Study of baryonic resonances in the channel $pp \rightarrow pp\pi^+\pi^-$ @ E=3.5 GeV with HADES

Amel Belounnas for the HADES Collaboration

École Doctorale PHENIICS Doctoral School

IPN Institut de Physique Nucléaire Orsay

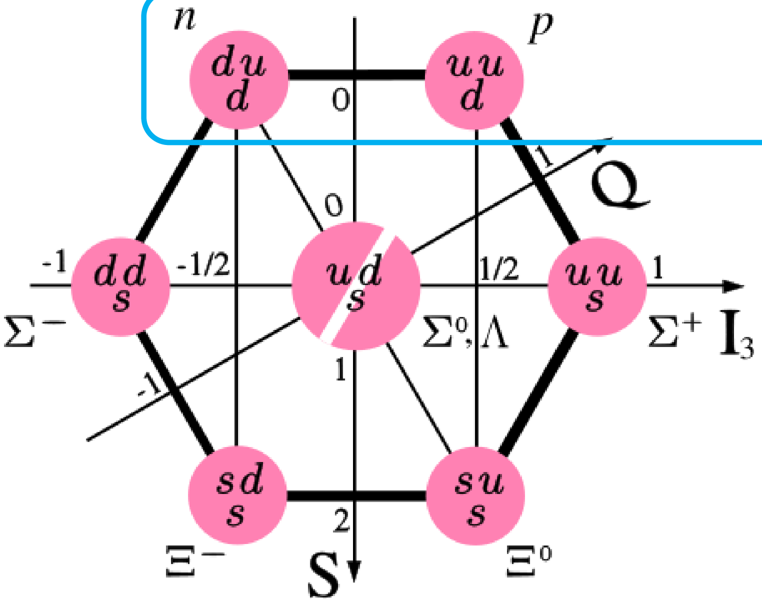
Université Paris Sud

1.
Introduction

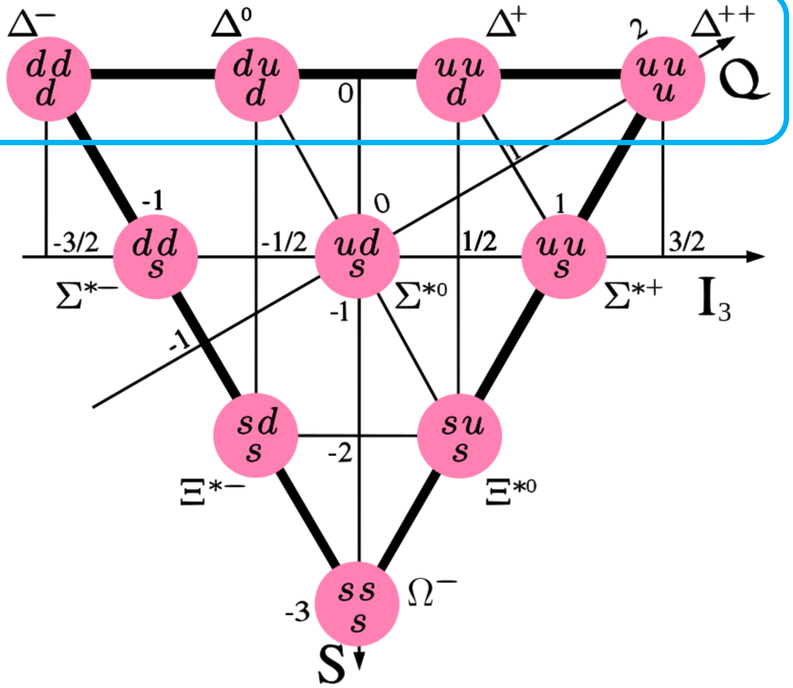
N* and Δ Baryonic Resonances

Short-lived excited states of nucleons

J= 1/2 Baryon Octuplets



J= 3/2 Baryon Decuplets



N* and Δ Baryonic Resonances

Actual state

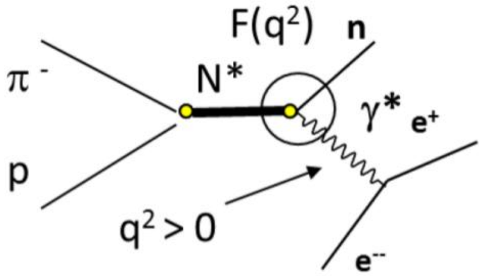
Particle	J^P	overall	$N\gamma$	$N\pi$	$N\eta$	$N\sigma$	$N\omega$	ΛK	ΣK	$N\rho$	$\Delta\pi$
N	$1/2^+$	****									
$N(1440)$	$1/2^+$	****	****	****		***				*	***
$N(1520)$	$3/2^-$	****	****	****	***					***	***
$N(1535)$	$1/2^-$	****	****	****	****					**	*
$N(1650)$	$1/2^-$	****	****	****	***			***	**	**	***
$N(1675)$	$5/2^-$	****	****	****	*			*		*	***
$N(1680)$	$5/2^+$	****	****	****	*	**				***	***
$N(1700)$	$3/2^-$	***	**	***	*			*	*	*	***
$N(1710)$	$1/2^+$	****	****	****	***		**	****	**	*	**
$N(1720)$	$3/2^+$	****	****	****	***			**	**	**	*
$N(1860)$	$5/2^+$	**		**						*	*
$N(1875)$	$3/2^-$	***	***	*			**	***	**		***
$N(1880)$	$1/2^+$	**	*	*		**		*			
$N(1895)$	$1/2^-$	**	**	*	**			**	*		
$N(1900)$	$3/2^+$	***	***	**	**		**	***	**	*	**
$N(1990)$	$7/2^+$	**	**	**					*		
$N(2000)$	$5/2^+$	**	**	*	**			**	*	**	
$N(2040)$	$3/2^+$	*		*							
$N(2060)$	$5/2^-$	**	**	**	*				**		
$N(2100)$	$1/2^+$	*		*							
$N(2120)$	$3/2^-$	**	**	**				*	*		
$N(2190)$	$7/2^-$	****	***	****			*	**		*	
$N(2220)$	$9/2^+$	****		****							
$N(2250)$	$9/2^-$	****		****							
$N(2300)$	$1/2^+$	**		**							
$N(2570)$	$5/2^-$	**		**							
$N(2600)$	$11/2^-$	***		***							
$N(2700)$	$13/2^+$	**		**							

Particle	J^P	overall	$N\gamma$	$N\pi$	$N\eta$	$N\sigma$	$N\omega$	ΛK	ΣK	$N\rho$	$\Delta\pi$
$\Delta(1232)$	$3/2^+$	****	****	****	F						
$\Delta(1600)$	$3/2^+$	***	***	***	o					*	***
$\Delta(1620)$	$1/2^-$	****	***	****		r				***	***
$\Delta(1700)$	$3/2^-$	****	****	****		b				**	***
$\Delta(1750)$	$1/2^+$	*		*		i					
$\Delta(1900)$	$1/2^-$	**	**	**			d		**	**	**
$\Delta(1905)$	$5/2^+$	****	****	****			d		***	**	**
$\Delta(1910)$	$1/2^+$	****	**	****			e		*	*	**
$\Delta(1920)$	$3/2^+$	***	**	***				n	***		**
$\Delta(1930)$	$5/2^-$	***		***							
$\Delta(1940)$	$3/2^-$	**	**	*	F						
$\Delta(1950)$	$7/2^+$	****	****	****	o				***	*	***
$\Delta(2000)$	$5/2^+$	**				r					**
$\Delta(2150)$	$1/2^-$	*		*		b					
$\Delta(2200)$	$7/2^-$	*		*		i					
$\Delta(2300)$	$9/2^+$	**		**			d				
$\Delta(2350)$	$5/2^-$	*		*			d				
$\Delta(2390)$	$7/2^+$	*		*			e				
$\Delta(2400)$	$9/2^-$	**		**				n			
$\Delta(2420)$	$11/2^+$	****	*	****							
$\Delta(2750)$	$13/2^-$	**		**							
$\Delta(2950)$	$15/2^+$	**		**							

Study of baryons with HADES

Electromagnetic Dalitz Decay:

$R \rightarrow Ne^+e^-$ (never measured before)
(predicted BR: ~ 10^{-5})



Interest: electromagnetic structure of baryonic resonances
EM time-like form factor (eTFF).

Hadronic Decay:

Two body: $R \rightarrow N\pi$, $R \rightarrow \Lambda K$

Three body: $R \rightarrow N\pi\pi$
$R \rightarrow \Delta\pi \rightarrow N\pi\pi$
$R \rightarrow N\rho \rightarrow N\pi\pi$

Interest: Improve database for baryon spectroscopy.

HADES

Nope, not this one…!

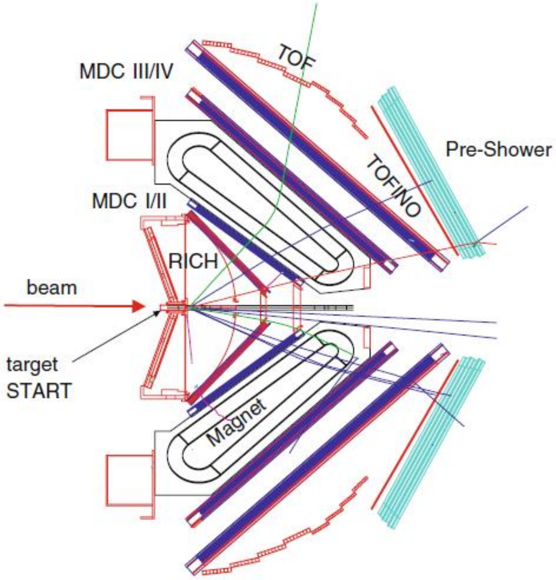
HADES

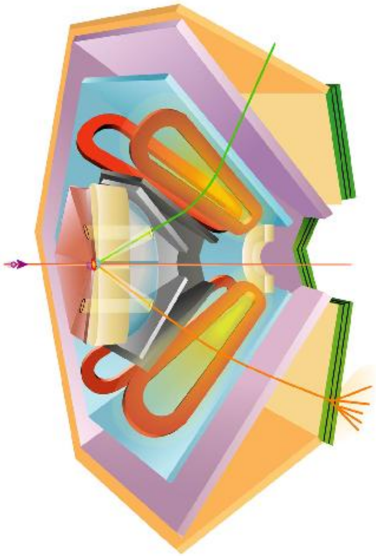
High Acceptance
DiElectron Spectrometer
(GSI, Darmstadt)

- **Acceptance:** Azimuthal angles 85% (6 sectors) polare angles: 18° - 85°
- **Detected particles:** $e^{\pm}$, p, $\pi^{\pm}$, $K^{\pm}$
- Tracking: MDC
- $e^{\pm}$ identification with RICH, TOF/PreShower
- p, $\pi^{\pm}$, $K^{\pm}$ identification TOF-Tracking

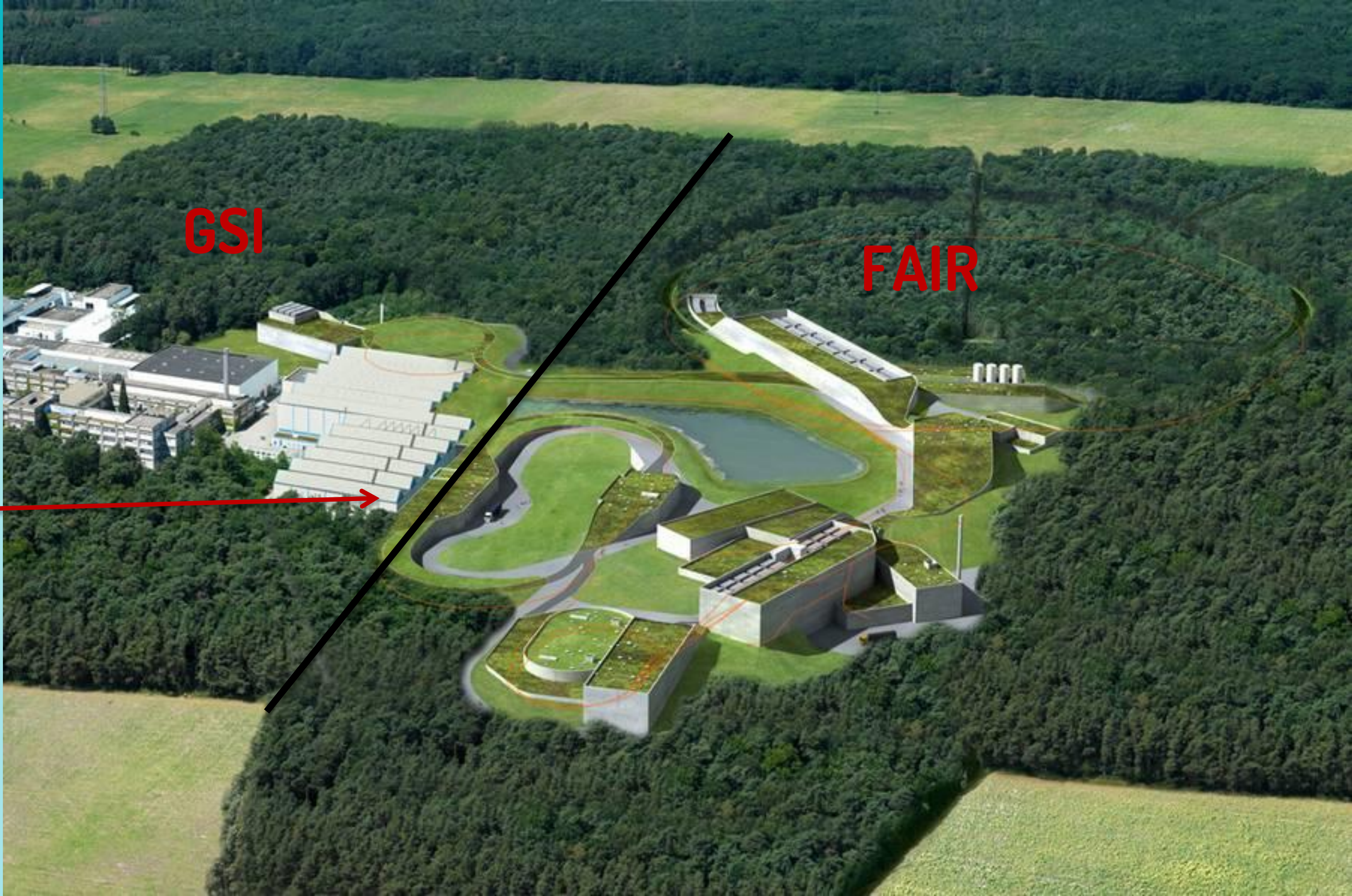
Mission

- Study of hadronic matter in A-A, p-A, π-A collisions.
- Study of baryonic resonances in p-p, d-p, and p- π collisions. (Baryon (N*, Δ) spectroscopy)





HADES
is here!

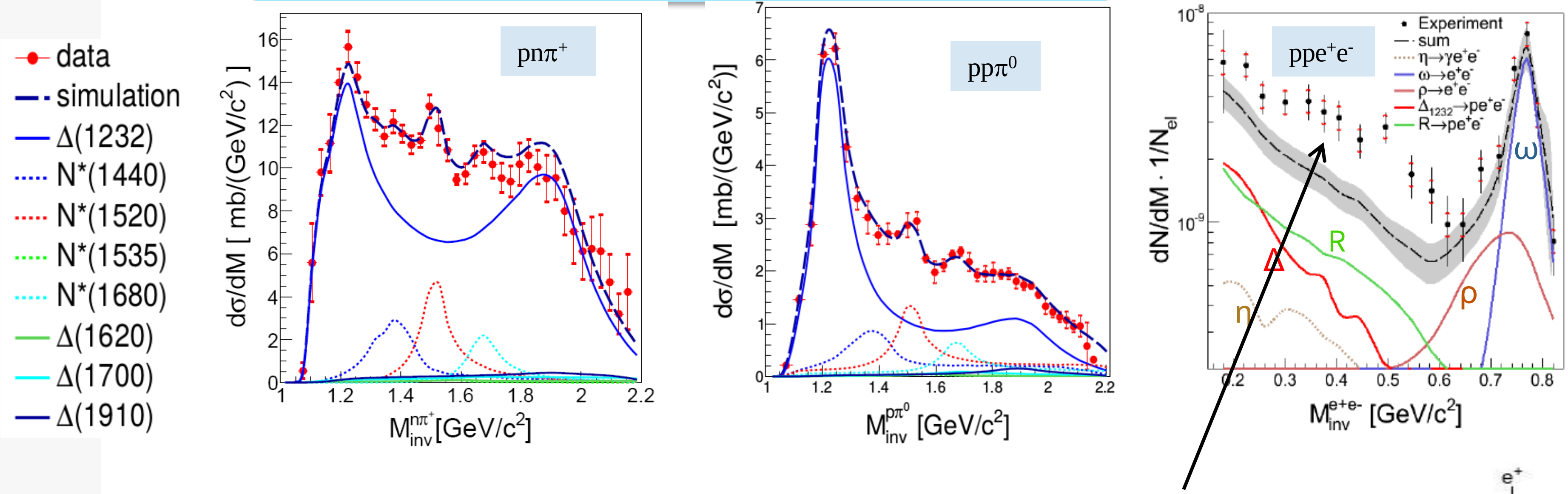


Motivation

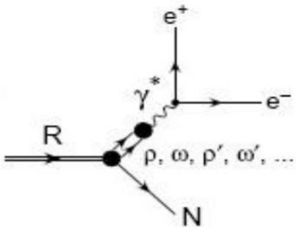
G. Agakishiev et al.
Eur.Phys.J. A50 (2014) 8

$pp \rightarrow n p \pi^+$, $pp \rightarrow pp\pi^0$ and $pp \rightarrow ppe^+e^-$ E=3.5 GeV

Cocktail of baryonic resonances obtained from the 1 π production



Effect of eTFF of the vector meson dominance type (coupling to ρ)



Interest of the channel **$pp \rightarrow pp\pi^+\pi^-$**:

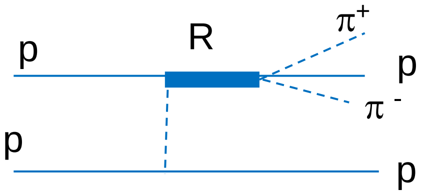
- Test the cocktail on the 2 pion production.
- Measure the ρ ($\rho \rightarrow \pi^+\pi^-$) production direct and coupled to resonances .

2.

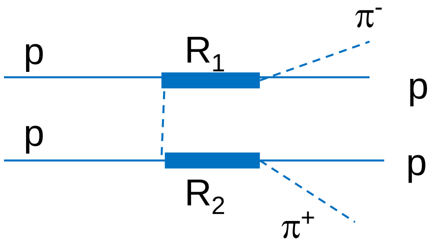
Study of the channel $pp \rightarrow pp\pi^+\pi^-$ @ E=3.5 GeV

What to expect in the 2π channel

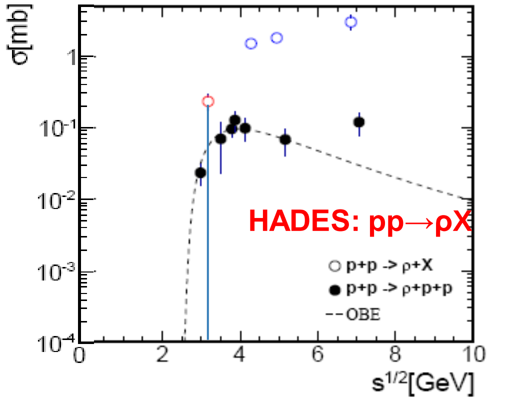
One resonance excitation



Double resonance excitation



Direct ρ production



Few precise measurements

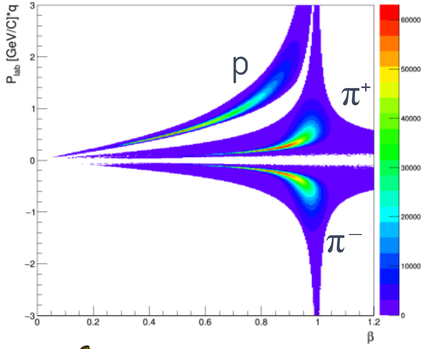
Models that include simple and double excitation:

- Cao Effective Lagrangian model
  X. Cao, B.-S. Zou and H.-S. Xu, Phys. Rev. ***C81*** *(2010) 12.*
- OPER model (one pion exchange reggeized)
  A.P. Jerusalimov et al., Eur. Phys. J. ***A51*** *(2015) 83.*
- Transport models: GiBUU.
- Valencia model: E< 1.4 GeV

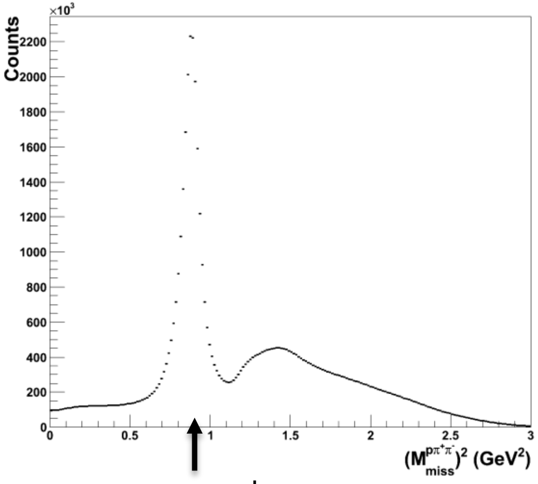
Data Analysis

- DST (Data Summary Tape): Calibration-> included tracks and physics observables, P, ToF, dE/dx…
- PAT(PostDST Analysis Tool): Particle Identification + channel selection: $1\pi^+ 1\pi^-$ and 1 proton at least

Velocity Vs Momentum



Cuts

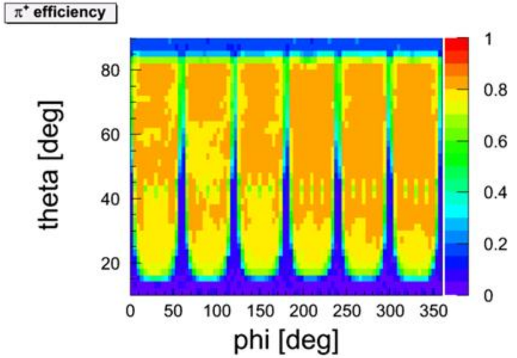


squared
proton mass

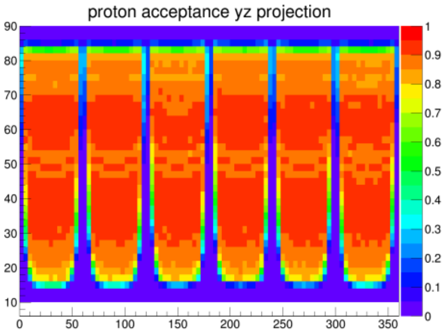
- FAT(Final Analysis Tool): File of events with all physical variables (invariant masses, angular distributions…)

Data Analysis

Efficiency Matrices



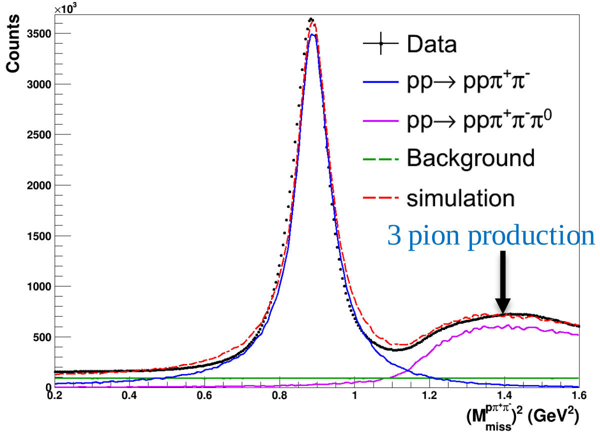
Acceptance Matrices



Data normalisation $\sigma_{pp(elastic)}$

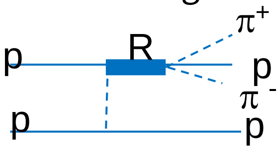
$$\sigma_{Data} = N_{Data} \frac{\sigma_{el}^{pp}}{N_{el}^{pp}}$$

Background subtraction



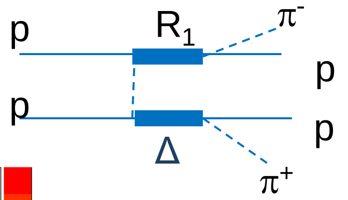
Data Analysis

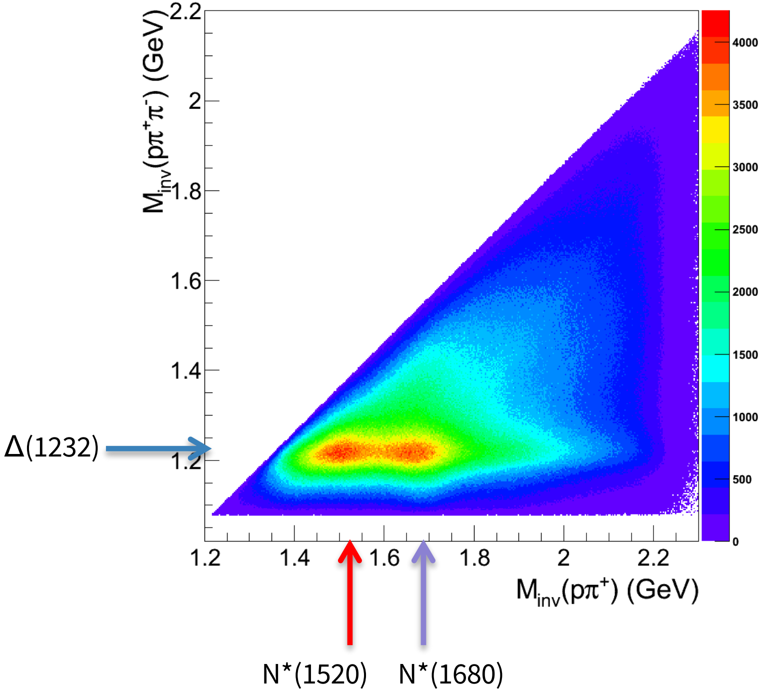
- 2D histograms are a good indication for some channels

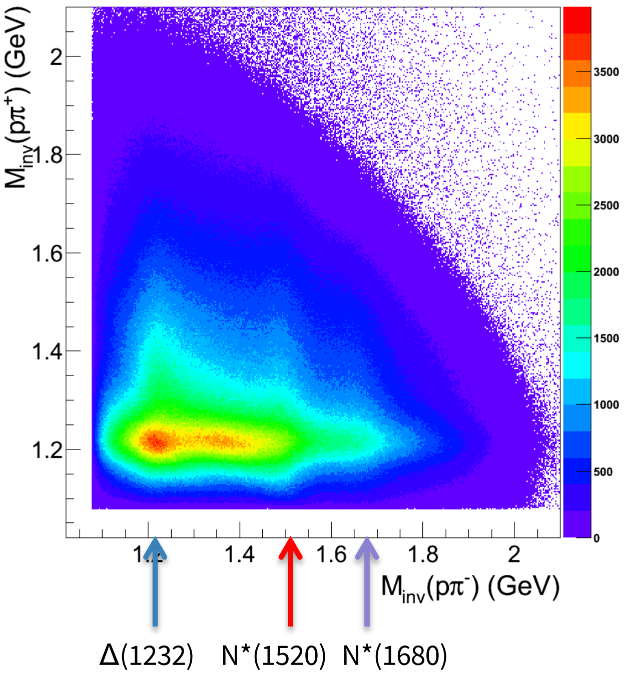


$R \rightarrow \Delta^{++}(1232)\,\pi^- \rightarrow p\,\pi^+\pi^-$

$\Delta^{++}(1232)\,R \rightarrow p\,\pi^+\;\;p\pi^-$







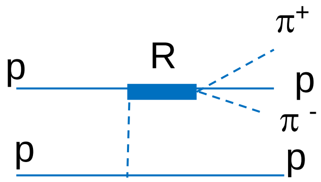
3.
PLUTO++ Simulations

Pluto is a monte carlo simulation framework developed by the HADES collaboration for heavy ion and hadronic-physics reactions.

I. Frolich et al. PoS ACAT2007 (2006)

Simulations

- One resonance excitation simulation $pp \rightarrow pR \rightarrow pp\ \pi^+\pi^-$
  - $\sigma_R(1\pi)$: from 1 π production analysis*



Resonance	BR(Nπ)	BR(Nππ) (PDG)	$\sigma_R(1\pi)$ (mb)
N(1440)	65%	30-40%	1.5 ± 0.4
N(1520)	55%	20-30%	1.9 ± 0.3
N(1535)	46%	3-14%	0.15 ± 0.02
N(1650)	80%	8-36%	$< 0.8 \pm 0.1$
N(1675)	45%	50-60%	$< 1.65 \pm 0.3$
N(1680)	65%	30-40%	$< 0.9 \pm 0.2$
N(1720)	20%	>70%	$< 4.4 \pm 0.7$
Δ(1700)	15%	80-90%	0.5 ± 0.2
Δ(1905)	15%	85-95%	$< 0.8 \pm 0.5$

PDecayChannel (PLUTO Class)

BR x I

$N1520 \rightarrow p\pi^+\pi^-$ (0.04) (6% x 2/3)

$N1520 \rightarrow \Delta^{++}\pi^-$ (0.12) (23% x 1/2)

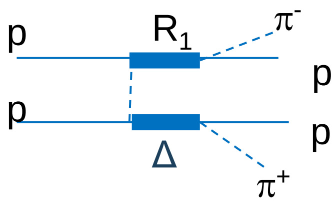
$N1520 \rightarrow \Delta^o\pi^+$ (0.04) (23% x 1/6)

$N1520 \rightarrow p\rho^o$ (0.003) (1% x 1/3)

*G. Agakishiev *et al.* Eur.Phys.J. A50 (2014) 8

Simulation

- Double resonance excitation simulation $pp \rightarrow RR' \rightarrow pp\,\pi^+\pi^-$

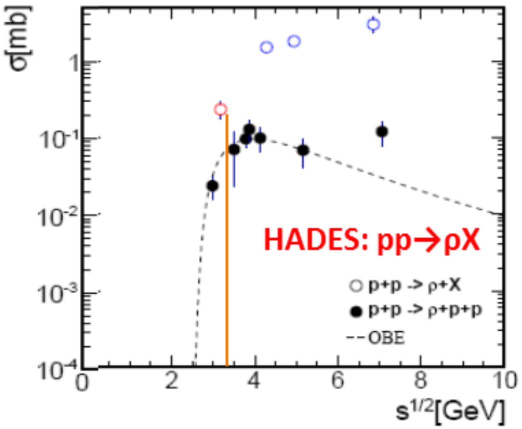


- ➢ Δ^{++}(1232) Δ^{o}(1232)
- ➢ Δ^{++}(1232) N^{o}(1440)
- ➢ Δ^{++}(1232) N^{o}(1520)
- ➢ Δ^{++}(1232) N^{o}(1535)
- ➢ Δ^{++}(1232) N^{o}(1650)
- ➢ Δ^{++}(1232) N^{o}(1680)
- ➢ Δ^{++}(1232) N^{o}(1720)
- ➢ Δ^{++}(1232) Δ^{o}(1700)

The BR(Nπ) for the second resonance are the same as in 1π analysis

- Direct ρ production simulation

σ = 70 μb (from existing data)



Angular Distribution Model

$$\frac{d\sigma_R}{dt} \sim \frac{1}{t^\alpha}$$

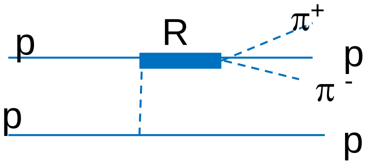
Angular distributions need to be implemented (isotropic in PLUTO)

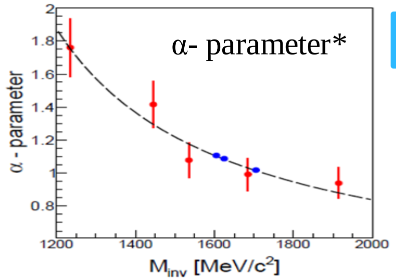
1R production:

$$t = (P_R - P_{beam})^2 \, if \cos\theta_R < 0$$

$$t = (P_R - P_{target})^2 \, if \cos\theta_R > 0$$

$$t_w = \frac{1}{t^\alpha}$$ (4-momentum transfer)





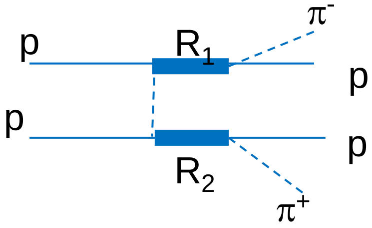
*1 π analysis

2R production:

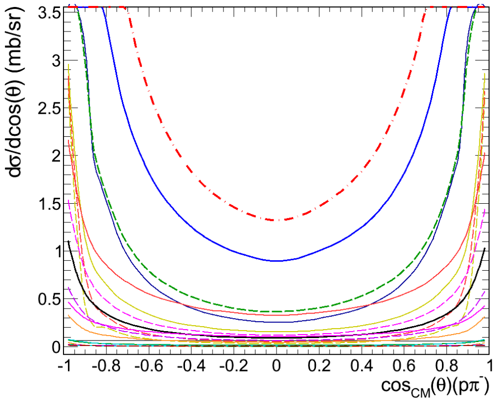
$$t = (P_{R_1} - P_{beam})^2 \, if \cos\theta_{R_1} < 0$$

$$t = (P_{R_1} - P_{target})^2 \, if \cos\theta_{R_1} > 0$$

$$t_w = \sqrt{\frac{1}{t^{\alpha_1}} \frac{1}{t^{\alpha_2}}}$$



The simulation is weighted by the **t_w**



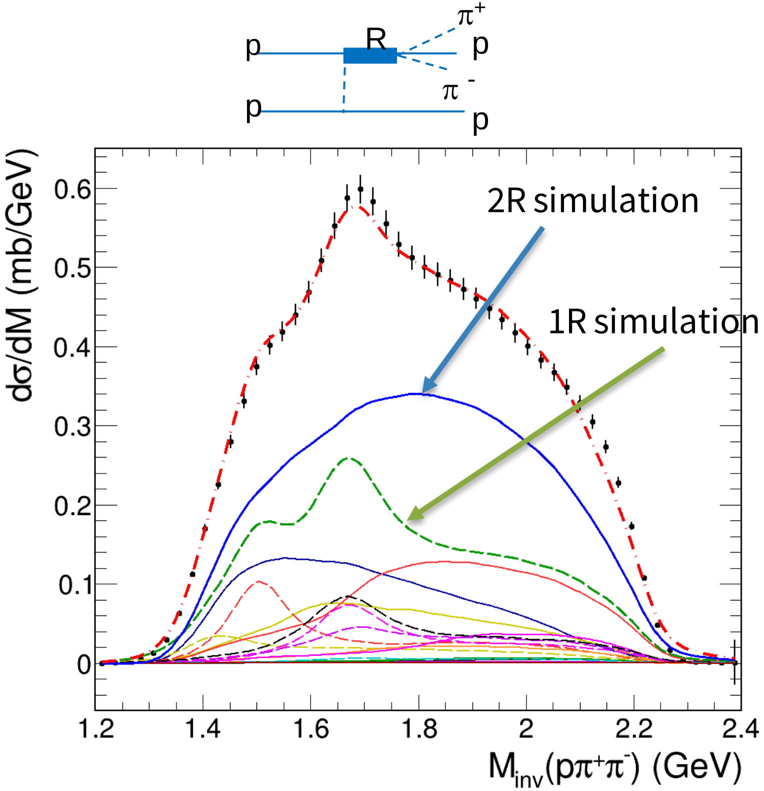
Before applying Acc. cuts

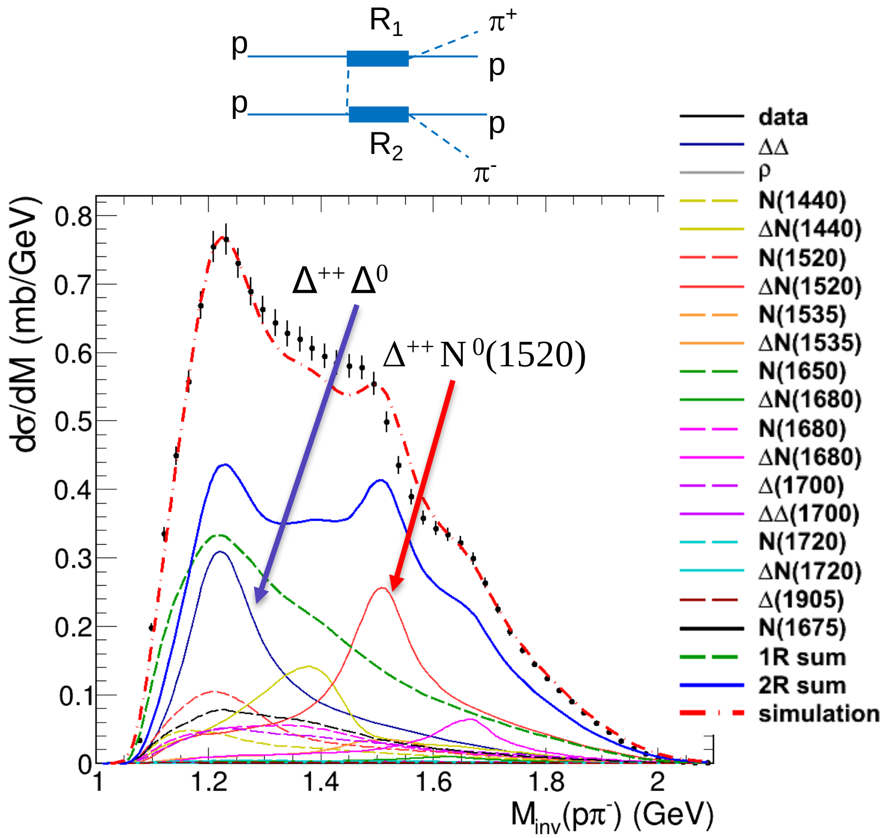
ρ production:

Phase space

4.
Analysis Results

Invariant Masses

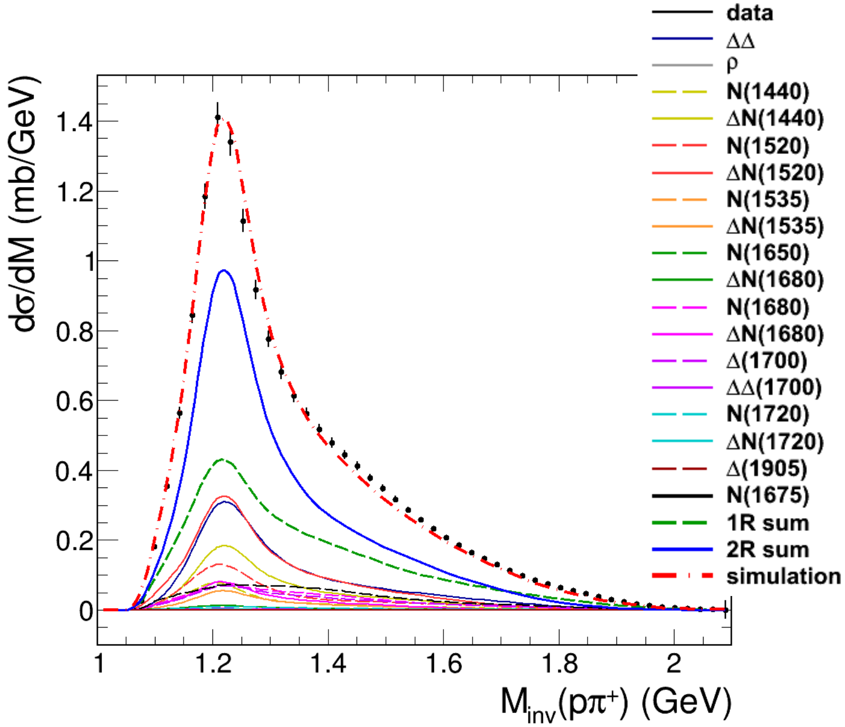


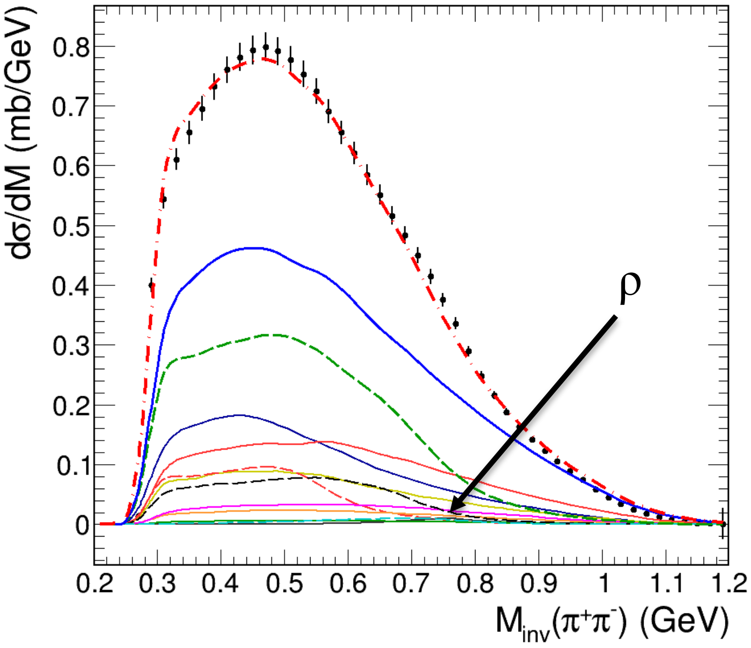


One peak in 1R (Dashed green) due to $N^+(1520)$ and a large peak due to $N^+(1675)$, $N^+(1680)$, $\Delta^+(1700)$.

3 peaks in 2R (blue) one due to $\Delta^{++}(1232)$, another to N°(1520), and another to N°(1680)

Invariant Masses



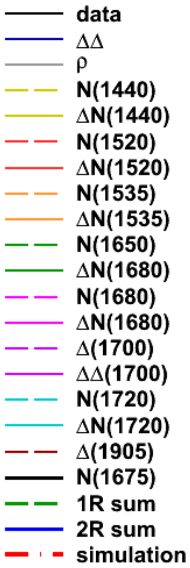


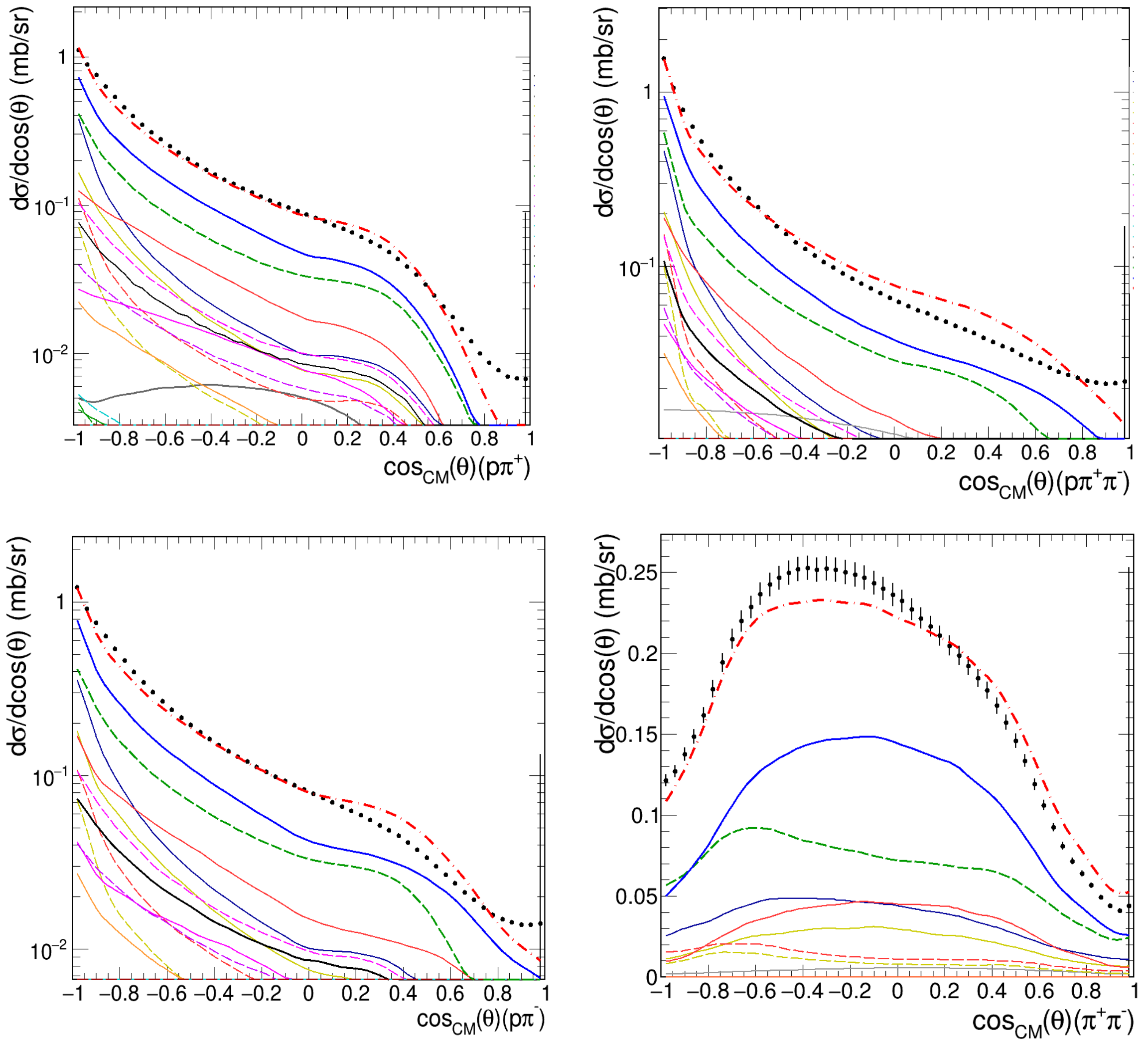
2R (blue) Strong dominance of $\Delta^{++}(1232)$, no significant contribution of heavier Δ^{++} resonances.

No clear evidence of direct ρ production

Angular Distributions

Angular distribution Gives information on the production mecanism.





The angular distribution model for 1R and 2R production is quite valid.

Cross Sections

List of simulated 1R with the used branching ratios and the given cross section

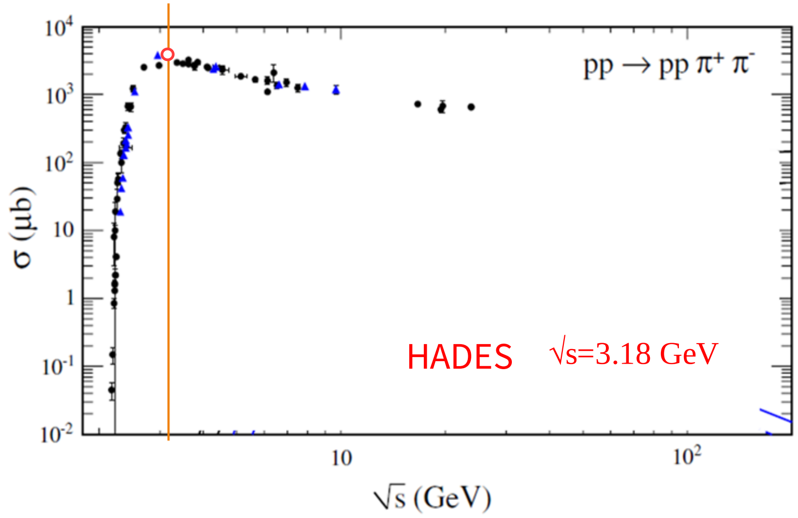
1 Resonance	BR($N\pi\pi$)	σ (2π anal.) (mb)	σ (1π anal) (mb)
$N^+(1440)$	30%	1.3 ± 0.2	1.5 ± 0.4
$N^+(1520)$	30%	1.6 ± 0.3	1.8 ± 0.3
$N^+(1535)$	10%	0.1 ± 0.05	0.15 ± 0.015
$N^+(1650)$	11%	0.3 ± 0.1	$< 0.81 \pm 0.13$
$N^+(1675)$	45%	1.9 ± 0.2	$< 1.65 \pm 0.27$
$N^+(1680)$	35%	1.6 ± 0.2	$< 0.9 \pm 0.15$
$N^+(1720)$	80%	0.06 ± 0.03	$< 4.4 \pm 0.7$
$\Delta^+(1700)$	55%	0.45 ± 0.1	0.45 ± 0.16
$\Delta^+(1905)$	90%	0.01 ± 0.01	$< 0.85 \pm 0.53$

List of simulated 2R with the used branching ratios and the given cross section

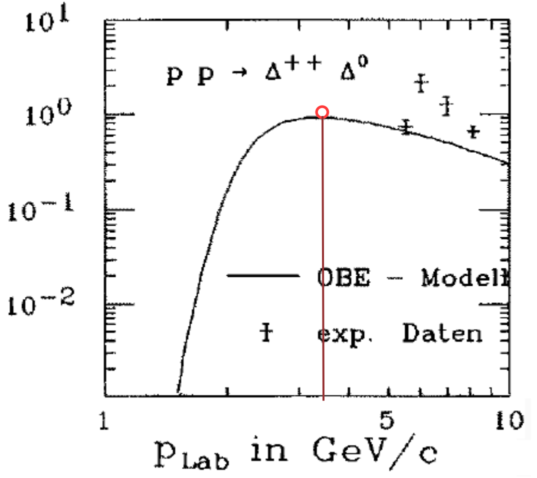
2 Resonances	BR($N\pi$)	σ (mb)
$\Delta^{++}(1232)N^\circ(1440)$	70%	0.95 ± 0.2
$\Delta^{++}(1232)N^\circ(1520)$	55%	1.5 ± 0.2
$\Delta^{++}(1232)N^\circ(1535)$	46%	0.3 ± 0.2
$\Delta^{++}(1232)N^\circ(1650)$	70%	0.05 ± 0.04
$\Delta^{++}(1232)N^\circ(1680)$	65%	0.4 ± 0.1
$\Delta^{++}(1232)N^\circ(1720)$	15%	0.05 ± 0.02
$\Delta^{++}(1232)\Delta^\circ(1700)$	15%	0.06 ± 0.02
$\Delta^{++}(1232)\Delta^\circ(1232)$	100%	4.2 ± 0.2

✓The resonance cocktail reproduces both 1π and 2π production. It gives additional consistency to the former dielectron analysis.
✓Based on the cocktail we estimate the total cross section $pp \to pp\,\pi^+\pi^-$: $\sigma \sim 3.9 \pm 0.4$ mb

Comparing to Existing Data



Lebedowicz et al., Phys. ReV D 81, 036003



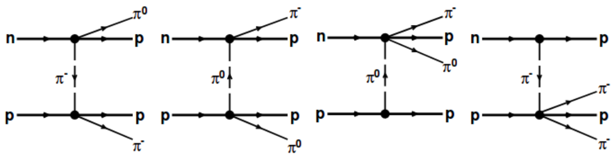
J. Aichelin, Nucl. Phys. A573, (1994) 587.

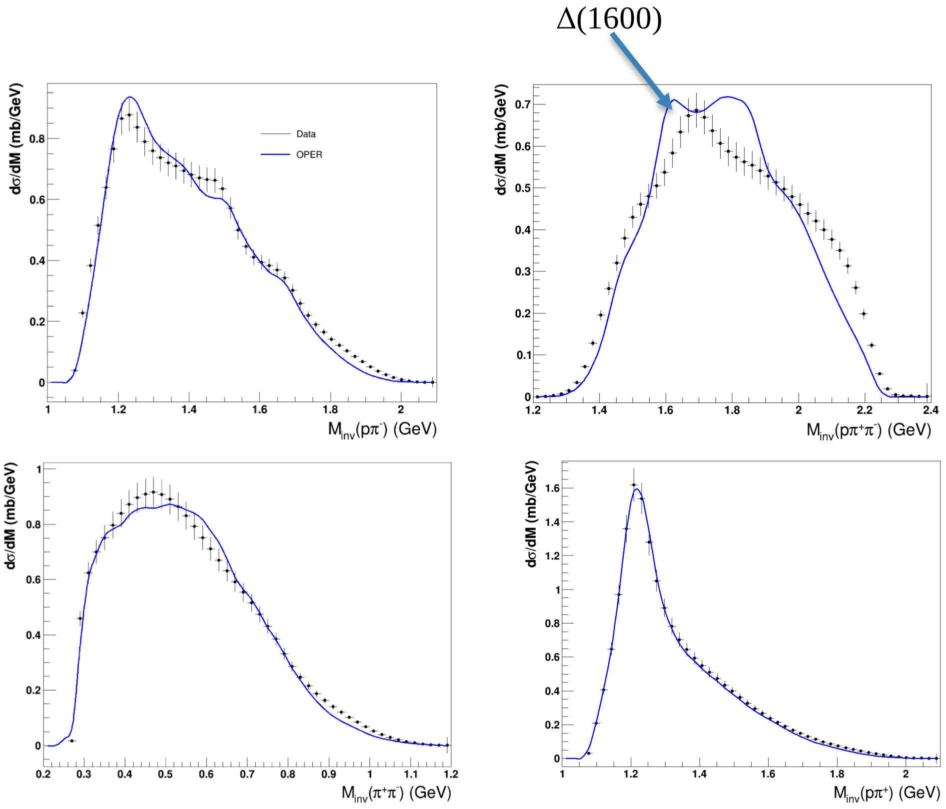
- Total cross section compatible with existing data. (HADES σ~3.9 mb)
- σ (ΔΔ)=1.3mb, compatible with OBE model

Comparing to Theoretical Models

OPER: One Pion Exchange Reggiezed

A.P Jerusalimov et al. ArXiv:1203.3330v1 [nucl-th]

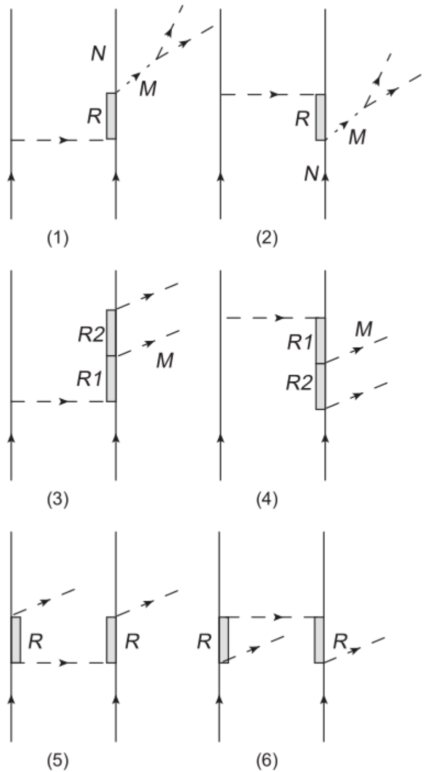


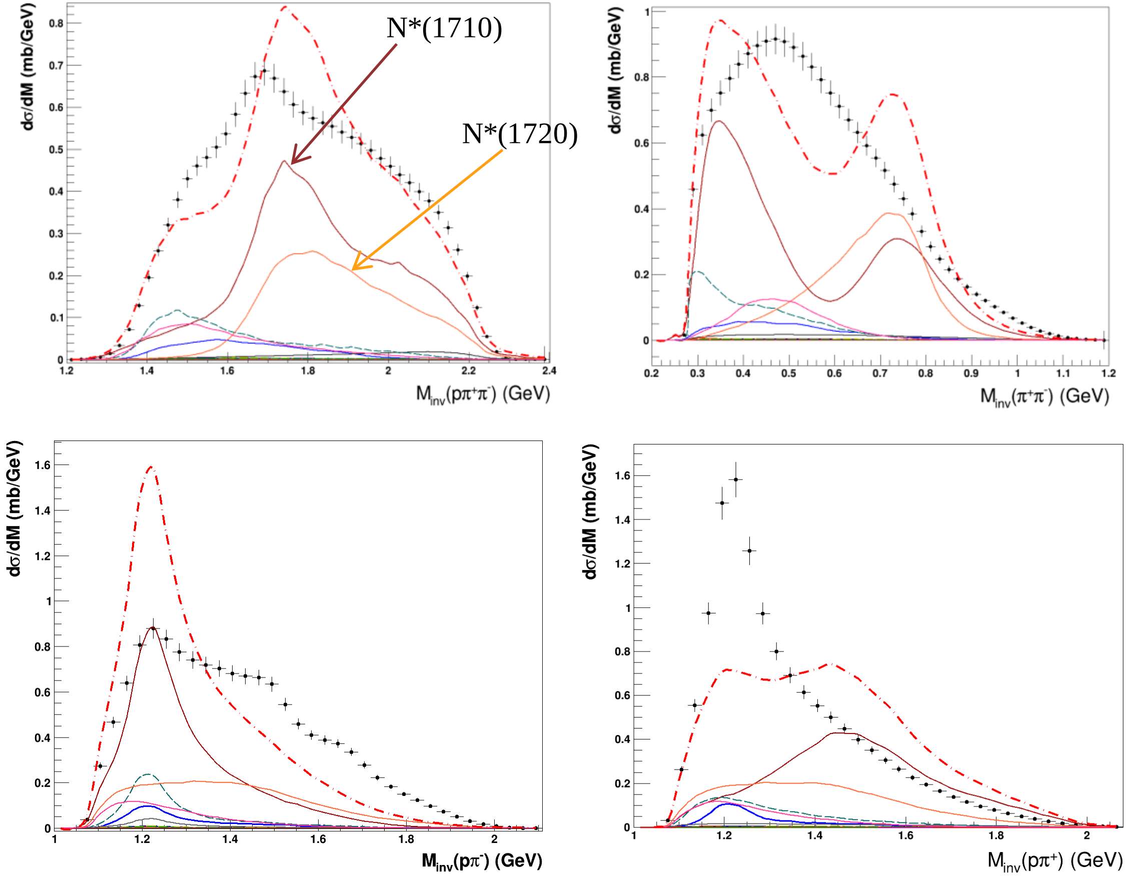


- Cross section adjusted to measured yield.
- Minv($p\pi^+\pi^-$) distribution shows a too large production of Δ(1600) and resonances with mass > 1.7 GeV

Comparing to Theoretical Models

Xu Cao effective Lagrangian model

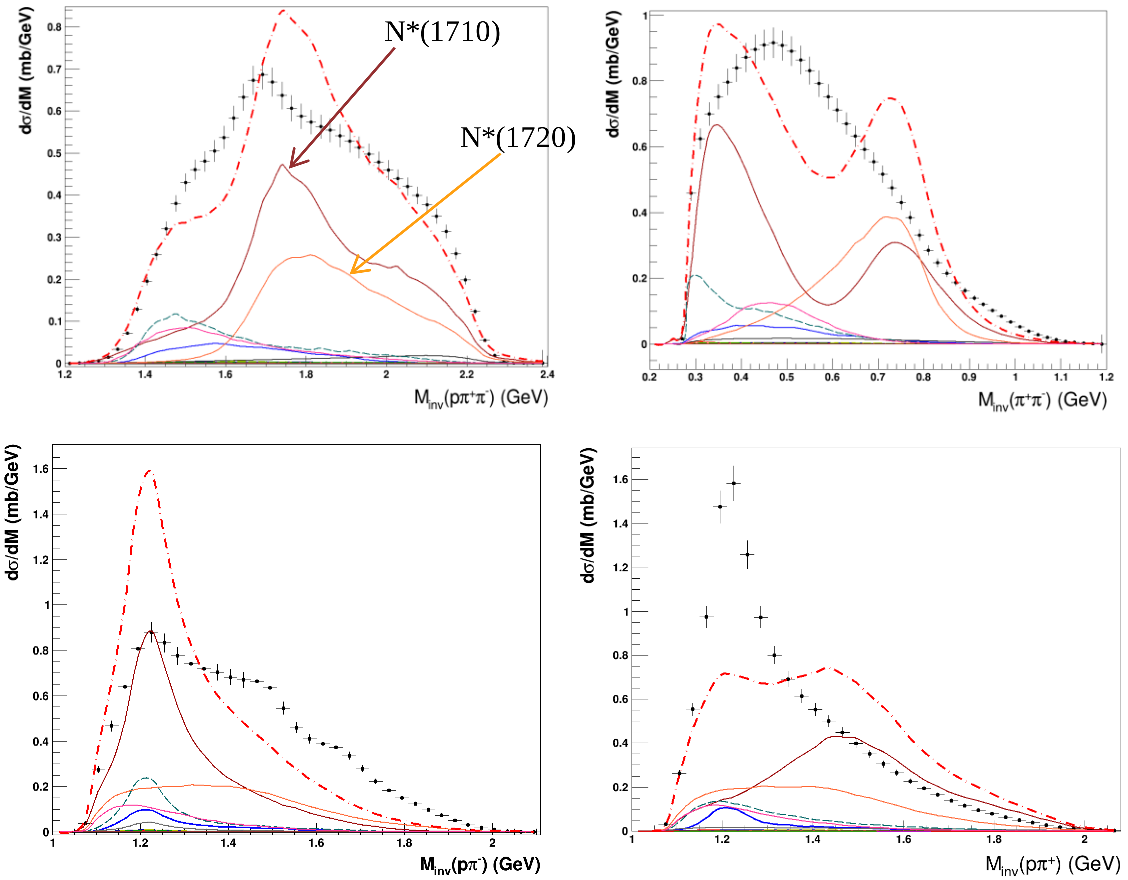




Comparing to Theoretical Models

Xu Cao effective Lagrangian model

- ➢ Only one 2R excitation contribution: $\Delta^{++}(1232)\Delta^{\circ}(1232)$
- ➢ Too large yield from $N^{*}(1710)$ and $N^{*}(1720)$ decaing to Nρ.
- ➢ $N^{*} \rightarrow N\rho$ is less probable than expected.

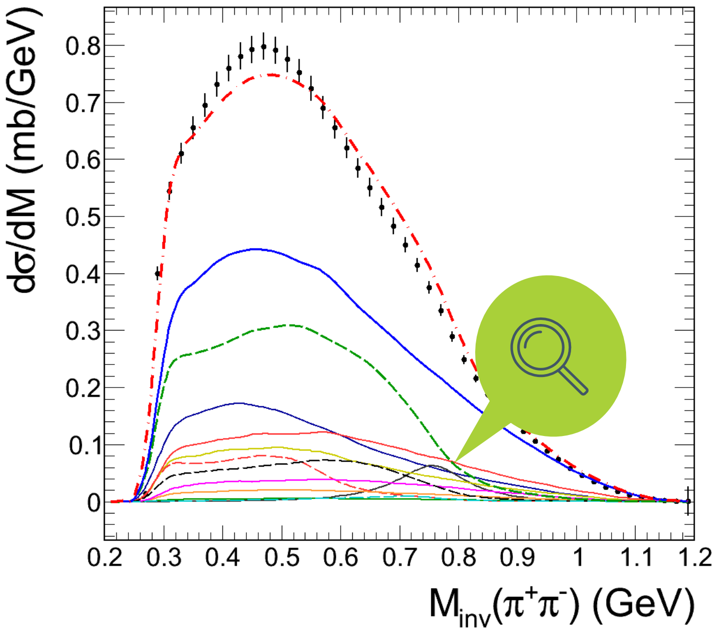


5.
Tracking down the ρ meson

Search for the direct "ρ"

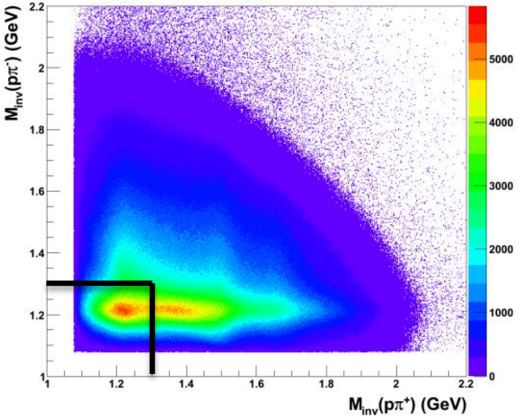
Apply kinematical cuts to reduce the baryonic resonance excitation background.

M(ρ) = 775 MeV
Γ(ρ) = 149 MeV

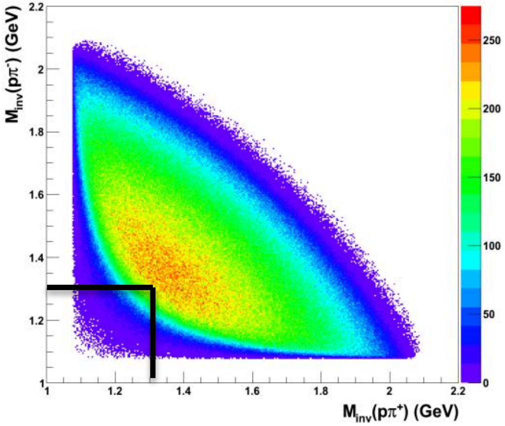


Search for the direct "ρ"

Data



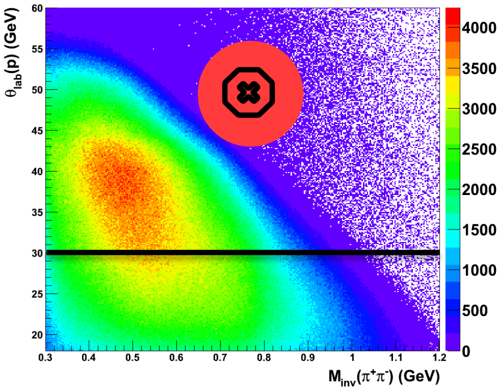
ρ simulation

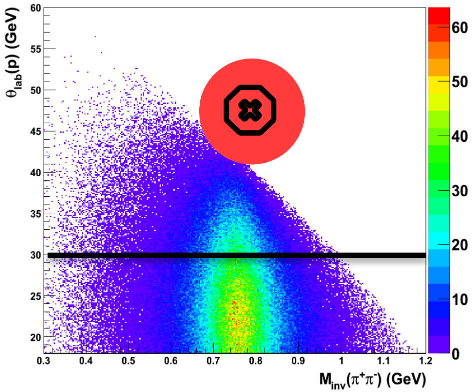


$M_{inv}(p\pi^+) > 1.3$ GeV

$M_{inv}(p\pi^-) > 1.3$ GeV

Supress ΔΔ



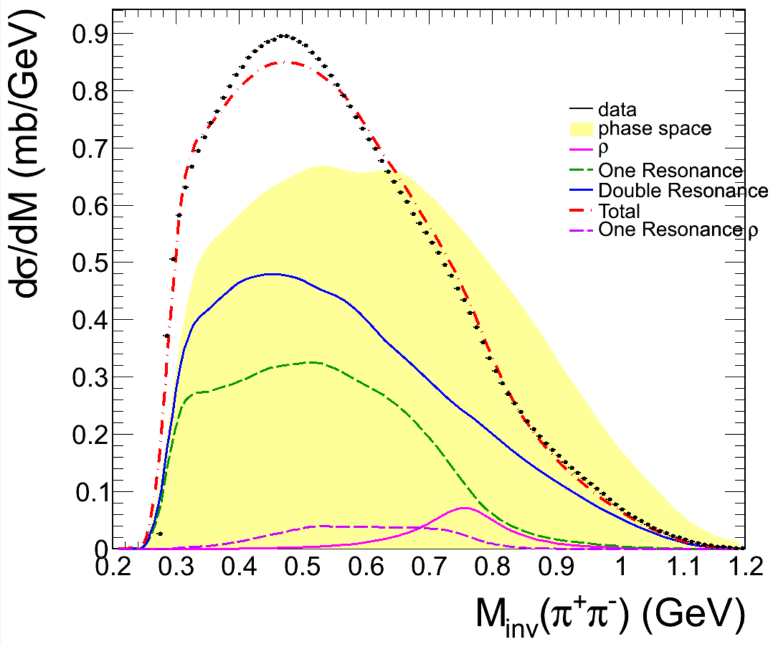


$\theta_{lab}(p) < 30°$

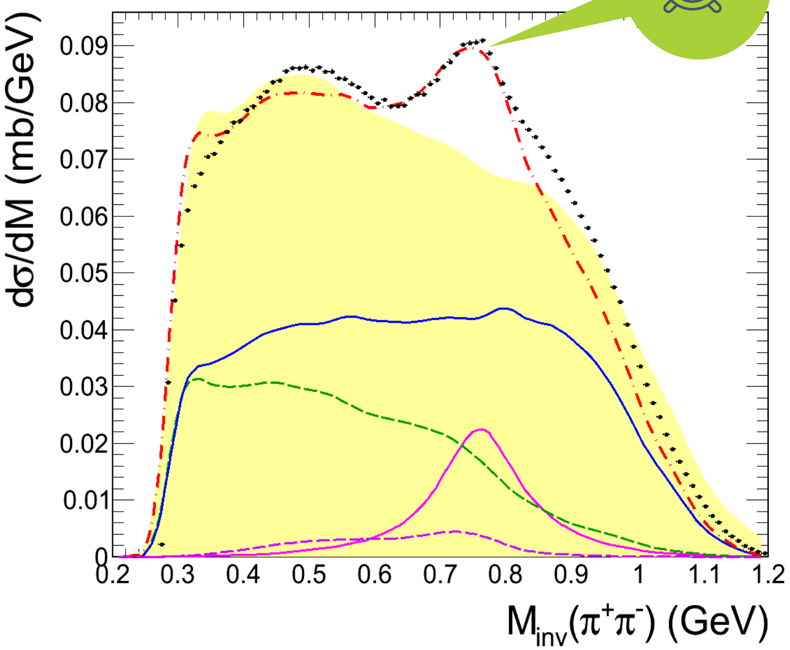
Supress remaining resonances

Search for the direct "ρ"

Before kinematical cuts

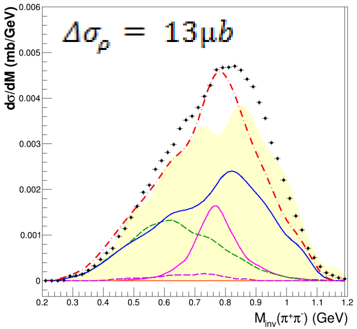


After kinematical cuts

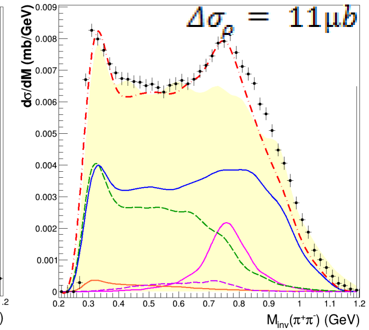


"ρ" Angular Distribution

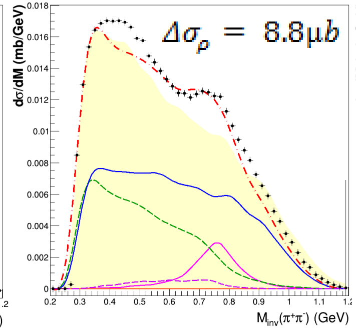
Evaluate σ_ρ in bins of $Cos_{CM}(\theta)(\pi^+\pi^-)$



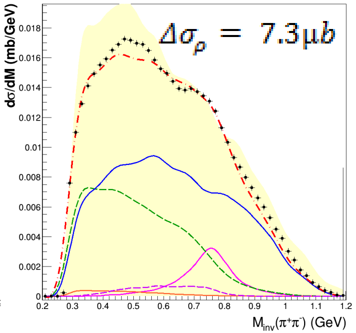
- 1 < Cos(θ) < - 0.8



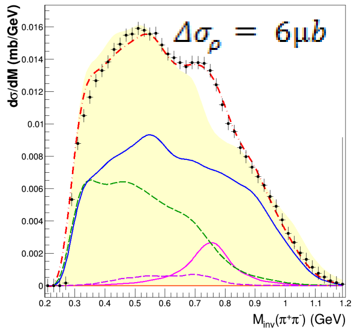
- 0.8 < Cos(θ) < - 0.6



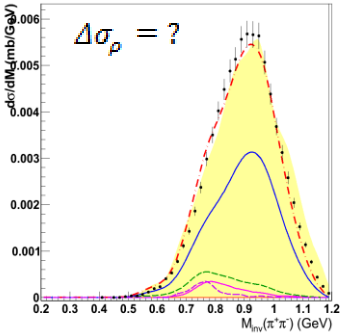
- 0.6 < Cos(θ) < - 0.4



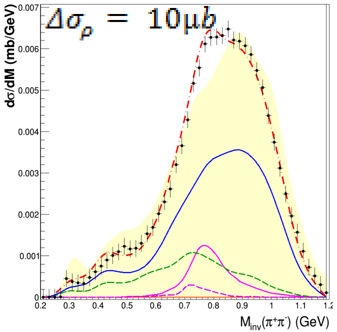
- 0.4 < Cos(θ) < - 0.2



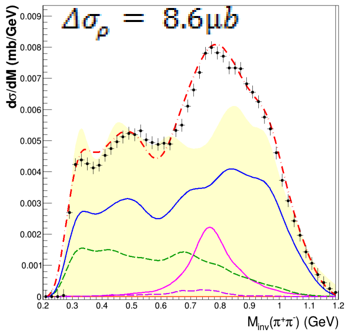
- 0.2 < Cos(θ) < 0



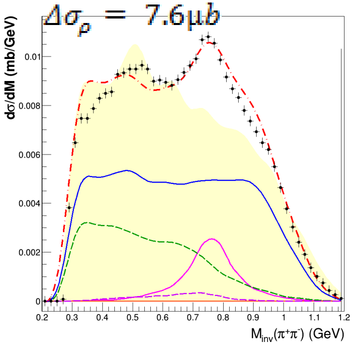
0.8 < Cos(θ) < 1



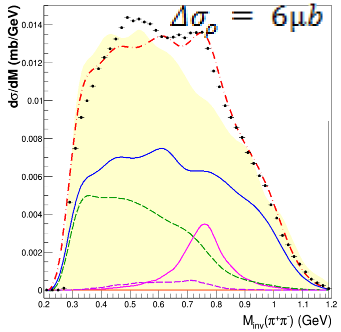
0.6 < Cos(θ) < 0.8



0.4 < Cos(θ) < 0.6



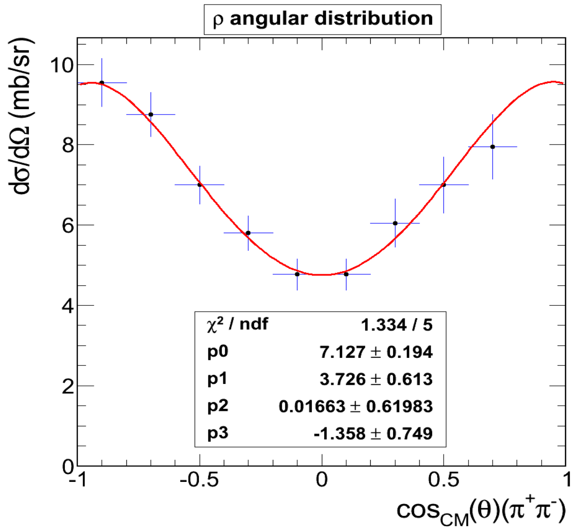
0.2 < Cos(θ) < 0.4

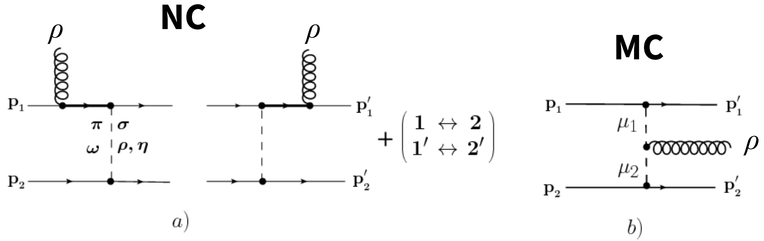


0 < Cos(θ) < 0.2

✓ Good backward/forward symetry

“ρ” angular distribution

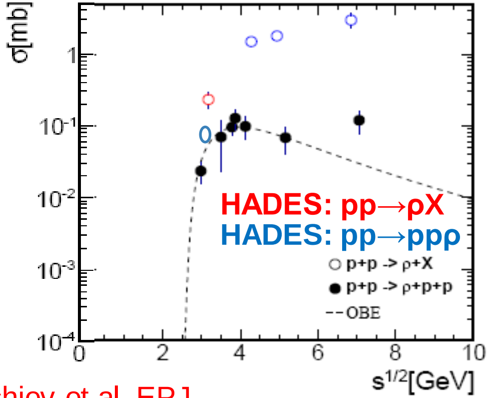


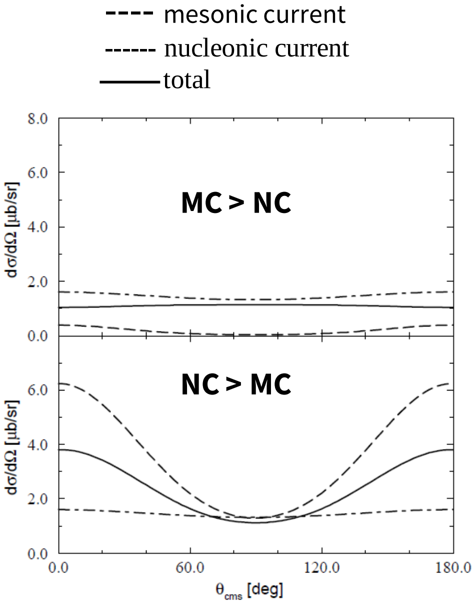


Fit with Legendre Polynomials:

$$\frac{d\sigma_\rho}{d\Omega} = (7.1 \pm 0.1)P_0 + (3.7 \pm 0.6)P_2 - (1.3 \pm 0.7)P_4$$

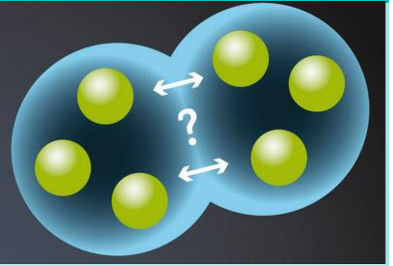
$$\Rightarrow \quad \sigma_\rho = 88 \pm 8\ \mu b$$





G. Agakishiev et al. EPJ A48 (2012) 64

Perspectives



Next channel: $pp \to pp\pi^+\pi^+\pi^-\pi^-$ investigation for d*(2380) (D_{30} dibaryon)

$$pp \to D_{30}\pi^-\pi^- \to \Delta^{++}\Delta^{++}\pi^-\pi^- \to pp\pi^+\pi^+\pi^-\pi^-$$

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Table I. $Y = 2$ states with zero strangeness predicted by the $\underline{490}$ multiplet.

Particle	T	J	SU(3) multiplet	Comment	Predicted mass
D_{01}	0	1	$\underline{10^*}$	Deuteron	A
D_{10}	1	0	$\underline{27}$	Deuteron singlet state	A
D_{12}	1	2	$\underline{27}$	S-wave N-N^* resonance	$A+6B$
D_{21}	2	1	$\underline{35}$	Charge-3 resonance	$A+6B$
D_{03}	0	3	$\underline{10^*}$	S-wave N^*-N^* resonance	$A+10B$
D_{30}	3	0	$\underline{28}$	Charge-4 resonance	$A+10B$

Baryon Full Listings

DIBARYONS

1988 PDG

NN(2250) ELASTICITY

VALUE	DOCUMENT ID		COMMENT
0.21	JAUCH	84	$NN \to NN\pi$ Deck + resonance
0 11 to 0.13	[9] BHANDARI	82	$NN \to NN$ PWA
0 096 ± 0 012	[10] SHAMU	82	np total cross section fit
0.2	HOSHIZAKI	78	$NN \to NN$ PWA
• • • We do not use the following data for averages, fits, limits etc • • •			
0 05	[8] FERREIRA	83	πd forward amplitude

NN(2250) POLE POSITION

REAL PART

Approximately equals the Breit Wigner mass

NN(2250) REFERENCES

ARNDT	87	PR D35 128	+Hyslop Roper	(VPI)
TATISCHEFF	85	PL 154B 107		(IPN)
Also	84	PRL 52 2022	Tatischeff Berthet Combes Didelez+	(IPN+)
JAUCH	84	PL 143B 509	+Konig Kroll	(WUPP)
STRAKOVSKII	84	SJNP 40 273	+Kravtsov Ryskin	(LENI)
		Translated from YAF 40 429		
Also	84	JP G9 L187	Kravtsov Tyskin Strakovskii	(LENI)
BHANDARI	83	PR D27 296		(VPI)
Also	83B	LNC 38 251	Bhandari	(NMSU)
FERREIRA	83	JP G9 169	+Munguia	(PUCB)
KLOET	83	NP A392 271	+Tjon	(ITPU)
BHANDARI	82	LNC 34 65		(VPI)
DAKHNO	82	PL 114B 409	+Kravtsov Lobachev Makarov Medvedev+	(LENI)
Also	82B	SJNP 36 83	Dakhno Kravtsov Lobachev Makarov+	(LENI)
		Translated from YAF 36 143		
GREIN	82	NP A377 505	+Kroll	(SIN WUPP)
SHAMU	82	PR D25 2008	+Soga Shilts Lisowski	(WMIU LASL)
UEDA	82	PL 119B 281		(OSAK)

Perspectives

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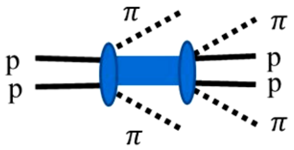
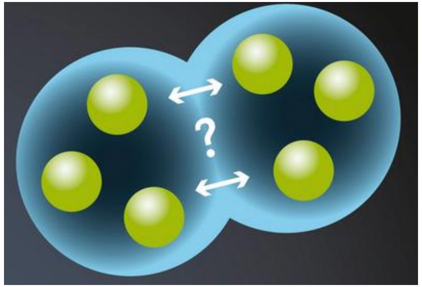
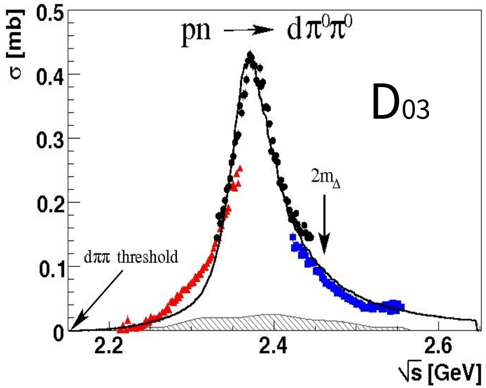






Complementary study to WASA experiment

Isospin factors

$pp \to \pi^-\pi^- d^{4+} \to \pi^-\pi^-\Delta^{++}\Delta^{++} \to pp\pi^+\pi^+\pi^-\pi^-$	**1**
$pp \to \pi^+\pi^- d^{2+} \to \pi^+\pi^-\Delta^{++}\Delta^{0} \to pp\pi^+\pi^+\pi^-\pi^-$	$2 \cdot \left(\frac{1}{15}\right)$
$pp \to \pi^+\pi^+ d^{0} \to \pi^+\pi^+\Delta^{+}\Delta^{-} \to pp\pi^+\pi^+\pi^-\pi^-$	$\left(\frac{1}{15}\right)$

Conclusion

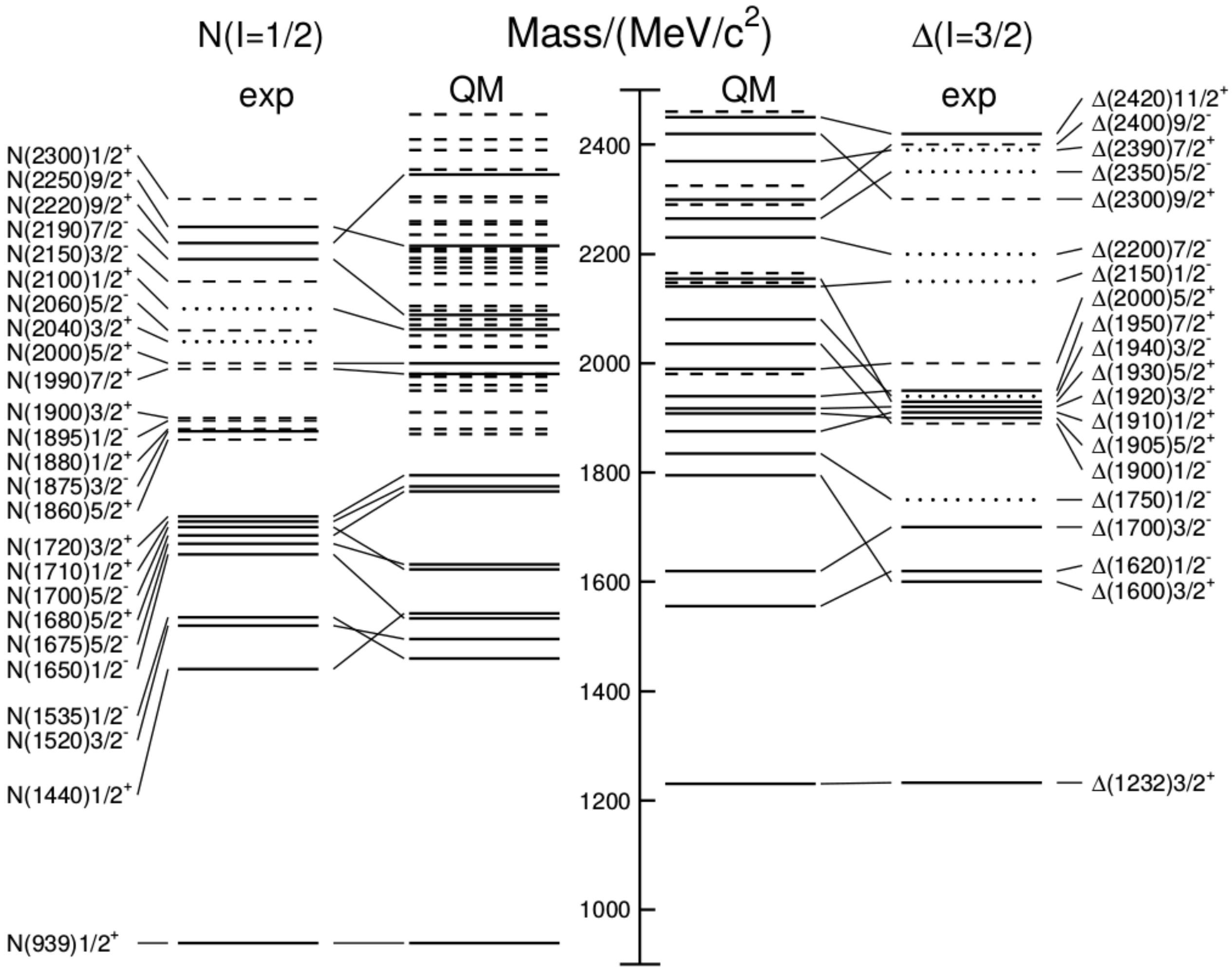
- *This analysis confirms the presence of three channels:*
  One and double baryonic resonance production , direct ρ production.
- The results show consistency between one and two pion production

  within the “HADES resonance model’’ .
- The results present valuable inputs for theoretical models.
- ρ signal was extracted by applying the necessary kinematical cuts.

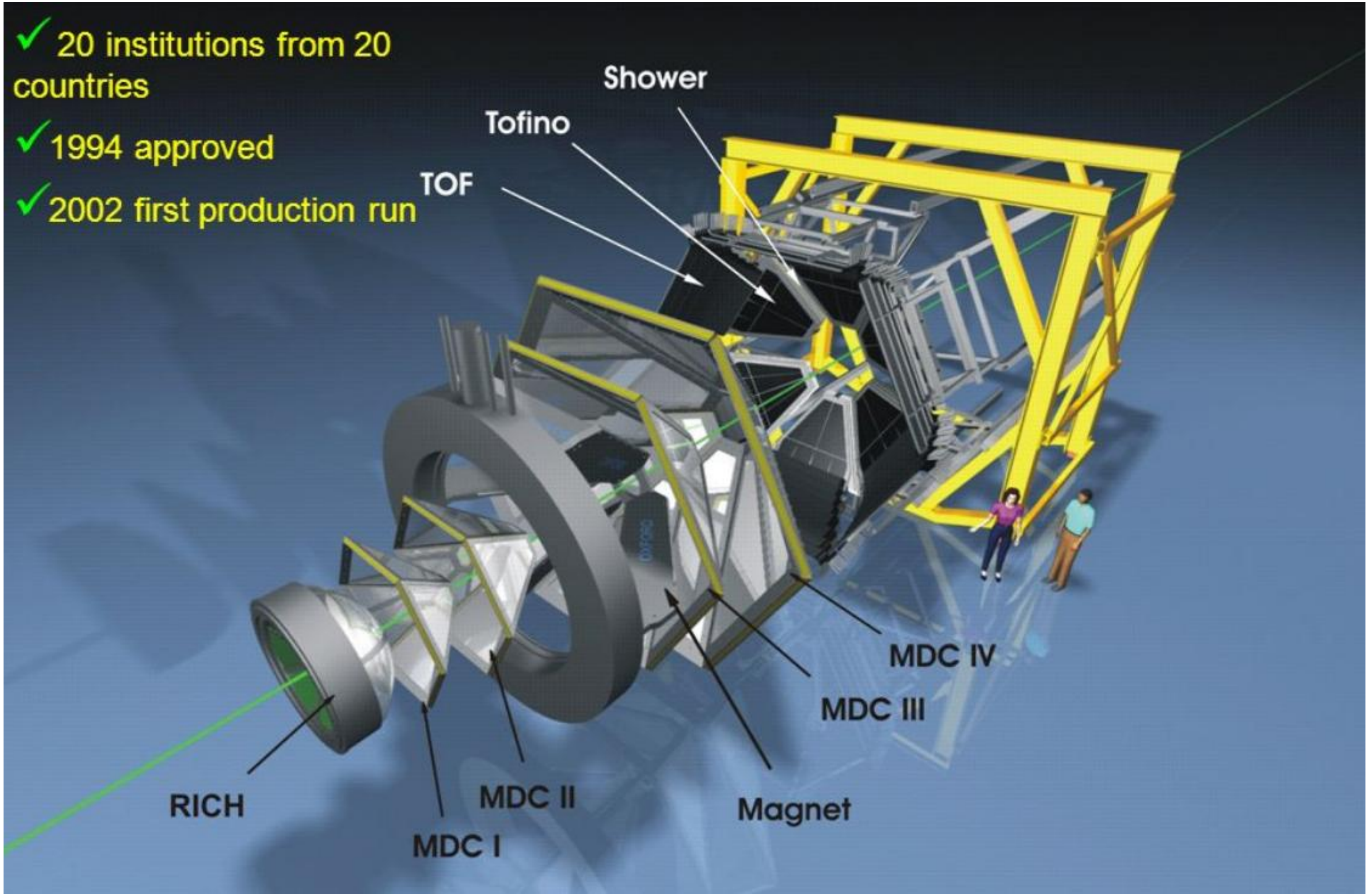
Sometimes the public says, "What's in it for Numero Uno? Am I going to get better television reception? Am I going to get better Internet reception?" Well, in some sense, yeah. ... All the wonders of quantum physics were learned basically from looking at atom-smasher technology. ... But let me let you in on a secret: We physicists are not driven to do this because of better color television. ... That's a spin-off. We do this because we want to understand our role and our place in the universe.

Dr Michio Kaku

”



N(I=1/2)
Mass/(MeV/c²)
Δ(I=3/2)
exp
QM
QM
exp
2400
2200
2000
1800
1600
1400
1200
1000
N(2300)1/2+
N(2250)9/2+
N(2220)9/2+
N(2190)7/2-
N(2150)3/2-
N(2100)1/2+
N(2060)5/2-
N(2040)3/2+
N(2000)5/2+
N(1990)7/2+
N(1900)3/2+
N(1895)1/2-
N(1880)1/2+
N(1875)3/2-
N(1860)5/2+
N(1720)3/2+
N(1710)1/2+
N(1700)5/2-
N(1680)5/2+
N(1675)5/2-
N(1650)1/2-
N(1535)1/2-
N(1520)3/2-
N(1440)1/2+
N(939)1/2+
Δ(2420)11/2+
Δ(2400)9/2-
Δ(2390)7/2+
Δ(2350)5/2-
Δ(2300)9/2+
Δ(2200)7/2-
Δ(2150)1/2-
Δ(2000)5/2+
Δ(1950)7/2+
Δ(1940)3/2-
Δ(1930)5/2+
Δ(1920)3/2+
Δ(1910)1/2+
Δ(1905)5/2+
Δ(1900)1/2-
Δ(1750)1/2-
Δ(1700)3/2-
Δ(1620)1/2-
Δ(1600)3/2+
Δ(1232)3/2+


✓ 20 institutions from 20 countries
✓1994 approved
✓2002 first production run
Shower
Tofino
TOF
MDC IV
MDC III
RICH
MDC II
Magnet
MDC I