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Momentum dependence of hadronic production of the Φ-meson and the in-medium Φ-width in nuclear matter

September 7th 2011, Michael Hartmann on behalf of the ANKE collaboration

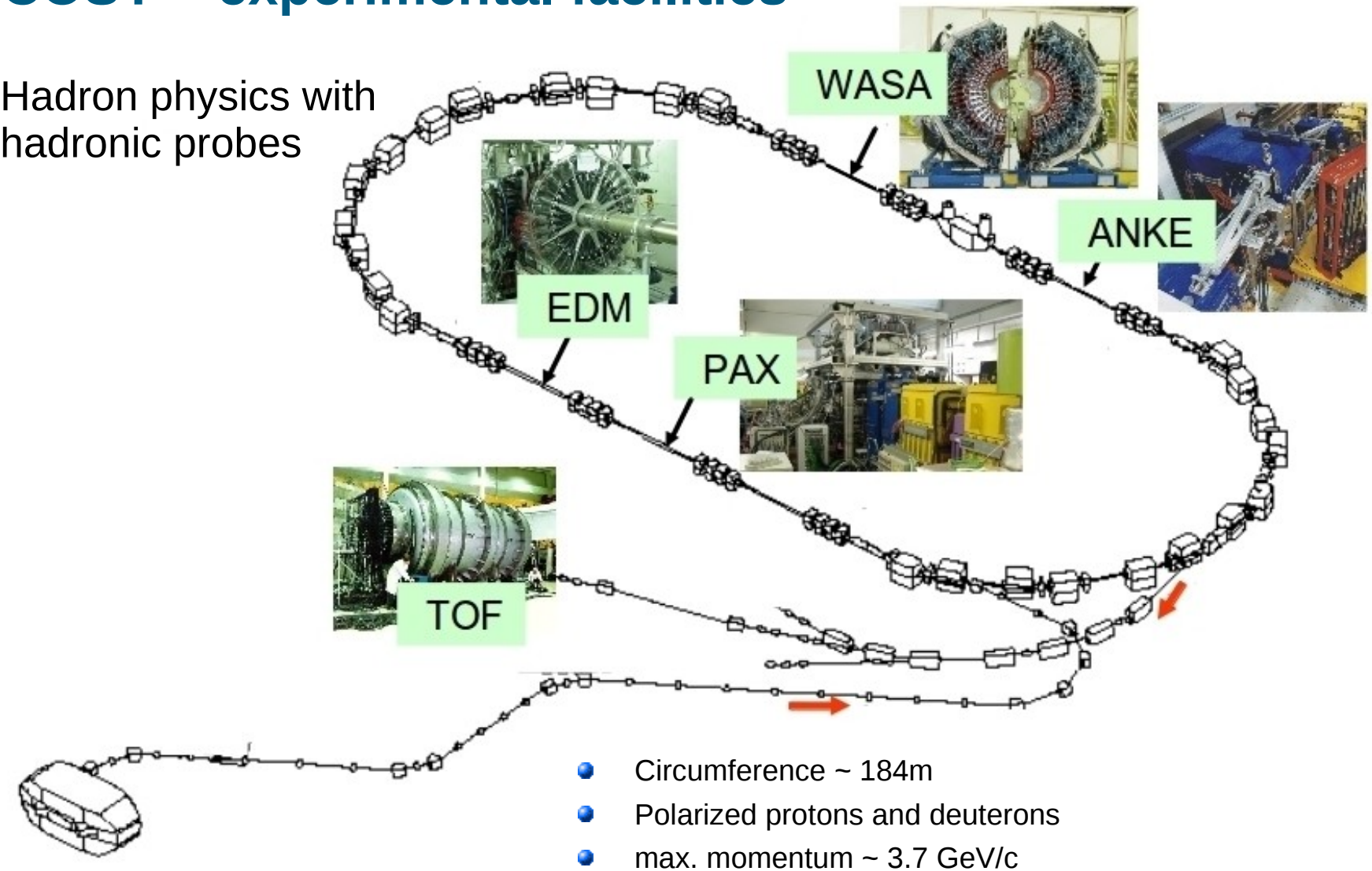
International Conference on Exotic Atoms and Related Topics - EXA2011

Scope of the talk

- COSY facilities, and some advertisement
- in-medium Φ width, short motivation and existing results
- proton induced production on nuclear targets (ANKE)
  $pA \rightarrow \Phi\,(K^+K^-)\,X$ @ Tp=2.83 GeV (ε = 76MeV free NN threshold)
  - in-medium Φ width and its momentum dependence, as well as differential cross sections

COSY – experimental facilities

Hadron physics with
hadronic probes

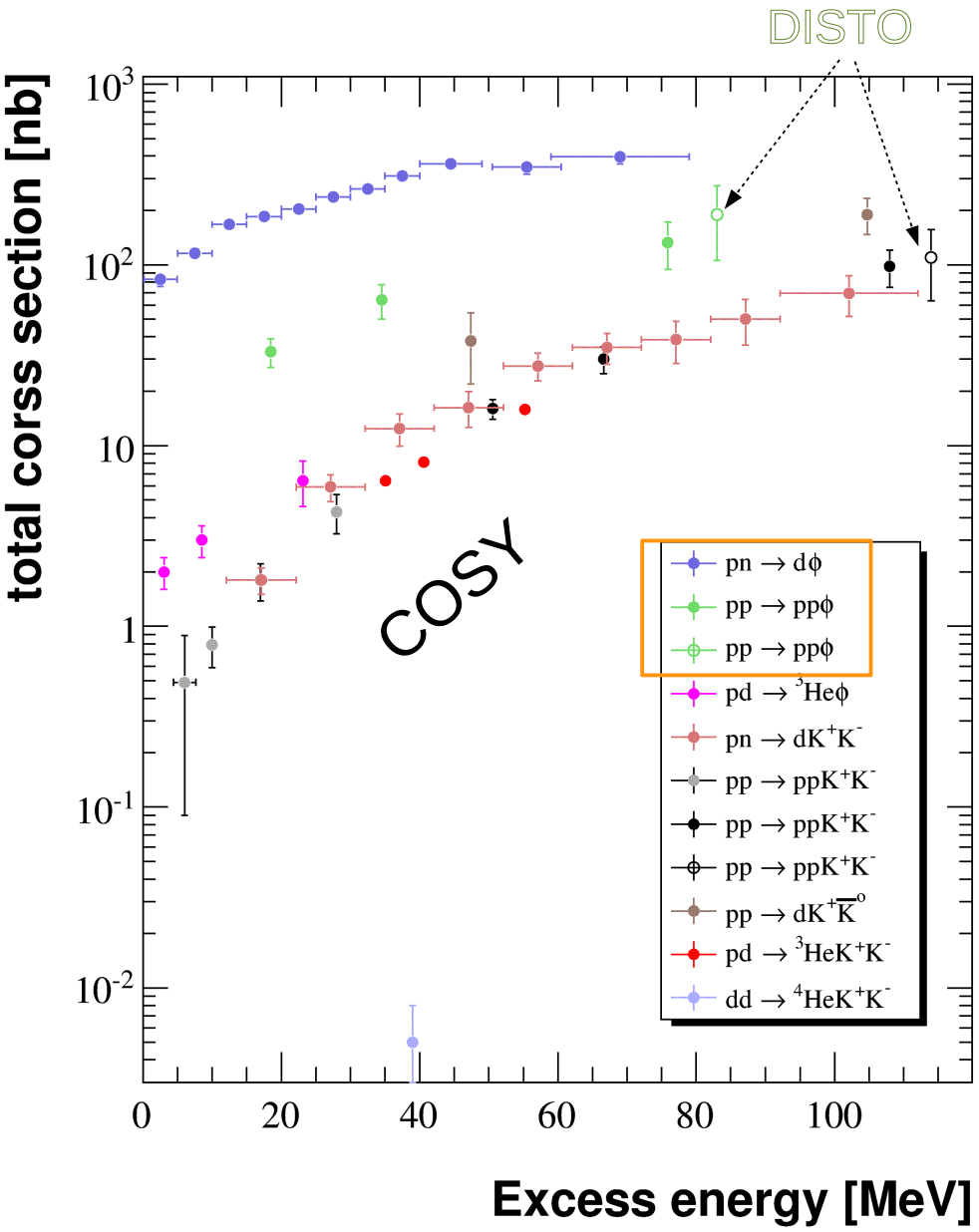


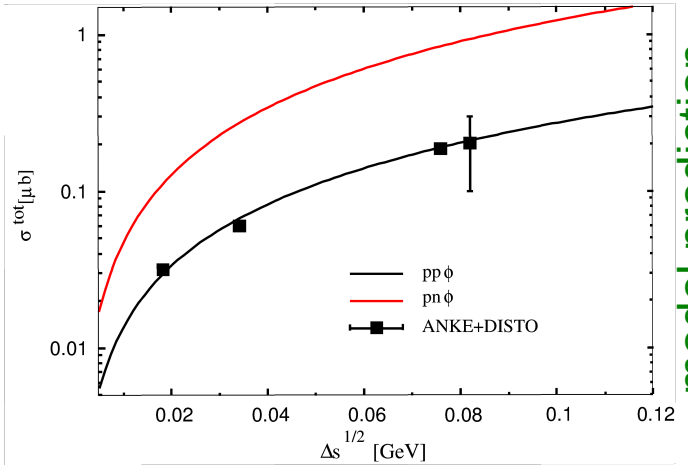
- Circumference ~ 184m
- Polarized protons and deuterons
- max. momentum ~ 3.7 GeV/c
- Electron and stochastic cooling

Advertisement: $K\bar{K}/\Phi$ production at COSY

(www.fz-juelich.de/ikp or M. Hartmann PoS 057 (2011))

$K\bar{K}$ & Φ production in pp, pd & dd (world data)





model prediction

Kaptari & Kaempfer, EPJA 23 (2005) 291

$\Phi(\rightarrow K^+K^-)$ production in pA

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:

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

Φ in nuclear matter

- Meson spectral function:

$$S^*(M) = \frac{1}{\pi} \frac{\overbrace{(\Gamma_0 - 2\mathrm{Im}\,U_{opt})/2}^{\Gamma^*}}{(M - (M_0 + ReU_{opt}))^2 + (\underbrace{(\Gamma_0 - 2\mathrm{ImU}_{opt})/2}_{\Gamma^*})^2}$$

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

  - mass modification is small

  - main medium effect on the Φ is a significant increase of its width by up to an order of magnitude

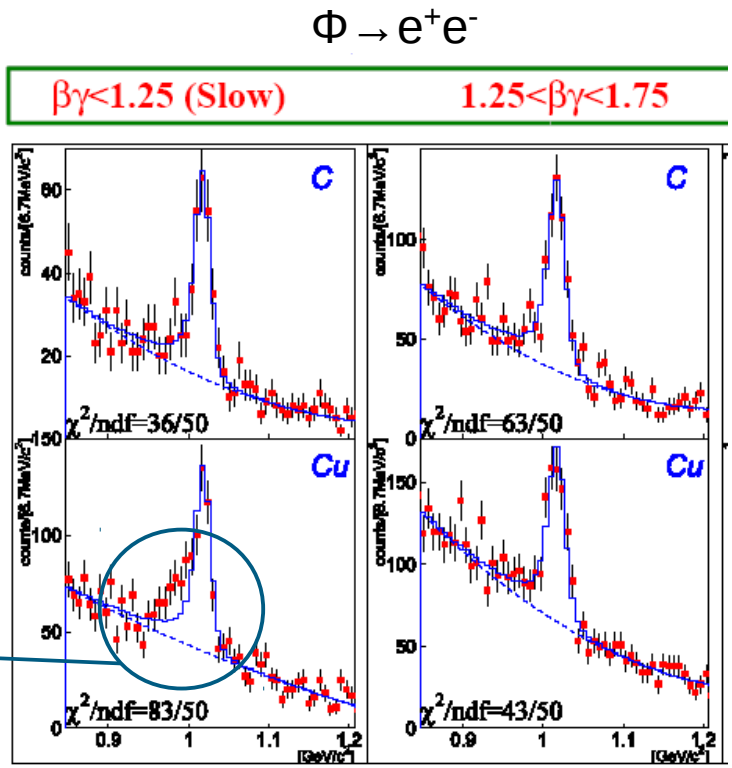
Methods of Φ-width measurement

- Study of the meson spectral function - measure low momentum Φ's via leptonic decays. Not really done yet.

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

KEK-PS: pA @ 12 GeV

Γ* ≈ 15 MeV, m* ≈ -3.4%)



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

Limited sensitivity to in-medium signal

$$\frac{d\sigma_{V\to X_1X_2}}{d\mu}\sim A(\mu)\;\frac{\Gamma_{V\to X_1X_2}}{\Gamma_{tot}}=\frac{\mu\,\Gamma_{tot}}{(\mu^2-m_V^2)^2+\mu^2\Gamma_{tot}^2}\,\frac{\Gamma_{V\to X_1X_2}}{\Gamma_{tot}}$$

experimental observed mass distribution = convolution of spectral function with the branching ratio into channel being studied

After integration over all nucleons and parameterizing strength function with Breit Wigner

$$\Gamma_{tot}=\Gamma_{vac}+\Gamma_{med}$$

$$\Gamma_{med}(\rho(r))=\Gamma_{med}(\rho_0)\frac{\rho(r)}{\rho_0}$$

In the low density approximation

3 effects limit sensitivity:

i. yield reduced by increase of in-medium width ($\Gamma_{med}>>\Gamma_{vac}$)

ii. reduced yield spreads out in mass, difficult to distinguish from background

iii. decays occur at low densities ($\rho << \rho_0$) even for low momentum selection

F.Eichstaedt *et al.*, PTPSuppl. 168 (2007) 495

Mosel/Leupold/Metag, PTP.Suppl. 186 (2010) 260

Methods of Φ-width measurement

- Attenuation measurements of the Φ flux
  SPring-8 photo-production, up-coming CLAS results.

$$D = \exp\left(-\int_z^{\infty} dl \, \frac{\Gamma^*(\rho(r))M_0}{p_\Phi}\right), \rho(r) - local\ nuclear\ density$$

Φ survival probability in the nucleus matter rest frame: In-medium width deduced from the target mass dependence.

dominate K^+K^- BR =0.49

SPring-8 / LEPS experiment

Reaction: γA → Φ X , via K^+K^- decay
γ-Energy: 1.5 — 2.4 GeV
Targets: Li, C, Al, Cu

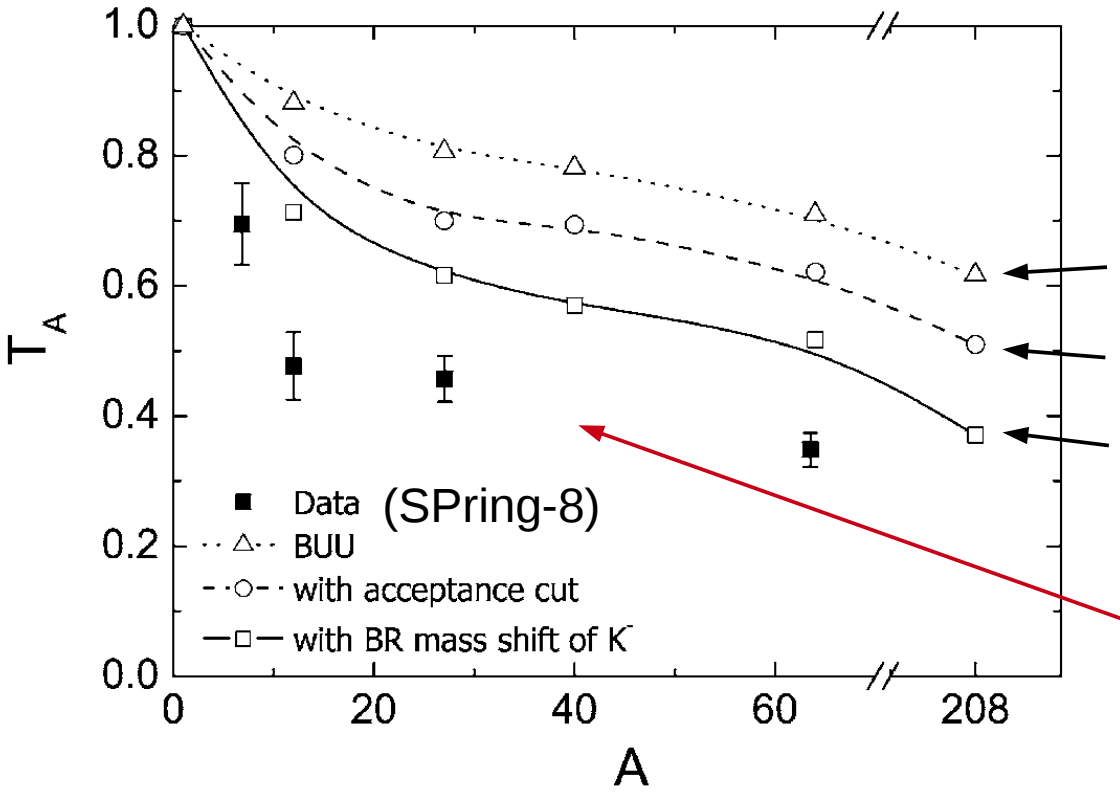
Result: large $\sigma_{\Phi N} = 35^{+17}_{-11}$ mb, using Glauber-type multi-scatt. theory (free $\sigma_{\Phi N} \approx$ 8-10 mb)

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

In general Giessen-BUU confirm the large $\sigma_{\Phi N}$ .....

Giessen-BUU calculations (SPring-8 data)

P. Muelich *et al.*, NPA 765 (2006) 188



$\Gamma_{free} + \Gamma_{coll.}$ (~10 mb)

+ acceptance

+ Γ_{decay} (K^+K^- : 2 to 20 MeV)

$\Gamma_{coll.}$ (~10 mb) x 2.6

$$\Gamma \approx 80\,MeV\,, 1.8\,GeV/c\,\phi's$$

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

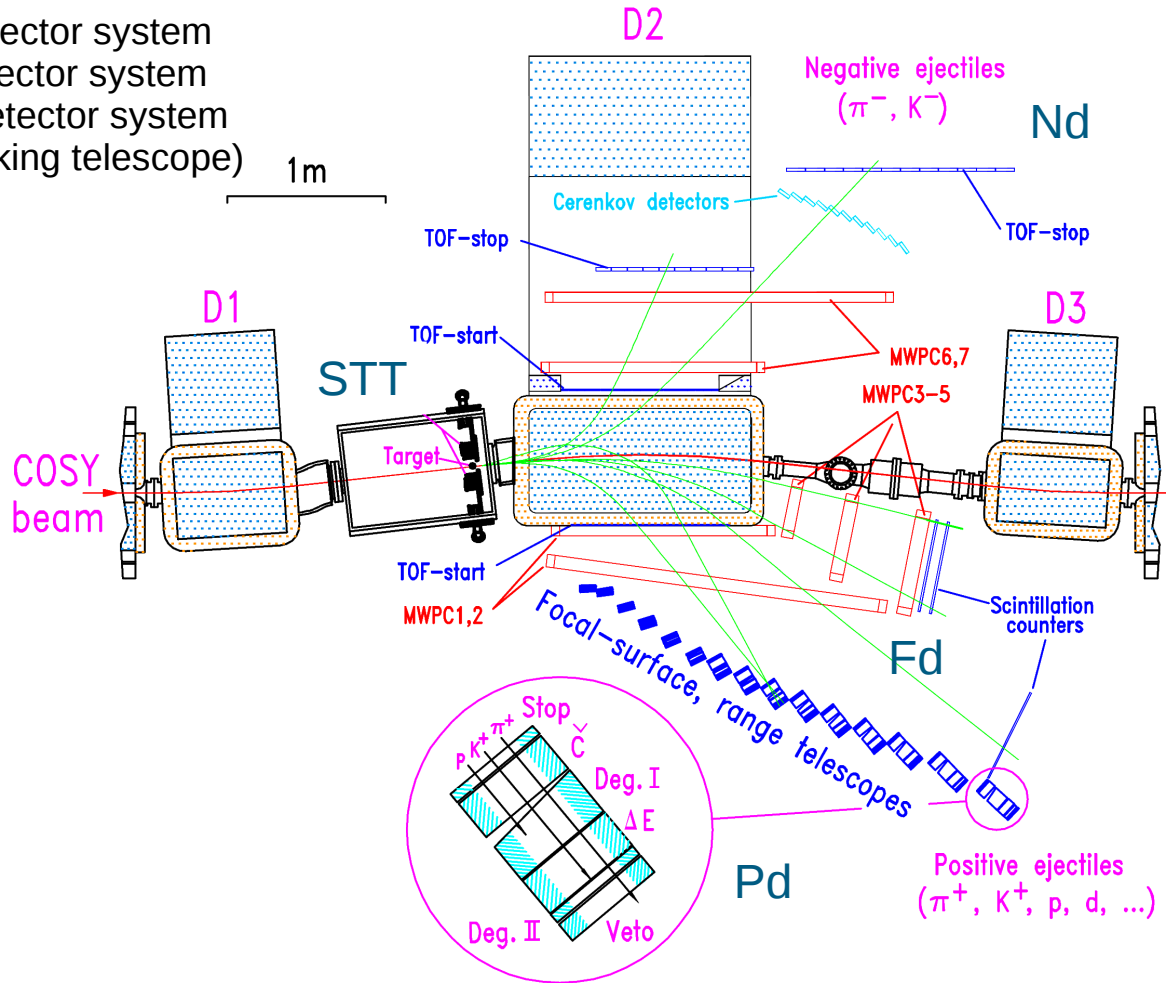
COSY experiment at ANKE

Reaction: pA → Φ X , via K^+K^- decay
p-Energy: 2.83 GeV ($\varepsilon_{\text{free NN}} \approx$ 76MeV)
Targets: C, Cu, Ag, Au

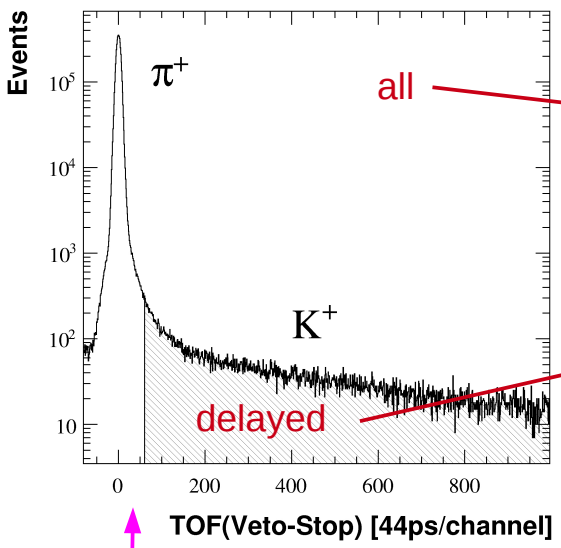
Momentum and angular range: (0.6 — 1.6) GeV/c, $0^o \leq \Theta_\Phi \leq 8^o$

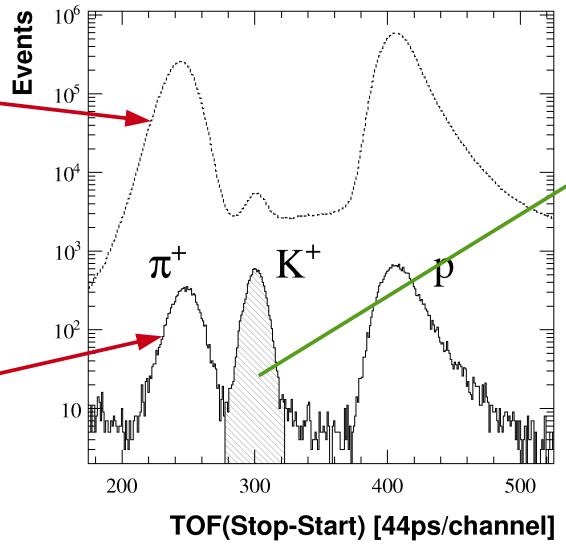
ANKE – forward angle magnetic spectrometer at internal target position of COSY

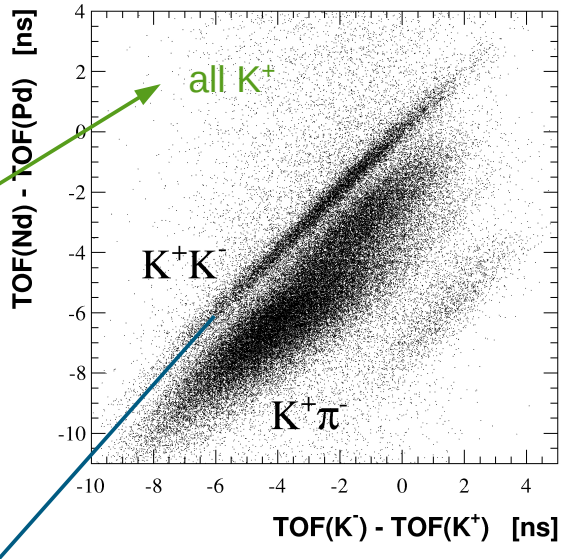
Pd – positive detector system
Fd – forward detector system
Nd – negative detector system
(STT – silicon tracking telescope)

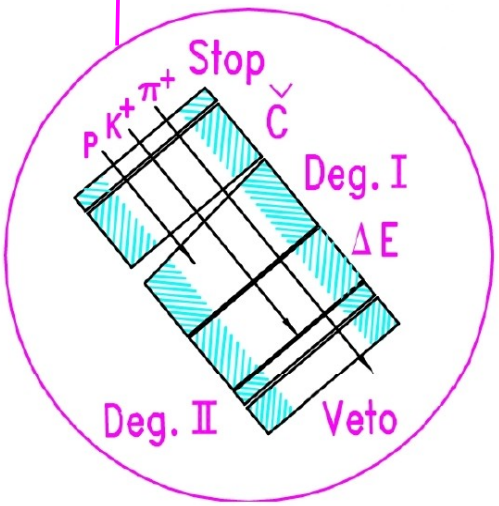


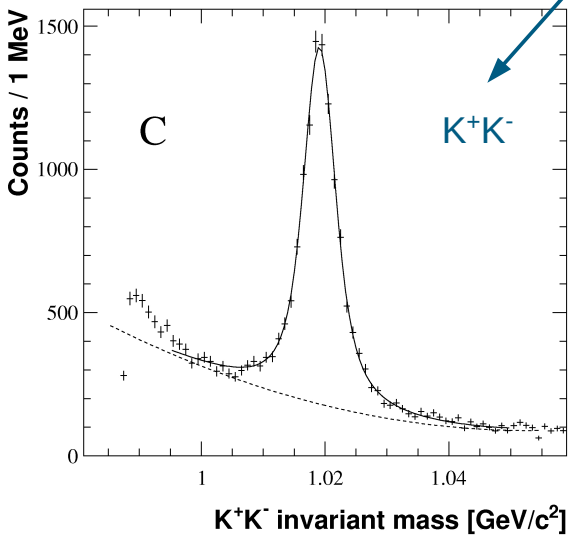
Φ / K^+K^- selection

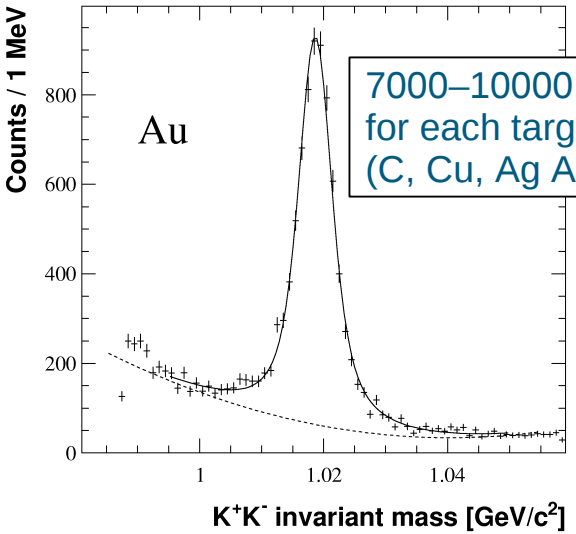












7000–10000 Φ's for each target (C, Cu, Ag Au)

Normalization of Φ production cross section

We present the A-dependence of the Φ production in the following form

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

nuclear transparency ratio

To normalize the Φ production cross section we use the known pion data

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

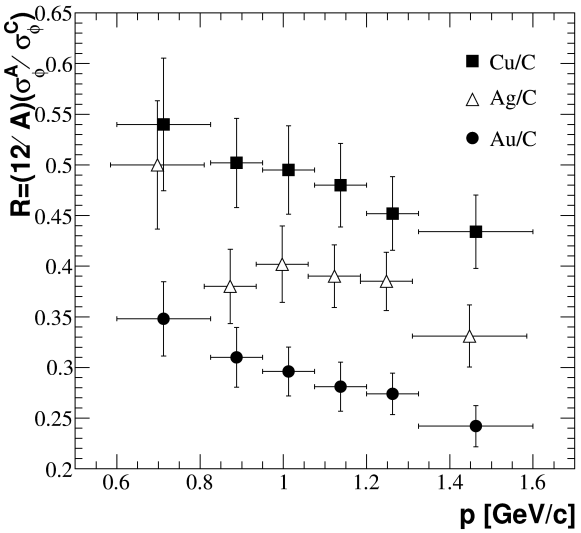
π^+: p = 0.5 GeV/c, Θ ~ 0^0

α_π = 0.38 ± 0.02 (@ 2.83GeV)

The Φ-meson yield (production cross section) follows a target mass dependence of $A^{0.56 \pm 0.03}$ (preliminary)

Transparency ratios: experiment

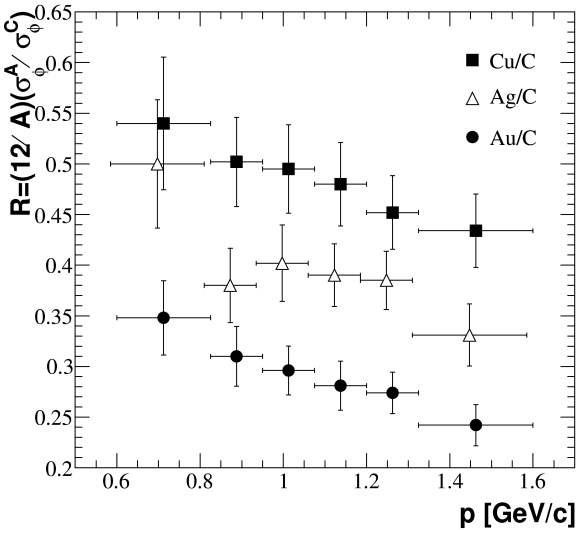
ANKE(preliminary)



Any interpretation of the transparency ratio has to rely on a detailed theoretical treatment

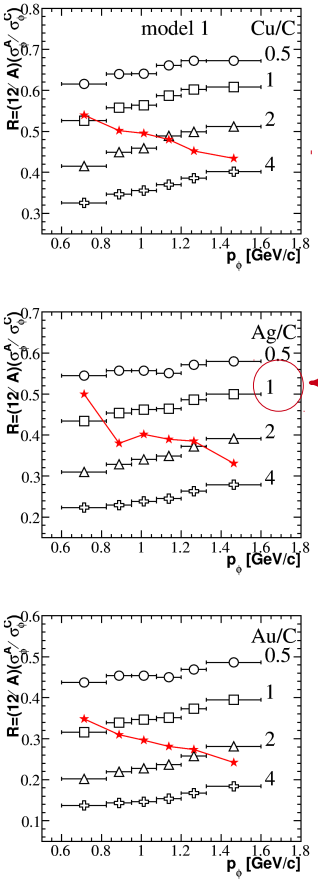
Transparency ratios: experiment

ANKE(preliminary)

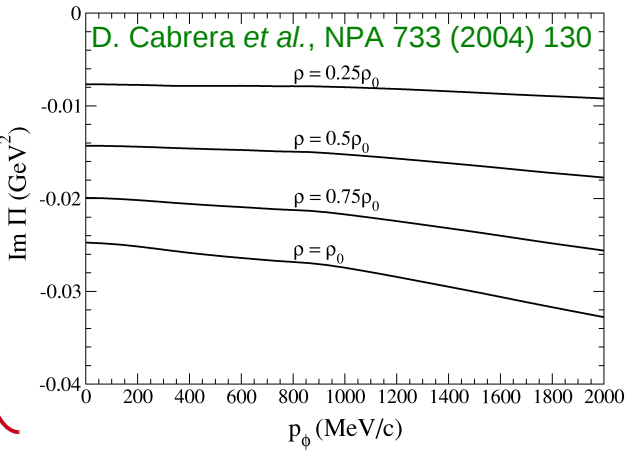


Valencia/E.Oset et al.

MC & Chiral Unitary Approach



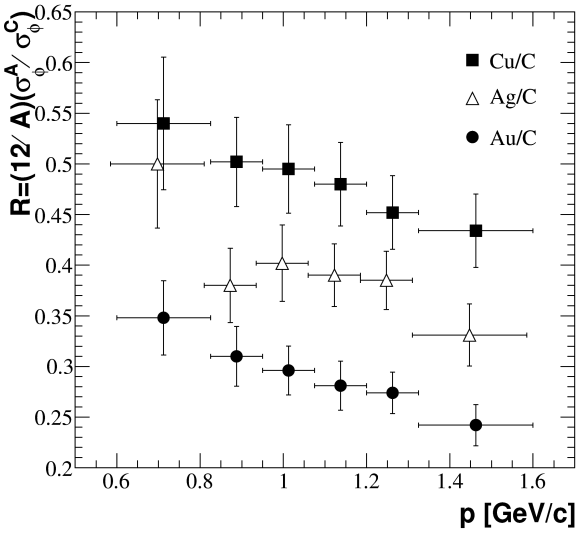
V.Magas *et al.*, PRC 71 (2005) 065202; L.Roca (private communication)



Prediction: 28 MeV for Φ at rest for $\rho=\rho_0$

Transparency ratios: experiment and models

ANKE(preliminary)



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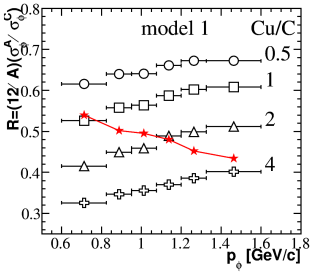
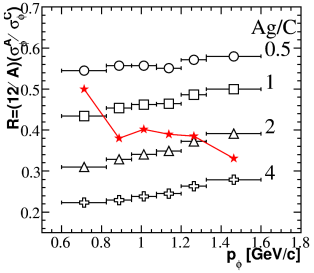
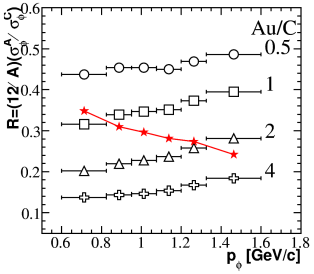


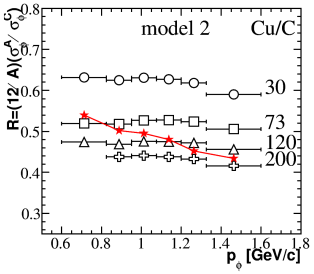


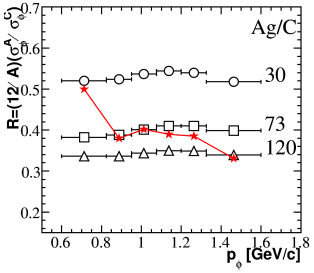


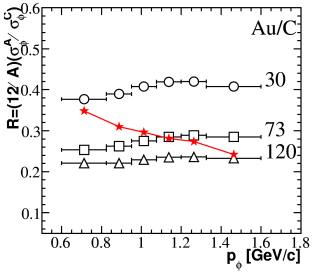
V.Magas *et al.*, PRC 71 (2005) 065202; L.Roca (private communication)

Moscow/E.Paryev

Nuclear Spectral Function Approach



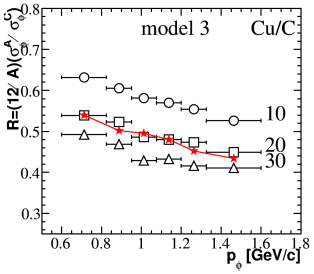


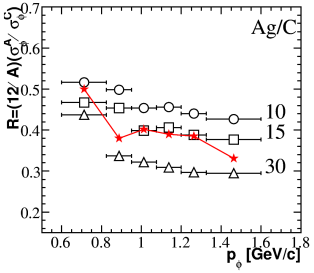


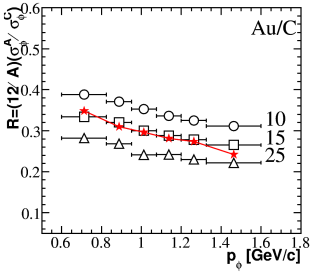
E.Paryev, J.Phys. G 36 (2009) 015103

Rossendorf/ B.Kämpfer *et al.*

BUU







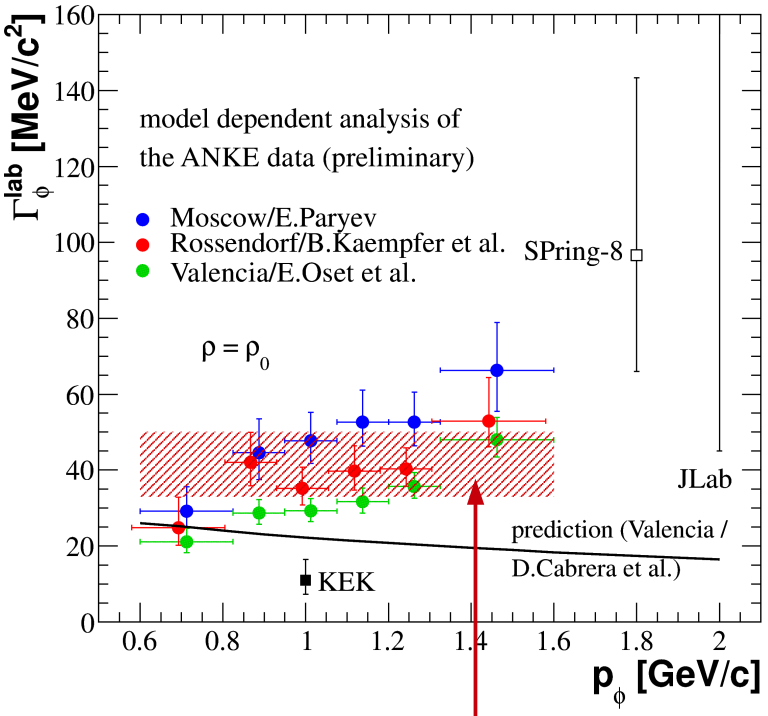
H.Schade, B.Kämpfer (private communication); cf. PRC 81 (2010) 034902:

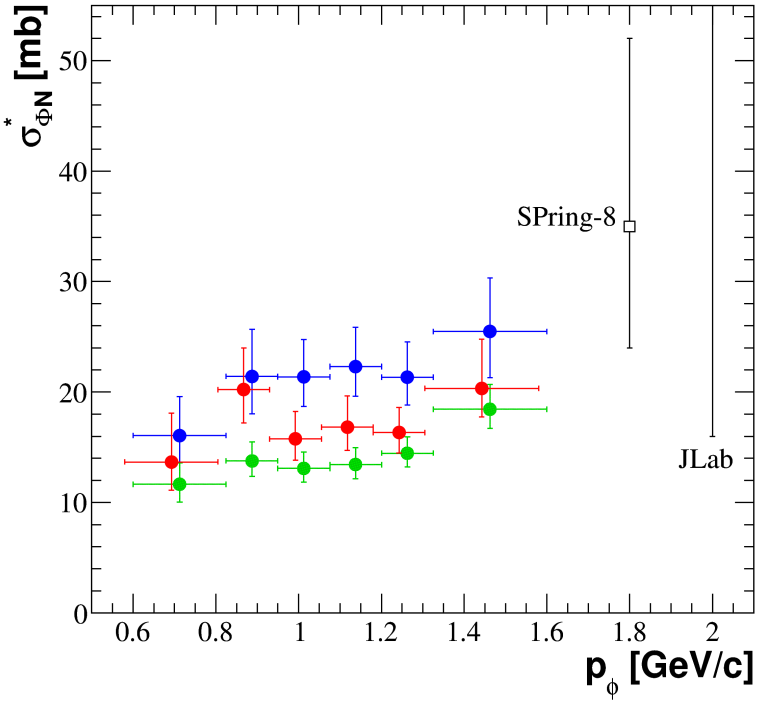
Relevant features for models:

- forward acceptance
- two-step production processes
- $\sigma_{pn \to pn\Phi}/\sigma_{pp \to pp\Phi} \approx 4$

In-medium width Γ_Φ and $\sigma^*_{\Phi N}$ cross section (preliminary)

LDA: $\Gamma_\Phi^{lab}(\rho_0) = \frac{p_\Phi}{E}\sigma^*_{\Phi N}\rho_0$



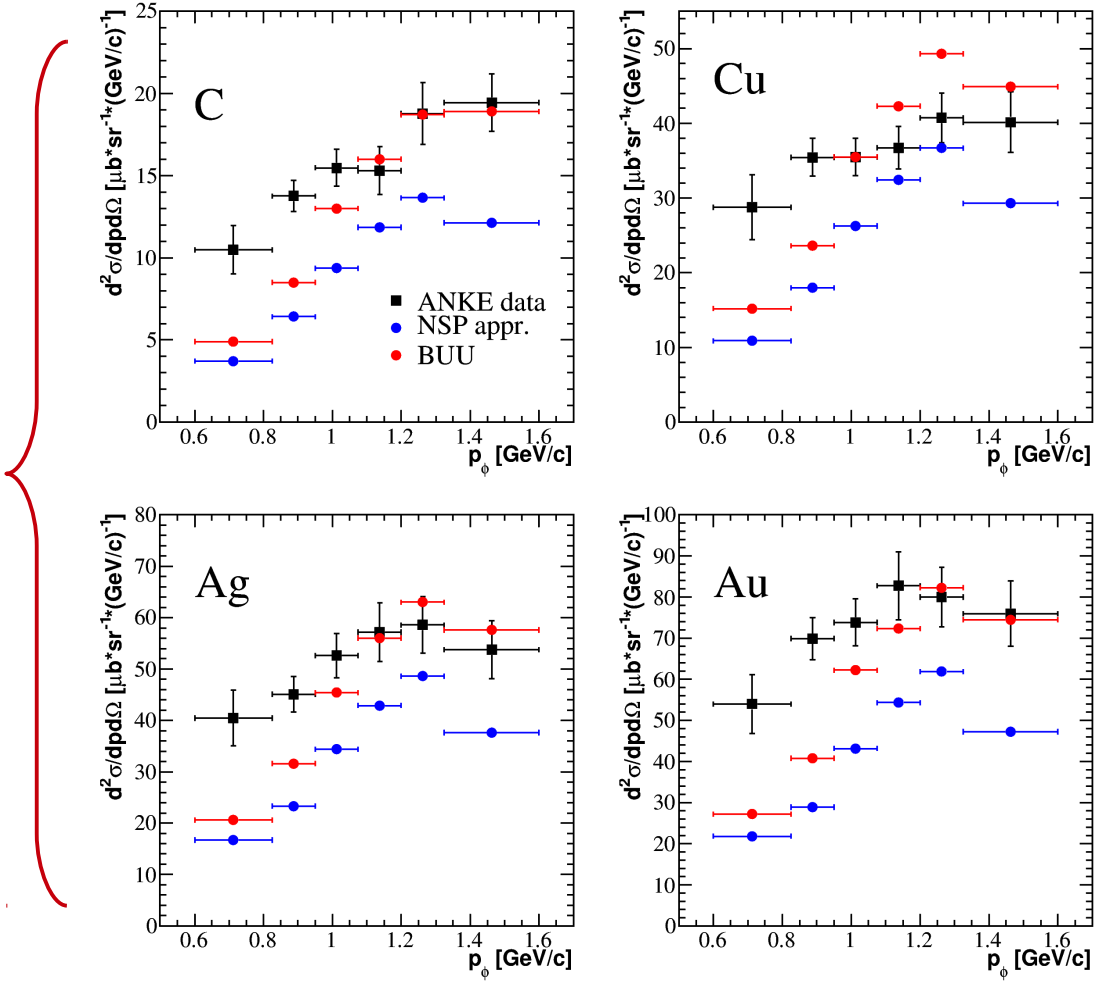


$\Gamma_\Phi^{lab} \approx$ 33-50 MeV ($\langle p_\Phi \rangle$ = 1.1 GeV/c, ρ_0 = 0.16 fm^{-3})

A.Polyanskiy *et al.*, **PLB 695 (2011) 74**

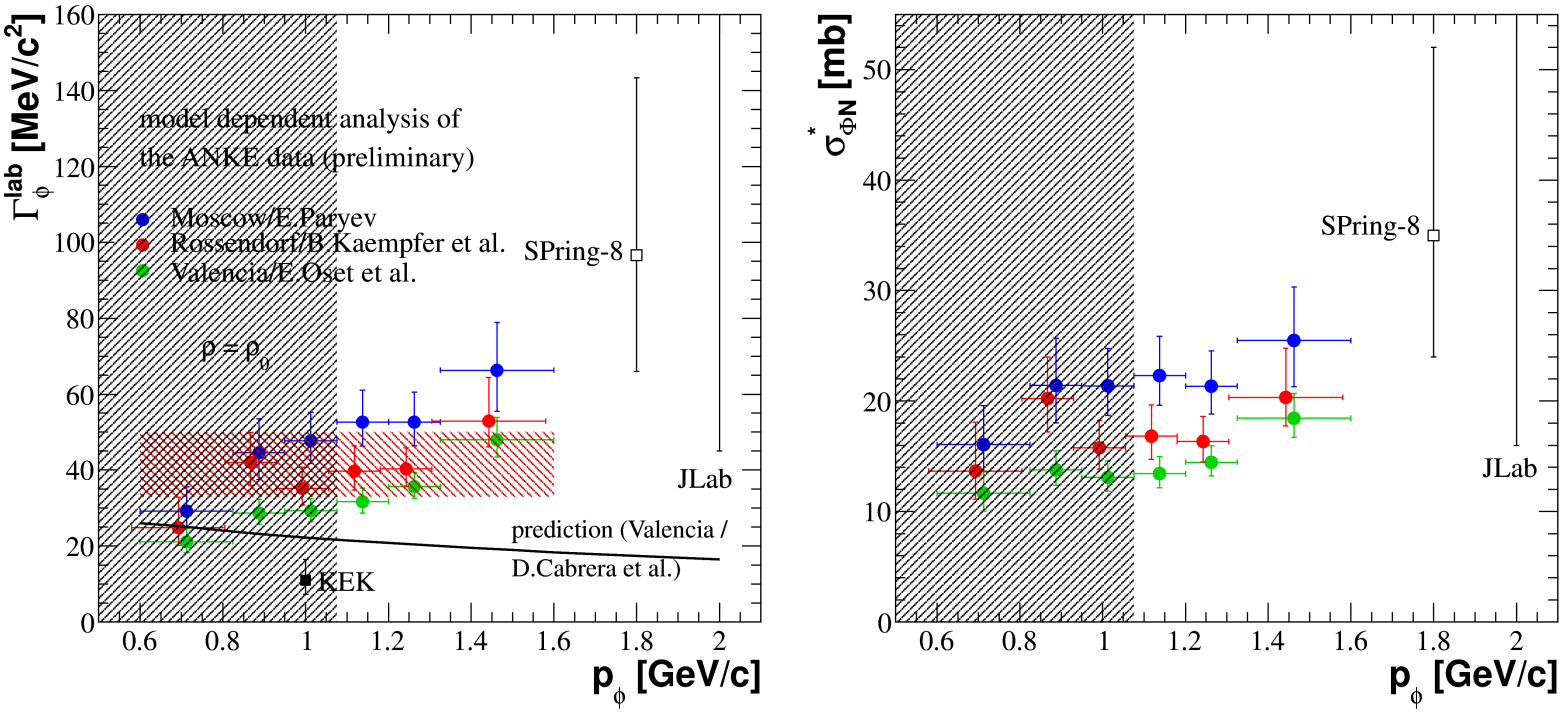
Double differential cross section of Φ production (preliminary)

Excess in low momentum part



+ common systematics ~ 20 %

In-medium width Γ_Φ and $\sigma^*_{\Phi N}$ cross section (preliminary)

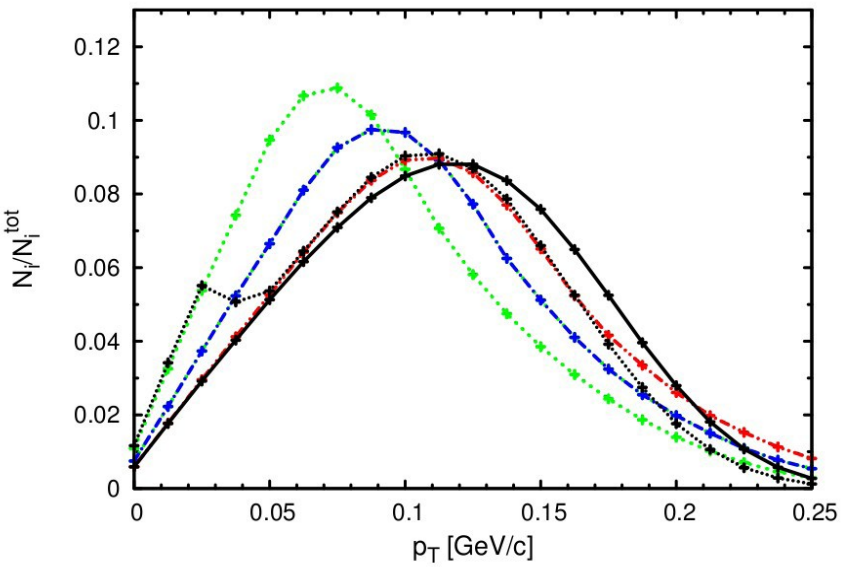


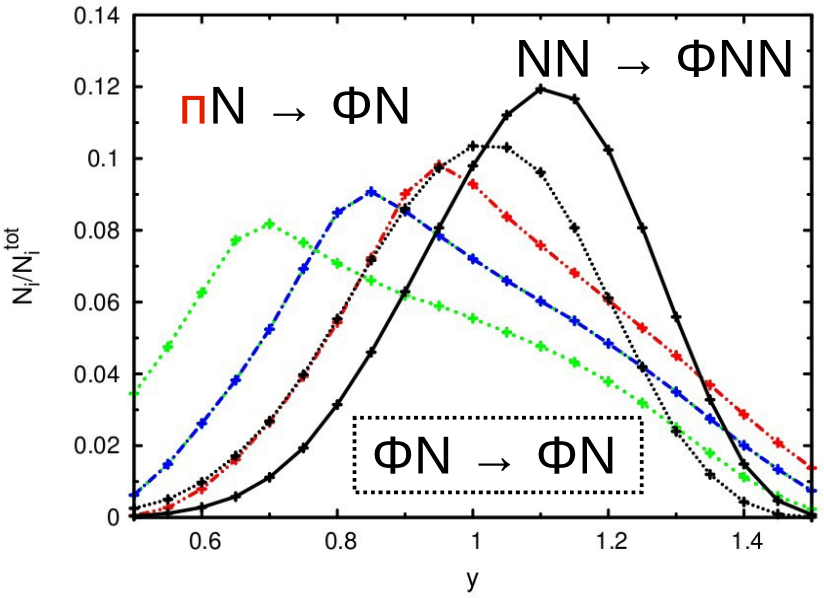
for $p_\Phi > 1.1$ GeV/c $\Gamma_\Phi^{lab} \approx 45$ MeV and/or $\sigma^*_{\Phi N} \approx 17$ mb

Low momentum – missing Φ multiplicity?

Kinematic phase space test with

"new" (2-step) channels: ηB → ΦX and ωB → ΦX , with B = N, Δ





H.Schade & B.Kämpfer (private communication)

Rossendorf BUU: η and ω channels

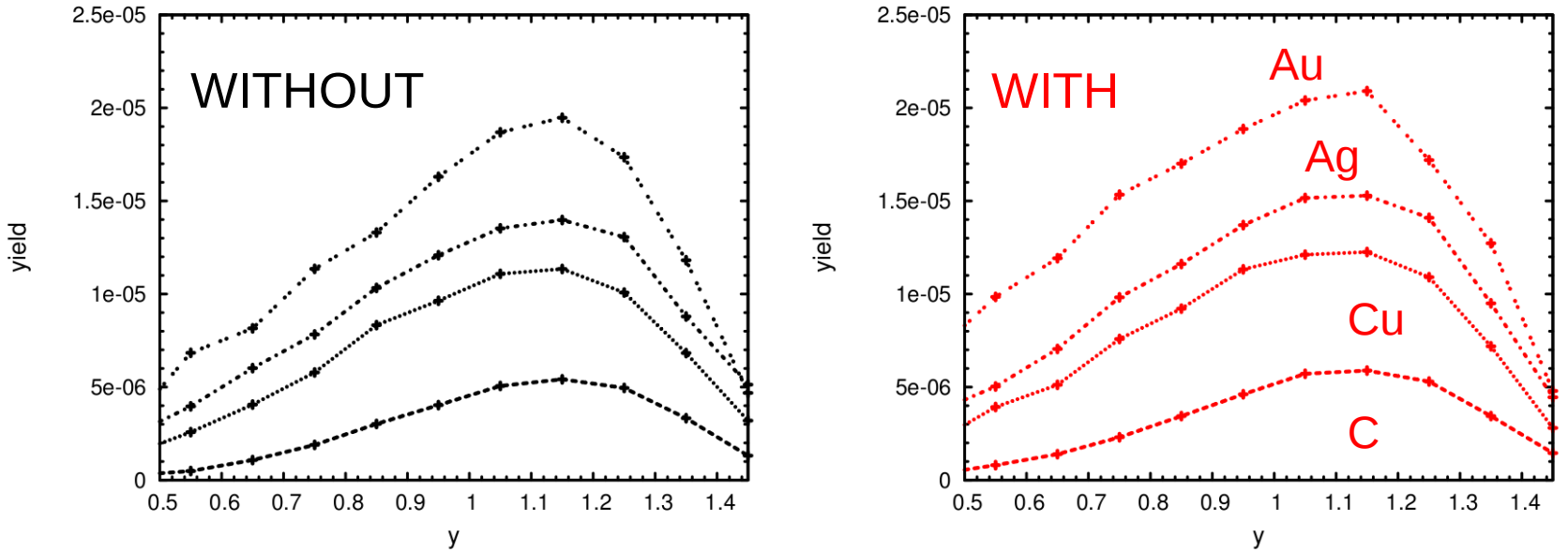
elastic collisions: $\sigma_{\Phi N \to \Phi N} = 2\,mb$

η and ω channels: $\sigma_{\eta N \to \Phi N} = \sigma_{\omega N \to \Phi N} = 0.07\,mb$

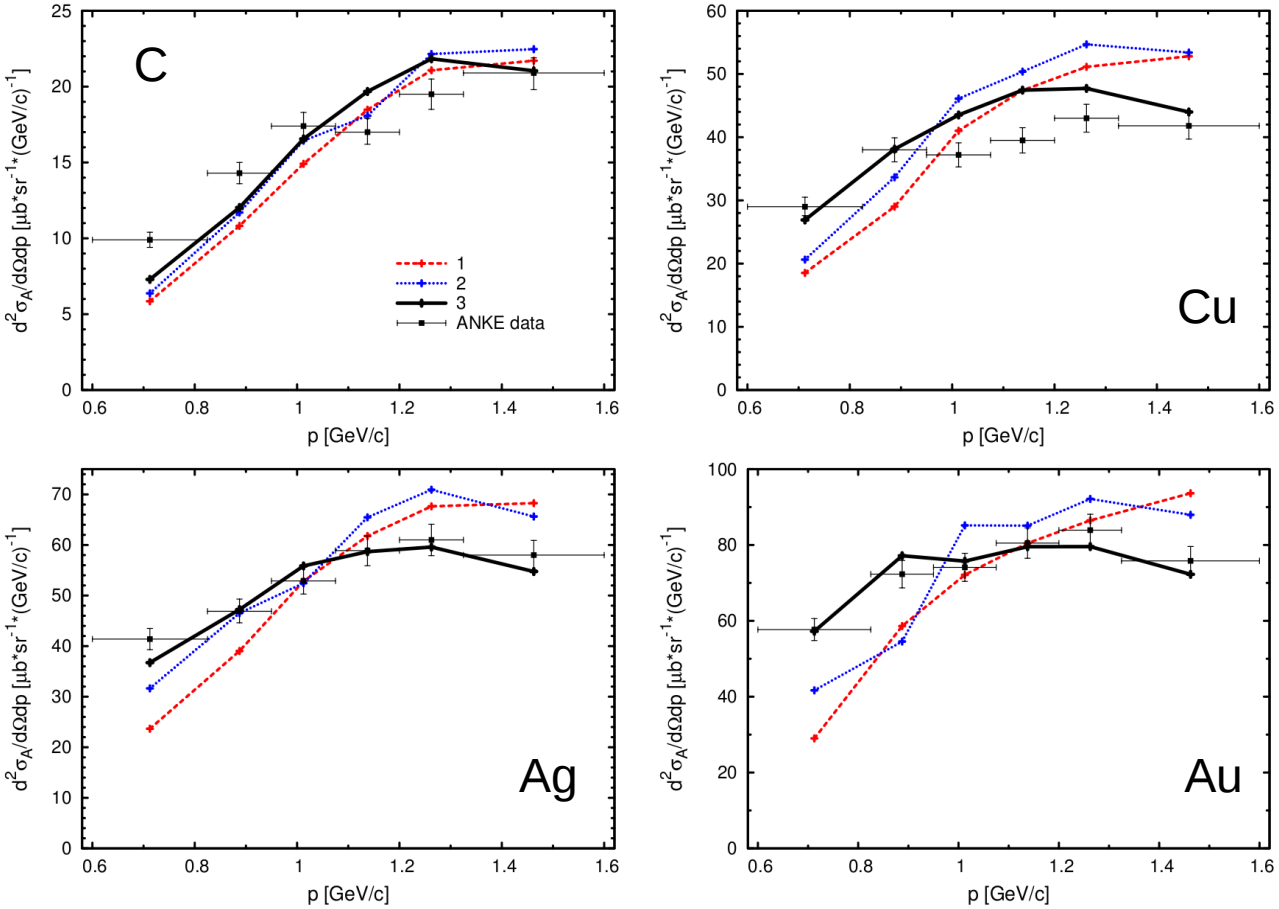
$\sigma_{\eta(\omega)\Delta \to \Phi N} = 2\,\sigma_{\eta(\omega) N \to \Phi N} = 0.07\,mb$

A. Sibirtsev *et al.*, EPJ A29 (2006)

shift of yields toward target rapidity



H.Schade & B.Kämpfer (private communication)



BUU vs. ANKE data (prel.)

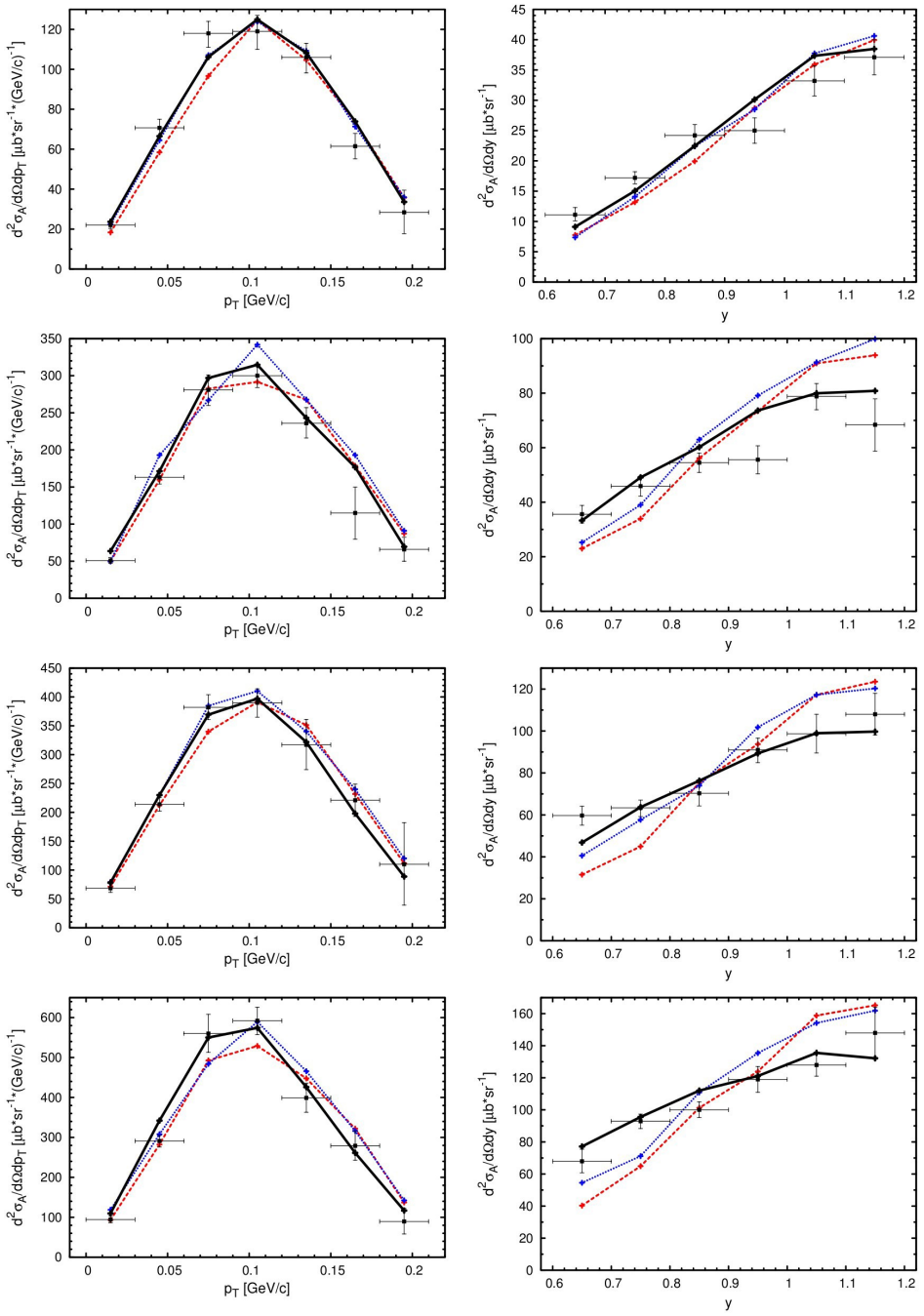
H.Schade & B.Kämpfer
(private communication)

σ_{abs} = 17 mb (const.)

σ_{abs} = linear in p

σ_{abs} = exp. in p

ANKE data



C

Cu

Ag

Au

transverse momentum

&

rapidity distributions

σ_{abs} = 17 mb (const.)

σ_{abs} = linear in p

σ_{abs} = exp. in p

ANKE data

H.Schade & B.Kämpfer
(private communication)

Absorption cross-section versus in-medium width

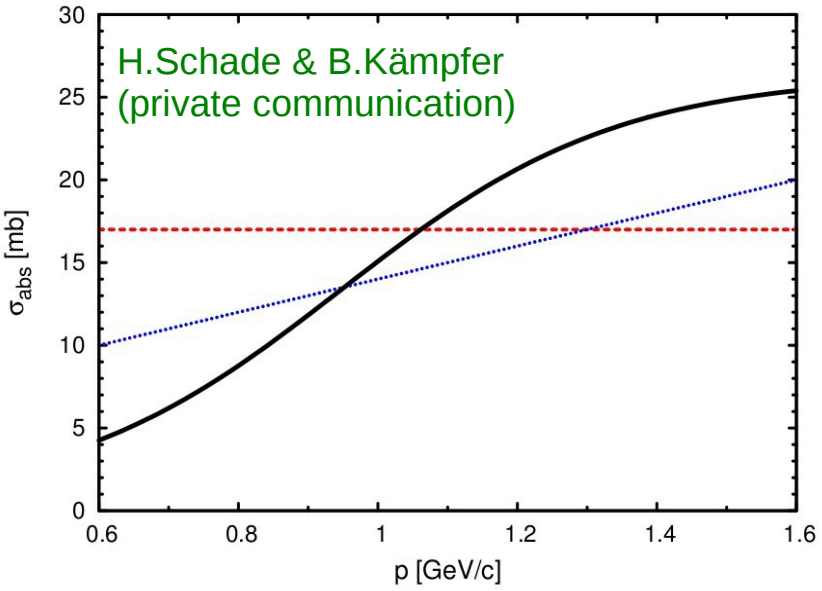
σ_{abs} = 17 mb (const.)

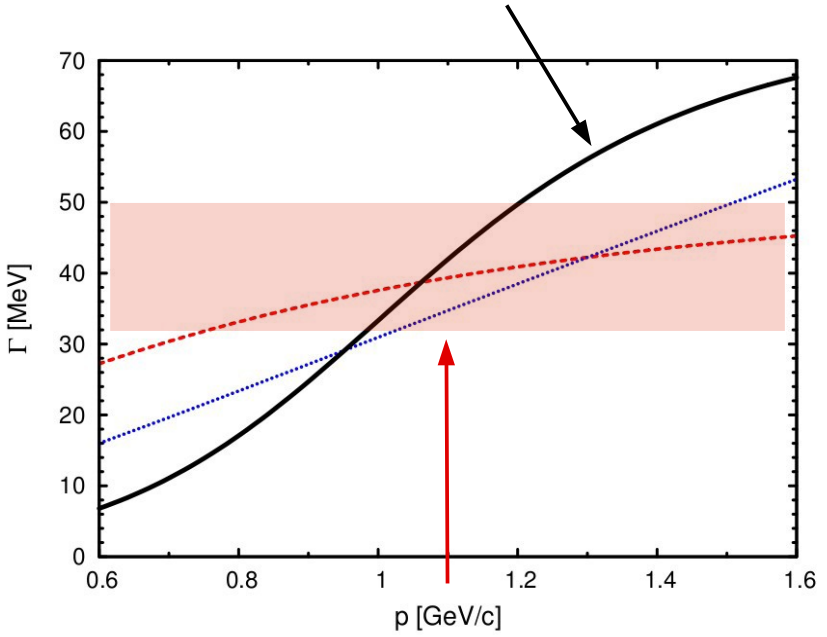
σ_{abs} = linear in p

σ_{abs} = exp. in p

Valencia/Moscow/Rossendorf
Γ ≈ 20 to 70 MeV

"new" Rossendorf BUU (preliminary)
Γ ≈ 8 to 68 MeV





$\Gamma_\Phi^{lab} \approx$ 33-50 MeV ($<p_\Phi>$ = 1.1 GeV/c, ρ_0 = 0.16 fm^{-3})

A.Polyanskiy *et al.*, **PLB 695 (2011) 74**

Current conclusion

- model dependent ANKE data analysis suggest:
  - large in-medium Φ-meson width / absorption (high momentum part),
  - increasing with momentum

  supported by Spring-8 & JLAB results

- preliminary differential cross sections are not completely reproduced by first model calculations (low momentum part)
  - improvement in recent R-BUU calculations (prel.): ΦN elastic, η,ω N → ΦN

- results differ from the Valencia predictions (Φ in-medium self-energy)

and outlook

- investigation of Φ–proton correlations (measured in parallel)

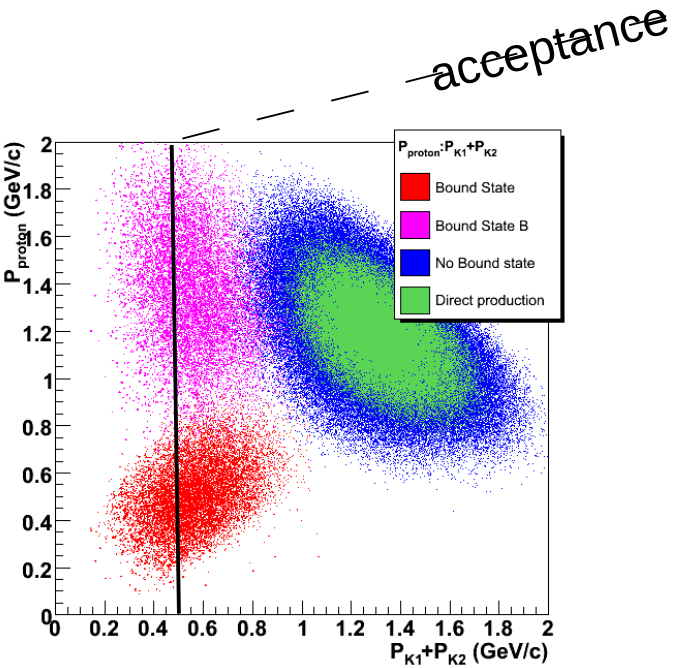
- investigation of the non-resonant $(K^+)K^-$ production, A-dependence and/or ratios of the K^- momentum distributions (A/C)

Thank you!

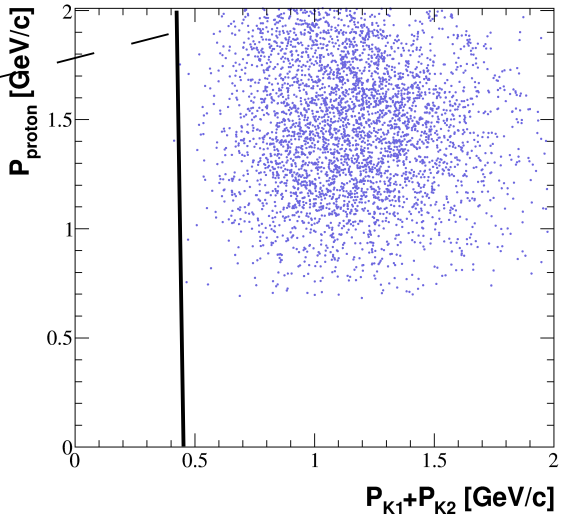
Extra slides:

Extra slides

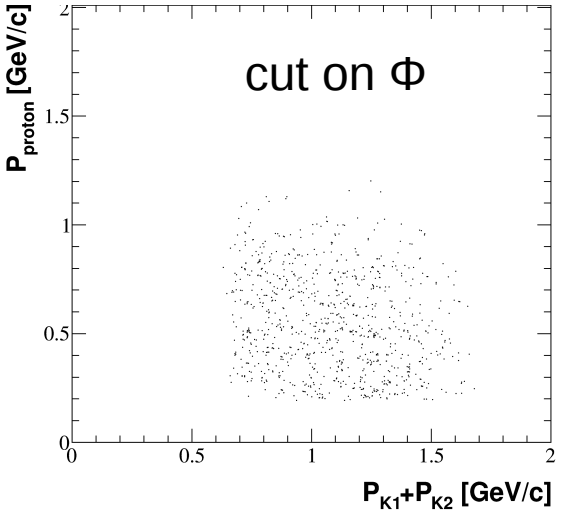
Φ/K^+K^--proton correlation



all KK



proton in forward



proton in side

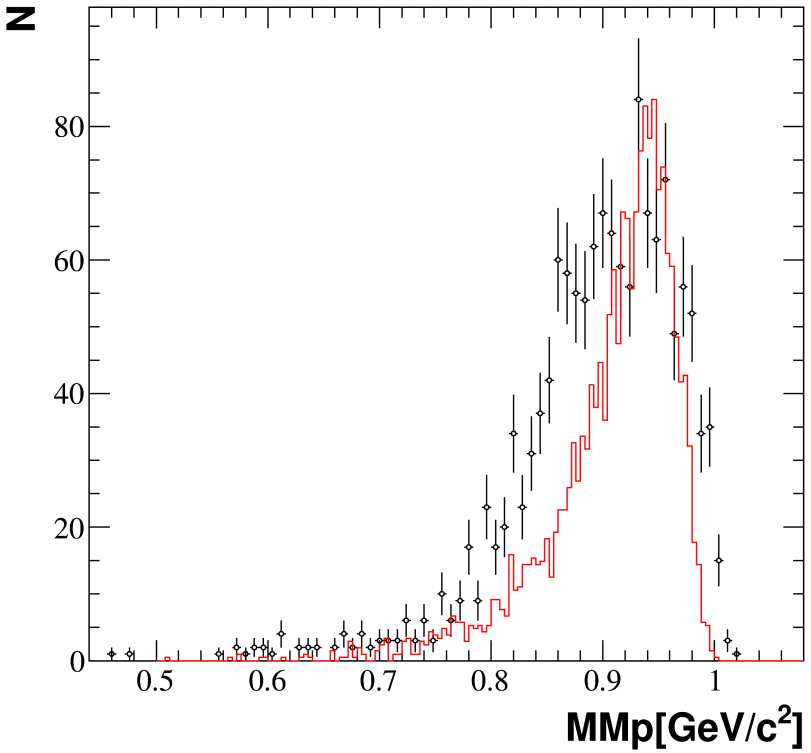
Haiyan Gao (private communication)

PRC 63 (2001) 022201, PRC 75 (2007) 058201,

Letter-Of-Intent JLAB (PAC33) "First search for Φ-N bound state"

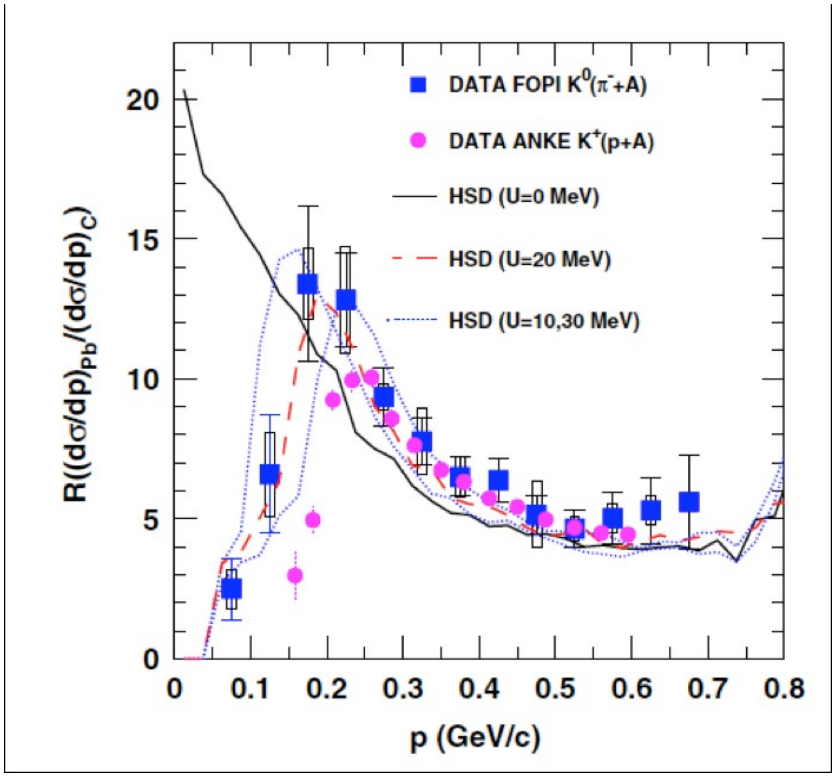
Φ-proton correlation

missing mass: data versus simulation (only primary production)



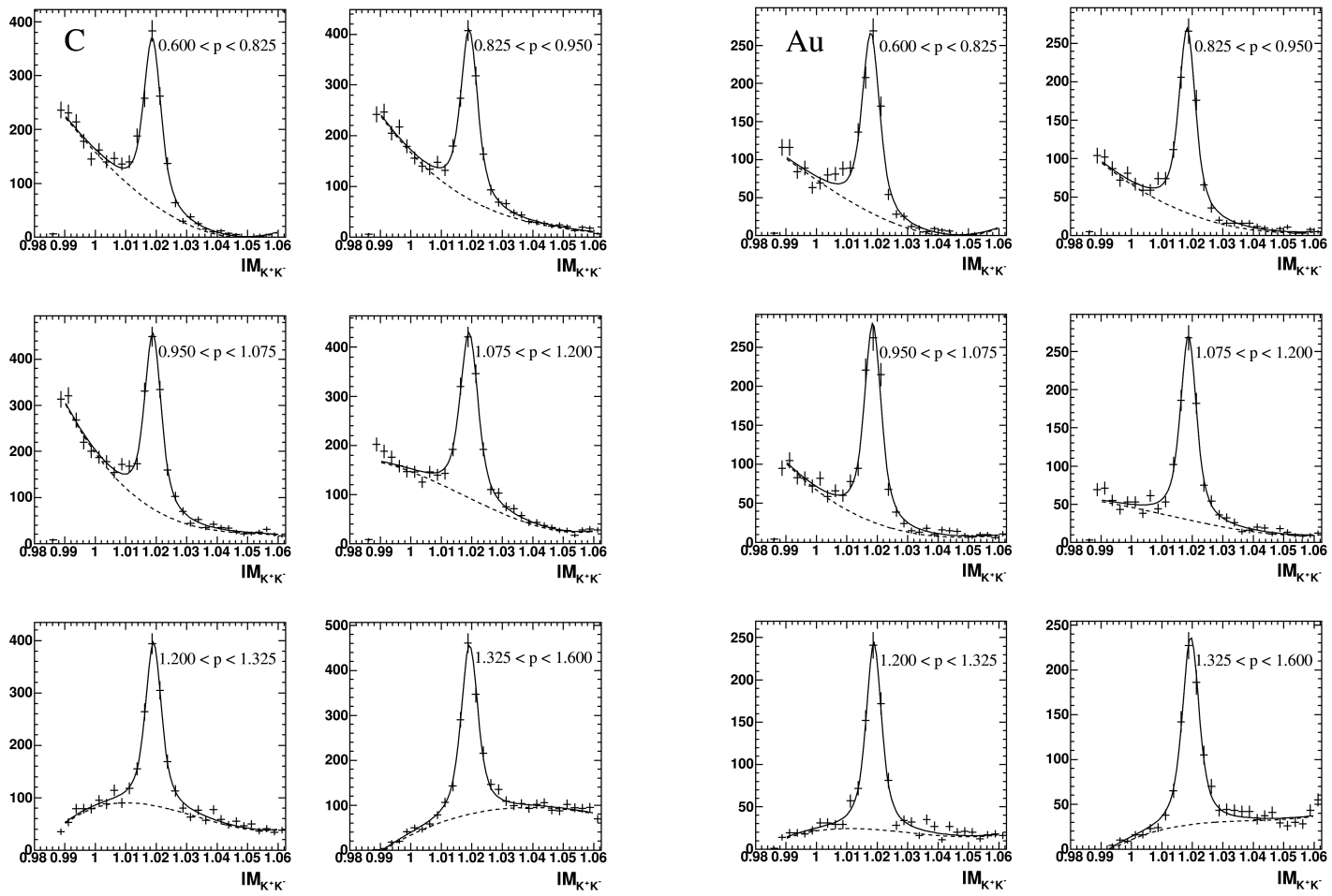
KN potential

Ratio of yields for K^0 (K^+) produced by pions (protons) an Pb and C seen in FOPI(ANKE) as a function of the kaon momentum.

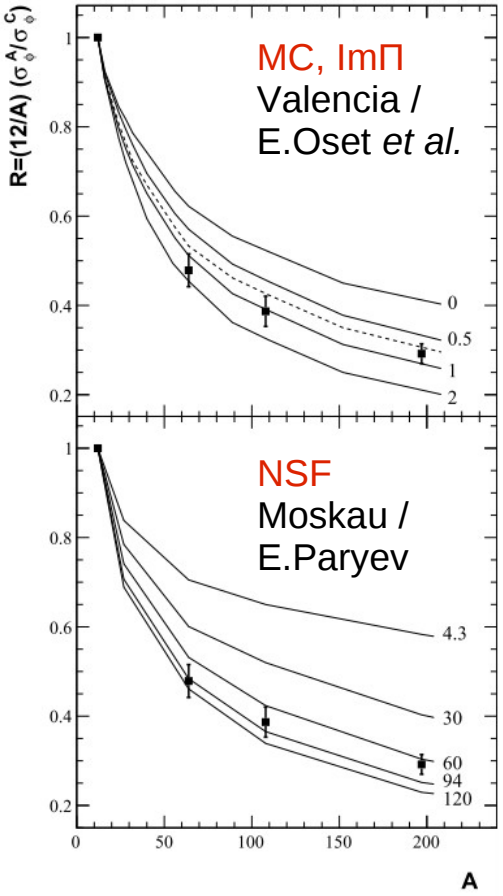


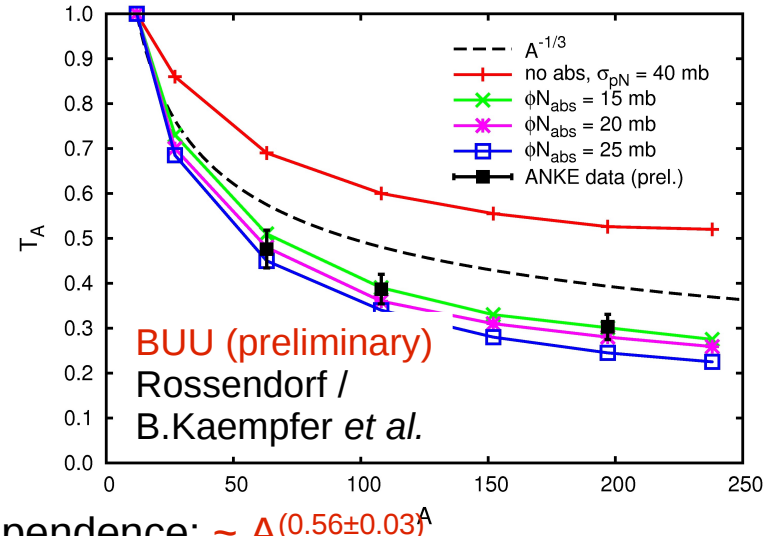
A repulsive KN potential of 20±5 MeV (at normal nuclear density) explain the FOPI and ANKE results.

Invariant mass spectra for 6 momentum bins



Comparison with three model calculations → Φ in-medium width, and …





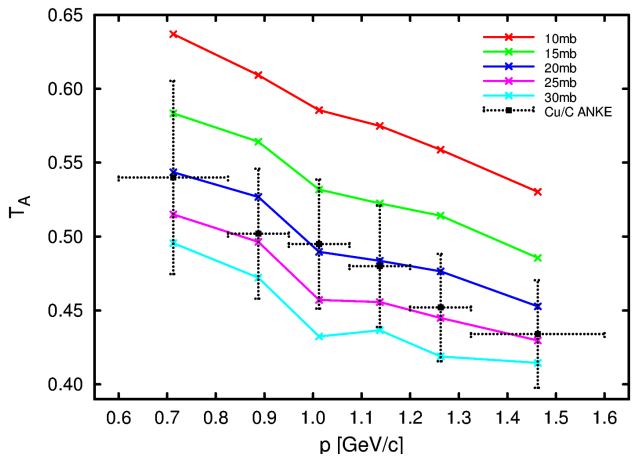
mass dependence: ~ $A^{(0.56\pm0.03)}$

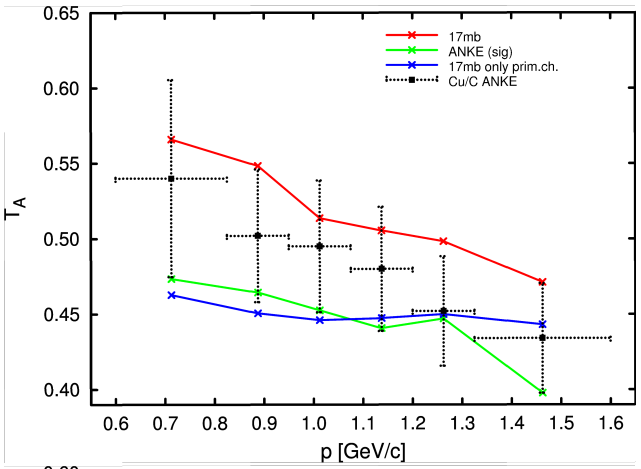
2step production (intermediate pions), factor(pn/pp) ≈ 4, forward acceptance

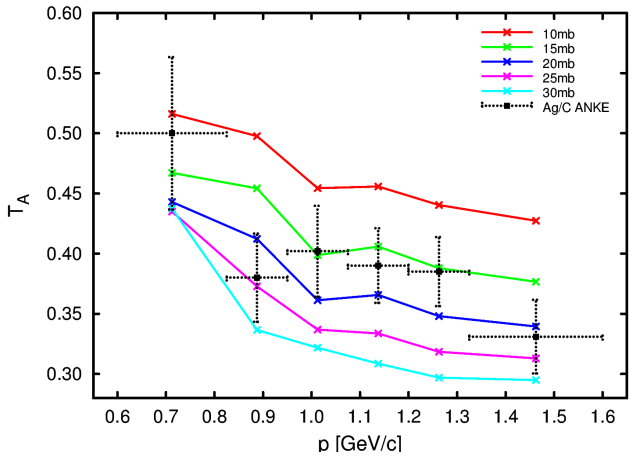
combining the three approaches:

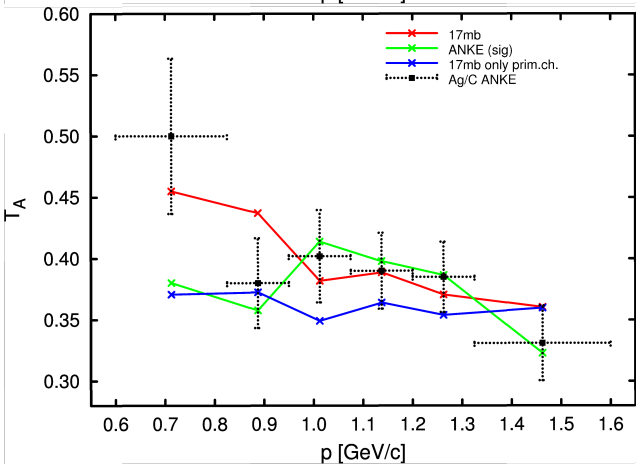
Γ_ϕ^{Lab} = (33-50) MeV/c^2 (<p_ϕ> = 1.1 GeV/c, ρ_0 = 0.16 fm^{-3})

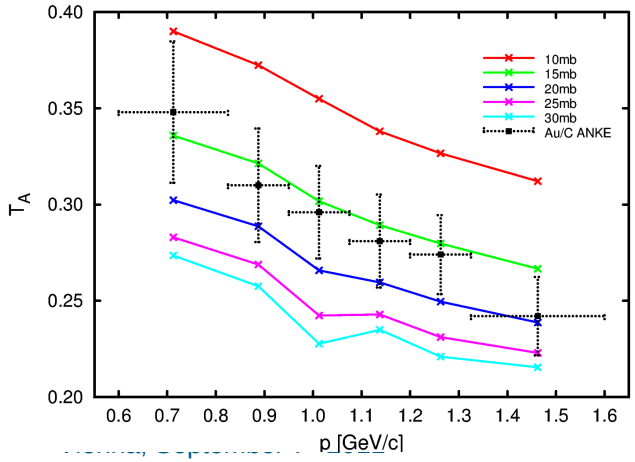
A. Polianskiy *et al.*, PLB 695 (2011) 74

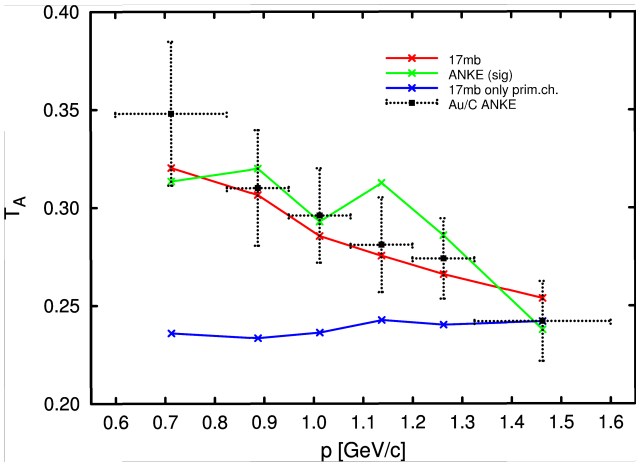






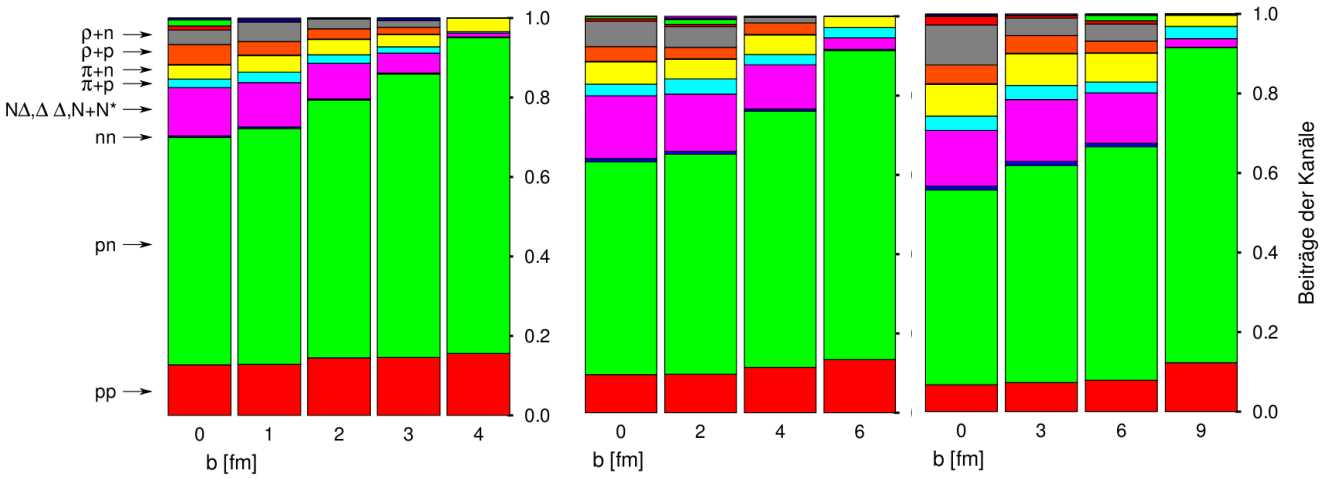






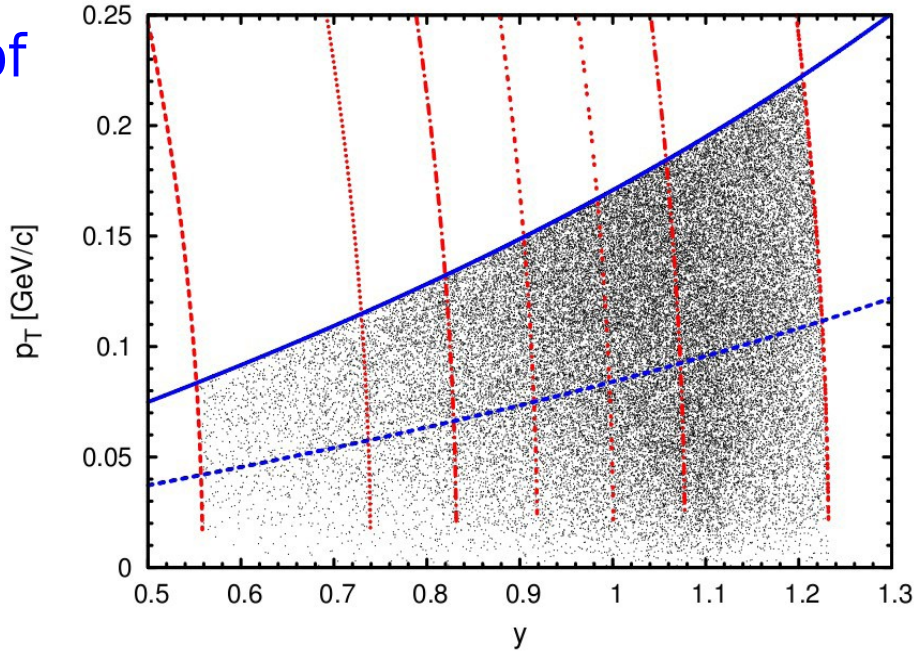
BUU-Rossendorf (preliminary)

B. Kaempfer &
H. Schade (private communication)



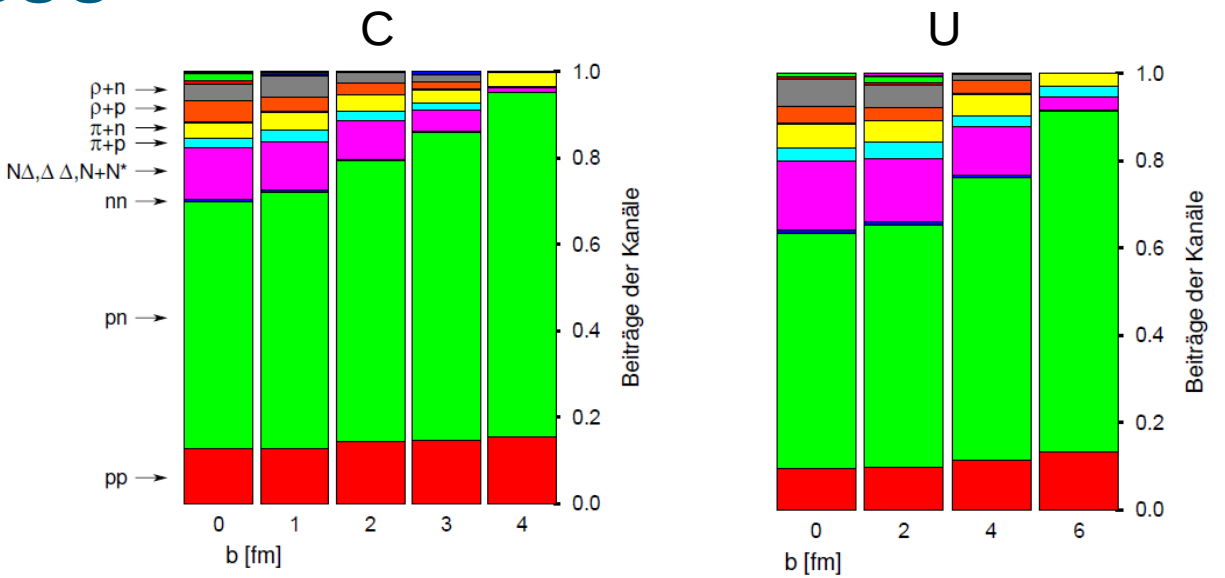
pA: p+C,Cu,Au
@ 2.83 GeV(ANKE)

phase space distribution of
ϕ in ANKE acceptance

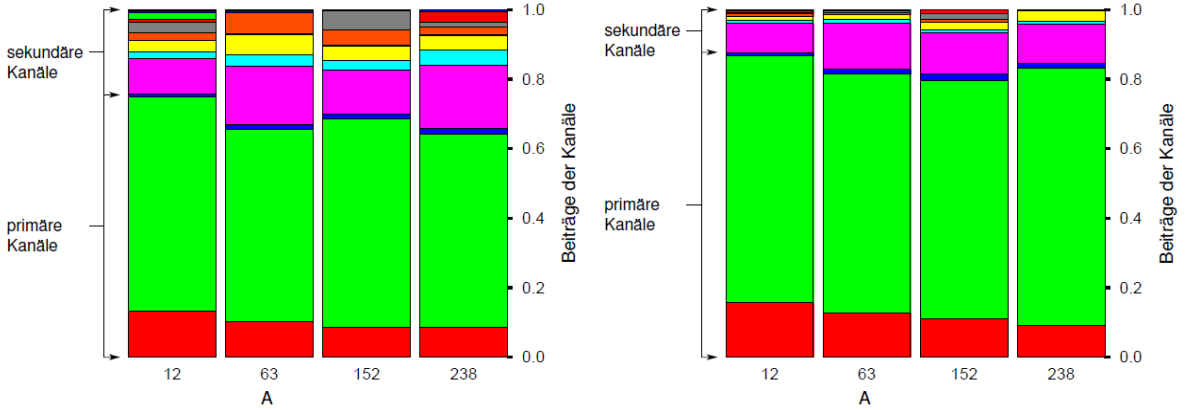


Rossendorf-BUU

impact parameter



<b> = C,Cu,Sm,U



(0.6 — 1.1) GeV/c and (1.1 — 1.6) GeV/c

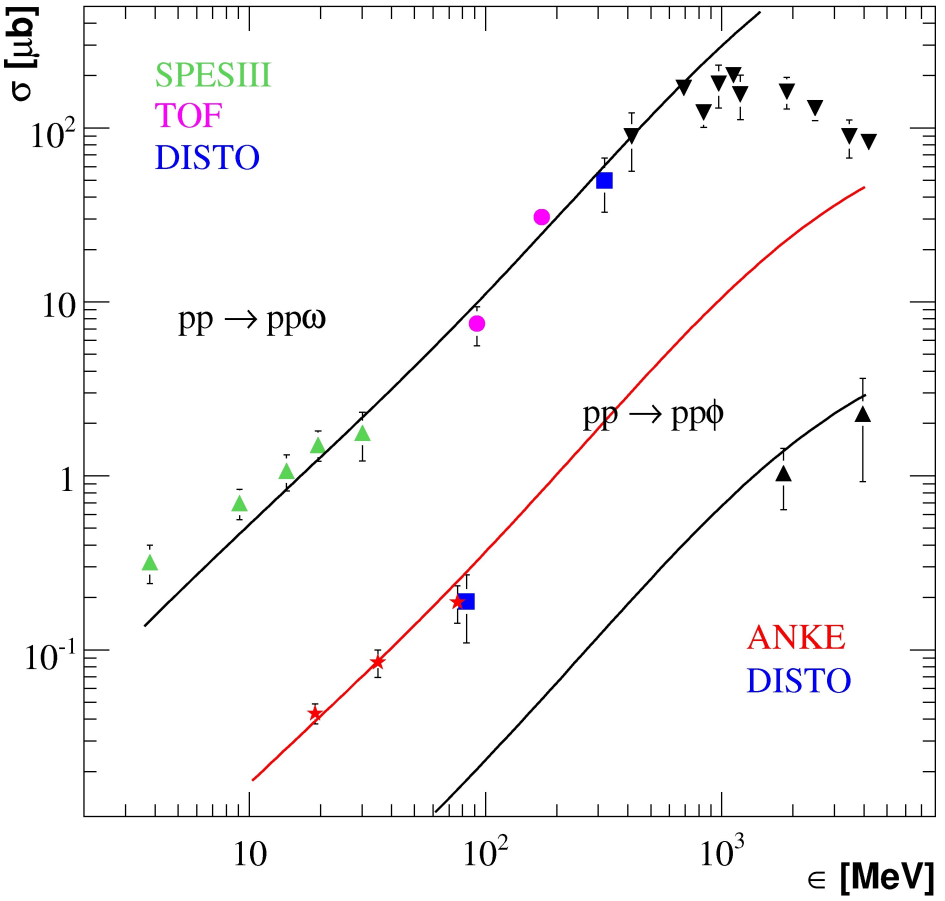
pp→ppΦ (energy dependence)

OZI rule: $4.2\times10^{-3} \equiv R_{OZI}$

$R_{\phi/\omega}$(high energy) ≈ (1 - 2.4)×R_{OZI}
(in agreement with πN data and
the φρπ and ωρπ coupling)

$R_{\phi/\omega}$(18.5-79.5 MeV, ANKE) ≈ 7×R_{OZI}

PRL 96 (2006) 242301



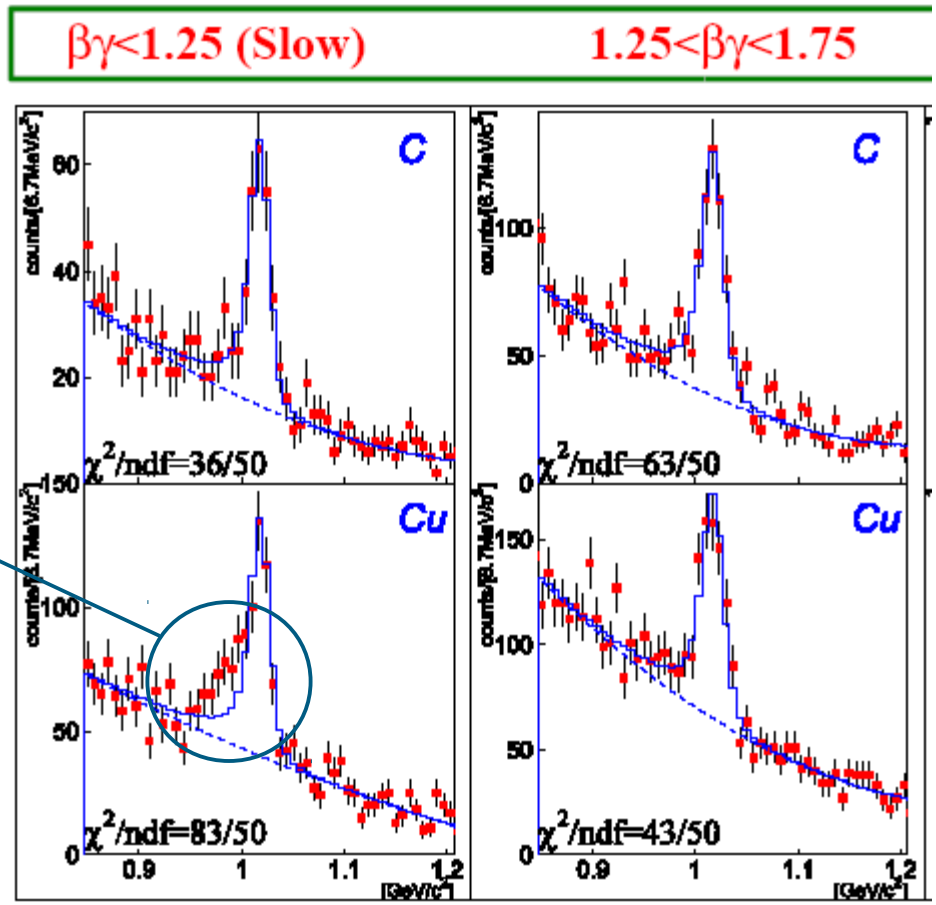
KEK-PS-E325 experiment

R.Muto *et al.*, PRL 98 (2007) 042501 $\Phi \rightarrow e^+e^-$

$m^*/m = 1 - k_1 \rho/\rho_0$,
$\Gamma^*/\Gamma = 1 + k_2 \rho/\rho_0$

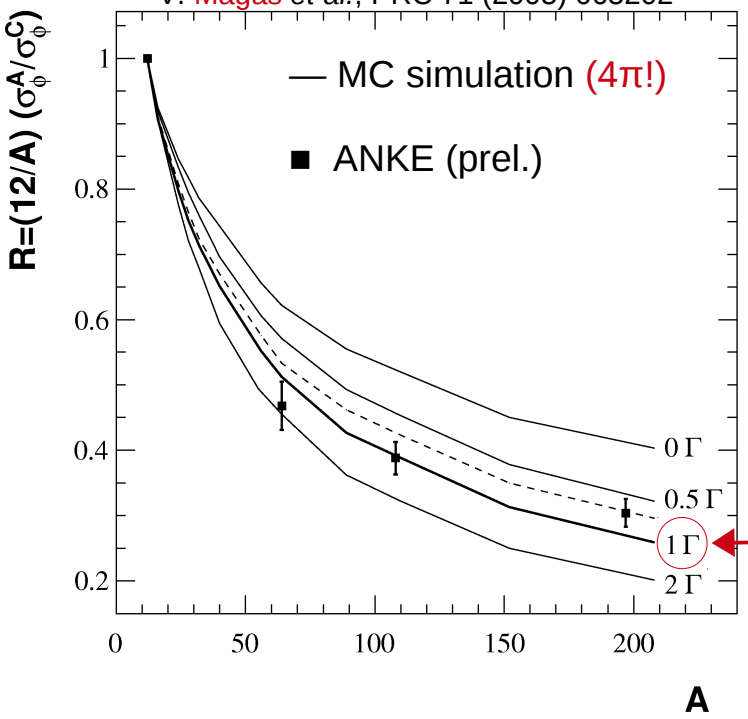
$k_1 = 3.4\ ^{+0.6}_{-0.7}\ \%$

$k_2 = 2.6\ ^{+1.8}_{-1.2}$

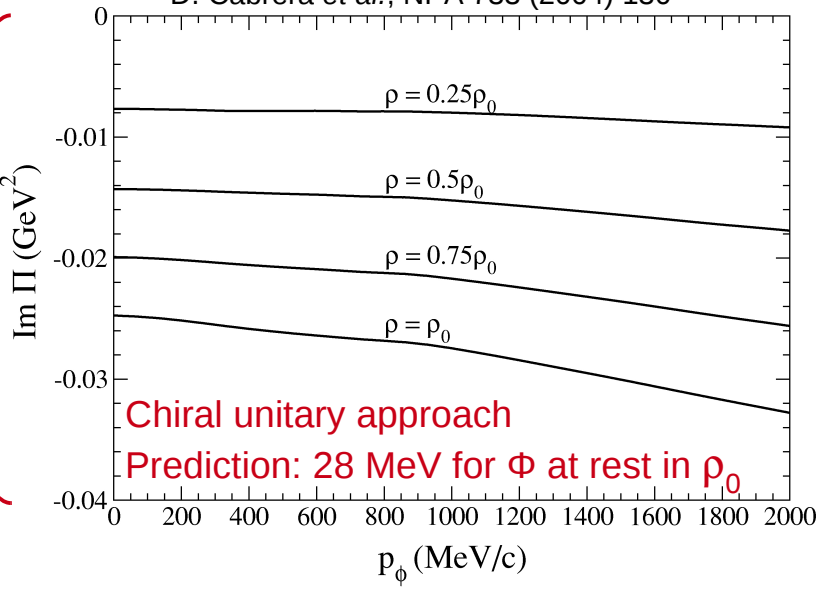


Comparison with model prediction & MC simulation (Magas/Cabrera)

V. Magas *et al.*, PRC 71 (2005) 065202



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



$\Gamma = 26^{+4}_{-3}\,MeV$

BUT!

2step (πN, ρN)

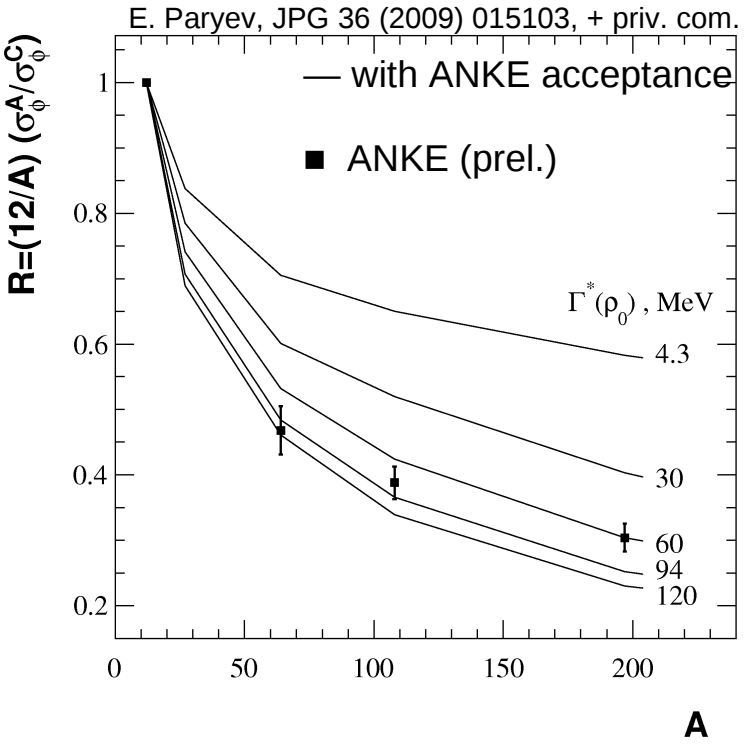
Δ intermediate states

pnΦ ≈ 4 ppΦ

$\Gamma = 43^{+11}_{-8}\,MeV$

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

Comparison with model calculations (Paryev)



In framework of a nuclear spectral function model:

pp → ppΦ, pn → pnΦ (≈ 4•pp),
pn → dΦ

K&K, EPJ A 23 (2005) 291

2step: πN → ΦN

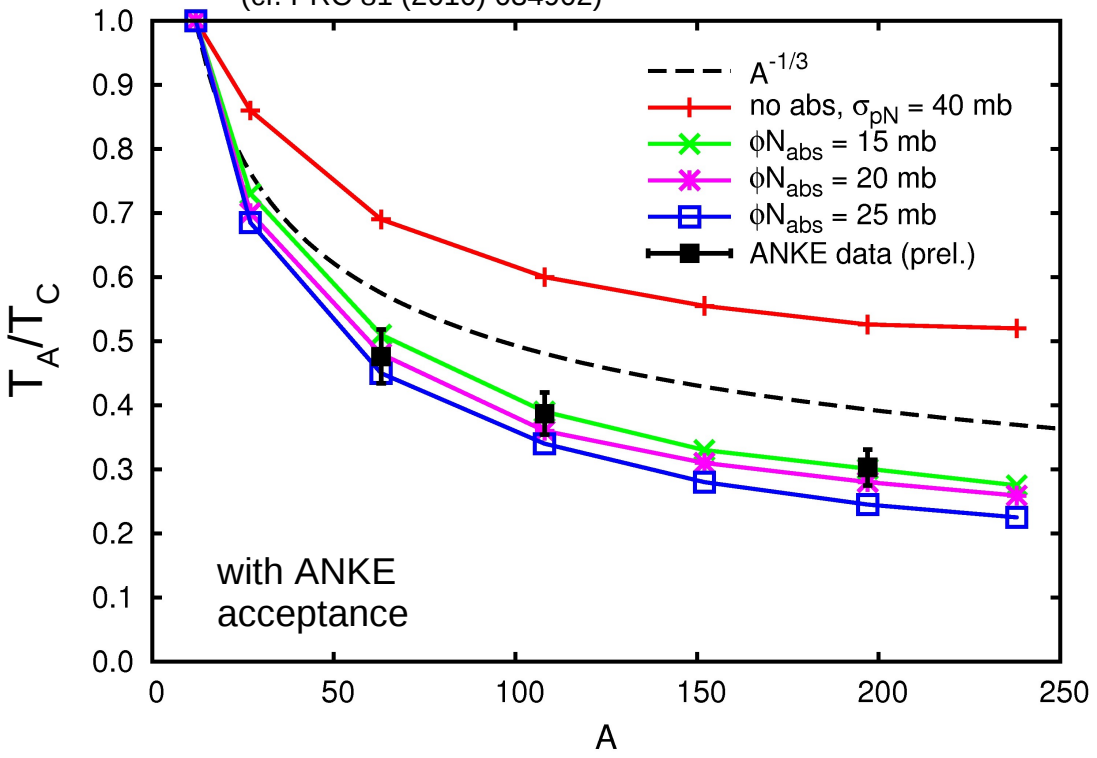
Total in-medium Φ-width is assumed to be momentum-independent

$$\Gamma^{\Phi} = 71^{+11}_{-9}\,MeV \qquad \Gamma \approx 49\,MeV\ ,1.1\,GeV/c\ \phi's\ ,\approx 20\,mb\,(l.d.a.)$$

$$\Gamma \approx 71\,MeV$$

Comparison with Rossendorf-BUU calculations (very preliminary)

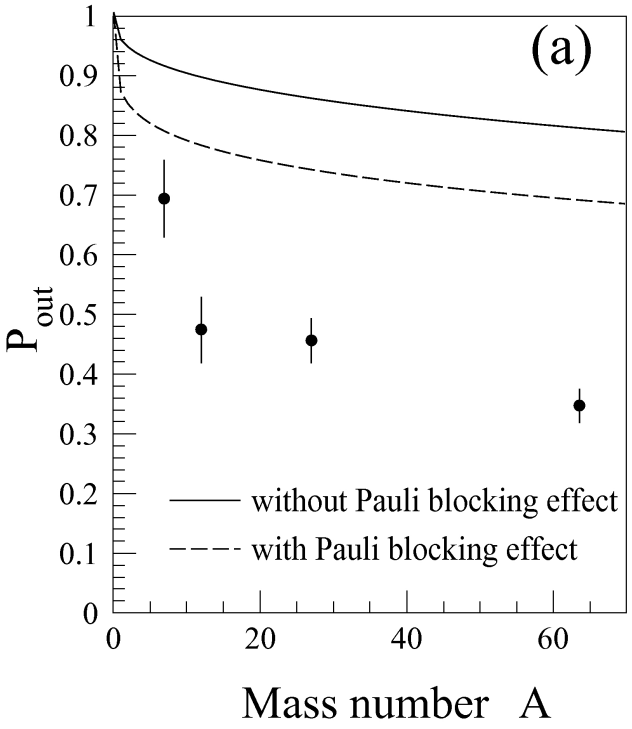
H. Schade, B. Kaempfer *et al.* (private communication)
(cf. PRC 81 (2010) 034902)

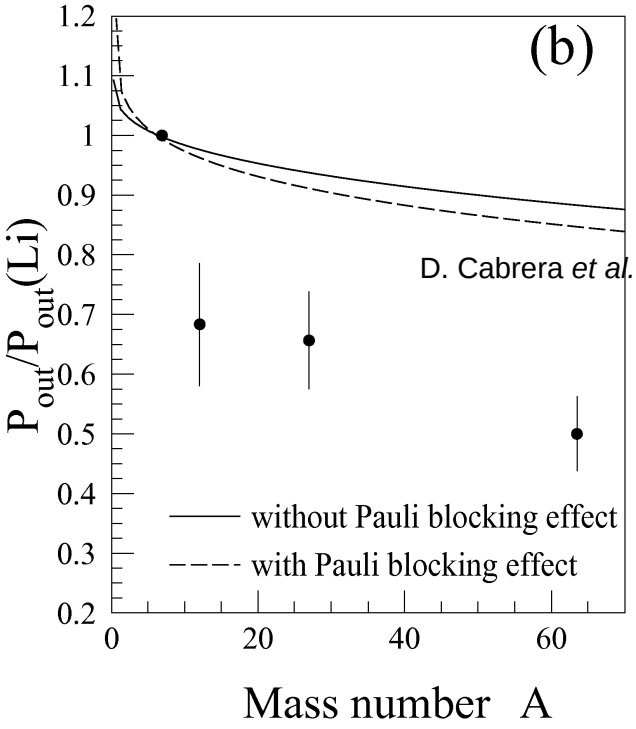


first Rossendorf-BUU result – “in between”

Valencia calculations (SPring-8-data)

E. Oset *et al.*, Pramana 66 (2006) 731





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

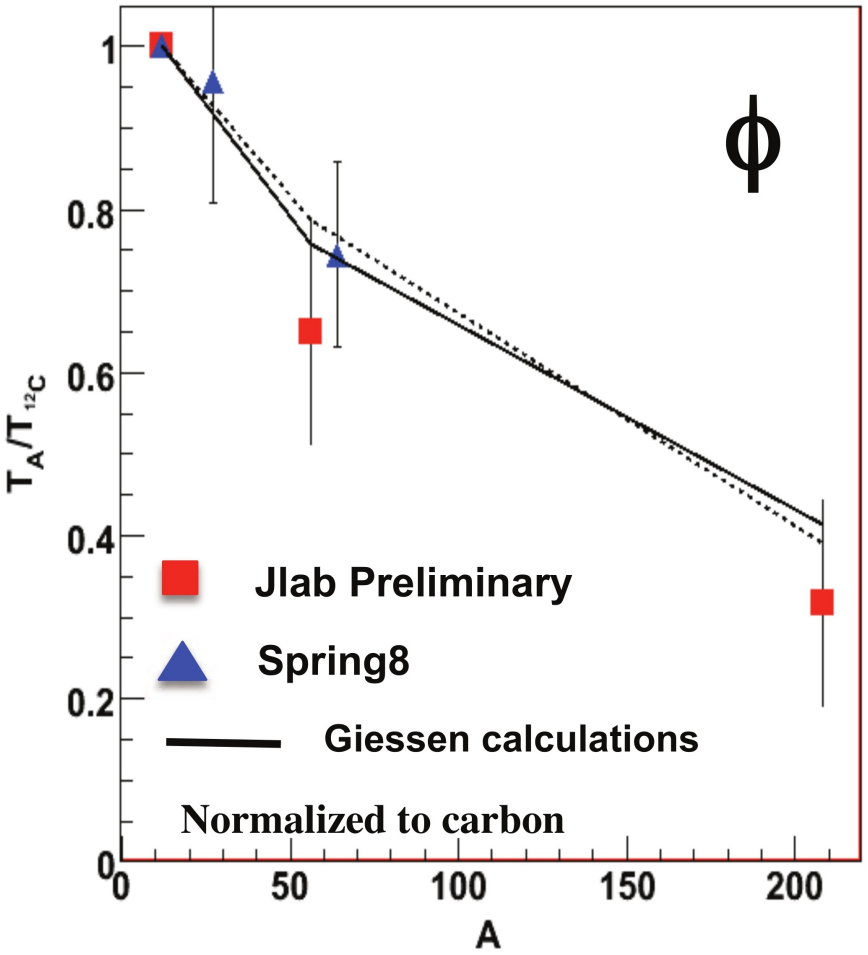
$$P_{out} = \frac{\sigma_{\phi}^{A}}{A\,\sigma_{\phi}^{N}}$$

SPring-8 and up-coming JLAB-g7 (CLAS) result

CLAS: $\gamma A \rightarrow \Phi(\rightarrow e^+e^-)X$

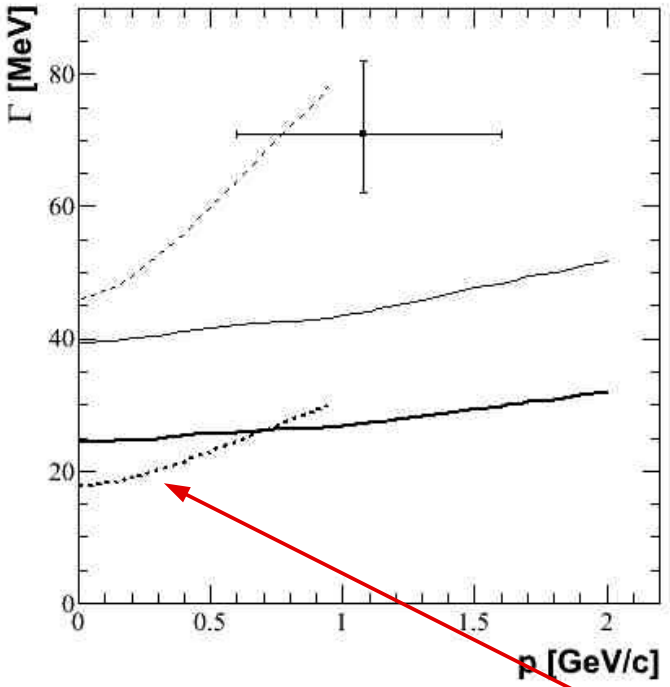
"agreement"

R. Nasseripour *et al.*, AIP 1056 (2008) 223

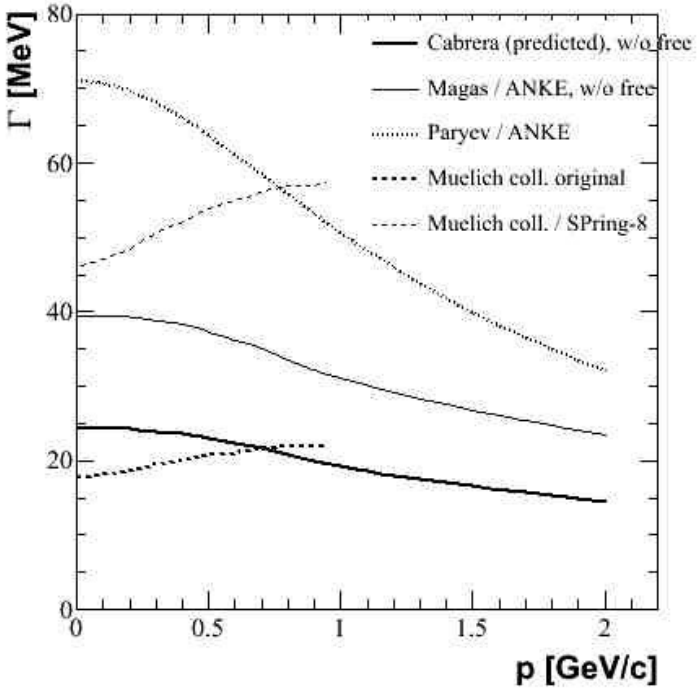


Momentum dependence of the in-medium Φ-width

"Φ frame"



"nuclear frame"



$$\mathcal{I}\mathrm{m}\Pi_{\mathrm{coll}}(q_0 = \sqrt{m_V^2 + \mathbf{q}^2}, \mathbf{q}, n_N(\mathbf{r})) = -4 \int \frac{d^3p}{(2\pi)^3} \Theta(|\mathbf{p}| - p_F) \frac{|\mathbf{k}_{\mathrm{cm}}|\sqrt{s}}{E_N(\mathbf{p})} \sigma_{VN}(s)$$

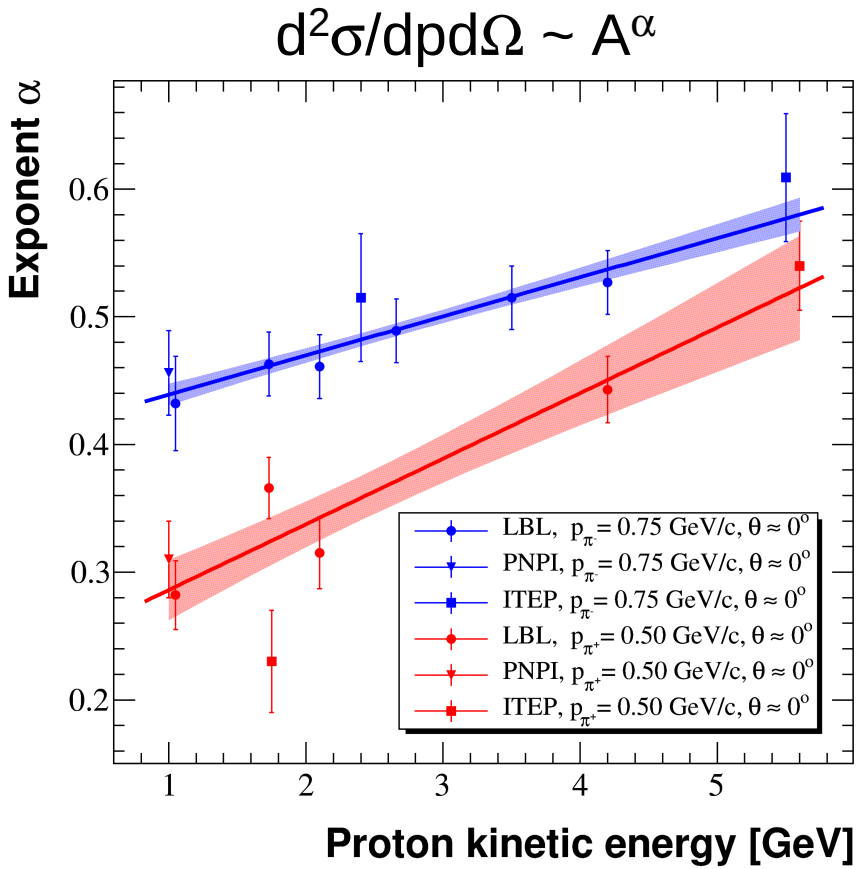
$$\Gamma_{\mathrm{coll}} = -\frac{\mathcal{I}\mathrm{m}\Pi_{\mathrm{coll}}}{m_\phi}$$

Determination of α for π production

At T_p = 2.83GeV:

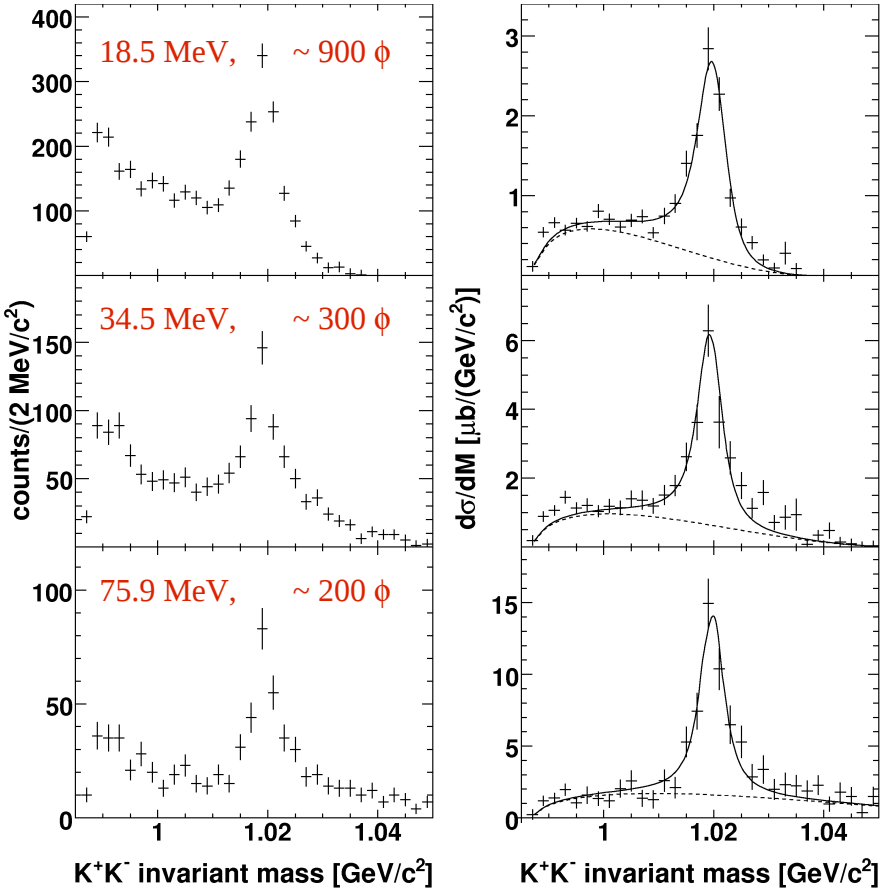
$\alpha(\pi^-) = 0.495 \pm 0.005$ (1%)

$\alpha(\pi^+) = 0.380 \pm 0.018$ (5%)

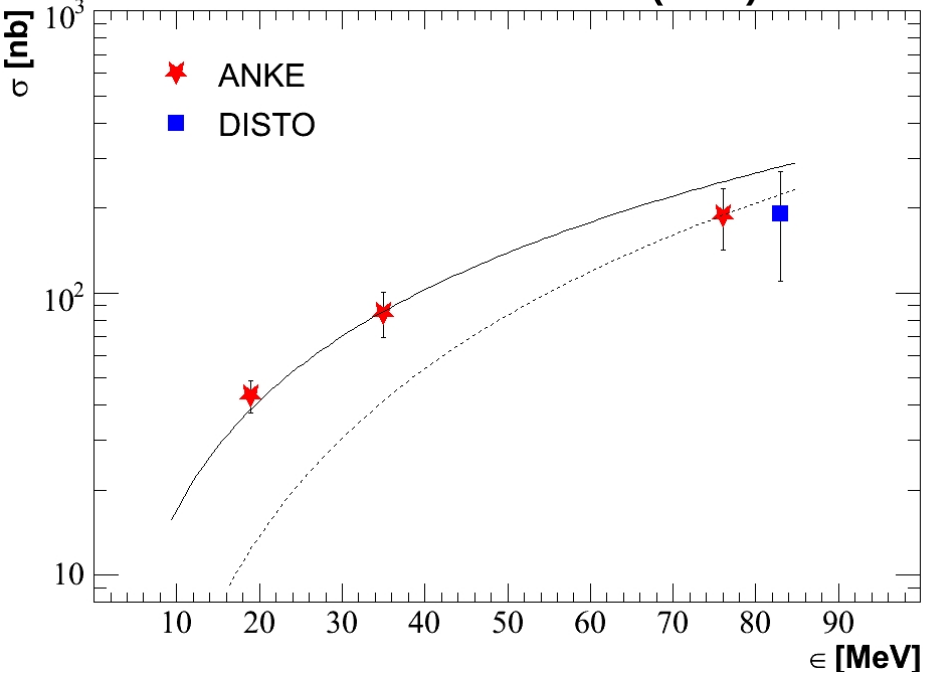


$\Phi(\rightarrow K^+K^-)$ production in pp & pd

pp→ppΦ (total cross sections)



PRL 96 (2006) 242301



dashed line: phase space
solid line: phase space + pp-FSI (Jost function)
(best fit to the ANKE points)

pp→ppΦ (differential cross sections)

ε = 18.5 MeV

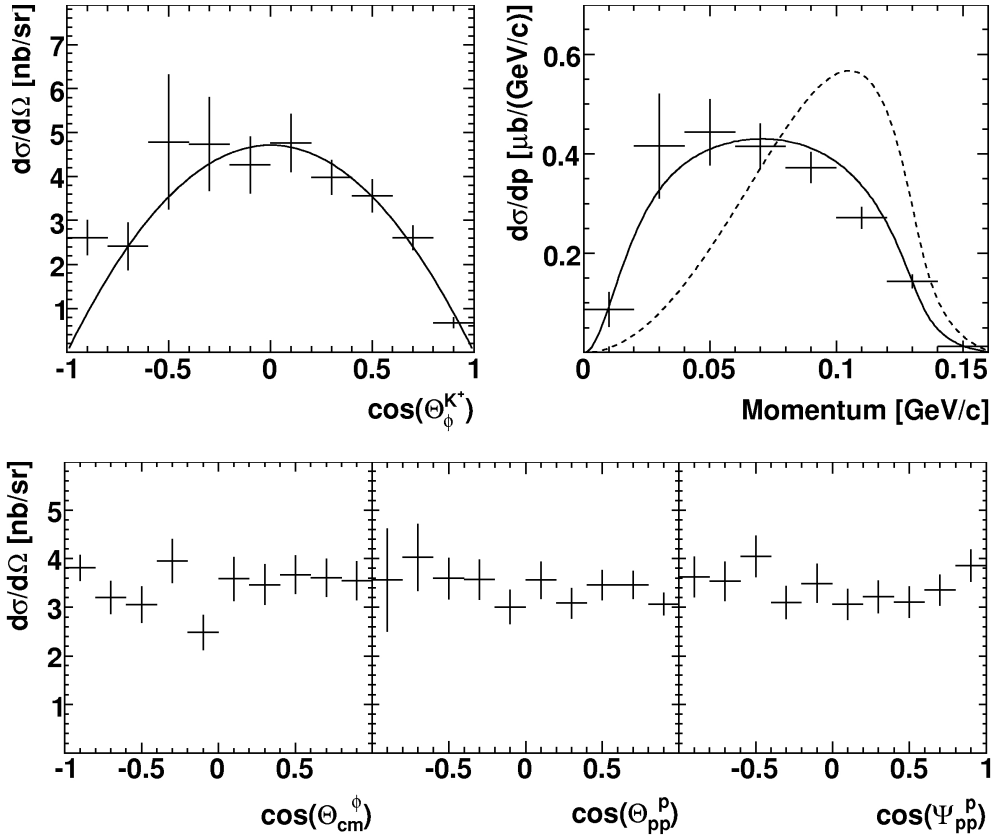
close to threshold the angular decay distribution must display a $\sin^2\Theta_\phi^{K^+}$

Φ in relative S-wave

transition from $^3P_1$ (pp)-entrance channel to $^1S_0$ (pp) final-state

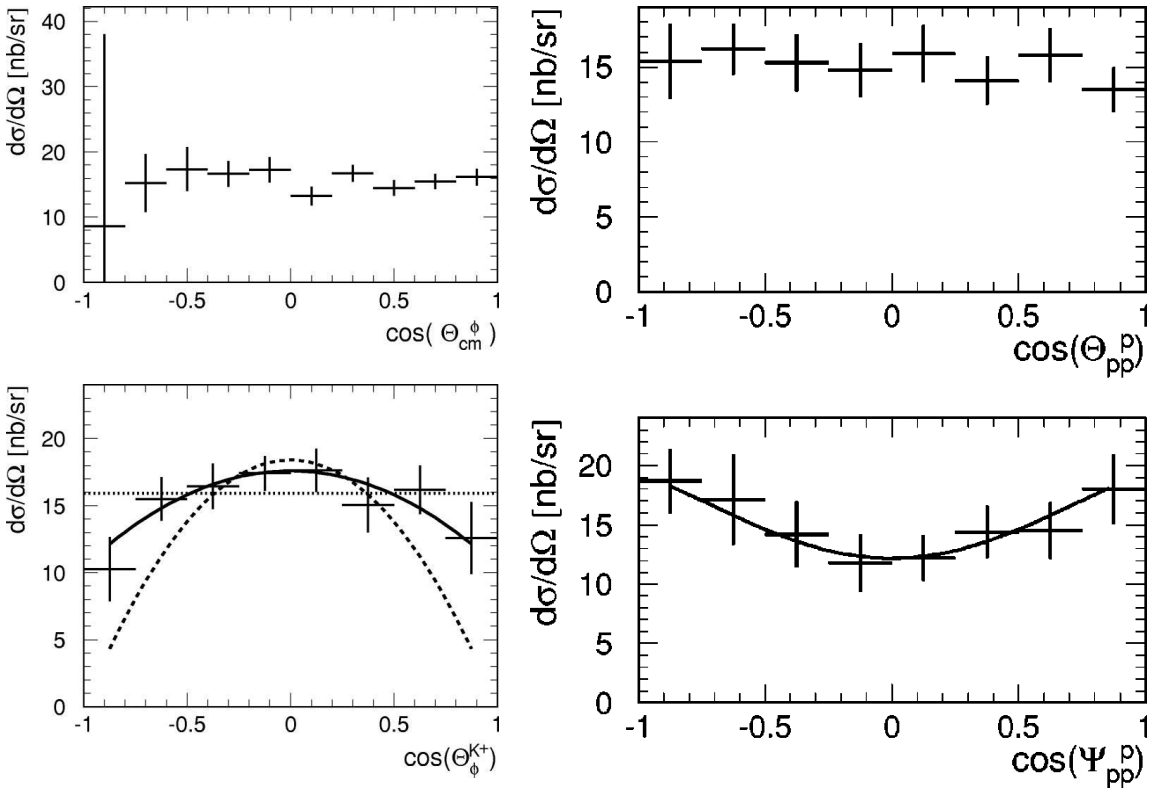
clear effect of pp-FSI

PRL 96 (2006) 242301



pp→ppΦ (differential cross sections), DISTO

DISTO, PRC 63 (2001) 024004

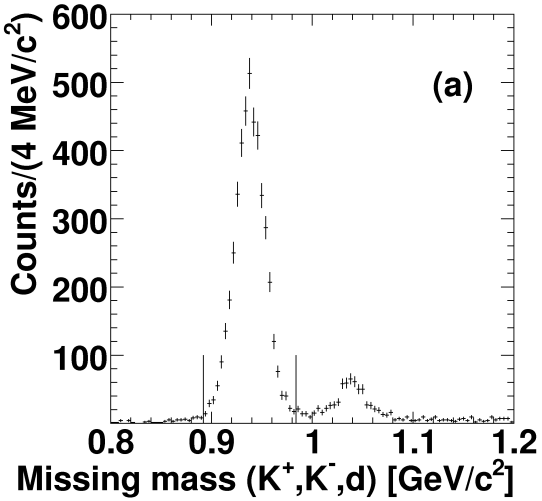


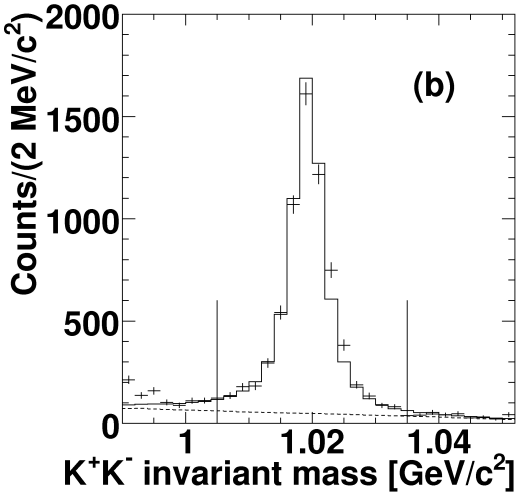
DISTO ~ 500 Φ's
@ ε = 85 MeV

ANKE ~ 5000 Φ's
@ ε = 76 MeV
new data, analysis in progress

Dominantly S-wave, best fit: (28±7)% P-wave contribution

pn→dΦ production (event selection)

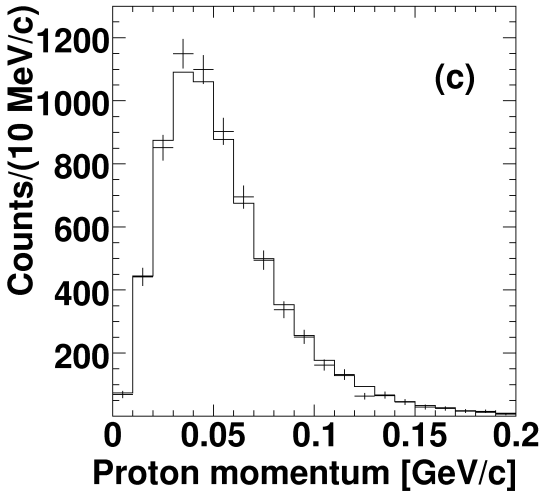


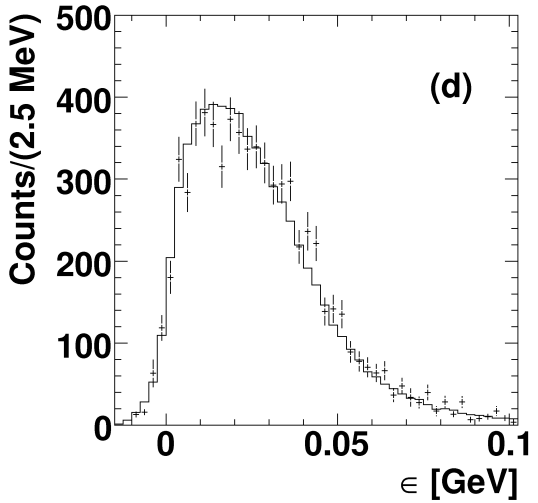


$T_p = 2.65$ GeV

$pd \rightarrow d\Phi(K^+K^-)p_{spectator}$

$pn \rightarrow d\Phi(K^+K^-)$





Monte Carlo simulation:
Fermi momentum in the target deuteron derived from Bonn potential.

extract cross section for ε< 80 MeV

pn→dΦ (differential cross sections)

1 S + 9 possible P-wave amplitudes !

				Ll_{J_q}
$^1P_1$	→	$^3S_1$	s	Ss
$^3S_1$	→	$^3S_1$	p	S^1p_0
$^3S_1$	→	$^3S_1$	p	S^1p_1
$^3S_1$	→	$^3S_1$	p	S^1p_2
$^3D_1$	→	$^3S_1$	p	S^2p_0
$^3D_1$	→	$^3S_1$	p	S^2p_1
$^3D_1$	→	$^3S_1$	p	S^2p_2

… and more …

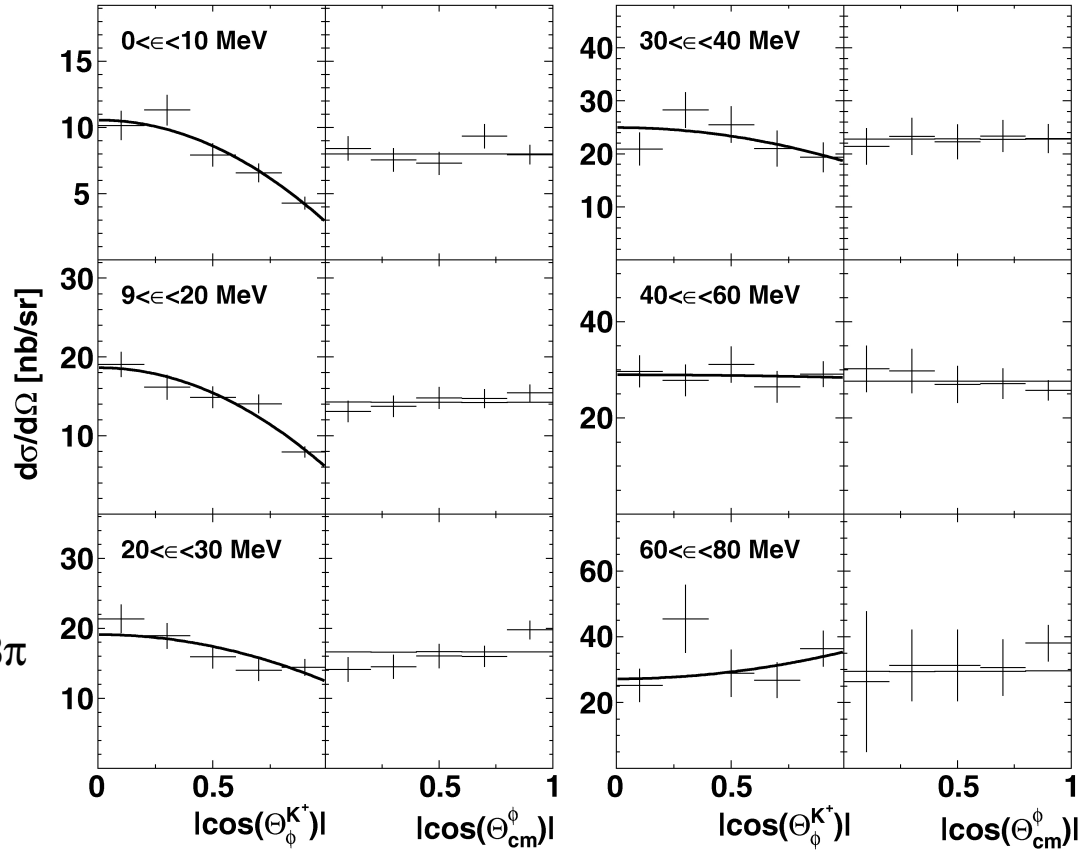
to allow for the possibility of higher partial waves …
most general form:

$d\sigma/d\Omega_\Phi^{K^+}=3(a \sin^2\Theta_\Phi^{K^+}+2b \cos^2\Theta_\Phi^{K^+})/8\pi$

$\sigma_{tot} = a+b$

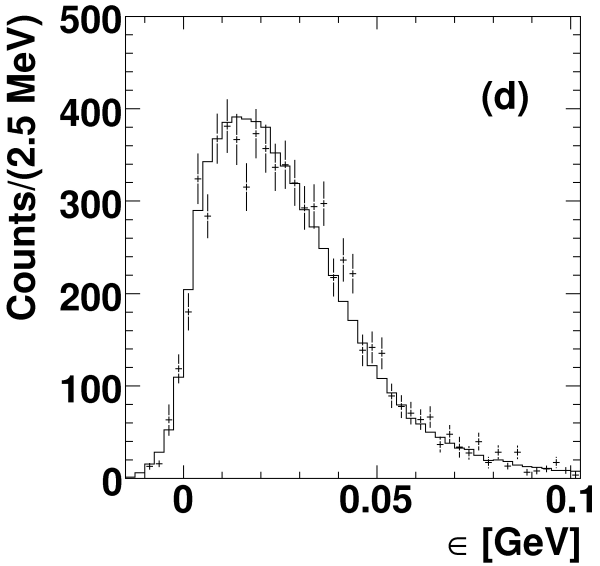
from fits to these data:
$b/a \approx (0.012 \pm 0.001)(\varepsilon/\text{MeV})$

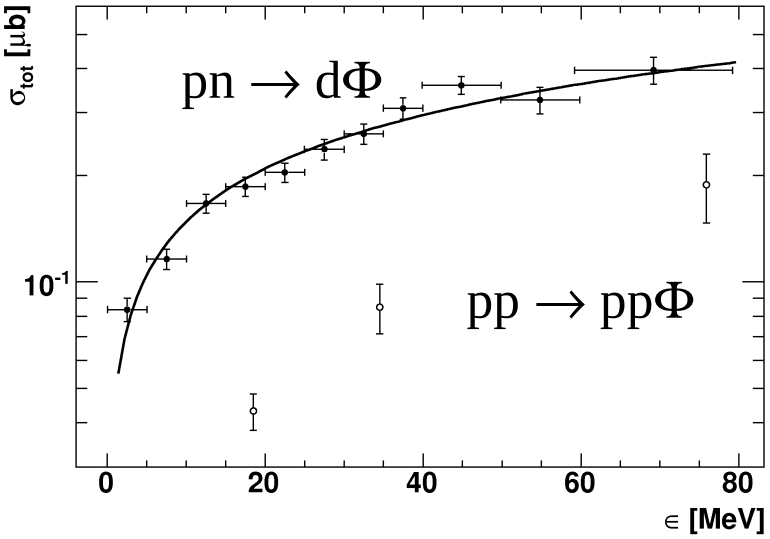
PRL 97 (2006) 142301

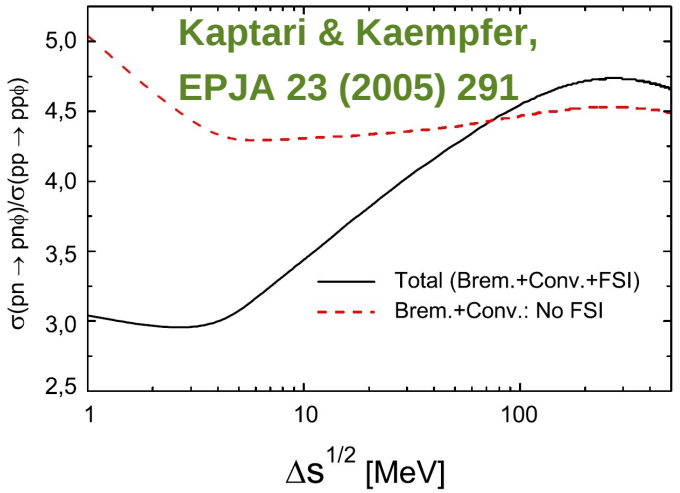


pn→dΦ (differential and total cross sections)

PRL 97 (2006) 142301





using final-state-interaction theory
(Fäldt, Wilkin) PLB 382 (1996) 209).

$\sigma(pn \to pn\Phi) / \sigma(pp \to pp\Phi) \approx 2.3 \pm 0.4$