# Charged kaon and ϕ Production in Au+Au Collisions at 1.23 AGeV measured with HADES

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for the HADES collaboration

GOETHE UNIVERSITÄT FRANKFURT AM MAIN

HADES

HIC for FAIR Helmholtz International Center

H-QM Helmholtz Research School Quark Matter Studies

HGS-HIRe for FAIR Helmholtz Graduate School for Hadron and Ion Research

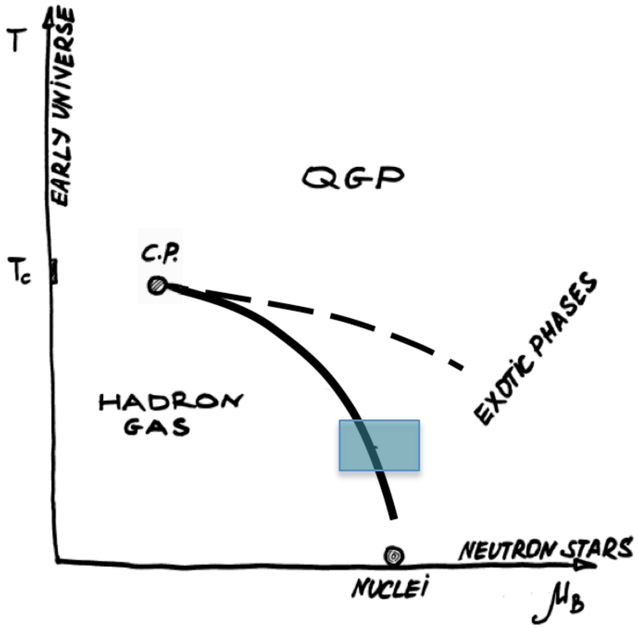
EMMI

# Outline

- Introduction
  - HADES mission
  - Charged kaon and ϕ production in the SIS18 energy regime
- Au + Au Measurement with HADES
  - Beam time specifications
  - HADES performance
- Results
  - Centrality dependence and comparison to other experiments
  - Comparison to phenomenological models
  - ϕ / $K^-$ - what do we learn about $K^-$ production
- Summary

# The HADES Mission

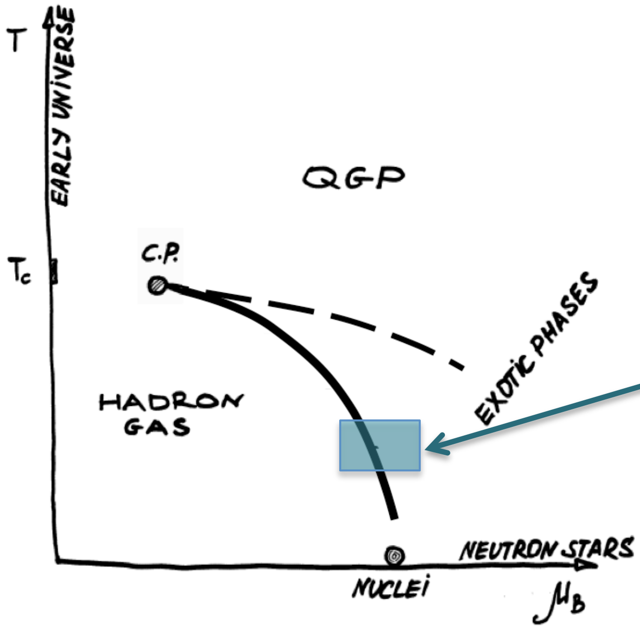
## Beams from SIS18: pions, protons & nuclei, $E_{kin}$=1-2 AGeV

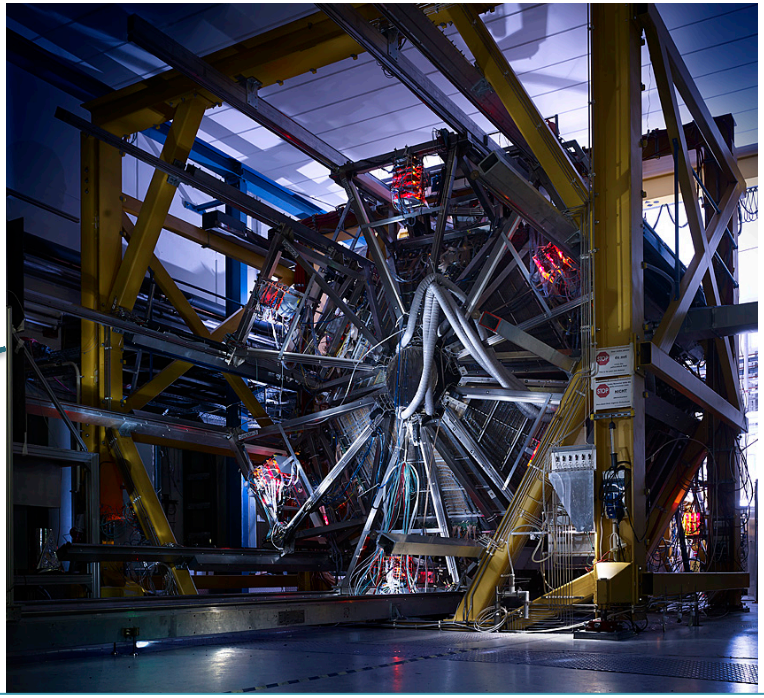



- Detailed study of matter properties at highest $\mu_B$ with rare and penetrating probes: di-leptons and strange hadrons
- Studying role of baryonic resonances for particle production

# The HADES Mission

## Beams from SIS18: pions, protons & nuclei, $E_{kin}$=1-2 AGeV



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- **Fast detector:** 10-50 kHz trigger rate
- **Large Acceptance:** Full azimuthal and polar angle coverage of Θ = 18° – 85°

- Detailed study of matter properties at highest $\mu_B$ with rare and penetrating probes: di-leptons and strange hadrons
- Studying role of baryonic resonances for particle production

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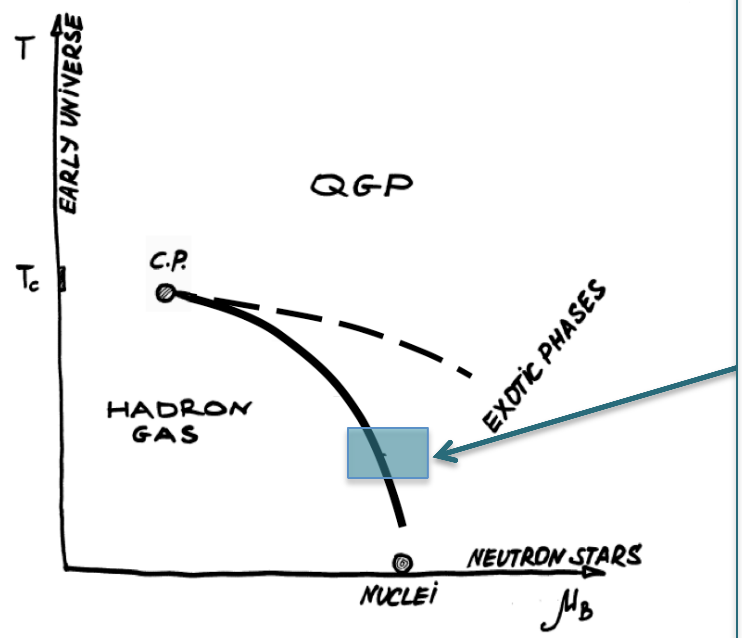
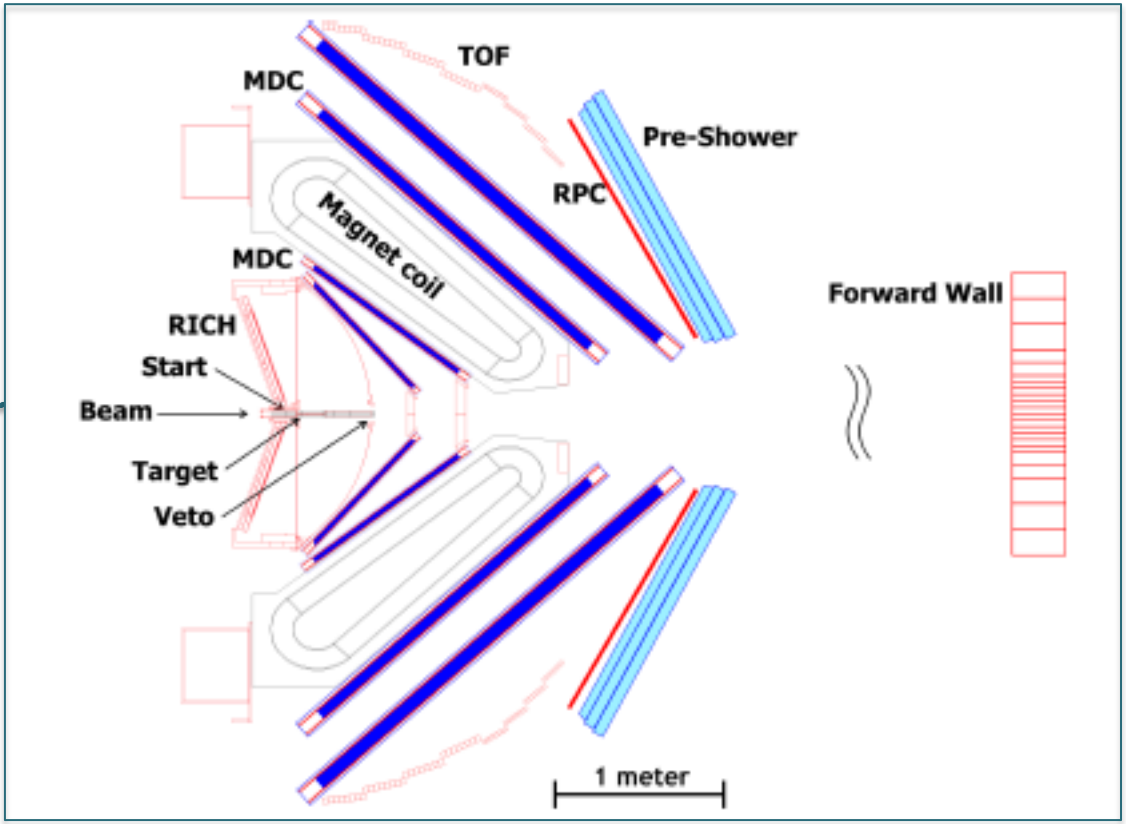


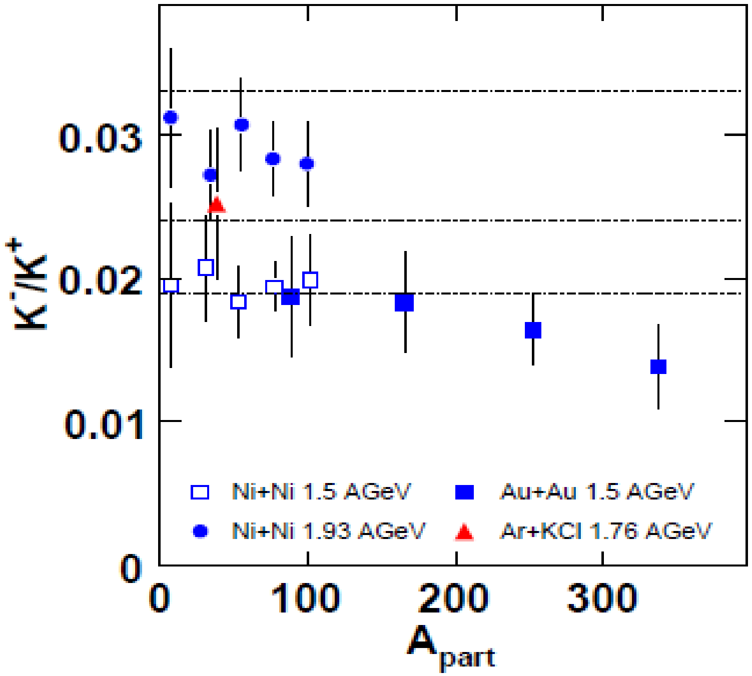



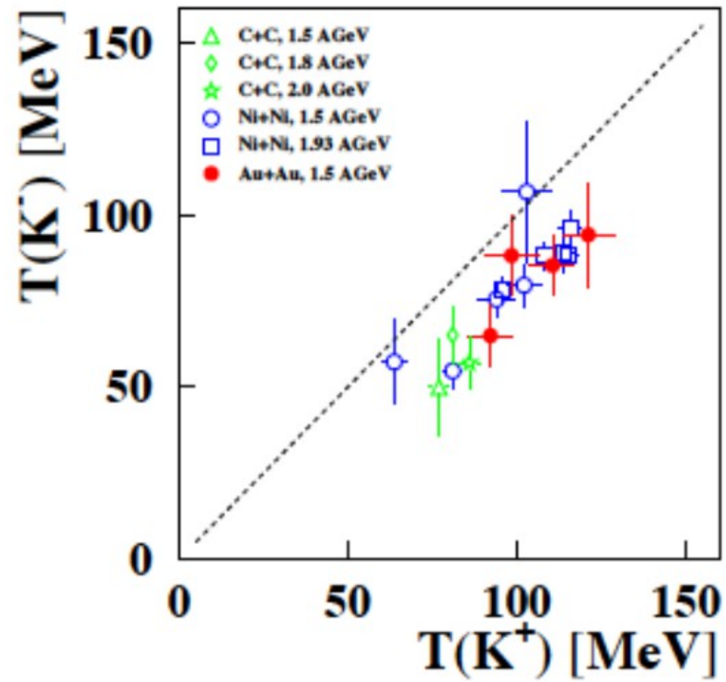

- Detailed study of matter properties at highest $\mu_B$ with rare and penetrating probes: di-leptons and strange hadrons
- Studying role of baryonic resonances for particle production

# Strangeness Production at SIS Energies

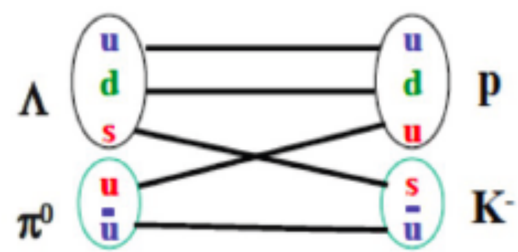
## Experimental results and interpretation on charged kaon production

Förster et. Al (KaoS)
PHYSICAL REVIEW C 75, 024906 (2007)




- $K^+$ and $K^-$ show similar $A_{part}$ dependence
- Inverse slope of $K^-$ systematically below $K^+$

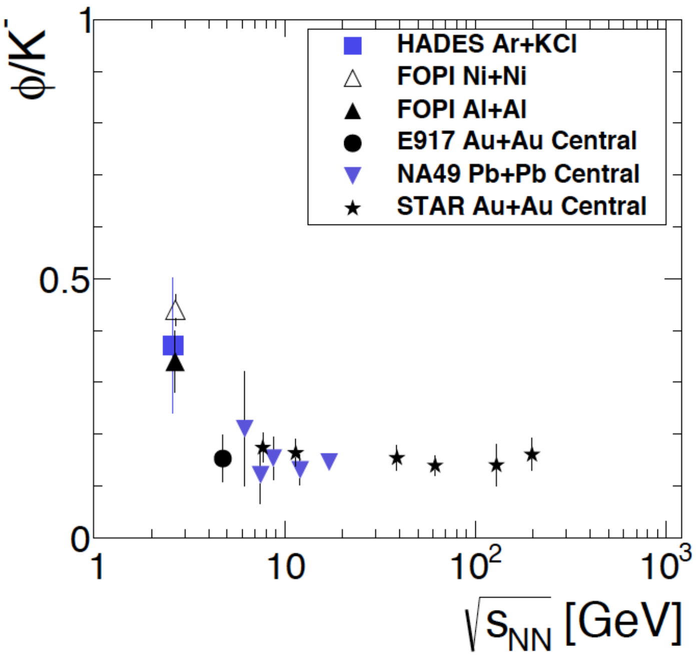



- *"Strangeness exchange mechanism dominant for $K^-$ production"*
- *"Later freeze-out of $K^-$ compared to $K^+$ due to coupling to baryons"*
- *"Strangeness production in HIC is very different from that in elementary interaction"*

Phys.Rept. 510 (2012) 119-200

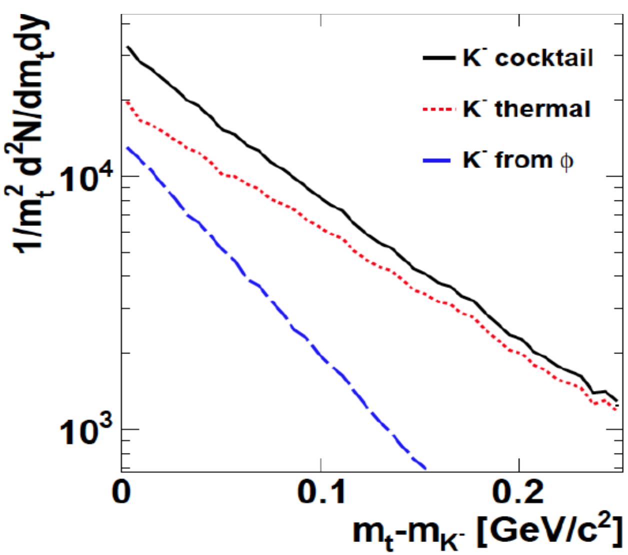
# Strangeness Production at SIS Energies

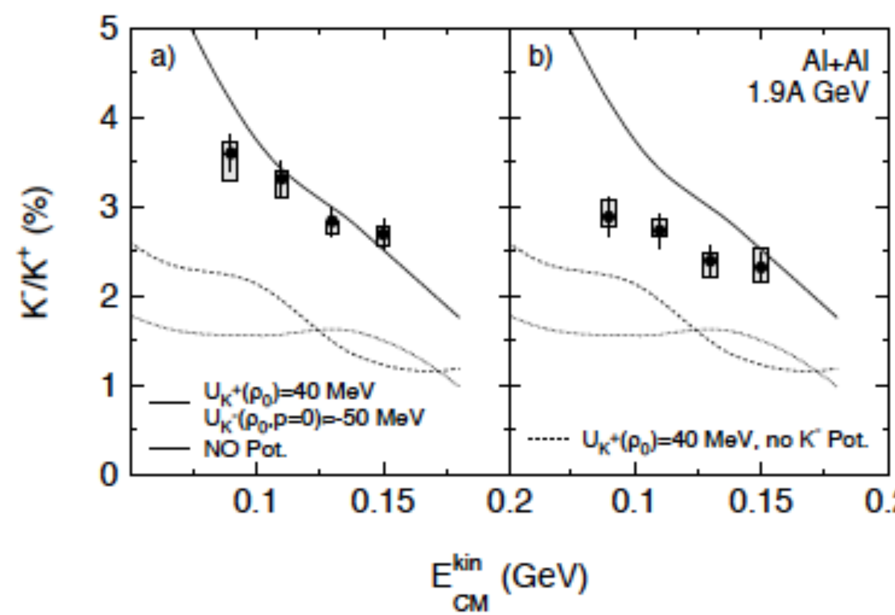
## Sizeable $\phi$ production






- 18% of measured $K^-$ originate from $\phi$-decays (HADES Ar+KCl @ 1.76 AGeV, confirmed from FOPI Ni+Ni and Al+Al @ 1.9 AGeV)
- Feed-down explains lower effective temperatures of $K^-$ and changes conclusion on in-medium potential (not taken into account before)
- $\phi$-meson one of the main players for understanding of $K^-$ production



# The ultimate test: Au+Au at 1.23 AGeV (√s=2.41 GeV)

## Subthreshold strangeness production in heavy system

| Production channel | $E_{Beam,thr}[GeV]$ | $\sqrt{s}_{thr}$ [GeV] | $\sqrt{s}_{AuAu} - \sqrt{s}_{thr}$ [GeV] |
|---|---|---|---|
| $NN \rightarrow NK^{+}\Lambda$ | 1.58 | 2.55 | -0.14 |
| $NN \rightarrow NNK^{+}K^{-}$ | 2.49 | 2.86 | -0.45 |
| $NN \rightarrow NN\phi$ | 2.59 | 2.9 | -0.49 |

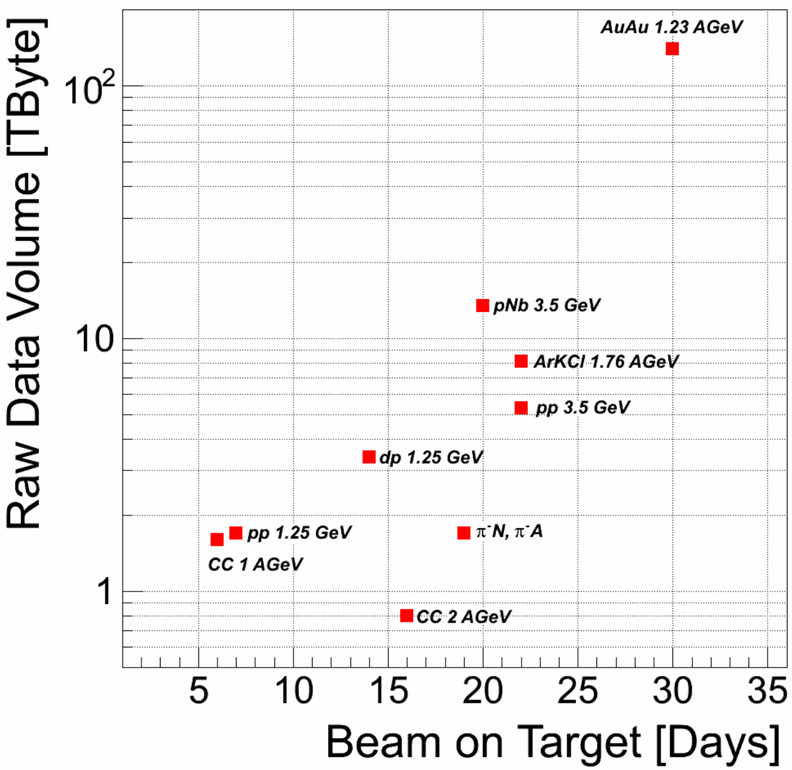
- Heaviest system at low energy
  - All strange hadrons produced far below NN-threshold
  - Sensitive to in-medium effects
  - Fast detector to collect unprecedented high statistics for multi-differential analysis of rare probes (and as many other observables as possible)

# The ultimate test: Au+Au at 1.23 AGeV

## Subthreshold strangeness production in heavy system

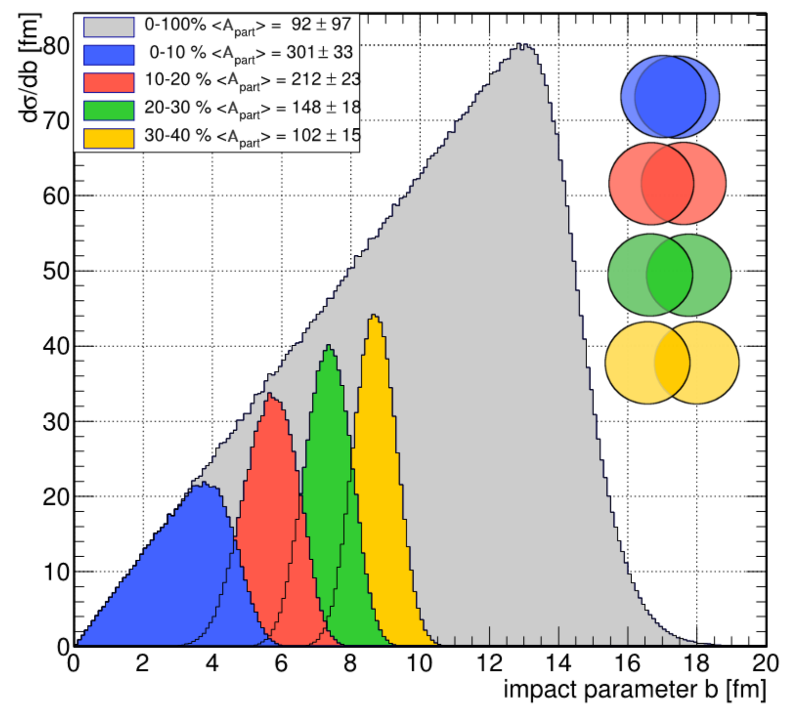
DAQ upgrade: high trigger rates of up to 8 kHz

- 7.4 x $10^9$ events recorded



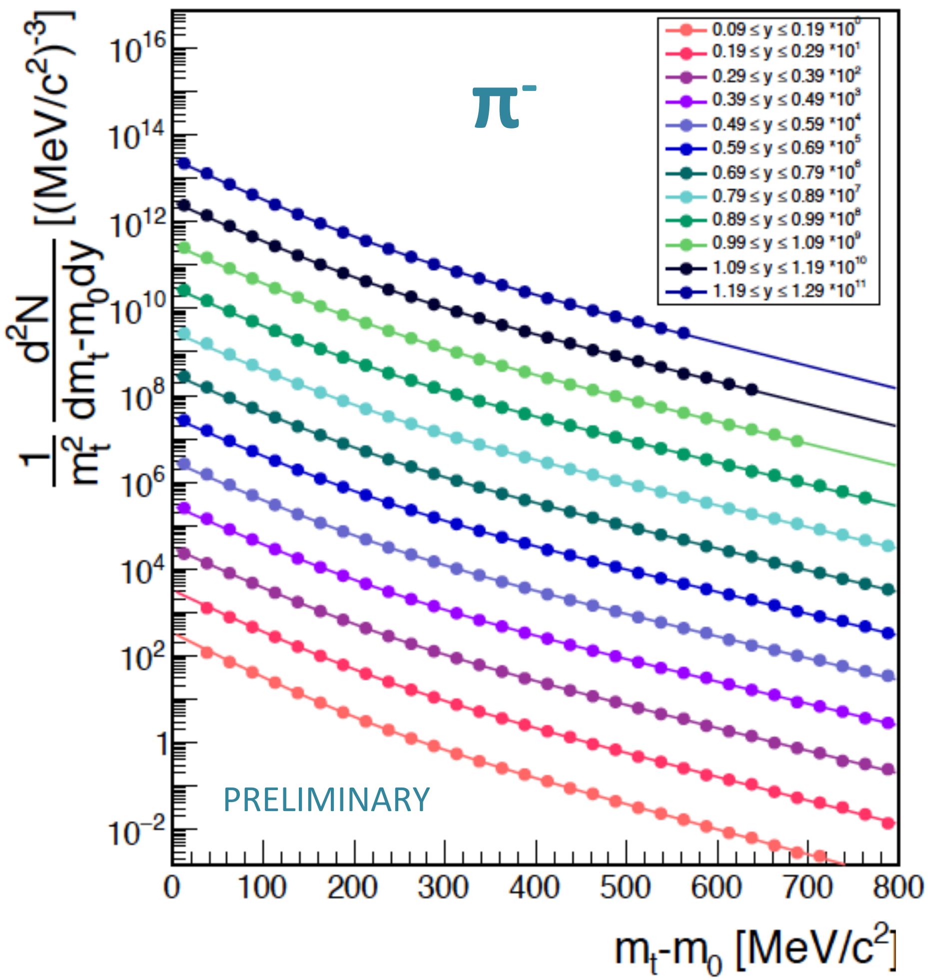

Trigger on 40% most central collisions

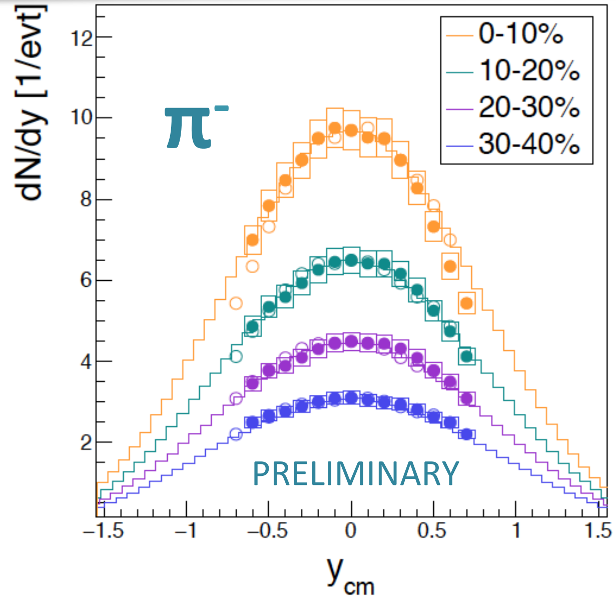
- $\langle A_{part} \rangle = 191 \pm 7$

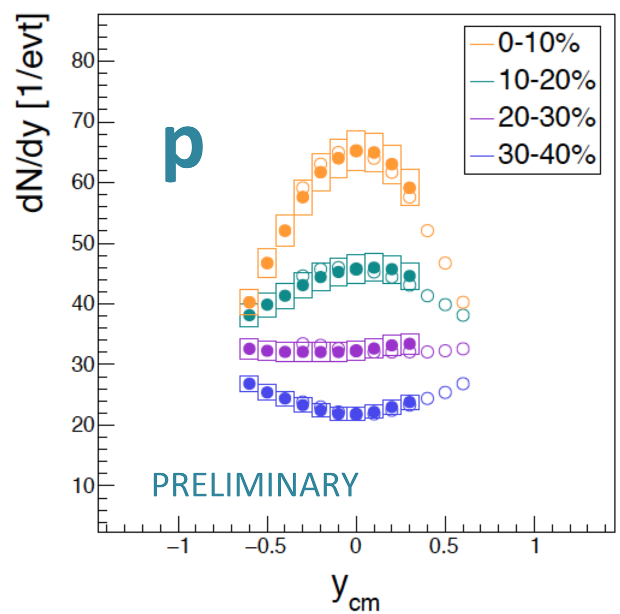


# Multi differential analysis of pions and protons

## High statistics (1 out of 30 days)



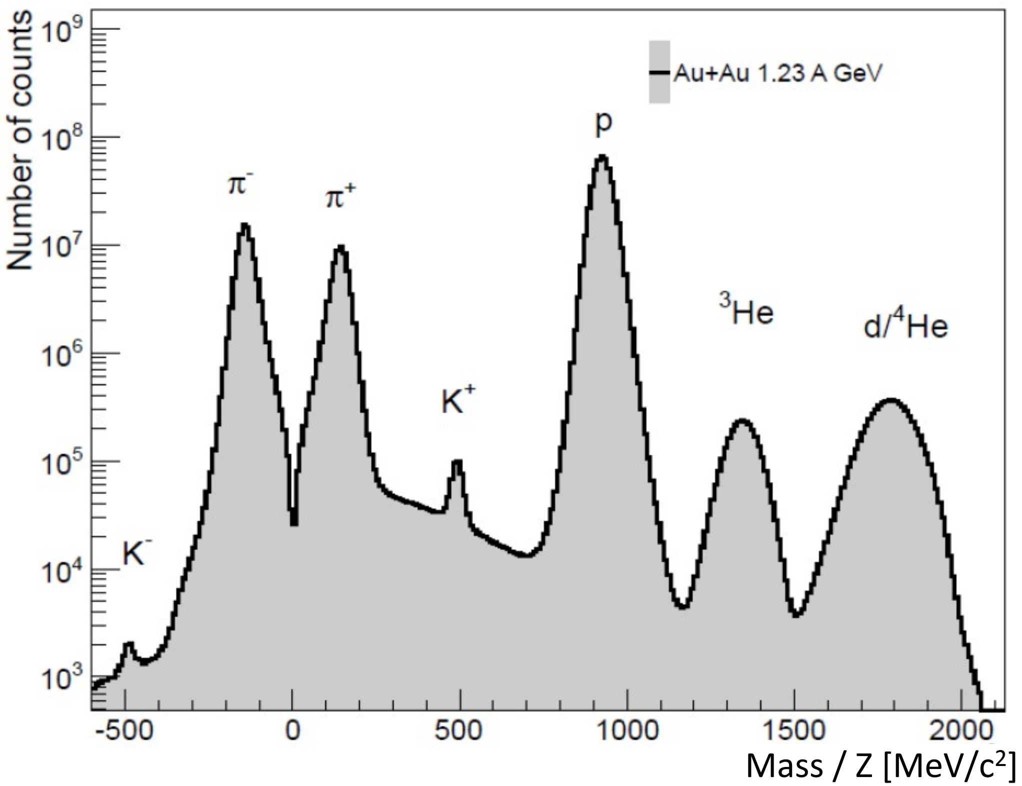



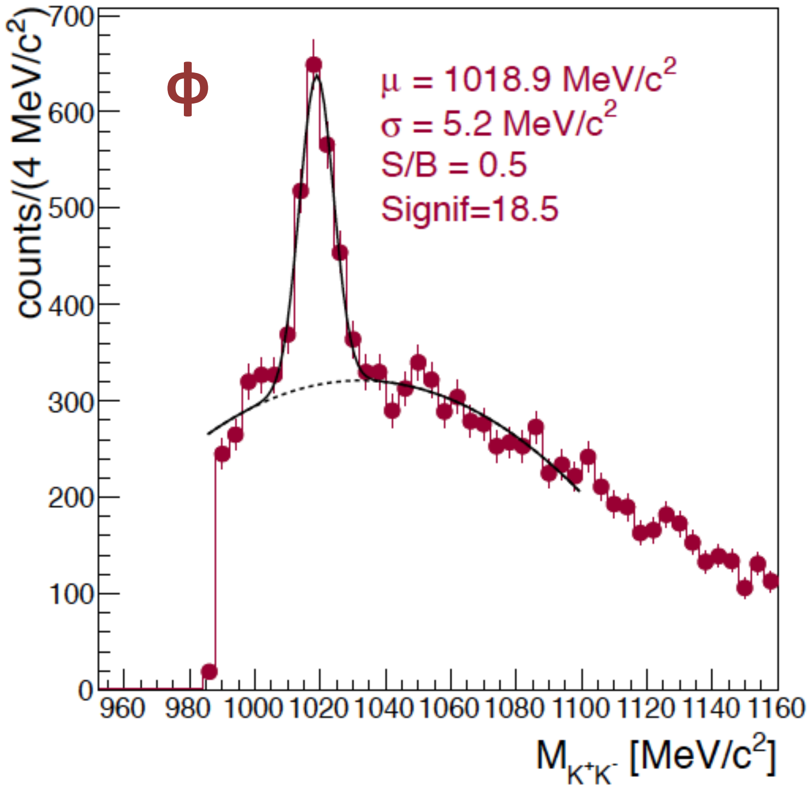
# First measurement of $K^-$ and $\phi$ at such low energies

$K^+$: $\sqrt{s_{AuAu}} - \sqrt{s_{thr}} = -0.14$ GeV

$K^-$: $\sqrt{s_{AuAu}} - \sqrt{s_{thr}} = -0.45$ GeV



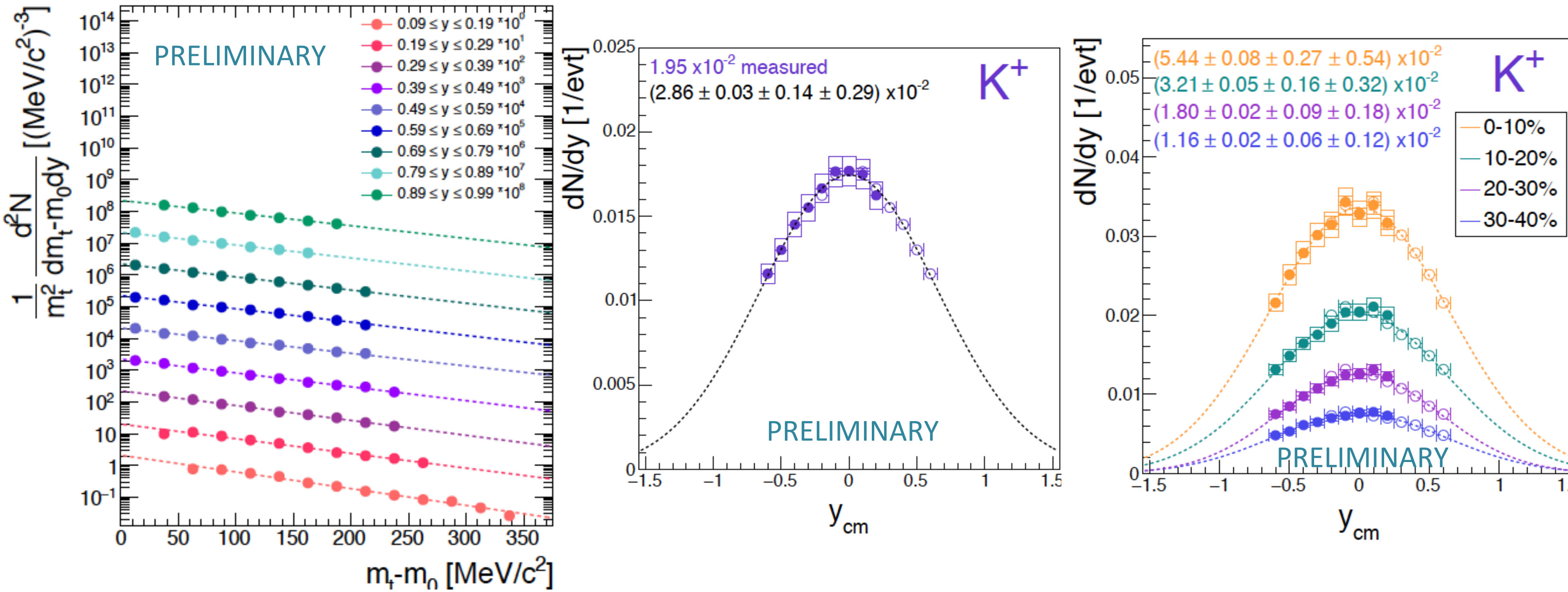

$\phi$: $\sqrt{s_{AuAu}} - \sqrt{s_{thr}} = -0.49$ GeV



# Results

# $K^+$ Production

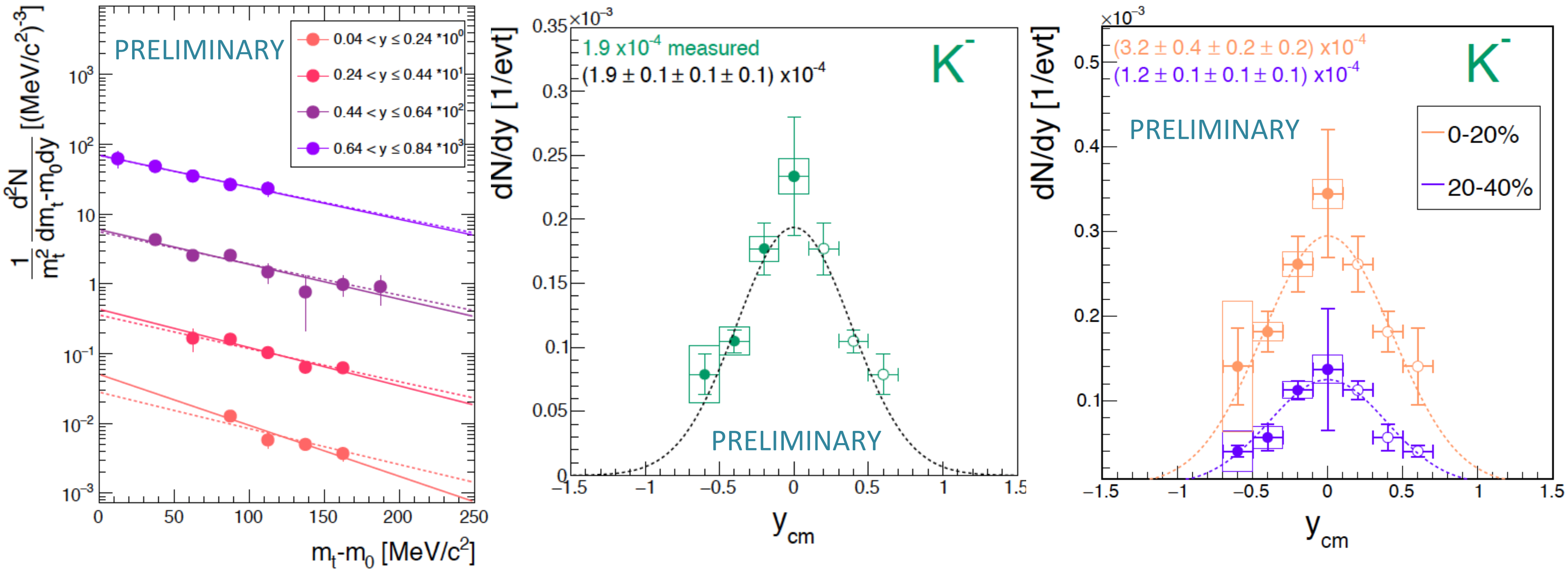
## Acceptance at mid-rapidity down to low transverse mass




- Boltzmann and/or blast wave parameterization to extrapolate to unmeasured transverse mass regions
  - Effective temperature
  - Rapidity density distribution
- Extrapolation to unmeasured rapidity regions with Gaussian parameterization

# $K^-$ Production

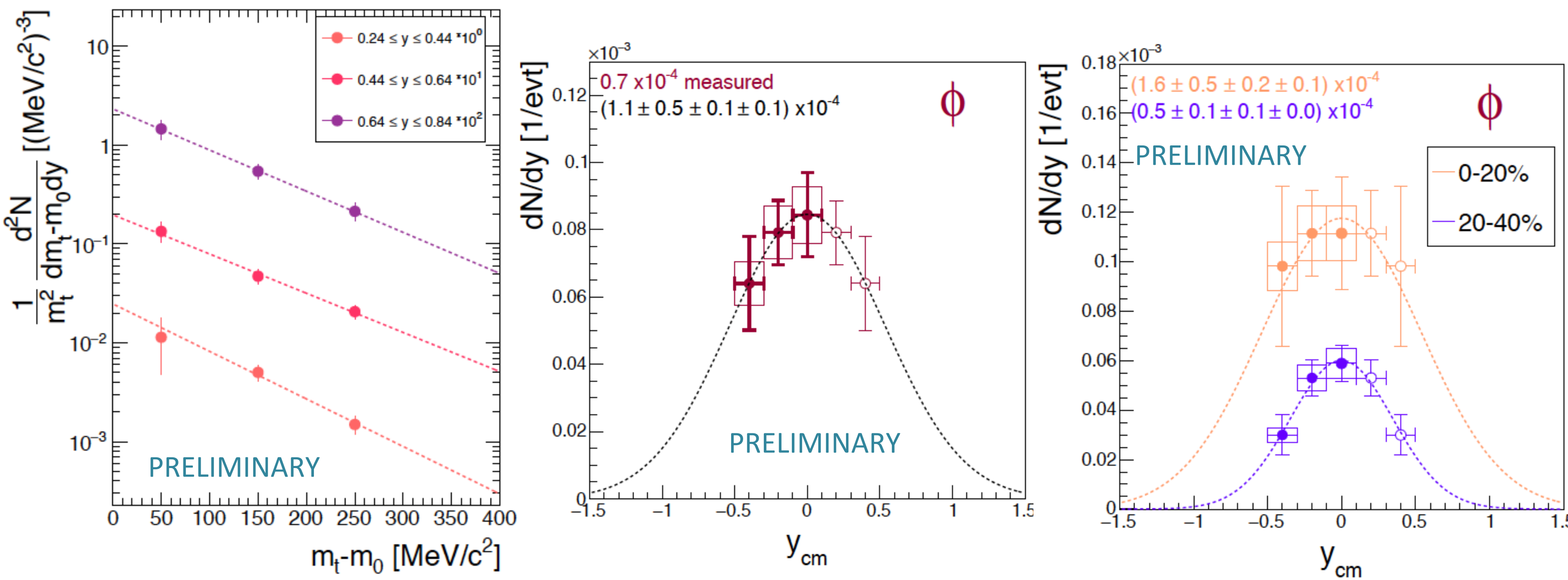
## Acceptance at mid-rapidity down to low transverse mass




- Boltzmann and/or blast wave parameterization to extrapolate to unmeasured transverse mass regions
  - ➢ Effective temperature
  - ➢ Rapidity density distribution
- Extrapolation to unmeasured rapidity regions with Gaussian parameterization

# ϕ Production

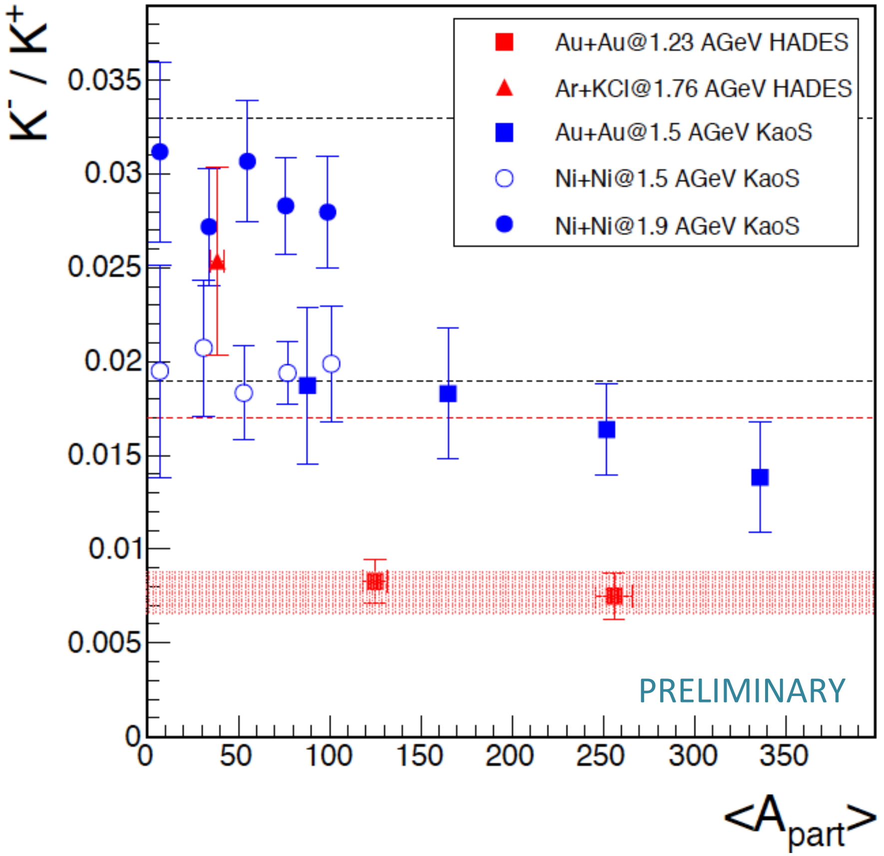
## Acceptance at mid-rapidity down to low transverse mass




- Boltzmann parameterization to extrapolate to unmeasured transverse mass regions
  - Effective temperature
  - Rapidity density distribution
- Extrapolation to unmeasured rapidity regions with Gaussian parameterization

# $K^-$ / $K^+$ ratio

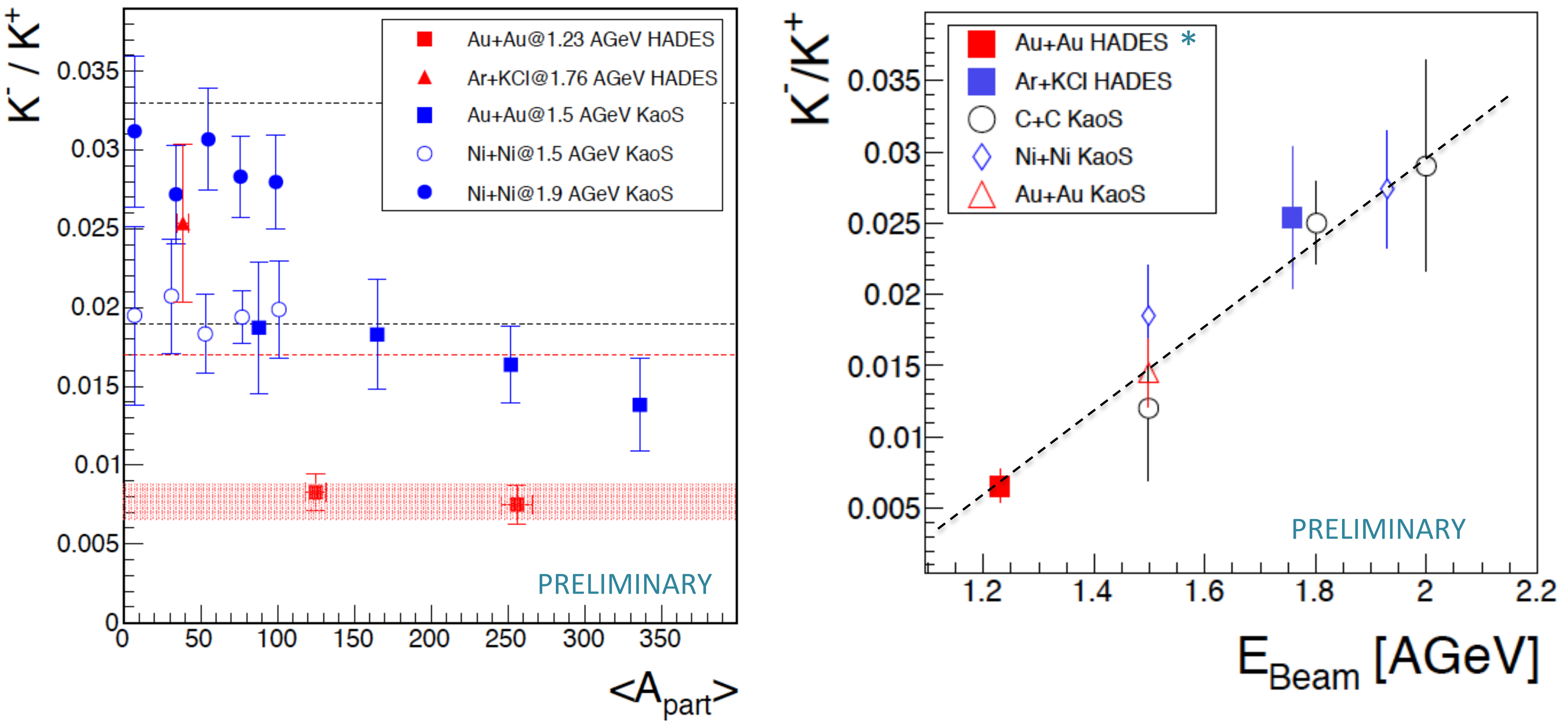
## Comparison to KaoS and centrality dependence




- $K^-$ / $K^+$ constant as a function of centrality

# $K^- / K^+$ ratio

## Centrality dependence and comparison to KaoS

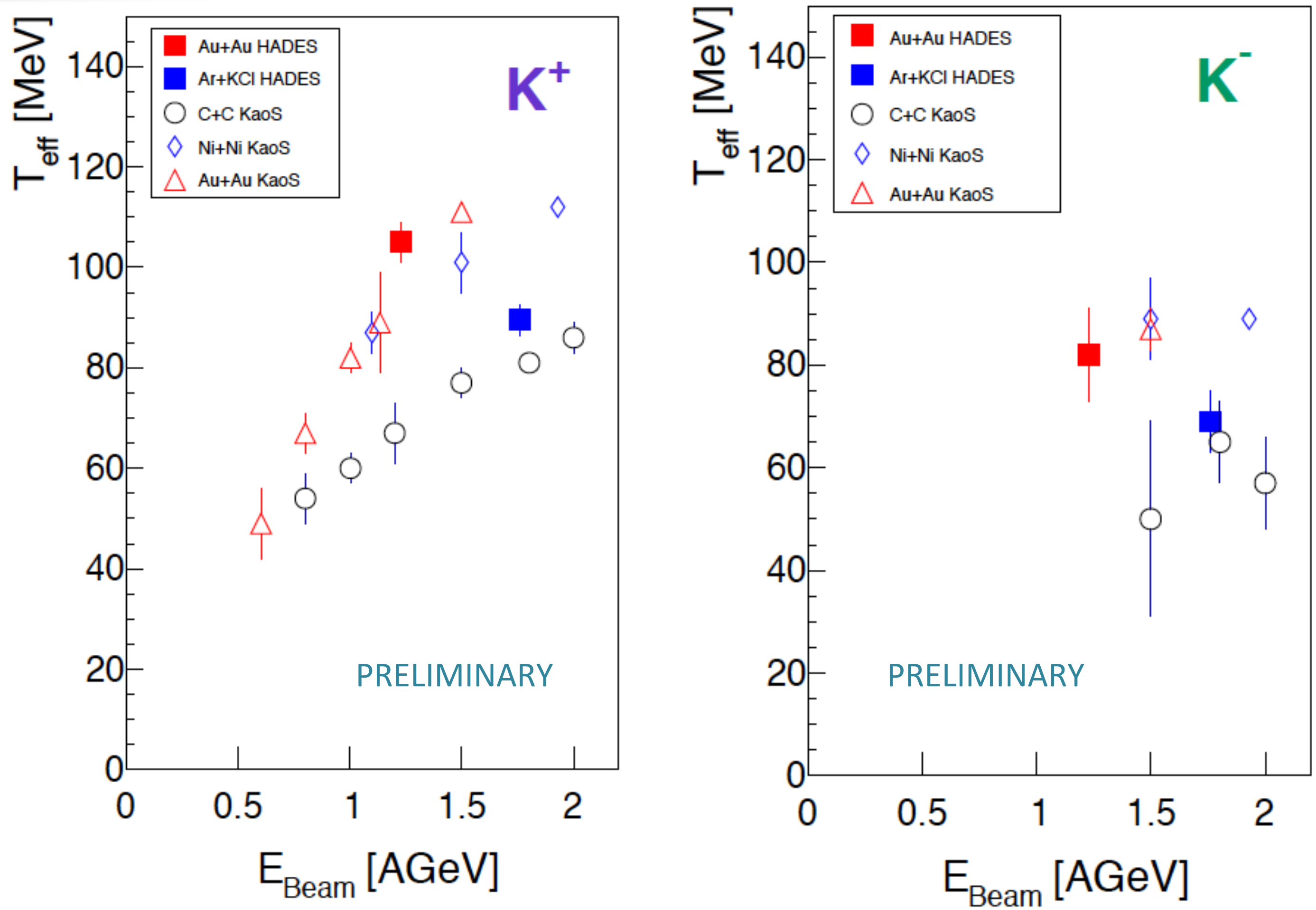



* 40% most central

- $K^- / K^+$ constant as a function of centrality
- $K^- / K^+$ ratio follows energy dependence as seen by other experiments

➢ Linear increase with kinetic beam energy

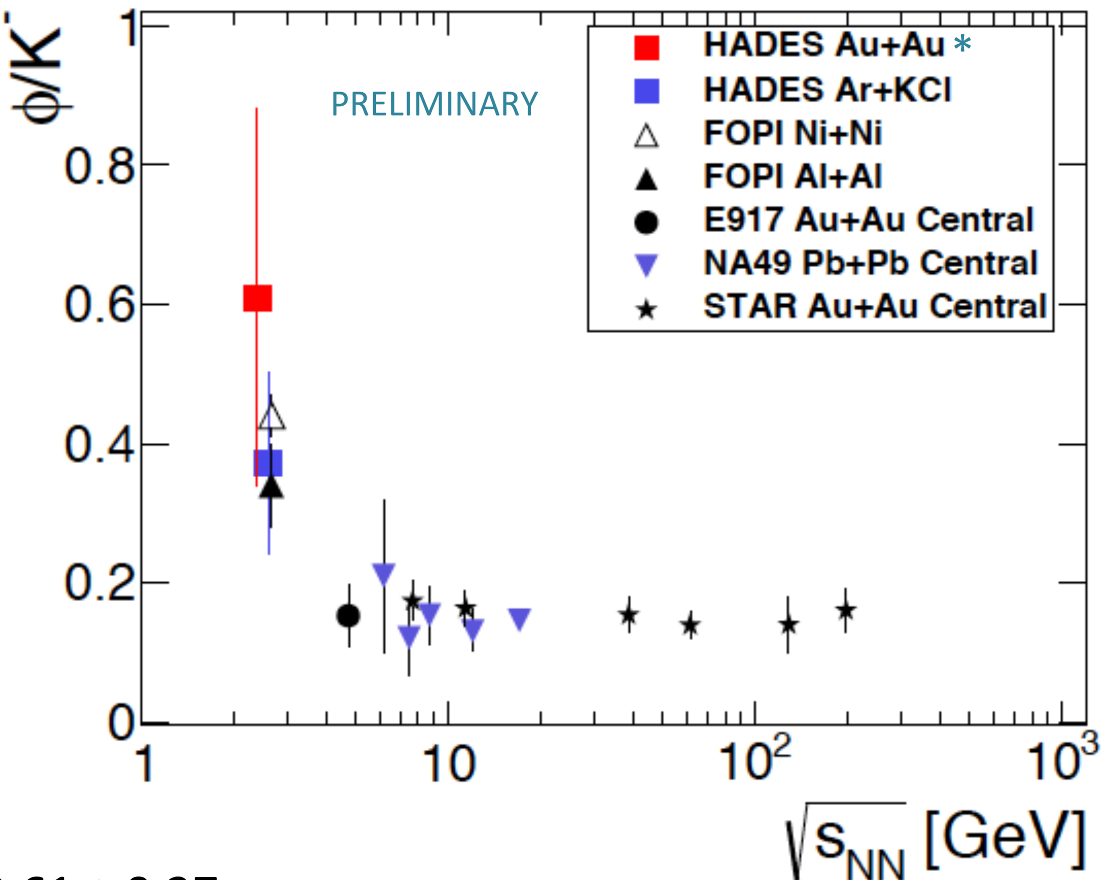
# Effective temperatures of charged kaons




- Effective temperature of $K^-$ systematically below $K^+$
- Effective temperature of kaons increases with beam energy and system size

# $\phi$ / $K^-$ ratio

## Excitation function

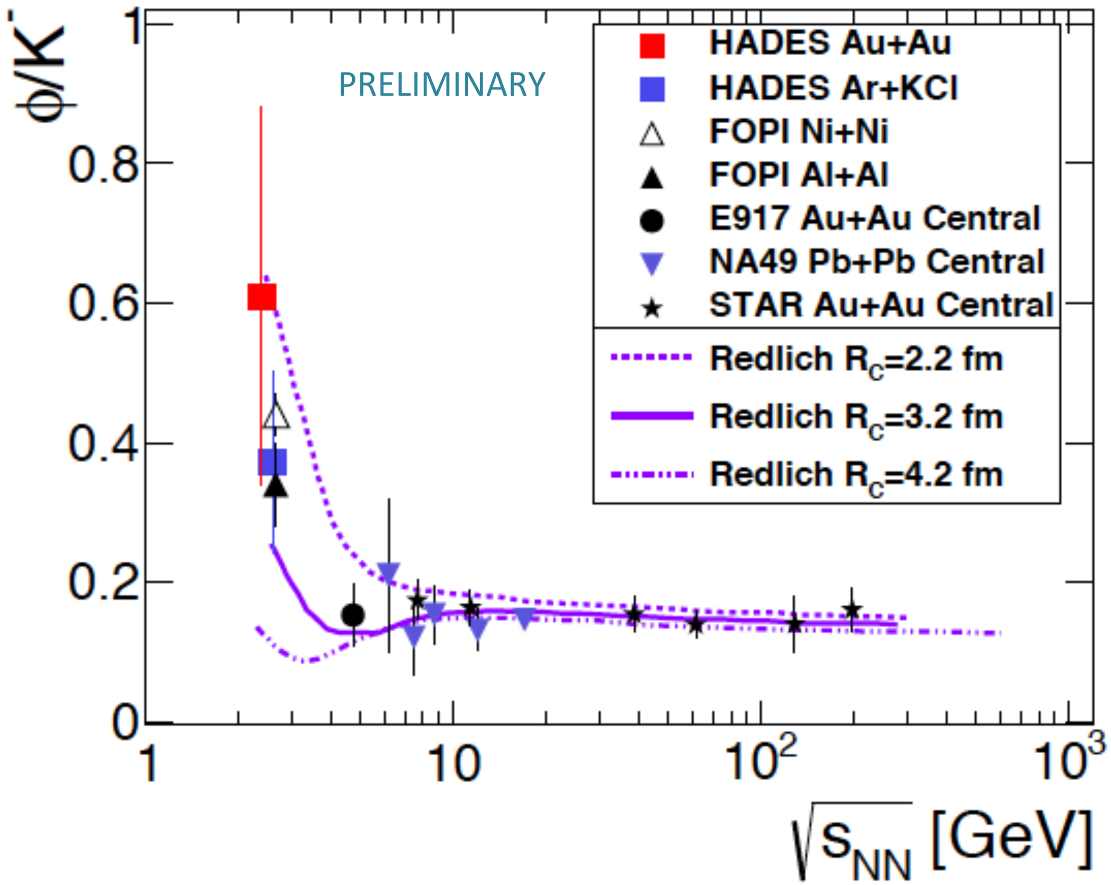



* 40% most central

- $\phi/K^-$ = 0.61 ± 0.27
  - ~30% of all measured $K^-$ from $\phi$ feed-down
  - How strong is the contribution from kaon pair production?

# $\phi$ / $K^-$ ratio

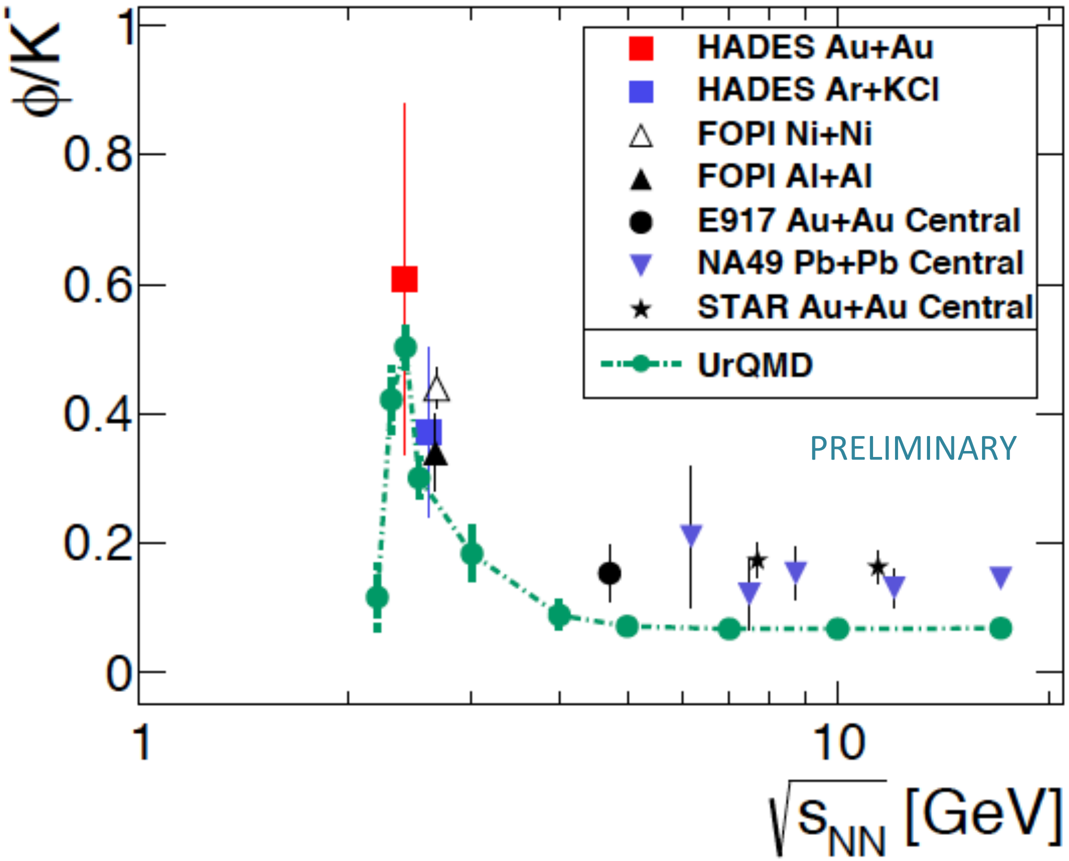
Excitation function in comparison to SHM

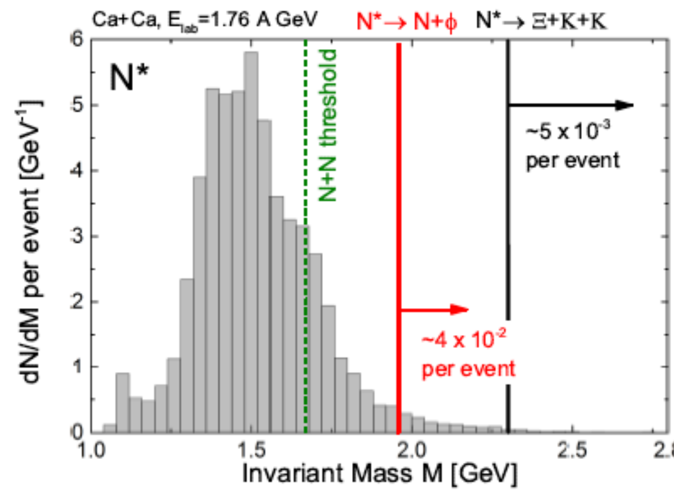


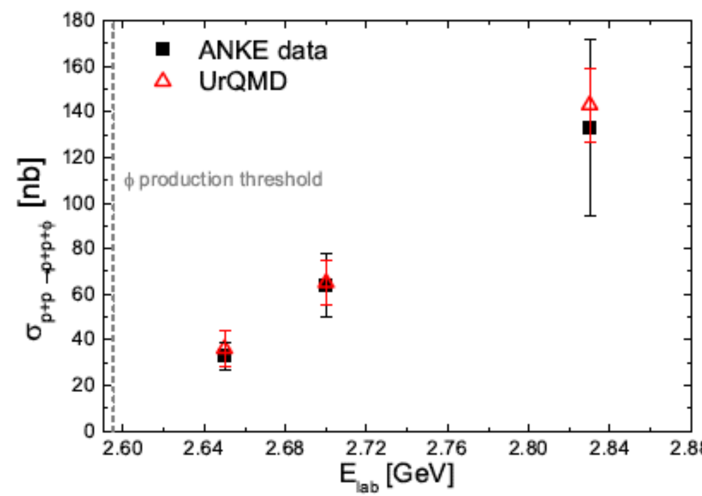

- $\phi/K^- = 0.61 \pm 0.27$
  - Trend expected from SHM for small $R_C$

# ϕ / K⁻ ratio

## Excitation function in comparison to UrQMD (tuned)




J.Phys. G43 (2016) 1, 015104

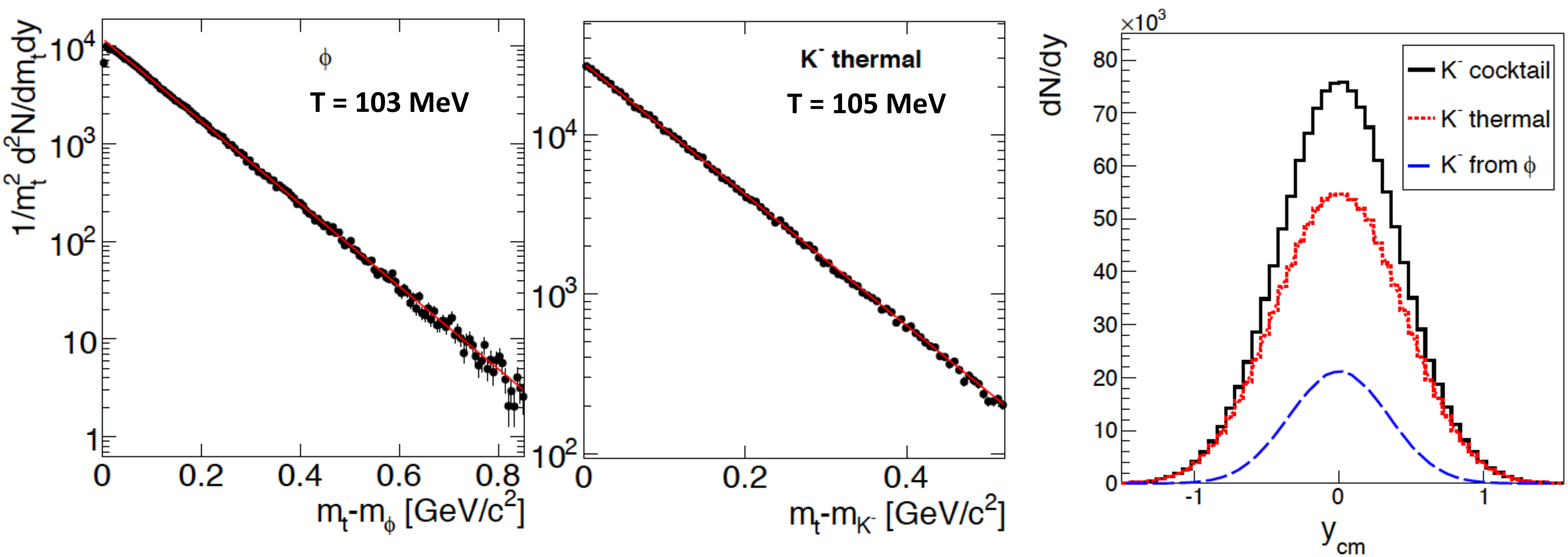
- $\phi/K^- = 0.61 \pm 0.27$
  - ➢ Trend expected from SHM for small $R_C$
  - ➢ Predicted from UrQMD (tuned) when including new decay channels from high mass baryonic resonances (tuned to match elementary data)

# φ / K⁻ ratio

## What do we learn about K⁻ production?

**2 component PLUTO cocktail simulation:**

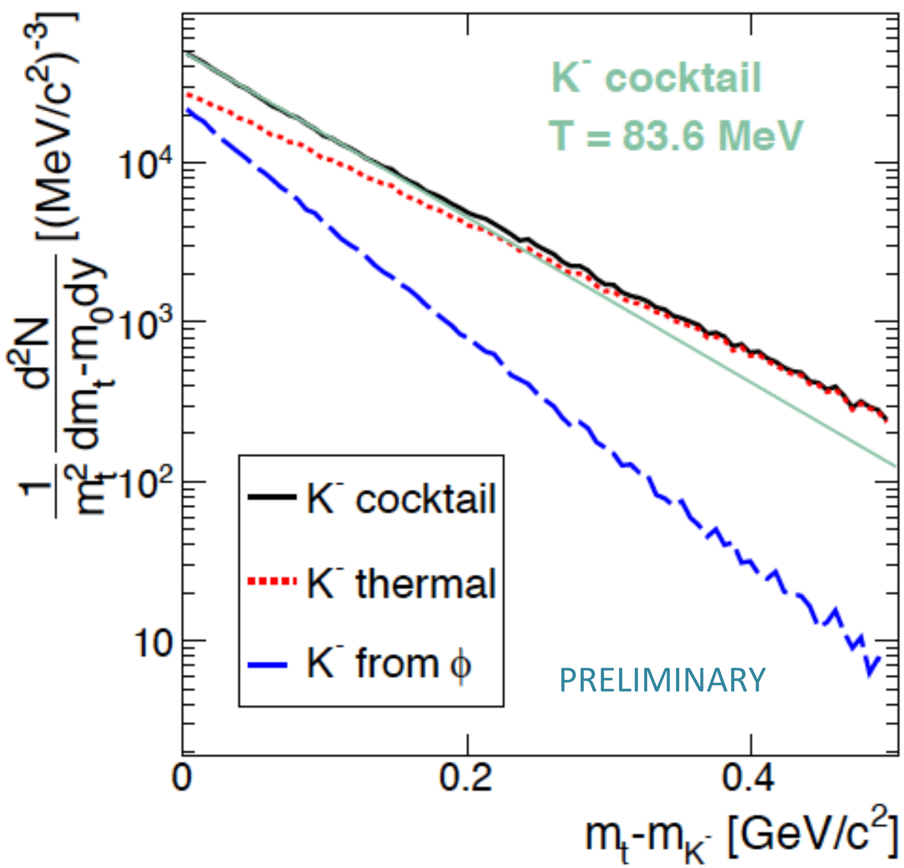
- Thermal $\phi \to K^+K^-$ T = 103 MeV
- Thermal $K^-$ T = $T_{K+}$ = 105 MeV
- Measured $\phi/K^-$ ratio



# ϕ / $K^-$ ratio

## What do we learn about $K^-$ production?

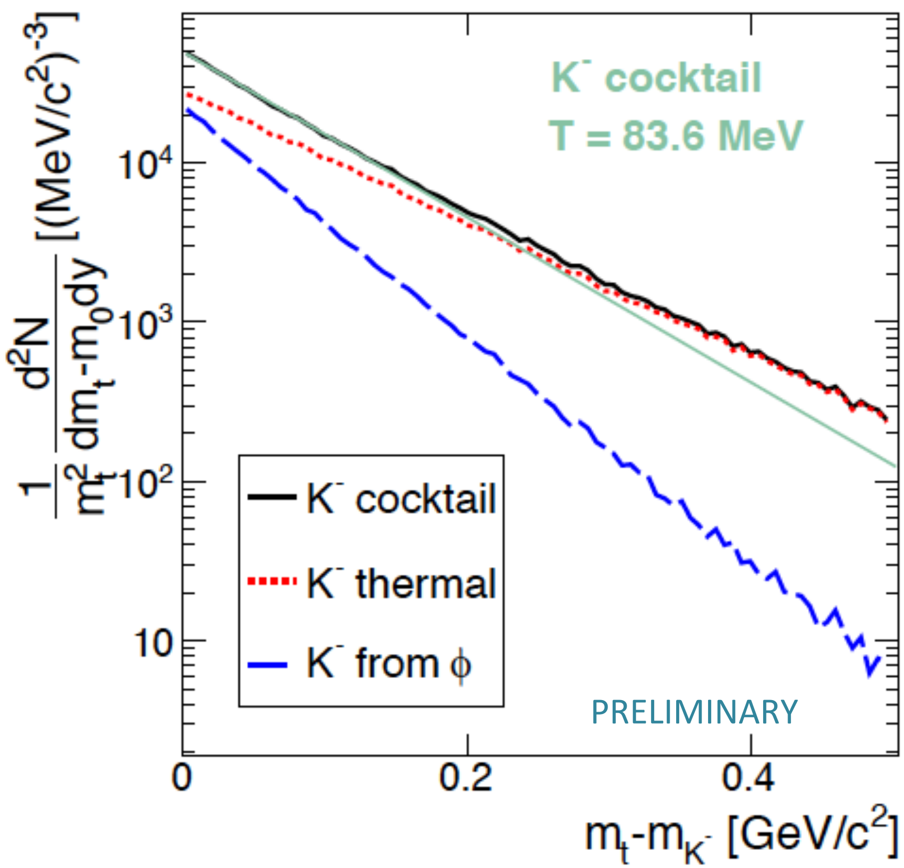
- High contribution from ϕ feed down can explain lower inverse slope parameter of $K^-$ spectrum ($T_{eff}$ = 82 ± 9 MeV) in comparison to the one of $K^+$ ($T_{eff}$ = 105 ± 3 MeV)

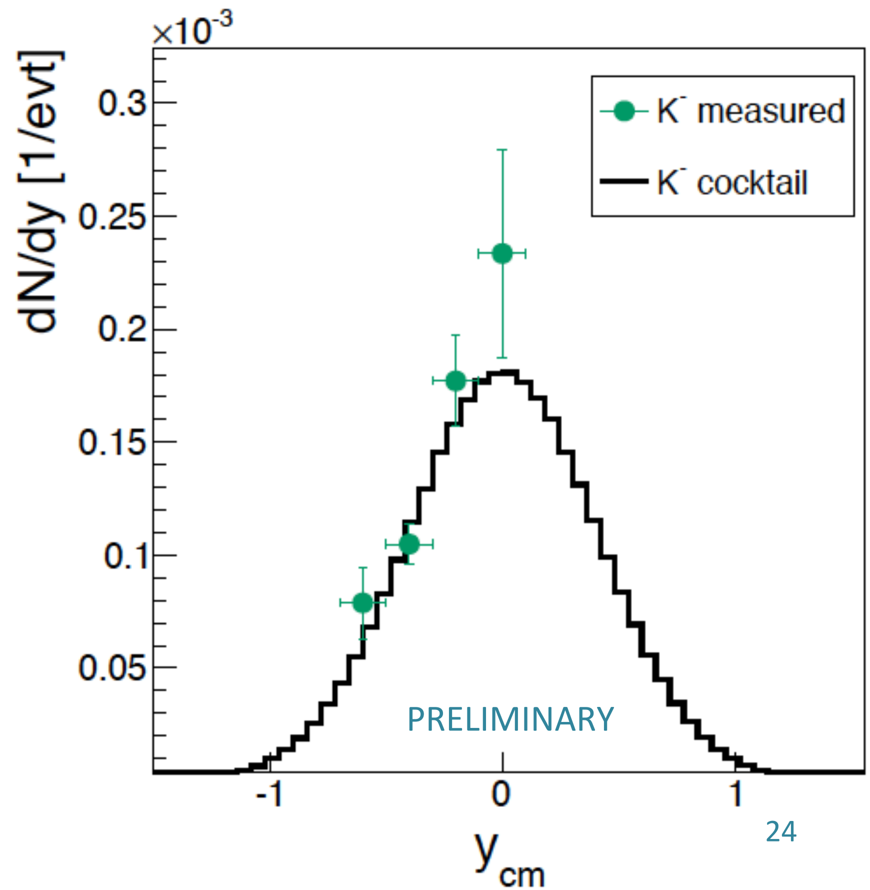


# $\phi$ / $K^-$ ratio

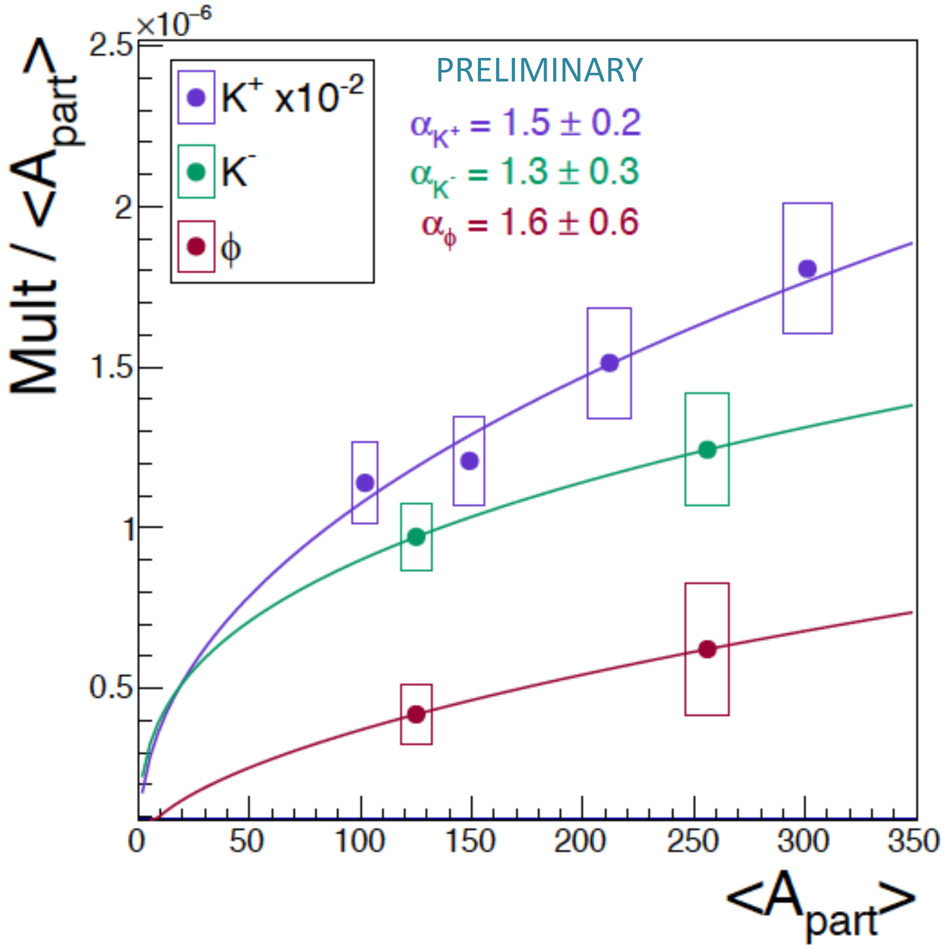
## What do we learn about $K^-$ production?

- High contribution from $\phi$ feed down can explain lower inverse slope parameter of $K^-$ spectrum ($T_{eff}$ = 82 ± 9 MeV) in comparison to the one of $K^+$ ($T_{eff}$ = 105 ± 3 MeV)
- Measured rapidity distribution nicely reproduced by cocktail



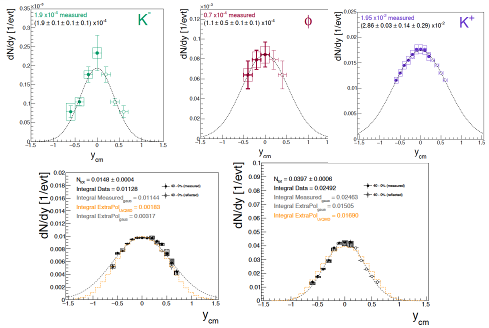
# Centrality dependence of multiplicities



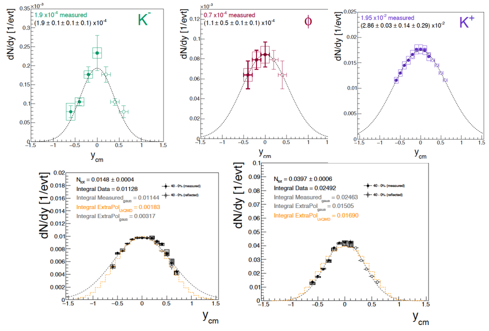

- Multiplicities increase towards more central collisions more than linear with $M \sim A_{part}^{\alpha}$
- $\alpha$ comparable within errors to KaoS and FOPI results for higher beam energies ($\alpha_{K+}$=1.34 ± 0.16, $\alpha_{K-}$=1.22 ± 0.27, $\alpha_{\phi}$ = 1.7 ± 0.5)
- Sensitive to multi particle interaction
  - Comparison to transport models and other strange hadrons
  - See Timos talk

# Summary

- Measurement of close to complete set of subthreshold produced open and hidden strange hadrons in Au+Au collisions 1.23 AGeV



# Summary

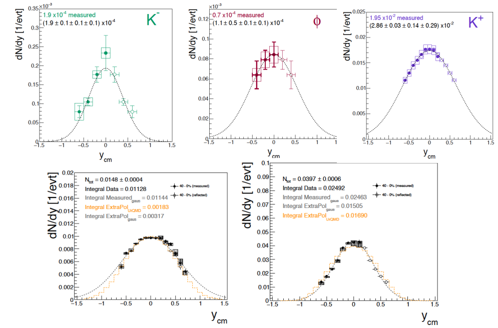



- Measurement of close to complete set of subthreshold produced open and hidden strange hadrons in Au+Au collisions 1.23 AGeV

- *“Strangeness exchange mechanism dominant for $K^-$ production”*
- *“Later freeze-out of $K^-$ compared to $K^+$ due to coupling to baryons”*
- *“Strangeness production in HIC is very different from that in elementary interaction”*

# Summary

- Measurement of close to complete set of subthreshold produced open and hidden strange hadrons in Au+Au collisions 1.23 AGeV

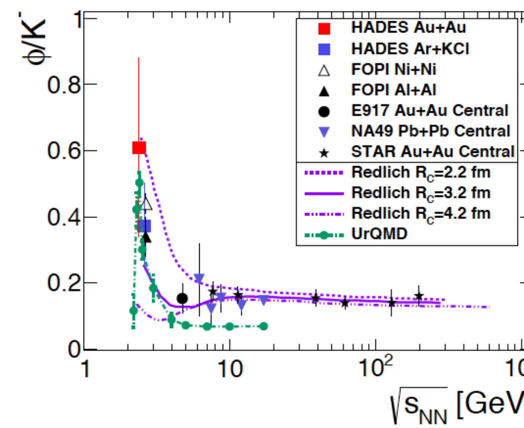


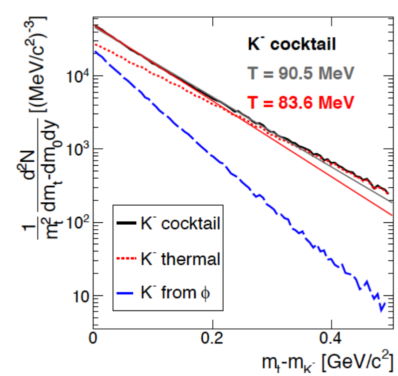

- *“Strangeness exchange mechanism dominant for $K^-$ production”*
- *“Later freeze-out of $K^-$ compared to $K^+$ due to coupling to baryons”*
- *“Strangeness production in HIC is very different from that in elementary interaction”*

➢ **$\phi$ / $K^-$ = 0.61 ± 0.27**

➢ Lower effective temperature and rapidity spectrum of $K^-$ can be reproduced by two component model simulation

➢ UrQMD (tuned with elementary cross-sections) predicts rise of $\phi$ / $K^-$ ratio towards lower energies



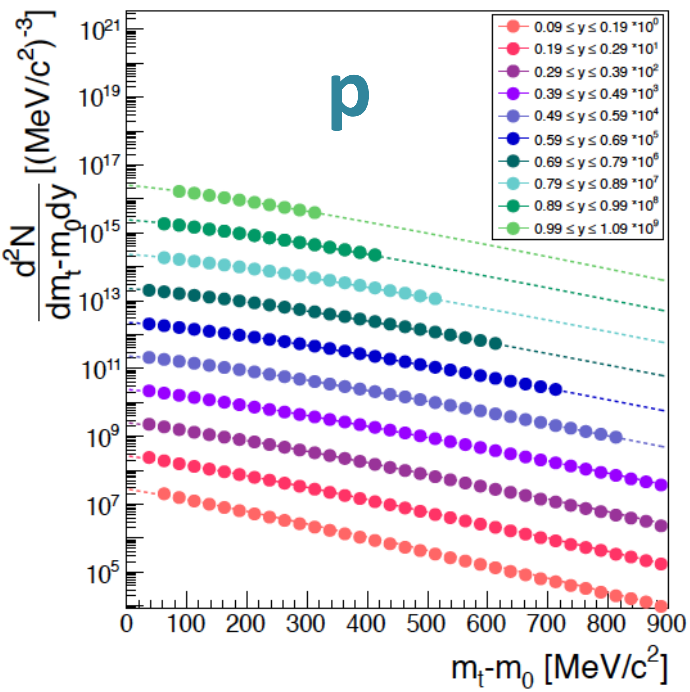
# The HADES Collaboration

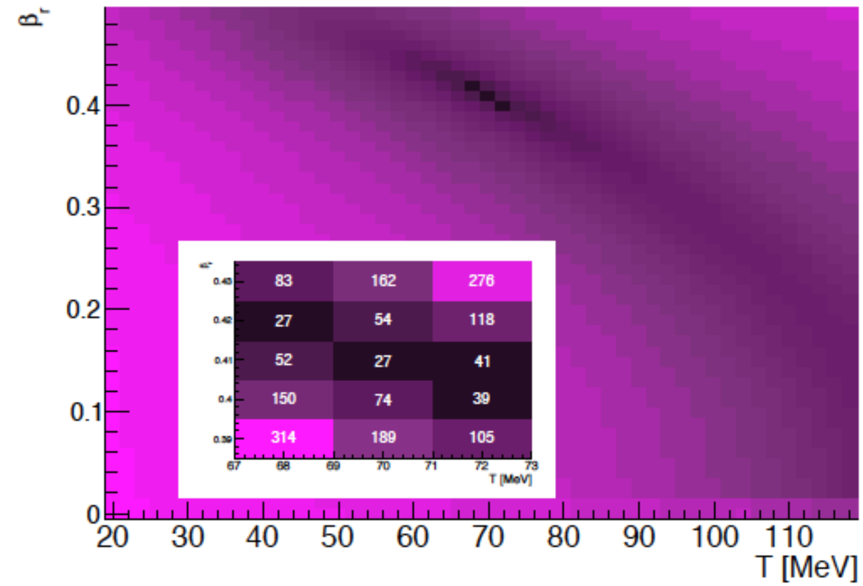
## Thank you for your attention!

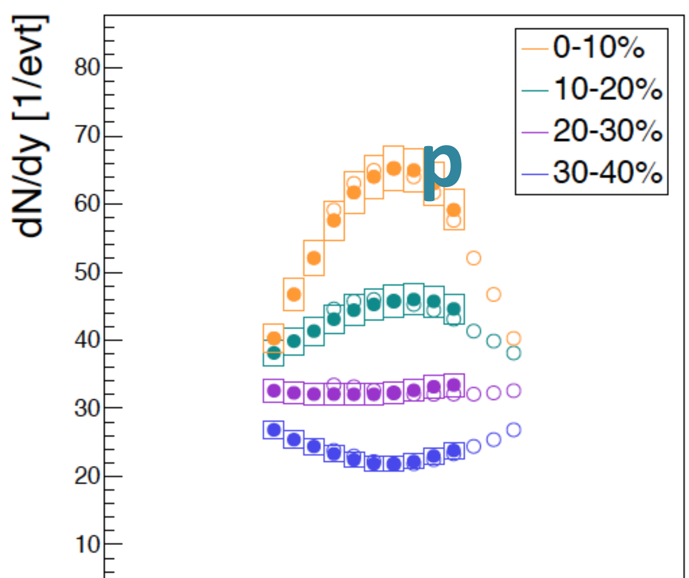
# Backup

# Proton Production

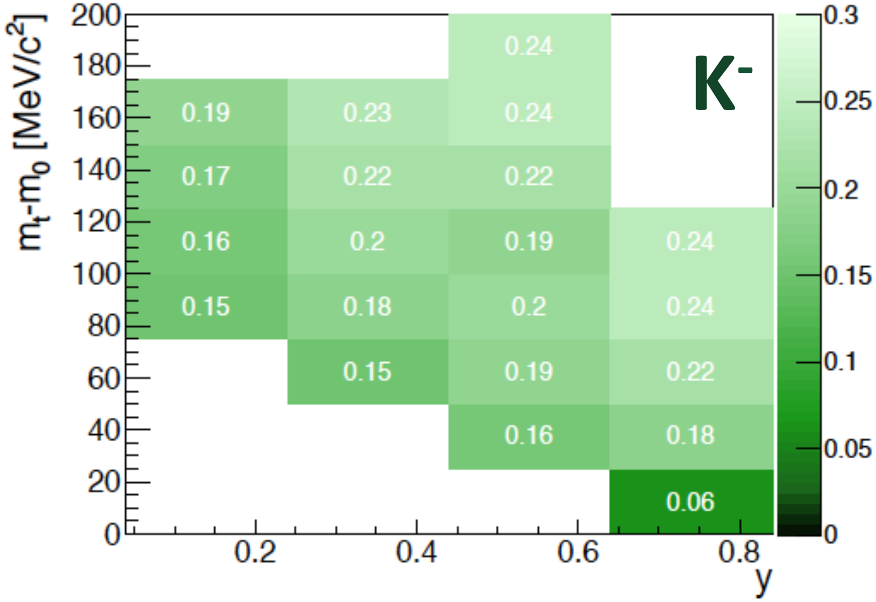
## Wide phase space coverage

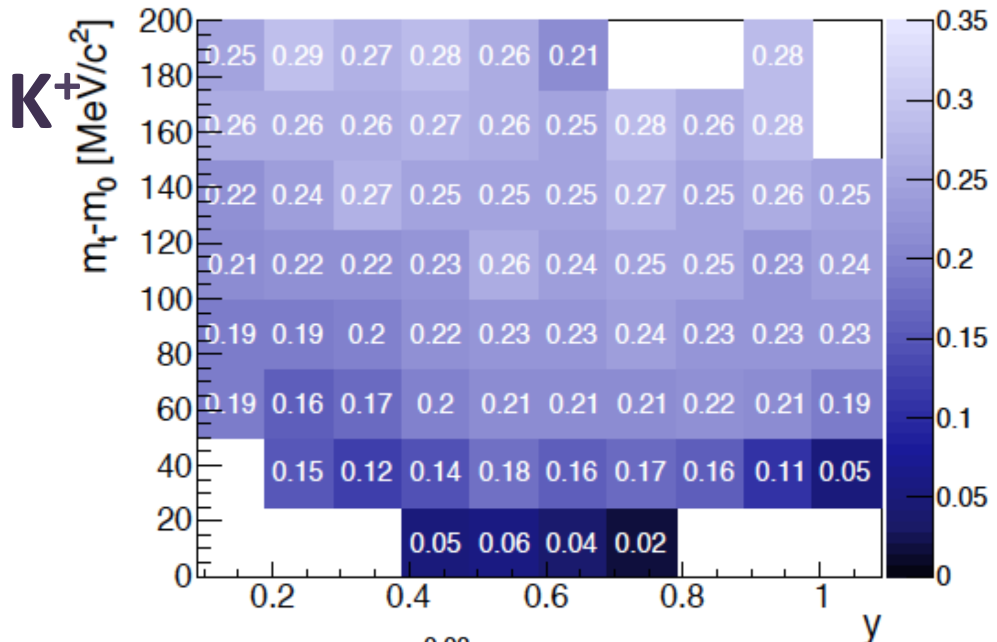


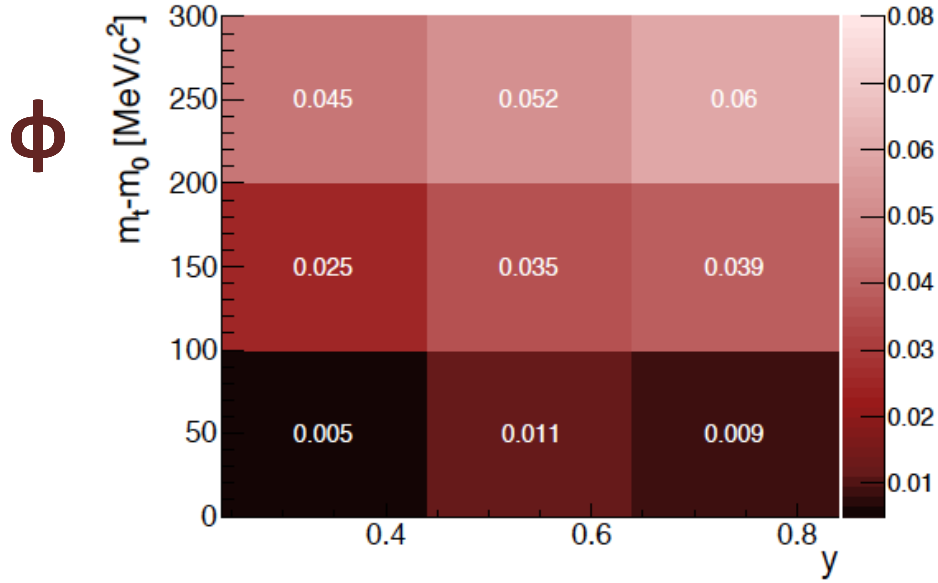



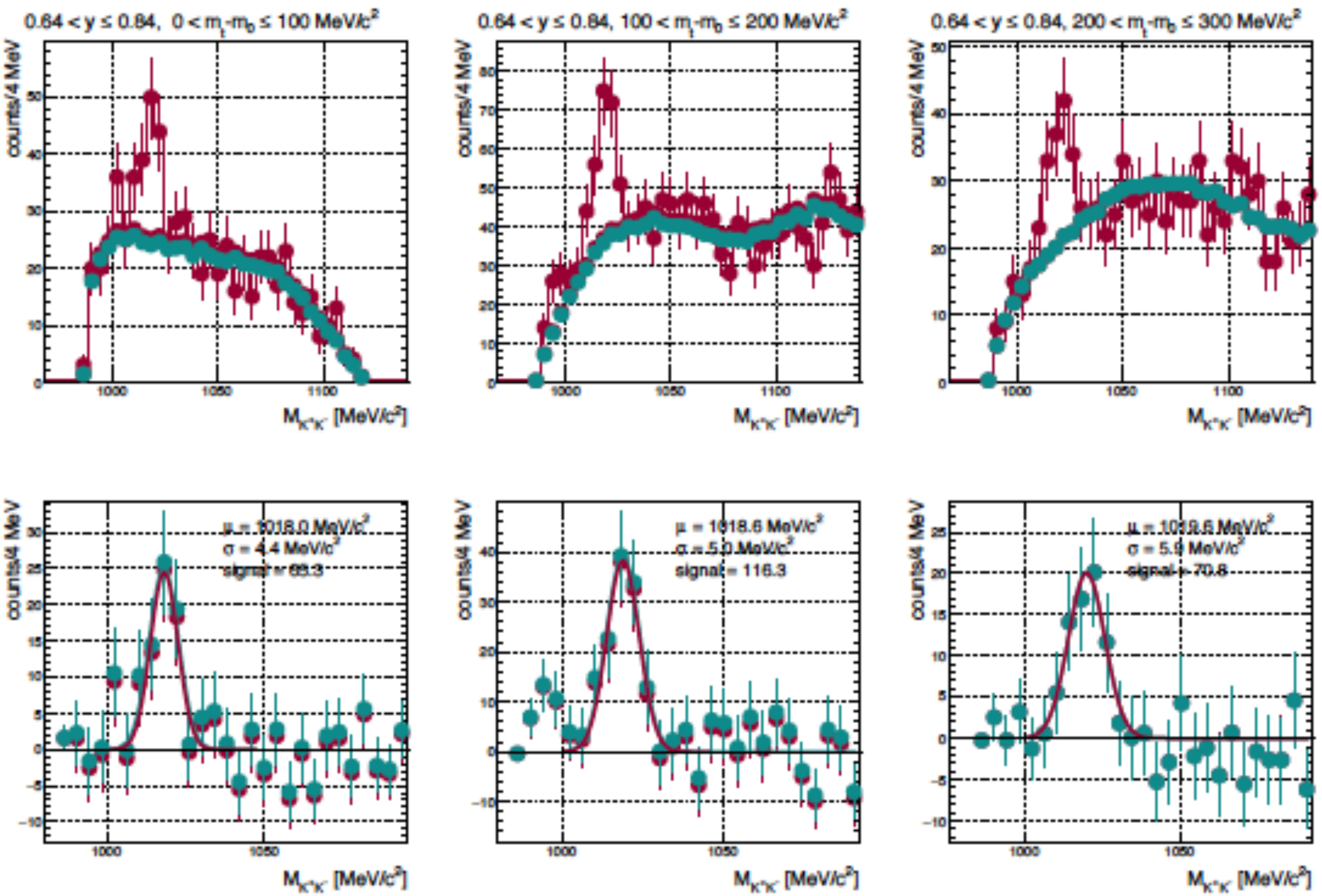
# Efficiency * acceptance



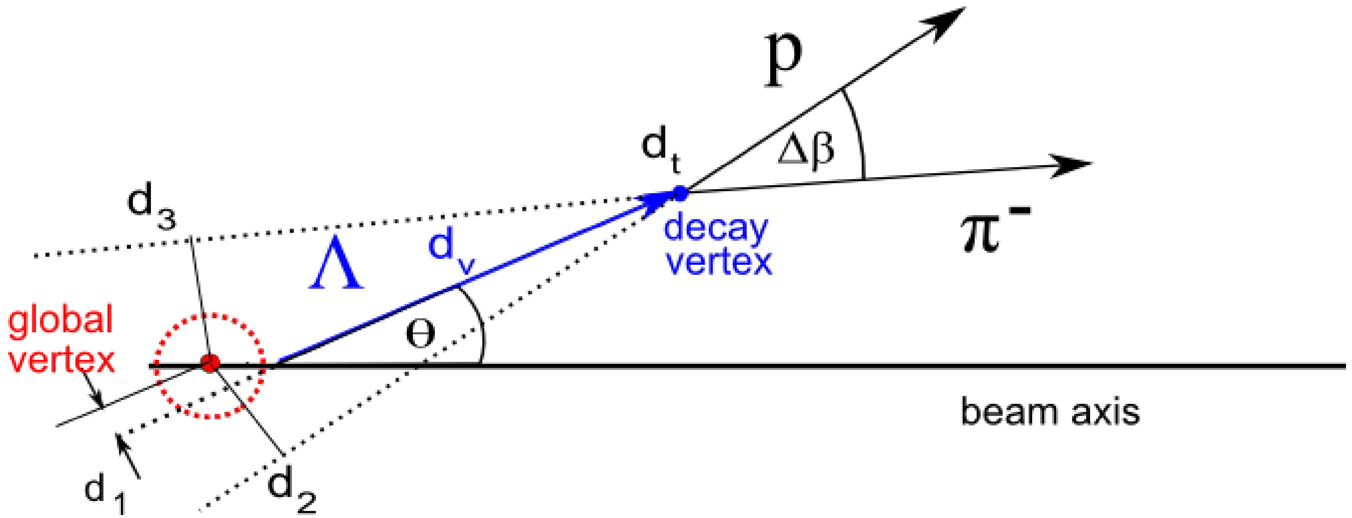



# Invariant mass ϕ



# Reconstruction of neutral hadrons

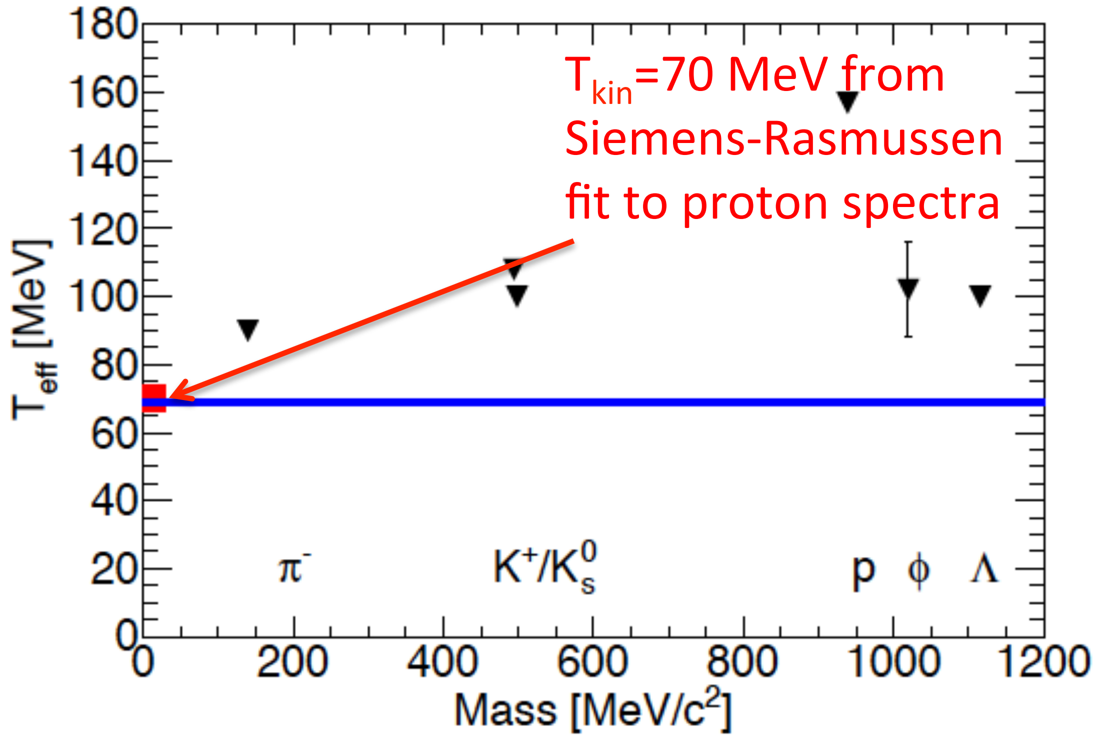
## Background suppression

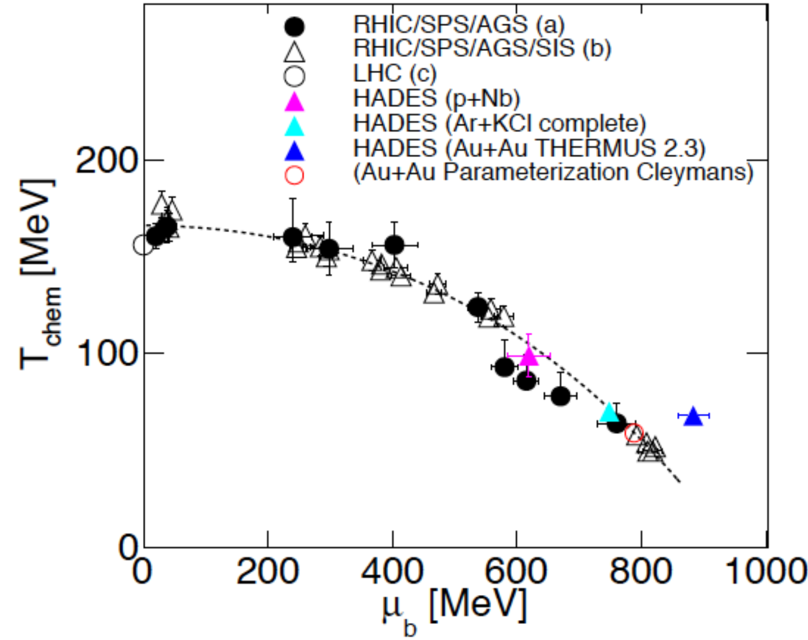



**$d_1$:** dist. primary particle track – prim. Vertex
**$d_v$:** dist. prim. vertex – decay vertex
**$d_2$:** min. dist. prim. vertex – $\text{daughter}_1$ track
**$d_3$:** min. dist. prim. vertex – $\text{daughter}_2$ track
**$d_t$ :** distance of closest approach of daughter particles

**Δβ:** opening angle

# Chemical vs. Kinetic Freeze-out

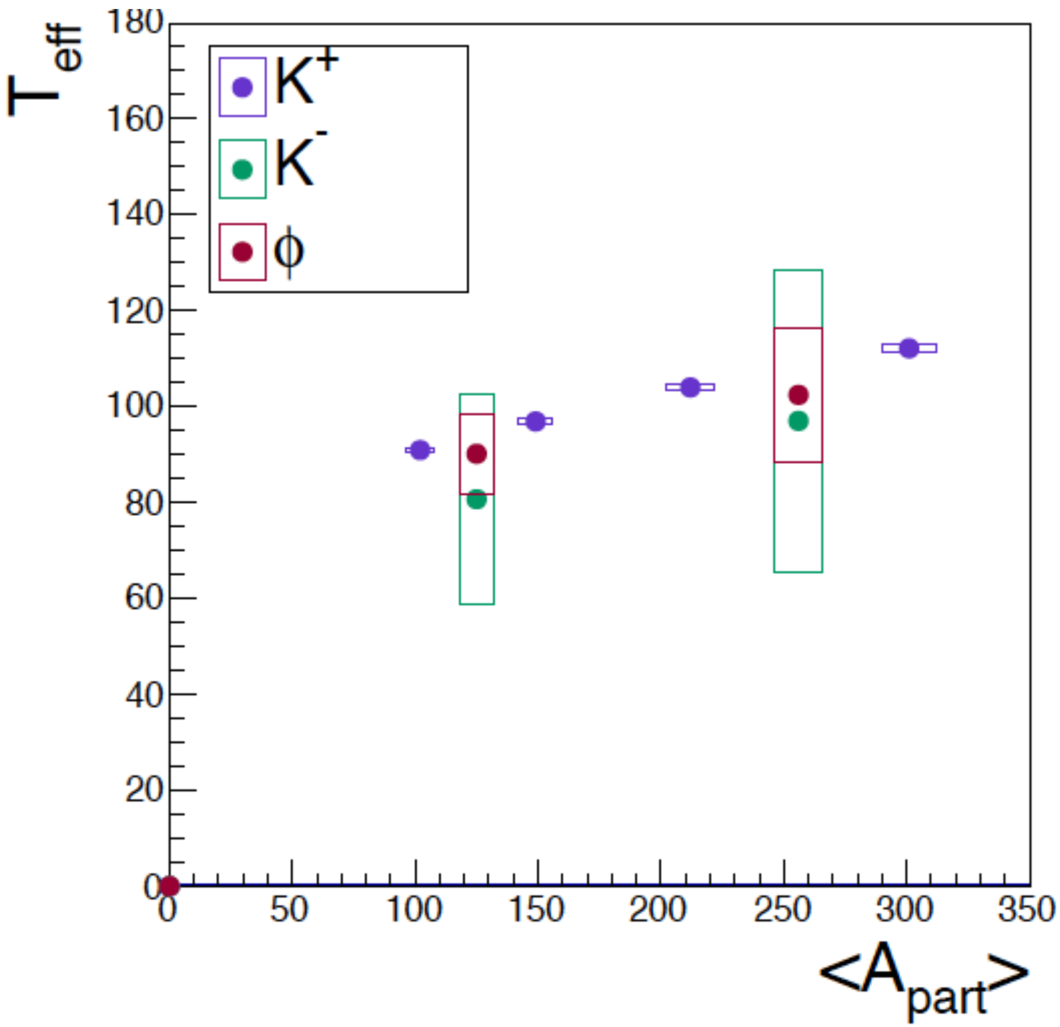



- $T_{chem}$ consistent with $T_{kin}$ obtained from Siemens-Rasmussen fits to proton transverse mass spectra

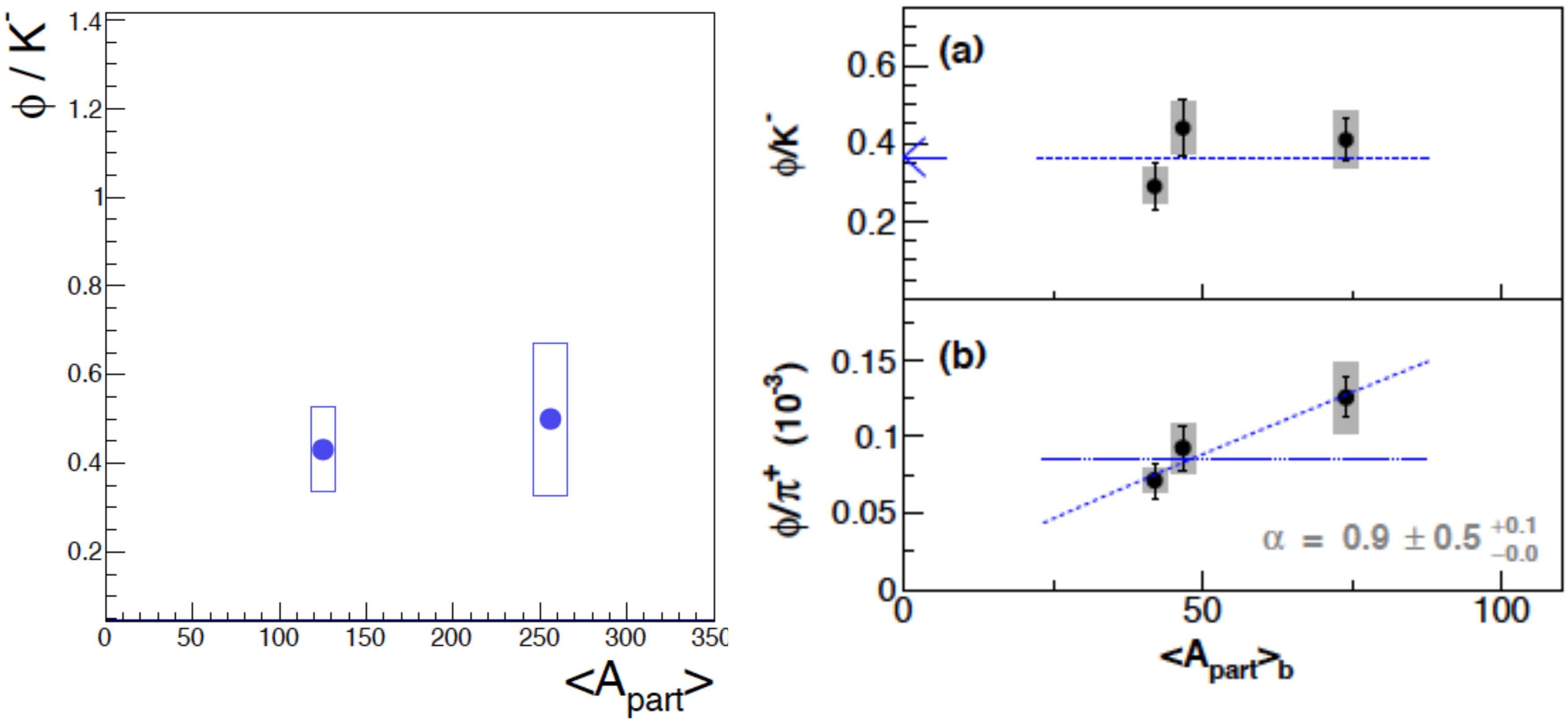
# Comparison

## Effective temperatures of charged kaons



# $\phi$ / $K^-$ ratio

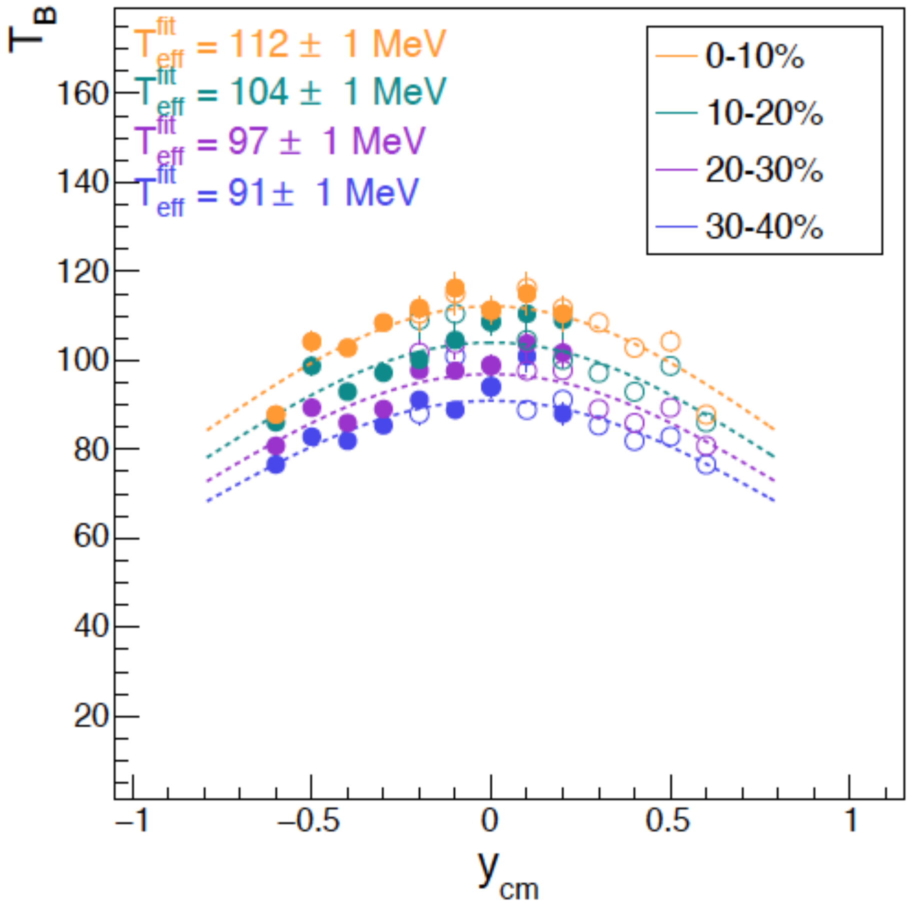
## Centrality dependence

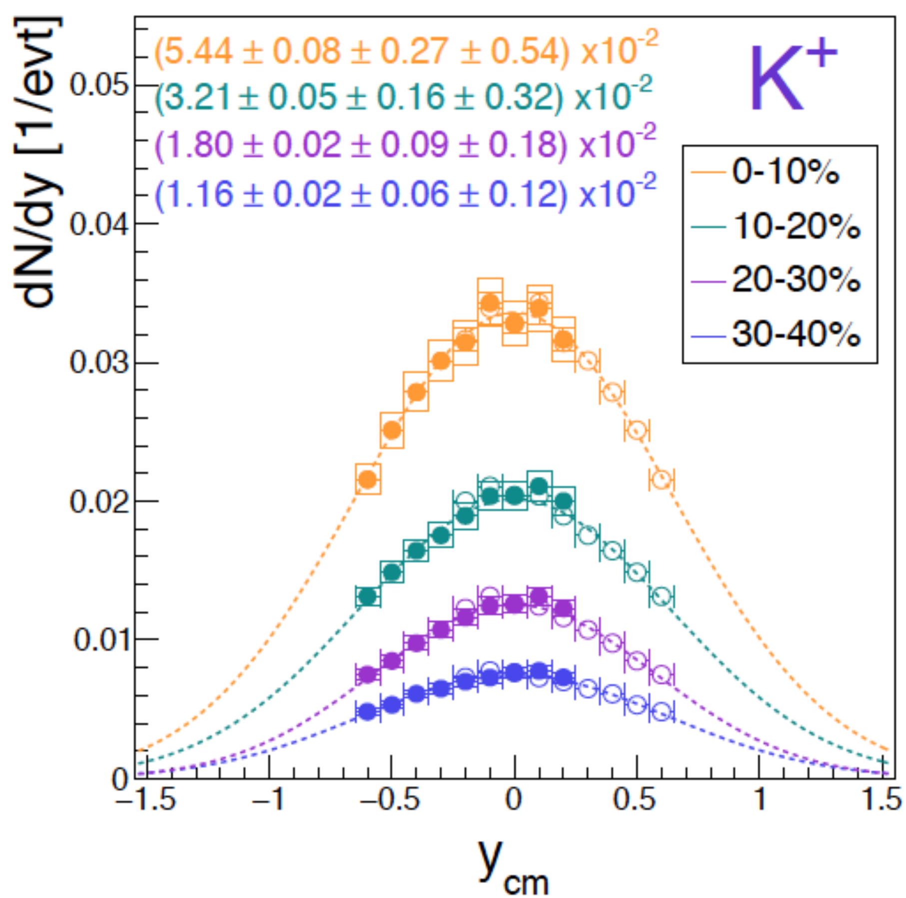



- $\phi/K^-$ ratio almost constant as function of centrality
- Similar trend observed from FOPI for Ni+Ni @ 1.9 AGeV

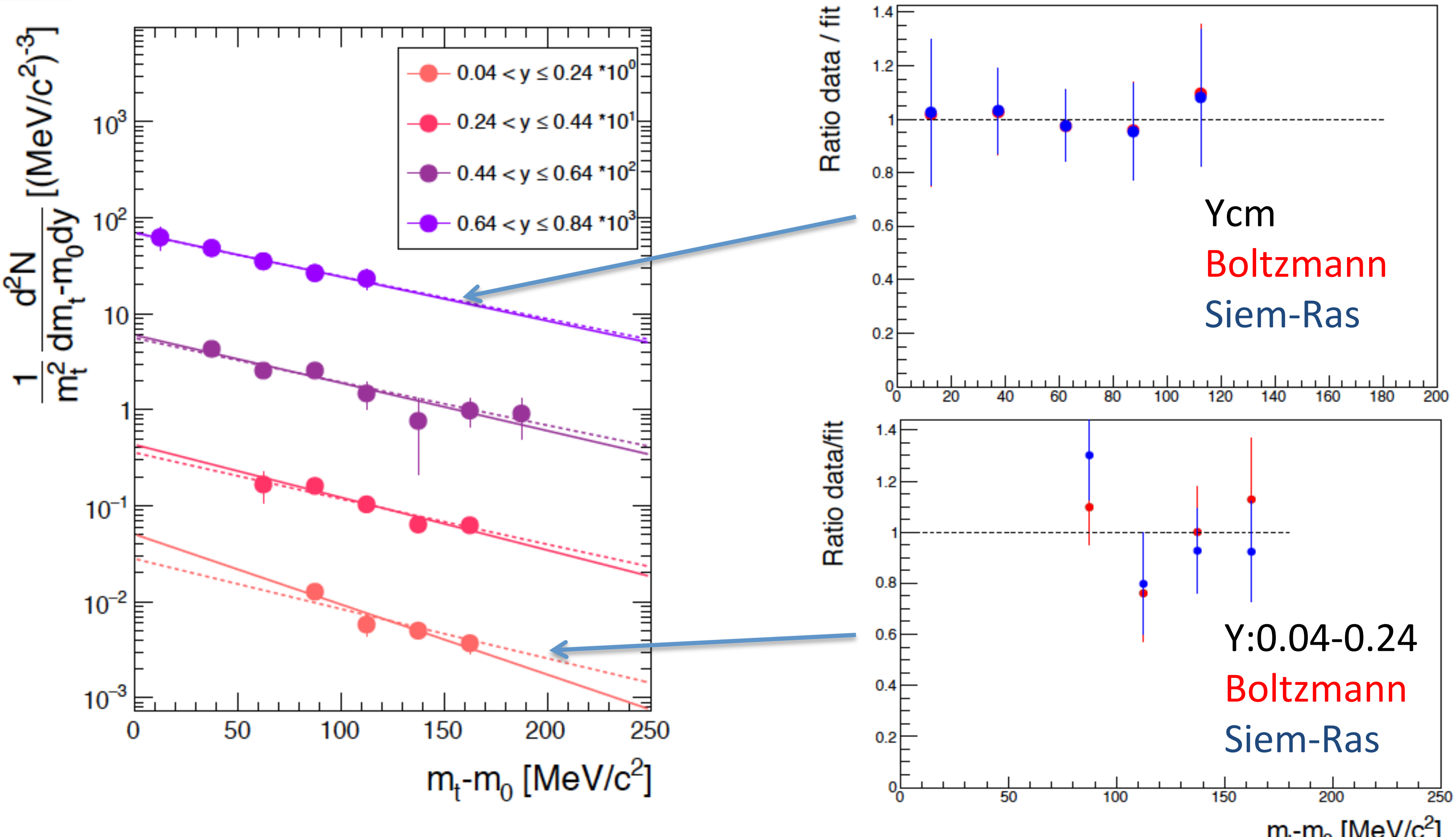
# $K^+$ Production

## Centrality dependent



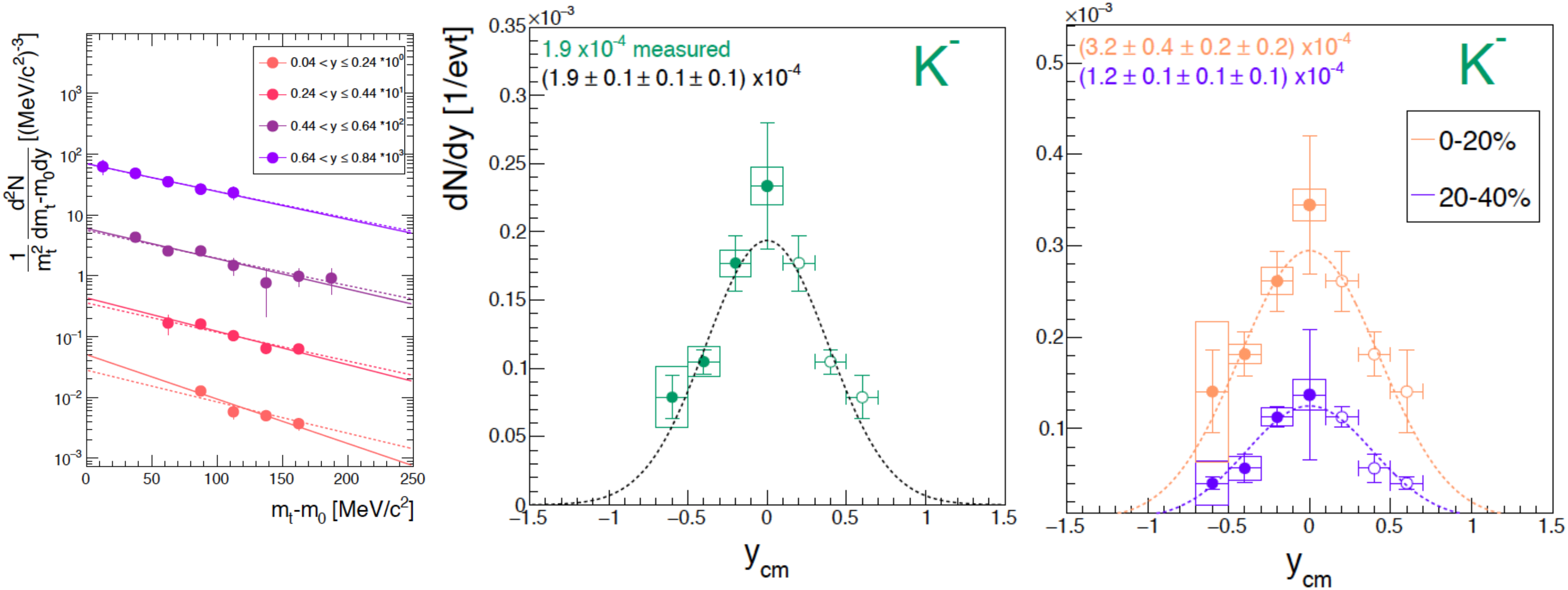



# $K^-$ Production



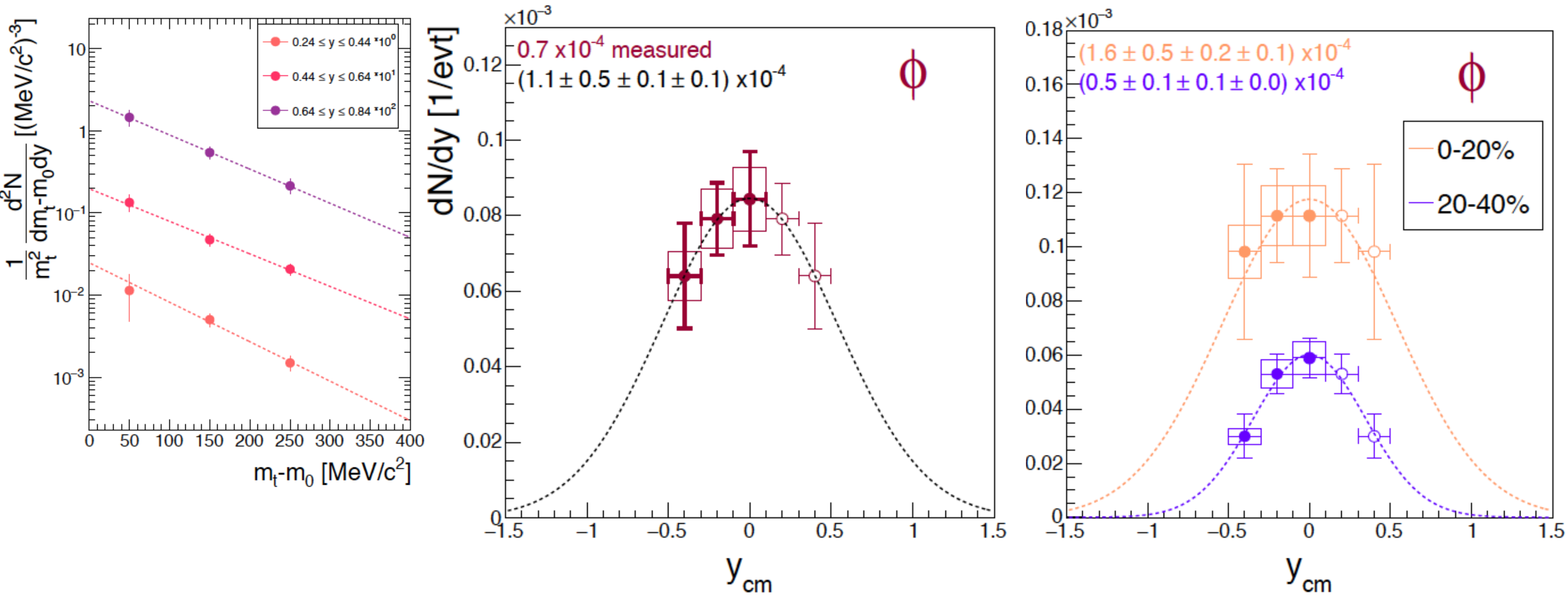

- Less phase space bins -> Boltzmann fit not perfectly constrained
- Average Boltzmann <–> Siemens-Rasmussen -> Rapidity distribution

# K⁻ Production




- Less phase space bins -> Boltzmann fit not perfectly constrained
- Average Boltzmann <–> Siemens-Rasmussen -> Rapidity distribution

# ϕ Production




- (Small) systematic error on mt-spectrum from difference of signal due to different mixed event normalization region
- 0-20% most central $\sigma_{Gauss}$ unphysical result (much too broad) -> fixed on σ(0-40%)