The π^0 and η meson decays and near threshold production and low energy QCD

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Various Faces of QCD,

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Outline

- Light pseudoscalar mesons π and η threshold production and decays - what can we learn from them?
- WASA experiment and world competition
- Theoretical description at low energies – Effective Chiral Lagrangian and OBE
- The $\eta \to 3\pi$ decays : light quarks masses
- Rare decays and new physics

Low energy regime

- The Lagrangian of QCD is invariant under the interchange of the three light quarks if $m_u = m_d = m_s$.

$$\mathcal{L}_{QCD} = \sum_{q=u,d,s} \left[i\bar{q}_L \not{D} q_L + i\bar{q}_R \not{D} q_R - m_q \left(\bar{q}_R q_L + \bar{q}_L q_R \right) \right] .$$

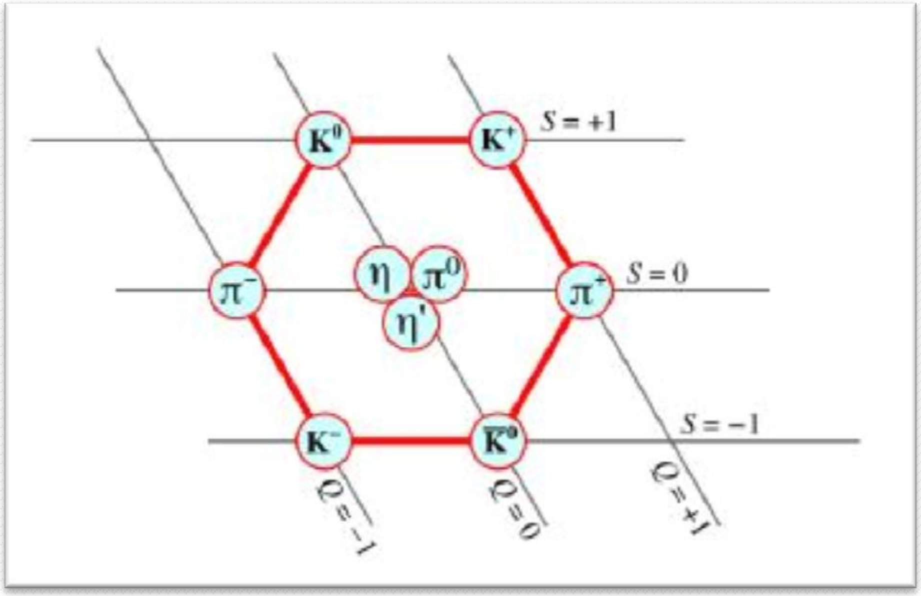
- If m_q=0 left and right handed particles can be rotated into each other

U(3)L x U(3)R Chiral Symmetry

- Symmetry is spontaneouly broken in real world
- Octet of pseudoscalar light mesons . Goldstone -Bosons

Light pseudoscalar octet

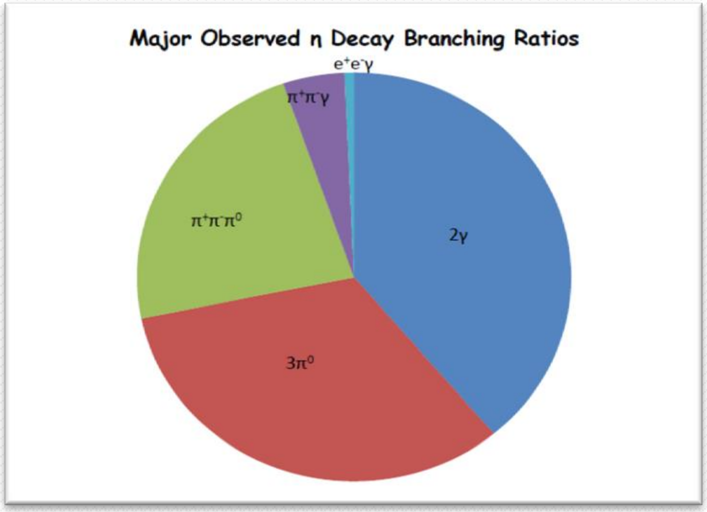
- η is one of key mesons for our understanding of low-energy hadron dynamics and underlying QCD



- Eigenstate of P, C, CP, and G:

Study violations of discrete symmetries

$$I^G J^{PC} = 0^+ 0^{-+}$$

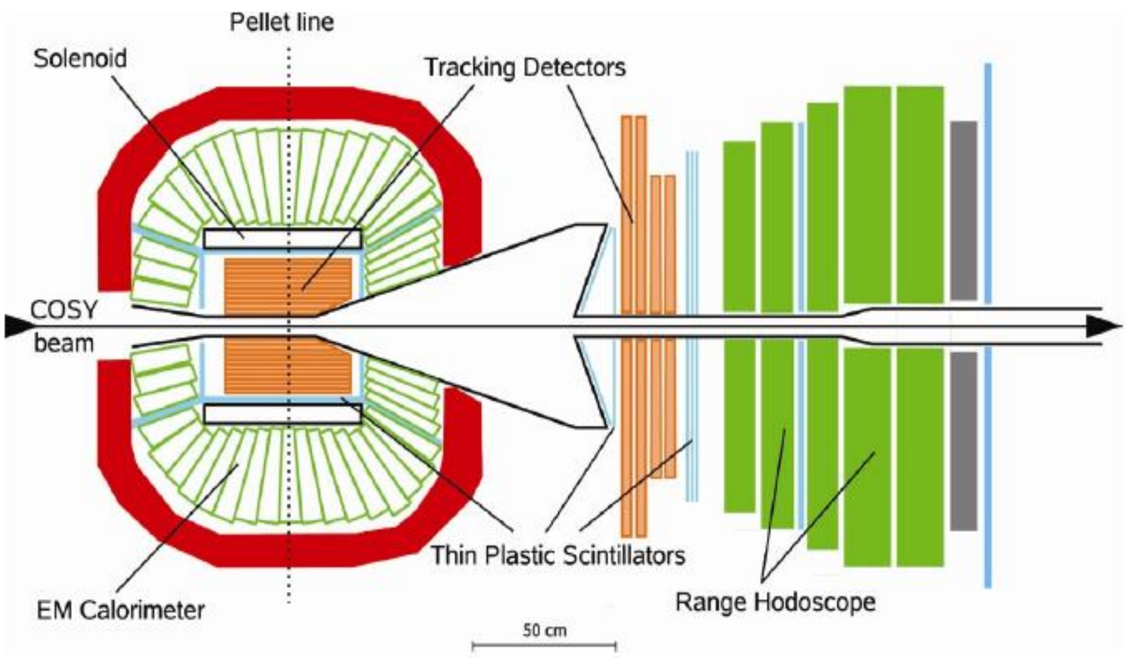


Experiment WASA at COSY accelerator
(at CELSIUS Storage Ring before 2006)

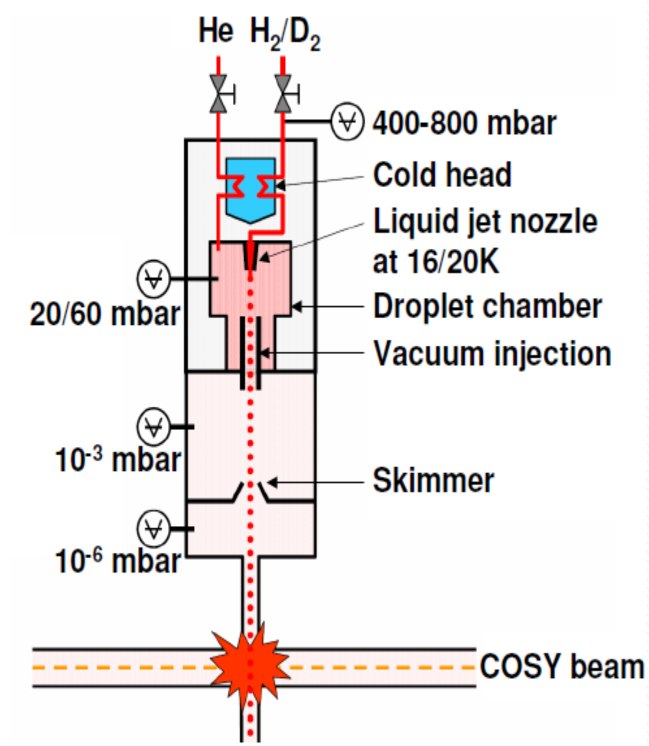
- Meson produced in $pp \rightarrow ppX$ or $pd \rightarrow {}^3HeX$ reaction

Experimental setup

The WASA detector system



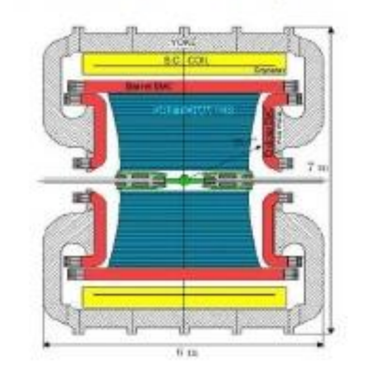
Pellet target



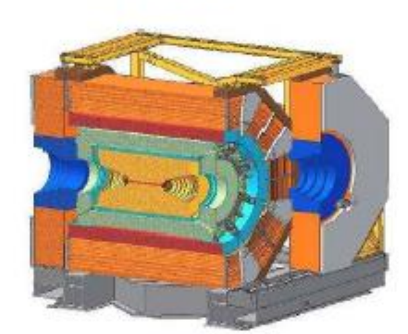
World Competition in η Decays

e^+e^- Collider

KLOE-2 at DAϕNE



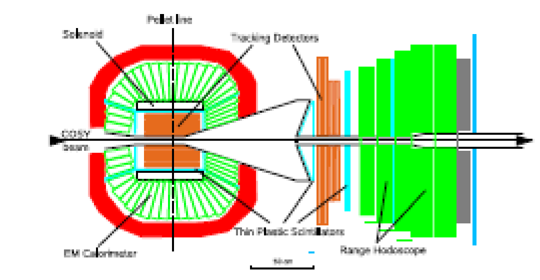
BESIII at BEPCII



Low energy η-facilities

Fixed-target

WASA at COSY

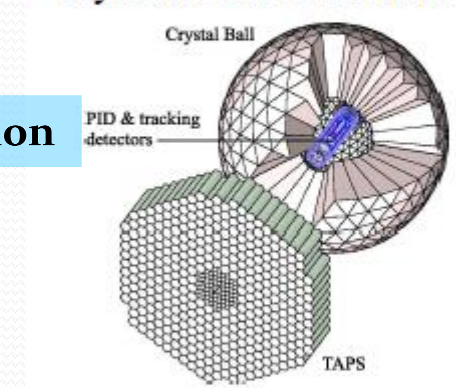


hadroproduction

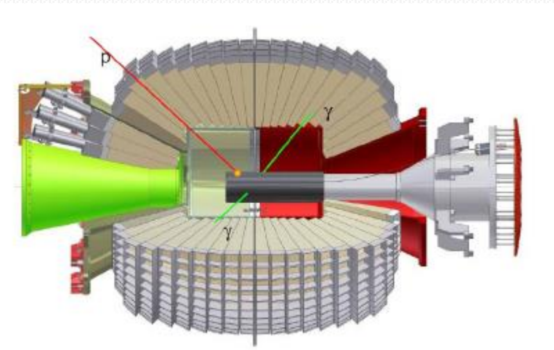
High energy η-facility

photoproduction

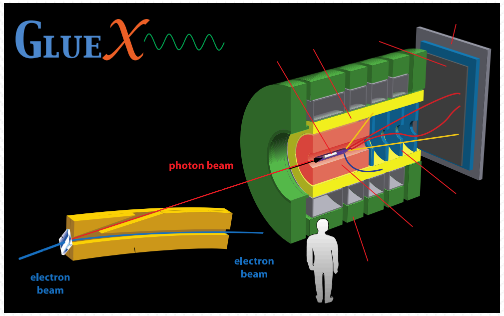
Crystall Ball at MAMI



CBELSA/TAPS at ELSA



JEF at Jlab



- At low energy the strong interaction between pseudoscalar mesons can be described by an Effective Chiral Lagrangian based on symmetry requirements

but

- The Langrangian depends on a number of coupling constants that are not determined by symmetries itselves

Isospin violating $\eta \to \pi^+\pi^-\pi^o$ decay

- Strong interaction – isospin violation connected to **$m_u - m_d$**
- A unique source of information on the light quarks mass difference

$$A(\eta \to 3\pi) \sim m_d - m_u \sim R^{-1} \sim Q^{-2} ,$$

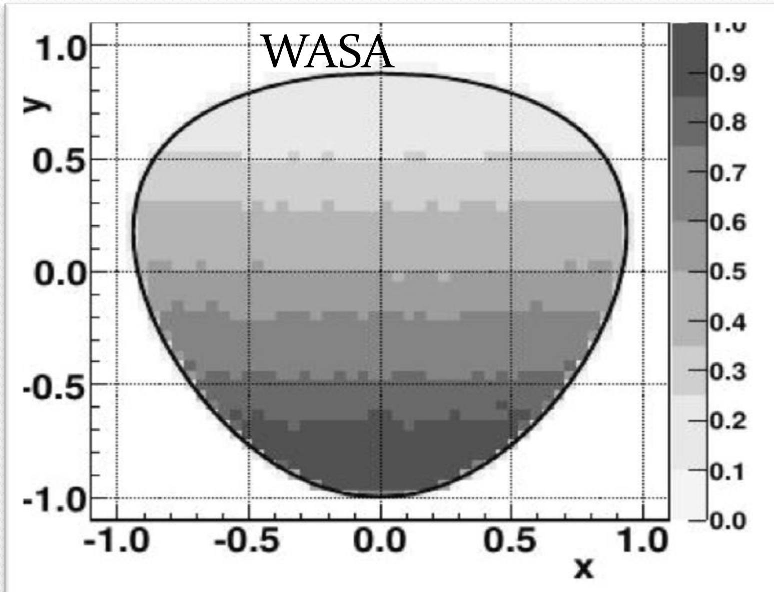
$$R = \frac{m_s - m_{ud}}{m_d - m_u}, \quad Q^2 = \frac{m_s^2 - m_{ud}^2}{m_d^2 - m_u^2} ,$$

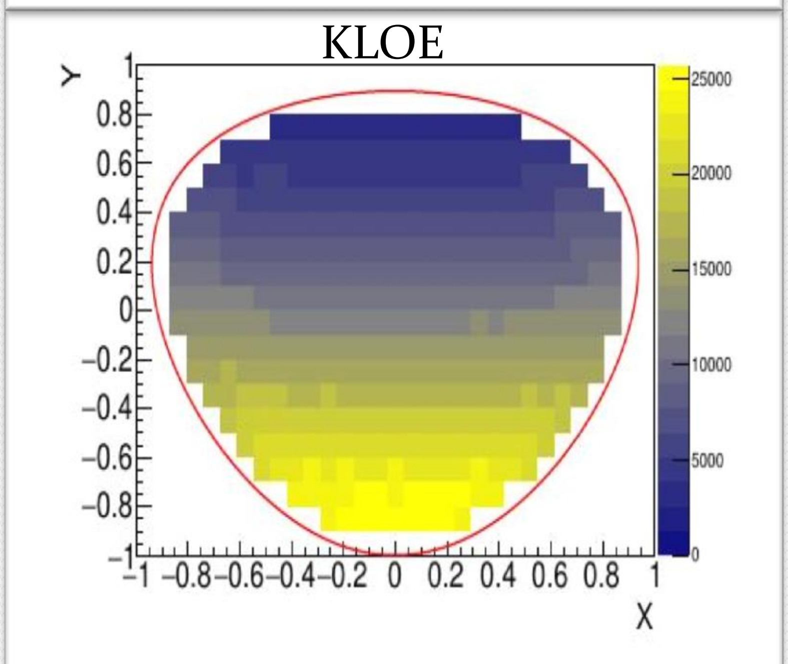
$$Q^2 = \left(1 + \frac{m_s}{m_{ud}}\right) R/2, \quad m_{ud} := (m_u + m_d)/2 .$$

Calculations:	*Q*
LO [10]	15.6
NLO [10]	20.1
NNLO [10]	22.9
dispersive [13]	22.7(8)
dispersive [14]	22.4(9)
dispersive (PLM) [15]	23.1(7)
Lattice QCD av. [16]	22.6(7)(6)

- Electromagnetic contributions are small [Bell, Sutherland(1968), et al. (2009)]

$\eta \rightarrow \pi^+ \pi^- \pi^0$ decay





$$X = \sqrt{3}\frac{T_{\pi^+} - T_{\pi^-}}{Q_\eta}$$

$$Y = \frac{3T_{\pi^0}}{Q_\eta} - 1$$

with

$$Q_\eta = T_{\pi^+} + T_{\pi^-} + T_{\pi^0} = m_\eta - 2m_{\pi^+} - m_{\pi^0}.$$

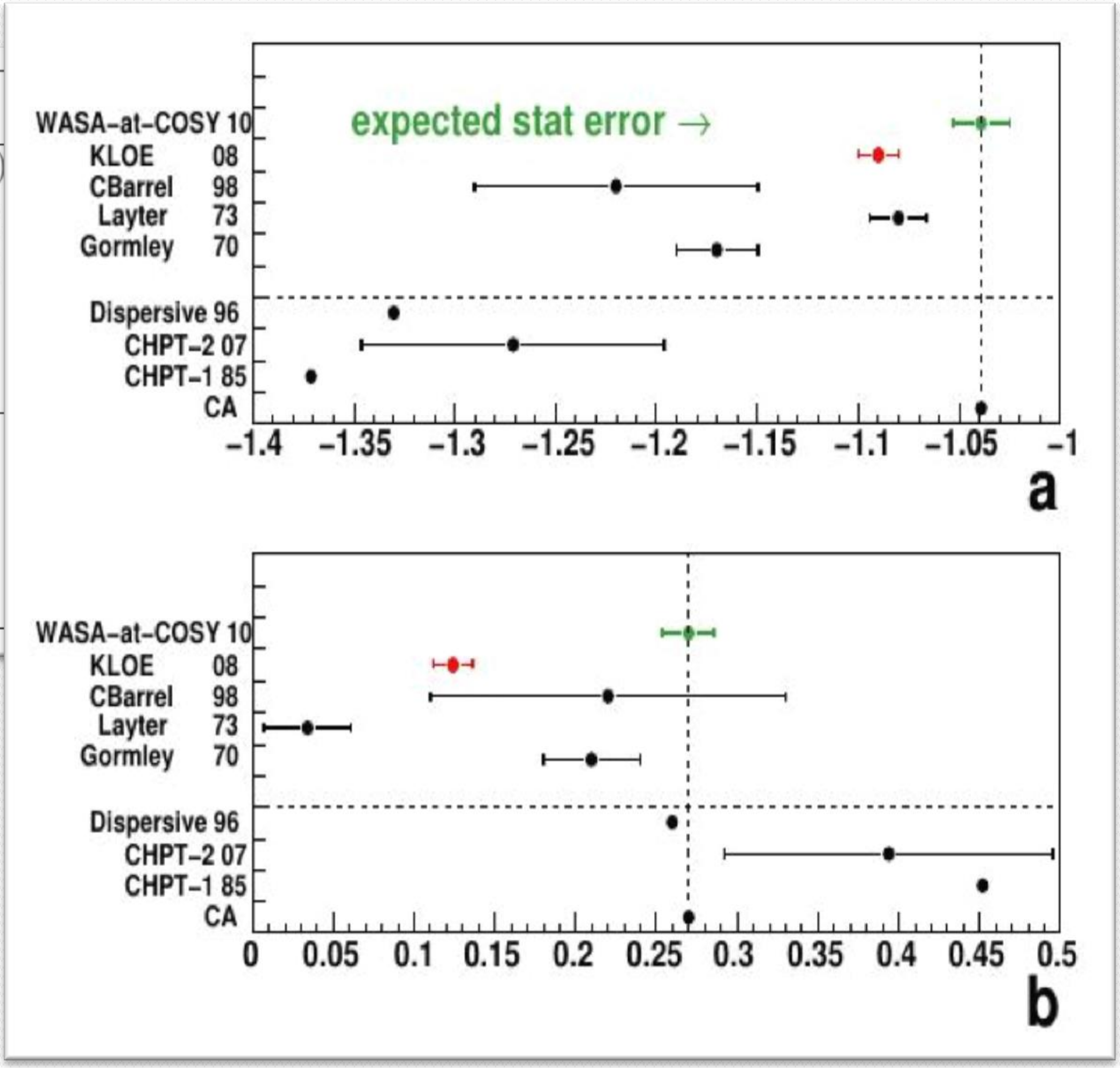
The Amplitude can be parametised as:

$$|A(X,Y)|^2 \simeq N(1 + aY + bY^2 + cX + dX^2 + eXY + fY^3 + gX^2Y + hXY^2 + lX^3 + \ldots).$$

Dalitz plot parameters : experiment vs theory

G.Ecker (2015)

	$-a$	b	d
WASA/COSY 2014 [79]	1.144(18)	0.219(19)(47)	0.086(18)(15)
BESIII 2015 [80]	1.128(15)(8)	0.153(17)(4)	0.085(16)(9)
KLOE 2015 [81]	$1.095(3)(^{+3}_{-2})$	0.145(3)(5)	$0.081(3)(^{+6}_{-5})$
my averages	1.099(4)	0.147(6)	0.082(6)
PDG 2014 [54]			
NNLO CHPT [67]	1.271(75)	0.394(102)	0.055(57)
NREFT [75]	1.213(14)	0.308(23)	0.050(3)
KKNZ [76]			
JPAC [77]	1.116(32)	0.188(12)	0.063(4)

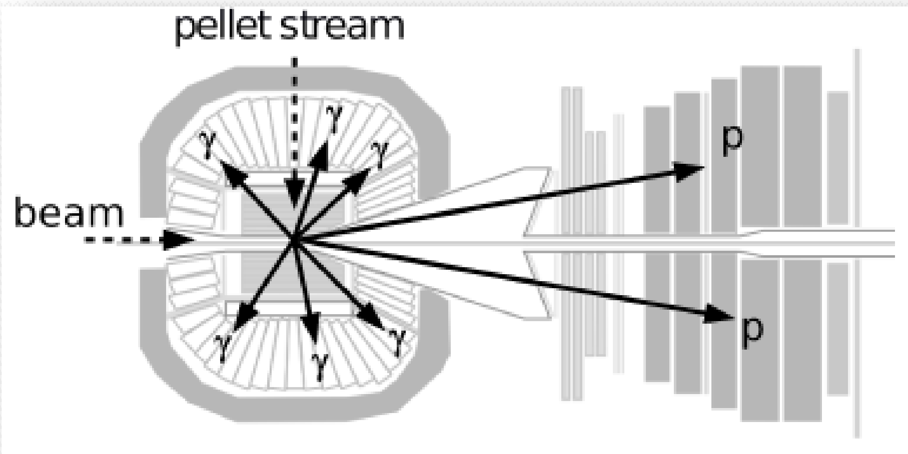


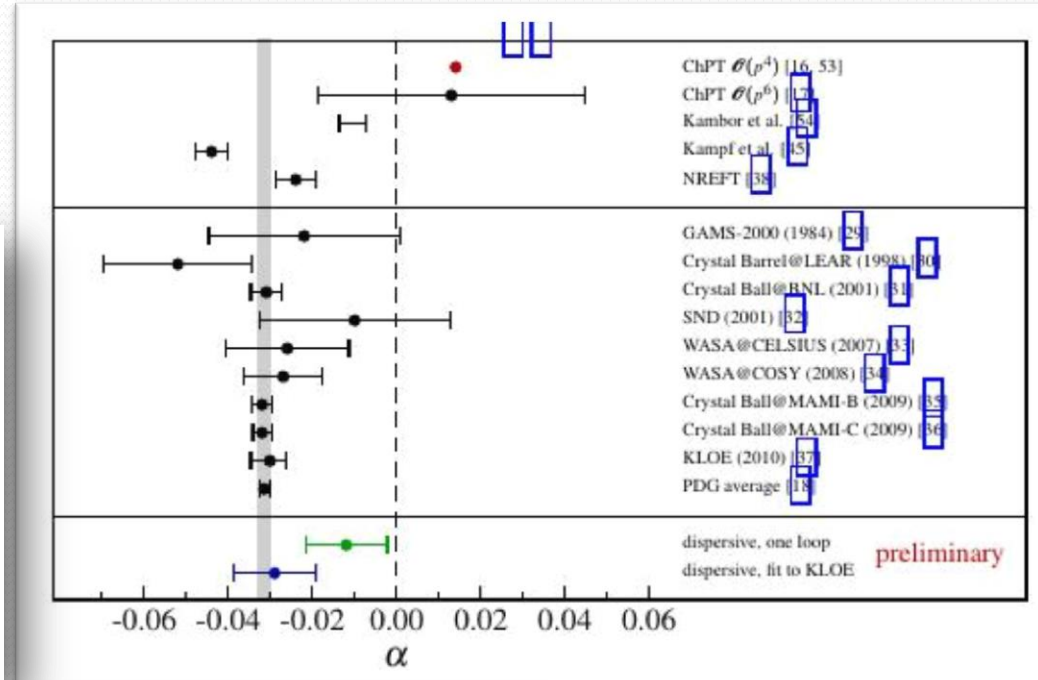
67-Bijnens (2007)
75-Schneider et al.(2011)
76-Kampf et al.(2011)
77-Guo et al.(2015)

$\eta \to 3\pi^0$ decay

$$|A_{\text{neutral}}|^2 = N(1+2\alpha z+\ldots)$$

$$Z = x^2 + y^2$$





		$\Gamma(\eta \to \pi^+\pi^-\pi^0)$/eV	r
LO	Osborn, Wallace 1970 [65]	66*	1.54
NLO	Gasser, Leutwyler 1985 [66]	160(50)*	1.46
NNLO	Bijnens, Ghorbani 2007 [67]		1.47
expt.	PDG 2014 [54]	300(12)	1.48(5)

Table 7: Successive orders in the chiral expansion for the decay rate $\Gamma(\eta \to \pi^+\pi^-\pi^0)$ and for the ratio $r = \Gamma(\eta \to 3\pi^0)/\Gamma(\eta \to \pi^+\pi^-\pi^0)$ in comparison with experiment. For the numbers with an asterisk $Q = 24.3$

π^0 production near threshold from $pp \to pp\pi^0$

Data from:

WASA/CELSIUS (A.Bondar et al)

and from Indiana Cooler (Meyer et al)

Dashed line – rescattering added

Dotted line - direct production only

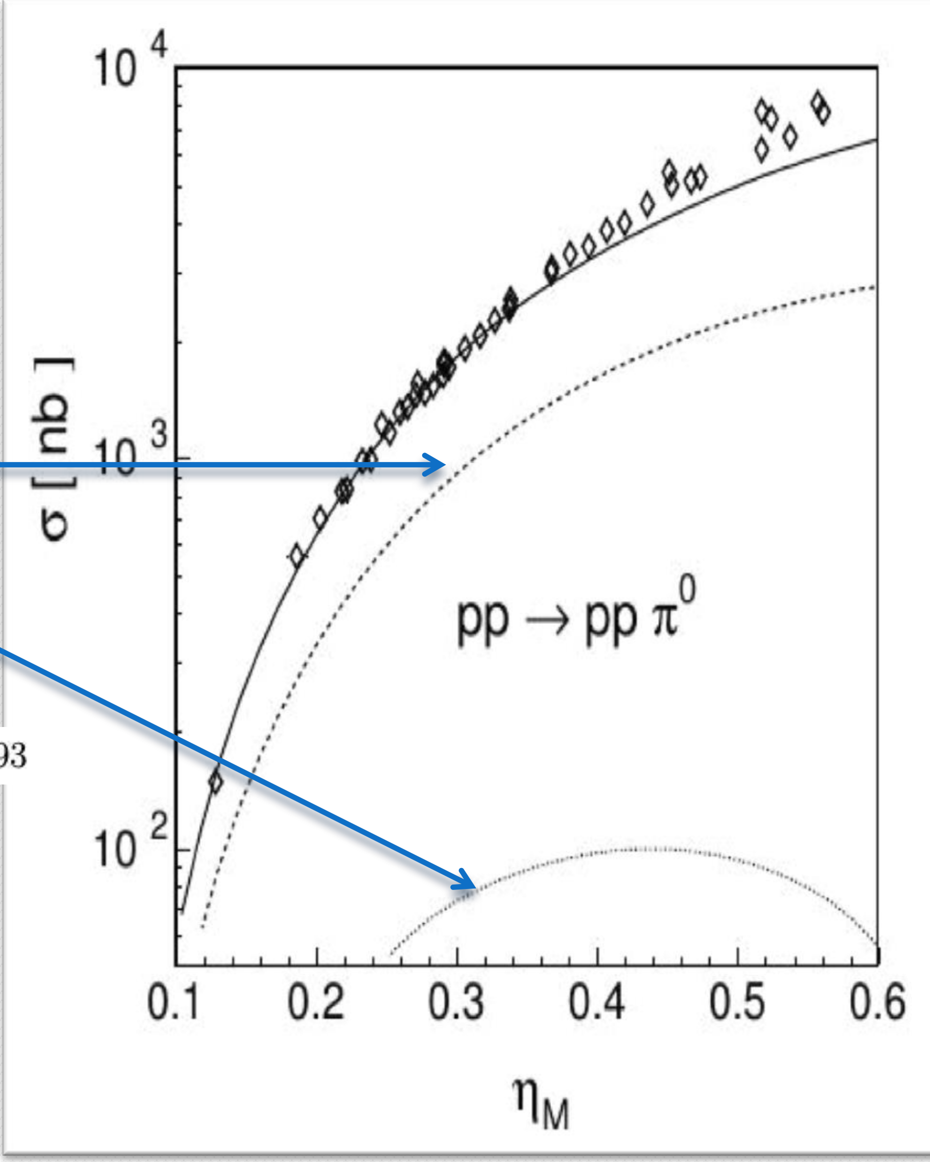
Full line – heavy meson exchnge included

J. Haidenbauer, C. Hanhart and J. Speth, *Acta Phys. Pol.* B 27 (1996) 2893

But rescattering with off-shell pions by Oset group seemed to explain the experimental results

A.Bondar et al., Phys. Lett. **B356** (1995) 8.

H.O.Meyer et al., Nucl. Phys. **A539** (1992) 683.

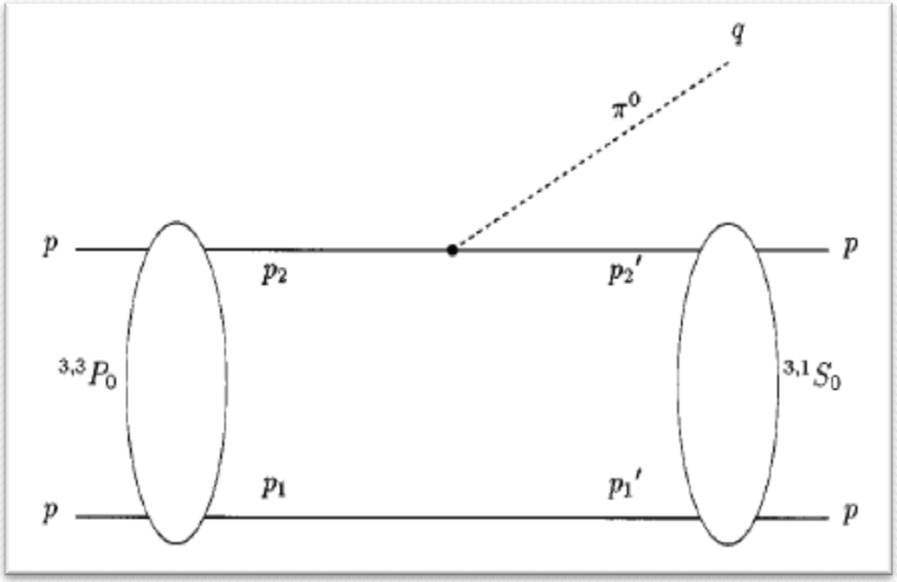


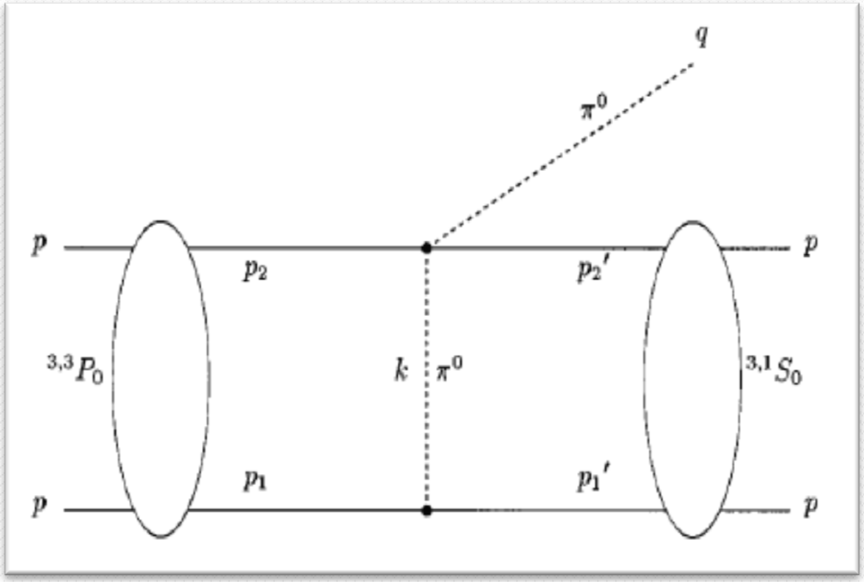
Maximum pion momentum in pion mass units

Heavy meson exchange or off shell π-p scattering amplitude?

- Which of these explanations, if either, is the correct one? [Cohen et al. Phys.Rev. C53 (1996)]
- Clearly both effects cannot simultaneously be as large as the authors of the papers suggested unless there are some compensating effects.
- For example, if the amplitude of the impulse term were added to the amplitude for both of these effects, the resulting cross section would be approximately 2–2.5 times larger than the experimental cross section.

- According to Park & al. (1995), using systematic ChPT, the rescattering term interferes destructively with the Born-term → addition of the heavy meson exchange contribution is needed



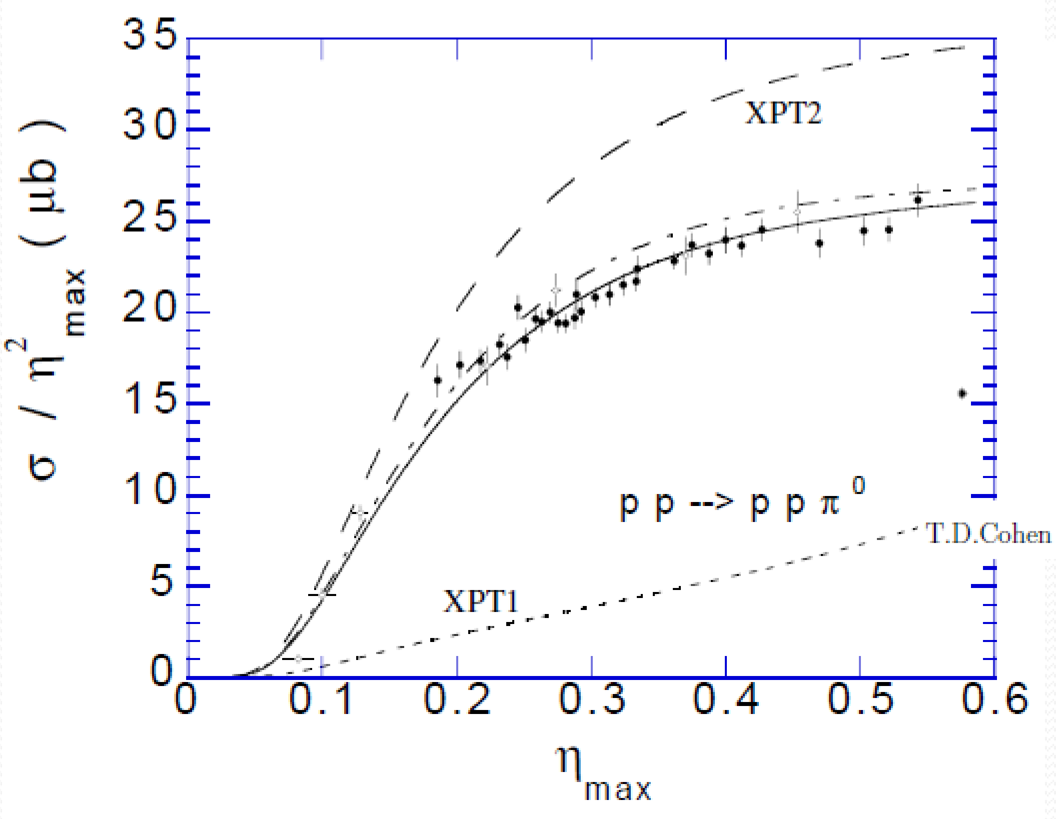


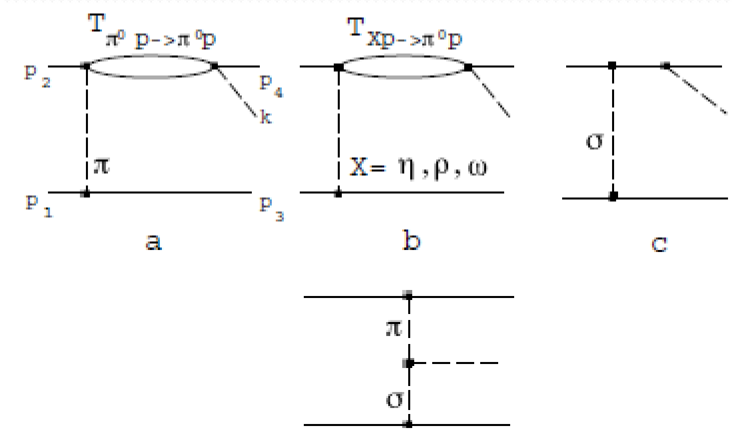
Park & al. Phys.Rev C, Vol 53(4), 1995

Chiral Perturbation Theory Calculations For S-wave π^0

E.Gedalin*, A.Moalem† and L.Razdolskaya‡

FIG. 4. Predictions for the total cross section vs. η_{max}, the maximal available momentum of pion in the center of mass system.





T.D.Cohen et al., Phys. Rev. **C53** (1996) 2661.

A.Bondar et al., Phys. Lett. **B356** (1995) 8.

H.O.Meyer et al., Nucl. Phys. **A539** (1992) 683.

Summary

- One can extract values for the quark mass ratio

  R and Q from $\eta \to 3\pi$ decays.
- The area of low energy tests of the SM via ChPT is an active and exciting one.
- With chiral SU(3) there is still room for improvements. ChPT seems unable to account for Dalitz plot for $\eta \to 3\pi$ even at NNLO.
- Slow convergence.
- Leptonic and semileptonic η decays are studied by the WASA collaboration.

Backup

The goldstone boson fields

$$\pi = \frac{1}{\sqrt{2}}\begin{bmatrix} \sqrt{\frac{1}{2}}\,\pi^0 + \sqrt{\frac{1}{6}}\,\eta & \pi^+ & K^+ \\ \pi^- & -\sqrt{\frac{1}{2}}\,\pi^0 + \sqrt{\frac{1}{6}}\,\eta & K^0 \\ K^- & \bar{K}^0 & -\frac{2}{\sqrt{6}}\eta \end{bmatrix},$$

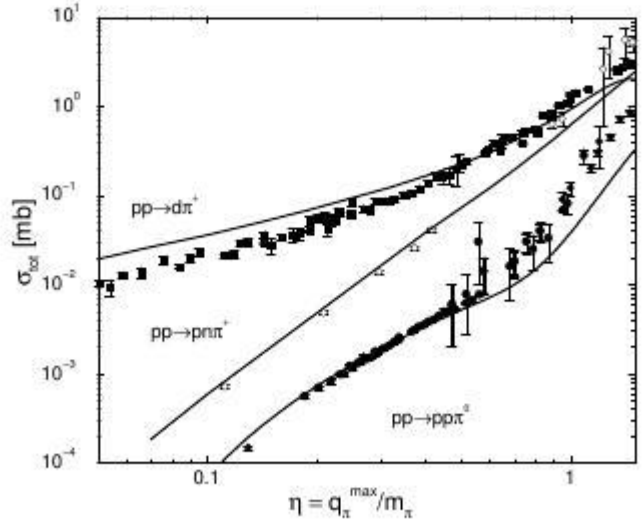
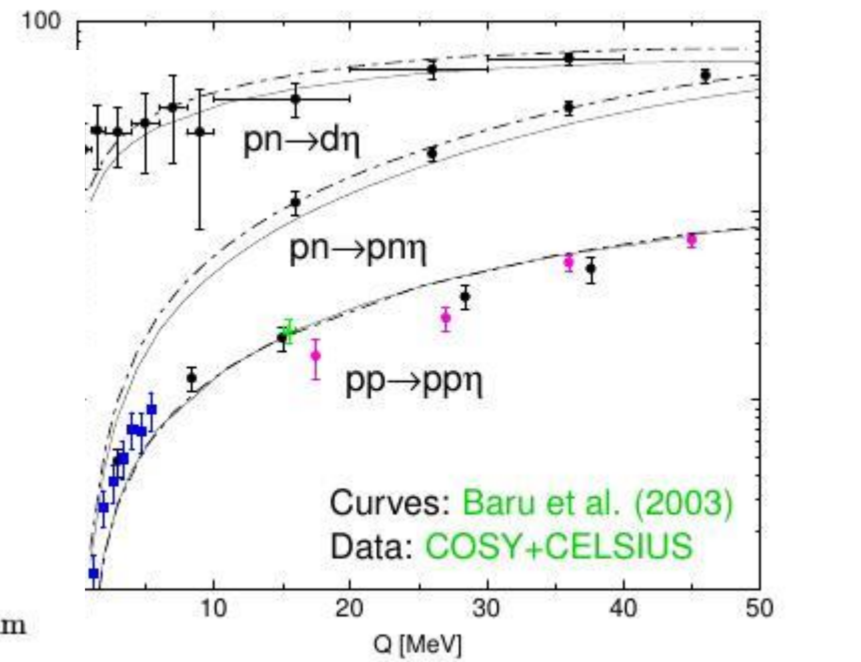


Fig. 3. Results for the different reaction channels as a function of η, the maximum center-of-mass momentum of the produced pion divided by the pion mass.



Production of η-mesons in hadron-induced reactions – p.12/22

Energy dependence of $\eta N \to \eta N$ amplitude most sensitive to S_{11} molecular component (Baru et al. (2004))

What do we know?

PDG 2004: Mass: 1520–1555 MeV ($m_\eta + M_N$ =1486 MeV)
Width: 100–200 MeV

Hadronic decay channels:

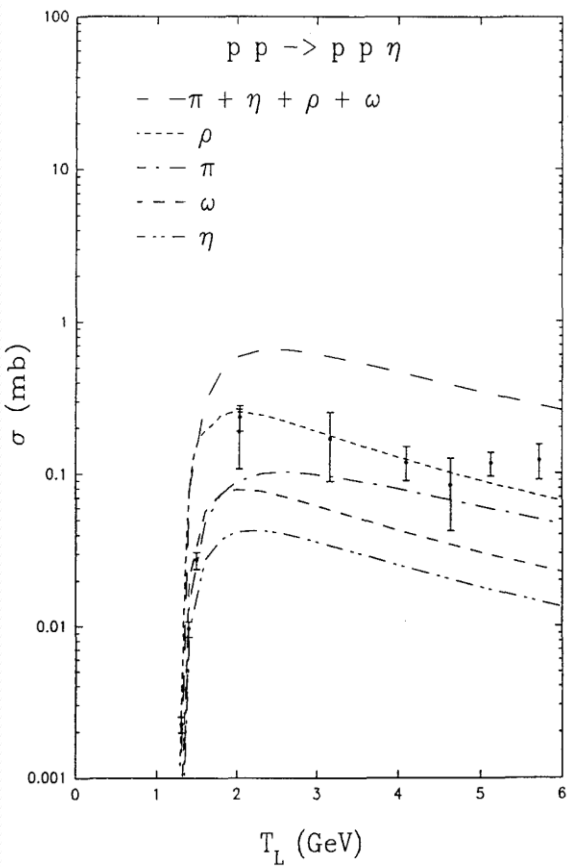
πN	$35 - 55\%$
ηN	$30 - 55\%$
$\pi\pi N$	$1 - 10\%$
$\pi\Delta$	$< 1\%$
ρN	$< 4\%$

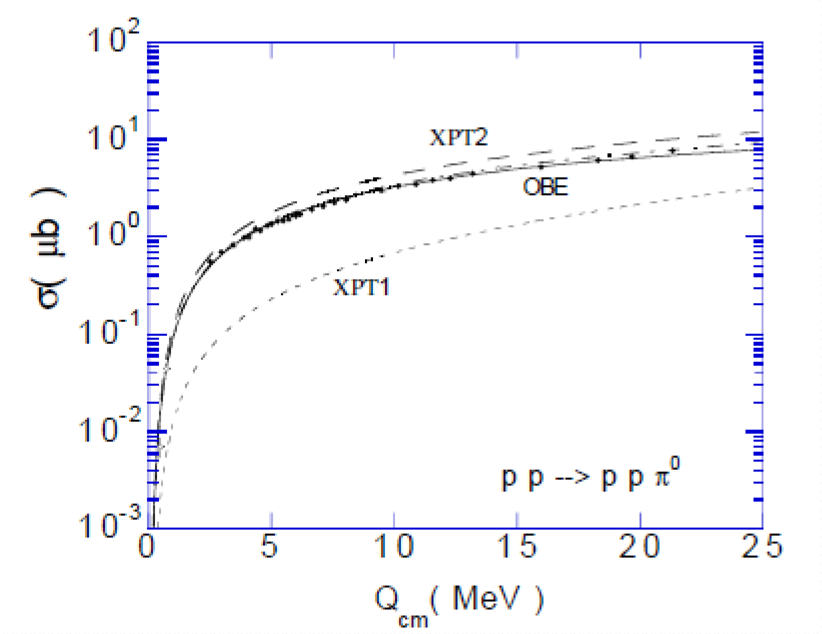
two pion channels neither well determined nor big

The goldstone boson fields

$$\pi = \frac{1}{\sqrt{2}} \begin{bmatrix} \sqrt{\frac{1}{2}}\,\pi^0 + \sqrt{\frac{1}{6}}\,\eta & \pi^+ & K^+ \\ \pi^- & -\sqrt{\frac{1}{2}}\,\pi^0 + \sqrt{\frac{1}{6}}\,\eta & K^0 \\ K^- & \bar{K}^0 & -\frac{2}{\sqrt{6}}\,\eta \end{bmatrix},$$

A.B. Santra, B.K. Jain / Nuclear Physics A 634 (1998) 309–324





10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
σ(μb)
XPT2
OBE
XPT1
p p --> p p π^0
0
5
10
15
20
25
Q_{cm} (MeV)