The double pion production in nucleon-(anti)nucleon collisions

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Motivation

- Experiment: $NN \to NN\pi\pi$

Old data before 1985: bubble chamber or magnetic spectrometer

New data after 2000:

Channel	Group (Tp(MeV))
$pp \to pp\pi^+\pi^-$	CELSIUS(650, 680, 750, 775, 895, 1100, 1360), Gatchina(717, 818, 861, 900, 980), COSY(750, 800) KEK(698, 780, 814, 908, 995, 1083, 1172)
$pp \to pp\pi^0\pi^0$	CELSIUS(650, 725, 750, 775, 895, 1000, 1100, 1200, 1300, 1360)
$pp \to nn\pi^+\pi^+$	CELSIUS(800, 1100)
$pp \to pn\pi^+\pi^0$	CELSIUS(725, 750, 775, 1100)
$pn \to pn\pi^+\pi^-$	KEK(698, 780, 814, 908, 995, 1083, 1172)
$pn \to pp\pi^-\pi^0$	KEK(698, 780, 814, 908, 995, 1083, 1172)

Motivation

- Experiment: $N\bar{N} \to N\bar{N}\pi\pi$

  JETSET, Z.Phys.C 1997;

  BNL, Nucl. Phys. B 1973; Argonne, PRD, 1973…..

  PANDA at FAIR,   Tlab: 1.5~15GeV

- Theory:

G. Wolf, Phys. Rev. 1966 — OPE model
M. Saleem, Prog. Theor. Phys. 1983 — Regge model

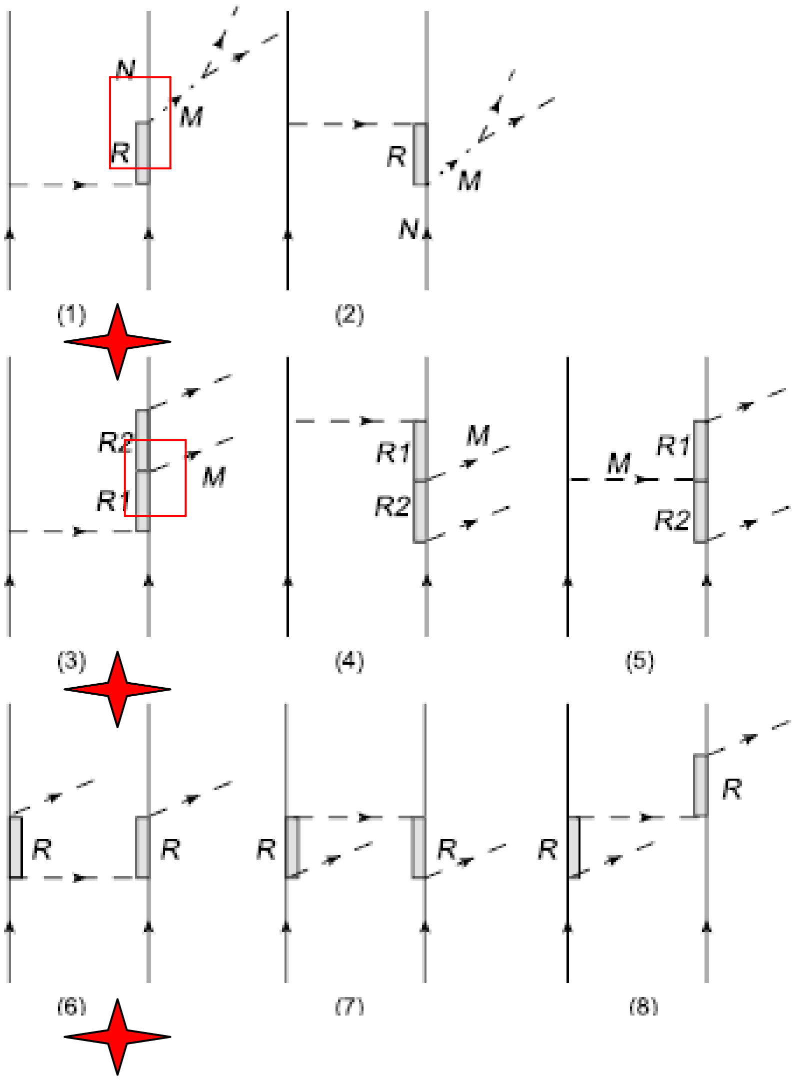
$N\bar{N} \to N\bar{N}\pi\pi$

E. Ferrari, Nuovo Cimento, 1963 — OPE model

Valencia Model, Nucl. Phys. A, 1999

$NN \to NN\pi\pi$

Feynman Diagrams



Formalism and Ingredients

$$\mathcal{L}_{\pi NN} = -\frac{f_{\pi NN}}{m_\pi}\overline{N}\gamma_5\gamma_\mu\vec{\tau}\cdot\partial^\mu\vec{\pi}N,$$

$$\mathcal{L}_{\pi\Delta\Delta} = \frac{f_{\pi\Delta\Delta}}{m_\pi}\overline{\Delta}^\nu\gamma_5\gamma_\mu\vec{\tau}\cdot\partial^\mu\vec{\pi}\Delta_\nu + h.c.,$$

$$\mathcal{L}_{\eta NN} = -ig_{\eta NN}\overline{N}\gamma_5\eta N,$$

$$\mathcal{L}_{\sigma NN} = g_{\sigma NN}\overline{N}\sigma N,$$

$$\mathcal{L}_{\rho NN} = -g_{\rho NN}\overline{N}(\gamma_\mu + \frac{\kappa}{2m_N}\sigma_{\mu\nu}\partial^\nu)\vec{\tau}\cdot\vec{\rho}^\mu N.$$

$1/2^-$

$$\mathcal{L}^{1/2^-}_{\pi NR} = g_{\pi NR}\overline{N}\vec{\tau}\cdot\vec{\pi}R + h.c.,$$

$$\mathcal{L}^{1/2^-}_{\rho NR} = g_{\rho NR}\overline{N}\gamma_5(\gamma_\mu - \frac{q_\mu \not{q}}{q^2})\vec{\tau}\cdot\vec{\rho}^\mu R + h.c.,$$

$$\mathcal{L}^{1/2^-}_{\pi\Delta R} = g_{\pi\Delta R}\overline{\Delta}_\mu\gamma_5\vec{\tau}\cdot\partial^\mu\vec{\pi}R + h.c.,$$

$1/2^+$

$$\mathcal{L}^{1/2^+}_{\pi NR} = g_{\pi NR}\overline{N}\gamma_5\gamma_\mu\vec{\tau}\cdot\partial^\mu\vec{\pi}R + h.c.,$$

$$\mathcal{L}^{1/2^+}_{\eta NR} = g_{\eta NR}\overline{N}\gamma_5\eta R + h.c.,$$

$$\mathcal{L}^{1/2^+}_{\sigma NR} = g_{\sigma NR}\overline{N}\sigma R + h.c.,$$

$$\mathcal{L}^{1/2^+}_{\rho NR} = g_{\rho NR}\overline{N}\gamma_\mu\vec{\tau}\cdot\vec{\rho}^\mu R + h.c.,$$

$$\mathcal{L}^{1/2^+}_{\pi\Delta R} = g_{\pi\Delta R}\overline{\Delta}_\mu\vec{\tau}\cdot\partial^\mu\vec{\pi}R + h.c.,$$

$3/2^+$

$$\mathcal{L}^{3/2^+}_{\pi NR} = g_{\pi NR}\overline{N}\vec{\tau}\cdot\partial^\mu\vec{\pi}R_\mu + h.c.,$$

$$\mathcal{L}^{3/2^+}_{\rho NR} = g_{\rho NR}\overline{N}\gamma_5\vec{\tau}\cdot\vec{\rho}^\mu R_\mu + h.c.,$$

$$\mathcal{L}^{3/2^+}_{\pi\Delta R} = g_{\pi\Delta R}\overline{\Delta}^\mu\gamma_5\vec{\tau}\cdot\vec{\pi}R_\mu + h.c.,$$

$$\mathcal{L}^{3/2^+}_{\pi N^*(1440)R} = g_{\pi N^*R}\overline{N^*}\vec{\tau}\cdot\partial^\mu\vec{\pi}R_\mu + h.c.;$$

Formalism and Ingredients

Main contributions

High energies

Resonance	Pole Position	BW Width	Decay Mode	Decay Ratio	$g^2/4\pi$
$\Delta^*(1232)P_{33}$	(1210, 100)	118	$N\pi$	1.0	19.54
$N^*(1440)P_{11}$	(1365, 190)	300	$N\pi$	0.65	0.51
			$N\sigma$	0.075	3.20
			$\Delta\pi$	0.135	4.30
$\Delta^*(1600)P_{33}$	(1600, 300)	350	$N\pi$	0.175	1.09
			$\Delta\pi$	0.55	59.9
			$N^*(1440)\pi$	0.225	289.1
$\Delta^*(1620)S_{31}$	(1600, 118)	145	$N\pi$	0.25	0.06
			$N\rho$	0.14	0.37
			$\Delta\pi$	0.45	83.7

Formalism and Ingredients

Negligible contributions

small branching ratios of double pion channel

$N^*(1535)S_{11}$ $N^*(1650)S_{11}$ $N^*(1700)D_{13}$

higher partial waves

$N^*(1520)D_{13}$ $N^*(1675)D_{15}$

lying beyond the considered energies

$N^*(1680)F_{15}$ $\Delta^*(1700)D_{33}$

$N^*(1710)P_{11}$ $N^*(1720)P_{13}$

Resonances with mass bigger than 1720MeV

the two pion branching ratios have large uncertainties

Form Factors

$F_M^{NN}(k_M^2) = \left(\frac{\Lambda_M^2 - m_M^2}{\Lambda_M^2 - k_M^2}\right)^n$	n=1 for π- and η-meson n=2 for ρ-meson.	$\Lambda_\pi = \Lambda_\eta = 1.0$ GeV, $\Lambda_\sigma = 1.3$ GeV, $\Lambda_\rho = 1.6$ GeV,
$F_M^{RN}(k_M^2) = \left(\frac{\Lambda_M^{*2} - m_M^2}{\Lambda_M^{*2} - k_M^2}\right)^n$	n=1 for N^* resonances n=2 for Δ resonances.	$\Lambda_\pi^* = 0.8$ for $\Delta^*(1600)$. Other $\Lambda_M^* = 1.0$ GeV
$F_R(q^2) = \frac{\Lambda_R^4}{\Lambda_R^4 + (q^2 - M_R^2)^2},$		$\Lambda_R = 1.0$ GeV $\Lambda_N = 0.8$ GeV
$B(Q_{N^*\Delta\pi}) = \sqrt{\frac{P_{N^*\Delta\pi}^2 + Q_0^2}{Q_{N^*\Delta\pi}^2 + Q_0^2}},$	$Q_{N^*\Delta\pi}^2 = \frac{(s_N^* + s_\Delta - s_\pi)^2}{4s_N^*} - s_\Delta,$ $P_{N^*\Delta\pi}^2 = \frac{(m_{N^*}^2 + m_\Delta^2 - m_\pi^2)^2}{4m_{N^*}^2} - m_\Delta^2,$	$Q_0 = 0.197327/R$ GeV/c, $R = 1.5$ fm
$F_\sigma^{\pi\pi}(\vec{q}^2) = \left(\frac{\Lambda^2 + \Lambda_0^2}{\Lambda^2 + \vec{q}^2}\right)^2$	$\mathcal{L}_{\sigma\pi\pi} = g_{\sigma\pi\pi}\partial^\mu\vec{\pi}\cdot\partial_\mu\vec{\pi}\sigma,$ $\mathcal{L}_{\rho\pi\pi} = g_{\rho\pi\pi}\vec{\pi}\times\partial_\mu\vec{\pi}\cdot\vec{\rho^\mu},$	$\Lambda = 0.8$ GeV

Propagators

For intermediate mesons:

$$G_{\pi/\eta}(k_{\pi/\eta}) = \frac{i}{k_{\pi/\eta}^2 - m_{\pi/\eta}^2},$$

$$G_\sigma(k_\sigma) = \frac{i}{k_\sigma^2 - m_\sigma^2 + i m_\sigma \Gamma_\sigma},$$

$$G_\rho^{\mu\nu}(k_\rho) = -i\frac{g^{\mu\nu} - k_\rho^\mu k_\rho^\nu / k_\rho^2}{k_\rho^2 - m_\rho^2},$$

$$G_N(q) = \frac{-i(\not{q} + m_N)}{q^2 - m_N^2}.$$

For intermediate resonances:

$$G_R^{1/2}(q) = \frac{-i(\not{q} + M_R)}{q^2 - M_R^2 + i M_R \Gamma_R}.$$

$$G_R^{3/2}(q) = \frac{-i(\not{q} + M_R) G_{\mu\nu}(q)}{q^2 - M_R^2 + i M_R \Gamma_R}.$$

$$G_R^{5/2}(q) = \frac{-i(\not{q} + M_R) G_{\mu\nu\alpha\beta}(q)}{q^2 - M_R^2 + i M_R \Gamma_R}.$$

$$G_{\mu\nu}(q) = -g_{\mu\nu} + \frac{1}{3}\gamma_\mu \gamma_\nu + \frac{1}{3M_R}(\gamma_\mu q_\nu - \gamma_\nu q_\mu) + \frac{2}{3M_R^2} q_\mu q_\nu,$$

$$G_{\mu\nu\alpha\beta}(q) = -\ \frac{1}{2}(\tilde{g}_{\mu\alpha}\tilde{g}_{\nu\beta} + \tilde{g}_{\mu\beta}\tilde{g}_{\nu\alpha}) + \frac{1}{5}\tilde{g}_{\mu\nu}\tilde{g}_{\alpha\beta} - \frac{1}{10}(\tilde{\gamma}_\mu \tilde{\gamma}_\alpha \tilde{g}_{\nu\beta} + \tilde{\gamma}_\nu \tilde{\gamma}_\beta \tilde{g}_{\mu\alpha} + \tilde{\gamma}_\mu \tilde{\gamma}_\beta \tilde{g}_{\nu\alpha} + \tilde{\gamma}_\nu \tilde{\gamma}_\alpha \tilde{g}_{\mu\beta}),$$

$$\tilde{g}_{\mu\nu}(q) = -g_{\mu\nu} + \frac{q_\mu q_\nu}{M_R^2}, \quad \tilde{\gamma}_\mu = -\gamma_\mu + \frac{\not{q} q_\mu}{M_R^2}.$$

Parameters

$f^2_{\pi NN}/4\pi = 0.078,\ g^2_{\eta NN}/4\pi = 0.4,$

$g^2_{\sigma NN}/4\pi = 5.69,\ g^2_{\rho NN}/4\pi = 0.9, \quad \kappa = 6.1$

$g^2_{\rho\pi\pi} = 2.91$

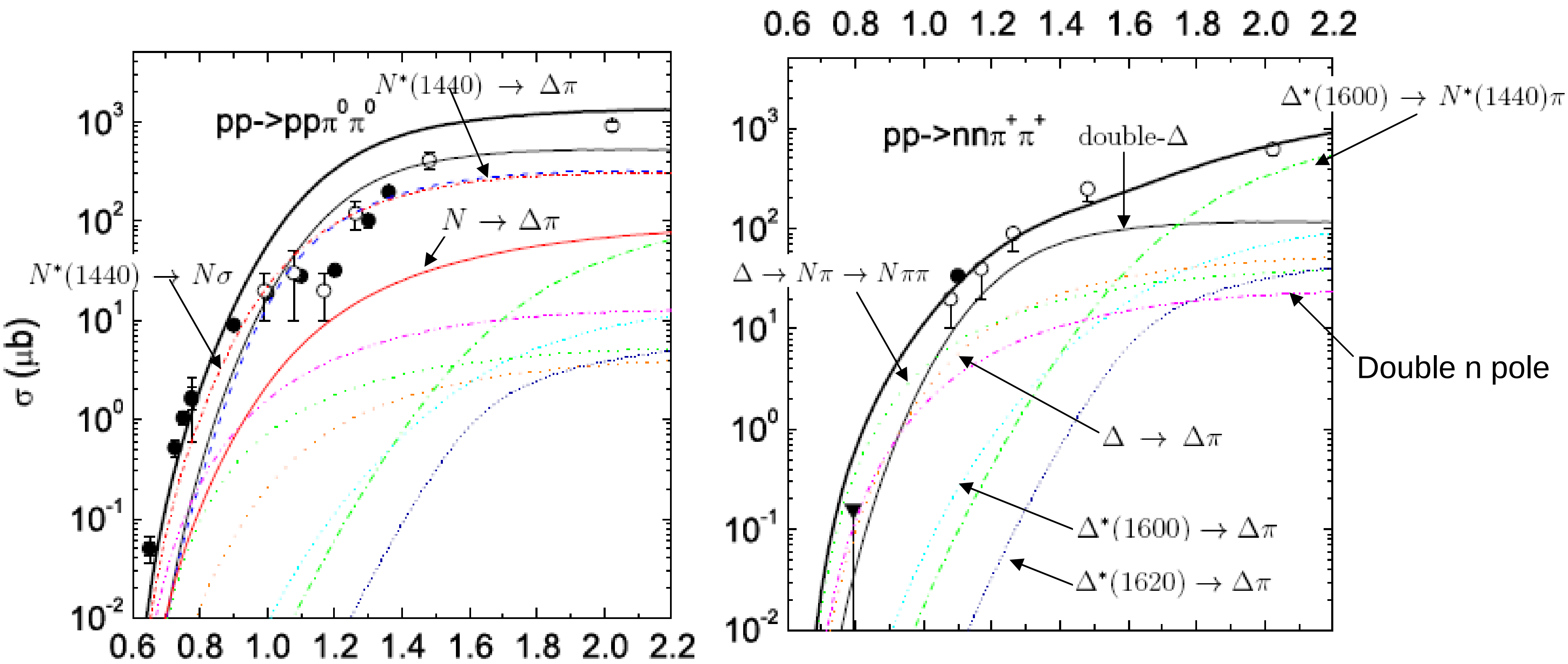
Well determined

$f_{\pi\Delta\Delta} = 4 f_{\pi NN}/5$ Quark model

$m_\sigma = 550 MeV \quad \Gamma_\sigma = 500 MeV$

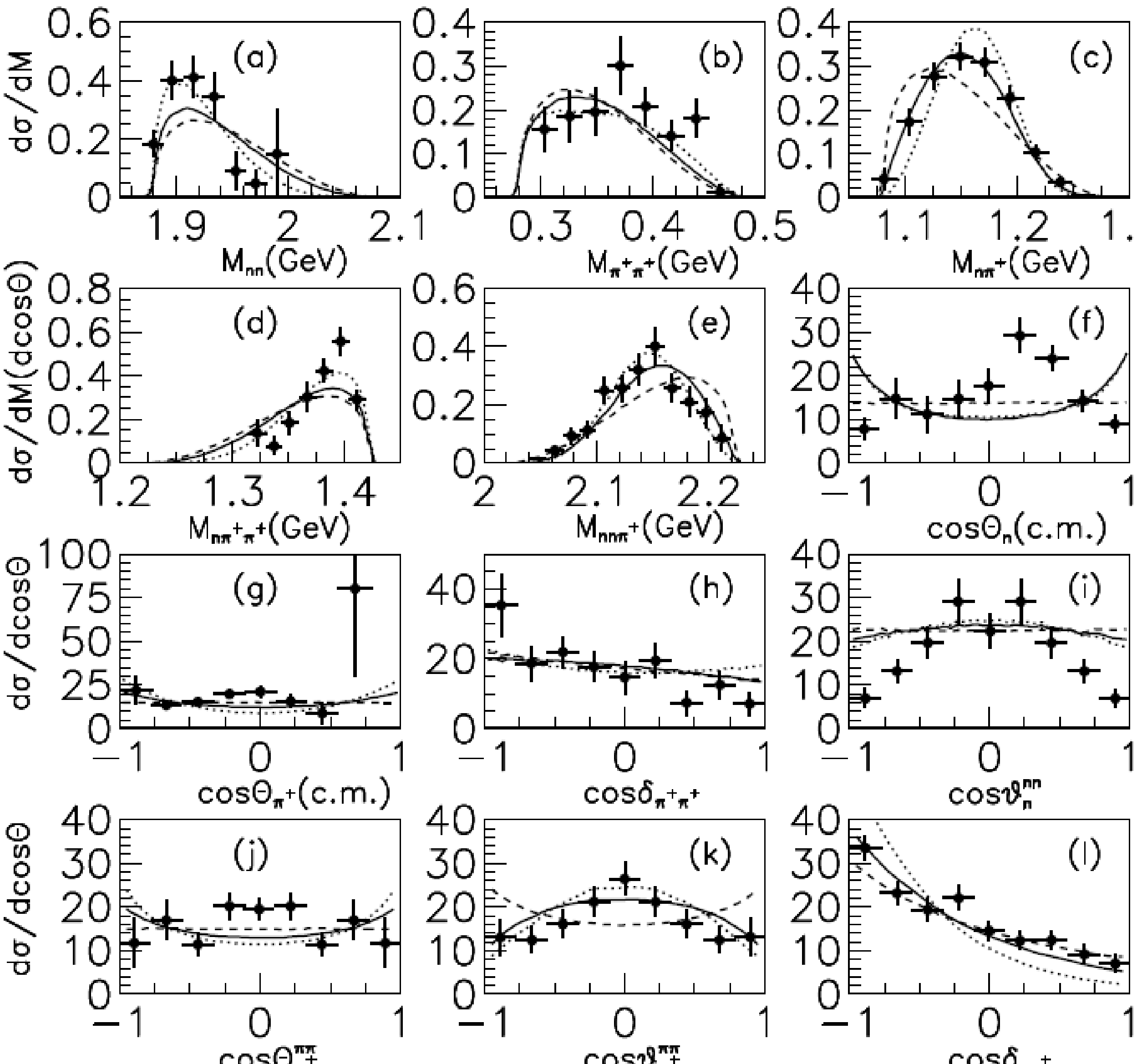
$g^2_{\sigma\pi\pi} = 6.06$

The double pion production in nucleon-nucleon collisions



? Double-Delta: $pp \to pp\pi^0\pi^0$ = 4 $pp \to nn\pi^+\pi^+$

The double pion production in nucleon-nucleon collisions



$pp \to nn\pi^+\pi^+$

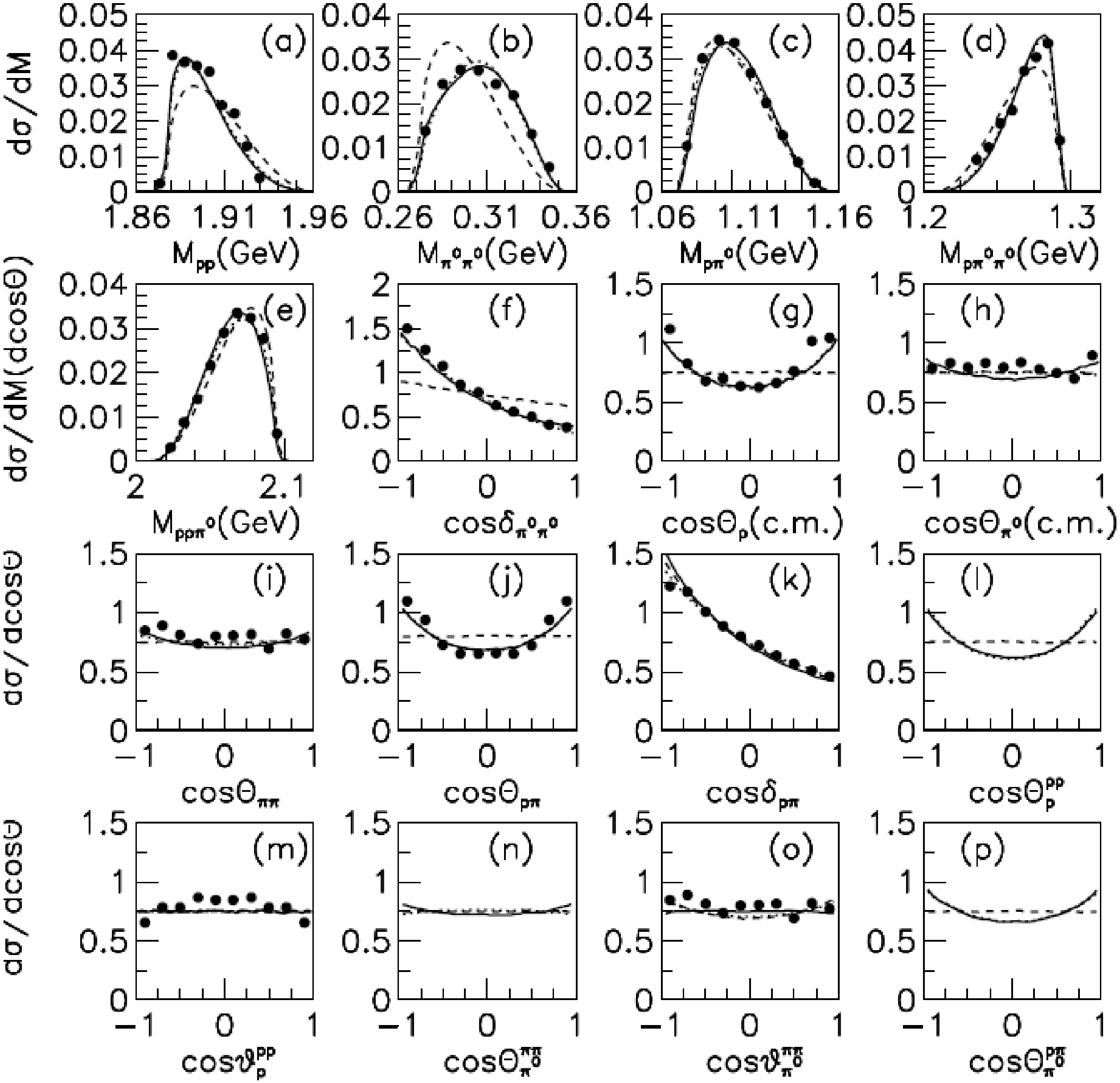
Tp=1100MeV

------- phase space

.... double-Δ

_____ full model

The double pion production in nucleon-nucleon collisions



$pp \rightarrow pp\pi^0\pi^0$

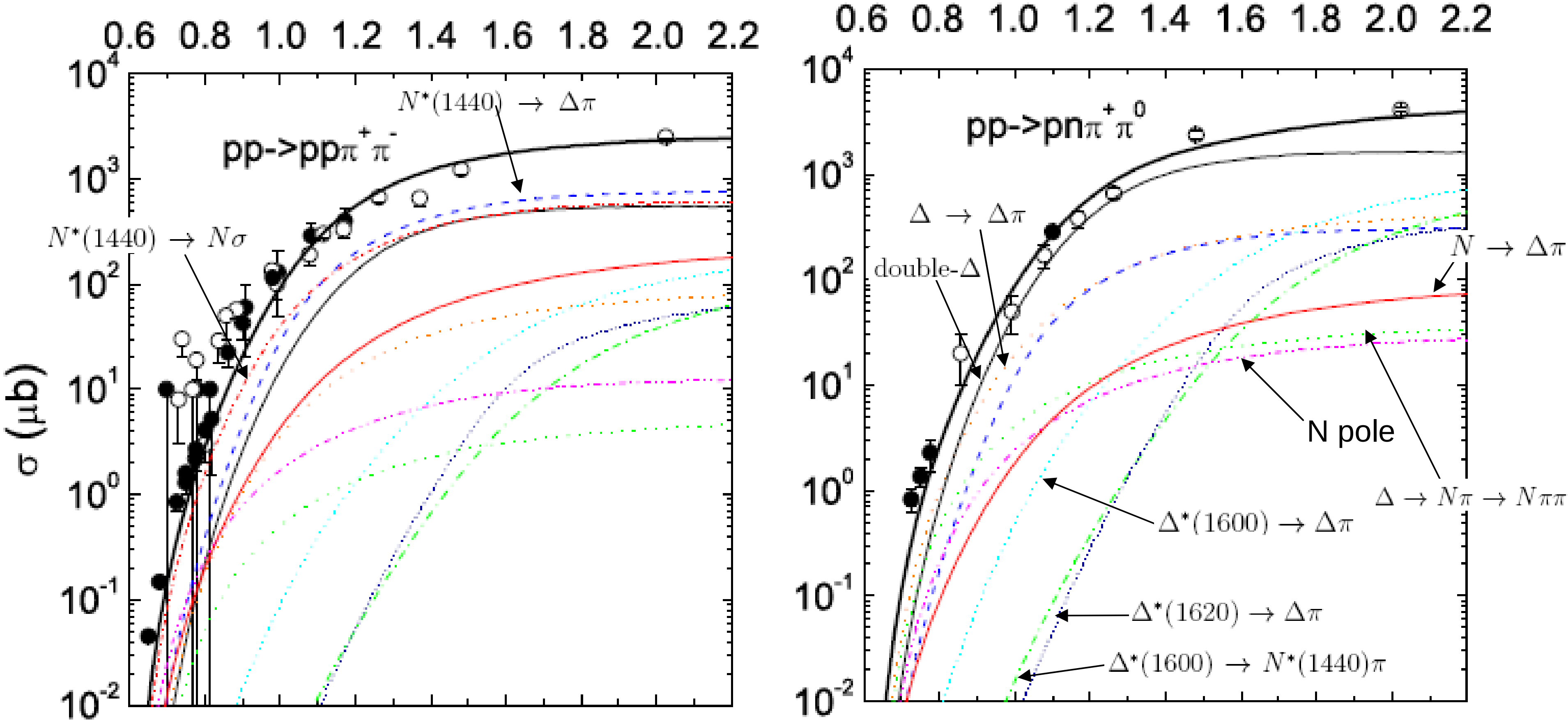
Tp=775MeV

------- phase space

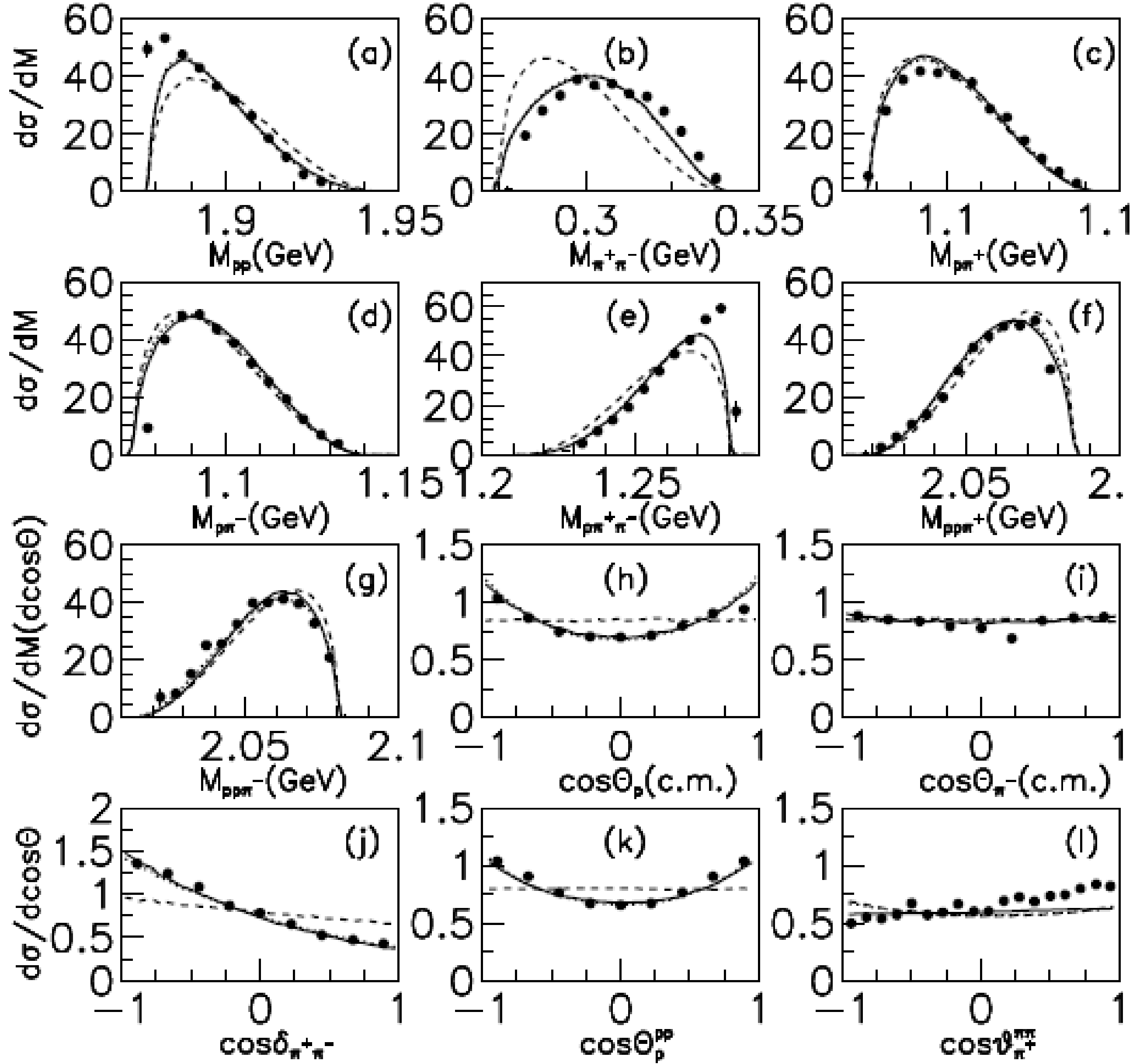
……. $N^*(1440) \rightarrow N\sigma$

_____ full model

The double pion production in nucleon-nucleon collisions



The double pion production in nucleon-nucleon collisions



$pp \to pp\pi^+\pi^-$

Tp=750MeV

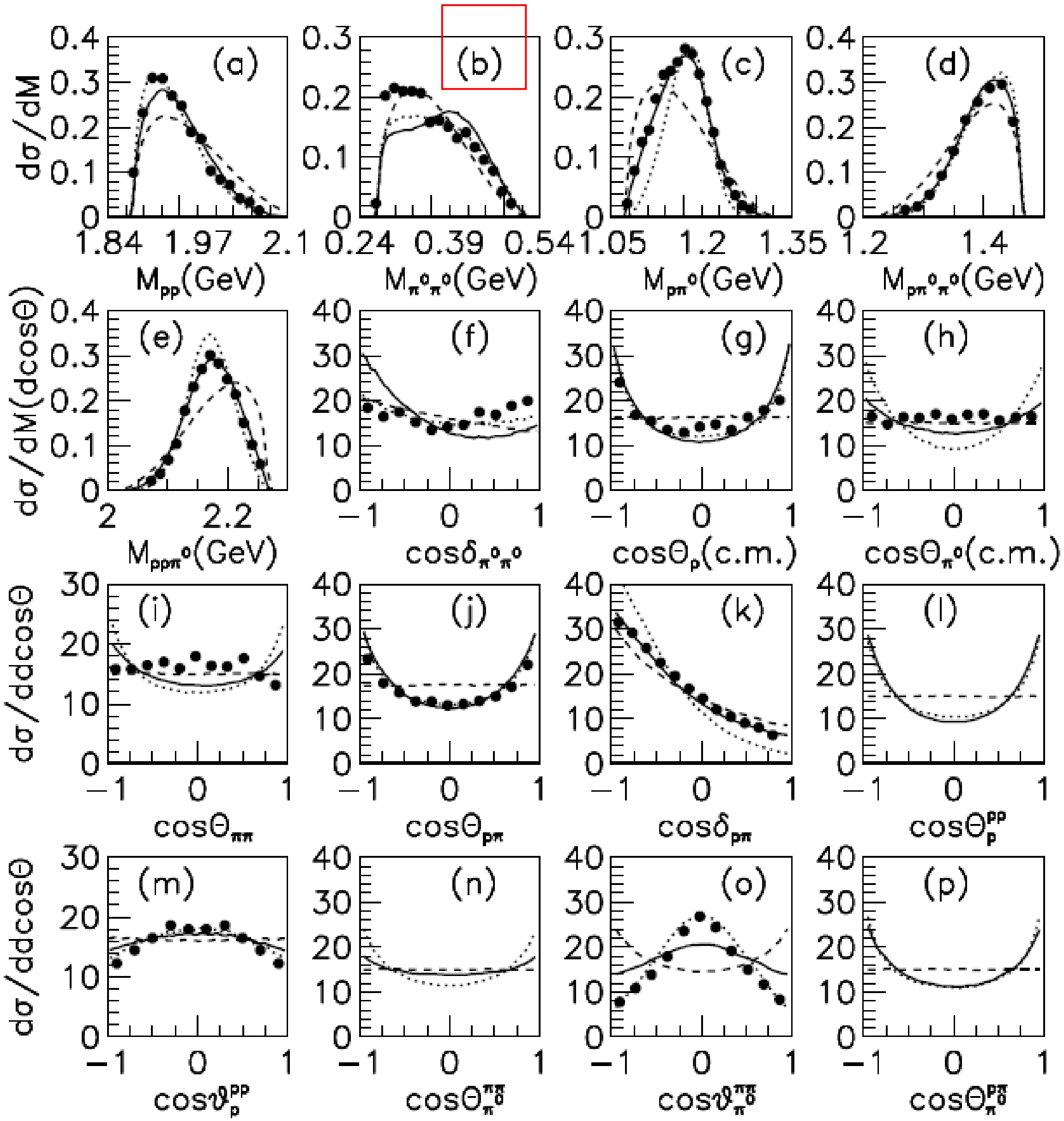
Tp=775MeV,
800MeV,
Well described too

------- phase space

.... $N^*(1440) \to N\sigma$

_____ full model

The double pion production in nucleon-nucleon collisions



$pp \rightarrow pp\pi^0\pi^0$

Tp=1200MeV

$M_{\pi^0\pi^0}$ at

Tp= 895MeV

1100MeV

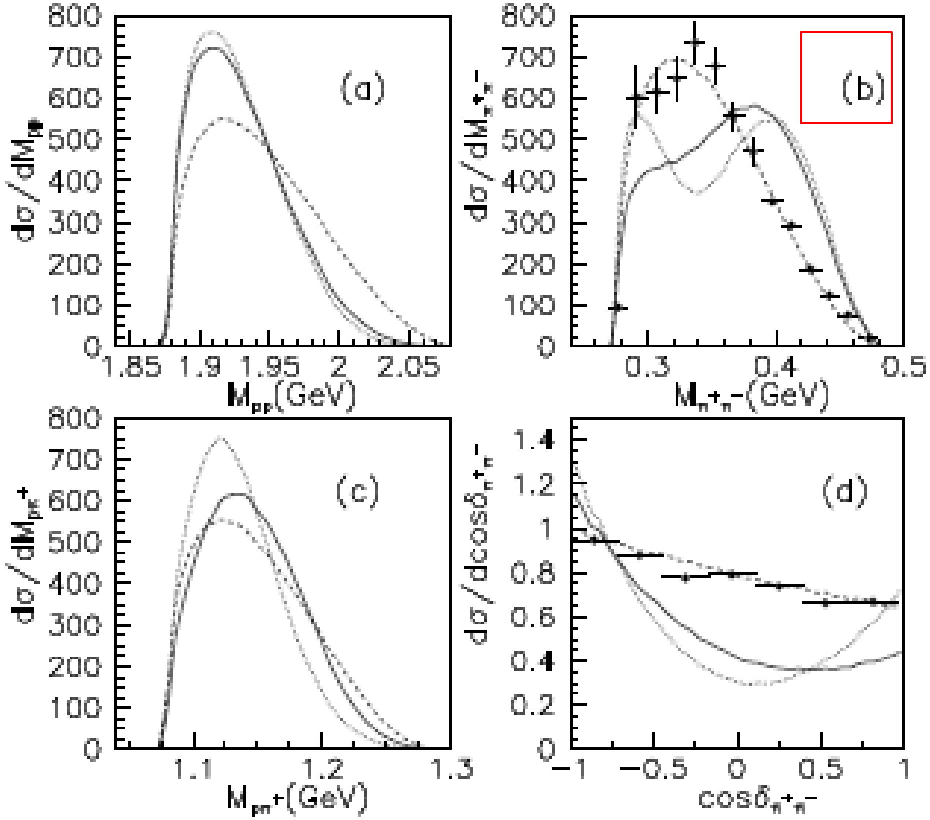
1300MeV

------- phase space

······· double-Δ

——— full model

The double pion production in nucleon-nucleon collisions



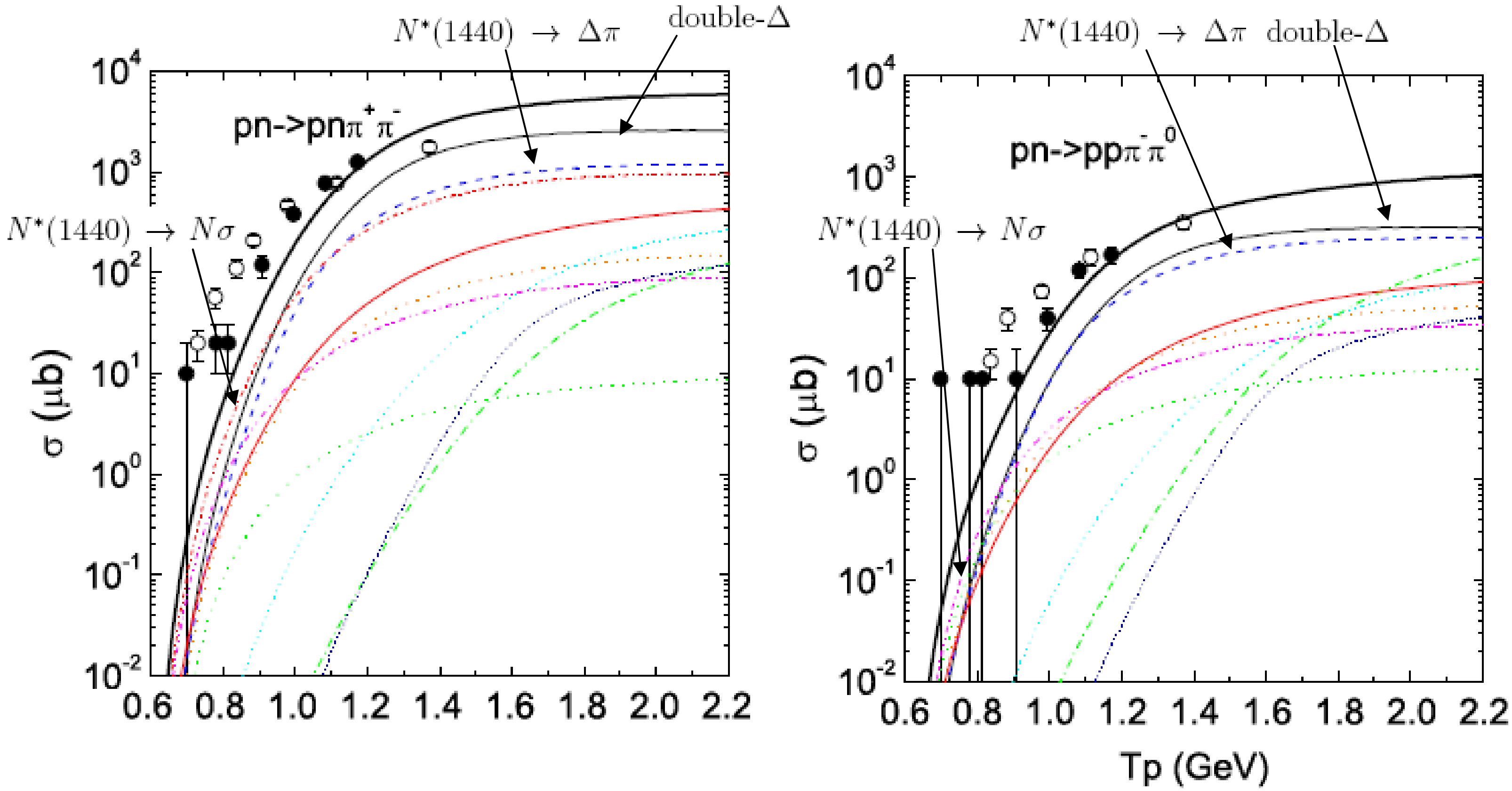
$pp \to pp\pi^+\pi^-$

Tp=1100MeV

Preliminary data
Also at Tp=1360MeV

------- phase space
……. $N^*(1440) \to \Delta\pi$
____ full model

The double pion production in nucleon-nucleon collisions



New data, black circles: KEK, PRC 62, 034001, 2000

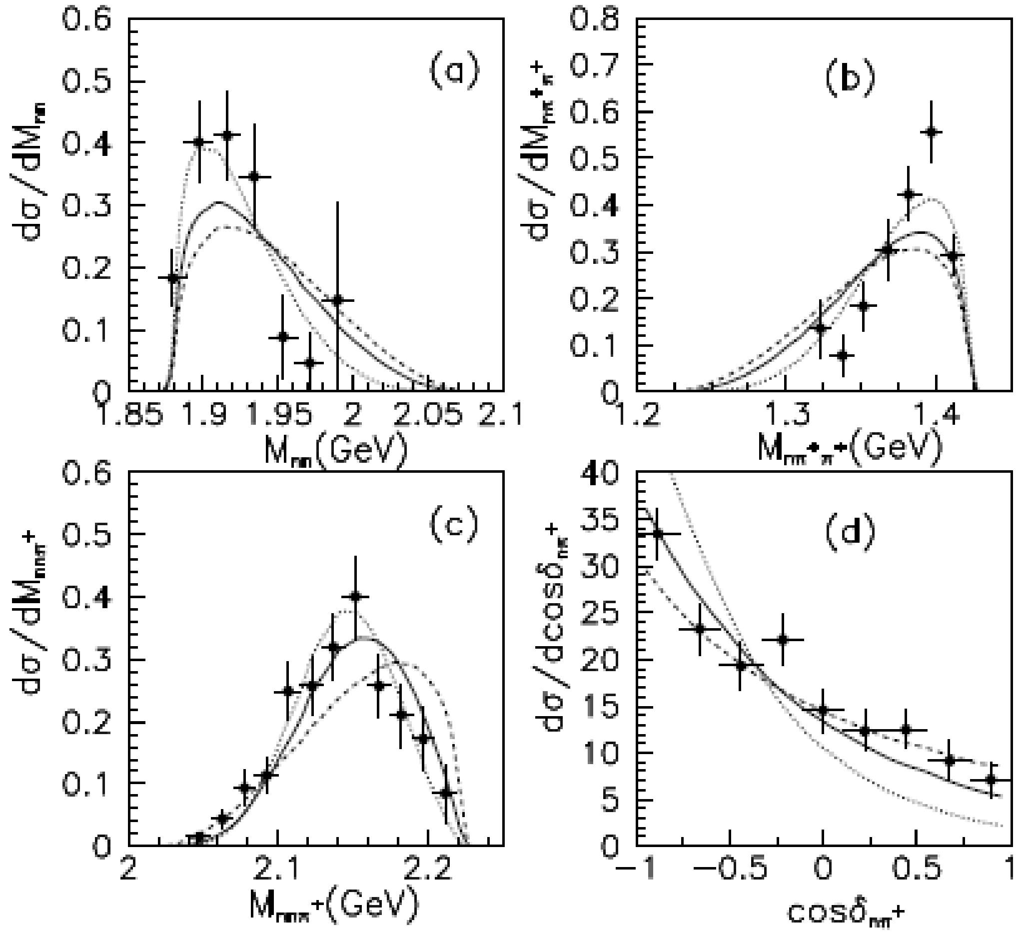
Excitation of Roper: isoscalar
isovector?

$pn \rightarrow d\pi^0\pi^0$

$pd \rightarrow {}^3\mathrm{He}\pi^0\pi^0$

ABC effect

The double pion production in nucleon-nucleon collisions

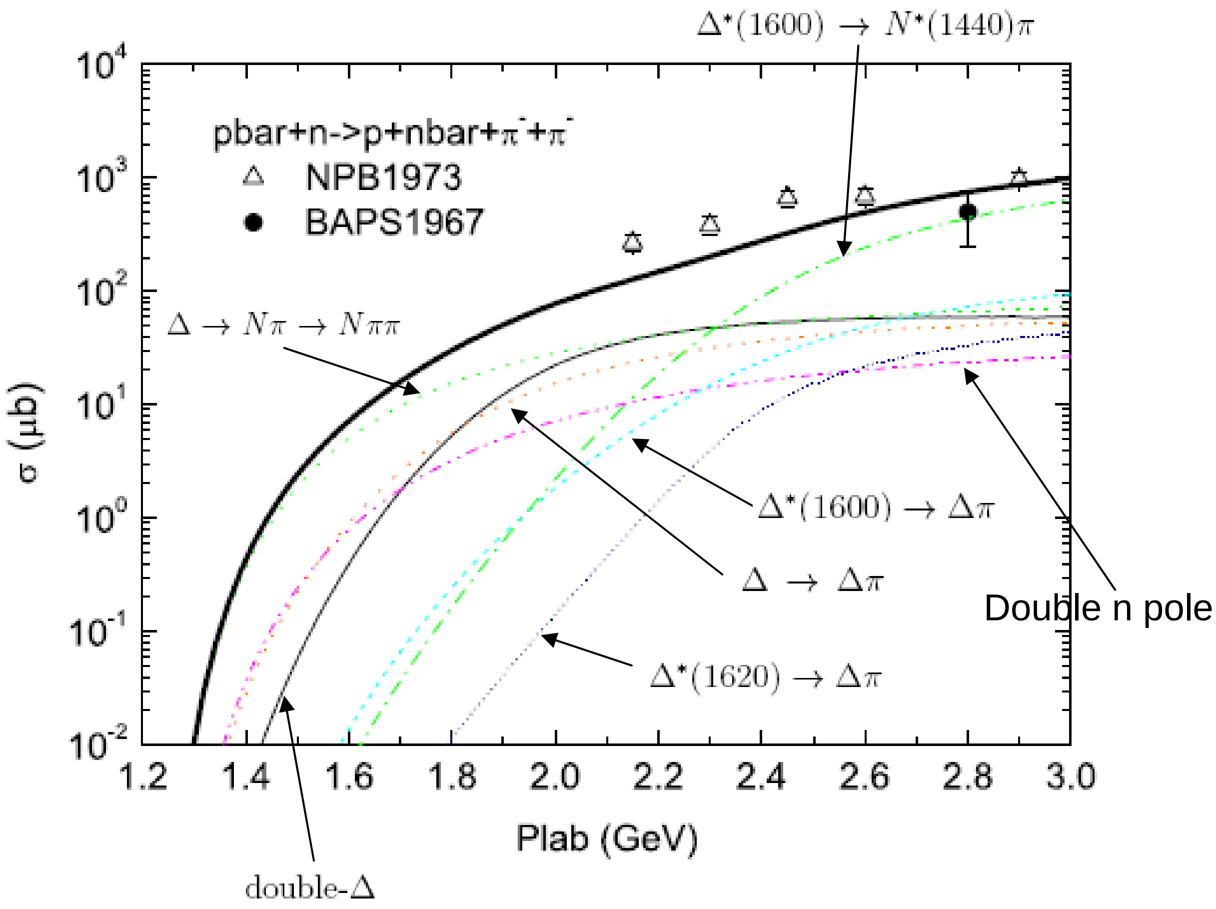


$pp \to nn\pi^+\pi^+$

Tp=1100MeV

------- phase space
……. with FSI
____ without FSI

The double pion production in nucleon-antinucleon collisions



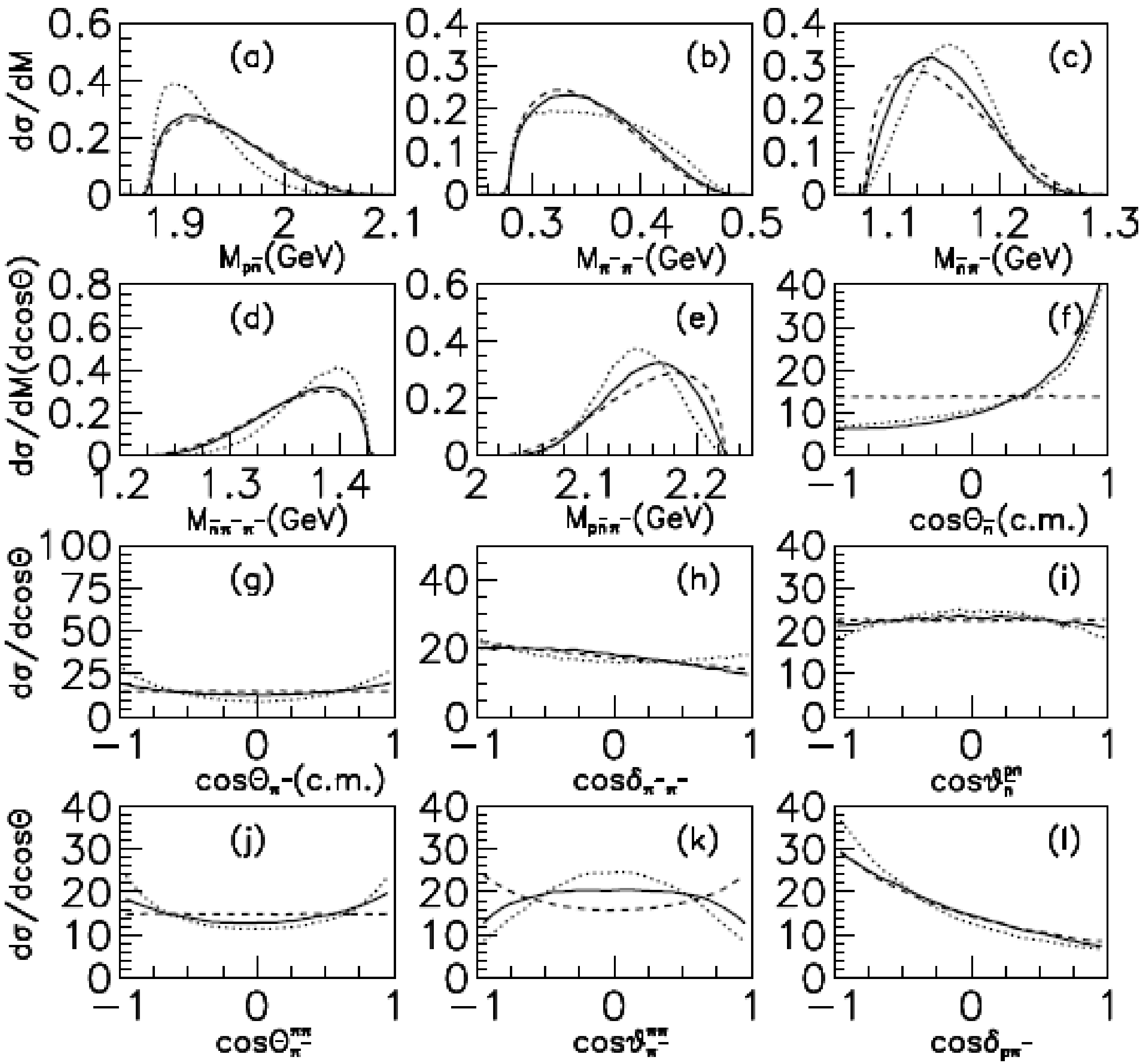
pp->nn$\pi^+\pi^+$

$\bar{p}n \to p\bar{n}\pi^-\pi^-$

deuteron target
spectator proton

Other $\bar{p}N$ channels could be complementary

The double pion production in nucleon-antinucleon collisions



$\bar{p}n \rightarrow p\bar{n}\pi^-\pi^-$

Tp=1100MeV

------- phase space

.... double-Δ

_____ full model

Summary

- Among 3 major ingredients, double-Δ, $N^*(1440) \rightarrow \Delta\pi$ and $N^*(1440) \rightarrow N\sigma$ terms, considered in the Valencia model, our model increases significantly the relative contribution from the $N^*(1440) \rightarrow N\sigma$ term by reducing the relative branching ratio of $N^*(1440) \rightarrow \Delta\pi$ and assuming a smaller cut-off parameter for the $\pi N \Delta$ vertex.

- Our model introduces significant contributions from $\Delta \rightarrow N\pi \rightarrow N\pi\pi$ at energies near threshold and from $\Delta^*(1600)$ and $\Delta^*(1620)$ at energies above 1.5 GeV.

Further improvement: ISI and FSI
$\pi\pi$ system

Thank you!

Experiments at CSR-Lanzhou

Hushan Xu STORI08'