

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

Amel Belounnas

2nd Year PhD Seminar

Outline

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



Introduction

Pion production Motivation



Hadron spectroscopy:

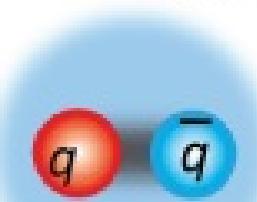
Mesons: $\rho \rightarrow \pi\pi$, $\omega \rightarrow \pi\pi\pi$...

Baryons: $\Delta/N^* \rightarrow N\pi$, $\Delta/N^* \rightarrow N\pi\pi$

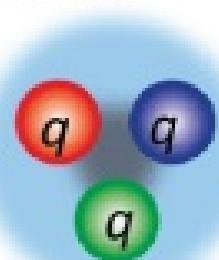


Reaction mechanism.

Standard Hadrons



Meson

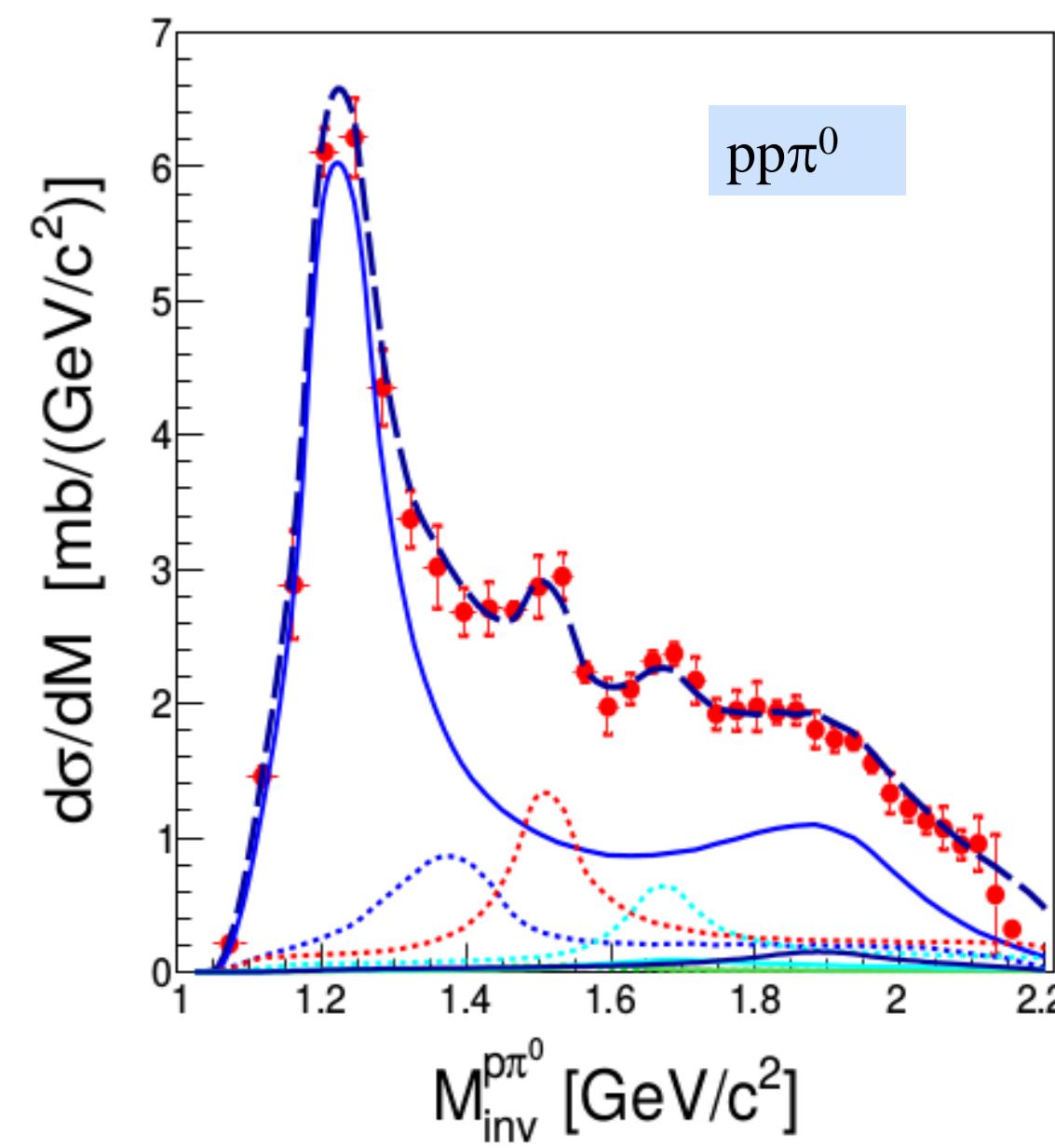
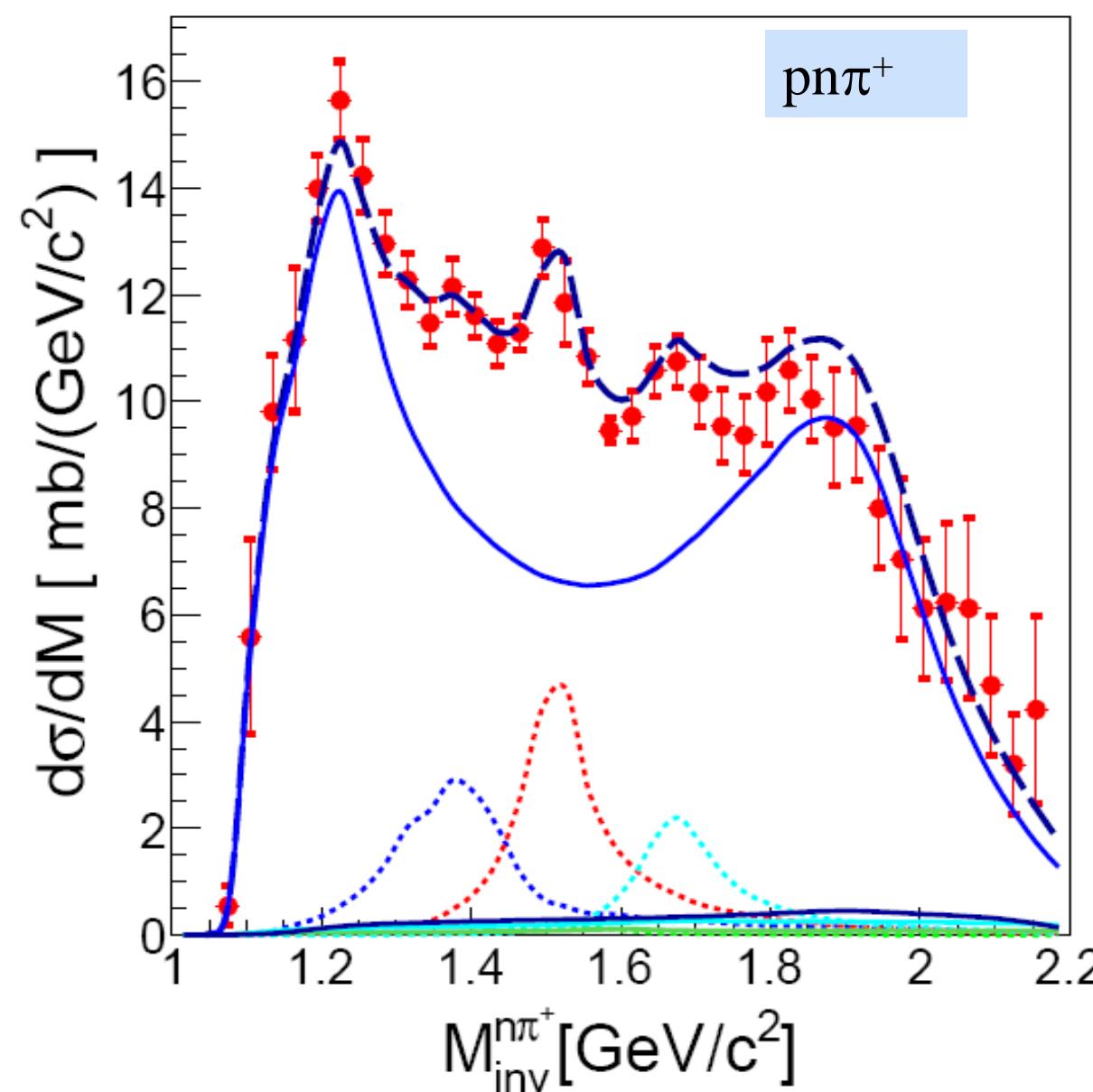


Baryon

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

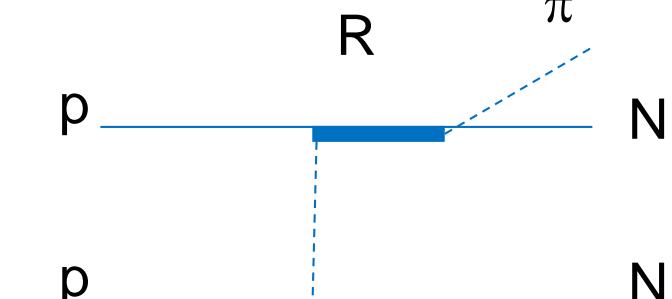
G. Agakishiev et al.
Eur.Phys.J. A50 (2014) 8

- data
- simulation
- $\Delta(1232)$
- ... $N^*(1440)$
- ... $N^*(1520)$
- ... $N^*(1535)$
- ... $N^*(1680)$
- $\Delta(1620)$
- $\Delta(1700)$
- $\Delta(1910)$



Cocktail of baryonic resonances obtained from the 1π production

$(\Delta/N^* \rightarrow N\pi)$

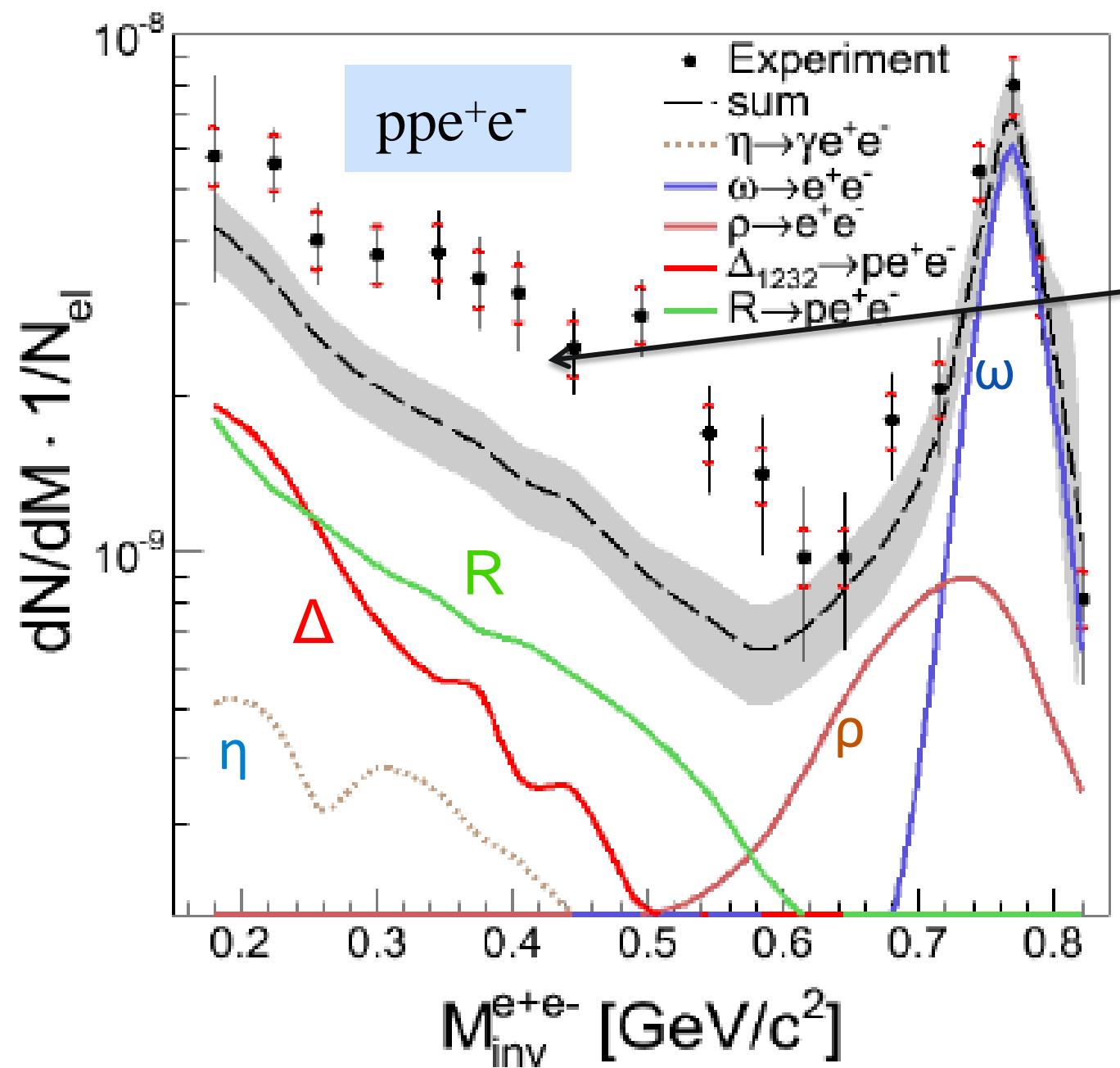


PhD Motivation

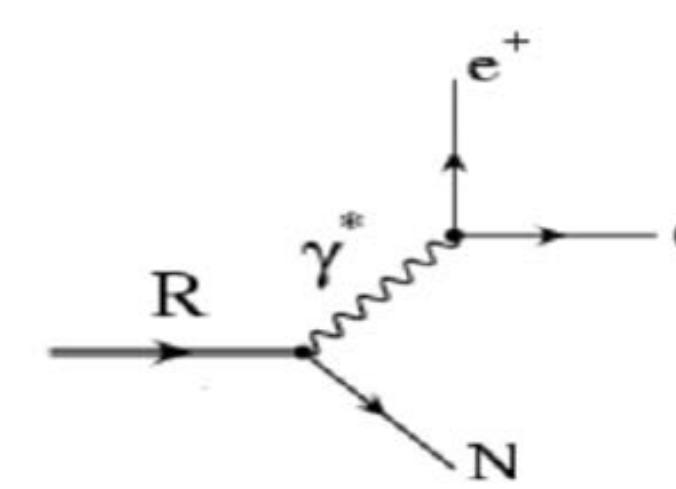
$pp \rightarrow ppe^+e^-$ @ $E = 3.5$ GeV

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

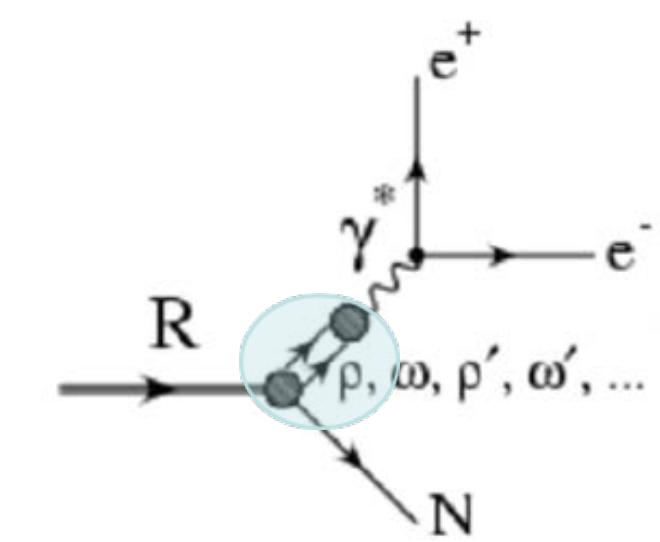
Dalitz decay of the resonance cocktail + ρ, ω and η



Effect of the coupling to ρ



QED: point-like $R-\gamma^*$ vertex



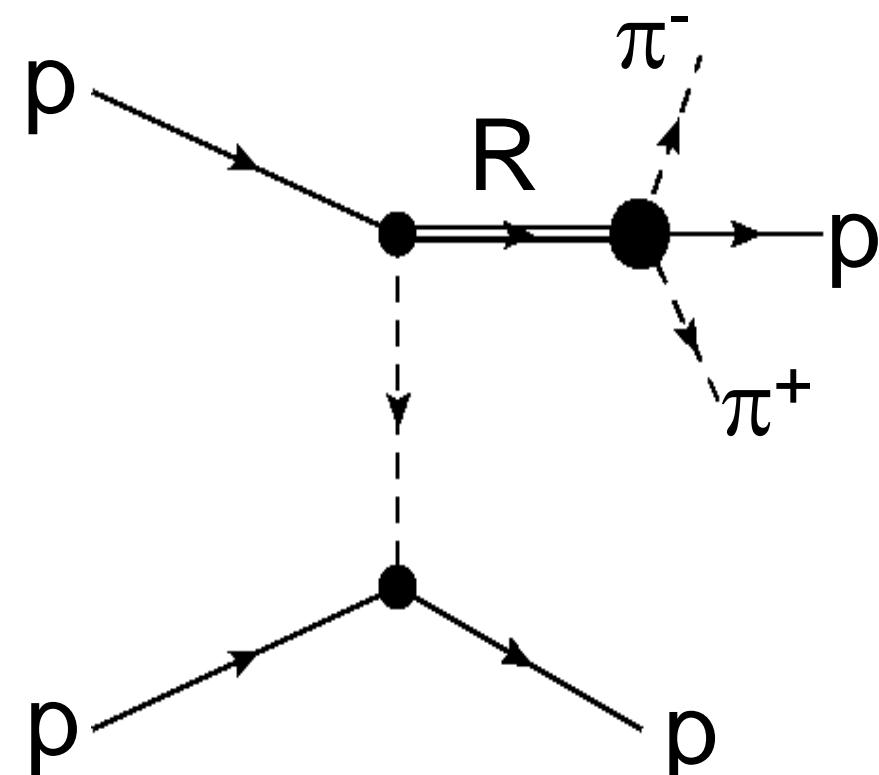
EM time-like form factor

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

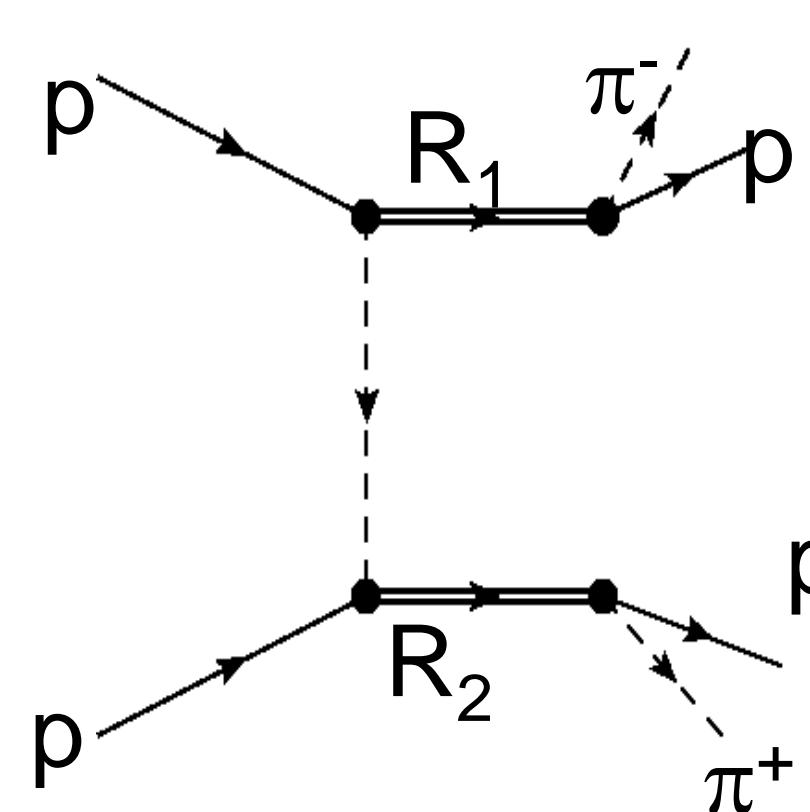
- ✓ Test the cocktail on the 2 pion production.
- ✓ Measure the ρ ($\rho \rightarrow \pi^+\pi^-$) production, direct and coupled to resonances .

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

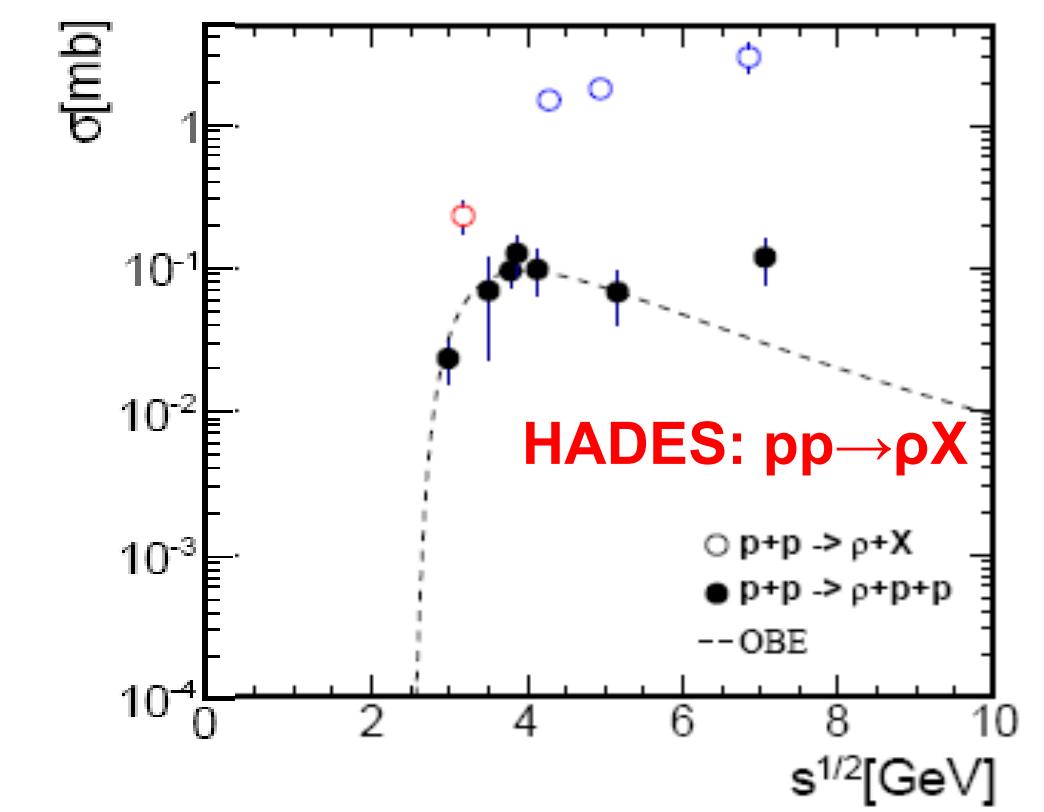
One resonance excitation (1R)



Double resonance excitation (2R)



Direct p production



Few precise measurements

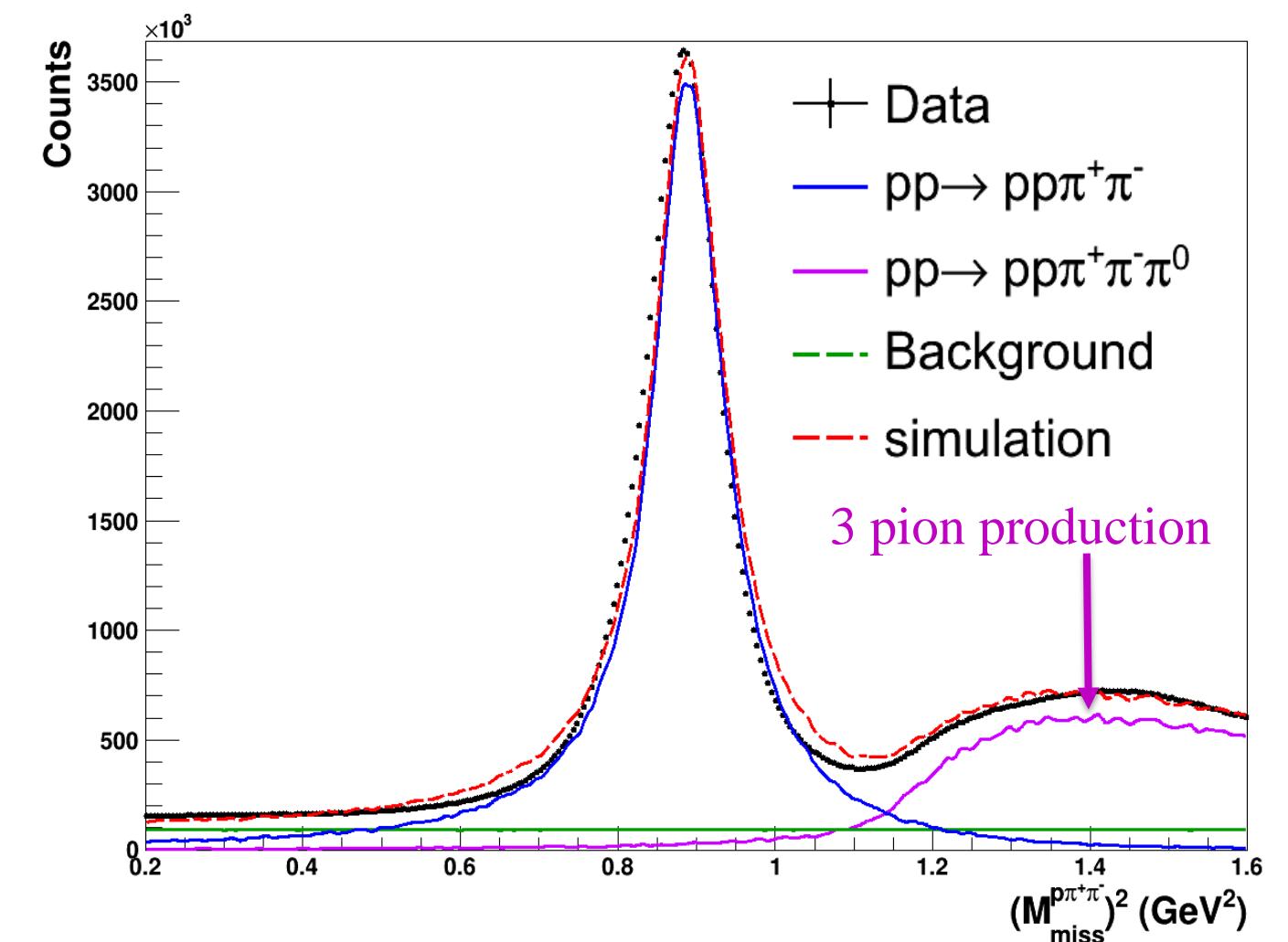


Data Analysis Method

Data Analysis

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

Background subtraction.



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

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

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

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



HADES Resonance Model

PLUTO++ Simulations

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

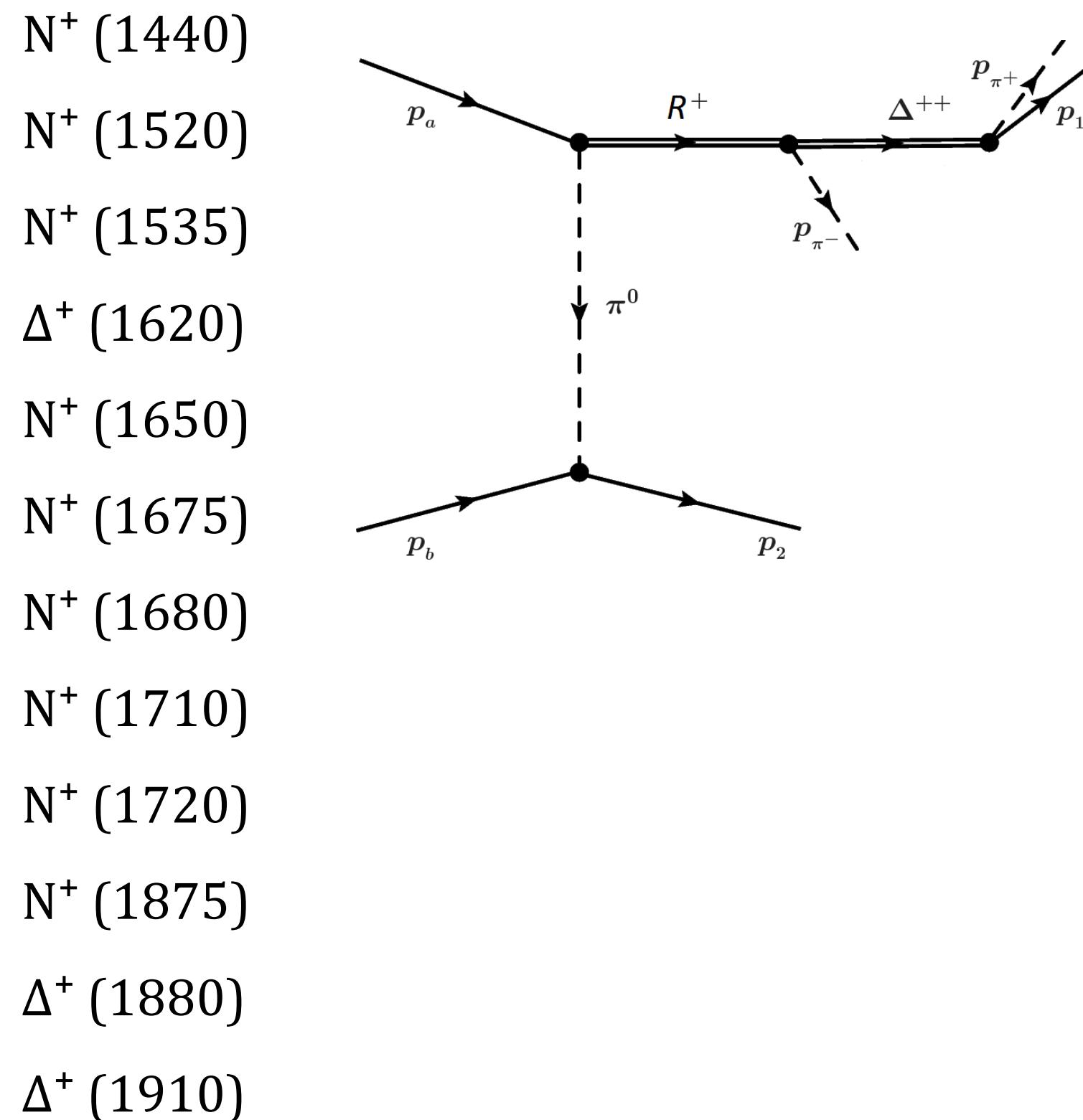
PDecayChannel (PLUTO Class)

BR x I
 $N_{1520} \rightarrow p\pi^+\pi^-$ (0.04) (6% x 2/3)
 $N_{1520} \rightarrow \Delta^{++}\pi^-$ (0.12) (23% x 1/2)
 $N_{1520} \rightarrow \Delta^0\pi^+$ (0.04) (23% x 1/6)
 $N_{1520} \rightarrow pp^0$ (0.003) (1% x 1/3)

Simulation (using PLUTO++)

✓ $\text{pp} \rightarrow \text{pR} \rightarrow \text{pp } \pi^+ \pi^- (1\text{R})$

(Using known cross sections from $1\pi^*$ and $\text{pK}\Lambda^{**}$ analysis)



✓ $\text{pp} \rightarrow \text{RR}' \rightarrow \text{pp } \pi^+ \pi^- (2\text{R})$

(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)}}

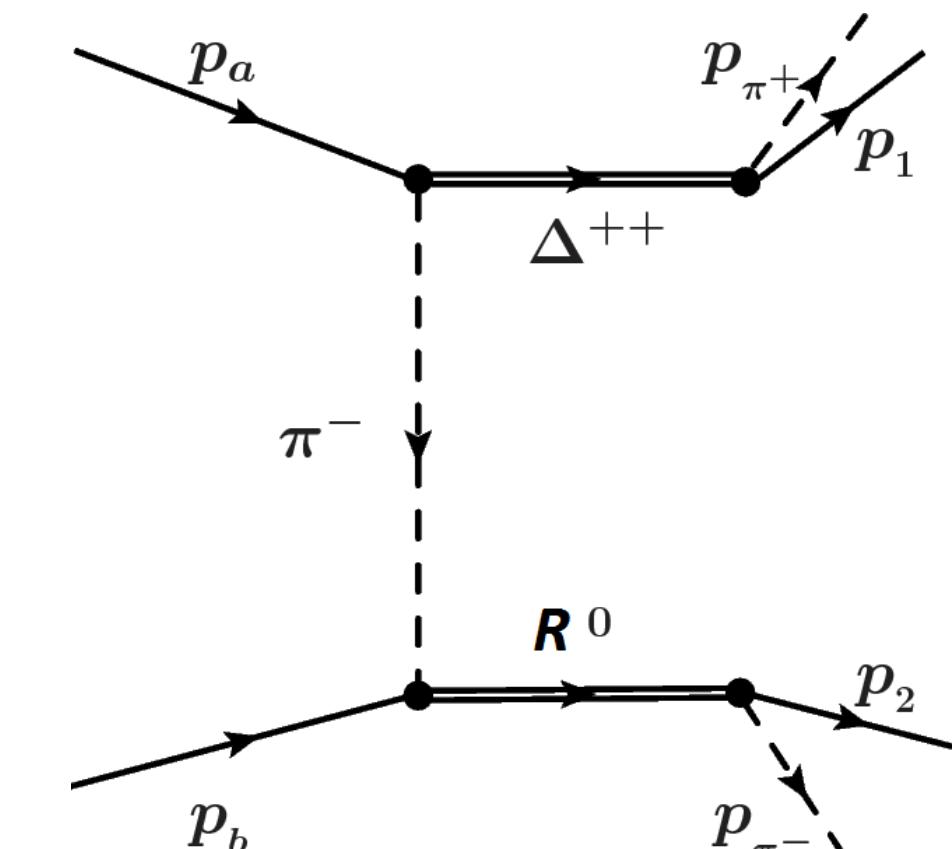
Δ^{++(1232) Δ^{o(1620)}}

Δ^{++(1232) N^{o(1650)}}

Δ^{++(1232) N^{o(1680)}}

Δ^{++(1232) N^{o(1720)}}

Δ^{++(1232) Δ^{o(1700)}}



✓ Direct p production simulation

$\sigma = 60 \text{ } \mu\text{b}$ (from existing data)

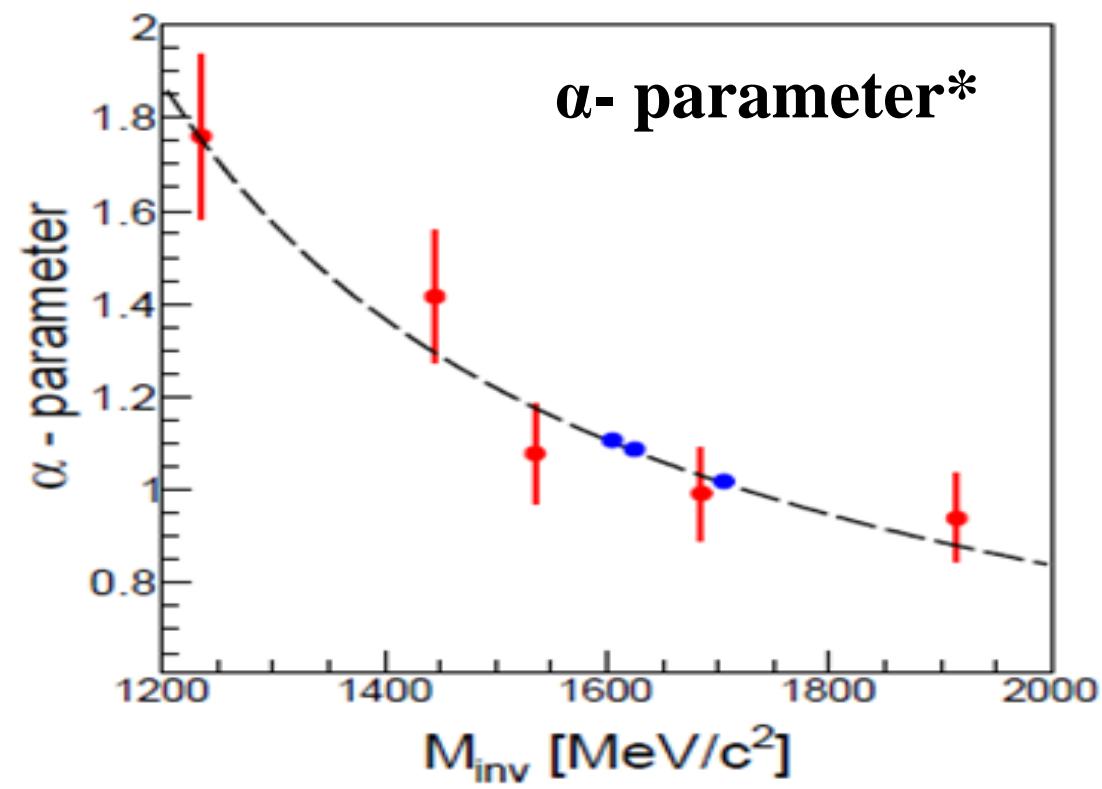
*G. Agakishiev et al. Eur.Phys.J. A50 (2014) 8

** R. Munzer et al. arXiv:1703.01978

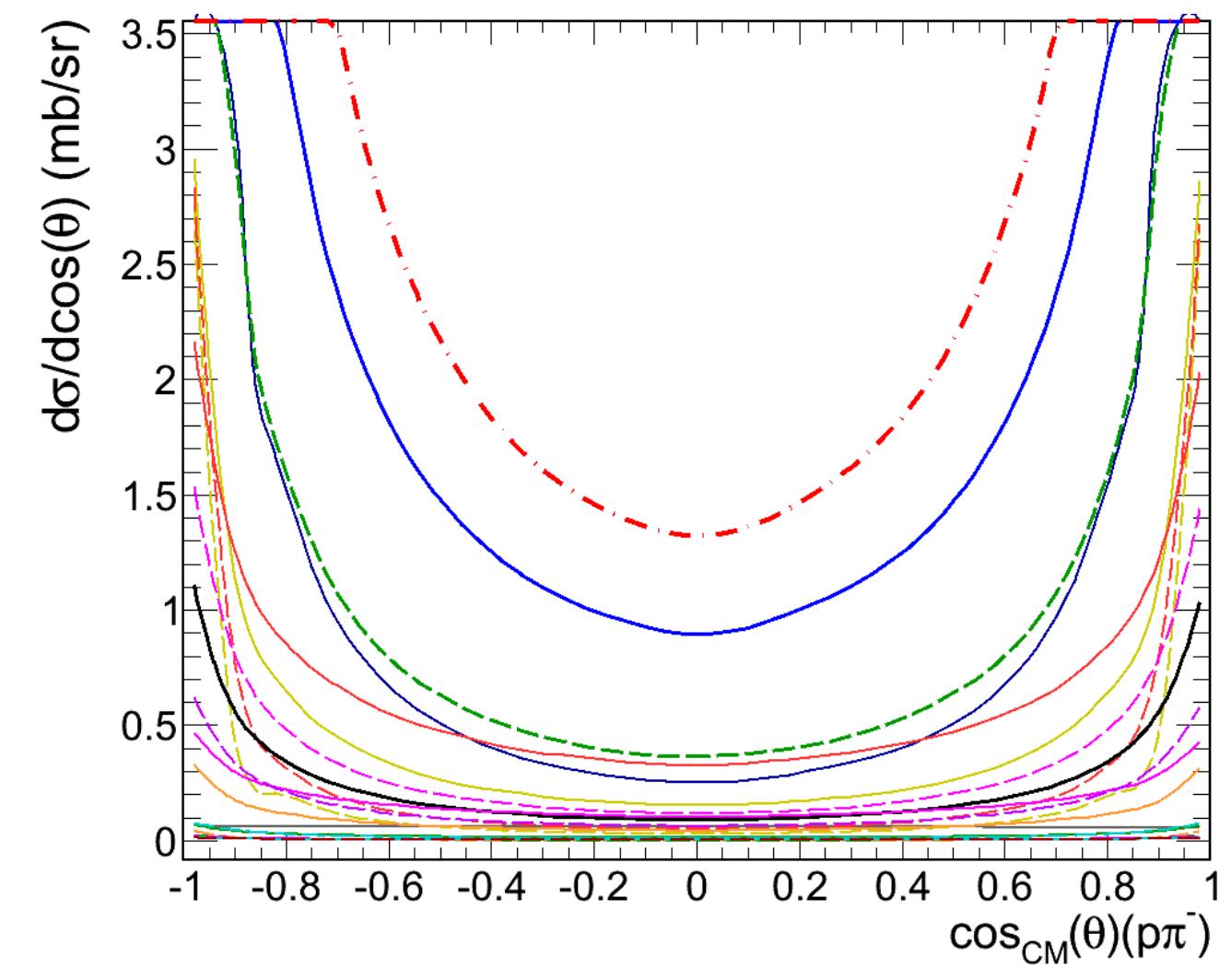
Angular Distribution Model

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

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



The simulation is weighted by t_w



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

Before applying Acc. cuts

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

* 1π analysis



Analysis results

All spectra include systematic errors

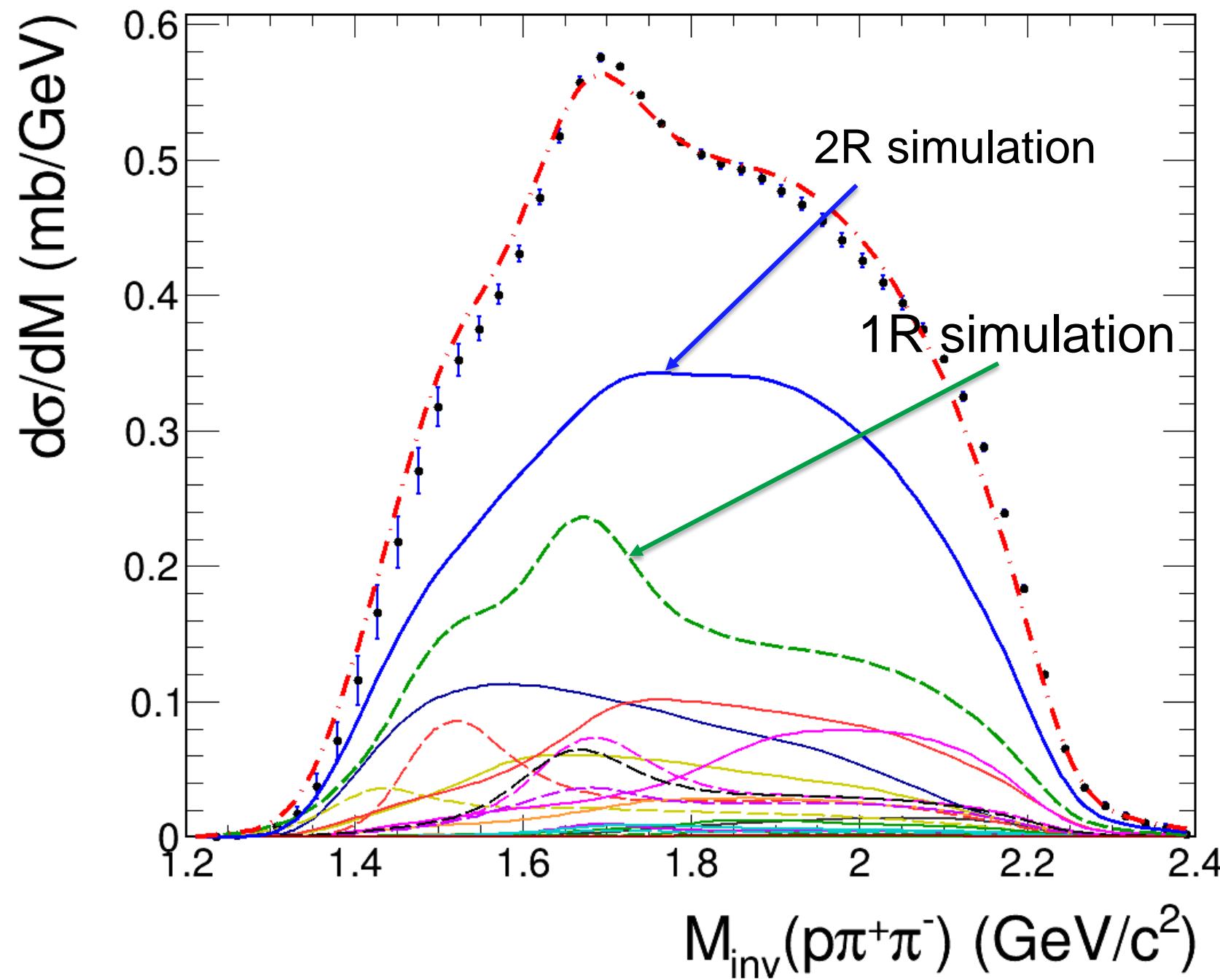
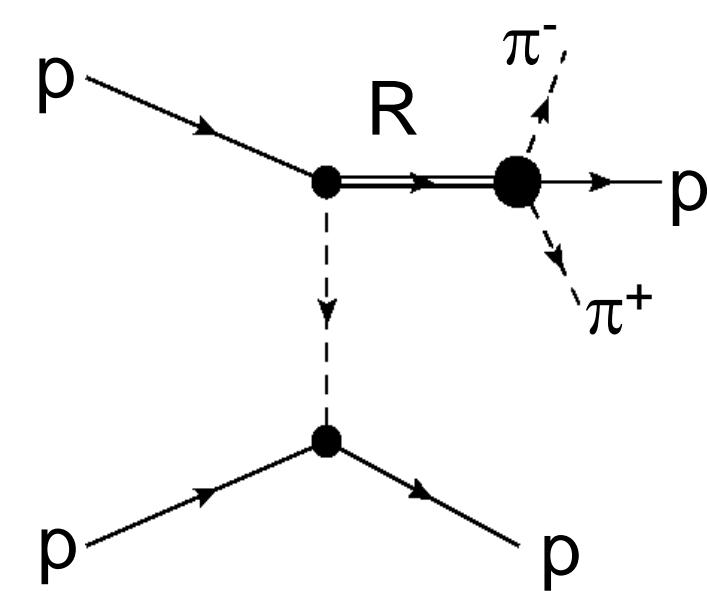
Background subtraction: 1-2%

Efficiency: 2%

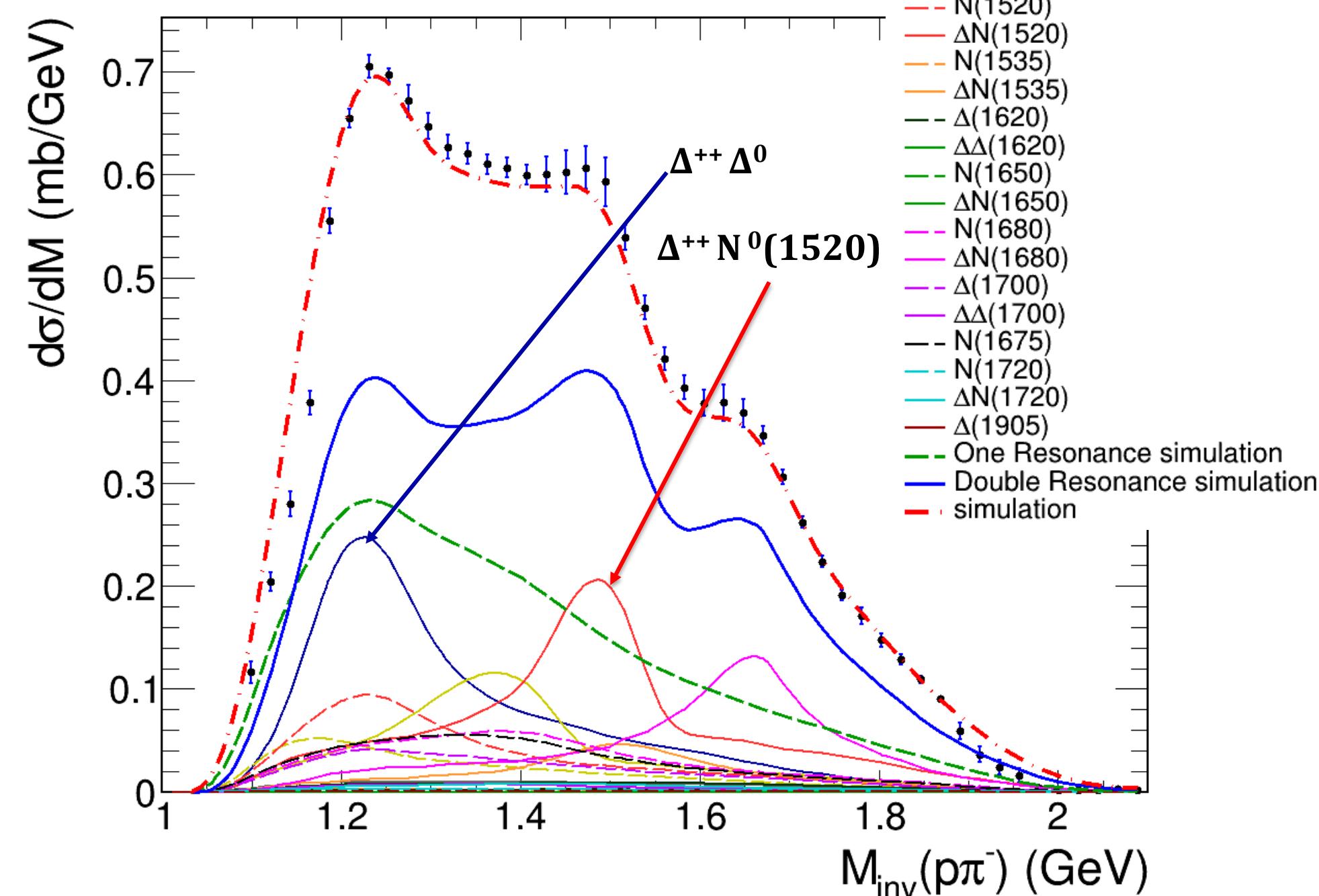
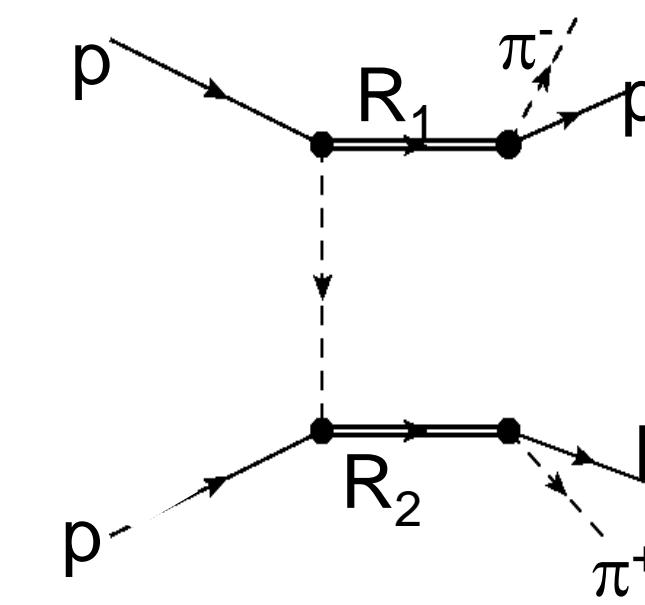
Normalization err: 6.5% (not included).

Stat.err are negligible

Invariant Masses Spectra

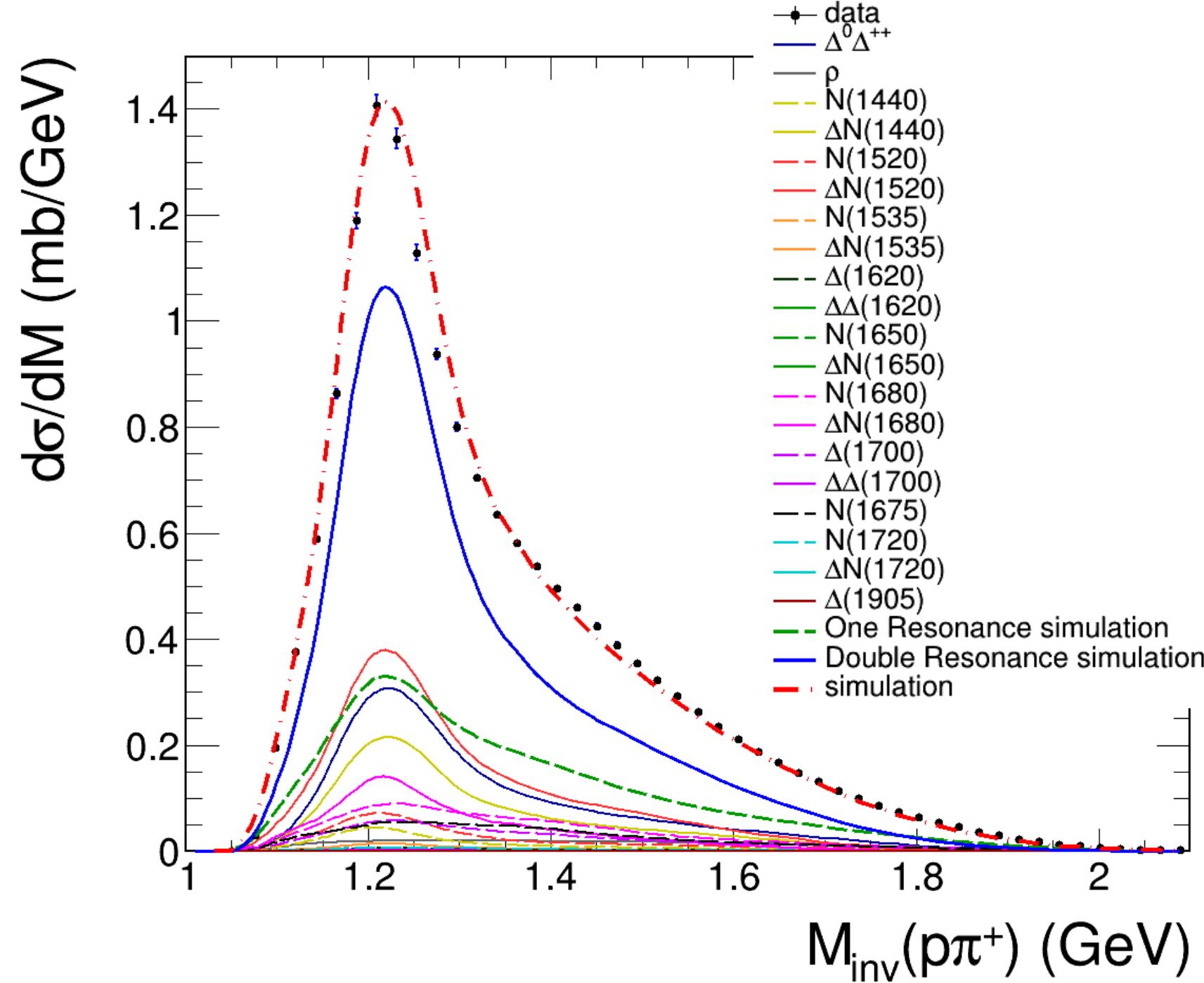


One peak in 1R (Dashed green) due to $N^+(1520)$ and a large peak due to $N^+(1675)$, $N^+(1680)$...

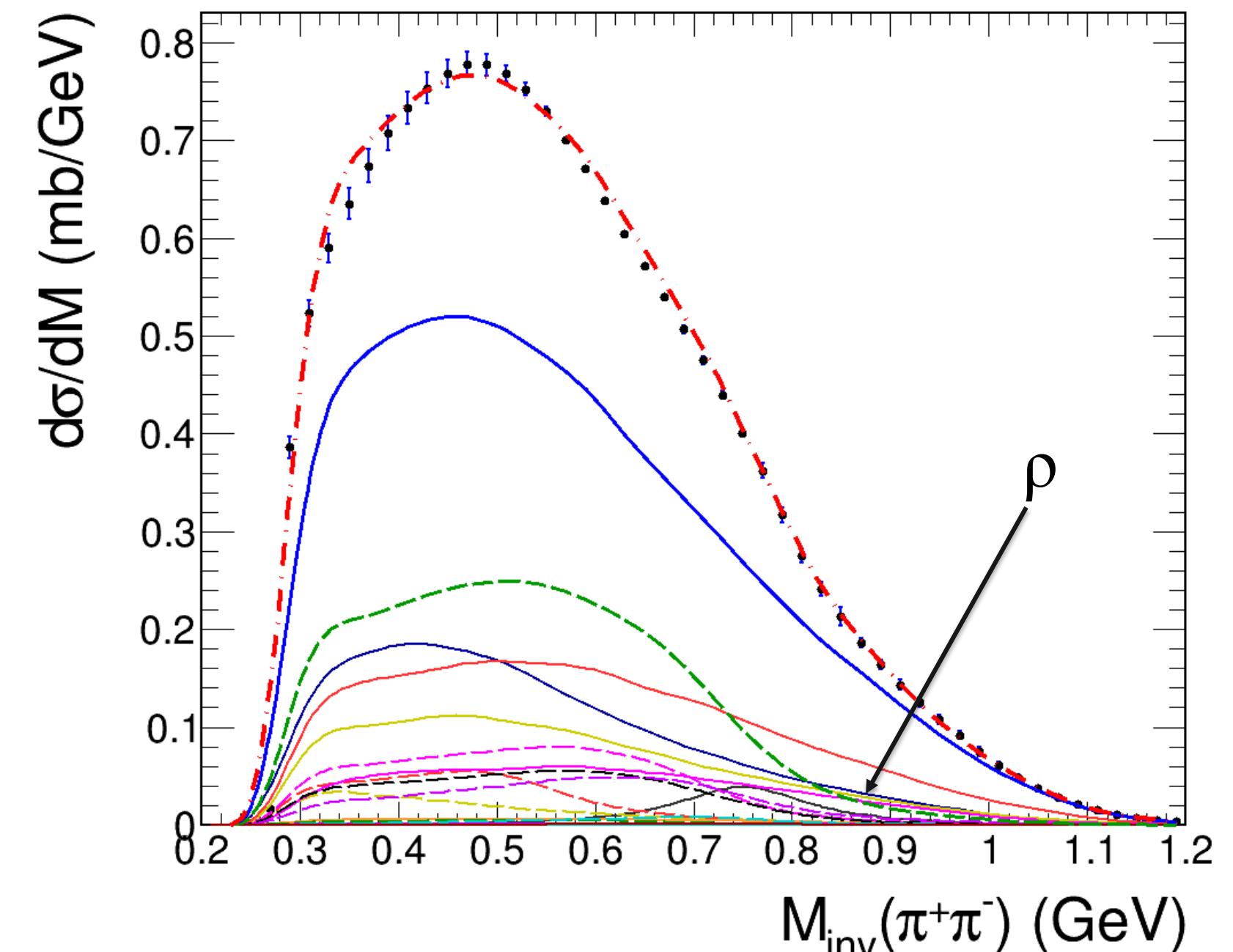


3 peaks in 2R (blue) one due to $\Delta^{++}(1232)$, another to $N^{\circ}(1520)$, and another to $N^{\circ}(1680)$

Invariant Masses Spectra

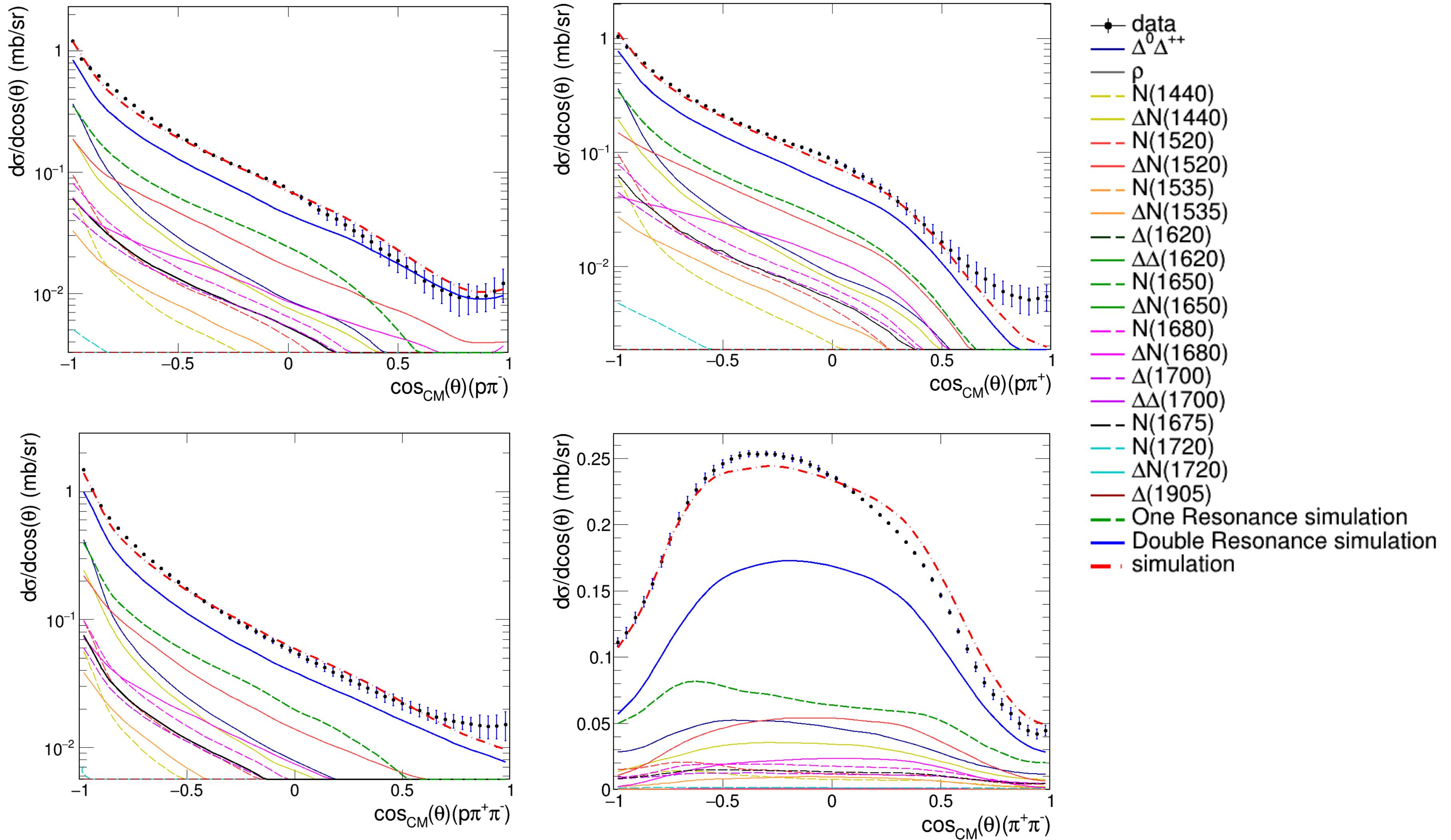


Strong dominance of $\Delta^{++}(1232)$, no significant contribution of heavier Δ^{++} resonances.



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($N\pi\pi$)	σ (2 π anal.) (mb)	σ (1 π 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%	$< 0.10 \pm 0.05$	$< 0.10 \pm 0.03$
$N^+(1650)$	11%	0.09 ± 0.03	$< 0.81 \pm 0.13$
$N^+(1675)$	45%	0.7 ± 0.1	$< 1.65 \pm 0.27$
$N^+(1680)$	35%	1.1 ± 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
$\Delta^+(1910)$	90%	$< 0.01 \pm 0.01$	$< 0.85 \pm 0.53$

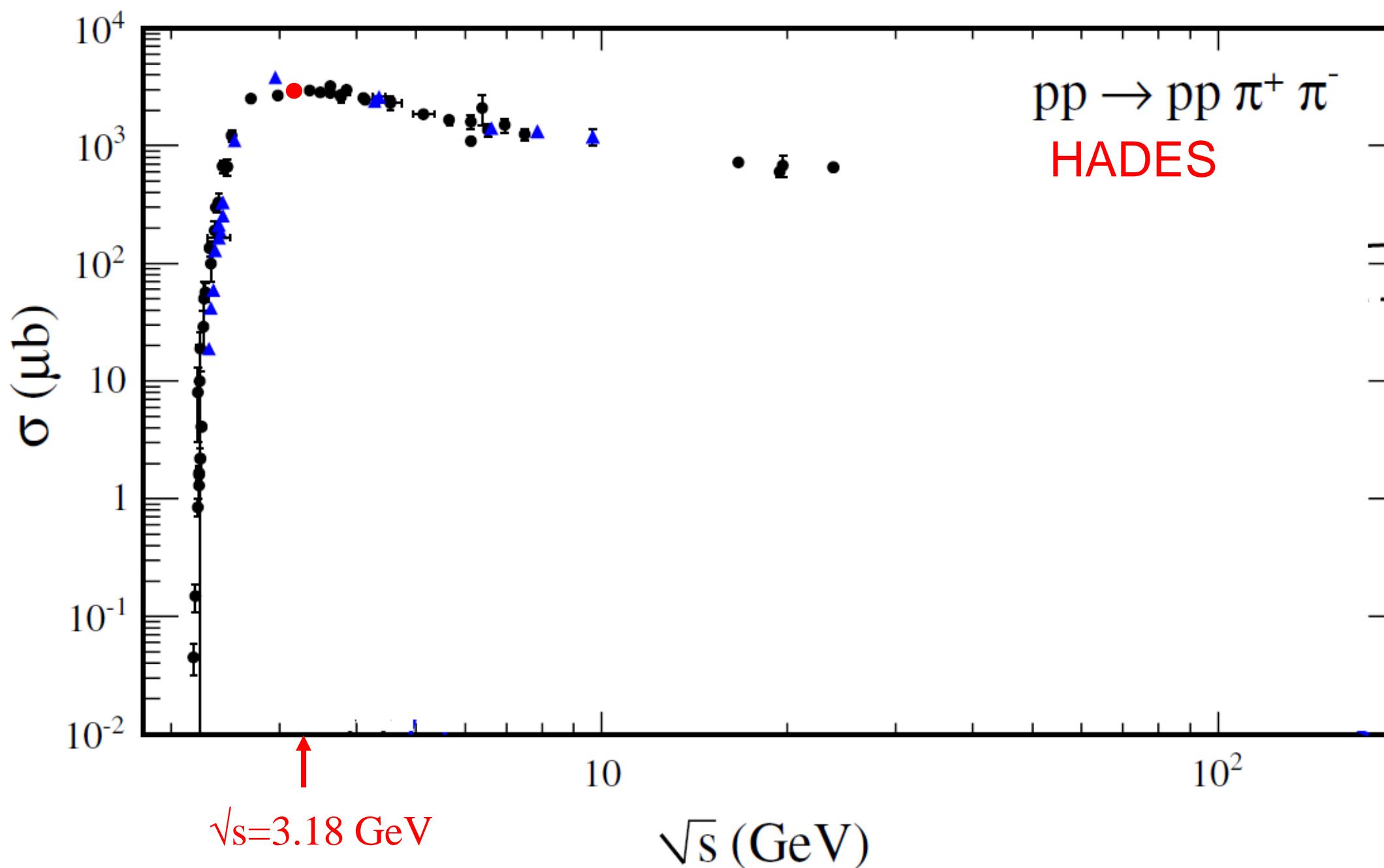
2 Resonances	BR($N\pi$)	σ (mb)
$\Delta^{++}(1232)\Delta^{\circ}(1232)$	100%	3.2 ± 0.2
$\Delta^{++}(1232)N^{\circ}(1440)$	70%	1.5 ± 0.2
$\Delta^{++}(1232)N^{\circ}(1520)$	55%	1.7 ± 0.2
$\Delta^{++}(1232)N^{\circ}(1535)$	46%	0.5 ± 0.1
$\Delta^{++}(1232)\Delta^{\circ}(1620)$	25%	$< 0.05 \pm 0.02$
$\Delta^{++}(1232)N^{\circ}(1650)$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

1 Resonance	BR($N\pi\pi$)	σ (2 π 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

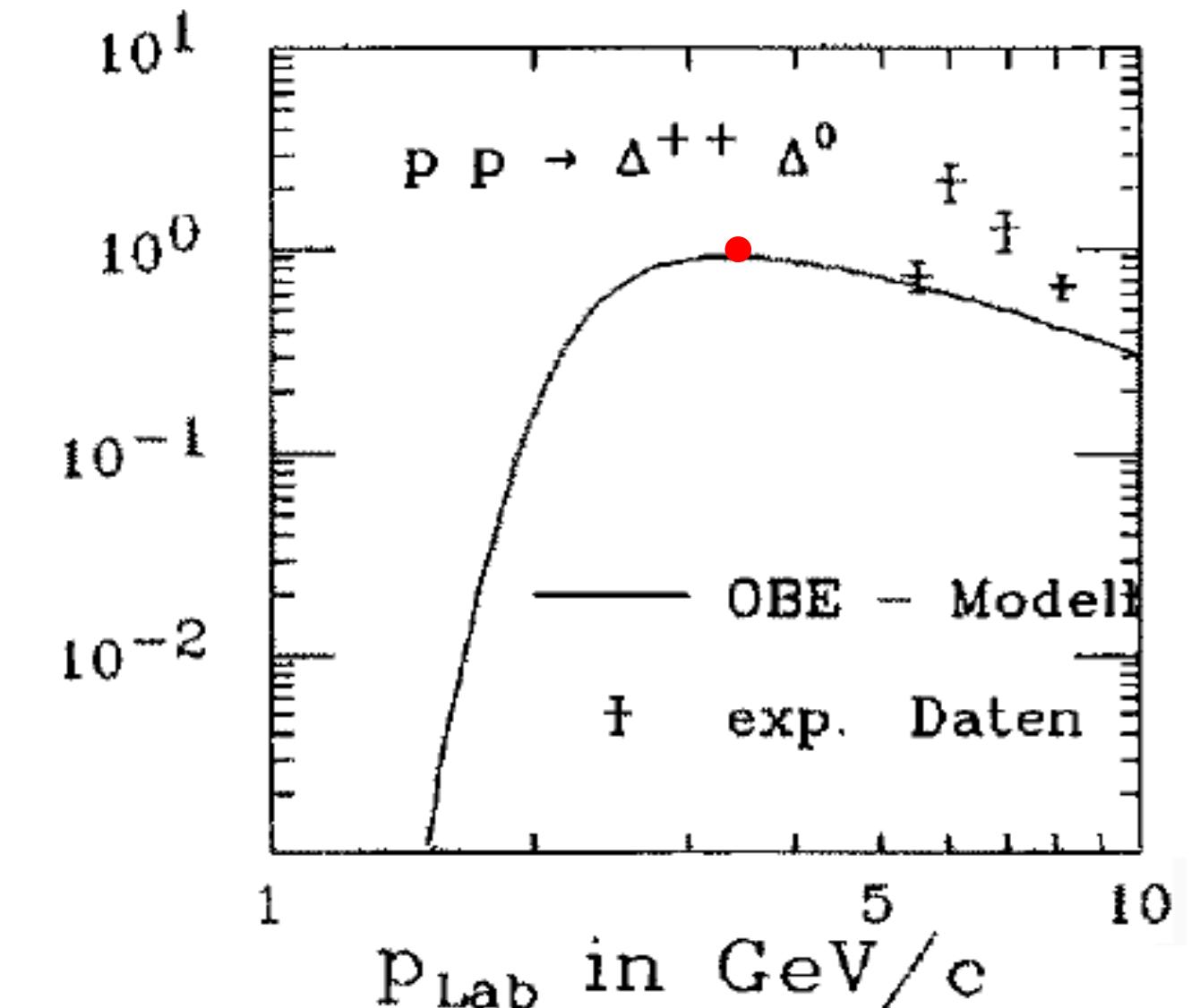
*G. Agakishiev et al. Eur.Phys.J. A50 (2014) 8
** R. Munzer et al. arXiv:1703.01978

- ✓ The resonance cocktail reproduces 1π , 2π and $K\Lambda$ production. It gives additional consistency to the former dielectron analysis.
- ✓ Based on the cocktail we estimate the total cross section $pp \rightarrow pp \pi^+ \pi^- : \sigma = 2.95 \pm 0.15$ mb

Comparing to Existing Data

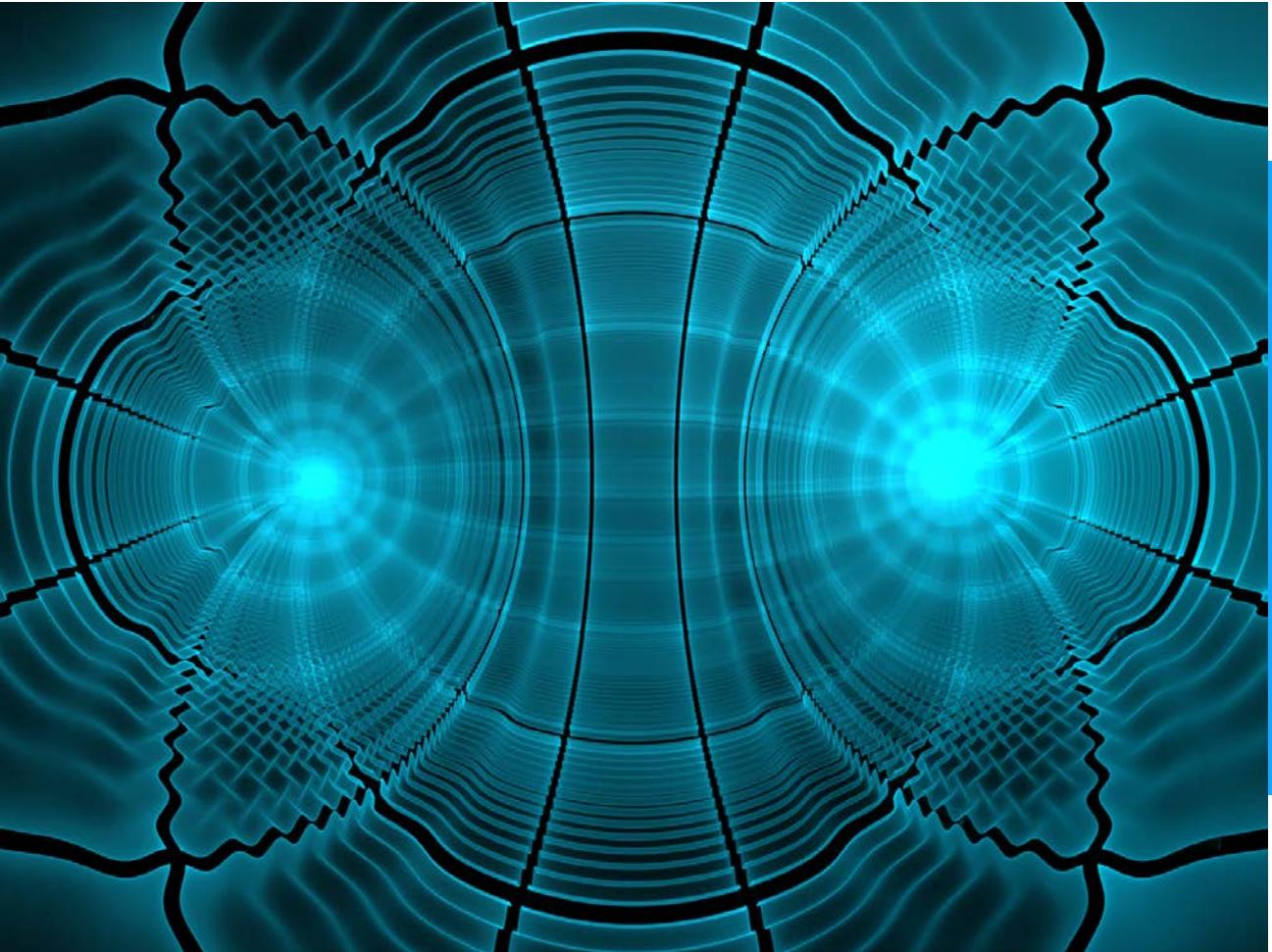


Lebedowicz et al., Phys. Rev D 81, 036003



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

- Total cross section compatible with existing data. (HADES $\sigma=2.95 \text{ mb}$)
- $\sigma (\Delta\Delta)=1.05 \text{ mb}$, compatible with OBE (One boson exchange) model.



Evaluating the interferences effect

HADES resonance model is an incoherent sum of resonances.

Theoretical test model

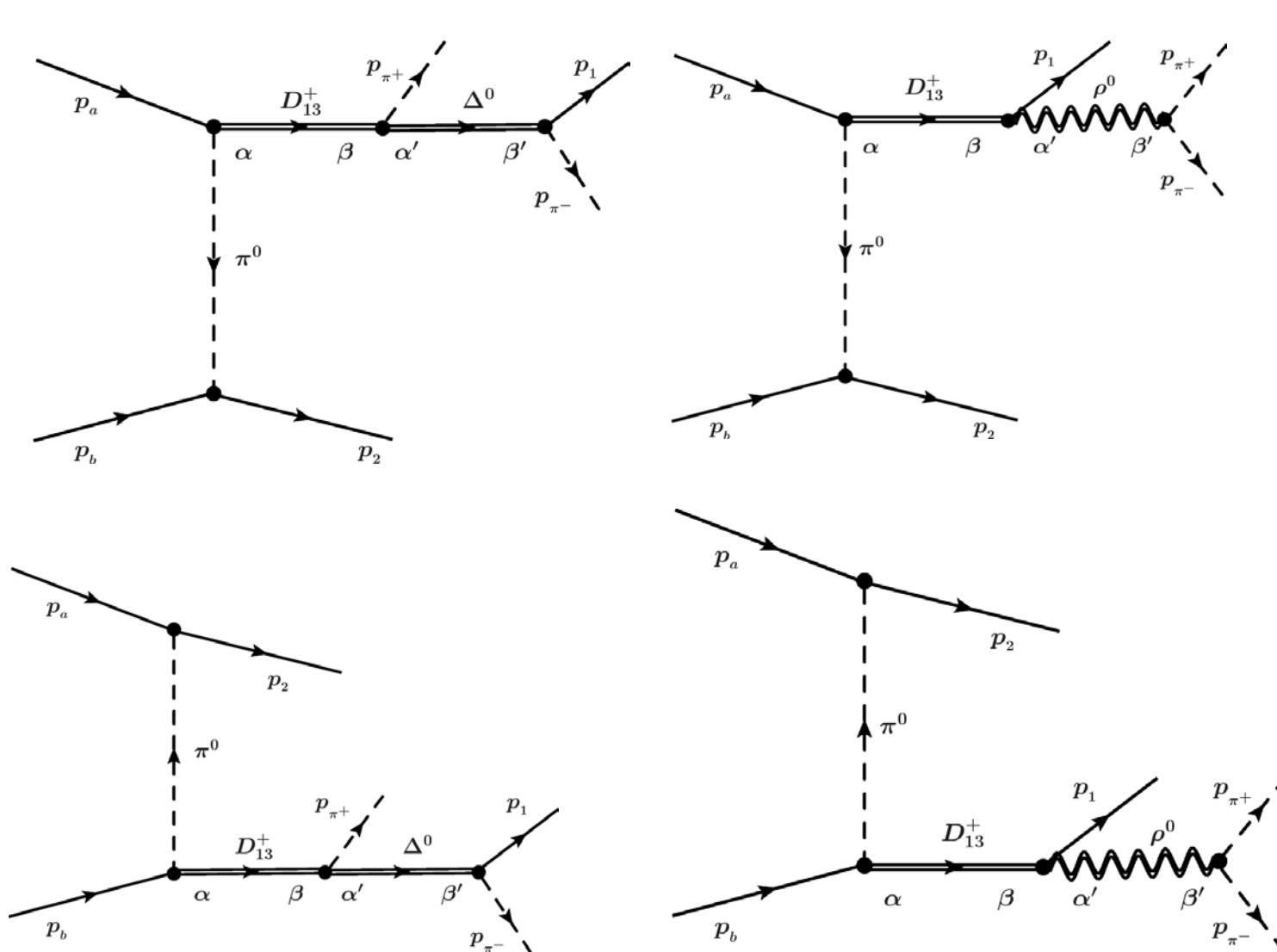
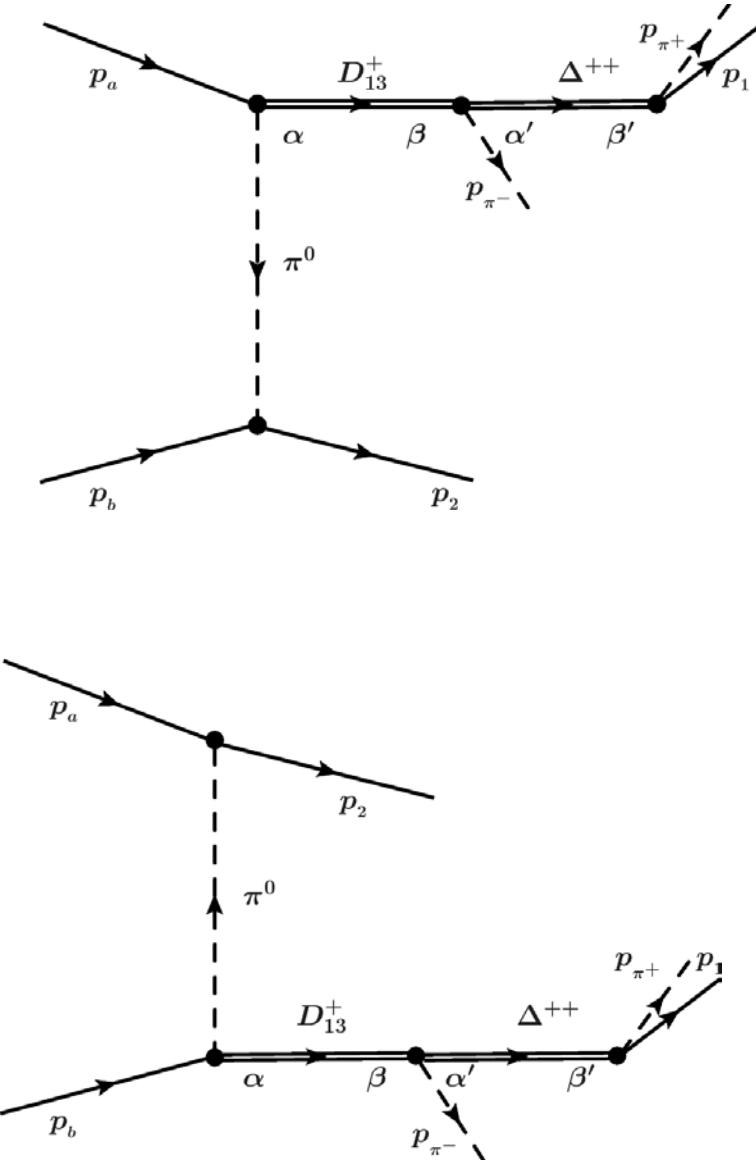
Our PLUTO resonance model is an incoherent sum of different processes.

To test the effect of interferences we created a Lagrangian model with Jacques Van de Wiele.



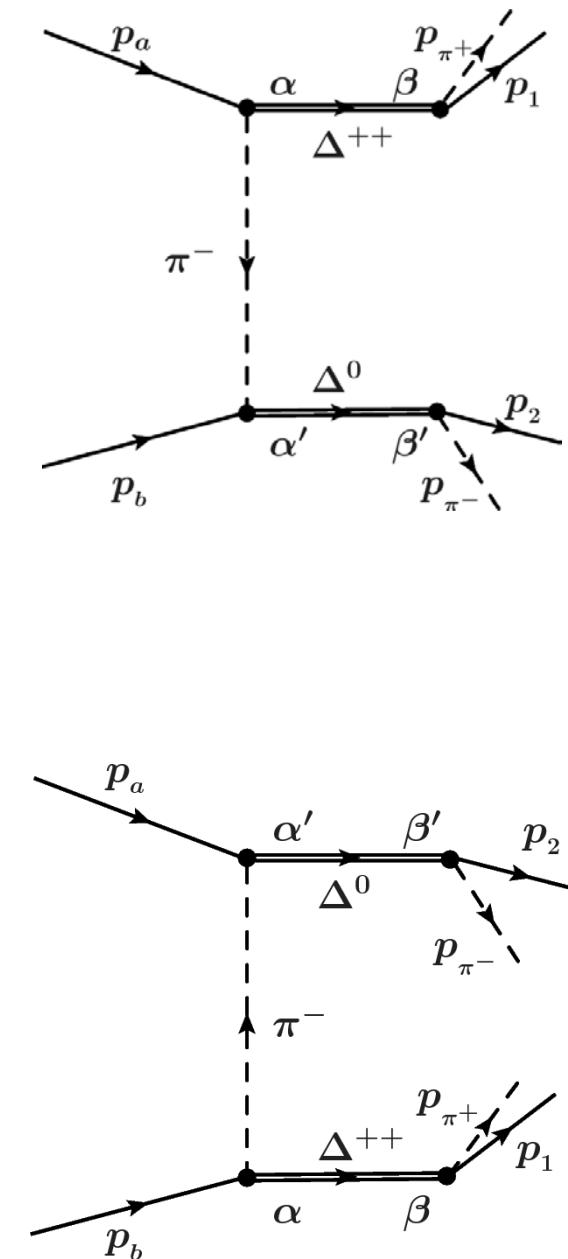
1R production: $N(1520)$ (D_{13})

12 diagrams (6 direct, 6 exchange)



2R production: $\Delta^{++}(1232)$ $\Delta^0(1232)$

4 diagrams (2 direct, 2 exchange)



Theoretical test model

Our PLUTO resonance model is an incoherent sum of different processes.

To test the effect of interferences we created a Lagrangian model with Jacques Van de Wiele.

✓ Model lagrangians (same as Xu Cao et al. *):

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

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

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

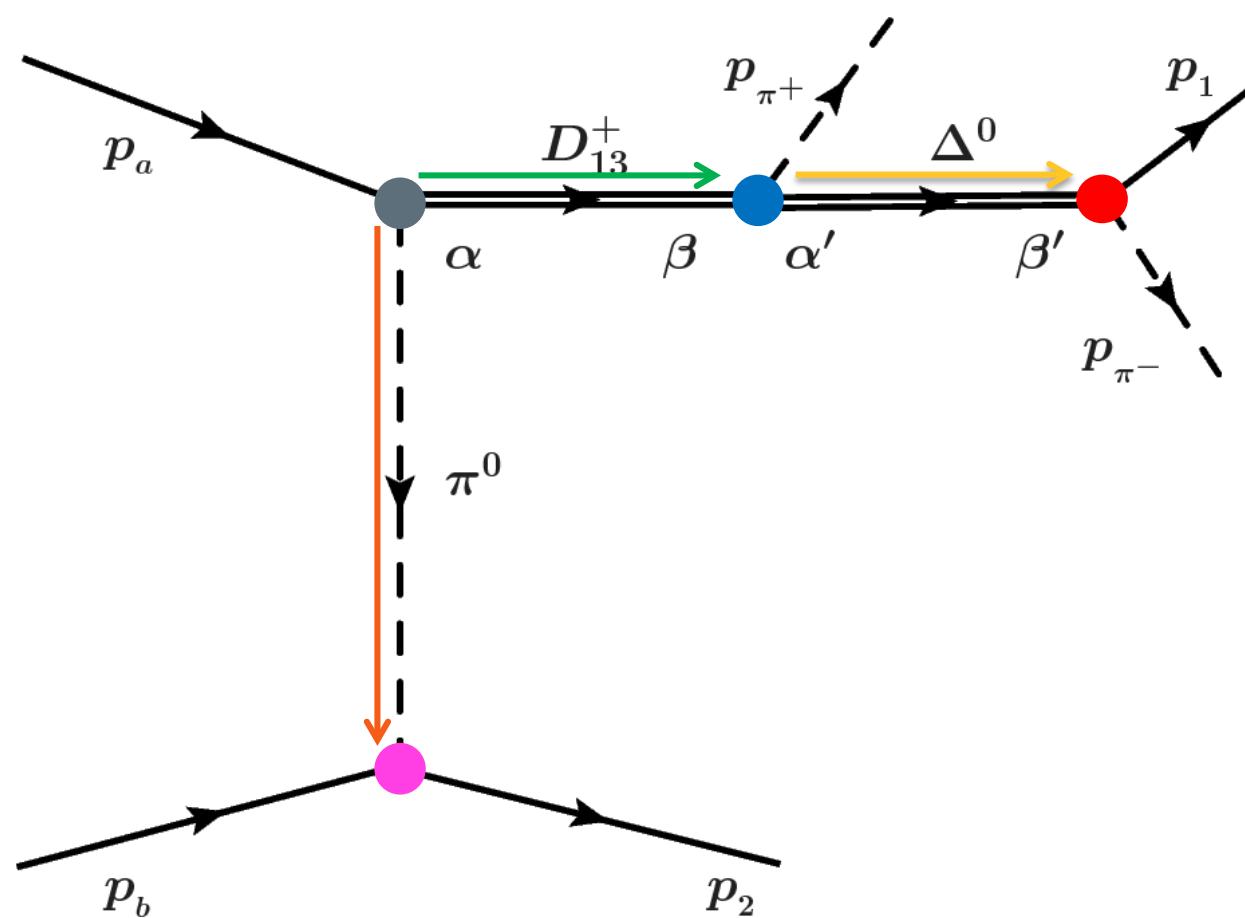
$$\mathcal{L}_{\pi \Delta R}^{3/2^-} = g_{\pi \Delta R} \bar{\Delta}^\mu \gamma_\nu \vec{\tau} \cdot \partial^\nu \vec{\pi} R_\mu + h.c.$$

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

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

Theoretical test model

✓ Amplitudes calculation:



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

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

Theoretical test model

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

- Ⓐ 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

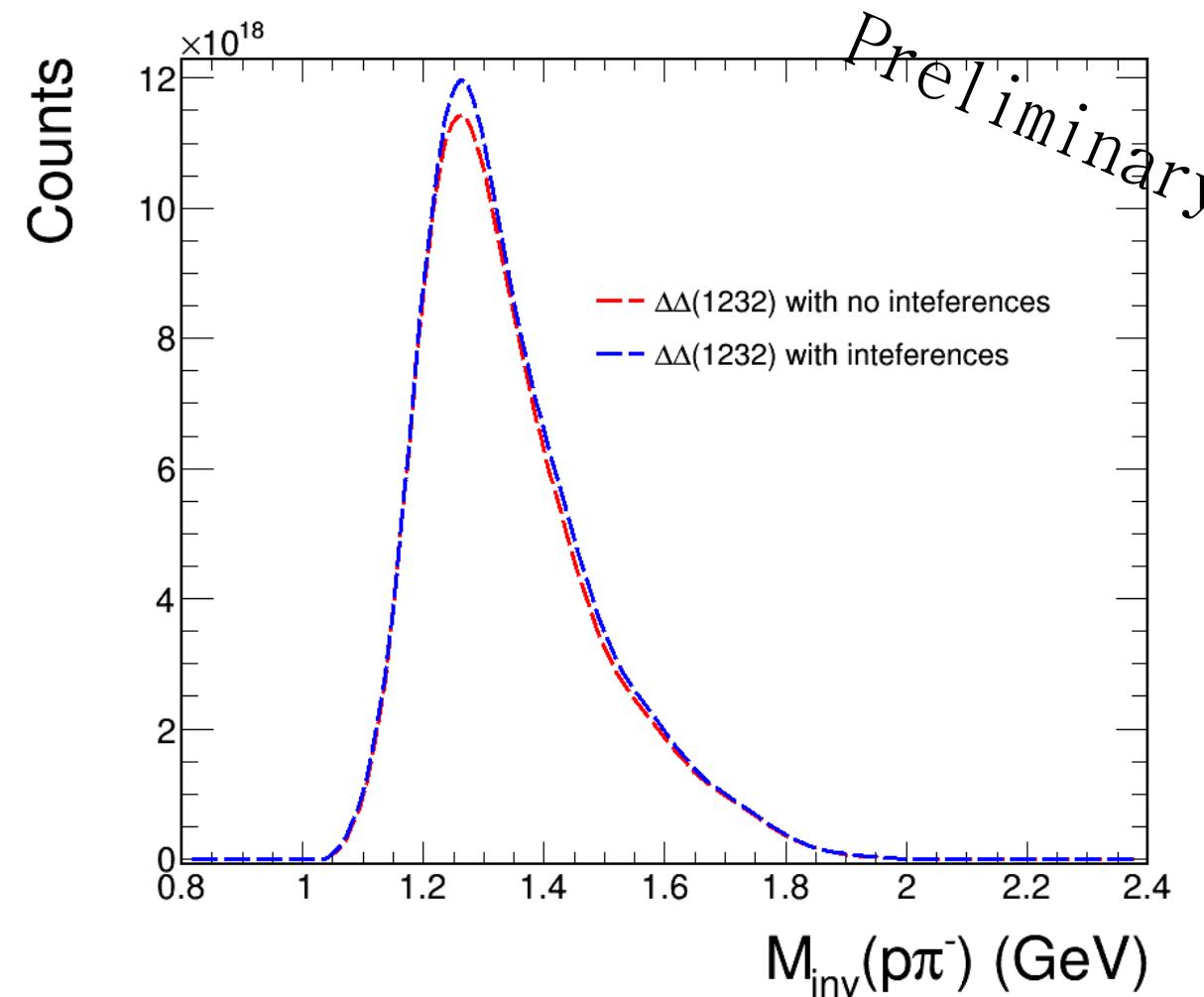
$$|\mathcal{M}|^2 = \sum_s |\mathcal{M}_1 + \mathcal{M}_2 + \dots + \mathcal{M}_n|^2$$

Ⓐ No Interference Model

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

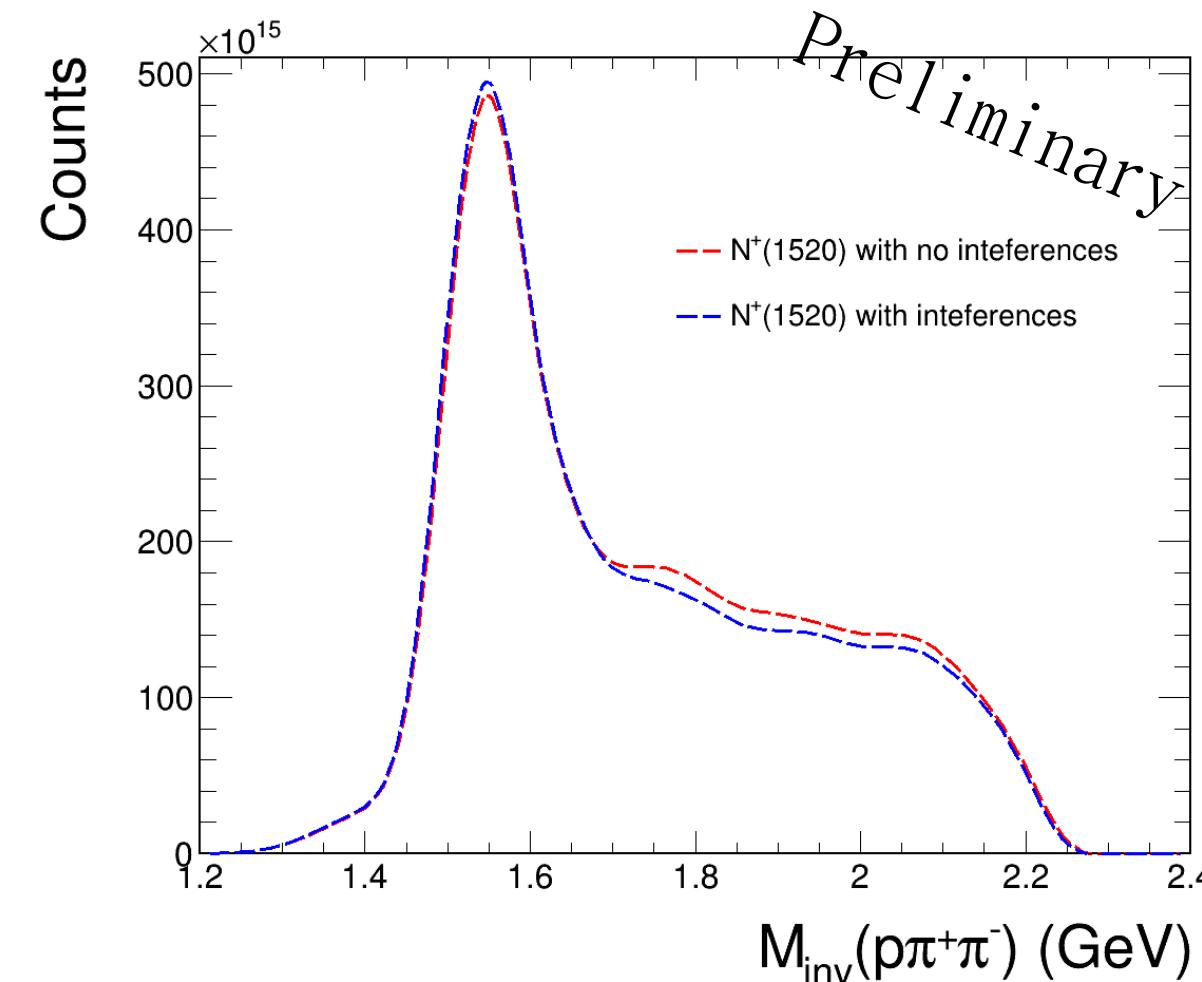
Theoretical test model results

$\Delta^{++}(1232)\Delta^{\circ}(1232)$

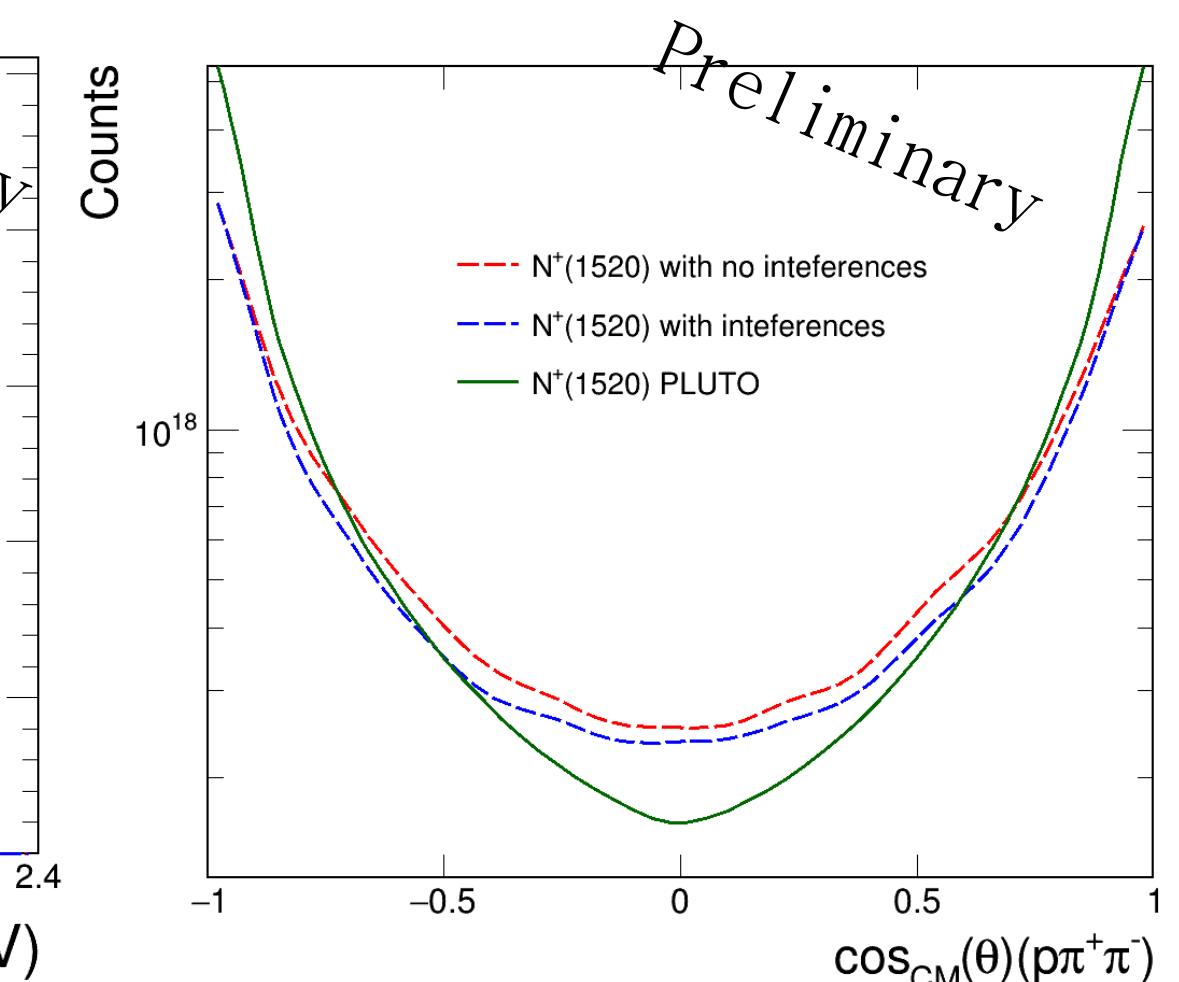


Difference between interference and no interference model is 1-2% in HADES acceptance

$N(1520)$

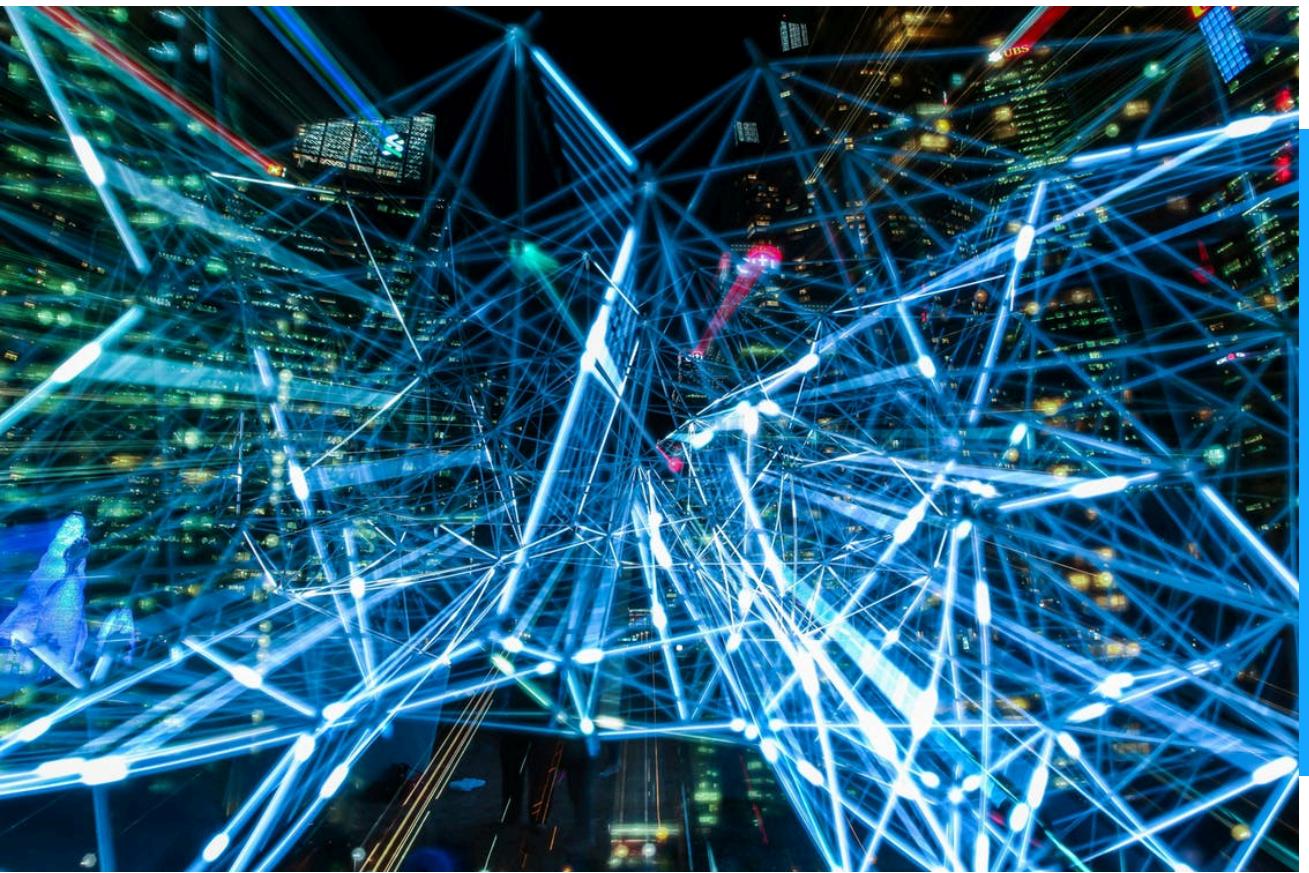


Difference between interference and no interference model is 2-3% in HADES acceptance



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

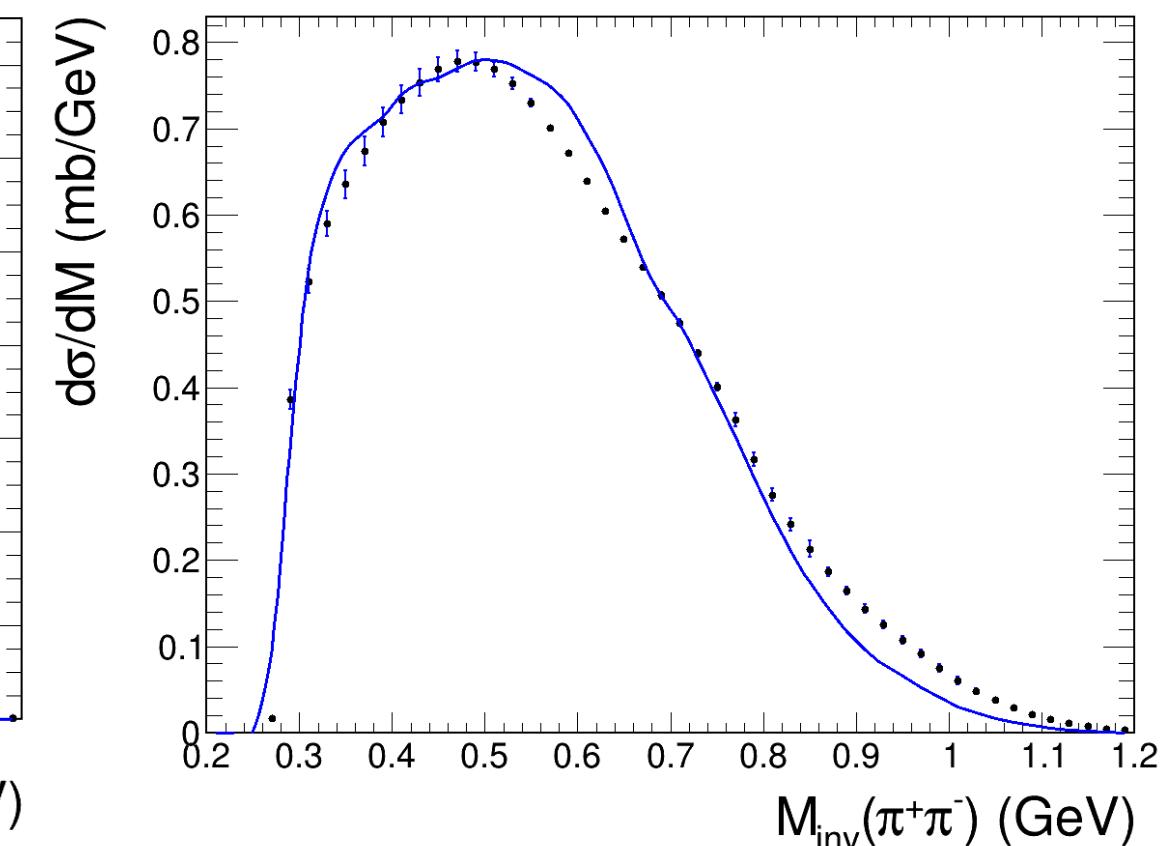
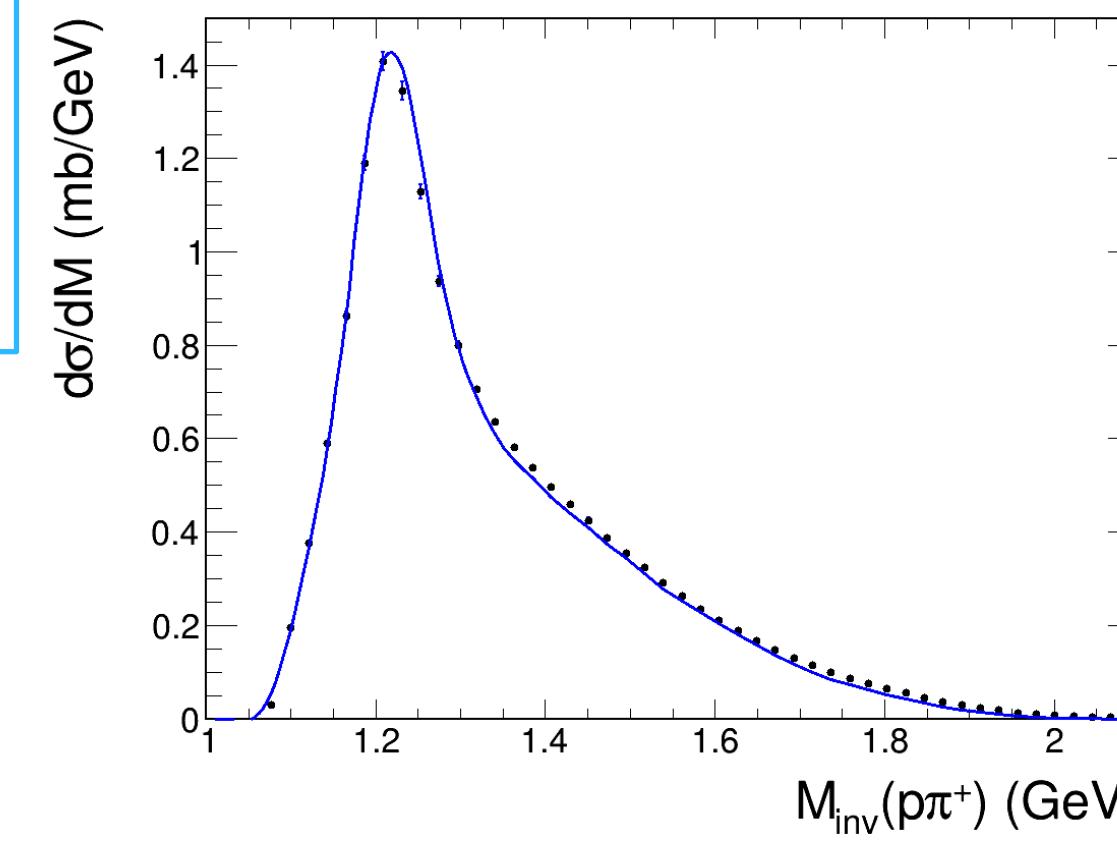
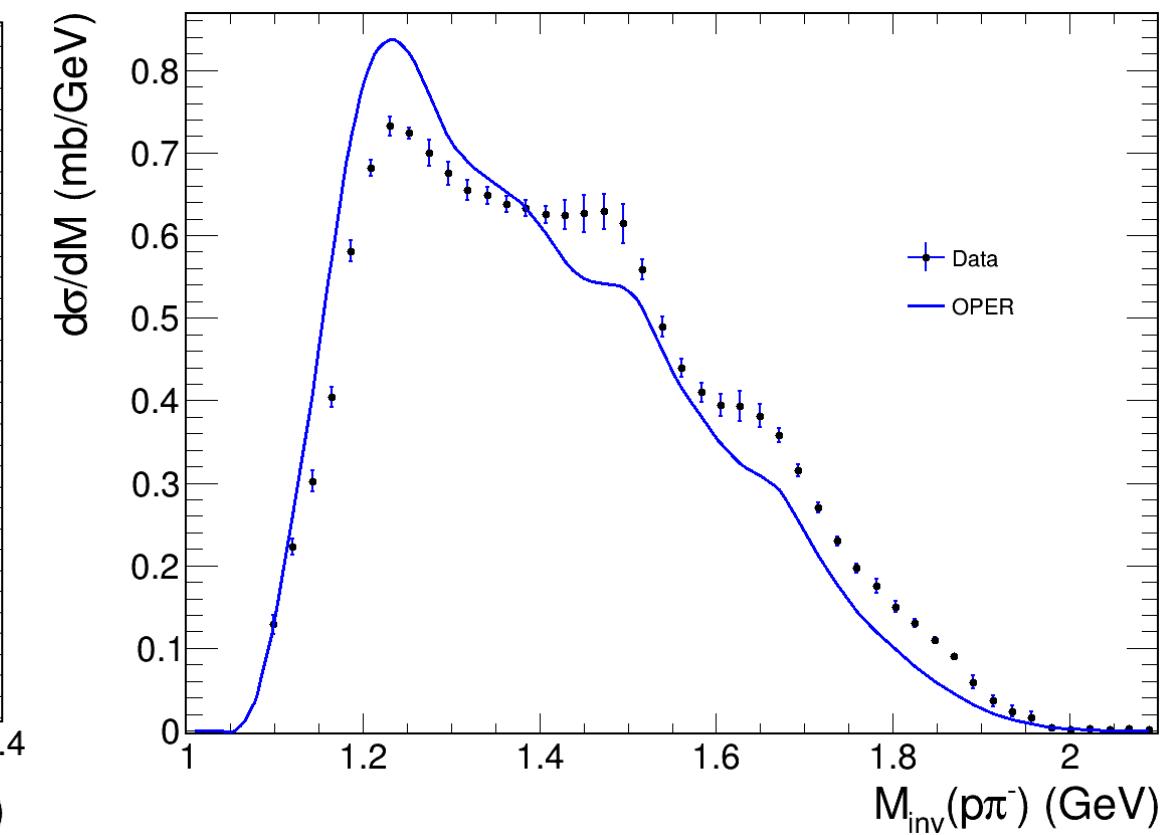
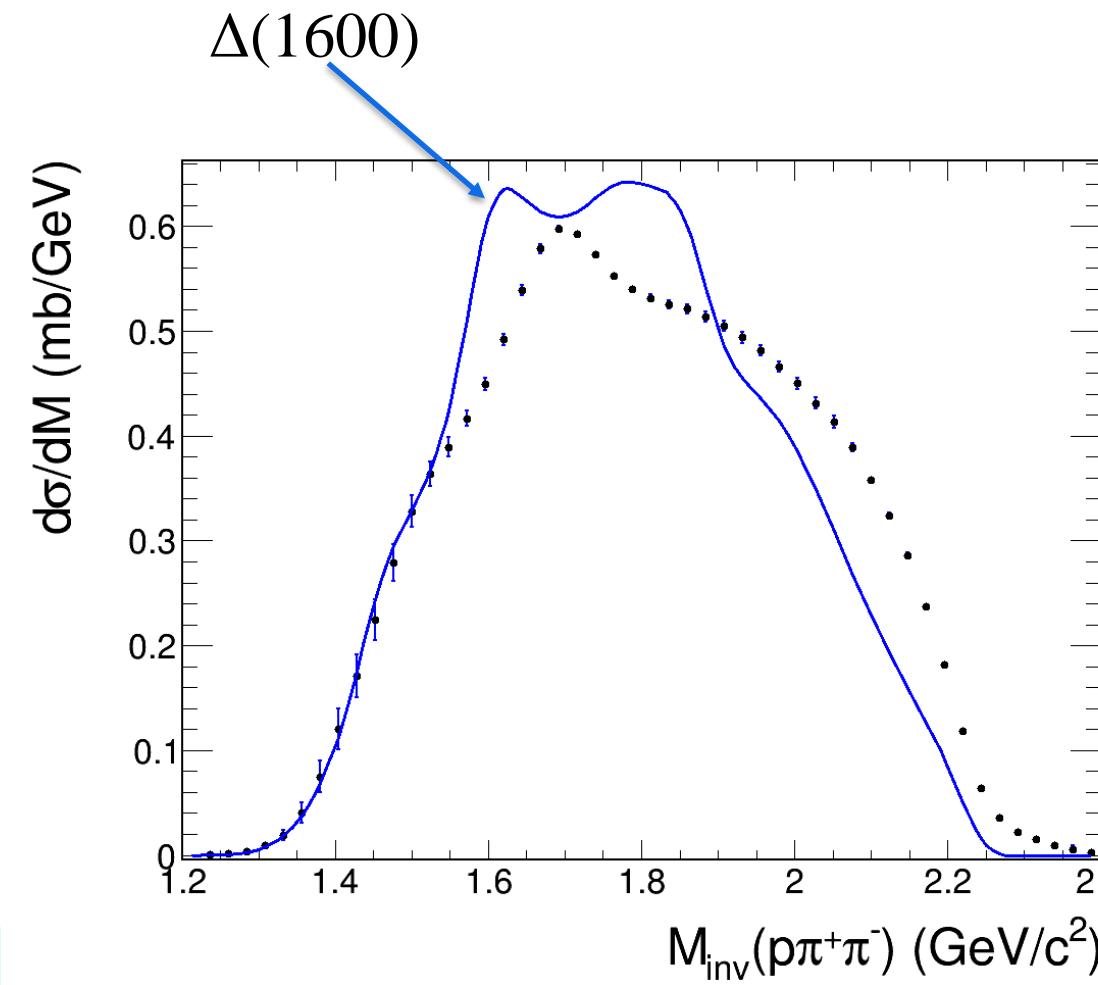
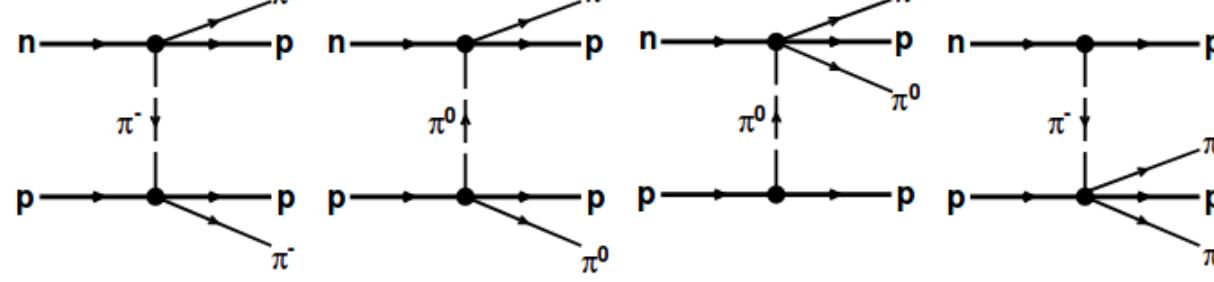
The theoretical test model shows that interference between different graphs is small and constructive .



Comparing to Theoretical Models

Comparing to Theoretical Models

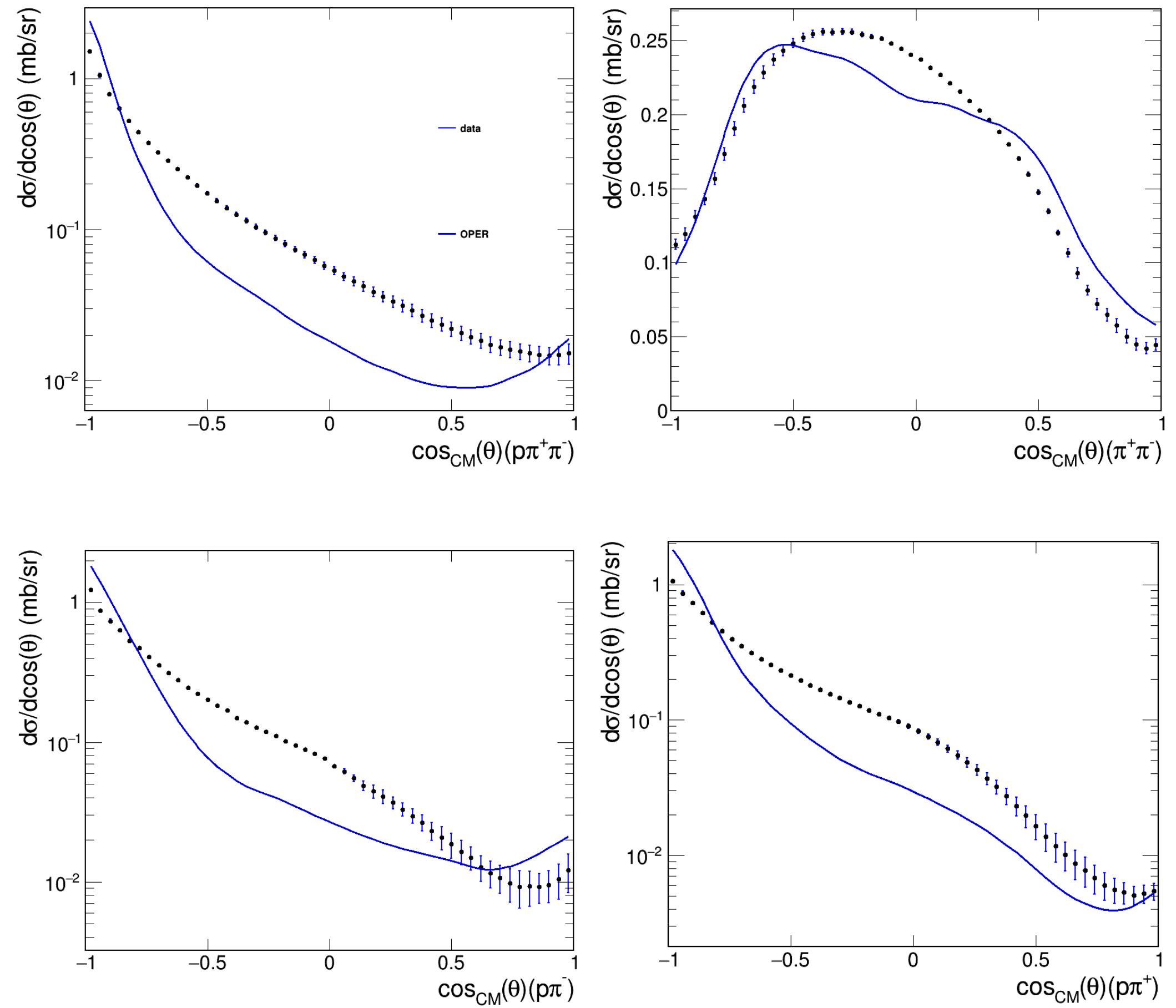
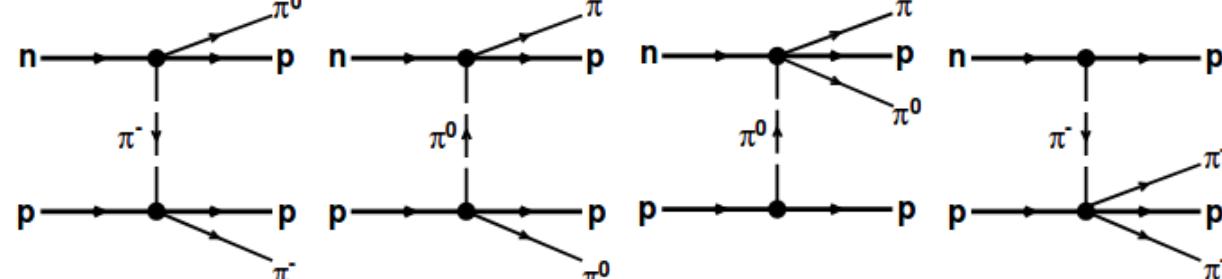
OPER*: One Pion Exchange Reggeized



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

Comparing to Theoretical Models

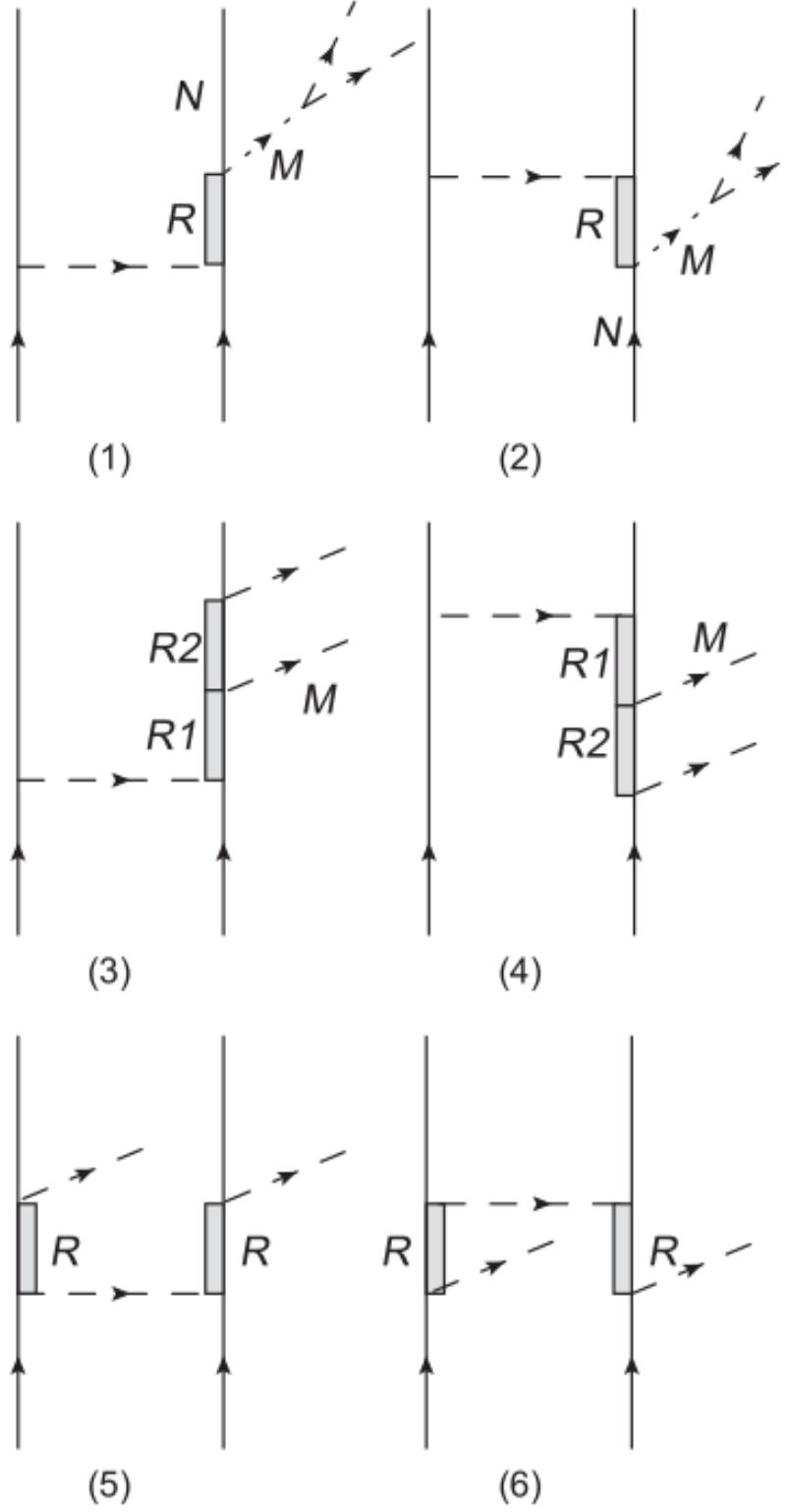
OPER*: One Pion Exchange Reggeized



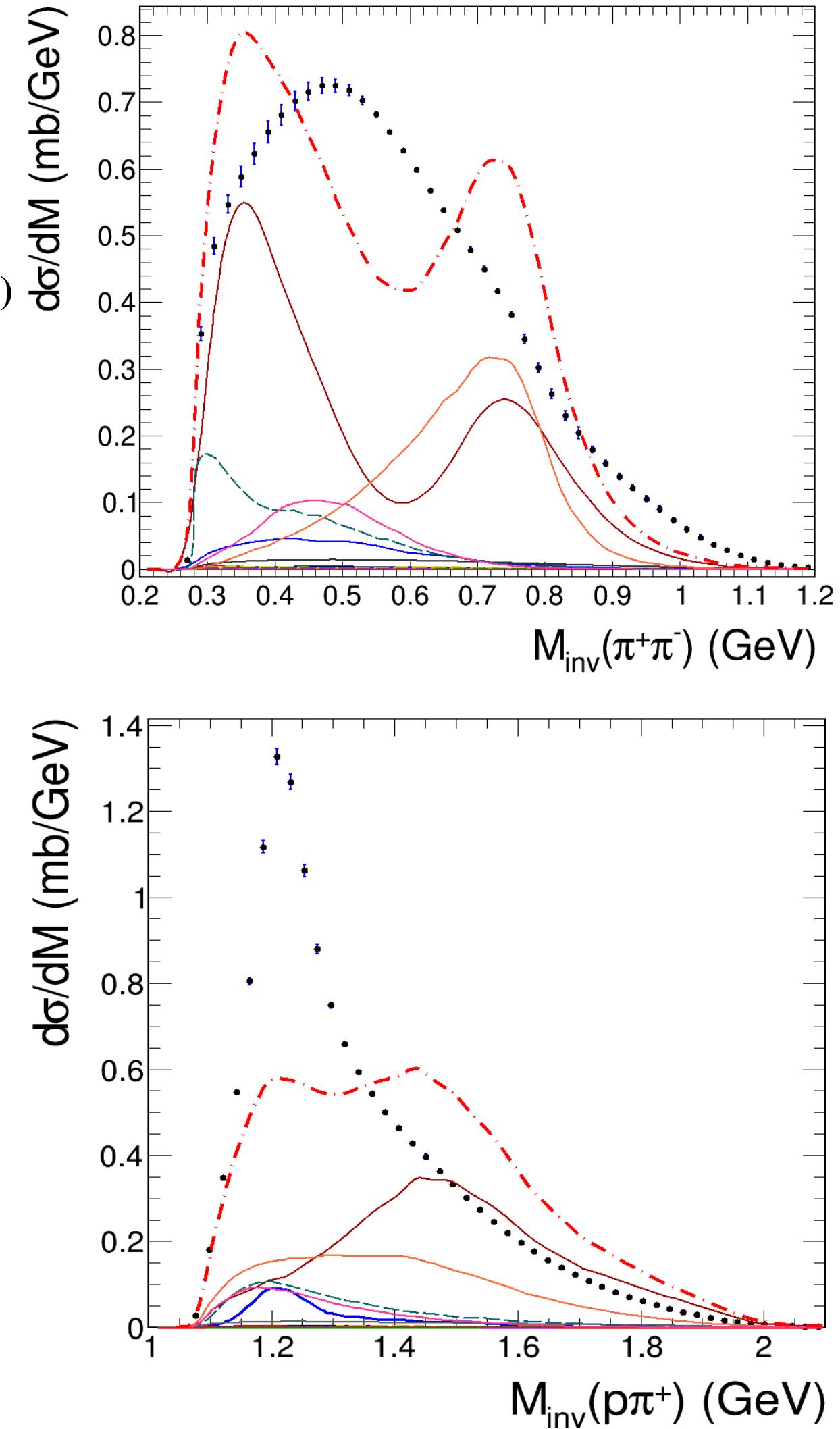
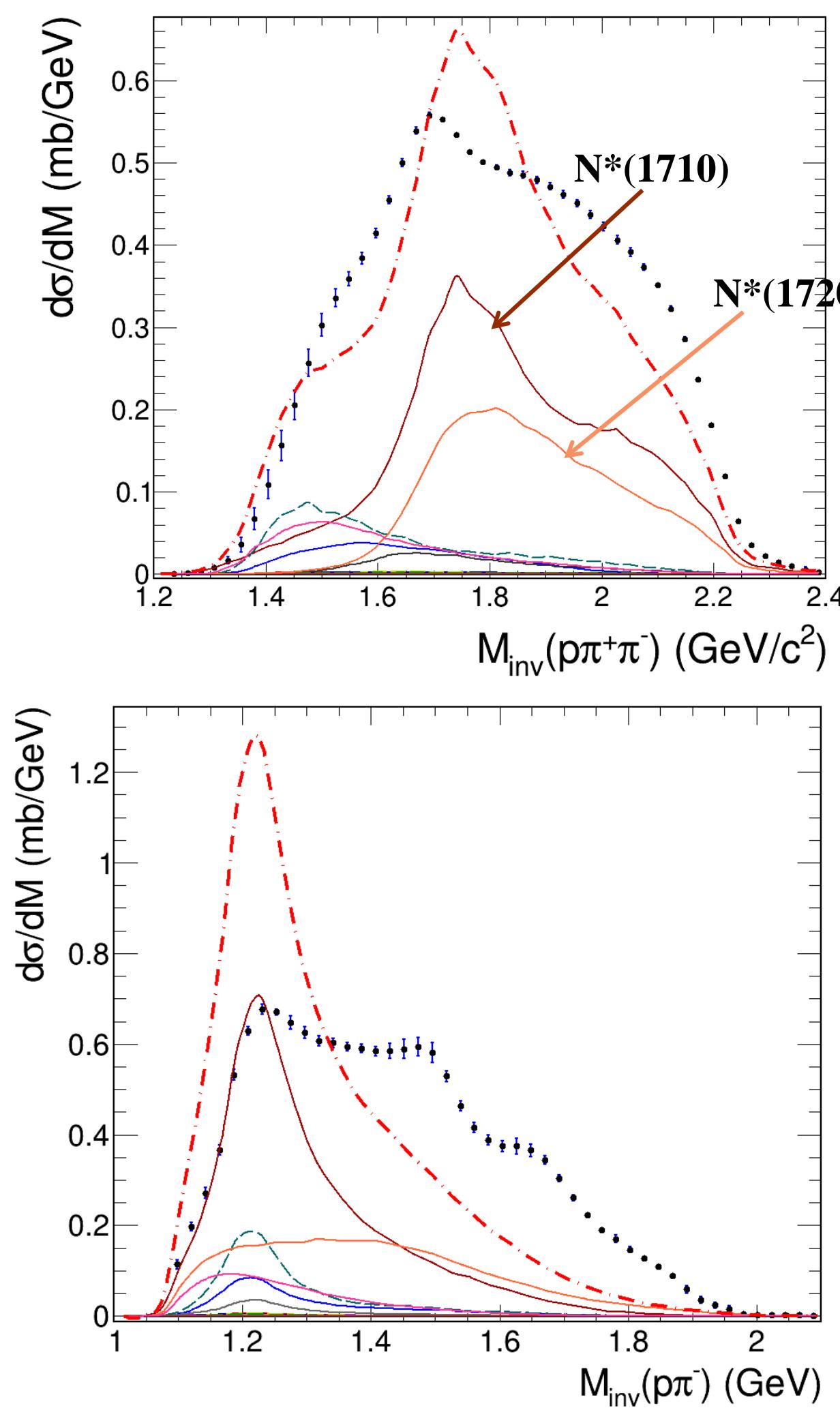
- Cross section adjusted to measured yield.
- Too steep angular distribution in the model.

Comparing to Theoretical Models

Cao effective Lagrangian model* :



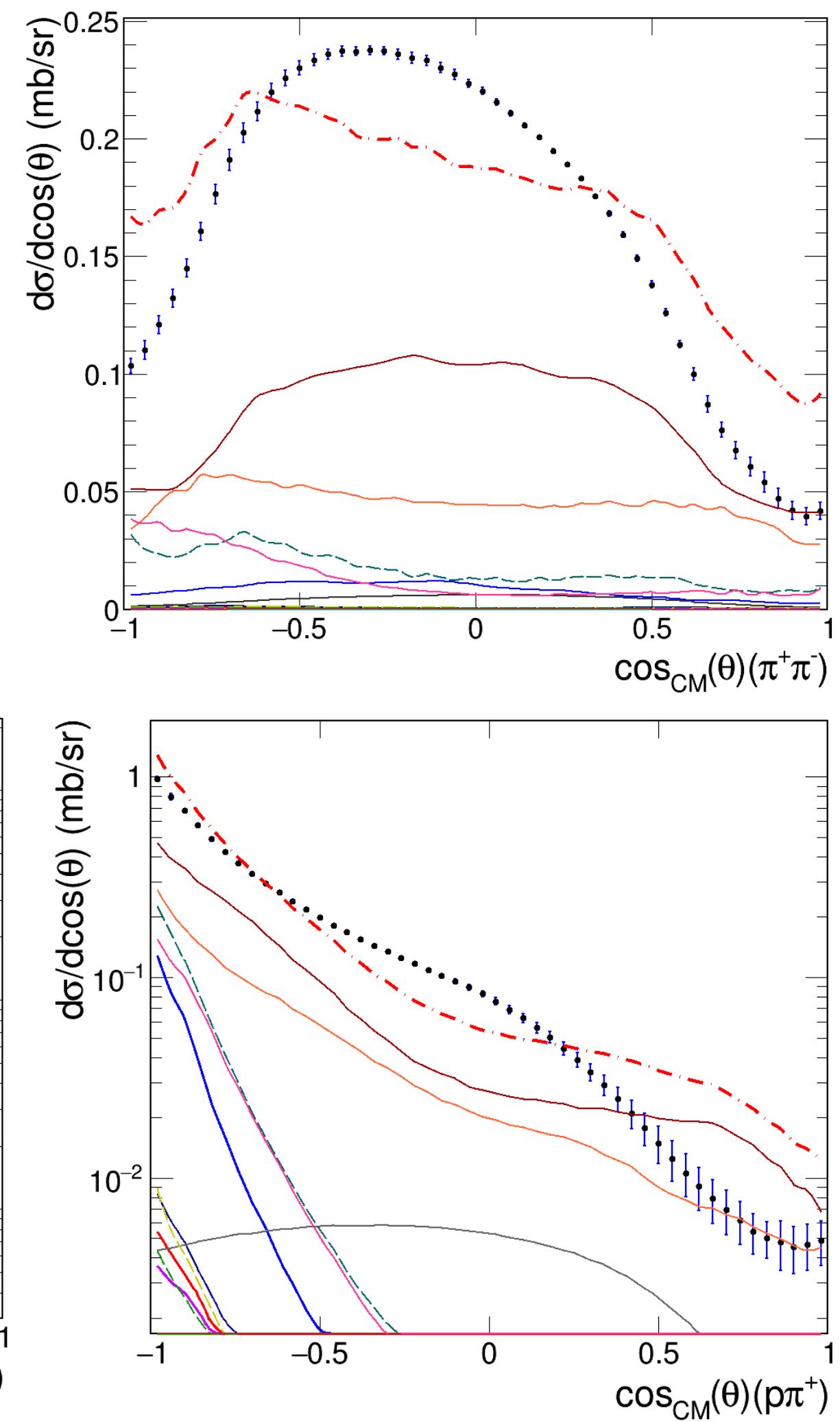
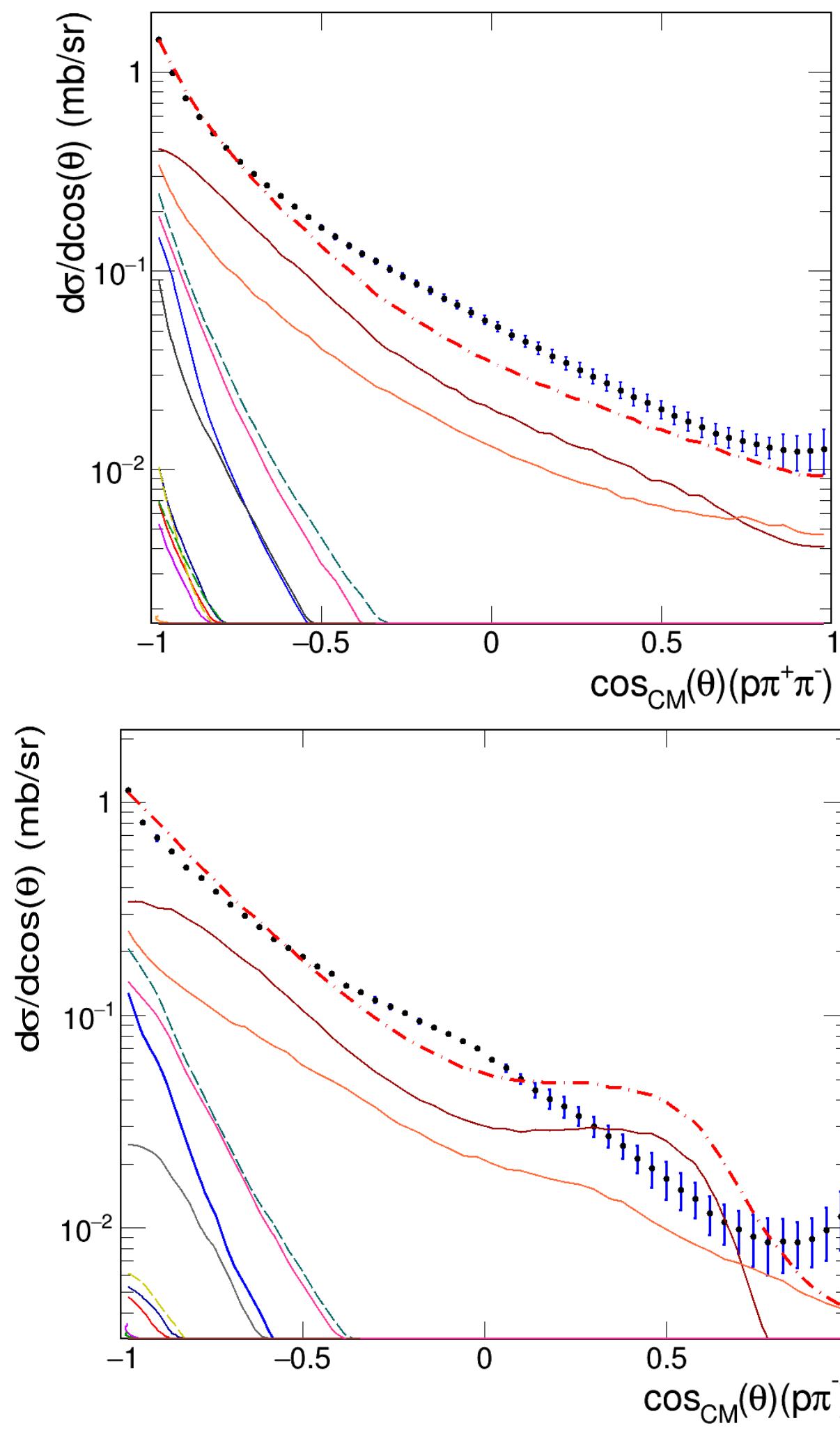
- Only one 2R excitation contribution: $\Delta^{++}(1232)\Delta^{\circ}(1232)$
- Too large yield from $N^*(1710)$ and $N^*(1720)$ decaying to $N\pi$.



Comparing to Theoretical Models

Cao effective Lagrangian model:

- data
- $\Delta(1232)\Delta(1232)$
- $N^*(1710) \rightarrow N \sigma$ (σ exc)
- $N^*(1440) \rightarrow N \sigma$ (π exc)
- $N^*(1440) \rightarrow \Delta \pi$ (π exc)
- $\Delta(1600) \rightarrow \Delta\pi$
- $\Delta(1620) \rightarrow \Delta\pi$ (π exc)
- $\Delta(1700) \rightarrow \Delta\pi$ (π exc)
- $\Delta(1620) \rightarrow \Delta\pi$ (ρ exc)
- $\Delta(1600) \rightarrow N$ pole π (π exc)
- $\Delta(1232) \rightarrow N$ pole π (π exc)
- N pole $\rightarrow \Delta(1232) \pi$ (π exc)
- N pole $\rightarrow \Delta(1232) \pi$ (σ exc)
- N pole $\rightarrow N$ pole π (π exc)
- N pole $\rightarrow N$ pole π (σ exc)
- double N pole (π exc)
- double N pole (σ exc)
- $N^*(1710) \rightarrow \Delta \pi$ (ρ exc)
- $N^*(1520) \rightarrow \Delta \pi$ (π exc)
- $N^*(1700) \rightarrow \Delta \pi$ (π exc)
- $N^*(1710) \rightarrow \Delta \pi$ (π exc)
- $N^*(1710) \rightarrow \Delta \pi$ (ρ exc)
- $N^*(1440) \rightarrow \Delta \pi$ (σ exc)
- $N^*(1720) \rightarrow N \rho$ (η exc)
- $N^*(1720) \rightarrow N \rho$ (π exc)
- $N^*(1440) \rightarrow N \sigma$ (σ exc)
- Xu Cao Model sum



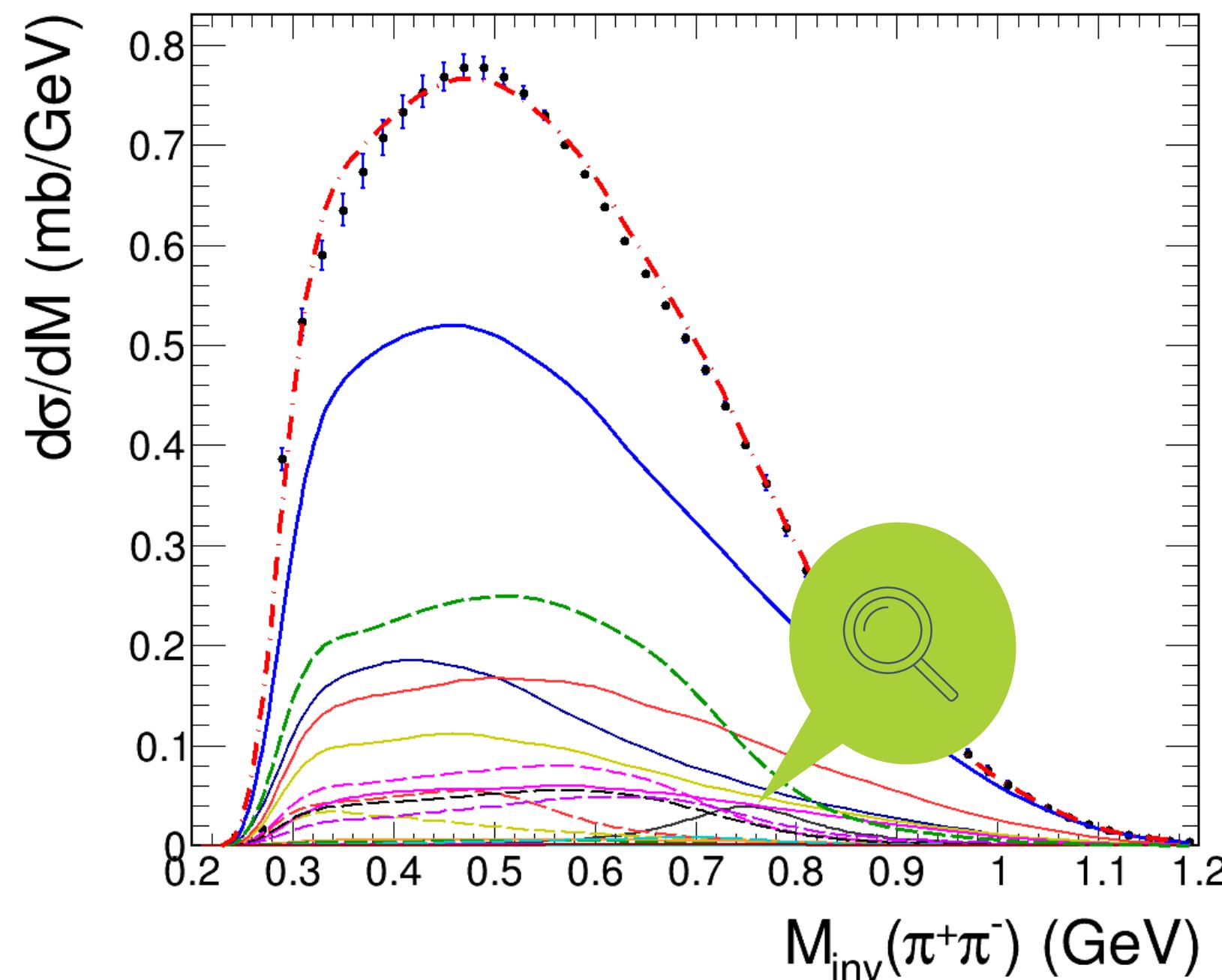
Tracking down the ρ meson



Search for the direct “ρ”

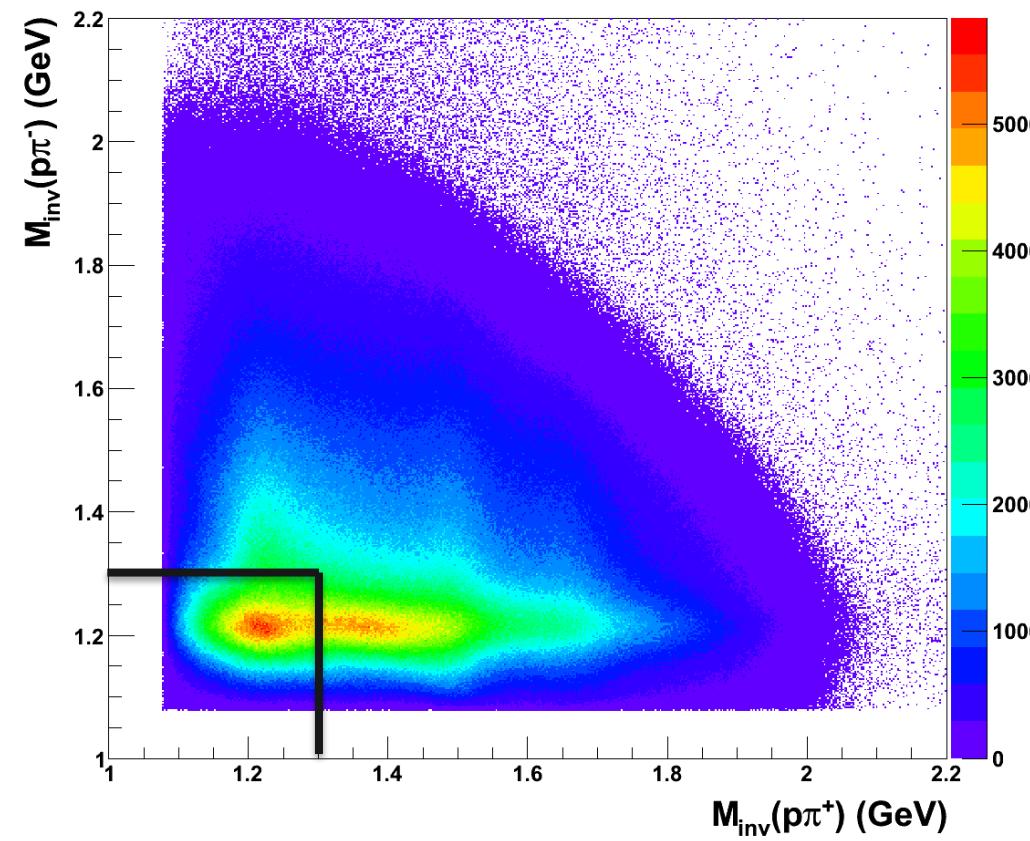
Apply kinematical cuts to reduce the baryonic resonance excitation background.

$$M(\rho) = 775 \text{ MeV}$$
$$\Gamma(\rho) = 149 \text{ MeV}$$

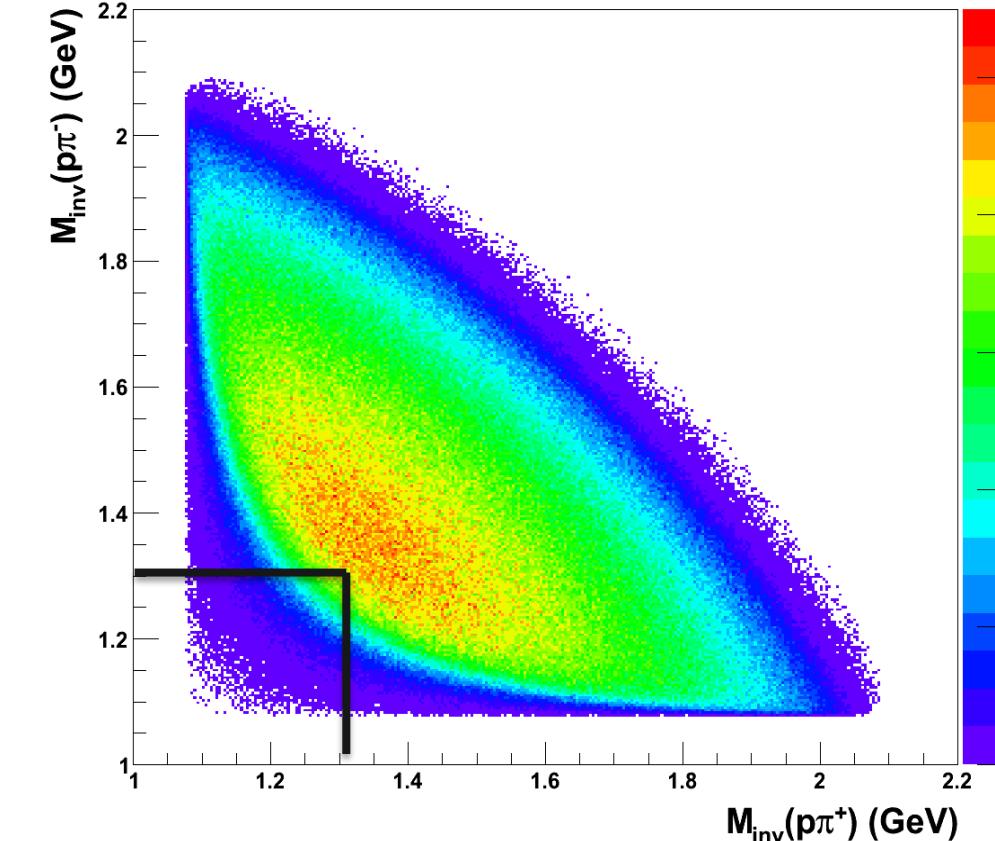


Search for the direct “ ρ ”

Data



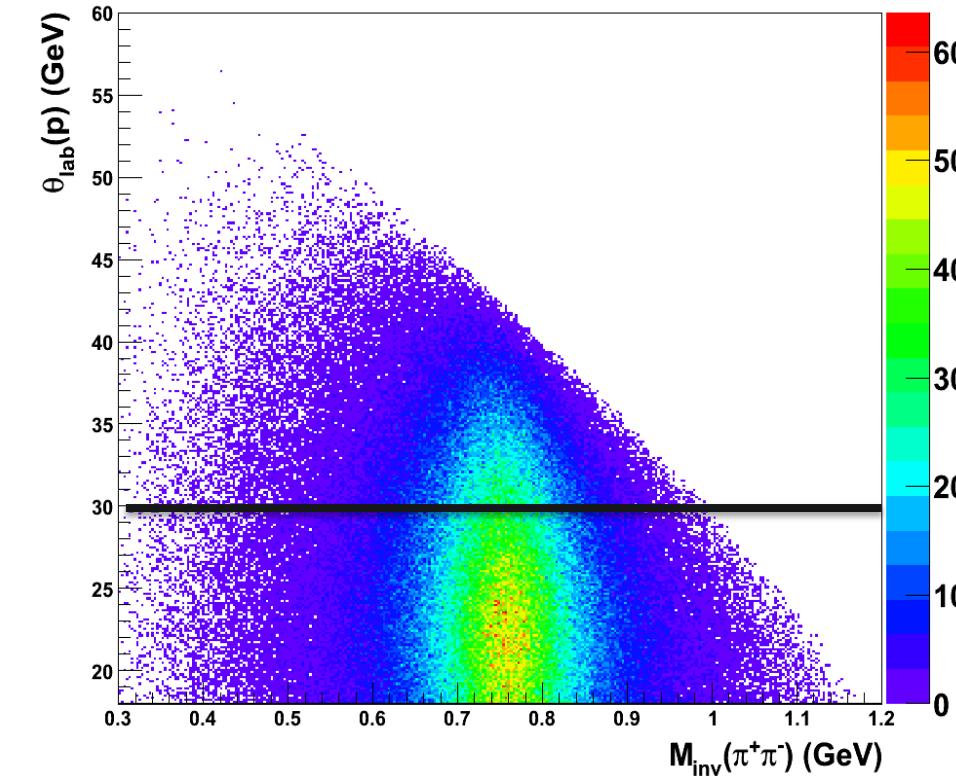
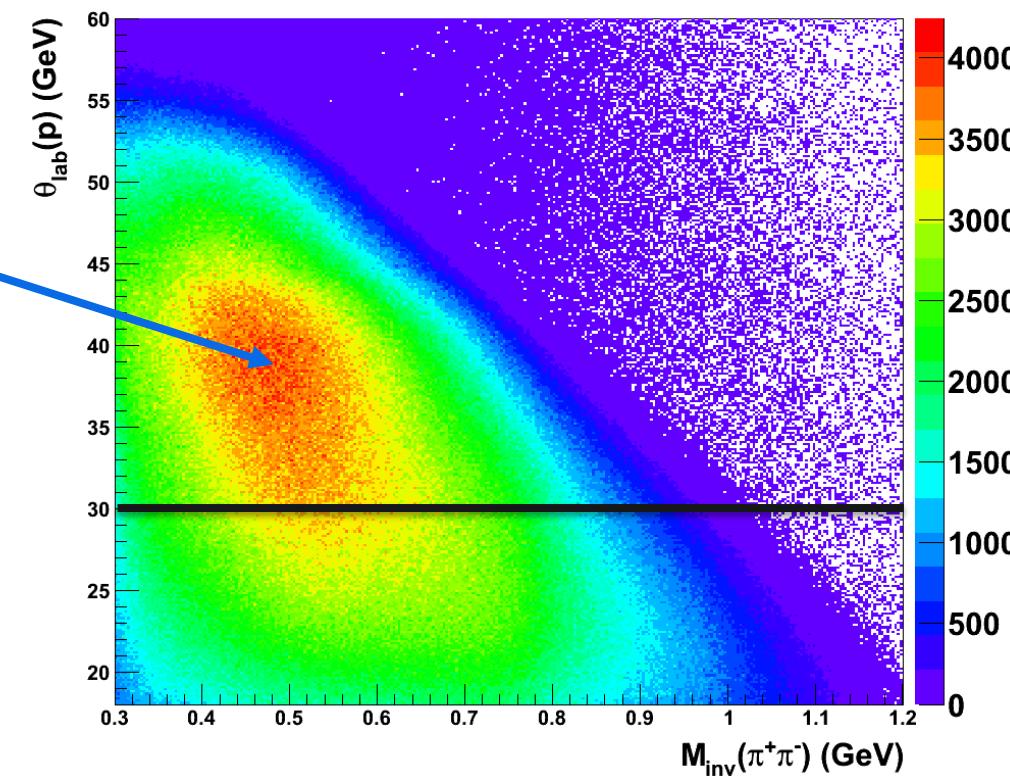
ρ simulation



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

Suppress $\Delta(1232)\Delta(1232)$

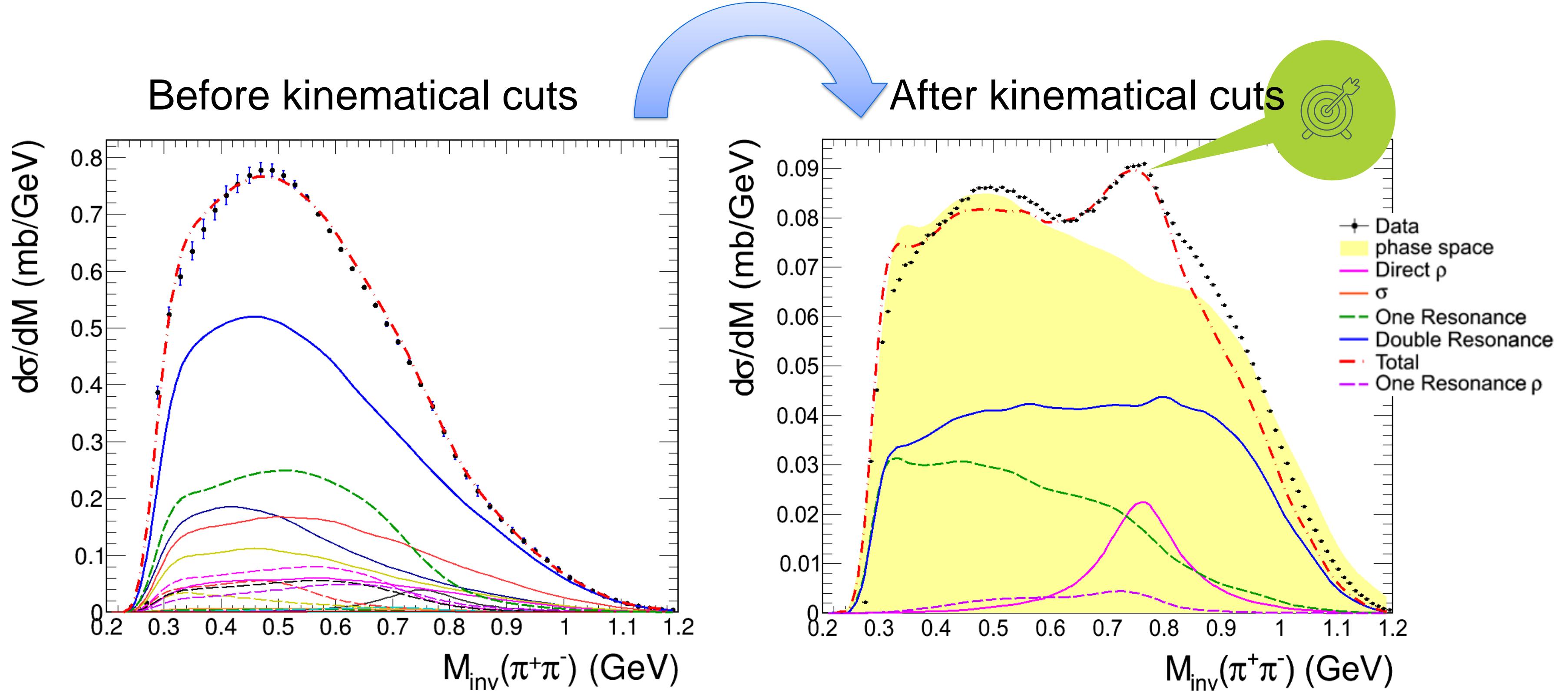
resonances



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

Suppress remaining
resonances

Search for the direct “ ρ ”

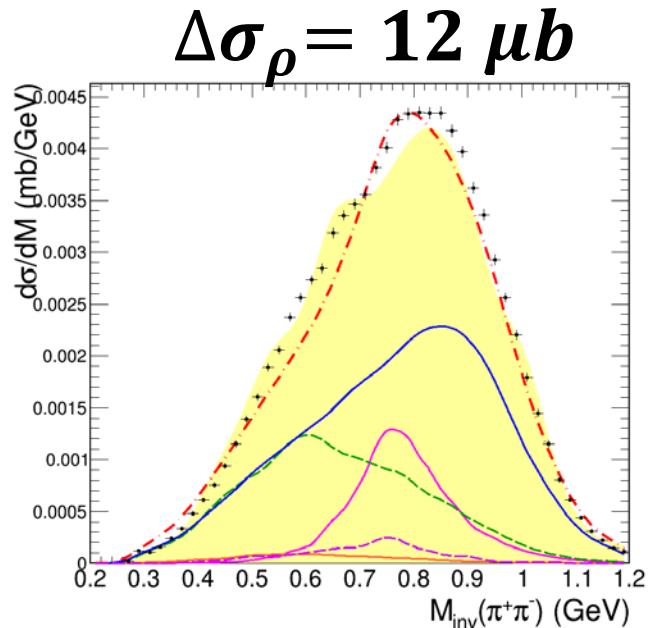


“ρ” Angular Distribution

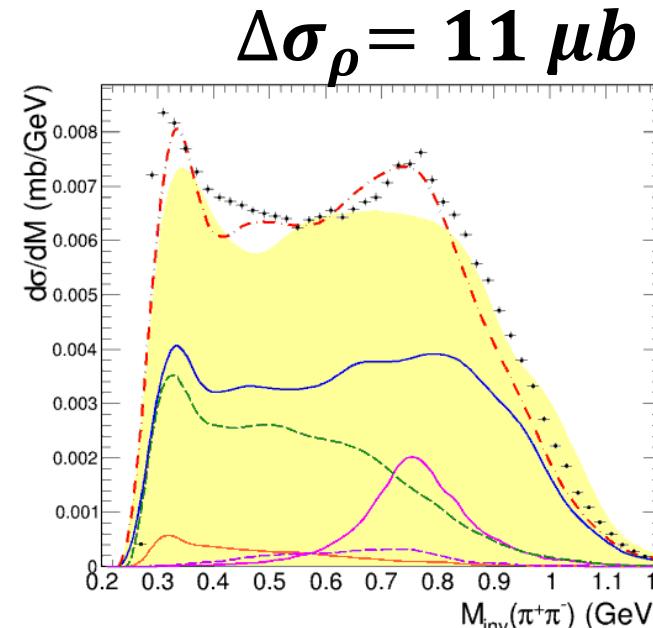
Evaluate σ_ρ in bins of $\cos_{CM}(\theta)(\pi^+\pi^-)$

- Data
- phase space
- Direct ρ
- σ
- One Resonance
- Double Resonance
- Total
- One Resonance ρ

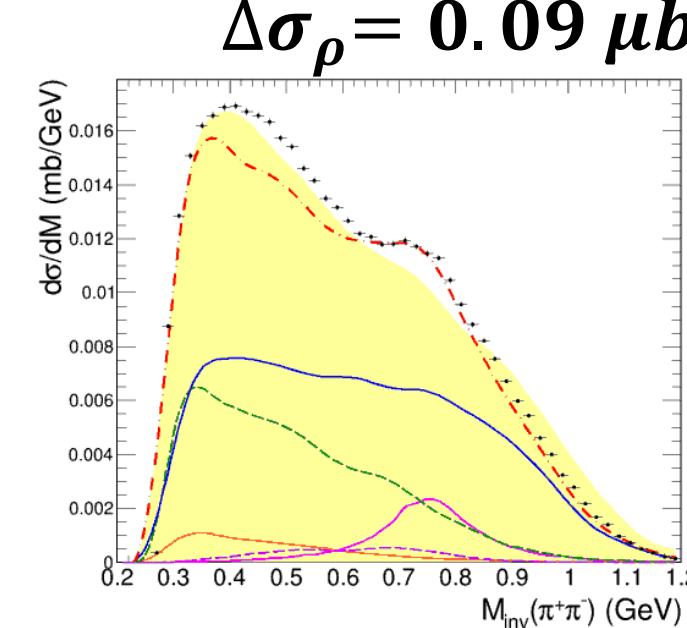
Backward



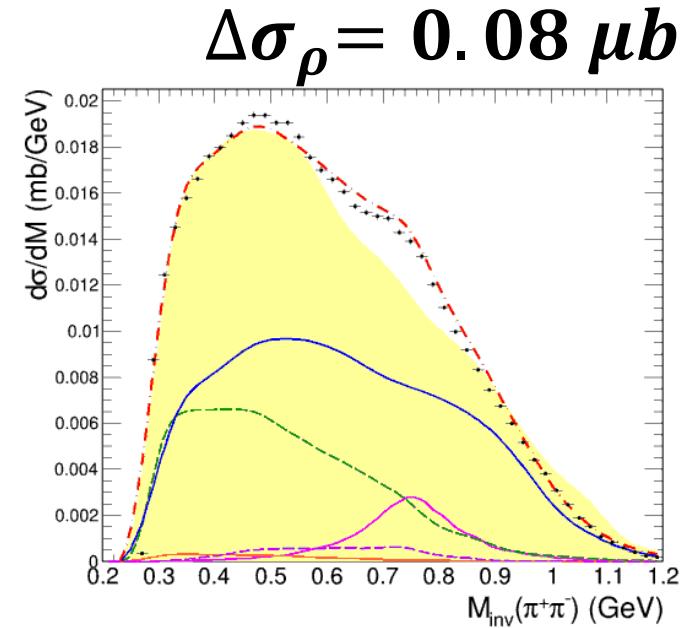
$-1 < \cos(\theta) < -0.8$



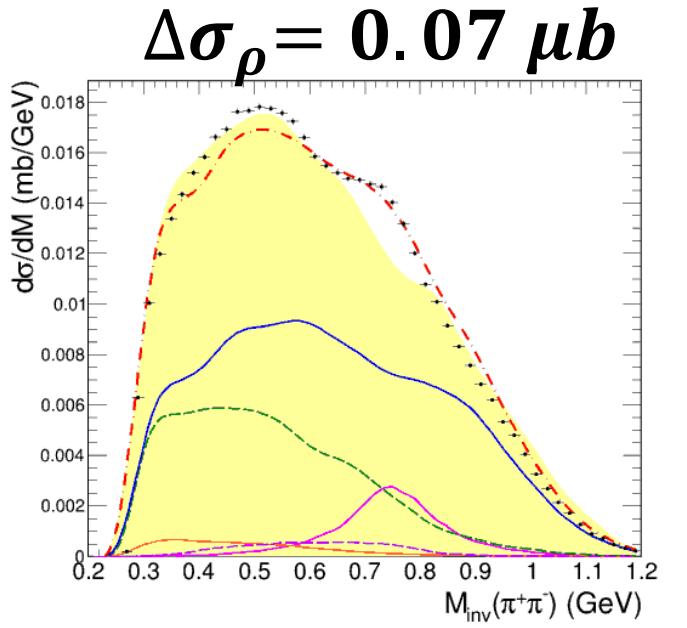
$-0.8 < \cos(\theta) < -0.6$



$-0.6 < \cos(\theta) < -0.4$



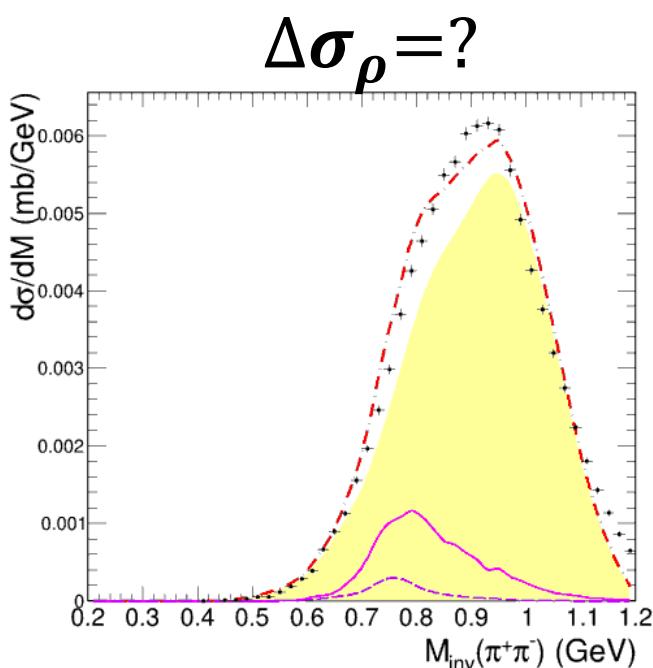
$-0.4 < \cos(\theta) < -0.2$



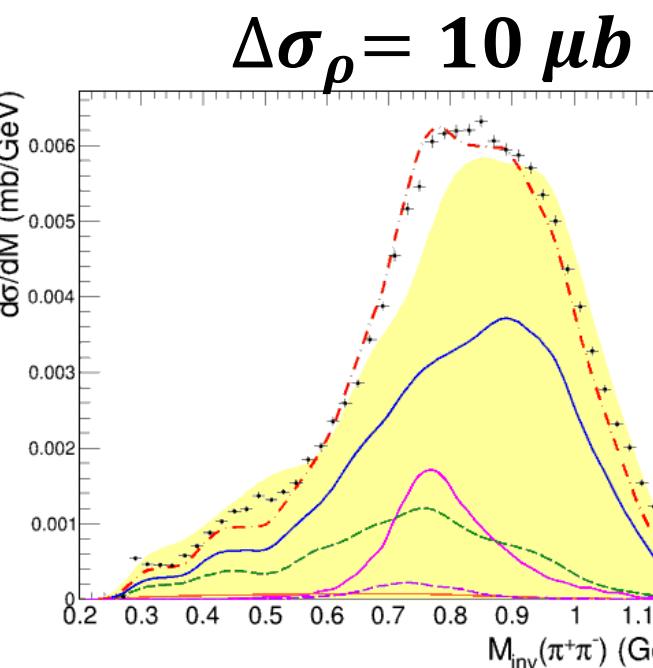
$-0.2 < \cos(\theta) < 0$



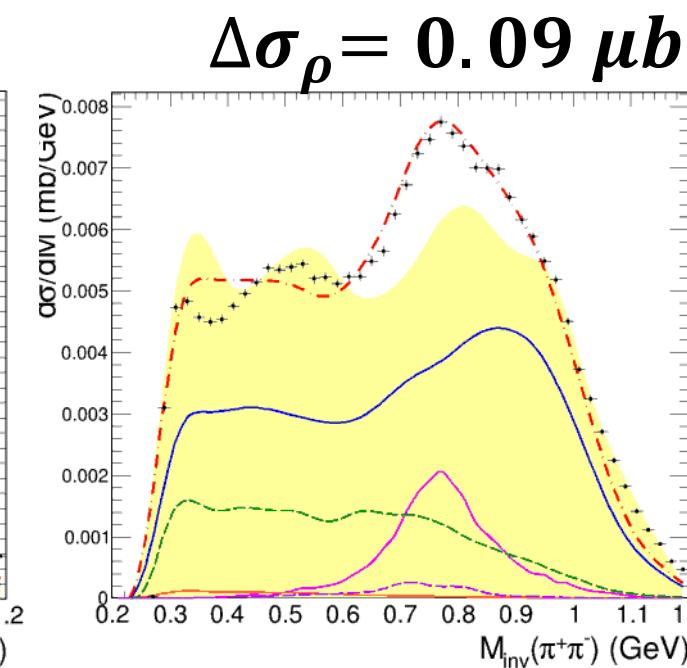
Forward



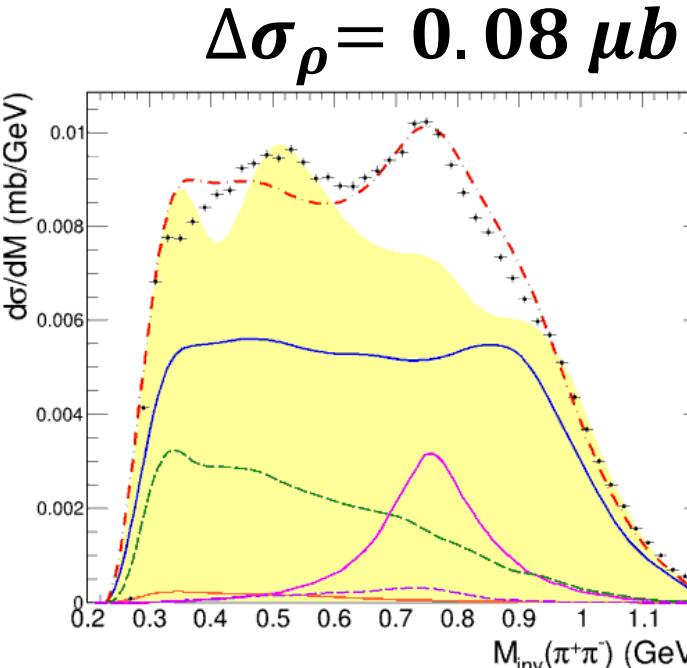
$0.8 < \cos(\theta) < 1$



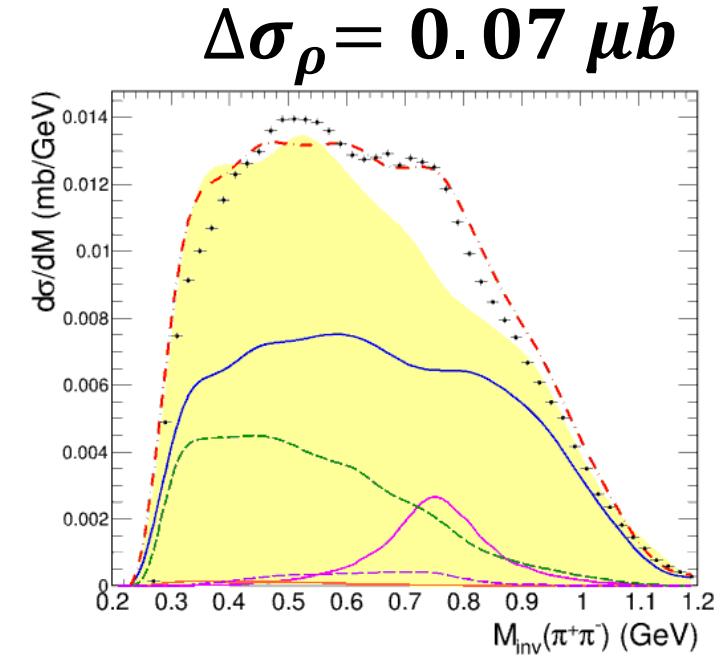
$0.6 < \cos(\theta) < 0.8$



$0.4 < \cos(\theta) < 0.6$



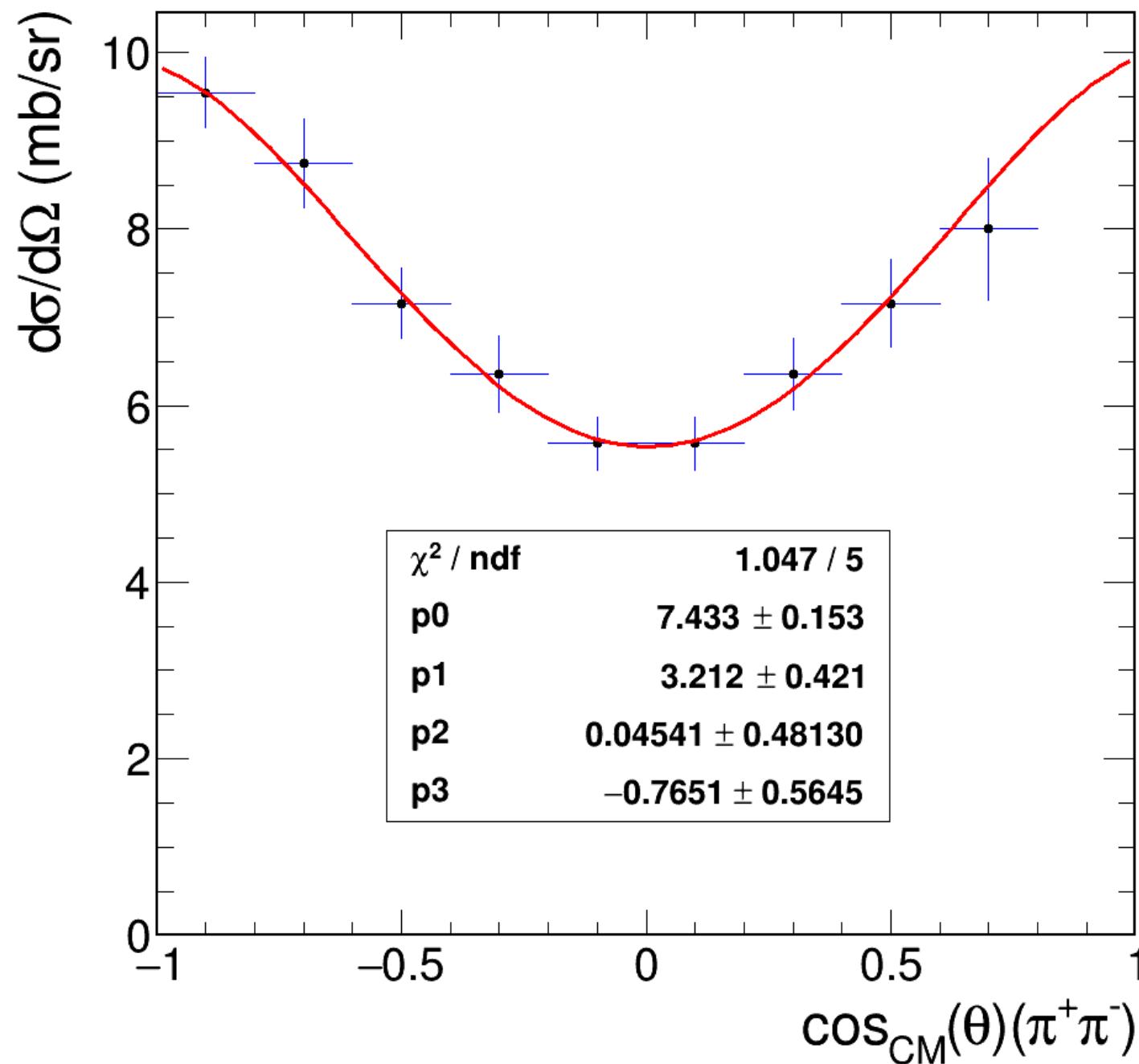
$0.2 < \cos(\theta) < 0.4$



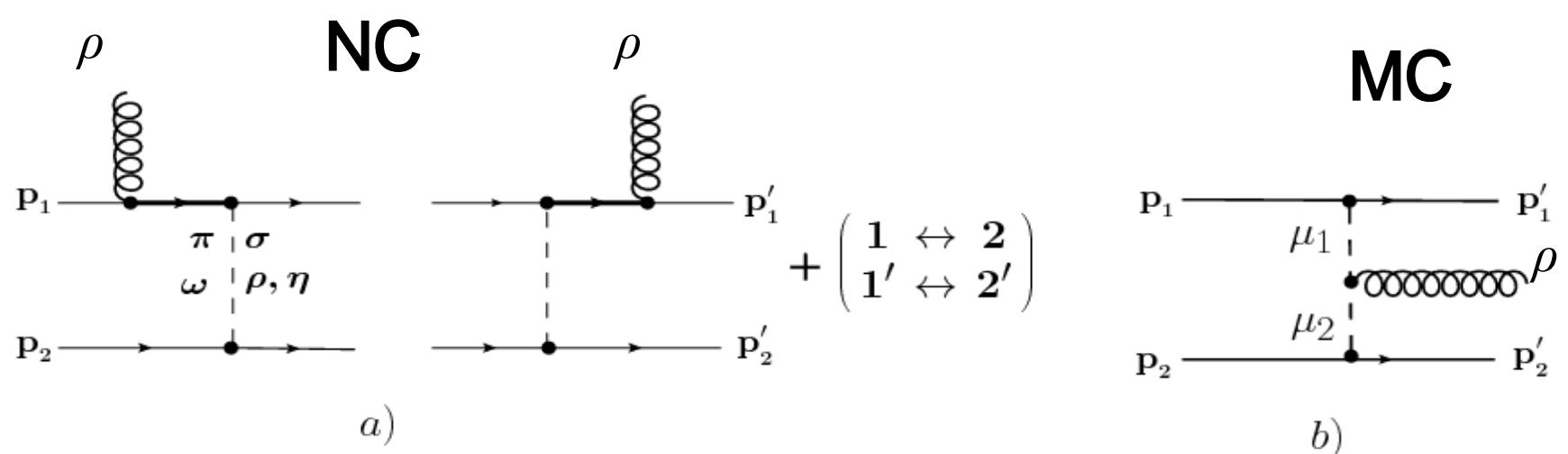
$0 < \cos(\theta) < 0.2$

- Good backward/forward symmetry

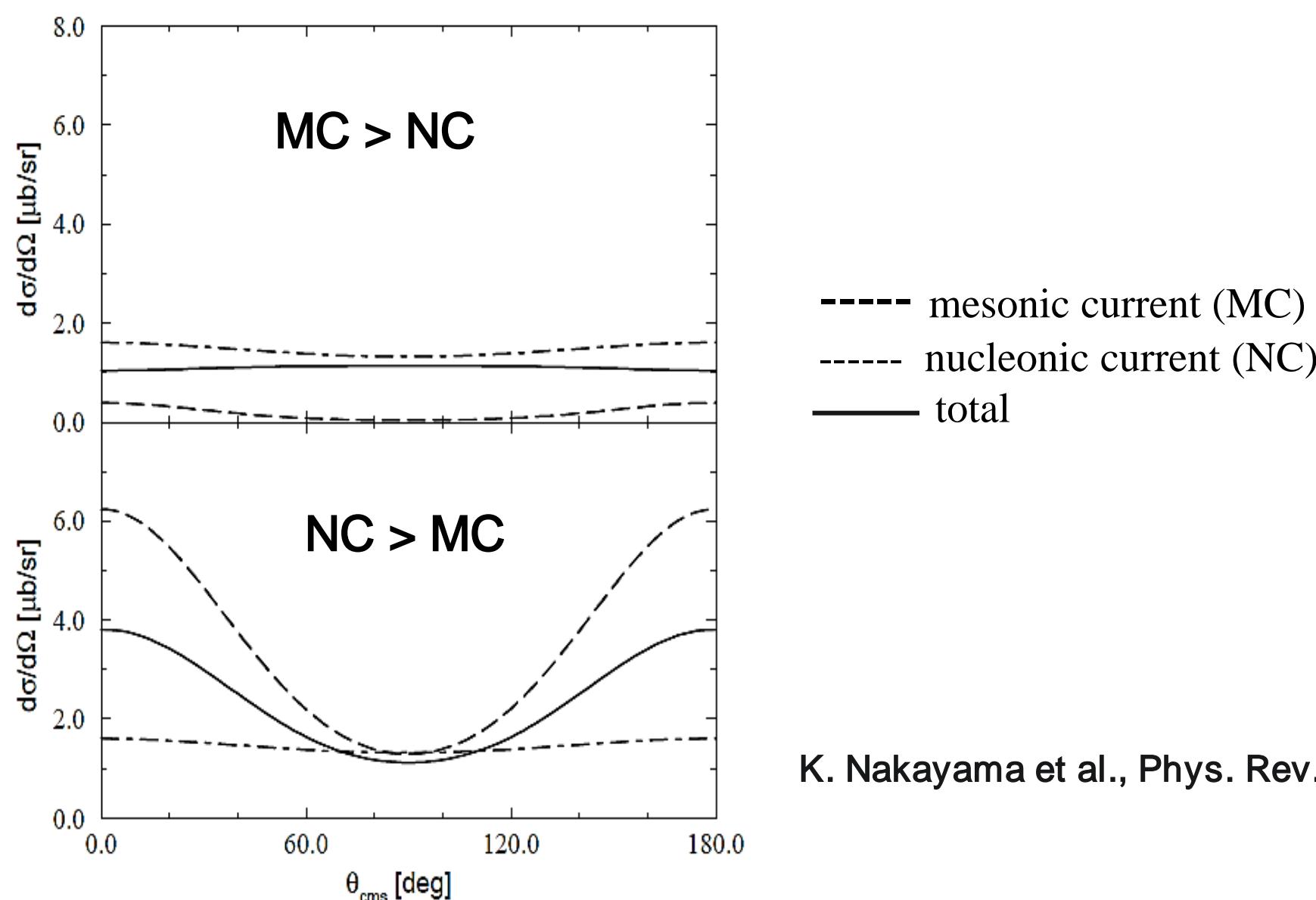
“ρ” Angular Distribution



$\frac{d\sigma}{d\Omega}$ expected to be isotropic for mesonic current (MC)
and forward/backward peaked for nucleonic current (NC)

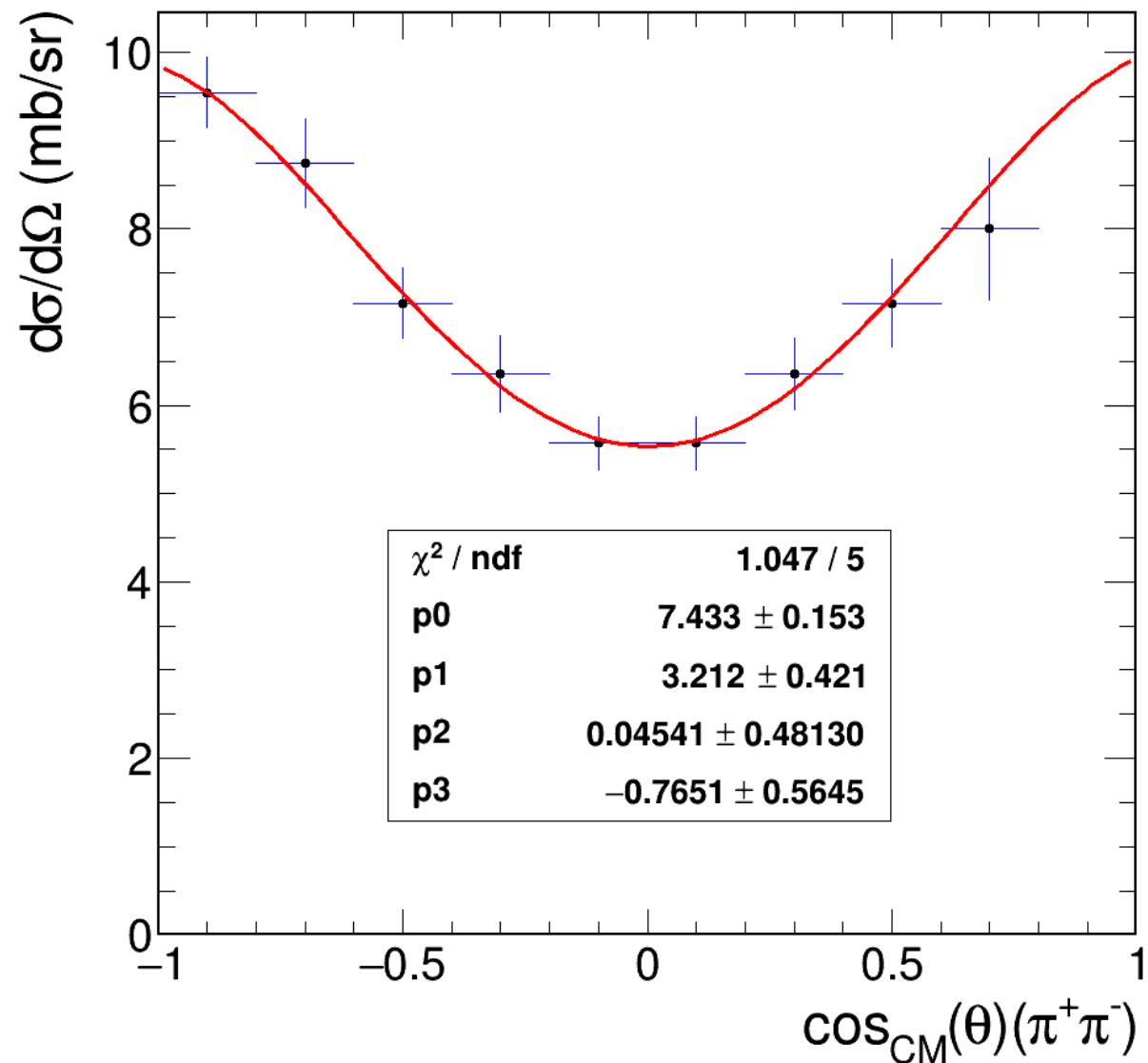


$\frac{d\sigma}{d\Omega}$ consistent with dominant nucluonic current (NC)



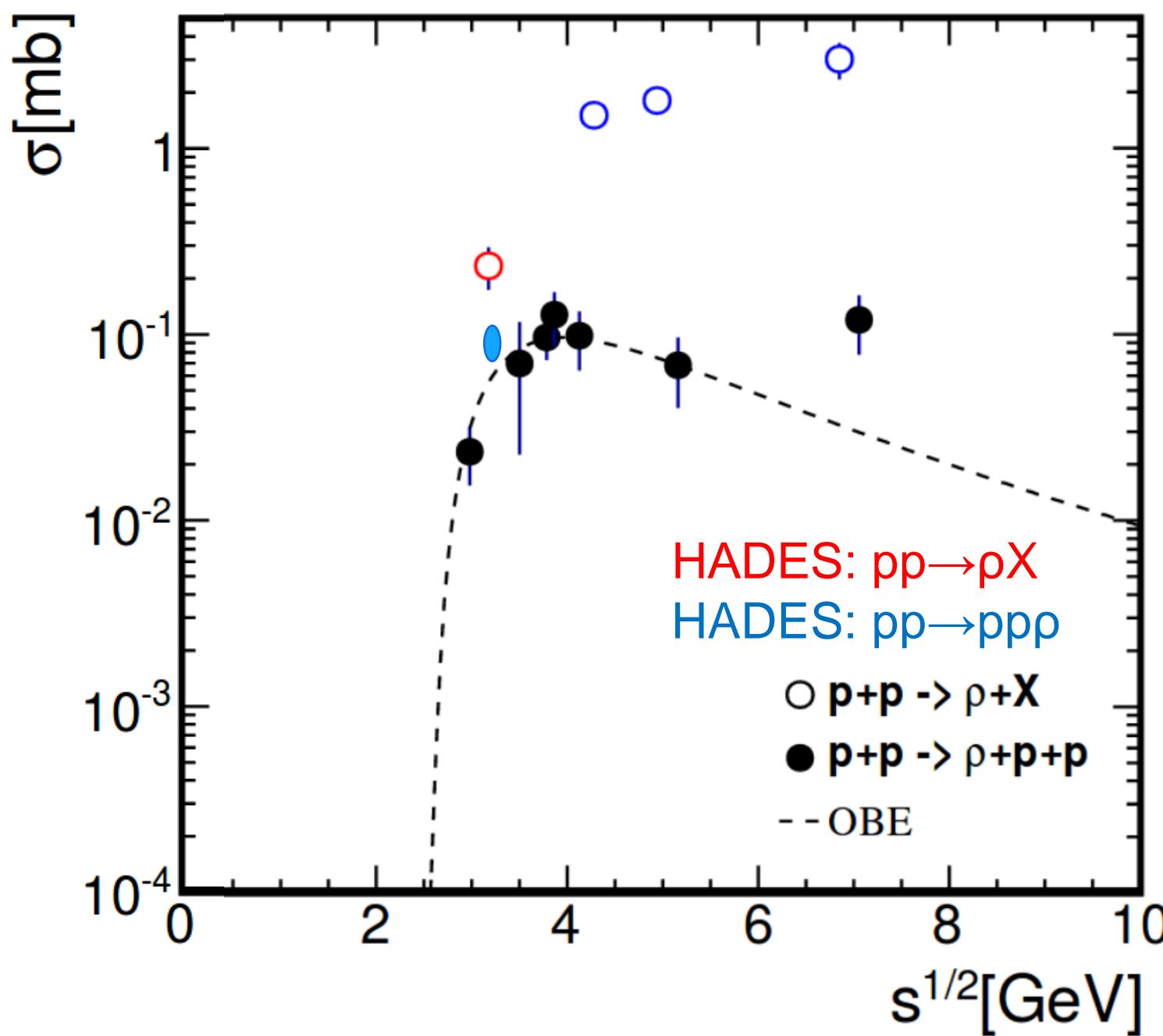
K. Nakayama et al., Phys. Rev. C57 (1998) 1580.

“ ρ ” Angular Distribution

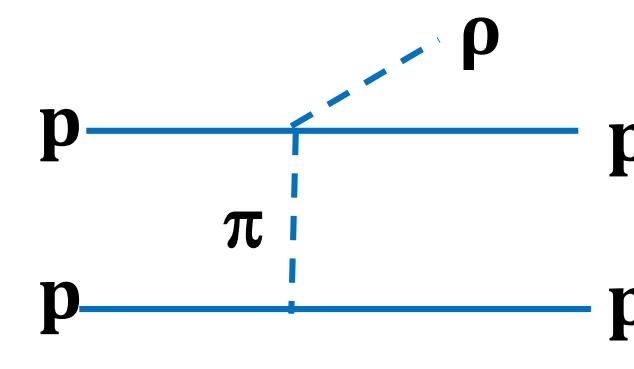


$$\frac{d\sigma_\rho}{d\Omega} = (7.4 \pm 0.2)P_0 + (3.2 \pm 0.6)P_2 - (0.7 \pm 0.7)P_4$$

→ $\sigma_\rho = 92 \pm 5 \mu b$

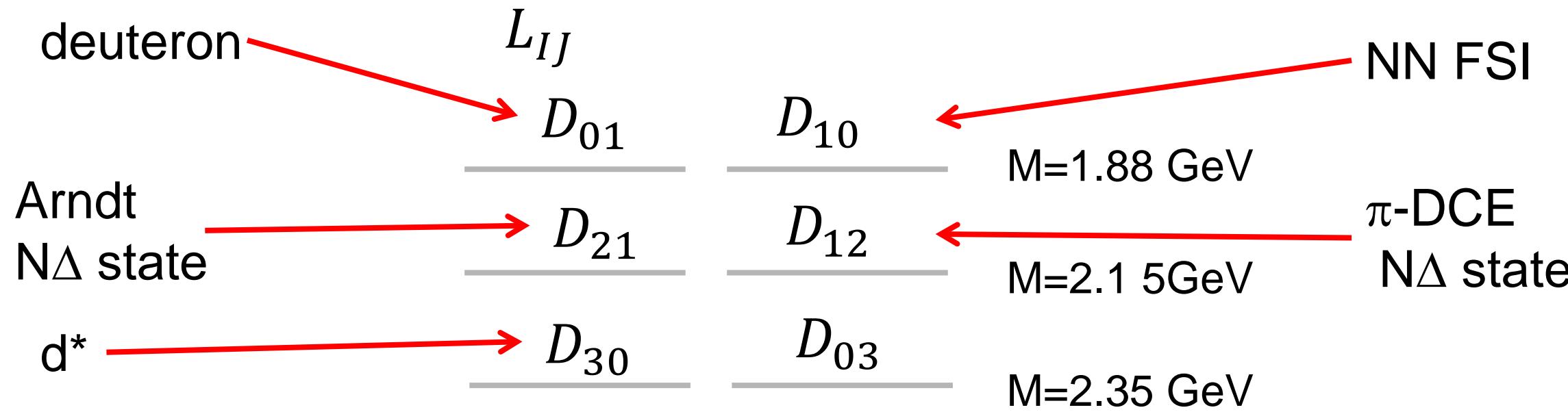


- New measurement of $\text{pp} \rightarrow \rho\rho\rho$ by HADES.
 - Consistent with previous data and much more precise.
 - Consistent with OBE model
- Based on $\pi p \rightarrow \rho p$



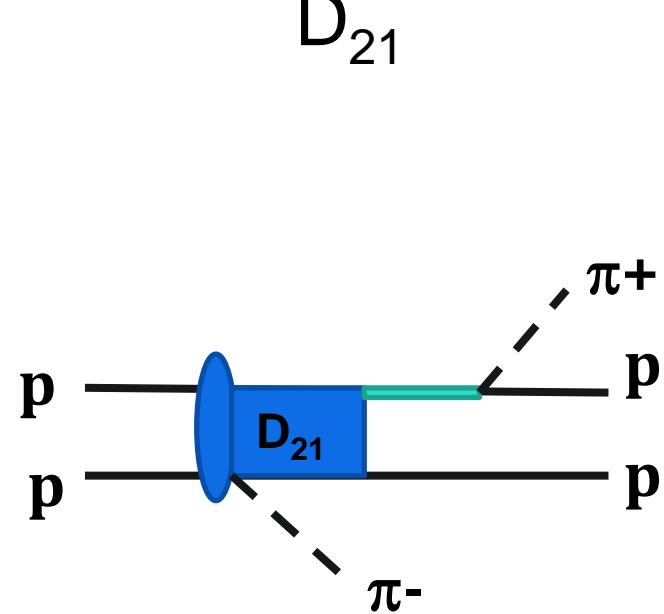
Dibaryon investigation

6 Non-strange B=2 states

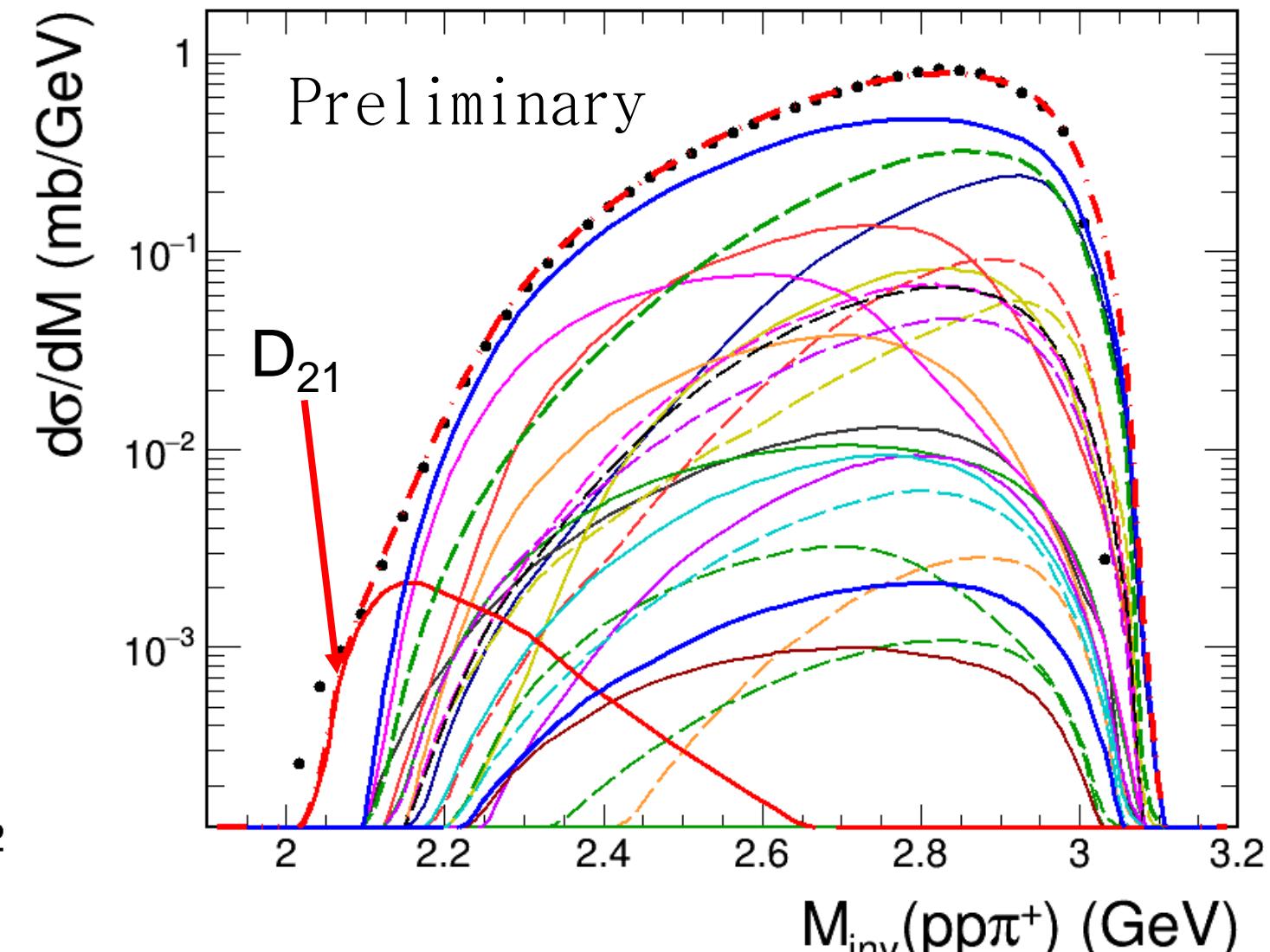
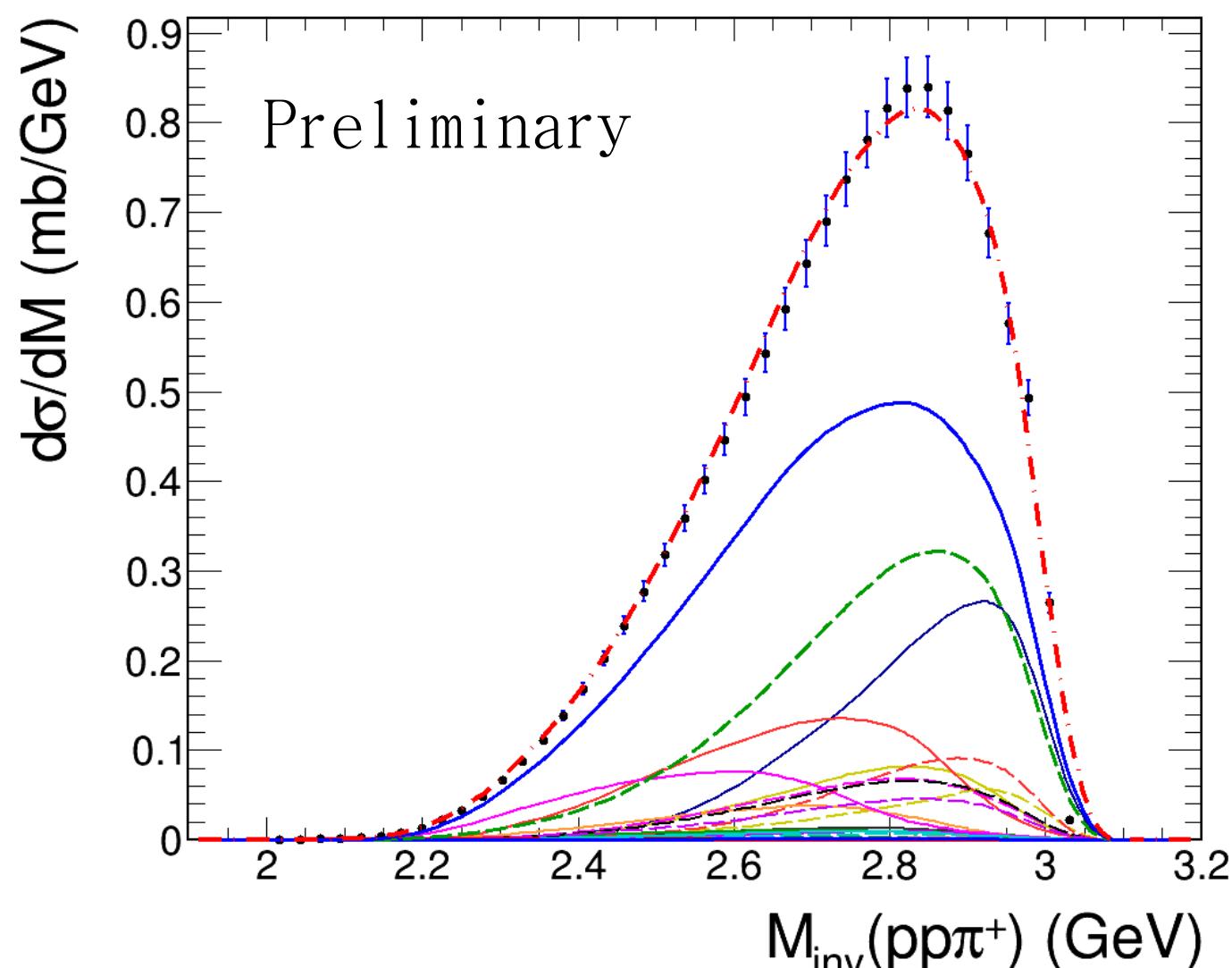


- Investigation for the dibaryon $D_{21}(2150)$

$pp \rightarrow pp\pi^+\pi^-$



$$\sigma_{D_{21}} < 7 \pm 2 \mu b$$

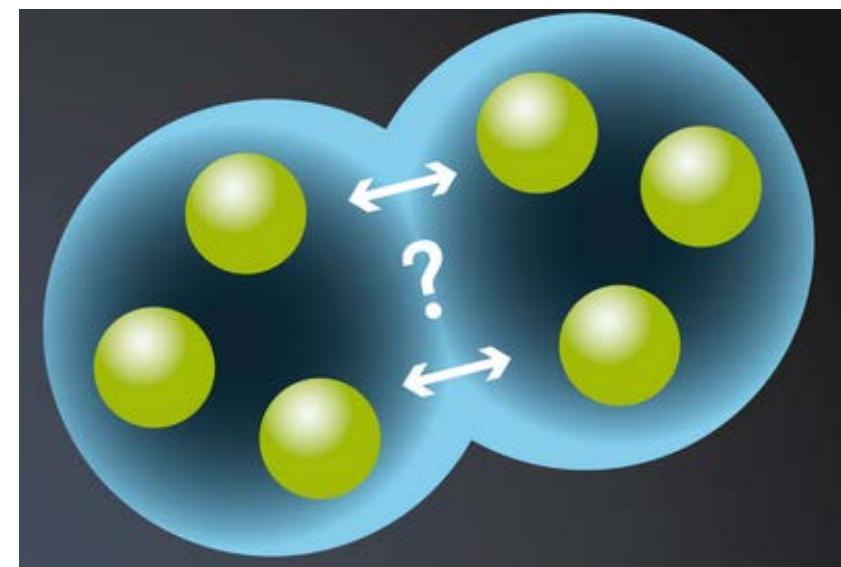
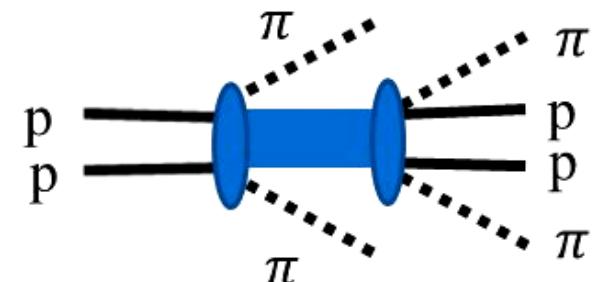


HADES resonances cocktail + D_{21}

Perspectives

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

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



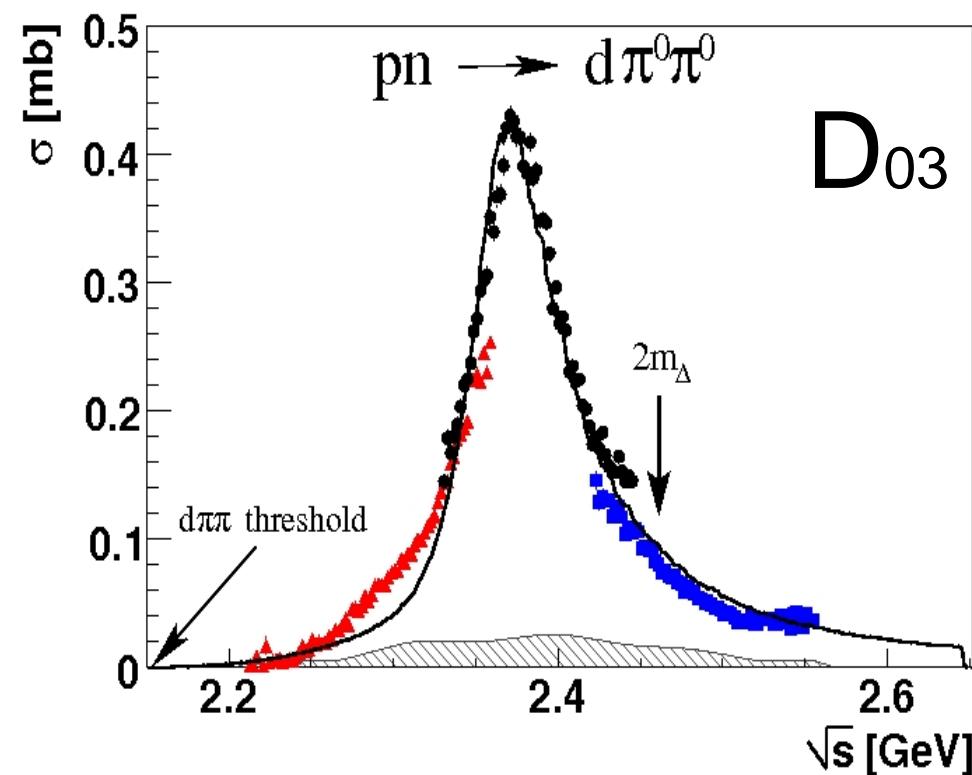
Isospin factors

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

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

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

Complementary study to WASA experiment



Conclusion



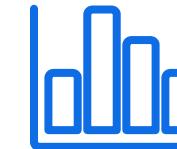
A

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”.



C

The results present valuable inputs for theoretical models.



D

Theoretical test model used to test the effect of interferences.



E

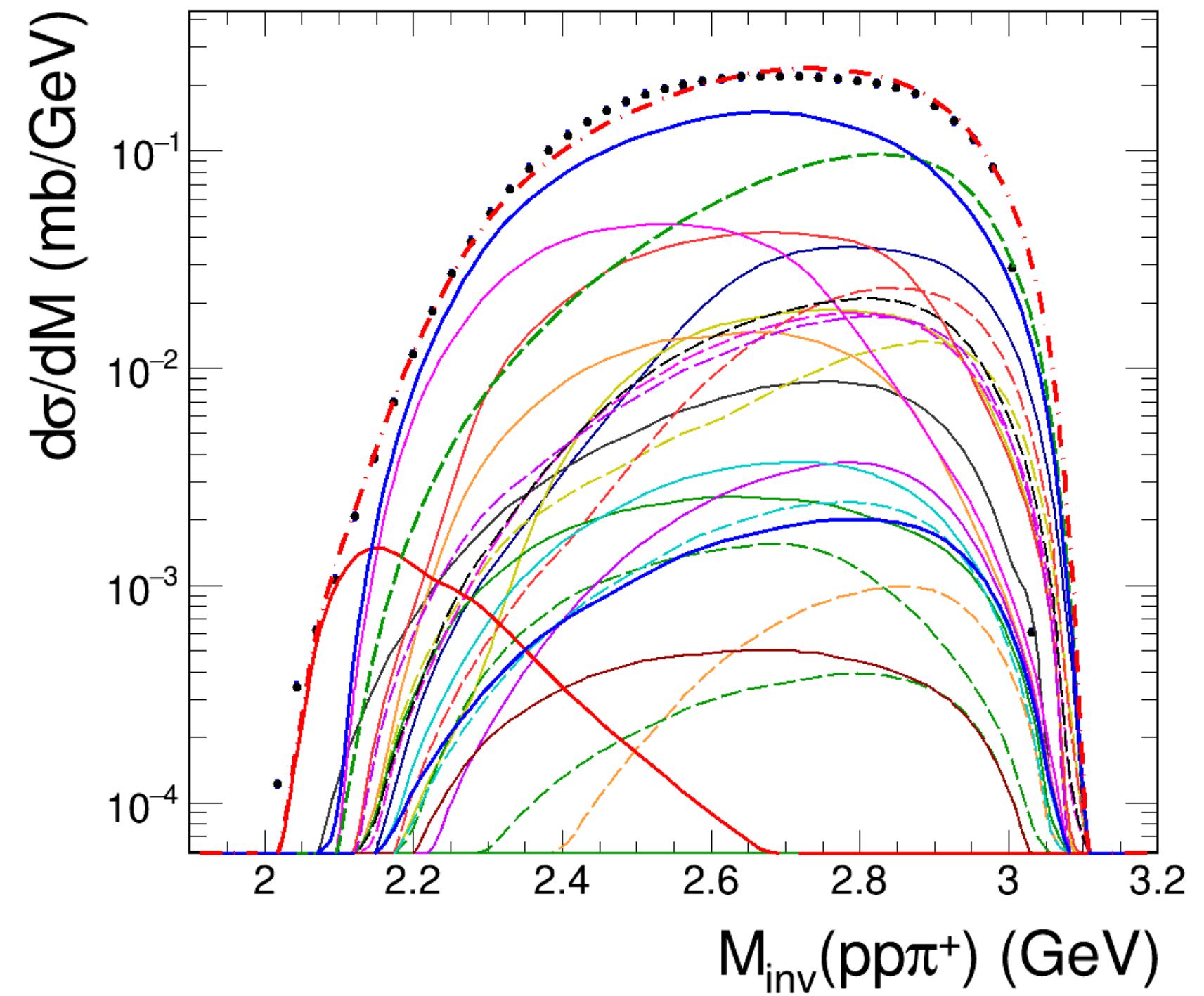
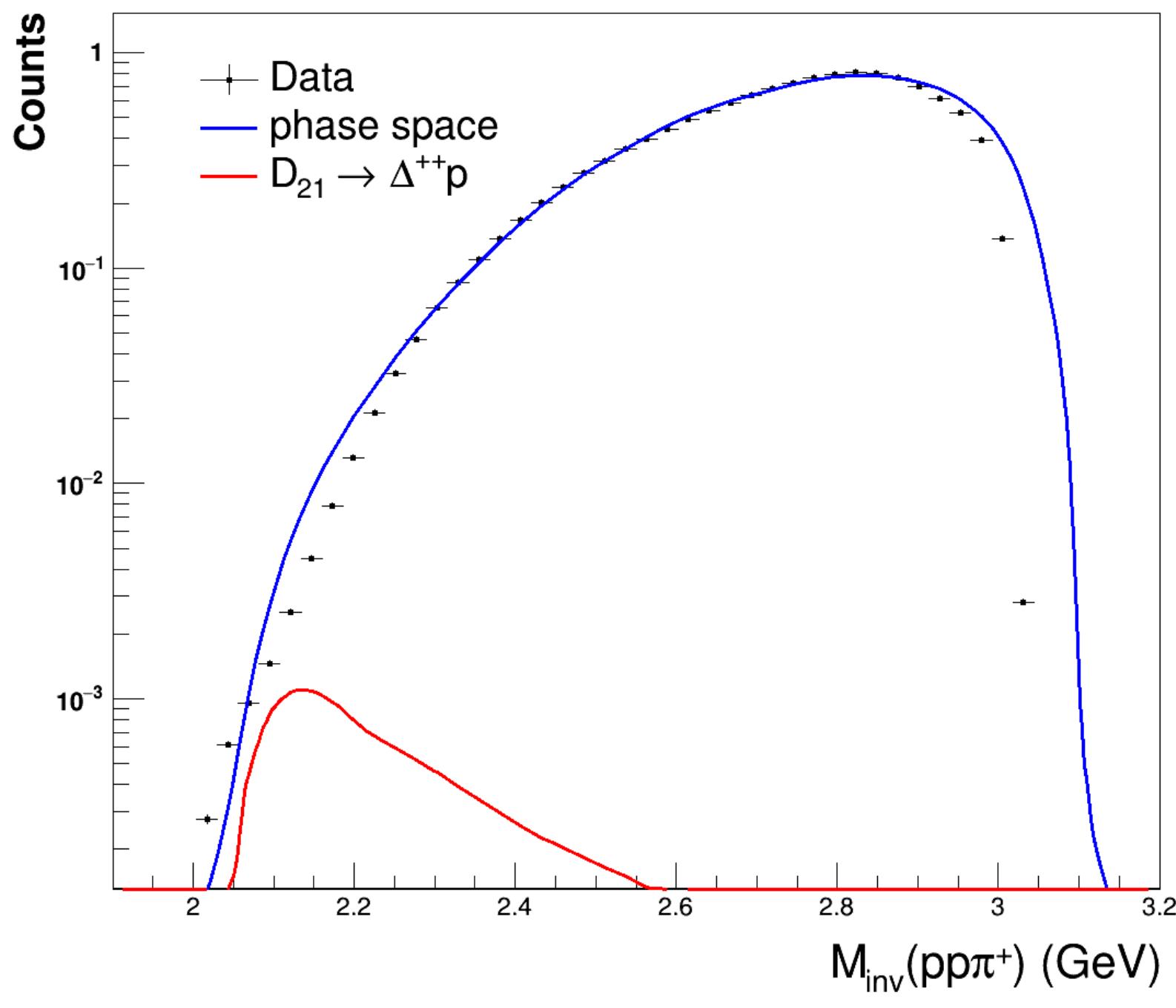
ρ signal was extracted by applying the necessary kinematical cuts.



**Thanks For
Your
Attention!**

Any questions?

Backup



$$-0.6 < \cos(p\pi^+) < 0.6$$