Effect of unitarity on three-pions decay of heavy meson resonances

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EBAC Collaborators

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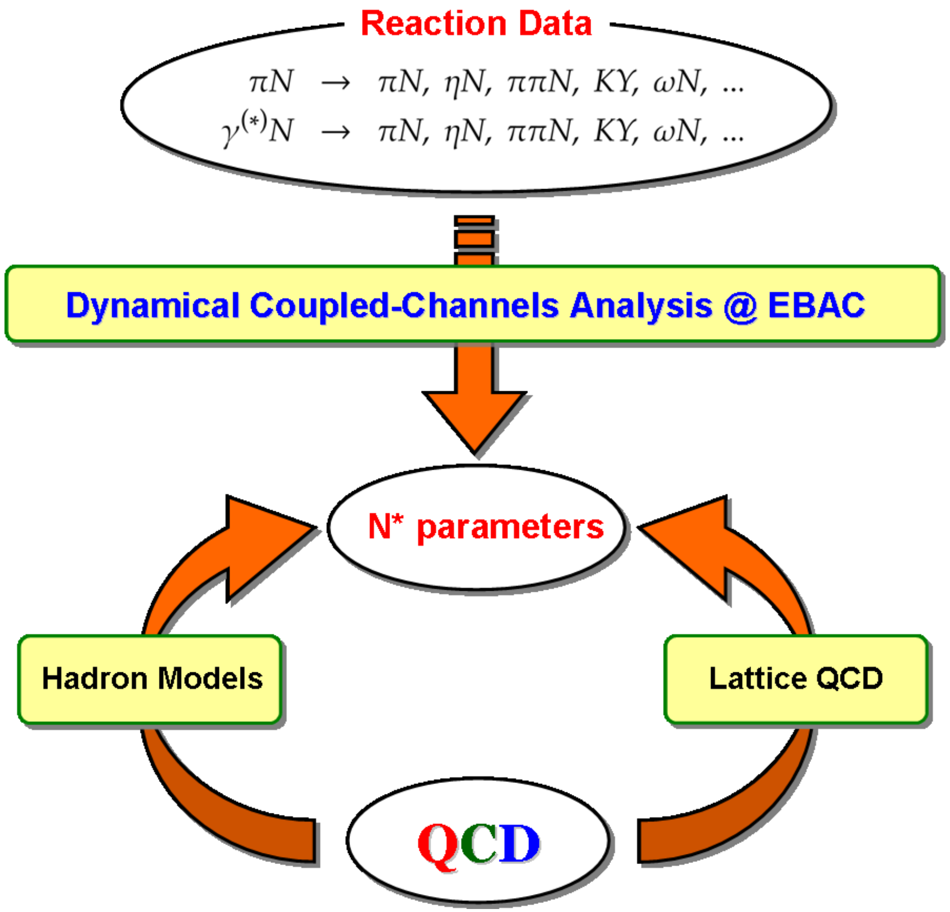
Harry Lee	(ANL)
Toru Sato	(Osaka Univ.)

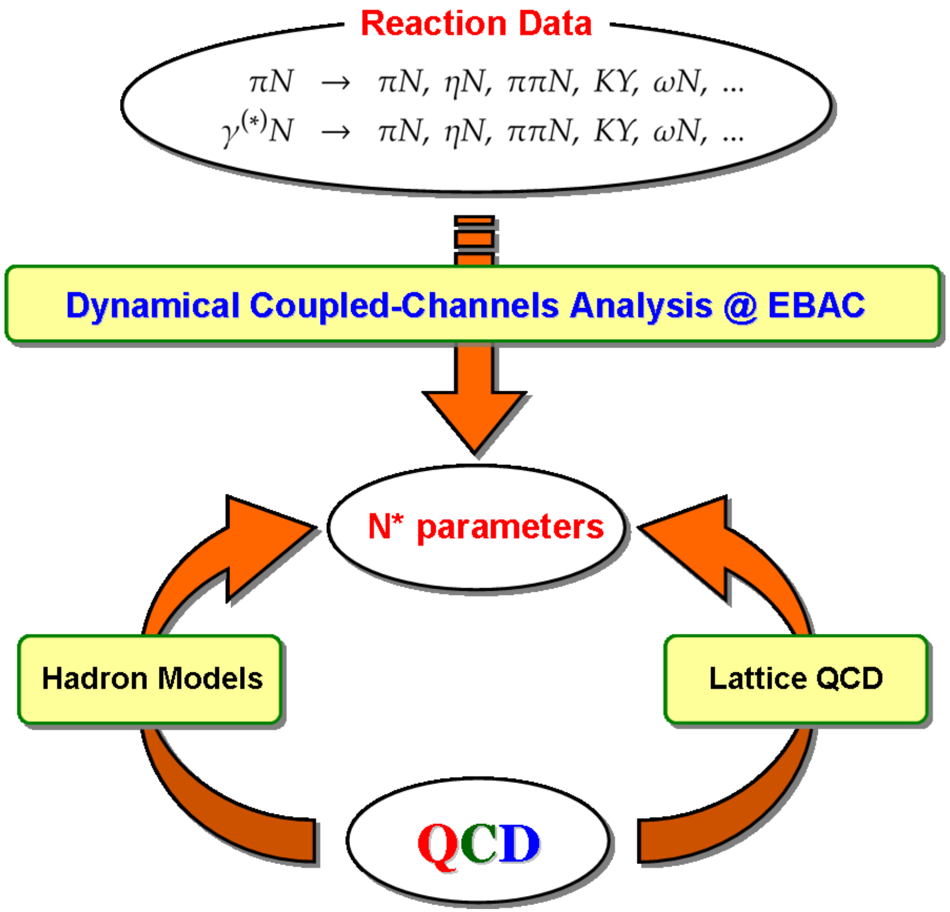
Summary of recent EBAC activity on N^*

Excited Baryon Analysis Center at Jefferson Lab



http://ebac-theory.jlab.org/

Excited Baryon Analysis Center at Jefferson Lab



http://ebac-theory.jlab.org/

Strategy Step 1

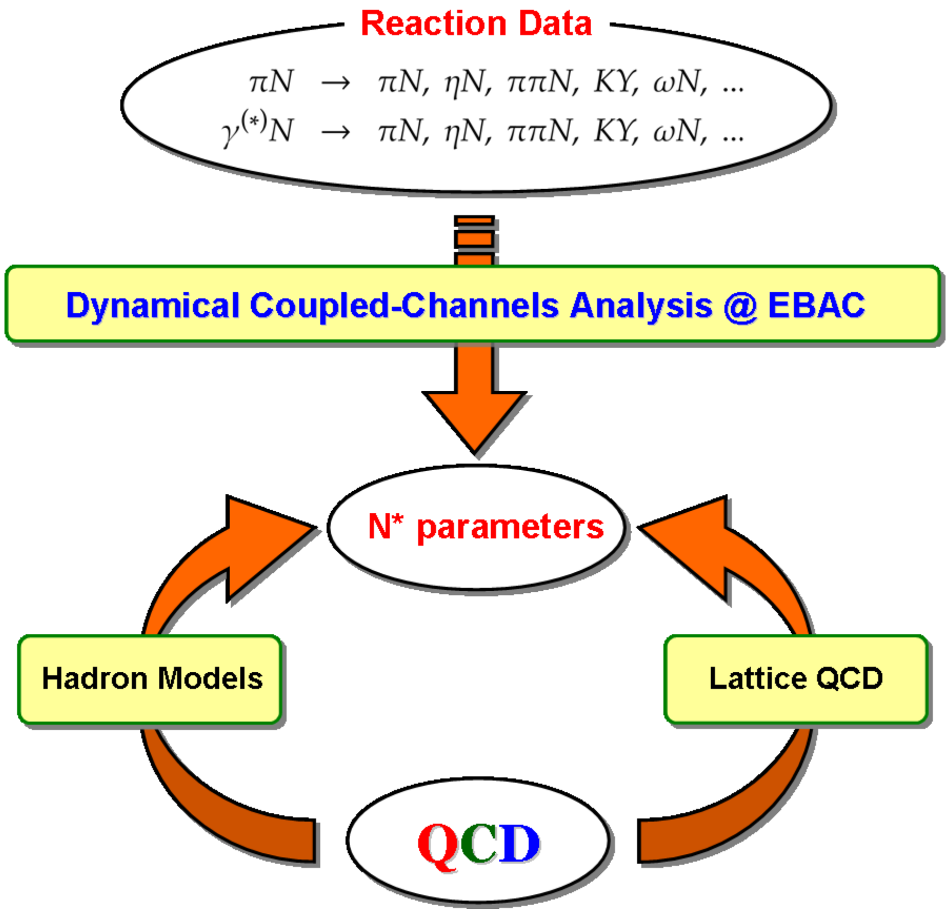
Comprehensive Dynamical Coupled-channels (DCC) analysis of $\pi N, \gamma N, N(e,e')$ reactions data

EBAC's DCC model

Matsuyama et al., Phys. Rep. **439**, 193 (2007)

DCC model provides reaction mechanism for interpreting N^* structure, dynamical origin

Excited Baryon Analysis Center at Jefferson Lab



http://ebac-theory.jlab.org/

Strategy Step 2

Extract N^* from DCC model

$*$ N^* pole positions

$N^* \rightarrow \gamma N, MB$ form factors

$*$ confirm or reject low-star N^*

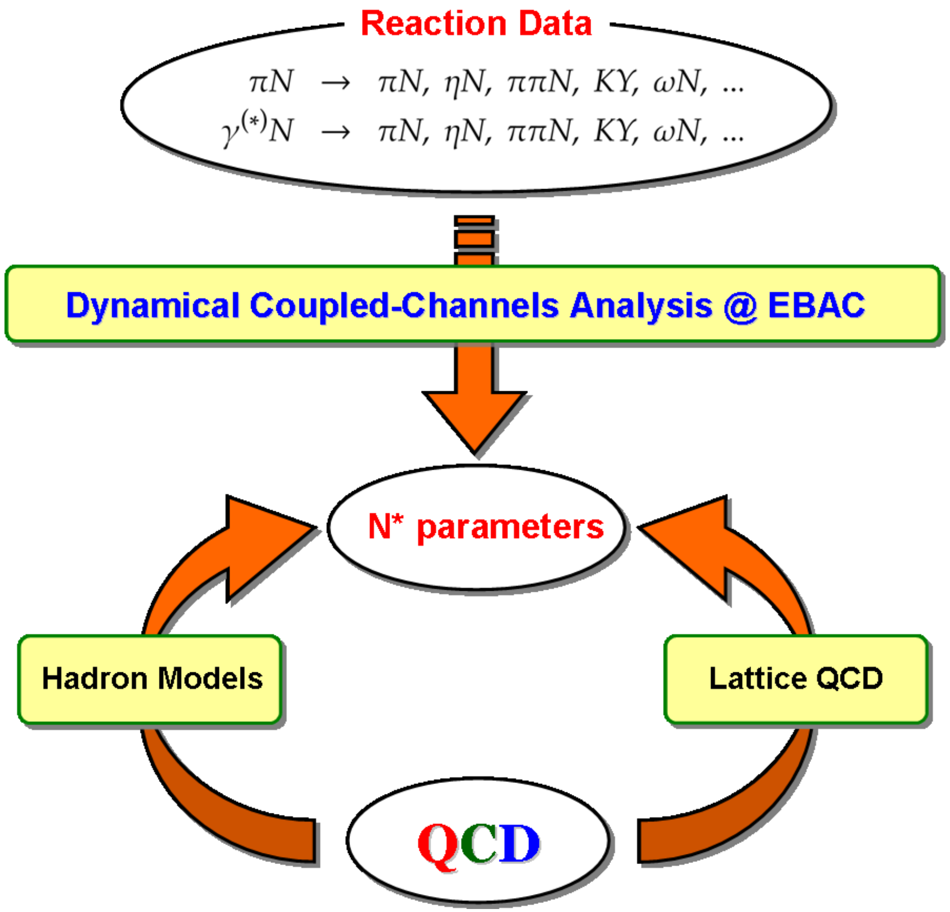
search for new N^*

Analytic continuation of amplitudes

to complex energy plane

Suzuki et al., PRC 79 025205; ibid, 82 045206

Excited Baryon Analysis Center at Jefferson Lab



Strategy Step 3

Make a connection between

extracted N^* to

hadron structure calculation

* Quark model
* Dyson Schwinger equation
* Lattice QCD

http://ebac-theory.jlab.org/

EBAC's DCC (Dynamical Coupled-Channel) model

Matsuyama et al., Phys. Rep. **439**, 193 (2007)

Lippmann-Schwinger equation

$$T_{ab} = V_{ab} + \sum_c V_{ac}\, G_c\, T_{cb}$$

$$V_{ab} = v_{ab} + \sum_{N^*} \frac{\Gamma^\dagger_{N^*,a}\, \Gamma_{N^*,b}}{E - m^0_{N^*}}$$

exchange-potentials — bare N* terms

$$\{a, b, c\} = \gamma^{(*)}N,\ \pi N,\ \eta N,\ \pi\pi N(\pi\Delta, \sigma N, \rho N)$$

EBAC's DCC (Dynamical Coupled-Channel) model

Matsuyama et al., Phys. Rep. **439**, 193 (2007)

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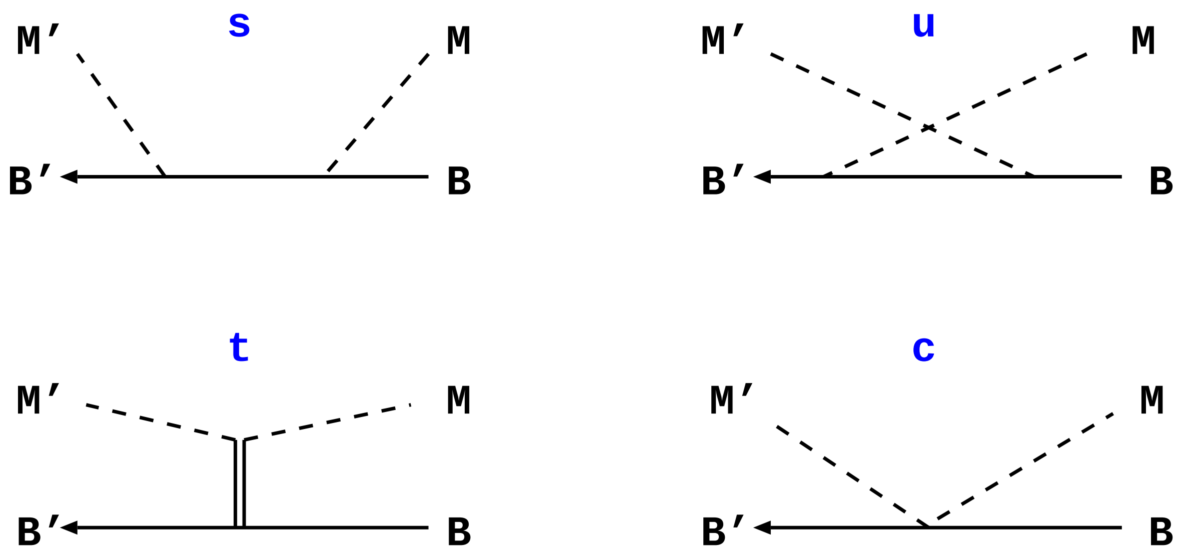
exchange-potentials　　　　bare N^* terms

$$\{a,b,c\} = \gamma^{(*)}N,\ \pi N,\ \eta N,\ \pi\pi N(\pi\Delta,\sigma N,\rho N)$$

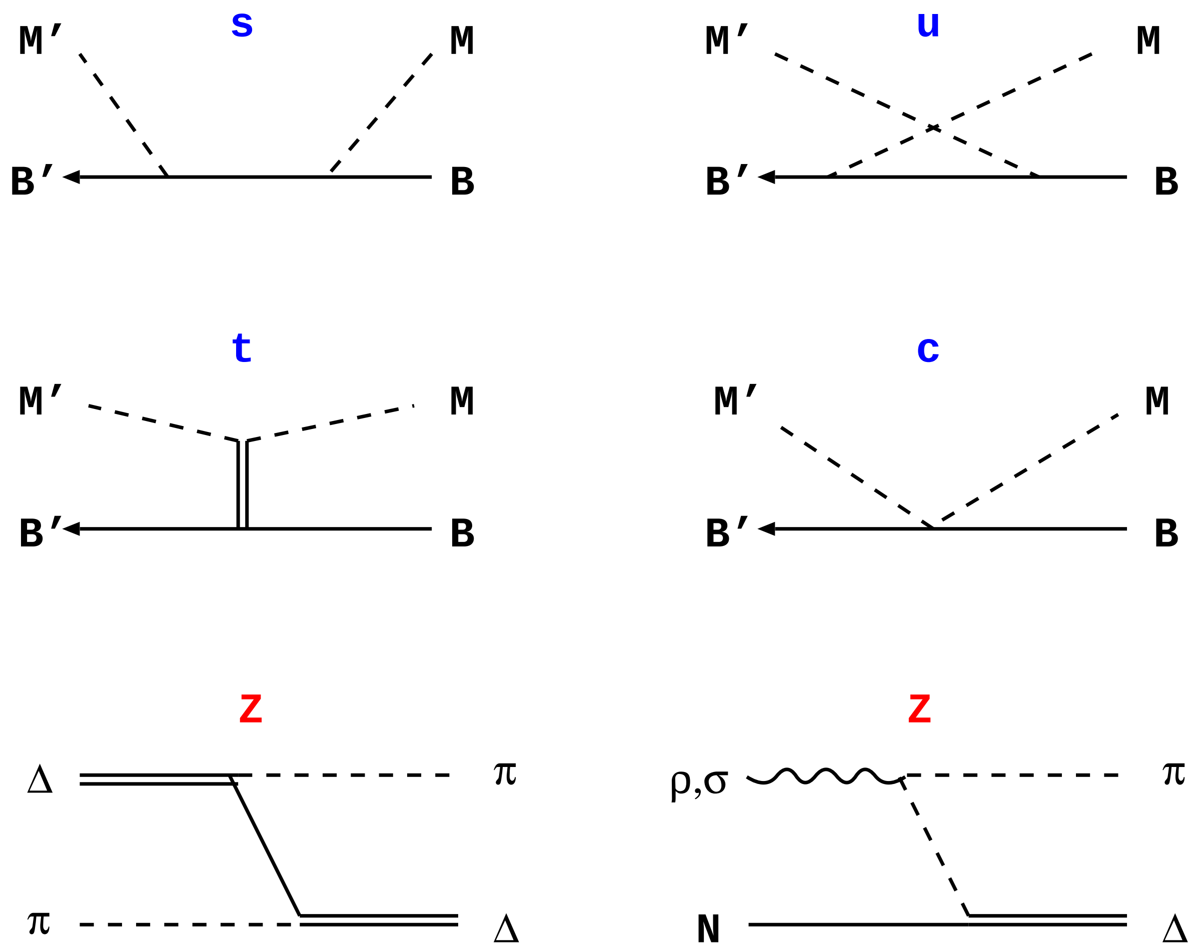
$$K\Lambda,\ K\Sigma,\ (\omega N)$$

Meson-exchange potentials (v_{ab}) for πN scattering



$$
\begin{aligned}
B,\ B' &= N,\ \Delta, Y \\
M,\ M' &= \pi,\ \eta,\ \rho,\ \sigma, K
\end{aligned}
$$

Meson-exchange potentials (v_{ab}) for πN scattering



Achievements so far (2006–2009)

- $\ast$ $\pi N \rightarrow \pi N$ fitted up to 2 GeV — PRC76 065201 (2007)
- $\ast$ $\pi N \rightarrow \pi\pi N$ up to 2 GeV — PRC79 025206 (2009)
- $\ast$ $\pi N \rightarrow \eta N$ fitted up to 2 GeV — PRC78 025204 (2008)
- $\ast$ $\gamma N \rightarrow \pi N$ fitted up to 1.6 GeV — PRC77 045205 (2008)
- $\ast$ $N(e, e'\pi)$ fitted up to Q^2 = 1.5 GeV^2 — PRC80 025207 (2009)
- $\ast$ $\gamma N \rightarrow \pi\pi N$ up to 1.6 GeV — PRC80 065203 (2009)
- $\ast$ Extraction of N* properties — PRL104 065203 (2010), PRC82 045206 (2010)

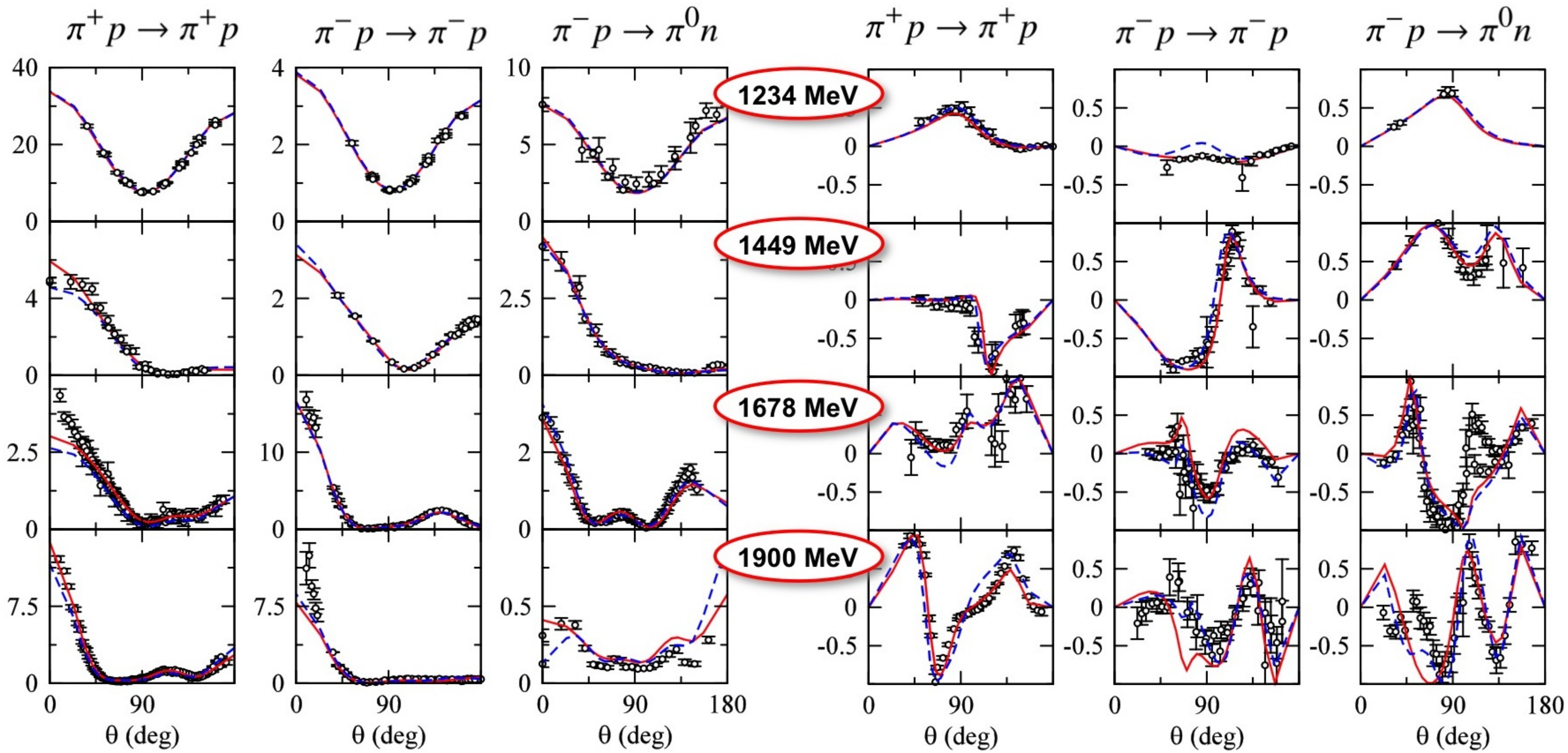
EBAC-DCC Analysis since 2010

	2006 – 2009	2010 $\sim$
# of coupled-channels	5 $(\pi N, \eta N, \pi\Delta, \sigma N, \rho N)$	7 $(\pi N, \eta N, \pi\Delta, \sigma N, \rho N, K\Lambda, K\Sigma)$
$* \ \pi N \to \pi N$	$<$ 2 GeV	$<$ 2 GeV
$* \ \gamma N \to \pi N$	$<$ 1.6 GeV	$<$ 2 GeV
$* \ \pi N \to \eta N$	$<$ 2 GeV	$<$ 2 GeV
$* \ \gamma N \to \eta N$	–	$<$ 2 GeV
$* \ \pi N \to KY$	–	$<$ 2.1 GeV
$* \ \gamma N \to K\Lambda$	–	$<$ 2.1 GeV

$\Downarrow$

Fully-combined Analysis of $\pi N, \gamma N \to \pi N, \eta N, KY$ (ωN) !

$\pi N \to \pi N$ (*preliminary*)

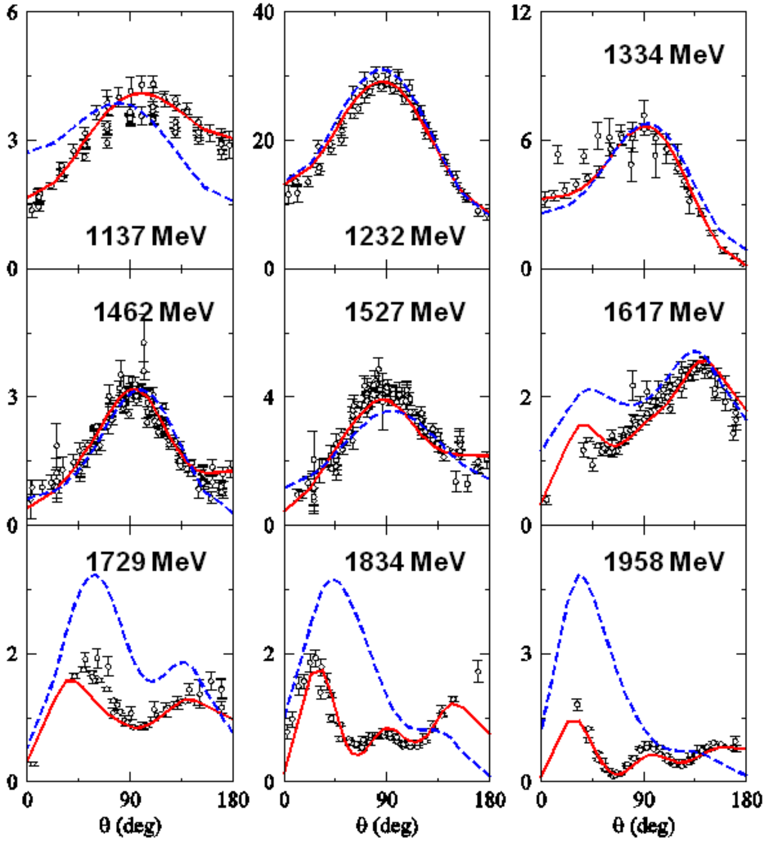


red: Current full-combined analysis

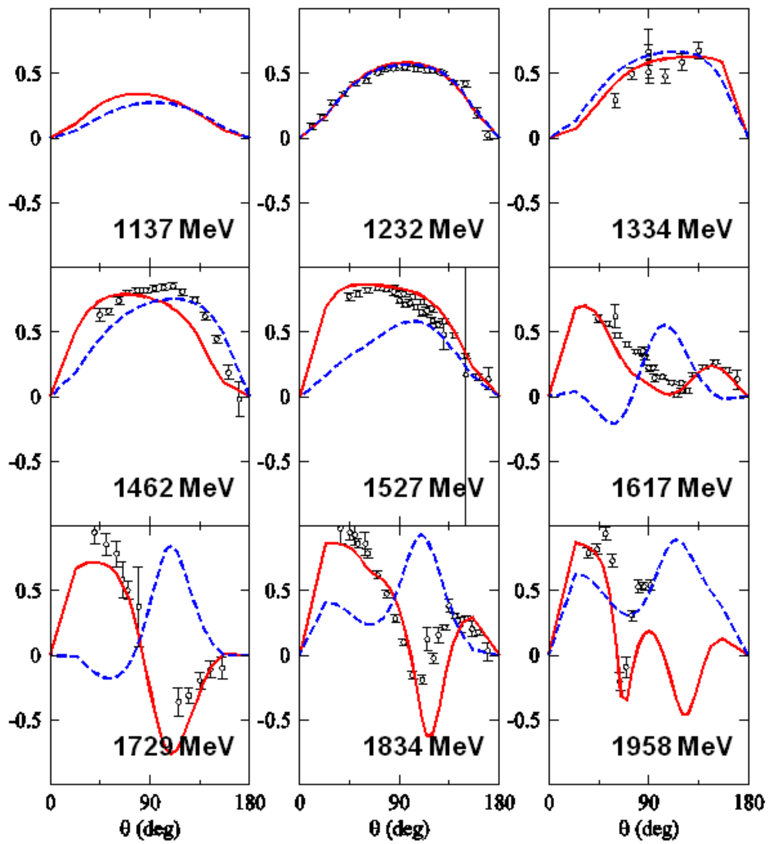
blue dashed: Previous model [PRC76, 065201 (2007)] fitted to $\pi N \to \pi N$ data only

$\gamma p \to \pi^0 p$ (*preliminary*)

Angular distribution $d\sigma/d\Omega$ (μb/sr)



Photon asymmetry Σ

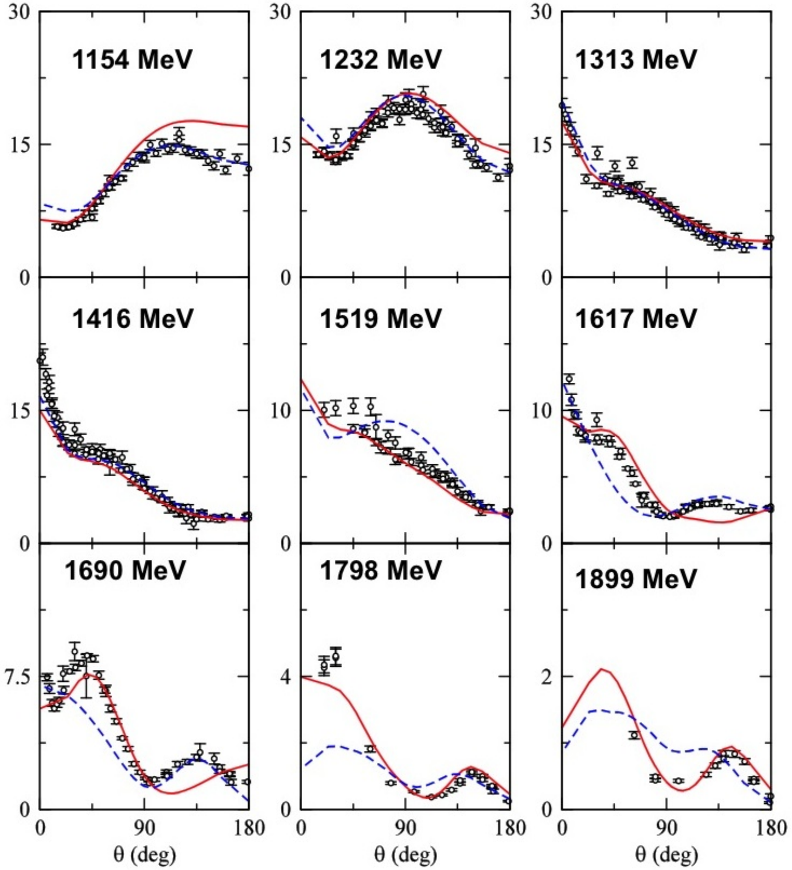


red: Current full-combined analysis

blue dashed: Previous model [PRC77, 045205 (2008)] fitted to $\gamma N \to \pi N$ data up to 1.6 GeV

$\gamma p \rightarrow \pi^+ n$ (*preliminary*)

Angular distribution $d\sigma/d\Omega$ (μb/sr)



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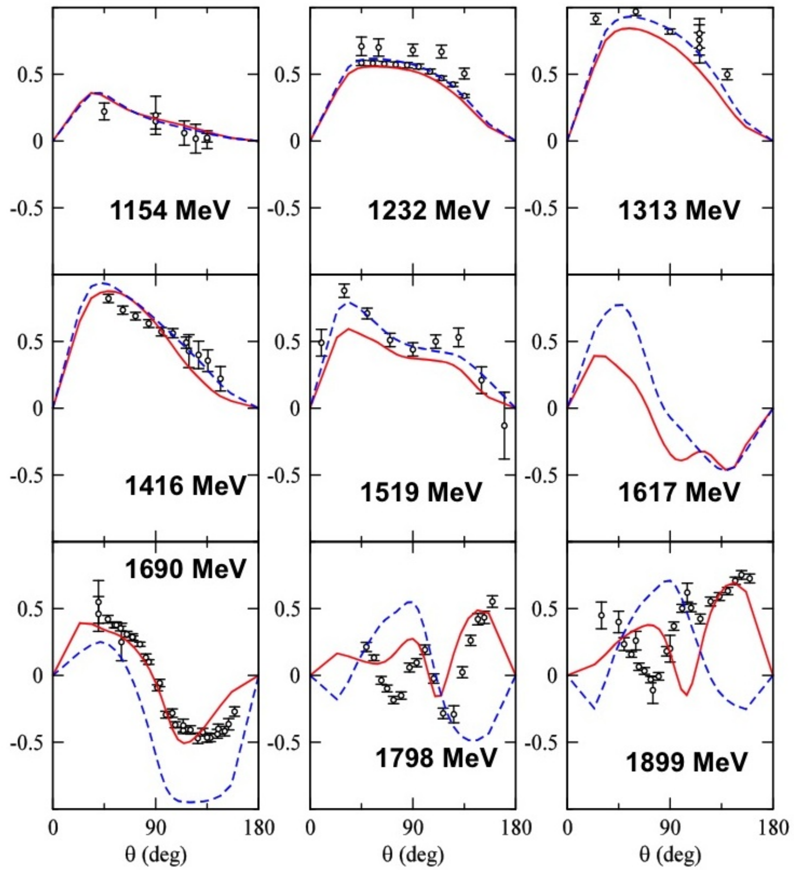


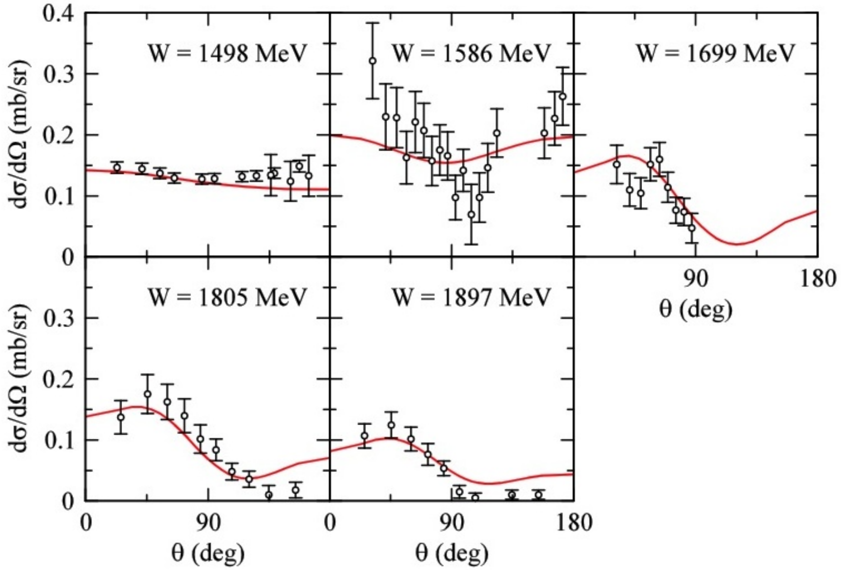
red: Current full-combined analysis

blue dashed: Previous model [PRC77, 045205 (2008)] fitted to $\gamma N \rightarrow \pi N$ data up to 1.6 GeV

η **productions** (*preliminary*)

$\pi^- p \to \eta n$

$d\sigma/d\Omega$ (mb/sr)



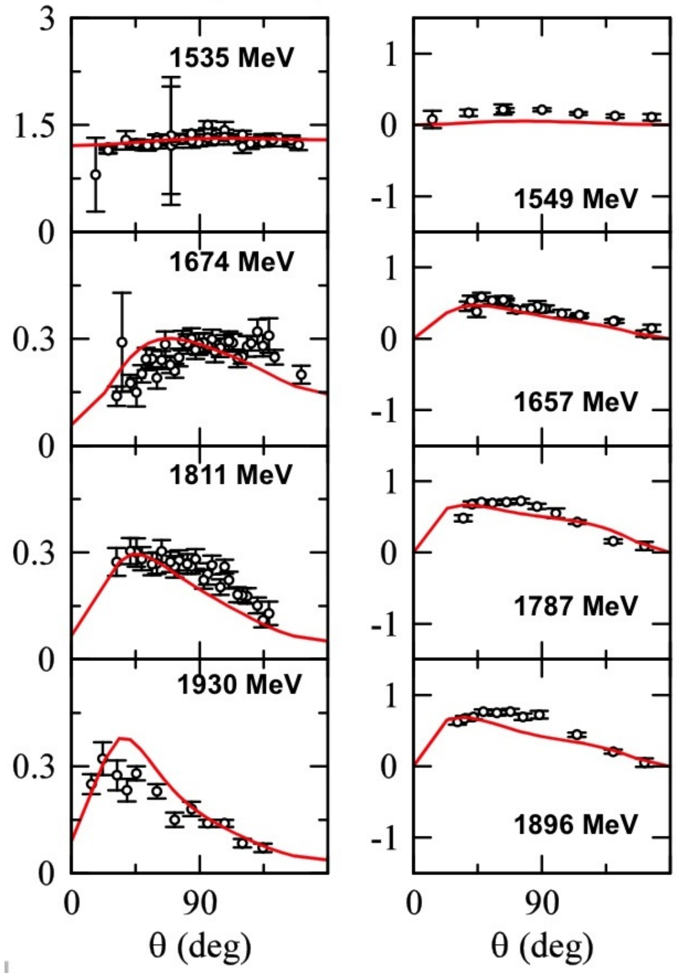
Data are selected following
Durand et al. PRC78 025204

Analyzed data up to $W = 2\,\mathrm{GeV}$

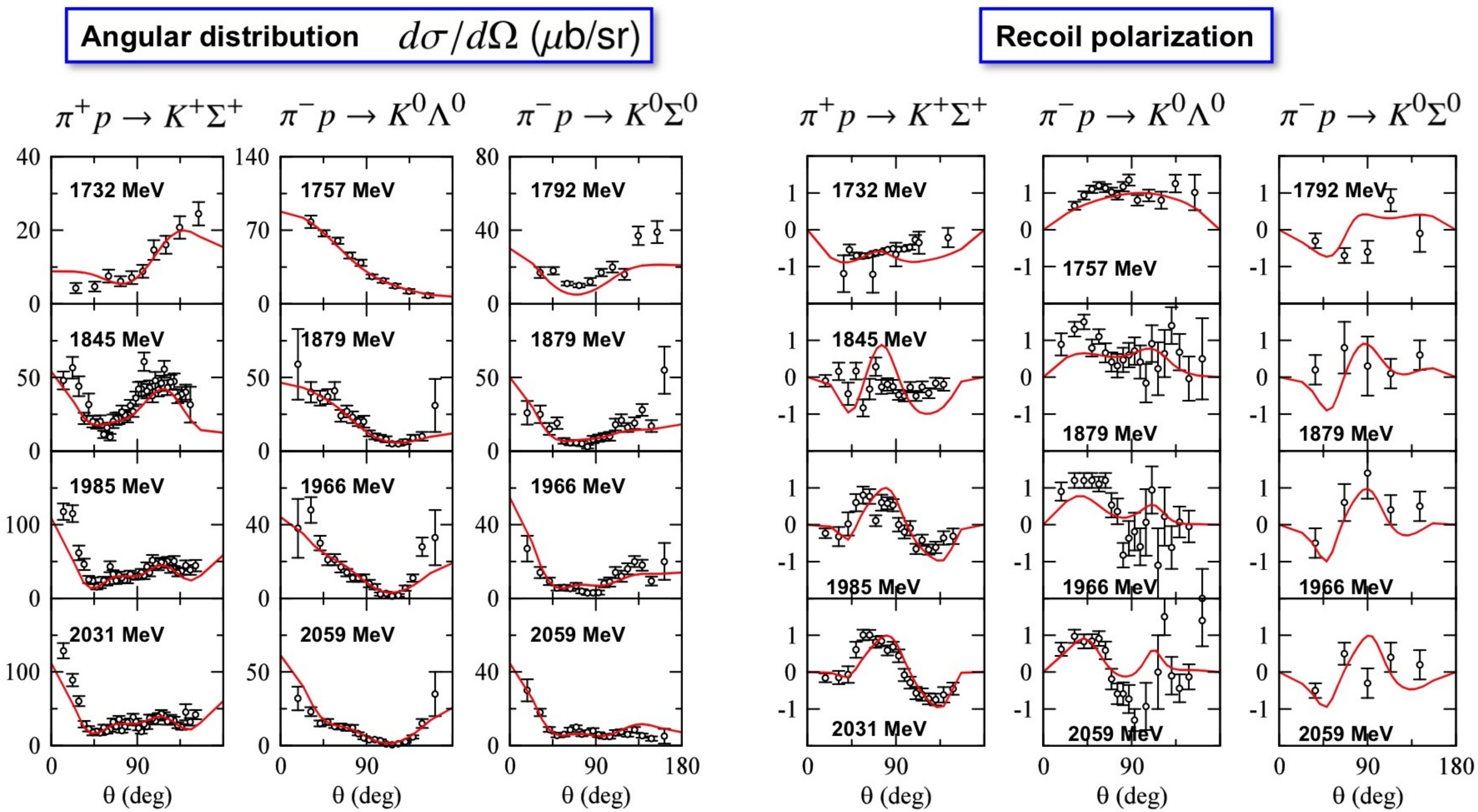
$\gamma p \to \eta p$

$d\sigma/d\Omega$ (μb/sr)

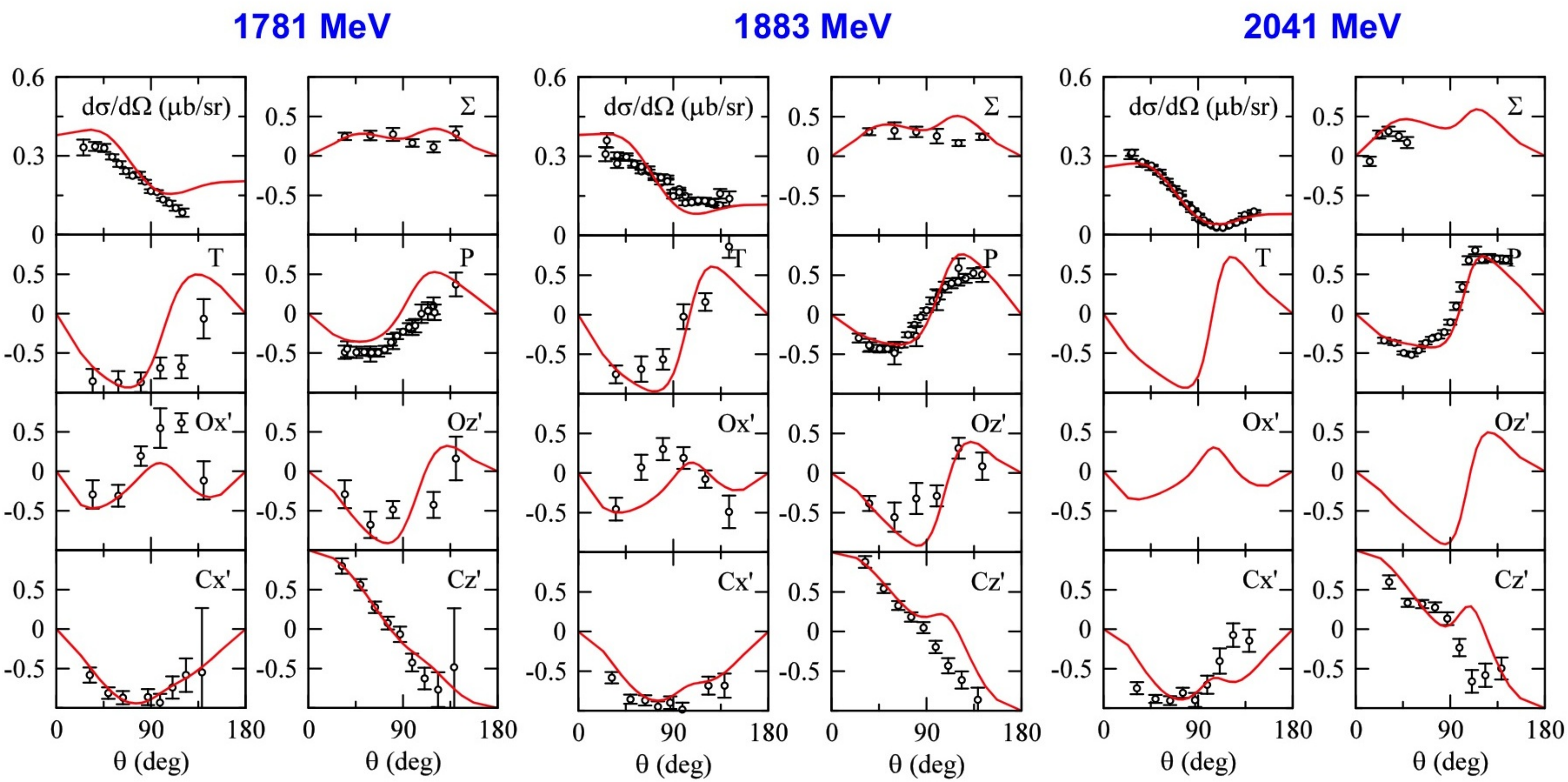
Photon asymmetry



$\pi N \to KY$ (*preliminary*)



$\gamma p \to K^+\Lambda$ (*preliminary*)



Over-complete experiment is planned by CLAS@JLAB

$\Longrightarrow$ New N^* states !

Effect of unitarity on three-pions decay of heavy meson resonances

Introduction

Why we care 3π ($\pi\pi K$, etc.) scattering ?

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Why we care 3π ($\pi\pi K$, etc.) scattering ?

$\Longrightarrow$ Information of interesting physics is hidden in 3π from heavy meson decays

e.g.,

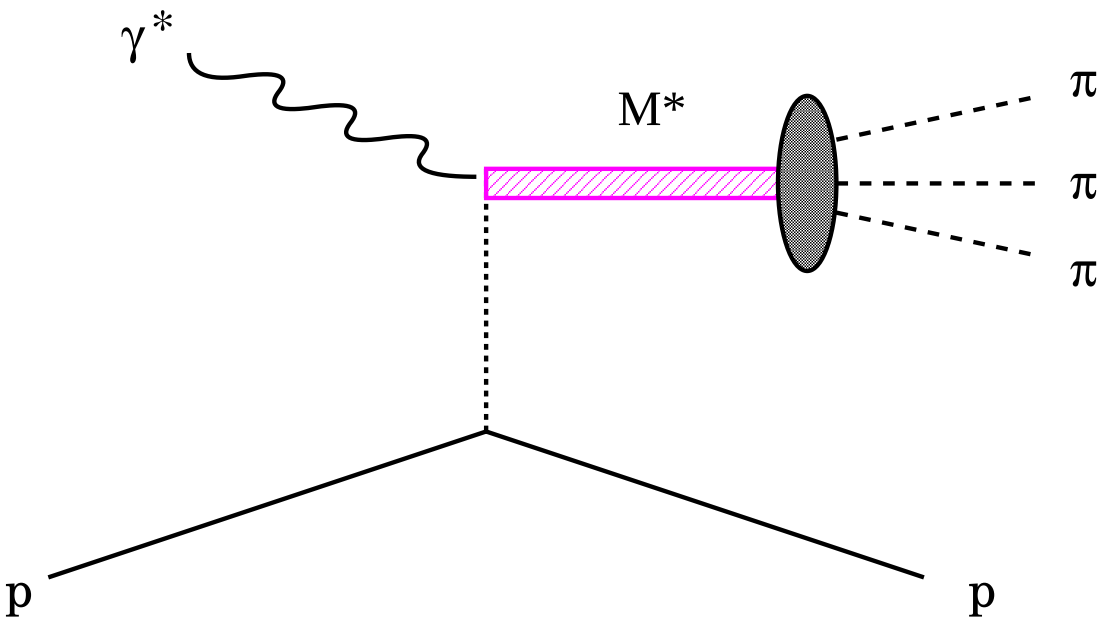
$*$ Exotic (hybrid) mesons (e.g.,$J^{PC} = 1^{-+}$) BNL(E852),JLab(GlueX,CLAS12)

$\Longrightarrow$ Gluon self interaction

$*$ CP-violation from B- and D-decays BABAR, Belle

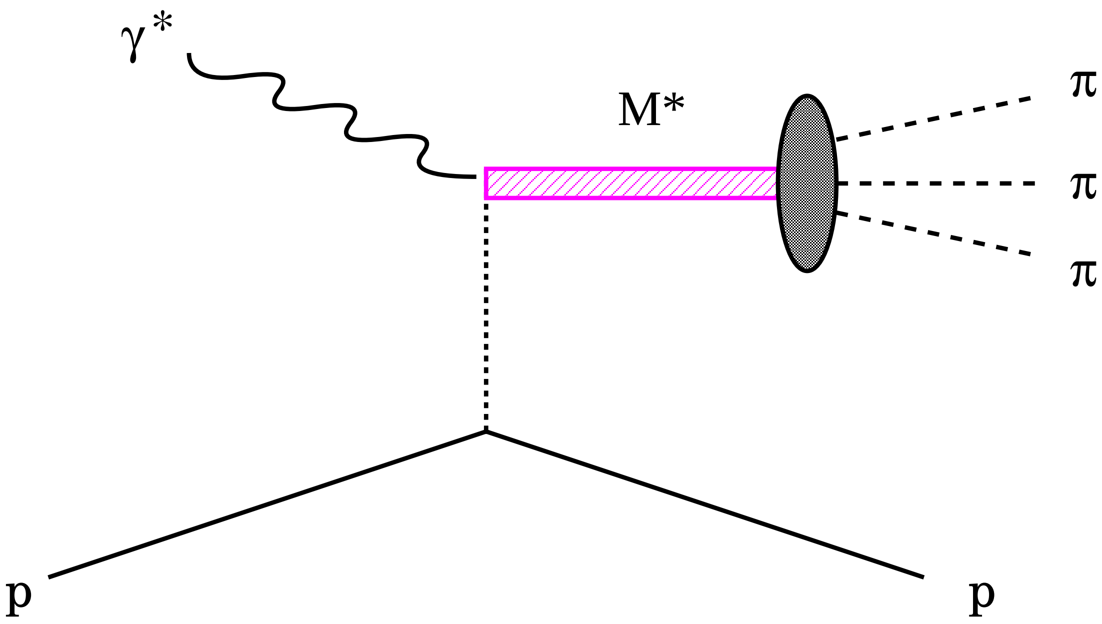
$\Longrightarrow$ CKM matrix, beyond SM contribution

GlueX,CLAS12 experiment (JLab, planned after 12 GeV upgrade)



New EBAC project : Analysis of 3π FSI in heavy meson decays

GlueX,CLAS12 experiment (JLab, planned after 12 GeV upgrade)

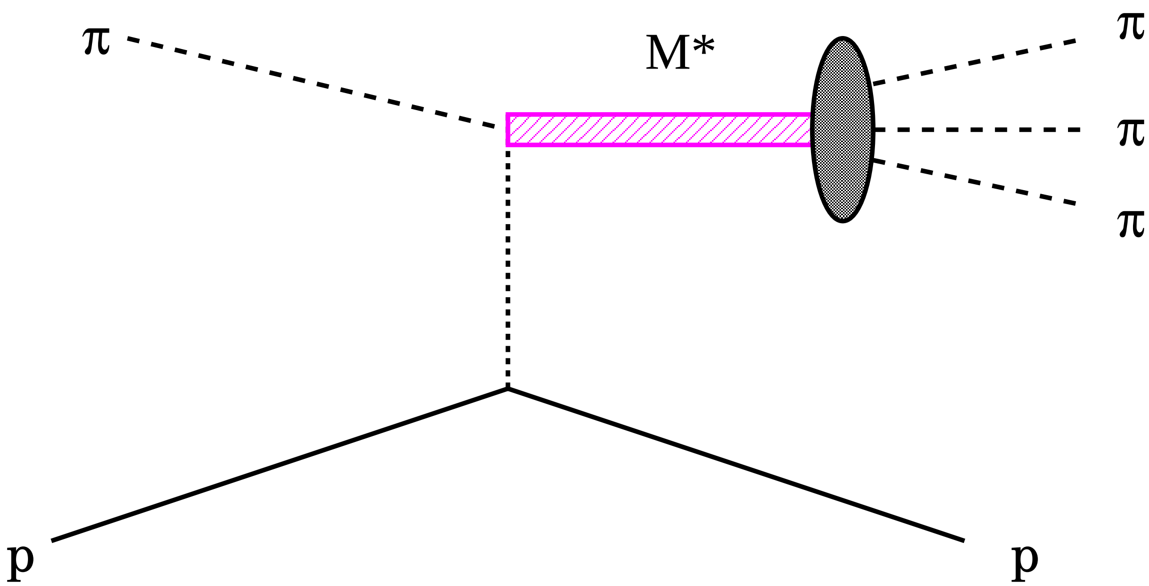


EBAC ⟶ EHAC ?

(Excited Hadron Analysis Center)

Previous analysis of 3π decay of M^*

E852 (BNL) $\pi^- p \to \pi^+ \pi^- \pi^- p$ Chung et al., PRD **65**, 072001 (2001)



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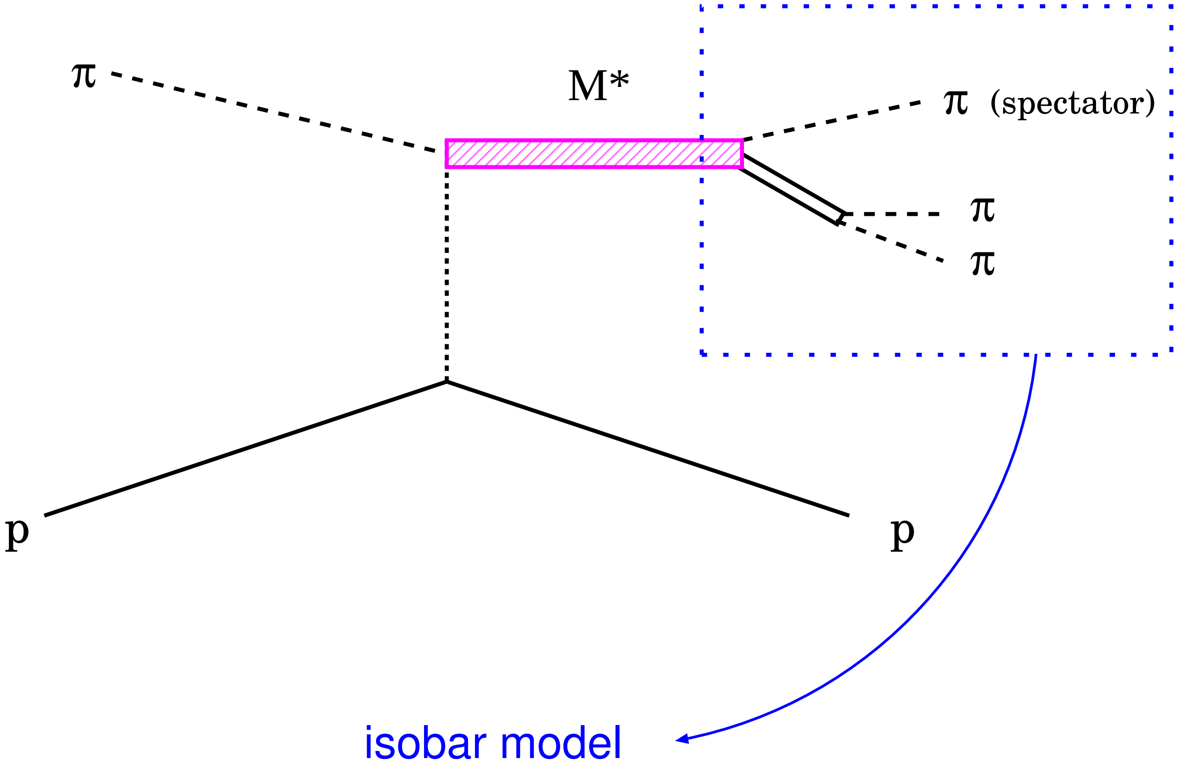


isobar model

$*$ $\pi\pi$ subsystem forms a resonance

$*$ 3rd π is a spectator (3π unitarity missing !)

Our objective

(This work)

Examine the effect of 3π unitarity on

* Pole position of heavy meson resonance
* Dalitz plot of heavy meson 3π decay

$\Longrightarrow$ address the basic assumption of the isobar model

(Long term)

Comprehensive development of reliable 3π ($\pi\pi K$ etc.) model

Coupled-Channels Model

Matsuyama, Sato, Lee, Phys. Rept. **439**, 193 (2007)

$M^* \to \pi R_{\pi\pi}$ (or $\bar{K} R_{\pi K}$) $\to \pi\pi\pi$

Channels $R_{\pi\pi}$: $f_0(600)$, $f_0(980)$, $\rho(760)$, $f_2(1270)$

$R_{\pi K}$: $K_0^*(800)$, $K_0^*(1430)$, $K^*(892)$, $K^*(1680)$

$R_{\pi\pi}$ ($R_{\pi K}$) : resonance in $\pi\pi$ (πK) scattering

(I) Develop $\pi\pi$ (πK) model

(II) Develop $\pi R_{\pi\pi}$ ($\bar{K} R_{\pi K}$) interaction

(III) Solve $\pi R_{\pi\pi}$ ($\bar{K} R_{\pi K}$) scattering equation

Simple $\pi\pi$ model

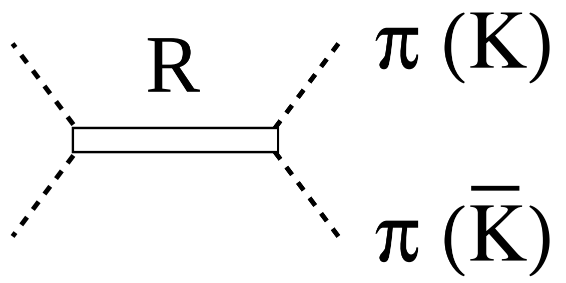
Coupled-channel scattering equation for $\pi\pi$ partial wave (L, I)

$$t^{LI}_{i,j}(p', p; W) = V^{LI}_{i,j} + \sum_k \int_0^\infty q^2 dq\, V^{LI}_{i,k}(p', q; W) \frac{1}{W - E_k(q) + i\epsilon} t^{LI}_{k,j}(q, p; W)$$

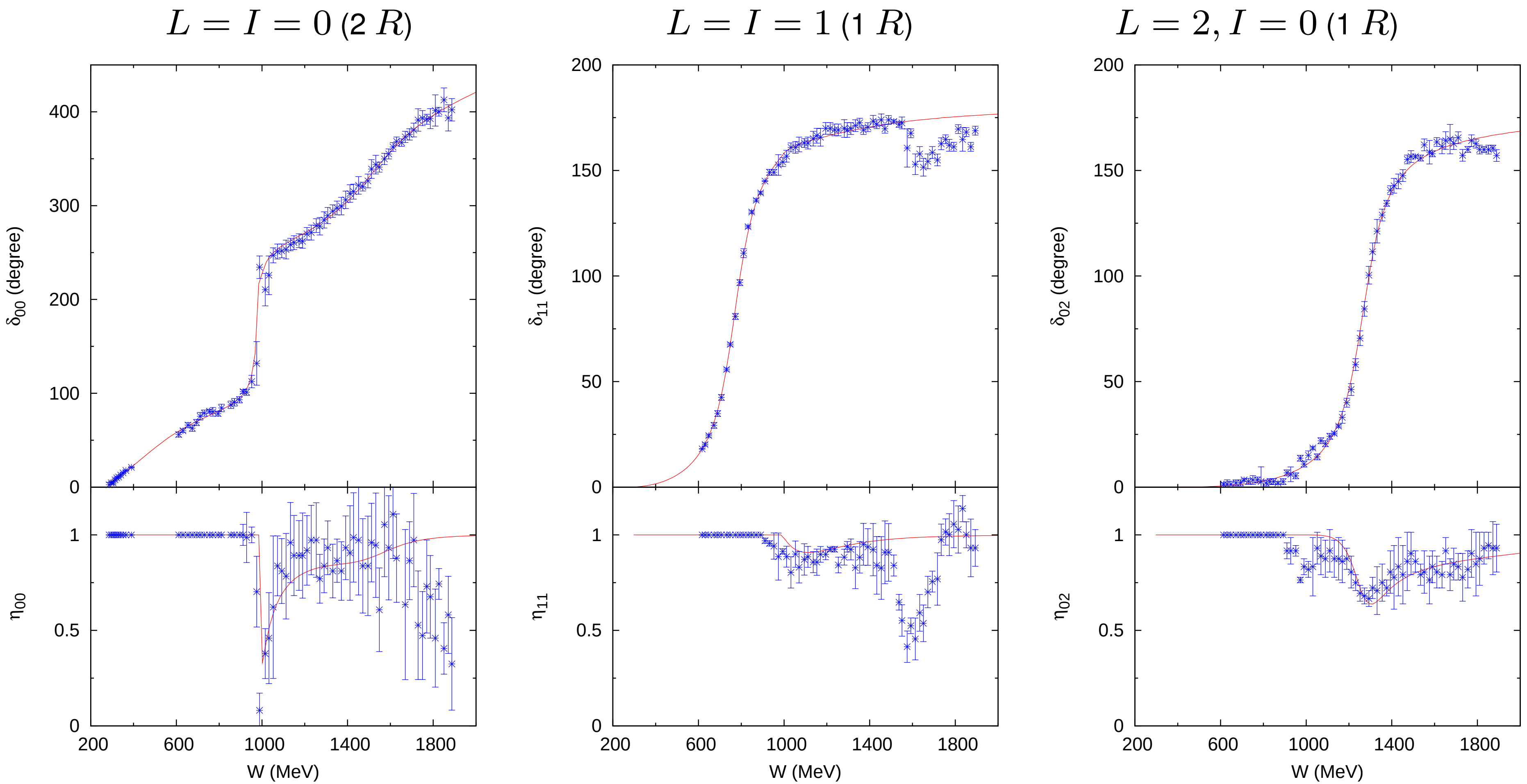
$$E_{\pi\pi}(q) = 2\sqrt{m_\pi^2 + q^2} \qquad\qquad (i, j, k = \pi\pi, K\bar{K})$$

$$V^{LI}_{i,j}(p', p; W) = \sum_R f^{LI}_{R,i}(p') \frac{1}{W - m_R} f^{LI}_{R,j}(p)$$

$$f^{LI}_{R,i}(p) = \frac{g_{R,i}}{\sqrt{m_\pi}} \frac{1}{(1 + (c_{R,i}p)^2)} \left(\frac{p}{m_\pi}\right)^L$$



Phase and inelasticity of $\pi\pi$ amplitude



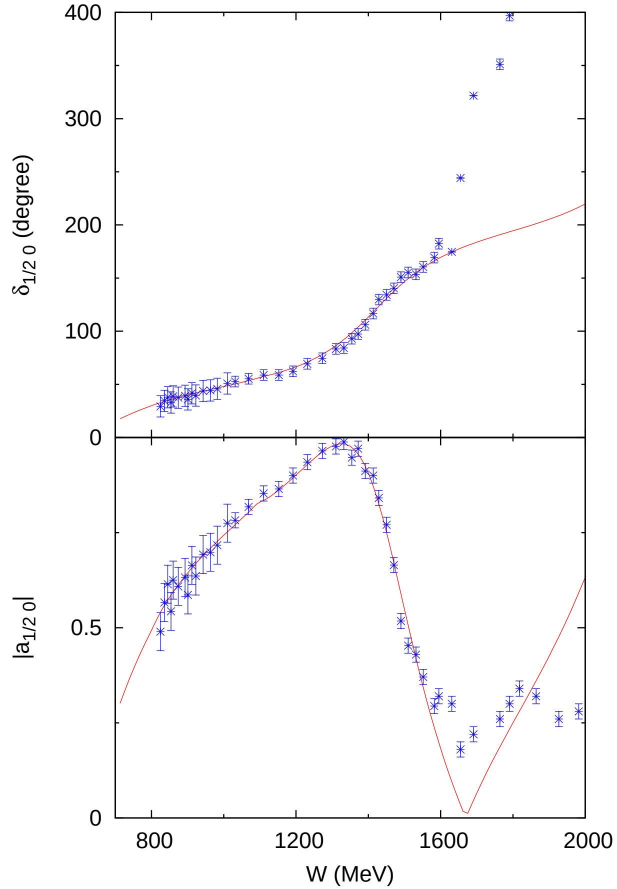
[Data: G. Gayer et al., NPB **75**, 189 (1974)]

Pole positions in $\pi\pi$ amplitude

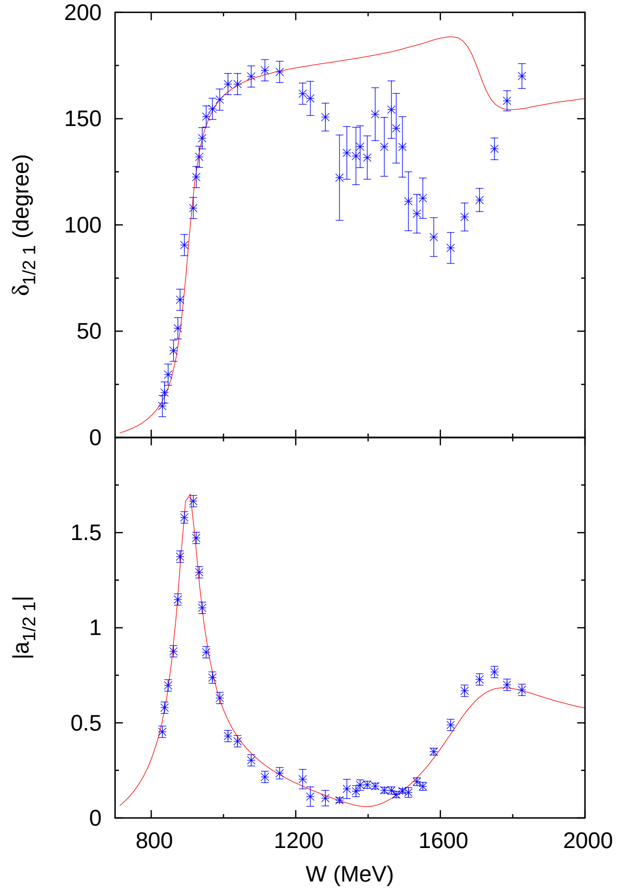
	Re[M_R] (MeV)		$-$Im[M_R] (MeV)	
	Ours	PDG	Ours	PDG
f_0 (600)	437	$400 - 1200$	256	$300 - 500$
f_0 (980)	897	980 ± 10	69	$20 - 50$
f_0 (1500)	1527	1505 ± 6	237	54.5 ± 3
ρ (760)	769	775.5 ± 0.3	81	74.5 ± 0.4
f_2 (1270)	1249	1275 ± 1.2	101	92.5 ± 1.3

Phase and magnitude of πK amplitude

$L = 0, I = 1/2$ (2 R)



$L = I, I = 1/2$ (2 R)

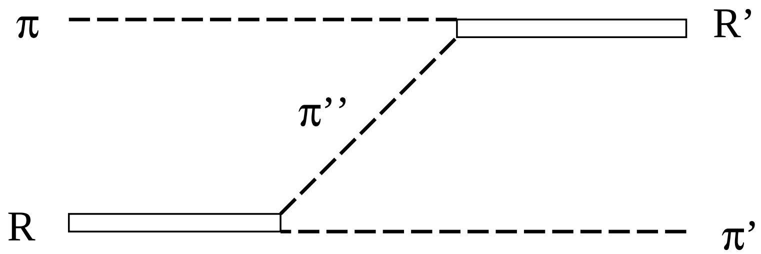


[Data: D. Aston et al. (LASS), NPB **296**, 493 (1988)]

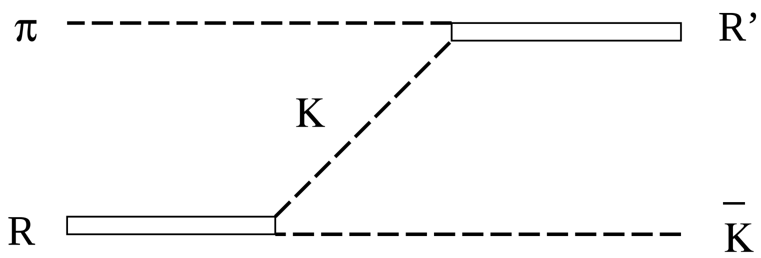
Pole positions in πK amplitude

	Re[M_R] (MeV)		−Im[M_R] (MeV)	
	Ours	PDG	Ours	PDG
K_0^* (800) (κ)	643	672 ± 40	238	275 ± 17
K_0^* (1430)	1422	1425 ± 50	168	185 ± 40
K^* (892)	901	891.7 ± 0.3	29	25.4 ± 0.5
K^* (1680)	1694	1717 ± 27	152	161 ± 55

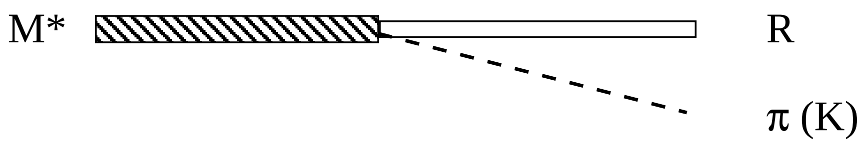
Quasi two-particle ($\pi R_{\pi\pi}, \bar{K} R_{\pi K}$) interaction



3 π Z-graph



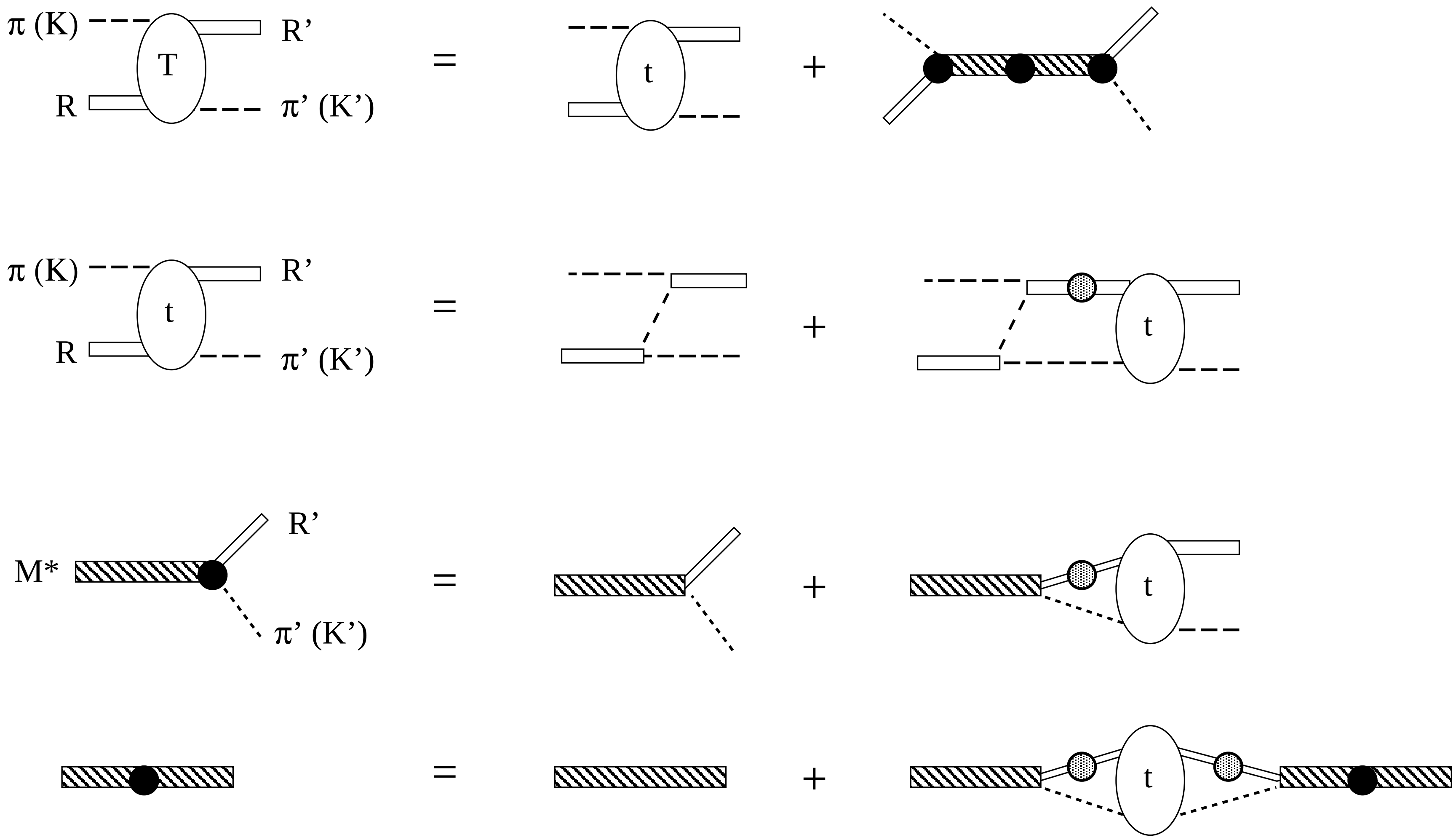
$\pi K \bar{K}$ Z-graph



M^* graph

Z-graphs play an essential role to maintain the 3-body unitarity !

Quasi two-particle ($\pi R_{\pi\pi}, \bar{K} R_{\pi K}$) scattering equation



Application

Effect of Z-graphs (unitarity) on $\pi_2(1670)$ and $\pi_2(2100)$ poles

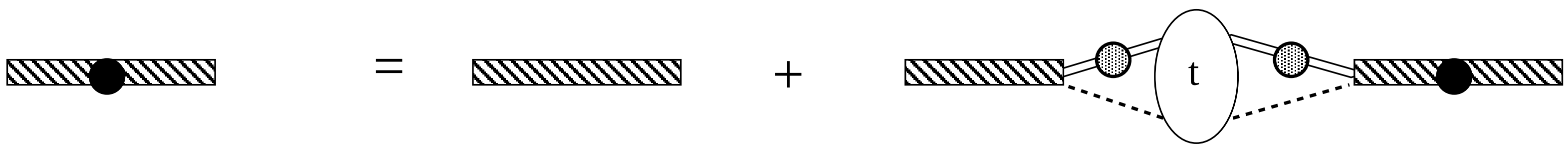
	M^*	$\pi_2(1670)$	$\pi_2(2100)$
	J^{PC}	2^{-+}	2^{-+}
	M_R	$1672 - 130i$ MeV	$2090 - 313i$ MeV
M^*	$\longrightarrow \pi f_2(1270)$	56 %	35%
	$\longrightarrow \pi \rho(760)$	31 %	19 %
	$\longrightarrow \pi f_0(600)$	11 %	45%

(Data from PDG)

Fit $M^0_{\pi_2}$, $g_{\pi_2 \to \pi R}$ to the pole and branching ratios for $\pi_2(1670)$, $\pi_2(2100)$

Pole search method : Analytic continuation of T-matrix to the unphysical Riemann sheet

Suzuki, Sato, Lee, PRC **79**, 025205 (2009); ibid, **82**, 045206 (2010)



Resonance pole : $W - M^0_{M^*} - \Sigma_{M^*}(W) = 0$

Fit $M^0_{\pi_2}$, $g_{\pi_2 \to \pi R}$ to the pole and branching ratios for $\pi_2(1670), \pi_2(2100)$

Pole search method : Analytic continuation of T-matrix to the unphysical Riemann sheet

Suzuki, Sato, Lee, PRC **79**, 025205 (2009); ibid, **82**, 045206 (2010)

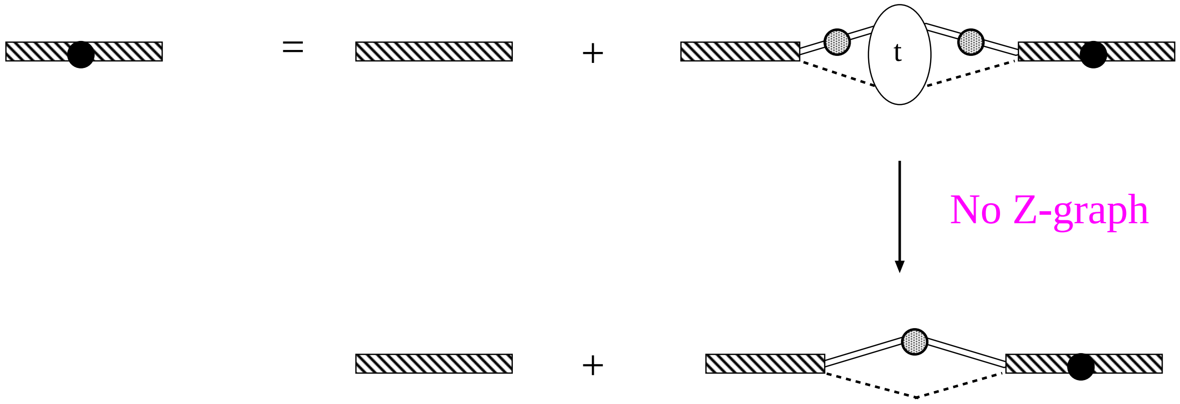
Partial width :

$$\Gamma(\pi_2 \to \pi R) \equiv -2\,\mathrm{Im}\left(g \frac{1}{W - E_\pi - E_R - \Sigma_R} g \right)$$

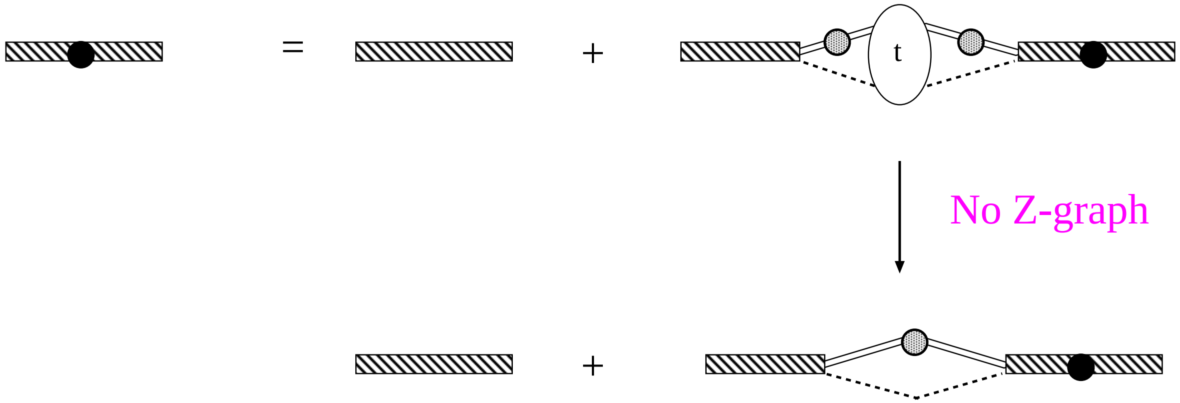
Branching ratio :

$$B(\pi_2 \to \pi R) = \frac{\Gamma_R}{\Gamma_{\text{total}}} = \frac{\Gamma_R}{\sum_{R'} \Gamma_{\mathrm{R'}}}$$

Effect of Z-graph on the π_2 pole position



Effect of Z-graph on the π_2 pole position



	$\pi_2(1670)$	$\pi_2(2100)$
w Z-graph	$1672 - 130\,i$ MeV	$2090 - 313\,i$ MeV
w/o Z-graph	$1689 - 133\,i$ MeV	$2084 - 346\,i$ MeV

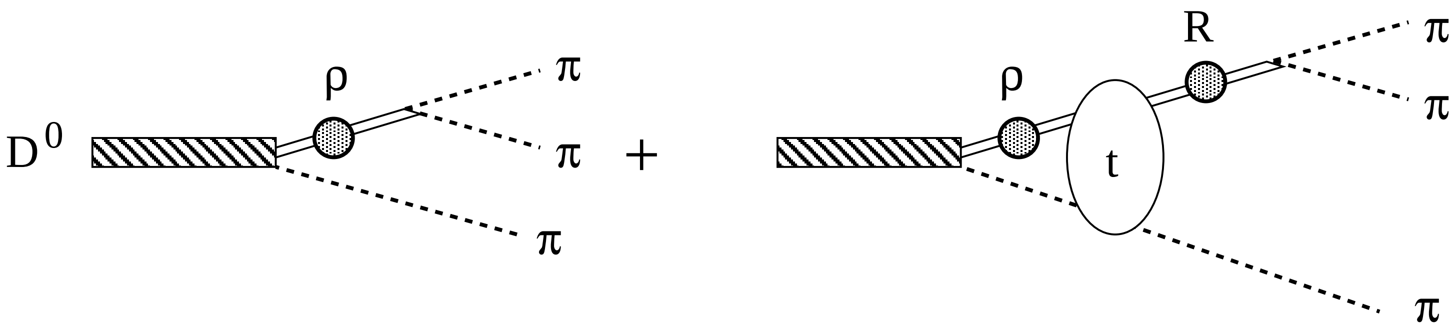
$*$ Z-graph effect on pole position is $\sim$10% for $\pi_2(2100)$ ($\sim$3% for $\pi_2(1670)$)

$*$ $\pi K \bar{K}$ Z-graph has negligible effect

Effect of Z-graphs (unitarity) on Dalitz plot (3 π Z-graph only, no fit, preliminary)

D^0 decay : $D^0\ (I = 1/2, J^P = 0^-) \rightarrow \rho\pi\ (I = 0) \rightarrow \pi^+\pi^-\pi^0$

Decay amplitude



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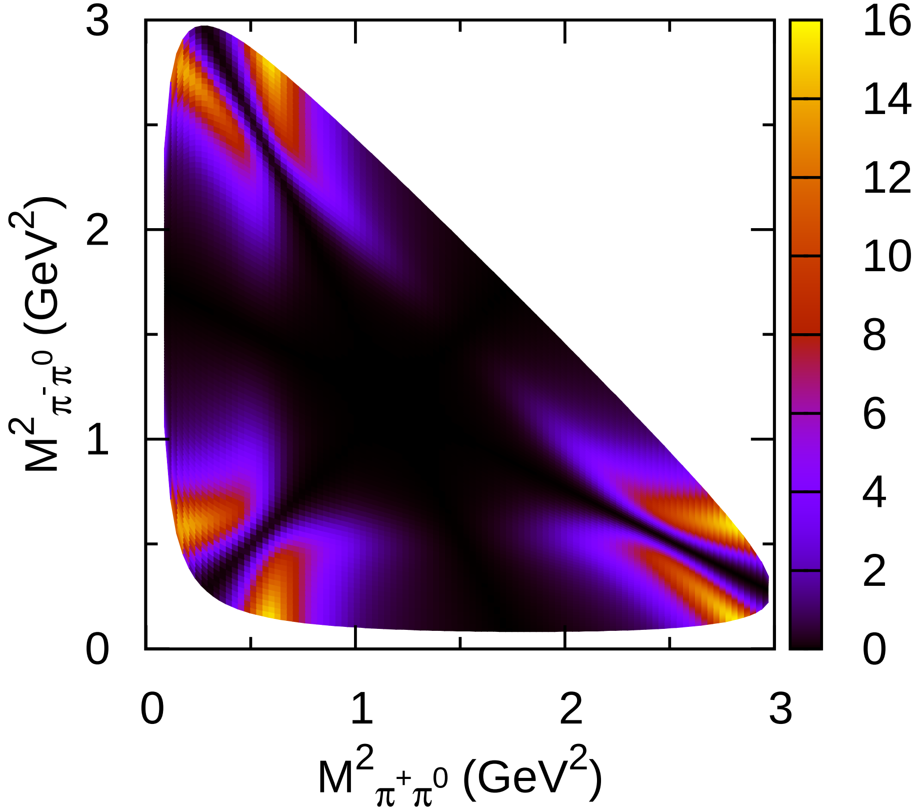

cf. BABAR, arXiv:1001.3317

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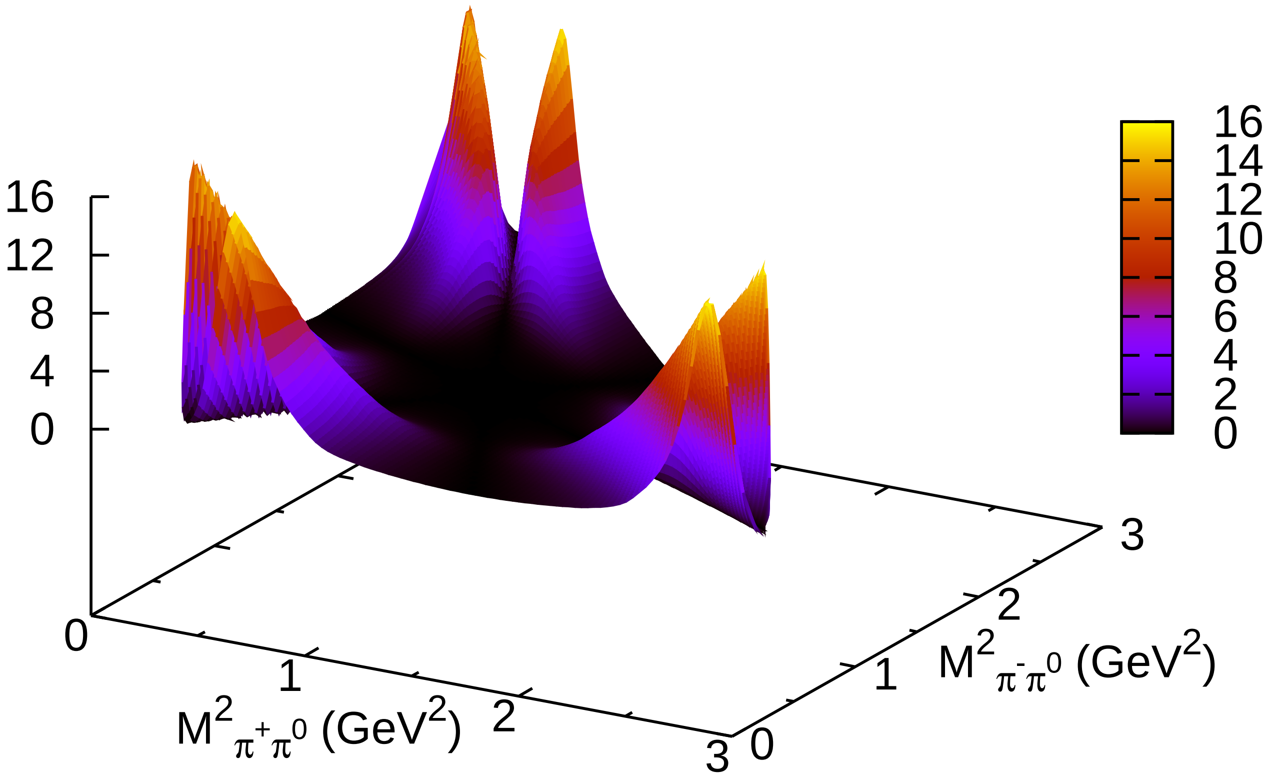
D^0 decay : $D^0\ (I=1/2) \rightarrow \rho\pi\ (I=0) \rightarrow \pi^+\pi^-\pi^0$



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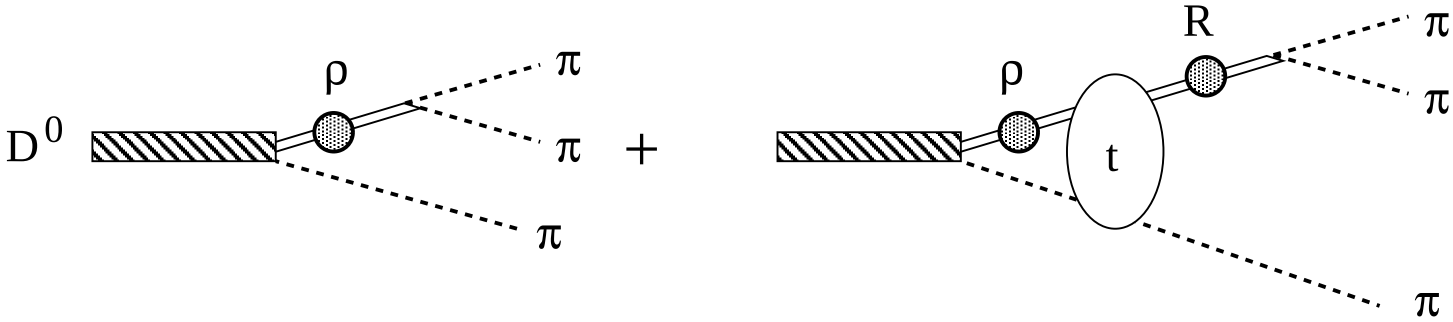
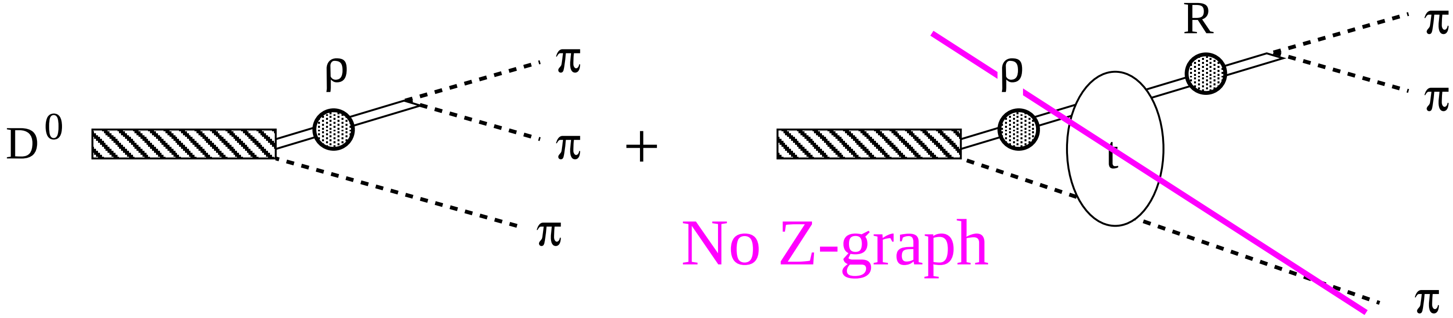
Effect of Z-graphs (unitarity) on Dalitz plot

D^0 decay : $\quad D^0\ (I = 1/2) \longrightarrow \rho\pi\ (I = 0) \longrightarrow \pi^+\pi^-\pi^0$



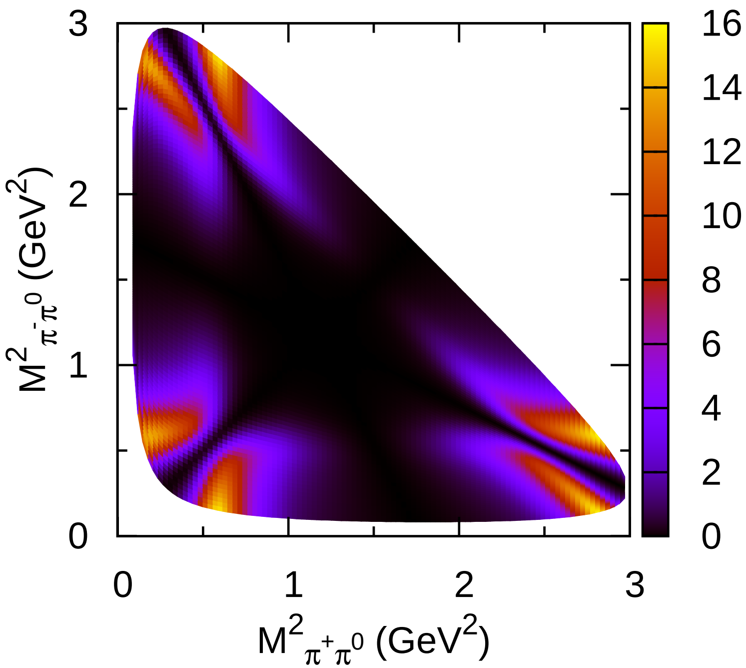
Effect of Z-graphs (unitarity) on Dalitz plot

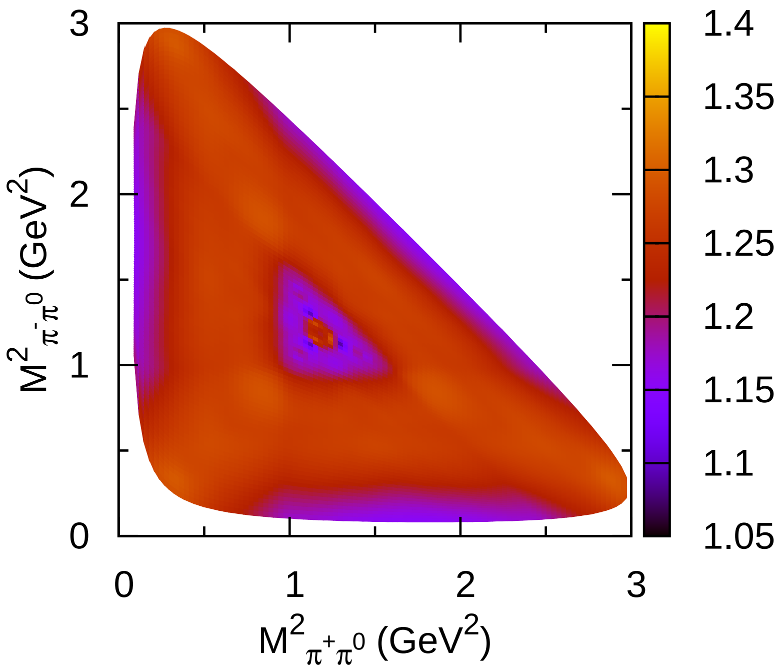
D^0 decay : $D^0\ (I=1/2) \rightarrow \rho\pi\ (I=0) \rightarrow \pi^+\pi^-\pi^0$



Effect of Z-graphs (unitarity) on Dalitz plot

Ratio of Dalitz plots with and w/o Z-graph

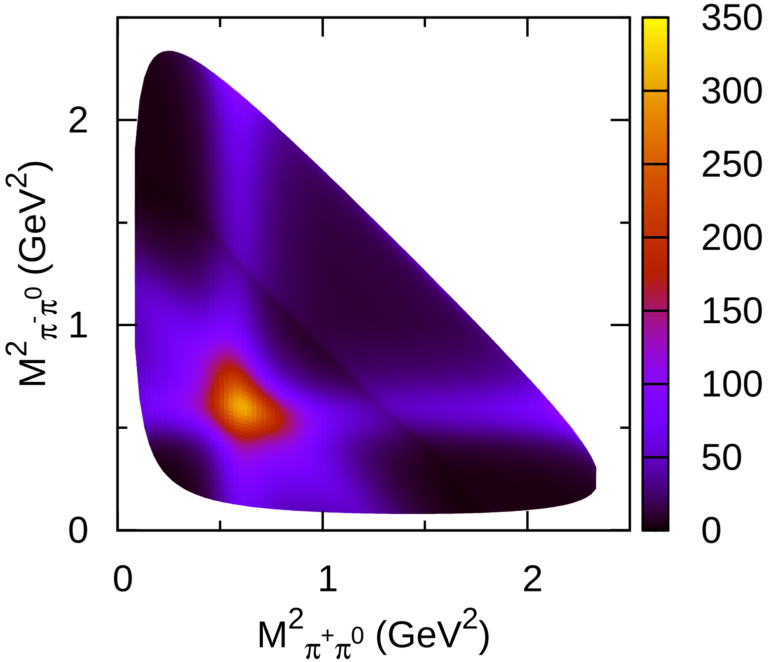


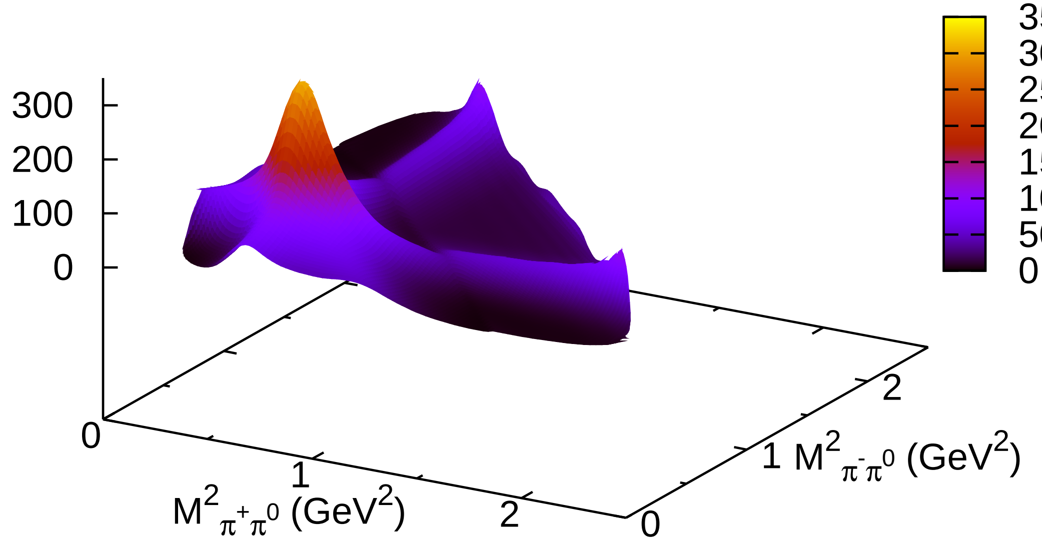


Z-graphs (3π unitarity) significantly change magnitude and shape of Dalitz plot !

More on Effect of Z-graphs (unitarity) on Dalitz plot

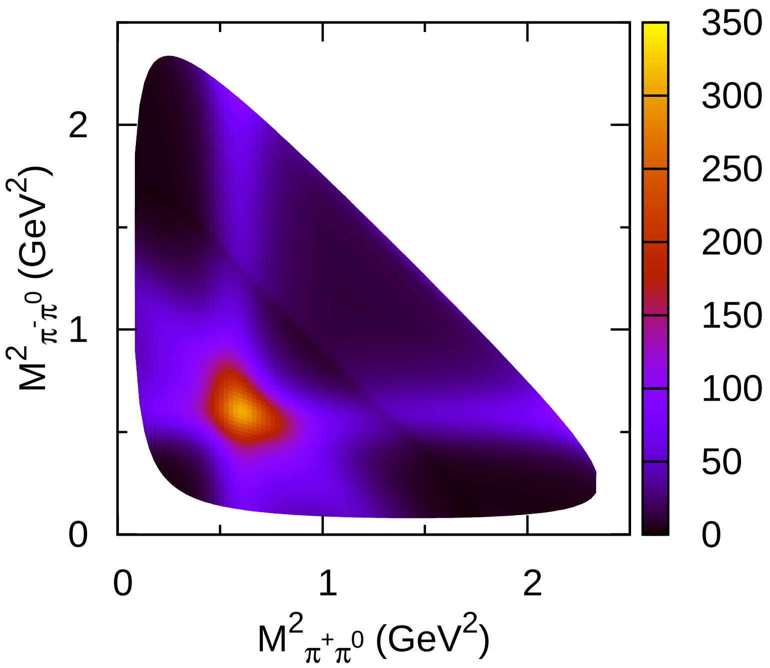
$\pi_2(1670)$ decay : $\pi_2\ (I=1) \longrightarrow R\pi\ (I=1) \longrightarrow \pi^+\pi^-\pi^0$

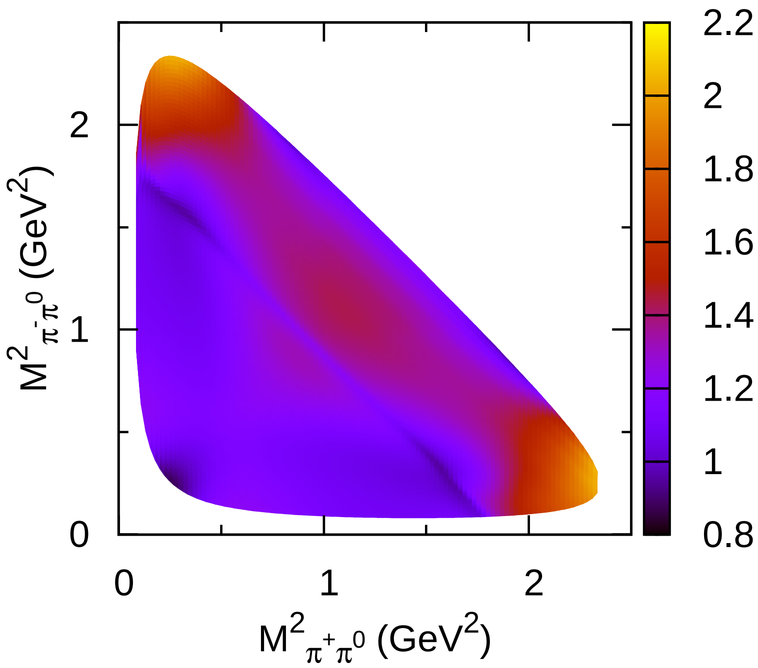




More on Effect of Z-graphs (unitarity) on Dalitz plot

$\pi_2(1670)$ decay : Ratio of Dalitz plot with and w/o Z-graphs



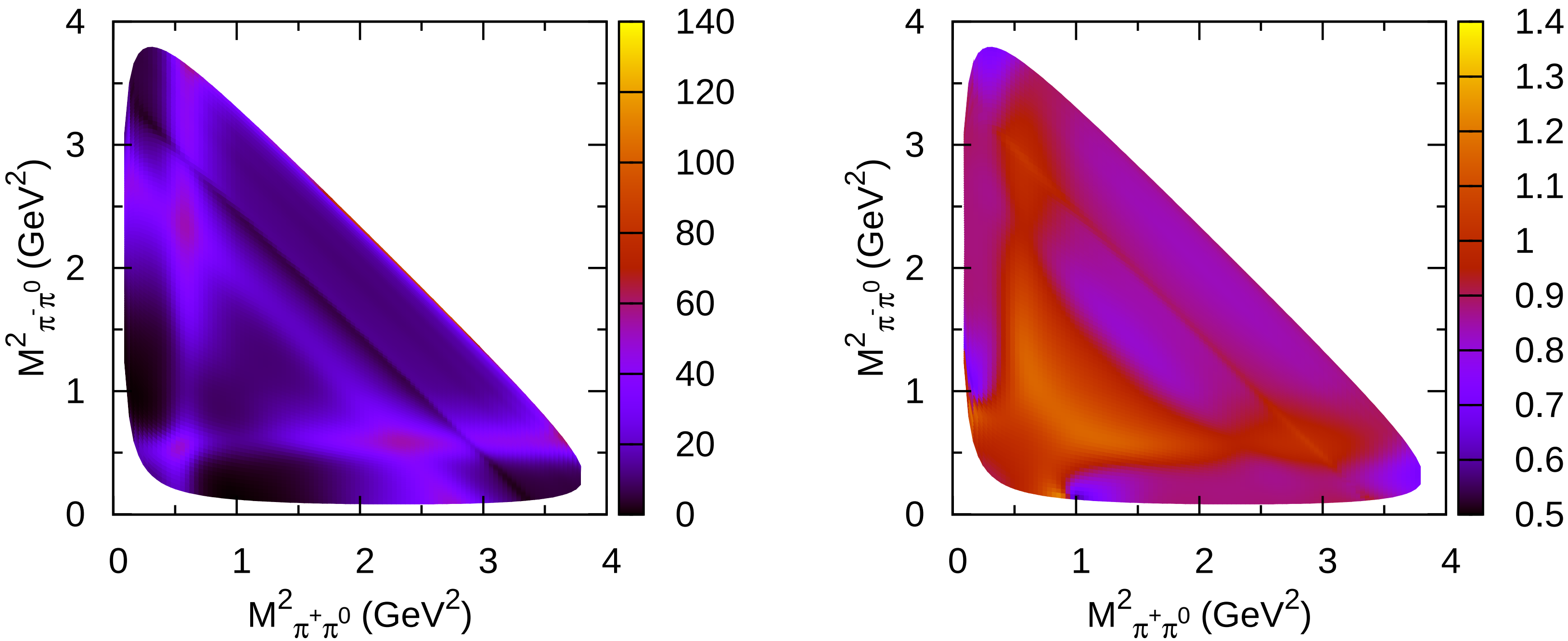


$*$ $\pi_2(1670)$ pole position is rather insensitive to Z-graphs (2-3%)

$*$ Effect of Z-graphs is more visible in Dalitz plot

More on Effect of Z-graphs (unitarity) on Dalitz plot

$\pi_2(2100)$ decay : Ratio of Dalitz plot with and w/o Z-graphs



$*$ $\pi_2(2100)$ pole position is somewhat sensitive to Z-graphs ($\sim$ 10%)

$*$ Effect of Z-graphs is even more visible in Dalitz plot

Summary

3π $(\pi\pi K)$ from heavy meson decay contains information of interesting physics !

exotic (hybrid) meson, light scalar mesons, CP violation

EBAC ($\longrightarrow$ EHAC?) steps toward developing reliable 3π model !

Coupled-channels quasi two-body ($\pi R, KR$) scattering model

- $\pi\pi$ and πK models
- 3π Z-graph, $\pi K\bar{K}$ Z-graph (essential for 3-body unitarity)
- Bare resonance (M^*) mechanism

Effect of 3π unitarity (Z-graphs) on resonance pole

* Simple $\pi\pi$ and πK models
* π_2 (1670), π_2 (2100) ; poles and branching ratios are fitted
* $\sim$ 10% (2–3%) shift of the pole due to Z-graph for π_2 (2100) (π_2 (1670))

Effect of 3π unitarity (Z-graphs) on Dalitz plot (preliminary)

* Generally, Z-graphs change both magnitude and shape of Dalitz plot
* D^0 decay Dalitz plot is considerably changed (30-40%)
* Z-graphs effect is more visible in π_2 decay Dalitz plot than pole position