MESON 2014
29 May - 3 June 2014, Kraków, Poland

Single pion production in proton-proton collisions at 1.25 GeV measured with HADES and the Bonn-Gatchina PWA description

Witold Przygoda, Jagiellonian University
for the HADES Collaboration

30 May 2014, Parallel Session A1, 15:40

p+p @ 1.25 GeV - plan

$p + p$ elementary reactions at E_{kin} = 1.25 GeV below ppη production threshold are well suited to investigate Δ(1232) Dalitz decay

I. NORMALIZATION (pp elastic)

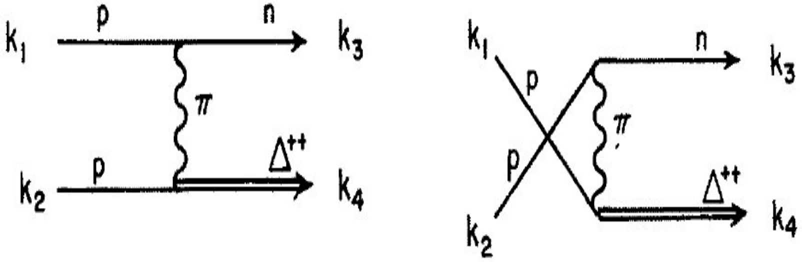
II. HADRON ANALYSIS ($np\pi^+$, $pp\pi^0$)

III. PWA 1-pion analysis

Resonance model

Z. Teis *et al.*,
Z. Phys. A**356** (1997) 421

V. Dmitriev *et al.*
Nucl. Phys. A**459** (1986) 503



Production: OPEM

Form factor at vertices:

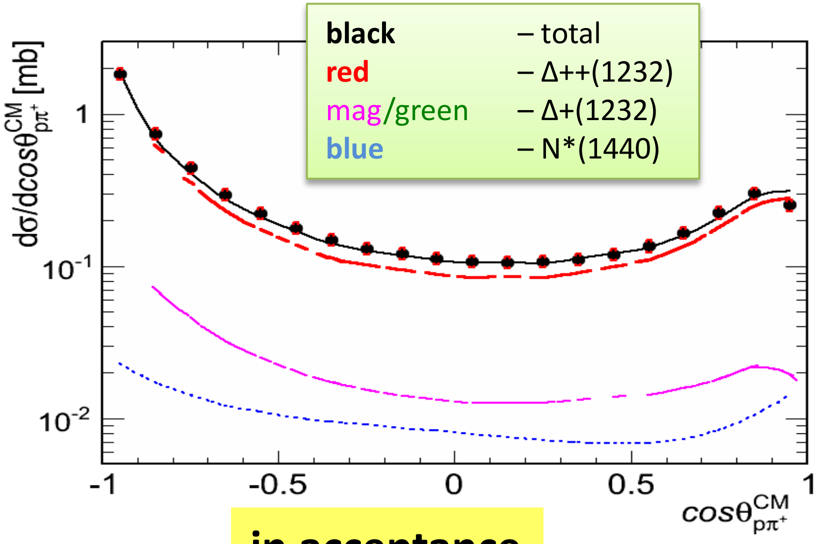
$$F(q^2) = \frac{{\Lambda_\pi}^2 - {m_\pi}^2}{{\Lambda_\pi}^2 - q^2}$$

Λ_π fitted in accordance with the data (Λ_π = 0.75)

G. Agakishiev *et al.*
Eur. Phys. J. A**48** (2012) 74

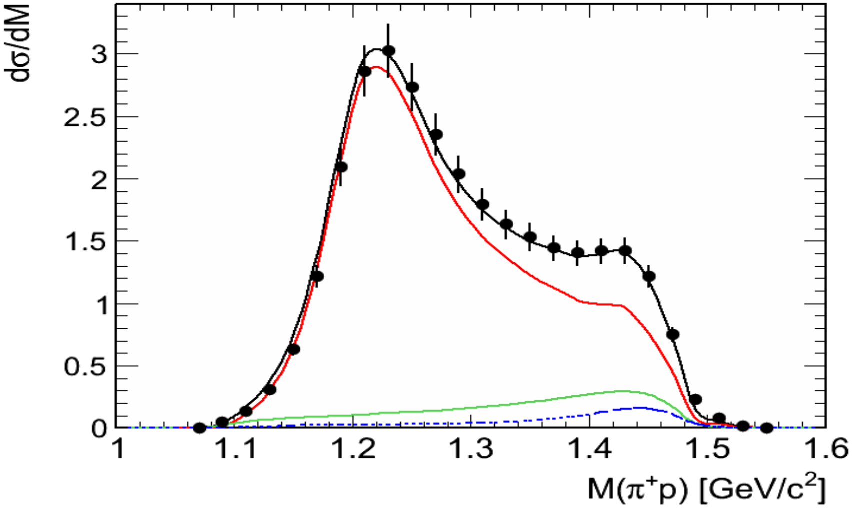
Δ production (n **p π⁺**)

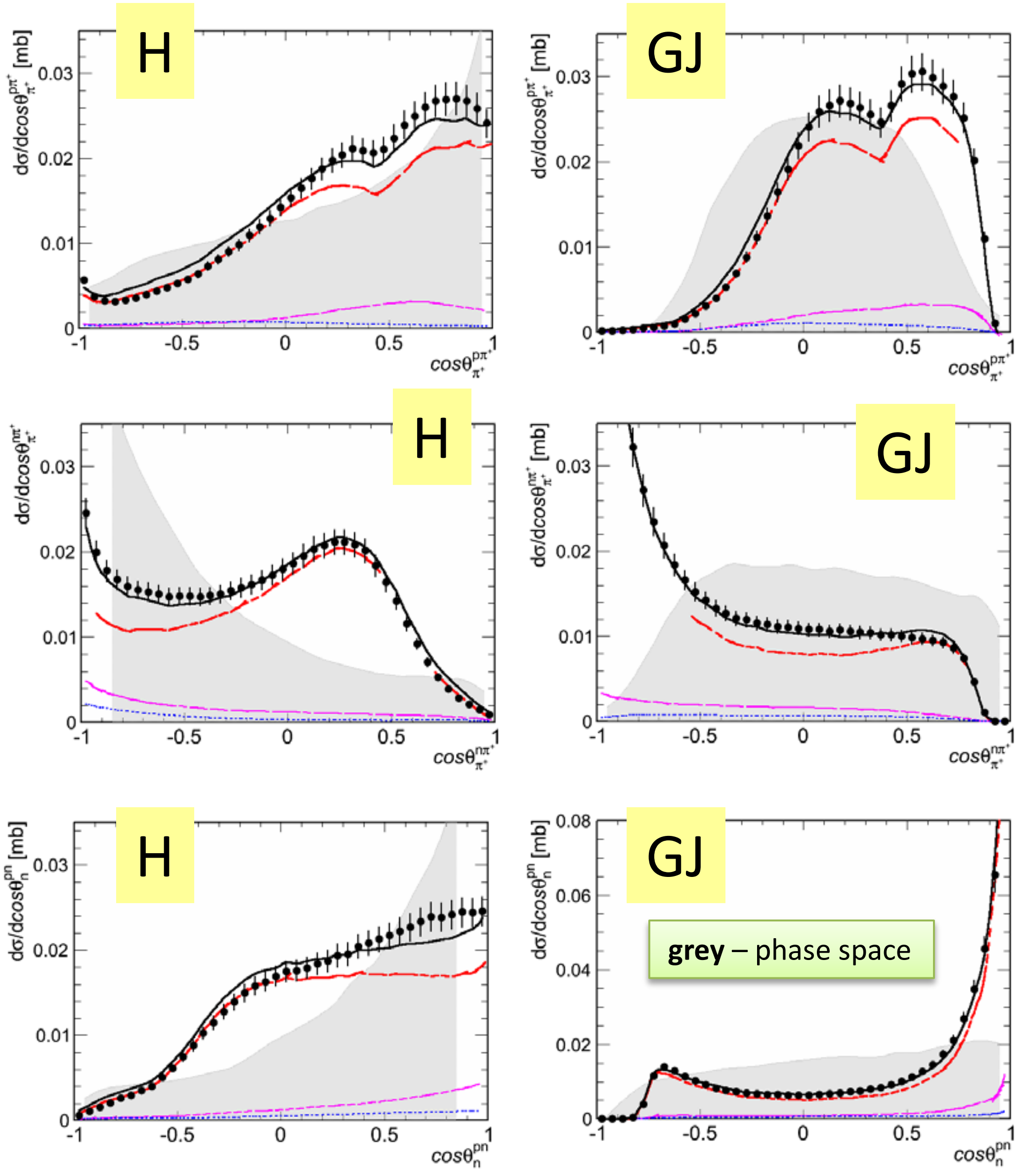
OPEM (Λ_π = 0.75 modified)
Δ resonance + FSI + N(1440) small



black – total
red – Δ++(1232)
mag/green – Δ+(1232)
blue – N*(1440)

in acceptance

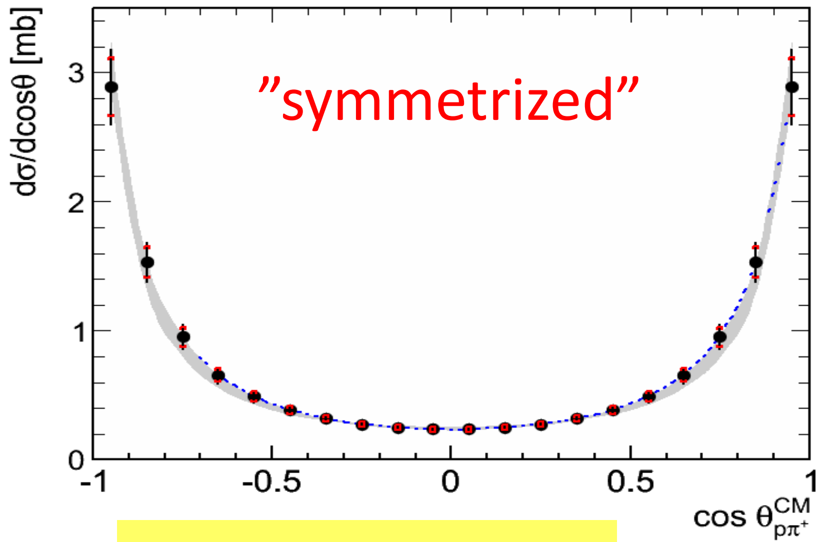




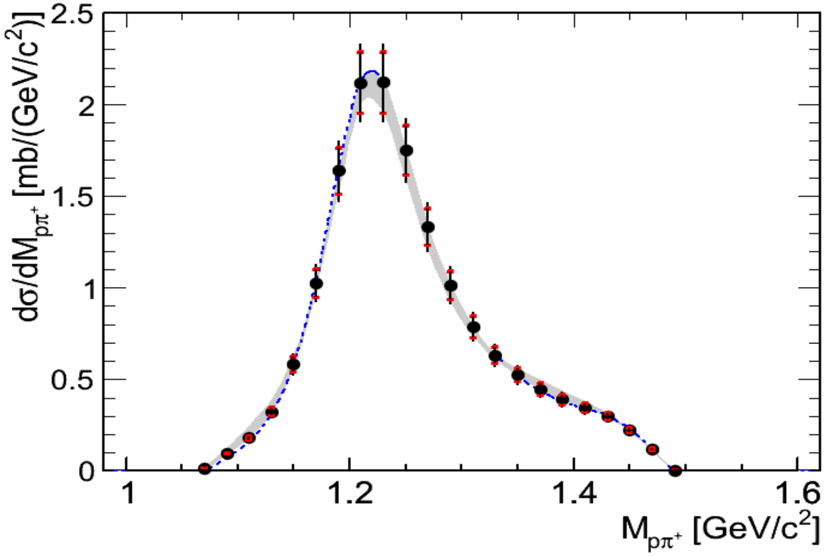
grey – phase space

Witold Przygoda (MESON 2014)

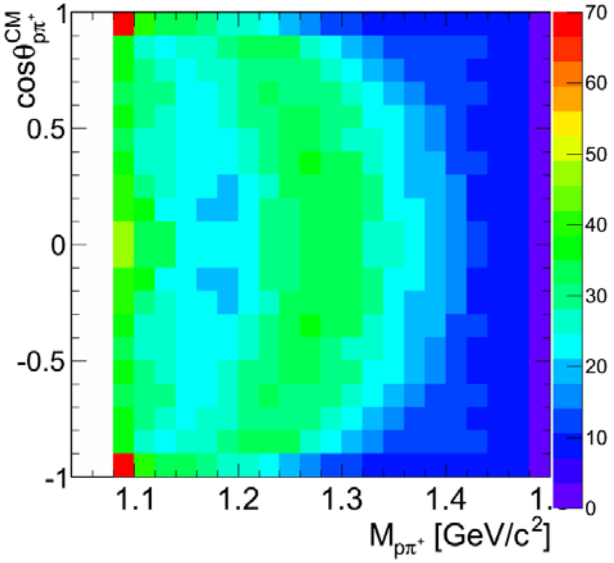
Δ production (n **p π⁺**) - acceptance corrected



ACCEPTANCE corrected



2-dim correction matrix:



blue curve: modified OPEM (total cross section 19.2 mb)

cross section:

16.5 ± 2.0 mb

Δ production (**p p** π^0)

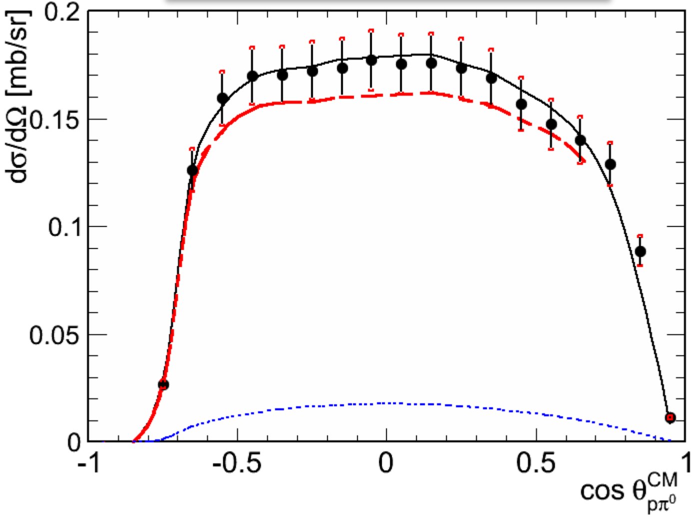
in acceptance

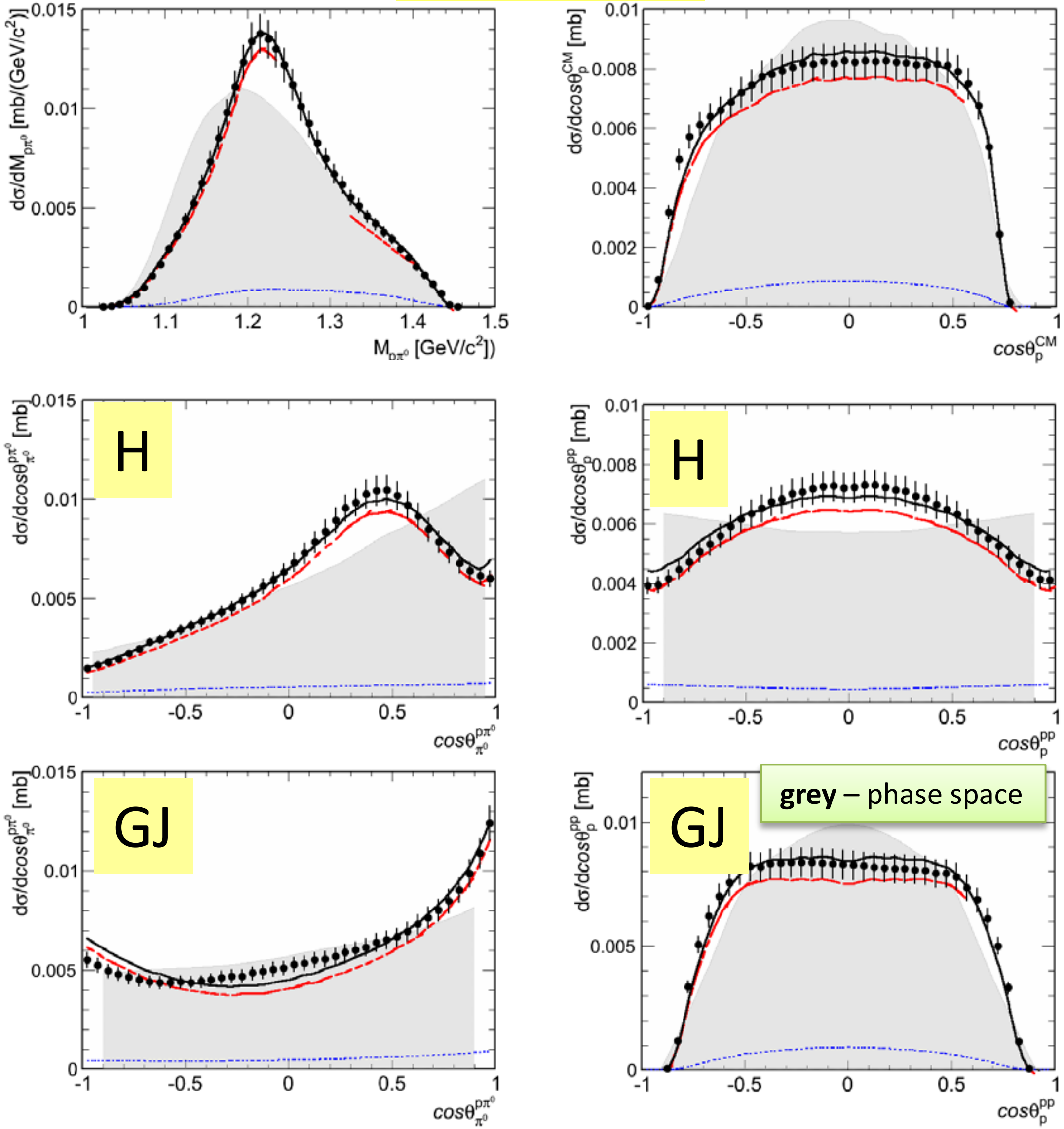
Identifying **2 protons**

- strongly reduces acceptance
- favors large 4-mom transfer

parameterization deduced from the $np\pi^+$ channel

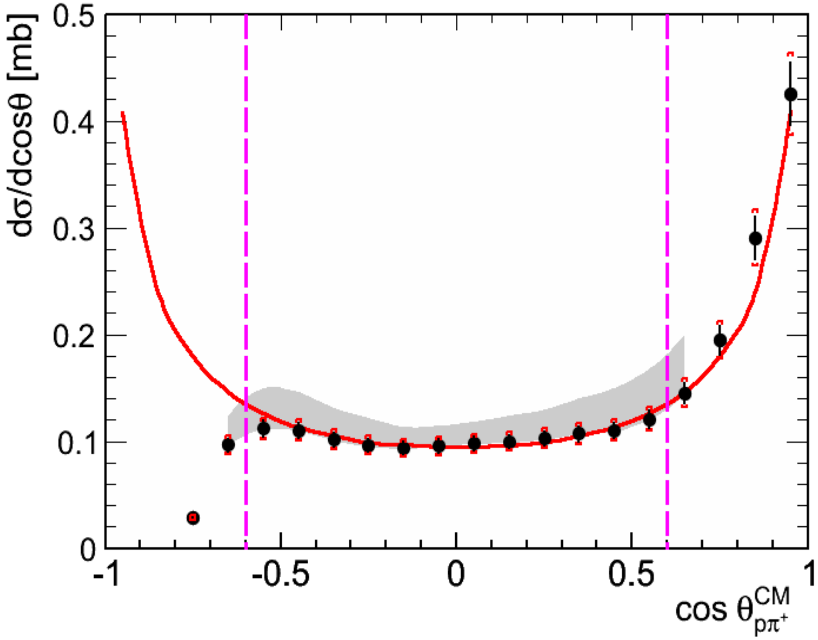
black – total
red – $P_{33}(1232)$
blue – $P_{11}(1440)$



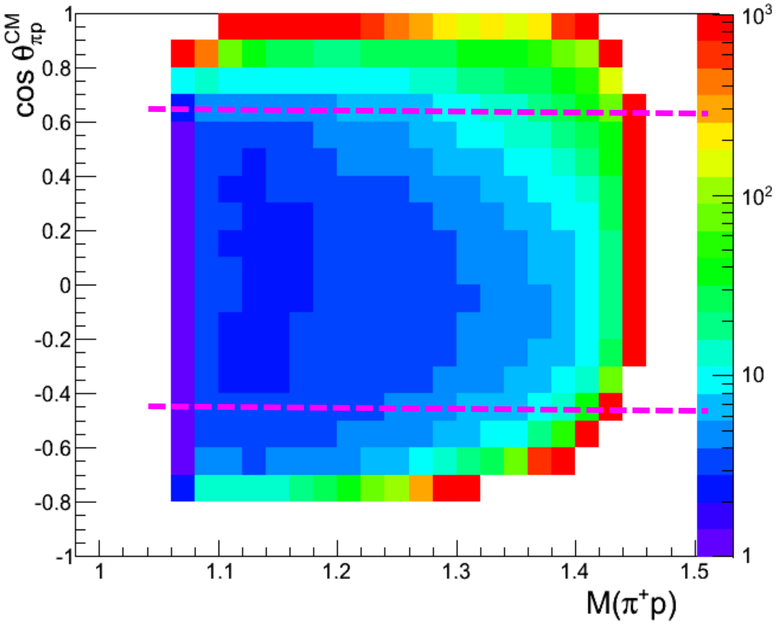


grey – phase space

Δ production (**p p** π^0) - acceptance corrected



Acceptance correction:



ACCEPTANCE corrected

"fiducial volume" in angular distribution
$-0.6 < \cos\theta < +0.6$
sufficient for the dilepton analysis

Witold Przygoda (MESON 2014)

cross section: **3.4 mb ± 0.8 mb**

Partial Wave Analysis

proton+proton (isospin I = 1)

$^{2S+1}L_J$

S – spin
L – orbital momentum
J – total spin

INITIAL PP STATES

$(-1)^{S+L+I} = -1$

for S=0: L even… L=0 (J=0) or L=2 (J=2)…
for S=1: L odd… L=1(J=0,1,2) or L=3 (J=2,3,4)…

FINAL STATES

S-, P-, D-waves in pp or pn-state
$P_{33}(1232)$ and $P_{11}(1440)$ in πN state

FORMALISM:

A. V. Anisovich *et al.*
Eur. Phys. J. A**34** (2007) 129

J	I = 1
0	$^1S_0$,$^3P_0$
1	$^3P_1$
2	$^1D_2$, $^3P_2$,$^3F_2$
3	$^3F_3$
4	$^3F_4$, $^1G_4$, $^3H_4$

Bonn-Gatchina PWA:
Andrey V. Sarantsev

cross section and amplitudes

Maximum likelihood method: event-by-event

$$d\sigma = \frac{(2\pi)^4|A|^2}{4|\vec{k}|\sqrt{s}}\, d\Phi_3(P, q_1, q_2, q_3)\ ,$$

$$A = \sum_{\alpha} A^{\alpha}_{tr}(s) Q^{in}_{\mu_1\ldots\mu_J}(SLJ) A_{2b}(i, S_2L_2J_2)(s_i) Q^{fin}_{\mu_1\ldots\mu_J}(i, S_2L_2J_2S'L'J)\ .$$

Angular-spin momentum operators $Q_{\mu_1\ldots\mu_J}(SLJ)$ are given in

A. V. Anisovich et. al Eur.Phys.J. A34 (2007) 129.

$$A^{\alpha}_{tr}(s) = \frac{a^{\alpha}_1 + a^{\alpha}_3\sqrt{s}}{s - a^{\alpha}_4}\, e^{i a^{\alpha}_2}$$

transition pw amplitudes between initial and final states

S L J – initial NN system

S_2 L_2 J_2 – system of two final particles

S’ L’ J’ = J – two-final particle system and spectator

final state amplitudes

Energy dependence (πN system) resonances $\Delta(1232)\frac{3}{2}^{+}$ and $N(1440)\frac{1}{2}^{+}$

$$A_{2body}^{S_2,L_2,J_2}(s_{12}) = \frac{k_{12}^{L_2}}{\sqrt{F(k_{12}^2, L_2, r_{12})}} \frac{1}{M_R^2 - s_{12} - M_R \Gamma}$$

$$\Gamma = \Gamma_R \frac{M_R\, k_{12}^{2L_2+1}\; F(k_R^2, L_2, r_{12})}{\sqrt{s_{12}}\, k_R^{2L_2+1}\; F(k_{12}^2, L_2, r_{12})}$$

Roper parameterized using couplings: A. V. Sarantsev *et al.* Phys. Lett. B**659** (2008) 94 for decays into πN, Δπ, N(ππ)$_{\text{S-wave}}$

Final NN interaction

$$A_{2body}^{S_2,L_2,J_2}(s_{23}) = \frac{\sqrt{s_{23}}}{1 - \frac{1}{2} r_{23}^{\beta} k_{23}^2 a^{\beta} + i k_{23} a^{\beta} \frac{k_{23}^{2L_2}}{F(k_{23}, r_{23}^{\beta}, L_2)}}$$

NN effective range

NN scattering length (fixed for S-waves)

Input for PWA – other data used

Bonn-Gatchina group
http://pwa.hiskp.uni-bonn.de/data.htm

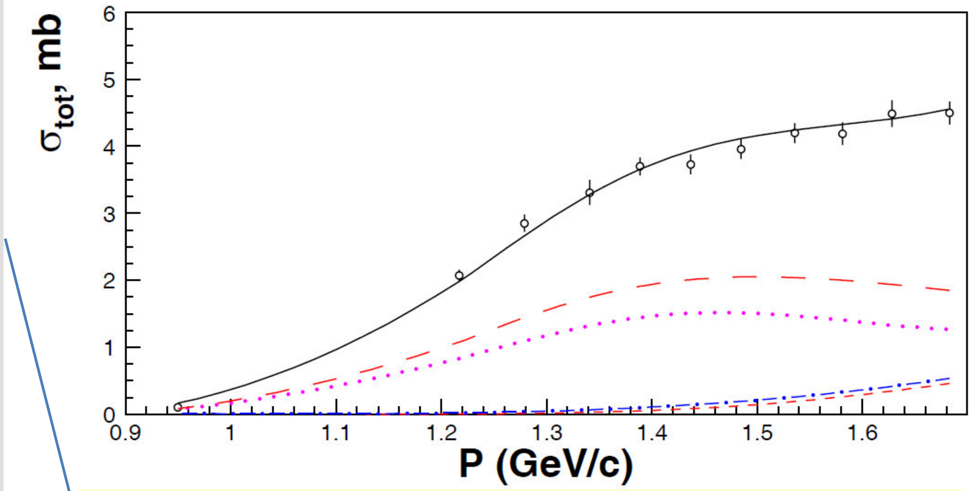
Experimental data samples

$\pi^0 p p$

Proton Momentum	Total cross section	Data (events)
950 MeV/c	100 ± 30 μb	154972
1217 MeV/c	2070 ± 90 μb	542
1279 MeV/c	2850 ± 130 μb	615
1341 MeV/c	3310 ±190 μb	882
1389 MeV/c	3700 ± 140 μb	993
1437 MeV/c	3730 ± 150 μb	914
1485 MeV/c	3960 ± 150 μb	996
1536 MeV/c	4200 ± 150 μb	1315
1581 MeV/c	4190 ± 170 μb	903
1628 MeV/c	4480 ± 200 μb	688
1683 MeV/c	4500 ± 170 μb	1086

$\pi^+ p n$

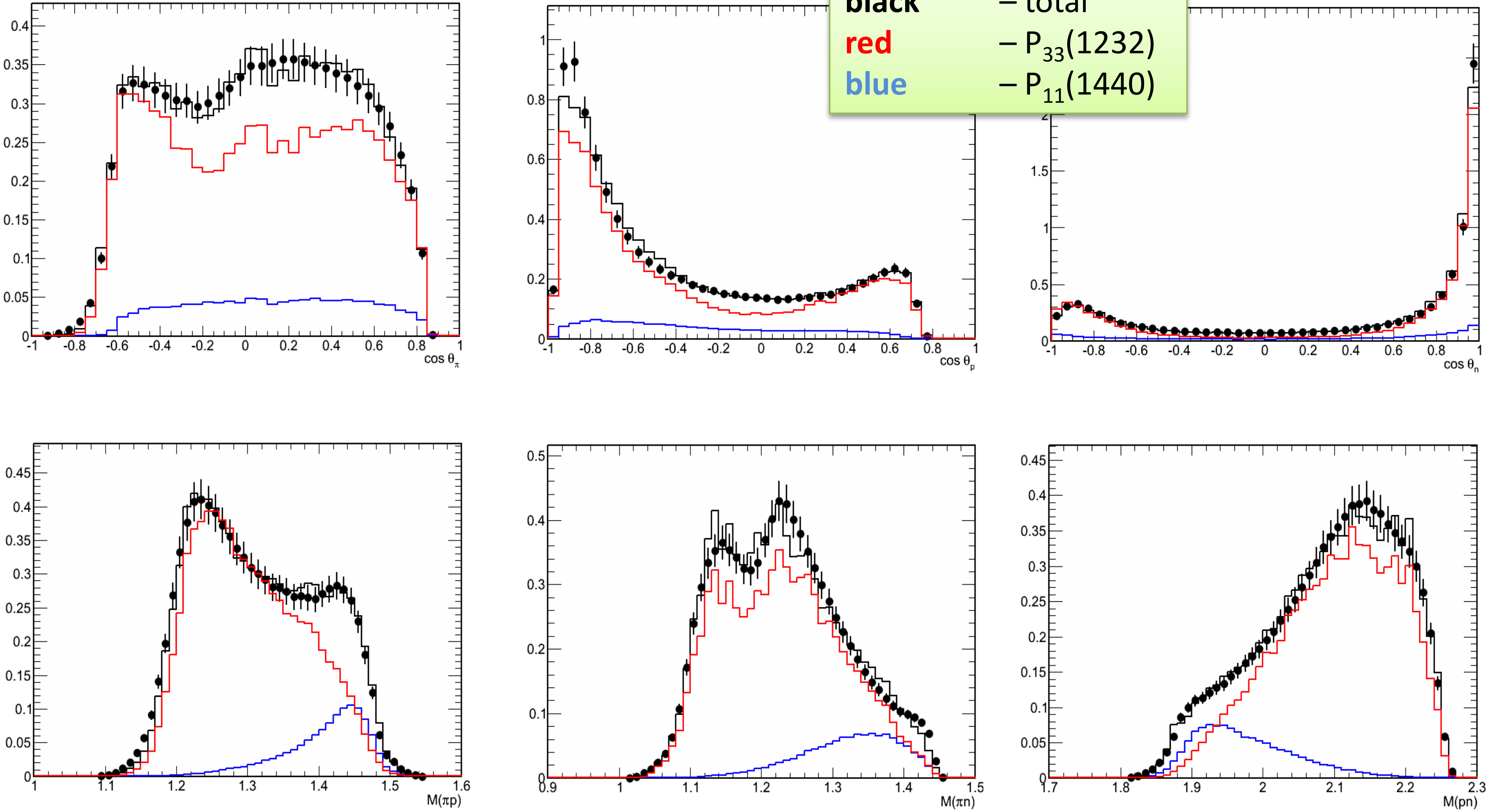
Proton Momentum	Total cross section	Data (events)
1581 MeV/c	1780 ± 40 μb	4276
1628 MeV/c	1760 ± 60 μb	2912



PW contributions (smooth energy dependence)

Minimization of log-likelihood value by a simultaneous fit of many data!

PWA (n **p π^+**) – in acceptance

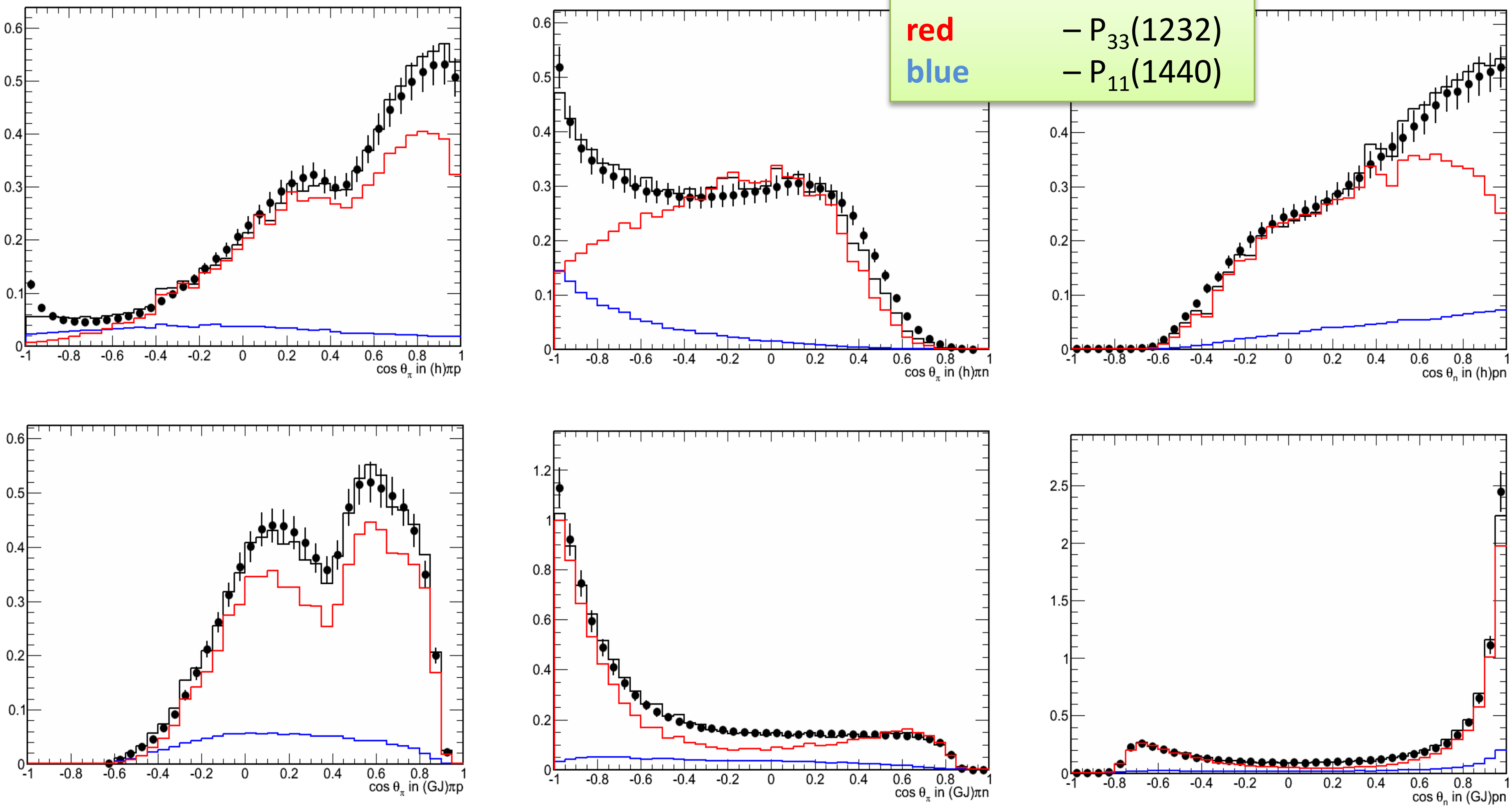


black – total

red – $P_{33}(1232)$

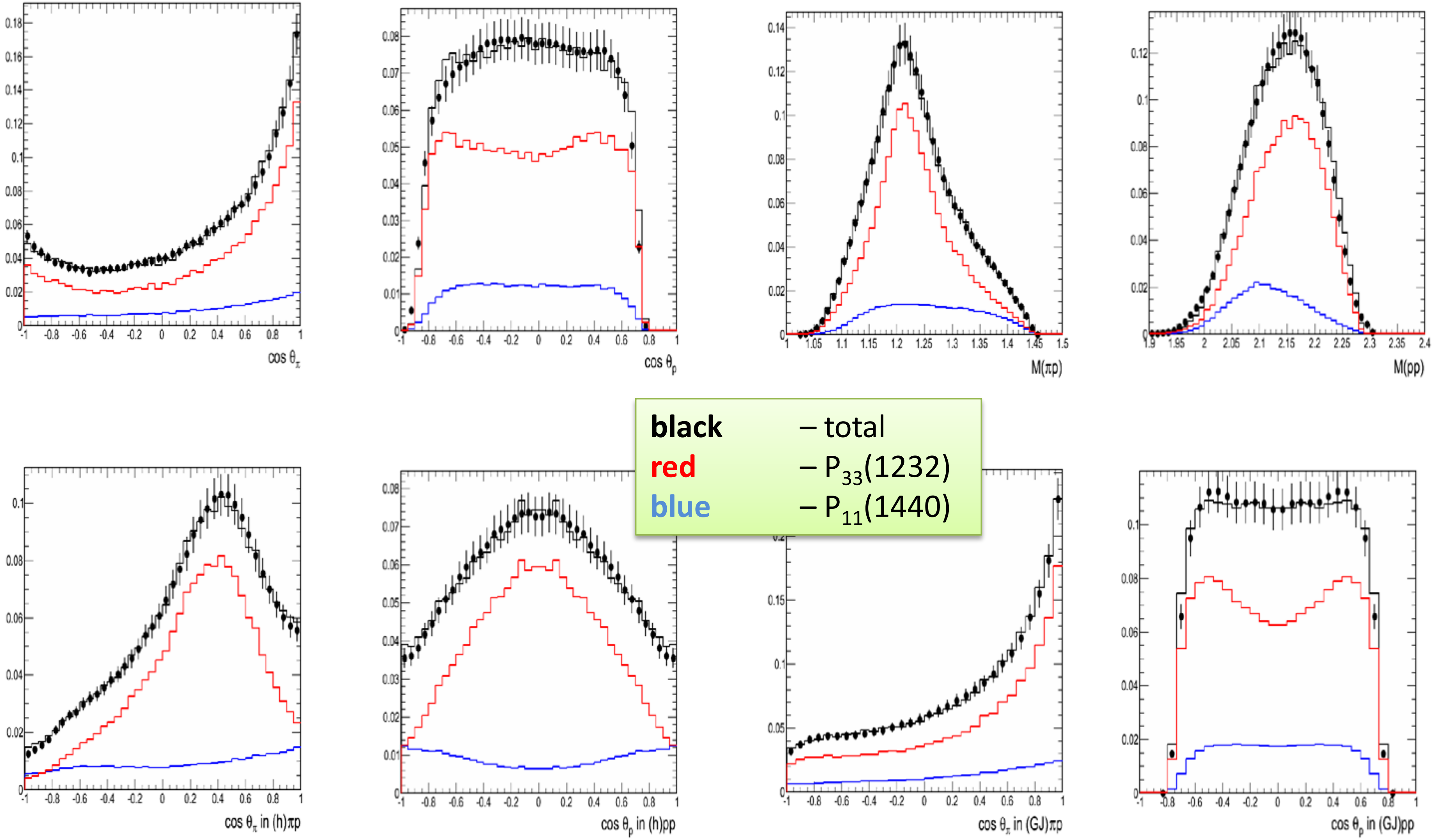
blue – $P_{11}(1440)$

PWA (n **p π$^+$**) – in acceptance



black – total
red – $P_{33}(1232)$
blue – $P_{11}(1440)$

PWA (**p p** π^0) – in acceptance



black	– total
red	– $P_{33}(1232)$
blue	– $P_{11}(1440)$

PWA solutions (n p π^+)

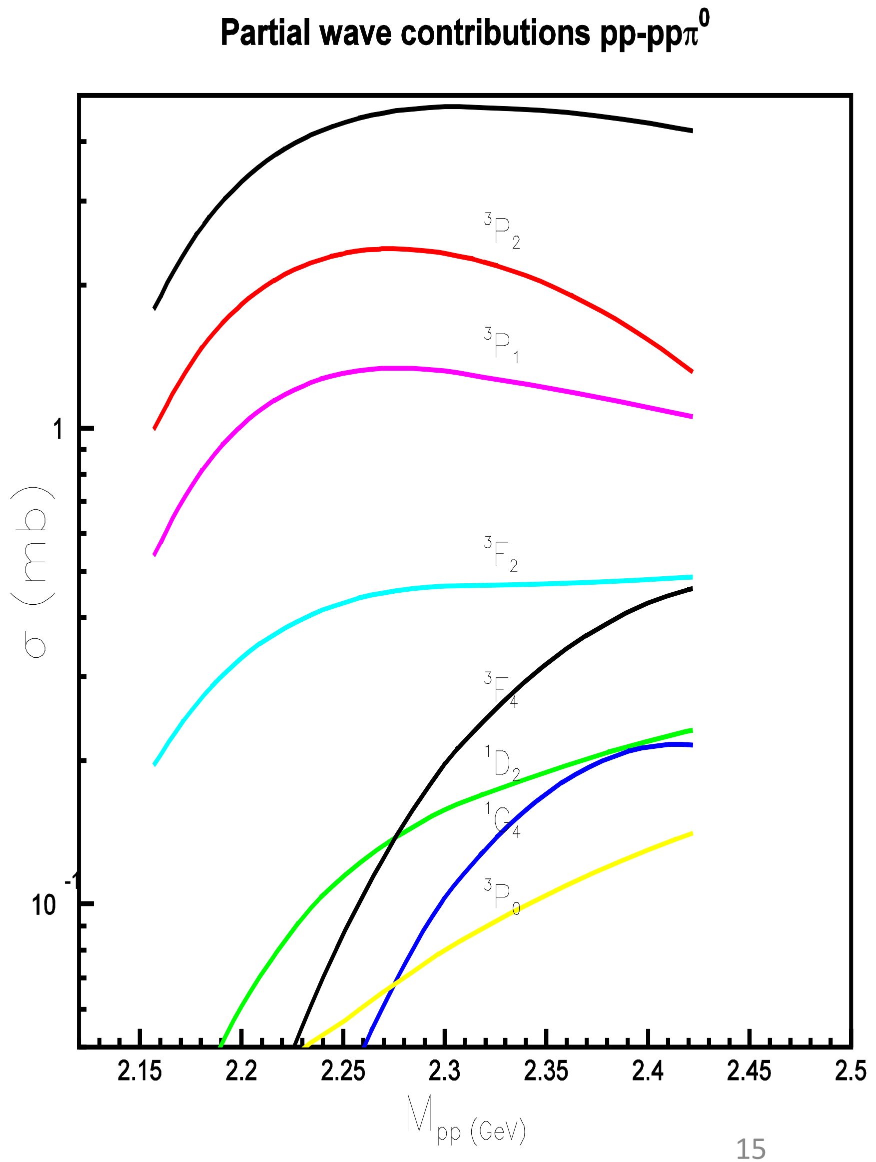
input partial waves	n p π^+ [%]			resonances [%]	
beam momentum **experiment**	1581 MeV/c **PNPI**	1628 MeV/c **PNPI**	1977 MeV/c **HADES**	Δ(1232)	N*(1440)
$^1S_0$	5.1	5.6	2.9	-	1.6
$^3P_0$	8	8.5	1.4	1.4	0.9
$^3P_1$	35	33	**22**	**9.0**	**10.3**
$^3P_2$	**38**	**38**	**36.5**	**34**	1
$^1D_2$	7.5	7.5	10.1	7.4	-
$^3F_2$	4.2	5.5	9.2	7.4	-
$^3F_3$	-	-	0.6	0.6	-
$^3F_4$	-	-	**10.7**	**10.7**	-
$^1G_4$	-	-	5.6	5.6	-
$^3H_4$	-	-	3.7	0.9	-

K.N. Ermakov *et al.*
Eur. Phys. J. A (2014) TBA

K.N. Ermakov *et al.*
Eur. Phys. J. A**47** (2011) 159

PWA solutions (**p p** π^0)

input partial waves	**p p** π^0 [%]	**resonances** [%]	
beam momentum **experiment**	1977 MeV/c **HADES**	**Δ(1232)**	**N(1440)**
$^1S_0$	1.4	-	1.4
$^3P_0$	4.7	2.6	1.9
$^3P_1$	27.6	9.8	**12.9**
$^3P_2$	67.8	**59.2**	1.5
$^1D_2$	8.9	8.1	-
$^3F_2$	18	**12.2**	-
$^3F_3$	1	1	-
$^3F_4$	20	**20**	-
$^1G_4$	9.1	9.1	-
$^3H_4$	10.7	10.7	-

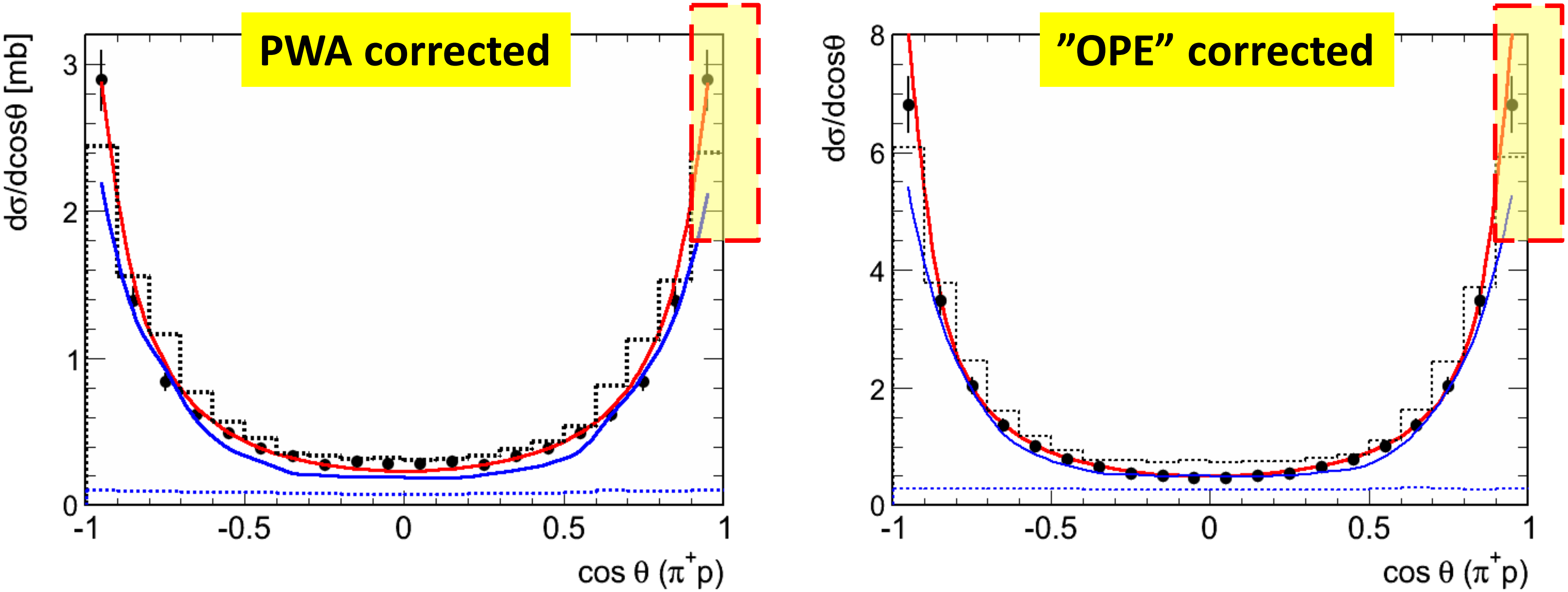


PWA solutions

cross section [mb] ("OPE" corr)	$n\,p\,\pi^+$ (16.5 ± 2 mb)	$p\,p\,\pi^0$ (3.4 ± 0.8 mb)
cross section [mb] (PWA)	**16.4**	**4.2**
P_{33}(1232) in 4π	**79%**	**71%**
P_{33}(1232) in acceptance	**81%**	**68%**
P_{11}(1440) in 4π	**11%**	**18%**
P_{11}(1440) in acceptance	**12%**	**15%**

- $n\,p\,\pi^+$ **dominant** contribution of **Δ resonance**
- $p\,p\,\pi^0$ also **dominant** contribution of **Δ resonance** (but lower and higher Roper contribution)

Comparison (4π) PWA / OPE (n **p π⁺**)



Legend:

(red curve) OPE modified (Λ_π = 0.75)

(blue curve) PWA – resonance P_{33}(1232)

(dashed black) PWA total

(dashed blue) – resonance P_{11}(1440)

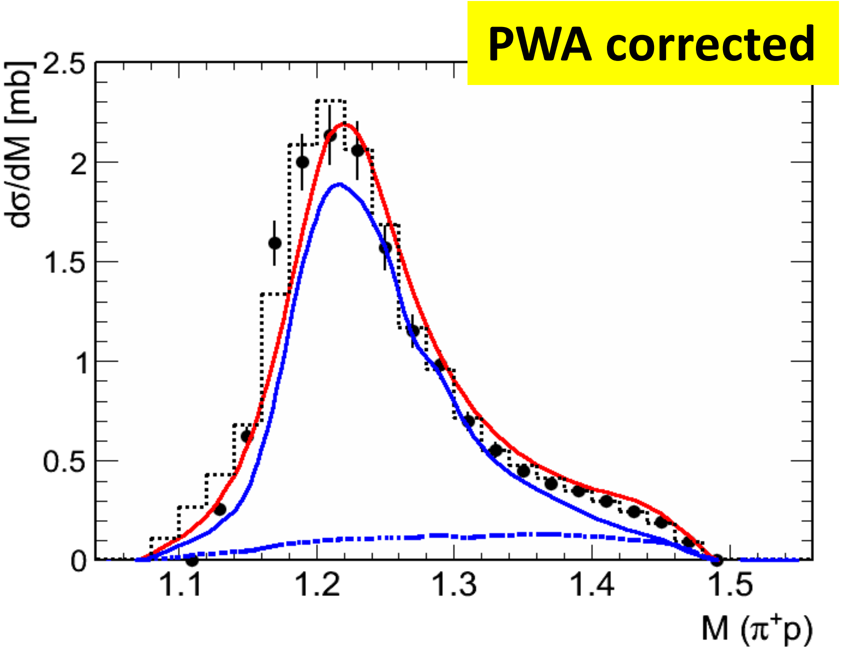
PWA Δ(1232) in 4π

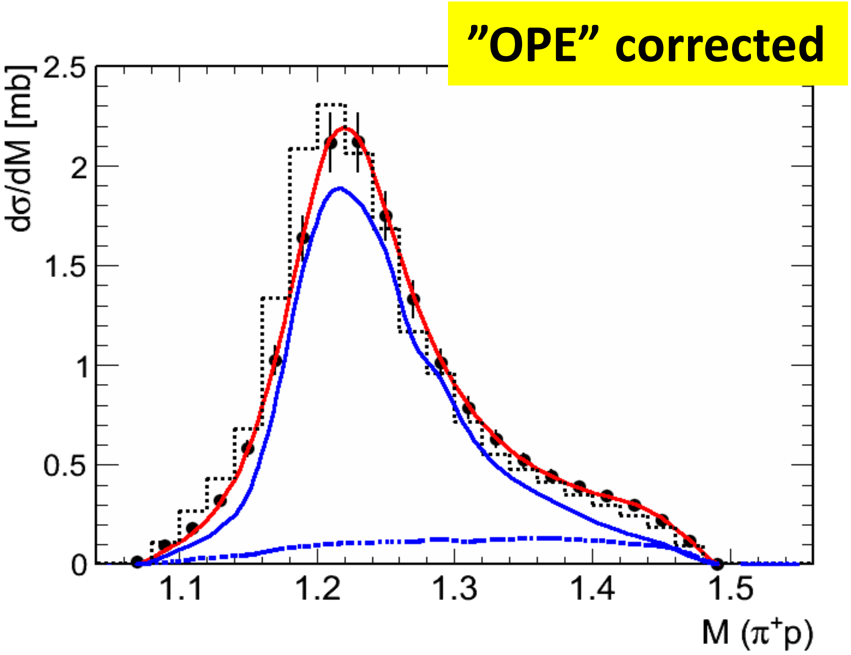
79% of total (blue curve)

PWA absolute normalization

- see the dashed black curve

Comparison (4π) PWA - OPE (n **p π^+**)





Legend:

(red line) OPE modified (Λ_π = 0.75)

(blue line) PWA – resonance P_{33}(1232)

(dashed black) PWA total

(dashed blue) – resonance P_{11}(1440)

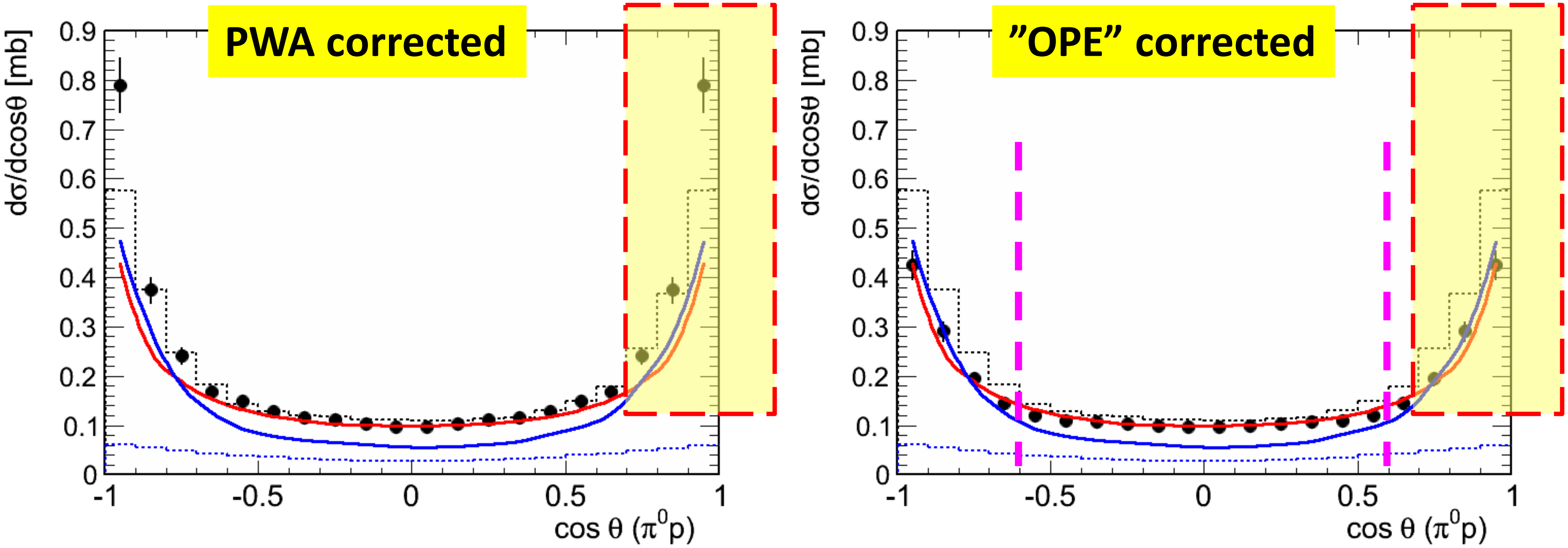
PWA N(1440) in 4π

11% of total (dashed blue)

PWA absolute normalization

- see the dashed black curve

Comparison (4π) PWA - OPE (**p p** π^0)



Legend:

(red curve) OPE modified ($\Lambda_\pi = 0.75$)

(blue curve) PWA – resonance P_{33}(1232)

(dashed black) PWA total

(dashed blue) – resonance P_{11}(1440)

Δ+ 71% of total

N* 18% of total

fiducial volume

$-0.6 < \cos\theta < +0.6$

PWA: 1.74 mb

OPE: 1.57 mb

9% difference

SUMMARY remarks

- **combined analysis of exclusive channels (1π)**
  π^+pn: 3 data samples, π^0pp: 11 data samples
- **smooth partial wave energy dependence**
- **higher energy → higher pw come into play → forward/backward angular distribution enhancement**
- **dominant P_{33}(1232) contribution but increasing P_{11}(1440)**
- **P_{11}(1440) destructive interferences with non resonant P-wave**
- **precise resonance contribution important for dilepton analysis (π^0 Dalitz decay, Δ Dalitz decay)**
- **ambiguities (errors) can be reduced with higher energy data included (pp @ 3.5 GeV)**

G. Agakishiev *et al.*
Eur. Phys. J. A**50** (2014) 82

CREDITS

The HADES Collaboration

Special thanks to **Andrey V. Sarantsev** (for PWA)