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

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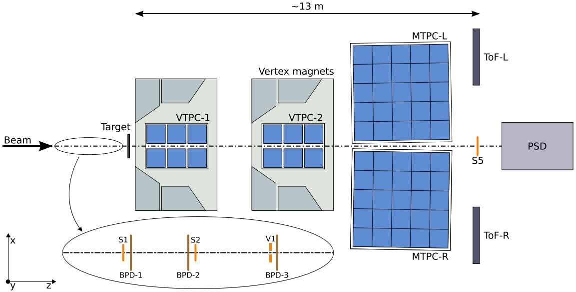
The 17th Workshop on Particle Correlations and Femtoscopy
4 Nov. 2024, Toulouse, France

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:

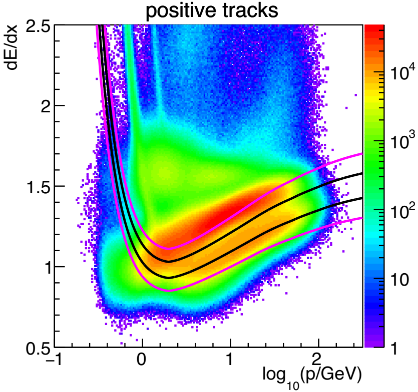
- 10% of the most central collisions
- well measured main vertex
- in the target

TPC track selection

- from main vertex
- well reconstructed
- enough points in TPCs
  (accurate dE/dx and momentum)
- PID cuts
  - $\pm 5\%$ band around Bethe-Bloch K curve
  - $\pm 13\%$ 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)



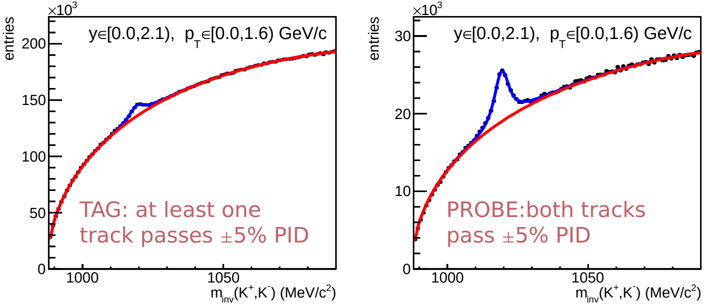
Tag and probe method (ATLAS, LHCb)

- This method allows to extract ϕ yield without knowledge of efficiency of kaon selection (ε)
- Spectra are fitted simultaneously to get N_ϕ

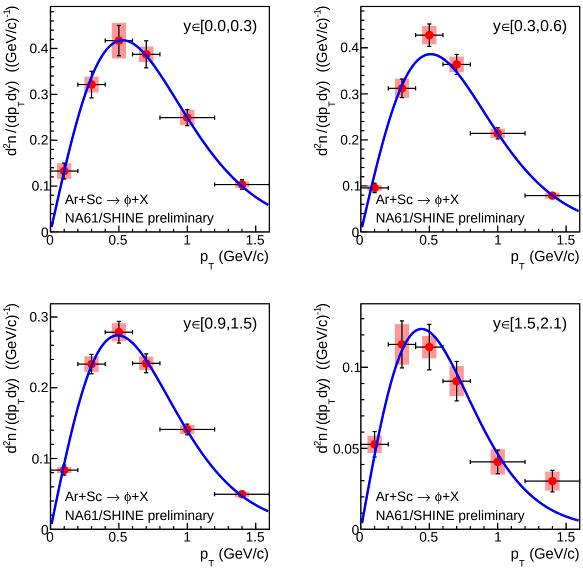
$$\begin{cases} N_t = N_\phi \varepsilon(2-\varepsilon) \\ N_p = N_\phi \varepsilon^2 \end{cases}$$

$N_{t/p} \rightarrow$ 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



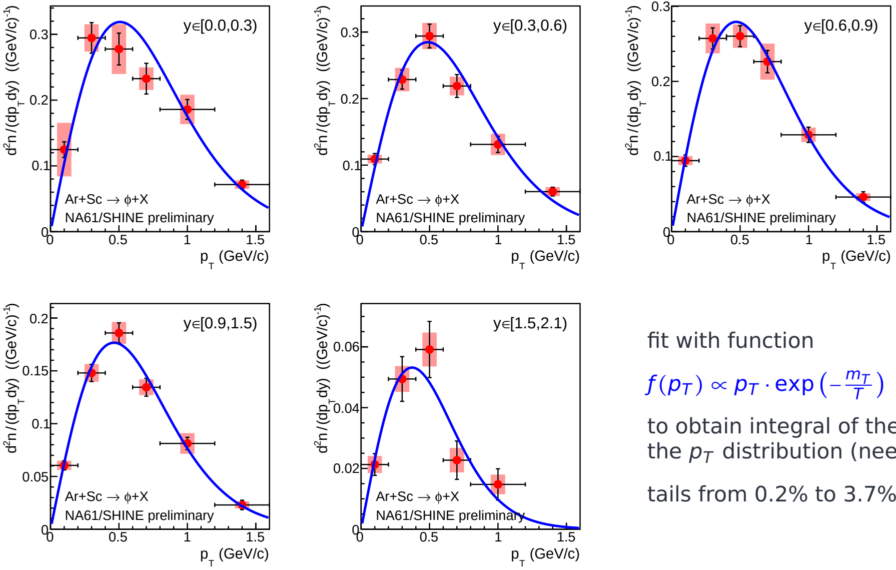
fit with function

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

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



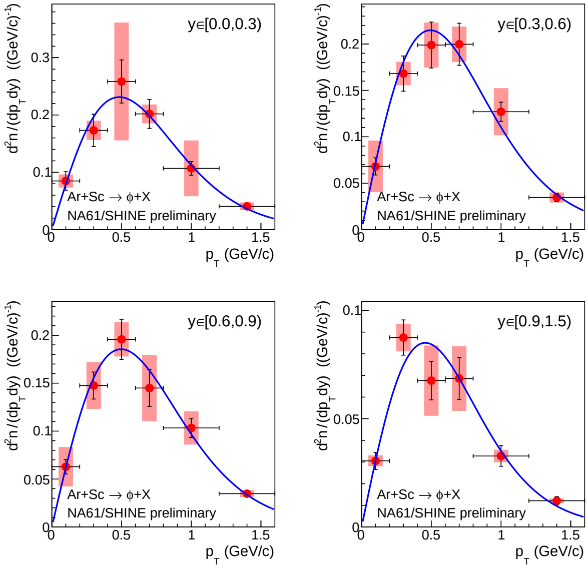
fit with function

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

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



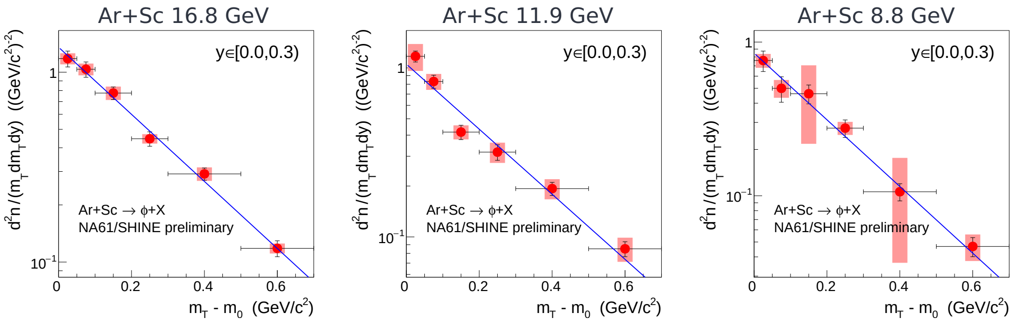
fit with function

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

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

tails from 1.6% to 2.5%

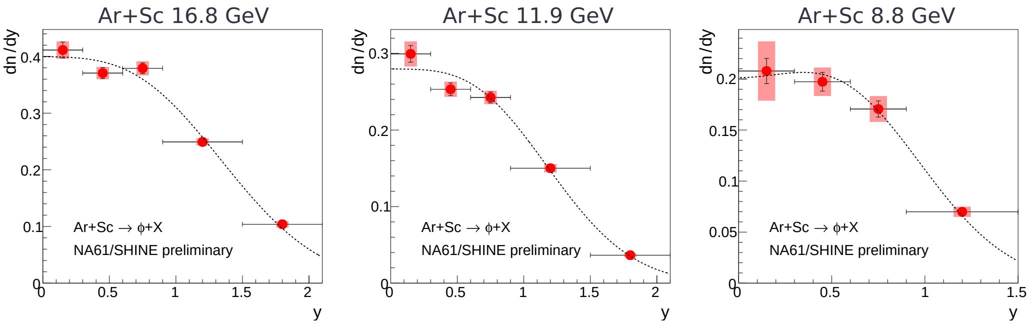
Transverse mass distributions



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

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

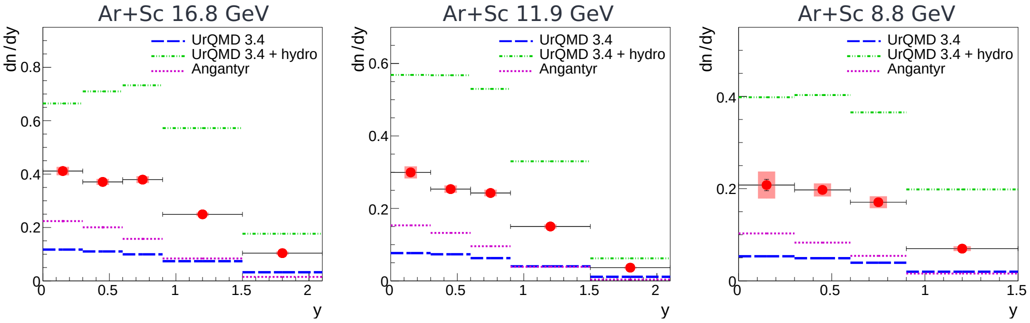
dn/dy distributions



tails from
0.8% to 2.5%

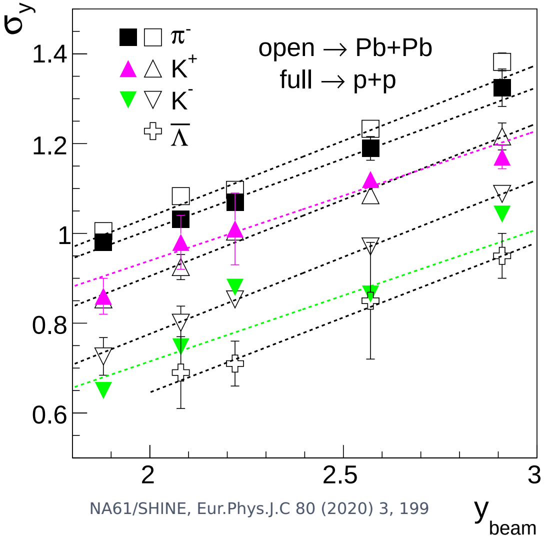
$\sqrt{s_{NN}}$ (GeV)	1000 $\langle\phi\rangle$	RMS (double Gaussian fit)
16.8	1148 ± 17 ± 21	0.994 ± 0.020 ± 0.018
11.9	707 ± 11 ± 14	0.866 ± 0.013 ± 0.010
8.8	438 ± 12 ± 22	0.703 ± 0.016 ± 0.021

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

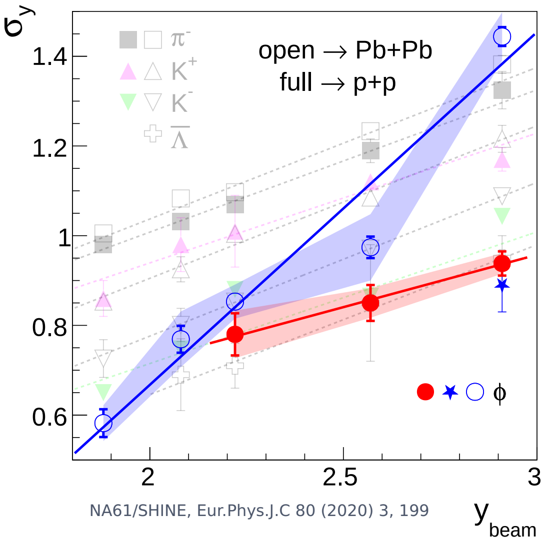
Width of rapidity distributions



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

- 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

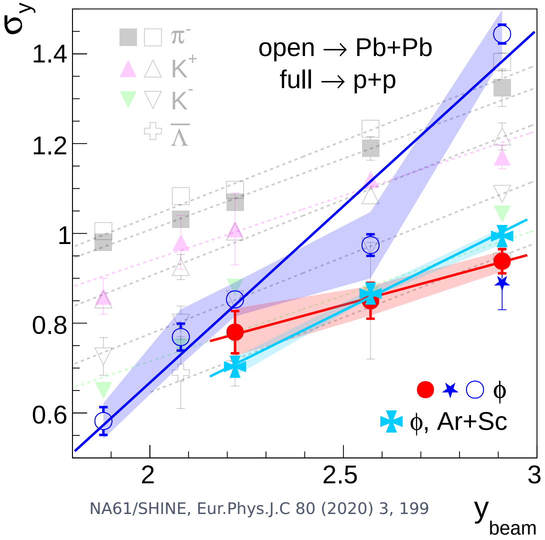
Width of rapidity distributions



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

- 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)

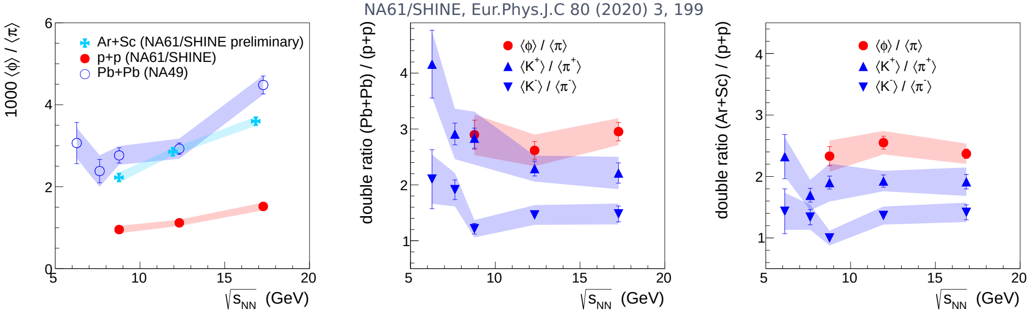
Width of rapidity distributions



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

- 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



- 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 ($\phi \rightarrow K^+ K^-$) 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)

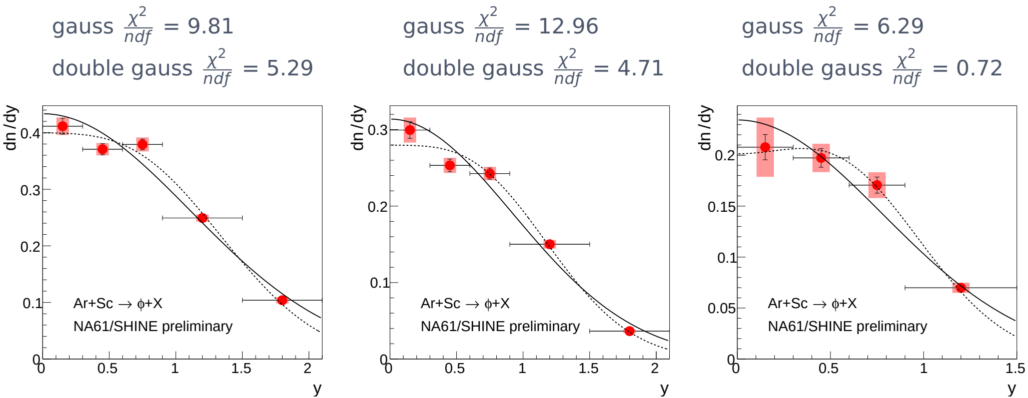
Thank you

This work was supported by the National Science Centre, Poland
(grant number 2023/51/D/ST2/02950)

The autor (Ł.R.) acknowledges financial support provided by the Polish National Agency for Academic Exchange NAWA under the Programme STER - Internationalisation of doctoral schools, Project no. BPI/STE/2023/1/00027/U/00001

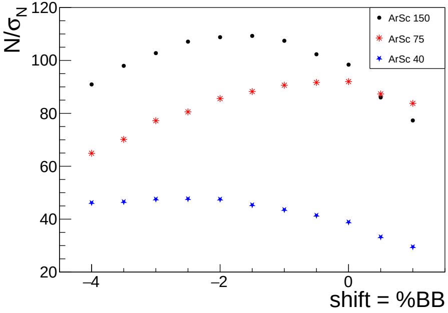
Extra slides

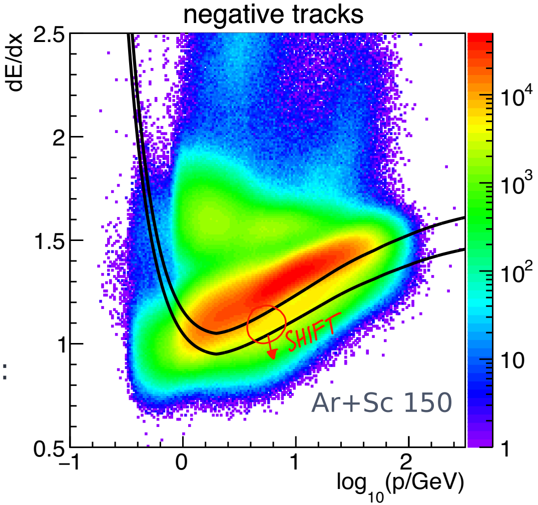
dn/dy distributions, Ar+Sc @ 150*A*, 75A and 40*A* GeV/*c*



- 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



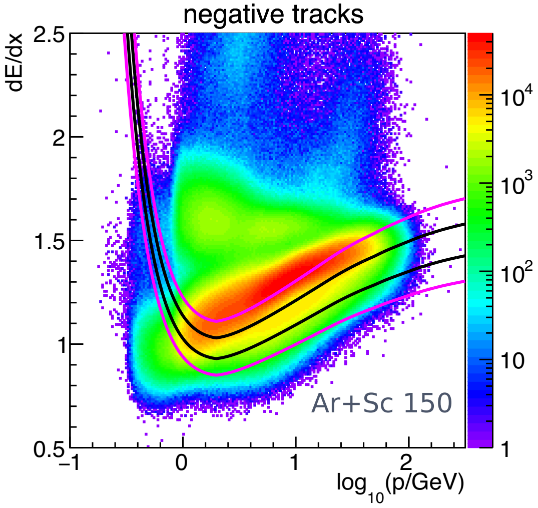


shift the inner cut band w.r.t. the BB:

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

Additions compared to p+p – outer PID cut

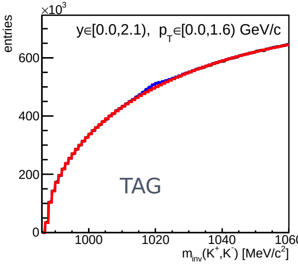
- apply outer BB band ±13% to reduce the background
- this affects only the tag sample

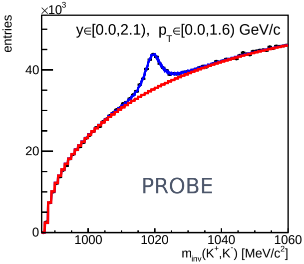


Tag and Probe Ar+Sc 150A GeV/c

no additions

Entries = 34771615
$N_{bkg,t}$ = 34669910 ± 6123
χ^2 / ndf = 7.3





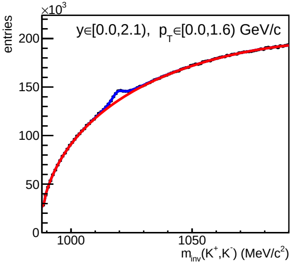
Entries = 2537205
$N_{bkg,p}$ = 2468589 ± 1784
χ^2 / ndf = 1.9

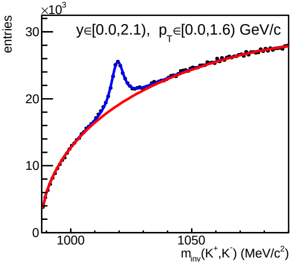
ε = 0.806 ± 0.013
N_ϕ = 107562 ± 3180

with additions

S/B ratio better

Entries = 15250597
$N_{bkg,t}$ = 15166907 ± 4264
$f_{K*,t}$ = 0.00340 ± 0.00048
χ^2 / ndf = 1.1





Entries = 2204224
$N_{bkg,p}$ = 2147608 ± 1611
$f_{K*,p}$ = 0.0087 ± 0.0013
χ^2 / ndf = 1.3

ε = 0.807 ± 0.012
N_ϕ = 86927 ± 2192

Tag and probe method

- Tag and probe method allows to extract ϕ yield without knowledge of efficiency of kaon selection
- Tag sample $\rightarrow$ at least one track in the pair passes PID condition
- Probe sample $\rightarrow$ 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})

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

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:

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

where

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