Status of the kaon-antikaon interaction studies

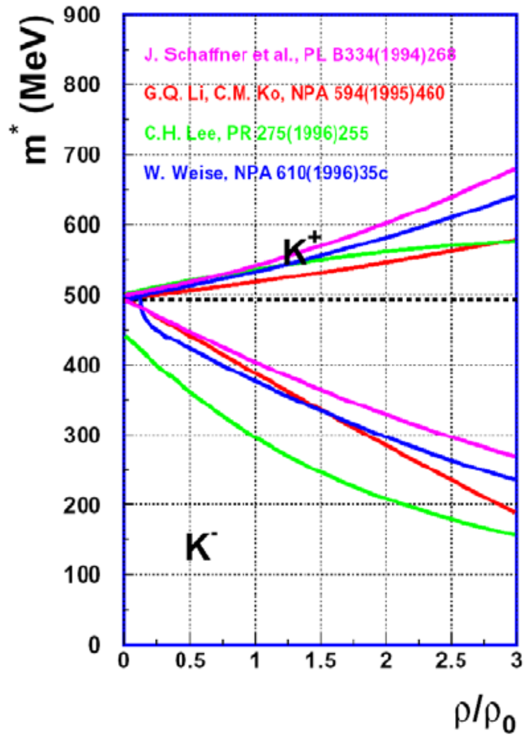
M. Silarski, L. Leśniak
Jagiellonian University

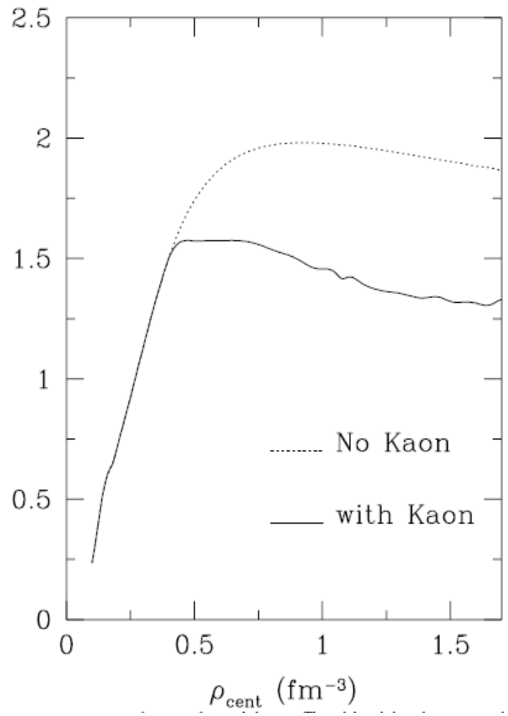
- Motivation
- Proton-proton collisions at K^+K^- threshold: COSY Perspectives for kaon-antikaon interaction studies at e^+e^- colliders
- Conclusions & outlook

International Conference on Exotic Atoms and Related Topics - EXA2017
10-15.09.2017, Vienna, Austria

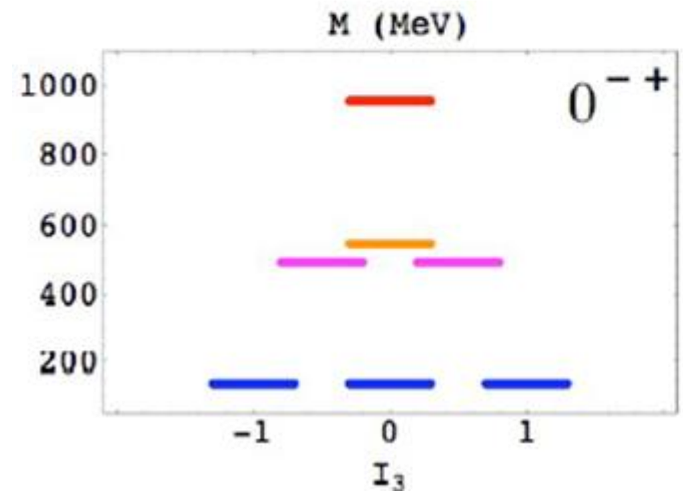
Motivation

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

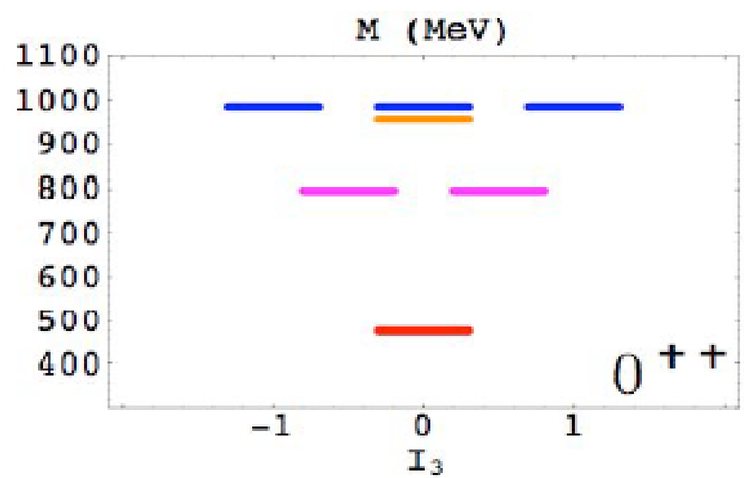




Pseudoscalar mesons



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



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

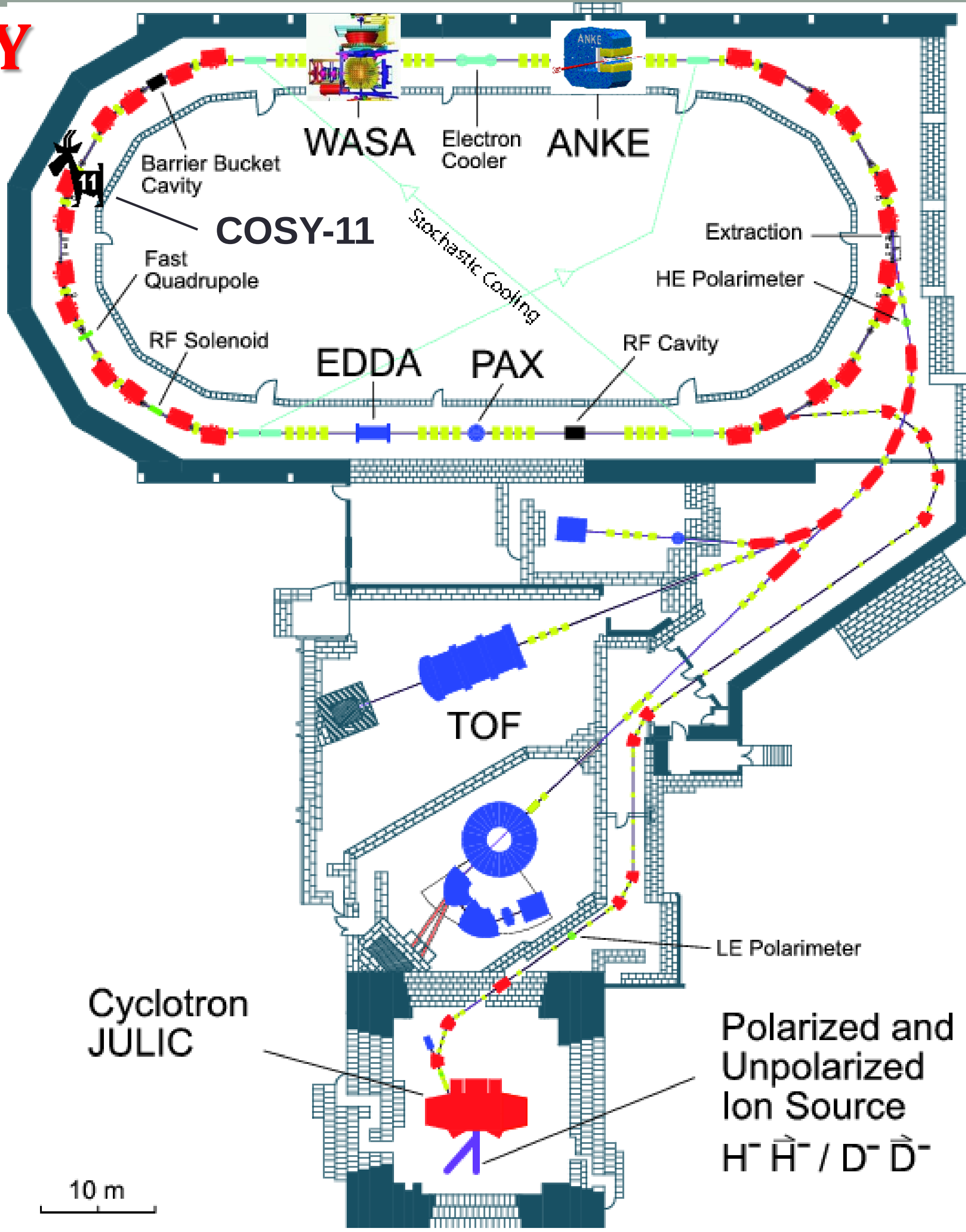
$pp \rightarrow ppK^+K^-$

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

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

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 ϕ(1020)
- **Precise beam momentum determination ($\Delta p/p \sim 10^{-3}$)**



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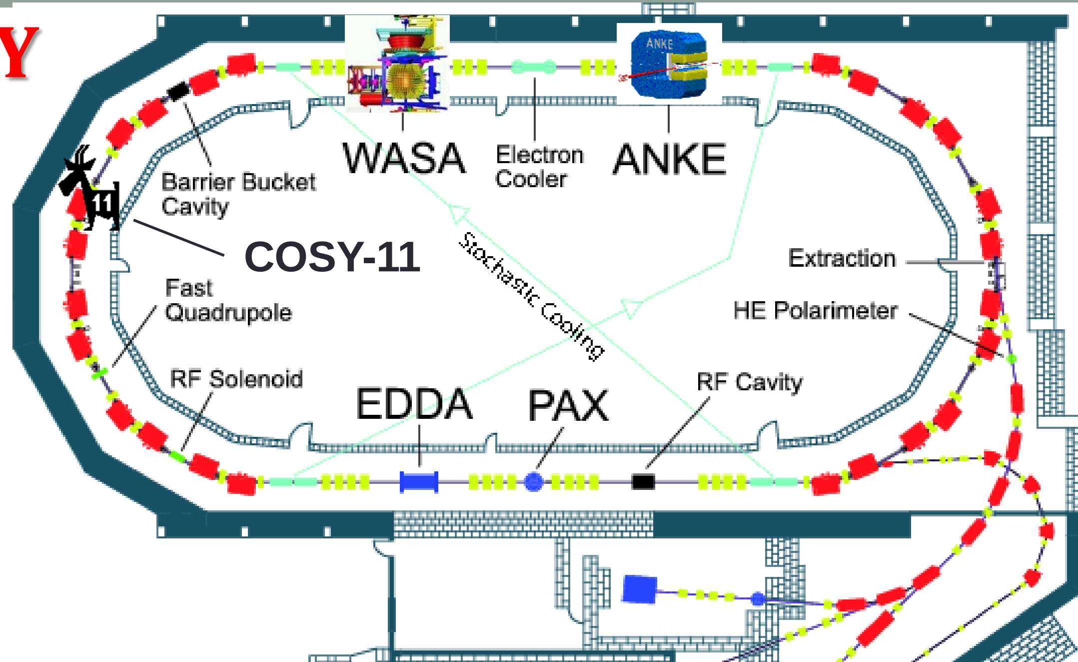
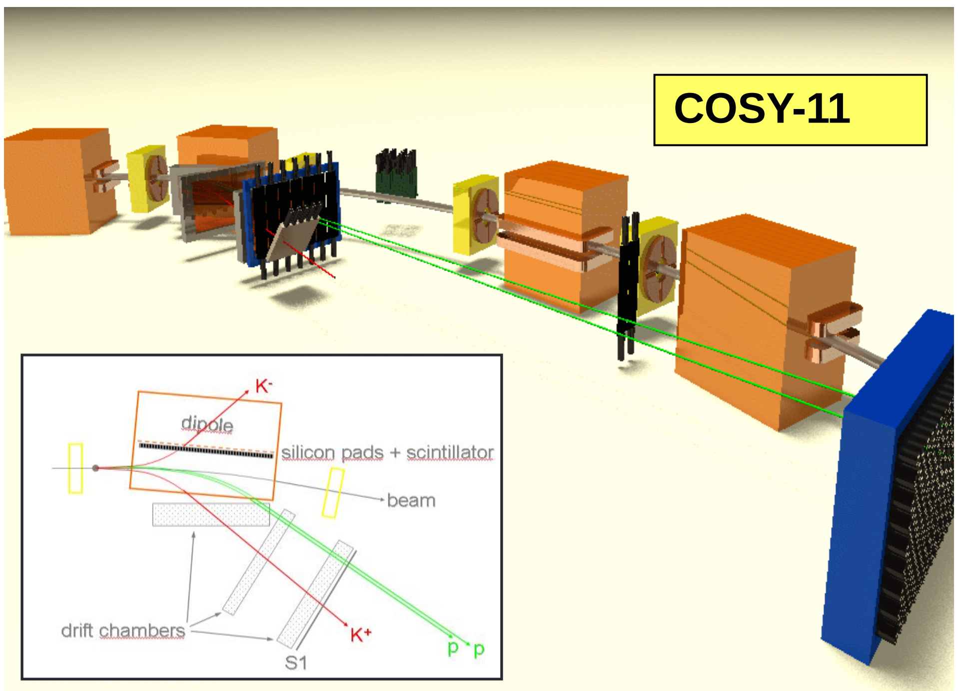
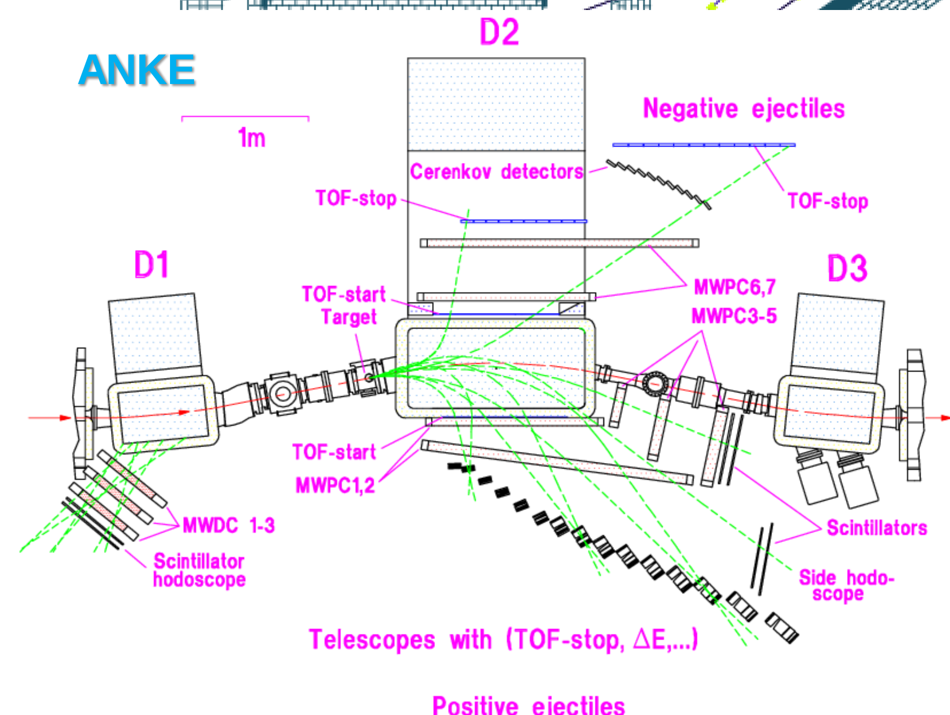
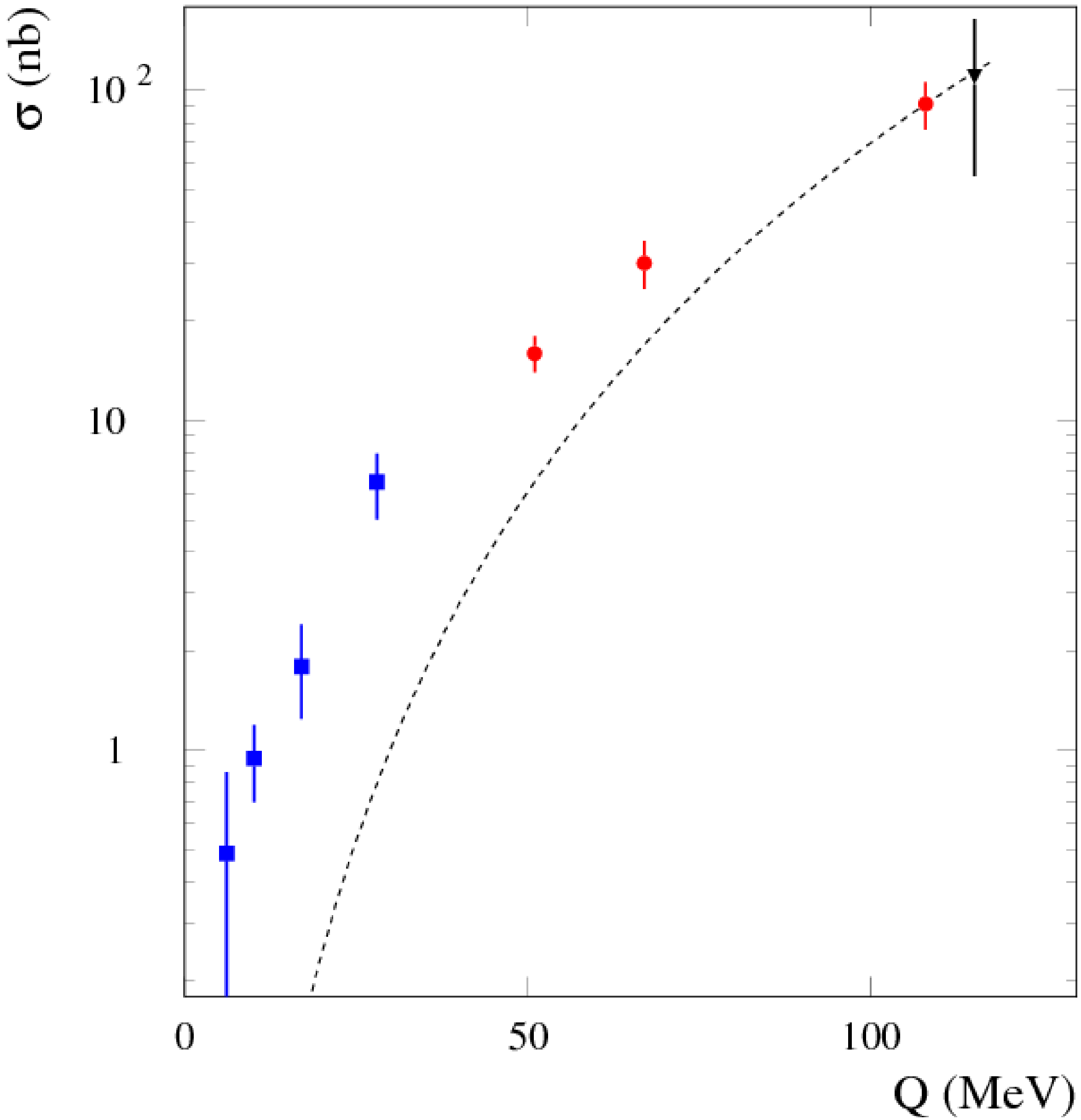






The pp→ppK$^+$K$^-$ excitation function



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

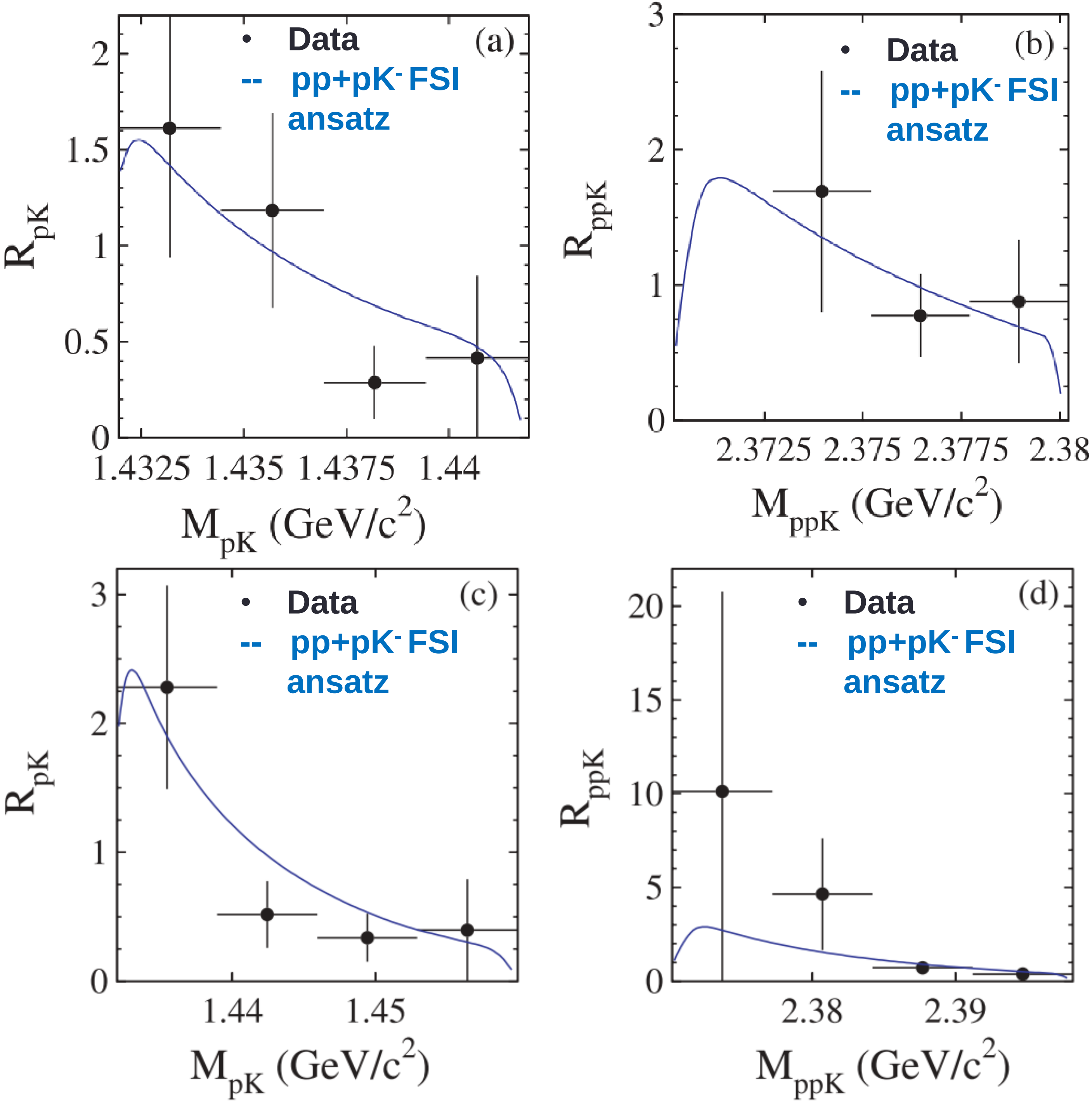
ANKE: Y.Maeda et al.,
Phys., Rev. C 77, 01524 (2008)

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

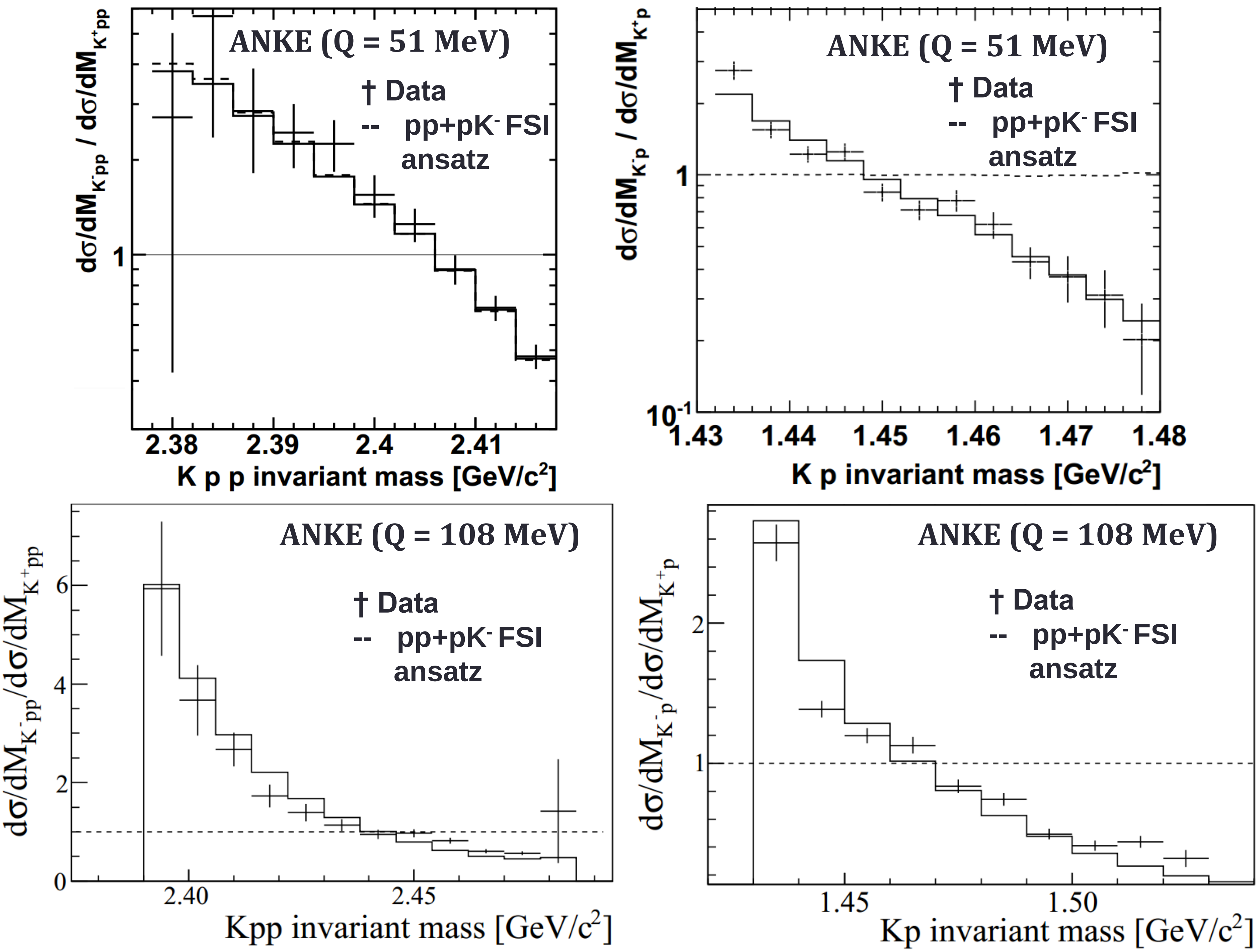


COSY-11
(Q = 10 MeV)

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

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

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

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

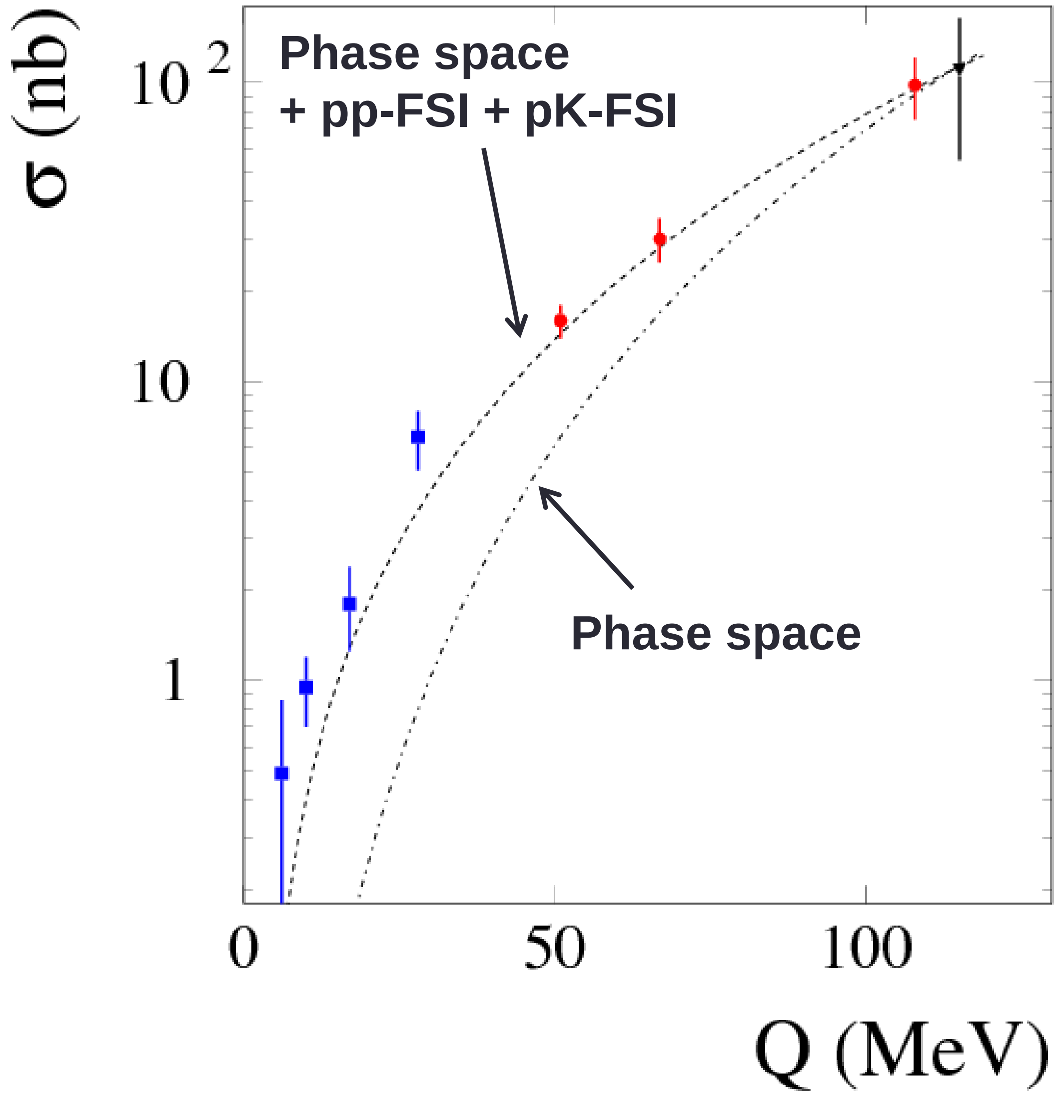
$$|M|^2 \approx |M_0|^2 |F_{FSI}|^2$$

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

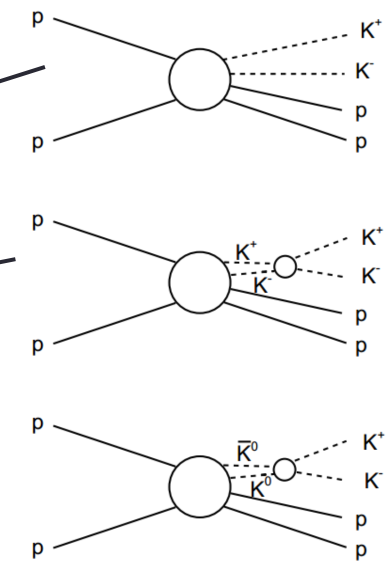
$$F_{pp}(q) = \frac{e^{i\delta_{pp}(^1S_0)} \times \sin\delta_{pp}(^1S_0)}{C \times q}$$

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

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



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

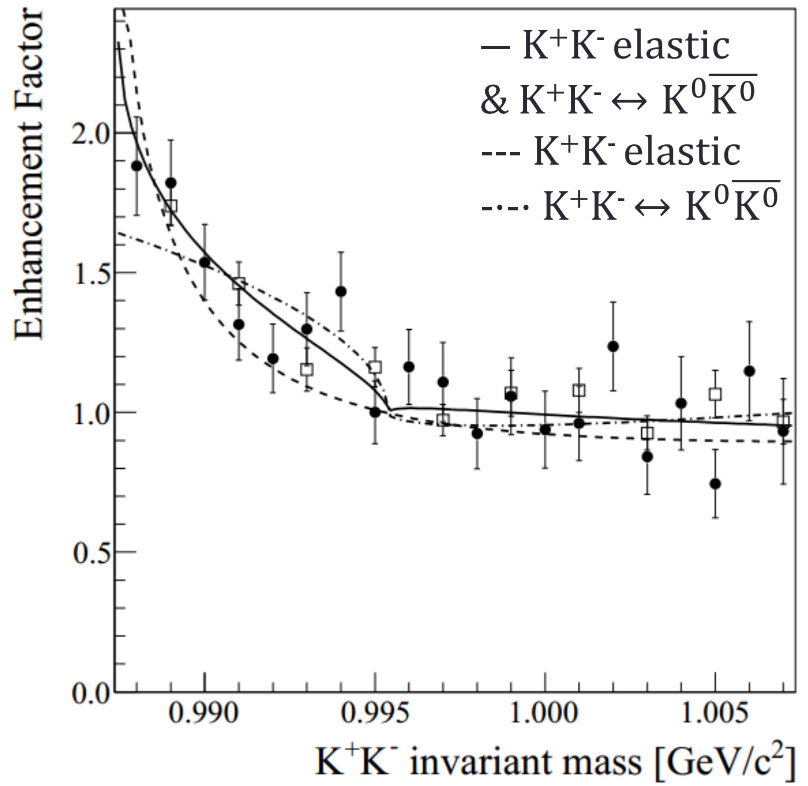


$$\mathcal{F} = \left| \frac{B_1/(B_1+B_0)}{\left(1 - i\frac{1}{2}q[A_1 - A_0]\right)(1 - ikA_1)} + \frac{B_0/(B_1+B_0)}{\left(1 - i\frac{1}{2}q[A_0 - A_1]\right)(1 - ikA_0)} \right|$$

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

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

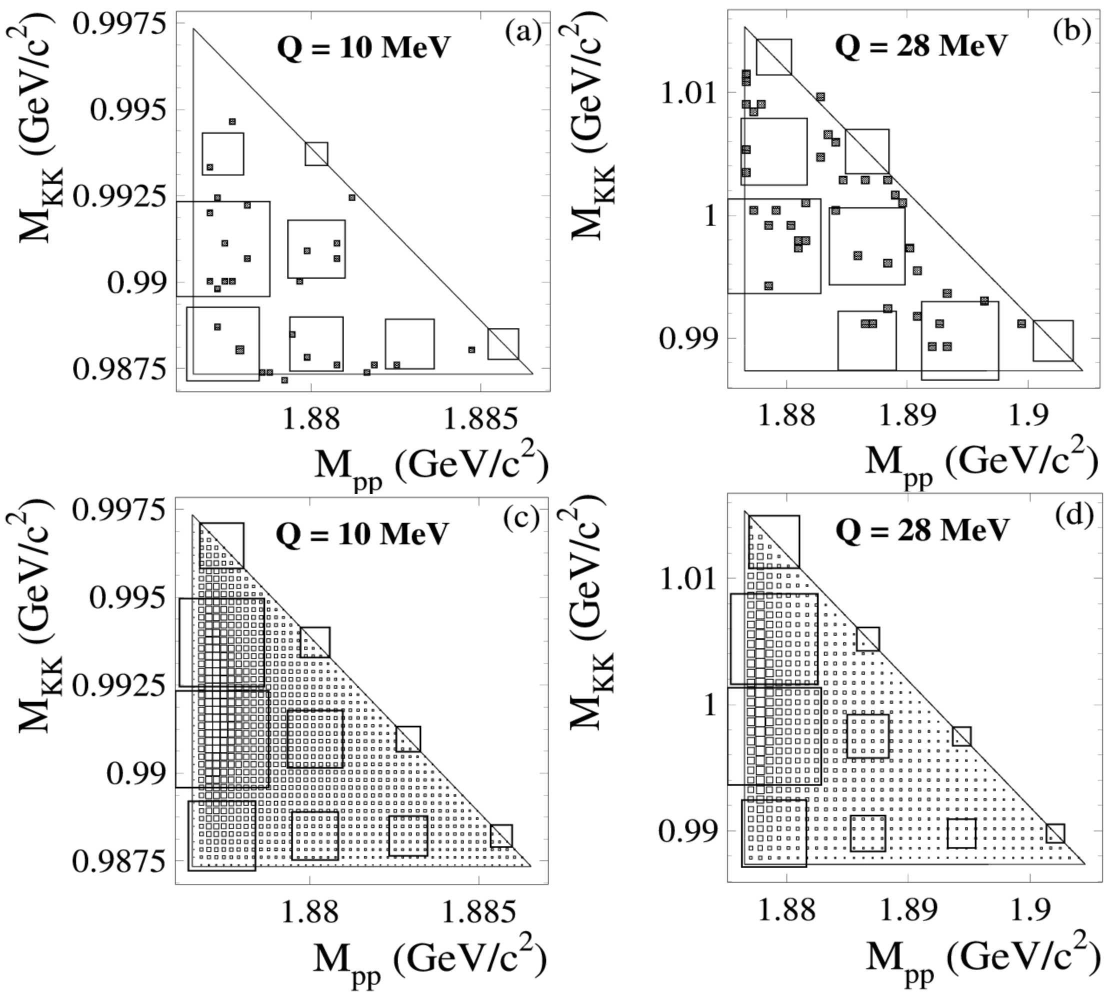
$$F_{FSI} = F_{pp}(q) \times F_{p_1K^-}(k_1) \times F_{p_2K^-}(k_2) \times F_{K^+K^-}(k_3)$$

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

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

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

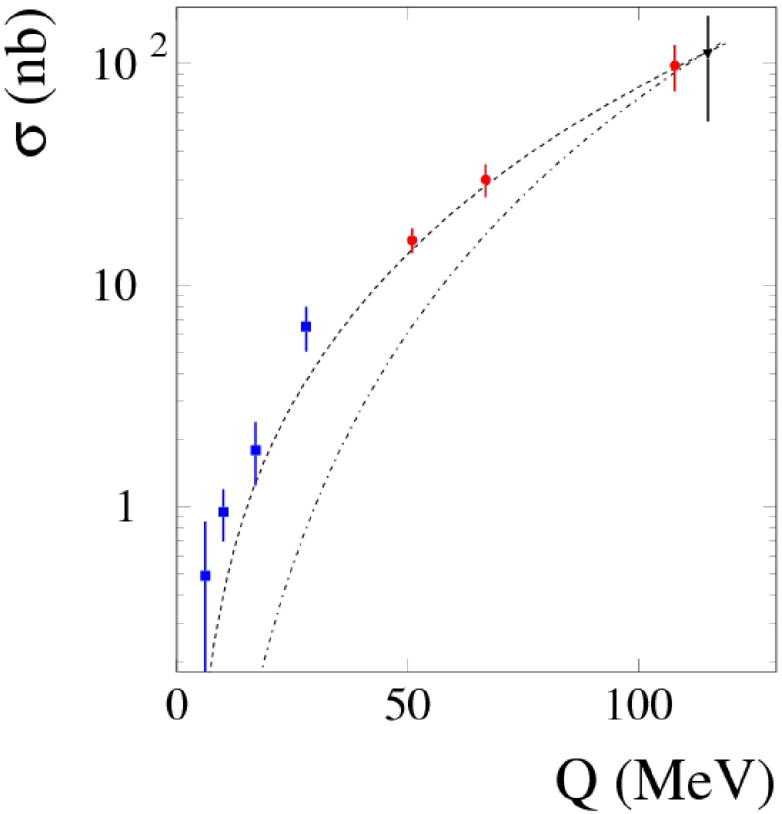
$$a_{pK^-} = (0 + i1.5)\,[\mathrm{fm}]$$

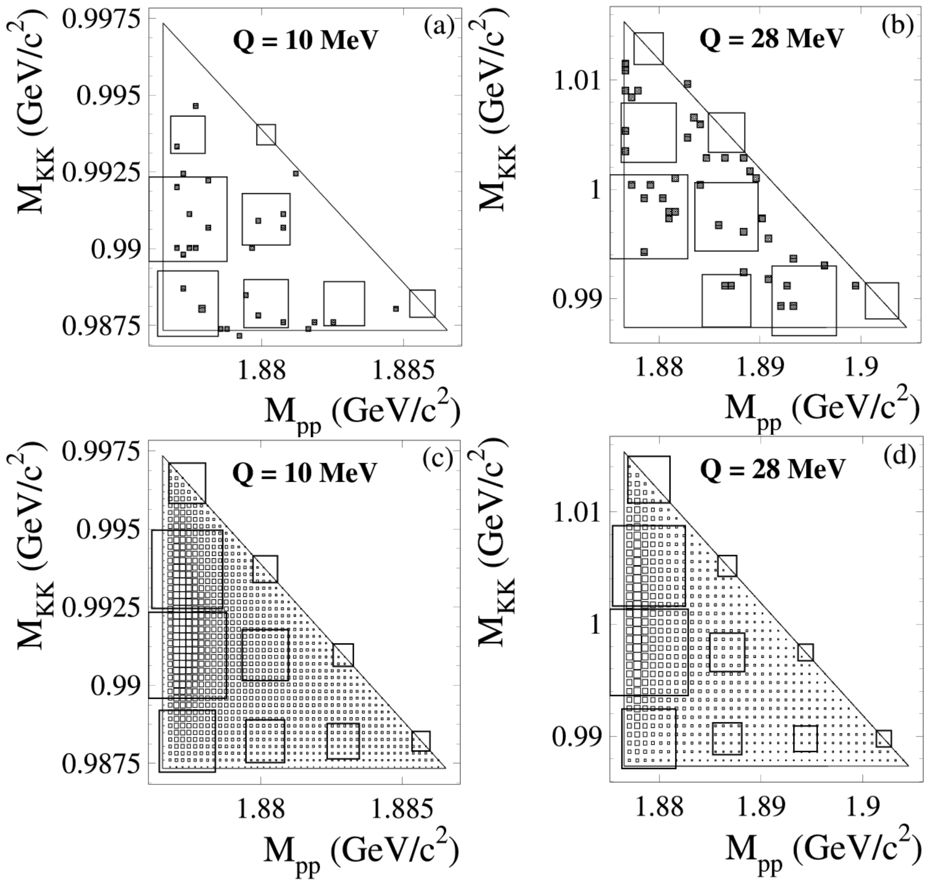


M. Silarski, et al.,Phys. Rev. C 80, 045202 (2009)

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

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





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

(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

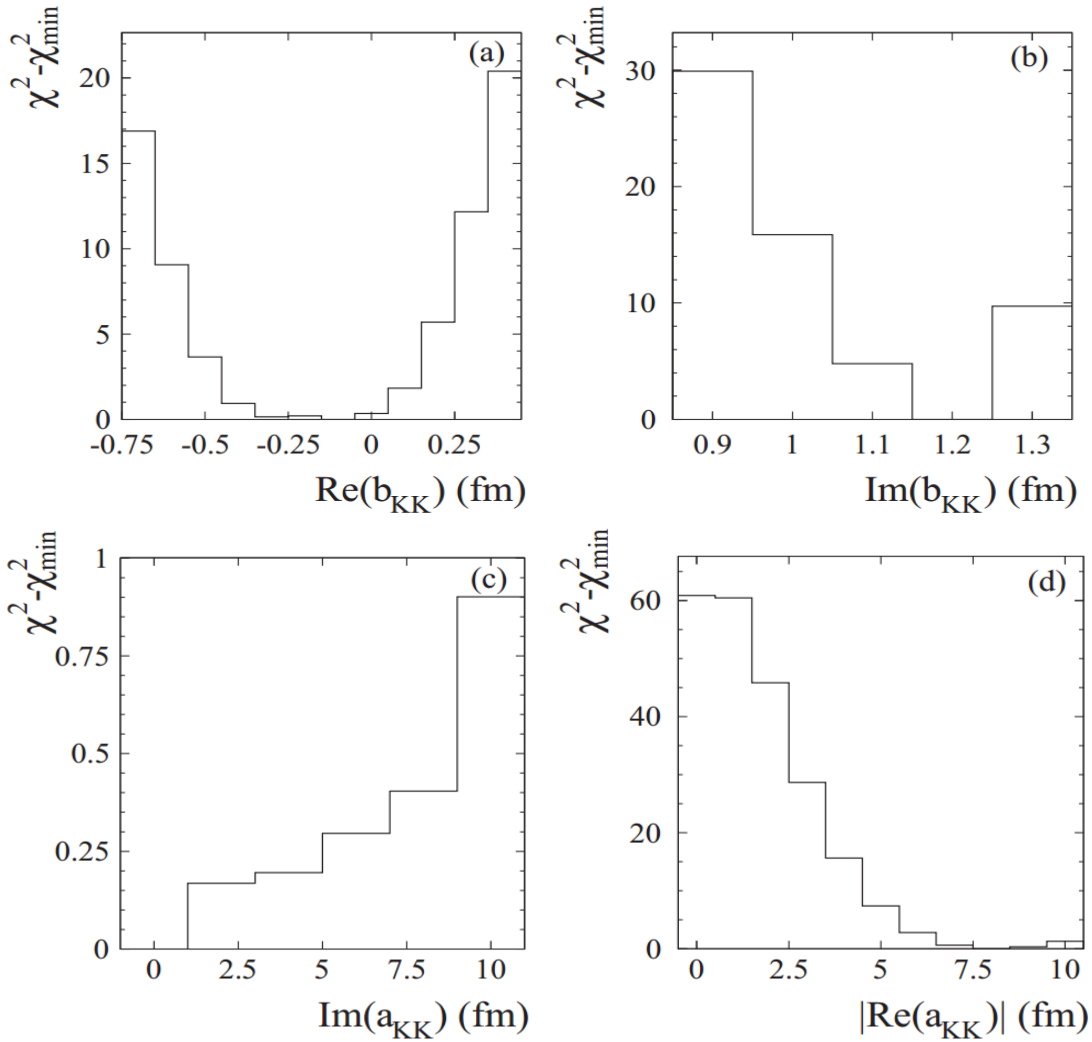
$$\mathrm{Re}(b_{K^+K^-}) = -0.1 \pm 0.4_{\mathrm{stat}} \pm 0.3_{\mathrm{sys}}\ \mathrm{fm}$$

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

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

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

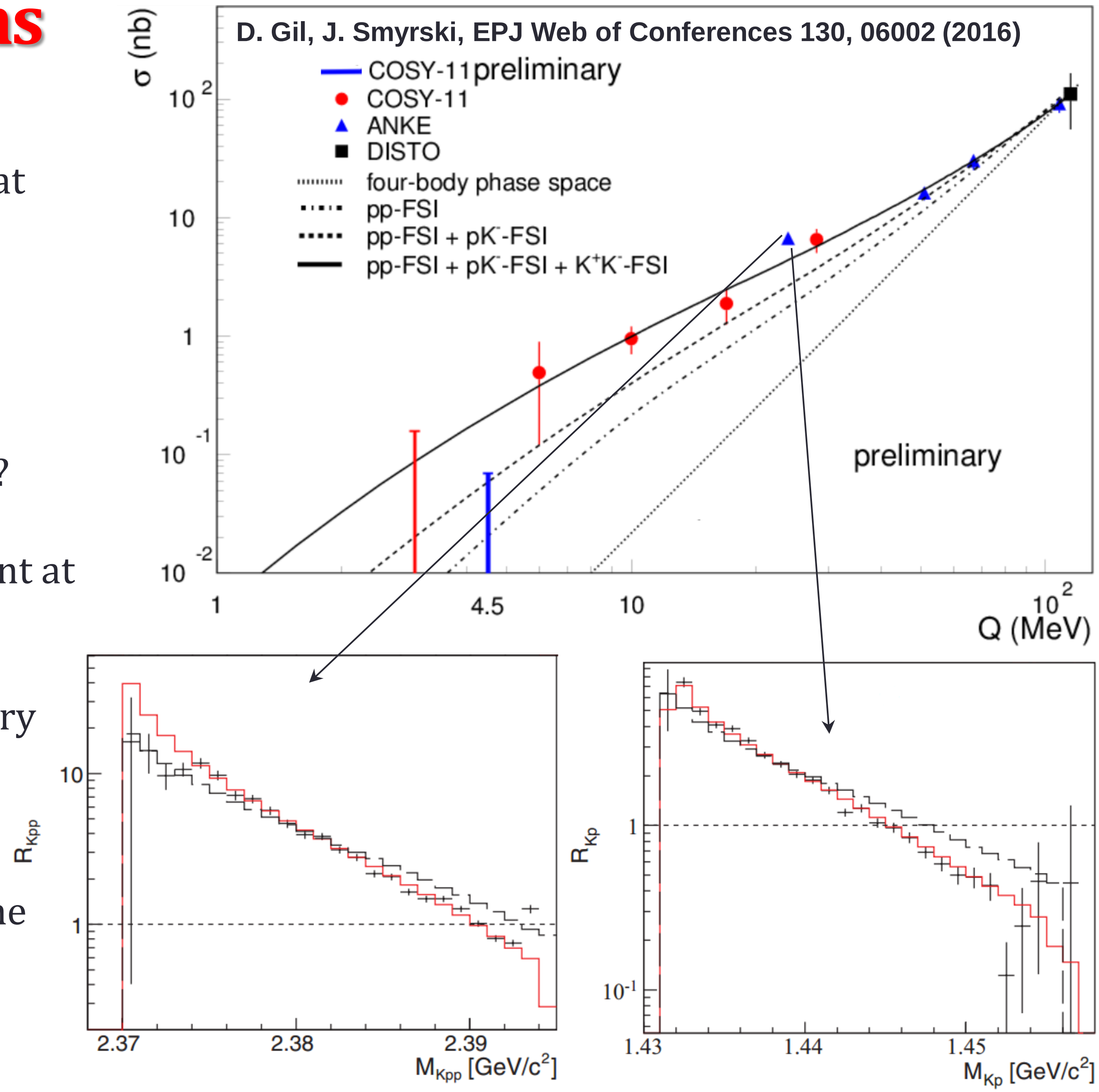
M. Silarski, P. Moskal,
Phys. Rev. C 88, 025205 (2013)



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

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→pK$^+$Λ(1405) reaction?
- ❖ Last COSY-11 measurement at Q=4.5 MeV (preliminary) suggests that we overestimated the data very close to threshold
- ❖ Possible improvment in the K+K- FSI undestanding in different processes

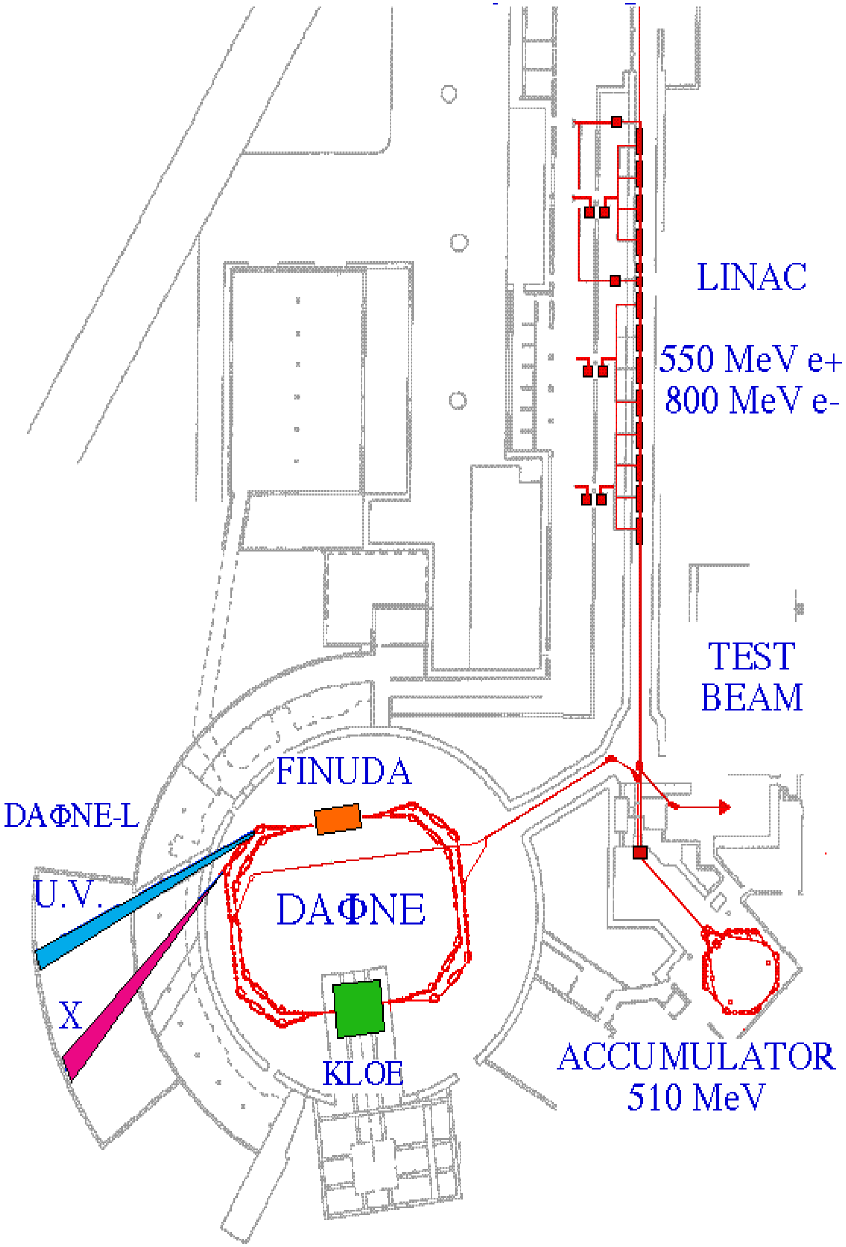


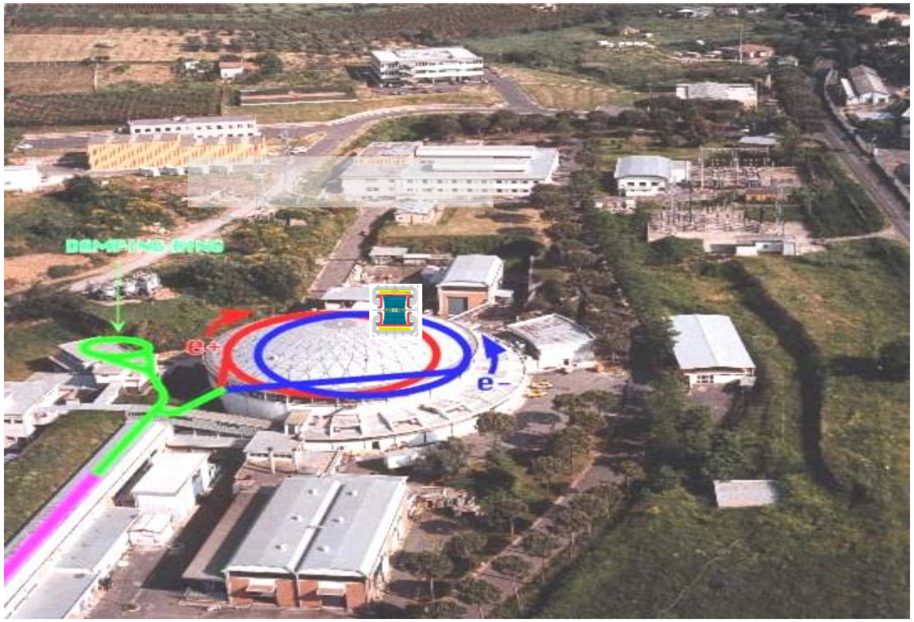
Q. J. Ye et al., Phys. Rev. C 87, 065203 (2013)

Promissing alternative: DAΦNE

$$e^+e^- \rightarrow K^+K^-\gamma$$
$$e^+e^- \rightarrow K^0\bar{K}\gamma$$

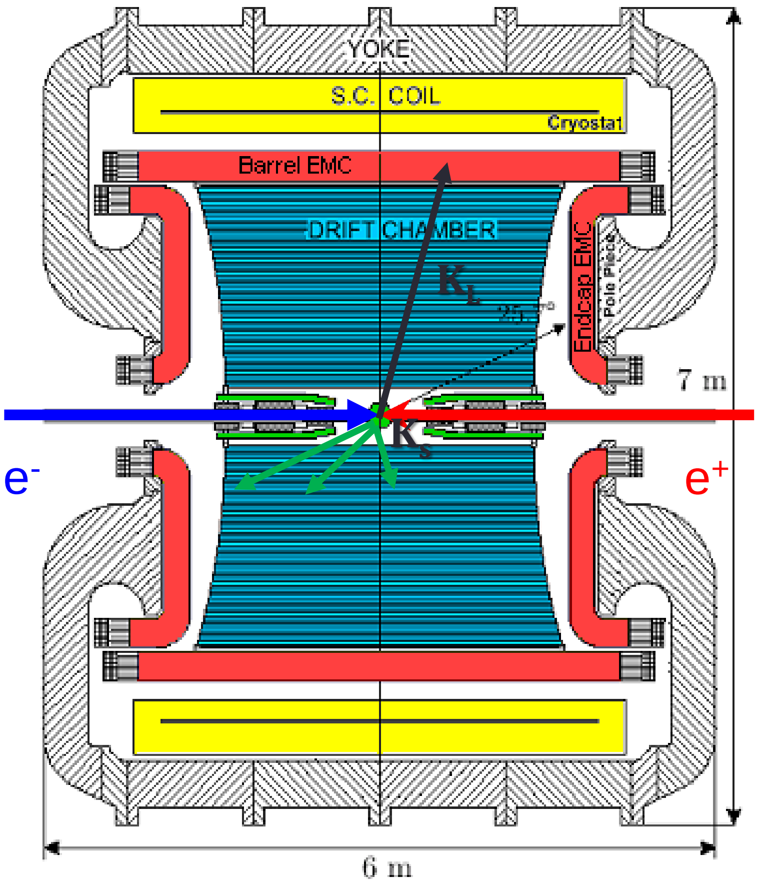
DAΦNE & KLOE

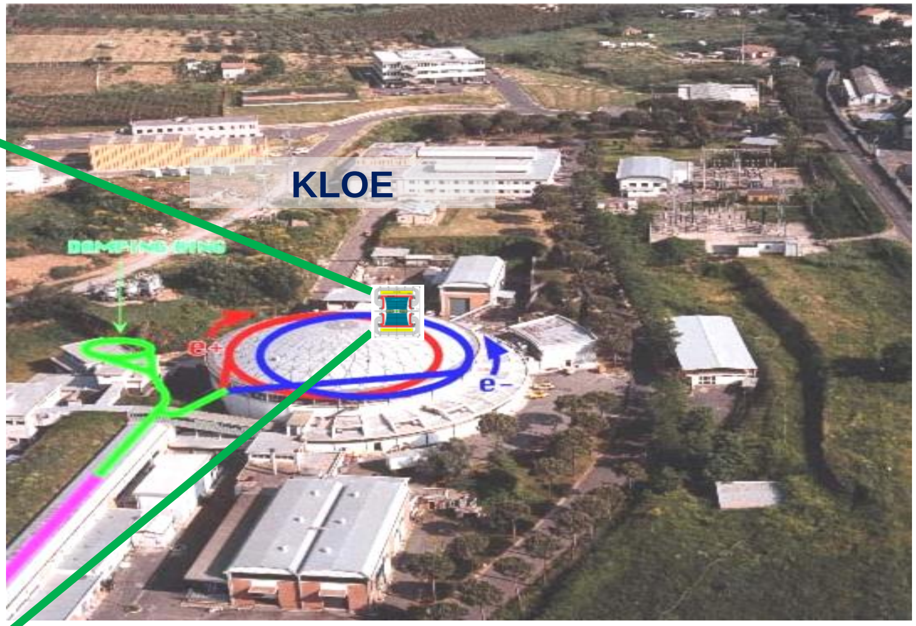




- ❑ e^+e^- collider @ $\sqrt{s} = M_\varphi = 1019.4$ MeV
- ❑ LAB momentum $p_\varphi \sim 15$ MeV/c
- ❑ $\sigma_{peak} \sim 3\ \mu b$
- ❑ Separate e^+e^- rings to reduce beam-beam interaction

DAΦNE & KLOE





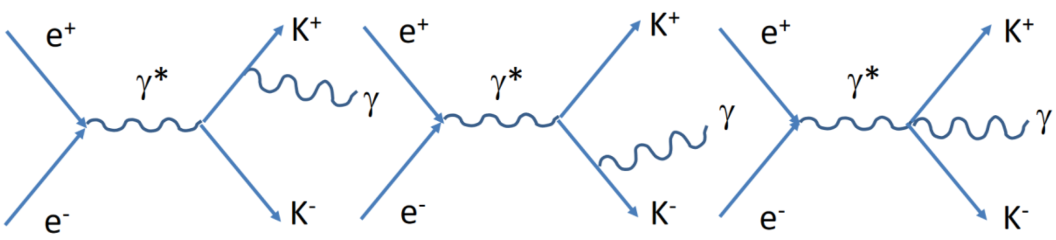
- ❑ e^+e^- collider @ $\sqrt{s} = M_\varphi = 1019.4$ MeV
- ❑ LAB momentum $p_\varphi \sim 15$ MeV/c
- ❑ $\sigma_{peak} \sim 3$ μb
- ❑ Separate e^+e^- rings to reduce beam-beam interaction

KK –FSI @ Φ-mass peak

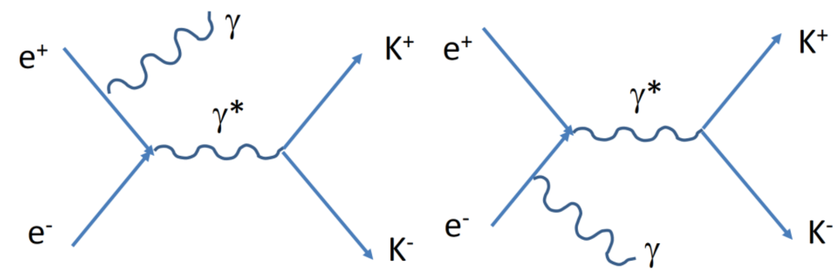
- **Advantage with respect to pp→ ppK^+K^- : only two interacting particles**
- The K+ K- threshold lies close to the DAFNE working point
- To fully describe the K^+K^- -FSI we need to measure:

$e^+e^- \rightarrow \pi^0\pi^0\gamma$ [EPJC49(2007)473]
$e^+e^- \rightarrow \pi^+\pi^-\gamma$ [PLB606(2005)12, PLB670(2009)285, PLB700(2011)102]
$e^+e^- \rightarrow \pi^0\eta\gamma$ [PLB681(2009)5]
$e^+e^- \rightarrow K_S K_S\gamma$ **[PLB679(2009)10]**
$e^+e^- \rightarrow K^+K^-\gamma$

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

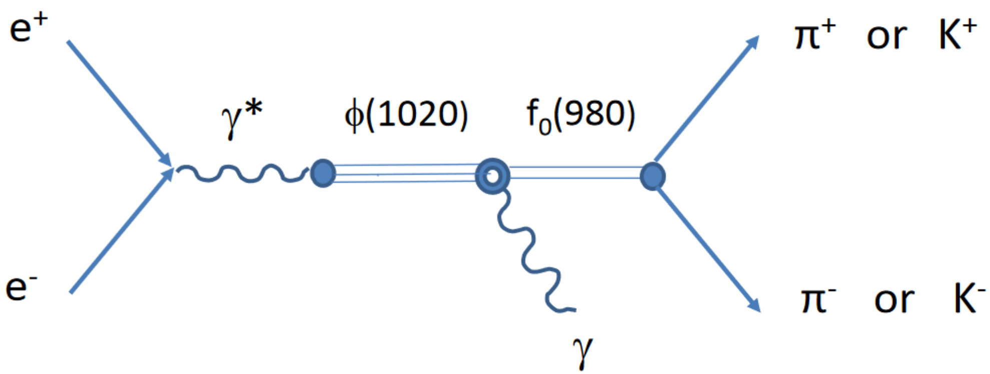


FSR – final state radiation



ISR – initial state radiation

Reaction mechanisms

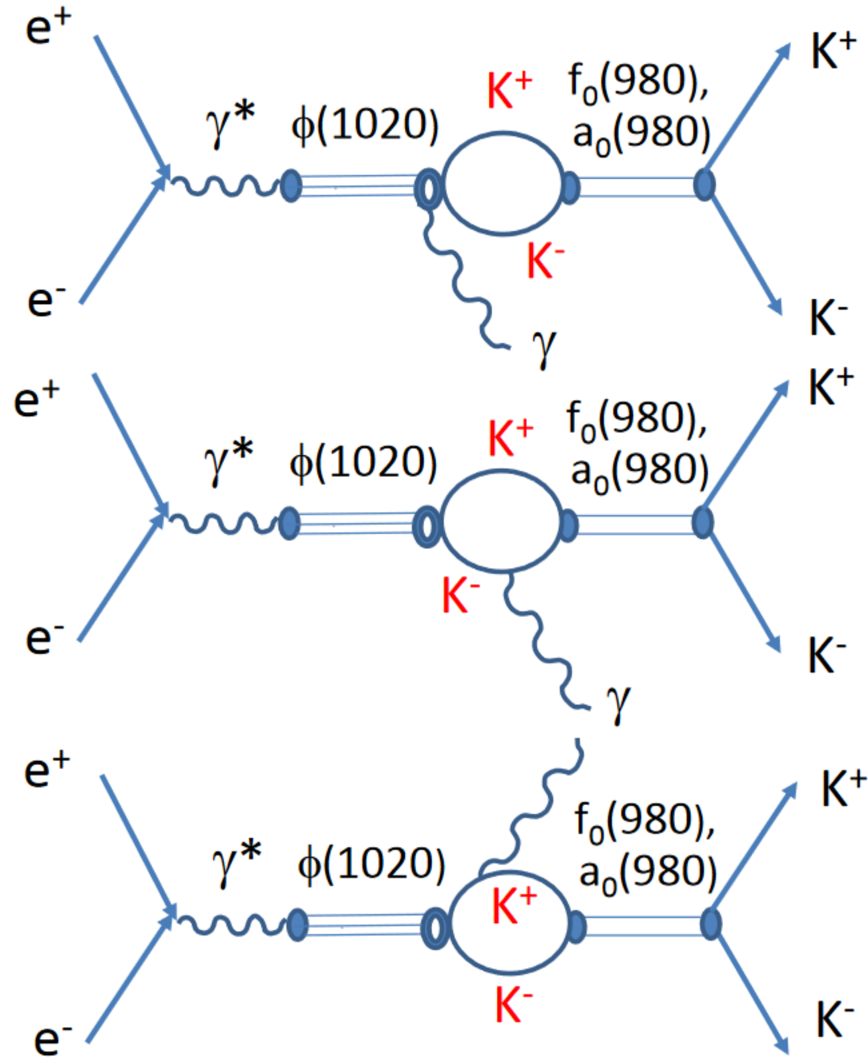


NS – no-structure model

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

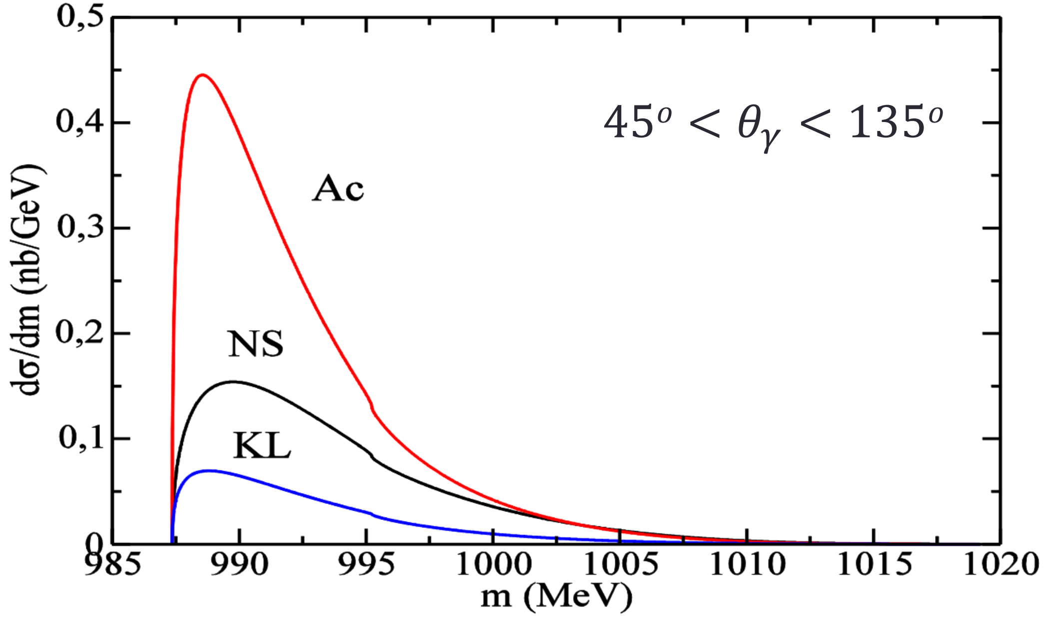


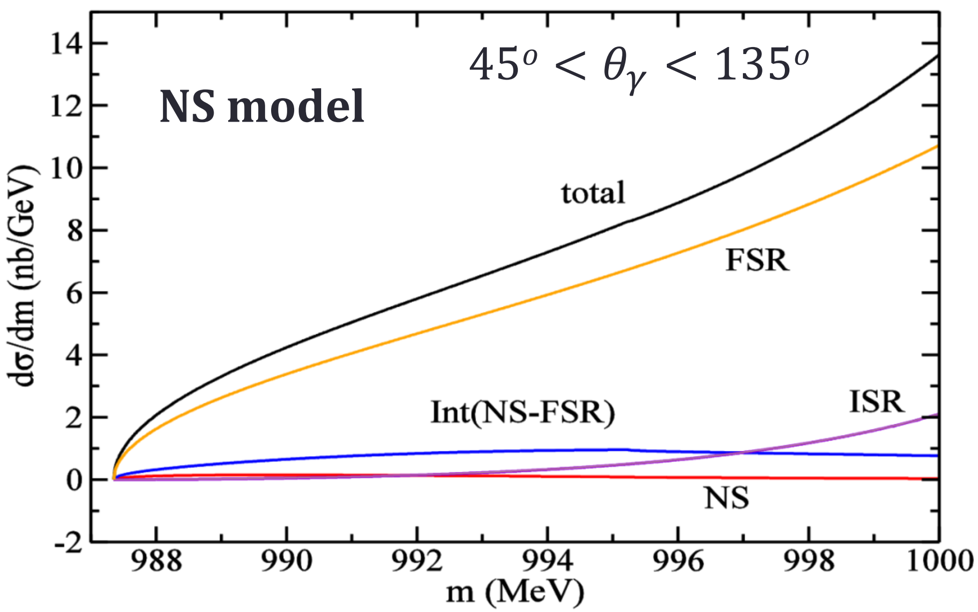
Kaon-loop model

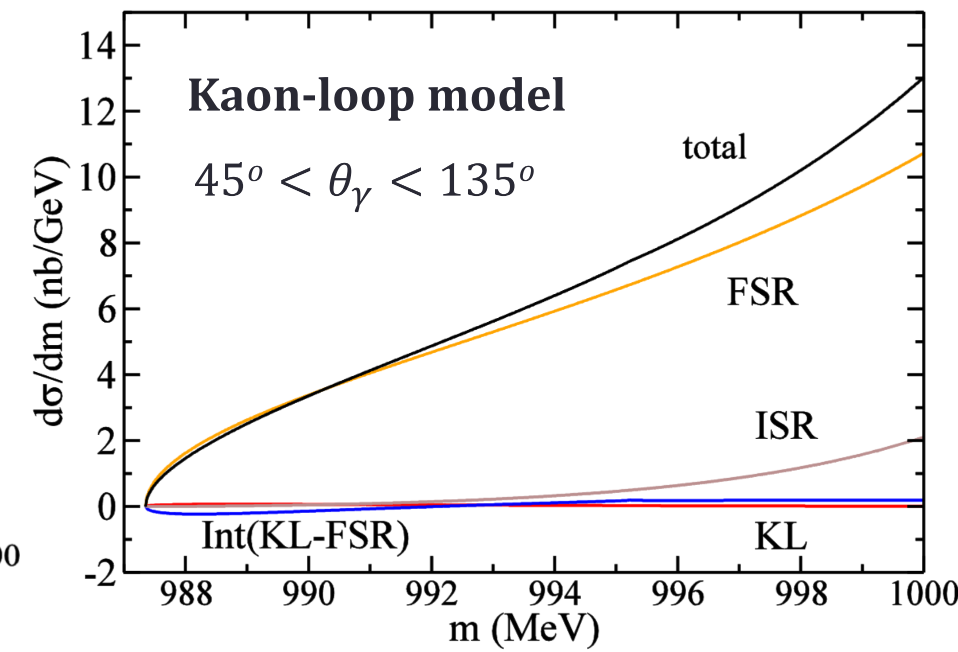
N. N. Achasov, V. V. Gubin, V. Shevchenko , PRD 56 (1997) 203

K^+K^- effective mass distributions

$$d\sigma = \frac{(2\pi)^4}{2\sqrt{s(s-4m^2{}_e)}}|M|^2 d\Phi_3$$







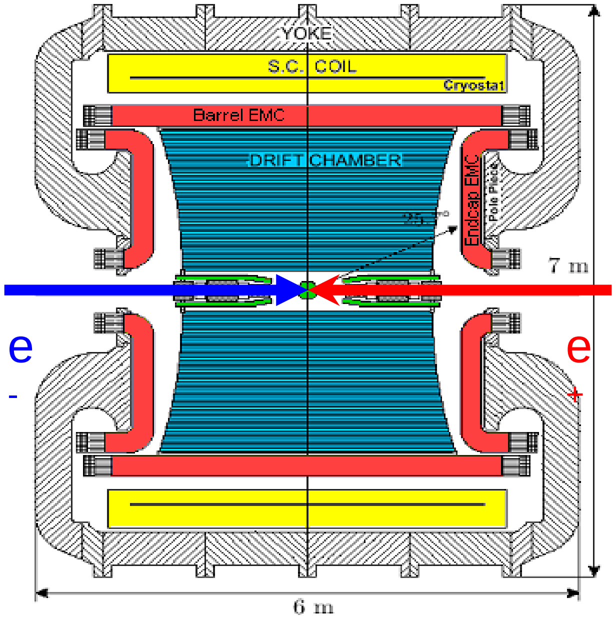
L. Leśniak, M. Silarski, EPJ Web Conf. 130 (2016) 06003

Perspectives for a measurement with KLOE

- Advantages:
  - Very good kaon momentum determination
  - High statistics (~10^5 events expected in total)

- Problems:
  - Low energy photons (< 32 MeV) ⇒ lower efficiency + energy resolution
  - Low p_t tracks for low K^+K^- invariant masses

- Challenging measurement



Mechanism	Total cross section (m up to 1009 MeV) [nb]	
	$24^o < \theta_\gamma < 156^o$	$45^o < \theta_\gamma < 135^o$
FSR	0.330	0.238
NS	0.0020	0.0014
NS-FSR Interference	0.021	0.0015
ISR	0.183	0.104
Total	0.536	0.358

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 coupled channel effects and production of f0(980)/a0(980) are up to now not distinguishable even with high statistic measurement

- The last ANKE measurement reveals that we still do not understand fully the dynamics of the near threshold $pp \rightarrow ppK^+K^-$

- The feasibility study to measure the the K^+K^- threshold parameters of the strong interaction amplitudes with the KLOE detector started

- We are developing 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]

$$\sigma^m = \int \frac{\pi^2 |M|^2}{8s\sqrt{-B}} \mathrm{d}M_{pp}^2 \mathrm{d}M_{K^+K^-}^2 \mathrm{d}M_{pK^-}^2 \mathrm{d}M_{ppK^-}^2 \mathrm{d}M_{ppK^+}^2 \qquad \beta_j = \frac{L_j \alpha \sigma_j^m}{N_j^{gen}}$$

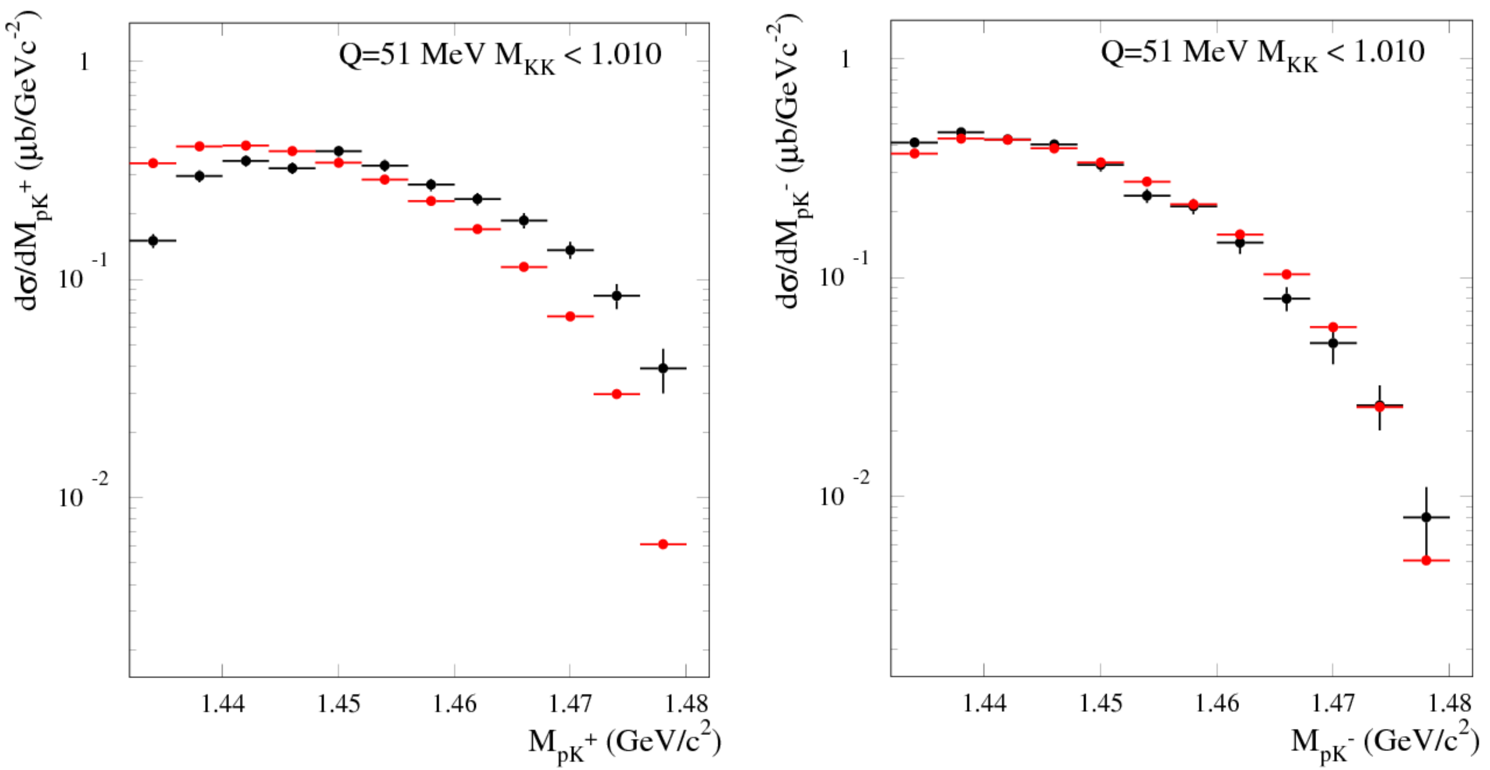
Open questions

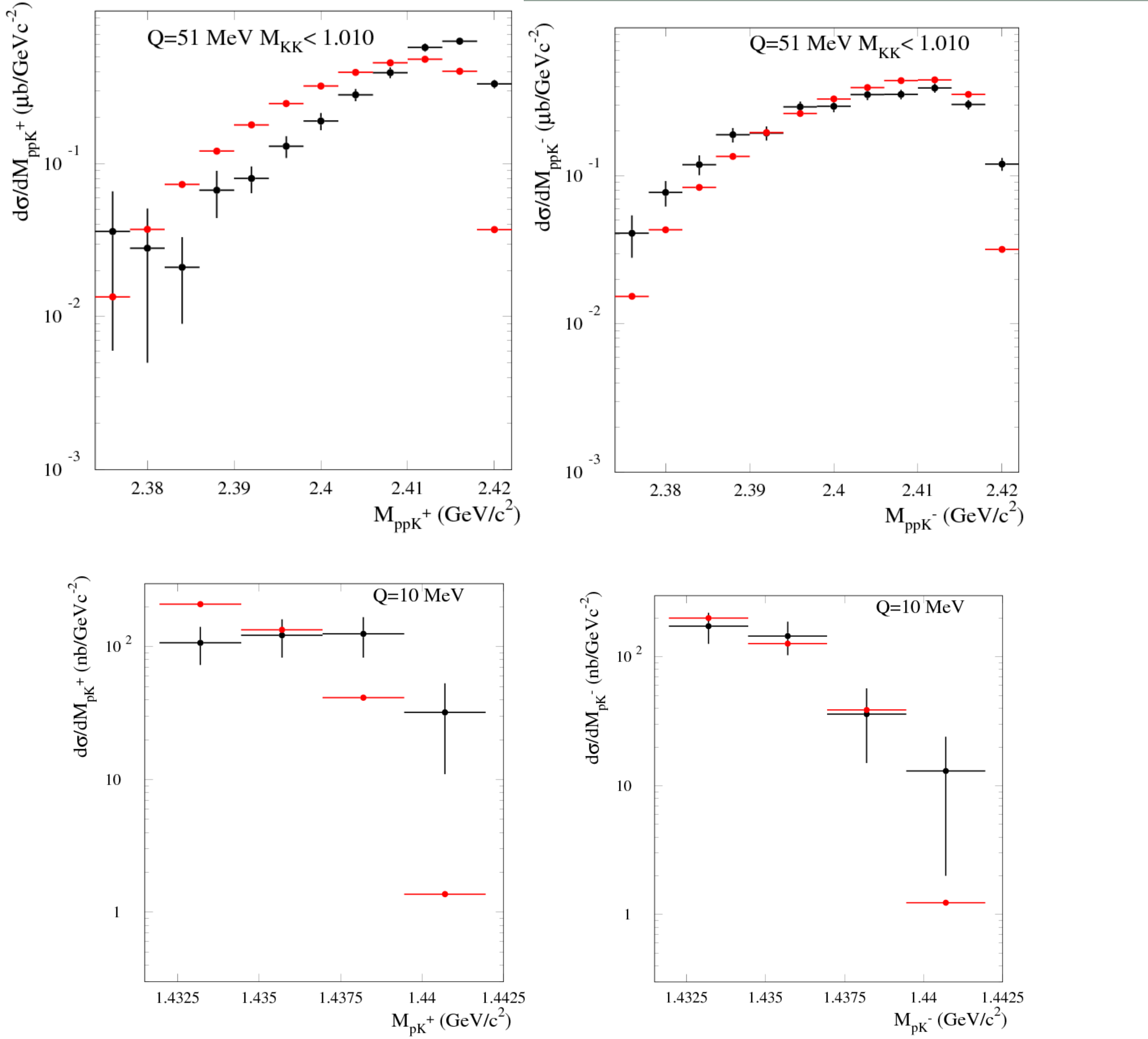
- ppK⁻ enhancement factor from from the Faddeev calculation

$$F_{ppK^-} = \left|1 + \frac{\beta + ik_1}{2}\left\{\frac{A_0}{1 - iA_0 k_1} + \frac{A_1}{1 - iA_1 k_1}\right\} 1 + \frac{\beta + ik_2}{2}\left\{\frac{A_0}{1 - iA_0 k_2} + \frac{A_1}{1 - iA_1 k_2}\right\} + \frac{a}{d}\cdot\frac{1 + idk_3}{1 - iak_3}\right|^2$$

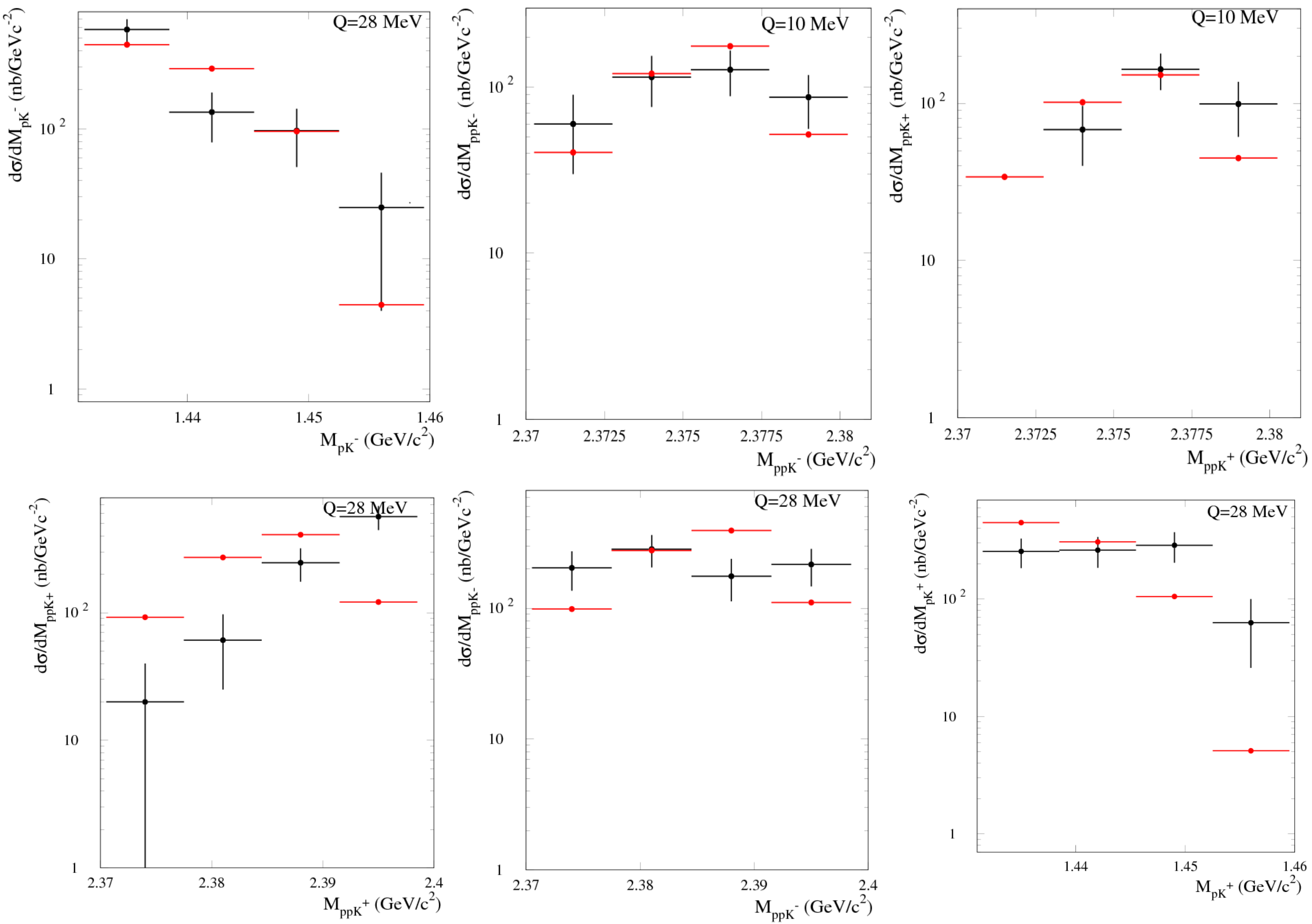
$$A_0 = (-1.68 + i0.531)\ fm; A_1 = (0.278 + i0.683)\ fm;\ \beta = 3.5\ fm^{-1};\ \ a = 10 fm; d = 2\ fm$$

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)

KLOE (K LOng Experiment)

Large cylindrical drift chamber

- Uniform tracking and vertexing in all volume
- Helium based gas mixture (90% He – 10% $IsoC_4H_{10}$)
- Stereo wire geometry

$\sigma_p/p = 0.4\ \%$

$\sigma_{xy} = 150\ \mu m$; $\sigma_z = 2$ mm

$\sigma_{vtx} \sim 3$ mm

$\sigma(M_{\pi\pi}) \sim 1$ MeV

Lead/scintillating-fiber calorimeter

- Hermetical coverage
- High efficiency for low energy photons

$\sigma_E/E = 5.7\% /\sqrt{E(GeV)}$

$\sigma_t = 57\ ps /\sqrt{E(GeV)} \oplus 140\ ps$

$\sigma_{vtx}(\gamma\gamma) \sim 1.5$ cm

Superconducting coil

B = 0.52 T