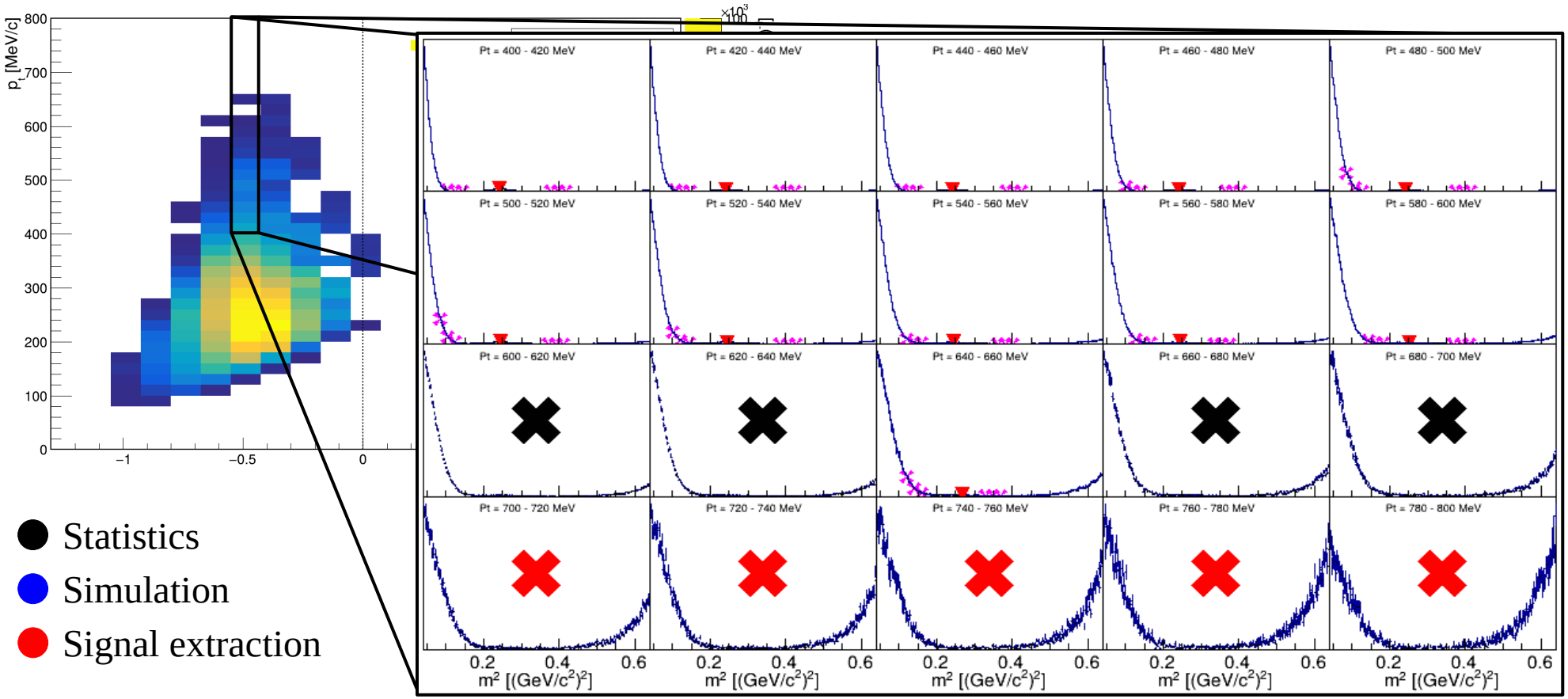


Figure 21: Differential mass spectra of K^+ candidates measured by the RPC detector.

K^+ : Raw Yields : SMASH

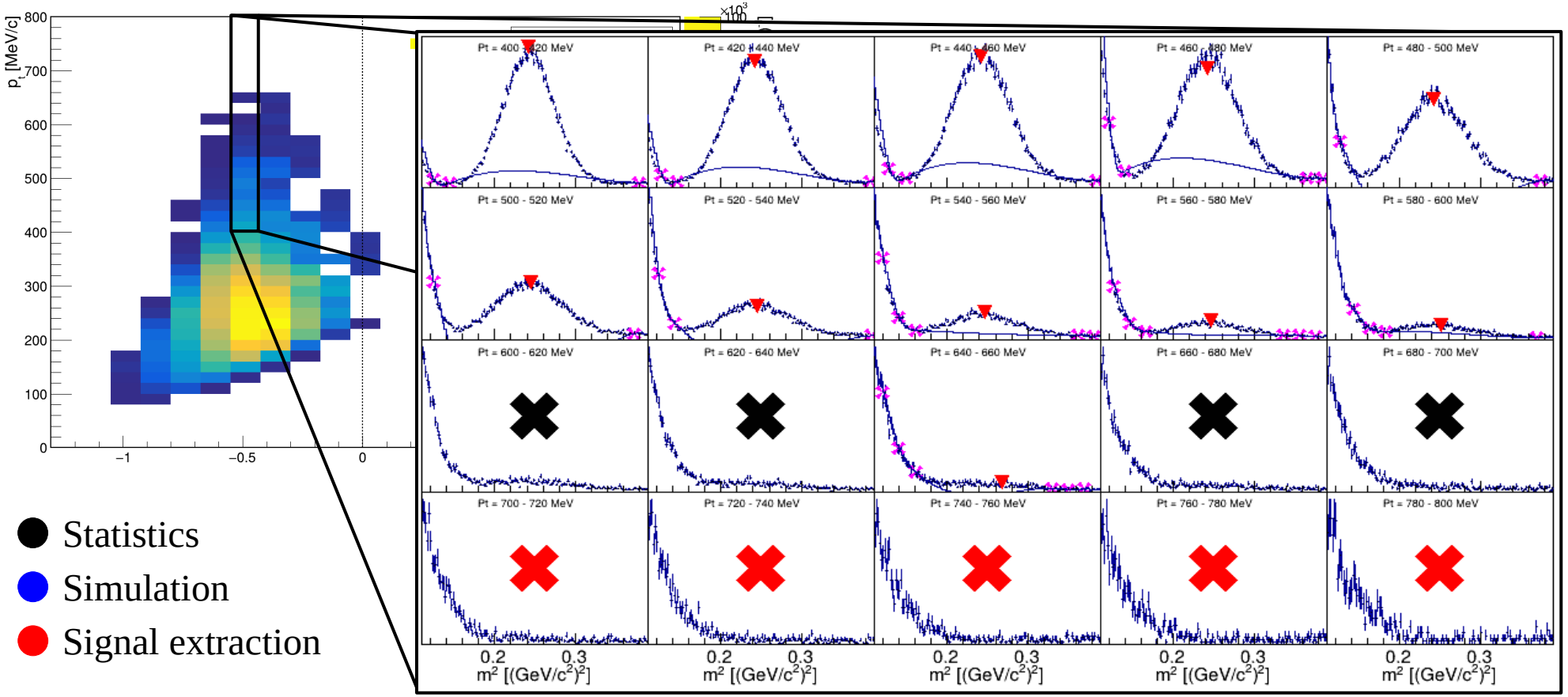
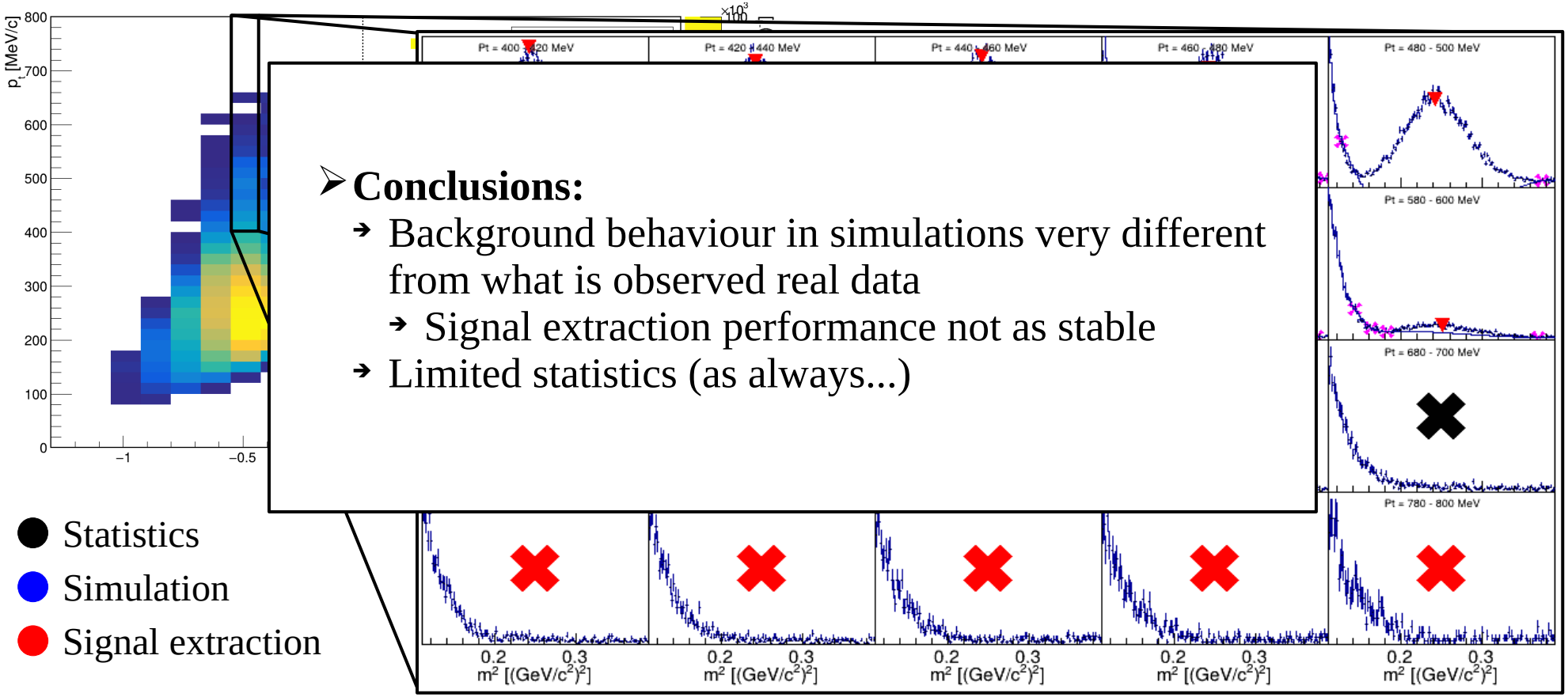


Figure 22: Differential mass spectra of K^+ candidates measured by the RPC detector.

K^+ : Raw Yields : SMASH



- **Conclusions:**
  - Background behaviour in simulations very different from what is observed real data
    - Signal extraction performance not as stable
  - Limited statistics (as always...)

Figure 22: Differential mass spectra of K^+ candidates measured by the RPC detector.

K^+ : Acceptance X Efficiency Matrices

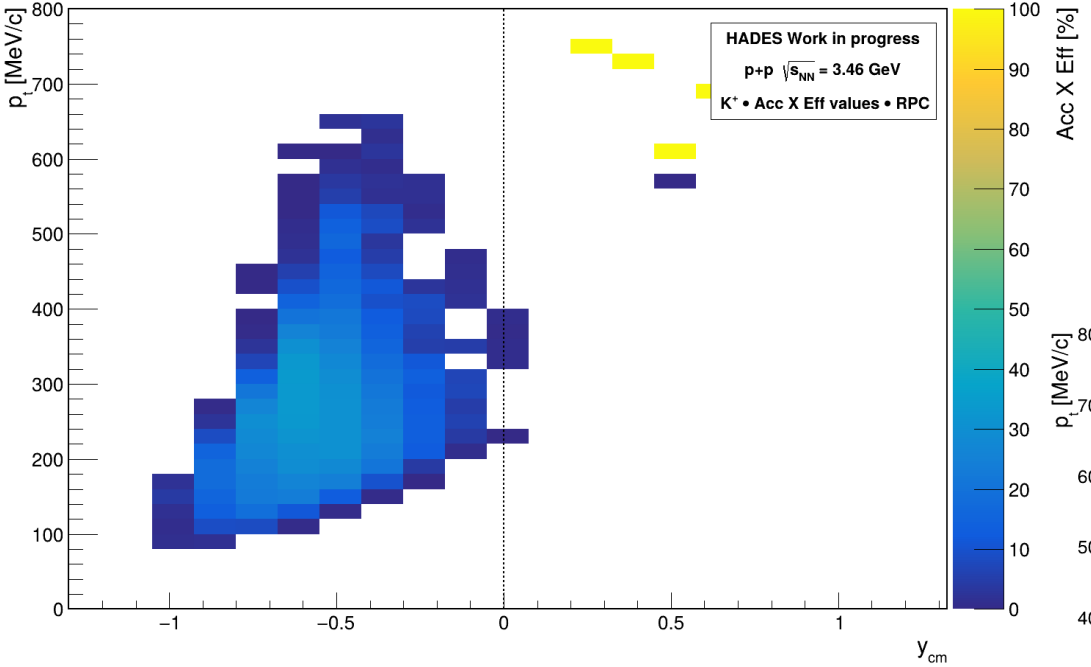
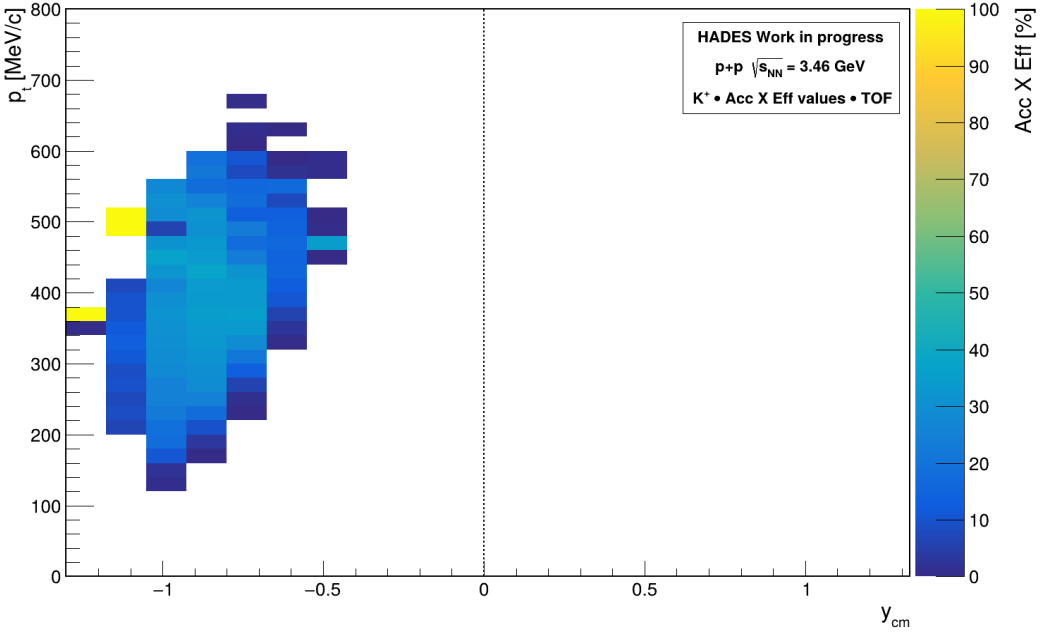


Figure 23: Acc X Eff values of K^+ measured by the RPC detector.

Figure 24: Acc X Eff values of K^+ measured by the TOF detector.



First Results : K^+ Multiplicities

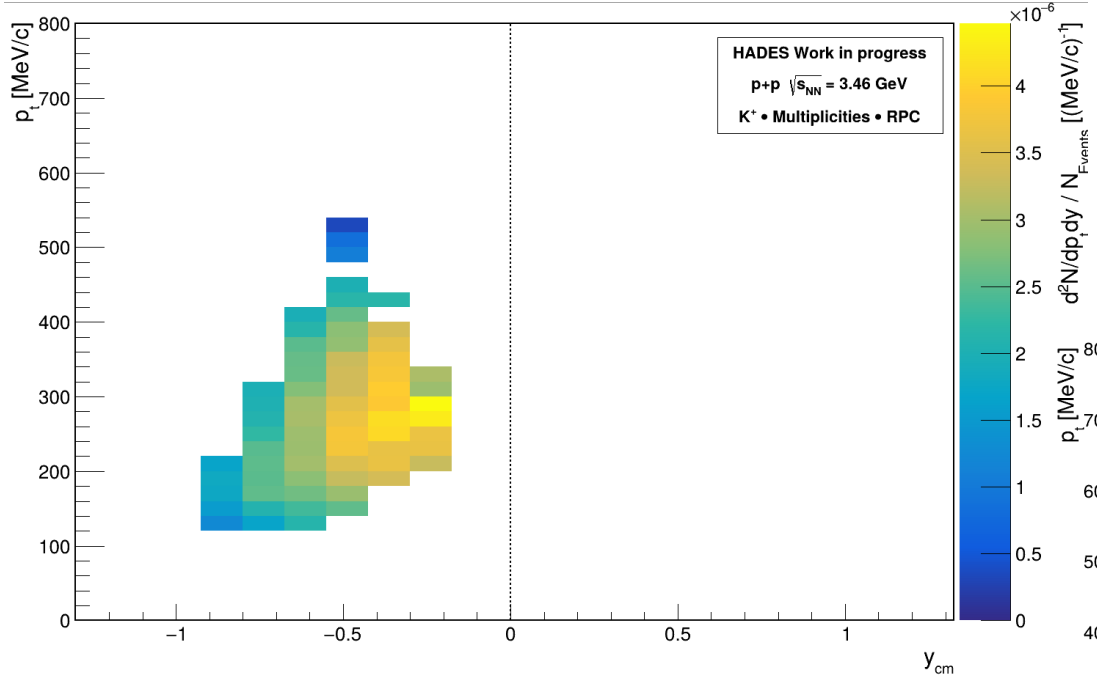
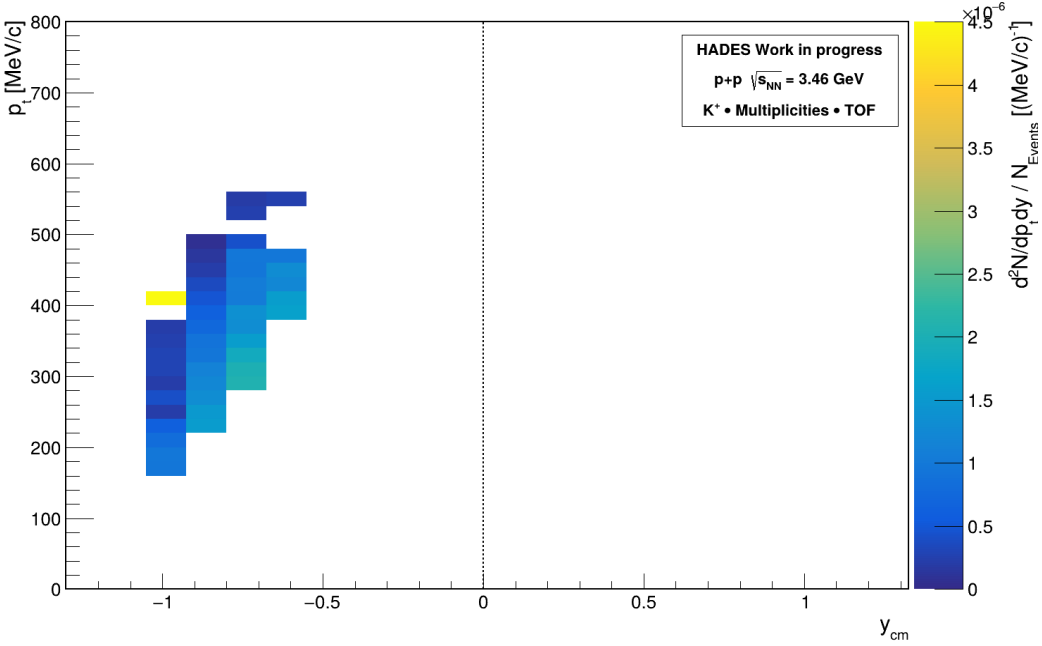


Figure 25: Corrected and normalized multiplicities of K^+ measured by the RPC detector.

Figure 26: Corrected and normalized multiplicities of K^+ measured by the TOF detector.



First Results : K^+ Multiplicities

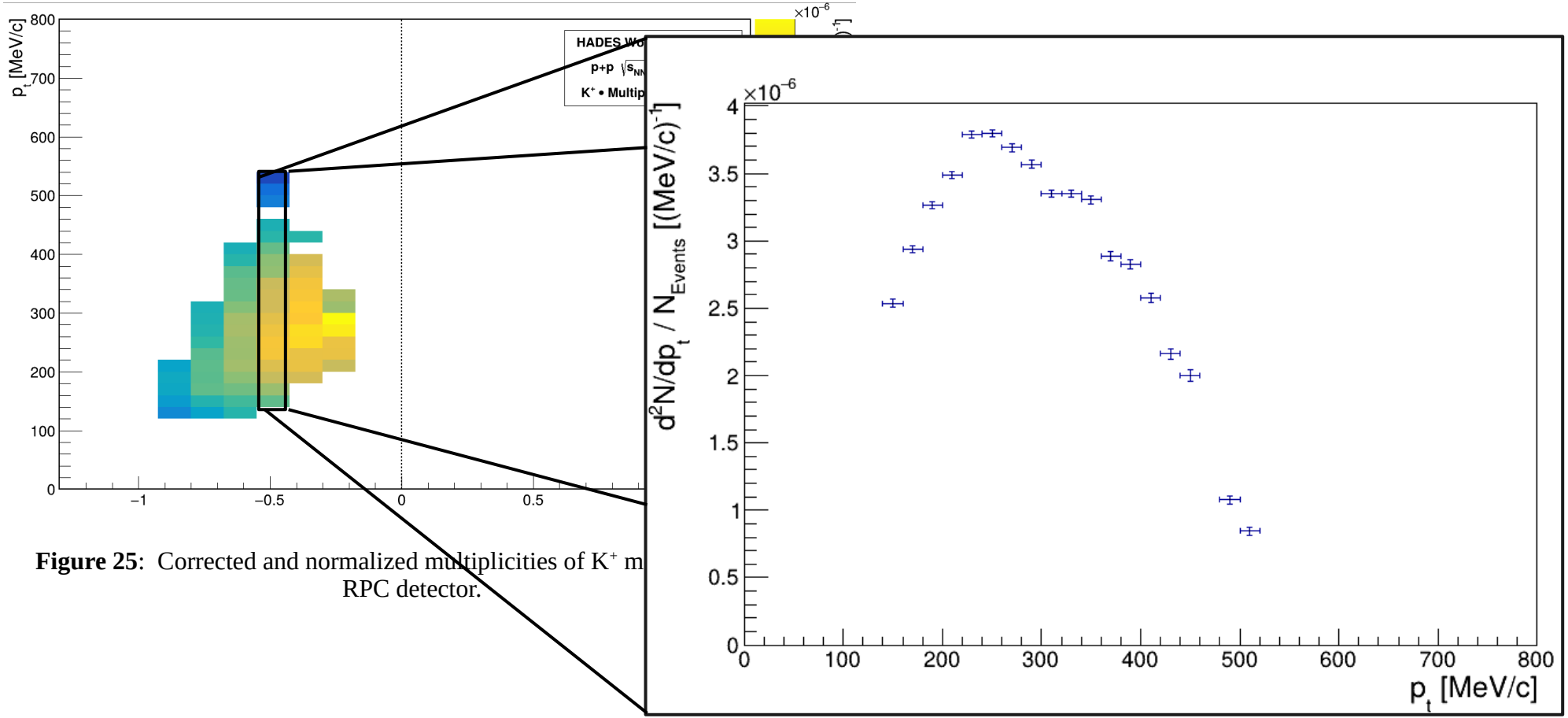


Figure 25: Corrected and normalized multiplicities of K^+ m
RPC detector.

K^- : Raw Yields

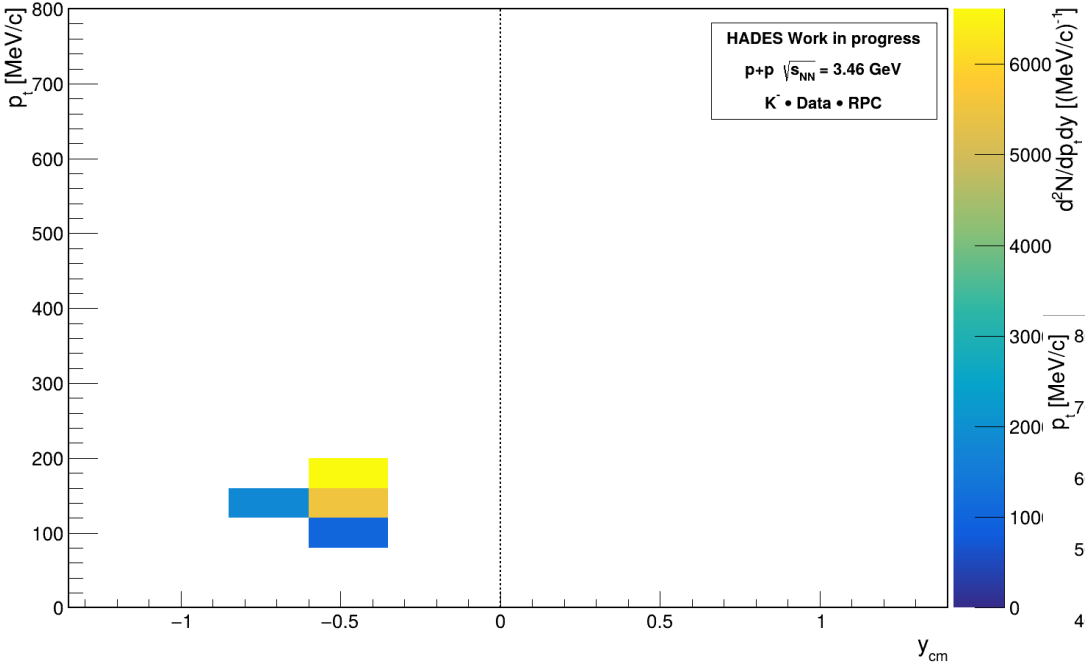
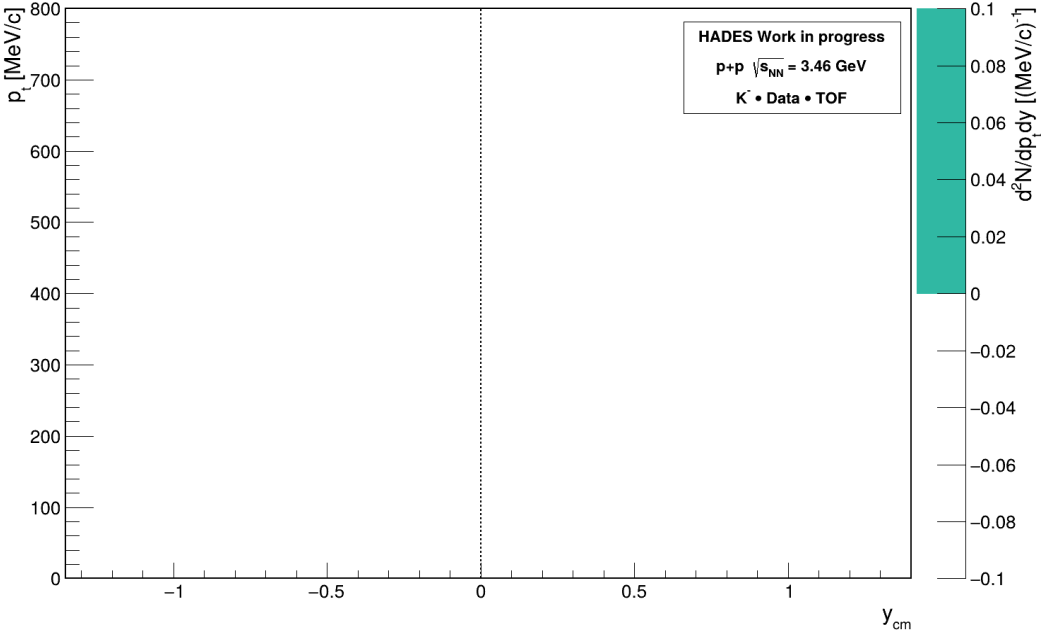
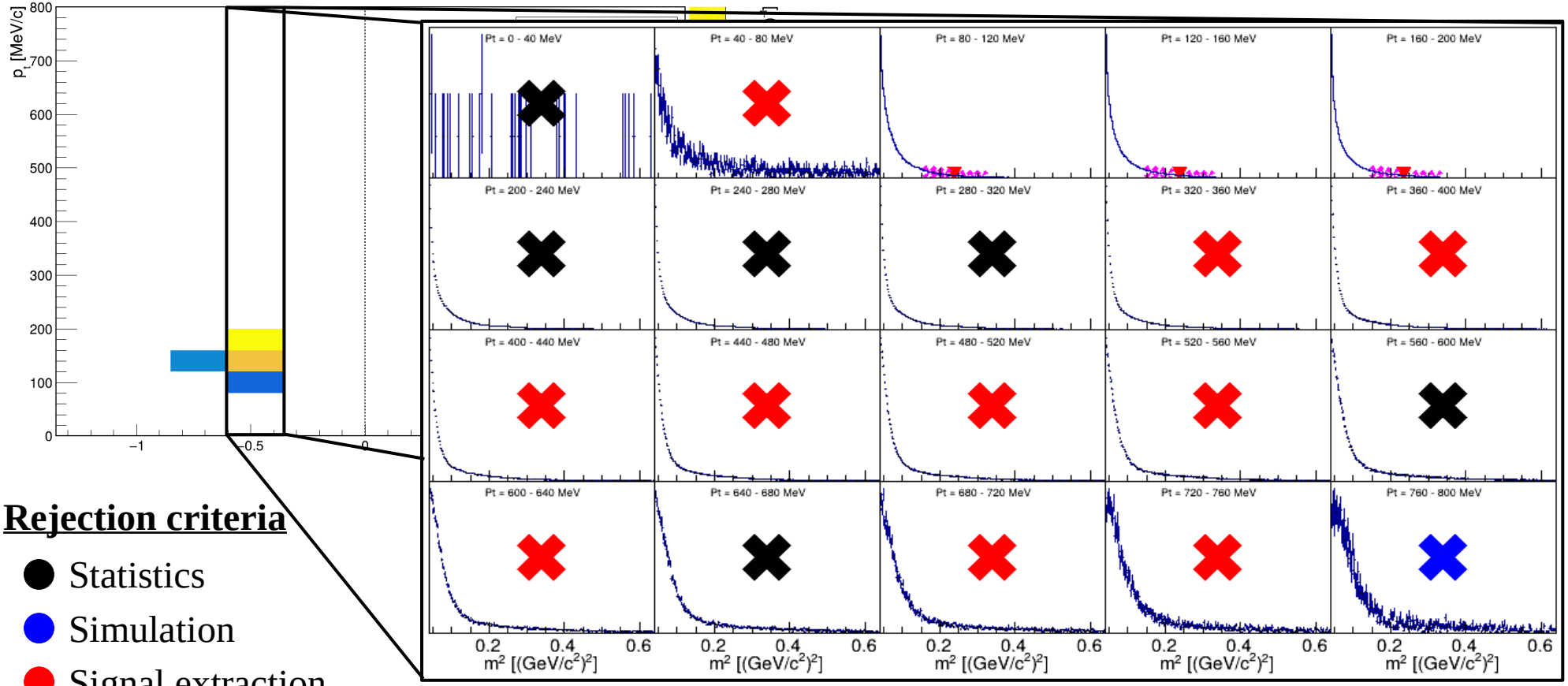


Figure 27: Reconstructed momentum-space distribution of K^+ measured by the RPC detector.

Figure 28: Reconstructed momentum-space distribution of K^+ measured by the TOF detector.



K^- : Raw Yields

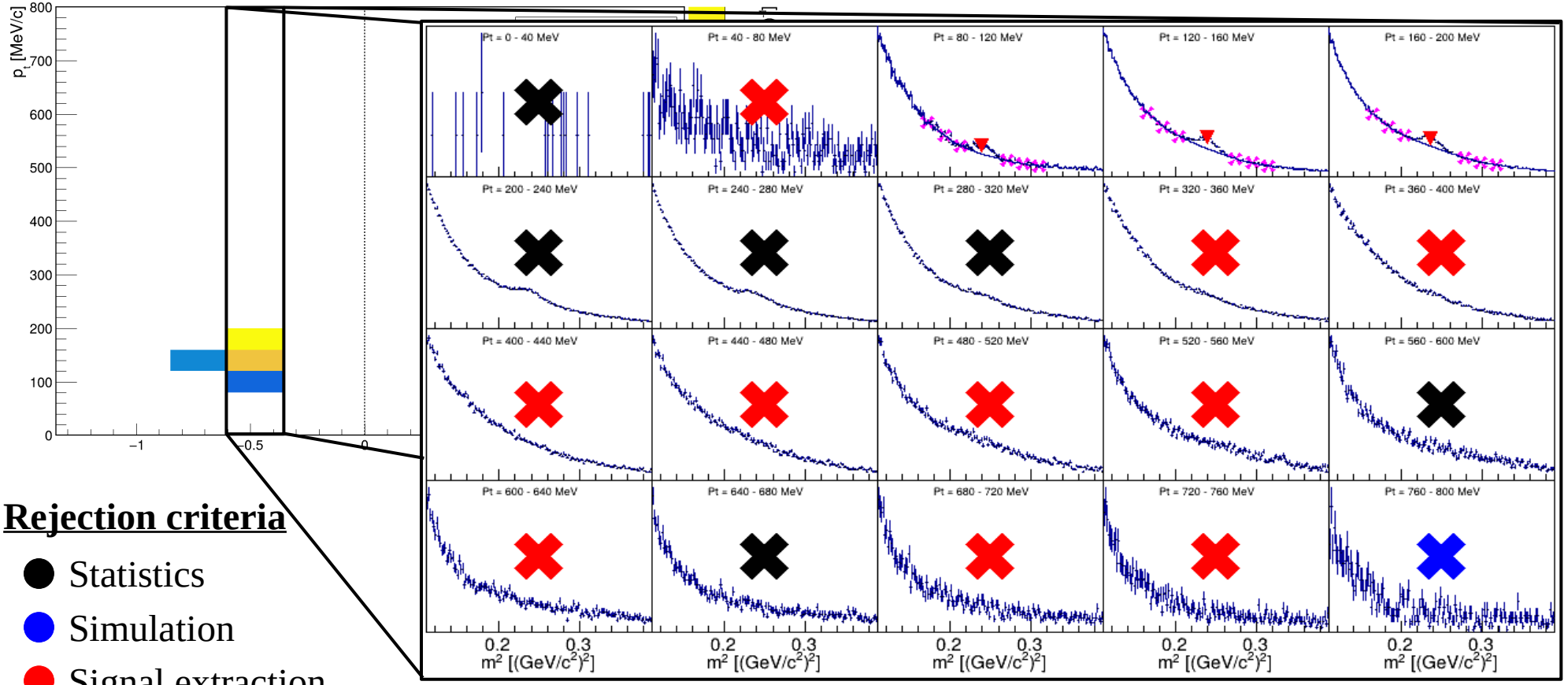


Rejection criteria

- Statistics
- Simulation
- Signal extraction

Figure 29: Differential mass spectra of K^+ candidates measured by the RPC detector.

K^- : Raw Yields

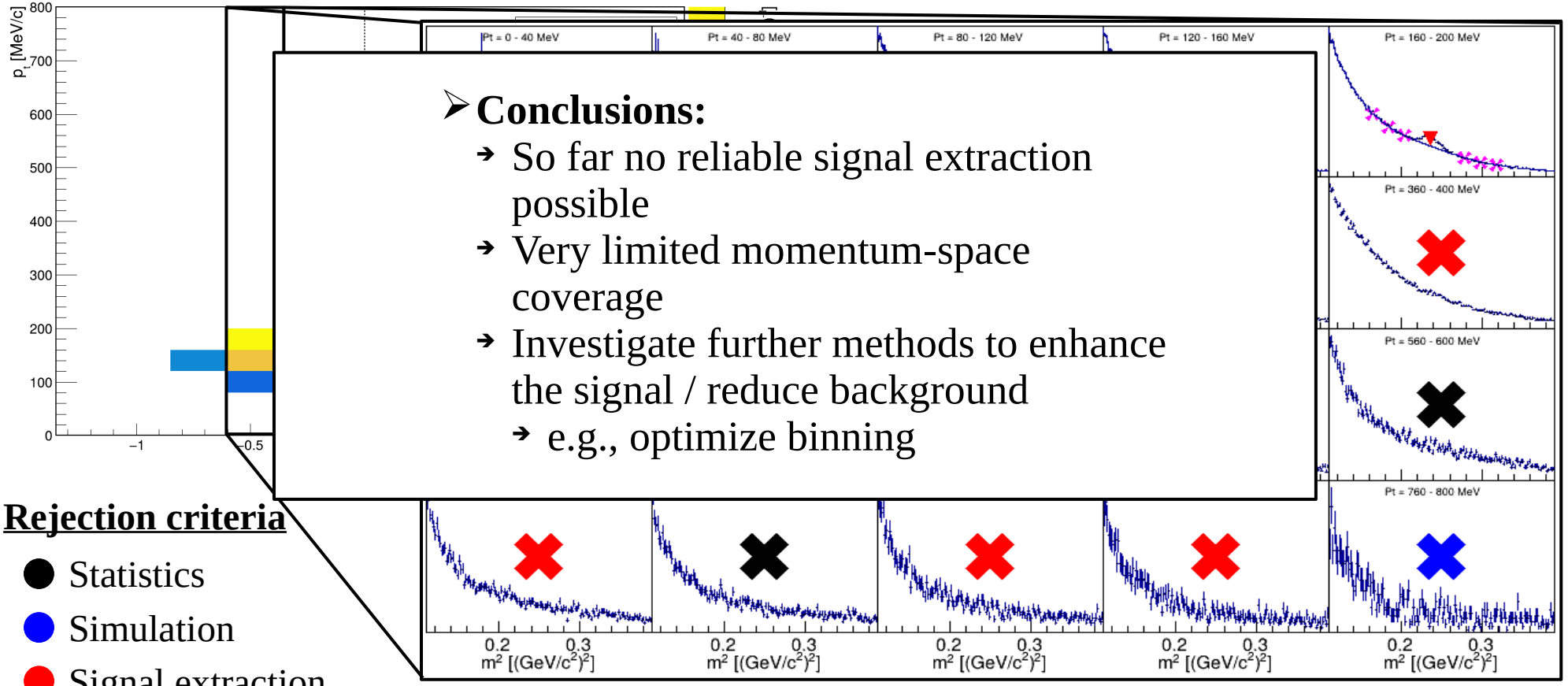


Rejection criteria

- Statistics
- Simulation
- Signal extraction

Figure 30: Differential mass spectra of K^+ candidates measured by the RPC detector.

K^- : Raw Yields



- **Conclusions:**
  - So far no reliable signal extraction possible
  - Very limited momentum-space coverage
  - Investigate further methods to enhance the signal / reduce background
    - e.g., optimize binning

Rejection criteria

- Statistics
- Simulation
- Signal extraction

Figure 30: Differential mass spectra of K^+ candidates measured by the RPC detector.

Cross Check : ϕ-Reconstruction

- Are we losing K^- candidates due to the preselection?
  - → Reconstruct Φ-mesons via decay channel

$\phi \rightarrow K^- K^+$ approx. 49.2%

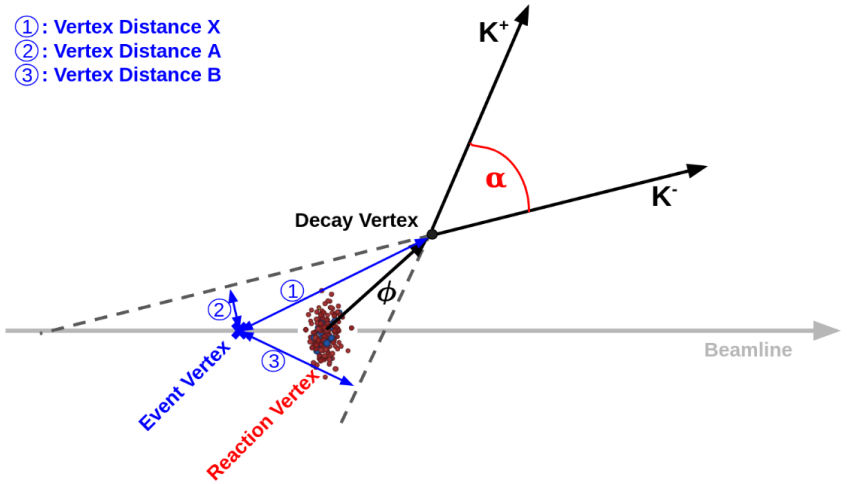


Figure 31: Decay topology (Depiction by M.Kohls)

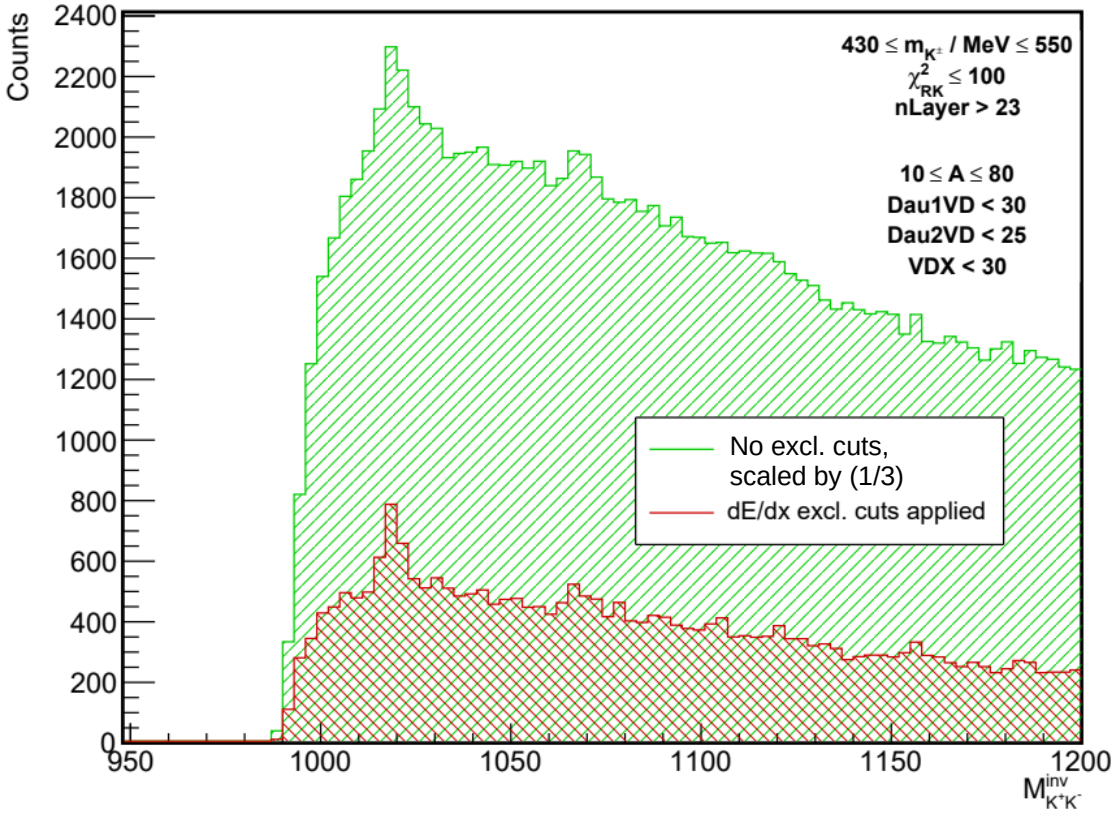


Figure 32: Invariant mass spectrum of K^+K^- pairs. Cut parameters obtained from F. Fritemeier.

Cross Check : ϕ-Reconstruction

- Are we losing K^- candidates due to the pres
  - Recor
    decay
    $\phi \rightarrow K^- K$

- **Conclusions:**
  - Investigate effects of selection criteria sets on reconstruction of ϕ as a cross check for K^-
  - Differential analysis will provide better insight

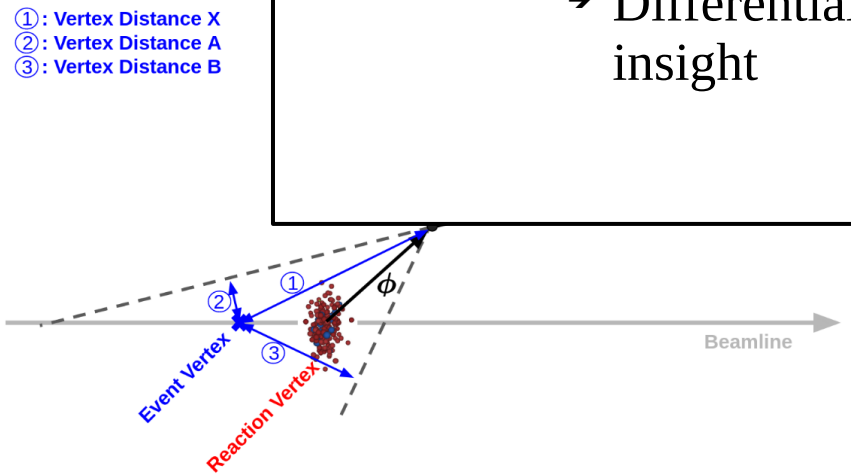


Figure 31: Decay topology (Depiction by M.Kohls)

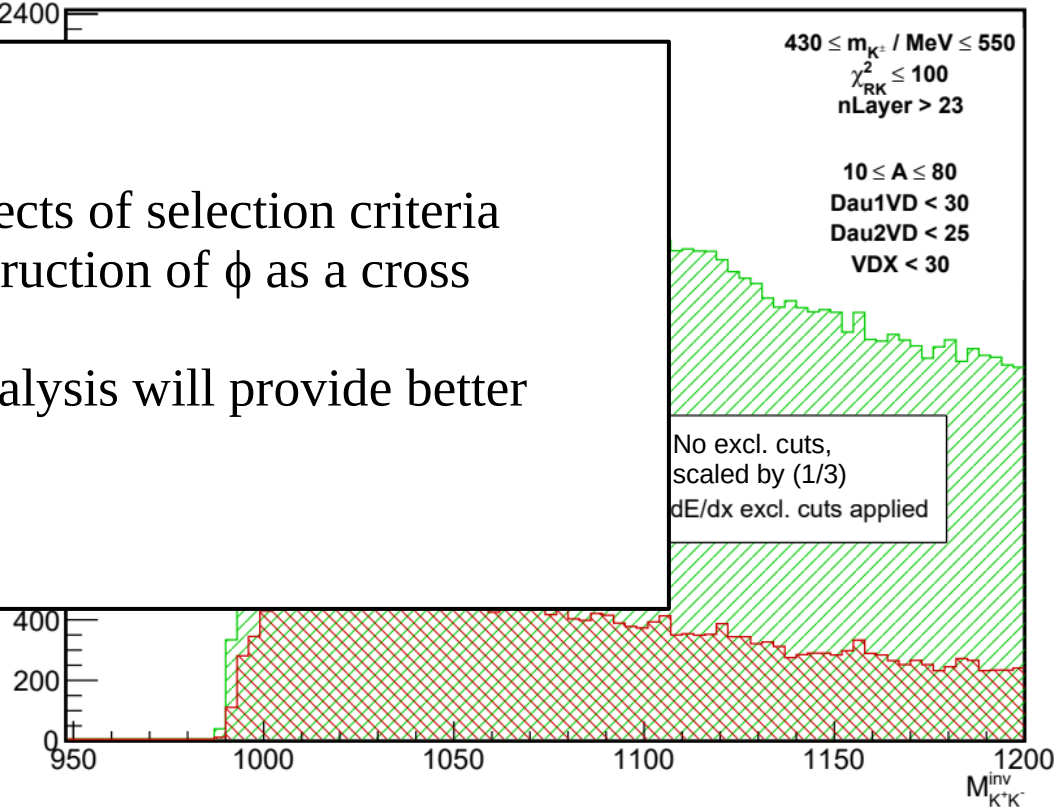


Figure 32: Invariant mass spectrum of K^+K^- pairs. Cut parameters obtained from F. Fritemeier.

Summary & Outlook

Summary

- Progress report on inclusive analysis of $K^{\pm}$ for p+p@4.5 GeV
- **K^+**
  - So far overall stable performance, first intermediate results presented
- **K^-**
  - So far no stable signal extraction achieved

Thank you!

Next Steps

- Further tune selection parameters, binning, signal extraction …
- Alternative simulations?
- **K^+**
  - Finalize multiplicities
  - Apply model extrapolation
  - Study systematic uncertainties
- **K^-**
  - Try further parameter combinations to achieve proper yield extraction
    - Differential reconstruction of ϕ may help