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

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In collaboration with:
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Motivation

- The number of predicted states is much more than that observed

  "missing" baryon states : non-existence / to be observed ?

  πN and γN

  NN and $\bar{N}N$

- The properties of Roper resonance

  the existence is well established:

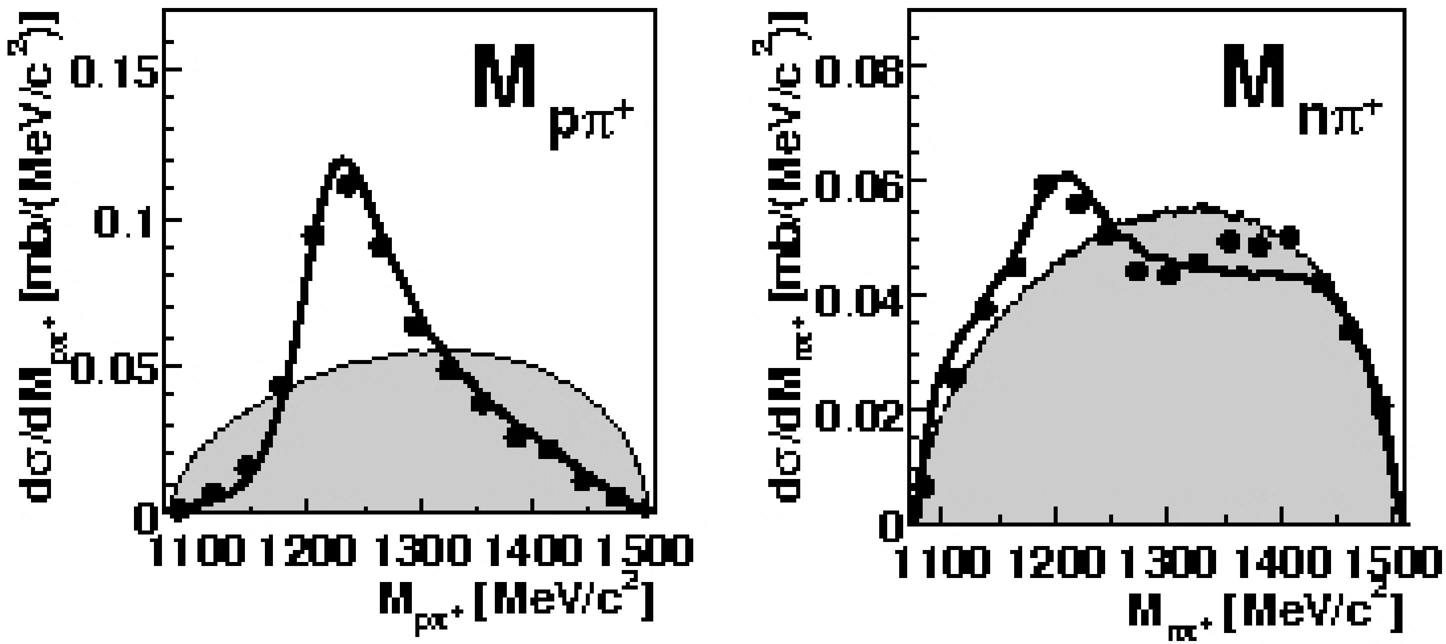
  four-star ranking in the particle data book

mass and width have rather large uncertainties and a large difference between BW and pole results

3-quark state? dynamically generated? breathing mode?

Motivation

$N^*(1440)$ resonance in the $pp \to pn\pi^+$ Tp=1.3GeV



T. Skorodko, Ph.D. thesis, University of Tuebingen, 2009.
Z. Ouyang, J. J. Xie, B.-S. Zou, and H.-S. Hu, Nucl. Phys. A 821, 220, 2009.

J.-J. Wu, B.-S. Zou, and H.-S. Hu, Phys. Rev. C 80, 045211, 2009.
N*(1440) : expected to be observed in the channel of $\bar{p}p \to \bar{p}n\pi^+$

Motivation

- Experiment:

JETSET, Z.Phys.C 1997;
BNL, Nucl. Phys. B 1973; Argonne, PRD, 1973….. $N\bar{N} \to N\bar{N}\pi\pi$
PANDA at FAIR, Plab: 1.5~15GeV

Old data before 1985: $NN \to NN\pi\pi$
bubble chamber or magnetic spectrometer

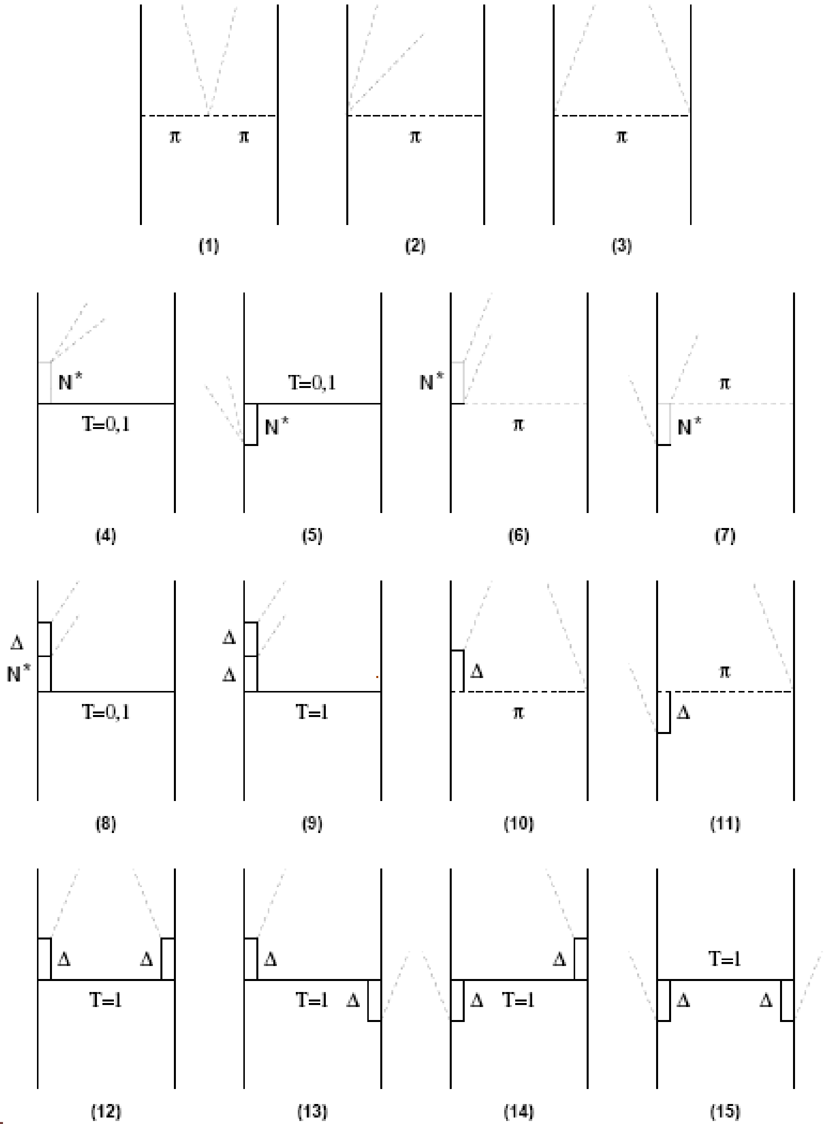
- Theory:

G. Wolf, Phys. Rev. 1966 OPE model $N\bar{N} \to N\bar{N}\pi\pi$
M. Saleem, Prog. Theor. Phys. 1983 Regge model

E. Ferrari, Nuovo Cimento, 1963 OPE model $NN \to NN\pi\pi$
Valencia Model, Nucl. Phys. A, 1999

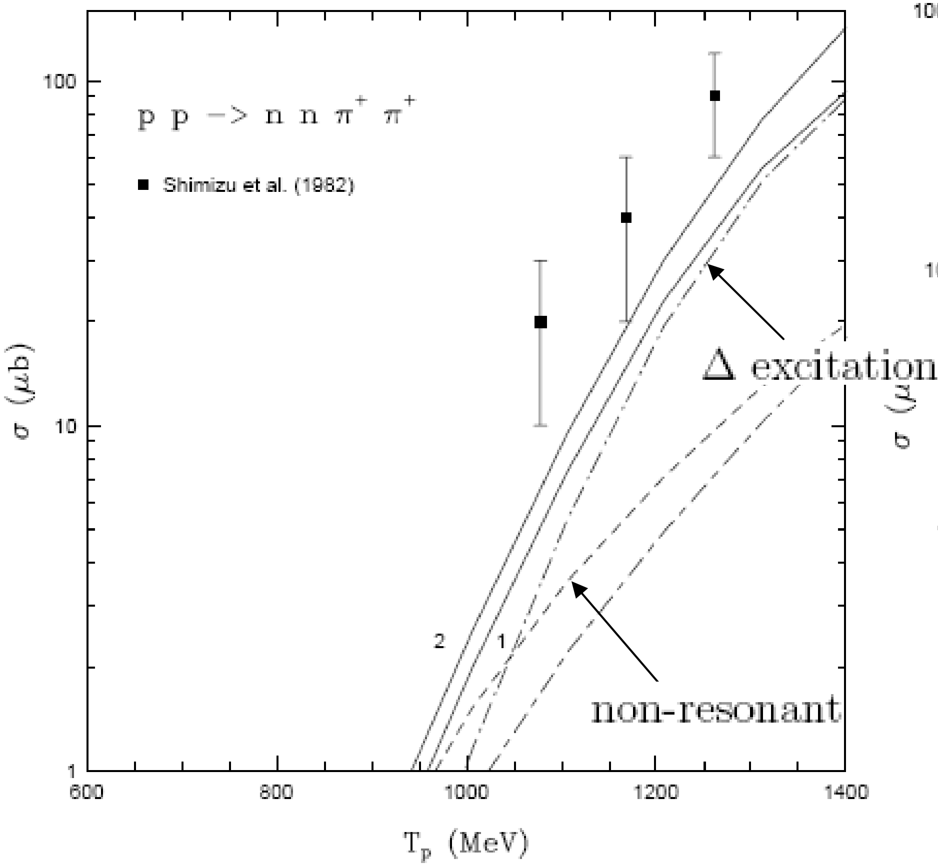
Valencia Model

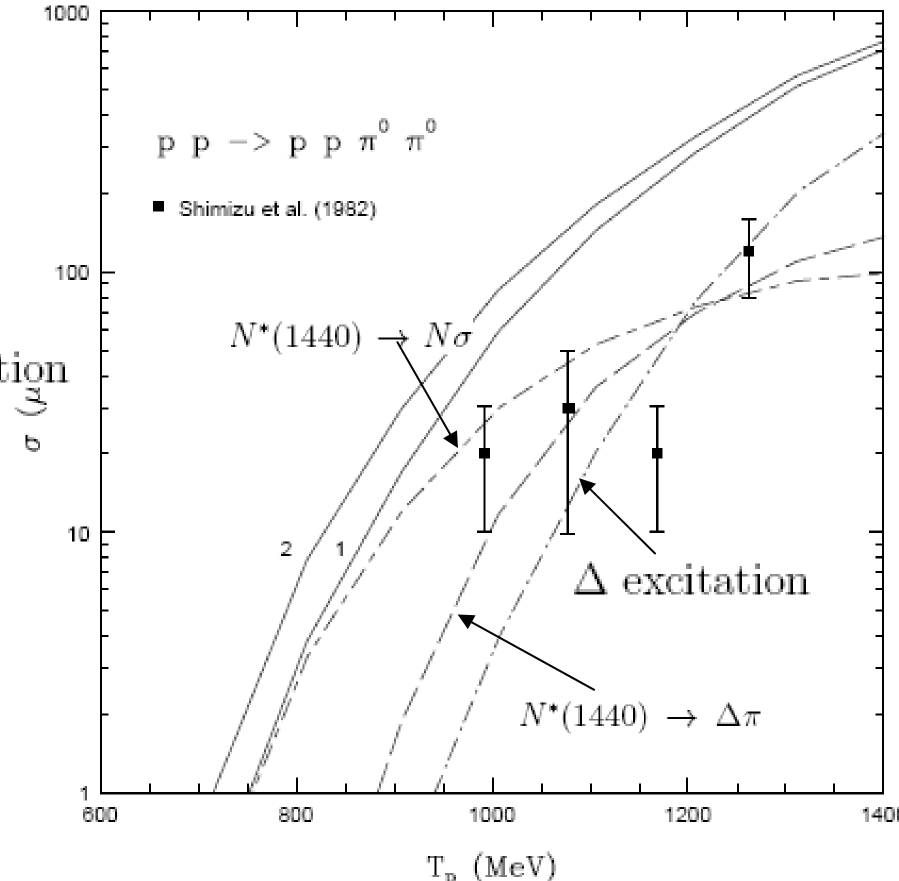
L. Alvarez-Ruso,
E. Oset,
E. Hernandez,
Nucl. Phys. A
633, 519 (1998)



Valencia Model

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





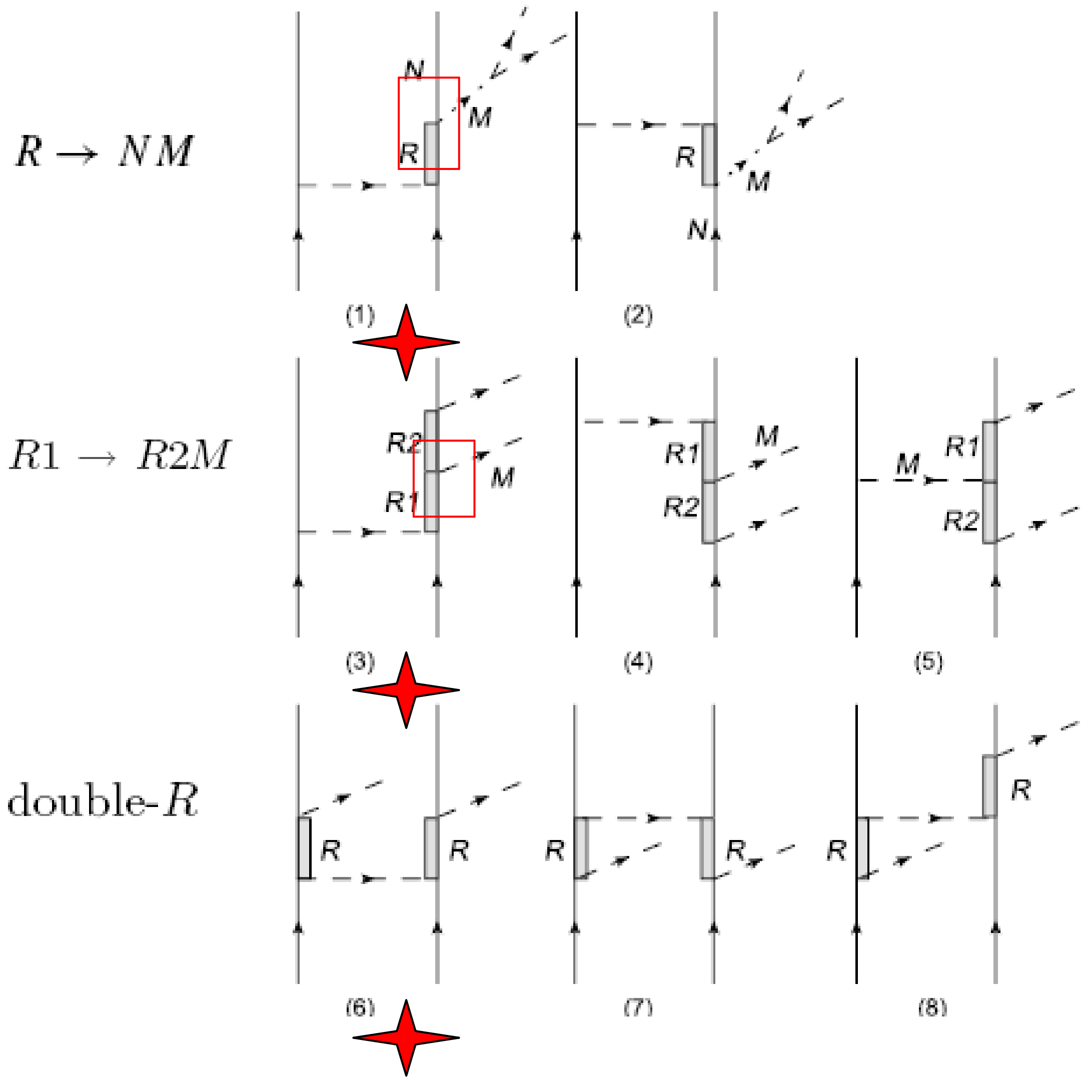
Data summary

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

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)

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

Neglígible 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

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

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

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

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

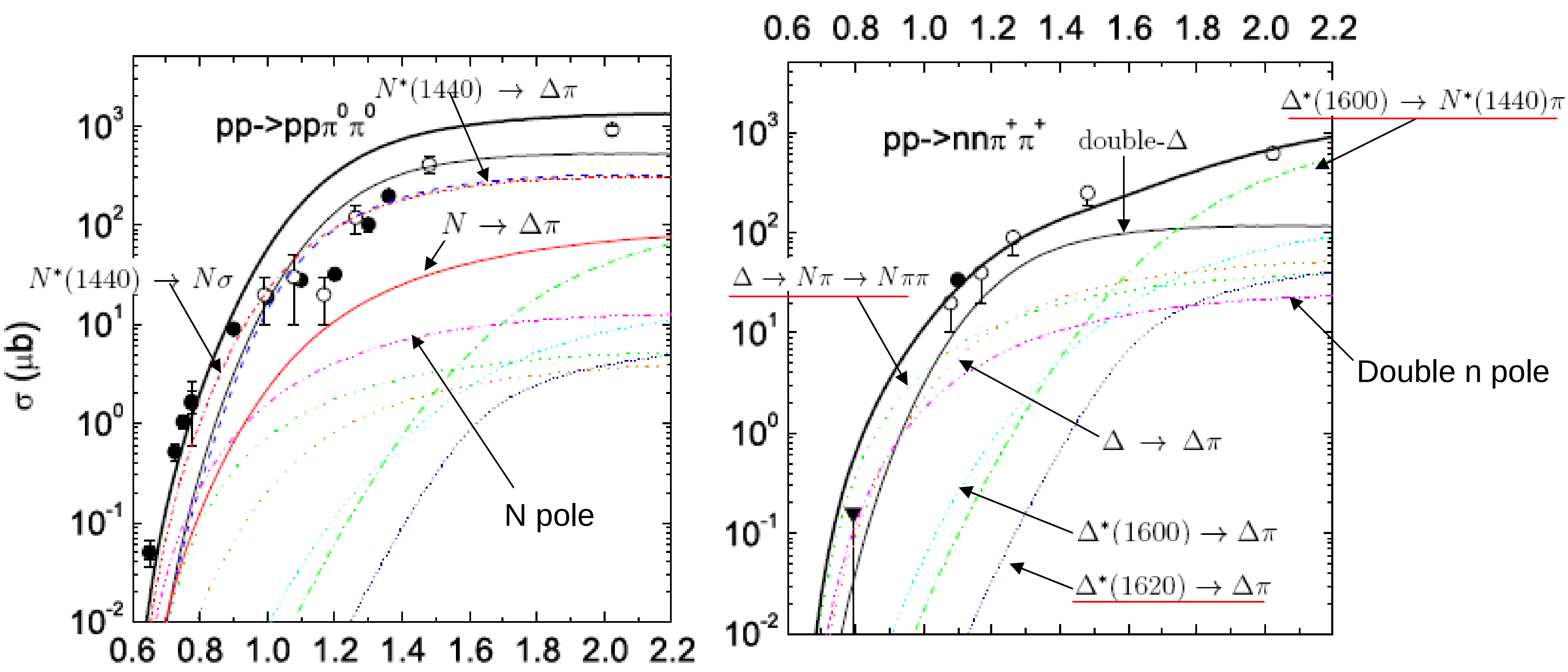
$$F_\sigma^{\pi\pi}(\vec{q}^2) = \left(\frac{\Lambda^2 + \Lambda_0^2}{\Lambda^2 + \vec{q}^2}\right)^2$$

$$\mathcal{L}_{\sigma\pi\pi} = g_{\sigma\pi\pi}\partial^\mu\vec{\pi}\cdot\partial_\mu\vec{\pi}\sigma,$$

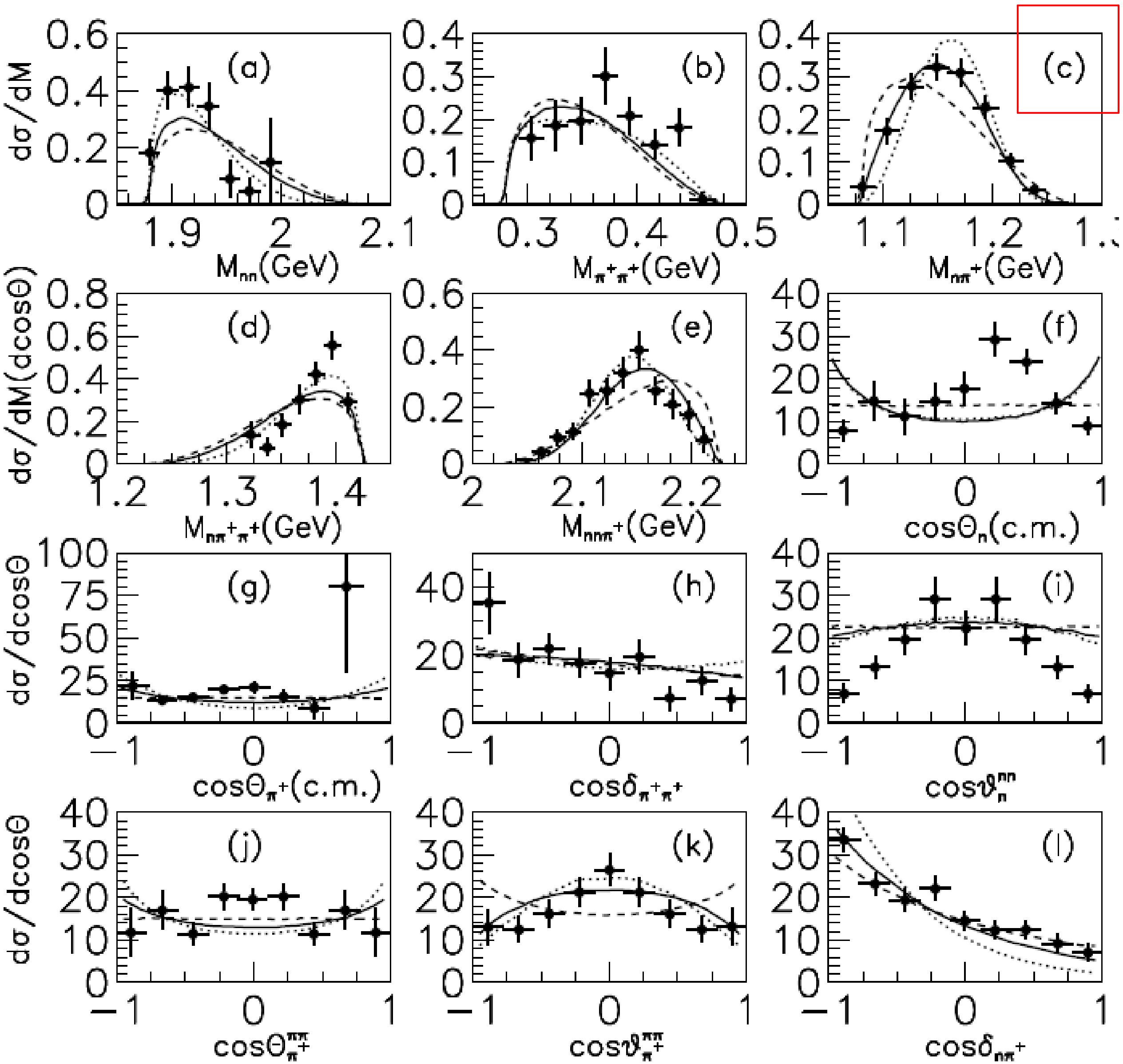
$$\mathcal{L}_{\rho\pi\pi} = g_{\rho\pi\pi}\vec{\pi}\times\partial_\mu\vec{\pi}\cdot\vec{\rho^\mu},$$

$\Lambda = 0.8$ GeV

The double pion production in nucleon-nucleon collisions



The double pion production in nucleon-nucleon collisions



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

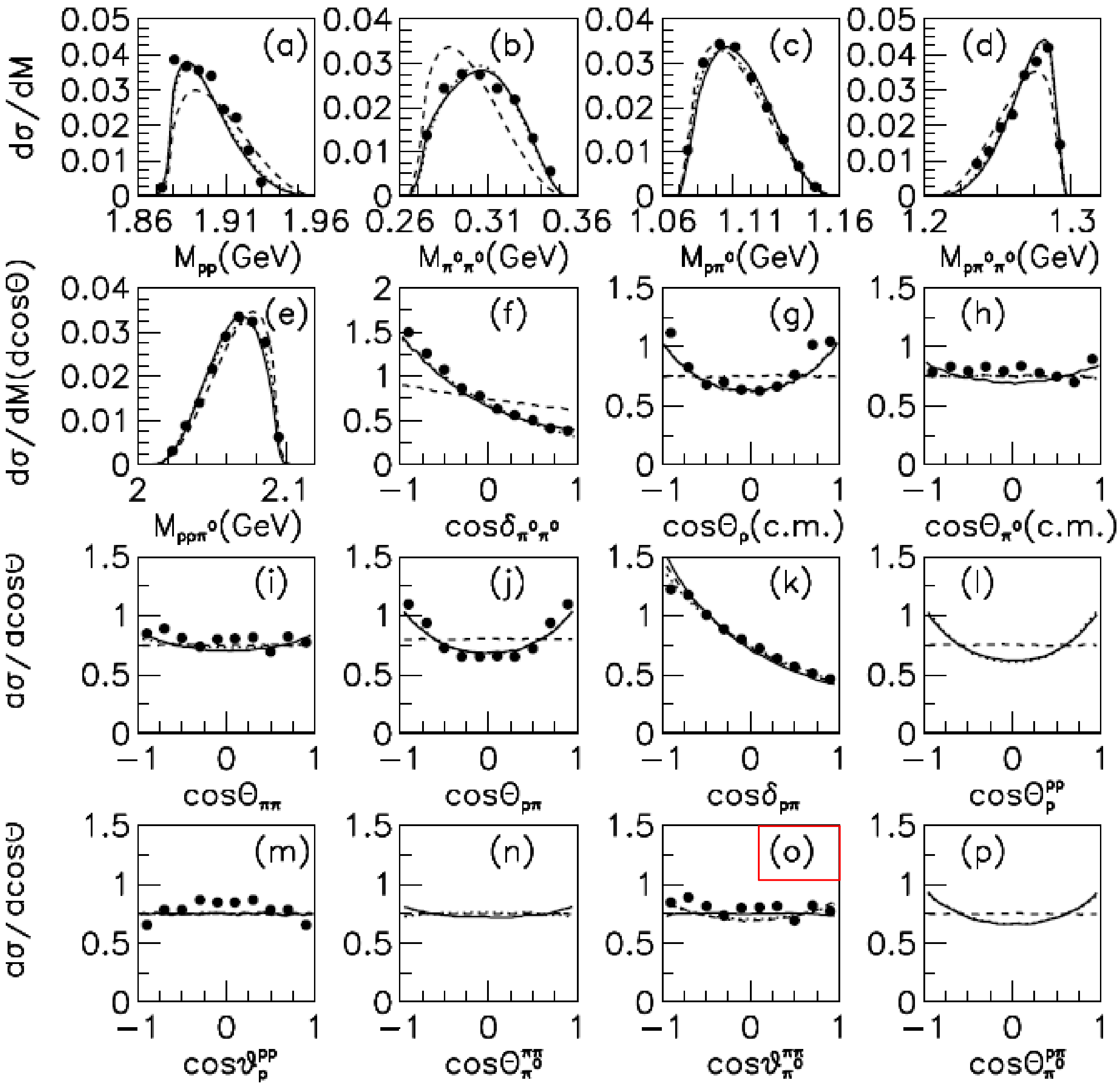
Tp=1100MeV

------- phase space

.... double-Δ

——— full model

The double pion production in nucleon-nucleon collisions



$pp \to pp\pi^0\pi^0$

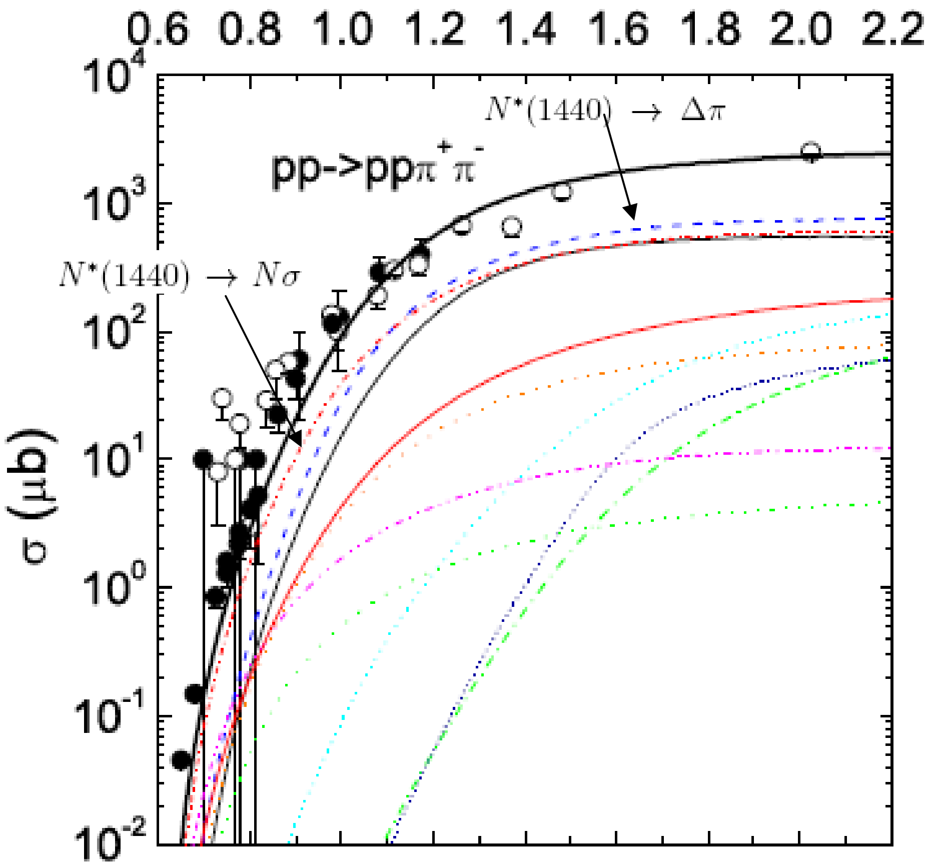
Tp=775MeV

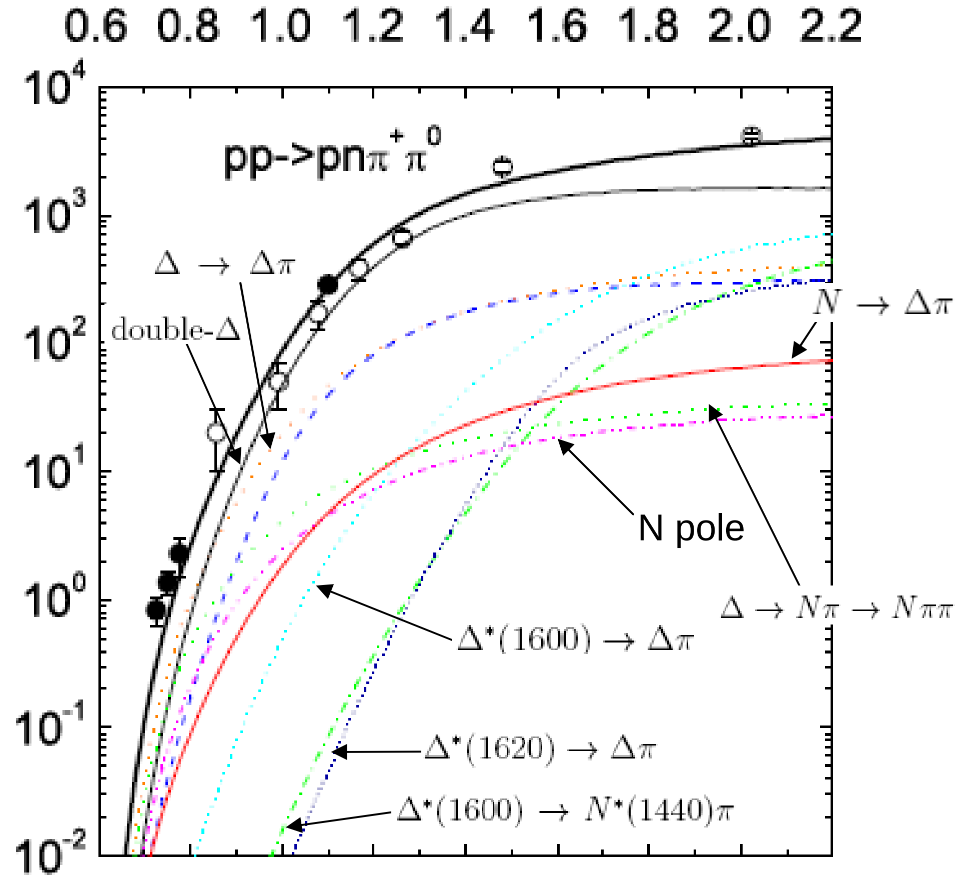
------- phase space

……. $N^*(1440) \to N\sigma$

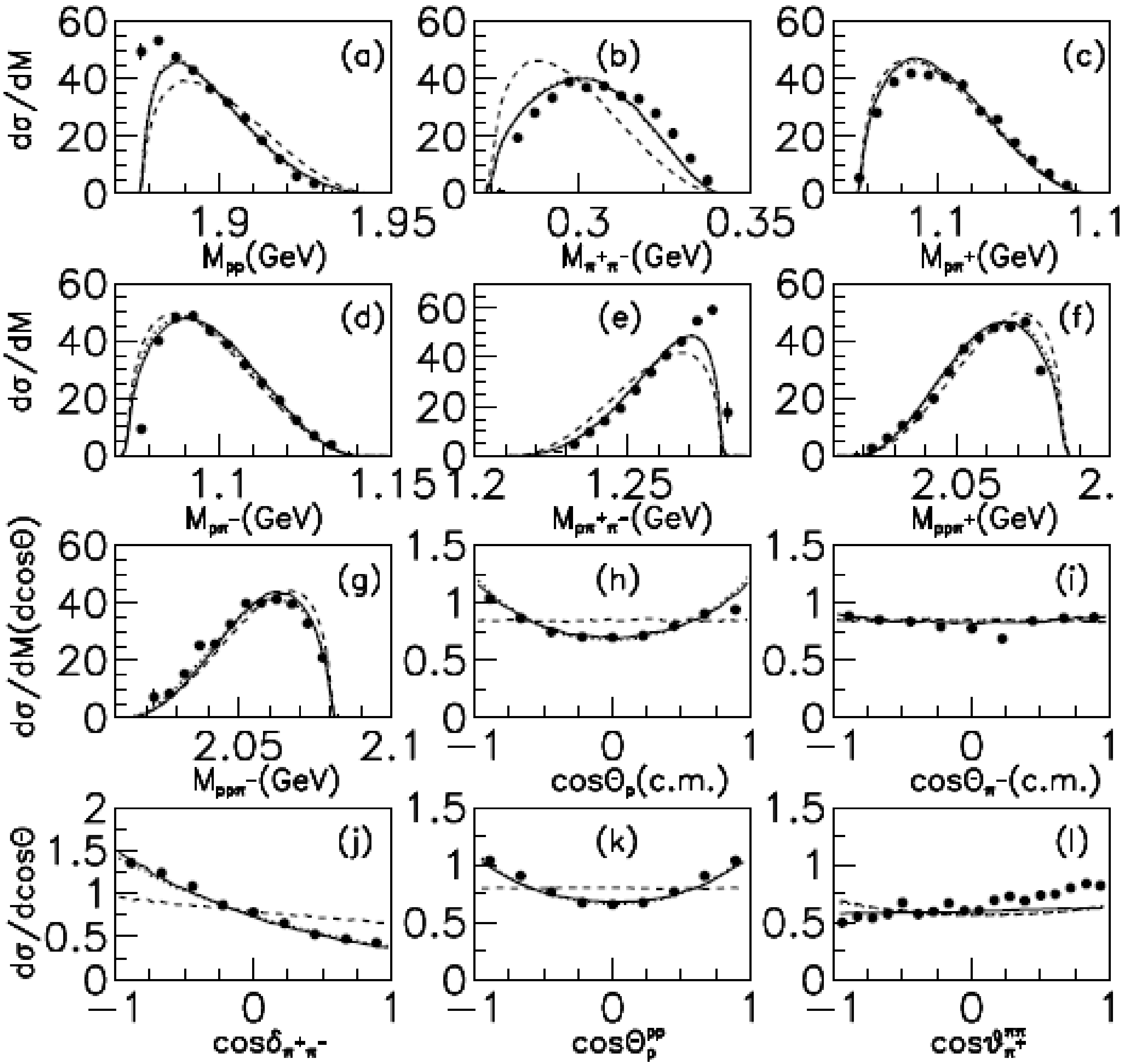
_____ full model

The double pion production in nucleon-nucleon collisions





The double pion production in nucleon-nucleon collisions



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

Tp=750MeV

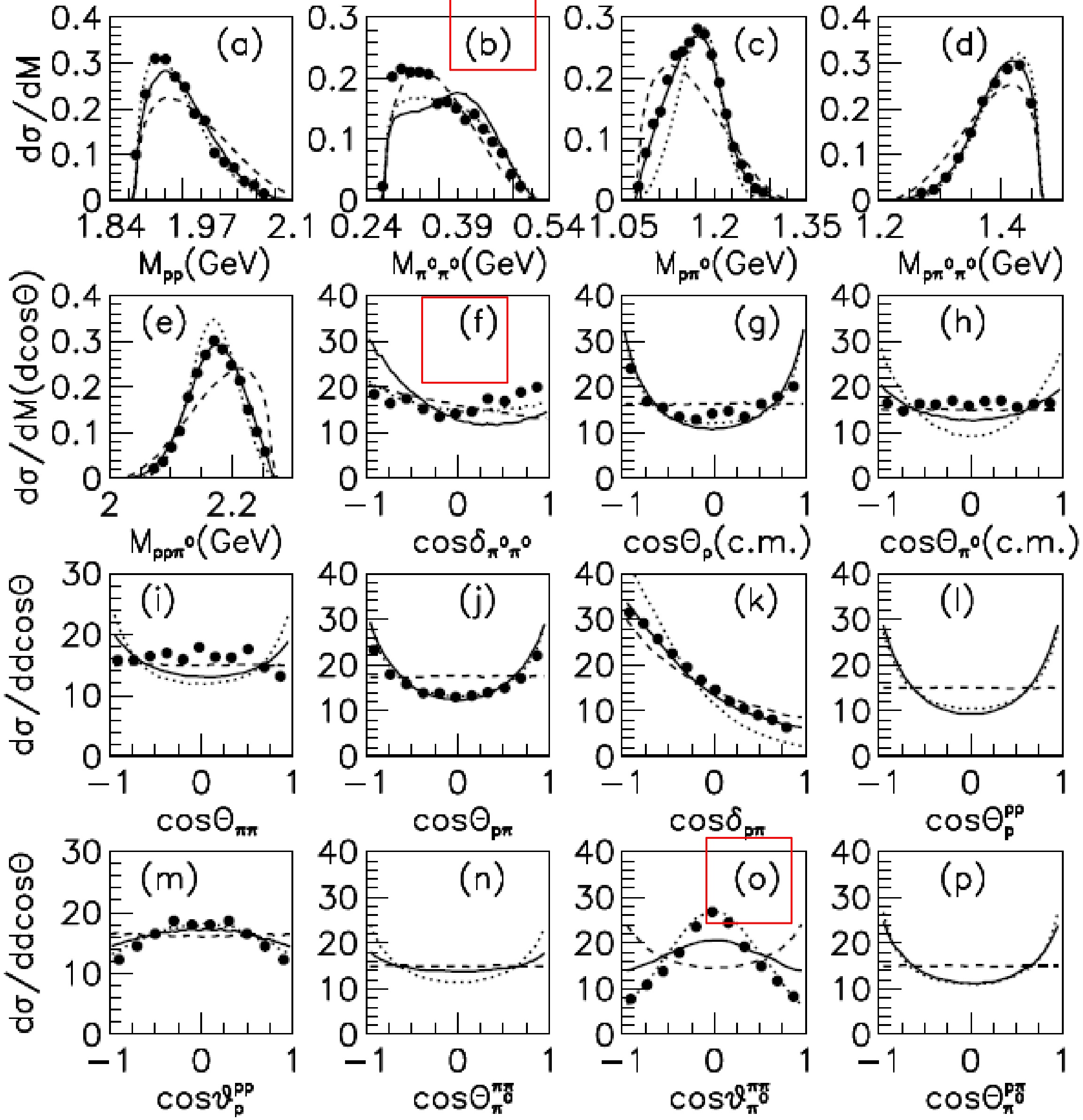
Tp=775MeV,
800MeV,
Well described too

------- phase space

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

——— full model

The double pion production in nucleon-nucleon collisions



$pp \to pp\pi^0\pi^0$

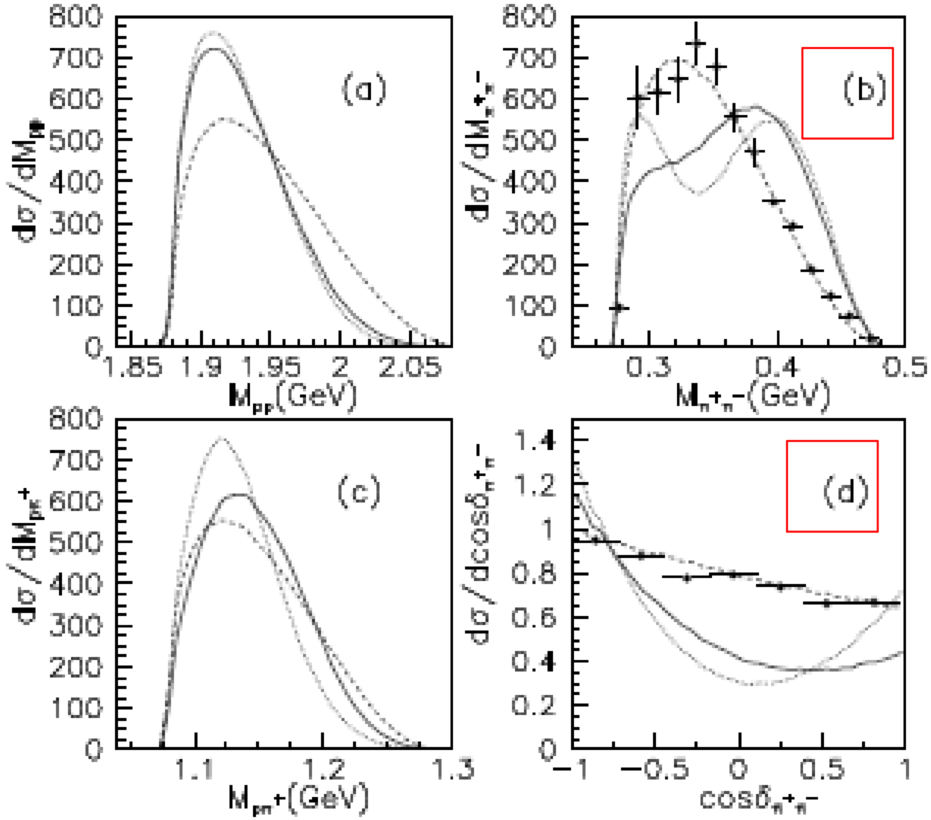
Tp=1200MeV

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

Tp= 895MeV
1100MeV
1300MeV

------- phase space
...... double-Δ
—— full model

The double pion production in nucleon-nucleon collisions



$pp \rightarrow pp\pi^+\pi^-$

Tp=1100MeV

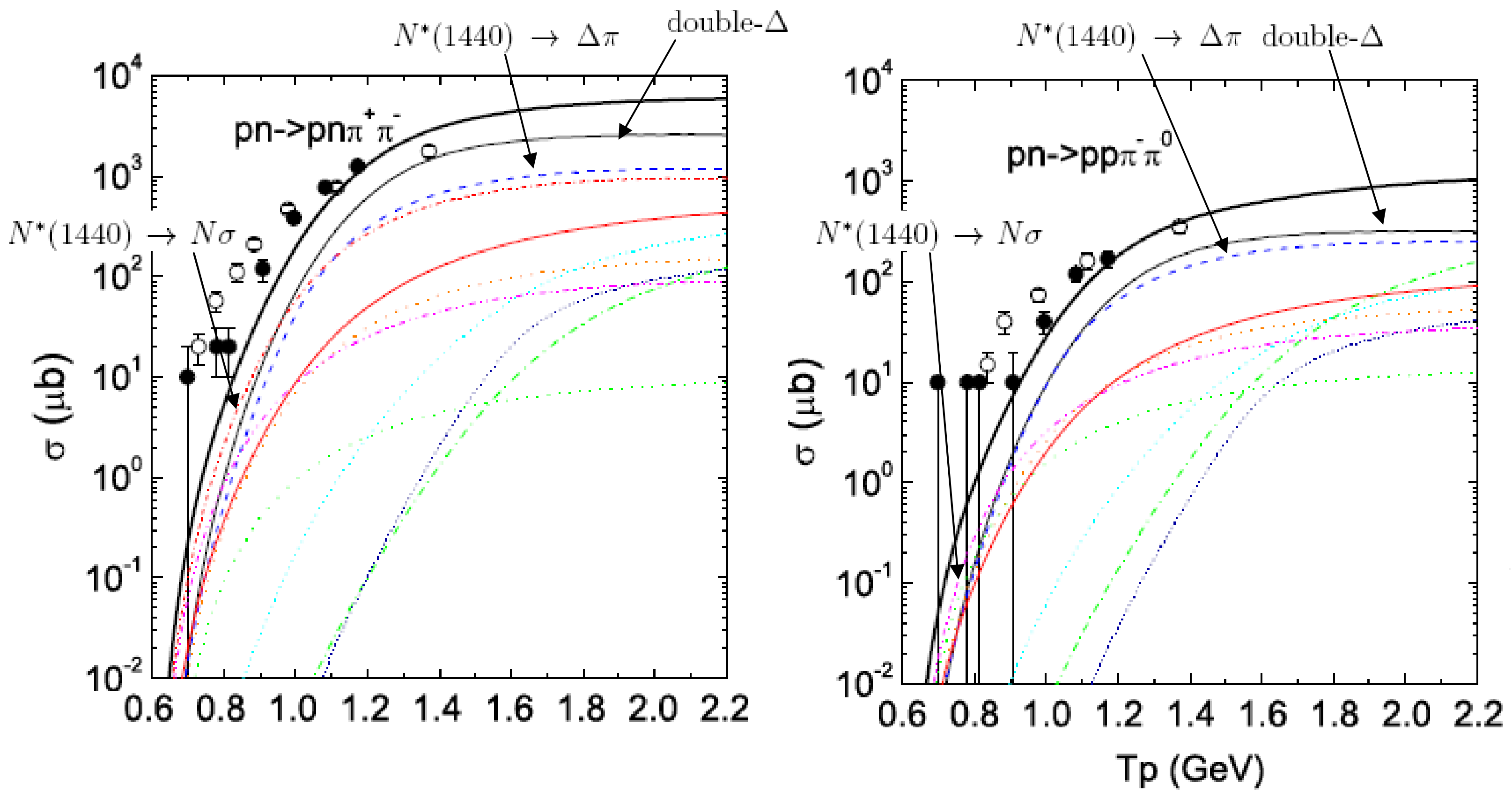
Preliminary CELSIUS data
Also at Tp=1360MeV

------- phase space

……. $N^*(1440) \rightarrow \Delta\pi$

_____ full model

The double pion production in nucleon-nucleon collisions



New data, black circles: KEK, PRC 62, 034001, 2000
HADES, new measurement, this conference.

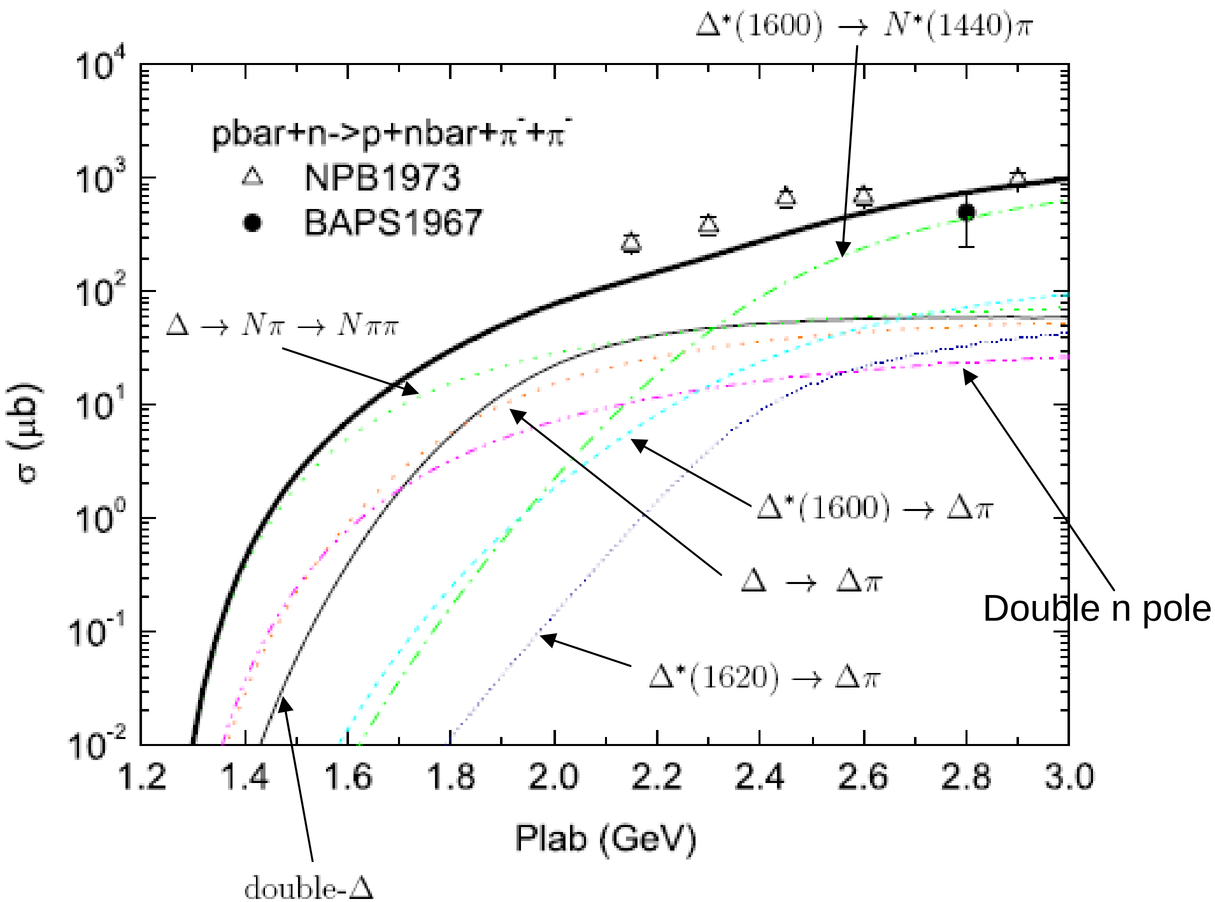
Excitation of Roper: isoscalar
isovector?

$pn \to d\pi^0\pi^0$

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

ABC effect

The double pion production in nucleon-antinucleon collisions



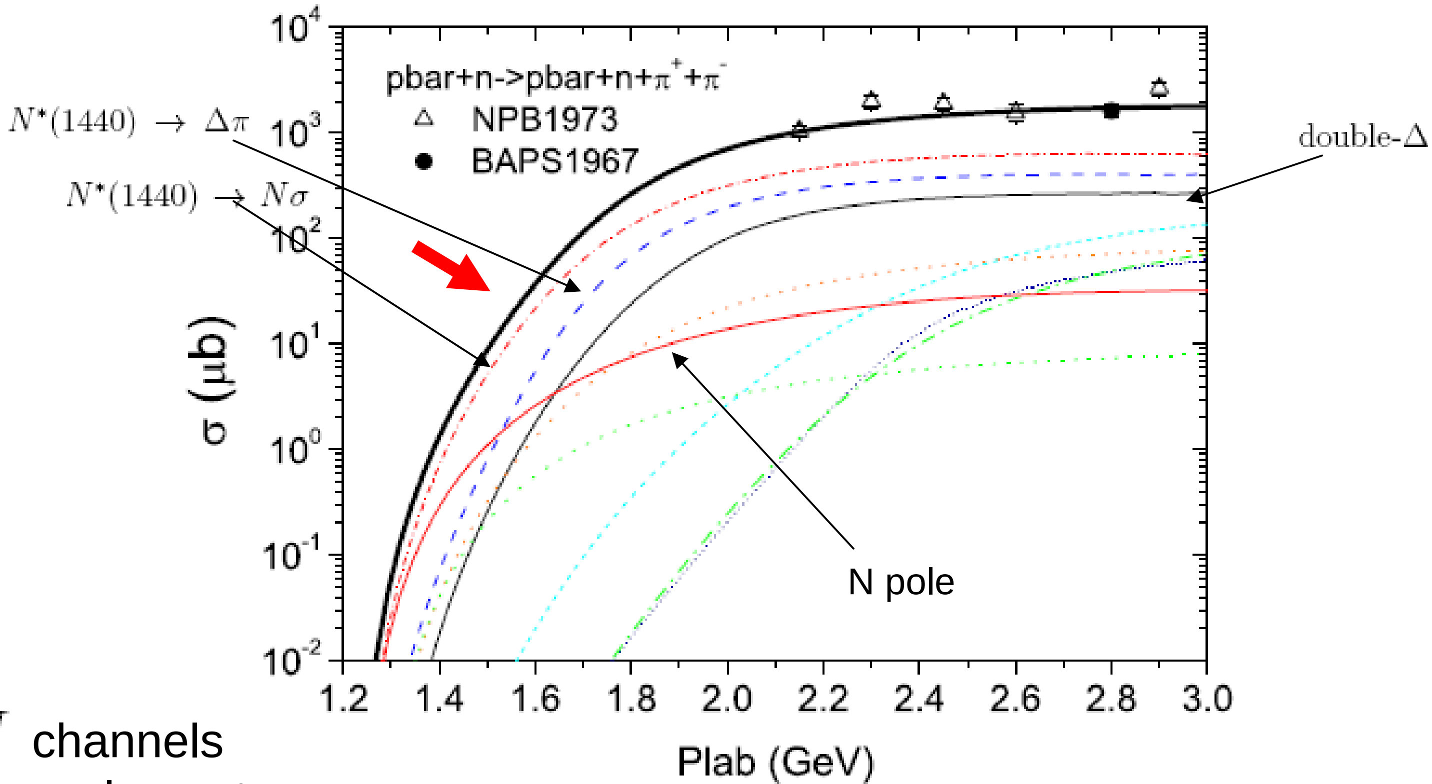
pp->nn$\pi^+\pi^+$

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

deuteron target
spectator proton

$$\bar{p}d \to p\bar{n}p_{spec}\pi^-\pi^-$$

The double pion production in nucleon-antinucleon collisions



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

$\bar{p}n \to \bar{p}n\pi^+\pi^-$ A more pure place for studying N*(1440)

Summary

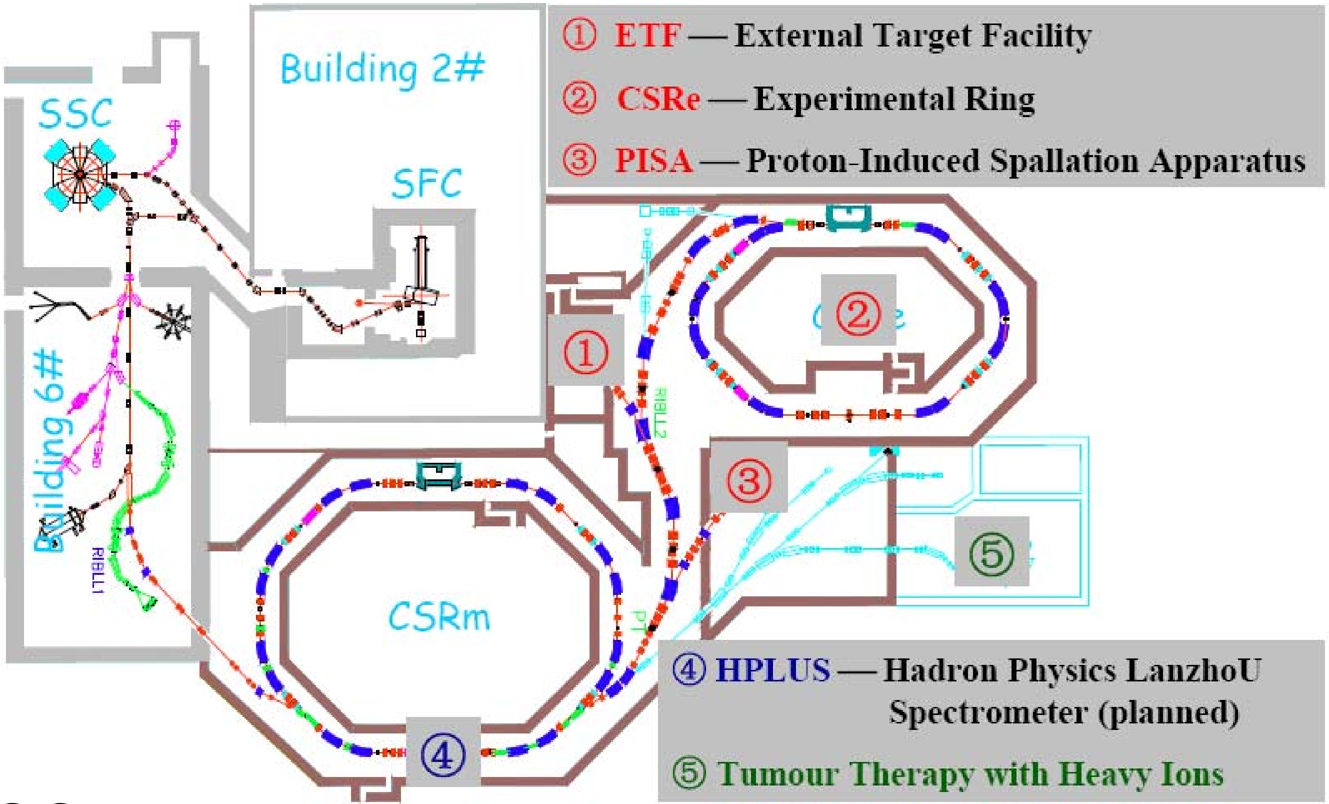
- Among 3 major ingredients, double-Δ, $N^*(1440) \to \Delta\pi$ and $N^*(1440) \to N\sigma$ terms, considered in the Valencia model, our model increases significantly the relative contribution from the term $N^*(1440) \to N\sigma$ by reducing the relative branching ratio of $N^*(1440) \to \Delta\pi$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

- Our model introduces significant contributions from $\Delta \to N\pi \to N\pi\pi$ 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

Experiments at CSR-Lanzhou

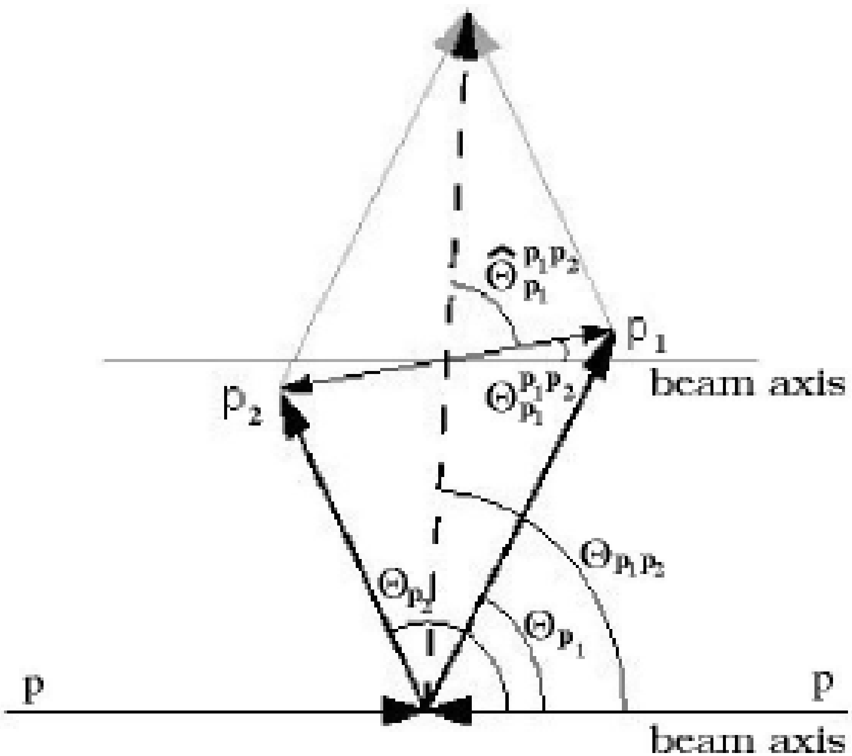
Hushan Xu STORI08'



HADES Group

Measurement are suggested in PANDA-FAIR

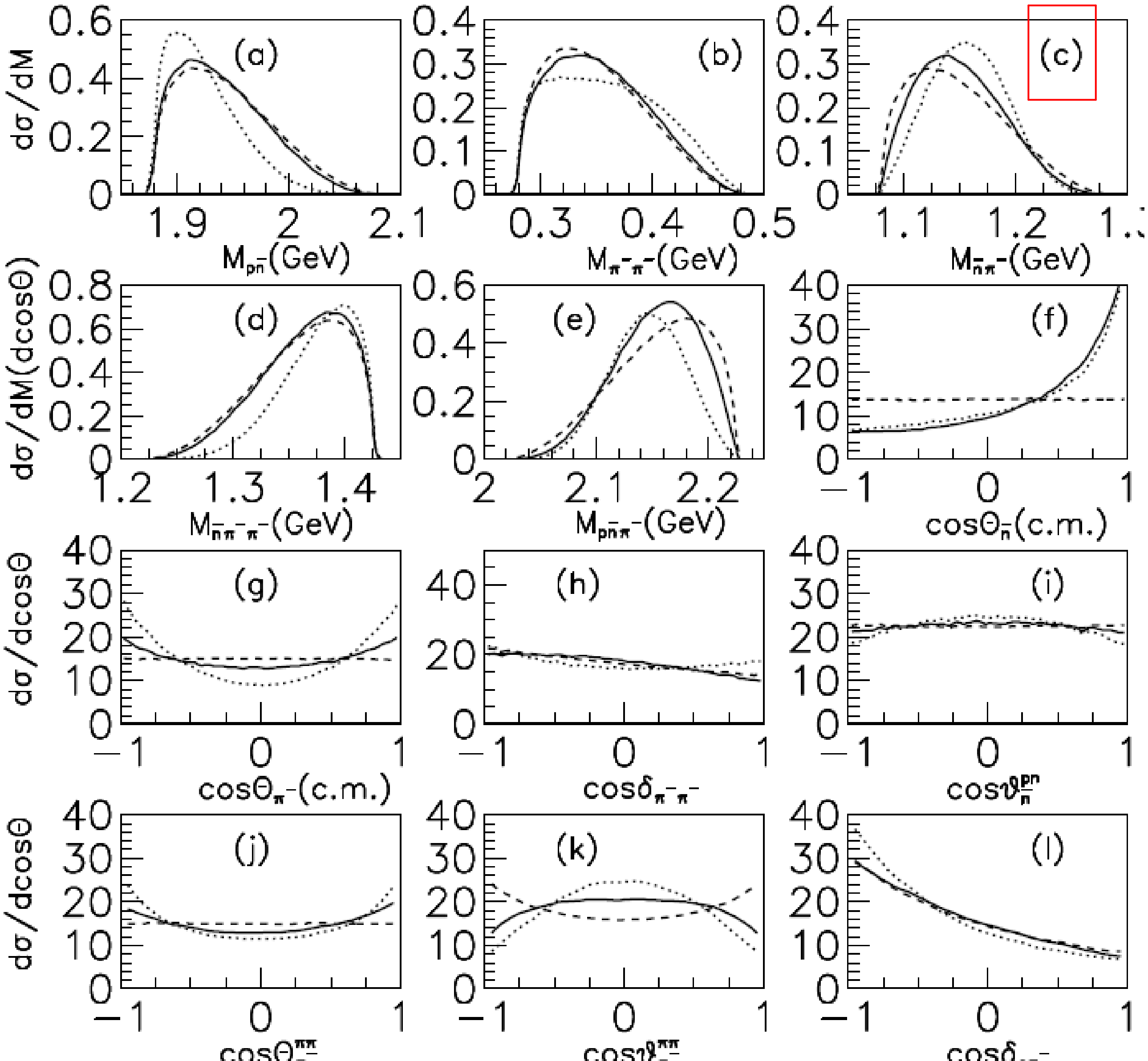
Thank you!



Definition of the different scattering angles.

T. Skorodko, Ph.D. thesis, University of Tuebingen, 2009.

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

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:

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

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

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

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

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

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