Resonance production and decay in proton and pion induced collisions with HADES

The 10th International Workshop on the Physics of Excited Nucleons NSTAR2015
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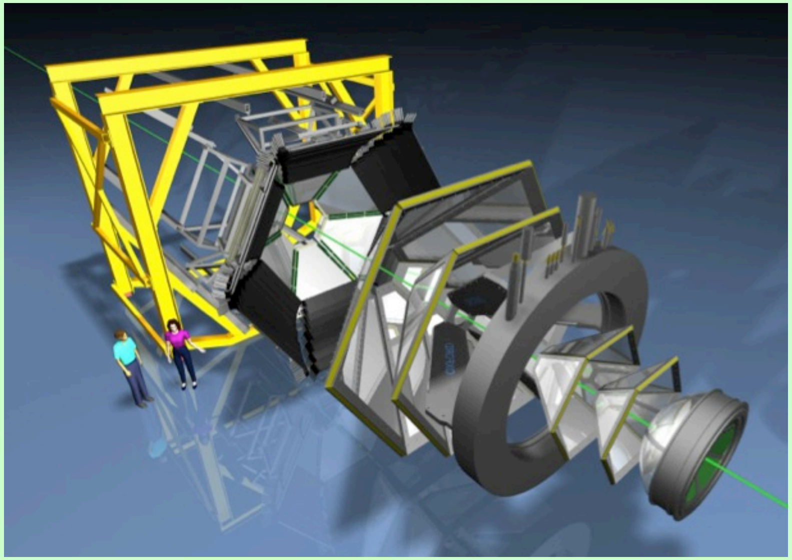
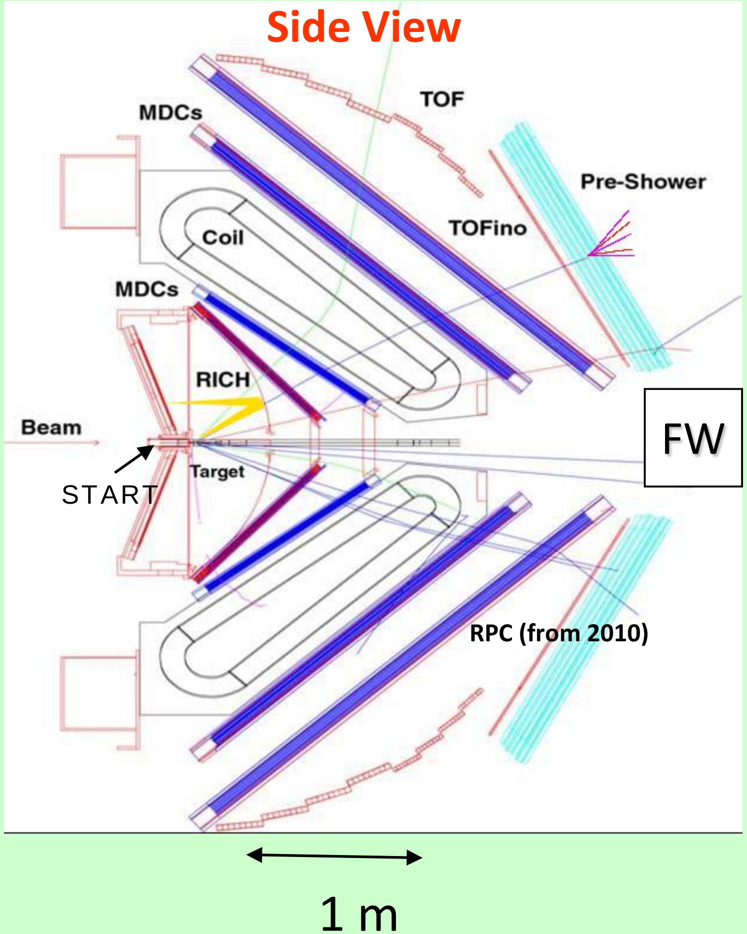
HADES Spectrometer

- SIS18 beams: protons (1-4 GeV), nuclei (1-2 AGeV)
  pions (0.4-2 GeV/c) – secondary beam
- spectrometer with $\Delta M/M$ - 2% at ρ/ω
- **detector for rare probes:**
  dielectrons: e+, e-
  strangeness: Λ, $K^{\pm,0}$, Ξ^-, φ
- particle identification π/p/K – combined dE/dx (MDC)
  and TOF : σ_{tof} ~80 ps (RPC)
  electrons : RICH (hadron blind), TOF/Pre-Shower
- upgrade(2010): new DAQ (~20 kHz) with Au+Au collisions



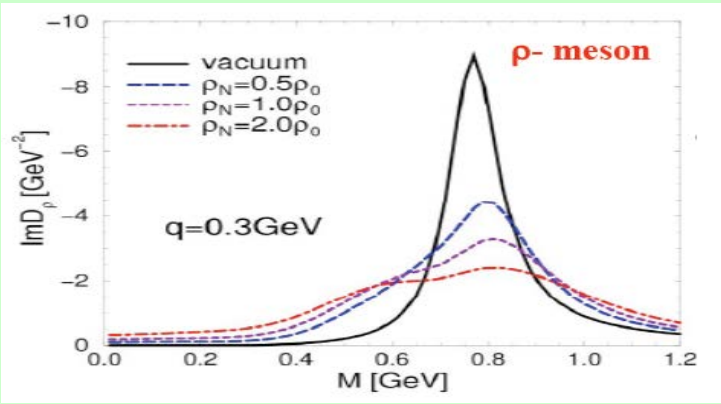


Geometry

- full azimuthal, polar angles 18° - 85°
- e^+e^- pair acceptance $\approx$ 0.35

dileptons: a probe of in-medium vector meson modifications

Present explanation of dilepton spectra



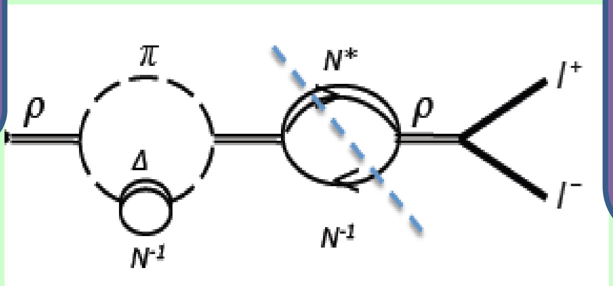
Rapp and Wambach EPJA 6 (1999) 415
Rapp, Chanfray and Wambach NPA 617, (1997) 472

S. Leupold, U. Mosel, V. Metag
Int. J. Mod. Phys. E **19** (2010) 147

« in-medium broadening »

In-medium spectral function depends on ρNN* coupling
Main players:
N(1520), N(1720), Δ (1910)

Source of ρ mesons at 1-2 AGeV
NN →NR →NNρ
πN →R →Nρ

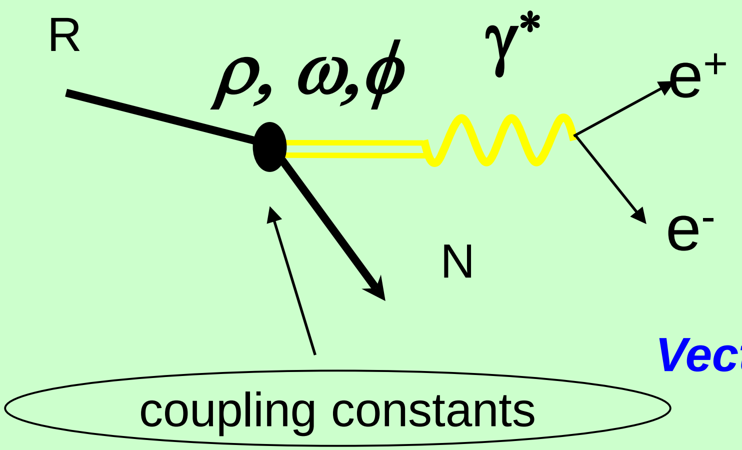


Dominant source of ρ mesons at ultra relativistic energies
$\pi^+\pi^- \rightarrow \rho$

Coupling of ρ to baryonic resonances can be studied in **NN** and **πN** collisions at 1-2 GeV

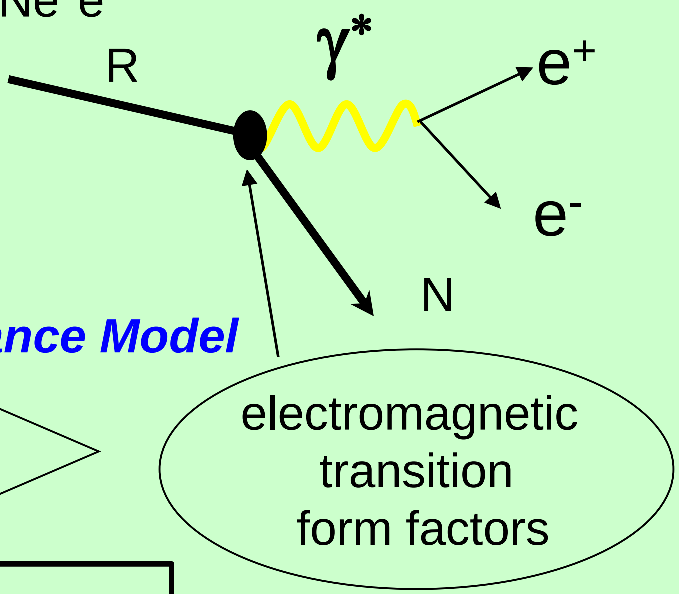
relation to electromagnetic structure of baryons

ρ meson production and decay



Dalitz decay of baryonic resonances

$R \rightarrow Ne^+e^-$



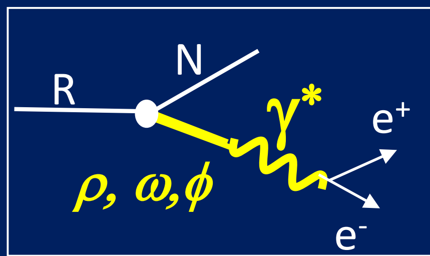
Vector Meson Dominance Model

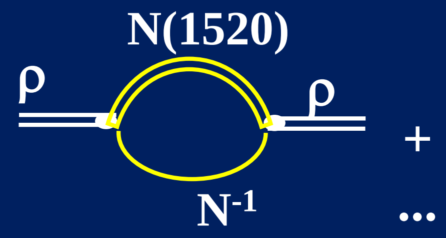
$\mathbf{q^2 = M^2_{inv}(e^+e^-) = M^2_{\gamma^*} > 0}$

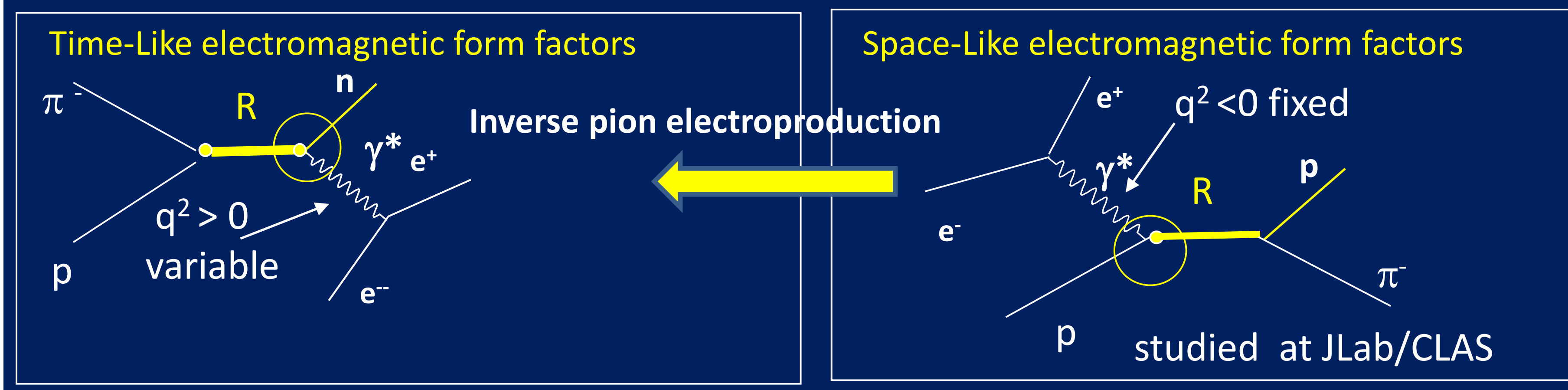
$\mathbf{q^2} \geq 0$: « time like « region

electromagnetic form factors are unknown!

off-shell ρ production ($\pi^- p \rightarrow n e^+ e^-$)







- below ρ/ω production threshold at √s = 1.52 GeV
- studying of time-like electromagnetic structure of N(1520)
- constrain in-medium modifications of the ρ meson spectra function

p (1.25 GeV) + p

both hadron and dilepton exclusive channels measurement

p (3.5 GeV) + p

$\pi^- + p$
(momenta: 0.656, 0.69, 0.748, 0.8 GeV/c)

HADES

p+p @ 1.25 GeV - plan

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

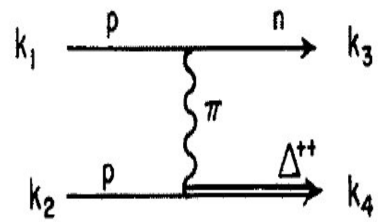
I. HADRON ANALYSIS ($np\pi^+$, $pp\pi^0$)

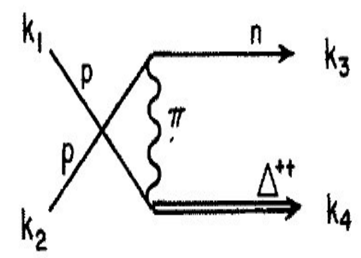
II. LEPTON ANALYSIS (ppe^+e^-, ppe^+e^-)

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

PWA – formalism for NN

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

Three (or more) final states
minimization of log-likelihood value

$$f = -\sum_{j}^{N(data)} ln \frac{\sigma_j(PWA)}{\sum\limits_{m}^{N(rec\,MC)} \sigma_m(PWA)}$$

Two body final states
χ^2 method

$$\chi^2 = \sum_{j}^{n} \frac{(\sigma_j(PWA) - \sigma_j(exp))^2}{(\Delta\sigma_j(exp))^2}$$

Cross section

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

Amplitude parameterization

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

initial NN system

system of two final particles

two-final particle system and spectator

Operators

$Q^{in}_{\mu_1\ldots\mu_J}$ $Q^{fin}_{\mu_1\ldots\mu_J}$

constructed for each event from momenta of the initial and final state particles

PWA – amplitudes parameterisation

Transition amplitude

$$A_{tr}^{\alpha}(s) = \frac{a_1^{\alpha} + a_3^{\alpha}\sqrt{s}}{s - a_4^{\alpha}} e^{ia_2^{\alpha}}$$

(Roper)

A. V. Sarantsev *et al.*
Phys. Lett. B**659** (2008) 94

Resonance production amplitude

$$A_{2b}(j,\beta)(s_{\pi N}) = \frac{g_{\pi N}^{R}}{M_R^2 - s_{\pi N} - iM_R\Gamma_R}$$

$$M_R\Gamma_{\pi N} = (g_{\pi N}^{R})^2 \frac{2k_{\pi N}}{\sqrt{s}_{\pi N}} \frac{1}{16\pi} \frac{k_{\pi N}^{2L}}{F(k_{\pi N}^2, L_{\pi N}, r)}$$

Non-resonant production amplitude

$$A_{2b}(j,\beta)(s_{NN}) = \frac{r^{\beta} a_{\beta}\sqrt{s_{NN}}}{1 - \frac{1}{2}r^{\beta}k_{NN}^2 a_{\beta} + \frac{ia_{\beta}k_{NN}^{2L_{\beta}+1}}{F(k_{NN}^2, r^{\beta}, L_{NN})}}$$

$$a(^1S_0) = -23.7 \text{ fm}, \quad r(^1S_0) = 2.8 \text{ fm}$$
$$a(^3S_1) = 5.3 \text{ fm} \qquad r(^3S_1) = 1.8 \text{ fm}$$

PWA – input pw and data samples

proton+proton (isospin I = 1)

INITIAL PP STATES

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

FINAL STATES

S-, P-, D-waves in pp or pn-state

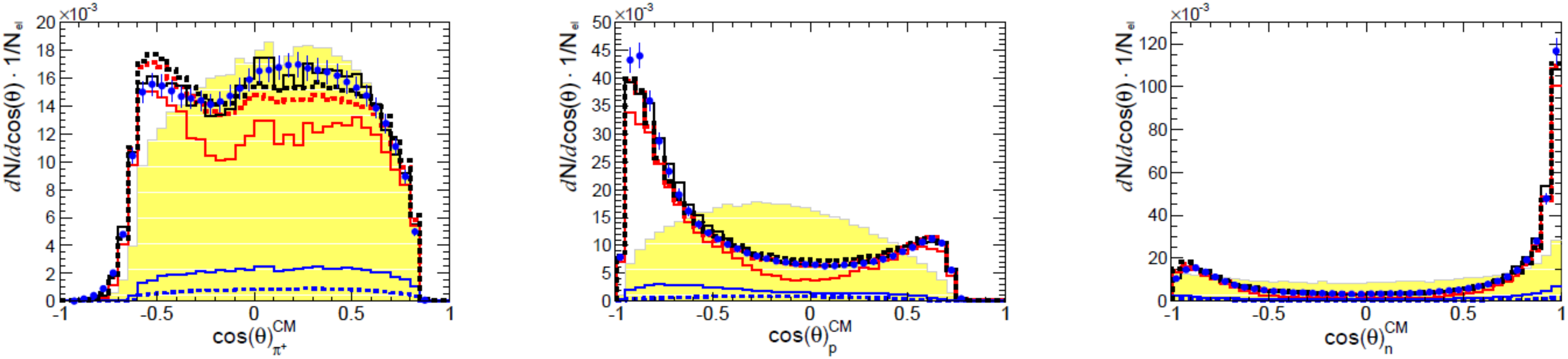
$P_{33}(1232)$ and $P_{11}(1440)$ in πN state

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

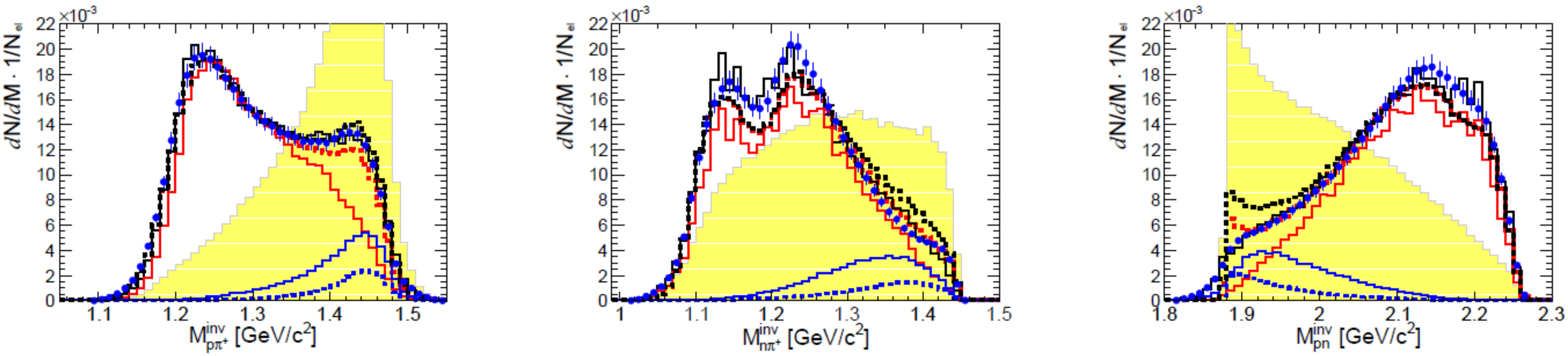
Experimental data samples

Reaction	$\sqrt{s}$ (MeV)	N_{data}	σ_{tot} (mb)
$pp \to \pi^0 pp$	2066	50000	0.10±0.03
$pp \to \pi^0 pp$	2157	542	2.07±0.09
$pp \to \pi^0 pp$	2178	615	2.85±0.13
$pp \to \pi^0 pp$	2200	882	3.31±0.19
$pp \to \pi^0 pp$	2217	993	3.70±0.14
$pp \to \pi^0 pp$	2234	914	3.73±0.15
$pp \to \pi^0 pp$	2251	996	3.96±0.15
$pp \to \pi^0 pp$	2269	1315	4.20±0.15
$pp \to \pi^0 pp$	2284	903	4.19±0.17
$pp \to \pi^0 pp$	2300	688	4.48±0.20
$pp \to \pi^0 pp$	2319	1086	4.50±0.17
$pp \to \pi^0 pp$	2422	60000	3.87±0.55
$pp \to \pi^+ pn$	2285	4153	17.8±0.4
$pp \to \pi^+ pn$	2300	2912	17.6±0.6
$pp \to \pi^+ pn$	2422	60000	17.0±2.2

(n p π⁺) – in acceptance (OPE & PWA)



(a) Angular distribution of π^+, p and n in c.m.s. reference frame.



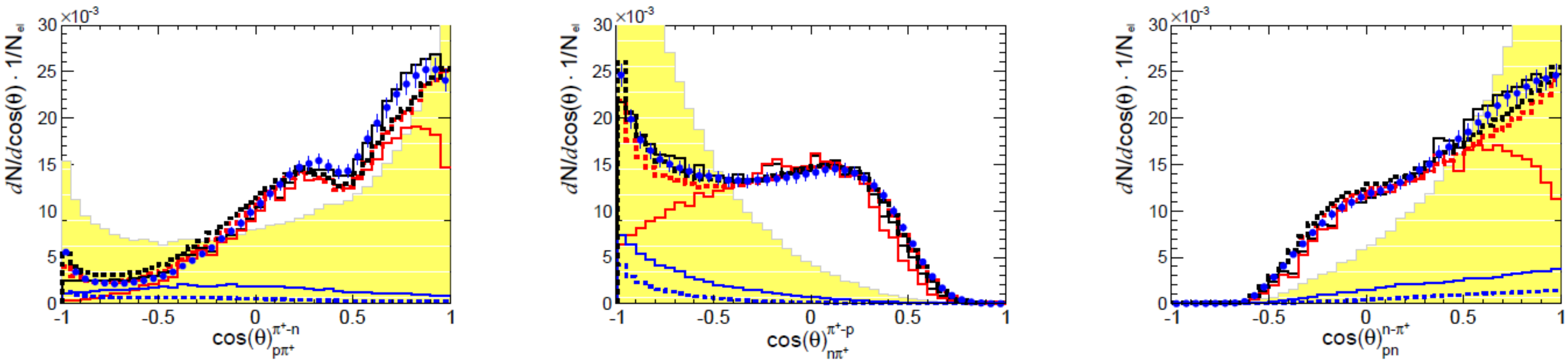
(b) Invariant mass of $p\pi^+$, $n\pi^+$ and pn.

SOLID (PWA) DASHED (OPE)
yellow – phasespace
black – total

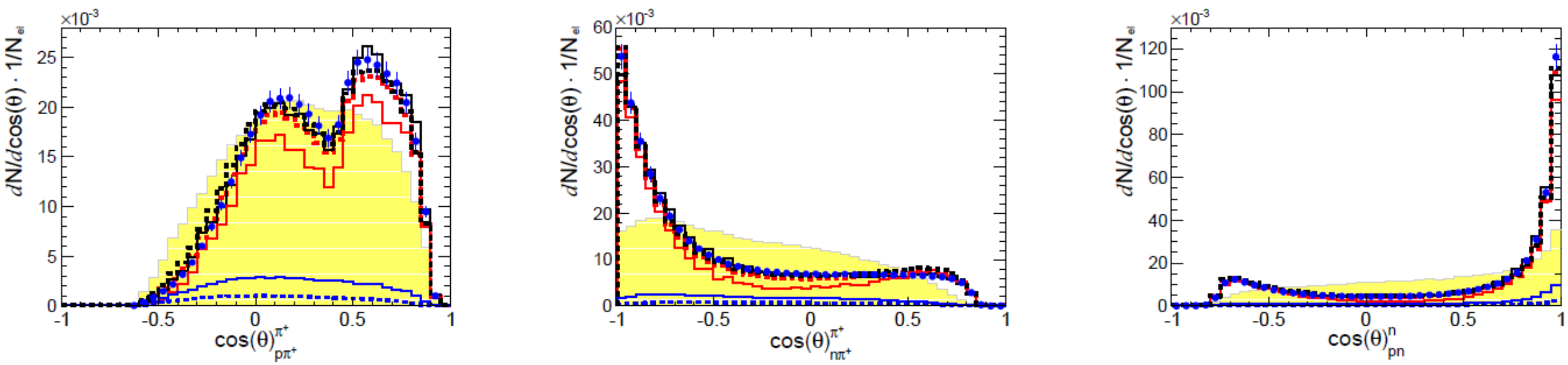
SOLID (PWA) DASHED (OPE)
red – $\Delta(1232)P_{33}$
blue – $N(1440)P_{11}$

blue – data points

(n p π⁺) – in acceptance (OPE & PWA)



(c) Helicity distribution of π^+ in $p\pi^+$ reference frame, π^+ in $n\pi^+$ reference frame and n in pn reference frame.



(d) Angular distribution of π^+ in $p\pi^+$ GJ reference frame, π^+ in $n\pi^+$ GJ reference frame and n in pn GJ reference frame.

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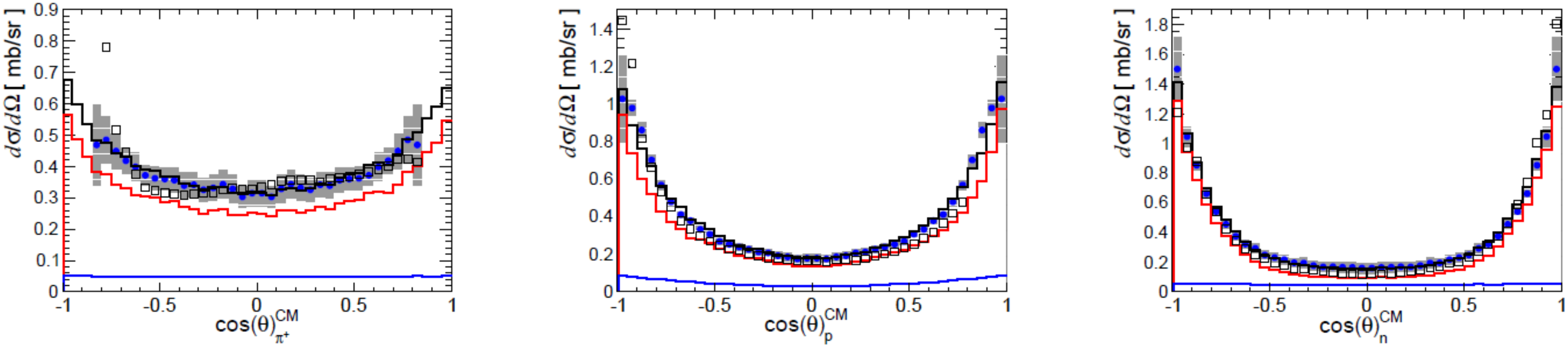
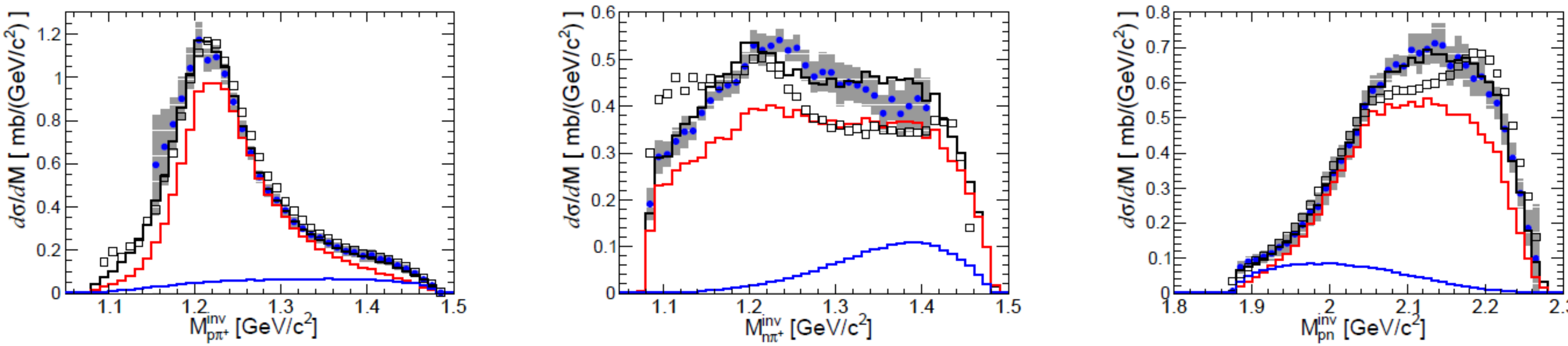
(n p π^+) – OPE, PWA acc corrected



(a) Acceptance and efficiency corrected angular distribution of π^+, p and n in c.m.s. reference frame.



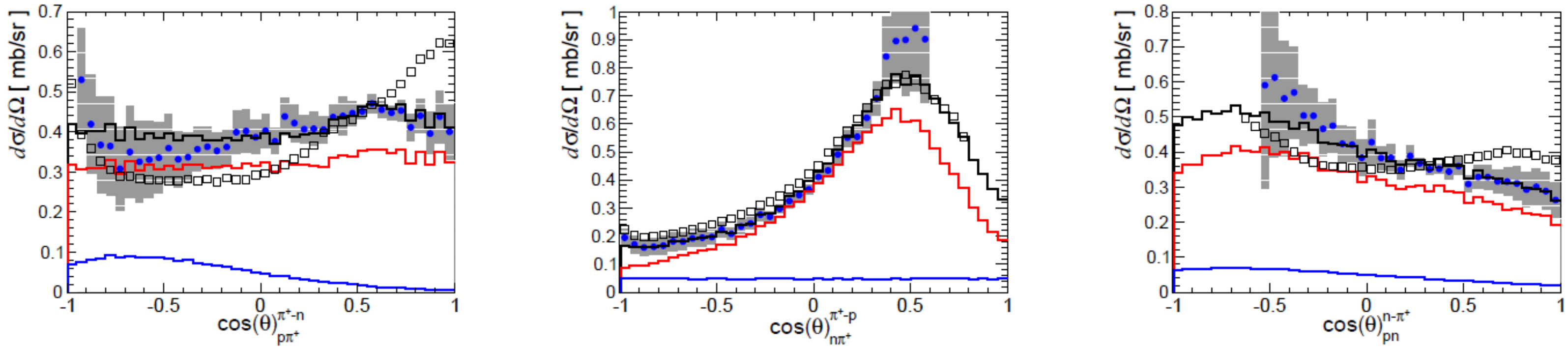
(b) Acceptance and efficiency corrected invariant mass of $p\pi^+$, $n\pi^+$ and pn.

SOLID (PWA)

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

blue dots – data points (PWA corr)
black open squares – data points (OPE corr)

(n p π^+) – OPE, PWA acc corrected



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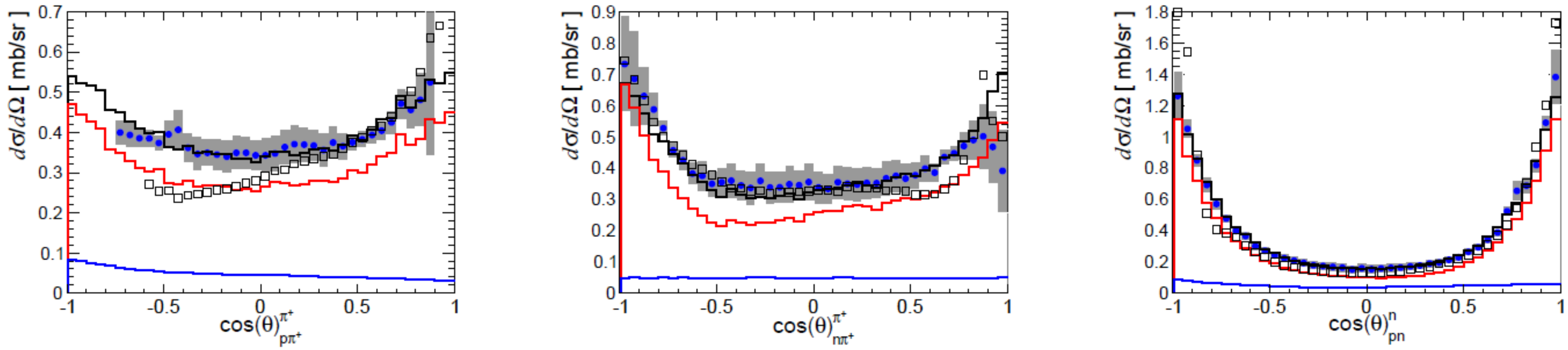

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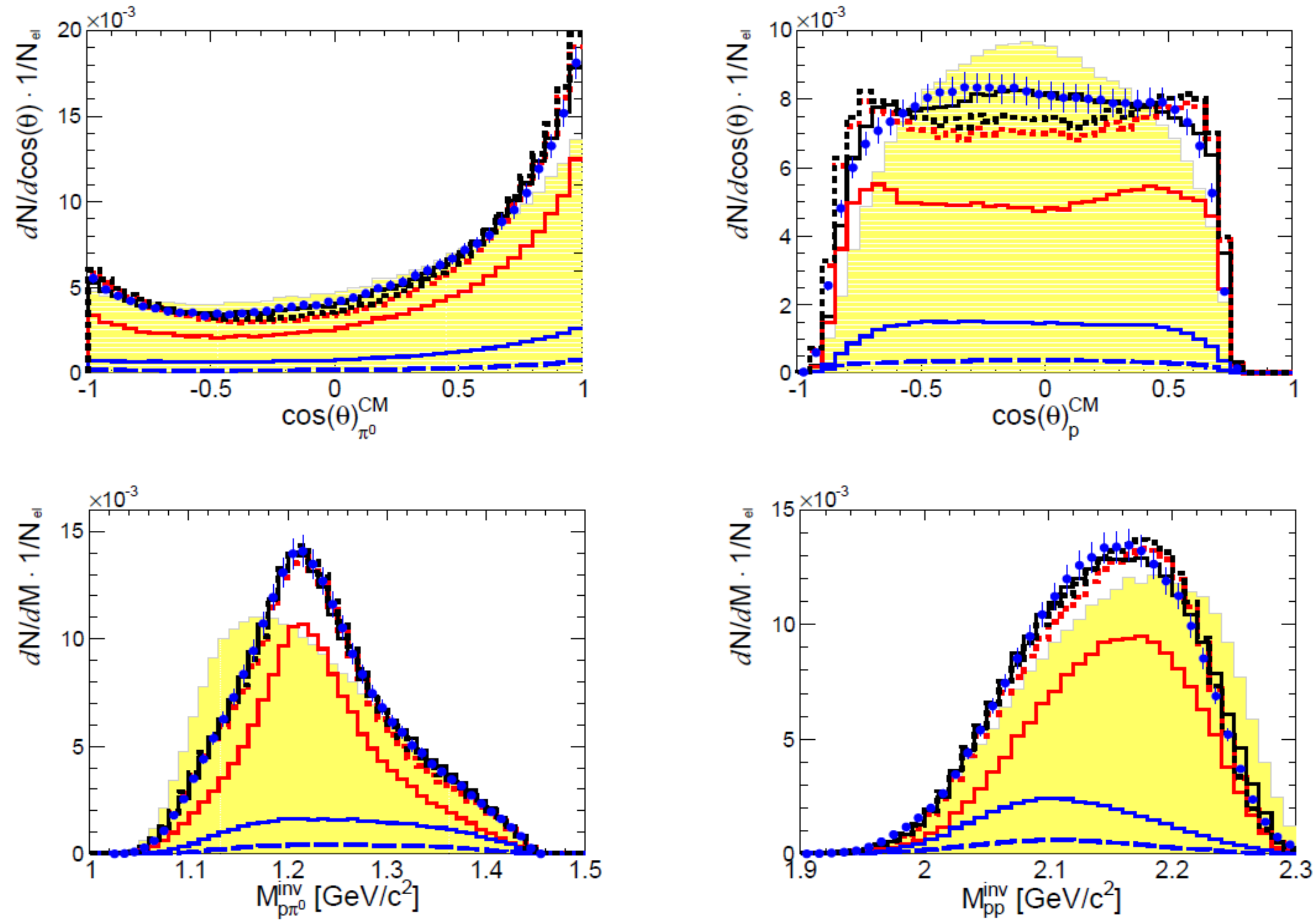
($p\ p\ \pi^0$) – in acceptance (OPE & PWA)



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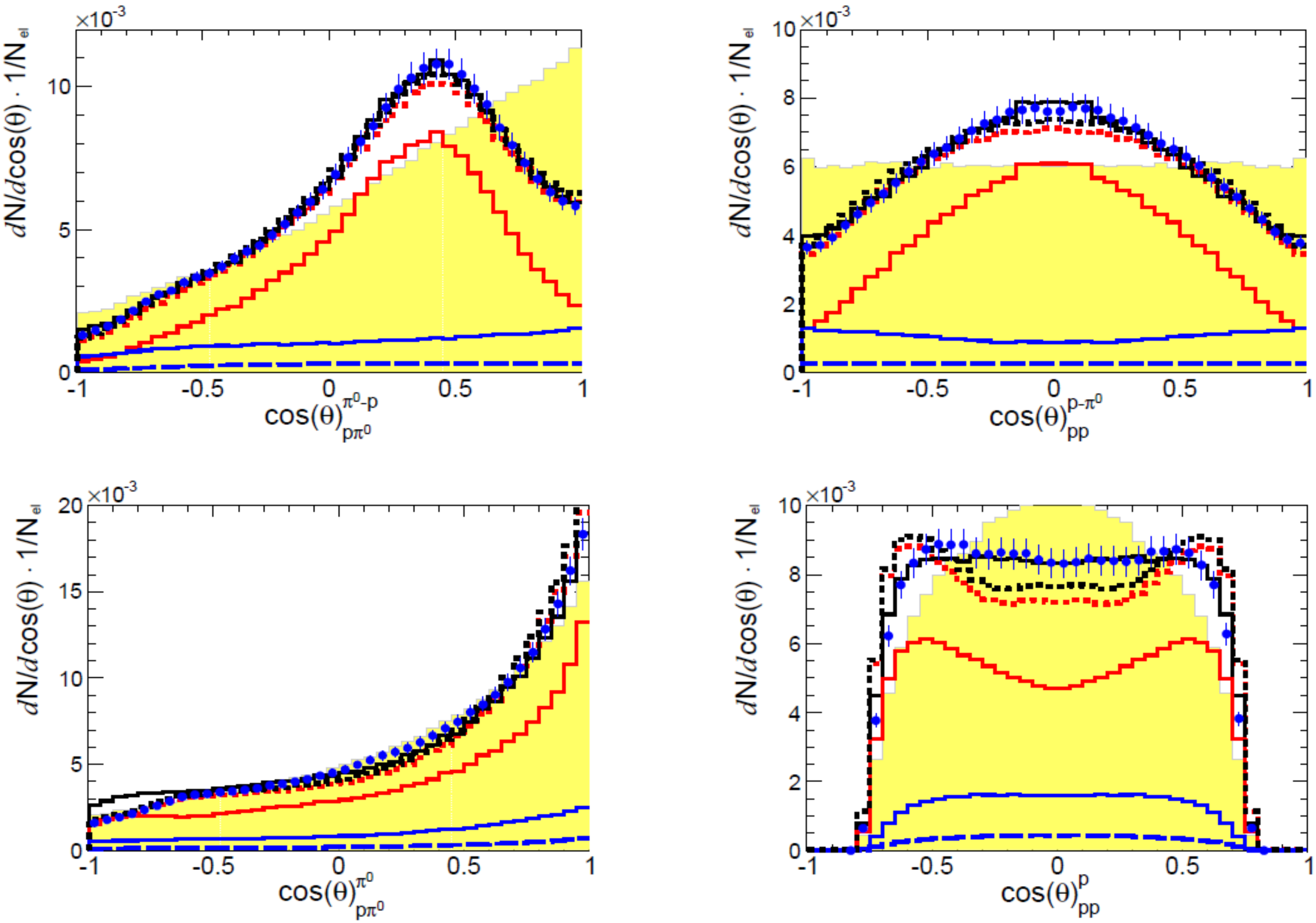
($p\ p\ \pi^0$) – in acceptance (OPE & PWA)



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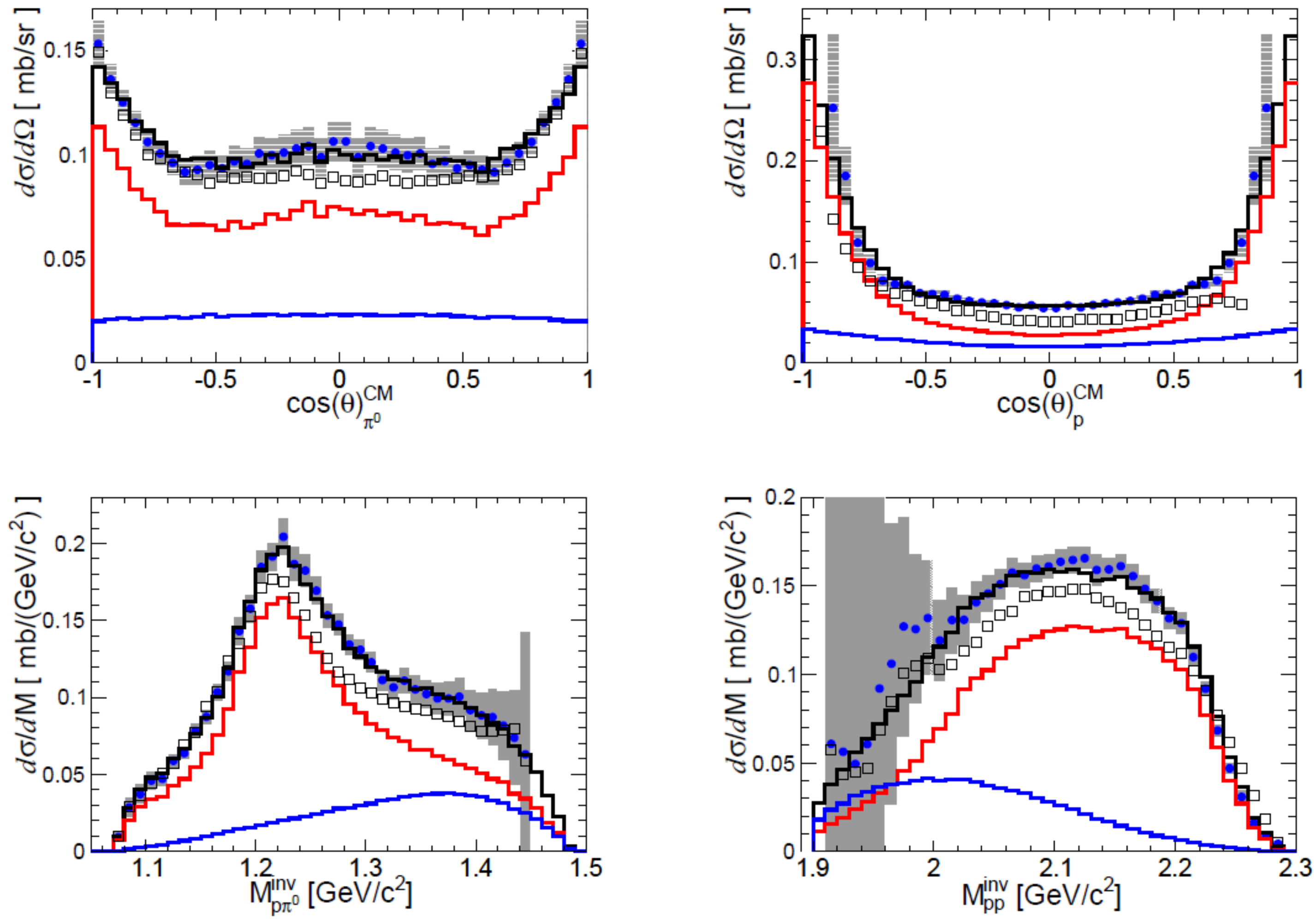
blue – data points

($p\ p\ \pi^0$) – OPE, PWA **acc corrected**



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blue dots – data points (PWA corr)

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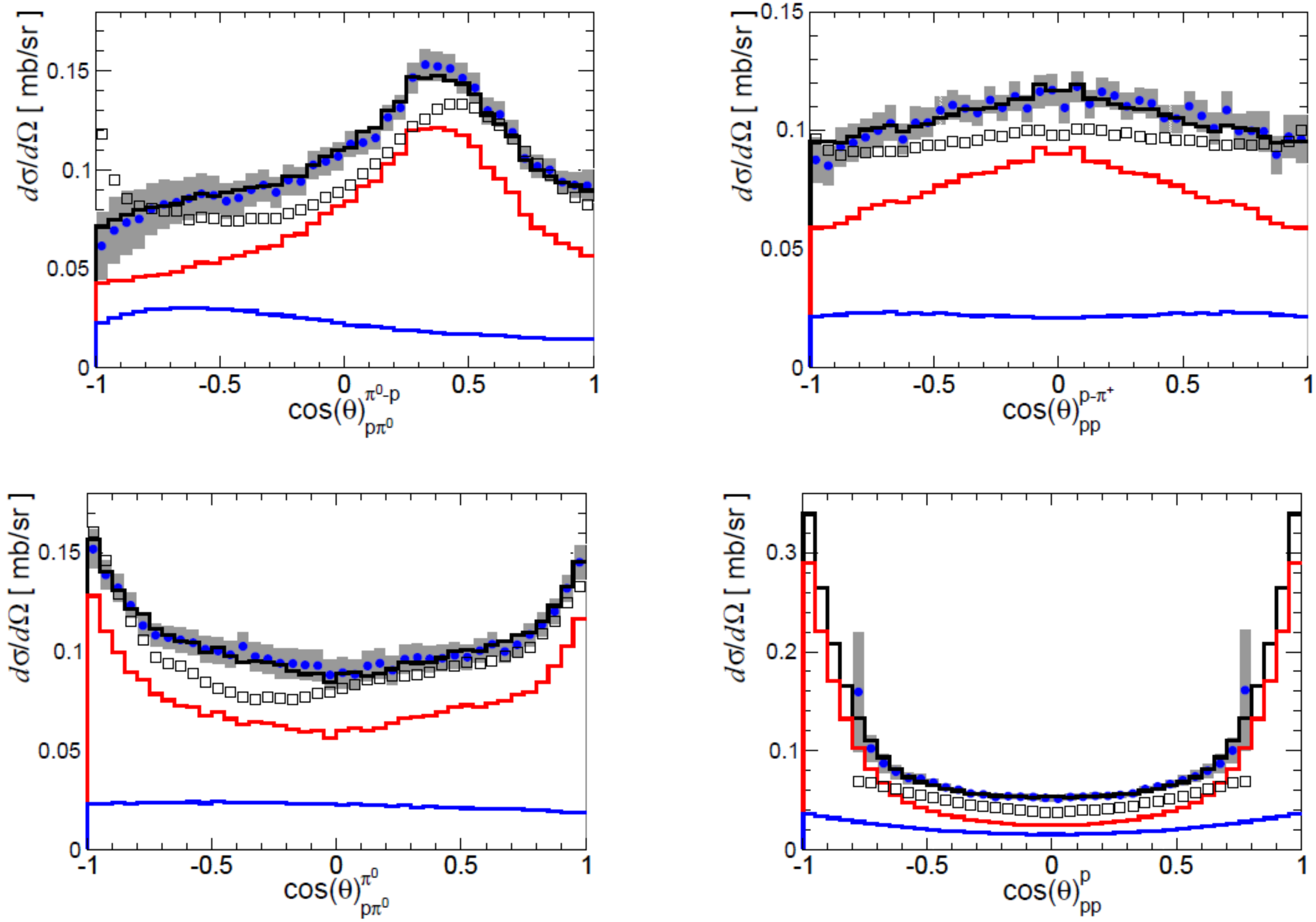
(p p π^0) – OPE, PWA acc corrected



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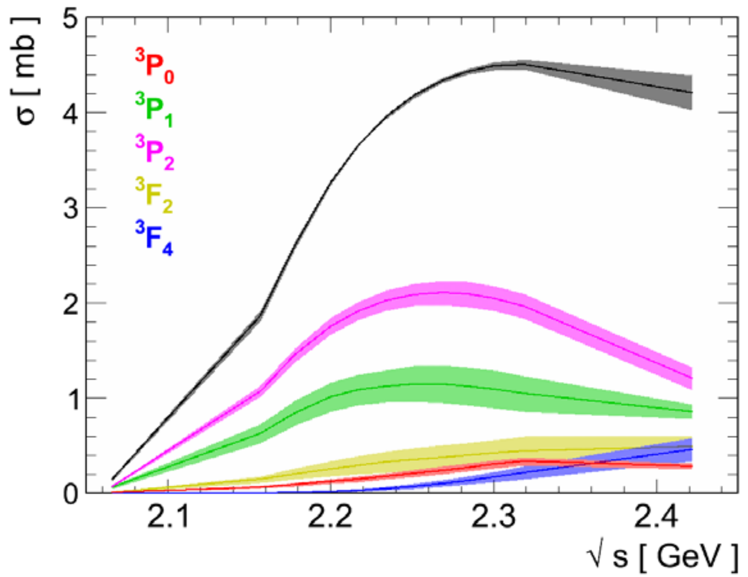
blue – $N(1440)P_{11}$

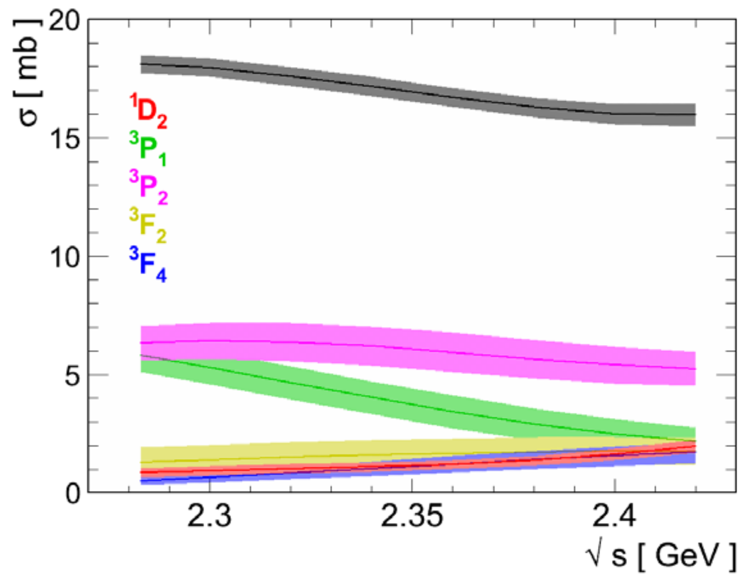
blue dots – data points (PWA corr)

black open squares – data points (OPE corr)

Partial Waves (**p p** π^0, n **p** π^+)

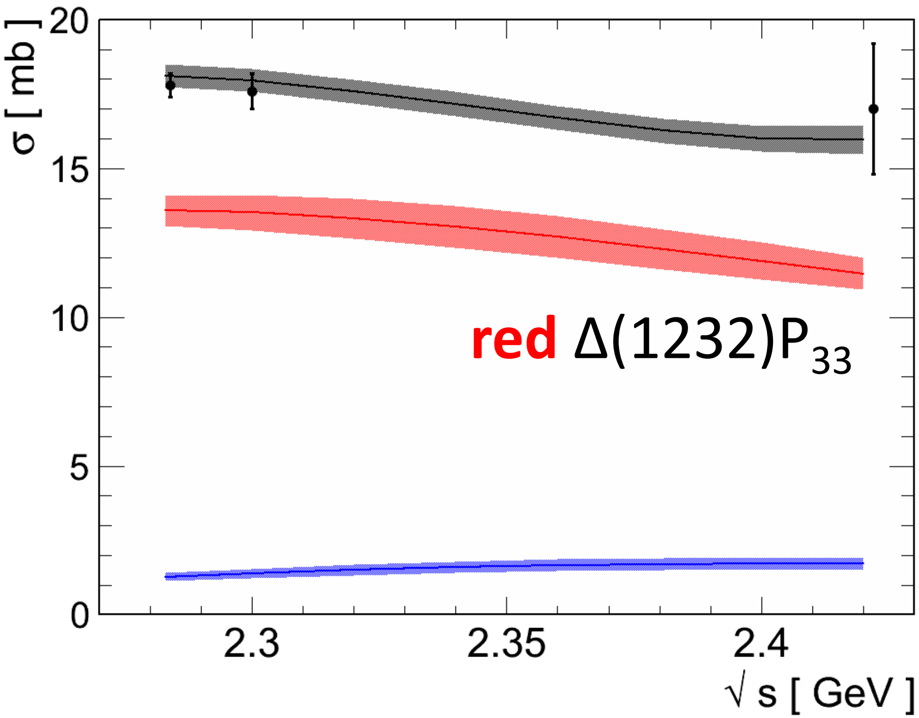
	Total	$\Delta(1232)N$	$N(1440)p$
	$pp \to pp\pi^0$		
$^1S_0$	1.8 ± 0.7	<1	1.8 ± 0.7
$^3P_0$	6.8 ± 1.0	1.5 ± 0.5	5.5 ± 1.0
$^3P_1$	21.0 ± 4.4	2.0 ± 1.0	12 ± 2.0
$^3P_2$	29.5 ± 3.5	30.5 ± 4.0	2.3 ± 1.0
$^1D_2$	4.9 ± 1.0	4.2 ± 1.0	<1
$^3F_2$	11.8 ± 2.0	6.5 ± 1.0	<1
$^3F_3$	2.0 ± 2.0	2.0 ± 2.0	<1
$^3F_4$	12.0 ± 3.5	12.0 ± 3.0	<1
$^1G_4$	4.0 ± 1.0	4.0 ± 1.0	<1
$^3H_4$	5.5 ± 1.0	5.5 ± 1.0	<1
	$pp \to pn\pi^+$		
$^1S_0$	3.5 ± 0.8	<1	2.2 ± 0.7
$^3P_0$	4.0 ± 1.5	1.0 ± 0.5	1.7 ± 0.4
$^3P_1$	14.0 ± 6.0	2.0 ± 1.0	6.7 ± 1.0
$^3P_2$	33.5 ± 3.0	29.5 ± 3.0	1.0 ± 0.5
$^1D_2$	11.8 ± 1.5	8.8 ± 1.3	<1
$^3F_2$	8.0 ± 1.0	6.5 ± 0.8	<1
$^3F_3$	2.0 ± 2.0	2.0 ± 2.0	<1
$^3F_4$	11.5 ± 2.5	11.5 ± 2.5	<1
$^1G_4$	5.0 ± 1.0	5.0 ± 1.0	<1
$^3H_4$	5.5 ± 1.0	5.5 ± 1.0	<1

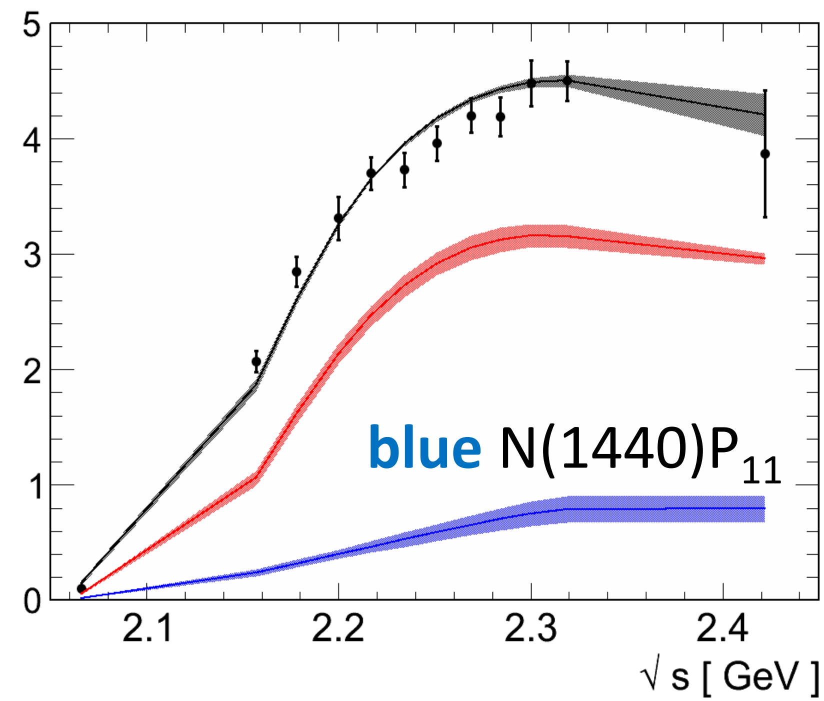




PWA cross section & resonances

final state	intermediate process	σ_{RES} (mb)	σ_{adj}^{RES} (mb)	σ_{PWA} (mb)	σ_{adj}^{PWA} (mb)
$np\pi^+$	$pp \to n\Delta^{++}(1232)$	16.90	14.86 ± 2.19	11.1 ± 0.4	-
	$pp \to p\Delta^{+}(1232)$	1.89	1.66 ± 0.24	1.2 ± 0.2	-
	$pp \to pN(1440)$	0.54	0.47 ± 0.07	1.70 ± 0.20	-
	$Total:$	19.35	17.00 ± 2.2	16.34 ± 0.8	16.26 ± 1.96
$pp\pi^0$	$pp \to p\Delta^{+}(1232)$	3.76	3.61 ± 0.54	2.96 ± 0.07	-
	$pp \to pN(1440)$	0.27	0.25 ± 0.06	0.86 ± 0.06	-
	$Total:$	4.03	3.87 ± 0.55	4.2 ± 0.15	4.1 ± 0.45



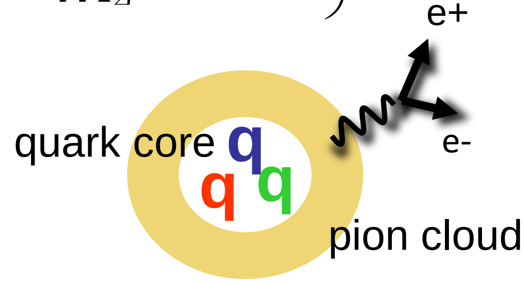


$\Delta \rightarrow N e^+ e^-$

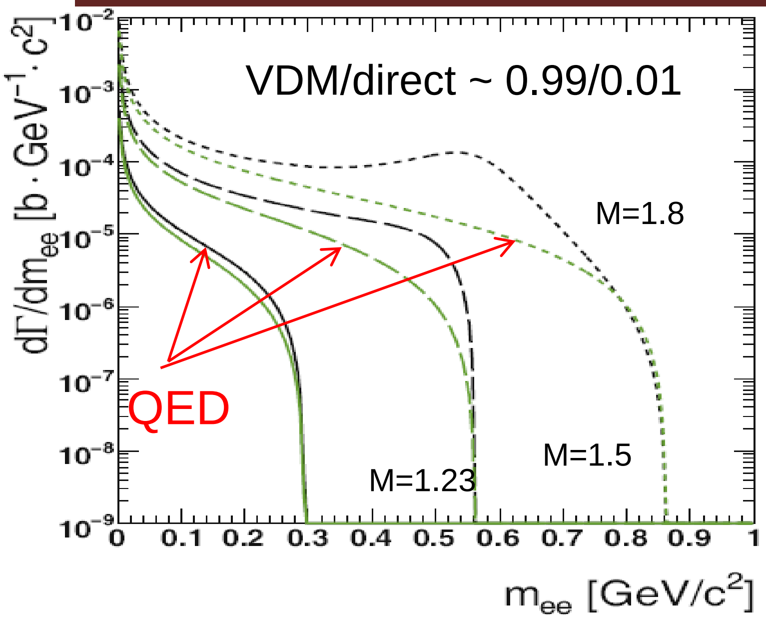
M.I. Krivoruchenko *et al.*
Phys. Rev. D**65** (2002) 017502

$$\frac{d\Gamma(\Delta \rightarrow N e^+ e^-)}{dq^2} = f\left(m_\Delta, q^2\right)\left(\left|G_M^2(q^2)\right| + 3\left|G_E^2(q^2)\right| + \frac{q^2}{2m_\Delta^2}\left|G_C^2(q^2)\right|\right)$$

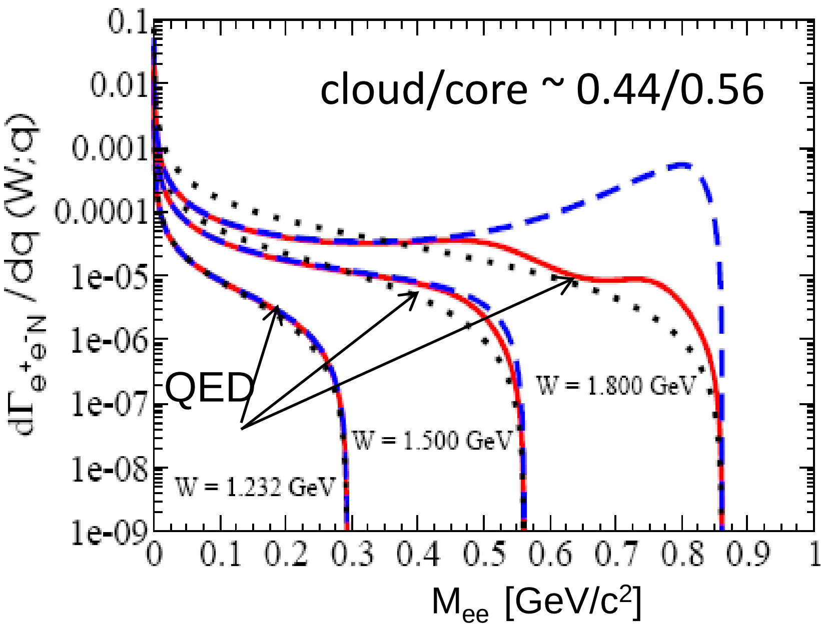
Time Like ($q^2 > 0$)
Δ (J=3/2) -> N (J=1/2) γ^* transition:



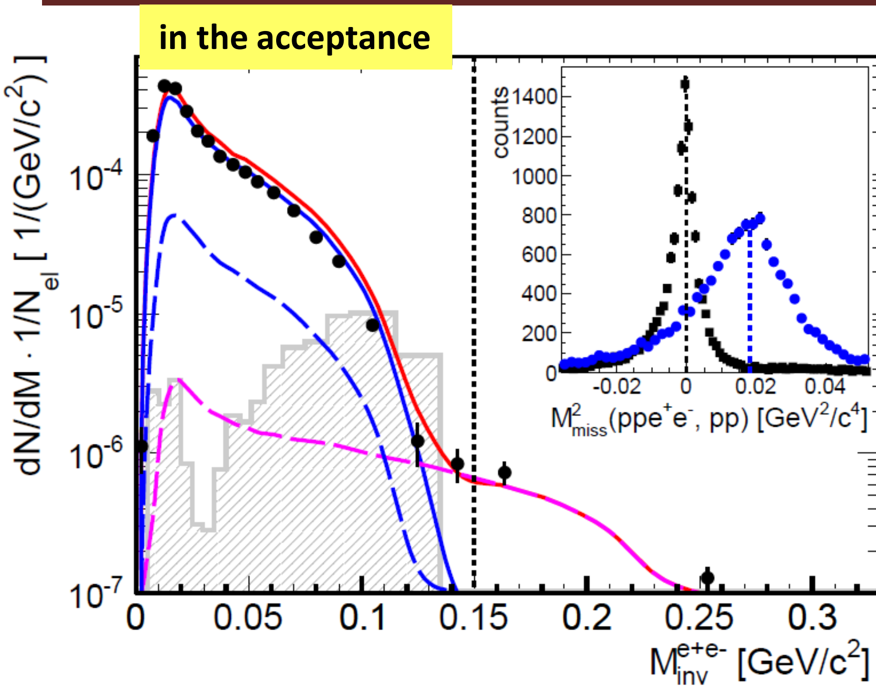
Q. Wann, F. Iachello
Int. J. Mod. Phys. A**20** (2005) 1846

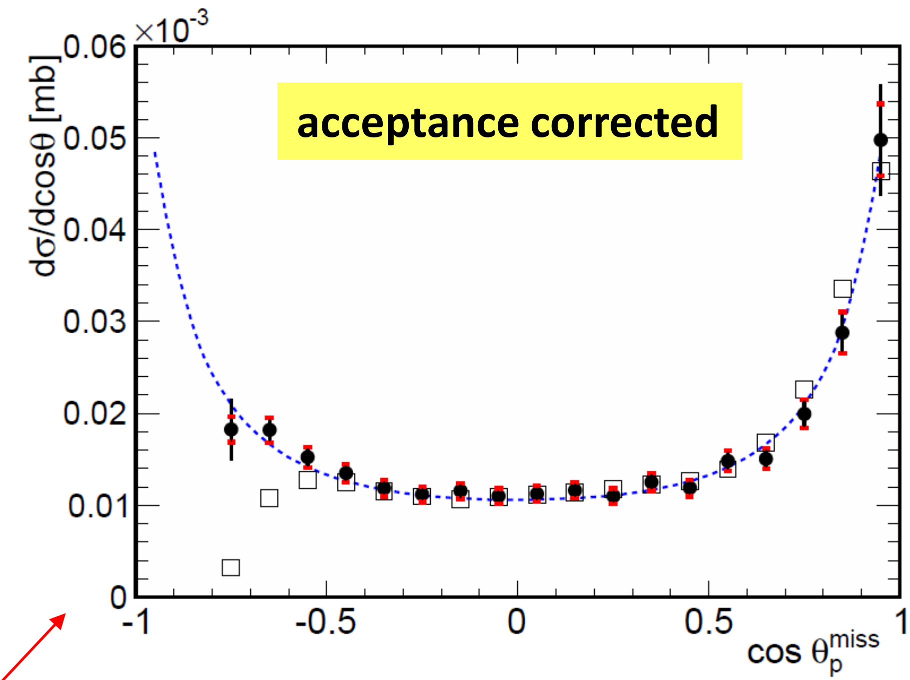


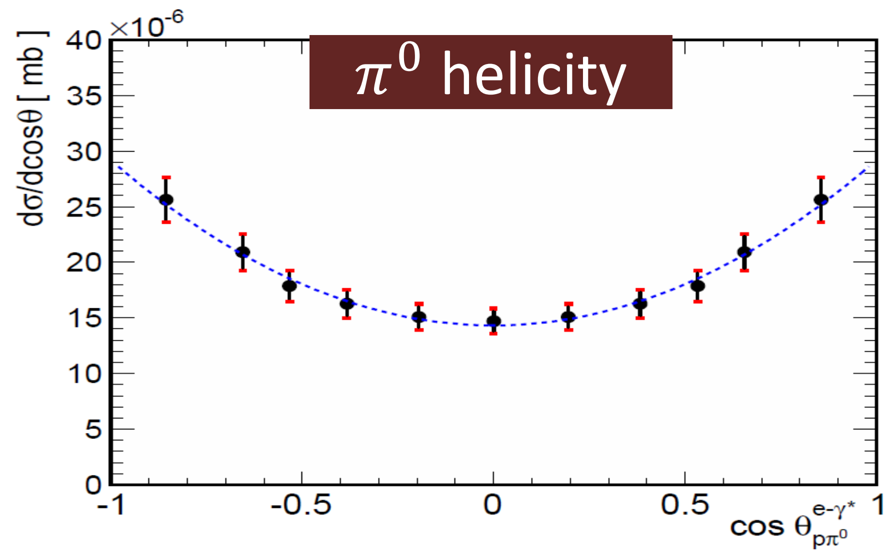
G. Ramalho, M. T. Peña
Phys. Rev. D**85** (2012) 113014



Δ+ identification via pp π^0 { → $e^+e^-\gamma$ }



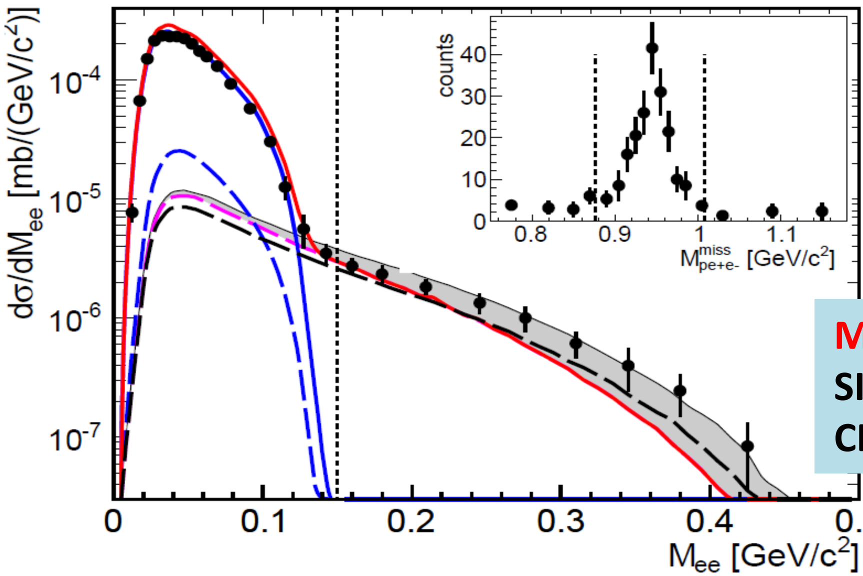




both channels with 2 protons
pp – open squares
ppe⁺e⁻ – black dots
support the description of
Δ angular distribution
according to OPE (modified)

Witold Przygoda (NSTAR 2015)

Δ^+ Dalitz decay via $pn\Delta^+ \{\rightarrow pe^+e^-\}$



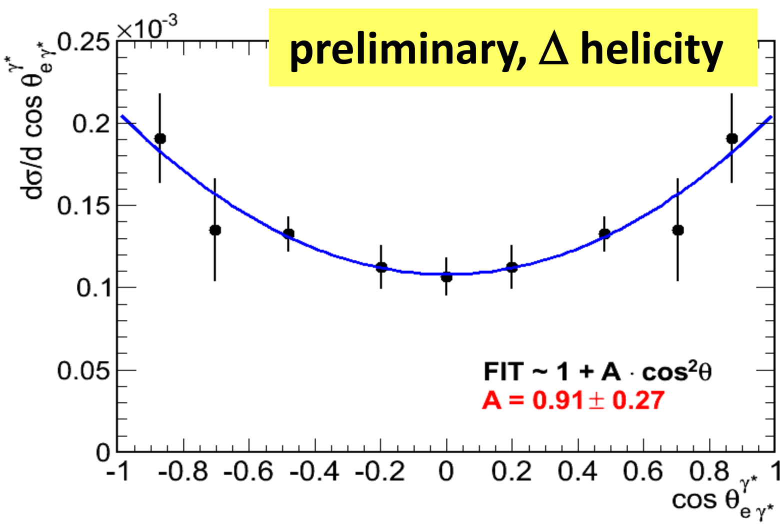
red line – total
blue – π^0 Dalitz
magenta – Δ Dalitz
grey band– (VMD)
dashed – Ramalho/Peña

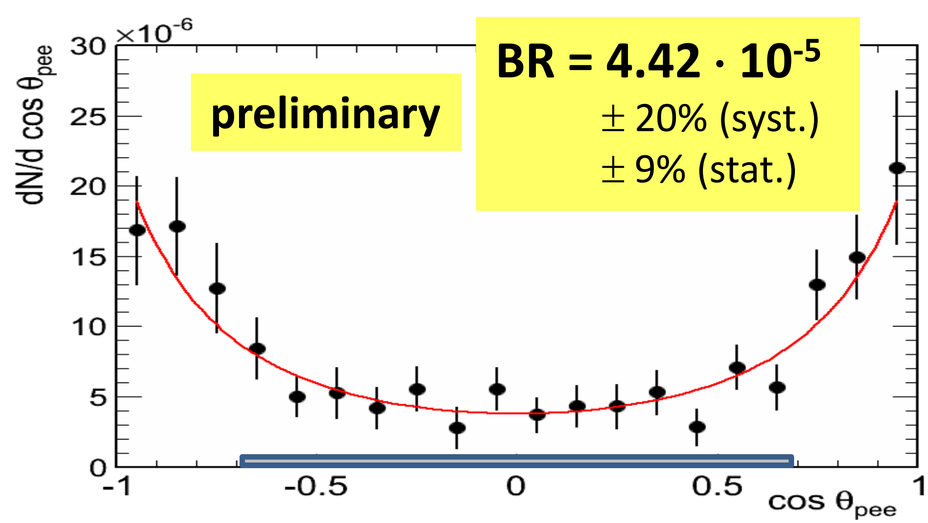
M_{ee} > 0.15
SIGNAL: 200
CB: 15

Δ Dalitz decay BR

$G_M(0)$~3
$G_E(0)$~0
$G_C(0)$~0

$$BR = \frac{N_{\Delta \rightarrow pe^+e^-}}{N_{\Delta \rightarrow p\pi^0}}$$





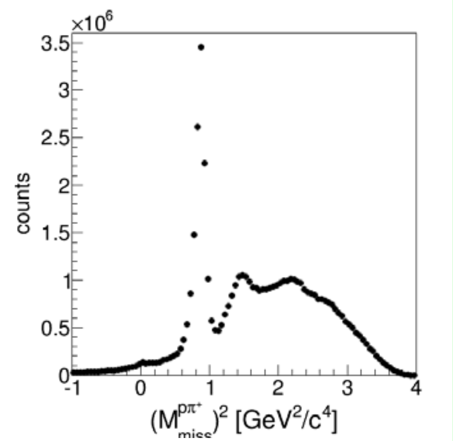
Witold Przygoda (NSTAR 2015)

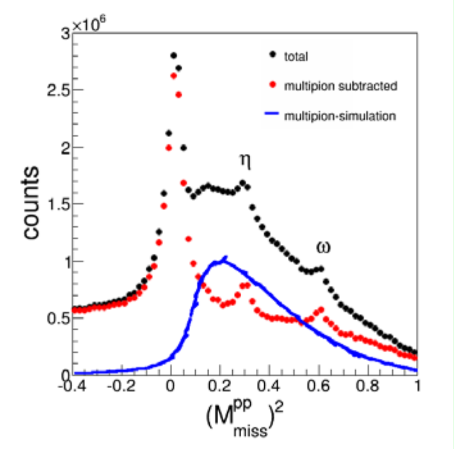
p+p @ 3. 5 GeV - plan

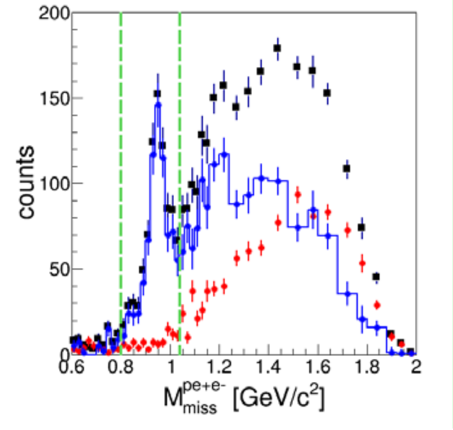
$p + p$ elementary reactions at E_{kin} = 3.5 GeV to investigate the wealth of baryonic resonances and their properties

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

II. LEPTON ANALYSIS
(ppe^+e^-)

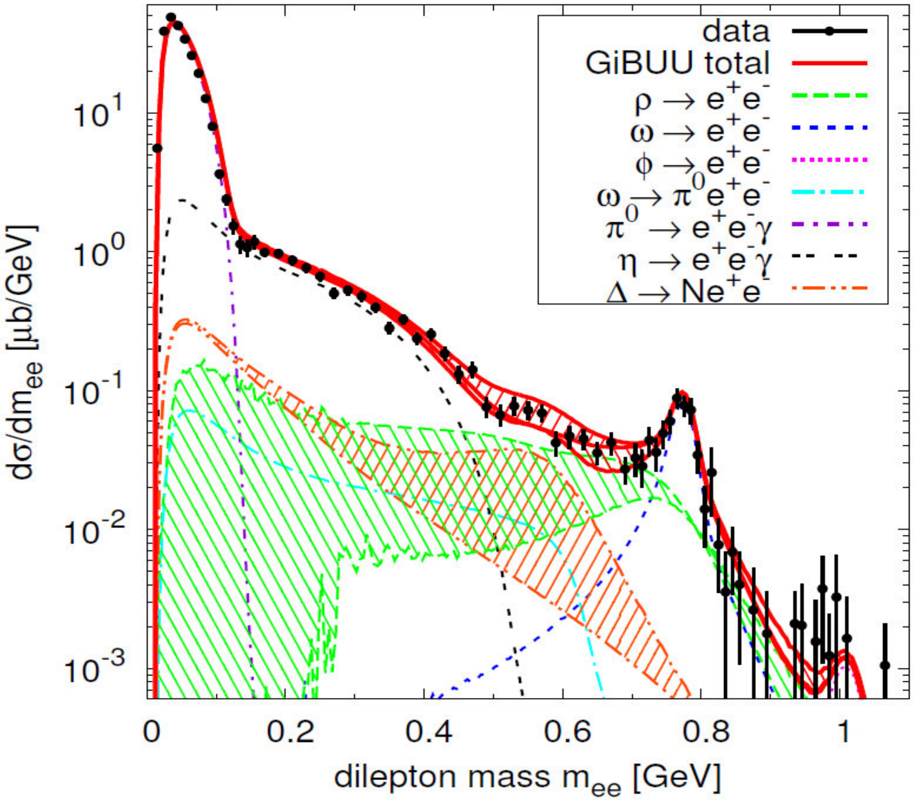






G. Agakishiev *et al*.
Eur. Phys. J. A **50** (2014) 82

Inclusive e^+e^- spectrum p+p @ 3.5 GeV



Cross sections deduction
PYTHIA+PLUTO (UrQMD)

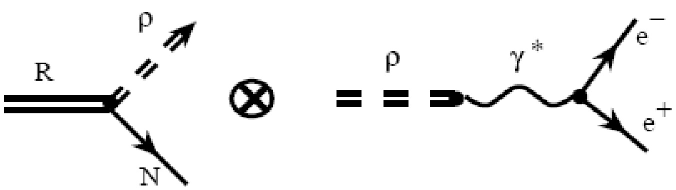
	π^o	η
σ_i [mb]:	18± 2.7 (16 ± 2.6)	1.14±0.2 (0.93± 0.14)

$\Delta^{o,+}$	ρ	ω
7.5 ± 1.3	0.233 ± 0.06	0.273 ± 0.07

for details, see:

G. Agakishiev *et al*. (HADES)
Eur. Phys. J. A **48** (2012) 64

J. Weil *et al*. (**GiBUU**)
Eur. Phys. J. A**48** (2012) 111



How to treat R → N e+ e-

- ρ mesons produced via baryonic resonances (**R → ρ N → e+ e− N**)
- Resonance model with **electromagnetic Transition Form Factor** from model seems to describe nicely data – *only* Δ?

Baryon resonances in p+p @ 3.5 GeV

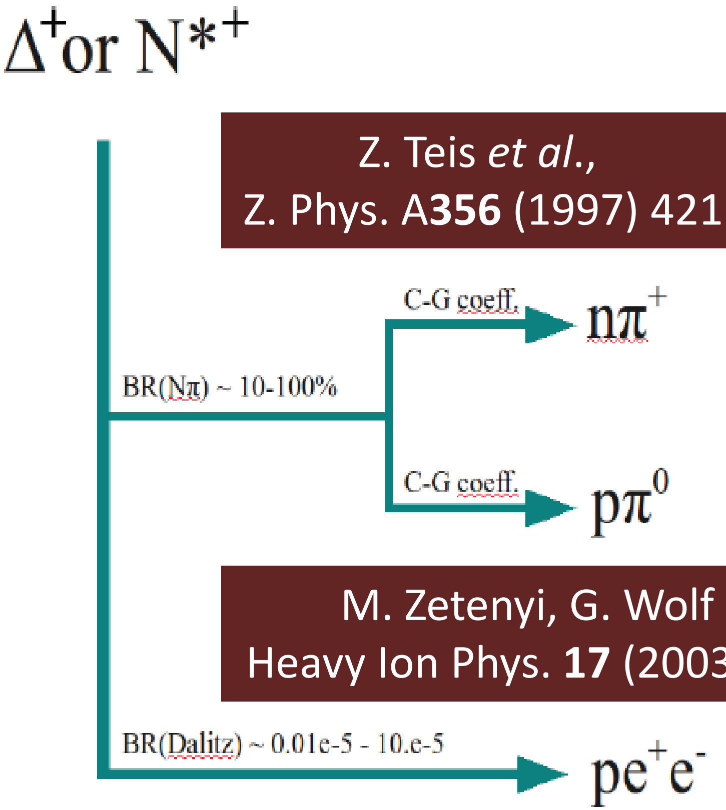
Study of 3 connected exclusive channels:

- pp → pnπ^+ to **fix R (Δ, N*) cross sections**
- pp → ppπ^0 to check the result (izospin relations)
- convert R → pe$^+$e$^-$ and check in pp → ppe$^+$e$^-$

Resonance model

production amplitude given by **incoherent** sum of resonance contributions + isospin relations

J^P	Resonances	Γ_R [MeV]	$BR(N\pi)$	$BR(pe^+e^-)$
$3/2^+$	**$\Delta(1232)$**	120	1	4.2e-5
$1/2^+$	**$N^*(1440)$**	350	0.65	3.06e-6
$3/2^-$	**$N^*(1520)$**	120	0.55	3.72e-5
$1/2^-$	**$N^*(1535)$**	150	0.46	1.45e-5
$3/2^+$	$\Delta(1600)$	350	0.15	0.73e-6
$1/2^-$	**$\Delta(1620)$**	150	0.25	1.73e-6
$1/2^-$	$N^*(1650)$	150	0.8	8.03e-6
$5/2^-$	$N^*(1675)$	150	0.45	1.02e-6
$5/2^+$	**$N^*(1680)$**	130	0.65	1.97e-5
$3/2^+$	$N^*(1720)$	150	0.2	3.65e-6
$3/2^-$	**$\Delta(1700)$**	300	0.15	1.38e-5
$5/2^+$	$\Delta(1905)$	350	0.15	1.46e-6
$1/2^+$	**$\Delta(1910)$**	280	0.25	0.73e-5
$7/2^+$	$\Delta(1950)$	285	0.4	3.06e-6

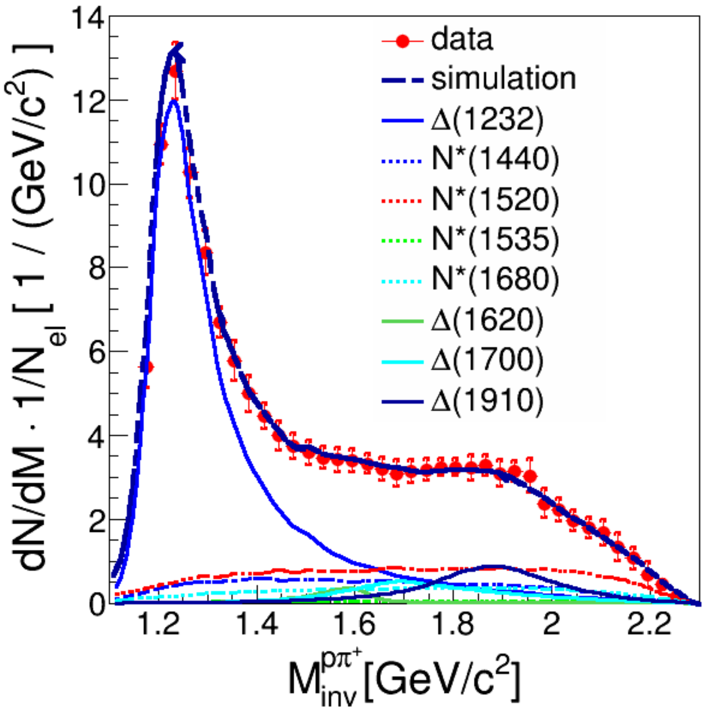


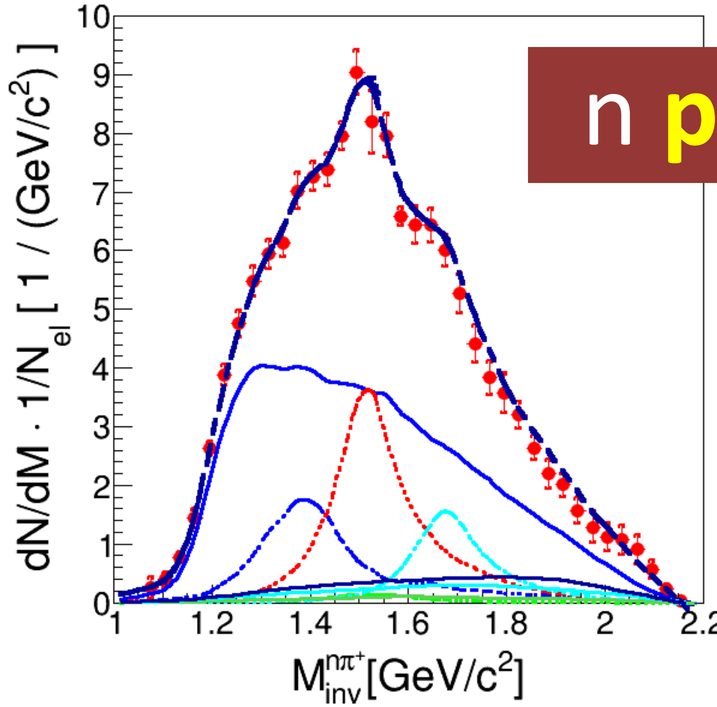
Z. Teis *et al.*,
Z. Phys. A**356** (1997) 421

M. Zetenyi, G. Wolf
Heavy Ion Phys. **17** (2003) 27

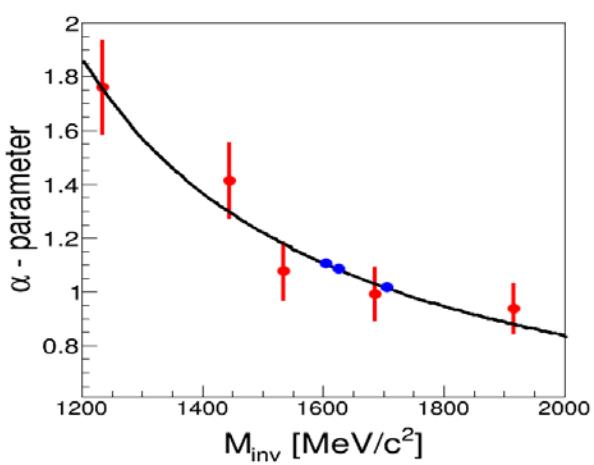
For the overlaping resonances only one resonance with largest BR(pe$^+$e$^-$) selected.

Resonance production (HADES acceptance)





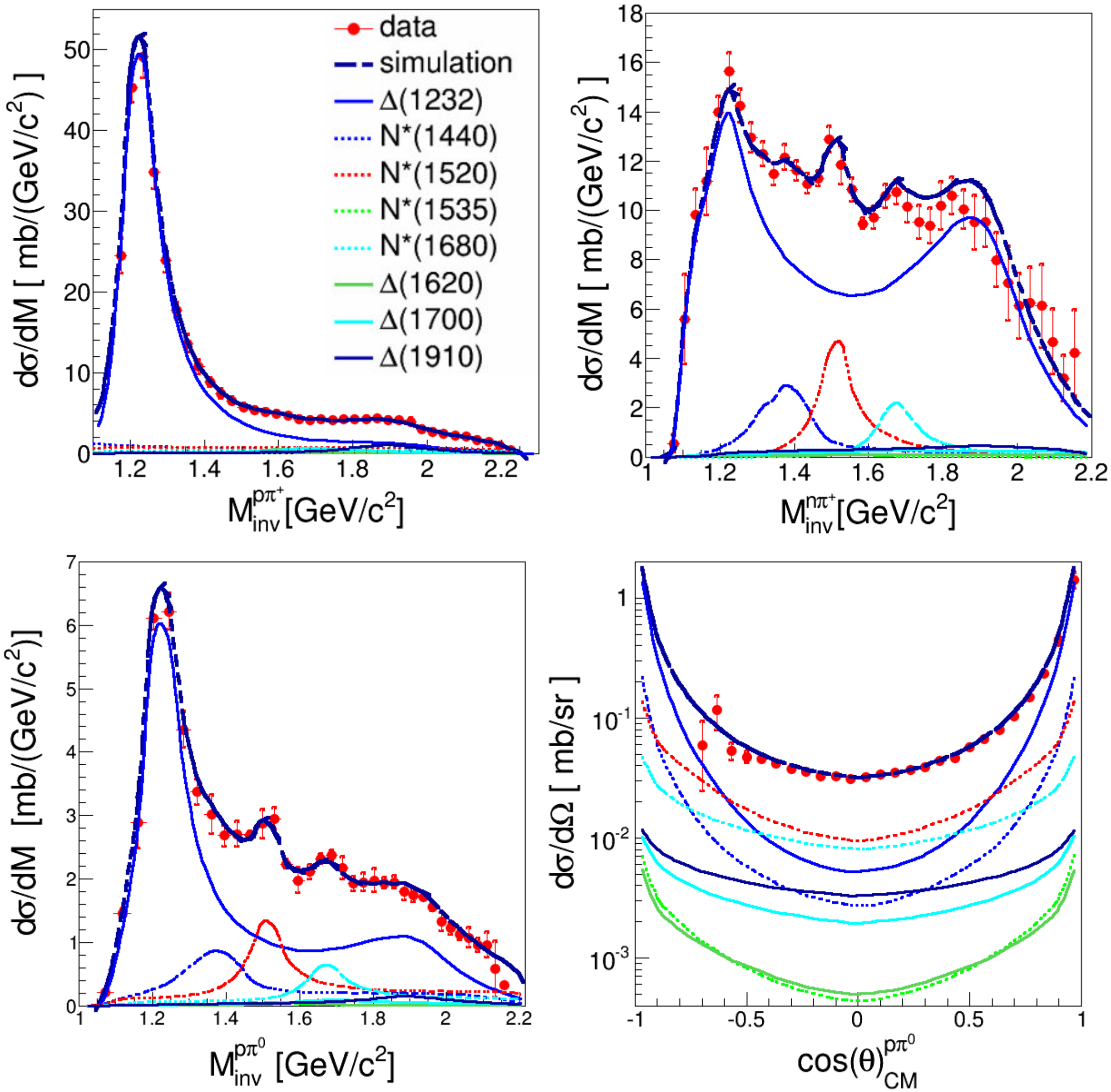
n **p π+**



extension of angular parametrisation as a function of ***t*** for **all resonances**

$$\frac{d\sigma}{dt}(M_R) \propto \frac{A}{t^{\alpha(M)}}$$

One pion production: acceptance corrected



n p π^+

- Δ^{++} (1232)

very good description of Δ-line shape ("Monitz" parametr.)

p p π^0

- Δ^{+}(1232)
- N*(1440)
- N*(1520)
- N*(1680)

Exclusive ω/η production in p+p @ 3. 5 GeV

Total cross section of exclusive η and ω production obtained from a parametrization of existing data:

$\sigma_\eta = 140 \pm 14$ µb
$\sigma_\omega = 146 \pm 15$ µb

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

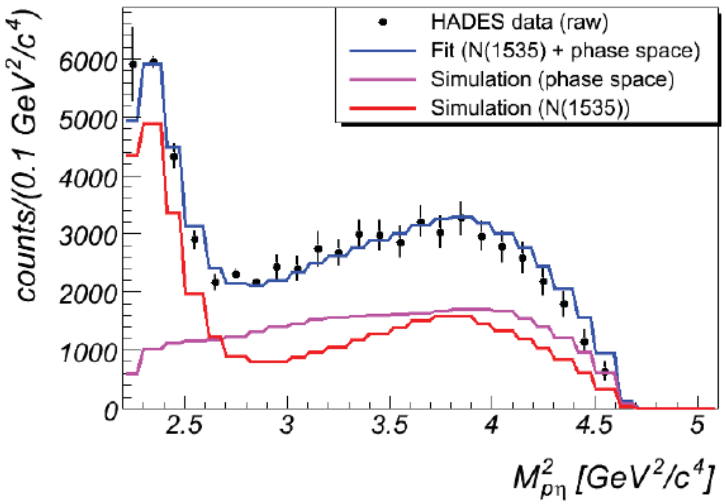
M. Abdel-Bary *et al*. (COSY-TOF)
Eur. Phys. J. A **44** (2010) 7

Total cross section for ρ taken from relations to ω production (DISTO observation)

$\sigma_{pp\rho} = ½ \cdot \sigma_{pp\omega}$

F. Balestra *et al*. (DISTO)
Phys. Rev. Lett. **89** (2002) 092001

K. Teilab (PhD Thesis)
Univ. Frankfurt (2011)



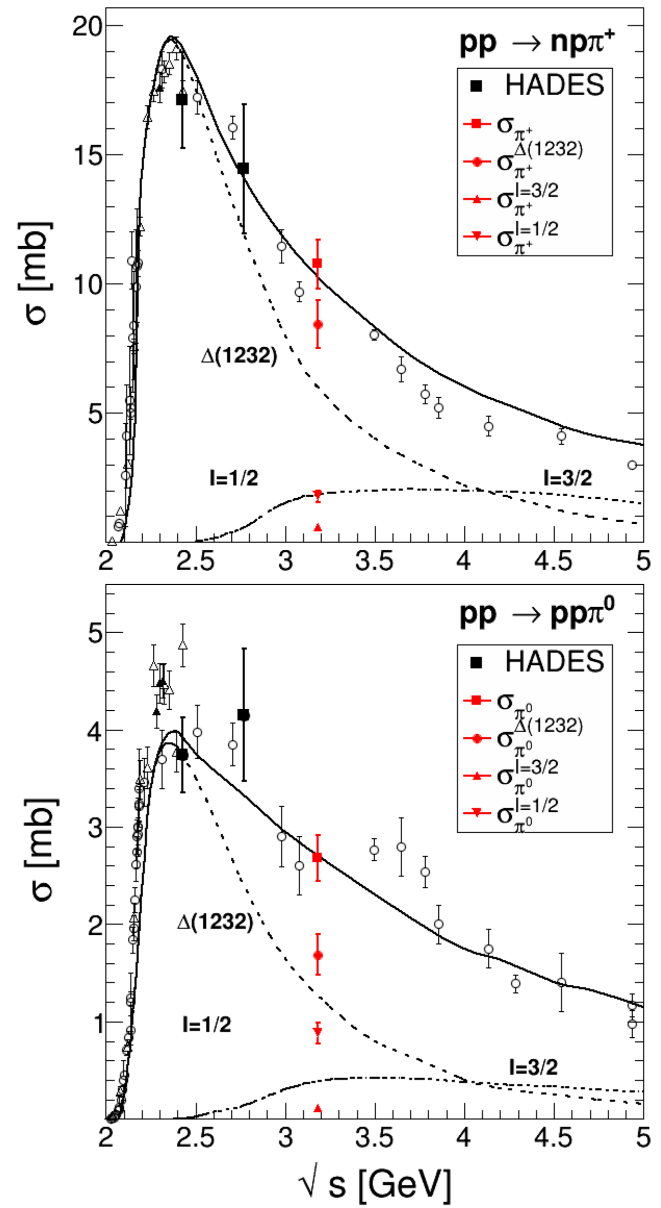
$N^*(1535)$ fixed from η Dalitz plot

$N^*(1535) \rightarrow p\eta$ BR(42%)

$\sigma_{N^*(1535)} \approx 157$ [µb]

Cross sections (HADES, Teis *et al.*, GiBUU, UrQMD)

Resonances	σ_R $[mb]$	$\sigma_R^{Teis}(GiBUU)$	σ_R^{UrQMD}
$\mathbf{\Delta(1232)}$	2.53 ± 0.31	2.0 (2.2)	1.7
$\mathbf{N^*(1440)}$	1.5 ± 0.37	0.83 (3.63)	1.15
$\mathbf{N^*(1520)}$	1.8 ± 0.3	0.22 (0.27)	1.7
$\mathbf{N^*(1535)}$	0.152 ± 0.015	0.53 (0.53)	0.8
$\Delta(1600)$	0.24 ± 0.1	0.70 (0.14)	0.4
$\mathbf{\Delta(1620)}$	0.1 ± 0.03	0.60 (0.1)	0.2
$N^*(1650)$	0.81 ± 0.13	0.23 (0.24)	0.4
$N^*(1675)$	1.65 ± 0.27	2.26 (0.94)	1.2
$\mathbf{N^*(1680)}$	0.9 ± 0.15	0.21 (0.22)	1.2
$N^*(1720)$	4.41 ± 0.72	0.15 (0.14)	0.68
$\mathbf{\Delta(1700)}$	0.45 ± 0.16	0.1 (0.06)	0.35
$\Delta(1905)$	0.85 ± 0.53	0.1 (0.06)	0.25
$\mathbf{\Delta(1910)}$	0.38 ± 0.11	0.71 (0.14)	0.08
$\Delta(1950)$	0.1 ± 0.06	0.08 (0.1)	0.25

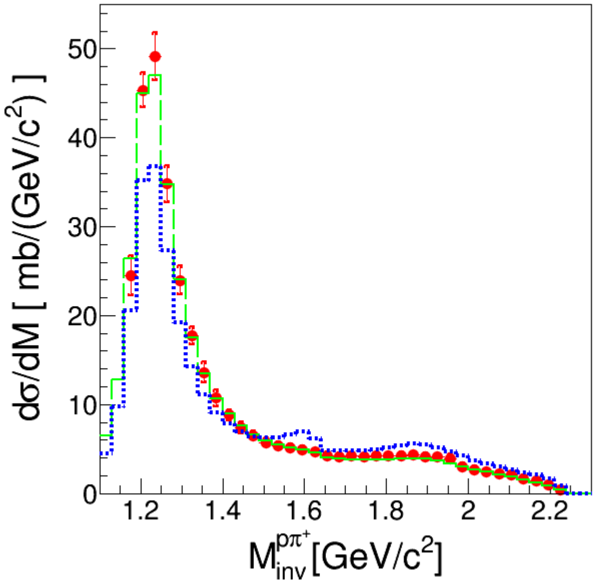


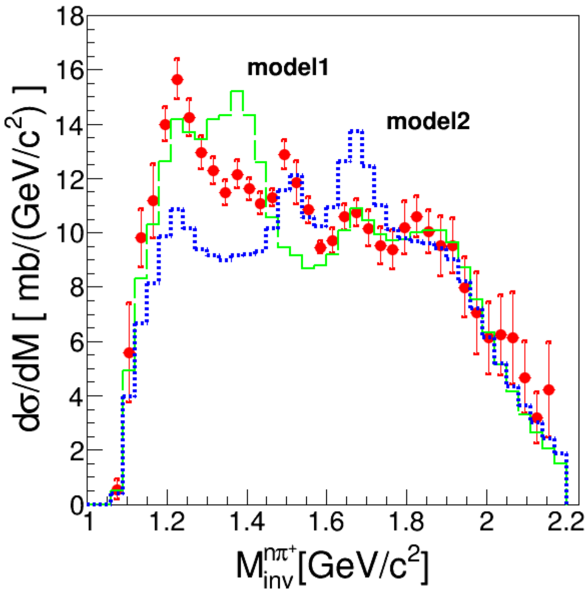
Z. Teis *et al.*,
Z. Phys. A**356** (1997) 421

J. Weil *et al.* (**GiBUU**)
Eur. Phys. J. A**48** (2012) 111

S.A. Bass *et al.* (**UrQMD**)
Prog. Part. Nucl. Phys. **41** (1998) 255

Cross sections (GiBUU – model1, UrQMD – model2)



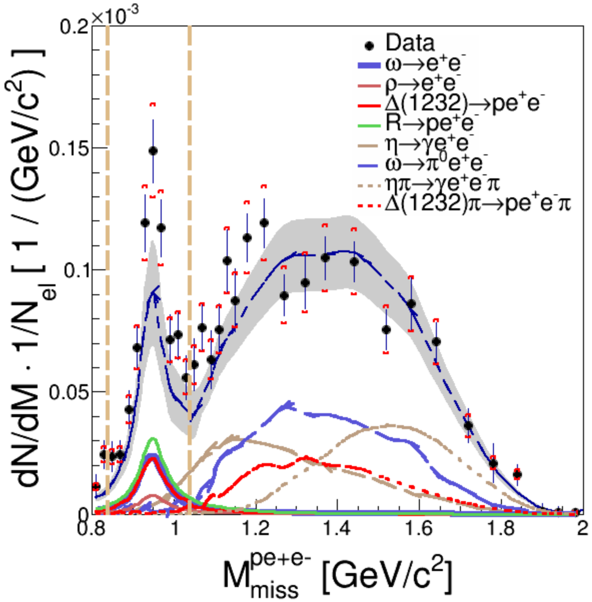


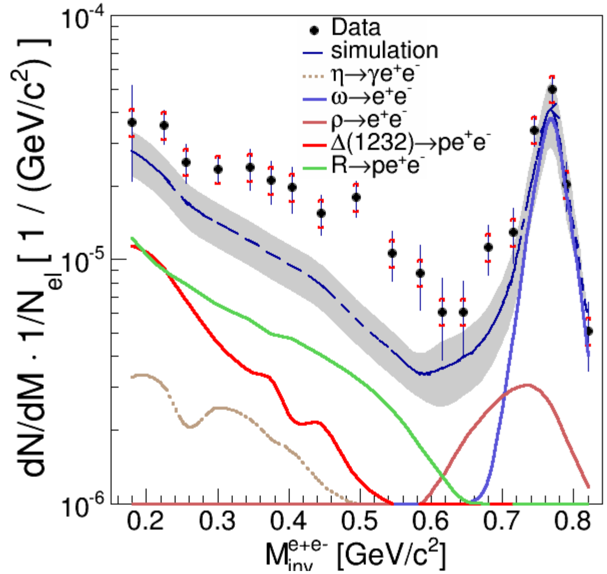
Resonances	HADES	Teis *et al.*	GiBUU	UrQMD
Δ(1232)	**2.53**			
N*(1440)	**1.5**			
N*(1520)	**1.8**			
N*(1535)	**0.15**			
Δ(1620)	**0.1**			
N*(1680)	**0.9**			
Δ(1700)	**0.45**			
Δ(1910)	**0.38**			

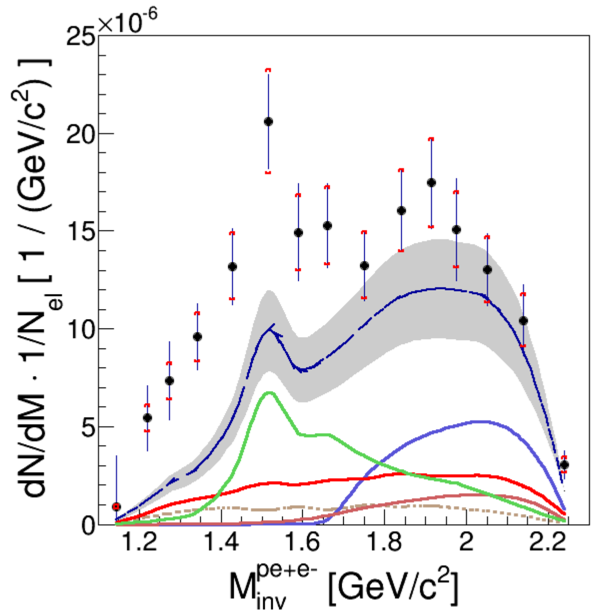
less	**similar**	**more**

Δ(1232) missing in UrQMD
N(1440) much more in GiBUU
N(1520) much less in GiBUU
N(1440) and N(1520) similar in UrQMD
N(1535) much larger in the transport codes
N(1680) overshoots in UrQMD

Exclusive p+p @ 3.5 GeV (dileptons)





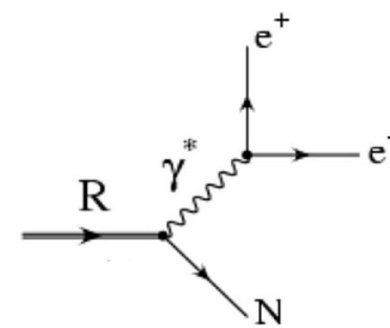


- ✓ constant eTTF
- ✓ no off shell coupling to vector mesons
- → lower limit for e^+e^- emission
- ✓ experimental σ for ω/ρ used
- ✓ missing yield related to low mass resonances

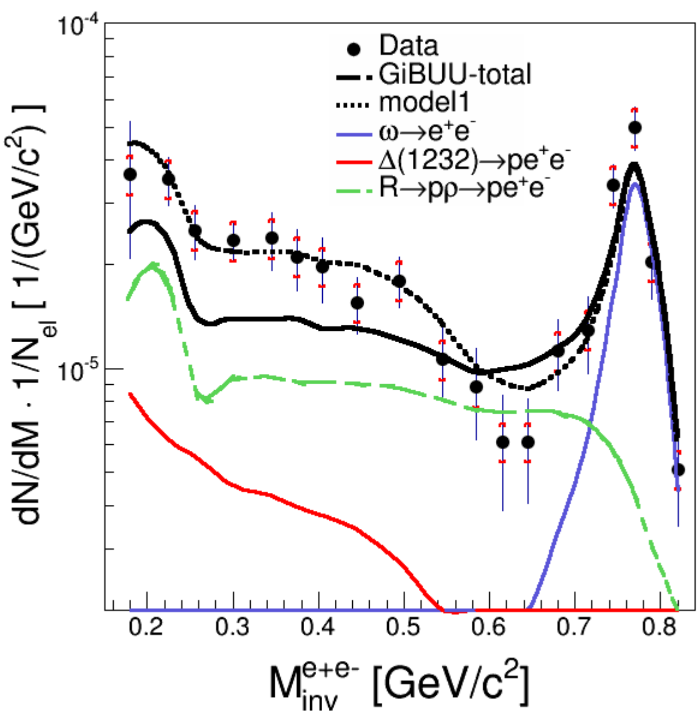
"QED model"

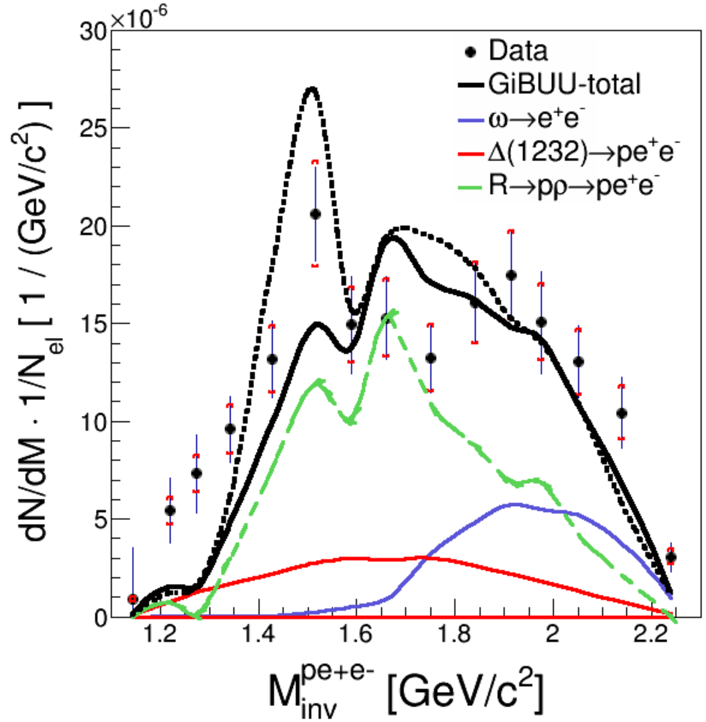
point-like R→Nγ* vertex

M. Zetenyi, G. Wolf
Phys. Rev. C**67** (2003) 044002



p+p @ 3.5 GeV (ρN coupling)





Branching ratios (in percent) for $R \to N\rho$

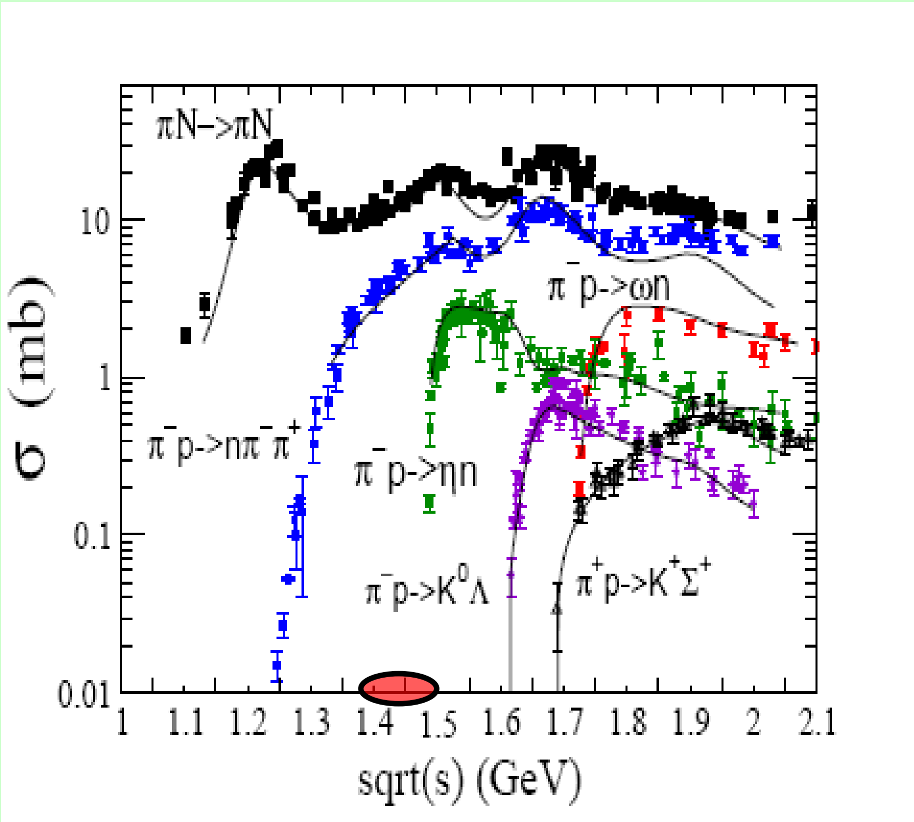
Resonances	GiBUU	UrQMD	KSU	BG	CLAS
$N^*(1520)$	21	15	20.9(7)	10(3)	13(4)
$\Delta(1620)$	29	5	26(2)	12(9)	16
$N^*(1720)$	87	73	1.4(5)	10(13)	-
$\Delta(1905)$	87	80	< 14	42(8)	-

KSU: M. Shresta, D.M. Manley
Phys. Rev. C**86** (2012) 055203

BG: A.V. Anisovich *et al*.
Eur. Phys. J. A**48** (2012) 15

CLAS: V. Mokeev *et al*.
Phys. Rev. C**86** (2012) 035203

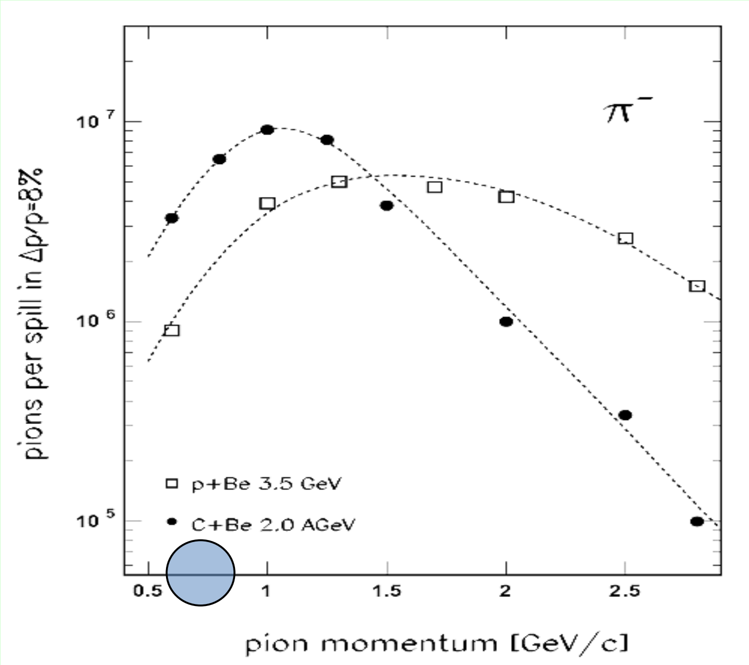
HADES physics for pion beams (2014)

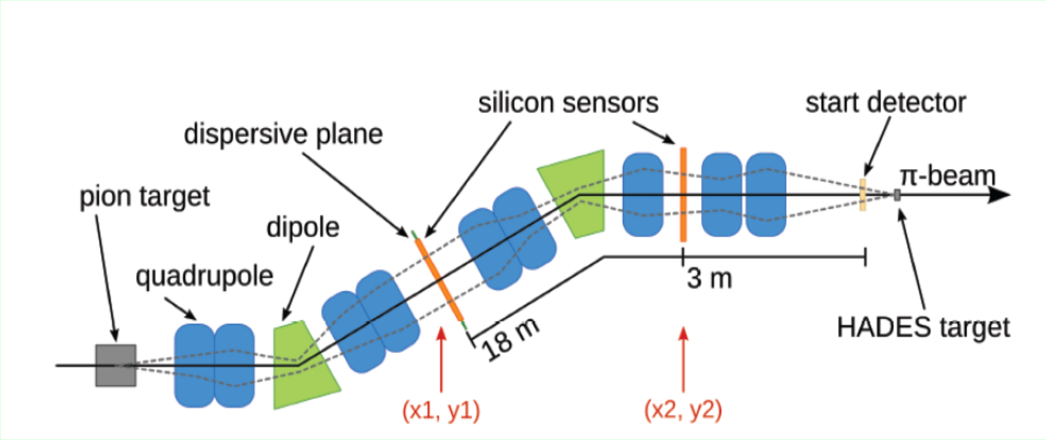


- improve the very scarce data base for pion-nucleon reactions
- differential distributions are even more scarse (or missing)

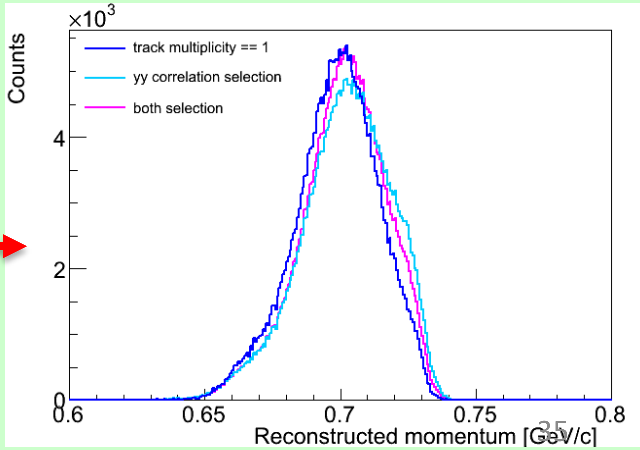
- resonance excitation can be controlled by the variation of the projectile (pion) momentum
- HADES starts with p = 0.656/0.69/0.748/0.8 GeV/c √s = 1.46-1.55 GeV: N(1520)
- $\pi^+\pi^-$ production: coupling of ρ to resonance
- most of data 1.3 < √s < 2 from Manley *et. al* PRD30 (1984) 904 based on 240.000 events (no differential distributions)
- e+e- never measured from pion induced reactions
- resonance Dalitz decays R→Ne+e- (reference for p+Nb)
- strangeness production of nucleus: $K^{\pm}$, K^0, φ

pion beam for HADES (2014)





- reaction: N+Be 8-10 · 10^{10} N_2 ions/spill (4s)
- secondary π^- with I ~ 3-4 · 10^5/spill @ 0.7 GeV/c
  - limited by the radioactivity safety
- pion momentum Δp/p =2.2% (σ) and ~50% acceptance @ central momentum
- in beam tracking system: (X1,Y1/X2,Y2) for pion momentum determination: Δp/p = 0.1%



tools & strategy & objectives

* analysis of single and double meson production in photon- and pion-induced reactions

$$\gamma p \rightarrow \pi N, \eta N, K\Lambda, K\Sigma, \pi\pi N, \pi\eta N$$

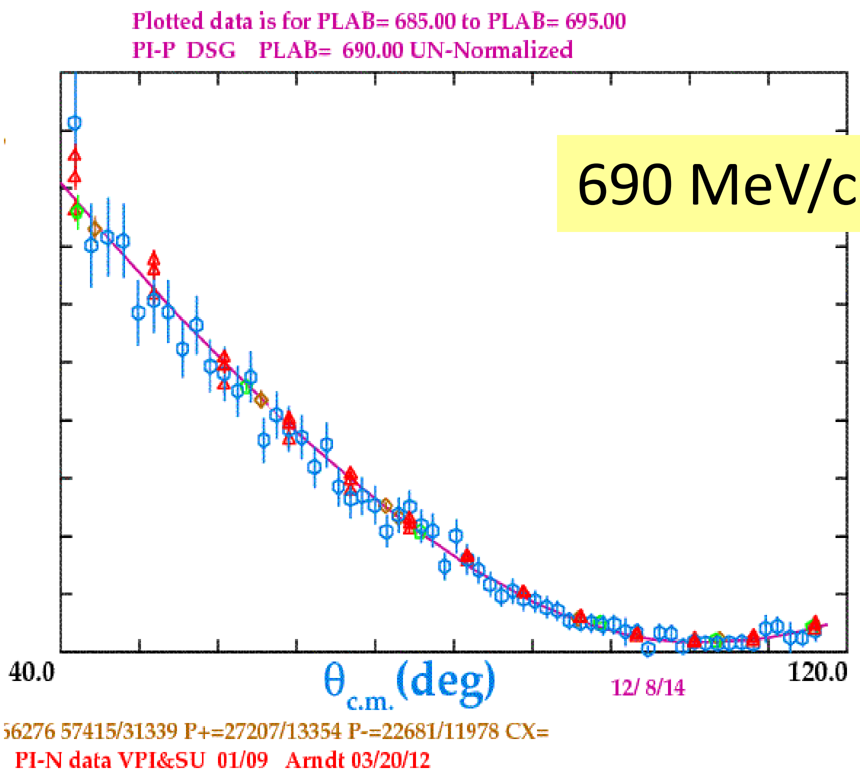
$$\pi N \rightarrow \pi N, \eta N, K\Lambda, K\Sigma, \pi\pi N$$

* energy dependent approach
* partial wave aplitude parametrization (poles: BW – i.e. energy depentend)
* combined analysis of lareg number of reactions
* D-matrix analysis

* $\pi^- p$ measured with: **$(CH_2)_n$** polyethylene target, **PE** and carbon (**C**) target
* four beam momenta: **656**, **690** (large statistics), **748**, **800** MeV/c
* elastic scattering
  - identification: $\pi^- p \rightarrow \pi^- p$
  - events from C target identified in PE events
  - comparison with SAID database & solution
  - luminosity extraction : $N_{beam} \otimes \rho \, d_{targ}$
  - absolute normalization of other channels via σ_{el}/N_{el}
* two-pion identification in channel: $n\pi^+\pi^-$ (exclusive channel via missing mass)
  - partial wave analysis focused on N(1520) and **ρ** production
* dilepton identification in channel: ne^+e^- (quasi-exclusive channel)
  - baryon resonance Dalitz decays and two-body **ρ** decay

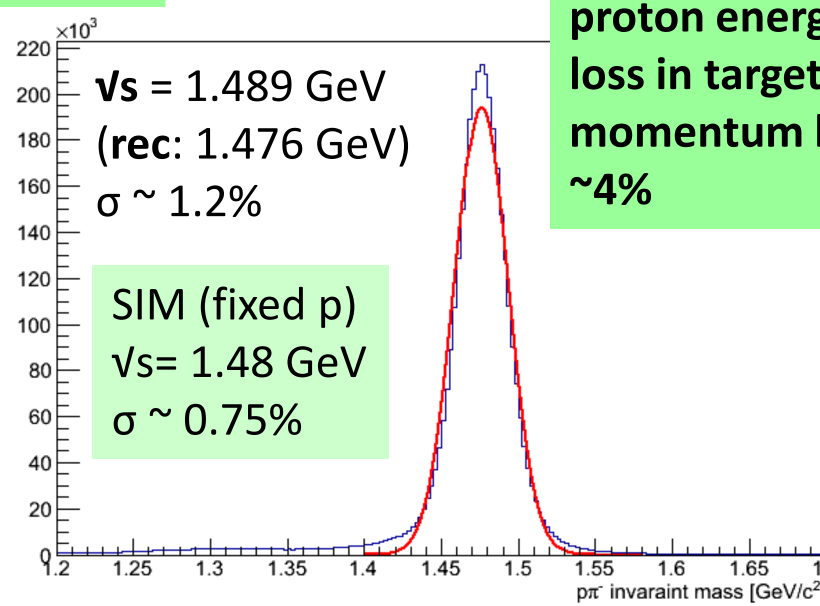
elastic scattering – SAID database

http://gwdac.phys.gwu.edu/analysis/pin_analysis.html

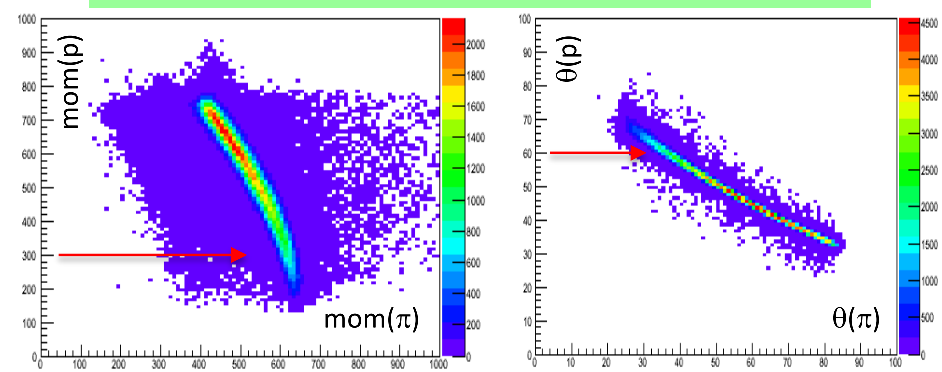


$\sigma(60^0 < \Theta_{CM} < 110^0) = \mathbf{3.07\ mb}$

proton energy loss in target momentum loss ~4%

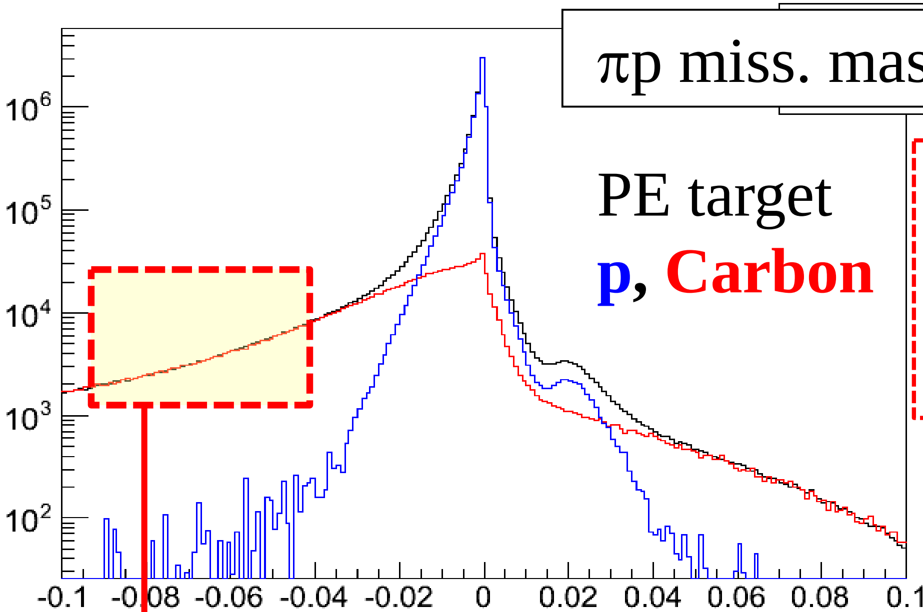


very slow protons p < 300 MeV/c at polar angles $\theta > 60^o$ ($\theta_{CM} < 60^o$)

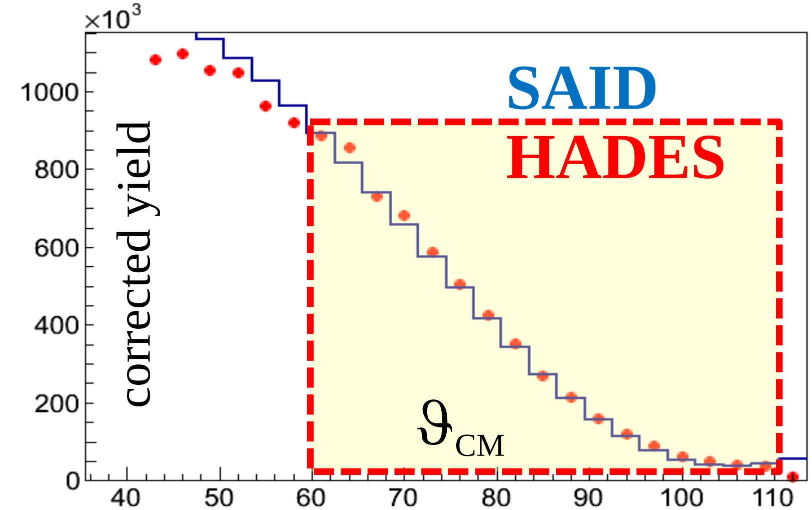


elastic events – comparison to SAID

690 MeV/c



- based on phasespace MC simulation: acc & eff correction
- exp normalized to the same area for **$60^o < \theta_{CM} < 110^o$**



- C subtraction
- C low missing mass tail scaled down to fit PE tail (blue)

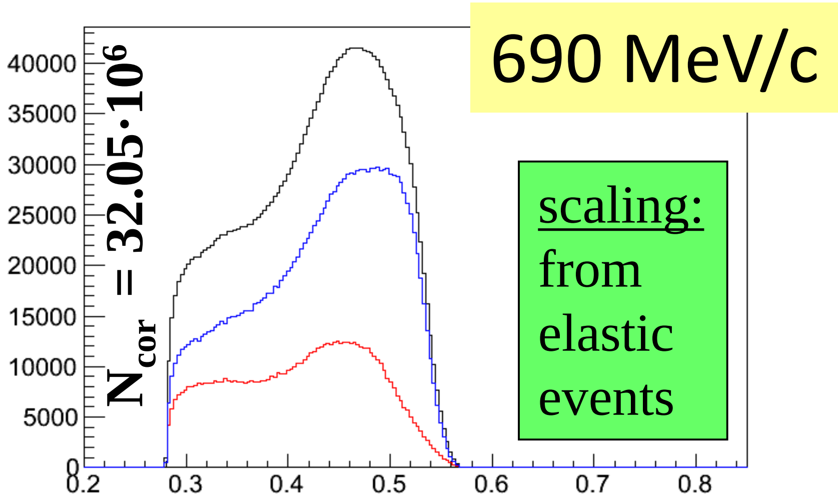
$$(\rho d)^{proton}_{target} = 4 \cdot 10^{23}\ at/cm^2$$

$$\mathbf{N_{el} = 32.05 \cdot 10^6 = N_{beam}\ \rho\, d\, \sigma_{el}}$$

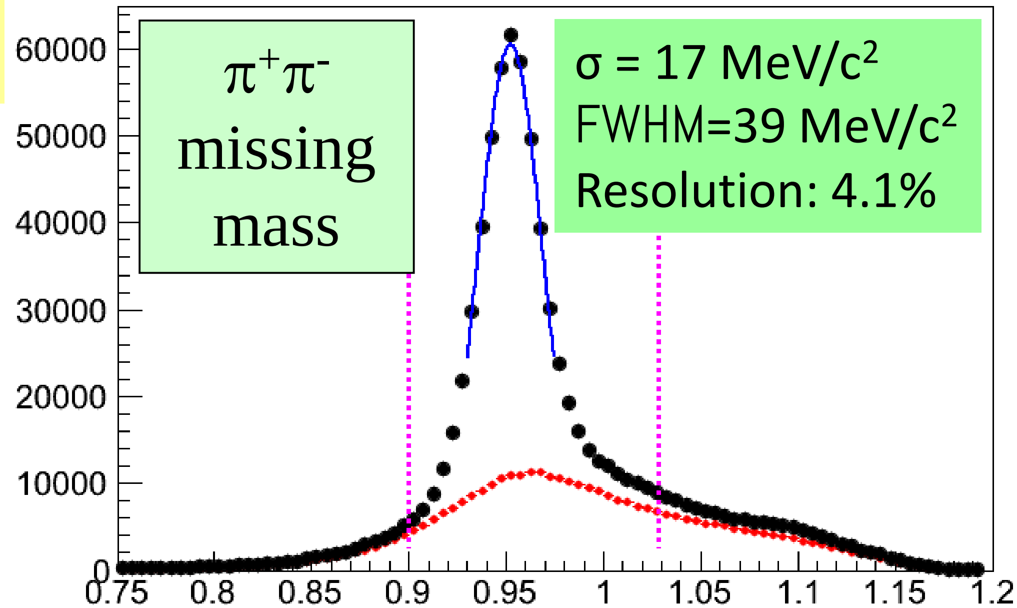
$$\mathbf{N_{beam} = 2.61 \cdot 10^{10}}$$

$$\mathbf{N_{norm} = 3.07\ mb\ /\ 32.05 \cdot 10^6}$$

C subtraction, $\pi^+\pi^-$ – reconstruction



$\pi^+\pi^-$ invariant mass



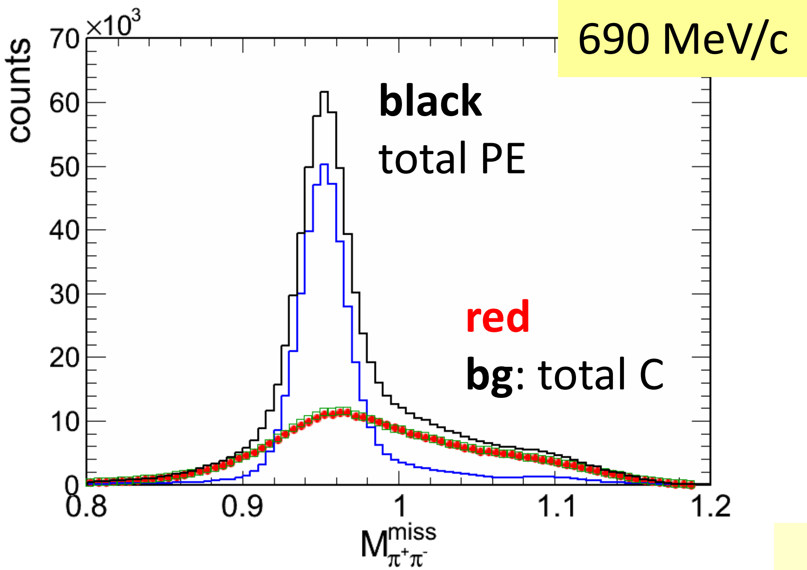
red: 35-42% C background (quasi-free πp)
peak shift due to energy loss in a target

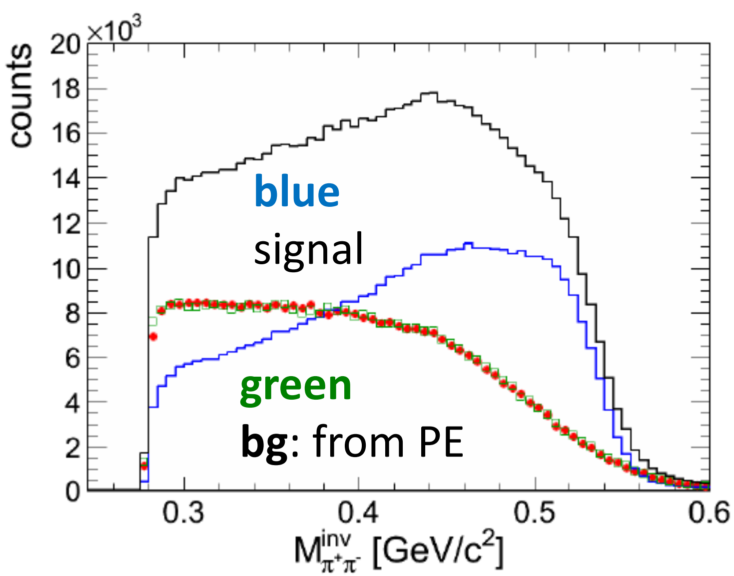
p [MeV/c]	N_{ev} (PE) x 10^6	σ [mb]
656	42.64	**0.856**
690	878.38	**0.858**
748	41.85	**0.842**
800	42.08	**0.889**

π+π- cross section (uncorrected) within the HADES acceptance

reduction on acc * eff for
π+π- phasespace mc: 5.3 – 6.3 times

(n $\pi^+\pi^-$) – events with signal extracted





- **goal**: separate signal (**π^-p**) from background (**π^-C**) based on PE events and C events
- relative normalization of PE events and C events deduced from **π^-p** elastic scattering

procedure: event from C **correlated** with event from PE based on χ^2 (miss. mass + momentum of π^+, π^-, n)

PWA done with:

✓ **four ππ data samples from HADES**

✓ **photon- and pion-induced reactions**

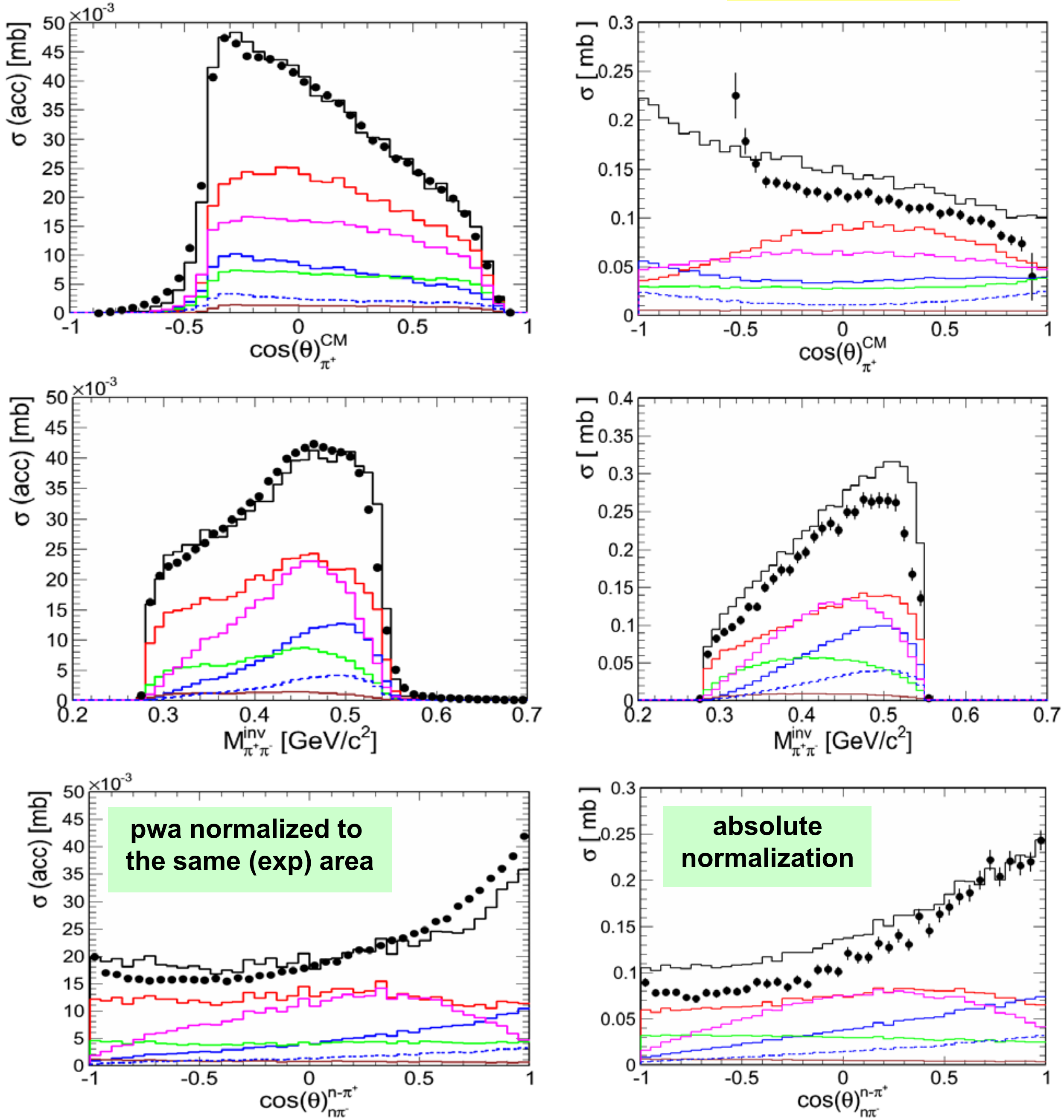
PWA results ($n\ \pi^+\pi^-$) example projections

690 MeV/c

very preliminary!

in the acceptance

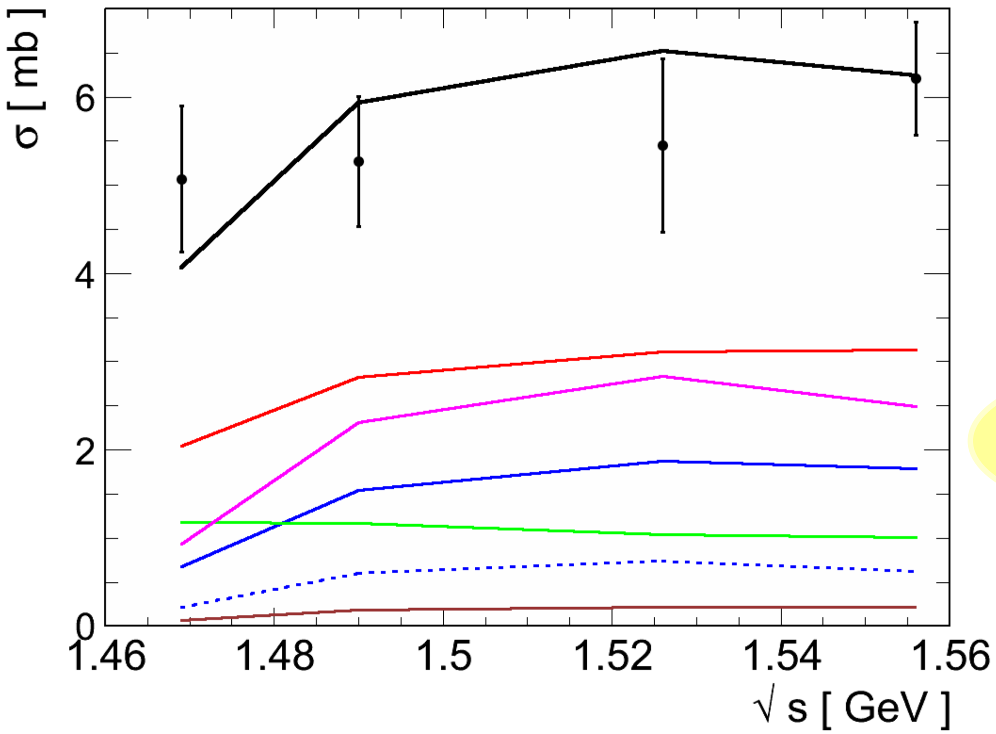
in the 4π



LEGEND

- Δ(1232)π
- N(1520)
- ρN
- ρN(939)
- σN(939)
- N(1400)π

PWA results (n $\pi^+\pi^-$) – cross section



PWA solution describes cross section with

20% uncertainty

very preliminary!

LEGEND

- Δ(1232)π
- N(1520)
- ρN (dashed)
- ρN(939)
- σN(939)
- N(1400)π

in this energy range cross sections: 5-7 mb (*Landolt-Börnstein* Database)

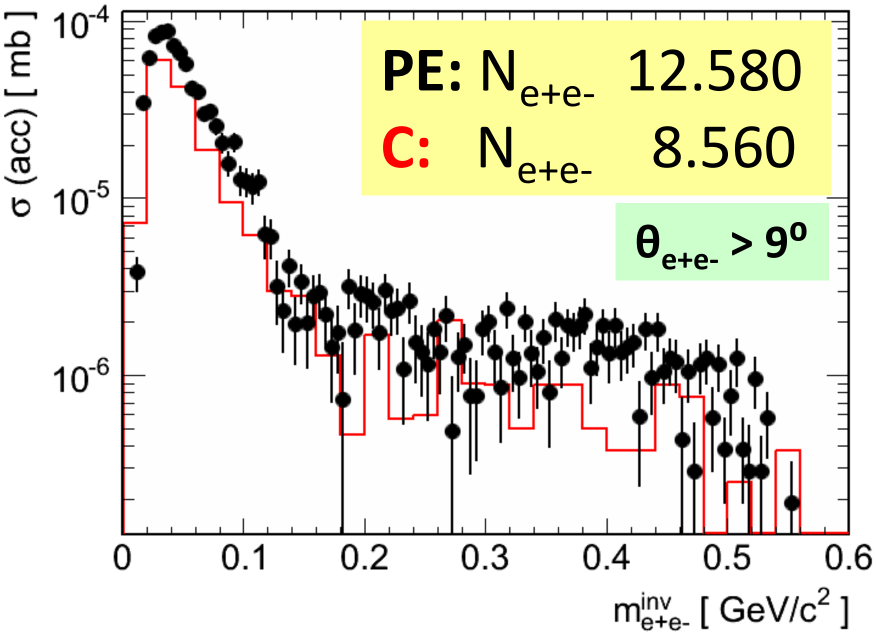
USEFUL INFORMATION FOR DILEPTON ANALYSIS

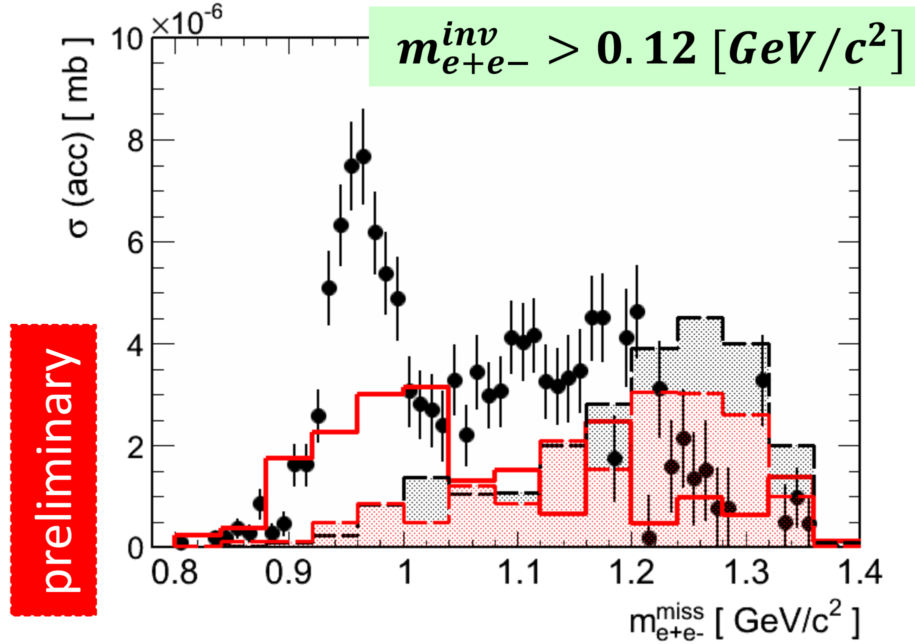
N(1520)D_{13} coupling to **ρN**: **24-26%**

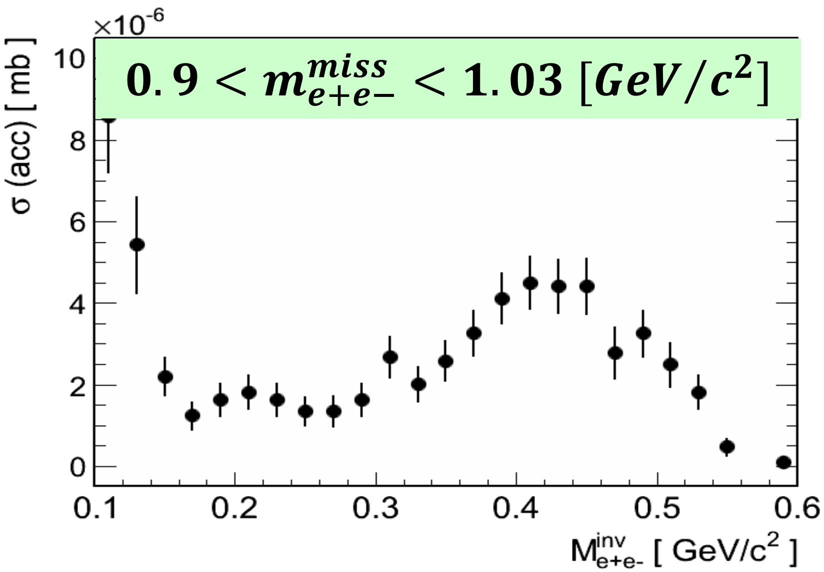
Total **ρN** contribution: **1.54 mb** (for 690 MeV/c)

Manley PWA analysis (Phys. Rev. D**30** (1984) 904) predicted much more!

e^+e^- invariant / missing mass







black dots – **PE** data (**e^+e^- signal**)
red – **C** data (scaling based on elastic events)
black dashed – **PE** combinatorial background
red dashed – **C** combinatorial background

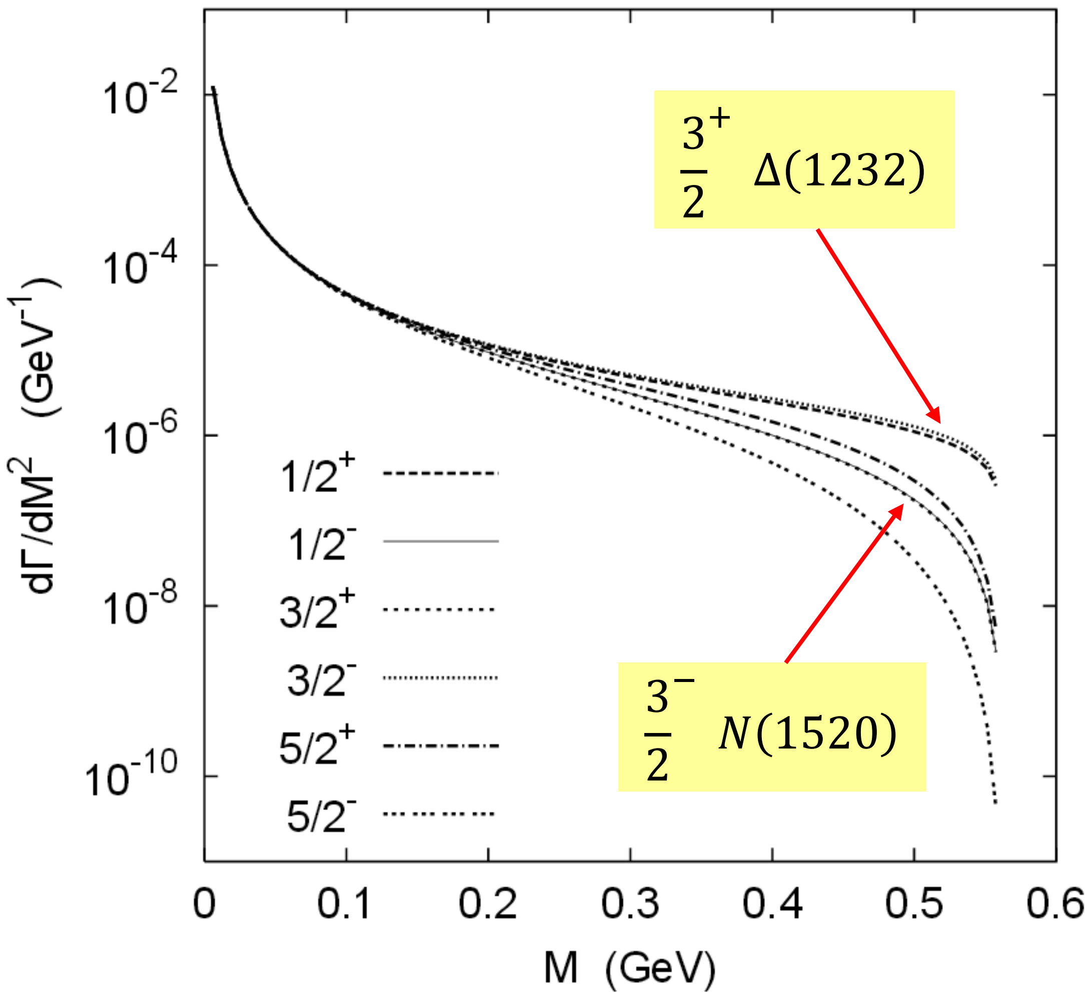
Signal inside missing mass cut:

PE: 700 counts, **C: 400** counts

C contribution in **PE: 50-58%**

Baryon resonances Dalitz decays

huge effect of spin-parity of baryon resonances for their Dalitz decays at high masses



M. Zetenyi, G. Wolf
Phys. Rev. C **67** (2003) 044002

differential Dalitz-decay width of hypothetical resonances with the same mass and photonic width but with different spin-parities

Witold Przygoda (NSTAR 2015)

e^+e^- simulated cocktail

LEGEND

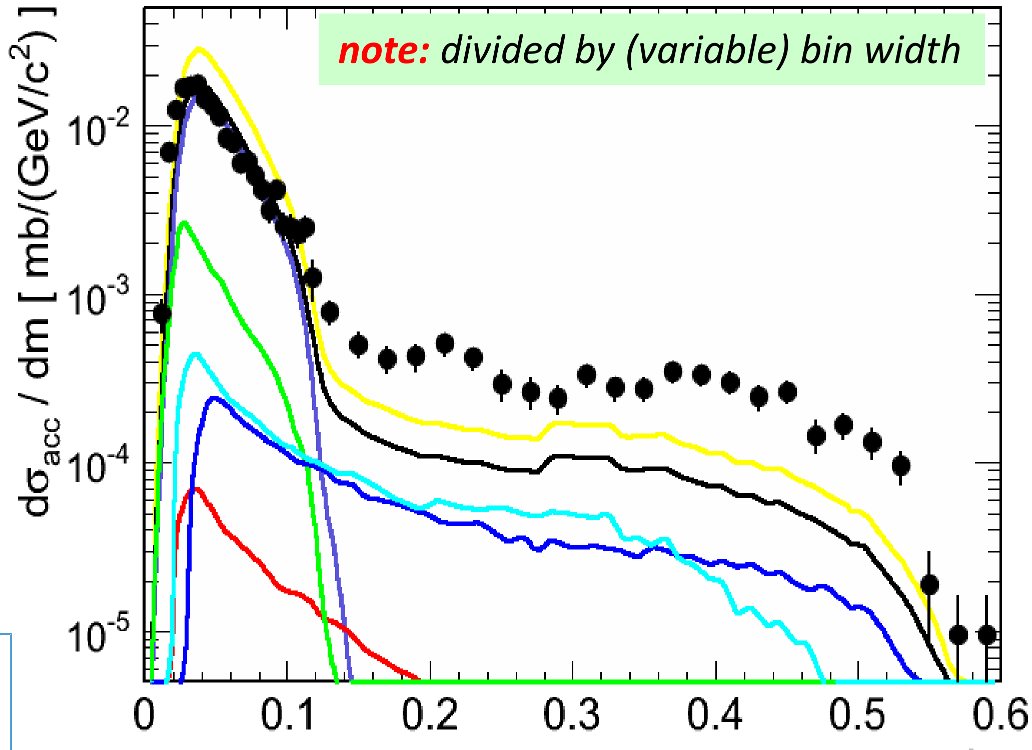
- total — total (scaled to π^0)
- [9.2 mb] $\pi^0 \rightarrow e^+e^-\gamma$
- [7.4 mb] $2{*}\pi^0(\rightarrow e^+e^-\gamma)$
- [1.0 mb] $\eta \rightarrow e^+e^-\gamma$
- [20.5 mb] $N(1520) \rightarrow n\, e^+e^-$
- [8.4 mb] $\Delta(1232) \rightarrow n\, e^+e^-$

CS need to be multiplied by BR

Branching Ratios

$\boldsymbol{\pi^0}$: 0.012, $\boldsymbol{\eta}$: 0.006

$\mathbf{N(1520)}$: $4 \cdot 10^{-5}$, $\mathbf{\Delta(1232)}$: $4 \cdot 10^{-5}$



preliminary

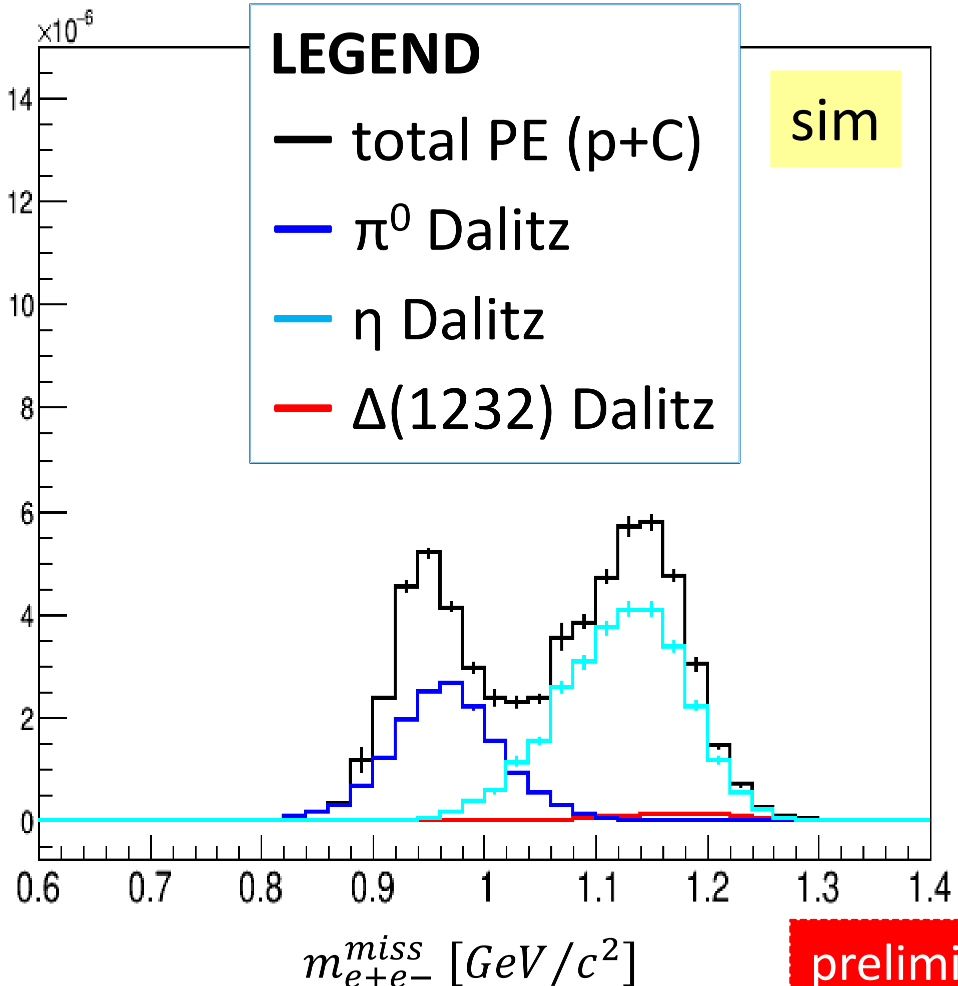
Dilepton cocktail

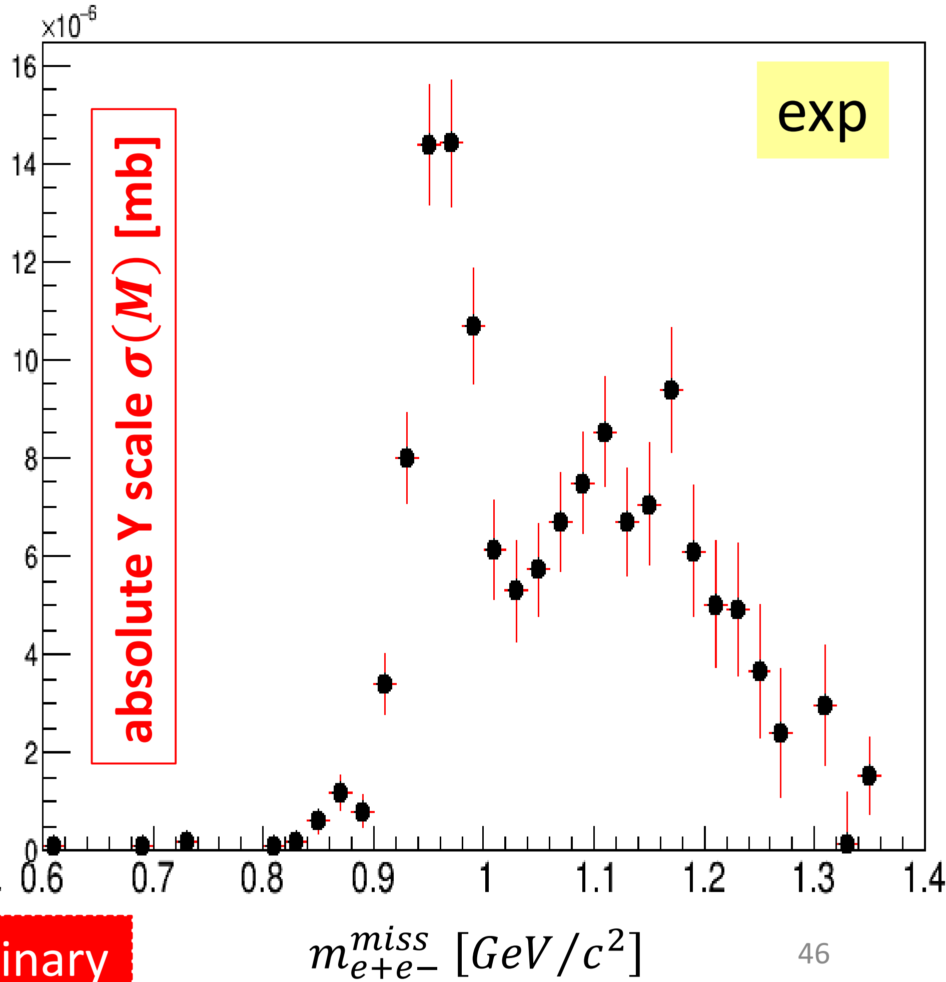
- **PLUTO event generator** Ingo Fröhlich *et al.* PoS ACTA2007 (2007) 076 **+ (acc * eff) filters** (includes realistic momentum distribution of nucleons in carbon)

e^+e^- cocktail PE target (no ρ)

missing mass for $m^{inv}_{e+e-} > 0.12\ [GeV/c^2]$

components are shown only for carbon contribution



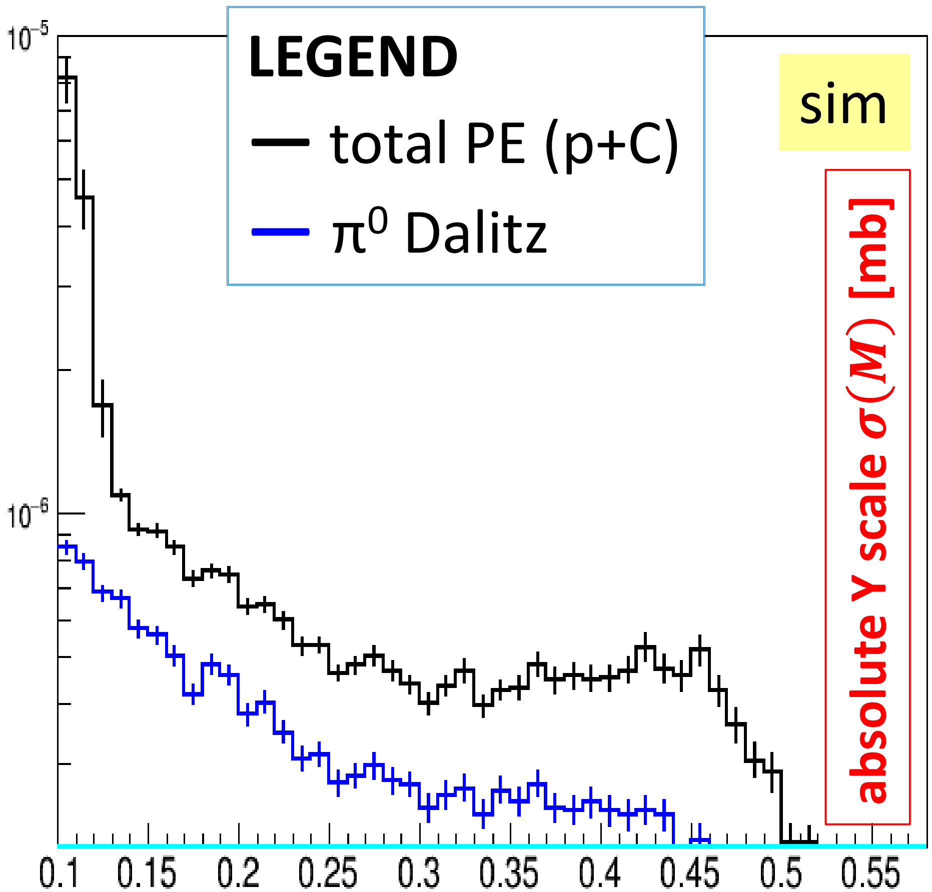


preliminary

e^+e^- cocktail PE target (no ρ)

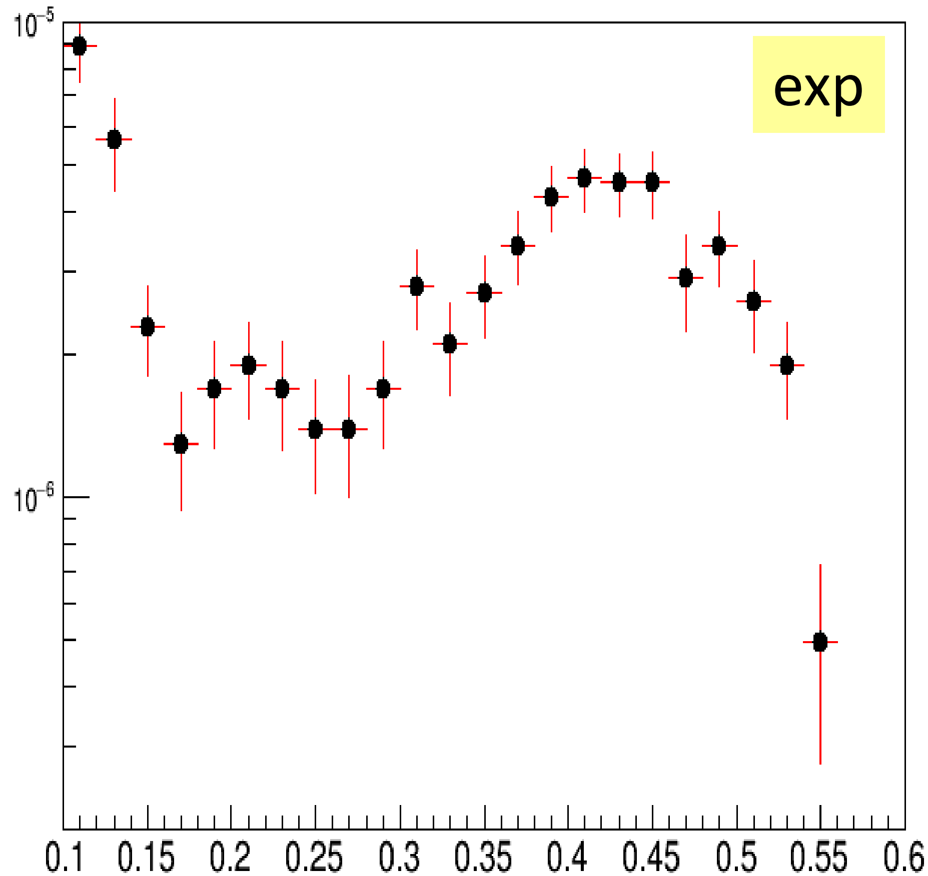
invariant mass for $0.9 < m_{e+e-}^{miss} < 1.03\ [GeV/c^2]$

components are shown only for carbon contribution



$m_{e+e-}^{inv}\ [GeV/c^2]$

preliminary

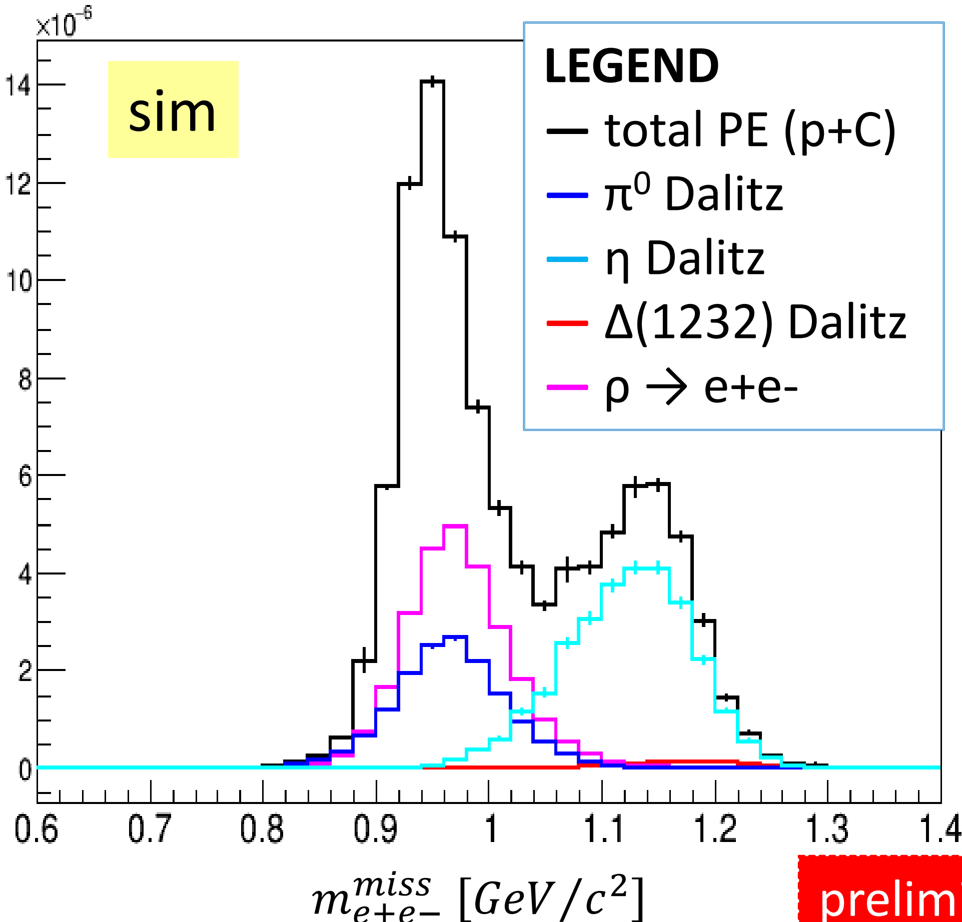


$m_{e+e-}^{inv}\ [GeV/c^2]$

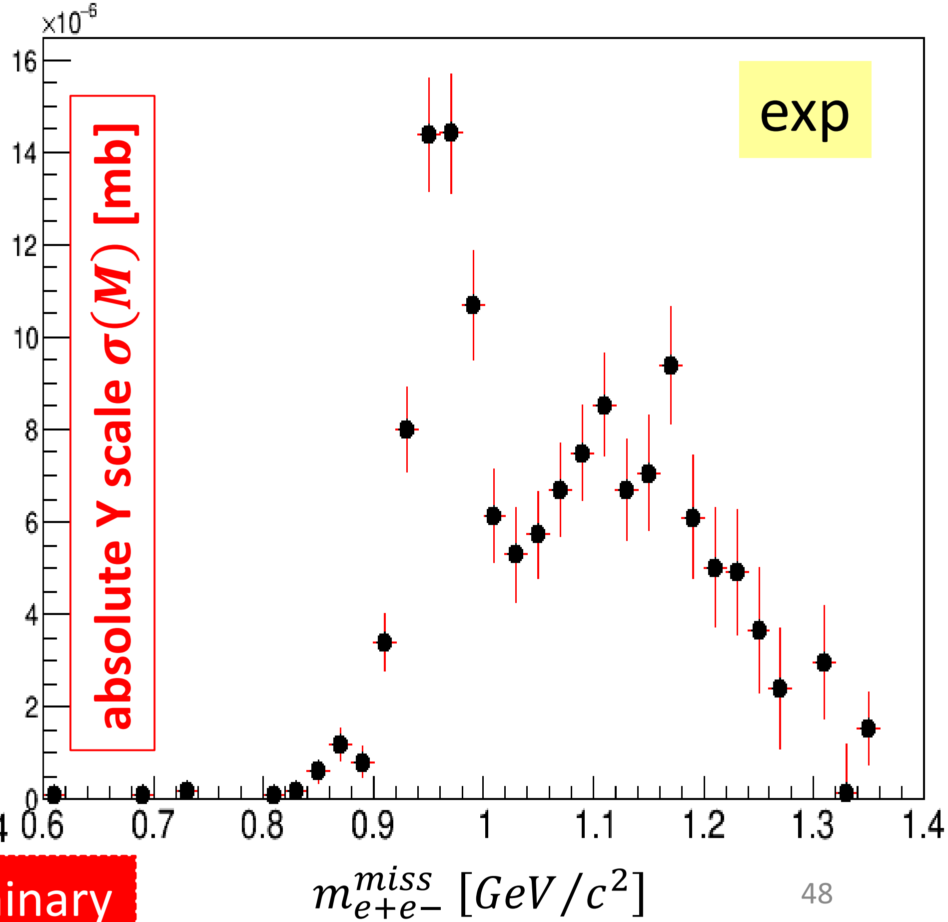
e^+e^- cocktail PE target (with ρ)

missing mass for $m^{inv}_{e+e-} > 0.12\ [GeV/c^2]$

- **contribution from $\pi^+\pi^-$ channel (PWA analysis): cross section 1.54 mb**
- **VDM scaling $\sim 1/M^3$ → much higher BR than the value at the pole**



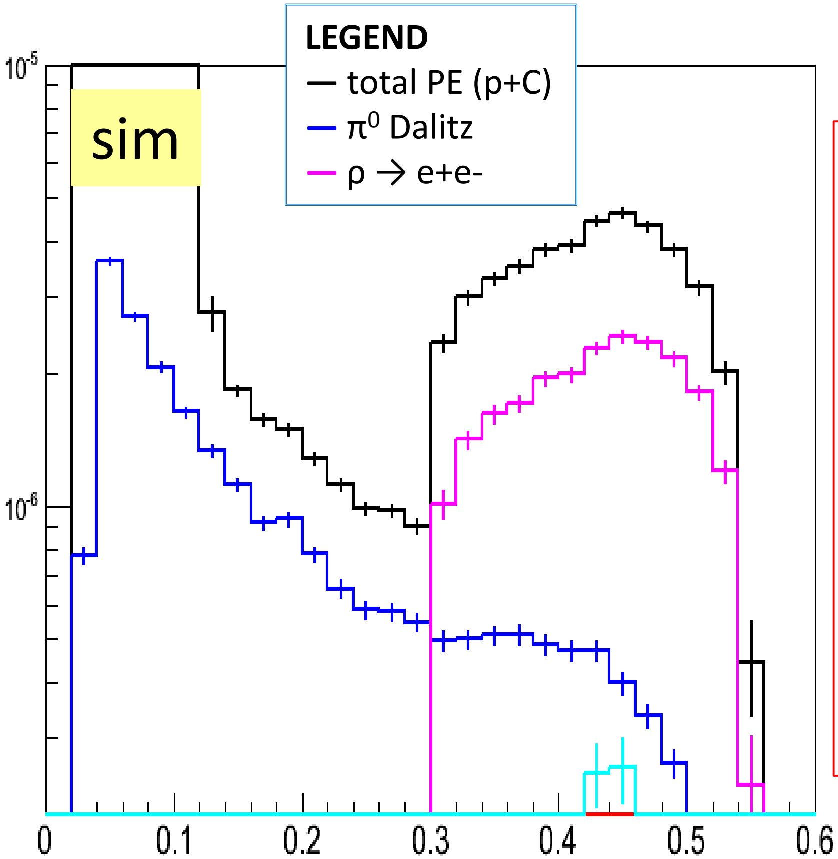
preliminary



e^+e^- cocktail PE target (with ρ)

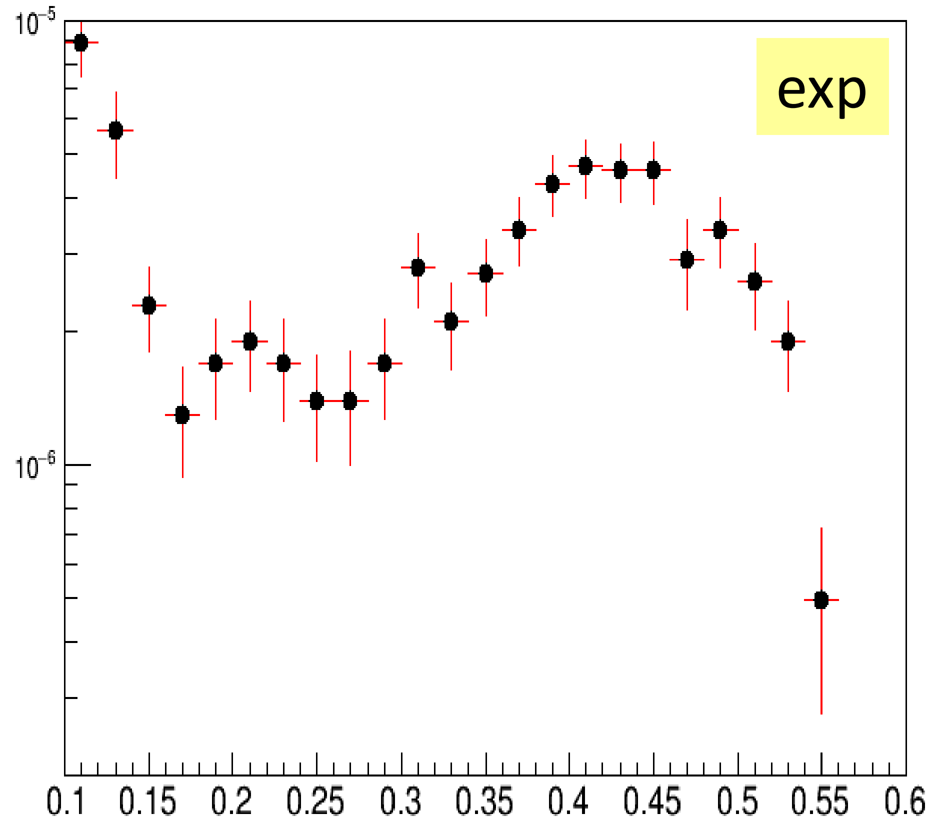
invariant mass for $0.9 < m^{miss}_{e+e-} < 1.03\ [GeV/c^2]$

components are shown only for carbon contribution



$m^{inv}_{e+e-}\ [GeV/c^2]$

absolute Y scale $\sigma(M)$ [mb]



$m^{inv}_{e+e-}\ [GeV/c^2]$

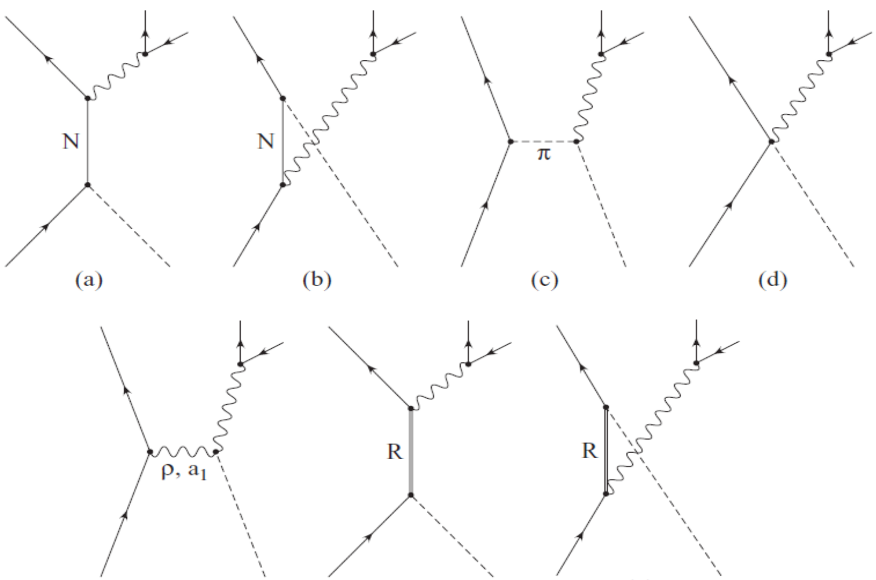
preliminary

Dilepton production in pion-nucleon collisions in an effective field theory approach

Miklós Zétényi* and György Wolf†

We present a model of electron-positron pair production in pion-nucleon collisions in the exclusive reaction $\pi N \to N e^+ e^-$. The model is based on an effective field theory approach, incorporating 16 baryon resonances below 2 GeV. Parameters of the model are fitted to pion photoproduction data. We present the resulting dilepton invariant mass spectra for $\pi^- p$ collisions up to $\sqrt{s} = 1.9$ GeV center-of-mass collision energy. These results are meant to give predictions for the planned experiments at the HADES spectrometer in GSI, Darmstadt.

Phys. Rev. C **86** (2012) 065209



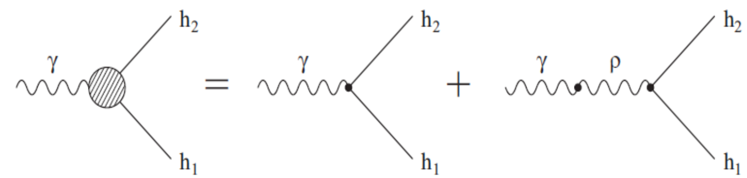
Feynman diagrams contributing to the proces

$\pi + N \to N + e^+ + e^-$

a) s- **b)** u- **c)** t-channel diagrams **d)** contact interaction term

e) vector meson exchange diagram

f) s- **g)** u-channel baryon resonance contributions

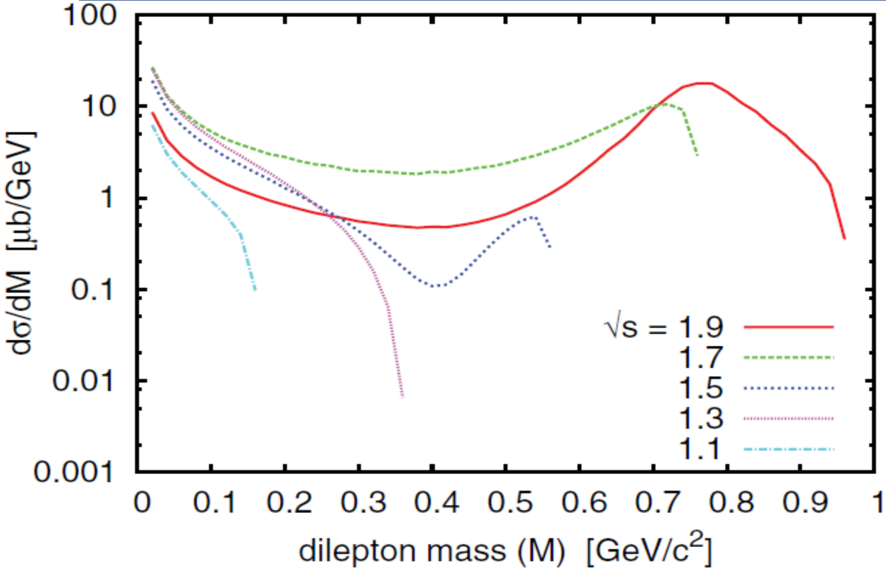


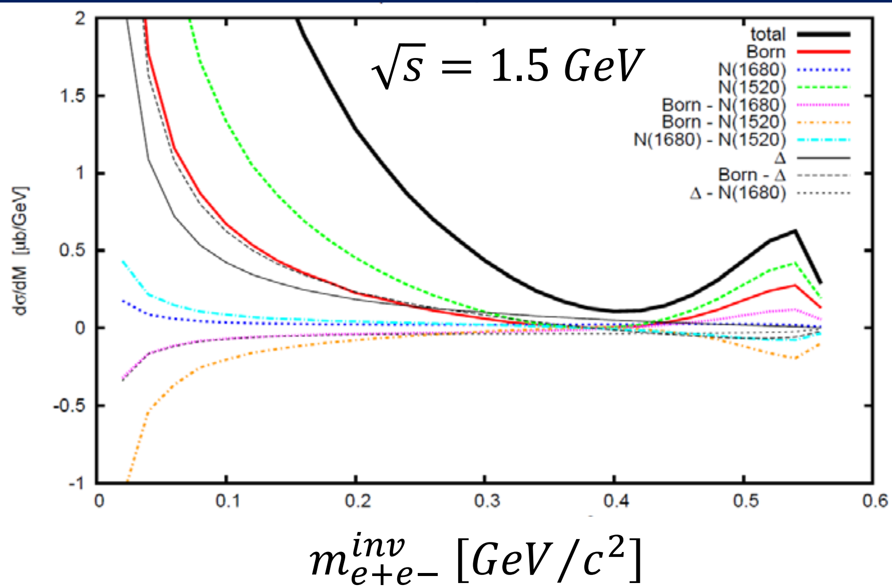
VMD form factor:

$$F_{\mathrm{VMD}}(k^2) = -\frac{e}{g_\rho} \frac{k^2}{k^2 - m_\rho^2 + i\sqrt{k^2}\,\Gamma_\rho(k^2)}$$

k^2 instead of m_ρ^2

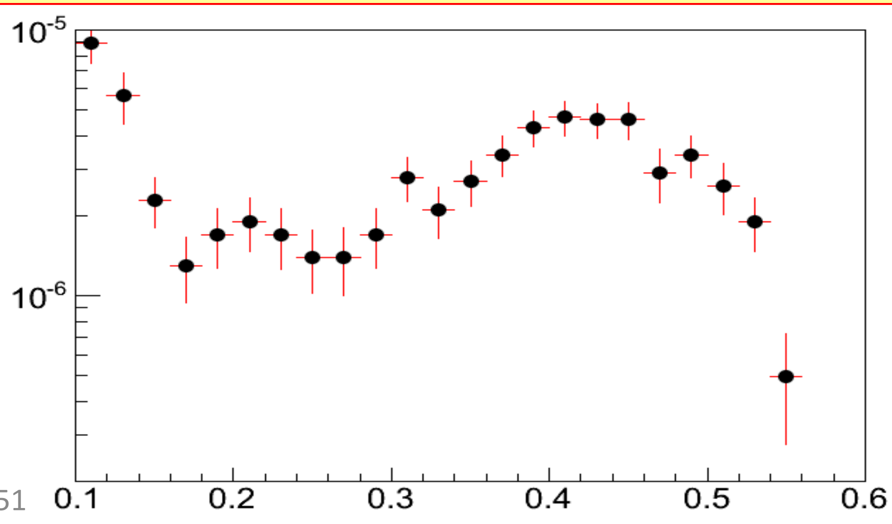
e^+e^- in effective field theory approach

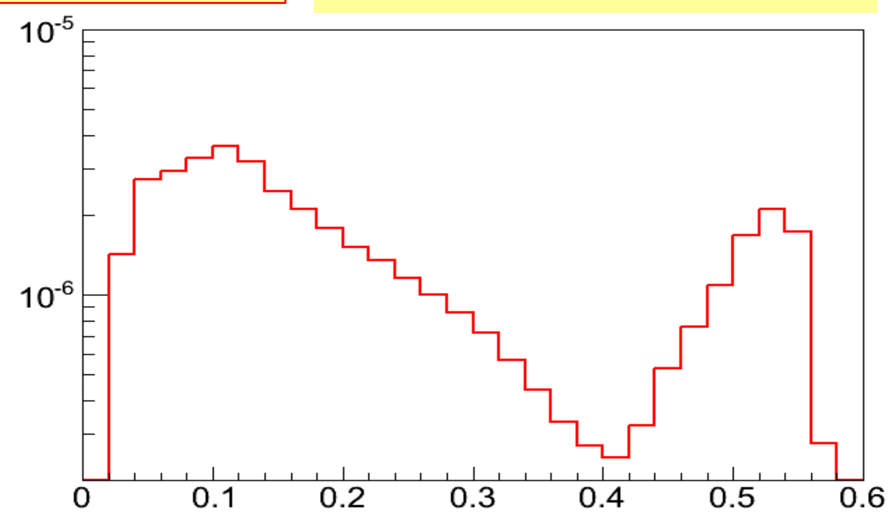




Zetenyi & Wolf: higher $\sqrt{s} = 1.5\ GeV\ (\boldsymbol{\pi^- p})$
HADES: $\sqrt{s} = 1.492\ GeV(\boldsymbol{\pi^- p})$ and $\sqrt{s} = 1.461\ GeV(\boldsymbol{\pi^- C})$

Folding the model with 1-dim (acc*eff) curve:





SUMMARY

- resonance production in NN and πN via exclusive chanels within PWA (Bonn-Gatchina approach)
- selective study of e^+e^- production from Dalitz decay of resonances $\rightarrow$ *sensitivity to baryonic resonances*
- time-like electromagnetic structure / coupling to ρN

Recent pion beam experiment:

- very promising data: $\pi^+\pi^-$ and e^+e^-
- expected determination of N(1520) coupling to ρN
- ruling on controversial yield predictions (destructive interferences ω/ρ)
- continuation at SIS18 in 2017-18

CREDITS

The HADES Collaboration

Special thanks to **Andrey V. Sarantsev** (Bn-Ga group)

BACKUP SLIDES

e^+e^- cocktail ingredients "cookbook"

- **contributions from $\pi^- p$ and $\pi^- C$ added together (ratio 1 : 2** experimentally deduced**)**

$\pi^- p$ mom. **0.69 GeV/c (√s=1.492 GeV)** $\pi^- C$ average **√s=1.461 GeV (**mom. **0.65 GeV/c)**

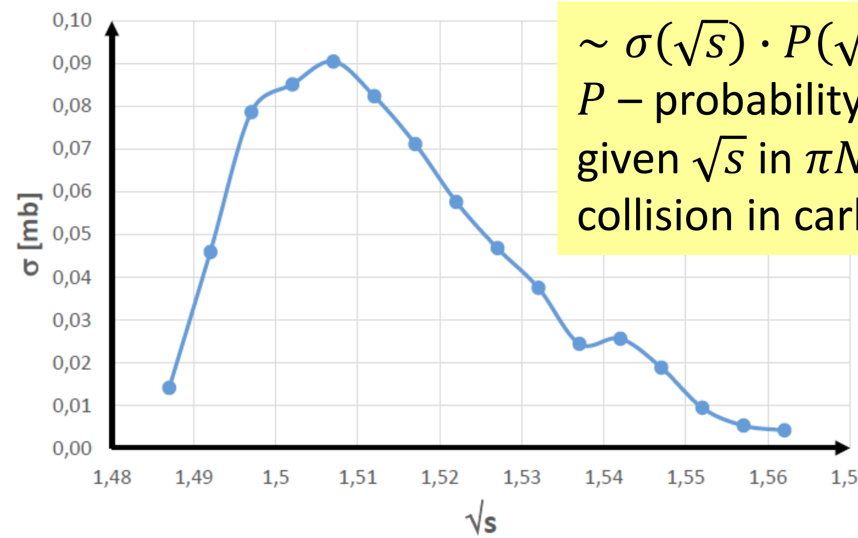
channel	σ [mb]	data source	Model
π^0 *Dalitz* from: $\pi^- p \to n\pi^0$	**9.2**	Landolt-Börnstein constant (±1 mb) for 0.6 < p < 0.72 GeV/c	$N(1520) - 45\%$ $N(1440) - 45\%$ $N(1535) - 10\%$
single π^0 *Dalitz* from: $\pi^- p \to n\pi^0\pi^0$ $\pi^- p \to p\pi^-\pi^0$	2 x **1.8** **3.72** sum**: 7.4**	Crystal Ball Landolt-Börnstein (for √s = 1.461 GeV 20% reduction)	$\Delta\pi^0 \to (N\pi)\pi^0$ $\to (N\pi)e^+e^-\gamma$
Δ *Dalitz* from: $\pi^- p \to \Delta\pi$	**8.4**	From single and double pion (isospin relations)	$\Delta^0\pi^0 \to ne^+e^-\pi^0$
N(1520) *Dalitz* from: $\pi^- p \to N(1520)$	**20.5**	Phys. Rev. C**86**, 065209 (2012)	Wolf / Zetenyi "QED" model (pole) **BR = 4.0 · 10^{-5}** $N(1520) \to ne^+e^-$
η *Dalitz* from: $\pi^- p \to n\eta$	**0.3 (p)** **0.7 (C)**	Parameterization from Landolt-Börnstein (see next slide)	

η contribution (mainly from C)

Landolt-Börnstein

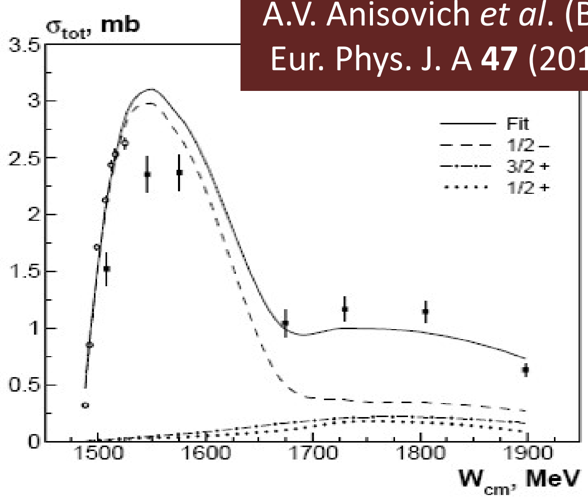
bin	sqrt(s)	p(sqrt(s))	XS_eta	product
98	1,487	4,70E-02	0,3	0,0141
99	1,492	5,10E-02	0,9	0,0459
100	1,497	4,47E-02	1,76	0,078672
101	1,502	3,87E-02	2,2	0,08514
102	1,507	3,74E-02	2,42	0,090508
103	1,512	3,05E-02	2,7	0,08235
104	1,517	2,48E-02	2,87	0,071176
105	1,522	1,96E-02	2,94	0,057624
106	1,527	1,56E-02	3	0,0468
107	1,532	1,21E-02	3,1	0,03751
108	1,537	7,88E-03	3,1	0,024428
109	1,542	8,00E-03	3,2	0,0256
110	1,547	5,88E-03	3,2	0,018816
111	1,552	2,94E-03	3,2	0,009408
112	1,557	1,64E-03	3,2	0,005248
113	1,562	1,29E-03	3,2	0,004128
			SUM	**0,697408**

η cross section in π-C at 0.69 GeV/c



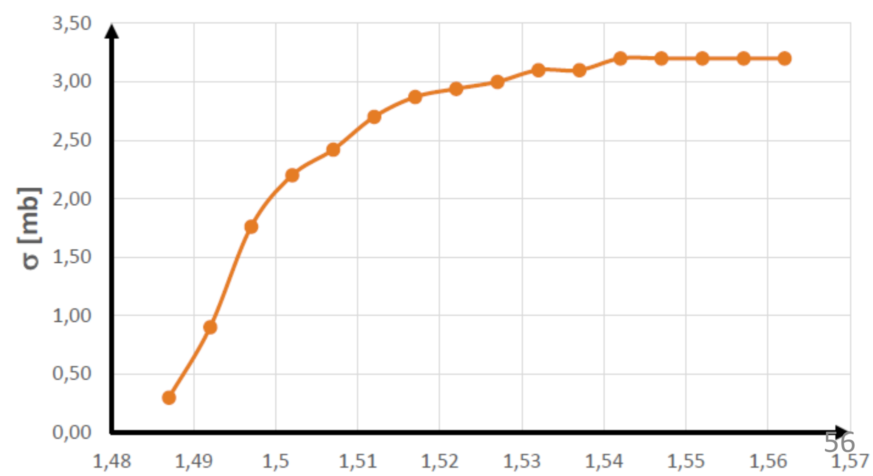
$\sim \sigma(\sqrt{s}) \cdot P(\sqrt{s})$
P – probability of given $\sqrt{s}$ in πN collision in carbon

A.V. Anisovich *et al.* (Bn-Ga)
Eur. Phys. J. A **47** (2011) 27



parameterization

η cross section in π-p



ρ contribution (off-shell)

- **contribution from $\pi^+\pi^-$ channel (PWA analysis): cross section 1.54 mb**
  - **VDM predicts scaling $\sim 1/M^3$ resulting in much higher BR as compared to the value at pole**

Line #1

mass	rho_XS	VDM (1/m3)	product
3,04E-01	4,19E-03	15,61366255	6,55E-02
3,14E-01	1,05E-02	14,20091609	1,49E-01
3,26E-01	1,68E-02	12,66505858	2,12E-01
3,37E-01	2,10E-02	11,50844232	2,41E-01
3,48E-01	2,52E-02	10,41514376	2,62E-01
3,59E-01	3,14E-02	9,455788455	2,97E-01
3,68E-01	3,14E-02	8,842060636	2,78E-01
3,81E-01	3,77E-02	7,96530894	3,01E-01
3,90E-01	4,19E-02	7,382426161	3,10E-01
4,01E-01	5,03E-02	6,813086495	3,43E-01
4,11E-01	5,56E-02	6,301052508	3,50E-01
4,24E-01	6,18E-02	5,73892679	3,55E-01
4,34E-01	6,60E-02	5,360496552	3,54E-01
4,46E-01	8,07E-02	4,959360928	4,00E-01
4,57E-01	9,01E-02	4,597528169	4,14E-01
4,67E-01	1,01E-01	4,314782768	4,34E-01
4,78E-01	1,07E-01	4,013707862	4,29E-01
4,90E-01	1,15E-01	3,739926802	4,31E-01
5,00E-01	1,16E-01	3,50778875	4,08E-01
5,12E-01	1,19E-01	3,278724205	3,92E-01
5,21E-01	1,22E-01	3,098015318	3,77E-01
5,33E-01	1,22E-01	2,903650904	3,53E-01
5,43E-01	1,07E-01	2,73782466	2,93E-01
5,54E-01	9,75E-02	2,584269529	2,52E-01
5,66E-01	7,23E-02	2,42132848	1,75E-01
5,77E-01	2,94E-02	2,281757596	6,70E-02
5,89E-01	7,34E-03	2,152336802	1,58E-02
SUM	**1,74E+00**		**7,96E+00**

Landolt-Börnstein

$$|\mathcal{M}(\pi^+\pi^- \to \rho^0 \to e^+e^-)|^2 = \frac{m_\rho^2 \Gamma_{\pi^+\pi^-} \Gamma_{e^+e^-}}{(s - m_\rho^2)^2 + m_\rho^2 \Gamma_\rho^2}$$

$$\Gamma_{e^+e^-} = bk / M^3_{e^+e^-}$$

even 4 times more