Search for kaonium at COSY and possible future experiments at DAFNE

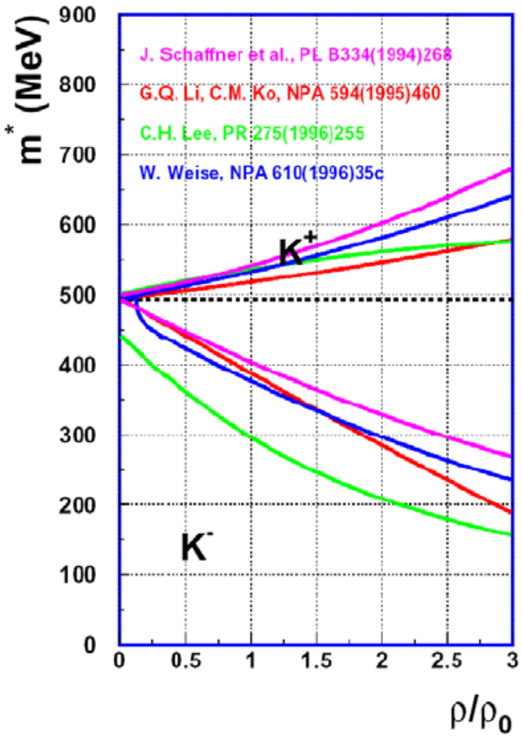
M. Silarski
Jagiellonian University

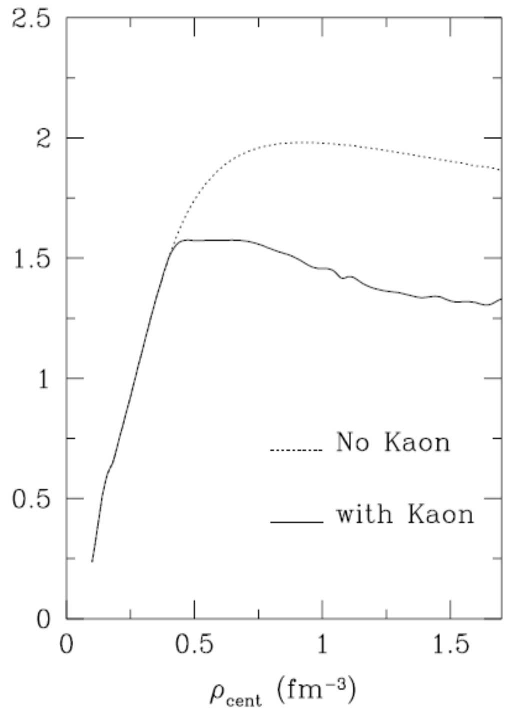
- **Motivation**
- **Proton-proton collisions at K^+K^- threshold: COSY**
- **Perspectives for kaon-antikaon interaction studies at e^+e^- colliders**
- **Conclusions & outlook**

Fundamental Physics at_the Strangeness_Fronter at DAFNE
25-26.02.2021

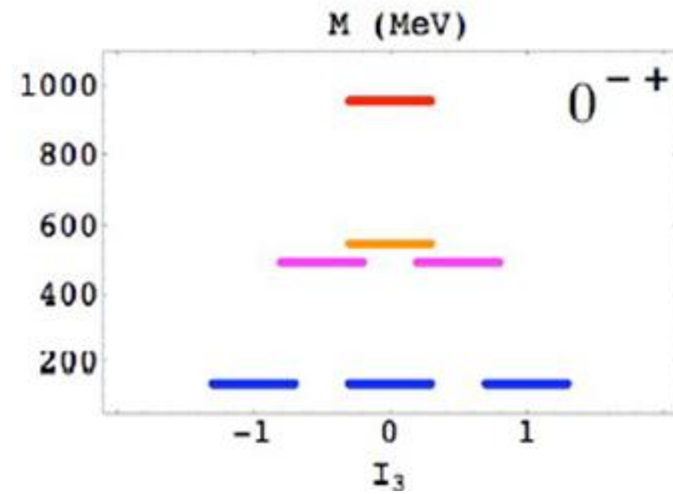
Motivation

- a_0 and f_0 mesons as a K^+K^- molecules
- Physics of neutron stars:kaon condensates

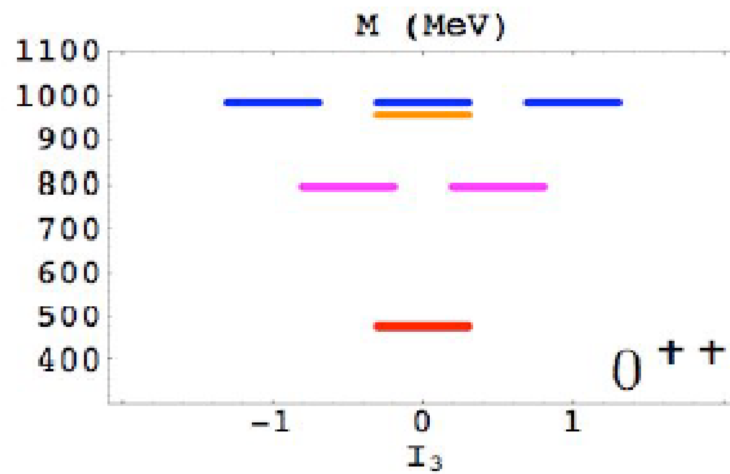




Pseudoscalar mesons



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



proton-proton collisions at K^+K^- threshold: COSY

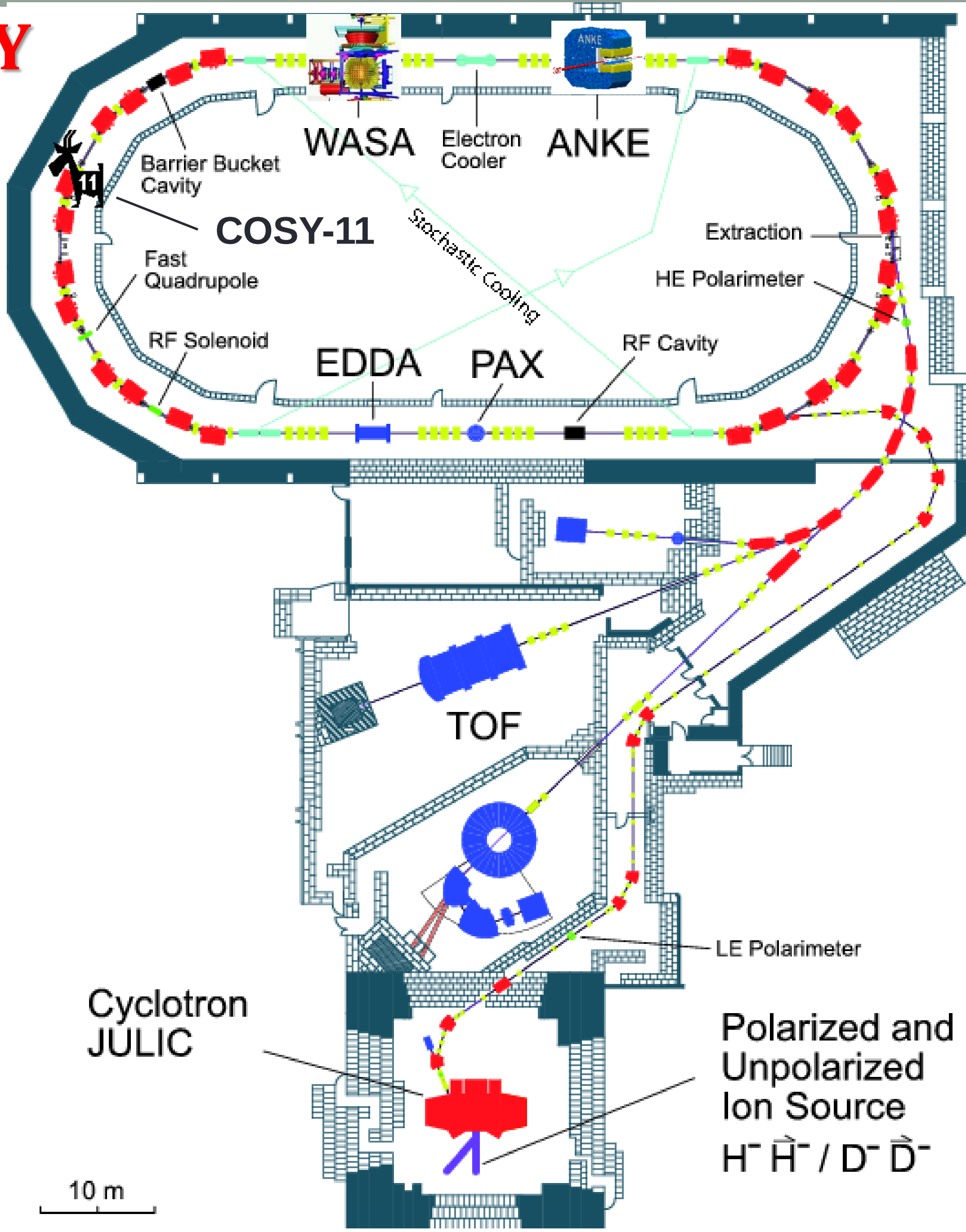
$$pp \rightarrow ppK^+K^-$$

$$pp \rightarrow ppa_0/f_0 \rightarrow ppK^+K^-$$

$$pp \rightarrow pK^+\Lambda(1405) \rightarrow ppK^+K^-$$

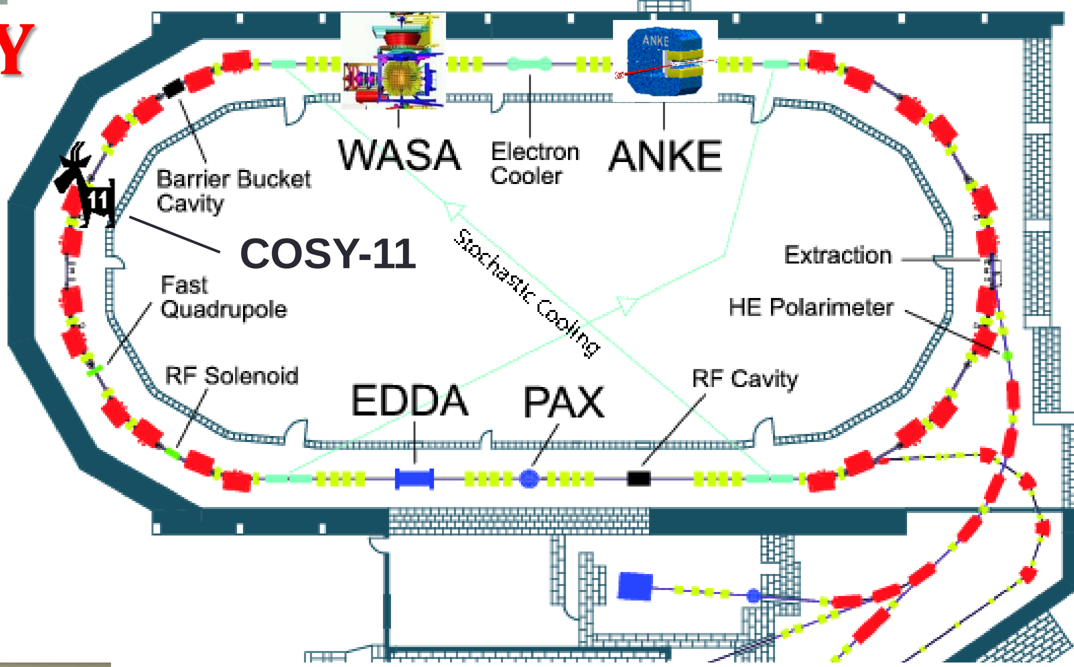
COoler Synchrotron COSY

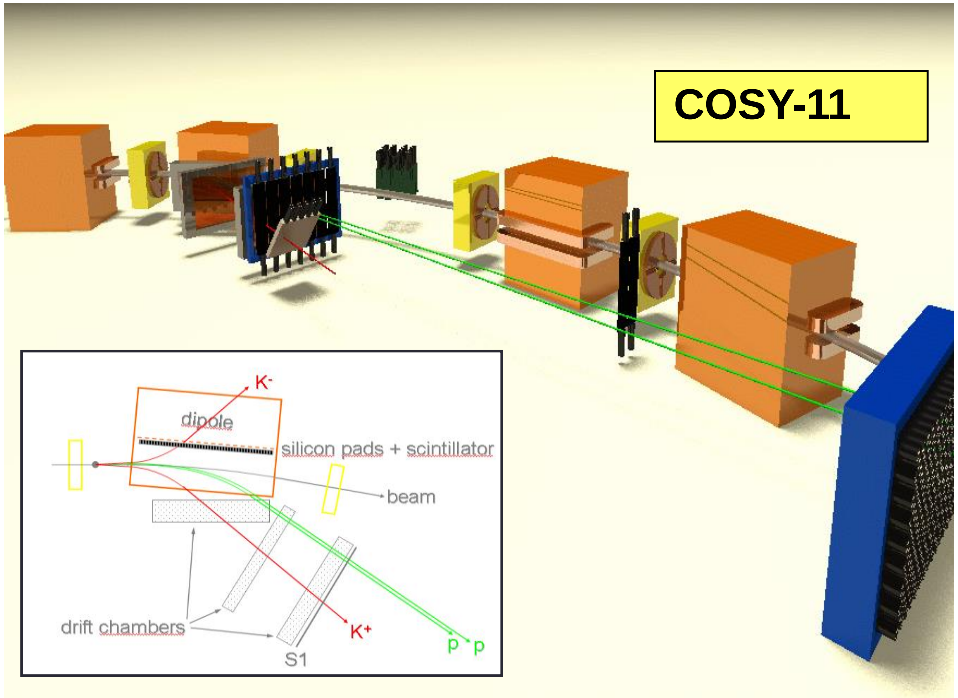
- Ring with a circumference of 184 m
- Polarised and unpolarised proton and deuteron beams
- Momentum range: 600 – 370 MeV/c
- Stochastic and electron cooling
- Meson production up to $\phi(1020)$
- **Precise beam momentum determination ($\Delta p/p \sim 10^{-3}$)**

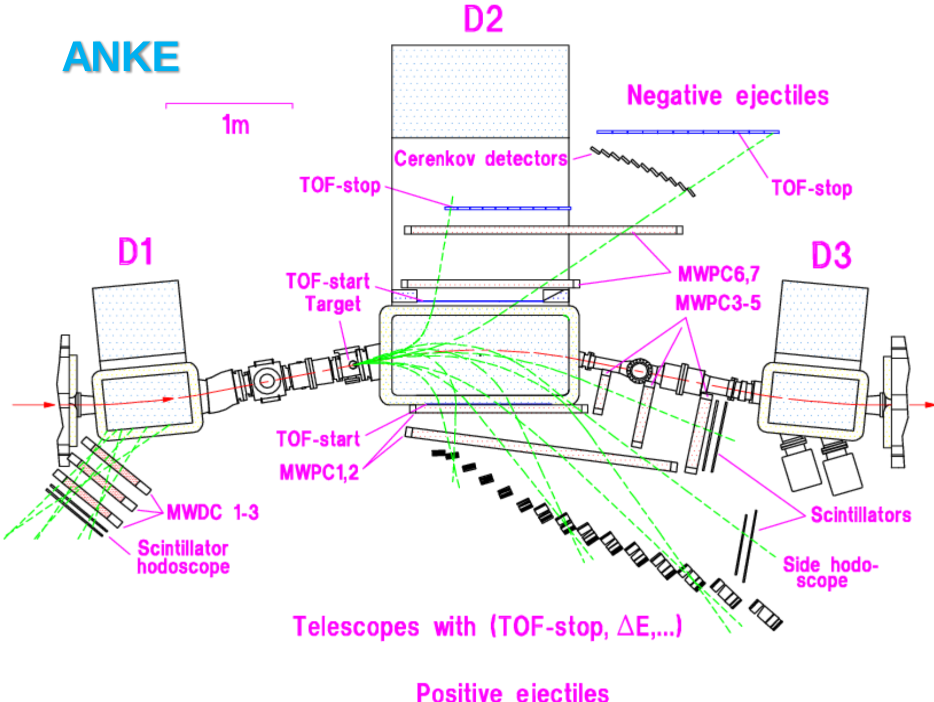


COoler Synchrotron COSY

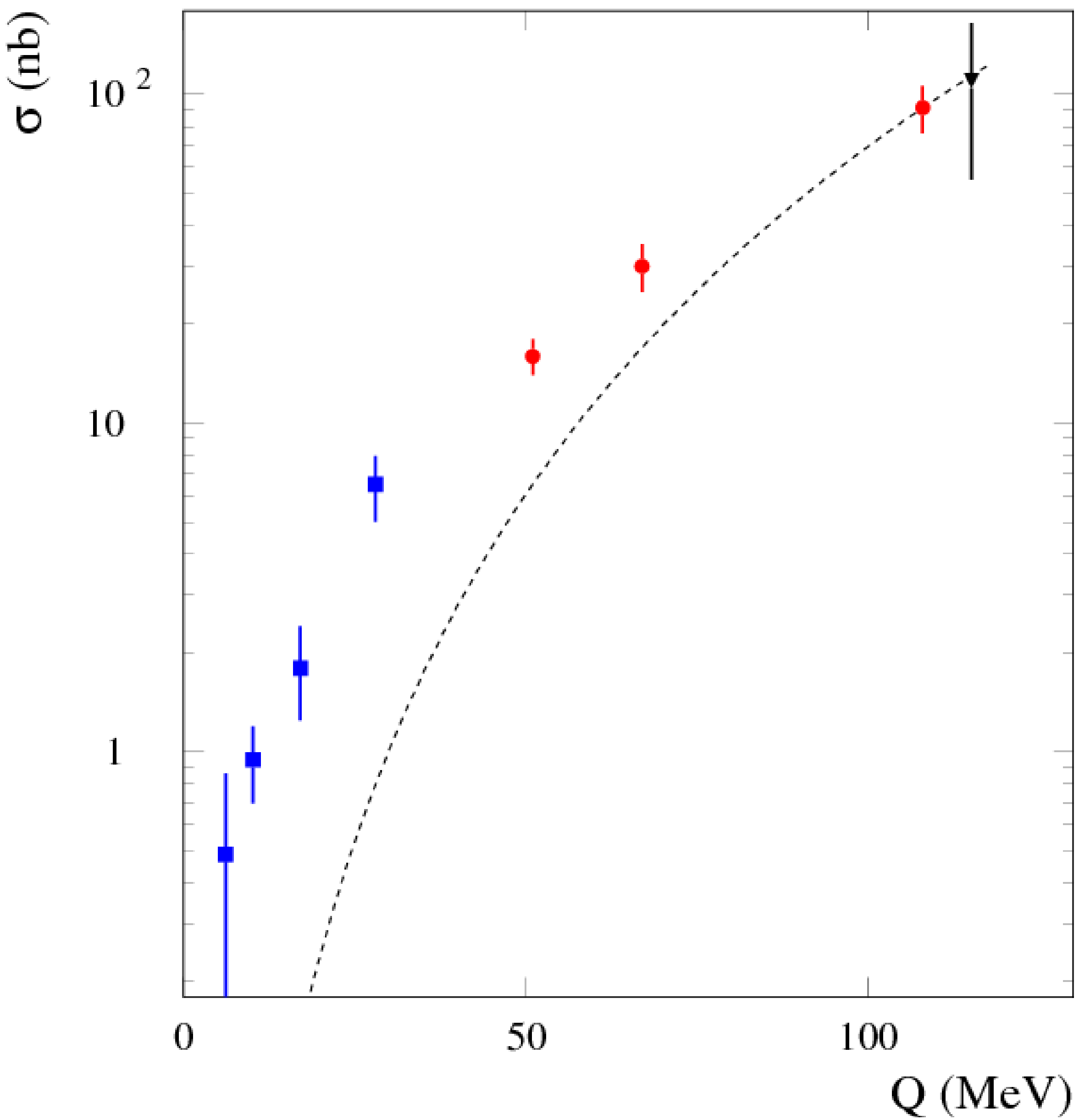
- Ring with a circumference of 184 m
- Polarised and unpolarised proton and deuteron beams
- Momentum range: 600 – 370 MeV/c
- Stochastic and electron cooling
- Meson production up to $\phi(1020)$
- **Precise beam momentum determination ($\Delta p/p \sim 10^{-3}$)**







The pp→ppK⁺K⁻ excitation function



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

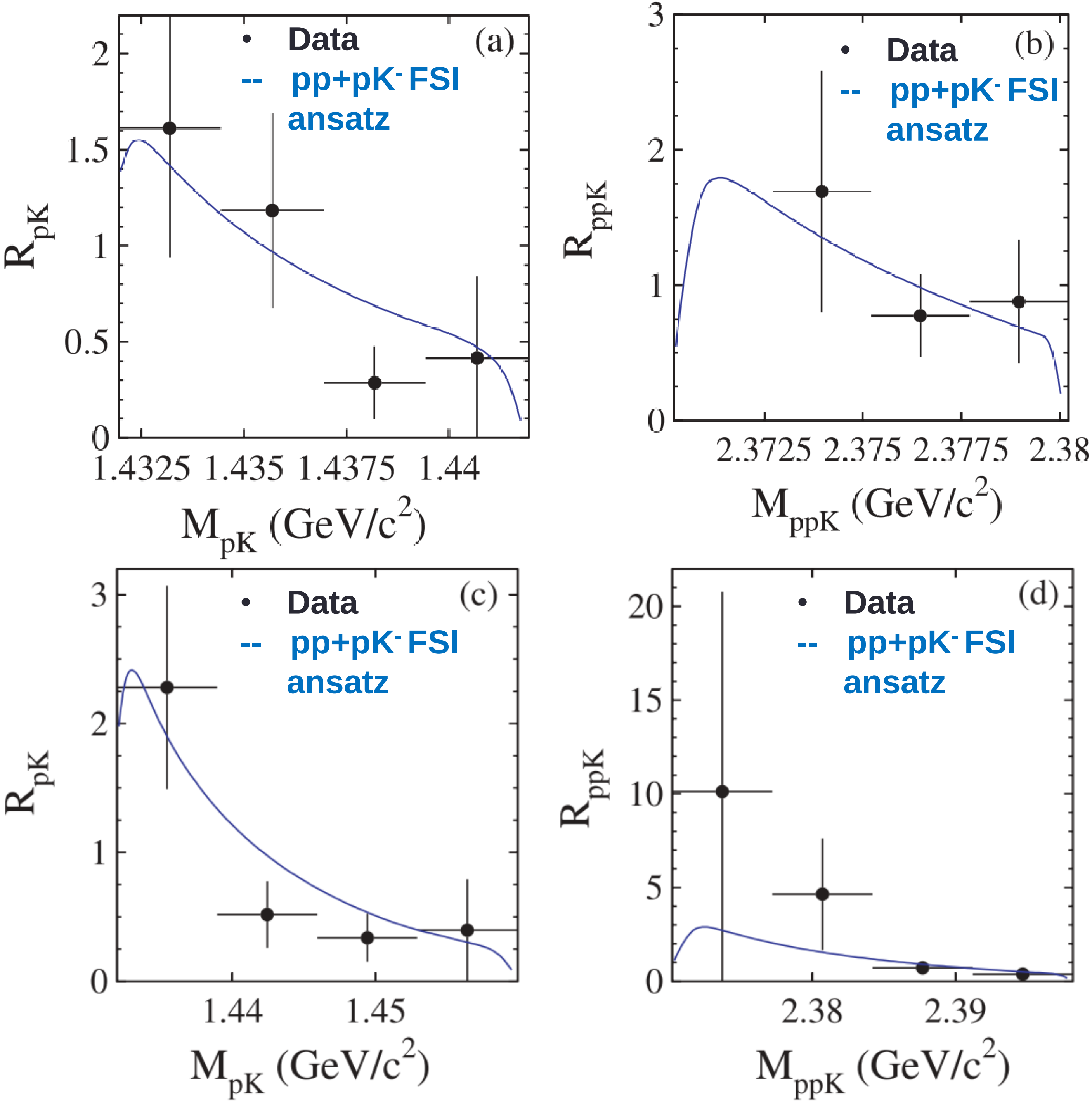
ANKE: Y.Maeda et al.,
Phys., Rev. C 77, 01524 (2008)

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

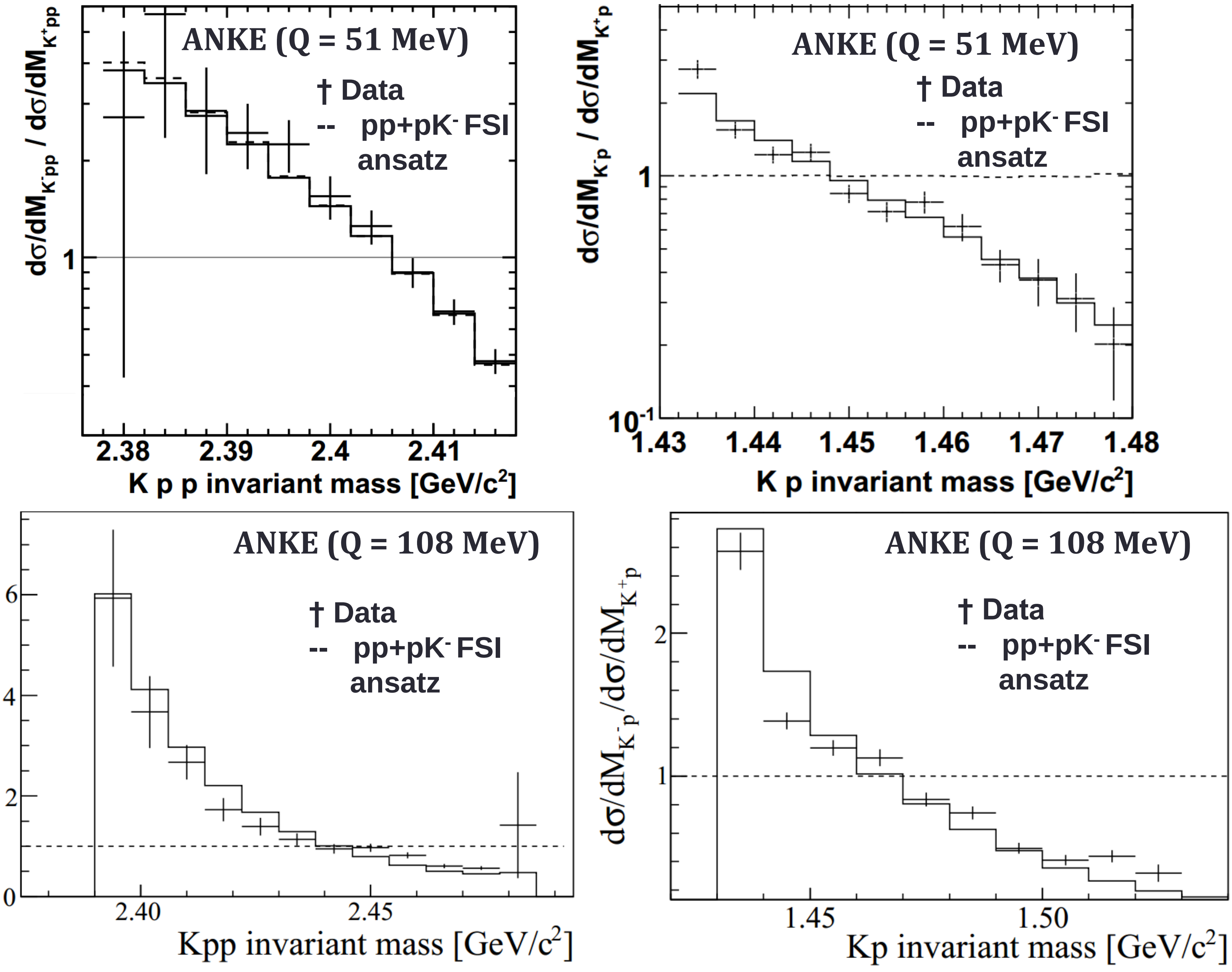


COSY-11
(Q = 10 MeV)

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

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

COSY-11
(Q = 28 MeV)


ANKE (Q = 51 MeV)
† Data
-- pp+pK⁻ FSI ansatz
dσ/dM_{K⁻pp} / dσ/dM_{K⁺pp}
1
2.38
2.39
2.4
2.41
K p p invariant mass [GeV/c²]
ANKE (Q = 51 MeV)
† Data
-- pp+pK⁻ FSI ansatz
dσ/dM_{K⁻p} / dσ/dM_{K⁺p}
1
10⁻¹
1.43
1.44
1.45
1.46
1.47
1.48
K p invariant mass [GeV/c²]
ANKE (Q = 108 MeV)
† Data
-- pp+pK⁻ FSI ansatz
dσ/dM_{K⁻pp}/dσ/dM_{K⁺pp}
0
2
4
6
2.40
2.45
Kpp invariant mass [GeV/c²]
ANKE (Q = 108 MeV)
† Data
-- pp+pK⁻ FSI ansatz
dσ/dM_{K⁻p}/dσ/dM_{K⁺p}
1
2
1.45
1.50
Kp invariant mass [GeV/c²]

Parametrization of the Final State Interaction

$$\sigma = \frac{1}{F}\int dV_{ps}\,|M|^2$$

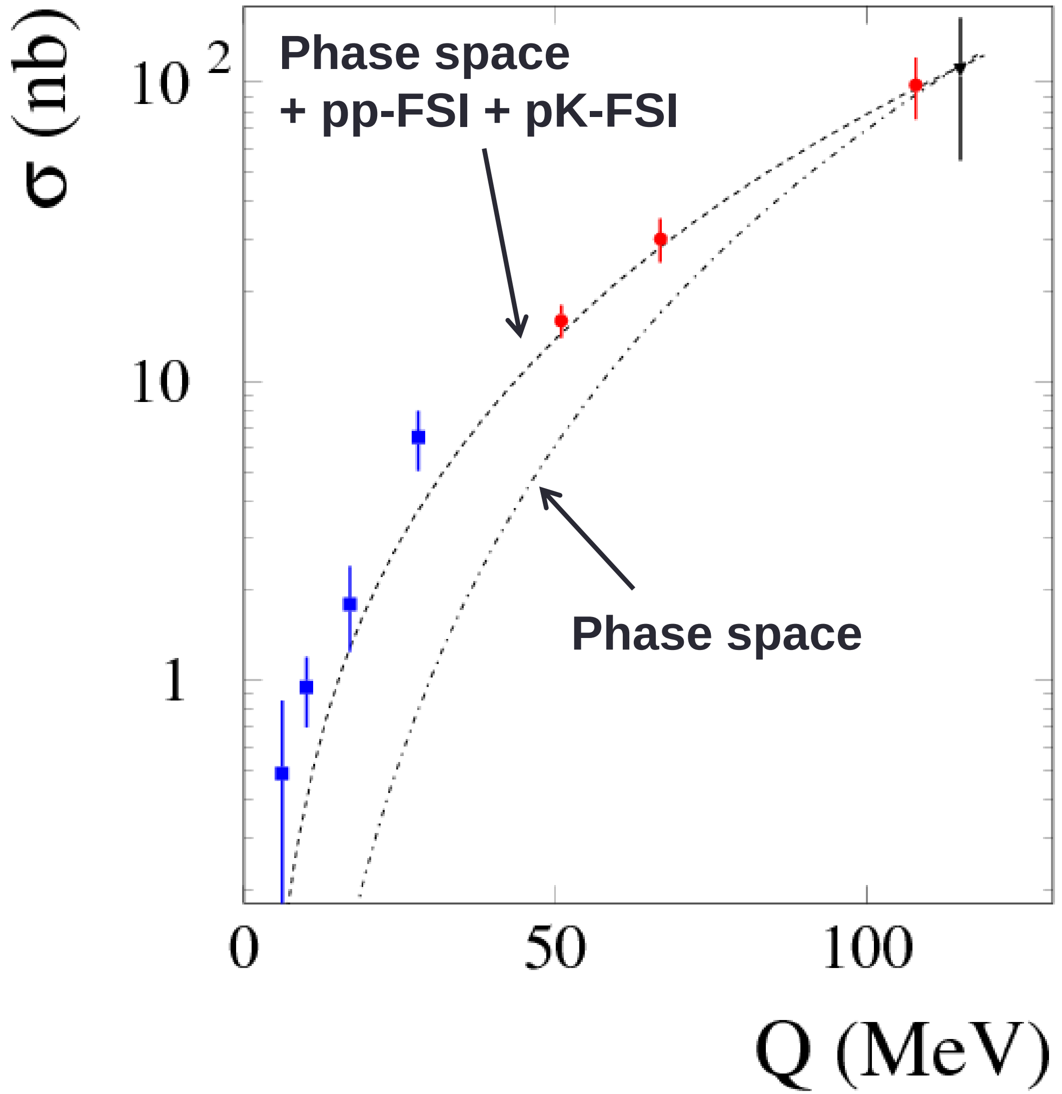
$$|M|^2 \approx |M_0|^2 |F_{FSI}|^2$$

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

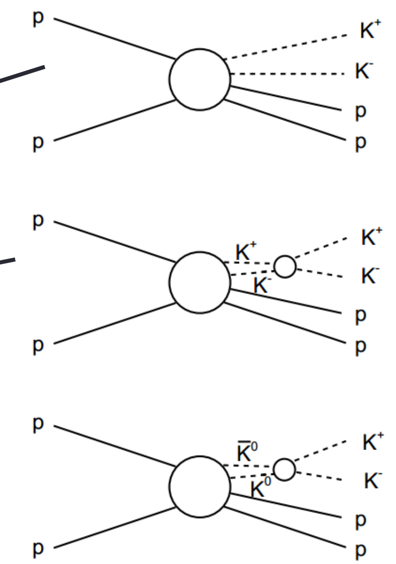
$$F_{pp}(q) = \frac{e^{i\delta_{pp}(^1S_0)} \times \sin\delta_{pp}(^1S_0)}{C \times q}$$

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

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



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

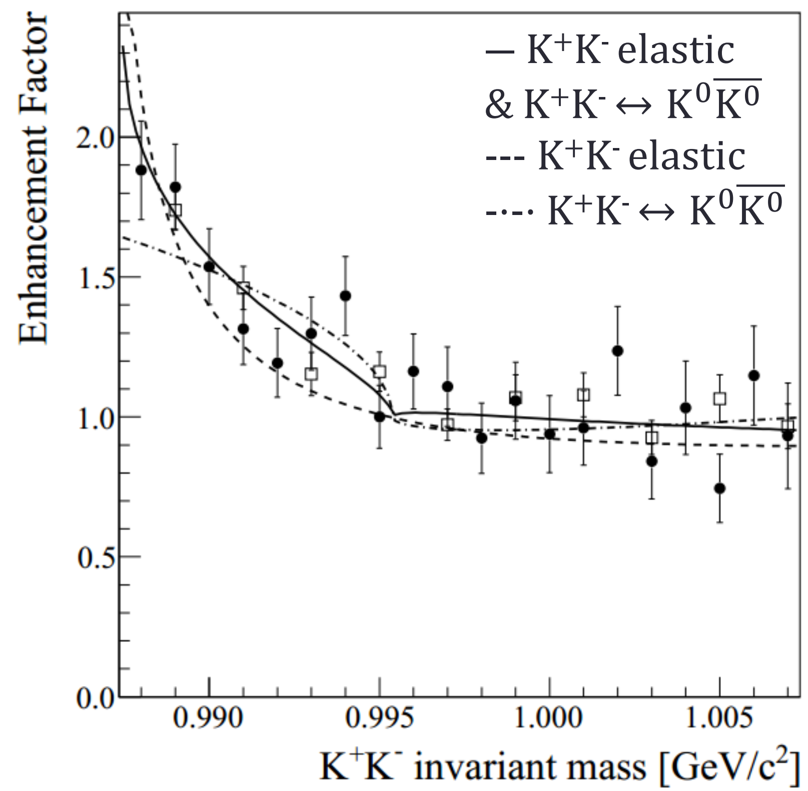


$$\mathcal{F} = \left| \frac{B_1/(B_1+B_0)}{\left(1 - i\frac{1}{2}q[A_1 - A_0]\right)(1 - ikA_1)} + \frac{B_0/(B_1+B_0)}{\left(1 - i\frac{1}{2}q[A_0 - A_1]\right)(1 - ikA_0)} \right|$$

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

$$|M|^2 \approx |M_0|^2 |F_{FSI}|^2$$

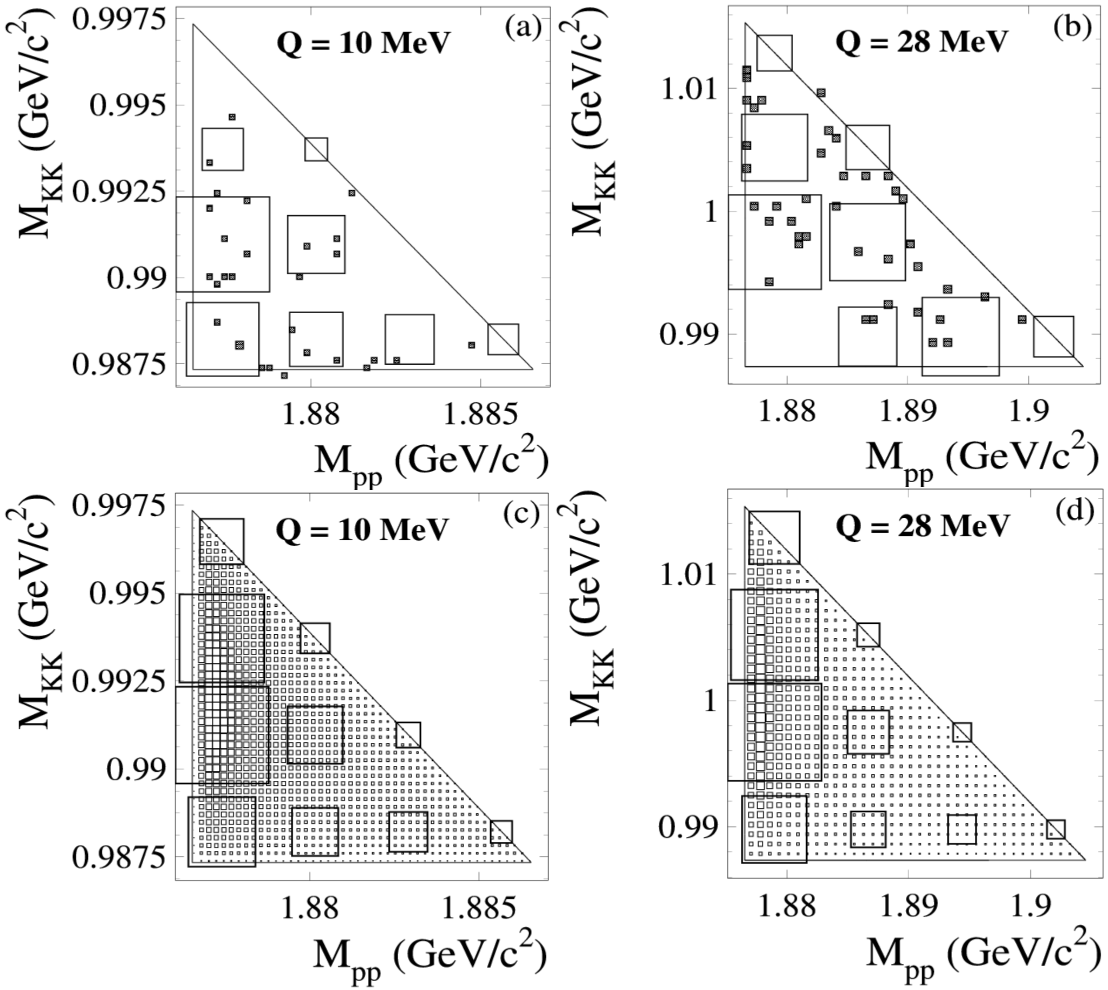
$$F_{FSI} = F_{pp}(q) \times F_{p_1K^-}(k_1) \times F_{p_2K^-}(k_2) \times F_{K^+K^-}(k_3)$$

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

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

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

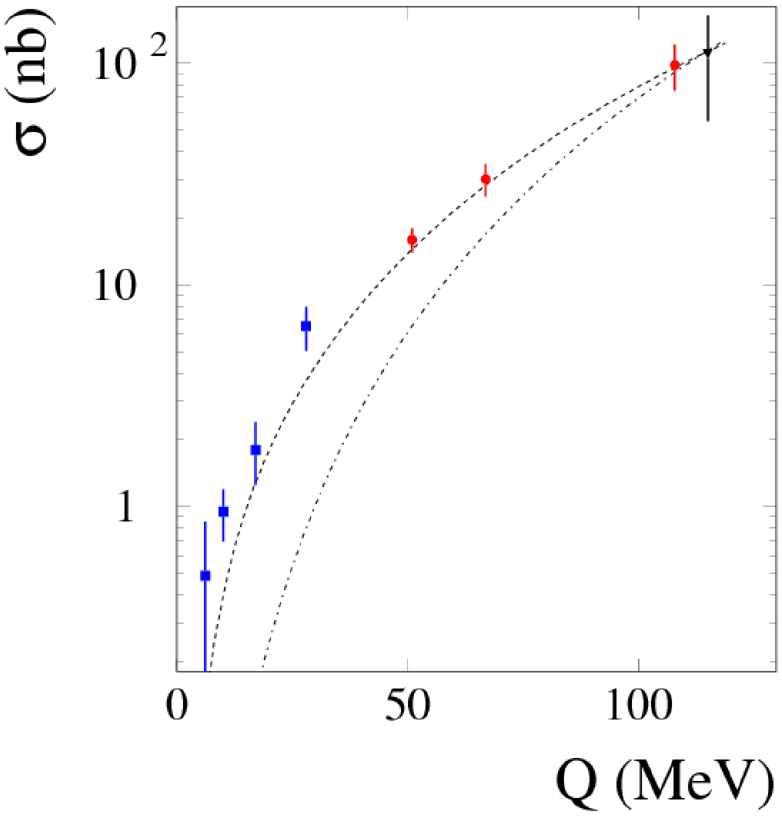
$$a_{pK^-} = (0 + i1.5)[\mathrm{fm}]$$

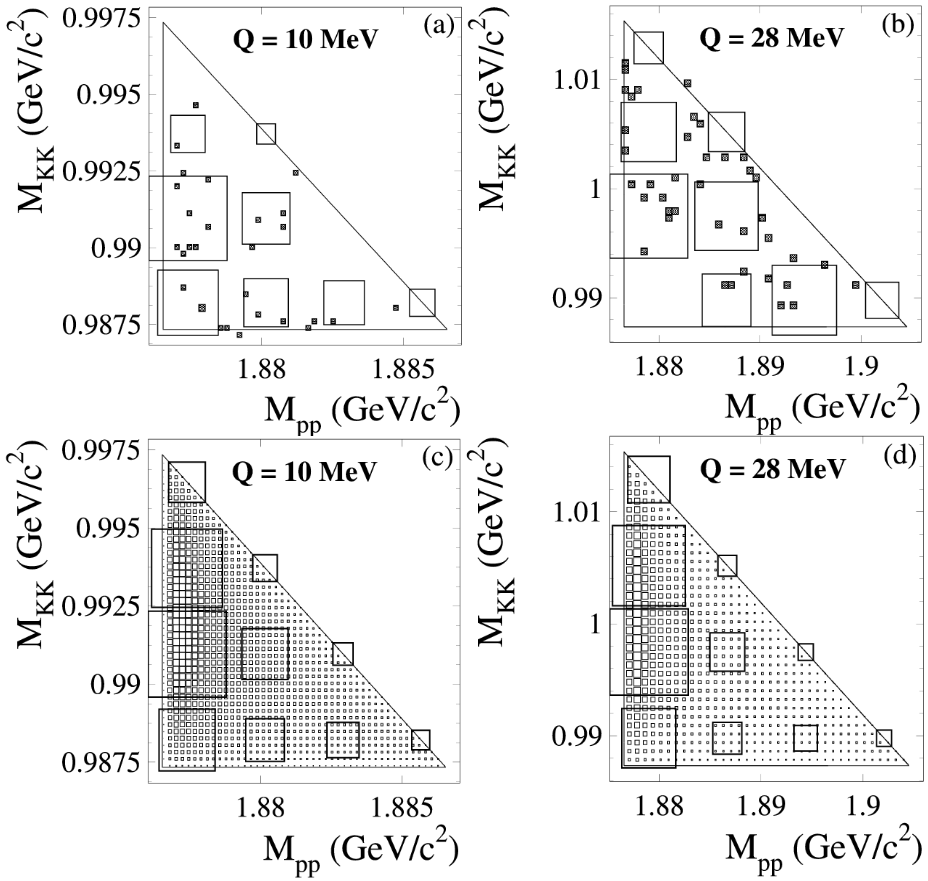


M. Silarski, et al.,Phys. Rev. C 80, 045202 (2009)

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

- 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])

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

Results for the effective range expansion fit

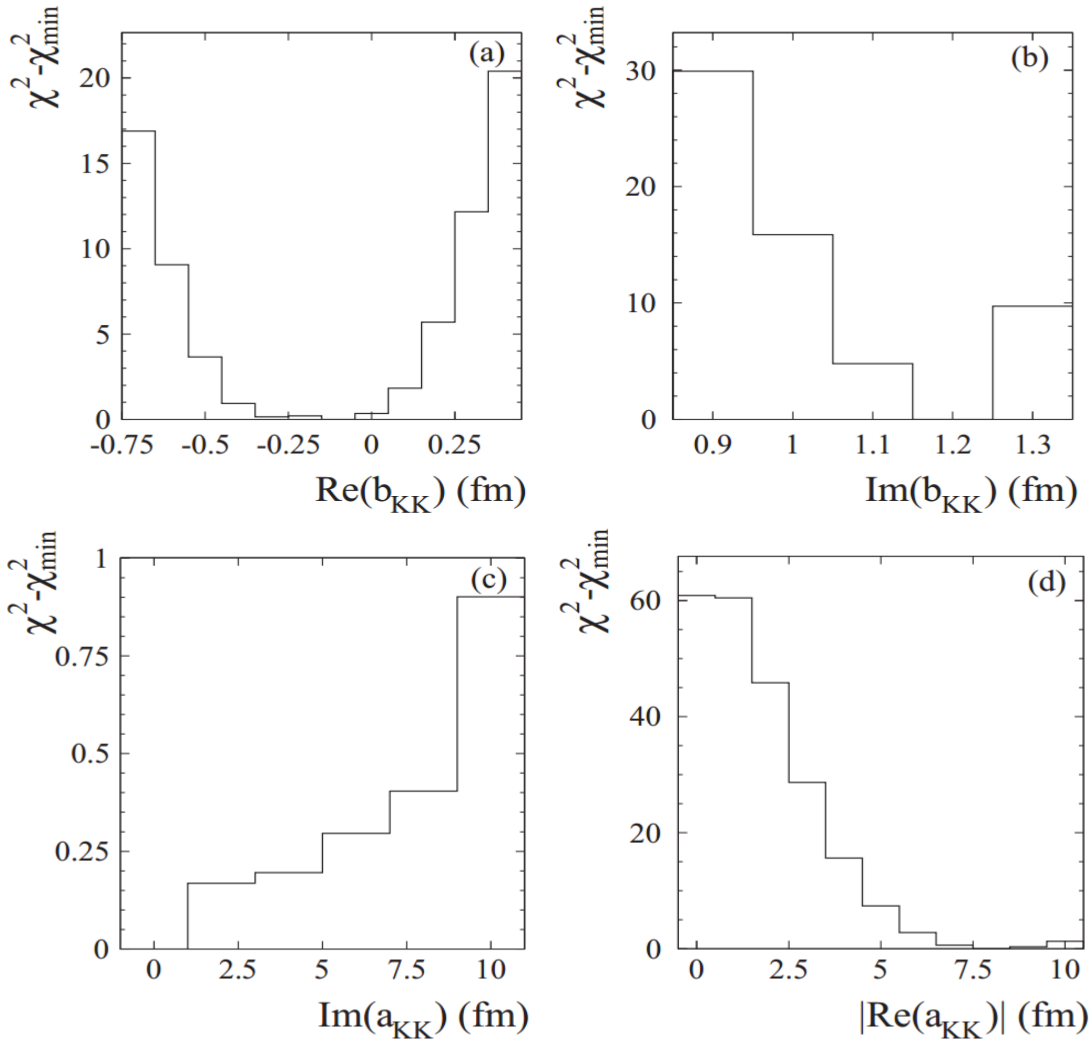
$$\mathrm{Re}(b_{K^+K^-}) = -0.1 \pm 0.4_{\mathrm{stat}} \pm 0.3_{\mathrm{sys}}\ \mathrm{fm}$$

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

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

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

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



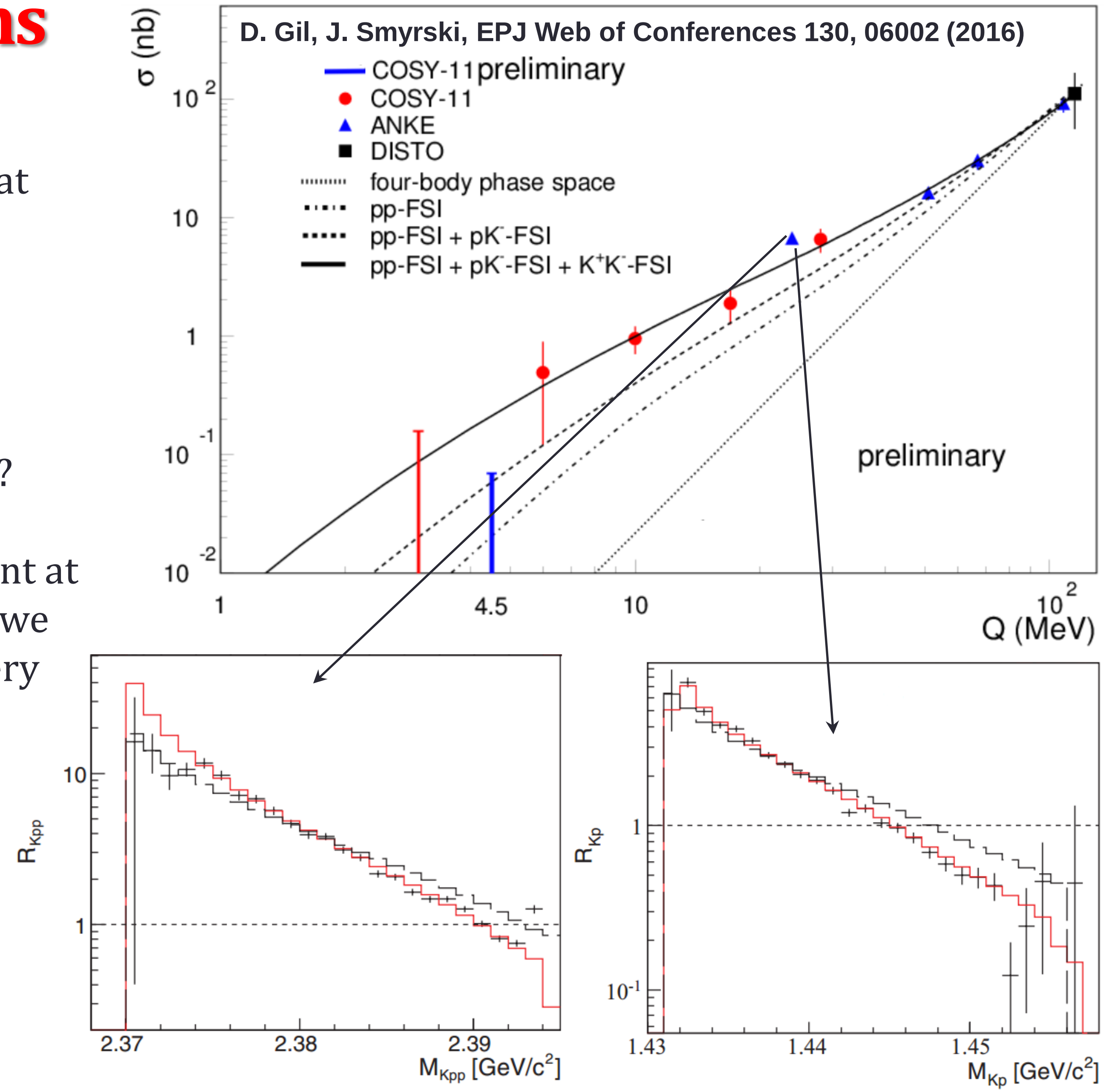
$$\chi^2\left(a_{K^+K^-},\alpha\right) = \sum_{i=1}^{8} \frac{(\sigma_i^{exp} - \alpha\sigma_i^{m})^2}{(\Delta\sigma_i^{exp})^2} + 2\cdot \sum_{j=1}^{2}\sum_{k=1}^{10}\left[\beta_j N_{jk}^s - N_{jk}^e + N_{jk}^e \ln\left(\frac{N_{jk}^e}{\beta_j N_{jk}^s}\right)\right]$$

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?

- Last COSY-11 measurement at Q=4.5 MeV suggests that we overestimated the data very close to threshold

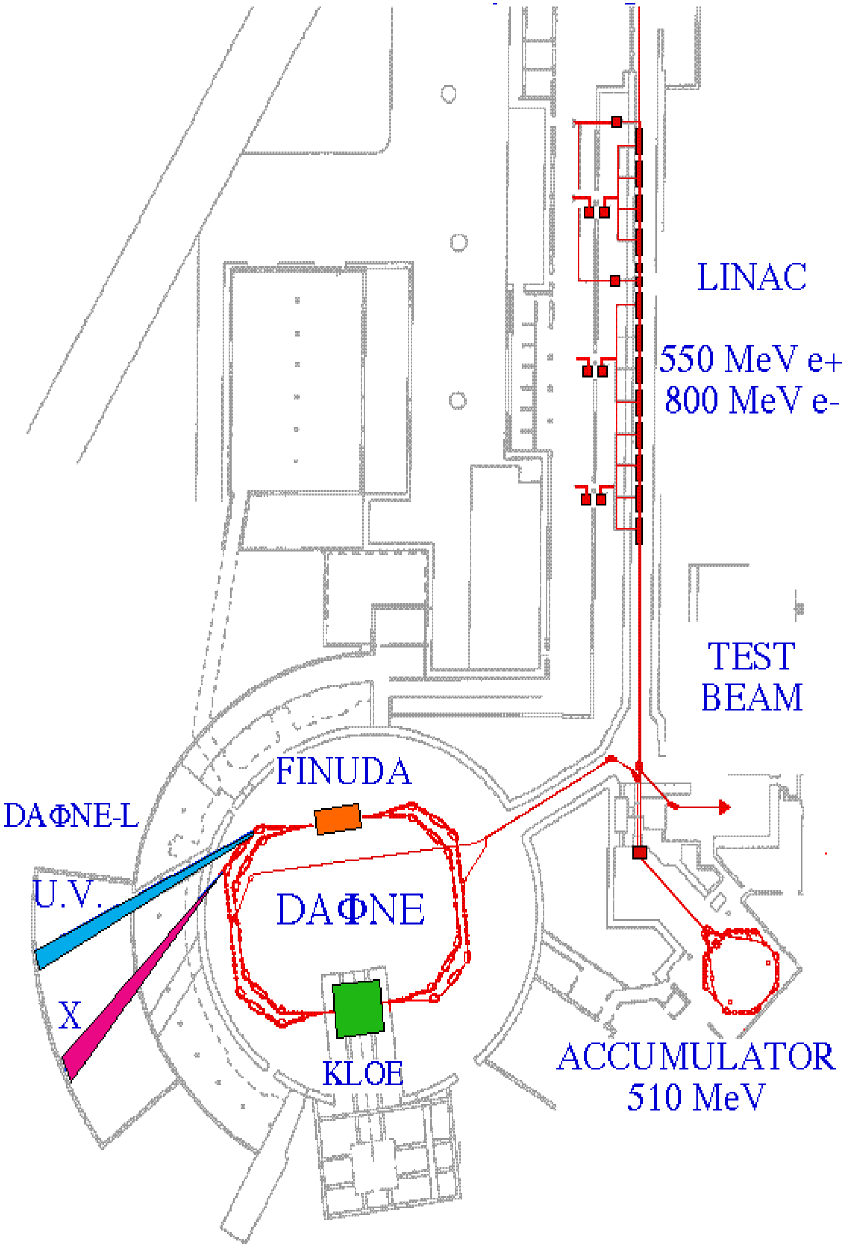


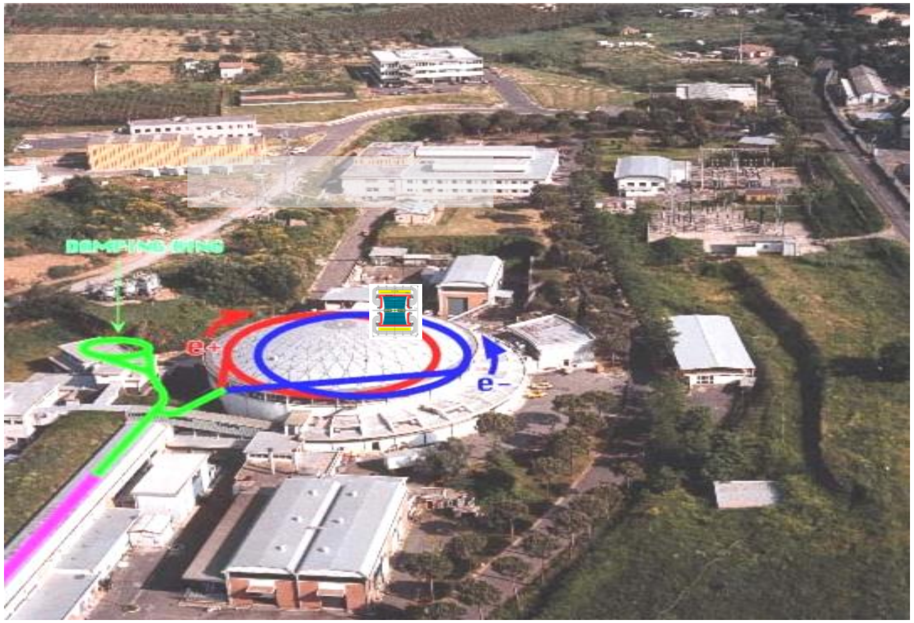
Q. J. Ye et al., Phys. Rev. C 87, 065203 (2013)

Promissing alternative: DAΦNE

$$e^+e^- \to K^+K^-\gamma$$
$$e^+e^- \to K^0\overline{K}\gamma$$

DAΦNE & KLOE





- e^+e^- collider @ $\sqrt{s} = M_\varphi = 1019.4$ MeV
- $\sigma_{peak} \sim 3\ \mu b$
- Separate e^+e^- rings to reduce beam-beam interaction

KK –FSI @ Φ-mass peak

- **Advantage with respect to pp→ ppK$^+$K$^-$: only two interacting particles**
- The K+ K- threshold lies close to the DAFNE working point
- To fully describe the K$^+$K$^-$ -FSI we need to measure:

$e^+e^- \to \pi^0\pi^0\gamma$ [EPJC49(2007)473]

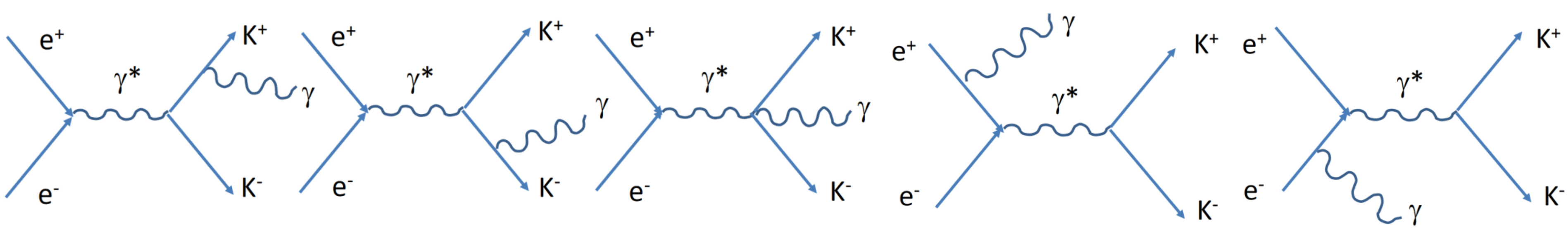
$e^+e^- \to \pi^+\pi^-\gamma$ [PLB606(2005)12, PLB670(2009)285, PLB700(2011)102]

$e^+e^- \to \pi^0\eta\gamma$ [PLB681(2009)5]

$\boldsymbol{e^+e^- \to K_S\, K_S\gamma}$ **[PLB679(2009)10]**

$\boldsymbol{e^+e^- \to K^+K^-\gamma}$

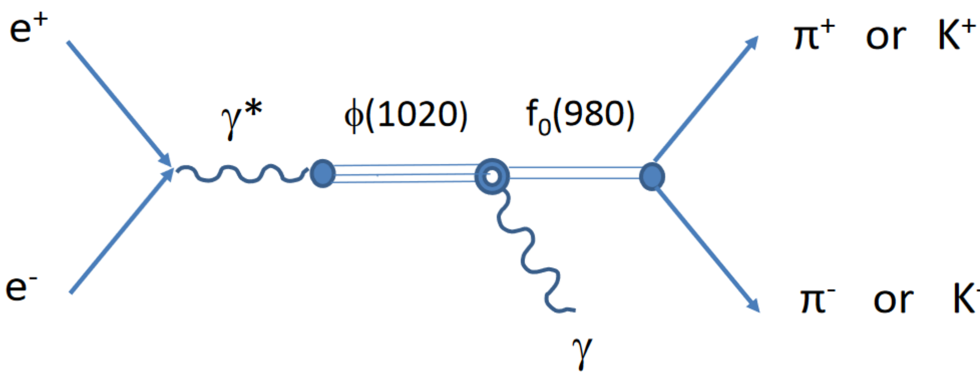
- Parameters of the scalar resonances found so far in experimental analyses are very much model dependent
- Huge background due to ISR and FSR processes



FSR – final state radiation

ISR – initial state radiation

Reaction mechanisms

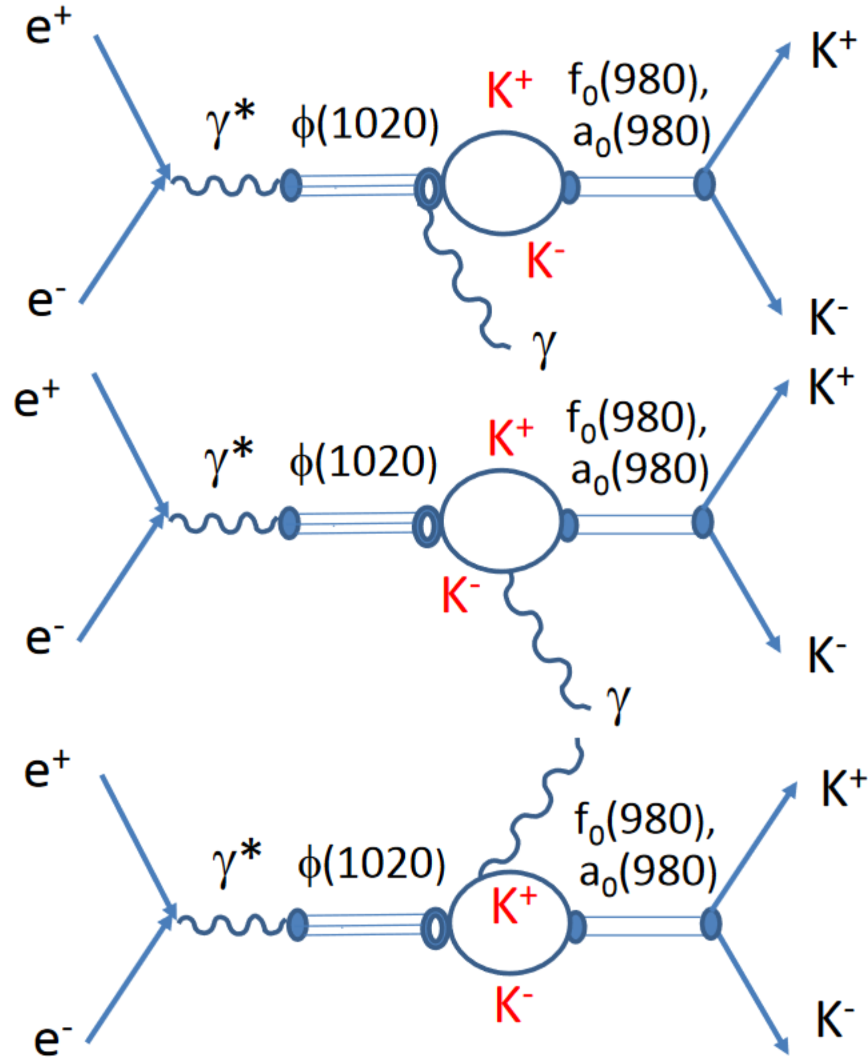


NS – no-structure model

G. Isidori, L. Maiani, M. Nicolaci, S. Pacetti JHEP 0605 (2006) 049.

$$|M_{tot}|^2 = |A_{ISR} + A_{FSR} + A_{KK-FSI}|^2$$

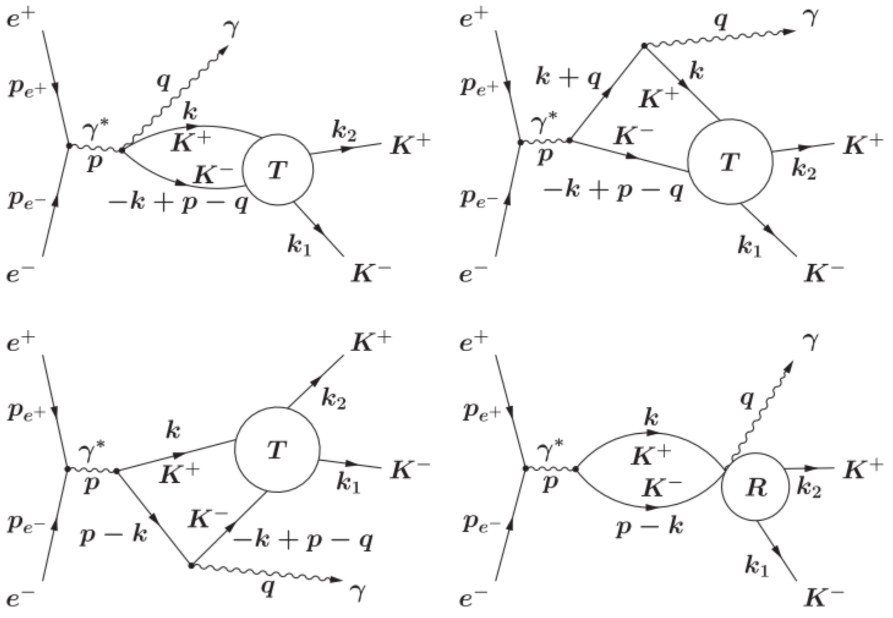
❖ If we choose experimental cuts symmetrically with respect to K^+-K^- interchange the FSR-ISR and ISR-FSI terms vanish

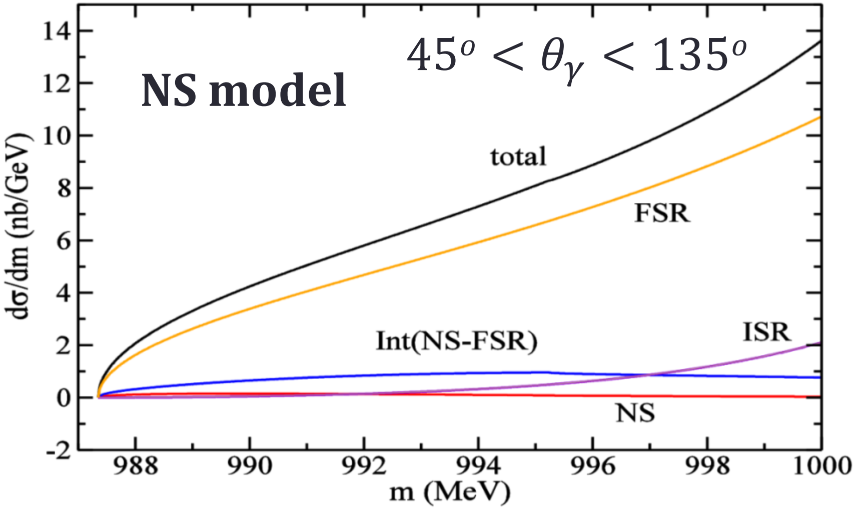


Kaon-loop model

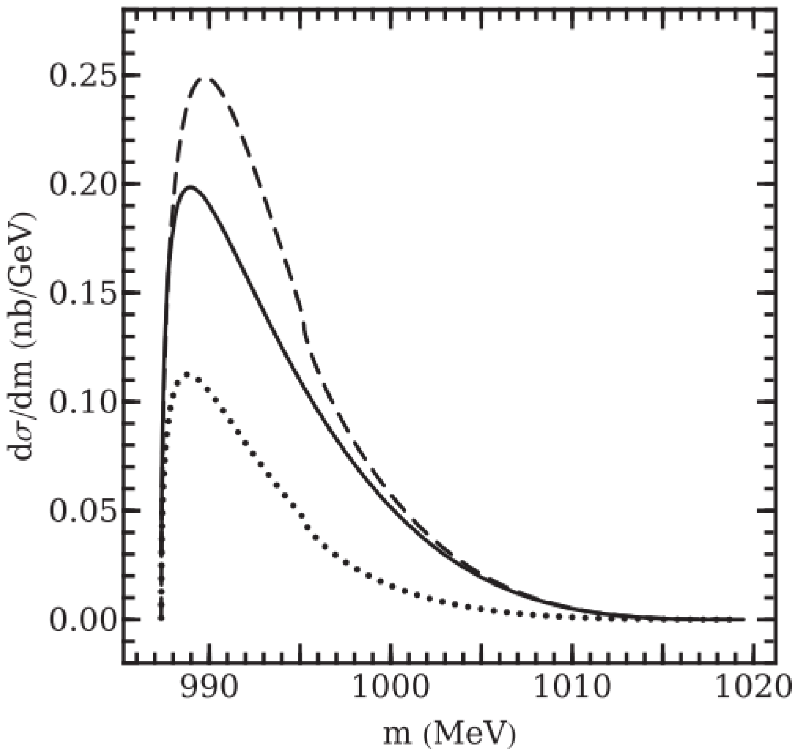
N. N. Achasov, V. V. Gubin, V. Shevchenko , PRD 56 (1997) 203

K^+K^- effective mass distributions





L. Leśniak, M. Silarski, EPJ Web Conf. 130 (2016) 06003

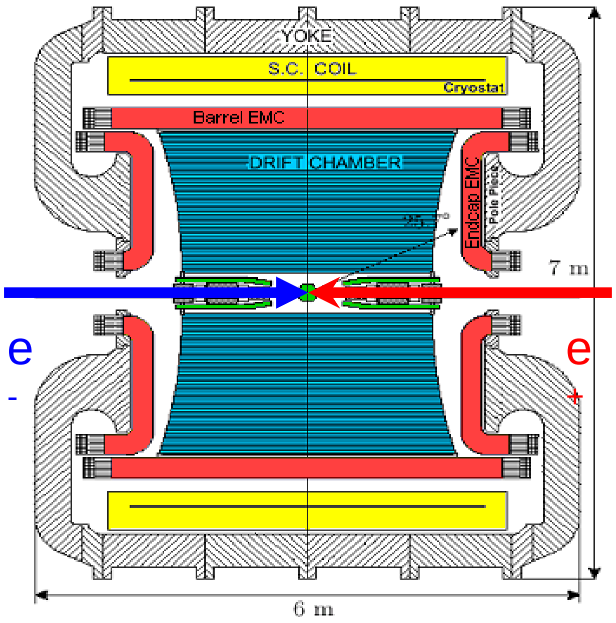


L. Leśniak, F. Sobczuk, M. Silarski, F. Morawski, Phys. Rev. D 98, 054013 (2018)

Leśniak et al. Can be used to describe all of the coupled channels needed to determine the K^+K^- scattering parameters

Measurement with a KLOE-like experiment @ DAFNE

- Estimated total cross sections for the $e^+e^- \to KK\gamma$ and corresponding branching fractions:
  $\sigma_{tot}(e^+e^- \to K^+K^-\gamma) \cong 0.85 - 3.37$ [pb]
  $BR(e^+e^- \to K^+K^-\gamma) \cong (2.05\text{-}8.13)\cdot 10^{-7}$
  $\sigma_{tot}(e^+e^- \to K^0\overline{K^0}\ \ \gamma) \cong 0.1\text{- }03.4$ [pb]
  $BR(e^+e^- \to K^0\overline{K^0}\ \ \gamma) \cong (2.5\text{-}8.1)\cdot 10^{-8}$



- Compact detection setup: tracker + calorimeter
- Requirements:
  - Very good kaon momentum determination
  - High statistics (for neutral kaon channel)
  - Precise measurement of low energy photons (E< 32 MeV)
  - Low p_t tracks for low K^+K^- invariant masses

- Might be used to measure the charged kaon mass as well..
- **Challenging measurement**

Conclusions & outlook

- The excitation function for the $pp \rightarrow ppK^+K^-$ reaction reveal an enhancement which may be assigned to the influence of the pK^- and K^+K^- interaction

- Unfortunately, the data does not give any conclusion about existence of the kaonium

- The measurement of K^+K^- threshold parameters of the strong interaction amplitudes with the KLOE detector is not possible.

- We have developed a new theoretical model to describe all the coupled channels in the e^+e^- collisions which may constrain more the parameters of scalar resonances

THANK YOU FOR ATTENTION

Generalization of the Dalitz Plot

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

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

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

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

[illegible]

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

$$\beta_j = \frac{L_j \alpha \sigma_j^m}{N_j^{gen}}$$

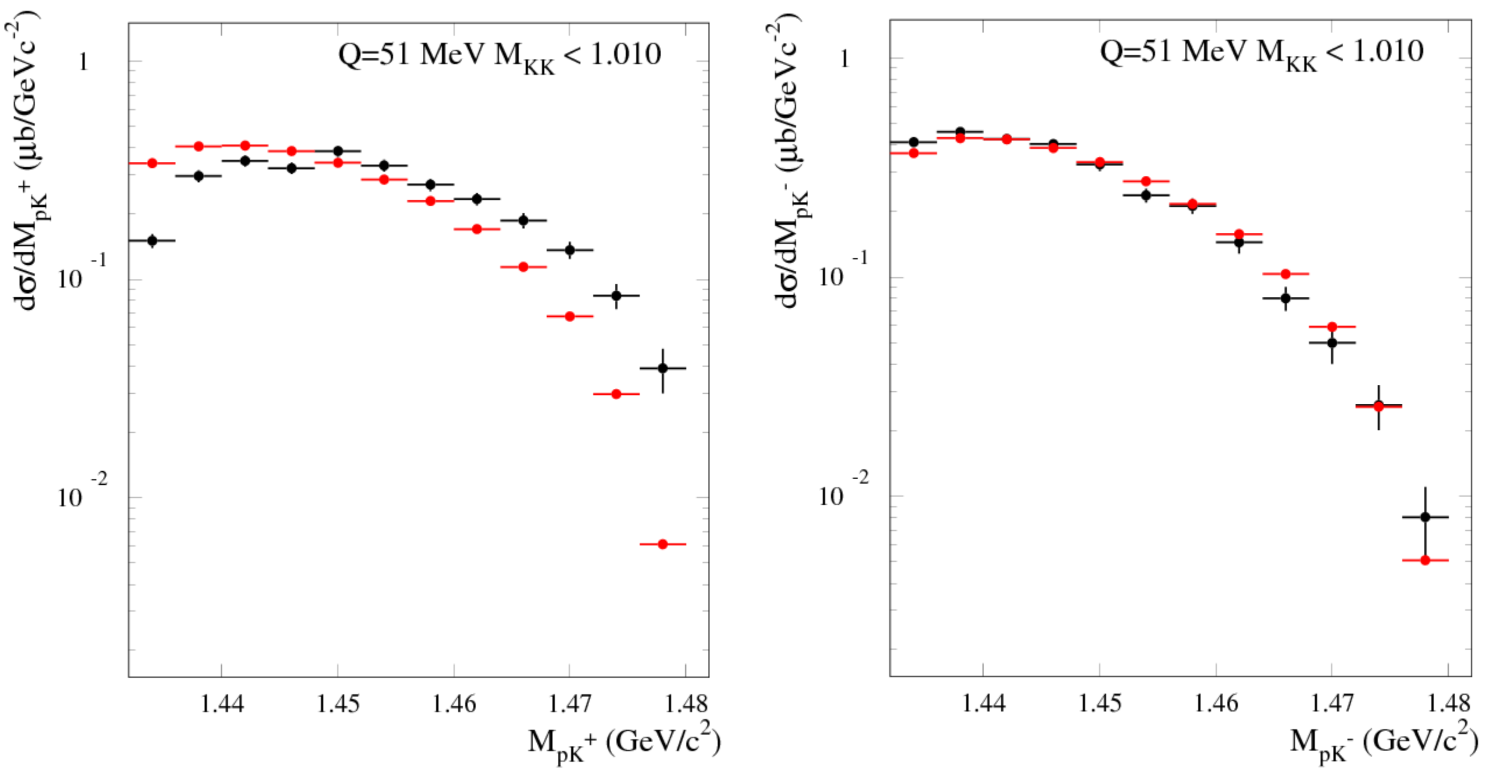
Open questions

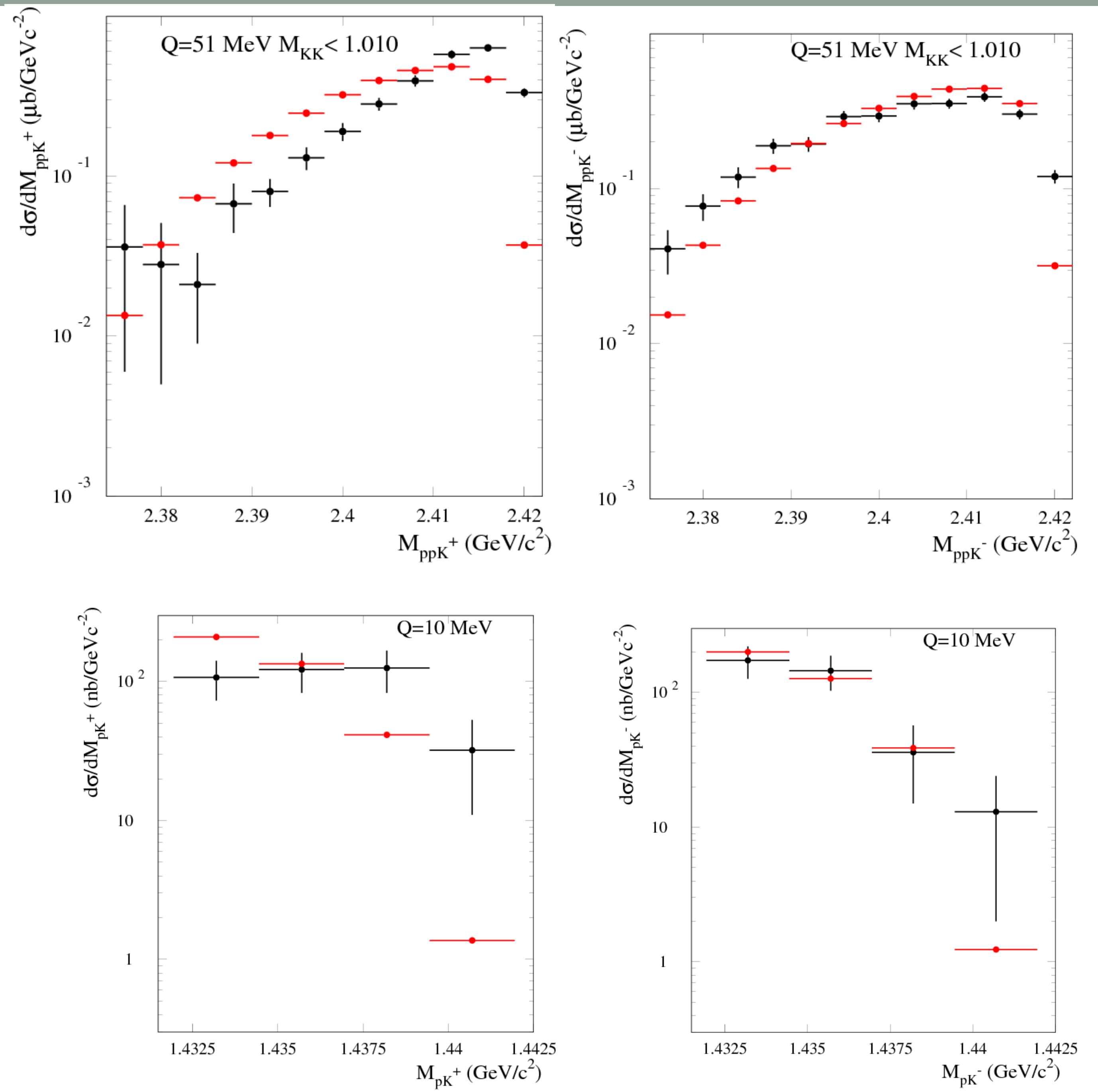
- ppK⁻ enhancement factor from from the Faddeev calculation

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

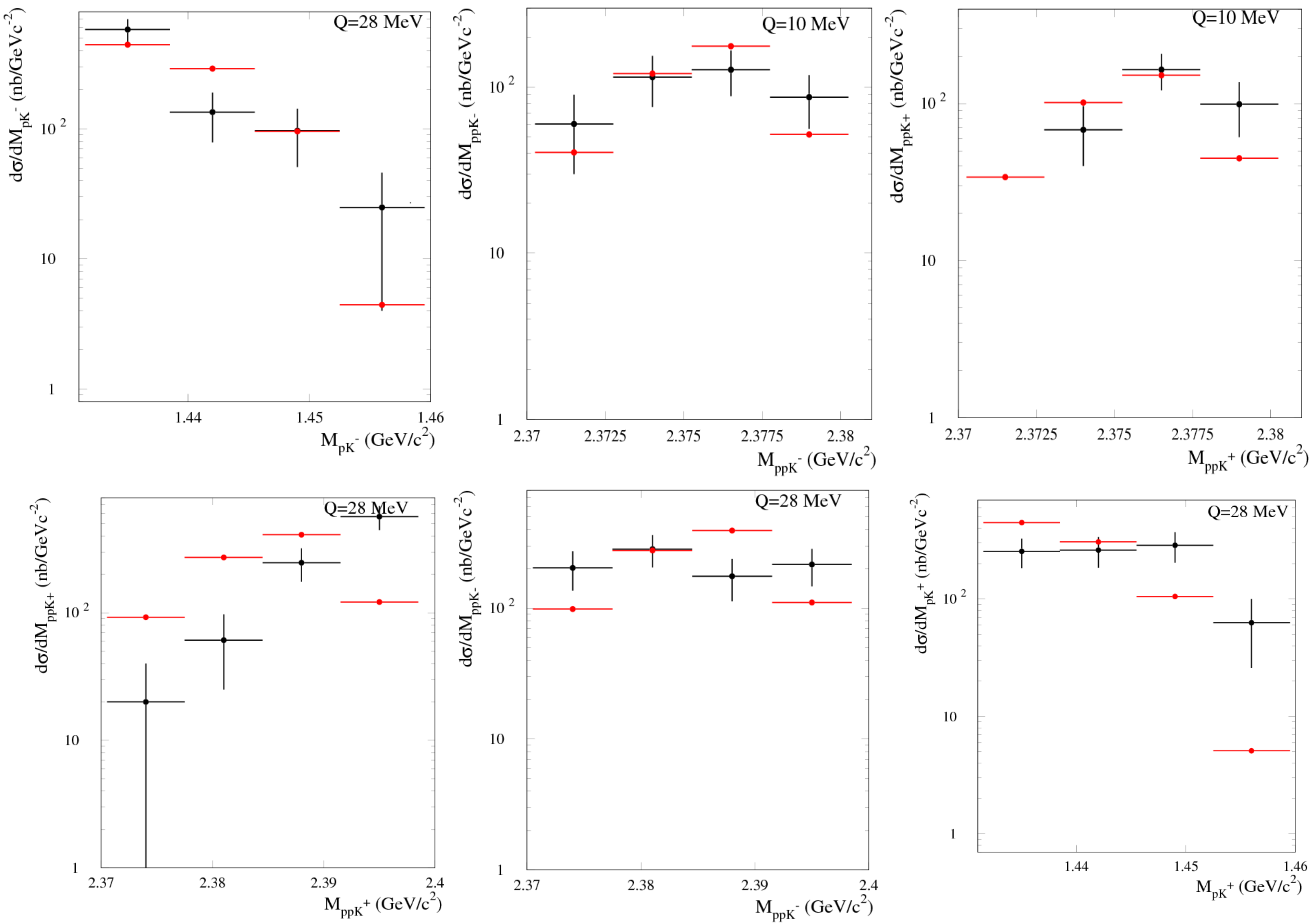
$$A_0 = (-1.68 + i0.531)\ fm;\ A_1 = (0.278 + i0.683)\ fm;\ \beta = 3.5\ fm^{-1};\ \ a = 10 fm;\ d = 2\ fm$$

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
dσ/dM_pK- (nb/GeVc^-2)
M_pK- (GeV/c^2)
1.44
1.45
1.46
1
10
10^2
Q=10 MeV
dσ/dM_ppK- (nb/GeVc^-2)
M_ppK- (GeV/c^2)
2.37
2.3725
2.375
2.3775
2.38
1
10
10^2
Q=10 MeV
dσ/dM_ppK+ (nb/GeVc^-2)
M_ppK+ (GeV/c^2)
2.37
2.3725
2.375
2.3775
2.38
1
10
10^2
Q=28 MeV
dσ/dM_ppK+ (nb/GeVc^-2)
M_ppK+ (GeV/c^2)
2.37
2.38
2.39
2.4
1
10
10^2
Q=28 MeV
dσ/dM_ppK- (nb/GeVc^-2)
M_ppK- (GeV/c^2)
2.37
2.38
2.39
2.4
1
10
10^2
Q=28 MeV
dσ/dM_pK+ (nb/GeVc^-2)
M_pK+ (GeV/c^2)
1.44
1.45
1.46
1
10
10^2