Production of $\phi(1020)$ mesons in nucleus-nucleus collisions at the CERN SPS

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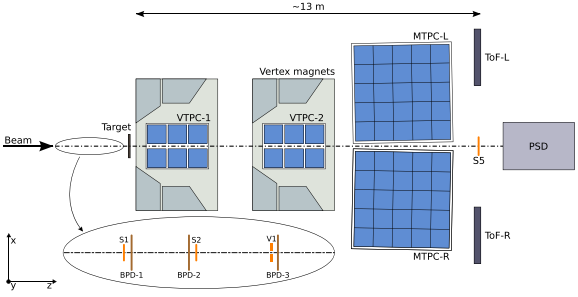
Introduction

1. ϕ meson
   - resonant particle (width = 4.266 MeV/c^2, $\tau \approx 50$ fm/c)
   - main decay channel $\phi \to K^+K^-$ (BR $\approx 50\%$)
   - the lightest particle (m = 1020 MeV/c^2) with hidden strangeness ($s\bar{s}$)
2. Data from NA61/SHINE Ar+Sc collisions at three beam momenta
   - 150A GeV/c ($\sqrt{s_{NN}}$ = 16.8 GeV)
   - 75A GeV/c ($\sqrt{s_{NN}}$ = 11.9 GeV)
   - 40A GeV/c ($\sqrt{s_{NN}}$ = 8.8 GeV)
3. Motivation
   - comparison with Pb+Pb and p+p data
   - constrain models (ϕ meson is interesting due to hidden strangeness)

NA61/SHINE detector

- fixed-target, multipurpose experiment (topics: ions, neutrinos, cosmic rays)
- direct measurement only for charged hadrons
- TPCs → particle tracks in 3D
- energy loss (dE/dx) → particle identification (PID)



NA61/SHINE, Eur.Phys.J.C 81 (2021) 5, 397

- detector at the time when Ar+Sc data was taken (2015)
- major hardware update was performed since then
  (see NA61/SHINE, Springer Proc.Phys. 250 (2020) 473-477)

Analysis methodology

Event selection:

- 10% of the most central collisions
- well measured main vertex
- in the target

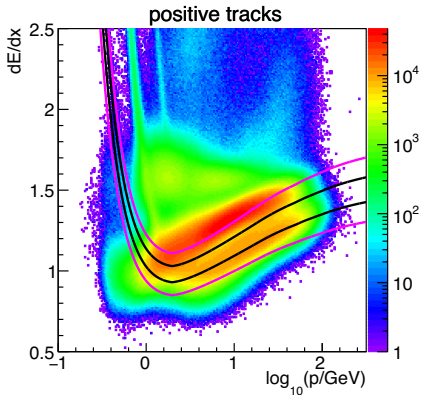
TPC track selection

- from main vertex
- well reconstructed
- enough points in TPCs
  (accurate dE/dx and momentum)
- PID cuts
  - ±5% band around Bethe-Bloch K curve
  - ±13% band around Bethe-Bloch K curve
    (better signal to bkg ratio in tag sample)

Signal extraction

- invariant mass spectra in y, p_T bins
- tag and probe method

ATLAS, Eur. Phys. J. C 74, 2895 (2014)
LHCb, Phys. Lett. B 703, 267 (2011)
SHINE, Eur. Phys. J. C 80, 199 (2020)



Tag and probe method (ATLAS, LHCb)

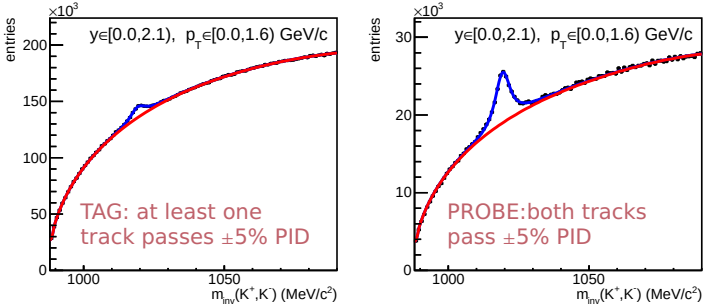
- This method allows to extract ϕ yield without knowledge of efficiency of kaon selection (ε)

$$\begin{cases} N_t = N_\phi \varepsilon (2 - \varepsilon) \\ N_p = N_\phi \varepsilon^2 \end{cases}$$

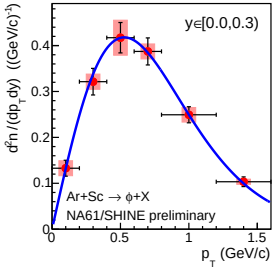
- Spectra are fitted simultaneously to get N_ϕ

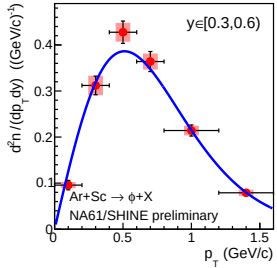
$N_{t/p} \rightarrow$ expected signal yields
$N_\phi \rightarrow \phi$ contributing to the spectra

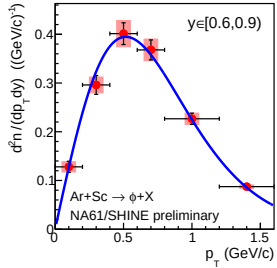
background event mixing + K*(892) template
signal convolution of relativistic Breit-Wigner and q-Gaussian

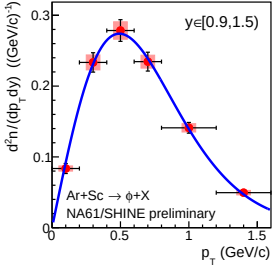


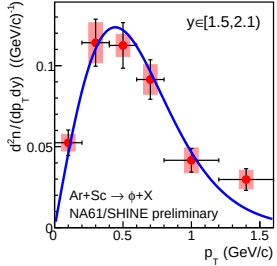
$dn^2/dydp_T$ distributions, central Ar+Sc at $\sqrt{s_{NN}}$ = 16.8 GeV











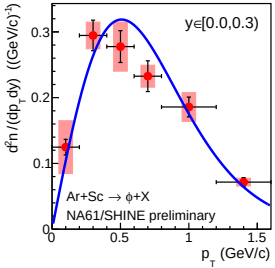
fit with function

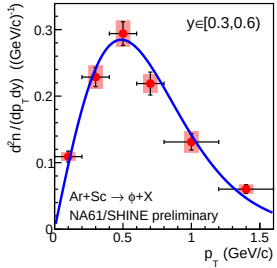
$f(p_T) \propto p_T \cdot \exp\left(-\frac{m_T}{T}\right)$

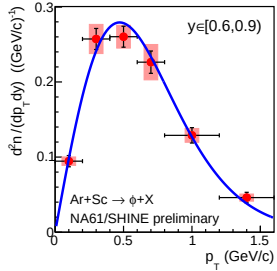
to obtain integral of the tail of the p_T distribution (needed for dn/dy)

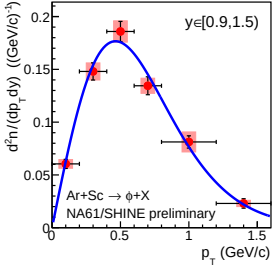
tails from 1.2% to 4.8%

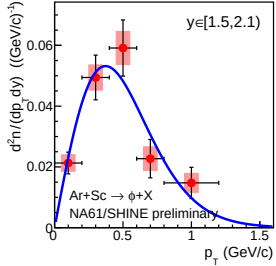
$dn^2/dydp_T$ distributions, central Ar+Sc at $\sqrt{s_{NN}}$ = 11.9 GeV











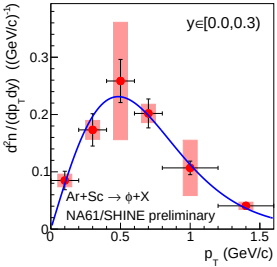
fit with function

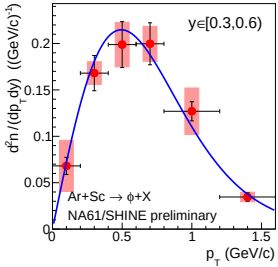
$f(p_T) \propto p_T \cdot \exp\left(-\frac{m_T}{T}\right)$

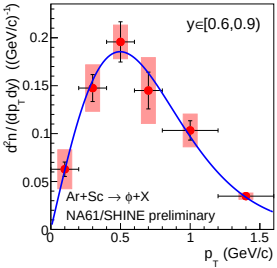
to obtain integral of the tail of the p_T distribution (needed for dn/dy)

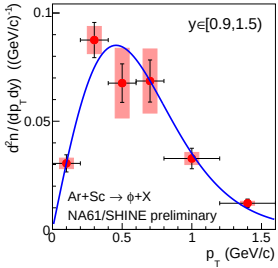
tails from 0.2% to 3.7%

$dn^2/dydp_T$ distributions, central Ar+Sc at $\sqrt{s_{NN}}$ = 8.8 GeV









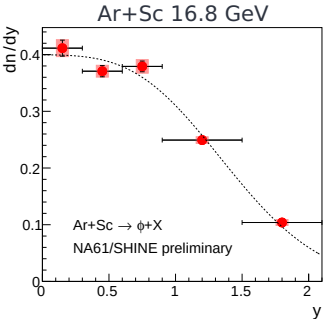
fit with function

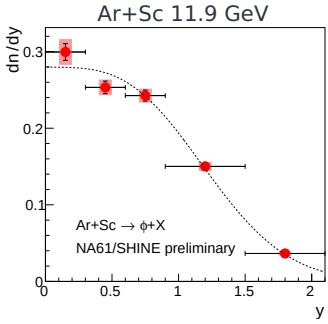
$f(p_T) \propto p_T \cdot \exp\left(-\frac{m_T}{T}\right)$

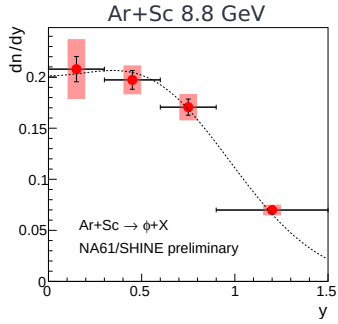
to obtain integral of the tail of the p_T distribution (needed for dn/dy)

tails from 1.6% to 2.5%

dn/dy distributions



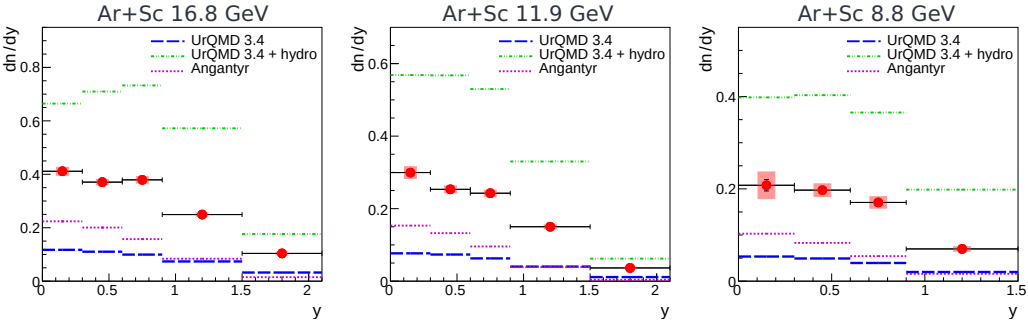




tails from
0.8% to 2.5%

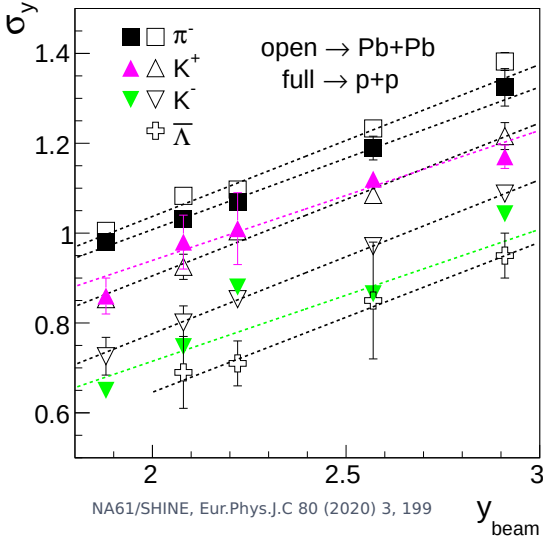
$\sqrt{s_{NN}}$ (GeV)	1000 $\langle\phi\rangle$	RMS (double Gaussian fit)
16.8	$1148 \pm 17 \pm 21$	$0.994 \pm 0.020 \pm 0.018$
11.9	$707 \pm 11 \pm 14$	$0.866 \pm 0.013 \pm 0.010$
8.8	$438 \pm 12 \pm 22$	$0.703 \pm 0.016 \pm 0.021$

dn/dy distributions



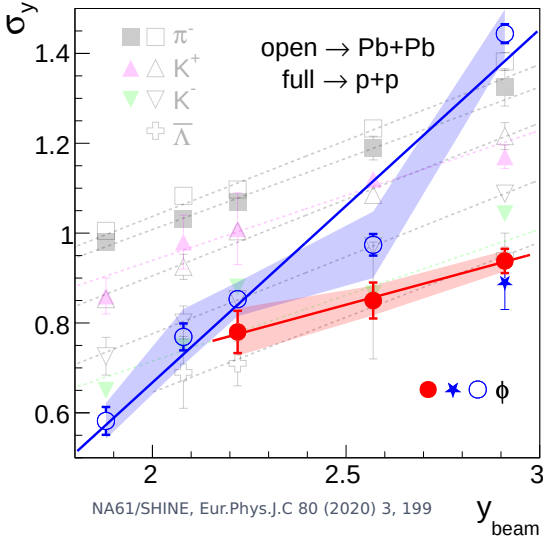
- Model calculations made by summer students **Sena Veli** (Technical University of Munich) and **Tomasz Janiec** (The University of Manchester)
- None of the models matches the experimental data points

Width of rapidity distributions



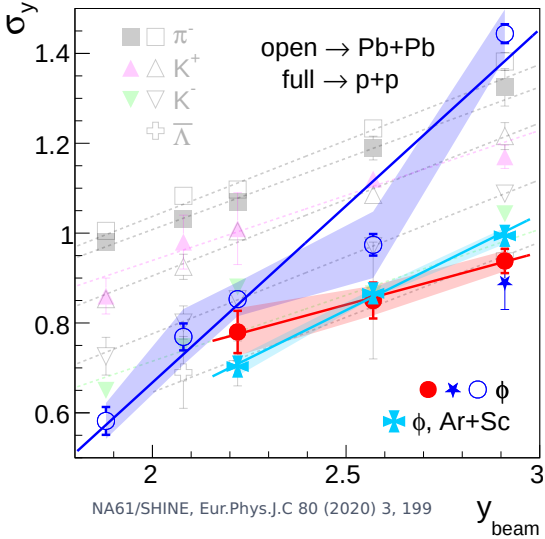
- Width of the rapidity distributions (σ_y) as a function of the beam rapidity (c.m.s.) for various particles from Pb+Pb and p+p collisions
- Lines are fitted to guide the eye

Width of rapidity distributions



- Width of the rapidity distributions (σ_y) as a function of the beam rapidity (c.m.s.) for various particles from Pb+Pb and p+p collisions
- Lines are fitted to guide the eye
- Width of the rapidity distributions of ϕ meson from:
  - Pb+Pb (NA49)
  - p+p (NA61), p+p (NA49)

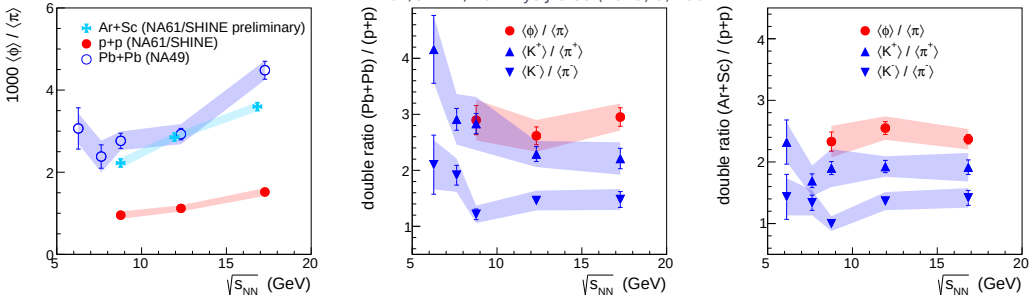
Width of rapidity distributions



- Width of the rapidity distributions (σ_y) as a function of the beam rapidity (c.m.s.) for various particles from Pb+Pb and p+p collisions
- Lines are fitted to guide the eye
- Width of the rapidity distributions of ϕ meson from:
  - Pb+Pb (NA49)
  - p+p (NA61), p+p (NA49)
  - Ar+Sc (NA61/SHINE preliminary)

$\phi(1020)$ enhancement

NA61/SHINE, Eur.Phys.J.C 80 (2020) 3, 199



- ϕ/π ratio for Ar+Sc is slightly lower than for Pb+Pb, but much higher than for p+p collisions
- ϕ enhancement over p+p collisions is slightly higher than for kaons in both Ar+Sc and Pb+Pb, and independent of the collision energy in the considered range

Summary

1. We analyzed ϕ meson production using central Ar+Sc data at $\sqrt{s_{NN}}$ = 16.8, 11.9 and 8.8 GeV from the NA61/SHINE experiment
2. We obtained double differential (y, p_T) spectra of ϕ mesons from invariant mass ($\phi \to K^+ K^-$) analysis (tag and probe procedure)
3. The widths of rapidity distributions from central Ar+Sc are similar to those from p+p reactions
4. Enhanced production of ϕ meson in central Ar+Sc comparable to p+p, but slightly lower than in Pb+Pb, independent of the collision energy (from $\sqrt{s_{NN}}$ = 8.8 to 16.8 GeV)

Thank you

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Extra slides

Tag and probe method

- Tag and probe method allows to extract ϕ yield without knowledge of efficiency of kaon selection
- Tag sample → at least one track in the pair passes PID condition
- Probe sample → both tracks in the pair pass PID condition
- Expected signal yields ($N_{t/p}$) depend on efficiency of K selection (ϵ) and number of ϕ contributing to the spectra (N_ϕ)

$$\begin{cases} N_t = N_\phi \epsilon (2 - \epsilon) \\ N_p = N_\phi \epsilon^2 \end{cases} \quad (1)$$

Spectra are fitted simultaneously to get N_ϕ

Tag and probe method

Single spectrum is fitted with a sum of

background event mixing + K* template
kaon candidate taken from the current event is combined with candidates from previous 100 events to create ϕ candidates in the mixed events spectrum

signal convolution of relativistic Breit-Wigner and q-Gaussian
(detector resolution)

fitting function:

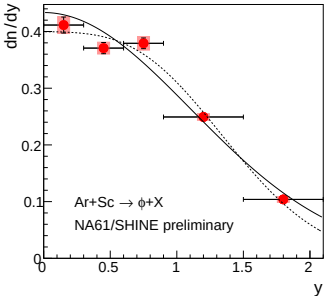
$$f_t(m_{inv}) = N_t(N_\phi, \epsilon) \cdot V(m_{inv}; m_\phi, \sigma) + N_{bkg,t} \cdot B_t(m_{inv}; f_{K^*,t}),$$
$$f_p(m_{inv}) = N_p(N_\phi, \epsilon) \cdot V(m_{inv}; m_\phi, \sigma) + N_{bkg,p} \cdot B_p(m_{inv}; f_{K^*,p}), \quad (2)$$

where

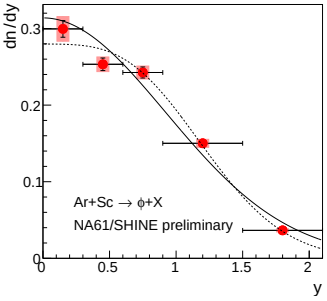
$$V = f_{\text{relBW}} * f_{\text{q-Gaus}}$$

dn/dy distributions, Ar+Sc @ 150*A*, 75A and 40*A* GeV/*c*

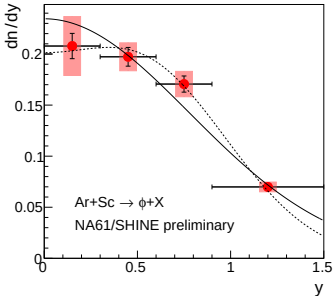
gauss $\frac{\chi^2}{ndf}$ = 9.81
double gauss $\frac{\chi^2}{ndf}$ = 5.29



gauss $\frac{\chi^2}{ndf}$ = 12.96
double gauss $\frac{\chi^2}{ndf}$ = 4.71

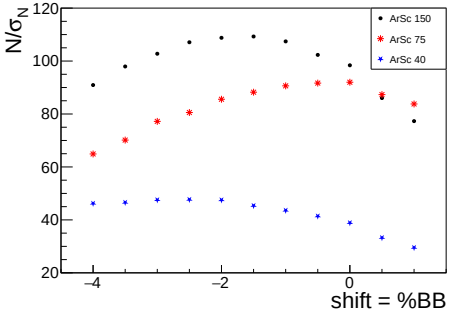


gauss $\frac{\chi^2}{ndf}$ = 6.29
double gauss $\frac{\chi^2}{ndf}$ = 0.72



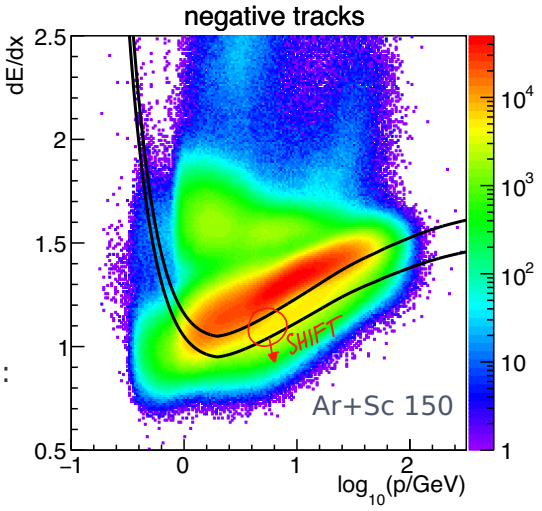
- solid line → gaussian
- dotted line → double gaussian
  - describes data points better
  - will be used for evaluation of *y* width

Additions compared to p+p – PID cut shift



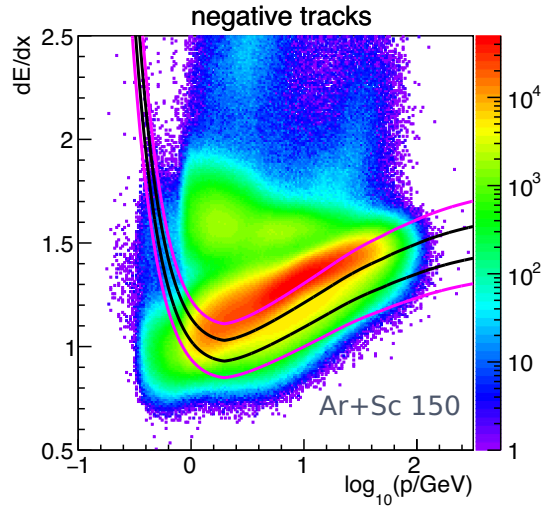
shift the inner cut band w.r.t. the BB:

- Ar+Sc 150 by -2%
- Ar+Sc 75 by -0.5%
- Ar+Sc 40 by -3%



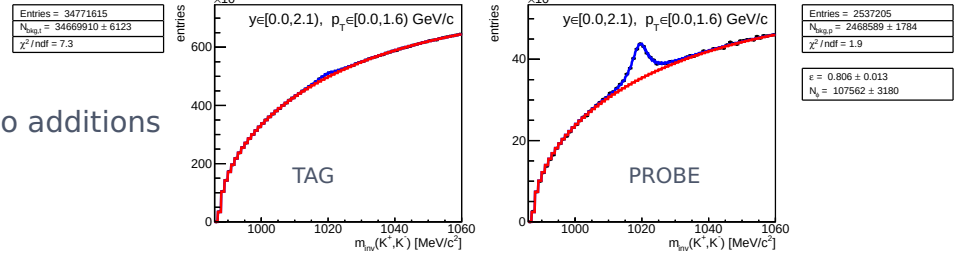
Additions compared to p+p – outer PID cut

- apply outer BB band ±13% to reduce the background
- this affects only the tag sample



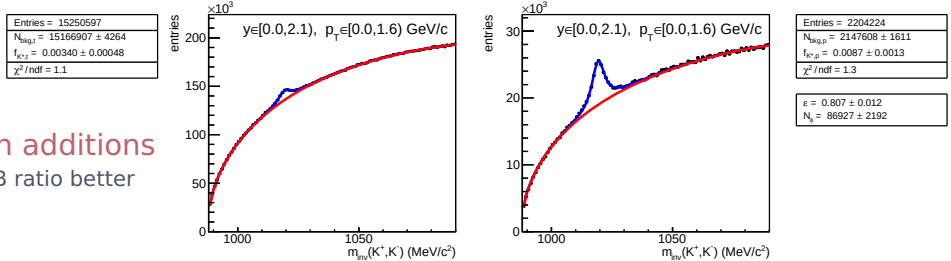
Tag and Probe Ar+Sc 150*A* GeV/*c*

no additions

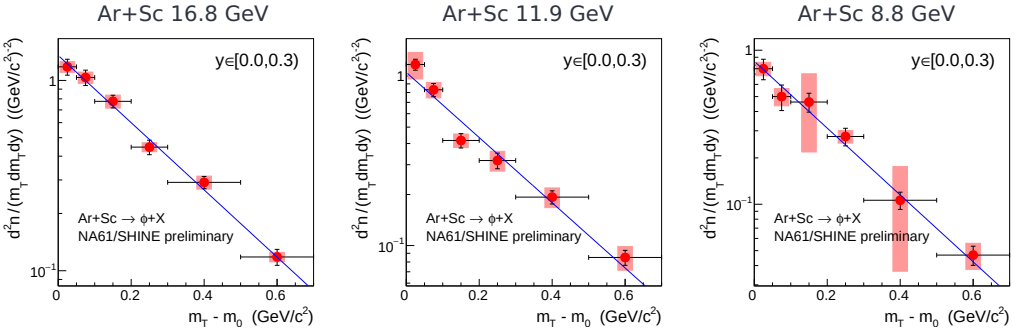


with additions

S/B ratio better



Transverse mass distributions



$\sqrt{s_{NN}}$ (GeV)	T(ϕ) (MeV)	T(K^+) (MeV)	T(K^-) (MeV)
16.8	$246 \pm 12 \pm 8$	$219.9 \pm 0.7 \pm 11.8$	$201.1 \pm 0.8 \pm 6.2$
11.9	$226 \pm 12 \pm 22$	$207.4 \pm 0.8 \pm 6.5$	$198.8 \pm 0.8 \pm 2.7$
8.8	$200 \pm 13 \pm 16$	$200.3 \pm 1.4 \pm 8.8$	$194.3 \pm 1.4 \pm 2.8$

NA61/SHINE, Eur.Phys.J.C 84 (2024) 4, 416