Phenomenology of the ppK$^+$K$^-$ system near threshold

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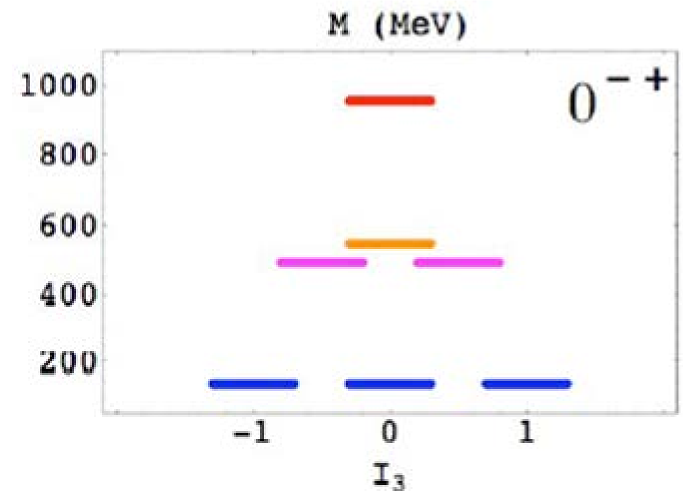
- Motivation
- Proton-proton collisions at K$^+$K$^-$ threshold: COSY
- Dynamics of the ppK$^+$K$^-$ system at threshold
- Conclusions & outlook

II International Symposium on Mesic Nuclei
Kraków, September 22 - 25, 2013

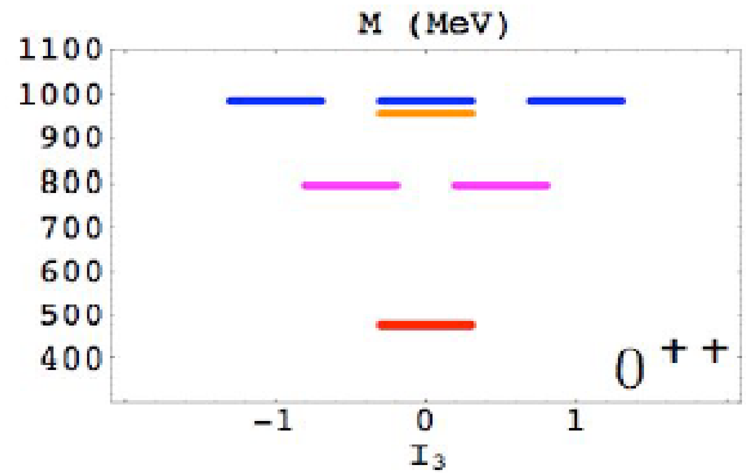
Motivation

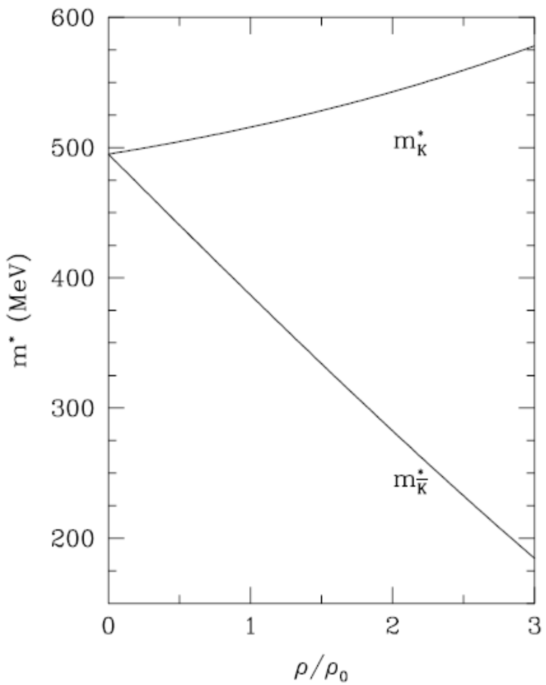
- a_0 and f_0 mesons as a K^+K^- molecules
- Physics of neutron stars: kaon condensates
- Structure of the $\Lambda(1405)$ hyperon

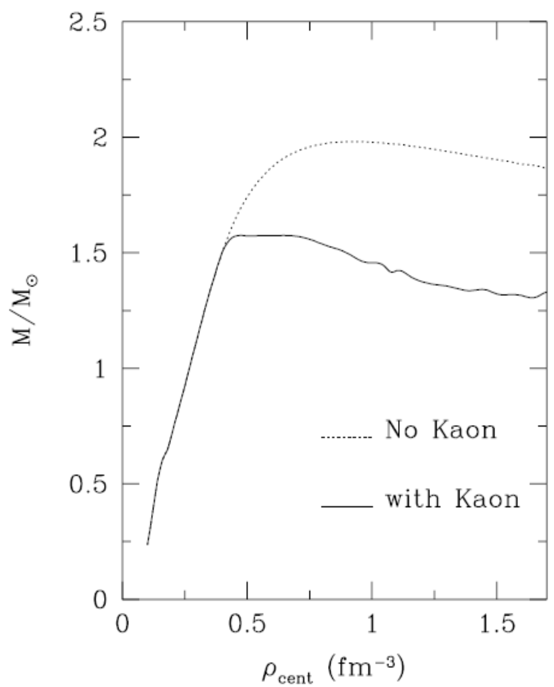
Pseudoscalar mesons



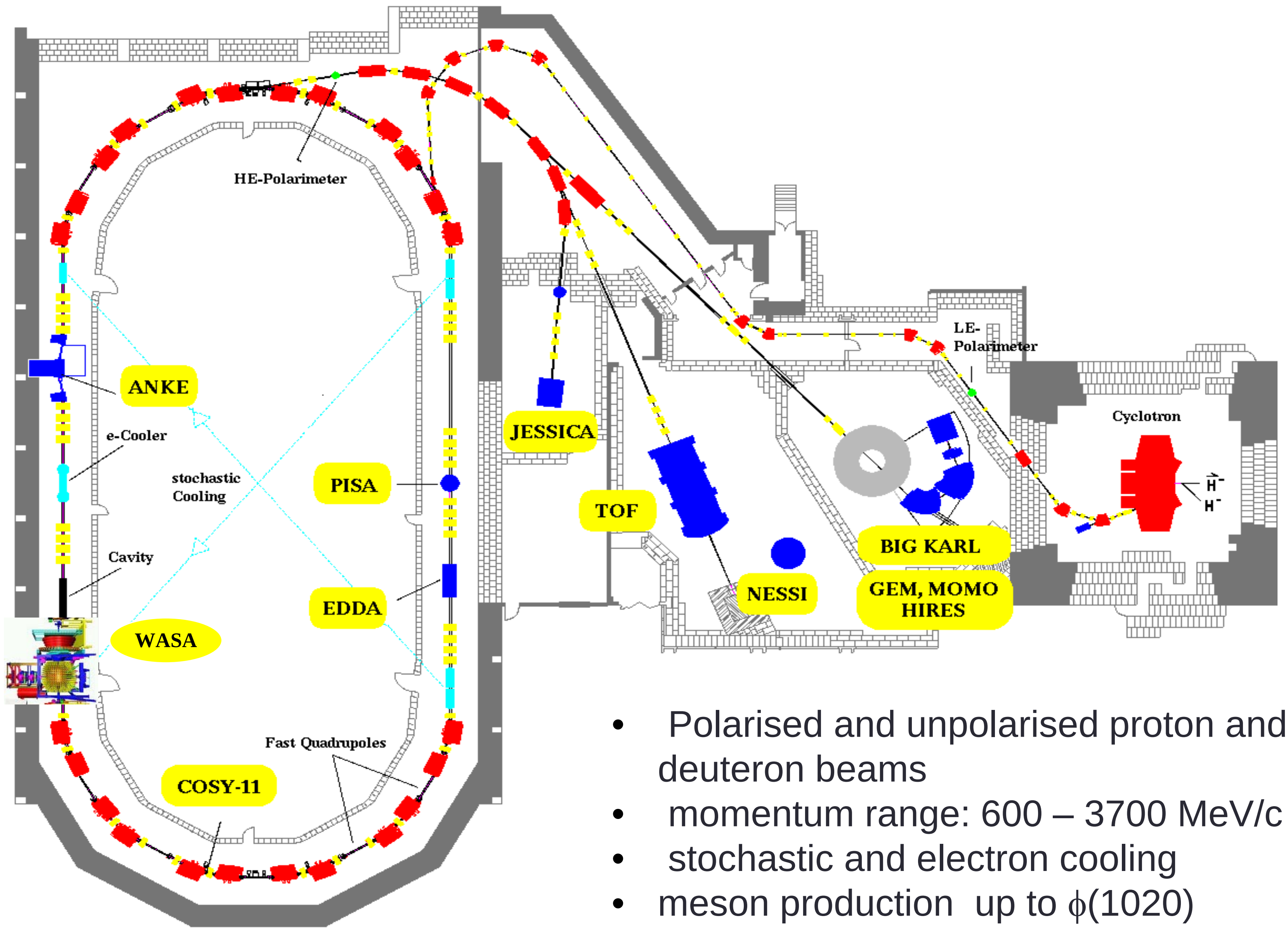
Scalar multiplet:
σ(500), κ(700), f_0(980), a_0(980)





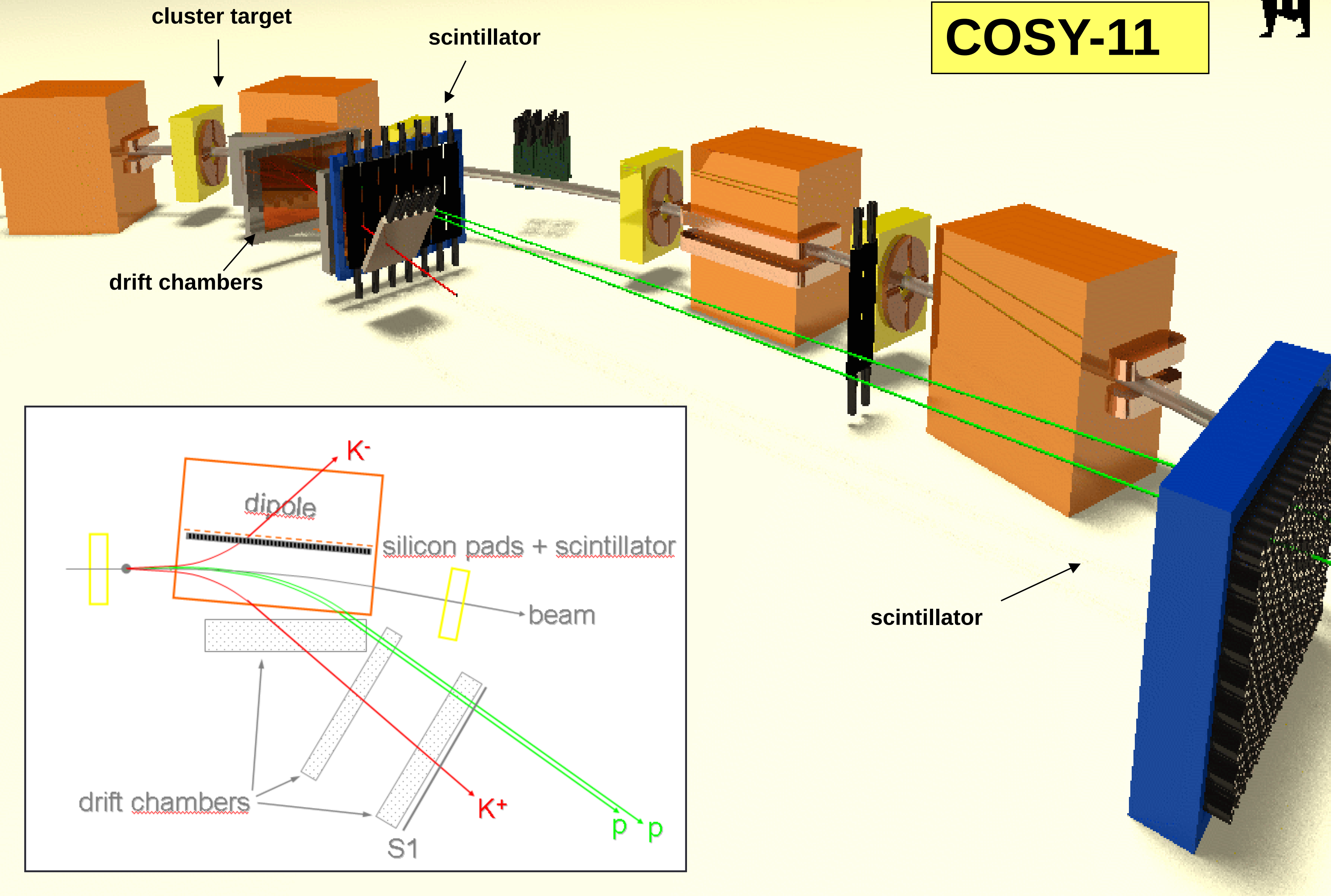


COoler SYnchrotron COSY



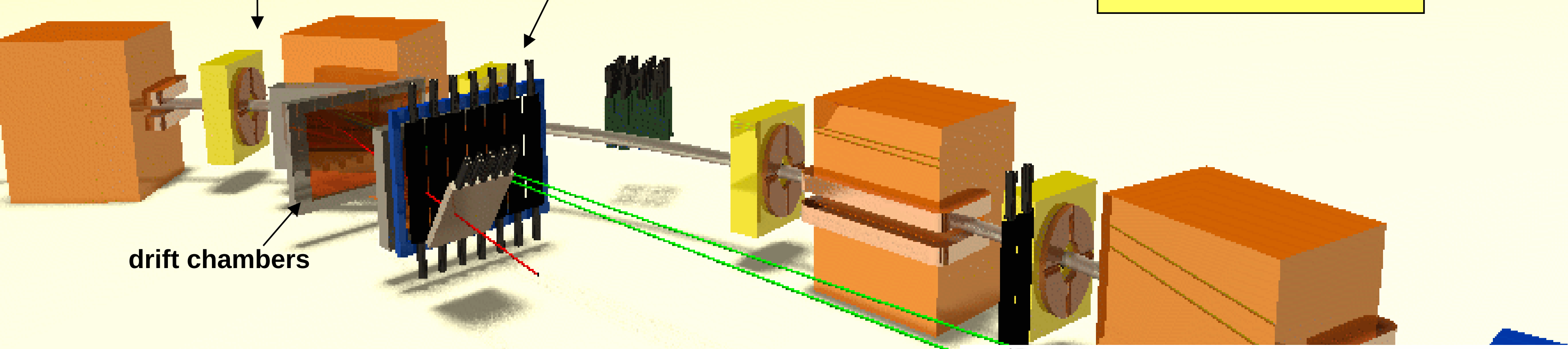
- Polarised and unpolarised proton and deuteron beams
- momentum range: 600 – 3700 MeV/c
- stochastic and electron cooling
- meson production up to ϕ(1020)

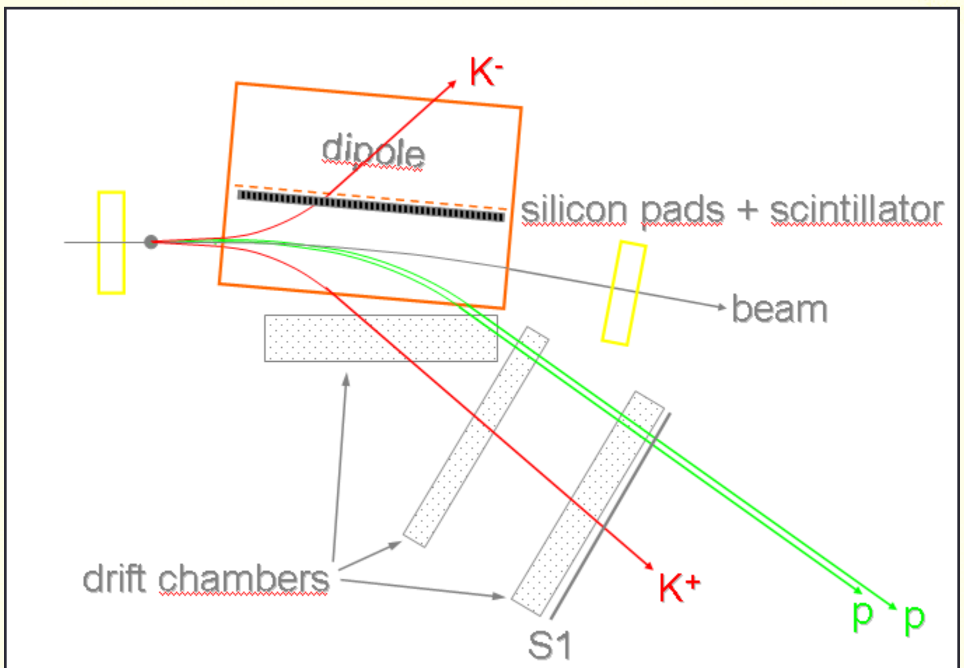
COSY-11

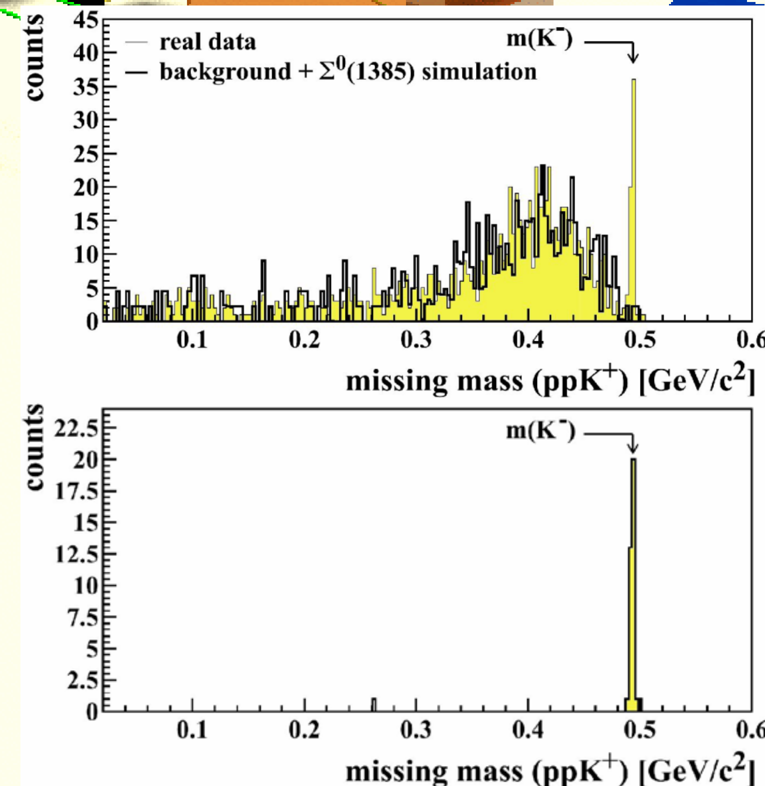


cluster target
scintillator
drift chambers
scintillator
K-
dipole
silicon pads + scintillator
beam
drift chambers
S1
K+
p
p

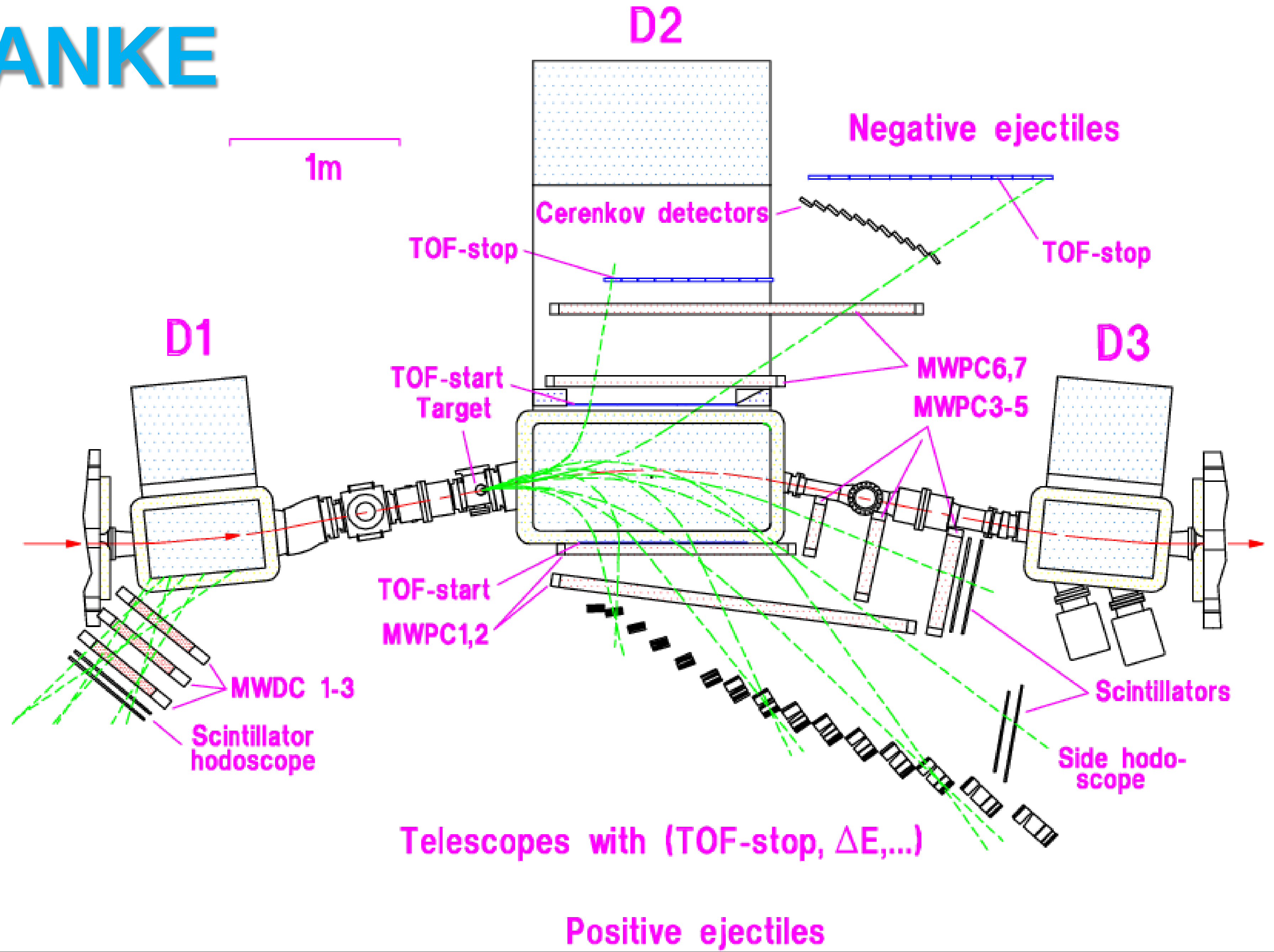
COSY-11

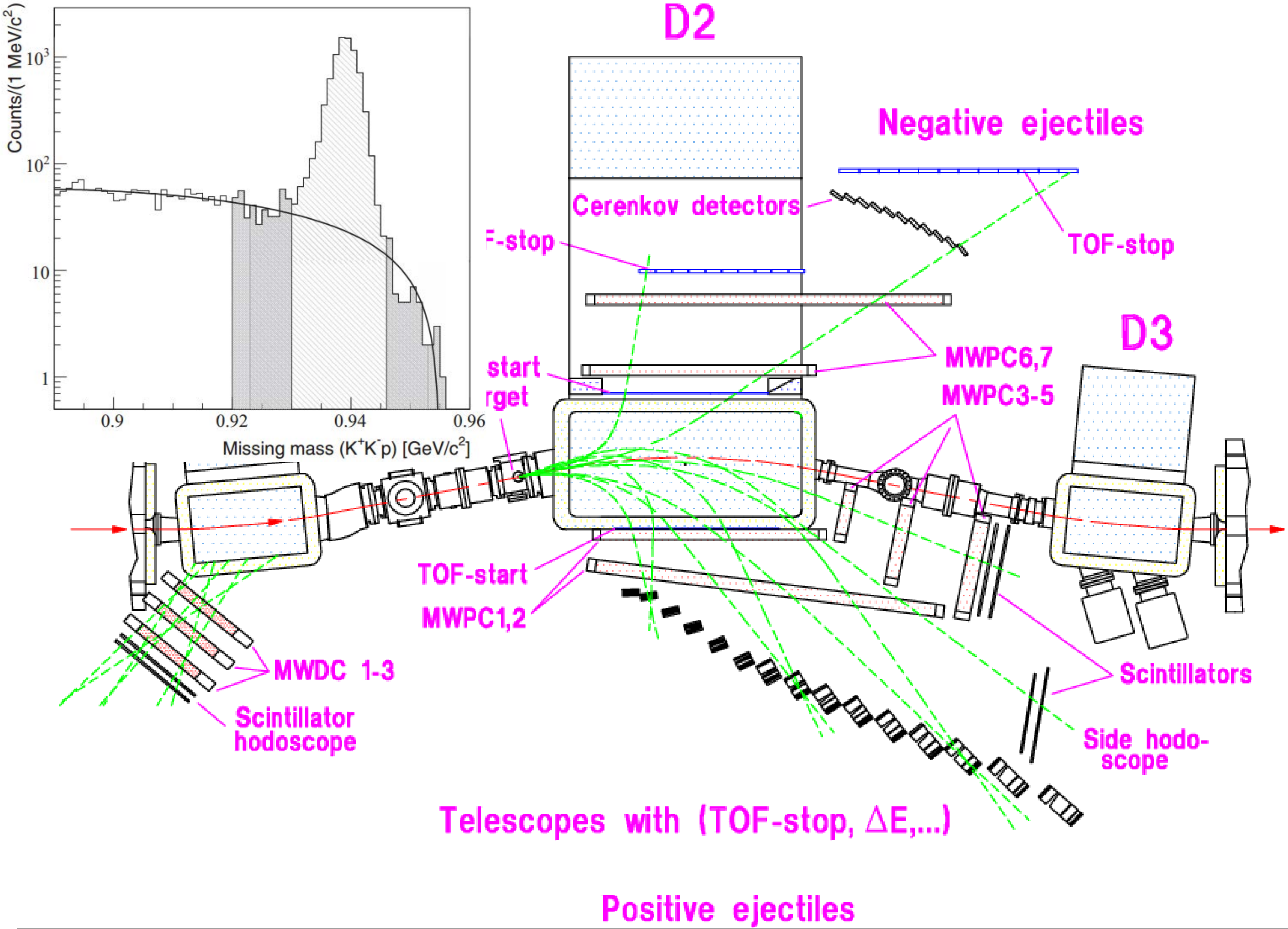

cluster target
scintillator
drift chambers


K-
dipole
silicon pads + scintillator
beam
drift chambers
S1
K+
p
p


counts
real data
background + Σ0(1385) simulation
m(K-)
missing mass (ppK+) [GeV/c2]
counts
m(K-)
missing mass (ppK+) [GeV/c2]

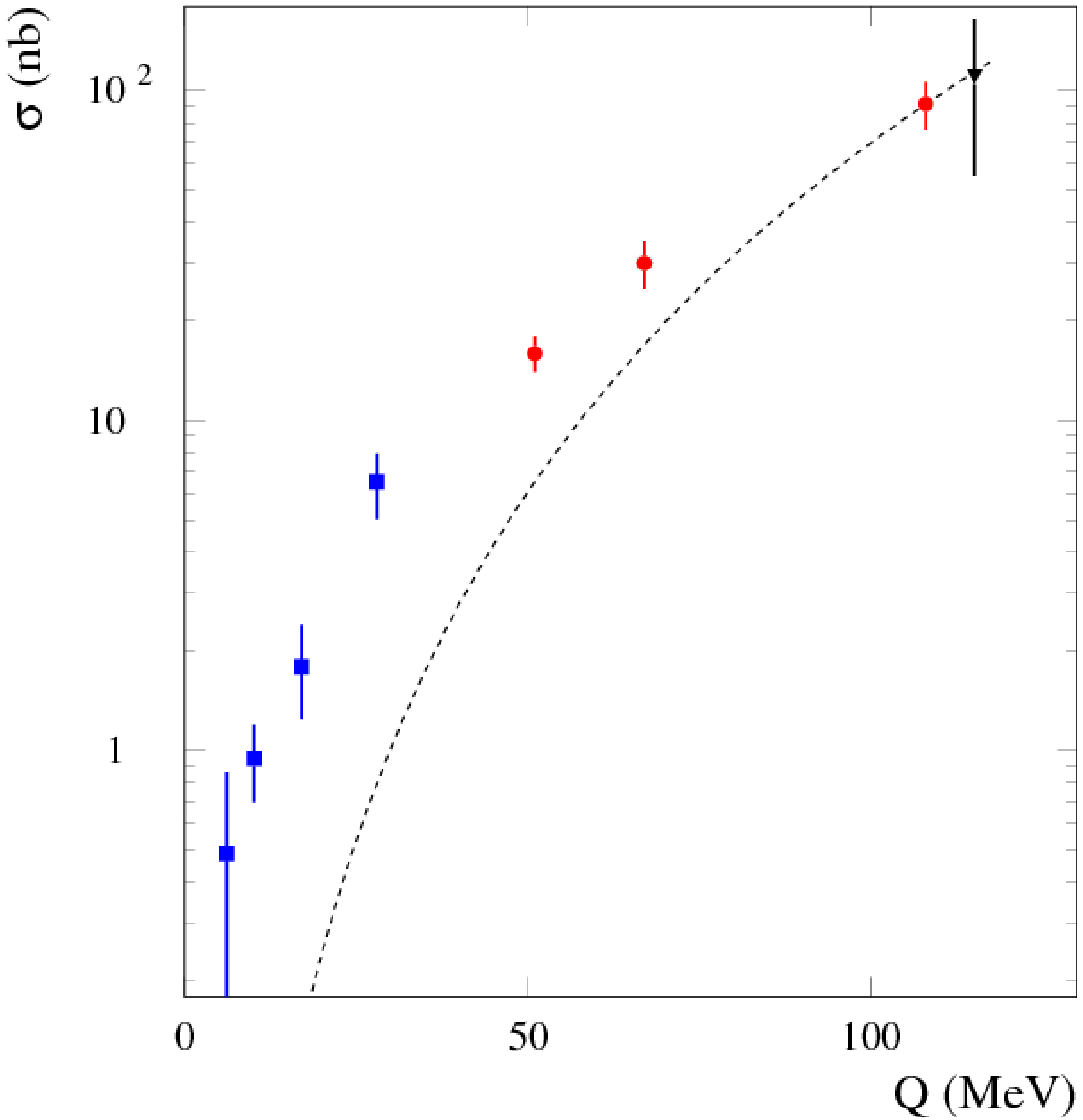
ANKE


D2
1m
Negative ejectiles
Cerenkov detectors
TOF-stop
TOF-stop
D1
MWPC6,7
D3
TOF-start
Target
MWPC3-5
TOF-start
MWPC1,2
MWDC 1-3
Scintillators
Scintillator
hodoscope
Side hodo-
scope
Telescopes with (TOF-stop, ΔE,...)
Positive ejectiles



Counts/(1 MeV/c²)
10³
10²
10
1
0.9
0.92
0.94
0.96
Missing mass (K⁺K⁻p) [GeV/c²]
D2
Negative ejectiles
Cerenkov detectors
F-stop
TOF-stop
MWPC6,7
D3
start
rget
MWPC3-5
TOF-start
MWPC1,2
MWDC 1-3
Scintillators
Scintillator
hodoscope
Side hodo-
scope
Telescopes with (TOF-stop, ΔE,...)
Positive ejectiles

The pp→ppK⁺K⁻ excitation function



DISTO: F. Balestra et al., Phys. Rev. C 63, 024004 (2001)

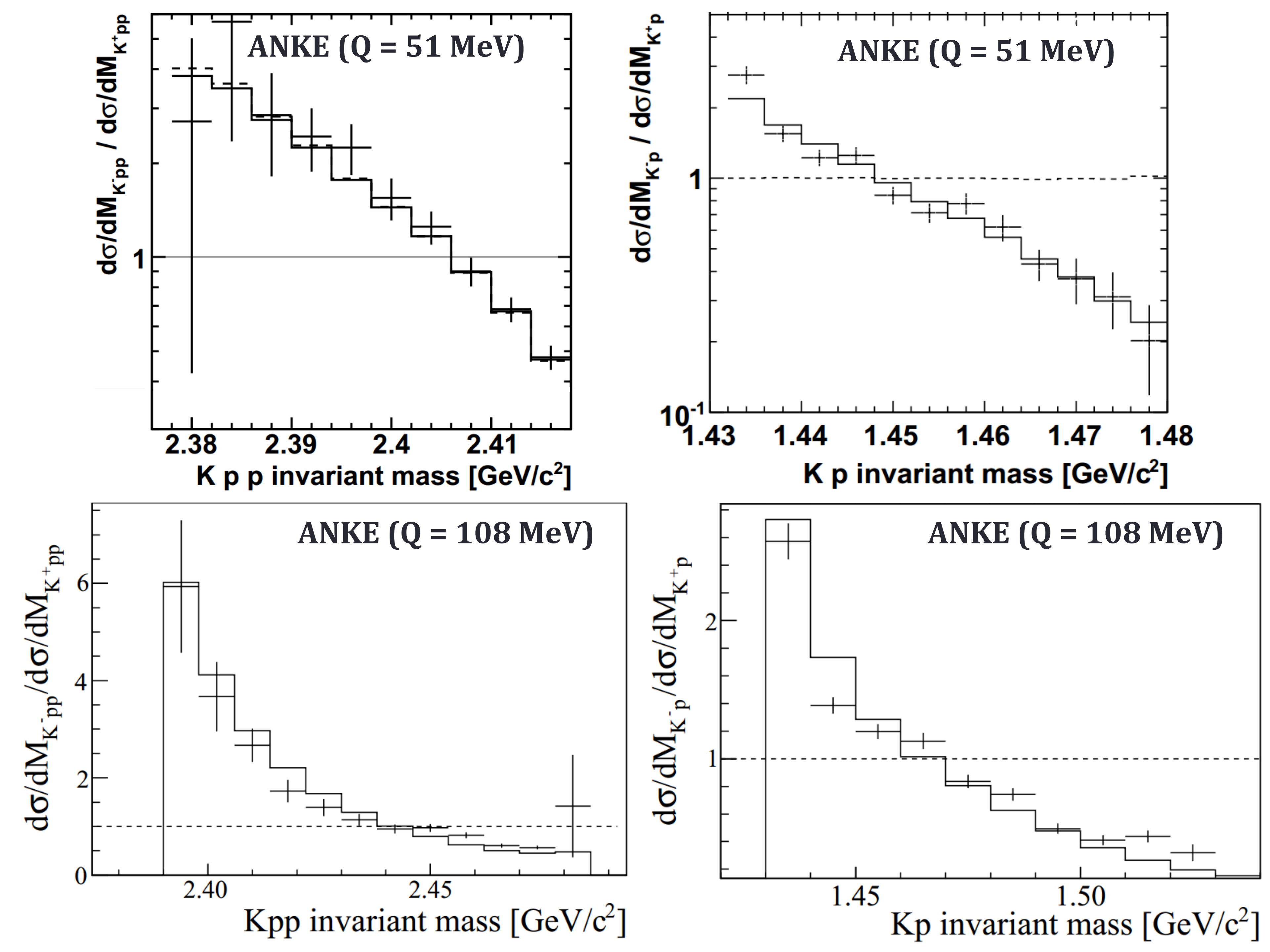
ANKE: Y.Maeda et al., Phys., Rev. C 77, 01524 (2008)

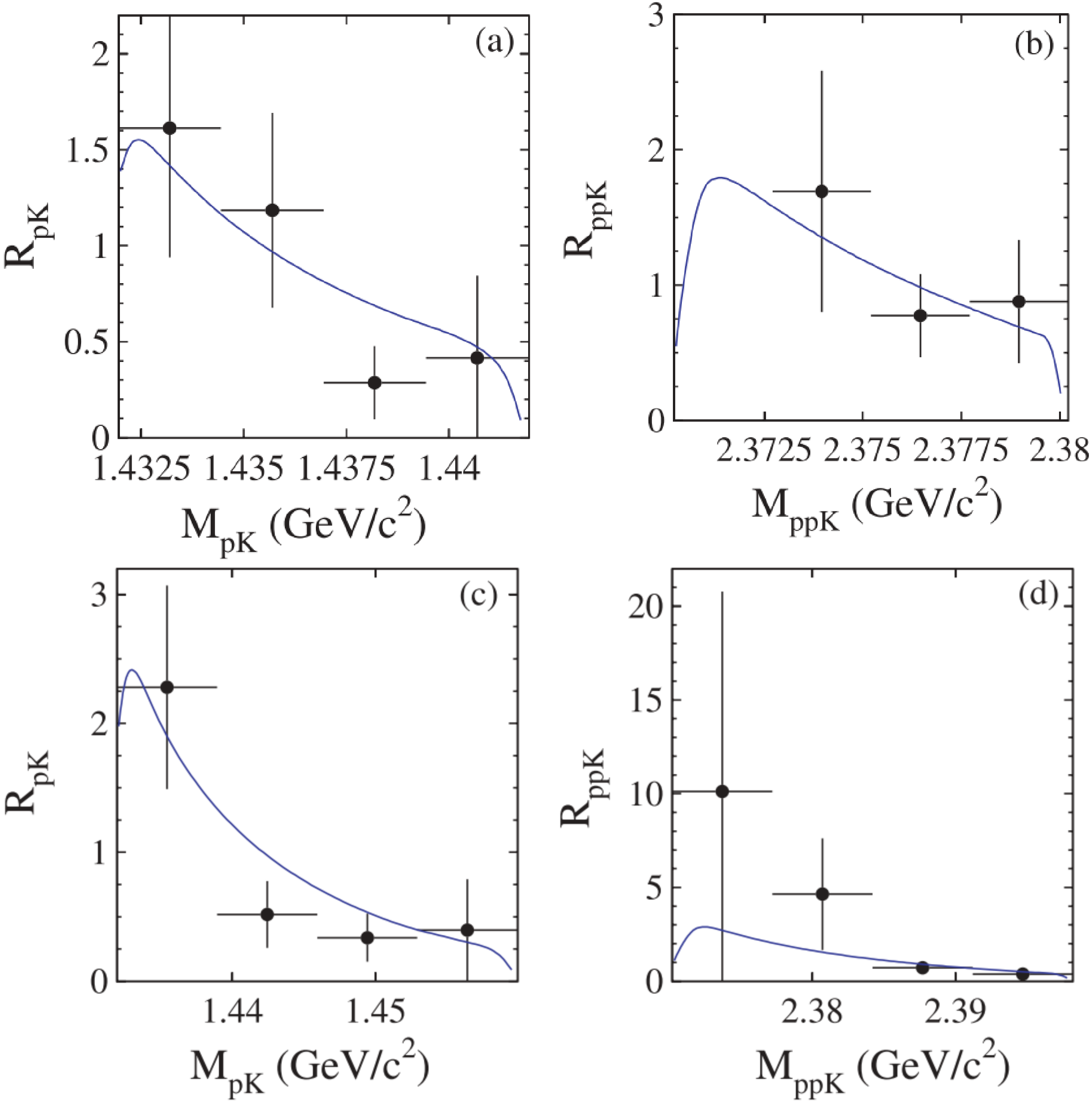
ANKE: Q. J. Ye et al., Phys. Rev. C 85, 035211 (2012)

COSY-11: C. Quentmeier et al., Phys.Lett. B 515 (2001) 276-282

COSY-11: P. Winter et al., Phys. Lett. B 635 (2006) 23-29

COSY-11: M. Wolke, PhD thesis


ANKE (Q = 51 MeV)
$d\sigma/dM_{K^-pp}$ / $d\sigma/dM_{K^+pp}$
1
2.38
2.39
2.4
2.41
K p p invariant mass [GeV/c^2]
ANKE (Q = 51 MeV)
$d\sigma/dM_{K^-p}$ / $d\sigma/dM_{K^+p}$
10^{-1}
1
1.43
1.44
1.45
1.46
1.47
1.48
K p invariant mass [GeV/c^2]
ANKE (Q = 108 MeV)
$d\sigma/dM_{K^-pp}/d\sigma/dM_{K^+pp}$
0
2
4
6
2.40
2.45
Kpp invariant mass [GeV/c^2]
ANKE (Q = 108 MeV)
$d\sigma/dM_{K^-p}/d\sigma/dM_{K^+p}$
1
2
1.45
1.50
Kp invariant mass [GeV/c^2]



COSY-11
(Q = 10 MeV)

$$R_{pK} = \frac{d\sigma/dM_{pK^-}}{d\sigma/dM_{pK^+}}$$

$$R_{ppK} = \frac{d\sigma/dM_{ppK^-}}{d\sigma/dM_{ppK^+}}$$

COSY-11
(Q = 28 MeV)

Parametrization of the Final State Interaction

- FSI indication in both total and differential cross sections at K^+K^- threshold

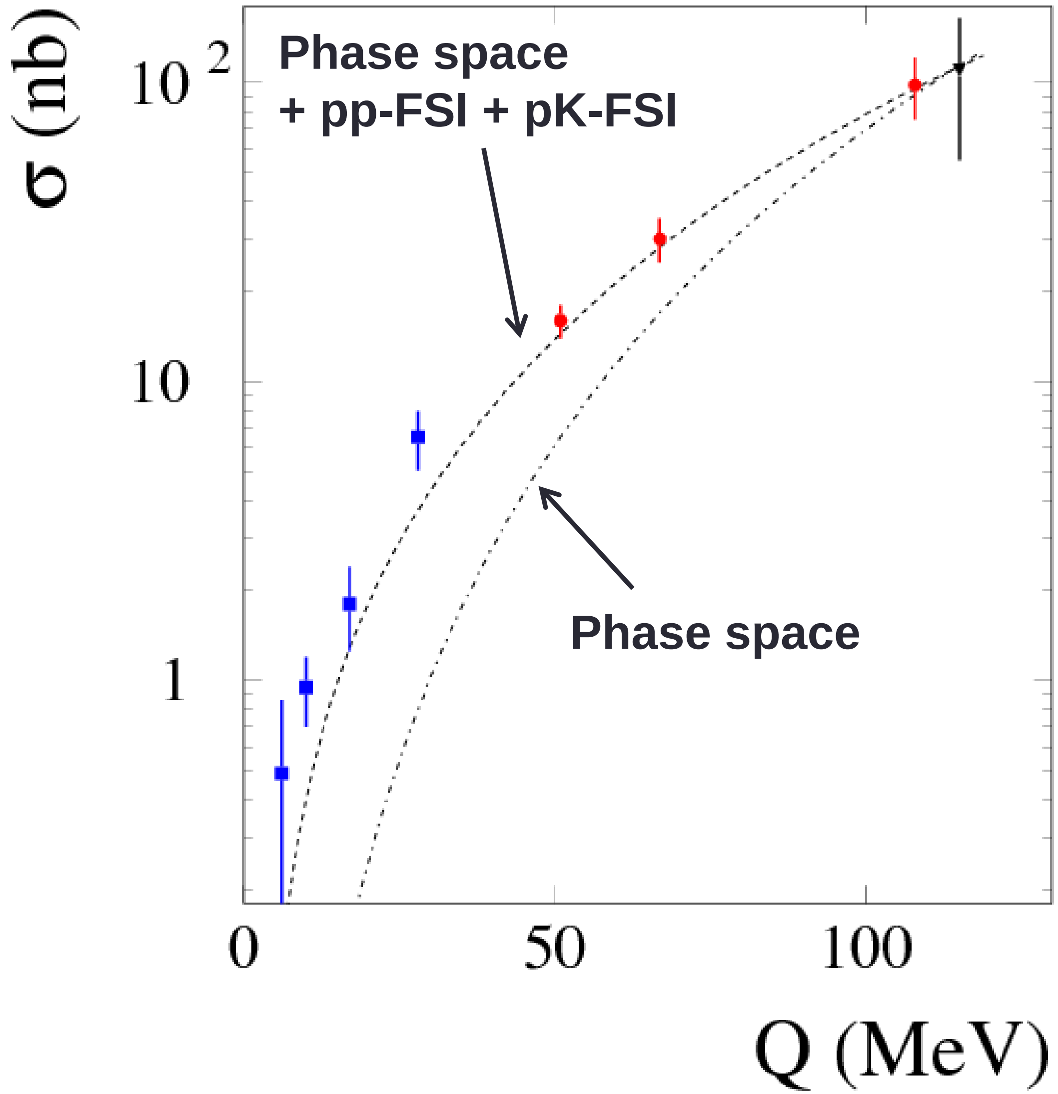
$$\left|M_{pp\to ppK^+K^-}\right|^2 \approx \left|M_0\right|^2 \left|F_{FSI}\right|^2$$

$$F_{FSI} = F_{pp}(q) \times F_{p_1K^-}(k_1) \times F_{p_2K^-}(k_2)$$

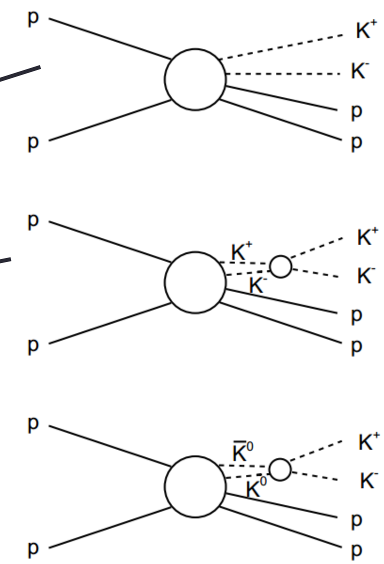
$$F_{pp}(q) = \frac{e^{i\delta_{pp}(^1S_0)} \times \sin\delta_{pp}(^1S_0)}{C \times q}$$

$$F_{pK^-}(k) = \frac{1}{1 - ika}$$

$$a = (0 + i1.5)[\mathrm{fm}]$$



K^+K^--FSI: coupled channel effects

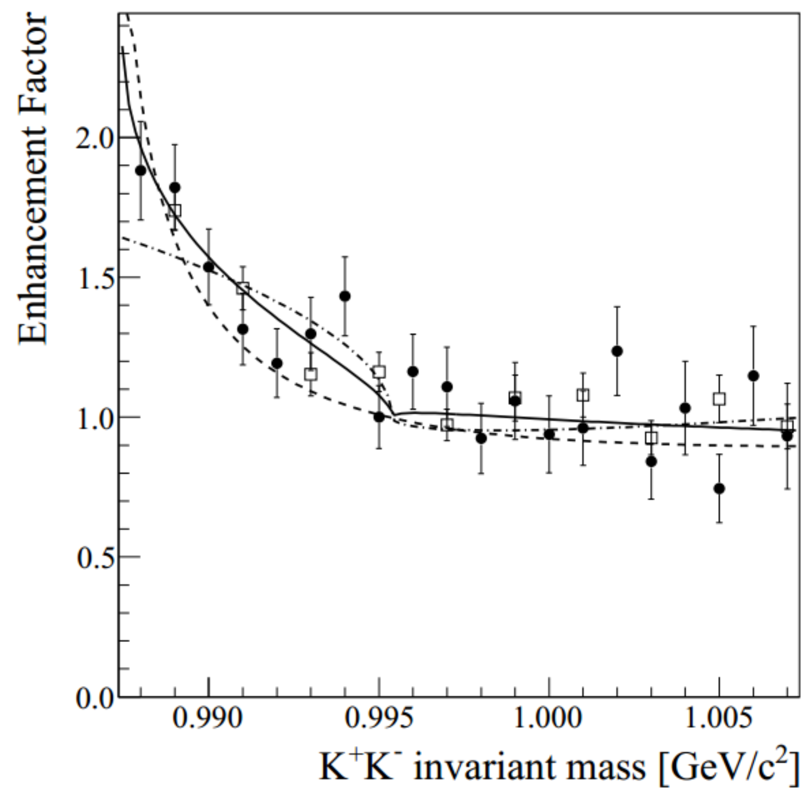


$$\mathcal{F} = \left| \frac{B_1/(B_1+B_0)}{\left(1 - i\frac{1}{2}q[A_1 - A_0]\right)(1 - ikA_1)} + \frac{B_0/(B_1+B_0)}{\left(1 - i\frac{1}{2}q[A_0 - A_1]\right)(1 - ikA_0)} \right|$$

ANKE: A. Dzyuba et al., Phys. Lett. B668, 315 (2008)

$A_0 = (-0.45 + i1.63)$ fm ; $A_1 = (0.1 + i0.7)$ fm
(M. Ablikim et al., Phys. Lett. B 607 (2005) 243;)

- ❖ With the ANKE statistics the expected cusp effects are not distinguishable from the elastic scattering of K^+ and K^-
- ❖ Isospin I= 0 state is favourable
- ❖ No indication of the $f_0(980)/a_0(980)$ influence
- ❖ More statics at lower excess energy needed



Analysis of the K^+K^--FSI at COSY-11

$$\left|M_{pp\to ppK^+K^-}\right|^2 \approx \left|M_0\right|^2\left|F_{FSI}\right|^2$$

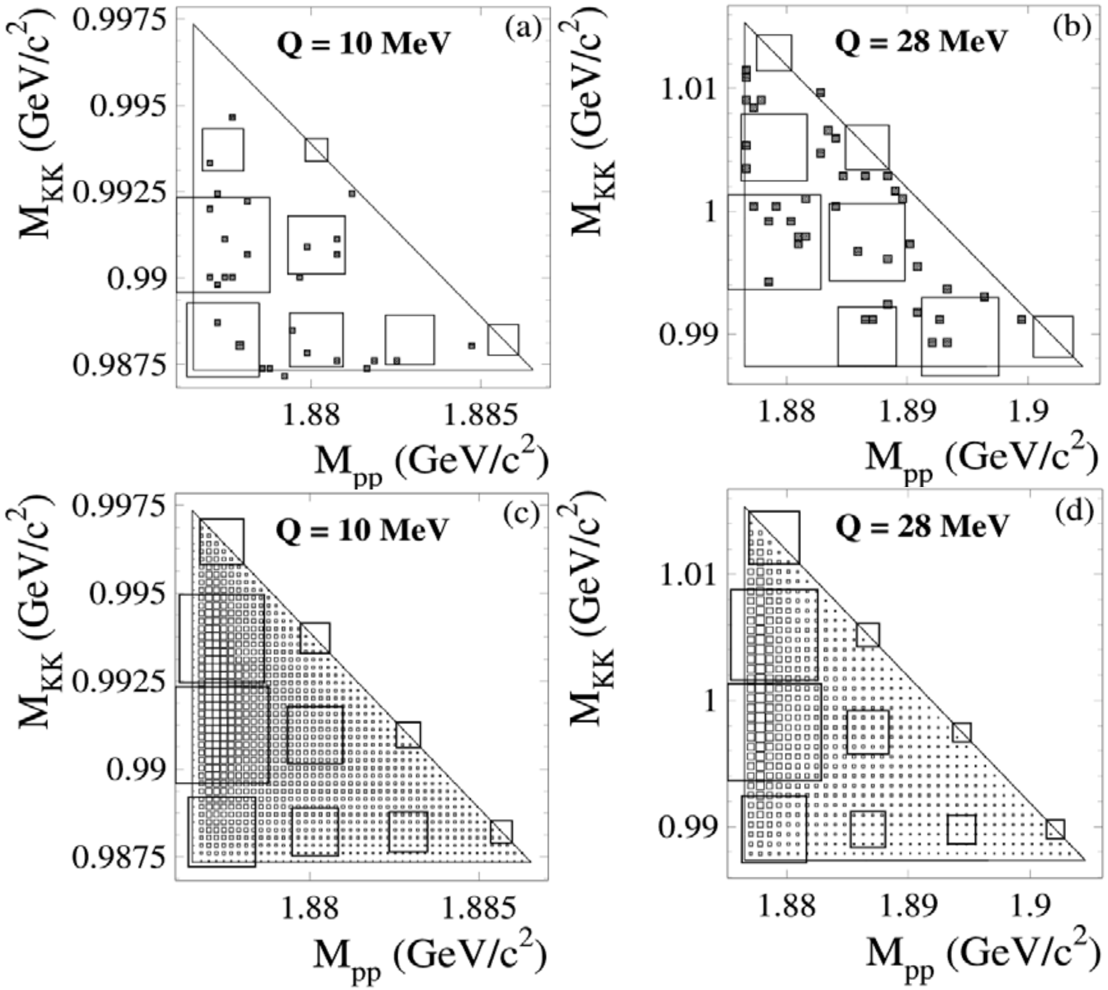
$$F_{FSI} = F_{pp}(q)\times F_{p_1K^-}(k_1)$$
$$\times F_{p_2K^-}(k_2)\times F_{K^+K^-}(k_3)$$

$$F_{pp}(q) = \frac{e^{i\delta_{pp}(^1S_0)}\times \sin\delta_{pp}(^1S_0)}{C\times q}$$

$$F_{pK^-}(k) = \frac{1}{1-ika_{pK^-}}$$

$$F_{K^+K^-}(k_3) = \frac{1}{1-ika_{K^+K^-}}$$

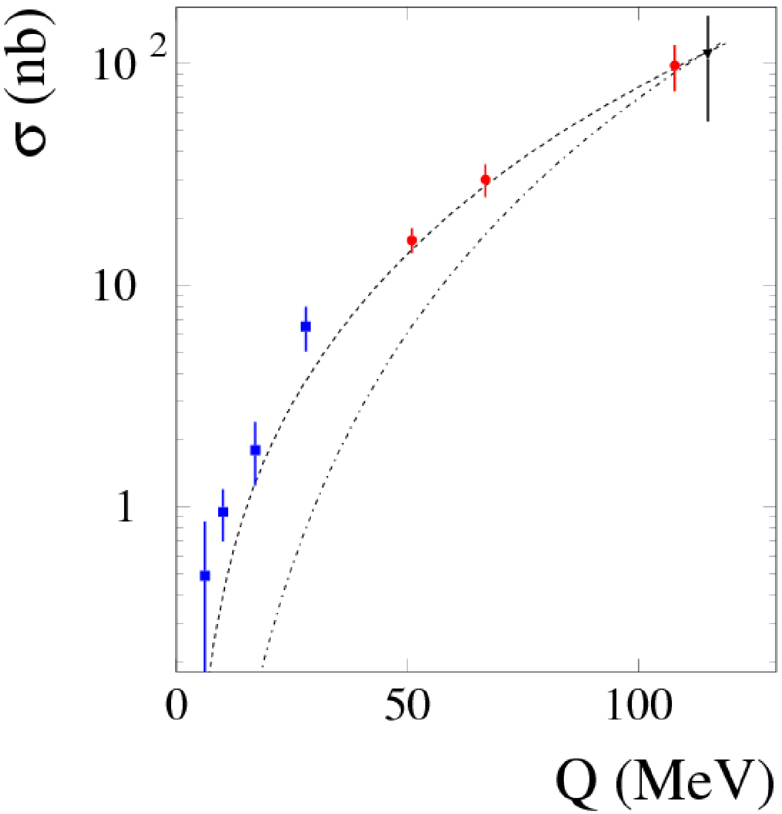
$$a_{pK^-} = (0+i1.5)[\mathrm{fm}]$$

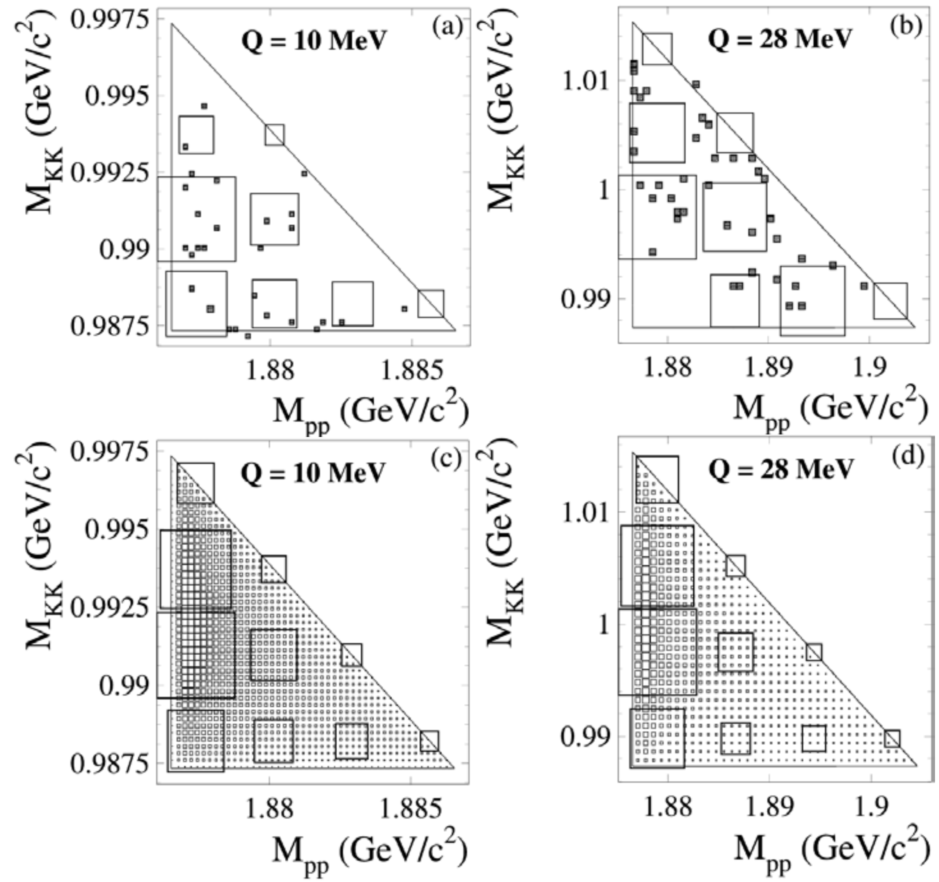


M. Silarski, et al.,Phys. Rev. C 80, 045202 (2009)

$$a_{K^+K^-} = \left[\left(0.5^{+4}_{-0.5}\right) + i(3\pm 3)\right]\,\mathrm{fm}$$

- Analysis of the Goldhaber plots measured at Q = 10 MeV (27 events) and Q = 28 MeV (30 events) + near threshold excitation function





$$a_{pK^-} = (-0.65 + i0.78)\,[\mathrm{fm}]$$

(Y. Yan, arXiv:0905.4818 [nucl-th])

$$F_{K^+K^-} = \frac{1}{\frac{1}{a_{K^+K^-}} + \frac{b_{K^+K^-}k_4^2}{2} - ik_4}$$

Results for the effective range expansion fit

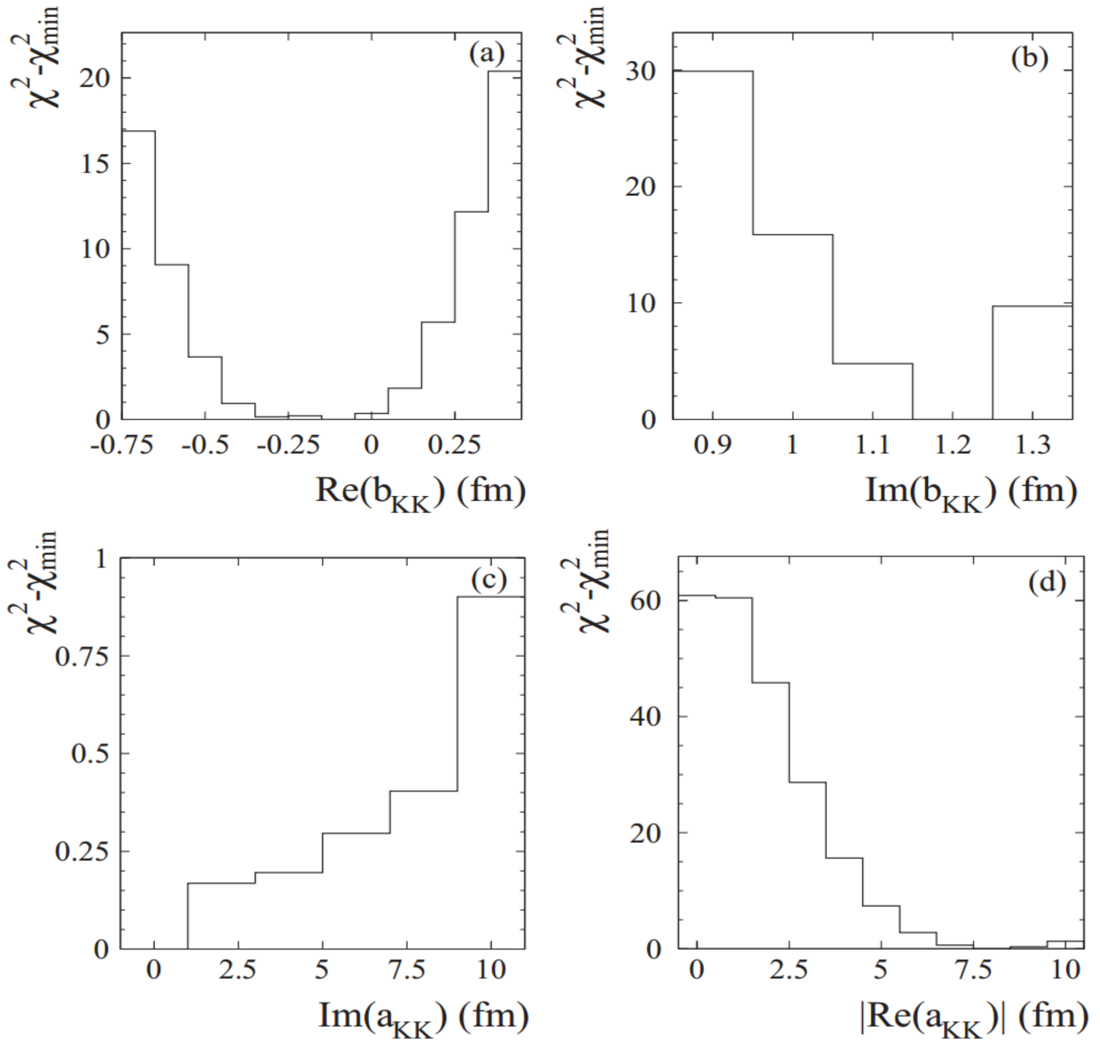
$$\mathrm{Re}(b_{K^+K^-}) = -0.1 \pm 0.4_{\mathrm{stat}} \pm 0.3_{\mathrm{sys}}\ \mathrm{fm}$$

$$\mathrm{Im}(b_{K^+K^-}) = 1.2^{+0.1_{\mathrm{stat}}+0.2_{\mathrm{sys}}}_{-0.2_{\mathrm{stat}}-0.0_{\mathrm{sys}}}\ \mathrm{fm}$$

$$|\mathrm{Re}(a_{K^+K^-})| = 8.0^{+6.0_{\mathrm{stat}}}_{-4.0_{\mathrm{stat}}}\ \mathrm{fm}$$

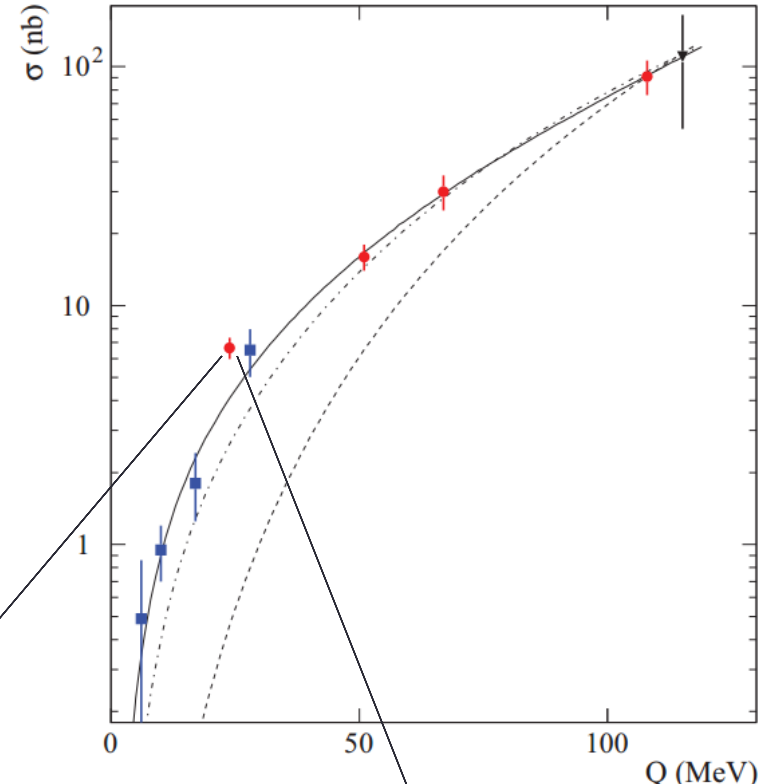
$$\mathrm{Im}(a_{K^+K^-}) = 0.0^{+20.0_{\mathrm{stat}}}_{-5.0_{\mathrm{stat}}}\ \mathrm{fm}$$

M. Silarski, P. Moskal,
Phys. Rev. C 88, 025205 (2013)



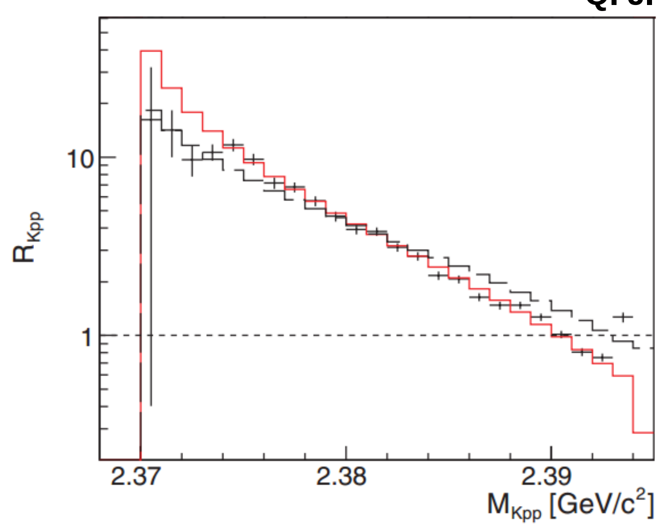
$$\chi^2(a_{K^+K^-}, \alpha) = \sum_{i=1}^{8} \frac{(\sigma_i^{exp} - \alpha\sigma_i^{m})^2}{(\Delta\sigma_i^{exp})^2} + 2 \cdot \sum_{j=1}^{2}\sum_{k=1}^{10} [\beta_j N_{jk}^s - N_{jk}^e + N_{jk}^e \ln(\frac{N_{jk}^e}{\beta_j N_{jk}^s})]$$

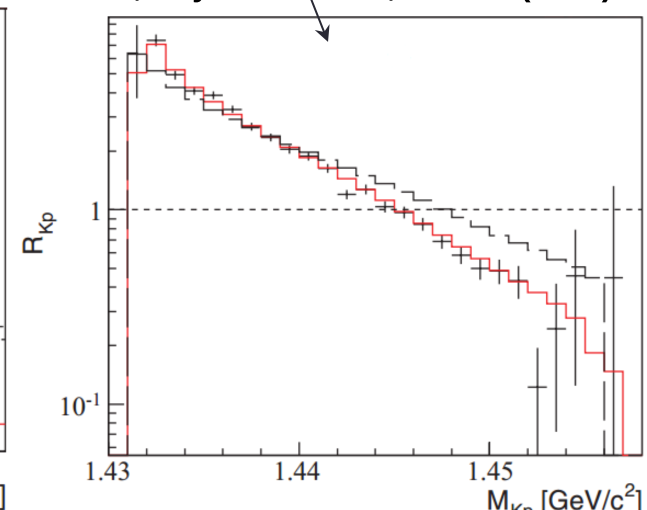
Open questions



- Differential distributions at Q=23.9 MeV cannot be desribed by pK^--FSI with $a_{pK^-} = i1.5$ fm.
- Possible influence of the $pp \rightarrow pK^+\Lambda(1405)$ reaction?
- Too simplified FSI model?

Q. J. Ye et al., Phys. Rev. C 87, 065203 (2013)





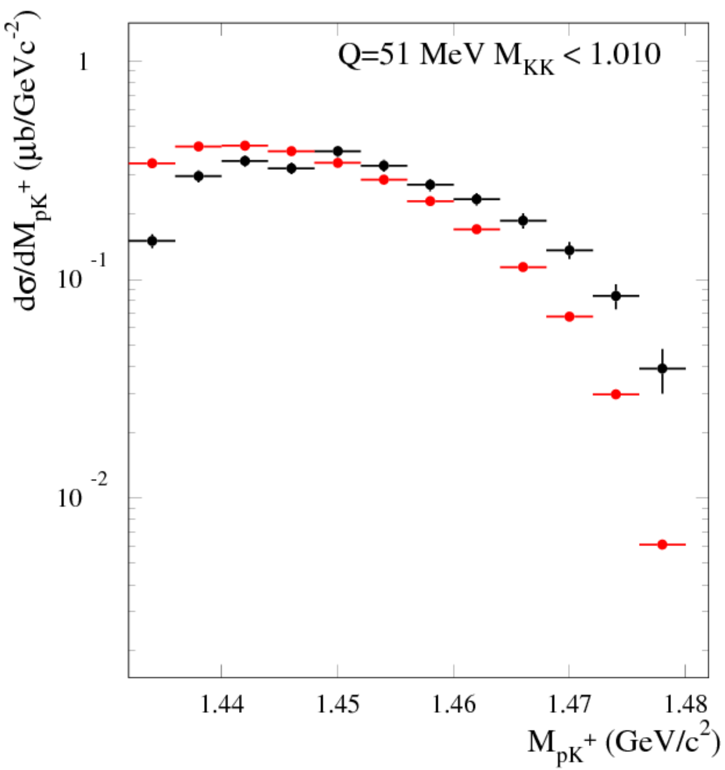
Open questions

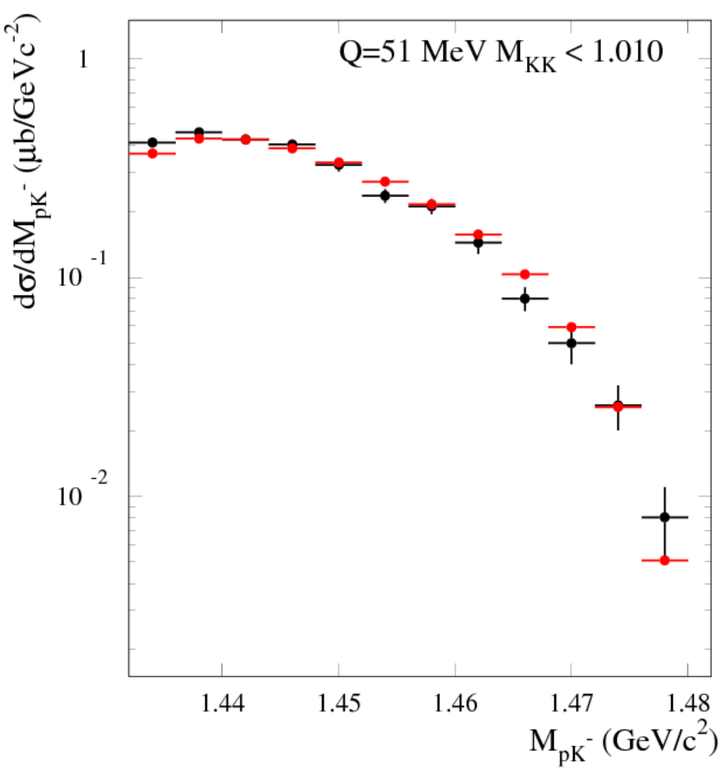
- ppK⁻ enhancement factor from from the Faddeev calculation

$$F_{ppK^-} = \left|1 + \frac{\beta + ik_1}{2}\left\{\frac{A_0}{1 - iA_0k_1} + \frac{A_1}{1 - iA_1k_1}\right\}1 + \frac{\beta + ik_2}{2}\left\{\frac{A_0}{1 - iA_0k_2} + \frac{A_1}{1 - iA_1k_2}\right\} + \frac{a}{d}\cdot\frac{1 + idk_3}{1 - iak_3}\right|^2$$

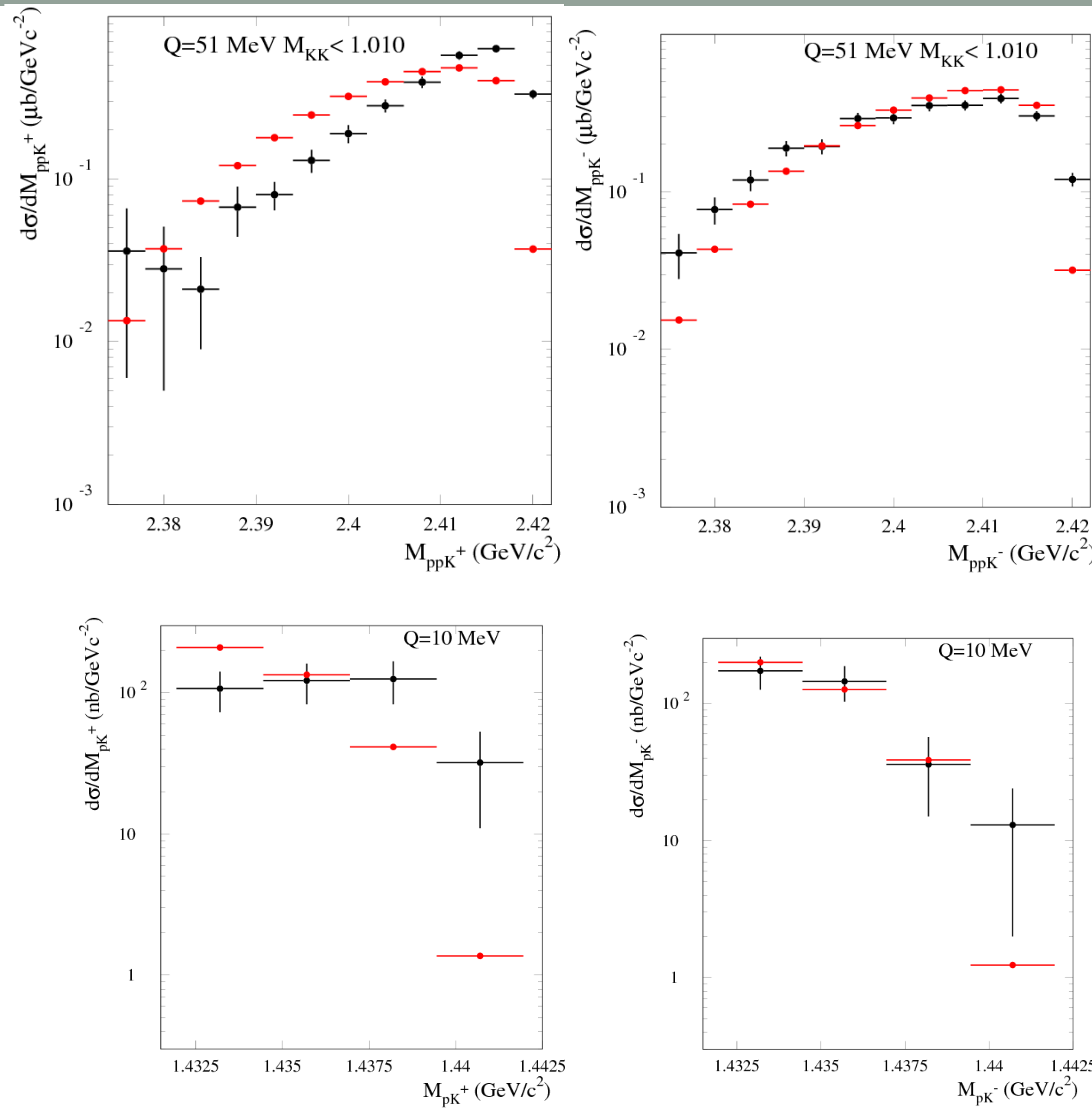
$$A_0 = (-1.68 + i0.531)\ fm; A_1 = (0.278 + i0.683)\ fm; \beta = 3.5\ fm^{-1};\ \ a = 10 fm; d = 2\ fm$$

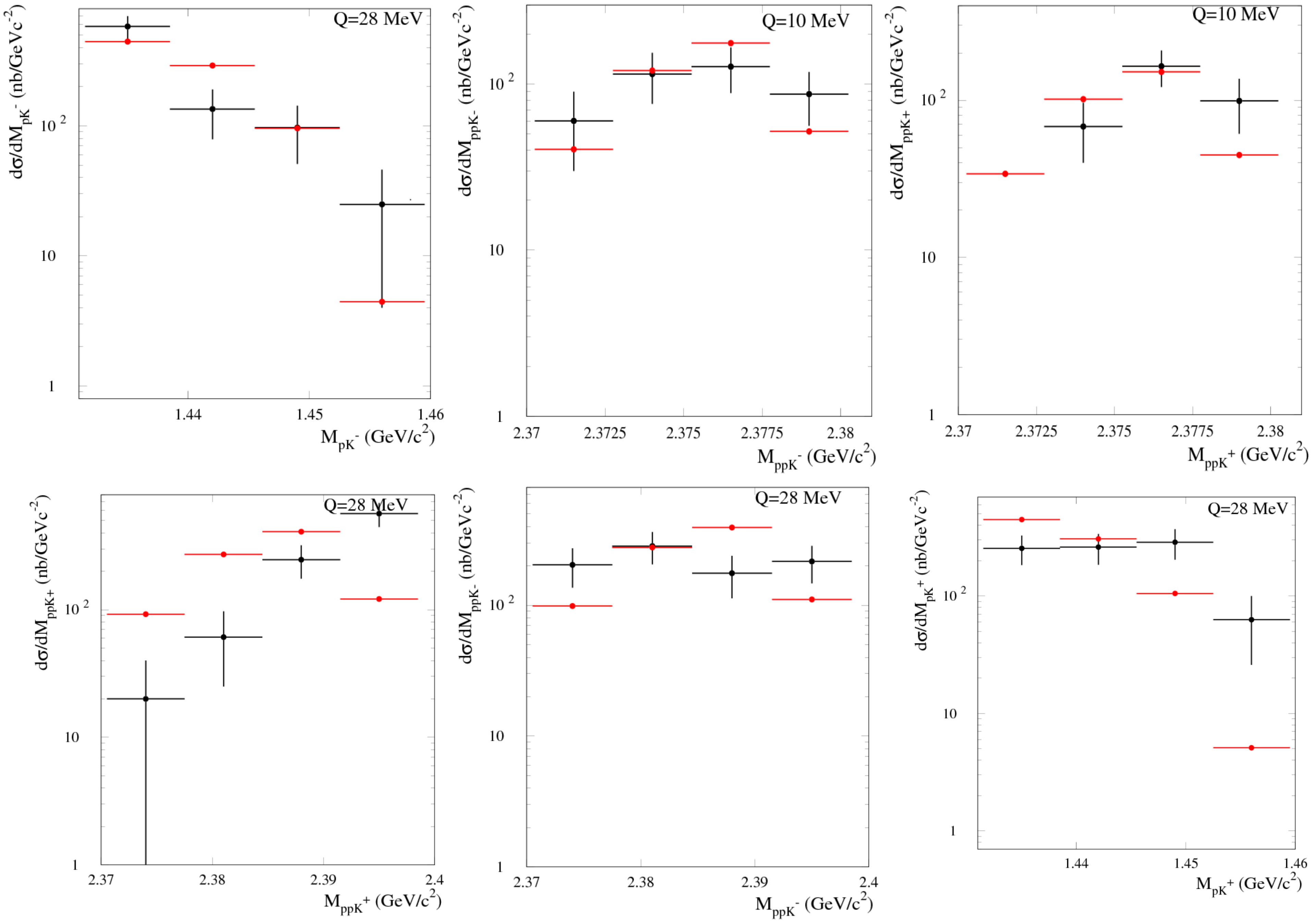
A. Deloff, private communication (based on N.V. Shevchenko, A. Gal and J. Mares, Phys. Rev. Lett. 98, 082301 (2007)





- Data
- Simulations

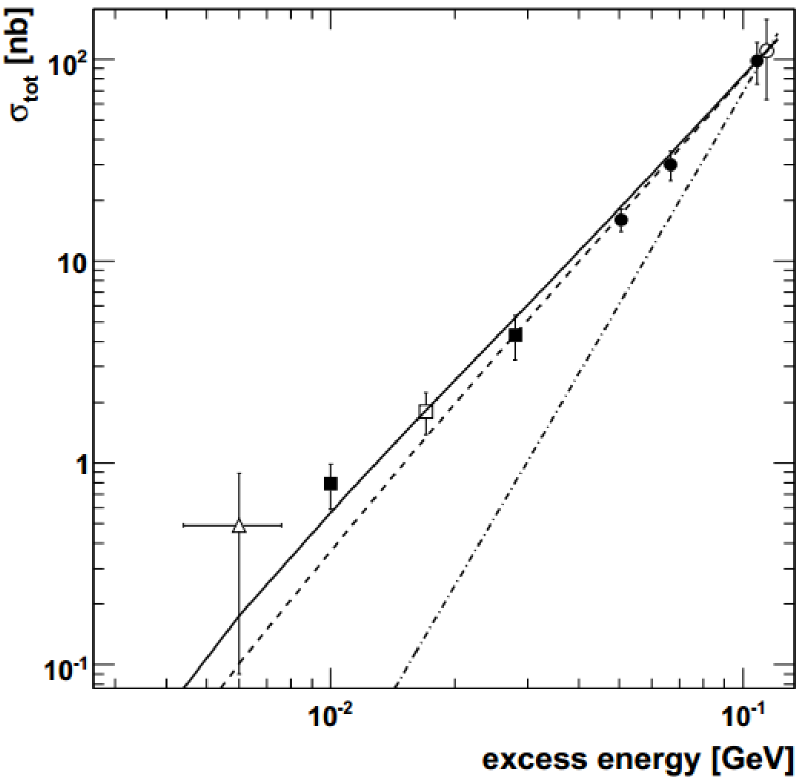



Q=28 MeV
$d\sigma/dM_{pK^-}$ (nb/GeVc^{-2})
M_{pK^-} (GeV/c^2)
Q=10 MeV
$d\sigma/dM_{ppK-}$ (nb/GeVc^{-2})
M_{ppK^-} (GeV/c^2)
Q=10 MeV
$d\sigma/dM_{ppK+}$ (nb/GeVc^{-2})
M_{ppK^+} (GeV/c^2)
Q=28 MeV
$d\sigma/dM_{ppK+}$ (nb/GeVc^{-2})
M_{ppK^+} (GeV/c^2)
Q=28 MeV
$d\sigma/dM_{ppK-}$ (nb/GeVc^{-2})
M_{ppK^-} (GeV/c^2)
Q=28 MeV
$d\sigma/dM_{pK^+}$ (nb/GeVc^{-2})
M_{pK^+} (GeV/c^2)

Conclusions & outlook

- The excitation function for the pp→ppK+K- reaction reveal an enhancement which may be assigned to the influence of the pK^- and K^+K^- interaction
- The ANKE factorization ansatz underestimates experimental data very close to threshold
- The coupled channel effects and production of f0(980)/a0(980) are up to now not distinguishable even with high statistic measuremens
- We have estimated the K+K- scattering length and effective range based on the near threshold data independently from a_{pK-} obtained by the ANKE group
- The last ANKE measurement reveals that we still do not understand fully the dynamics of the near threshold $pp \to ppK^+K^-$

THANK YOU FOR ATTENTION



$$\sigma^m = \int \frac{\pi^2 |M|^2}{8s\sqrt{-B}} \, \mathrm{d}M^2_{pp} \mathrm{d}M^2_{K^+K^-} \mathrm{d}M^2_{pK^-} \mathrm{d}M^2_{ppK^-} \mathrm{d}M^2_{ppK^+}$$

$$F_{K^+K^-}(k_3) = \frac{1}{1 - ik_3 a_{K^+K^-}}$$

$$\beta_j = \frac{L_j \alpha \sigma^m_j}{N^{gen}_j}$$

Generalization of the Dalitz Plot

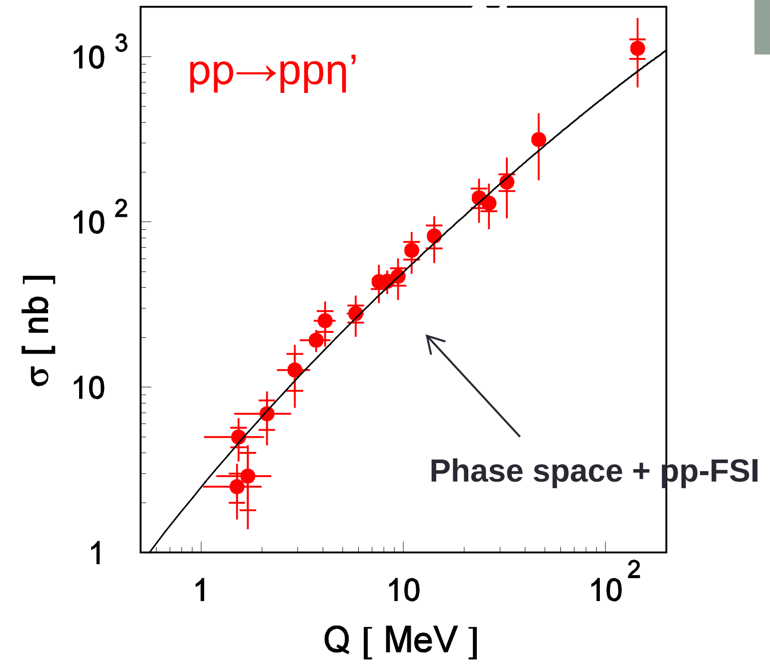
❑ Probability of reaction yielding a state with the *i*-th particle in momentum range dp_i (in CM):

$$d^{12}R = d^3 p_1 d^3 p_2 d^3 p_3 d^3 p_4 \frac{1}{16E_1E_2E_3E_4}\delta^3\left(\sum_j \vec{p}_j\right)\delta\left(\sum_j E_j - \sqrt{s}\right) f^2$$

❑ Assuming that f depends only on invariant masses of the particles one obtains (**Nyborg et al. Phys. Rev. 140 922 (1965)**):

$$d^5R = f^2 \frac{\pi^2}{8s\sqrt{-B}} dM_{12}^2 dM_{14}^2 dM_{34}^2 dM_{124}^2 dM_{134}^2$$

$$B = B\left(M_1^2, M_{21}^2, M_{43}^2, M_4^2, M_{21}^2, m_{431}^2, m_{24}^2, m_3^2, m_4^2, E^2\right)$$



$$\left|M_{pp\to ppK^+K^-}\right|^2 \approx \left|M_0\right|^2 \left|F_{FSI}\right|^2$$

$$F_{FSI} = F_{pp}(q) \times F_{p_1K^-}(k_1) \times F_{p_2K^-}(k_2)$$

$$F_{pp}(q) = \frac{e^{-i\delta_{pp}(^1S_0)} \times \sin\delta_{pp}(^1S_0)}{C \times q}$$

$$F_{pK^-}(k) = \frac{1}{1 - ika}$$

$$a = (0 + i1.5)[\mathrm{fm}]$$