

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

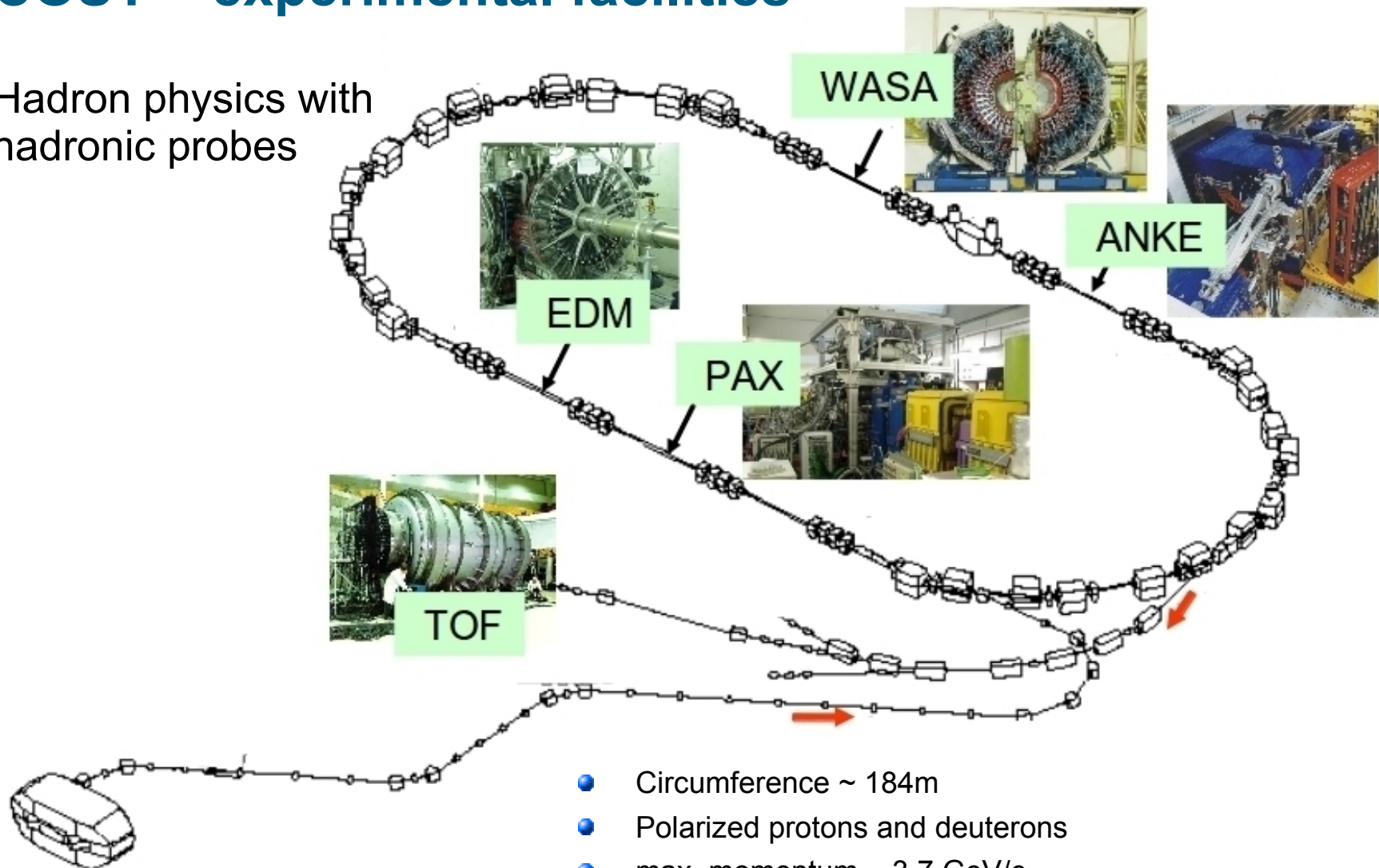
International Conference on Exotic Atoms and Related Topics -
EXA2011

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)
 $pA \rightarrow \Phi (K^+K^-) X$ @ $T_p = 2.83$ GeV ($\varepsilon = 76$ MeV free NN threshold)
 - in-medium Φ width and its momentum dependence, as well as differential cross sections

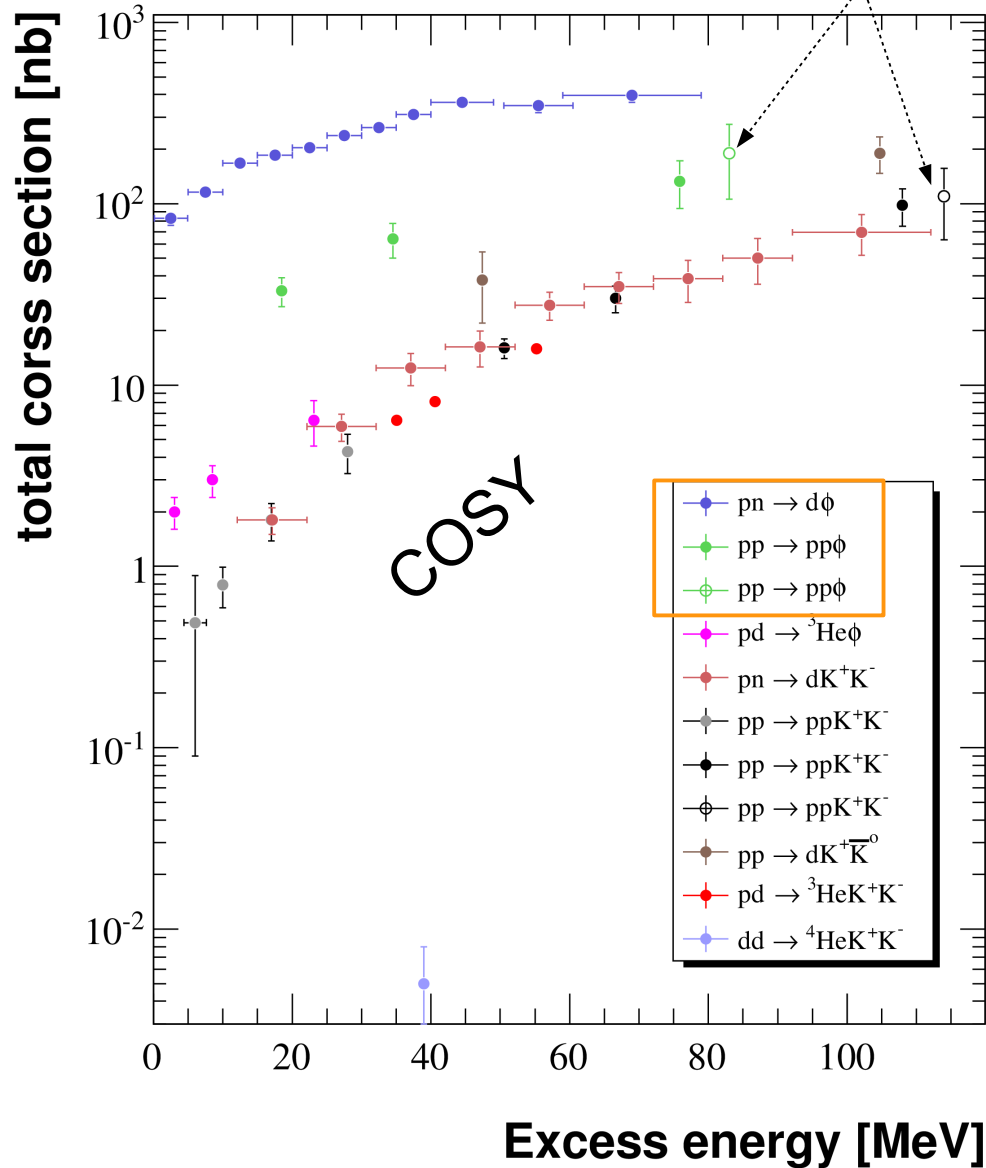
COSY – experimental facilities

Hadron physics with
hadronic probes



- Circumference $\sim 184\text{m}$
- Polarized protons and deuterons
- max. momentum $\sim 3.7\text{ GeV}/c$
- Electron and stochastic cooling

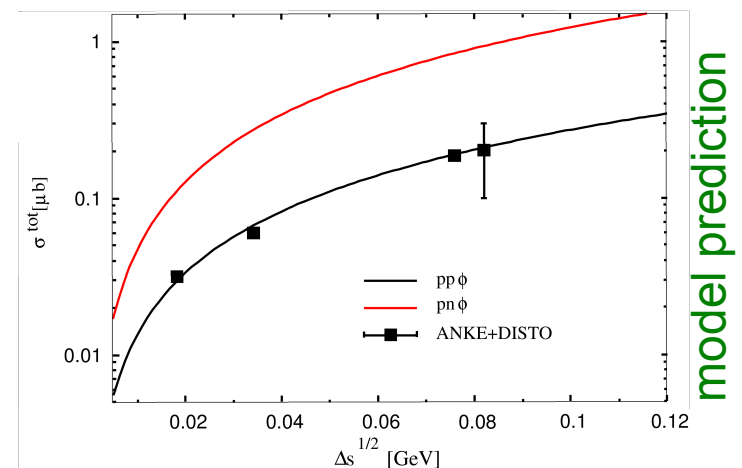
DISTO



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)



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

$$M_0 = 1.0195 \text{ GeV}$$

(PDG 2008)

$$\Gamma_0 = 4.26 \text{ MeV}$$

- Φ is a long-lived meson:

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

Φ in nuclear matter

- Meson spectral function:

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

- 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

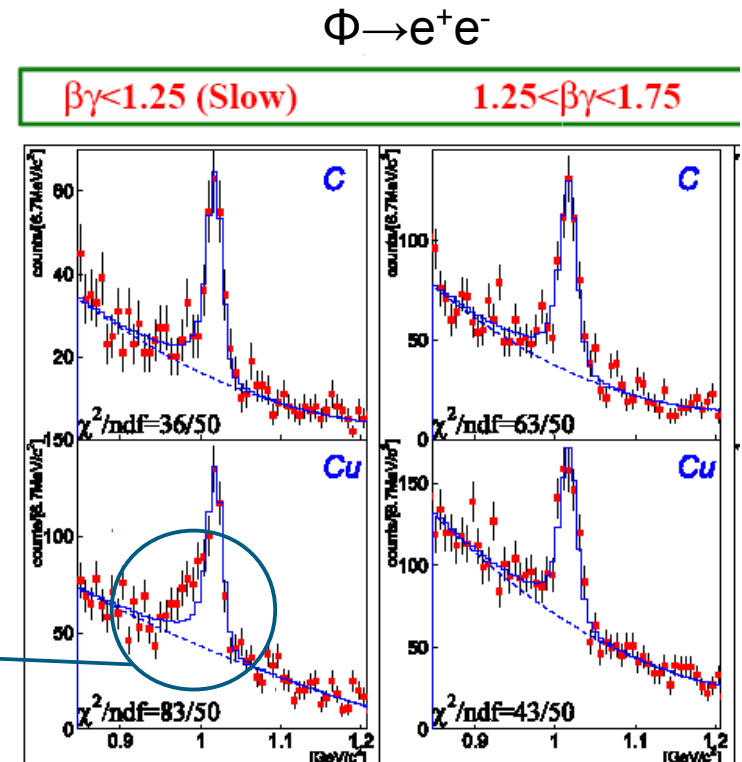
Methods of Φ -width measurement

- 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

$\Gamma^* \approx 15$ MeV, $m^* \approx -3.4\%$)



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

Limited sensitivity to in-medium signal

$$\underbrace{\frac{d\sigma_{V \rightarrow X_1 X_2}}{d\mu} \sim A(\mu)}_{\text{experimental observed mass distribution = convolution of spectral function with the branching ratio into channel being studied}} \underbrace{\frac{\Gamma_{V \rightarrow X_1 X_2}}{\Gamma_{tot}} = \frac{\mu \Gamma_{tot}}{(\mu^2 - m_V^2)^2 + \mu^2 \Gamma_{tot}^2} \frac{\Gamma_{V \rightarrow X_1 X_2}}{\Gamma_{tot}}}_{\text{After integration over all nucleons and parameterizing strength function with Breit Wigner}}$$

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 ($\Gamma_{med} \gg \Gamma_{vac}$)
- ii. reduced yield spreads out in mass, difficult to distinguish from background
- iii. decays occur at low densities ($\rho \ll \rho_0$) even for low momentum selection

Methods of Φ -width measurement

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

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

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: $\gamma A \rightarrow \Phi X$, via K^+K^- decay

γ -Energy: 1.5 — 2.4 GeV

Targets: Li, C, Al, Cu

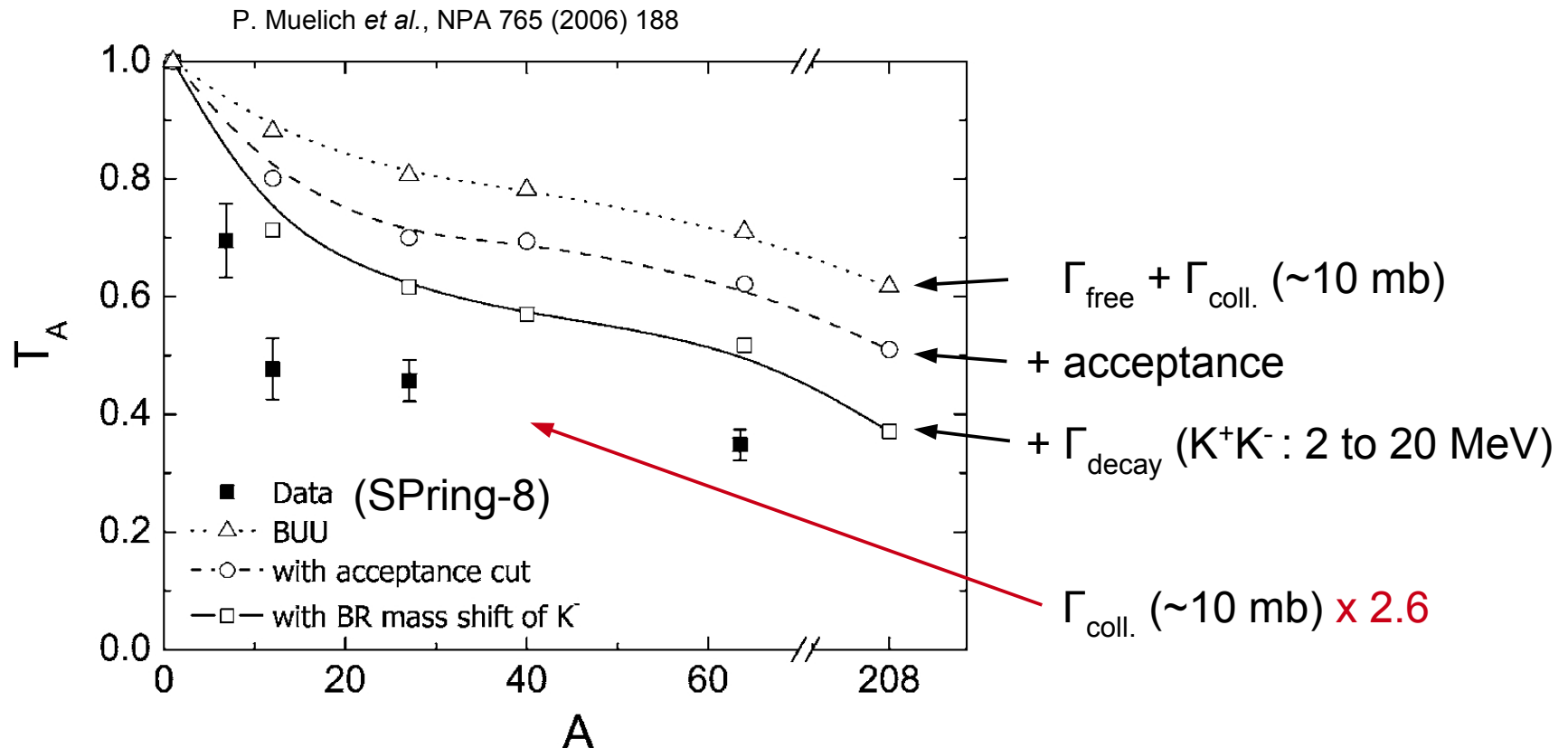
Result: large $\sigma_{\Phi N} = 35^{+17}_{-11}$ mb, using
 Glauber-type multi-scatt. theory
 (free $\sigma_{\Phi N} \approx 8\text{-}10$ mb)

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

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



Giessen-BUU calculations (SPring-8 data)



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

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

COSY experiment at ANKE

Reaction: $pA \rightarrow \Phi X$, via K^+K^- decay

p-Energy: 2.83 GeV ($\varepsilon_{\text{free NN}} \approx 76\text{MeV}$)

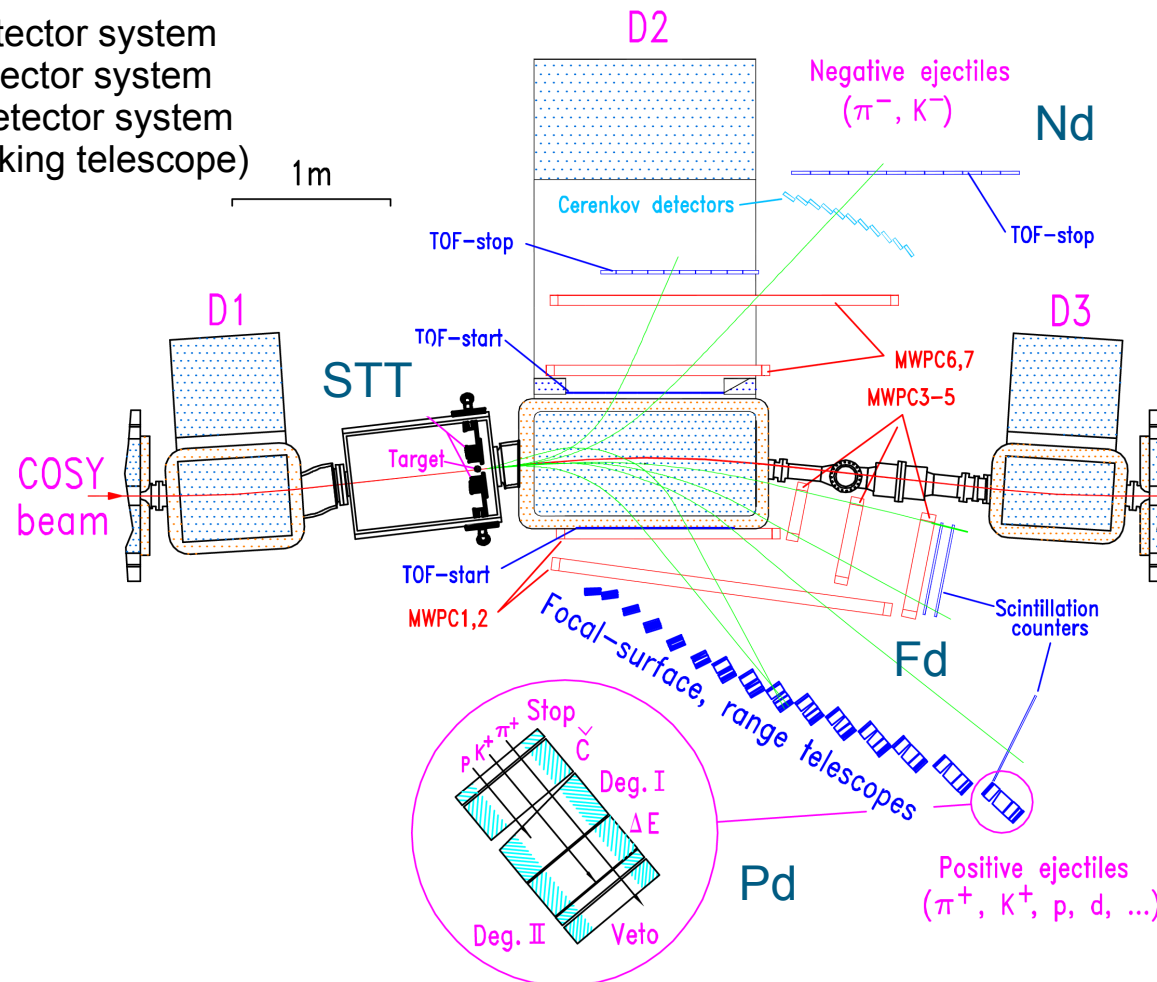
Targets: C, Cu, Ag, Au

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

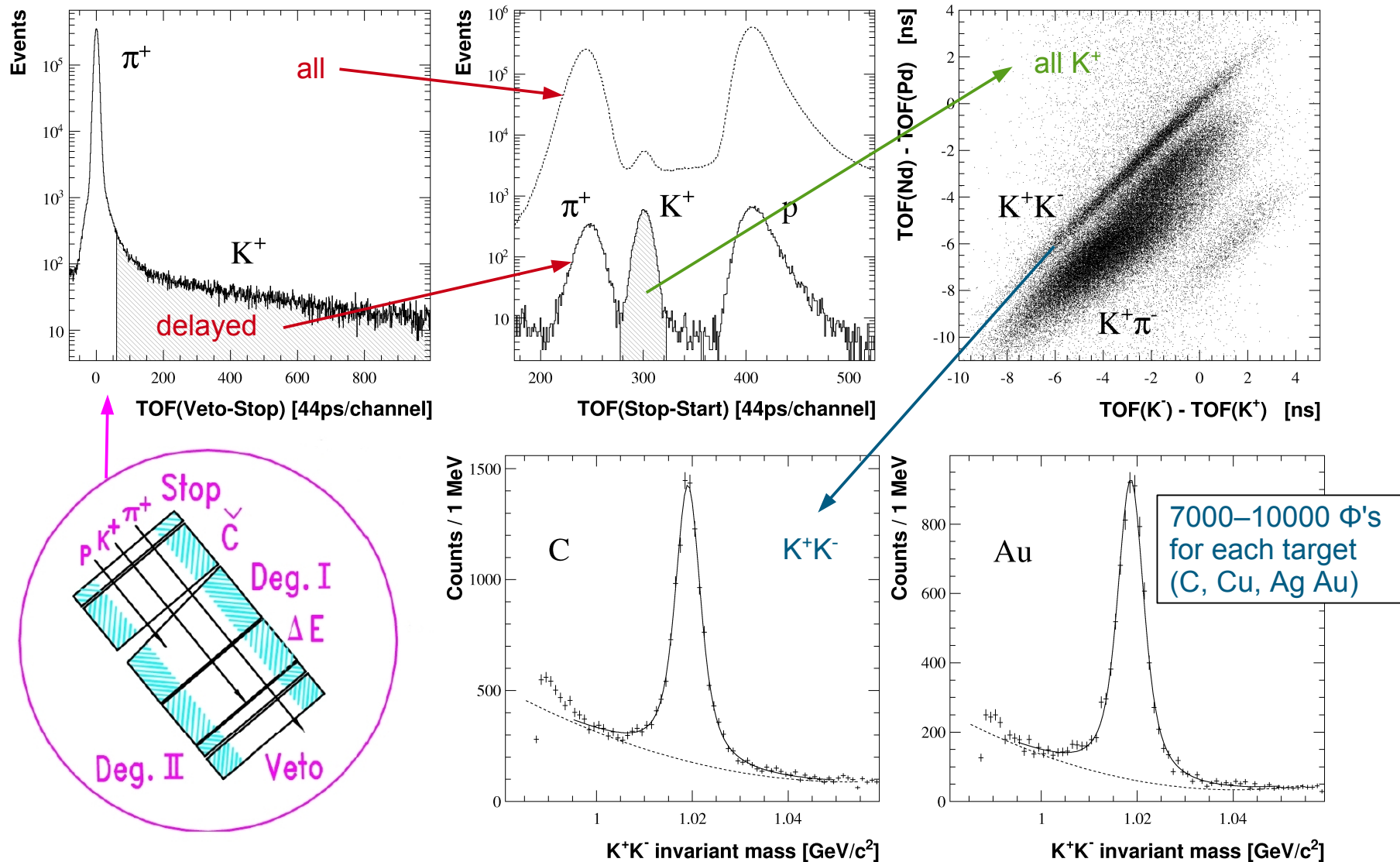


ANKE – forward angle magnetic spectrometer at internal target position of COSY

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



Φ / K^+K^- selection



Normalization of Φ production cross section

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

$$R = \frac{T_A}{T_C} = \frac{12}{A} \frac{\sigma_{\Phi}^A}{\sigma_{\Phi}^C}, \quad T_A = \frac{\sigma_{\Phi}^A}{A \sigma_{\Phi}^N} \quad \text{nuclear transparency ratio}$$

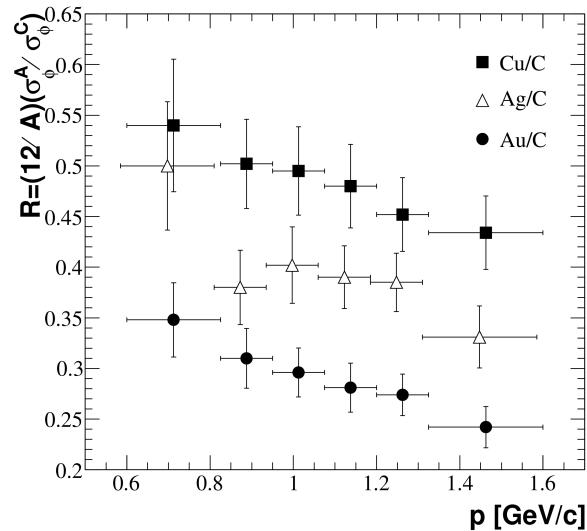
To normalize the Φ production cross section we use the known pion data

$$\frac{\sigma_{\Phi}^A}{\sigma_{\Phi}^C} = \frac{N_{\Phi}^A}{N_{\Phi}^C} \frac{N_{\pi}^C}{N_{\pi}^A} \frac{\sigma_{\pi}^A}{\sigma_{\pi}^C}, \quad \frac{\sigma_{\pi}^A}{\sigma_{\pi}^C} = \left(\frac{A}{12} \right)^{\alpha_{\pi}} \quad \begin{array}{l} \pi^+: p = 0.5 \text{ GeV}/c, \Theta \sim 0^\circ \\ \alpha_{\pi} = 0.38 \pm 0.02 \text{ (@ } 2.83 \text{ GeV)} \end{array}$$

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)

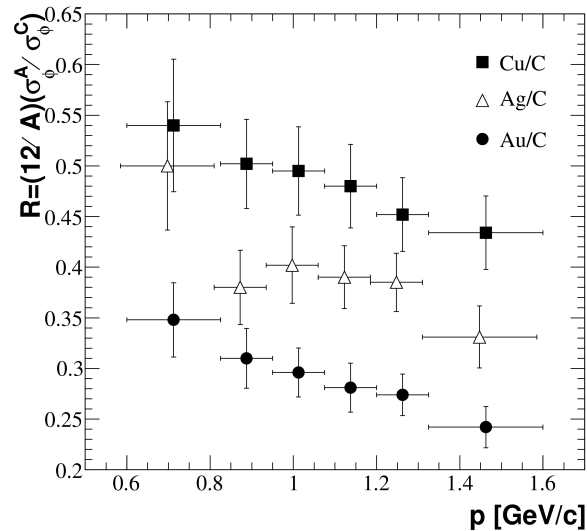


Any interpretation of the transparency ratio has to rely on a detailed theoretical treatment

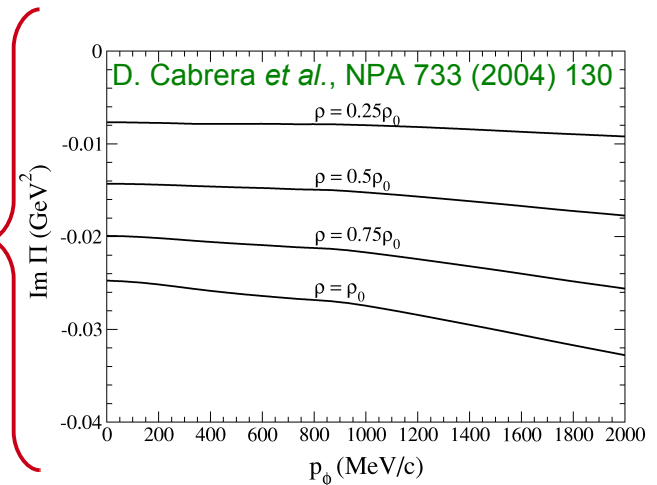
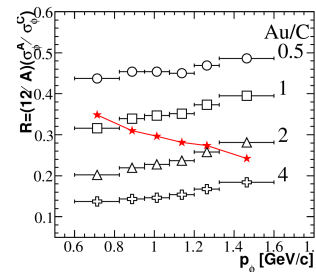
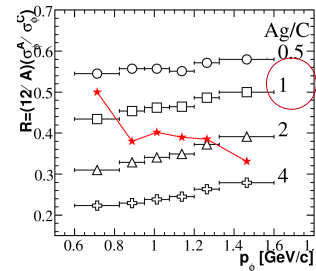
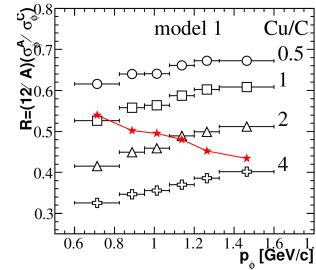


Transparency ratios: **experiment**

ANKE(preliminary)



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

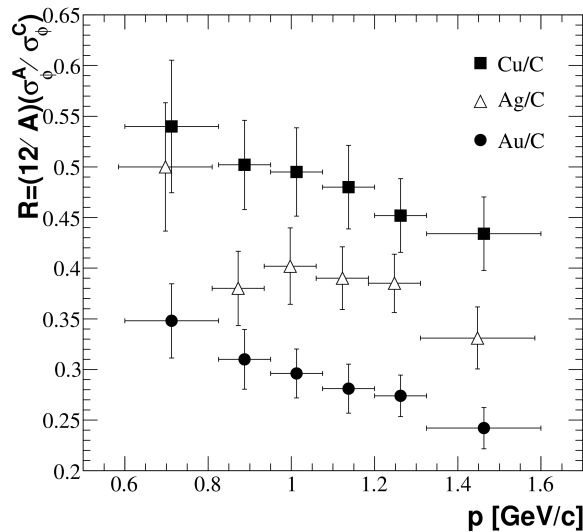


Prediction: 28 MeV for Φ at rest for $\rho = \rho_0$

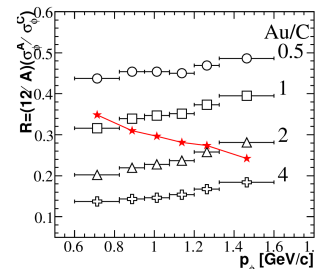
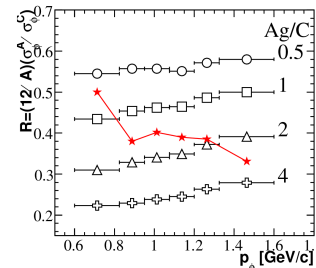
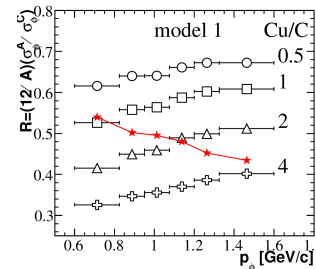
V.Magas et al., PRC
 71 (2005) 065202;
 L.Roca (private
 communication)

Transparency ratios: **experiment** and models

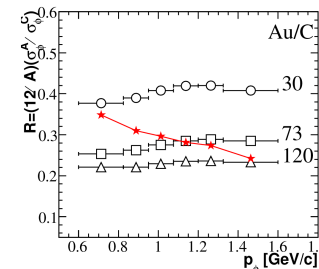
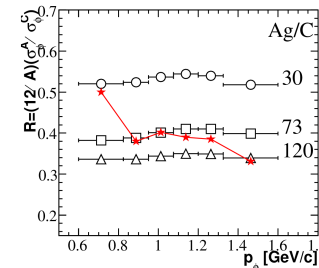
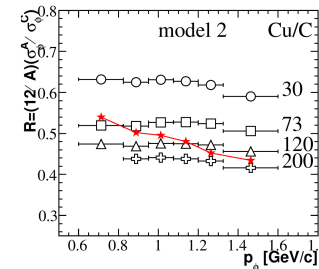
ANKE (preliminary)



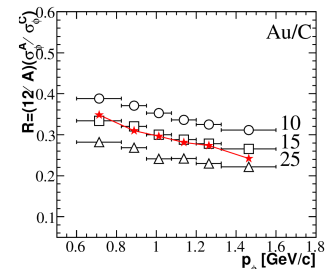
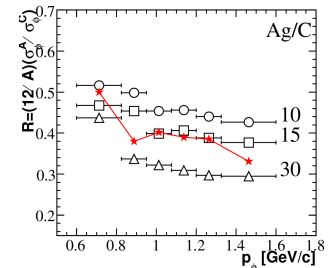
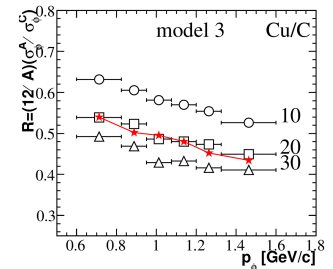
Valencia/E.Oset *et al.*
MC & Chiral Unitary
Approach



Moscow/E.Paryev
Nuclear Spectral Function
Approach



Rosendorf/
B.Kämpfer *et al.*
BUU



Relevant features for models:

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

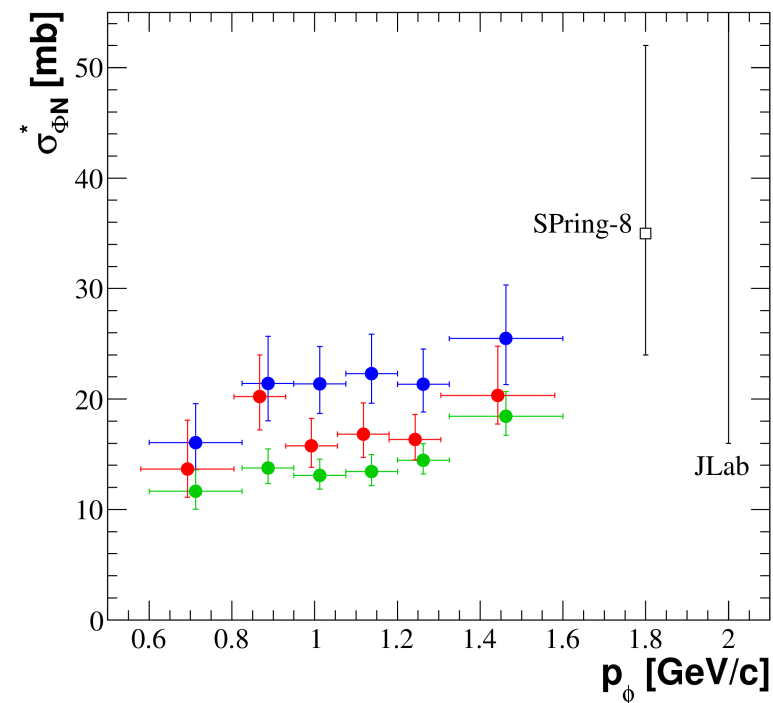
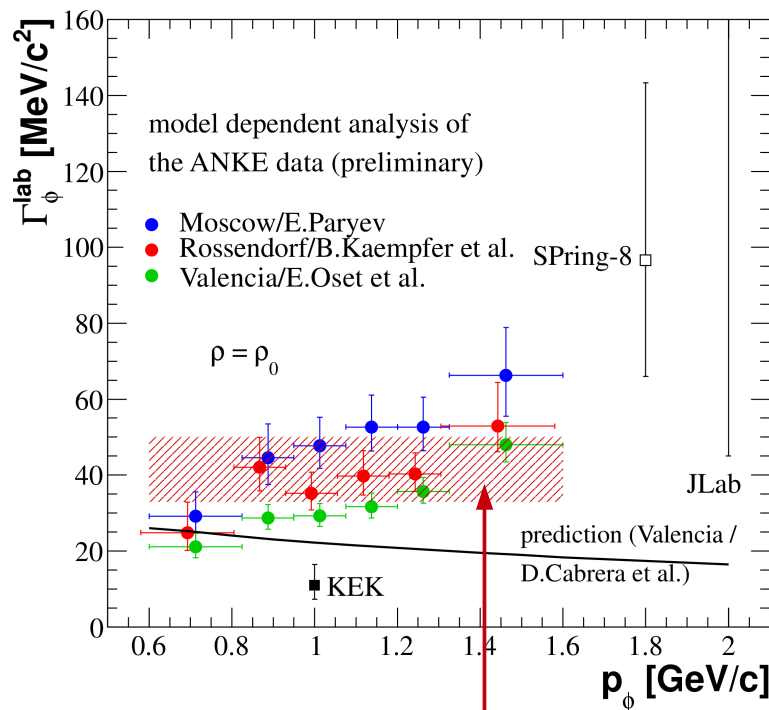
V.Magas *et al.*, PRC
71 (2005) 065202;
L.Roca (private
communication)

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

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

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

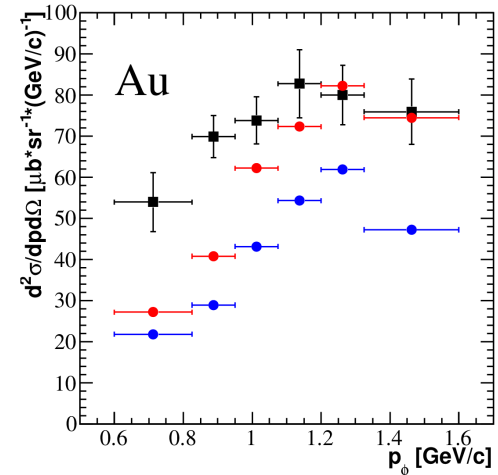
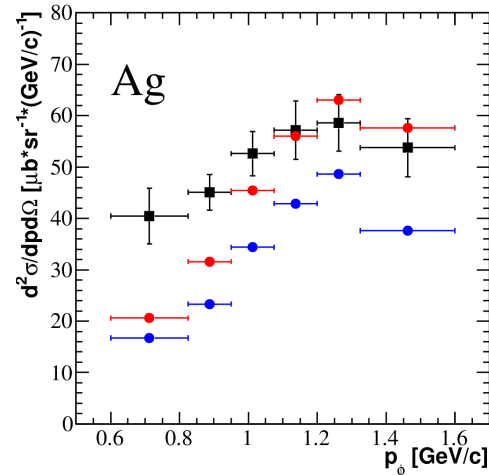
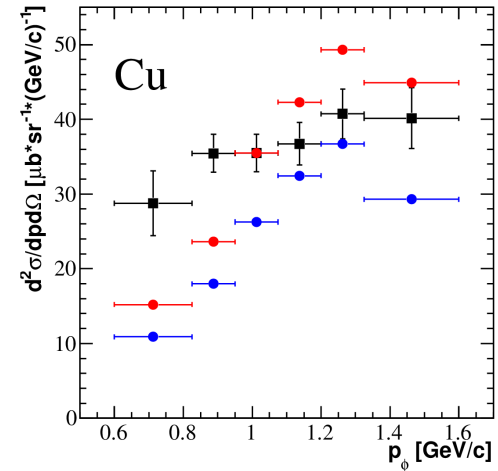
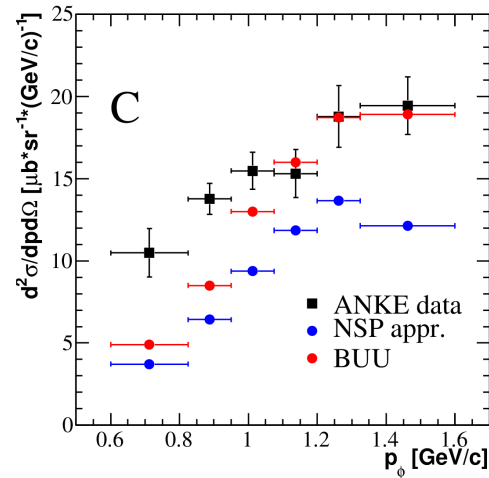
$$\text{LDA: } \Gamma_\Phi^{\text{lab}}(\rho_0) = \frac{p_\Phi}{E} \sigma_{\Phi N}^* \rho_0$$



$\Gamma_\Phi^{\text{lab}} \approx 33\text{-}50 \text{ MeV} \text{ (} \langle p_\Phi \rangle = 1.1 \text{ GeV/c, } \rho_0 = 0.16 \text{ fm}^{-3} \text{)}$
A.Polyanskiy *et al.*, **PLB 695 (2011) 74**

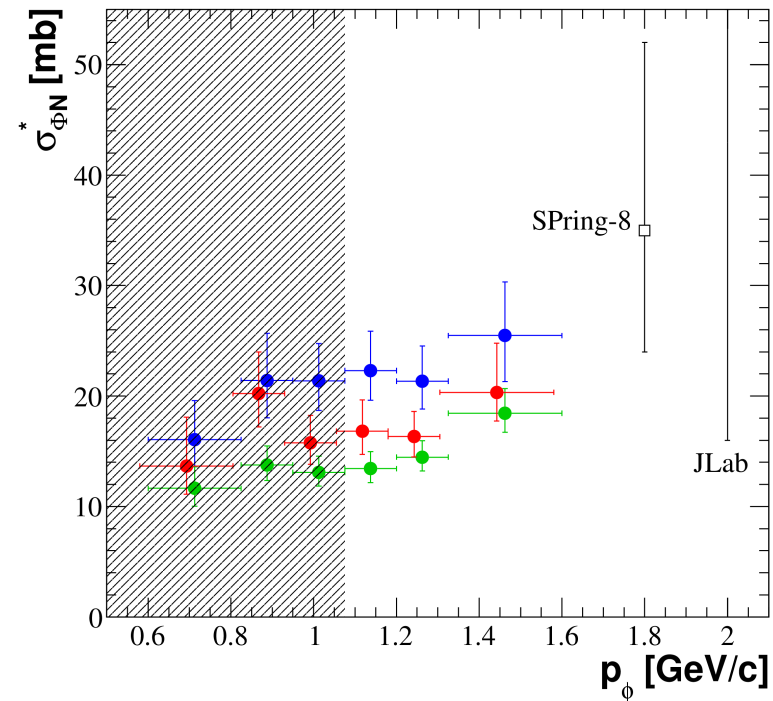
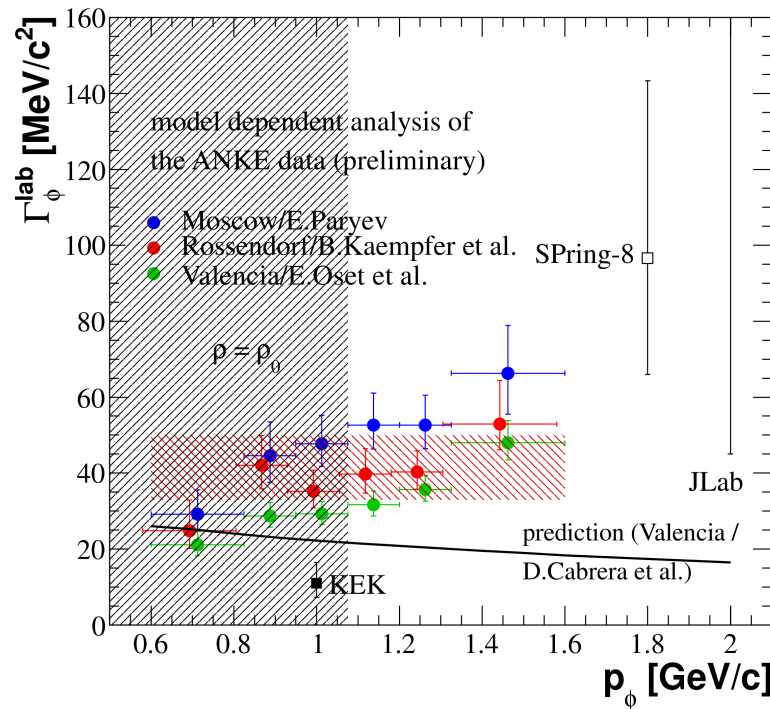
Double differential cross section of Φ production (preliminary)

Excess in low
momentum part



+ common systematics ~ 20 %

In-medium width Γ_ϕ and $\sigma_{\phi N}^*$ cross section (preliminary)

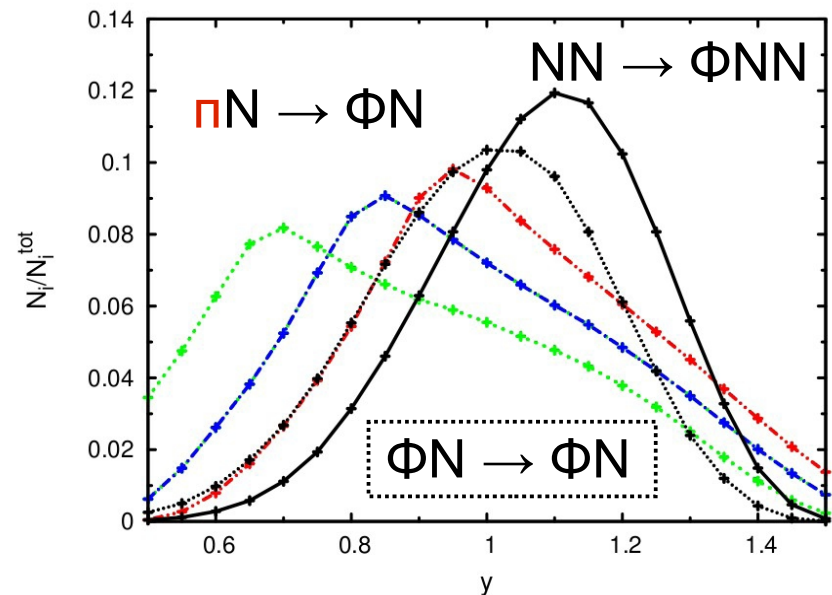
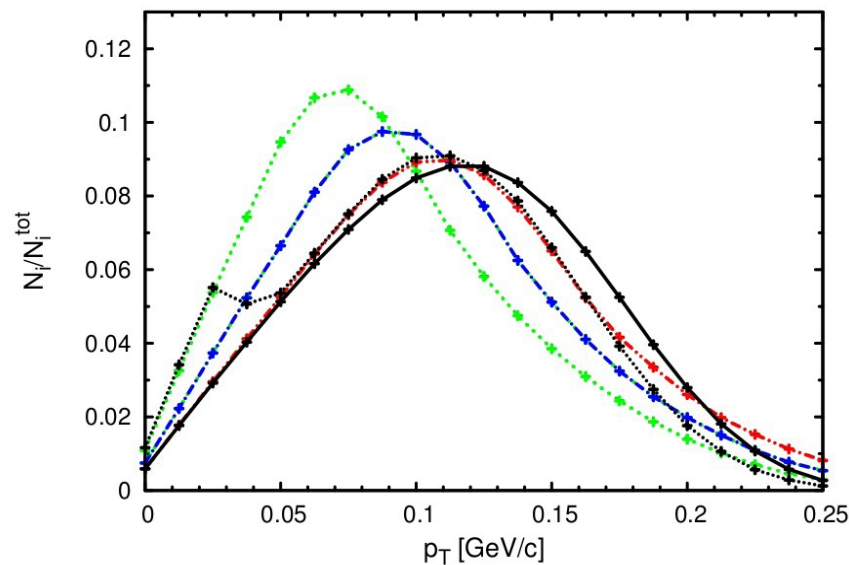


for $p_\phi > 1.1 \text{ GeV}/c$ $\Gamma_\phi^{\text{lab}} \approx 45 \text{ MeV}$ and/or $\sigma_{\phi N}^* \approx 17 \text{ mb}$

Low momentum – missing Φ multiplicity?

Kinematic phase space test with

“new” (2-step) channels: $\eta B \rightarrow \Phi X$ and $\omega B \rightarrow \Phi X$, with $B = N, \Delta$



H.Schade & B.Kämpfer (private communication)

Rossendorf BUU: η and ω channels

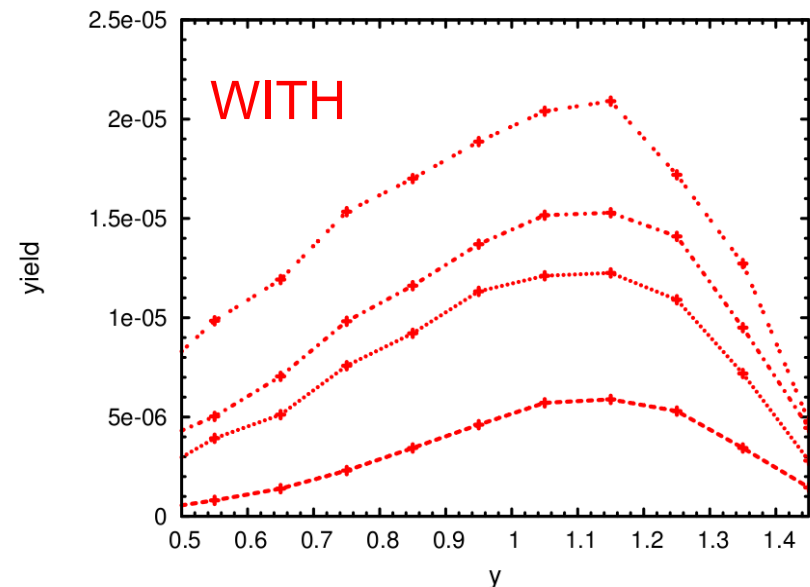
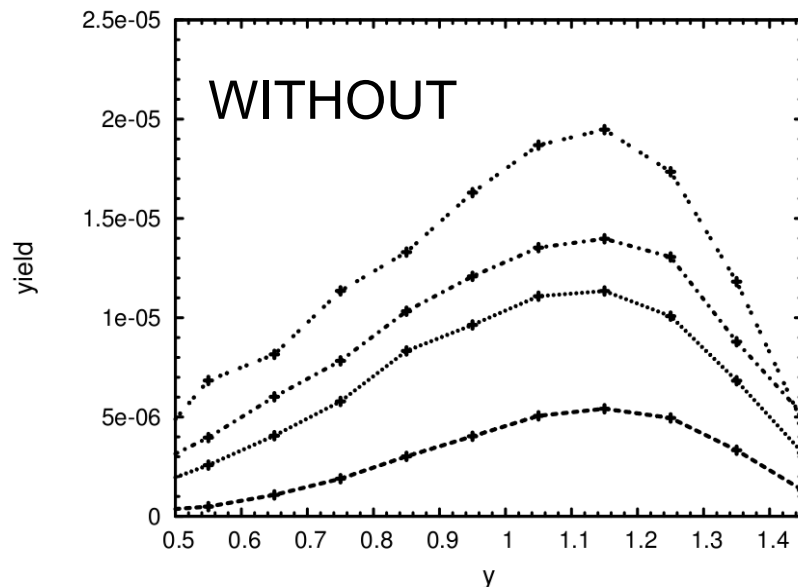
elastic collisions: $\sigma_{\Phi N \rightarrow \Phi N} = 2 \text{ mb}$

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

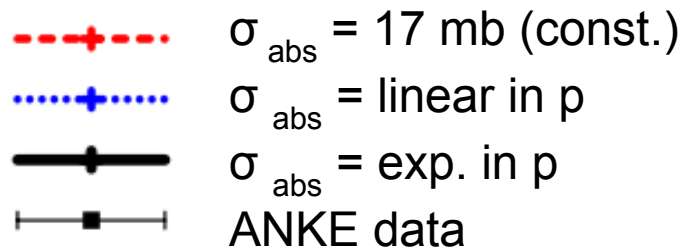
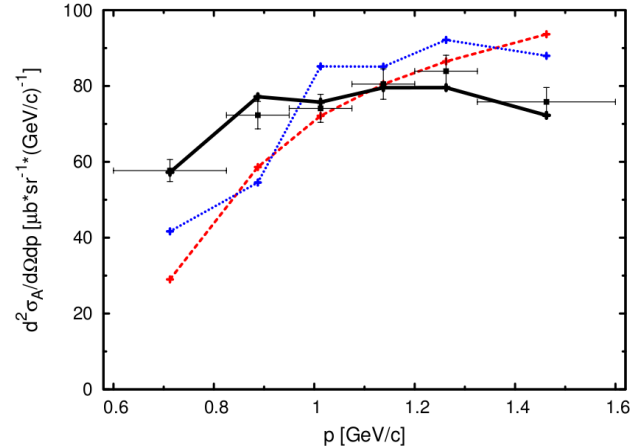
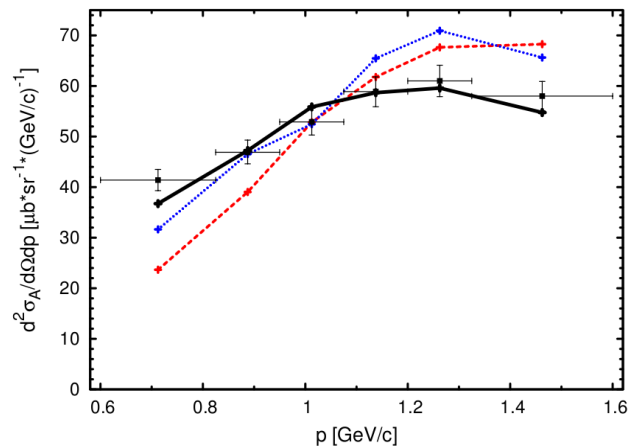
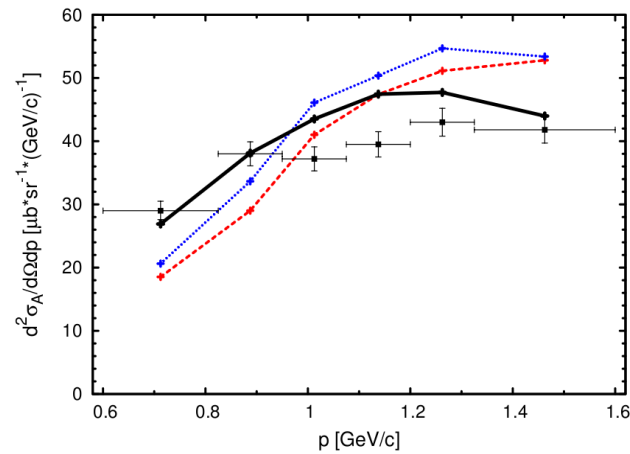
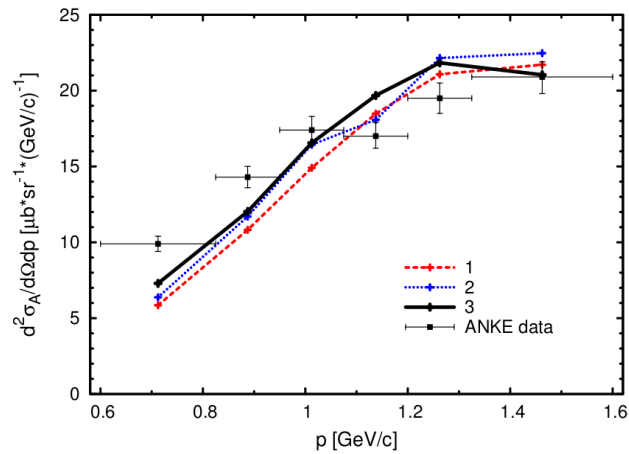
$\sigma_{\eta(\omega) \Delta \rightarrow \Phi N} = 2 \sigma_{\eta(\omega) N \rightarrow \Phi N} = 0.07 \text{ mb}$

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

shift of yields toward target rapidity



H.Schade & B.Kämpfer (private communication)



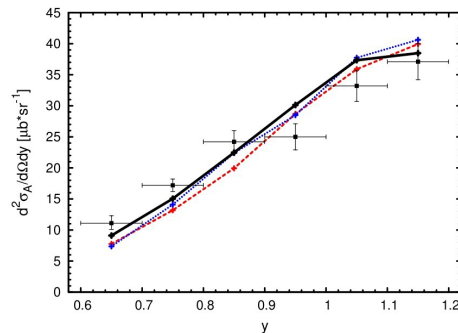
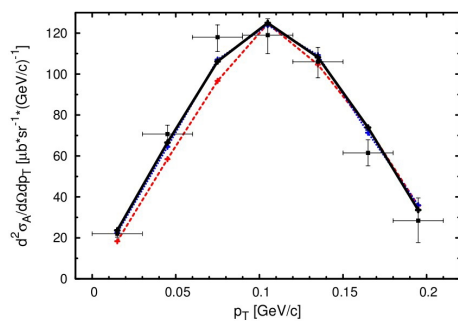
**BUU vs. ANKE
data (prel.)**

H.Schade & B.Kämpfer
(private communication)

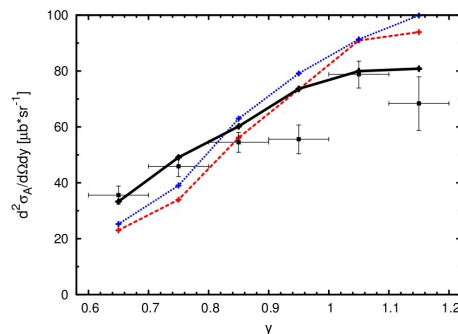
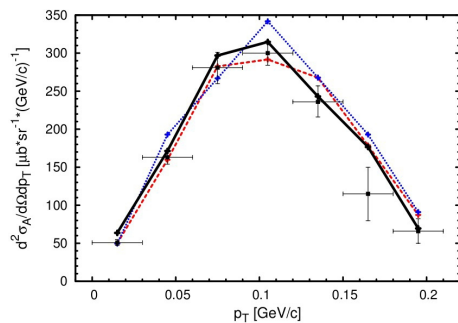
transverse
momentum

&

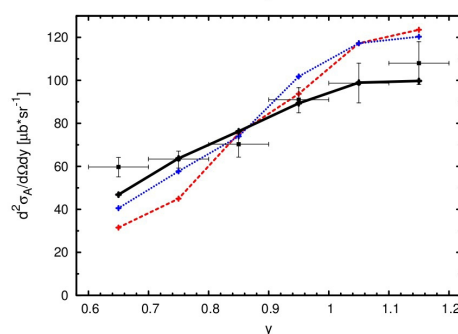
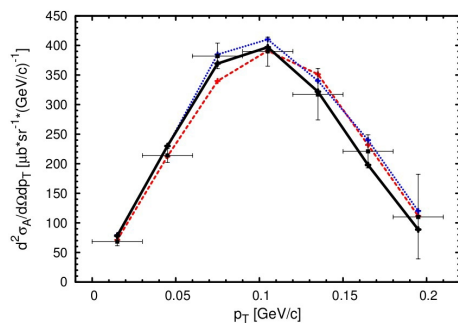
rapidity
distributions



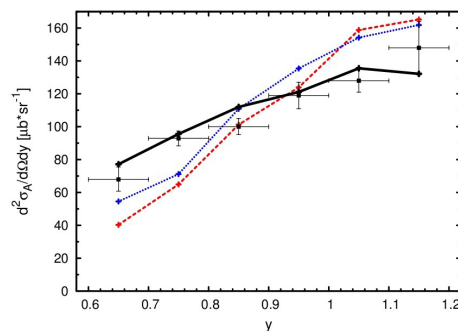
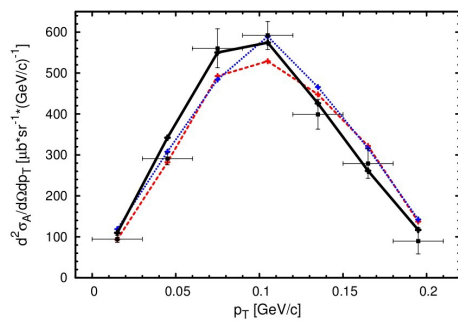
C



Cu



Ag



Au



$\sigma_{\text{abs}} = 17 \text{ mb (const.)}$



$\sigma_{\text{abs}} = \text{linear in } p$



$\sigma_{\text{abs}} = \text{exp. in } p$



ANKE data

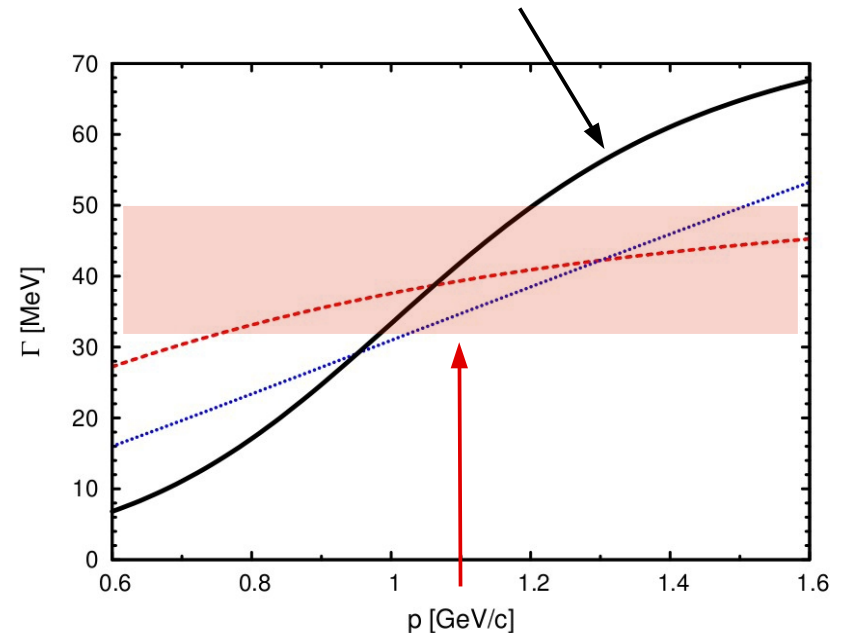
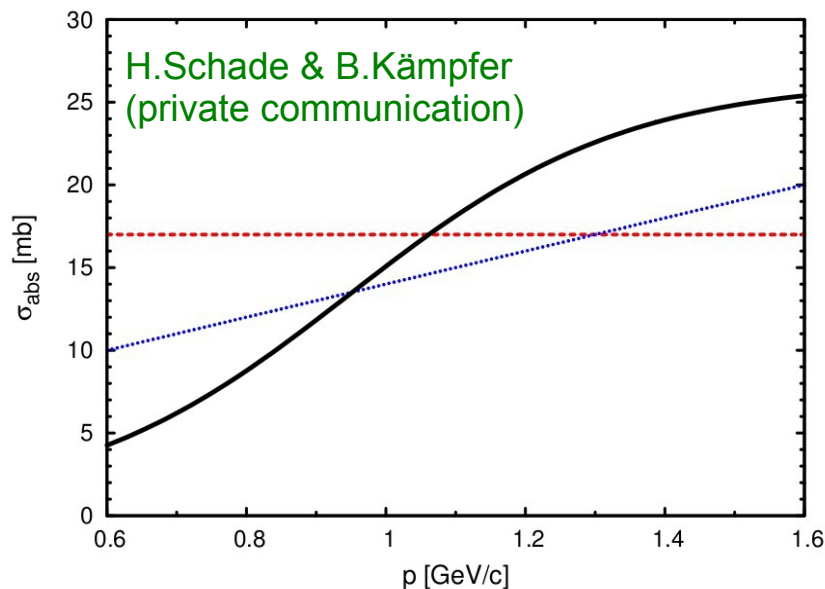
H.Schade & B.Kämpfer
(private communication)

Absorption cross-section versus in-medium width

- - - + - - - $\sigma_{\text{abs}} = 17 \text{ mb (const.)}$
- ... + ... $\sigma_{\text{abs}} = \text{linear in } p$
- + — $\sigma_{\text{abs}} = \text{exp. in } p$

Valencia/Moscow/Rosendorf
 $\Gamma \approx 20 \text{ to } 70 \text{ MeV}$

“new” Rosendorf BUU (preliminary)
 $\Gamma \approx 8 \text{ to } 68 \text{ MeV}$



$$\Gamma_{\Phi}^{\text{lab}} \approx 33\text{-}50 \text{ MeV} \quad (\langle p_{\Phi} \rangle = 1.1 \text{ GeV/c}, \rho_0 = 0.16 \text{ fm}^{-3})$$

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 momentumsupported 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,
 $\eta, \omega N \rightarrow \Phi N$
- results differ from the Valencia predictions (Φ in-medium self-energy)

and outlook

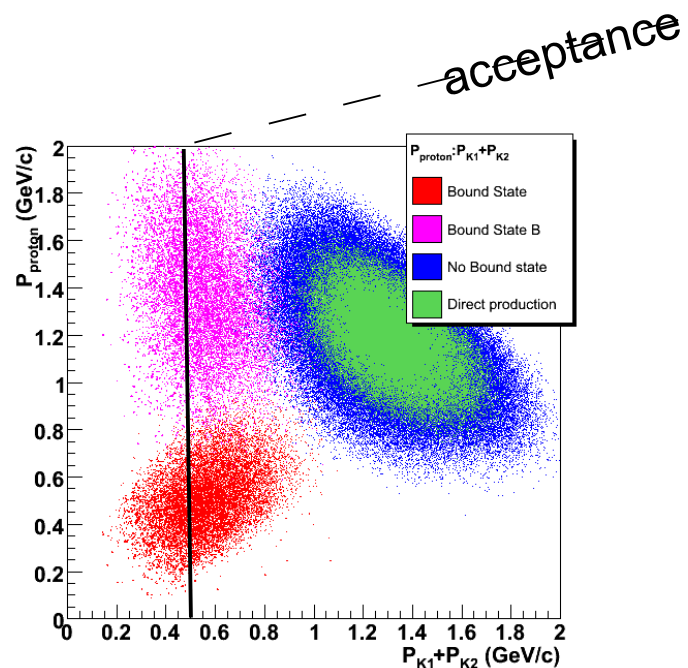
- investigation of Φ –proton correlations (measured in parallel)
- investigation of the non–resonant $(K^+)K^-$ production, A-dependence and/or ratios of the K^- momentum distributions (A/C)

Thank you!

Extra slides:

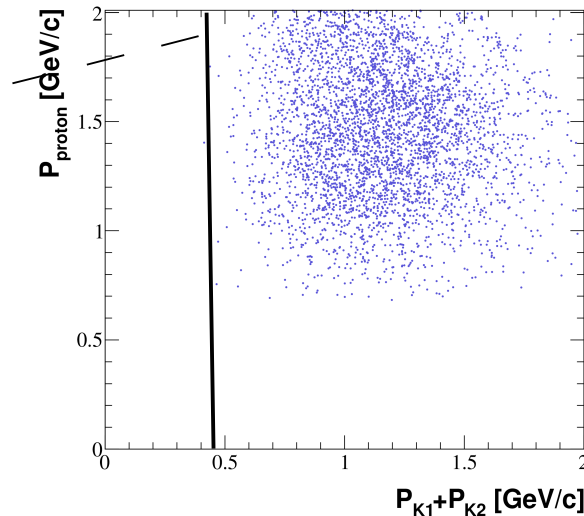
Extra slides

Φ/K^+K^- -proton correlation

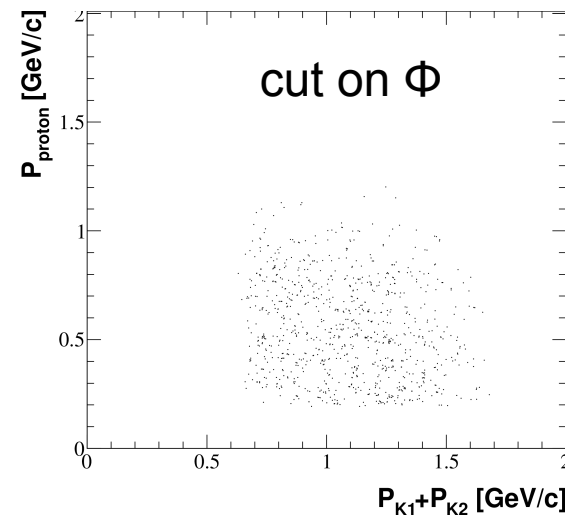


Haiyan Gao (private communication)
 PRC 63 (2001) 022201, PRC 75 (2007) 058201,
 Letter-Of-Intent JLAB (PAC33) "First search for
 Φ -N bound state"

all KK



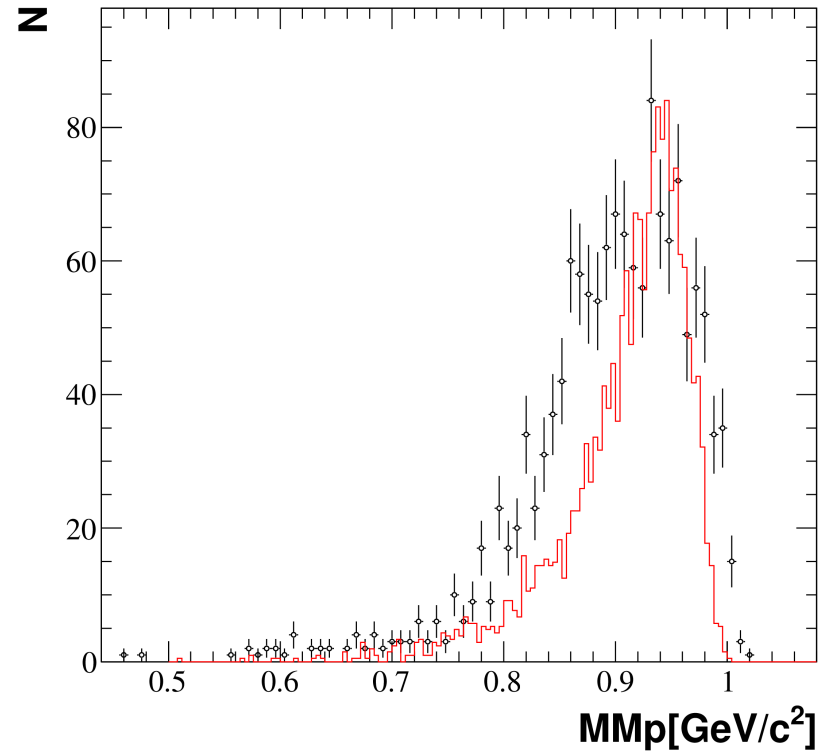
proton in
forward



proton in
side

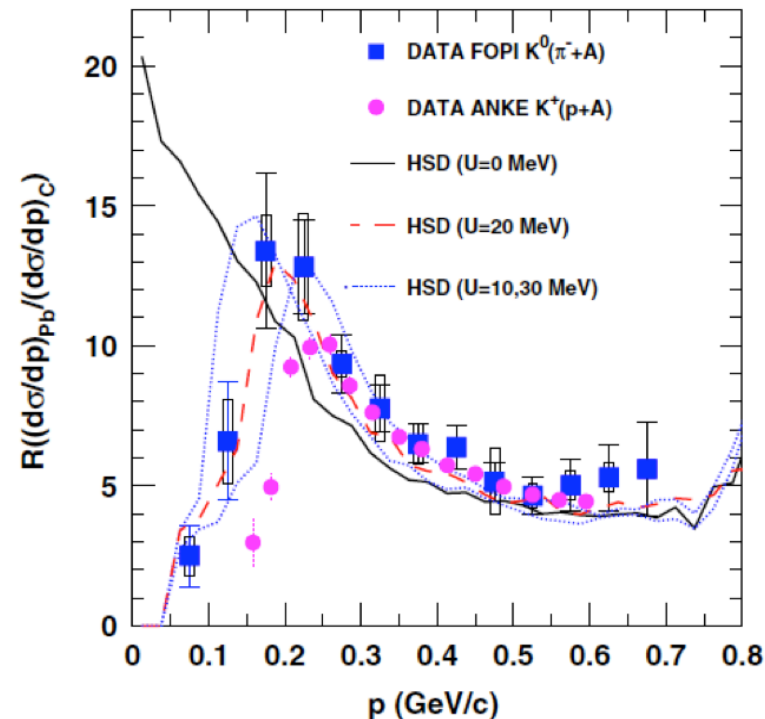
Φ -proton correlation

missing mass: data versus
 simulation (only primary
 production)



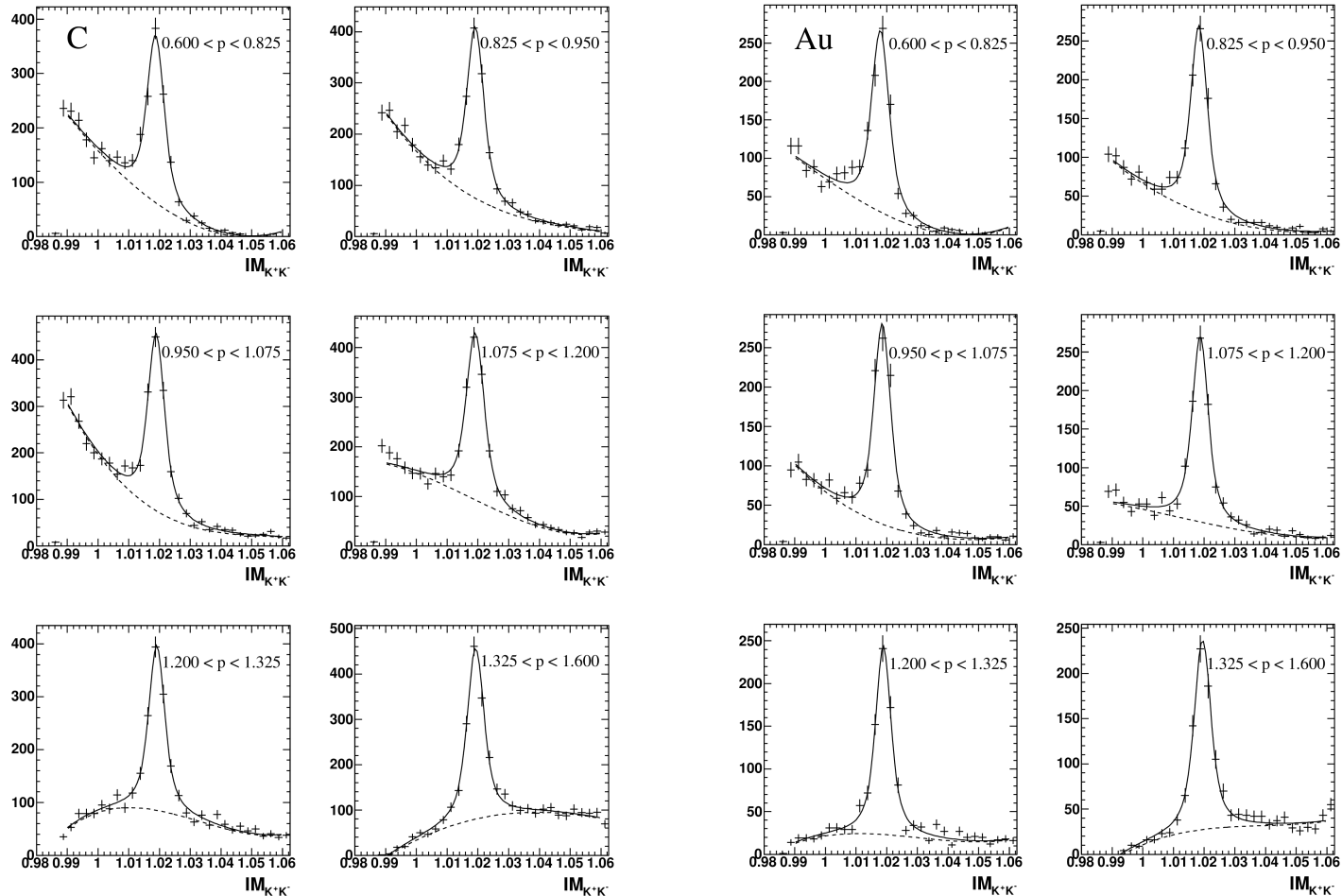
KN potential

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

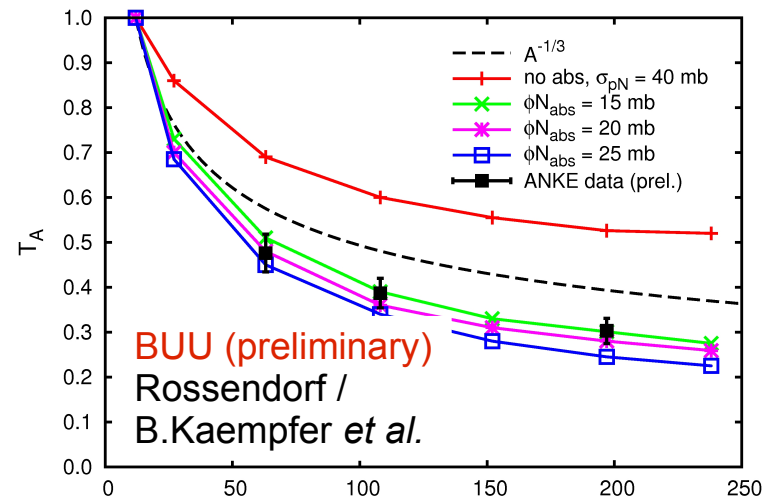
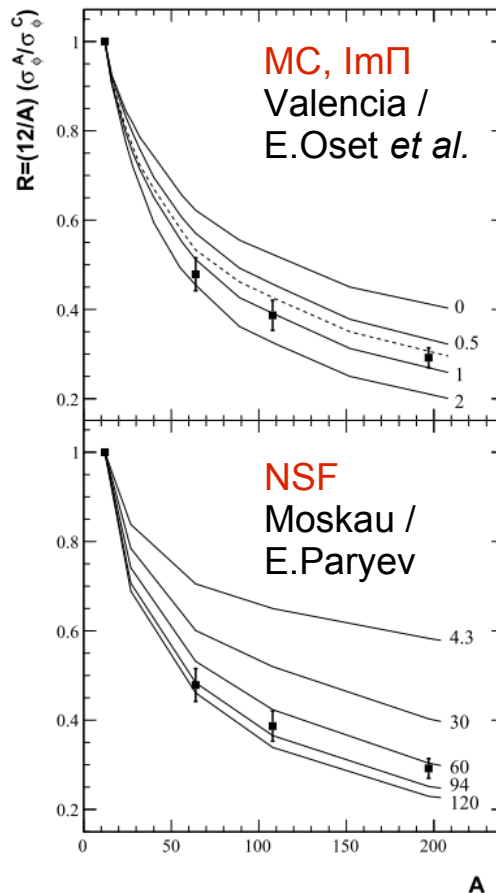


A repulsive KN potential of 20 ± 5 MeV (at normal nuclear density) explain the FOPI and ANKE results.

Invariant mass spectra for 6 momentum bins



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



mass dependence: $\sim A^{(0.56 \pm 0.03)}$

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

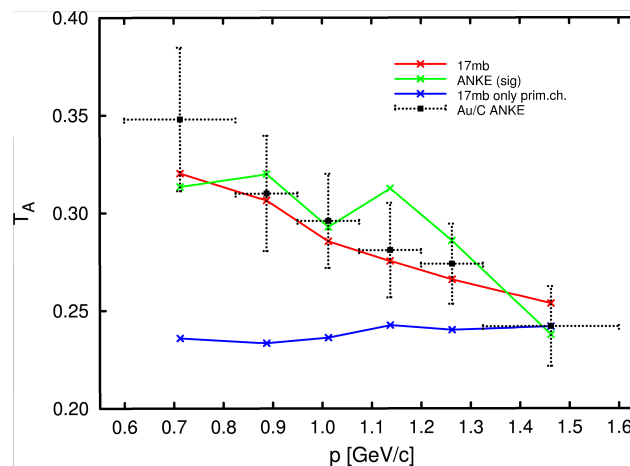
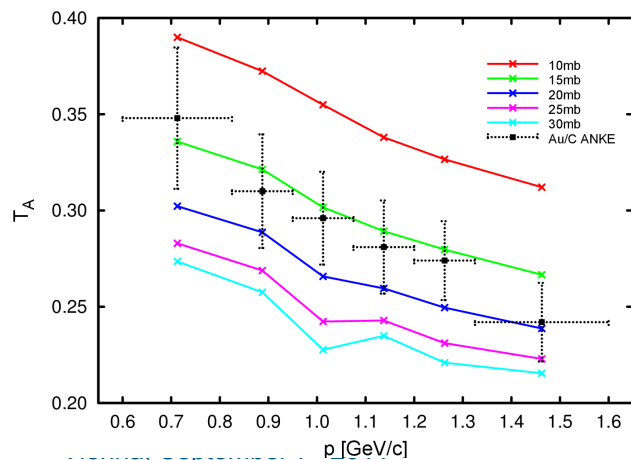
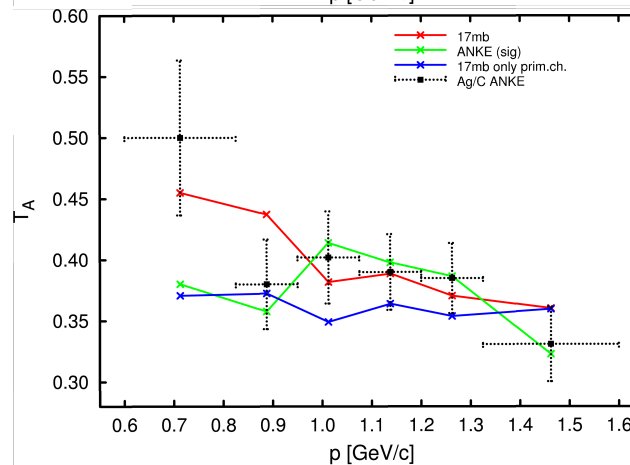
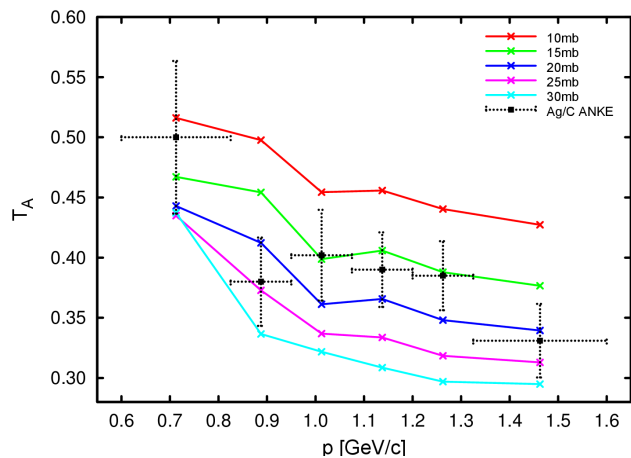
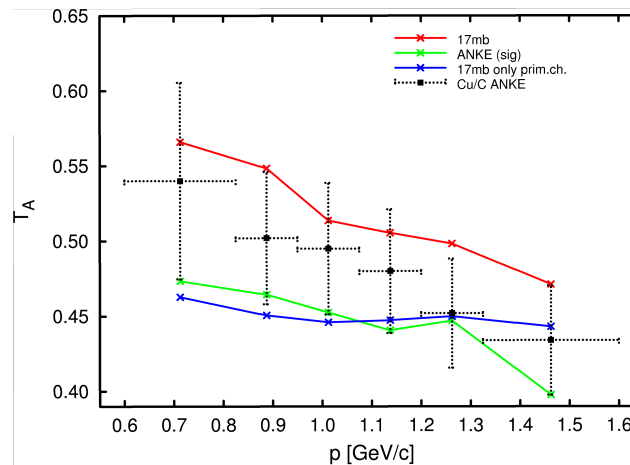
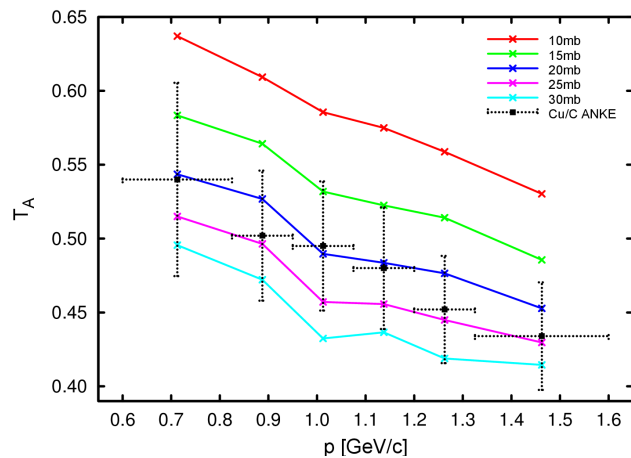
combining the three approaches:

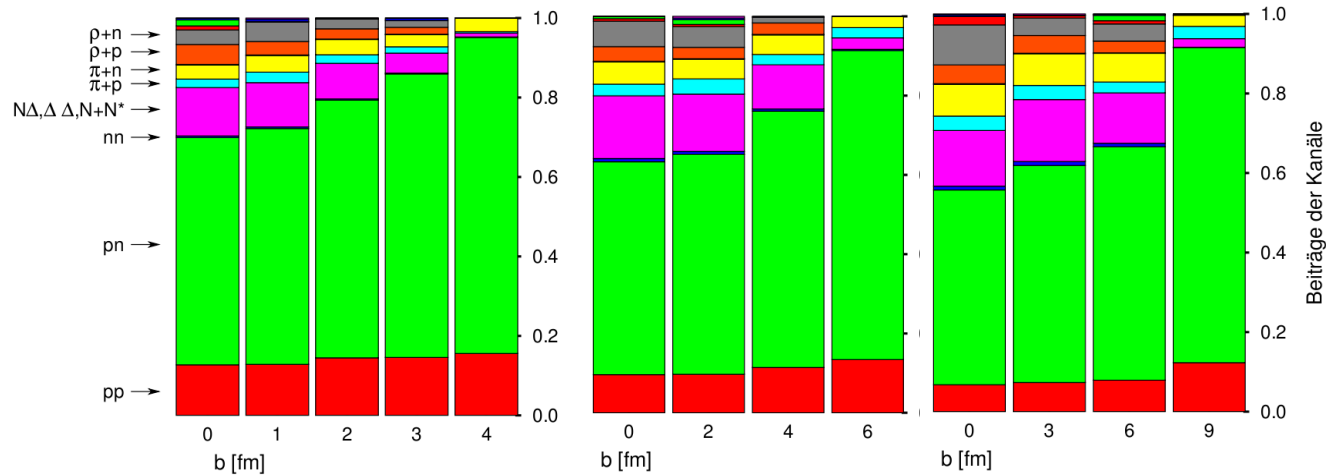
$$\Gamma_{\phi}^{\text{Lab}} = (33-50) \text{ MeV}/c^2 \quad (\langle p_{\phi} \rangle = 1.1 \text{ GeV}/c, \rho_0 = 0.16 \text{ fm}^{-3})$$

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

BUU-Rossendorf (preliminary)

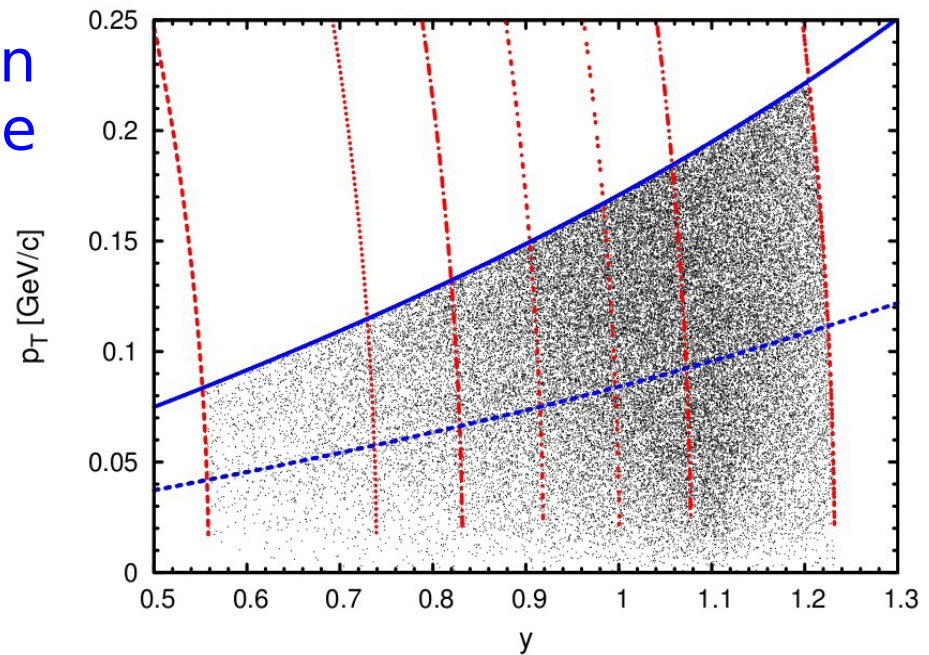
B. Kaempfer &
H. Schade (private
communication)





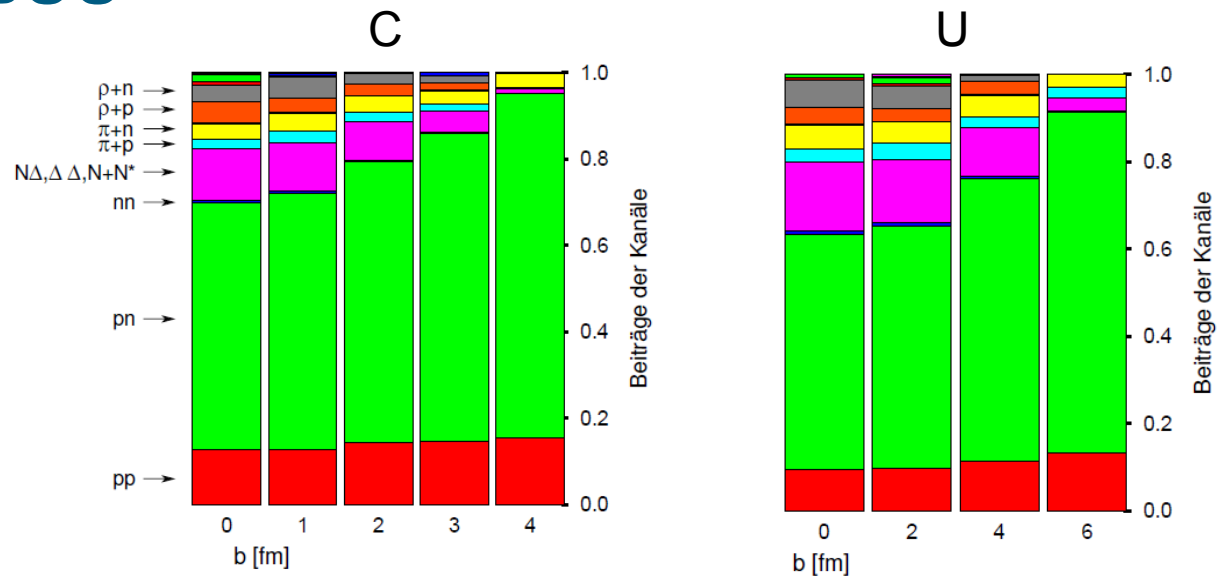
pA: p+C,Cu,Au
@ 2.83 GeV(ANKE)

phase space distribution
of ϕ in ANKE acceptance

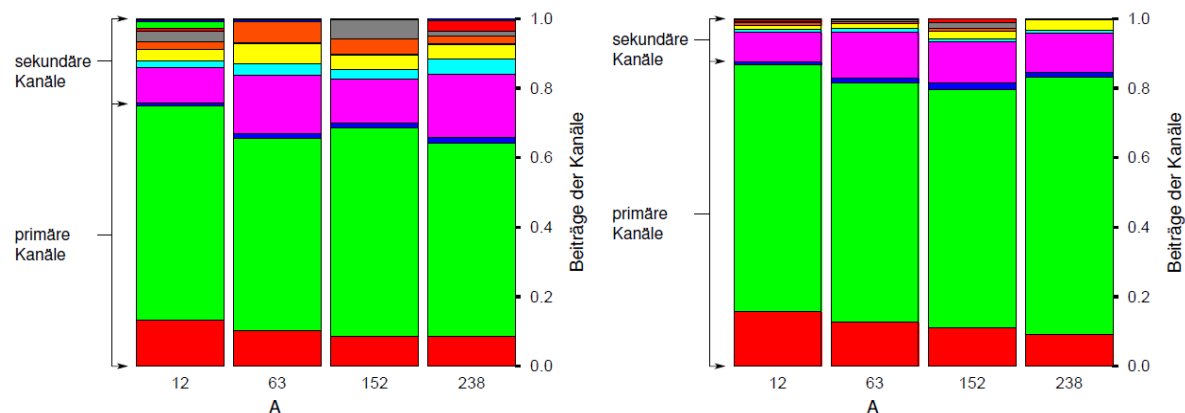


Rossendorf-BUU

impact parameter



$\langle b \rangle = C, Cu, Sm, U$



(0.6 — 1.1) GeV/c

and

(1.1 — 1.6) GeV/c

$pp \rightarrow pp\Phi$ (energy dependence)

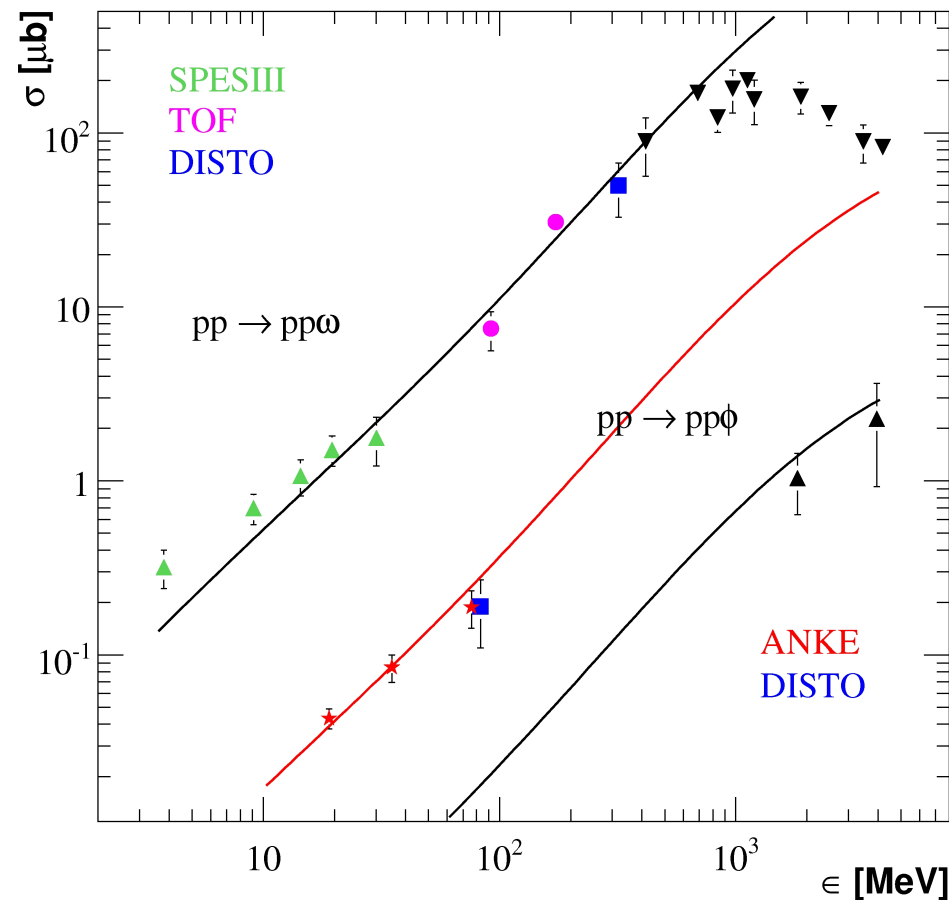
OZI rule: $4.2 \times 10^{-3} \equiv R_{\text{OZI}}$

$R_{\phi/\omega}(\text{high energy}) \approx (1 - 2.4) \times R_{\text{OZI}}$

(in agreement with πN data and the $\phi\rho\pi$ and $\omega\rho\pi$ coupling)

$R_{\phi/\omega}(18.5\text{-}79.5 \text{ MeV, ANKE}) \approx 7 \times R_{\text{OZI}}$

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KEK-PS-E325 experiment

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

$\Phi \rightarrow e^+e^-$

$\beta\gamma < 1.25$ (Slow)

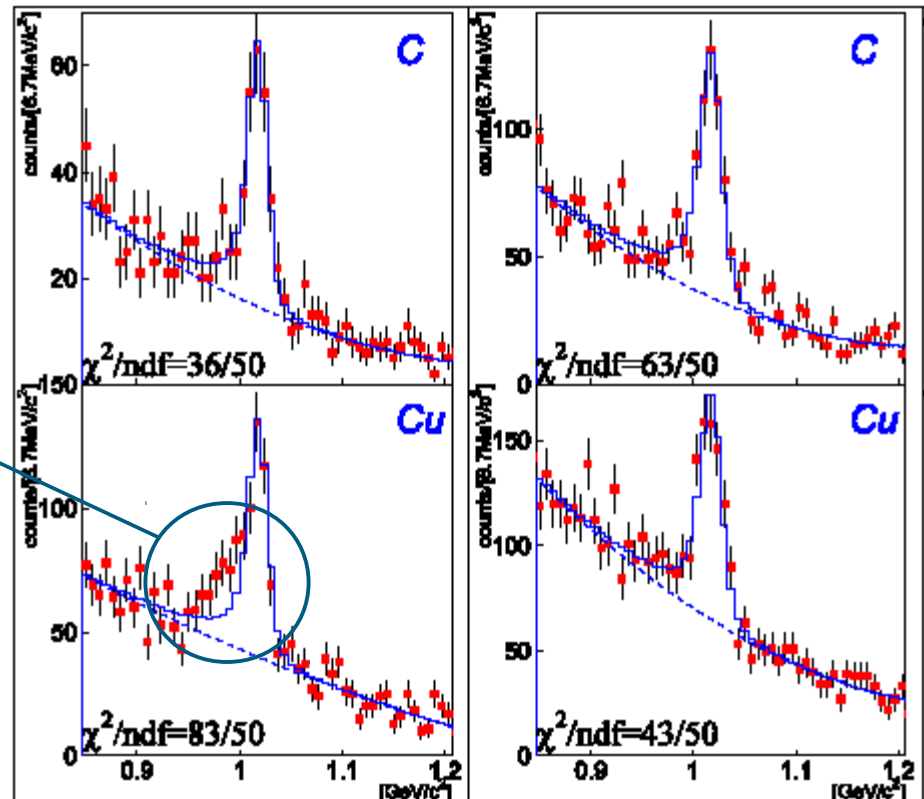
$1.25 < \beta\gamma < 1.75$

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

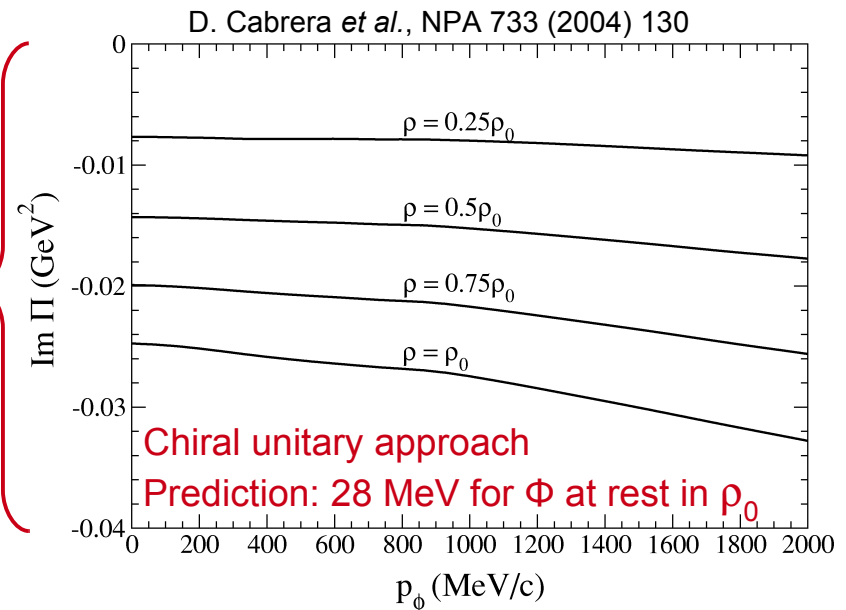
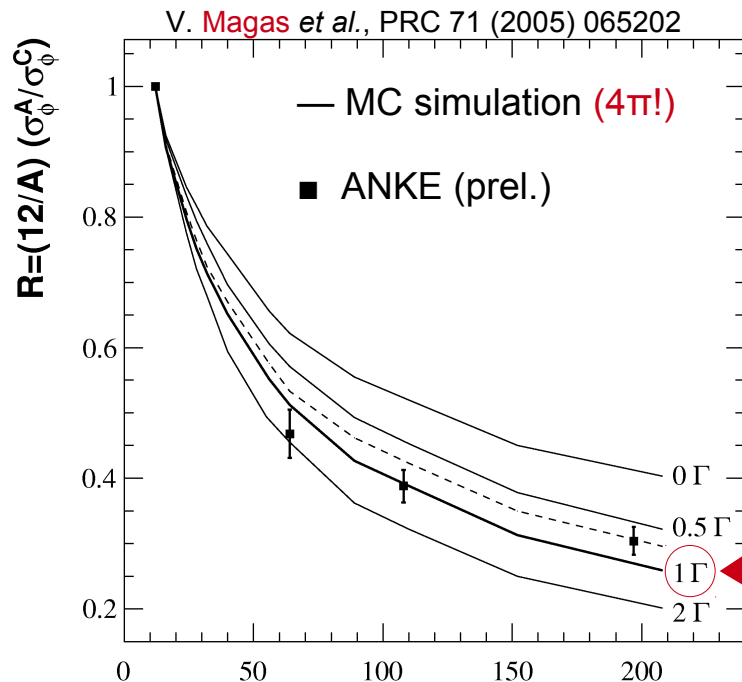
$$\Gamma^*/\Gamma = 1 + k_2 \rho/\rho_0$$

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

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



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



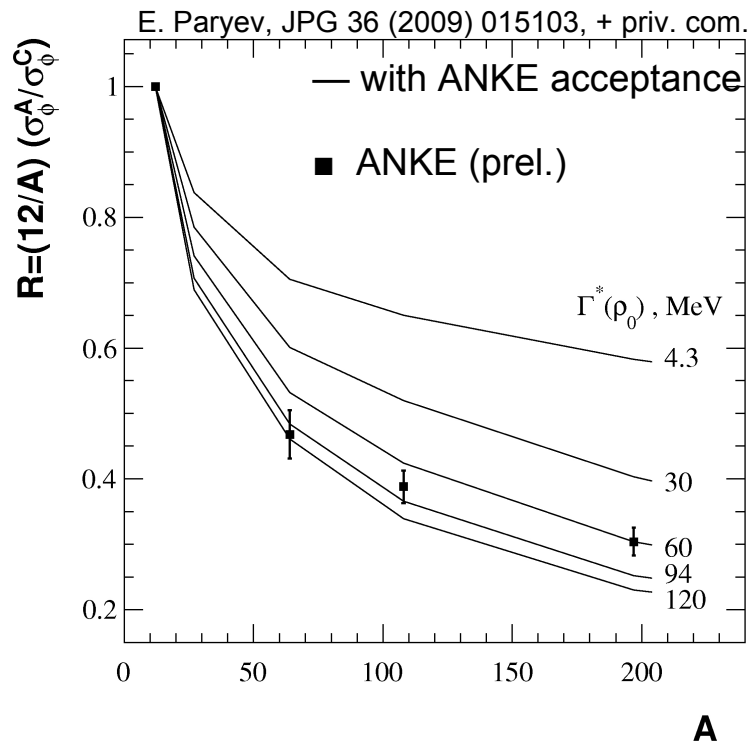
$$\Gamma = 26_{-3}^{+4} \text{ MeV}$$

BUT!
 2step (πN , $p N$)
 Δ intermediate states
 $p n \Phi \approx 4 \text{ } p p \Phi$

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

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

Comparison with model calculations (Paryev)



In framework of a **nuclear spectral function** model:

$pp \rightarrow pp\Phi, pn \rightarrow pn\Phi (\approx 4 \cdot pp),$
 $pn \rightarrow d\Phi$

K&K, EPJ A 23 (2005) 291

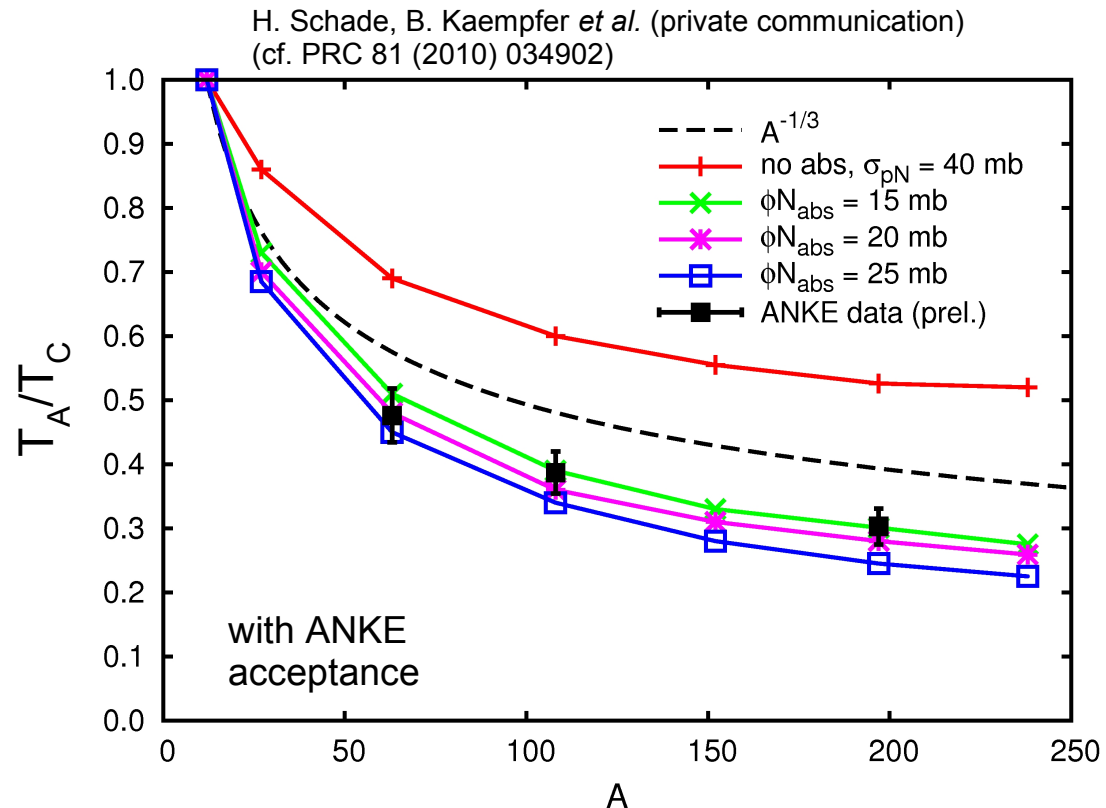
2step: $\pi N \rightarrow \Phi N$

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

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

$$\underline{\Gamma \approx 71 \text{ MeV}}$$

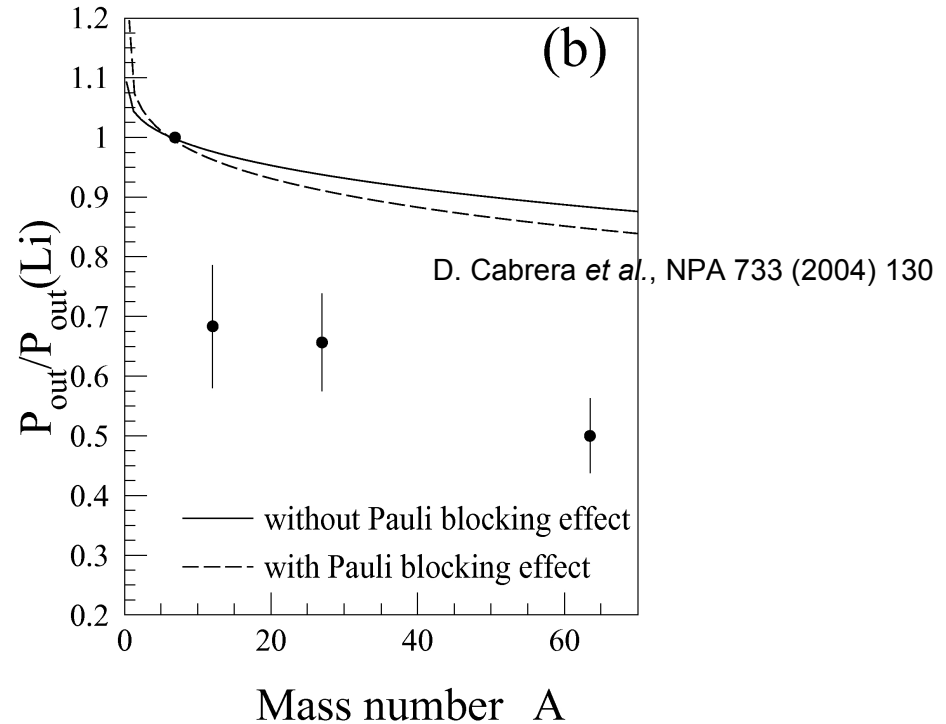
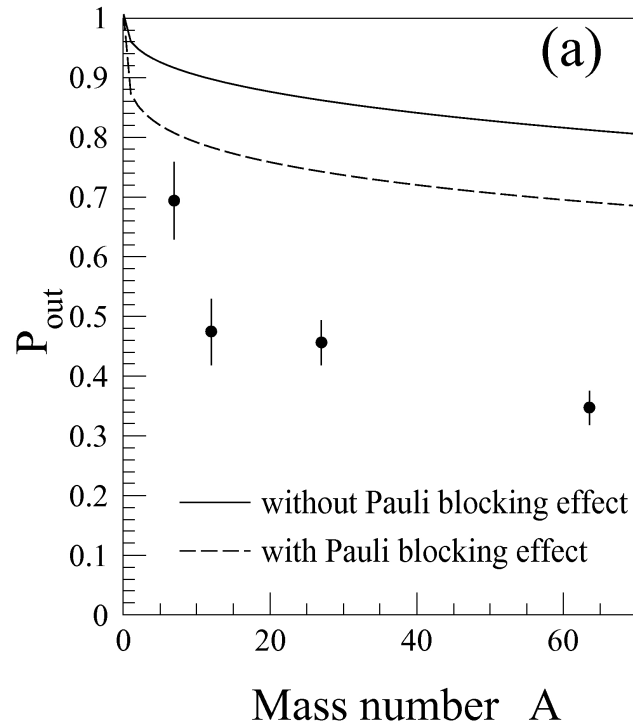
Comparison with Rossendorf-BUU calculations (very preliminary)



first Rossendorf-BUU result – “in between”

Valencia calculations (SPring-8-data)

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



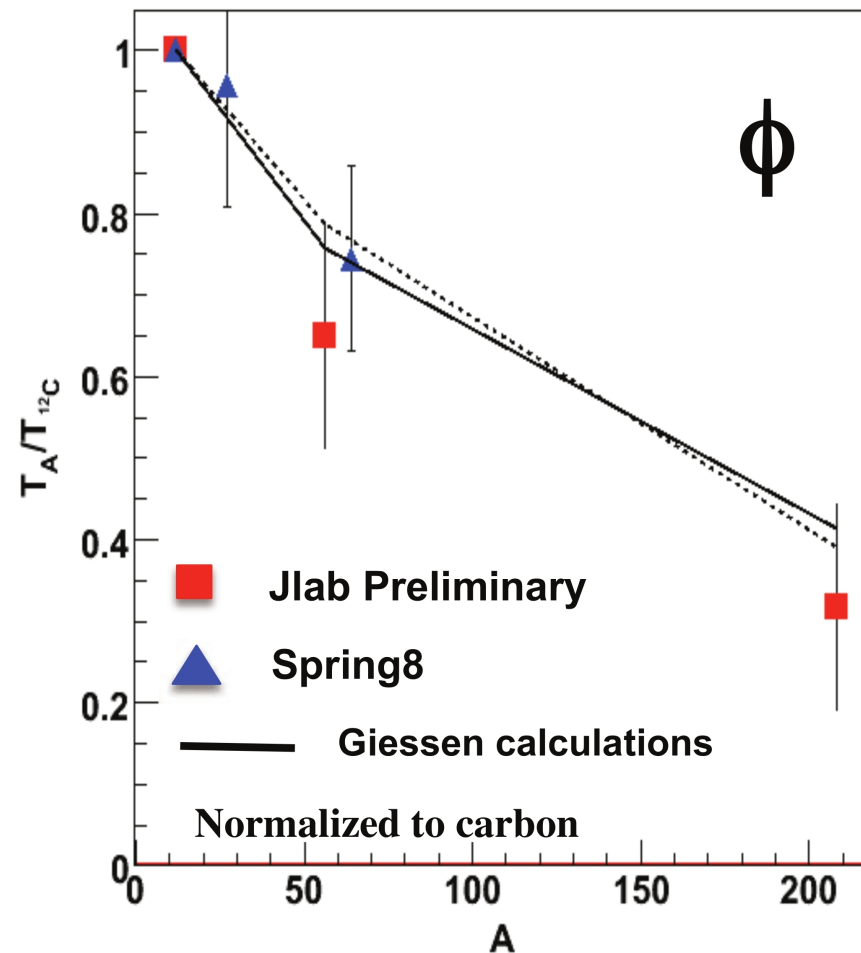
$$P_{out} = \frac{\sigma_{\phi}^A}{A \sigma_{\phi}^N}$$

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

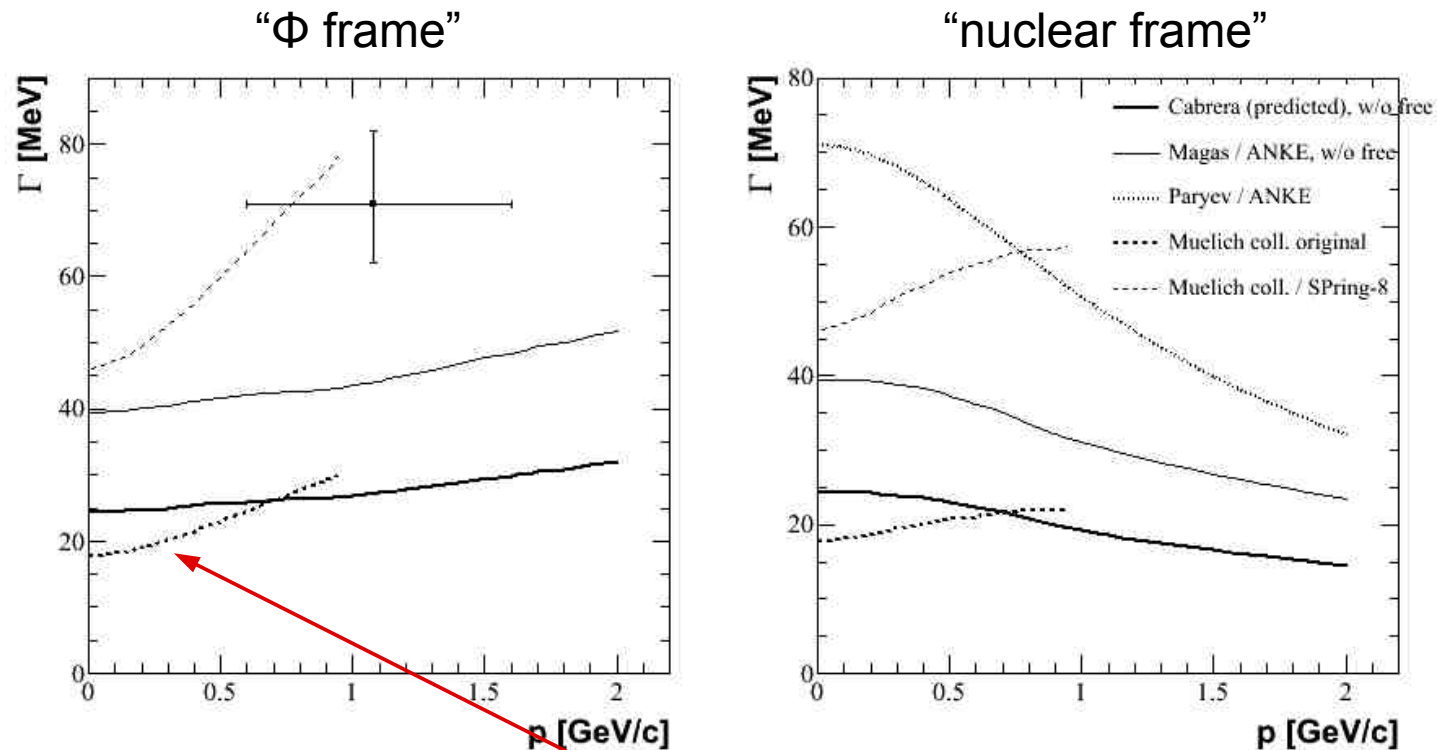
R. Nasseripour *et al.*, AIP 1056 (2008) 223

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

“agreement”



Momentum dependence of the in-medium Φ -width



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

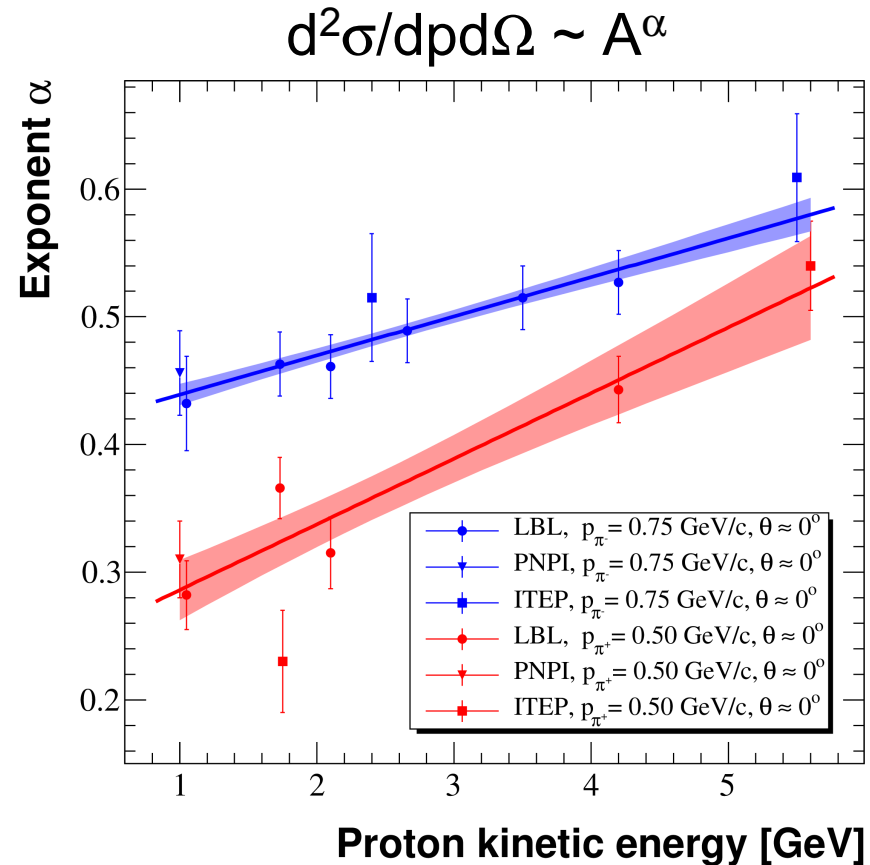
$$\Gamma_{\text{coll}} = -\frac{\mathcal{I}\text{m}\Pi_{\text{coll}}}{m_\phi}$$

Determination of α for π production

At $T_p = 2.83\text{GeV}$:

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

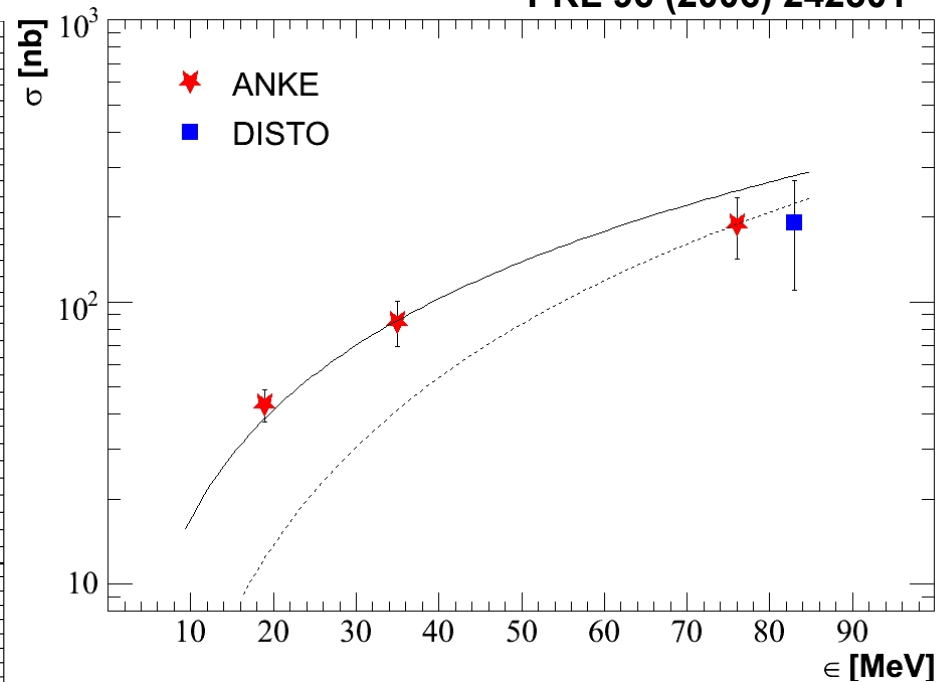
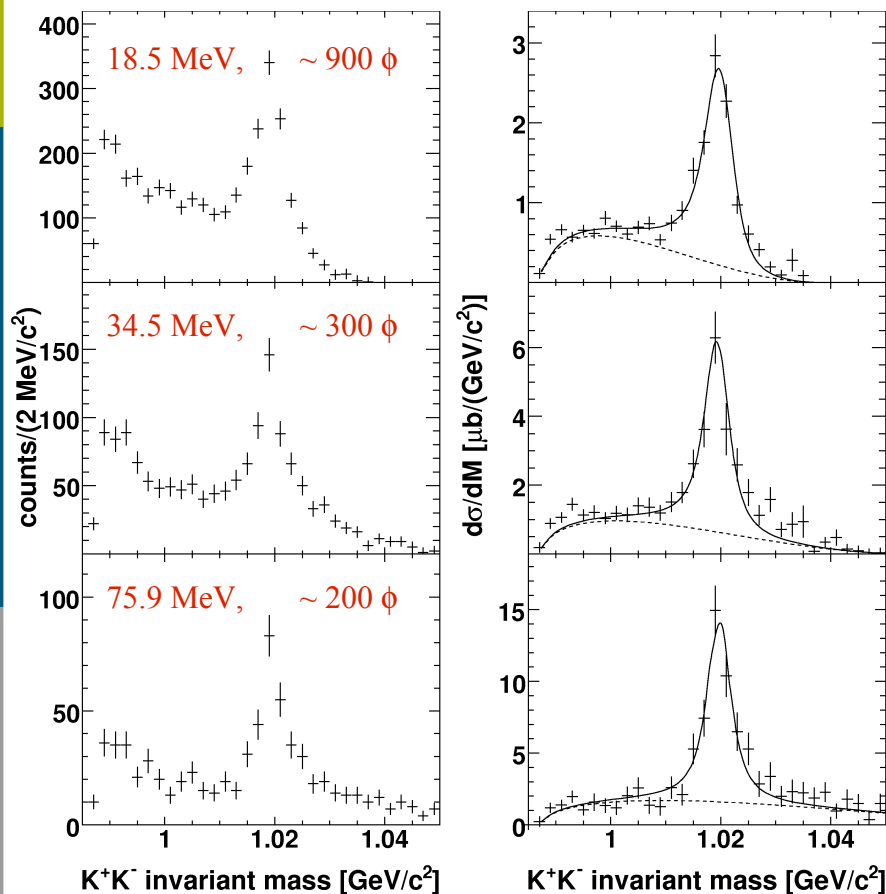
$$\alpha(\pi^+) = 0.380 \pm 0.018 \text{ (5\%)}$$



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

pp→ppΦ (total cross sections)

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

pp→ppΦ (differential cross sections)

$\epsilon = 18.5 \text{ MeV}$

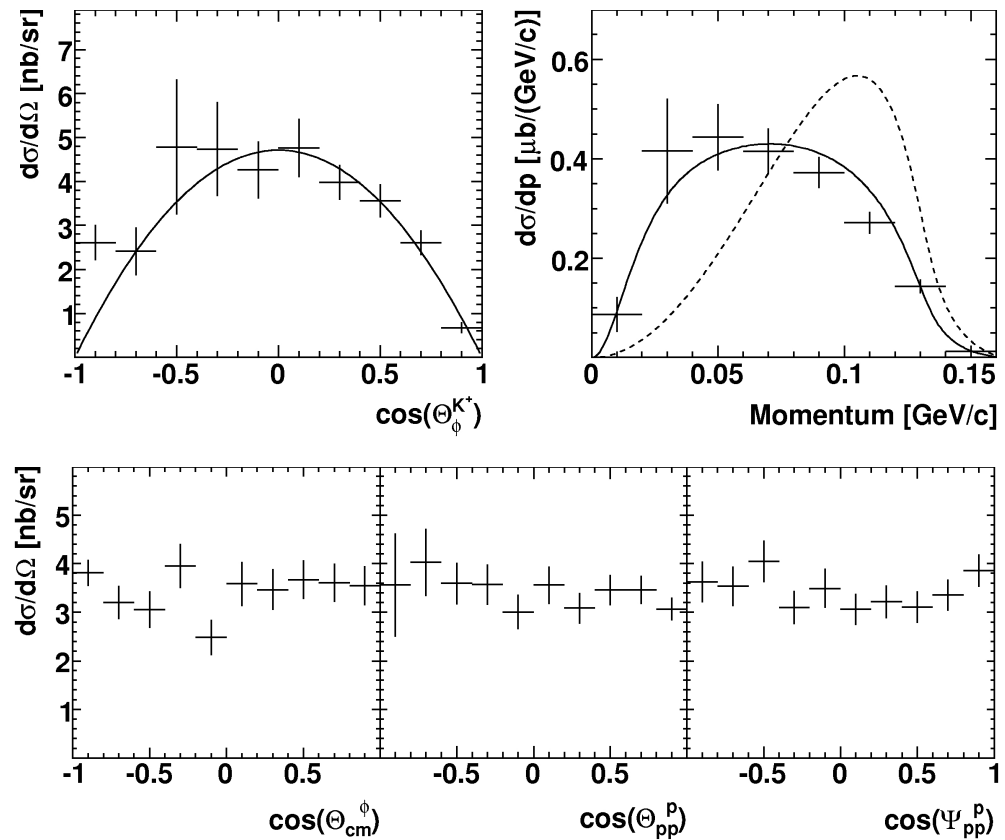
close to threshold the angular decay distribution must display a $\sin^2\Theta_\phi^{K^+}$

Φ in relative S-wave

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

clear effect of pp-FSI

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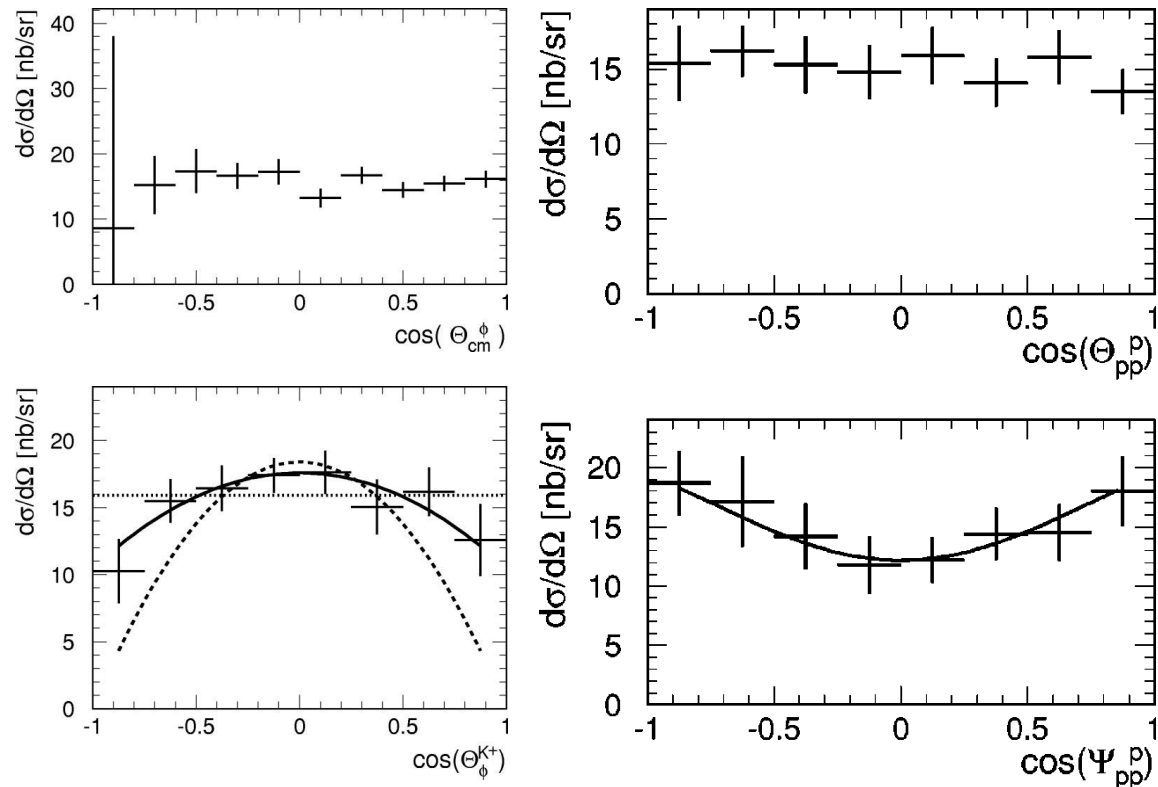


$pp \rightarrow pp\Phi$ (differential cross sections), DISTO

DISTO, PRC 63 (2001) 024004

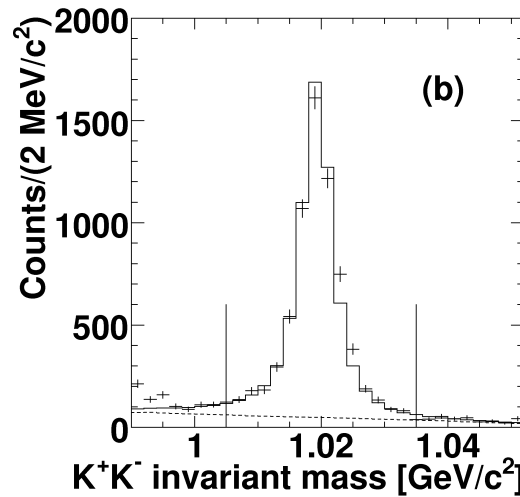
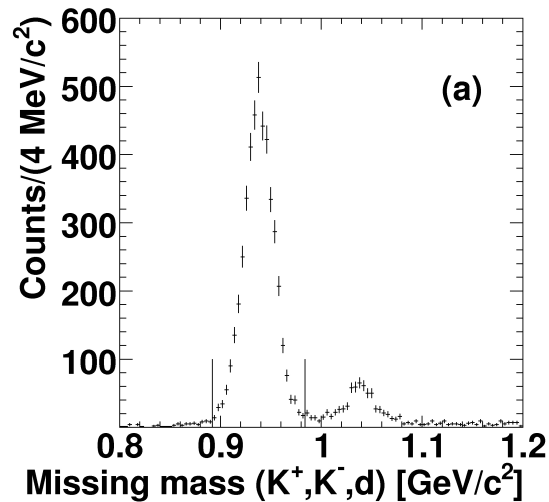
DISTO ~ 500 Φ 's
 @ $\varepsilon = 85$ MeV

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



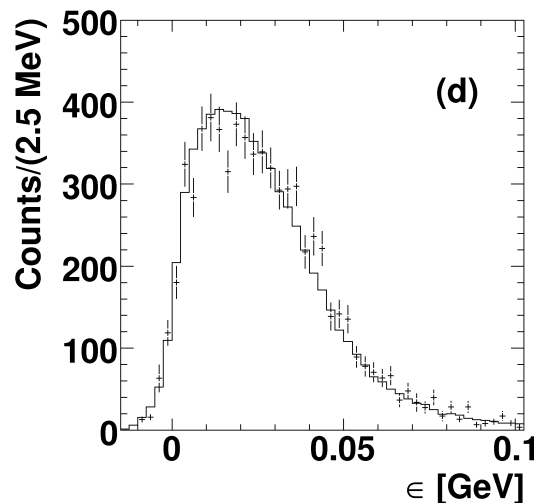
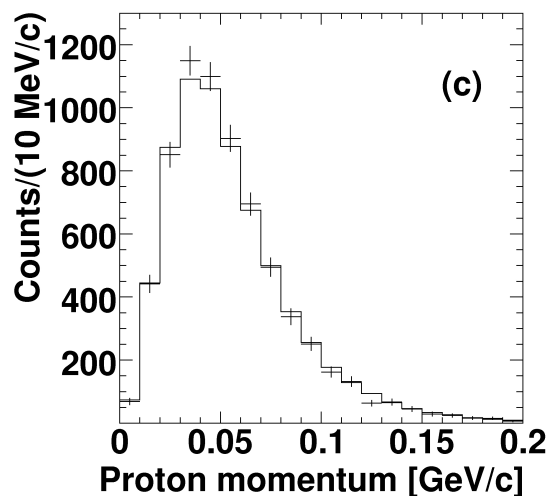
Dominantly S-wave, best fit: $(28 \pm 7)\%$ P-wave contribution

pn→dΦ production (event selection)



$T_p = 2.65 \text{ GeV}$

pd → dΦ(K⁺K⁻)_{p_{spectator}}
pn → dΦ(K⁺K⁻)



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

extract cross section for $\epsilon < 80 \text{ MeV}$

pn→dΦ (differential cross sections)

1 S + 9 possible P-wave amplitudes !

		LlJ_q
$^1P_1 \rightarrow ^3S_1$	s	Ss
$^3S_1 \rightarrow ^3S_1$	p	S^1p_0
$^3S_1 \rightarrow ^3S_1$	p	S^1p_1
$^3S_1 \rightarrow ^3S_1$	p	S^1p_2
$^3D_1 \rightarrow ^3S_1$	p	S^2p_0
$^3D_1 \rightarrow ^3S_1$	p	S^2p_1
$^3D_1 \rightarrow ^3S_1$	p	S^2p_2

... and more ...

to allow for the possibility of higher partial waves ...

most general form:

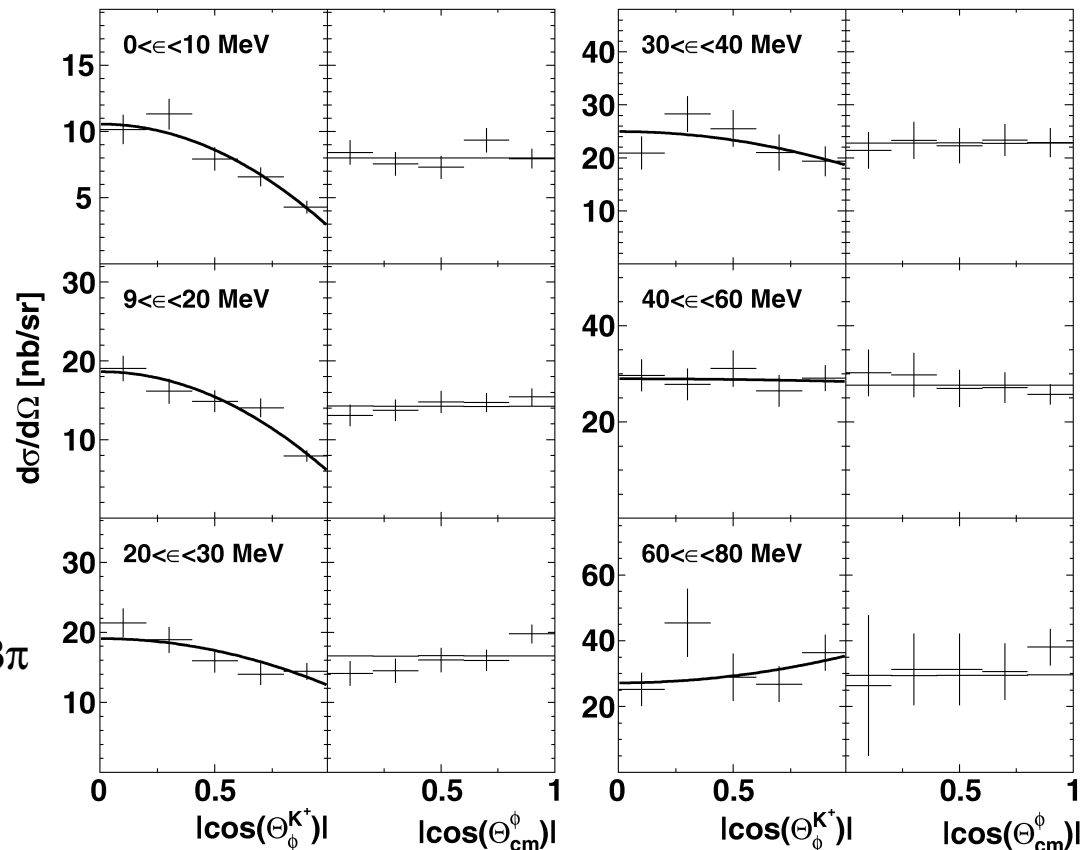
$$d\sigma/d\Omega_{\Phi}^{K^+} = 3(a \sin^2\Theta_{\Phi}^{K^+} + 2b \cos^2\Theta_{\Phi}^{K^+})/8\pi$$

$$\sigma_{\text{tot}} = a + b$$

from fits to these data:

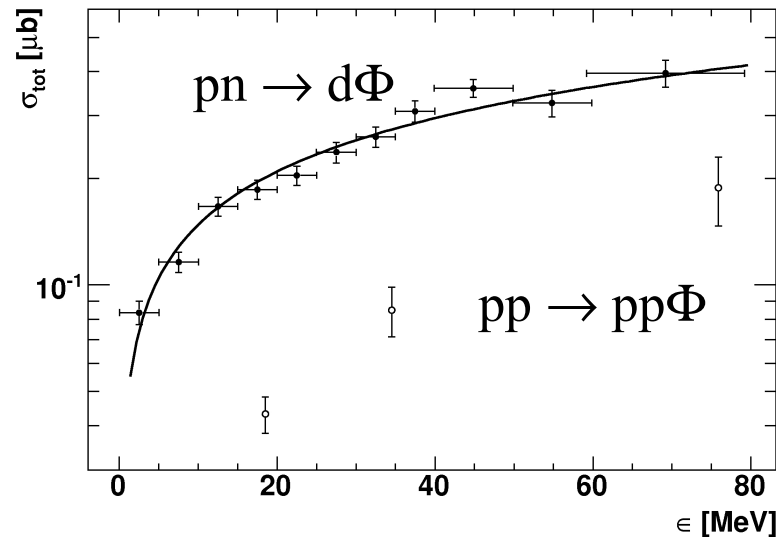
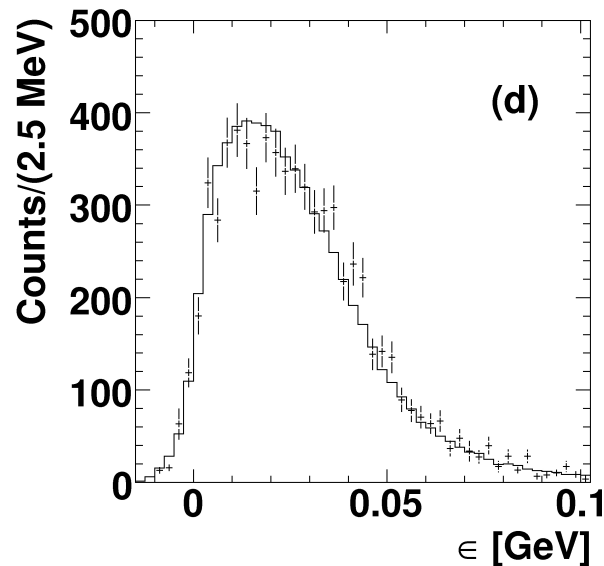
$$b/a \approx (0.012 \pm 0.001)(\epsilon/\text{MeV})$$

PRL 97 (2006) 142301



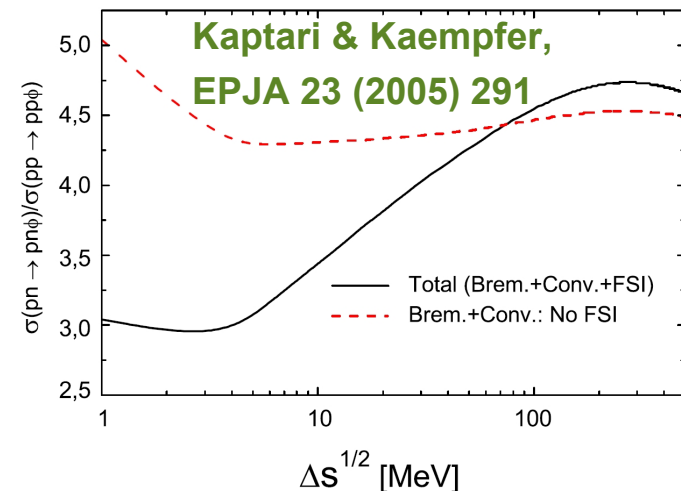
pn→dΦ (differential and total cross sections)

PRL 97 (2006) 142301



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

$$\sigma(\text{pn} \rightarrow \text{pn}\Phi) / \sigma(\text{pp} \rightarrow \text{pp}\Phi) \approx 2.3 \pm 0.4$$



model prediction