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In-medium ϕ-meson width extracted from proton-nucleus collisions

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for the ANKE collaboration

MESON 2012, Krakow, June 1st 2012

Scope of the talk

- Physics motivation
- Experiment at ANKE
- Data analysis
- Results and discussion

ϕ in free space

- Meson spectral function:

$$S(m) = \frac{1}{\pi} \frac{\Gamma_0/2}{(m-m_0)^2 + (\Gamma_0/2)^2},$$

m_0 – pole mass, Γ_0 – meson width

m_0 = 1.0195 GeV

Γ_0 = 4.26 MeV

(*PDG 2008*)

- ϕ is a long-lived meson:

$$\lambda_{\mathrm{dec}} = \hbar c/\Gamma_0 = 44 \text{ fm} >> \mathrm{R(Au)}$$

ϕ in nuclear matter

- Meson spectral function:

$$S^*(m) = \frac{1}{\pi} \frac{\overbrace{\left(\Gamma_0 - 2\,\mathrm{Im}\,U_{opt}\right)}^{\Gamma^*}/2}{\left(m - \left(m_0 + Re U_{opt}\right)\right)^2 + \left(\underbrace{\left(\Gamma_0 - 2\,\mathrm{Im}\,U_{opt}\right)}_{\Gamma^*}/2\right)^2},$$

- A general picture of numerous studies in different approaches, e.g. effective Lagrangians and QCD sum rules

  - mass modification is small (not more than 10 MeV/c^2)

  - main medium effect on the ϕ is significant increase of its width (up to an order of magnitude)

Methods of the ϕ in-medium width measurement I

- Study of the meson spectral function: a measurement of low momentum ϕ-mesons:

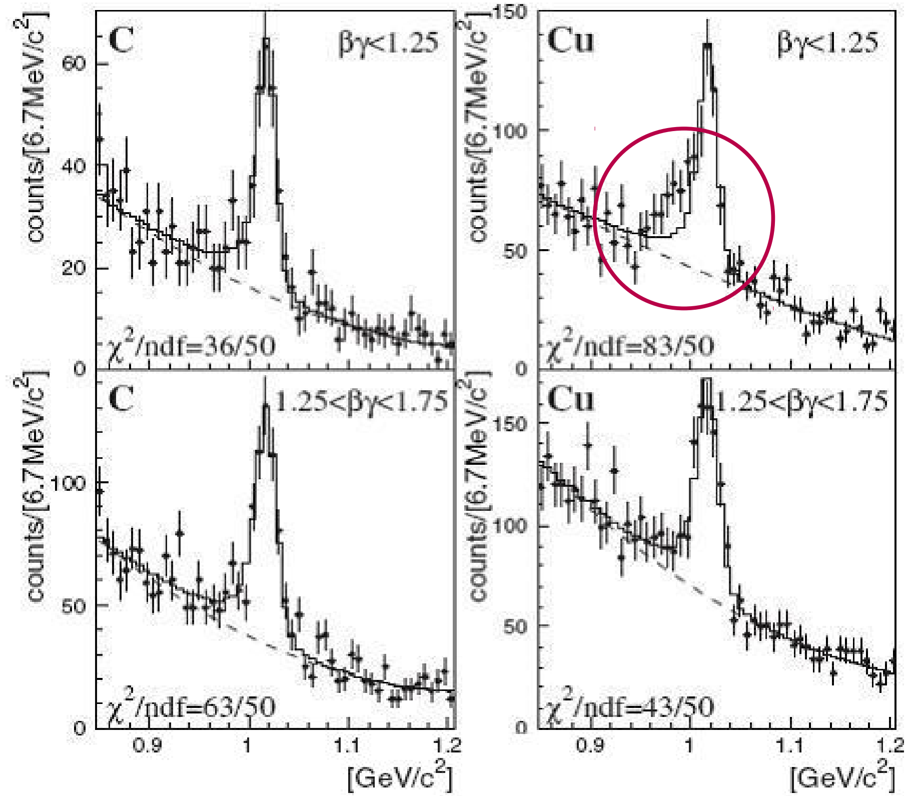
- $\phi \rightarrow e^+e^-$ (BR = $3 \cdot 10^{-4}$)
- $\phi \rightarrow K^+K^-$ (BR = 0.49, K^- FSI, hadronic potential)

- Experiment

KEK-PS-E325:

Reaction: $pA \rightarrow \phi X$, $\phi \rightarrow e^+e^-$
p-Energy: 12 GeV
Targets: C, Cu
Result: at $\rho_0 = 0.16\ \mathrm{fm}^{-3}$
$\Delta m/m_0 = -3.4\%$

$\Gamma^*/\Gamma_0 = 3.6 \rightarrow \Gamma^* \approx 8$ MeV
for $\langle p_\phi \rangle = 1.8$ GeV/c



R.Muto et al., PRL 98 (2007) 042501

Methods of the ϕ in-medium width measurement II

- Attenuation measurement of the ϕ flux: analysis of the target mass dependence for the ϕ production cross section

The ϕ survival probability *D* in the nucleus matter rest frame:

$$D = \exp\left(-\int dl \frac{\Gamma^*\left(p_\phi, \rho\left(r\right)\right) m_0}{p_\phi}\right),$$

$\rho(r)$ – local nuclear density.

- Experiments

Spring-8/LEPS:
Reaction: $\gamma A \rightarrow \phi X$, $\phi \rightarrow K^+K^-$
γ-Energy: 1.5 - 2.4 GeV
Targets: Li, C, Al, Cu
Result: $\sigma^*_{\phi N} = 35^{+17}_{-11}$ mb
$\Gamma^* \approx 100$ MeV
for $\langle p_\phi \rangle = 1.8$ GeV/c

T. Ishikawa et al., PLB 608 (2005) 215

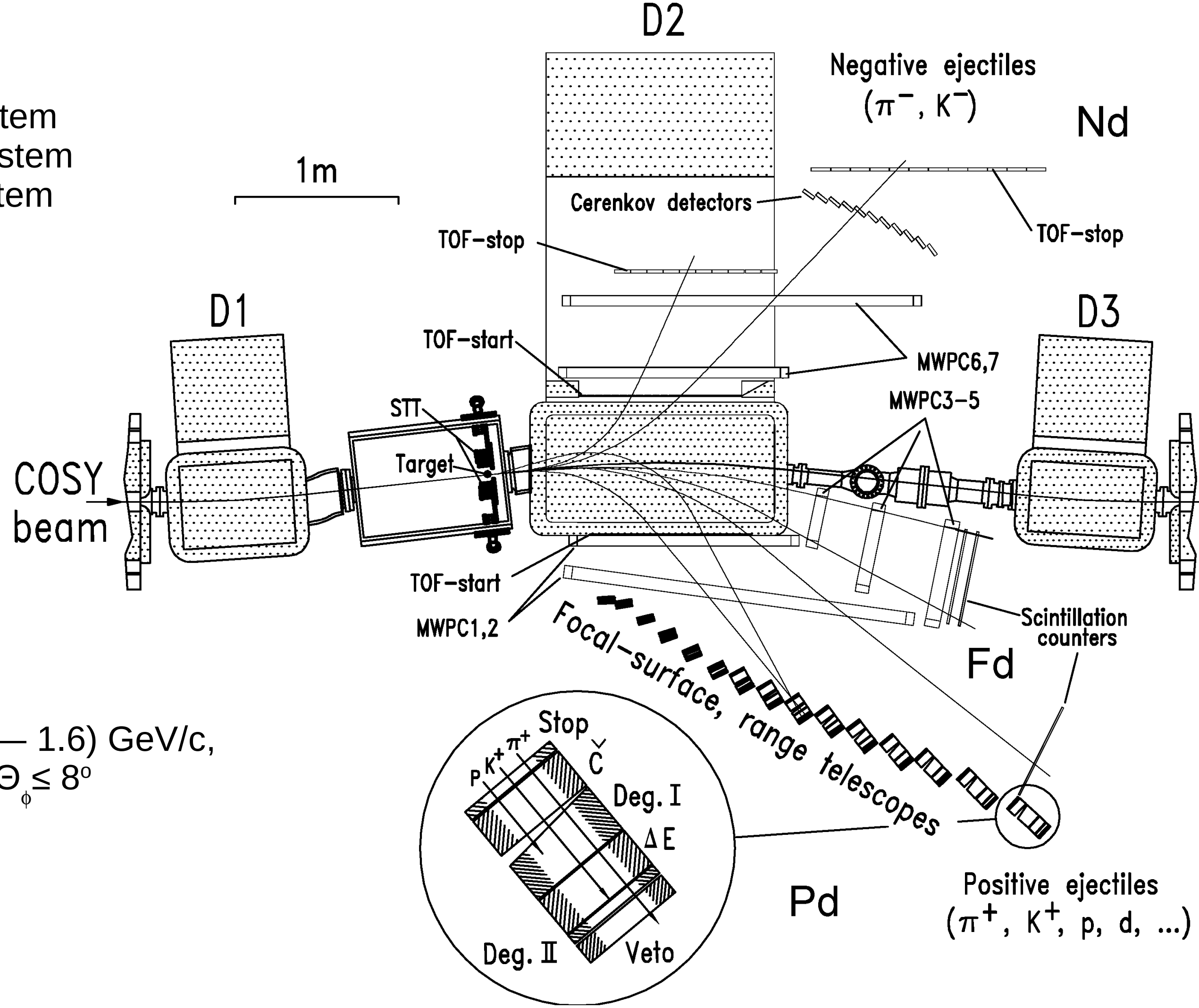
JLab/CLAS:
Reaction: $\gamma A \rightarrow \phi X$, $\phi \rightarrow e^+e^-$
γ-Energy: up to 4 GeV
Targets: ^{2}H, C, Ti-Fe, Pb
Result: $\sigma^*_{\phi N} = 16 – 70$ mb
for $\langle p_\phi \rangle = 2.0$ GeV/c

M.H. Wood et al., PRL 105 (2010) 112301

COSY/ANKE:
Reaction: $pA \rightarrow \phi X$, $\phi \rightarrow K^+K^-$
p-Energy: 2.83 GeV ($\varepsilon_{NN} \approx 76$MeV)
Targets: C, Cu, Ag, Au
Result: ...

ANKE – forward angle magnetic spectrometer at internal target position of COSY

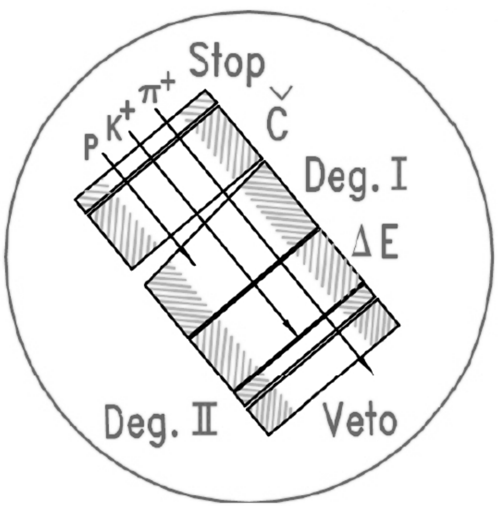
Pd – positive detector system
Nd – negative detector system
Fd – forward detector system

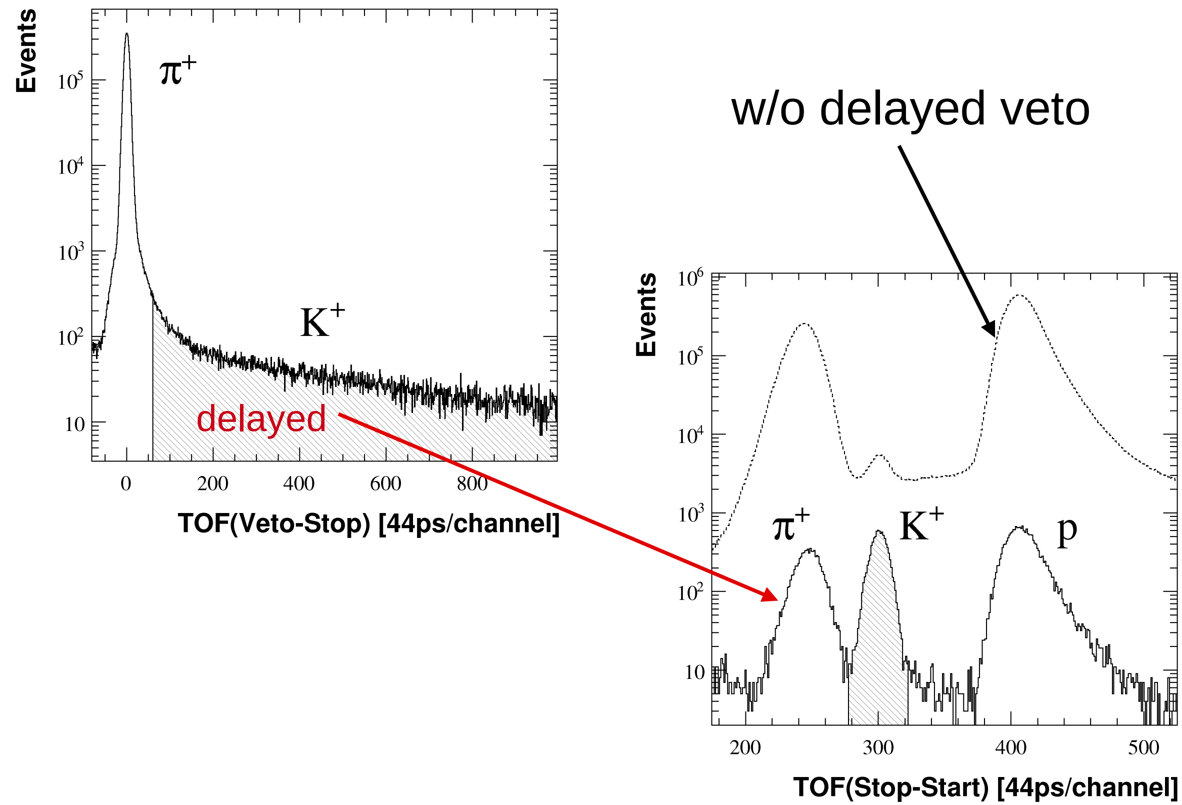


ϕ momentum (0.6 — 1.6) GeV/c,
and angular range: $0^o \leq \Theta_\phi \leq 8^o$

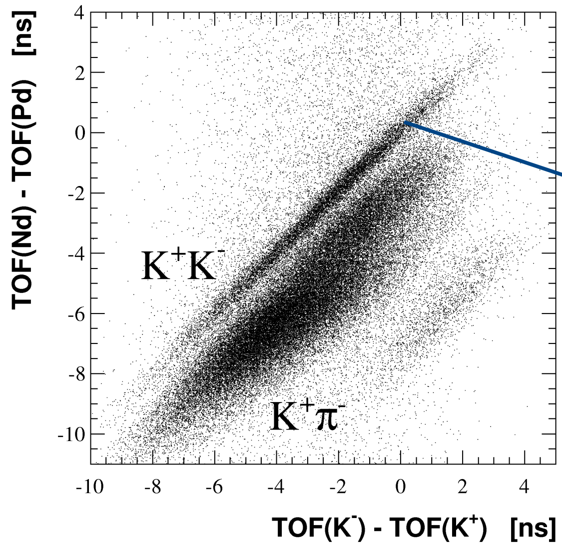
Analysis: K⁺ selection

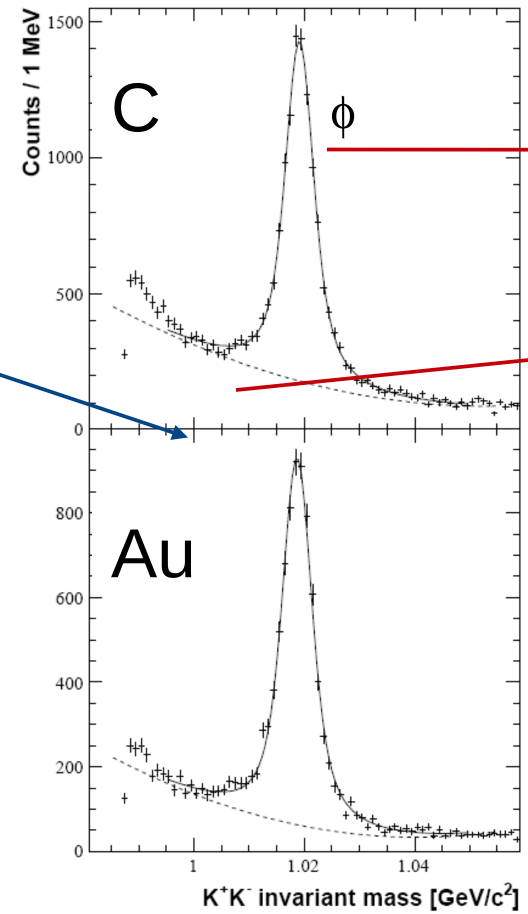
- Delayed Veto Technique
- TOF Stop-Start





Analysis: ϕ/K^+K^- pairs identification





$pA \rightarrow \phi X$

$pA \rightarrow K^+K^-X$
"+"
background

7000-10000 ϕ's
for each target
(C, Cu, Ag Au)

A-dependence of the ϕ production cross section

- A-dependence in the form

$$R=\frac{T_A}{T_C}=\frac{12}{A}\frac{\sigma_\phi^A}{\sigma_\phi^C} \qquad T_A=\frac{\sigma_\phi^A}{A\sigma_\phi^N}$$

T_A – nuclear transparency ratio

- Absolute and relative normalization of the ϕ production cross section – use of the know pion data

relative normalization:

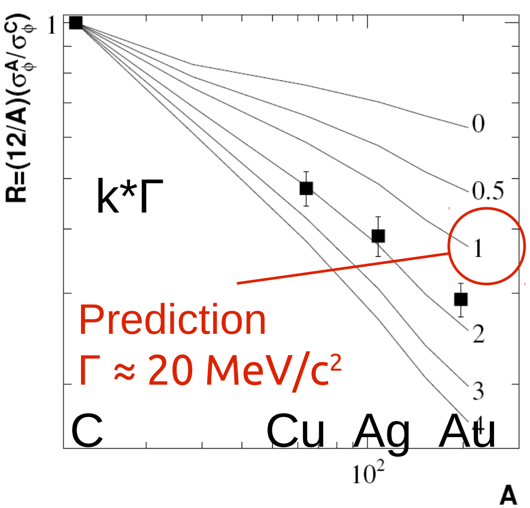
$$\frac{\sigma_\phi^A}{\sigma_\phi^C}=\frac{N_\phi^A}{N_\phi^C}\frac{N_\pi^C}{N_\pi^A}\frac{\sigma_\pi^A}{\sigma_\pi^C} \qquad \frac{\sigma_\pi^A}{\sigma_\pi^C}=\left(\frac{A}{12}\right)^{\alpha_\pi}$$

π^+: p = 0.5 GeV/c, θ ~ 0^0
α_π = 0.38 +/- 0.02

J. Papp et al., Phys. Rev. Lett. 34 (1975) 601;
V. V. Abaev et al., J. Phys. G 14 (1988) 903;
Yu. T. Kiselev et al., Preprint ITEP 56-96, Moscow (1996).

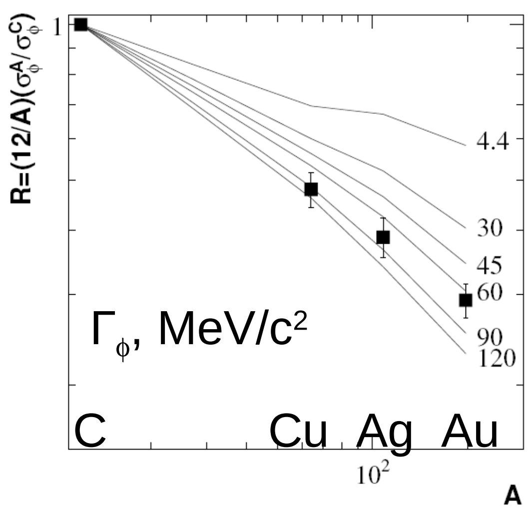
Transparency ratio R for $<p_\phi> = 1.1$ GeV/c and comparison with model calculations

Model 1
Valencia/E.Oset et al.
MC & Chiral Unitary Approach



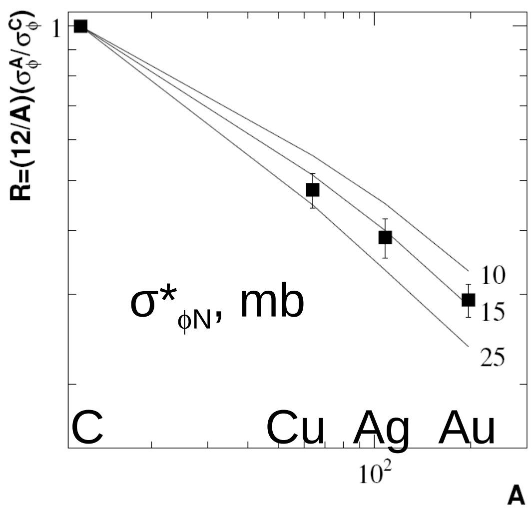
V.K.Magas et al., PRC 71 (2005) 065202;
V.K.Magas, L.Roca (private communication)

Model 2
Moscow/E.Ya.Paryev
Nuclear Spectral Function Approach



E.Paryev, J.Phys. G 36 (2009) 015103

Model 3
Rossendorf/
B.Kämpfer et al.
BUU



H.Schade, B.Kämpfer (private communication); cf. PRC 81 (2010) 034902:

In-medium ϕ-meson width for $\langle p_\phi \rangle$ = 1.1 GeV/c at normal nuclear density

- Results

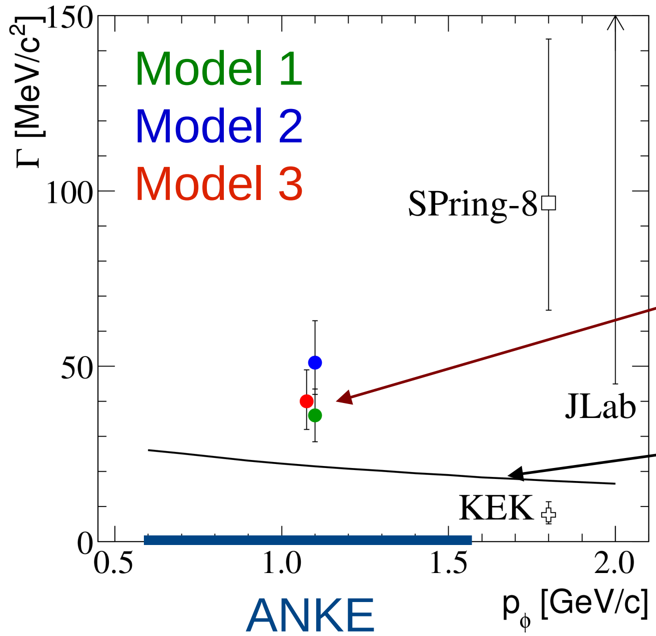
  Model 1: $\Gamma = 51^{+12}_{-9}$ MeV/c^2

  Model 2: $\Gamma = 36^{+5}_{-5}$ MeV/c^2

  Model 3: $\sigma^*_{\phi N} = 15.8^{+3.6}_{-3.0}$ mb → $\Gamma \approx 40$ MeV/c^2

  $\Gamma \approx 36 – 51$ MeV/c^2

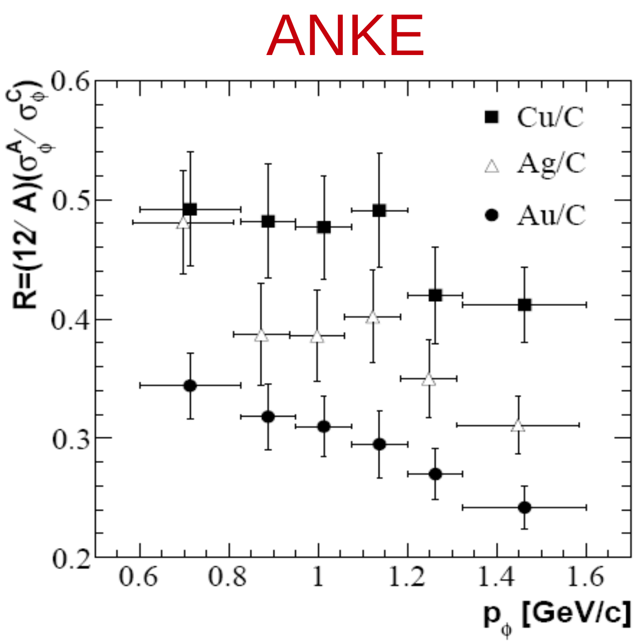
- Comparison with other experiments

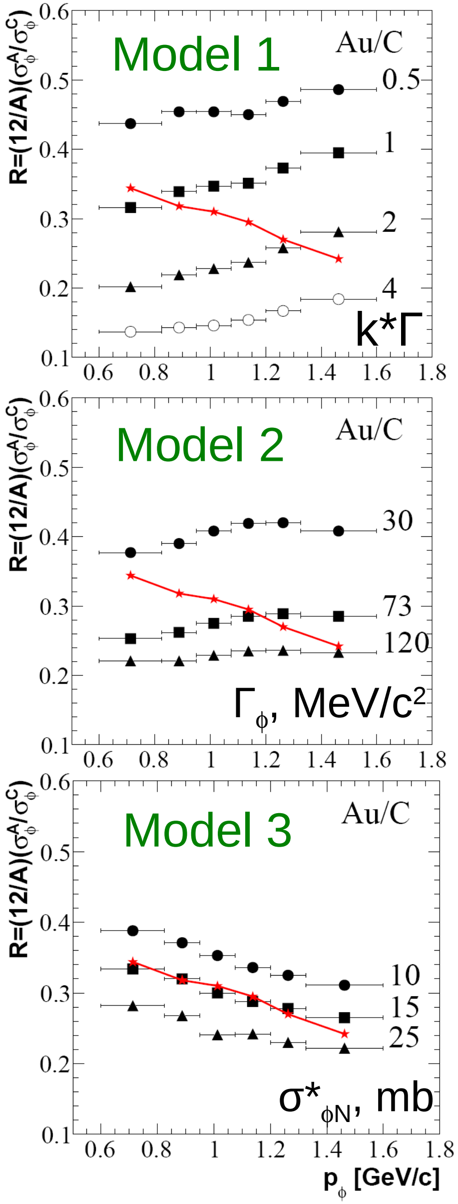


PLB 695 (2011) 74

Theoretical prediction
D. Cabrera et al., NPA 733 (2004) 130

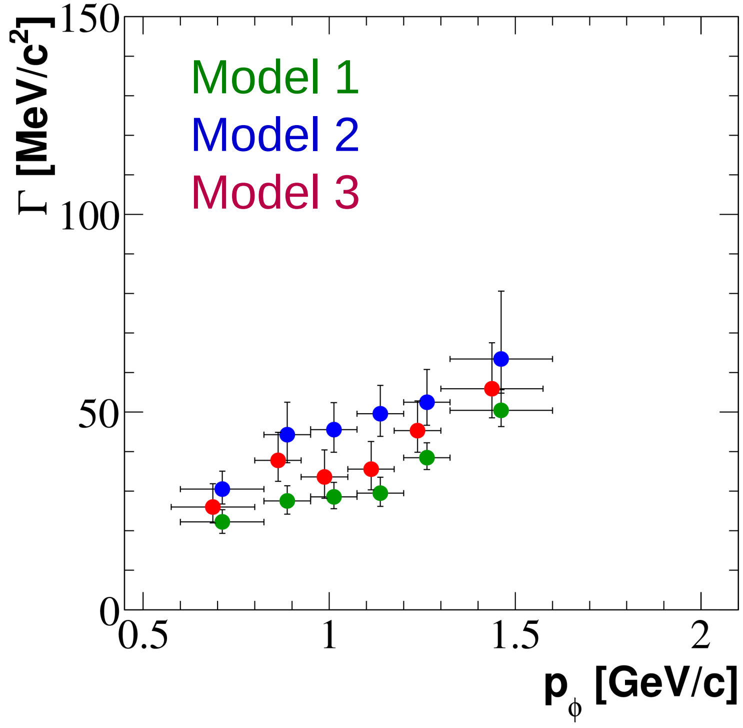
Momentum dependence of the transparency ratio R and comparison with model calculations

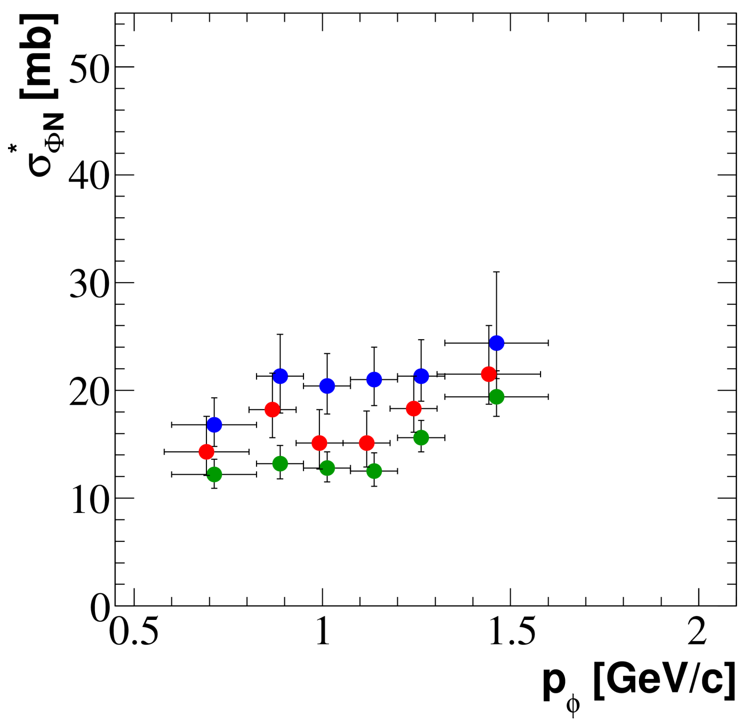




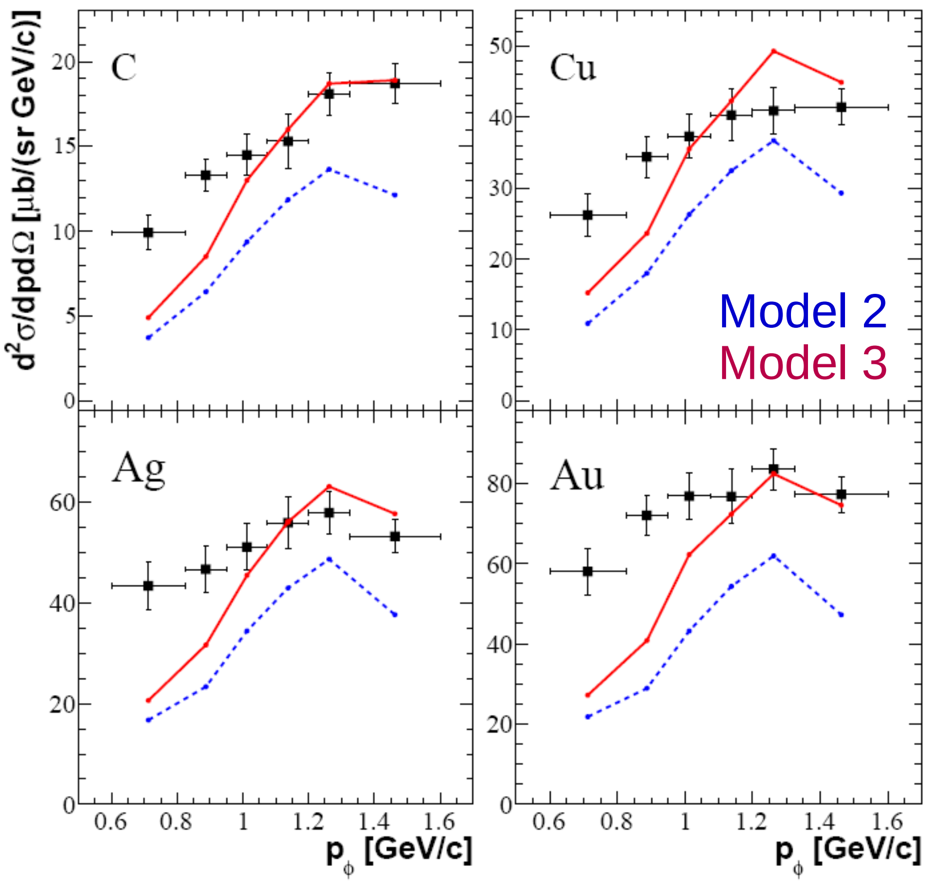
Momentum dependence of the in-medium width Γ and absorption cross section $\sigma^*_{\phi N}$

In the low-density approximation: $\Gamma_{\phi}^{lab}(p) = \rho_0 \sigma^*_{\phi N} \frac{p}{E}$





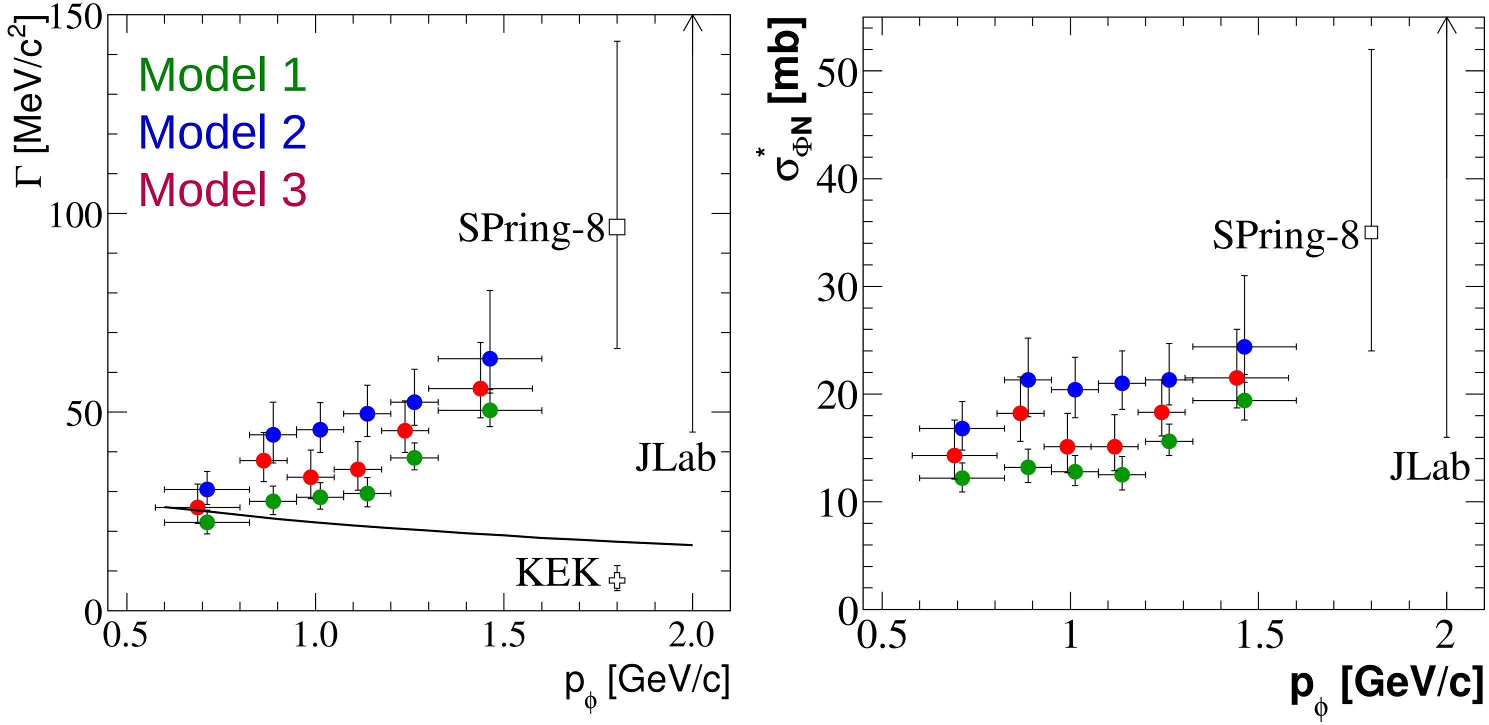
Double differential cross section for ϕ production



+ common systematics ~ 20 %

- Direct production ($pN \rightarrow pN\phi$) dominates for p_ϕ > 1 GeV/c
- Excess in the low momentum part
  - $pN \rightarrow \omega(\eta)N$, $\omega(\eta)N \rightarrow \phi N$
  - $\phi N \rightarrow \phi N$
  - $\phi N \rightarrow \phi X$
  - ...

Momentum dependence of the in-medium width Γ and absorption cross section $\sigma^*_{\phi N}$



Model analysis evidences for an increase of the ϕ absorption in nuclei

PRC 85 (2012) 035206

Summary

Momentum dependence of the ϕ-meson production under forward angles has been studied at ANKE:

- Model analysis evidences for an increase of the ϕ absorption in nuclei

- Differential cross sections are not completely reproduced by model calculations in the low momentum part

Thank You!

Extra Slides

Chiral symmetry is spontaneously broken in vacuum

- There are non-degenerate chiral partners, e.g.:

  $\pi(138)$ and $\sigma(400)$

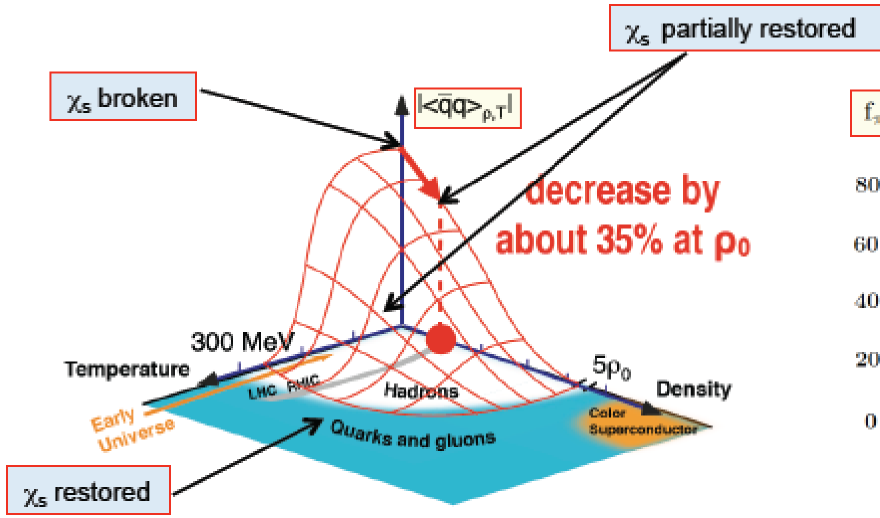
  $\rho(770)$ and $a_1(1260)$

  $N(938)$ and $S_{11}(1535)$

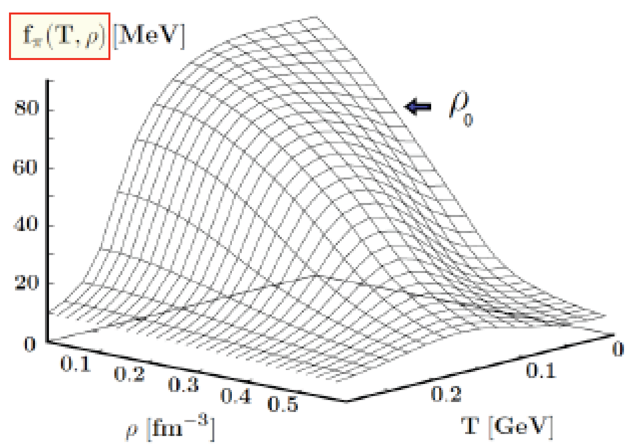
- Non zero order parameters (measure of how much the symmetry is broken):
  - quark-antiquark condensate $\langle\bar{q}q\rangle \approx -(240\text{MeV})^3$;
  - pion decay constant $f_\pi \approx 93$ MeV
- Pions are the Nambu-Goldstone bosons. Due to the explicit chiral symmetry breaking ($m_u = 5$ MeV, $m_d = 10$ MeV) the pions aren't massless.
- Gell-Mann – Oakes – Renner relation:

$$m^2_\pi f^2_\pi \approx 2\, m_q \langle\bar{q}q\rangle,\ m_\pi \rightarrow 0 \text{ if } m_q \rightarrow 0$$

Properties of <$\bar{q}$q> and f_π in nuclear matter



Hatsuda et al, PRL55 (1985)158
Weise et al, NPA 553(1993)59



Ratti et al, PRD73(2006)014019
S. Klimt et al, PLB249(1990)386

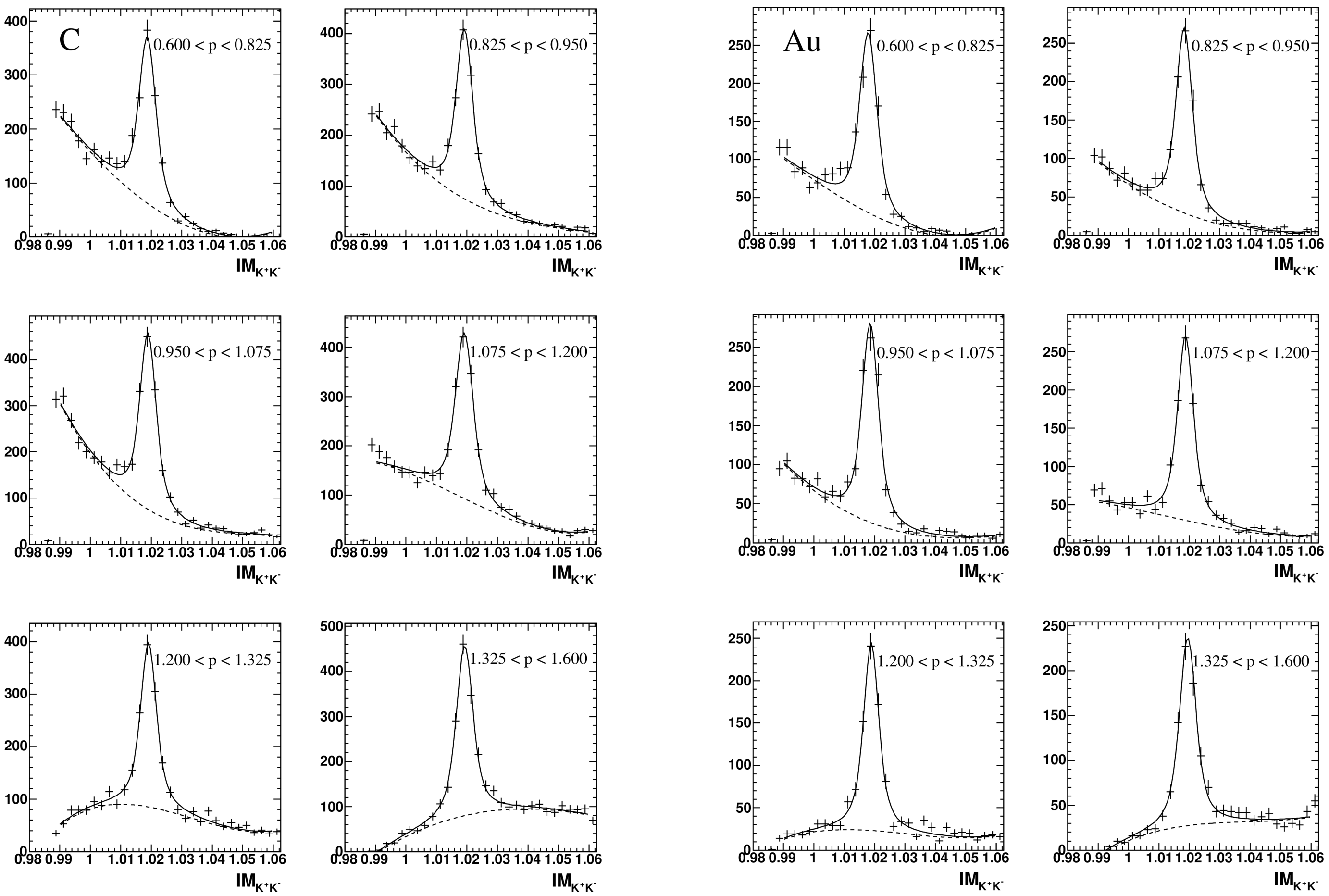
With T and ρ dependence of the type:

$$\frac{f_\pi^2(T,\rho)}{f_\pi^2(0)} \approx \frac{<0\,|\,q\bar{q}\,|\,0>_{T,\rho}}{<0\,|\,q\bar{q}\,|\,0>_0} = 1 - \frac{T^2}{8 f_\pi^2} - \frac{\sigma_N}{m_\pi^2 f_\pi^2}\rho + \ldots$$

NPB 321 (1989) 387.
PRC 45 (1992) 1881.
PLB 357(1995)199

from C.Djalali's talk (Hadron 2009)

Invariant mass spectra for six momentum bins

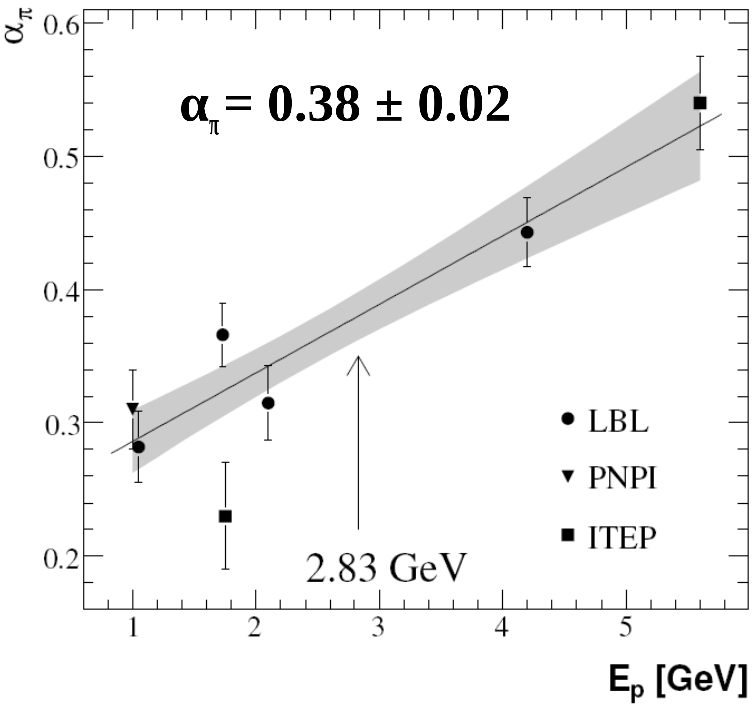


Relative normalization

- Transparency ratio R

$$R = \frac{12}{A} \frac{N_\phi^A}{N_\phi^C} \frac{N_\pi^A}{N_\pi^C} \frac{\sigma_\pi^A}{\sigma_\pi^C}, \qquad \frac{\sigma_\pi^A}{\sigma_\pi^C} = \left(\frac{A}{12}\right)^{\alpha_\pi}$$

- Exponent α_π



π^+: p_π = 0.5 GeV/c

$\theta_\pi \sim 0^o$

J. Papp et al., Phys. Rev. Lett. 34 (1975) 601;
V. V. Abaev et al., J. Phys. G 14 (1988) 903;
Yu. T. Kiselev et al., Preprint ITEP 56-96, Moscow (1996).

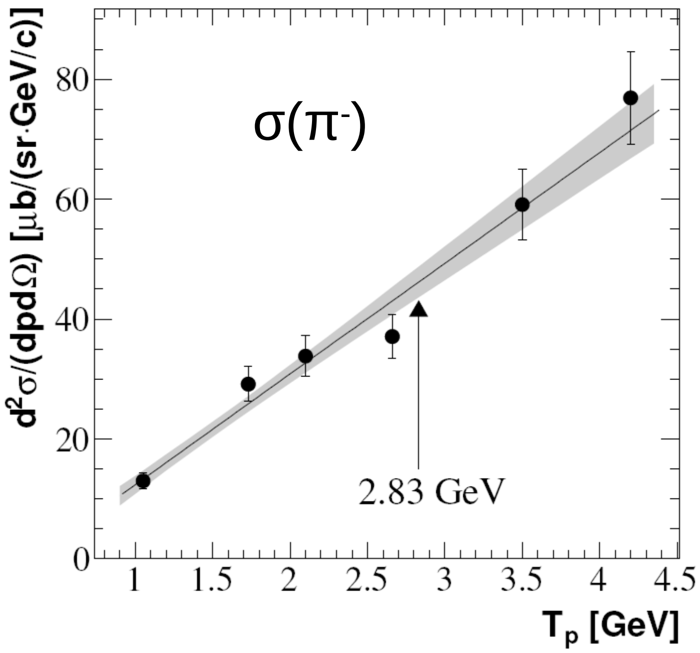
Absolute normalization

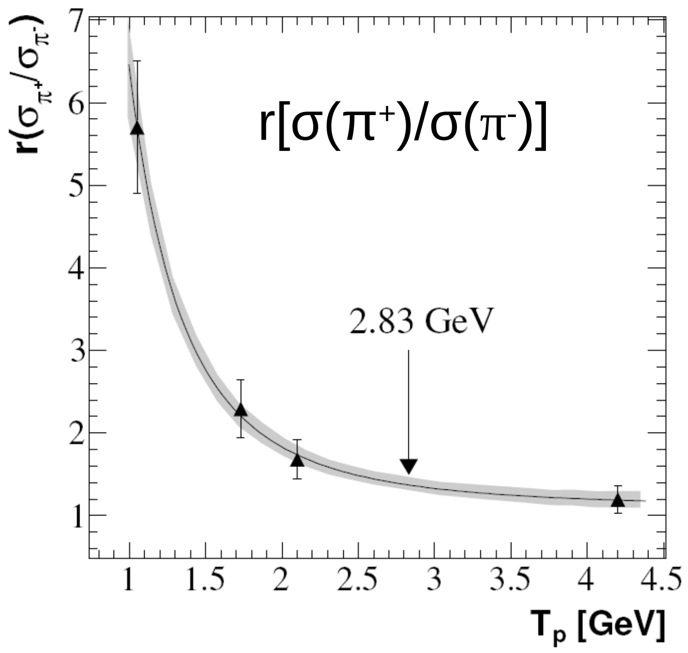
- Double differential cross section for ϕ production

$$\frac{d^2\sigma_\phi^A}{dp\,d\Omega} = \frac{1}{(\Delta p \Delta\Omega)} \frac{N_\phi^A}{\varepsilon_\phi L^A}, \qquad L^A = \frac{N_\pi^A}{\varepsilon_\pi} \left(\frac{d^2\sigma_\pi^A}{dp\,d\Omega} (\Delta p \Delta\Omega) \right)^{-1}$$

- Double differential cross section for π^+ production

$$\sigma(\pi^+) = \sigma(\pi^-) * r[\sigma(\pi^+)/\sigma(\pi^-)]$$





Models

Model 1
Valencia/E.Oset et al.

- Local fermi sea approach
- Direct production
  $pN \rightarrow pN\phi$
- Two-step production processes
  $pN \rightarrow \Delta N$, $\Delta N \rightarrow NN\phi$
- In-medium ϕ-meson width predicted within the Chiral Unitary approach ($\Gamma \approx 20$ MeV/c^2)

V. K. Magas et al., PRC 71 (2005) 065202
D. Cabrera et al., NPA 733 (2004) 130
V. K. Magas and L. Roca, private communication

Model 2
Moscow/E.Ya.Paryev

- Nuclear spectral function approach
- Direct production
  $pN \rightarrow pN\phi$
  $pn \rightarrow d\phi$
- Two-step production processes
  $pN \rightarrow \pi X$, $\pi N \rightarrow \phi N$
- Calculations for different values of the in-medium width Γ_ϕ in the ϕ rest frame

E.Paryev, J.Phys. G 36 (2009) 015103

Model 3
Rossendorf/B.Kämpfer et al.

- BUU Rossendorf
- Various one-step and two-step ϕ-meson production processes
- Attenuation of ϕ-meson flux described by the absorption cross section $\sigma^*_{\phi N}$

H.Schade, B.Kämpfer (private communication); cf. PRC 81 (2010) 034902.

- All models take into account the ANKE kinematical cuts (acceptance)
- $\sigma(pn \rightarrow pn\phi)/\sigma(pp \rightarrow pp\phi) \approx 4$

L.P. Kaptari and B. Kämpfer, EPJ A 23 (2005) 291

Observable line shape