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

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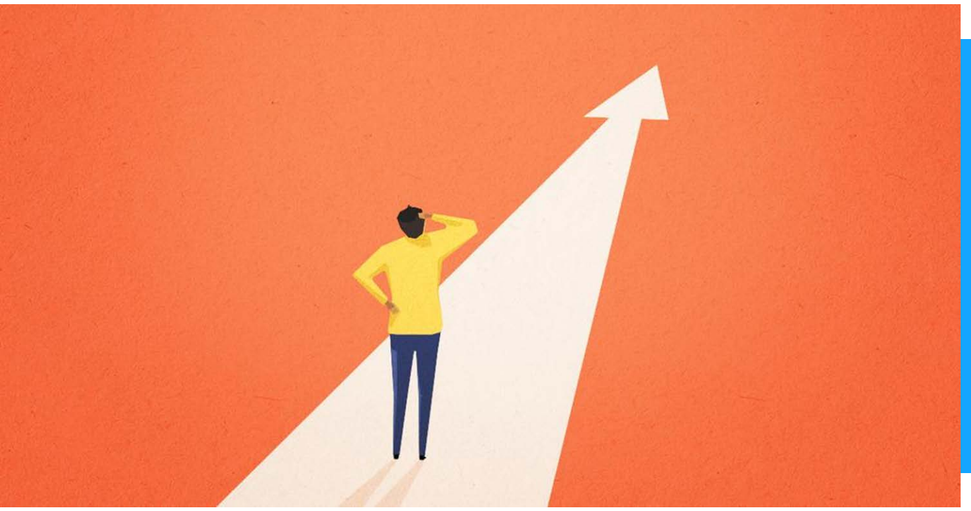
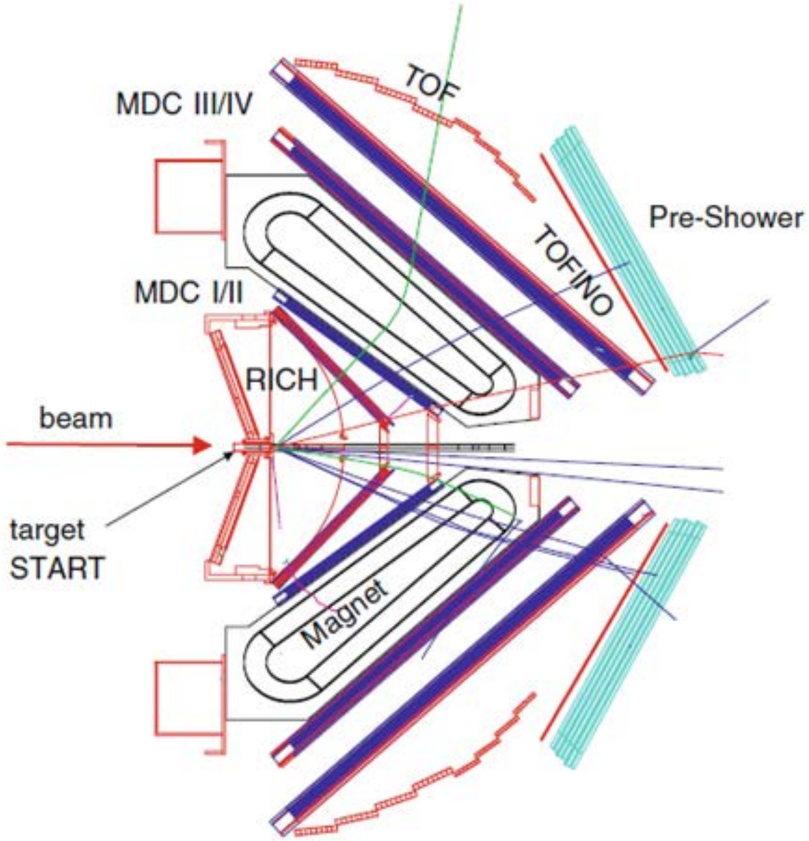
2018 PHENIICS Fest

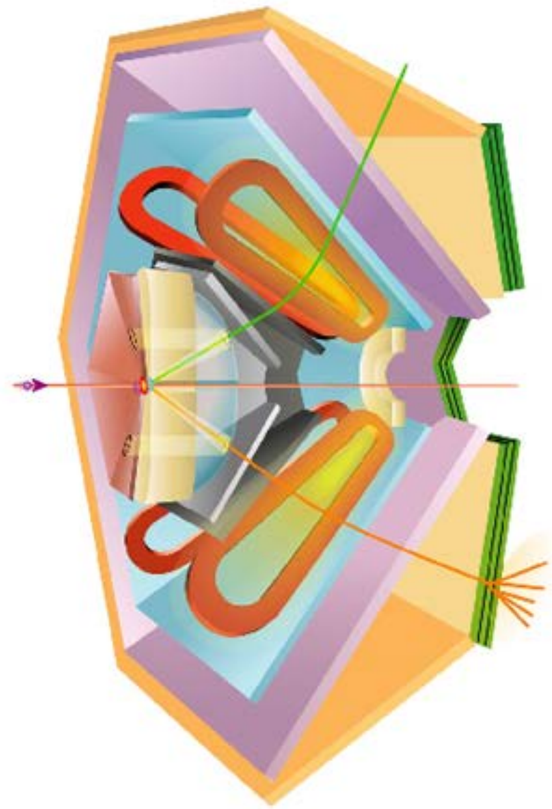
Outline

- Introduction.
- Data Analysis method.
- HADES resonance model (simulation).
- Analysis results.
- Conclusion & Perspectives.



Introduction

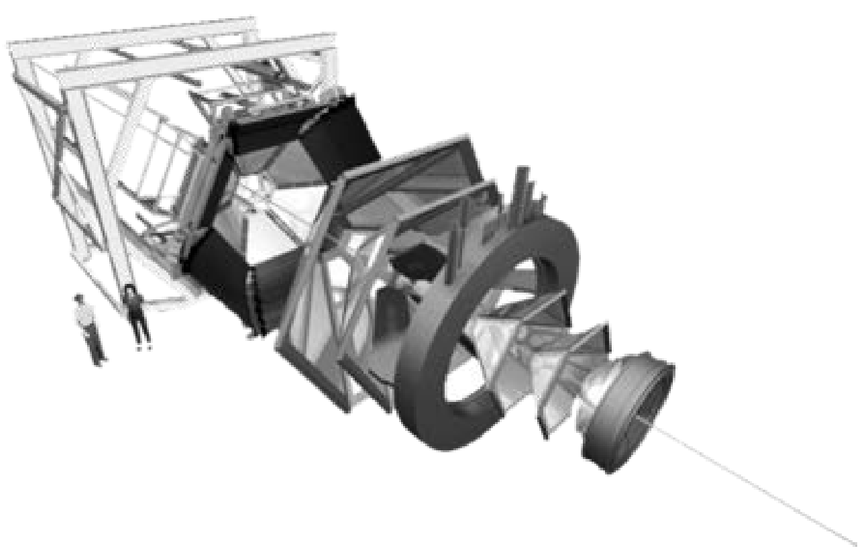




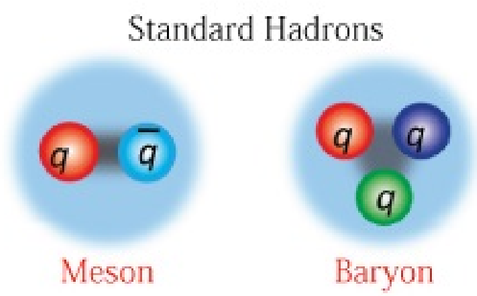
HADES

High Acceptance Di-Electron Spectrometer

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



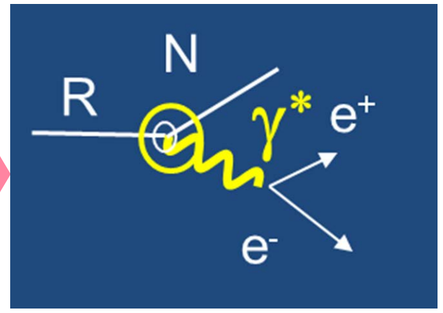
Study of baryons with HADES



Electromagnetic Dalitz Decay:

$R \rightarrow N e^+ e^-$
First measurement of
$\Delta(1232)^+ \rightarrow p e^+ e^-$
$4.2 * 10^{-5}$*

Interest
electromagnetic structure of baryonic resonances



Hadronic Decay:

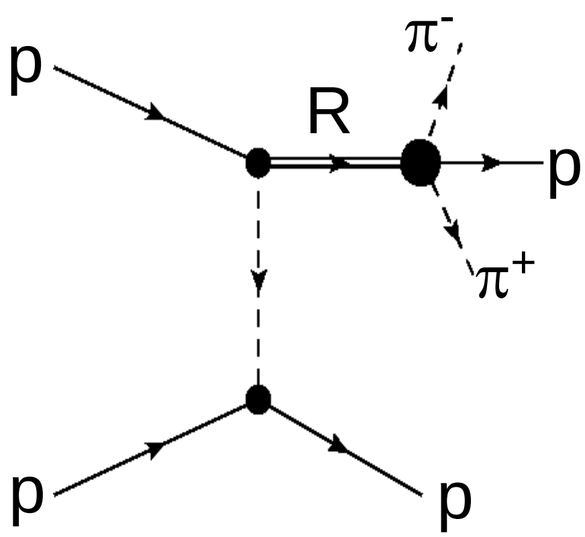
Two body: $R \rightarrow N \pi$, $R \rightarrow \Lambda K$
Three body: $R \rightarrow N \pi\pi$
$R \rightarrow \Delta\pi \rightarrow N \pi\pi$
$R \rightarrow N\rho \rightarrow N \pi\pi$

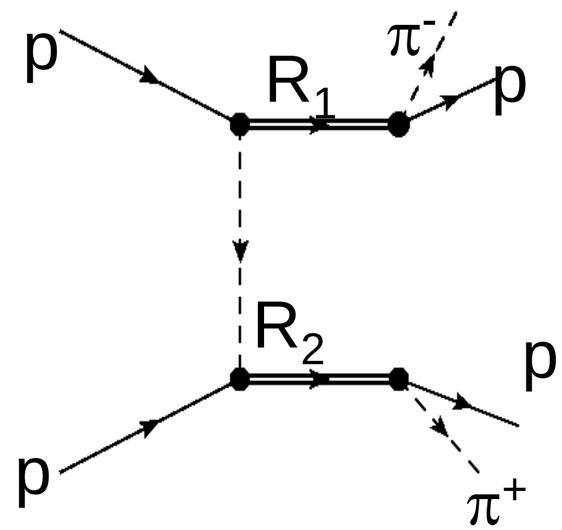
Interest
Control of the resonances production for the analysis of the e^+e^- chanels
Extract the branching ratios ($\Delta\pi$, $N\rho$)

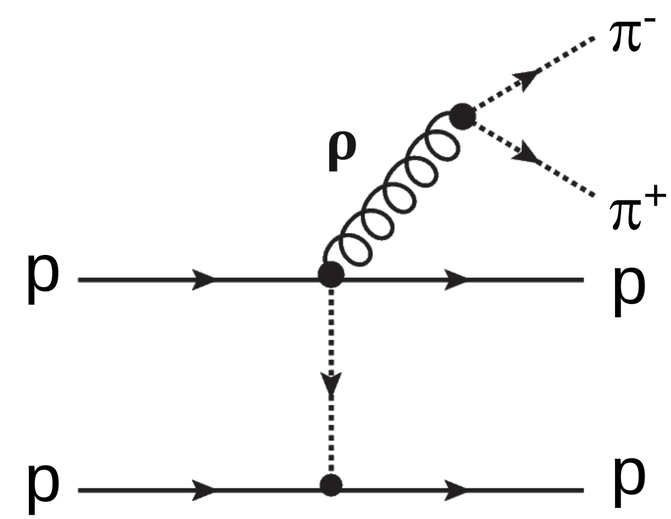
*HADES Collaboration Phys.Rev. C95 (2017) no.6, 065205

Study of the channel pp→ppπ+π- @ E=3.5 GeV

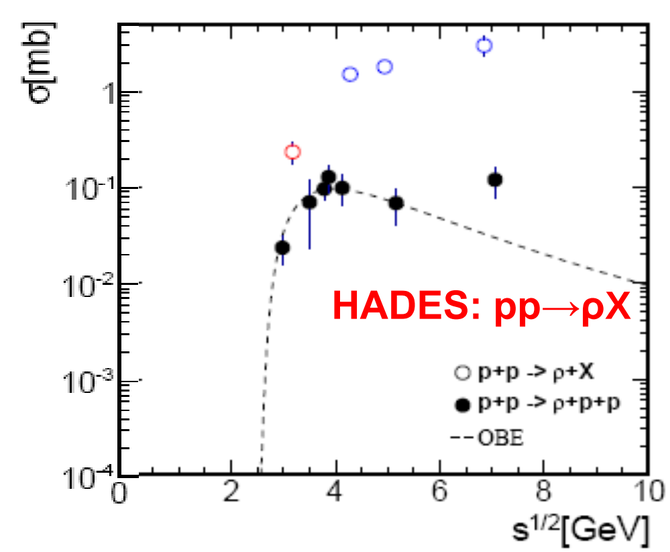
- One resonance excitation (1R)
- Double resonance excitation (2R)
- Direct ρ production







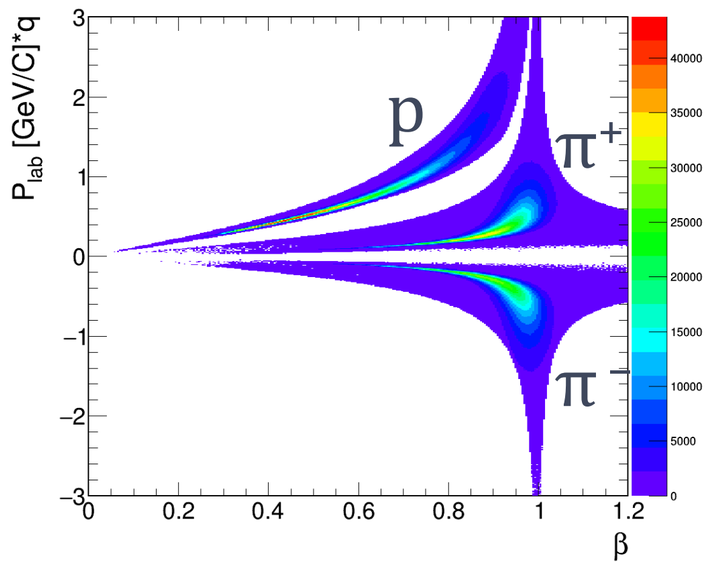
Few precise measurements

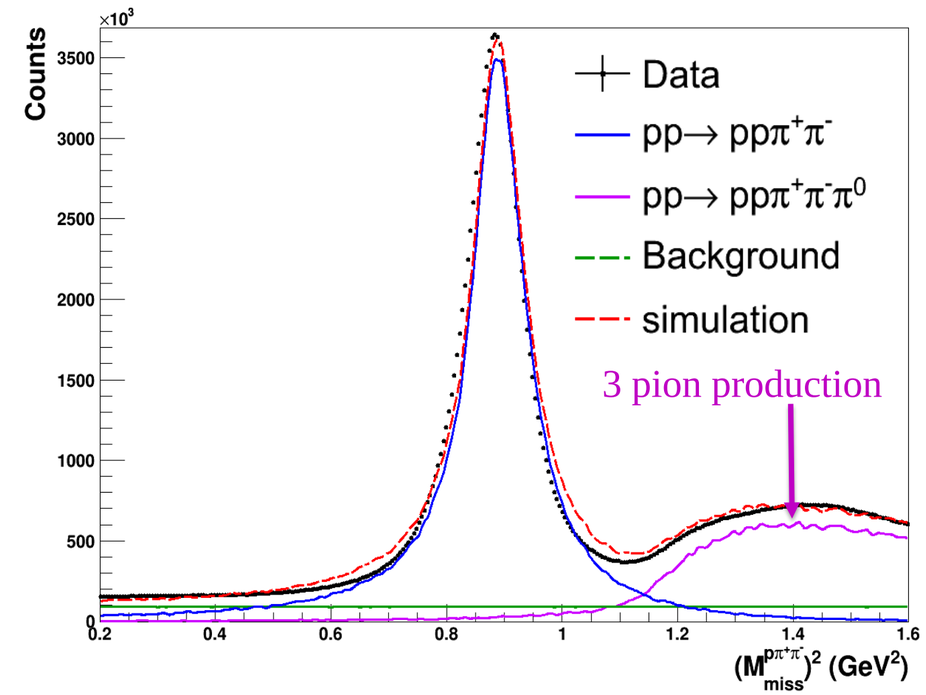


Data Analysis Method

Data Analysis

- Channel selection: $1\pi^+ 1\pi^-$ and 1 proton at least



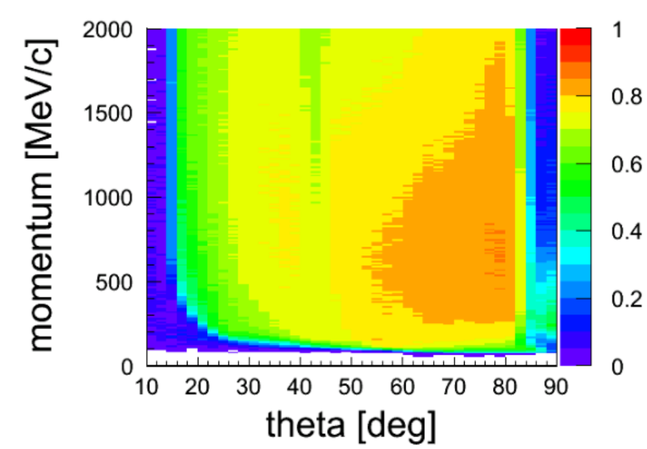


Squared missing mass pp → $p\pi^+\pi^-$ X

- Background subtraction.

- Efficiency correction: using efficiency matrices $Eff(p,\theta,\varphi) = \frac{N_{reconstructed}}{N_{accepted}}$

$$Eff_{total} = Eff_p * Eff_{\pi^+} * Eff_{\pi^-}$$



- Normalisation: $\frac{d\sigma}{dM_{inv}} = \frac{dN}{dM}\frac{\sigma_{el}^{pp}}{N_{el}^{pp}}$, $\sigma_{Data} = N_{Data}\frac{\sigma_{el}^{pp}}{N_{el}^{pp}}$

HADES Resonance Model

PLUTO++ Simulations

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

PDecayChannel (PLUTO Class)	BR x I
N1520 → $p\pi^+\pi^-$	(0.04) (6% x 2/3)
N1520 → $\Delta^{++}\pi^-$	(0.12) (23% x 1/2)
N1520 → $\Delta^0\pi^+$	(0.04) (23% x 1/6)
N1520 → $p\rho^0$	(0.003) (1% x 1/3)

* I. Frolich et al. PoS ACAT2007 (2006)

Simulation (using PLUTO++)

pp → pR → pp $\pi^+\pi^-$(1R)

(Using known cross sections from 1π* and pKΛ** analysis)

N^+ (1440)

N^+ (1520)

N^+ (1535)

Δ^+ (1620)

N^+ (1650)

N^+ (1675)

N^+ (1680)

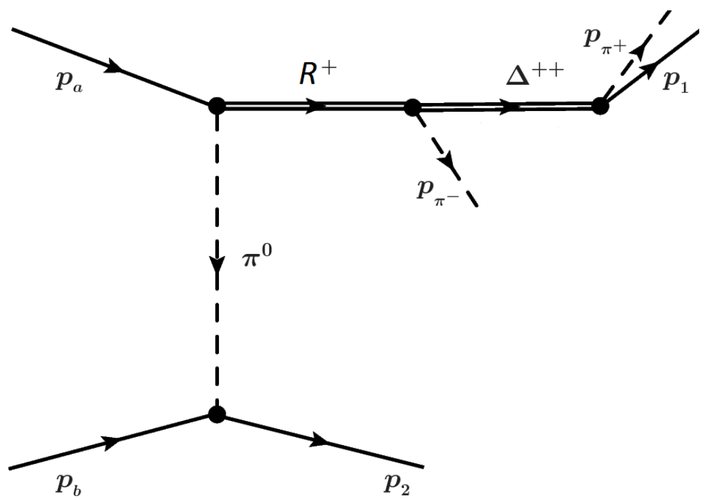
N^+ (1710)

N^+ (1720)

N^+ (1875)

Δ^+ (1880)

Δ^+ (1910)



pp → R R' → pp $\pi^+\pi^-$ (2R)

(cross sections adjusted to the data)

Δ^{++}(1232) Δ^o(1232)

Δ^{++}(1232) N^o(1440)

Δ^{++}(1232) N^o(1520)

Δ^{++}(1232) N^o(1535)

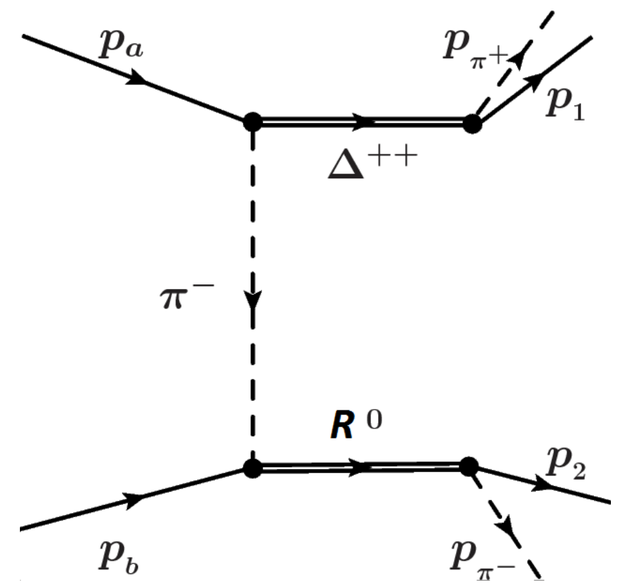
Δ^{++}(1232) Δ^o(1620)

Δ^{++}(1232) N^o(1650)

Δ^{++}(1232) N^o(1680)

Δ^{++}(1232) N^o(1720)

Δ^{++}(1232) Δ^o(1700)



***G. Agakishiev et al.** **Eur.Phys.J. A50 (2014) 8**
pp → npπ^+ and pp → ppπ^0 @ E=3.5 GeV

**** R. Munzer et al. arXiv:1703.01978**
pp→pK$^+\Lambda$ @ E=3.5 GeV

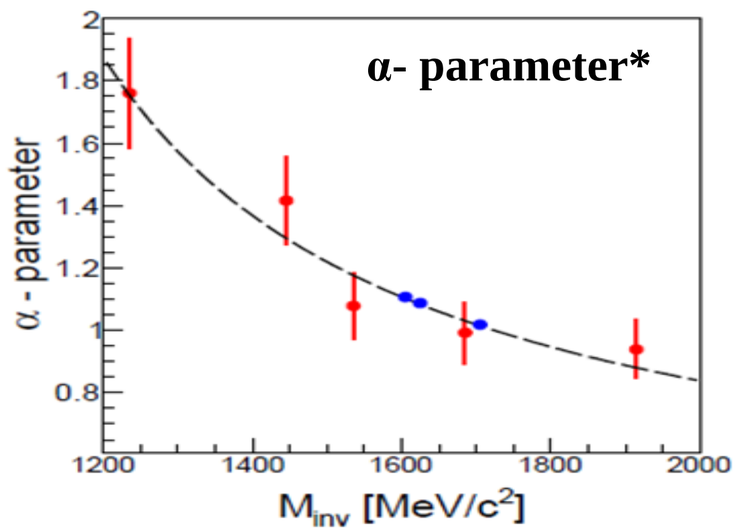
Direct ρ production simulation

σ = 60 μb (from existing data)

Angular Distribution Model

Angular distributions need to be implemented (PLUTO = phase space)

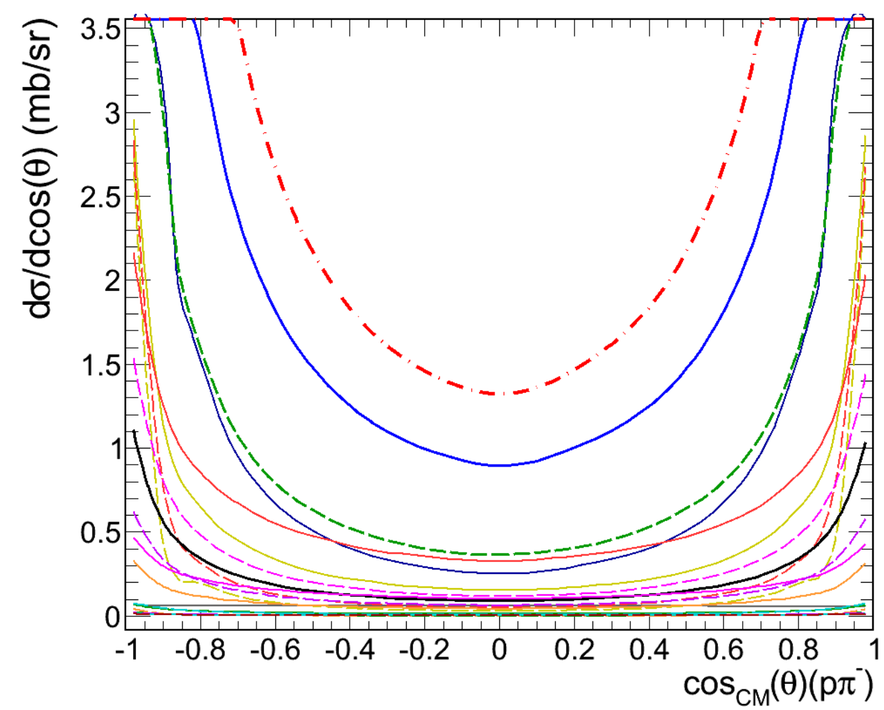
$$\frac{d\sigma_R}{dt} \sim \frac{1}{t^{\alpha}}$$



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

- Model validated in *1* π analysis.
- Extended to 2R production

The simulation is weighted by t_w



Before applying Acc. cuts

*1 π analysis

Analysis results

All spectra include systematic errors

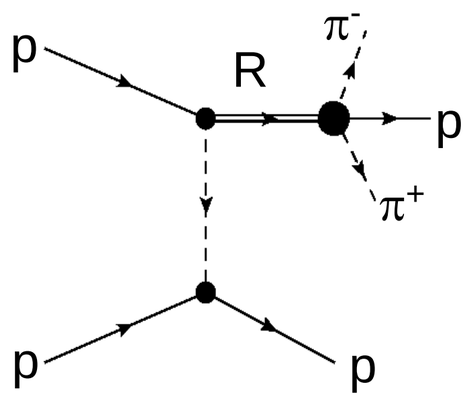
Background subtraction: 1-2%

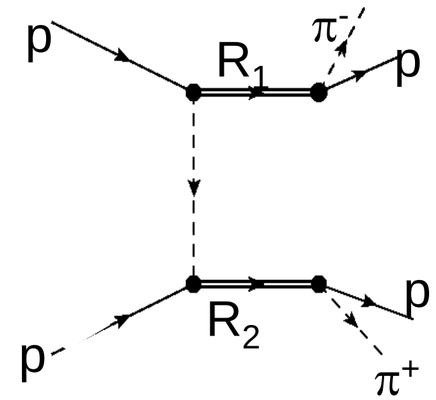
Efficiency: 2%

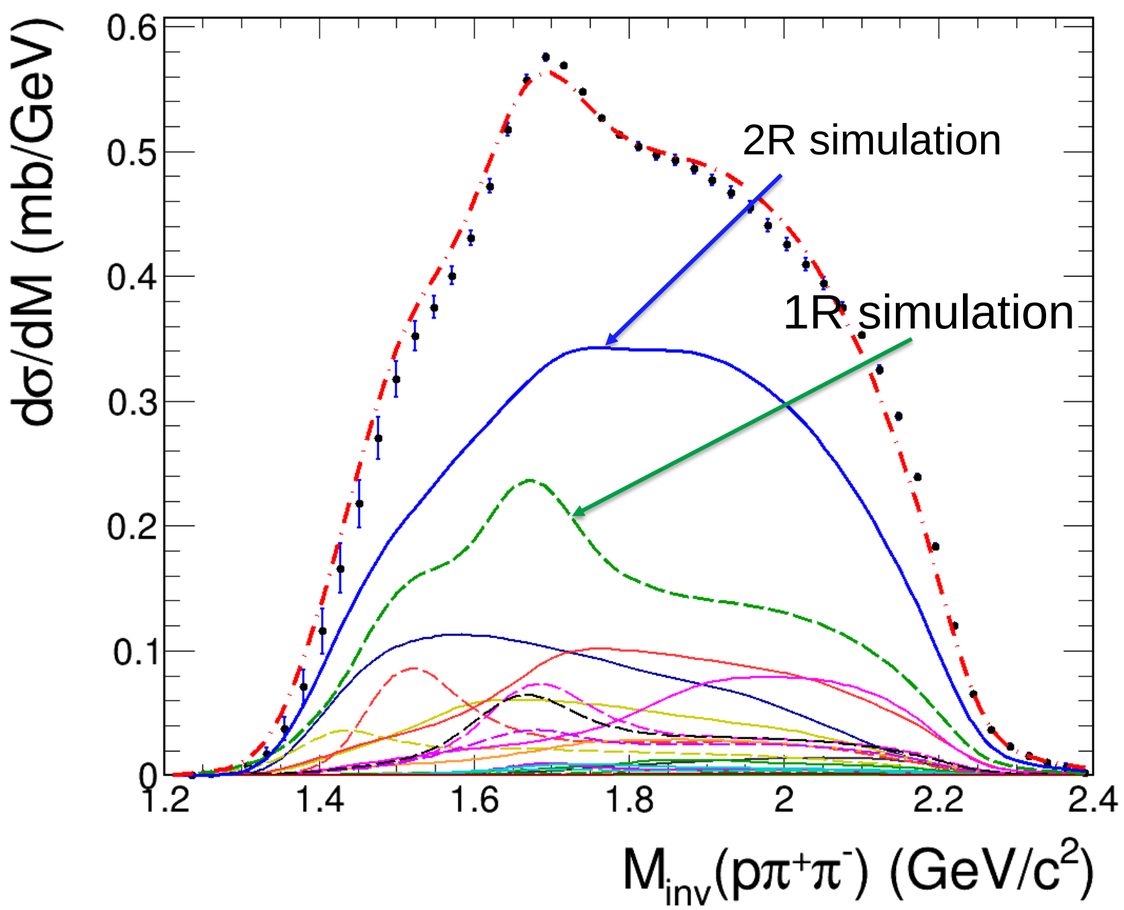
Normalization err: 6.5% (not included).

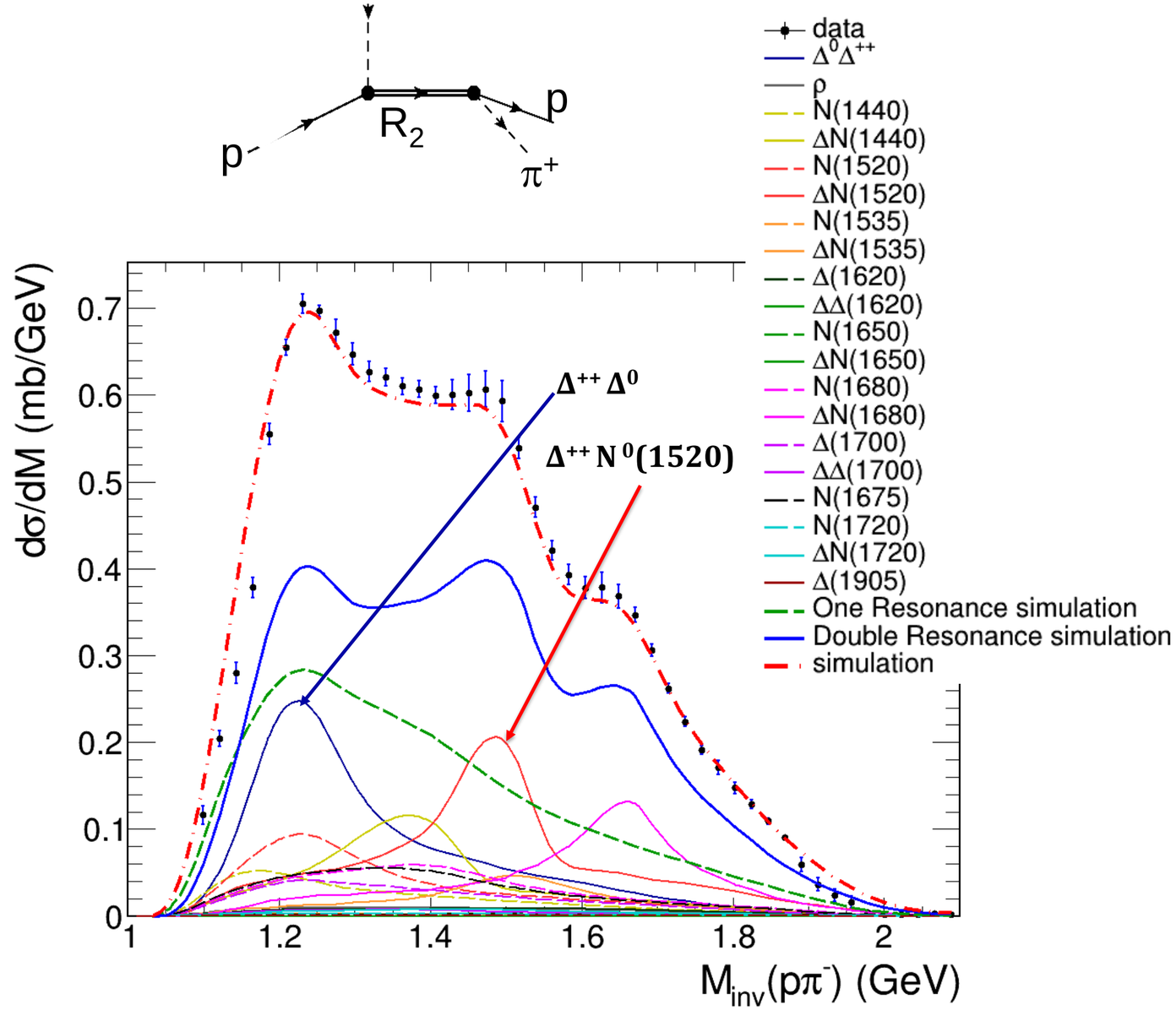
Stat.err are negligible

Invariant Masses Spectra





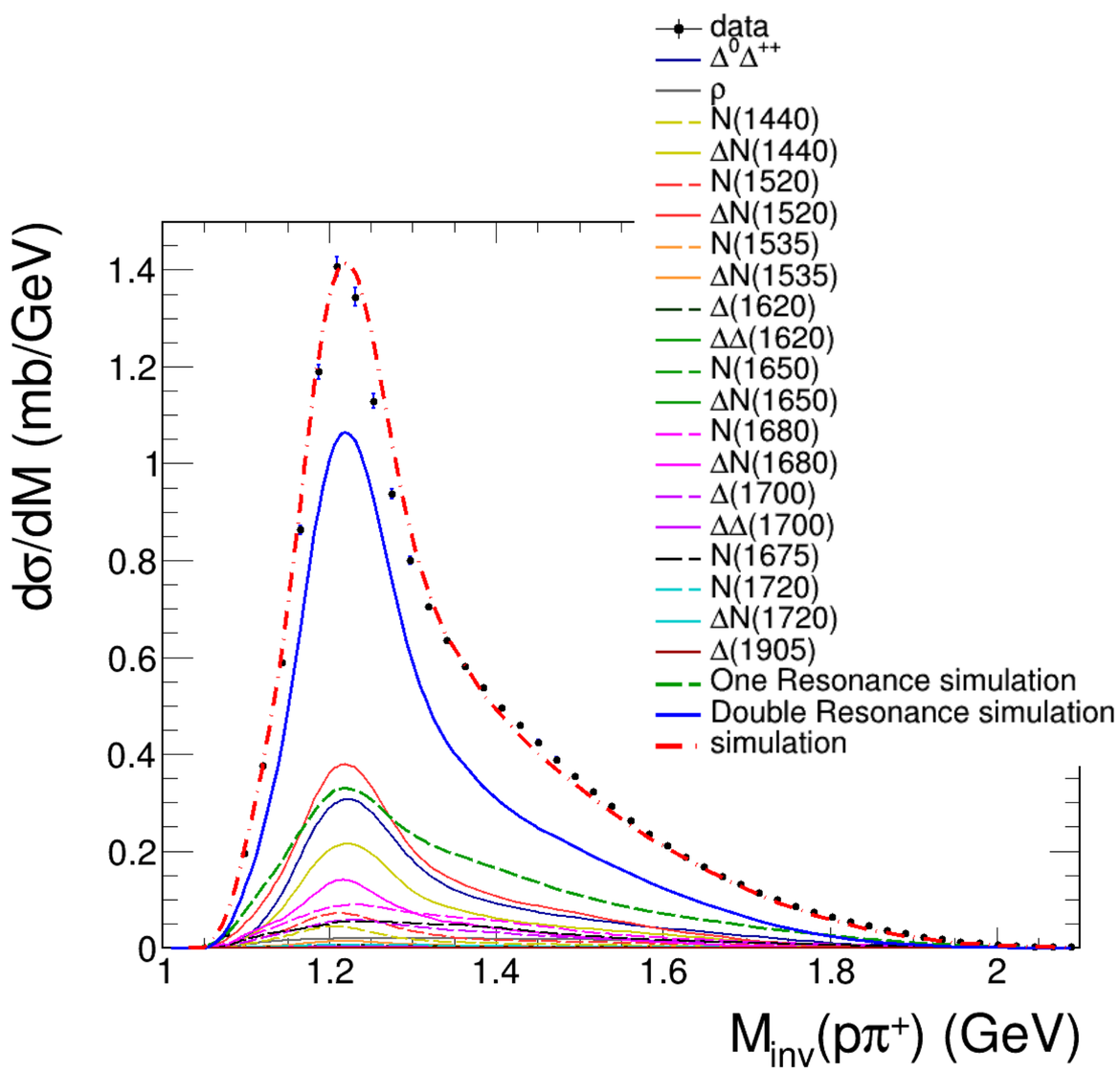


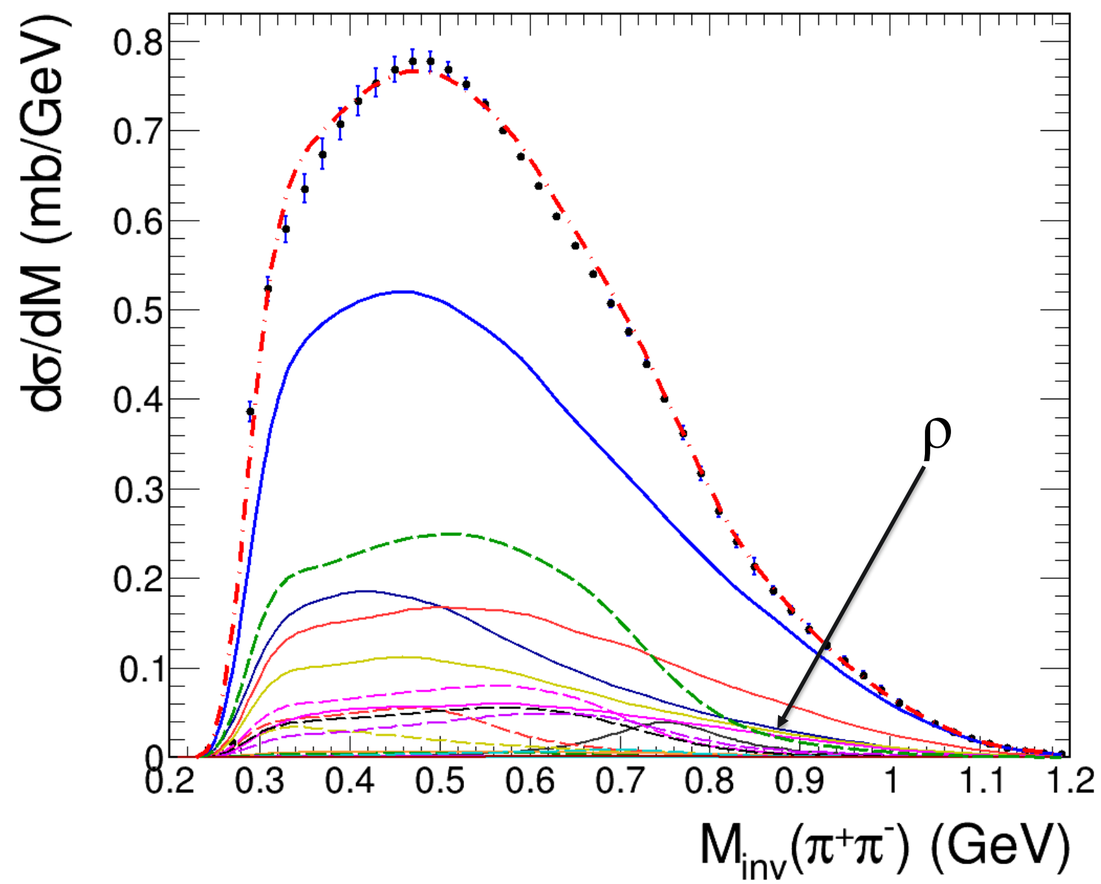


One peak in 1R (Dashed green) due to $N^{+}(1520)$ and a large peak due to $N^{+}(1675)$, $N^{+}(1680)$...

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

Invariant Masses Spectra

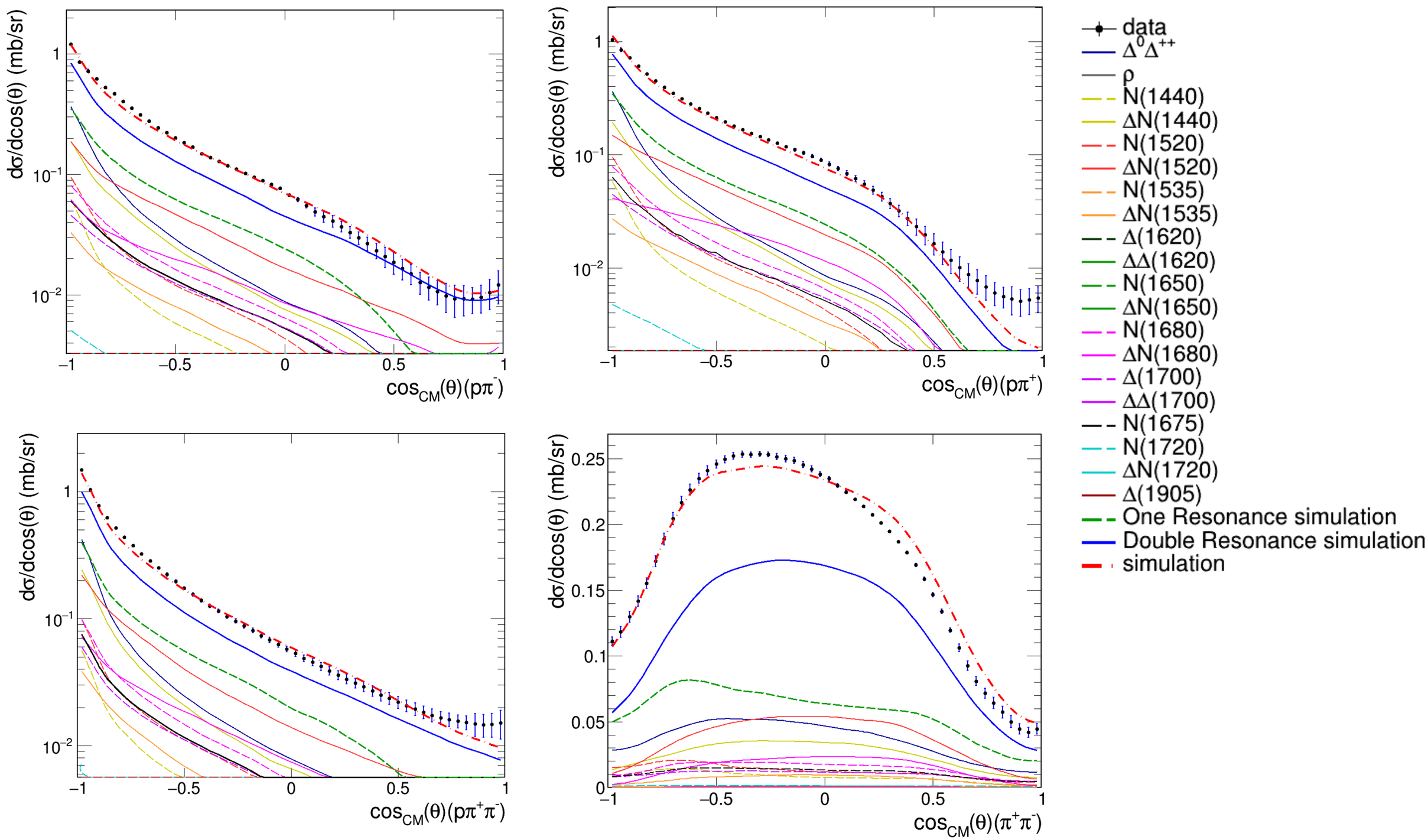




Strong dominance of $\Delta^{++}(1232)$, no significant contribution of heavier Δ^{++} resonances.

No clear evidence of direct ρ production

Angular Distributions



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

Cross Sections

1 Resonance	BR(Nππ)	σ (2π anal.) (mb)	σ (1π anal.*) (mb)
$N^+(1440)$	30%	1.5 ± 0.2	1.5 ± 0.4
$N^+(1520)$	30%	1.7 ± 0.2	1.8 ± 0.3
$N^+(1535)$	10%	0.15 ± 0.05	0.15 ± 0.015
$\Delta^+(1620)$	70%	< 0.10 ± 0.05	< 0.10 ± 0.03
$N^+(1650)$	11%	0.09 ± 0.03	< 0.81 ± 0.13
$N^+(1675)$	45%	0.7± 0.1	<1.65± 0.27
$N^+(1680)$	35%	1.1 ± 0.2	< 0.9 ± 0.15
$N^+(1720)$	80%	0.06 ± 0.03	< 4.4 ± 0.7
$\Delta^+(1700)$	55%	0.45 ± 0.1	0.45 ± 0.16
$\Delta^+(1910)$	90%	< 0.01 ± 0.01	< 0.85 ± 0.53

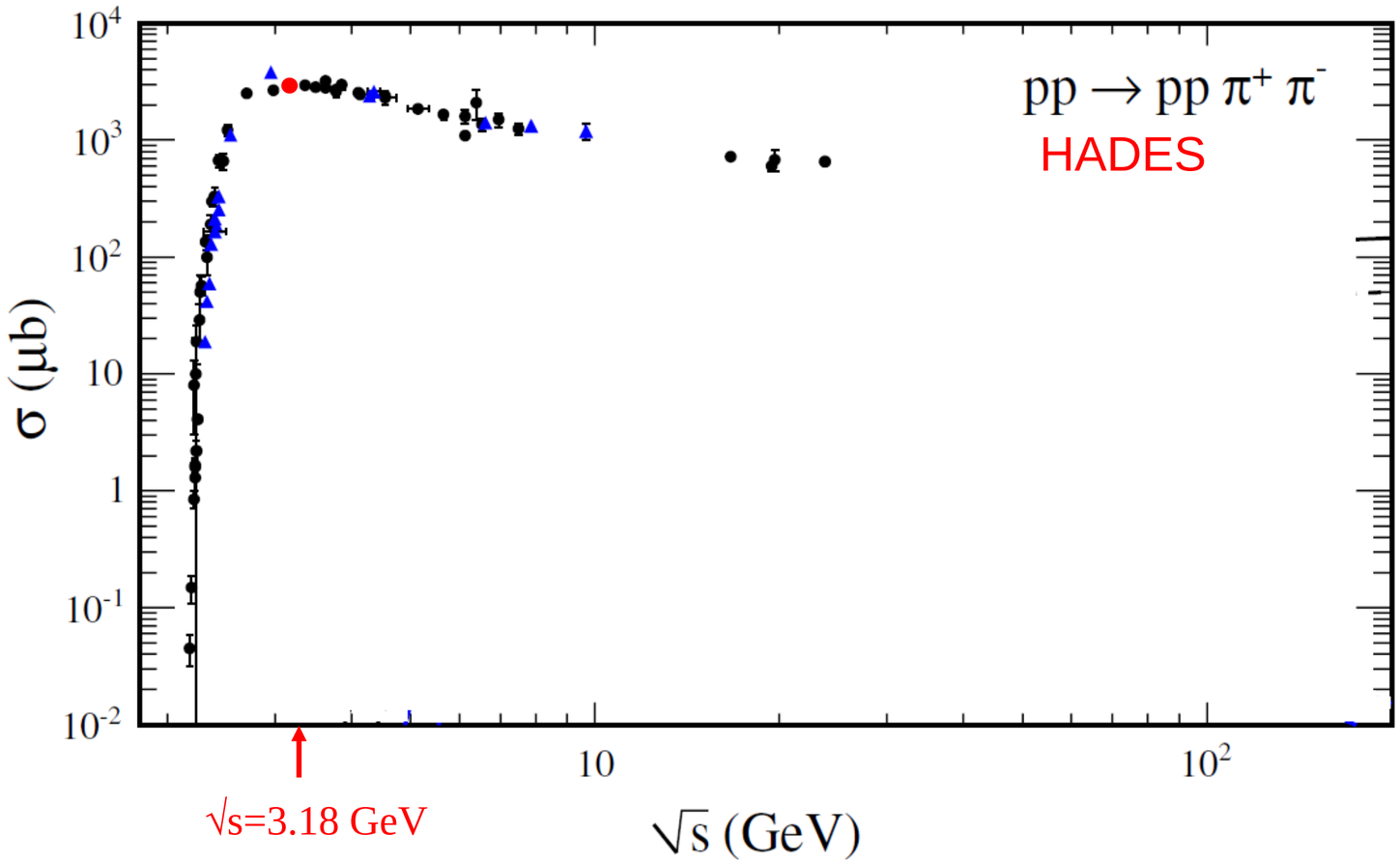
2 Resonances	BR(Nπ)	σ (mb)
$\Delta^{++}(1232)\Delta^{\circ}(1232)$	100%	3.2± 0.2
$\Delta^{++}(1232)N^{\circ}(1440)$	70%	1.5 ± 0.2
$\Delta^{++}(1232)N^{\circ}(1520)$	55%	1.7 ± 0.2
$\Delta^{++}(1232)N^{\circ}(1535)$	46%	0.5 ± 0.1
$\Delta^{++}(1232)\Delta^{\circ}(1620)$	25%	< 0.05 ± 0.02
$\Delta^{++}(1232)N^{\circ}(1650)$	70%	< 0.05 ± 0.04
$\Delta^{++}(1232)N^{\circ}(1680)$	65%	0.9 ± 0.1
$\Delta^{++}(1232)N^{\circ}(1720)$	15%	< 0.02 ± 0.02
$\Delta^{++}(1232)\Delta^{\circ}(1700)$	15%	< 0.04 ± 0.02

1 Resonance	BR(Nππ)	σ (2π anal.) (mb)	σ ($pK^+\Lambda$ anal.**) (mb)
$N^+(1650)$	38%	0.09 ± 0.03	0.12 ± 0.06
$N^+(1710)$	23%	0.05 ± 0.02	0.078 ± 0.05
$N^+(1720)$	80%	0.06 ± 0.01	0.06± 0.015
$N^+(1875)$	70%	0.038 ± 0.02	0.038 ± 0.018
$N^+(1880)$	63%	0.4± 0.1	0.74 ± 0.37

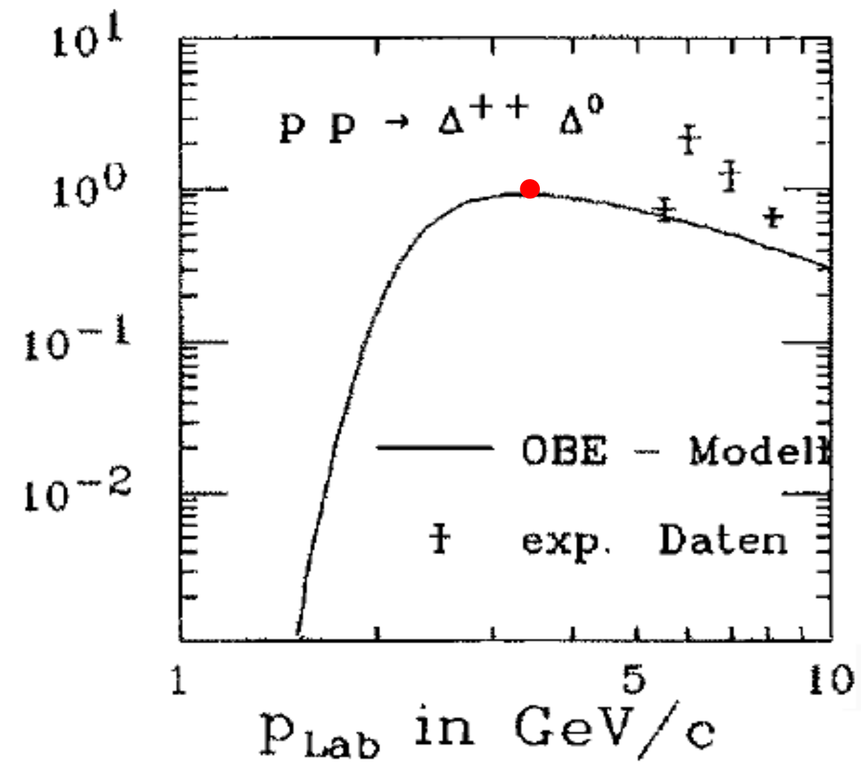
*G. Agakishiev et al. Eur.Phys.J. A50 (2014) 8
** R. Munzer et al. arXiv:1703.01978

✓The resonance cocktail reproduces 1π , 2π and KΛ production. Based on the cocktail we estimate the total cross section pp → pp $\pi^+\pi^-$: σ = 2,95 ± 0.15 mb

Comparing to Existing Data

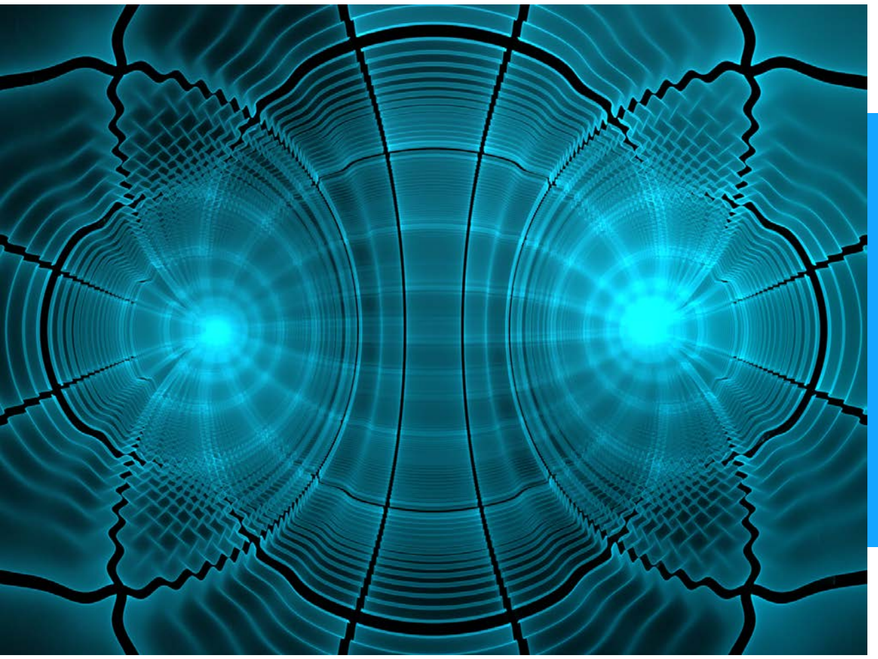


Lebedowicz et al., Phys. ReV D 81, 036003



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

- Total cross section compatible with existing data. (HADES σ=2,95 mb)
- σ (ΔΔ)=1.05 mb, compatible with OBE (One boson exchange) model.



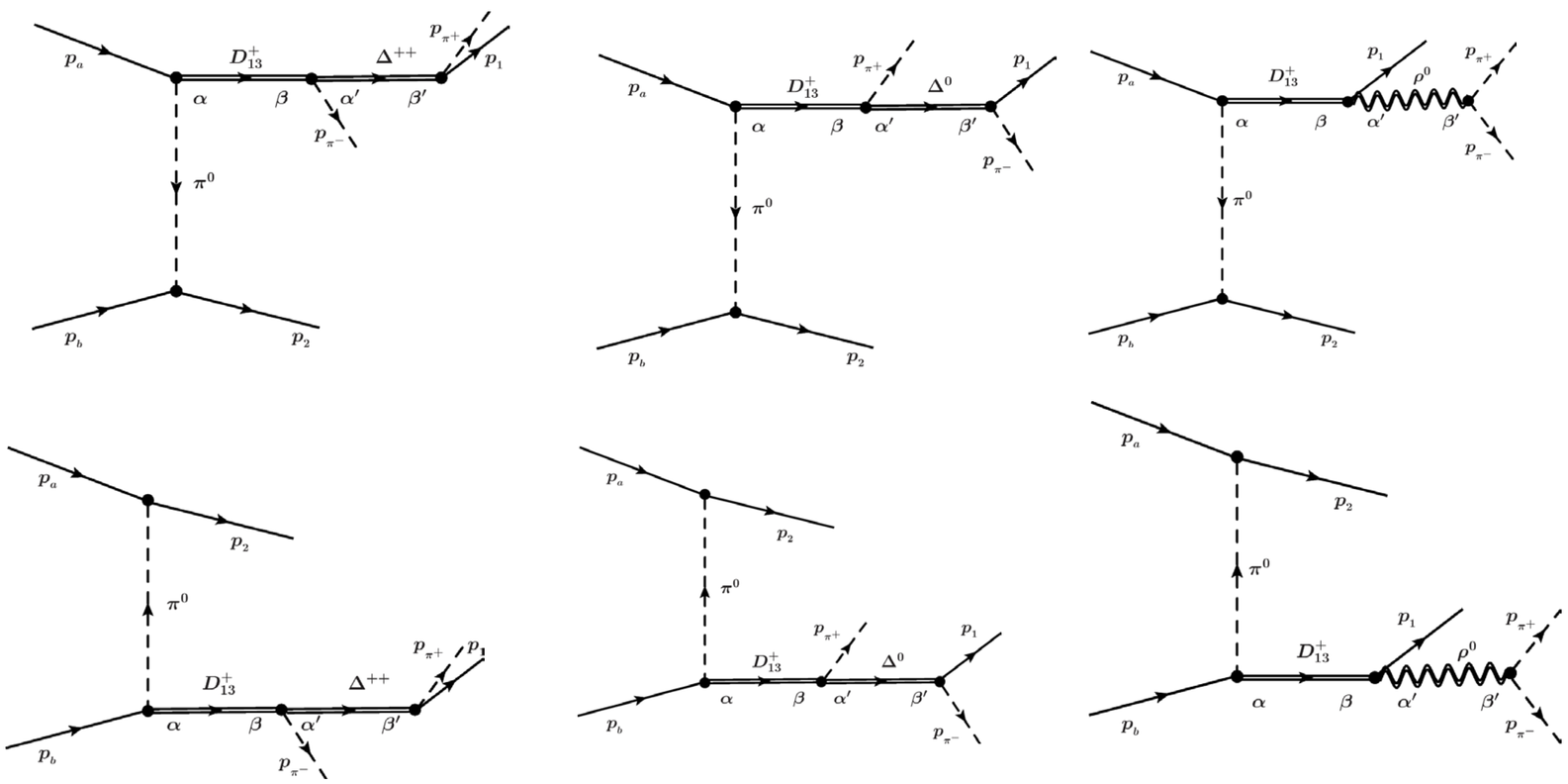
Evaluating the interferences effect

HADES resonance model is an incoherent sum of resonances.

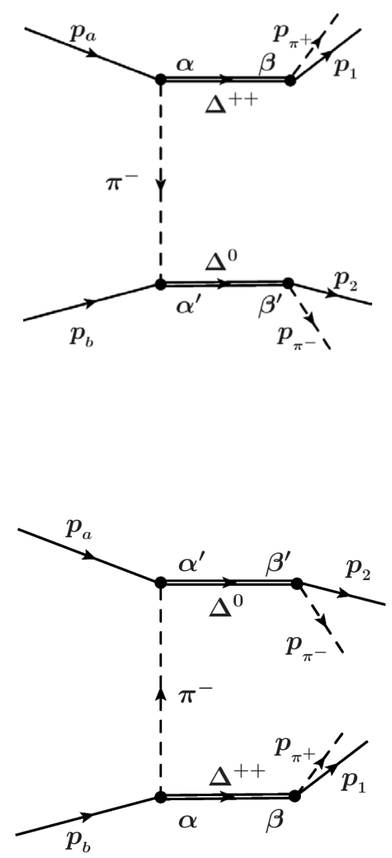
Theoretical test model

Our PLUTO resonance model is an incoherent sum of different prosesses.
To test the effect of interferences we created a Lagrangian model with Jacques Van de Wiele.

1R production: N(1520) (D_{13})
12 diagrams (6 direct, 6 exchange)



2R production: Δ^{++} (1232) Δ°(1232)
4 diagrams (2 direct, 2 exchange)



Theoretical test model

Our PLUTO resonance model is an incoherent sum of different prosesses.
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Model lagrangians (same as Xu Cao et al. *):

$$\mathcal{L}_{\pi NN} = -\frac{f_{\pi NN}}{m_\pi}\,\overline{N}\gamma_5\gamma_\mu\vec{\tau}\cdot\partial^\mu\vec{\pi}N$$

$$\mathcal{L}^{3/2^-}_{\pi NR} = g_{\pi NR}\overline{N}^\mu\gamma_5\gamma_\mu\vec{\tau}\cdot\partial^\mu\partial^\nu\vec{\pi}R_\nu + h.c.$$

$$\mathcal{L}^{3/2^-}_{\rho NR} = g_{\rho NR}\overline{N}\vec{\tau}\cdot\vec{\rho}^\mu R_\mu + h.c.$$

$$\mathcal{L}^{3/2^-}_{\pi\Delta R} = g_{\pi\Delta R}\overline{\Delta}^\mu\gamma_\nu\vec{\tau}\cdot\partial^\nu\vec{\pi}R_\mu + h.c.$$

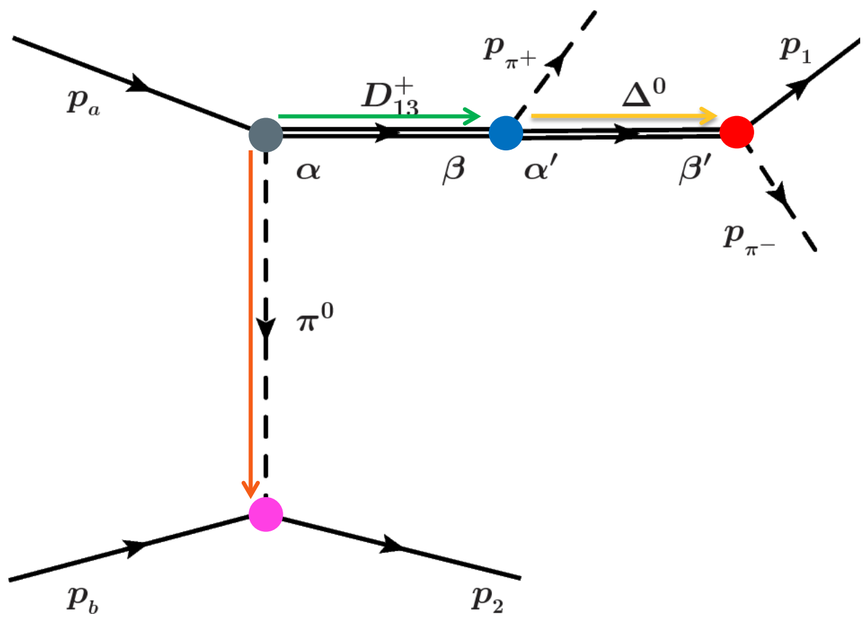
$$\mathcal{L}_{\pi\Delta\Delta} = -\frac{f_{\pi\Delta\Delta}}{m_\pi}\,\overline{\Delta}^\nu\gamma_5\gamma_\mu\vec{\tau}\cdot\partial^\mu\vec{\pi}\Delta_\nu + h.c.$$

$$\mathcal{L}_{\rho\pi\pi} = g_{\rho\pi\pi}\,\left(\vec{\pi}\times\partial_\mu\vec{\pi}\right)\cdot\vec{\rho}^\mu$$

* X. Cao, B.-S. Zou and H.-S. Xu, Phys. Rev. C81 (2010) 12.

Theoretical test model

Amplitudes calculation:



$$\mathcal{M}(m_1, m_2, m_a, m_b) = \bar{u}_1(p_1, m_1)\ V(\Delta^{0\ \beta'} \to p_1 + p_{\pi^-})\ i\,P_F^{\alpha' \to \beta'}(\Delta^0, p_{\Delta^0} = p_1 + p_{\pi^-})\ V(D_{13}^{+\ \beta} \to \Delta^{0\ \alpha'} + p_{\pi^+})$$

$$i\,P_F^{\alpha \to \beta}(D_{13}^+, p_{D_{13}^+})\ V(p_a \to D_{13}^{+\ \alpha} + \pi^0)\ u_a(p_a, m_a)\ i\,P_F(\pi^0, p_{\pi^0})\ \bar{u}_2(p_2, m_2)\ V(p_b + \pi^0 \to p_2)\ u_b(p_b, m_b)$$

Theoretical test model

$$\frac{\mathrm{d}^8\sigma}{dE_1 d\Omega_1 dE_2 d\Omega_2 d\Omega_3} = \frac{1}{64(2\pi)^8}\frac{\mathbf{p}_1\mathbf{p}_2}{\mathbf{p}_a m_b}\sum_{p_3}\frac{\mathbf{p}_3^2|\mathcal{M}|^2}{E_4\mathbf{p}_3 + E_3(\mathbf{p}_3 - \mathbf{p}_a - \mathbf{p}_1 - \mathbf{p}_2)}$$

- Generate events with PLUTO: $|\mathcal{M}|^2$=1 (phase space)

- Calculate the squared amplitude $|\mathcal{M}|^2$ event by event and apply it as a weight:

- ***Interference Model***

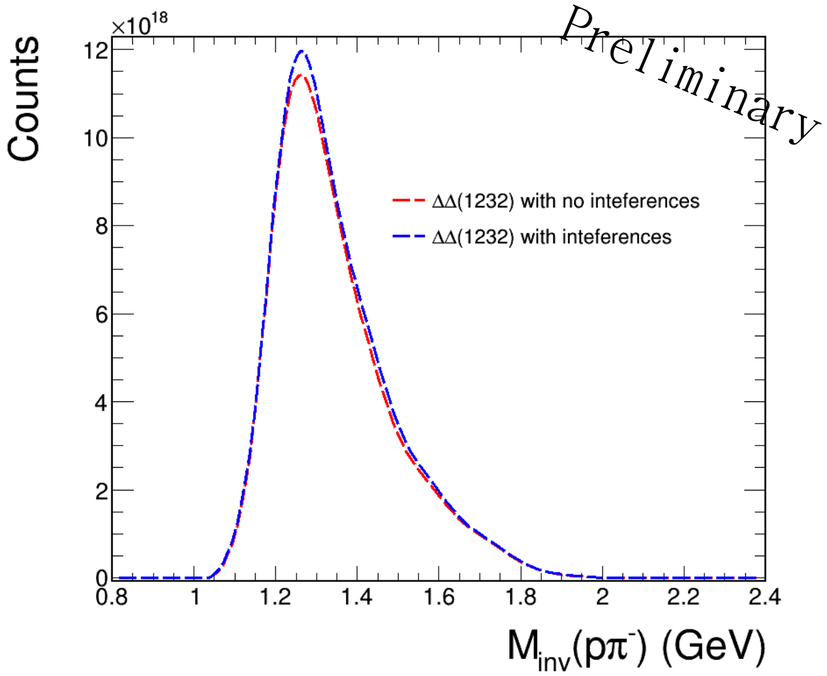
$$|\mathcal{M}|^2 = \sum_s |\mathcal{M}_1 + \mathcal{M}_2 + \cdots + \mathcal{M}_n|^2$$

- ***No Interference Model***

$$|\mathcal{M}|^2 = \sum_s |\mathcal{M}_1|^2 + \sum_s |\mathcal{M}_2|^2 + \cdots + \sum_s |\mathcal{M}_n|^2$$

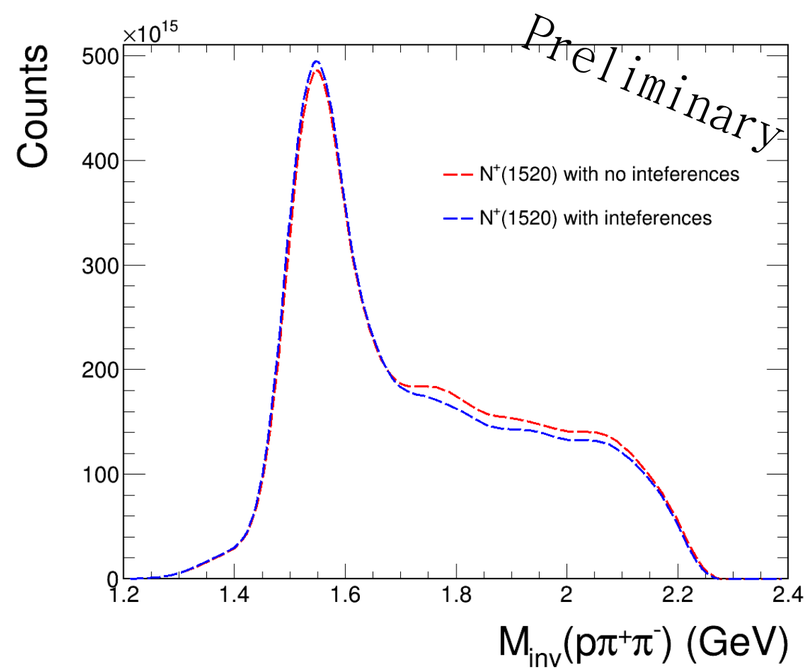
Theoretical test model results

Δ⁺⁺ (1232)Δ°(1232)

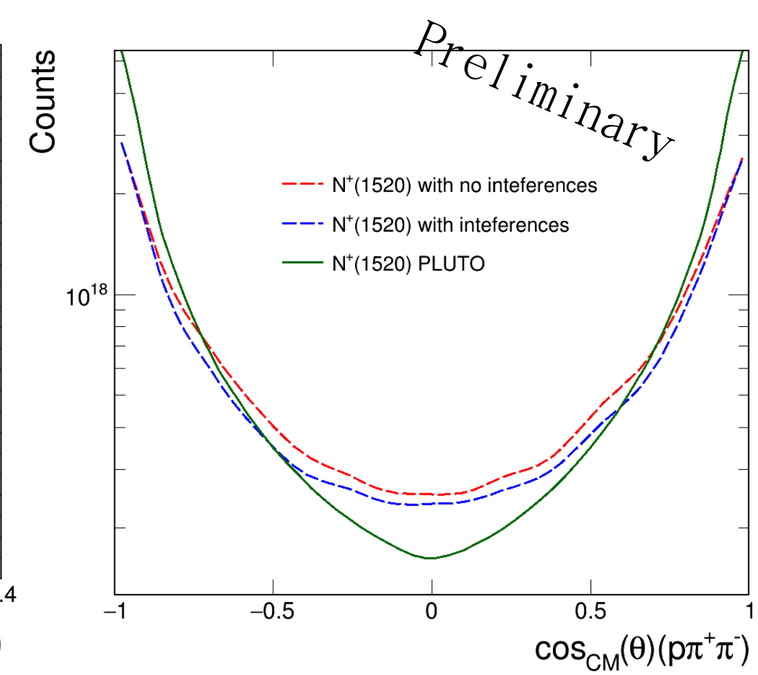


Difference between interference and no interference model is 1-2% in HADES acceptance

N (1520)



Difference between interference and no interference model is 2-3% in HADES acceptance



PLUTO resonance model shows a narrower angular distribution than the theoretical model

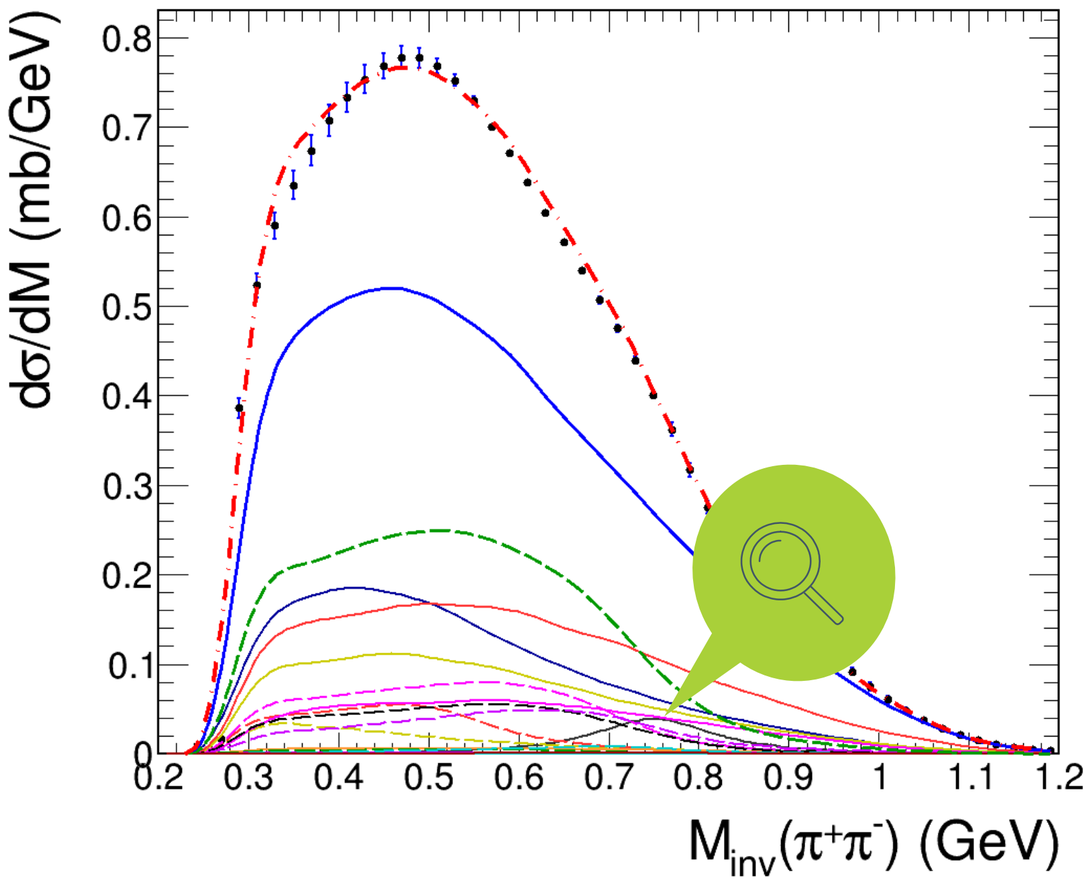
The theoretical test model shows that interferences between different graphs is small and constructive .

Tracking down the ρ meson

Search for the direct “ρ”

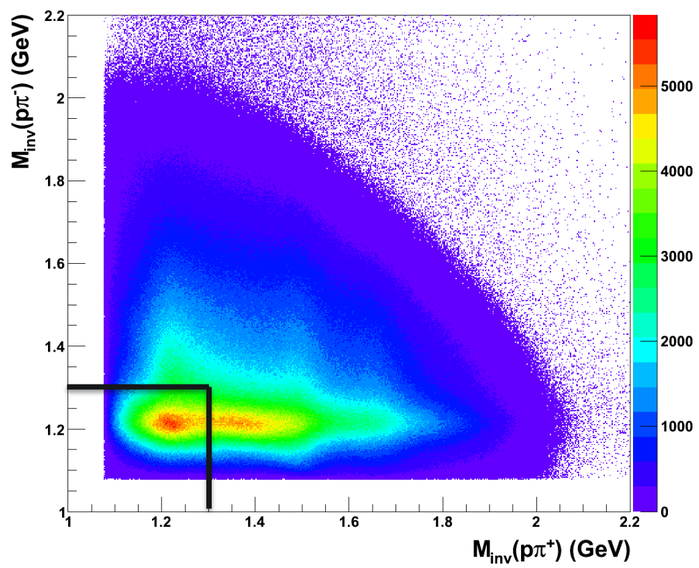
Apply kinematical cuts to reduce the baryonic resonance excitation background.

$M(\rho) = 775$ MeV
$\Gamma(\rho) = 149$ MeV

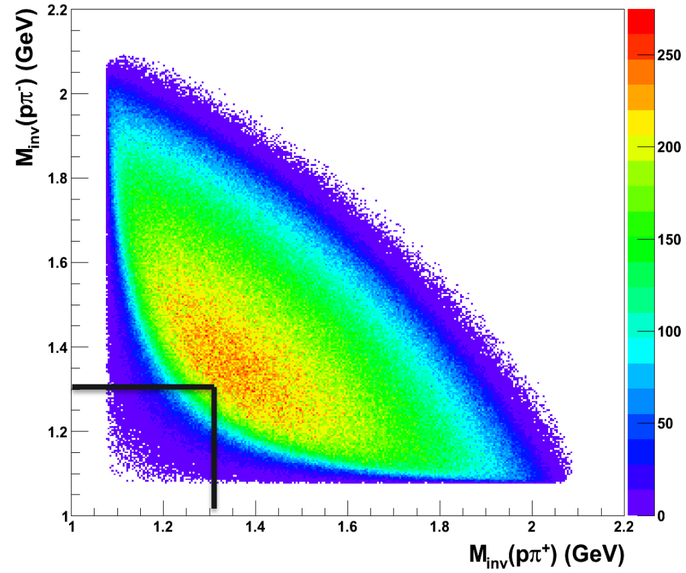


Search for the direct “ρ”

Data



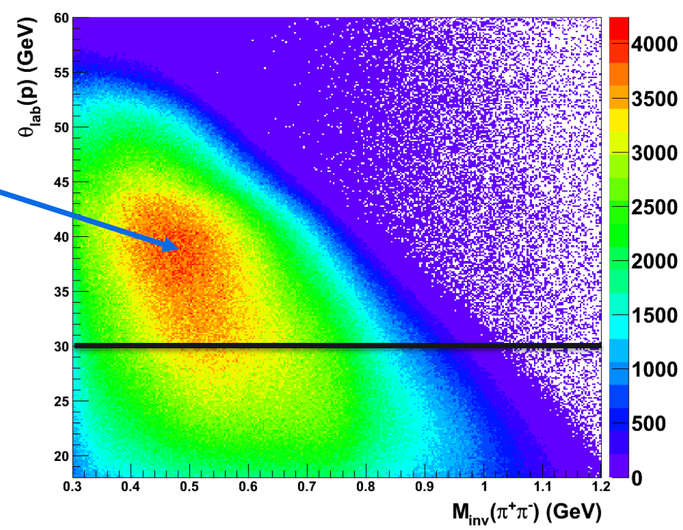
ρ simulation

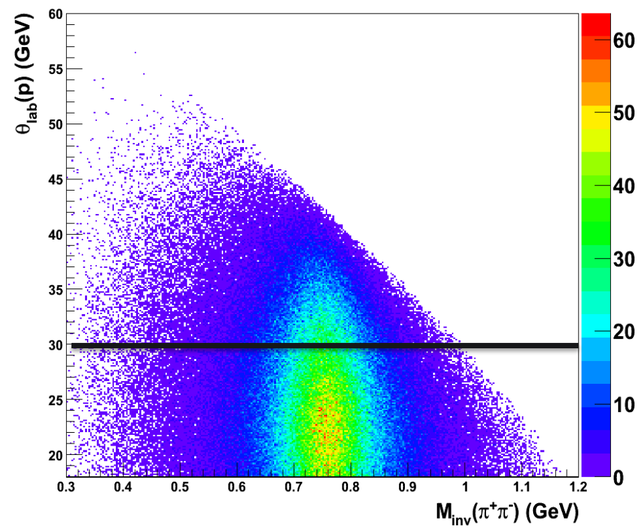


$$\begin{cases} M_{inv}(p\pi^+) > 1.3\ GeV \\ M_{inv}(p\pi^-) > 1.3\ GeV \end{cases}$$

Suppress Δ(1232)Δ(1232)

resonances



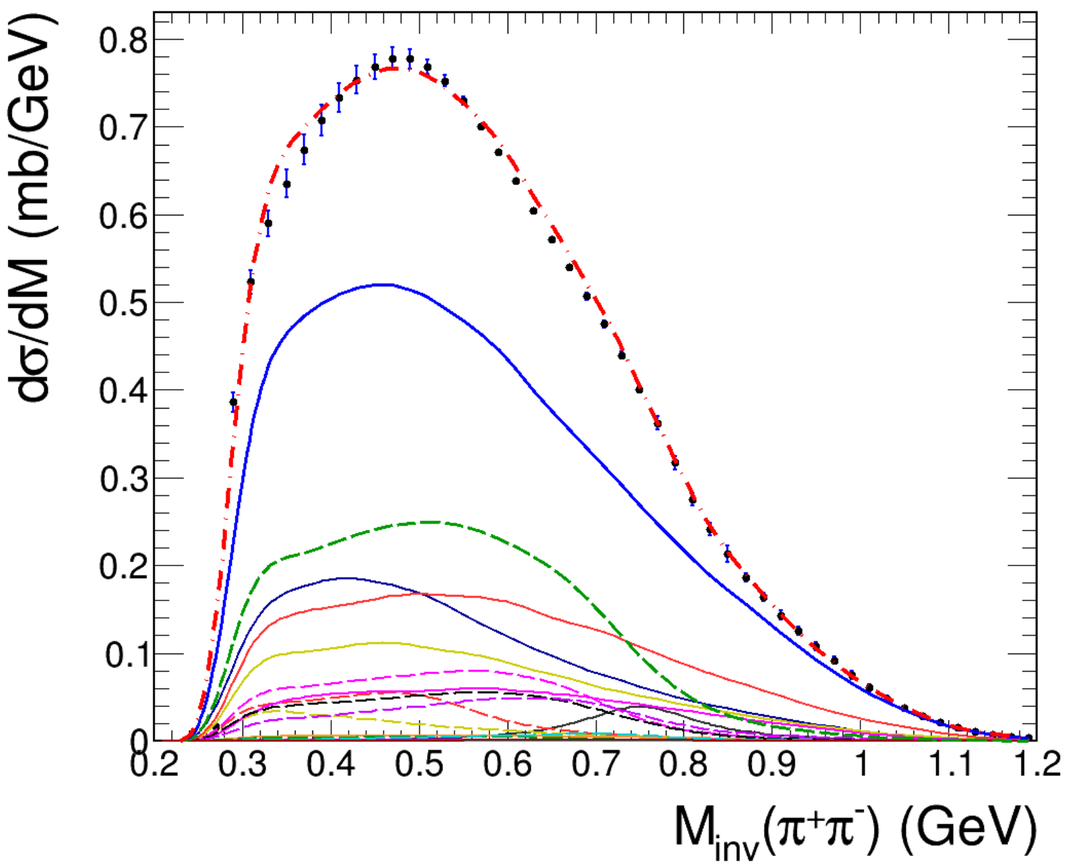


$$\begin{cases} \theta_{lab}(p) < 30^\circ \end{cases}$$

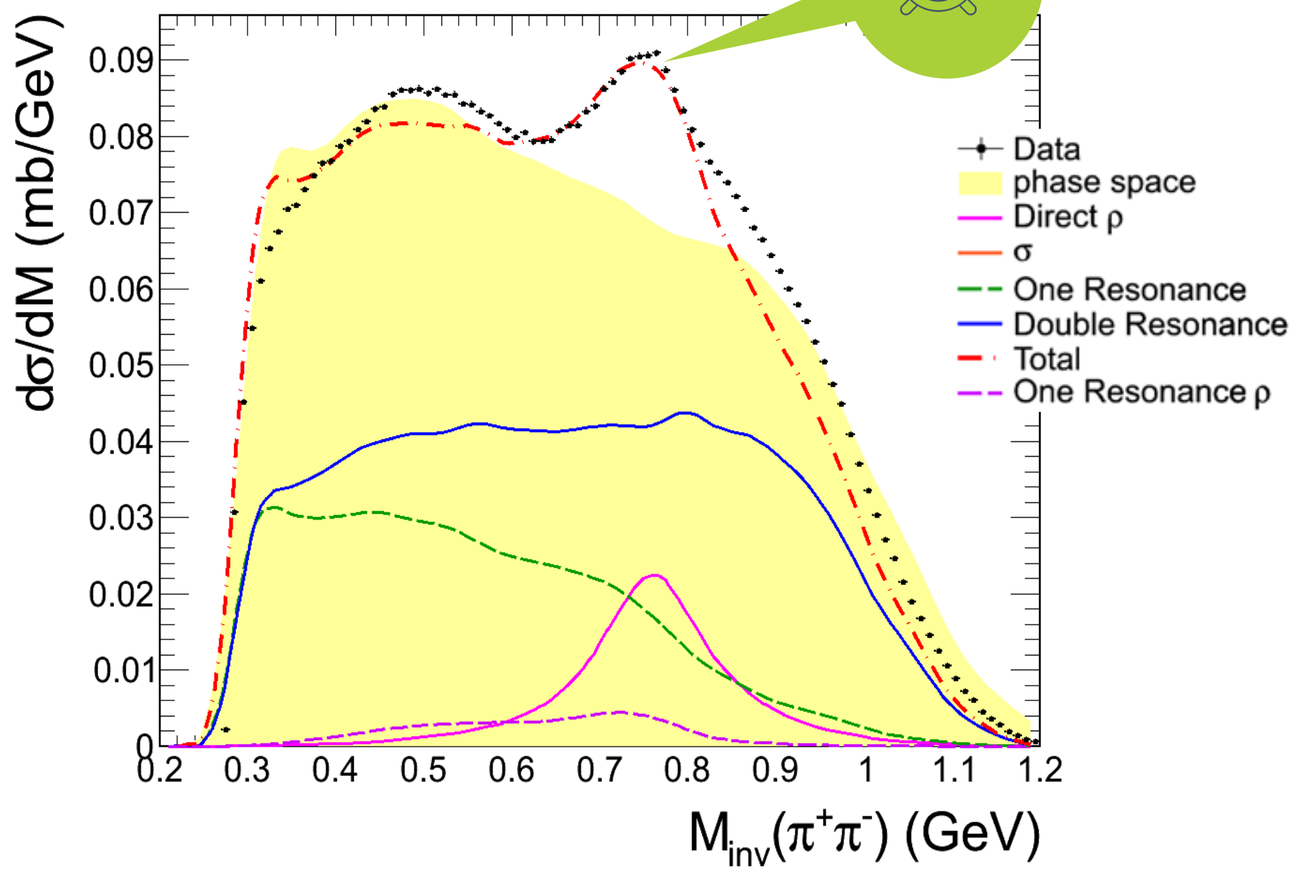
Suppress remaining resonances

Search for the direct “ρ”

Before kinematical cuts

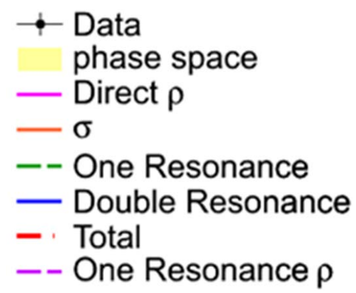


After kinematical cuts



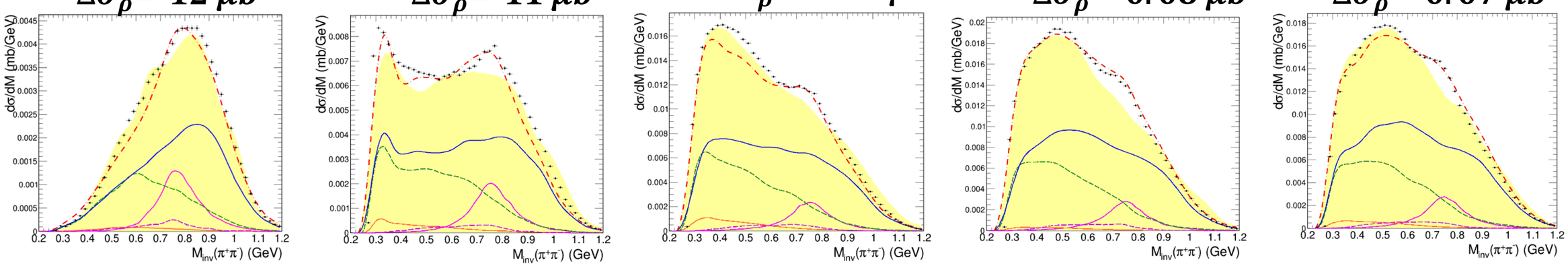
“ρ” Angular Distribution

Adjust σ_ρ in bins of $cos_{CM}(\theta)(\pi^+\pi^-)$
After reducing the resonances background



Backward

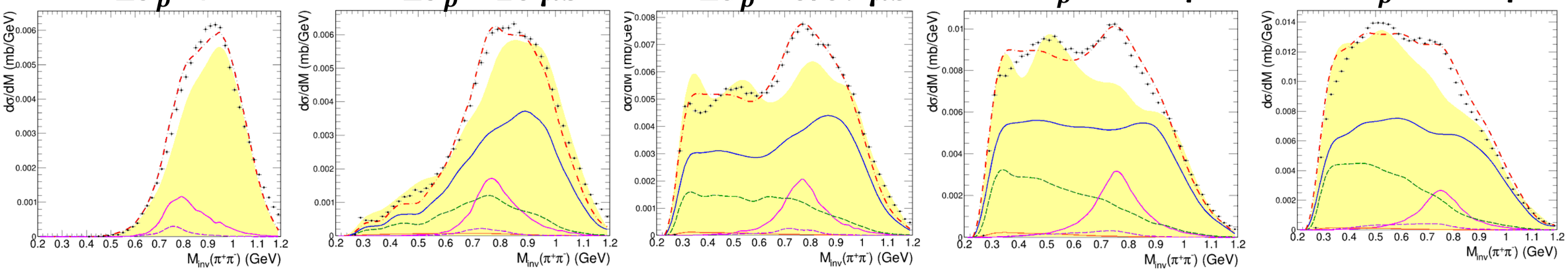
$\Delta\sigma_\rho = 12\ \mu b$ | $\Delta\sigma_\rho = 11\ \mu b$ | $\Delta\sigma_\rho = 0.09\ \mu b$ | $\Delta\sigma_\rho = 0.08\ \mu b$ | $\Delta\sigma_\rho = 0.07\ \mu b$



$-1 < \cos(\theta) < -0.8$ | $-0.8 < \cos(\theta) < -0.6$ | $-0.6 < \cos(\theta) < -0.4$ | $-0.4 < \cos(\theta) < -0.2$ | $-0.2 < \cos(\theta) < 0$

Forward

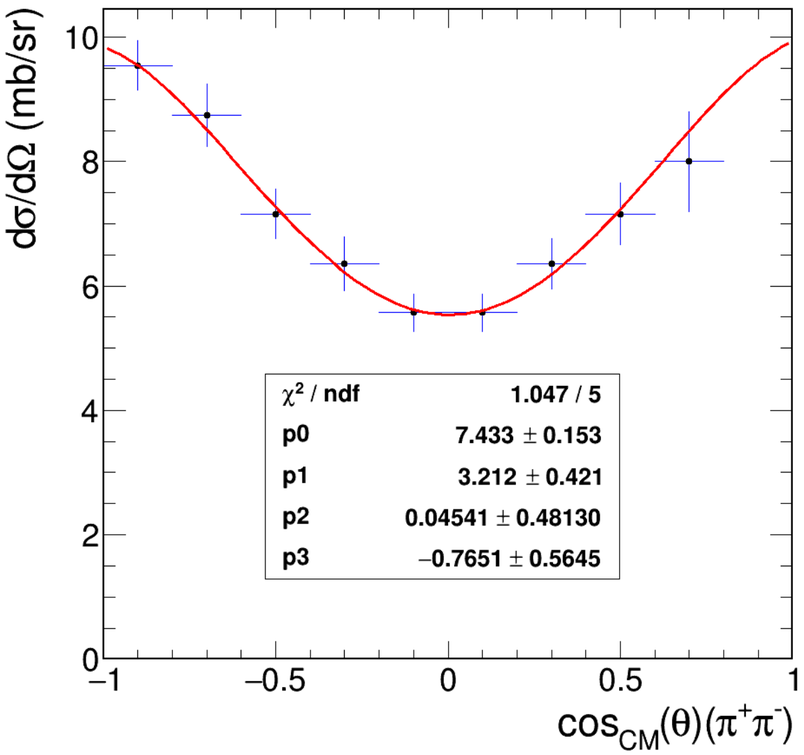
$\Delta\sigma_\rho = ?$ | $\Delta\sigma_\rho = 10\ \mu b$ | $\Delta\sigma_\rho = 0.09\ \mu b$ | $\Delta\sigma_\rho = 0.08\ \mu b$ | $\Delta\sigma_\rho = 0.07\ \mu b$



$0.8 < \cos(\theta) < 1$ | $0.6 < \cos(\theta) < 0.8$ | $0.4 < \cos(\theta) < 0.6$ | $0.2 < \cos(\theta) < 0.4$ | $0 < \cos(\theta) < 0.2$

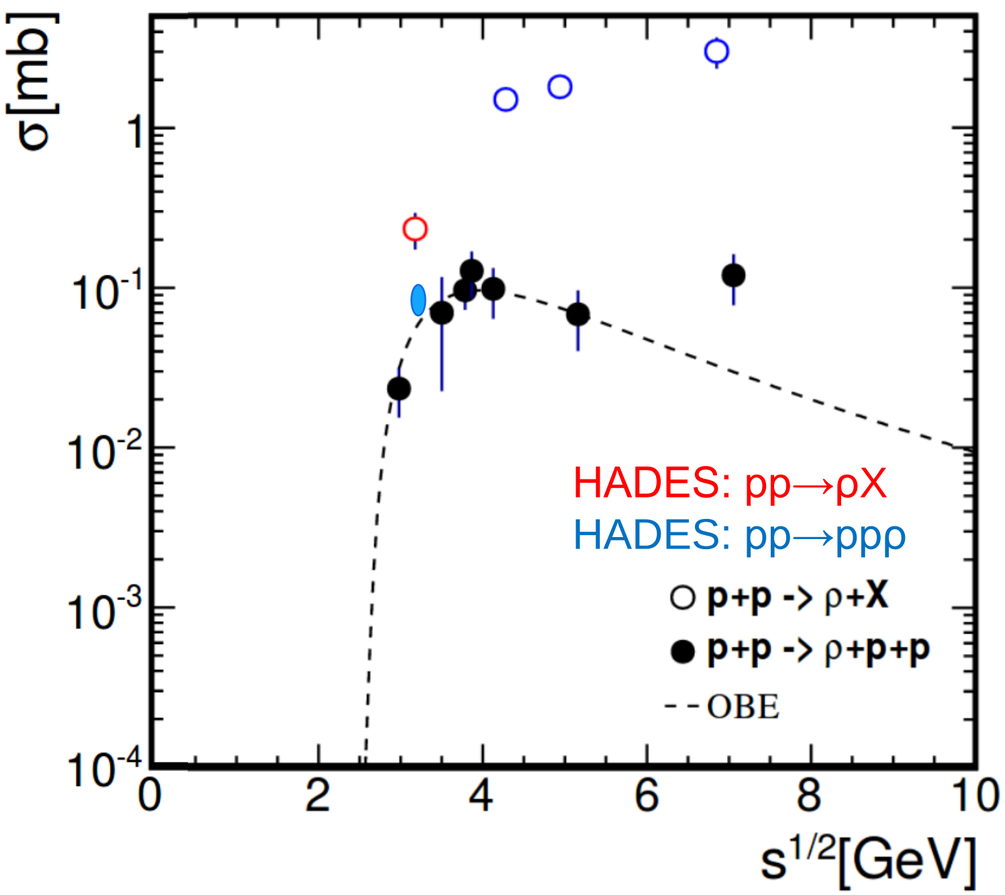
- Good backward/forward symetry

“ρ” Angular Distribution

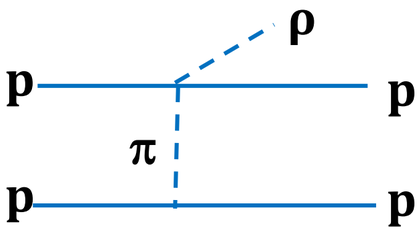


$$\frac{d\sigma_\rho}{d\Omega} = (7.4 \pm 0.2)P_0 + (3.2 \pm 0.6)P_2 - (0.7 \pm 0.7)P_4$$

$\sigma_\rho = 90 \pm 5\ \mu b$



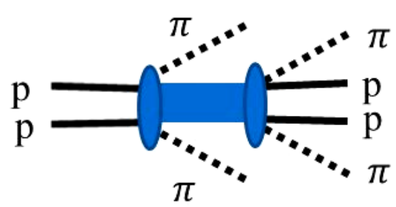
- New measurement of pp→ppρ by HADES.
- Consistent with previous data and much more precise.
- Consistent with OBE model

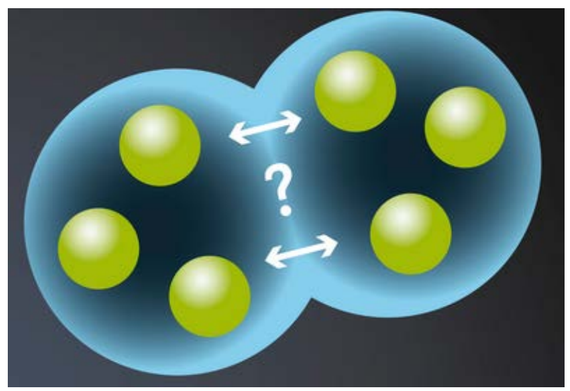


Perspectives

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

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





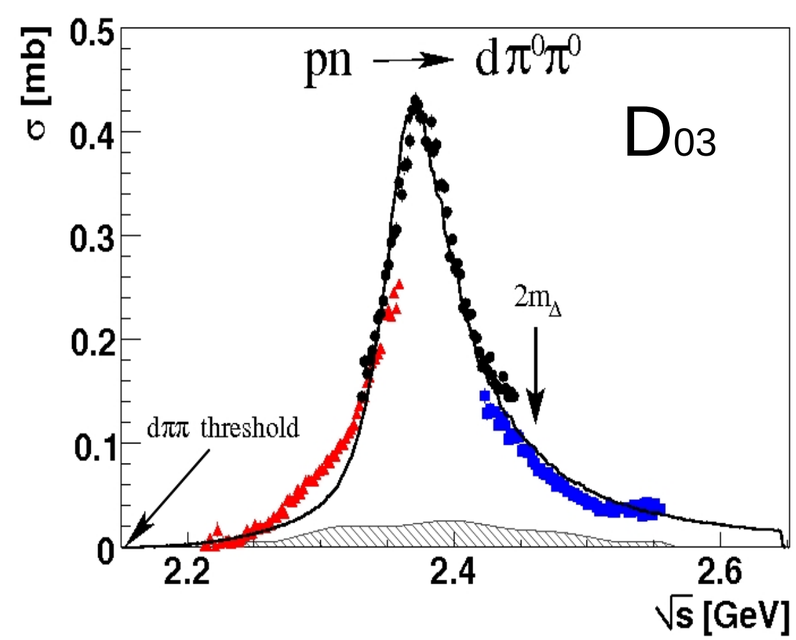
Isospin factors

$$pp \rightarrow \pi^-\pi^- d^{4+} \rightarrow \pi^-\pi^-\Delta^{++}\Delta^{++} \rightarrow pp\pi^+\pi^+\pi^-\pi^- \qquad \mathbf{1}$$

$$pp \rightarrow \pi^+\pi^- d^{2+} \rightarrow \pi^+\pi^-\Delta^{++}\Delta^{0} \rightarrow pp\pi^+\pi^+\pi^-\pi^- \qquad \mathbf{2}\cdot\left(\frac{\mathbf{1}}{\mathbf{15}}\right)$$

$$pp \rightarrow \pi^+\pi^+ d^{0} \rightarrow \pi^+\pi^+\Delta^{0}\Delta^{0} \rightarrow pp\pi^+\pi^+\pi^-\pi^- \qquad \left(\frac{\mathbf{1}}{\mathbf{15}}\right)$$

Complementary study to WASA experiment



Conclusion

A

This analysis confirms the presence of three channels: One and double baryonic resonance production , direct ρ production.

B

The results show consistency between one and two pion production within the “HADES resonance model” .

E

ρ signal was extracted by applying the necessary kinematical cuts (Crutial for e+e- production analysis).

C

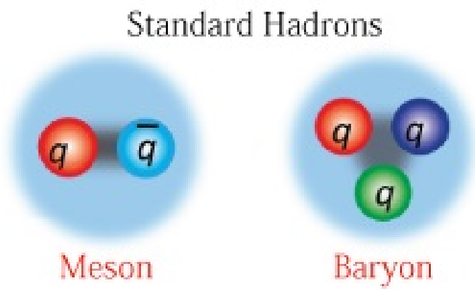
The results present valuable inputs for theoretical models, benchmark test for descpiption of e+e- production (Ongoing comparison).
(Only existing data at this energy level)

Thanks For Your Attention!

Any questions?

Pion production Motivation

- Hadron spectroscopy:
  - Mesons: $\rho \to \pi\pi$, $\omega \to \pi\pi\pi$ …
  - Baryons: Δ /N* $\to$ N π , Δ /N* $\to$ N $\pi\pi$
- Reaction mechanism.



$pp \to np\pi^+$ and $pp \to pp\pi^0$ @ E=3.5 GeV

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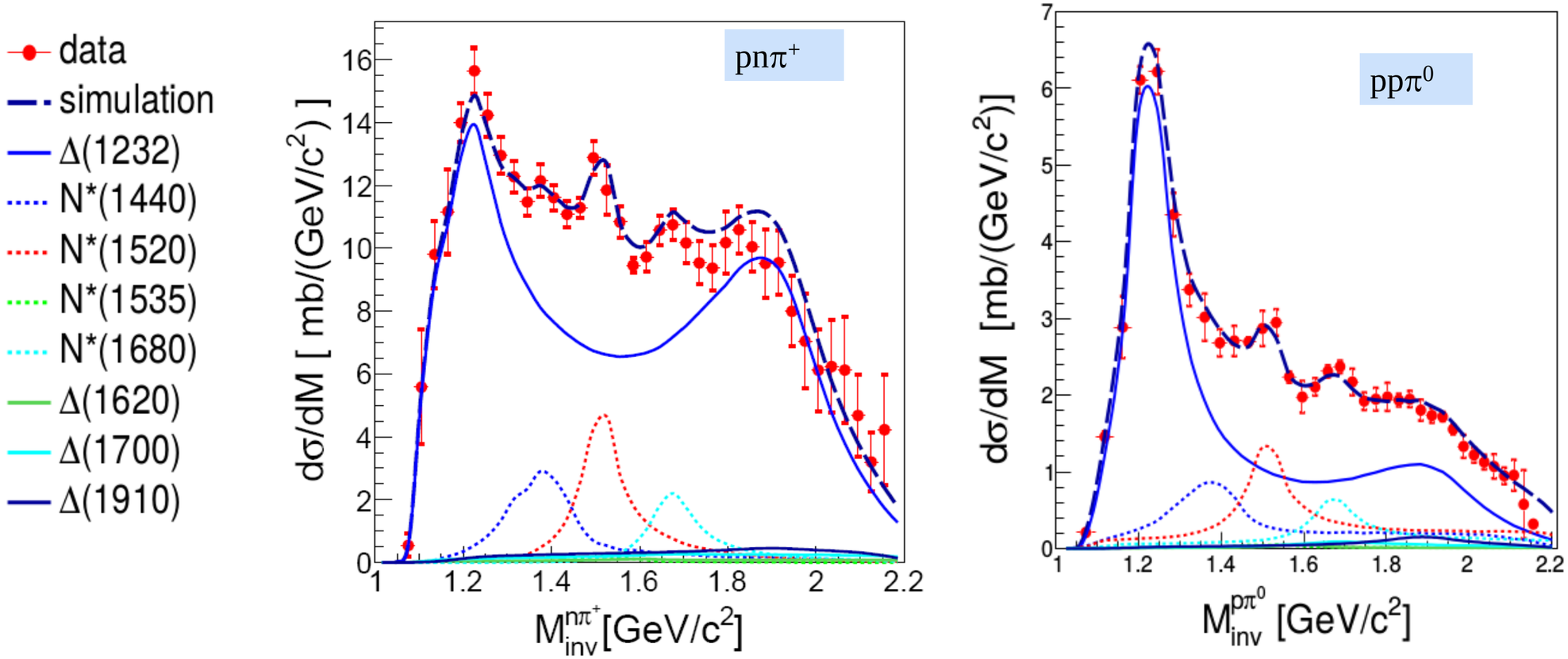
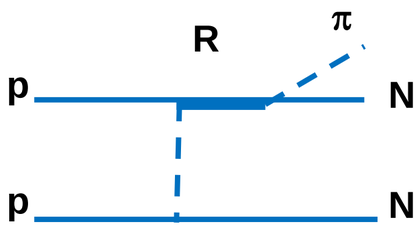
Cocktail of baryonic resonances obtained from the 1 π production (Δ /N* $\to$ N π)





PhD Motivation

pp → ppe⁺e⁻ @ E=3.5 GeV

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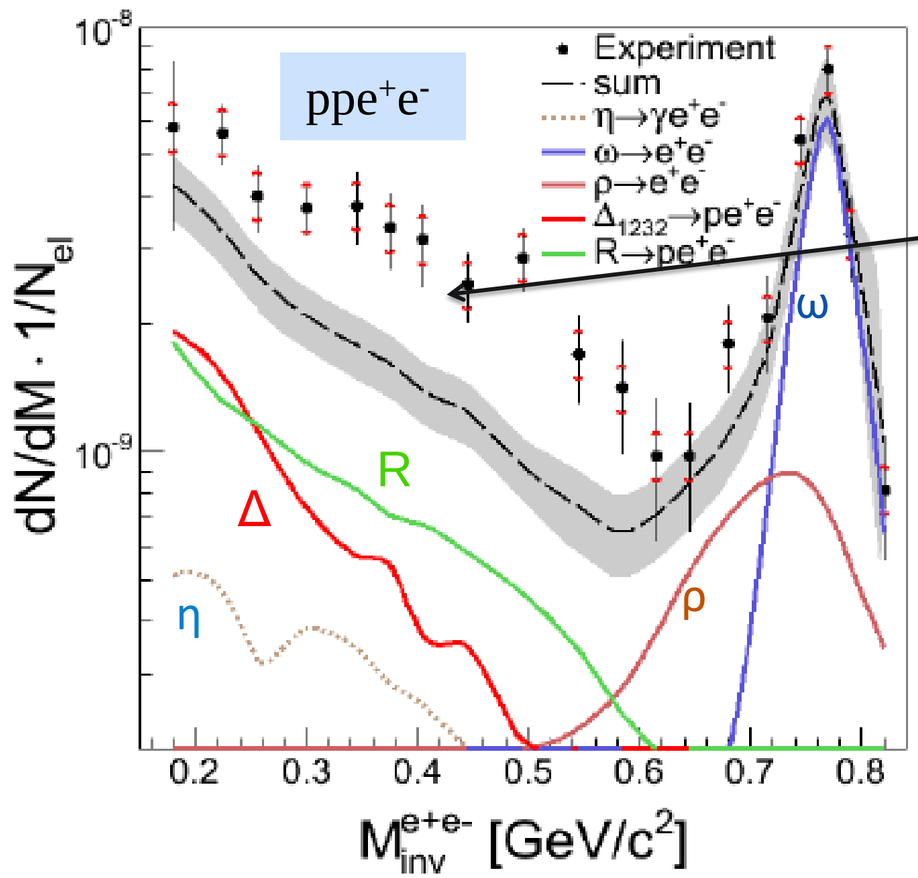
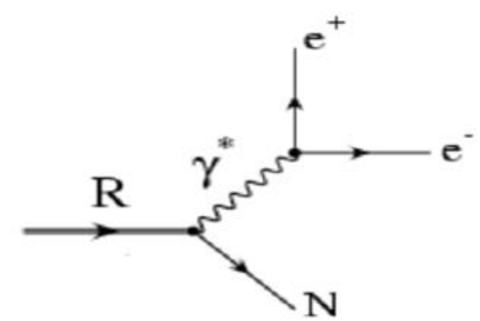
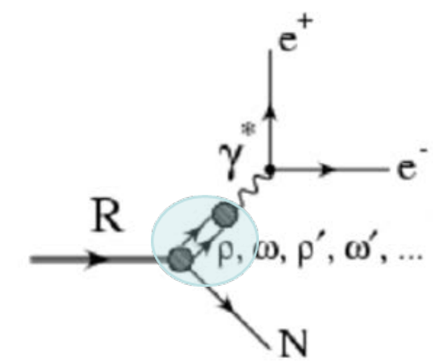
Dalitz decay of the resonance cocktail + ρ,ω and η



Effect of the coupling to ρ



QED: point-like R-γ^* vertex



EM time-like form factor

Interest of the channel **pp→ppπ⁺π⁻** :

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