Towards a further understanding on two-pion production

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Methodology for resonance study

- resonance: unstable and couple strongly to meson-baryon states
- Build models to extract parameters

- $(\pi, \gamma)N$ reactions
  Unitarity,Analiticity....

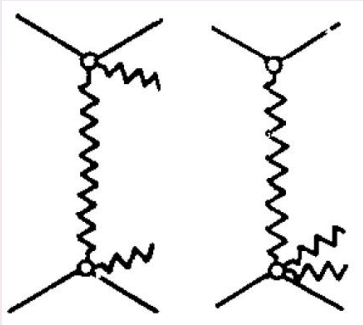
1. isobar models
2. coupled-channel models
   - KSU
   - GWU/SAID
   - Mainz/MAID
   - Bonn-Gatchina
   - Giessen
   - Juelich
   - EBAC
   - ....

- NN reactions
  Unitarity,Analiticity?

1. 3-body final states at least
2. Final state interaction?
3. isobar models
   only Four groups
4. PWA may be inconclusive.

History of theory

1. E. Ferrari, Nuovo Cimento, 1963
   - OPE model



2. Valencia Model, Nucl. Phys. A, 1999
   - double-Δ,$N^*(1440)$,non-resonant
3. Xu CAO et al., Phys. Rev. C 2010
   - more resonances in PDG
4. JINR, Dubna, 2012
   - reggeized π exchange(OPER) + one baryon exchange(OBE)

History of experiment

- data before '1985: bubble-chamber, tcs only
- 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)

- new data expected from HADES

Effective Lagrangian model

- Feynman diagrams: tree level. The interference terms between different diagrams are neglected because the relative phases of amplitudes are not known.
- Resonances which are experimentally observed are included in our model. Mesons exchanged are restricted to those observed in the decay channels of the adopted resonances.
- Effective Lagrangians: Lorentz covariant orbital-spin scheme for the vertices. The coupling constants appearing in relevant resonances could be determined by the empirical partial decay width of the resonances taken from Particle Data Group.
- Final state interactions: usually important for describing the near threshold behavior.
  Watson-Migdal factorization: only serve as a qualitative illustration.
- Cutoff parameters in the form factors: fit to the empirical data.

Effective Lagrangian model

Table: Relevant parameters used in our calculation. The masses, widths and branching ratios (BR) are taken from central values of PDG except the BR for $N^*(1440) \to \Delta\pi$.

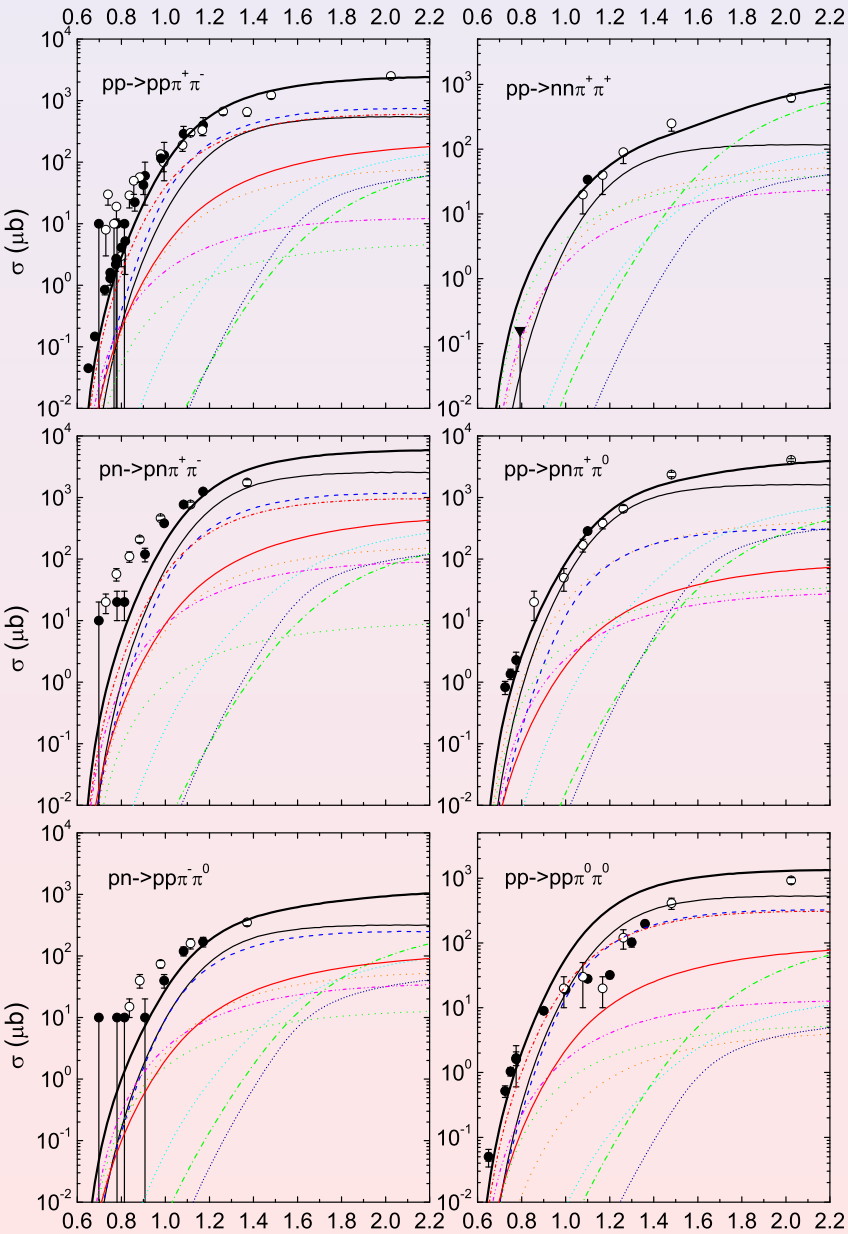
Resonance	BW Width	Decay Mode	Decay Ratio	$g^2/4\pi$
$\Delta^*(1232)P33$	118	$N\pi$	1.0	19.54
$N^*(1440)P11$	300	$N\pi$	0.65	0.51
		$N\sigma$	0.075	3.20
		$\Delta\pi$	0.135	4.30
$\Delta^*(1600)P33$	350	$N\pi$	0.175	1.09
		$\Delta\pi$	0.55	59.9
		$N^*(1440)\pi$	0.225	289.1
$\Delta^*(1620)S31$	145	$N\pi$	0.25	0.06
		$N\rho$	0.14	0.37
		$\Delta\pi$	0.45	83.7

Effective Lagrangian model

- Negligible contributions:

- small branching ratios of double pion channel:
  $S_{11}(1535), S_{11}(1650), D_{13}(1700)$
- higher partial waves:
  $D_{13}(1520), D_{15}(1675)$
- lying beyond the considered energies:
  $F_{15}(1680), D_{33}(1700), P_{11}(1710), P_{13}(1720)$
- Resonances with mass bigger than 1720MeV:
  the two pion branching ratios have large uncertainties

Effective Lagrangian model



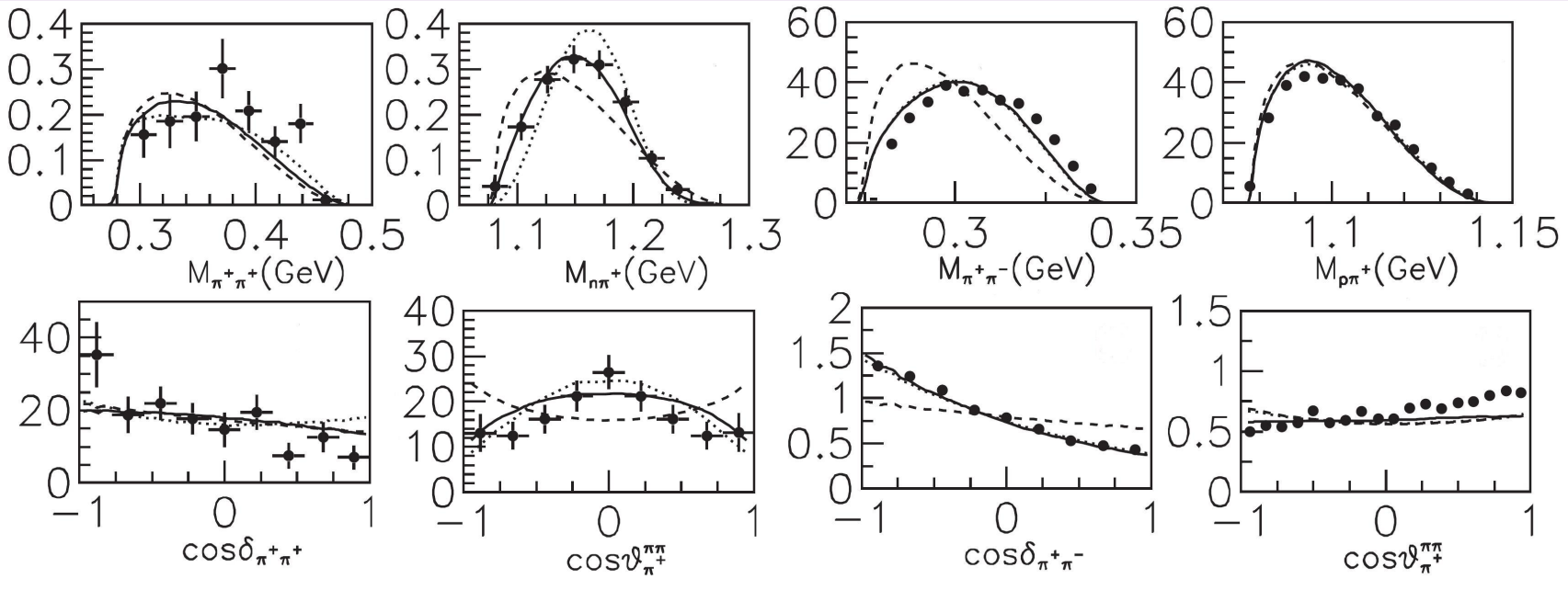
$\leftarrow P_{33}(1600)$ in $pp \to nn\pi^+\pi^+$

$\leftarrow$ Good description in pn reactions

$\leftarrow P_{11}(1440)$: isoscalar excitation

$\leftarrow$ a step in $pp \to pp\pi^0\pi^0$

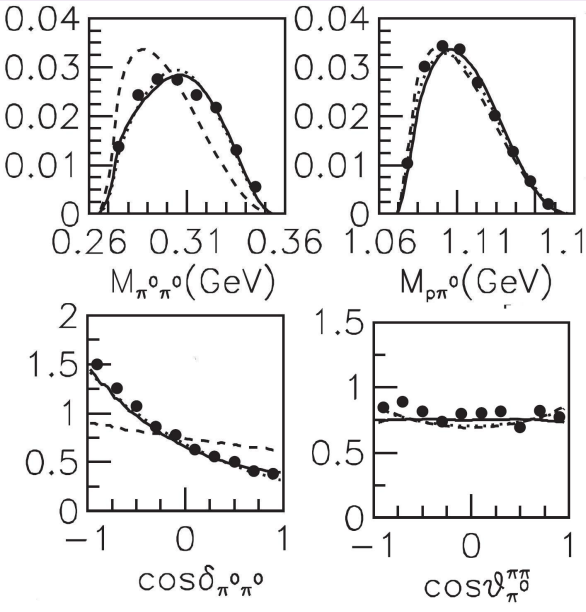
Effective Lagrangian model



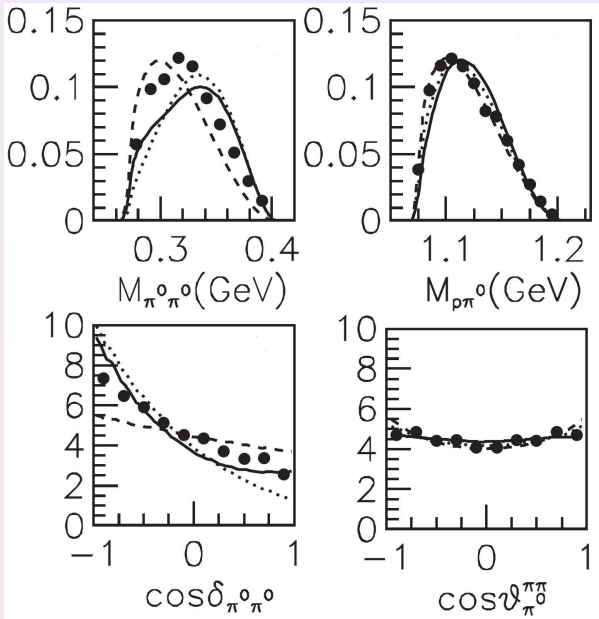
- $pp \to nn\pi^+\pi^+$
- $T_p = 1100$ MeV

- $pp \to pp\pi^+\pi^-$
- $T_p = 750$ MeV

Effective Lagrangian model

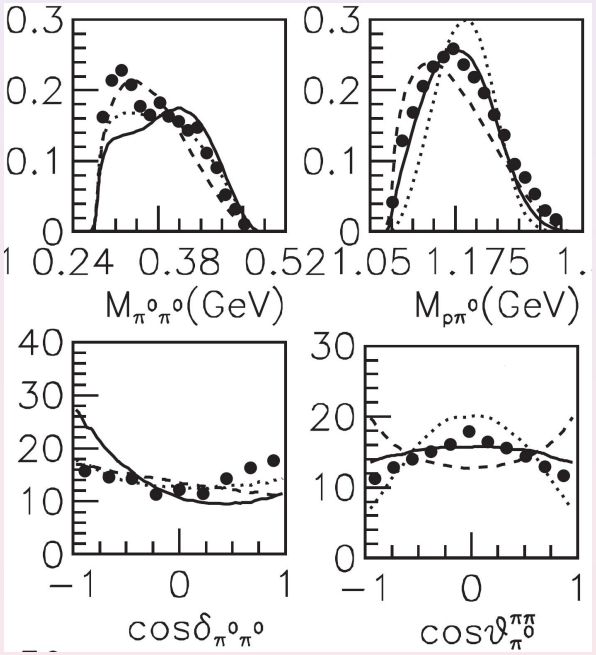


- $pp \to pp\pi^0\pi^0$
- $T_p = 775$ MeV



- $pp \to pp\pi^0\pi^0$
- $T_p = 895$ MeV

Effective Lagrangian model



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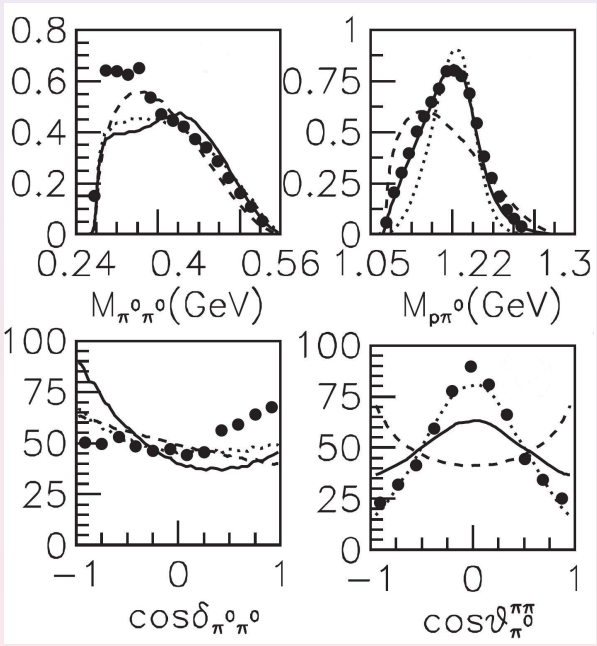


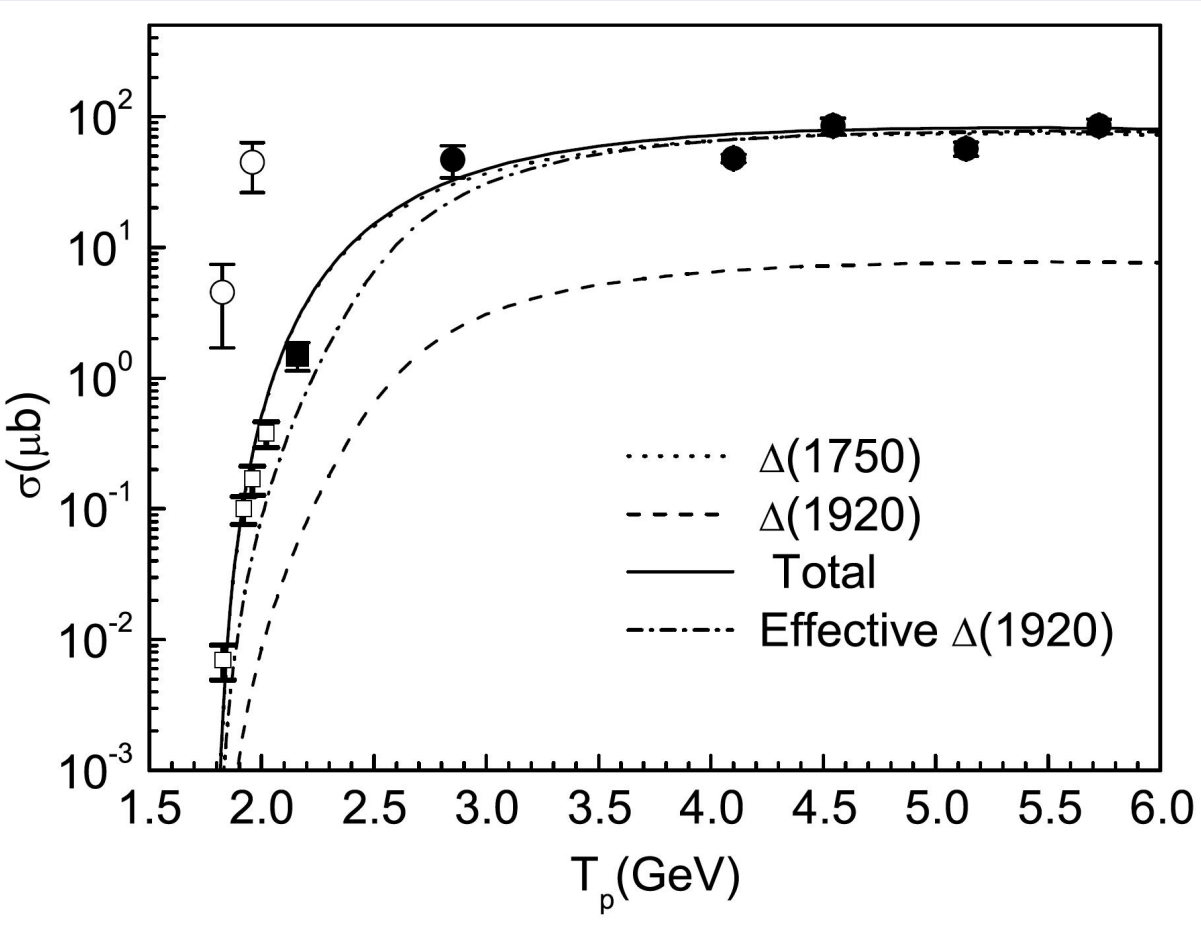
- $pp \to pp\pi^0\pi^0$
- $T_p = 1300$ MeV

Outlook

- A general understanding is achieved.
- Further understanding is definitely needed.

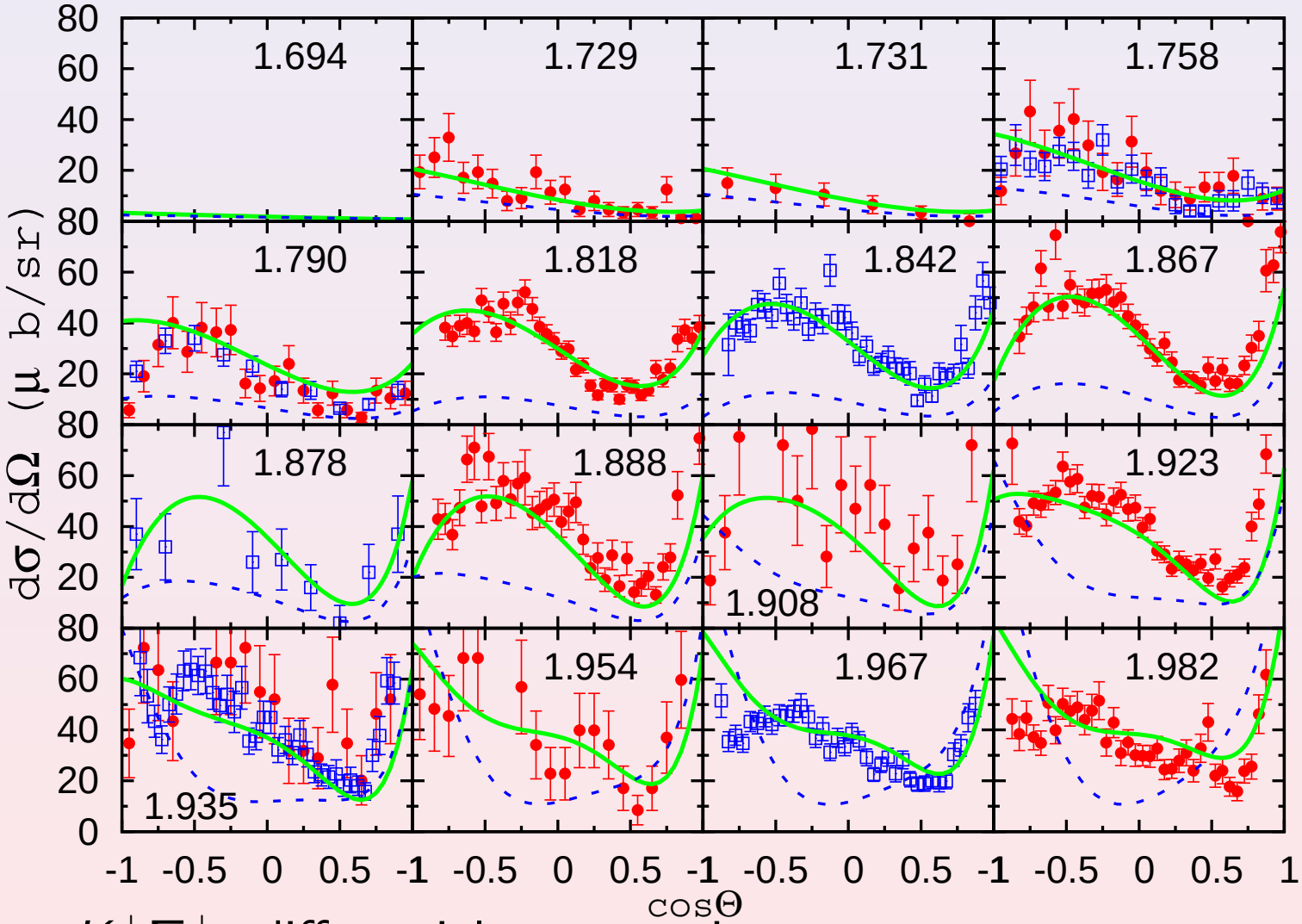
- The couplings of resonances to $\pi\pi N$ extracting from the branching ratios have big uncertainties.
- So theoretical and experimental efforts in $(\pi, \gamma)N \to \pi\pi N$ are favored.

Outlook



- $pp \to nK^+\Sigma^+$: total cross section
- Resonance model: J. J. Xie, C. Wilkin, X. CAO, B. S. Zou

Outlook



- $\pi^+ p \to K^+ \Sigma^+$: differential cross section
- Giessen model with and without the $P_{31}(1750)$ resonance

Outlook

- Possible direction in the improvement of the model.

1. $\pi\pi$ dynamics?
2. a step in tcs of $pp \to pp\pi^0\pi^0$
   interference? but how to treat the relative phase?
3. several form factors in each diagrams

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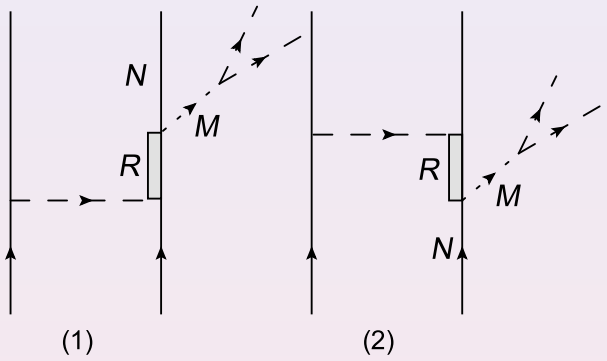

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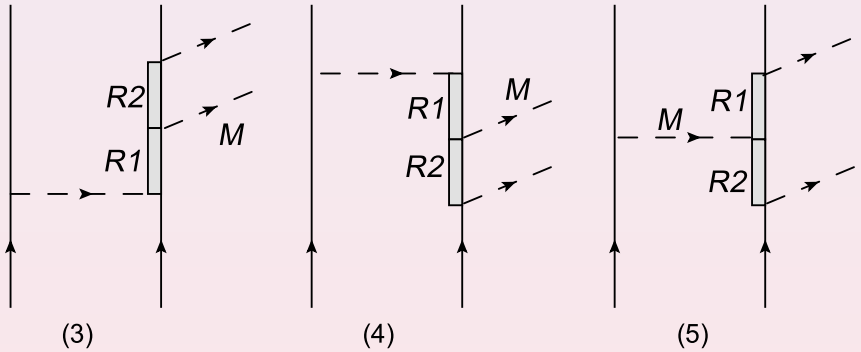
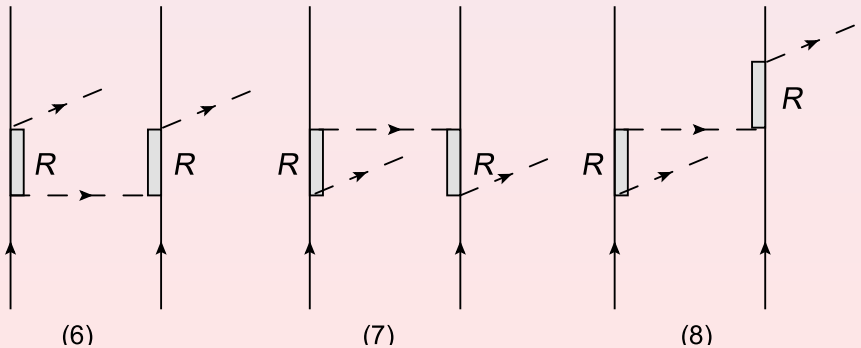
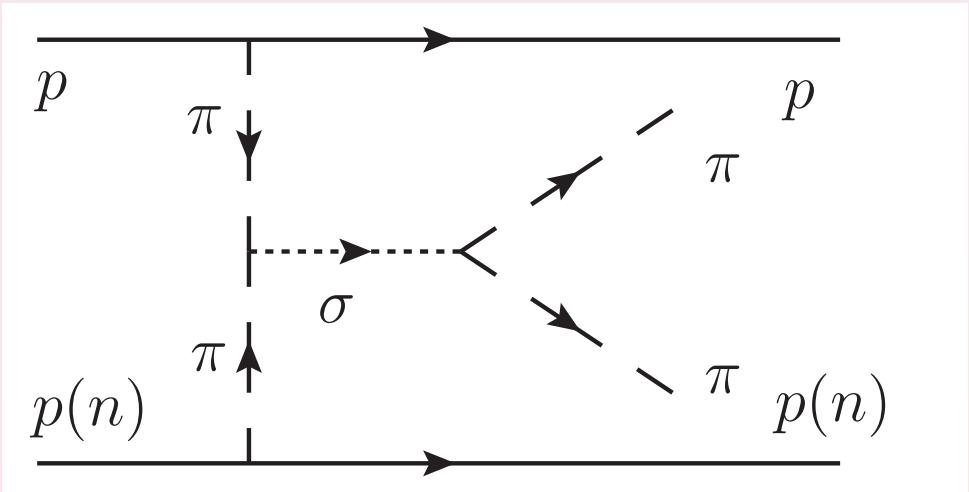


- double-R



Outlook

- σ-mesonic current
- forbidden in channels with $I_{\pi\pi} \neq 0$,
  i.e. $pp \to nn\pi^+\pi^+$,$pn \to pp\pi^-\pi^0$,$pp \to pn\pi^+\pi^0$



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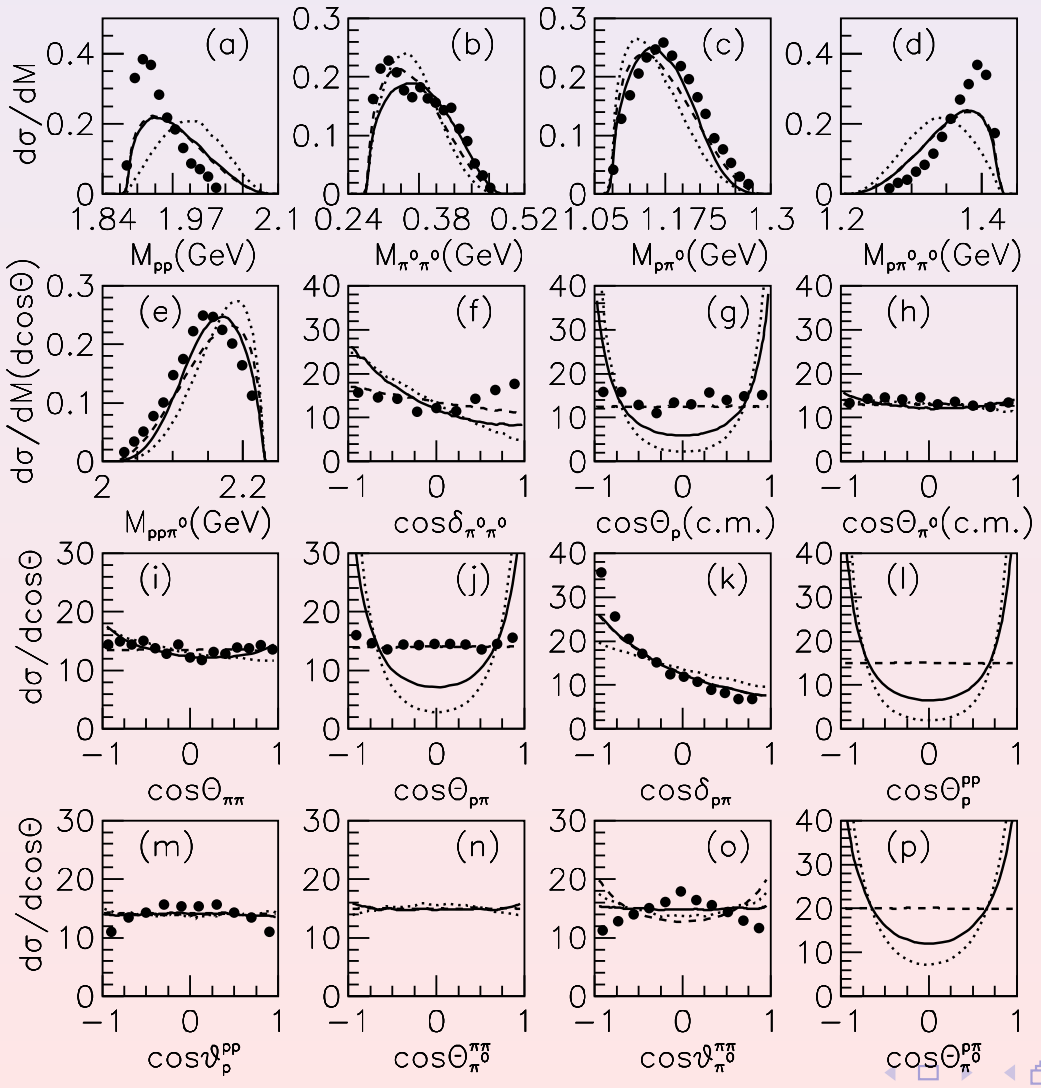
Outlook

- $pp \to pp\pi^0\pi^0$ at $T_p = 1100$ MeV
- $m_\sigma = 250$ MeV



Summary

1. Effective Lagrangian model gave a general understanding on the two pion production.
2. main contribution: nucleon pole,Δ,$N^*(1440)$,$\Delta(1600)$,$\Delta(1620)$
3. A full model including properly the interference and $\pi\pi$ dynamics is called for.
4. Some difficulties in the model building are addressed.
5. Data in channels with $I_{\pi\pi} \neq 0$ is expected to be helpful.
6. Efforts in $(\pi, \gamma)N \to \pi\pi N$ are useful to pin down the parameters.
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