How to discover a particle?

$d^*(2380)$ story

Mikhail Bashkanov,   mikhail.Bashkanov@york.ac.uk

Early days: ABC effect

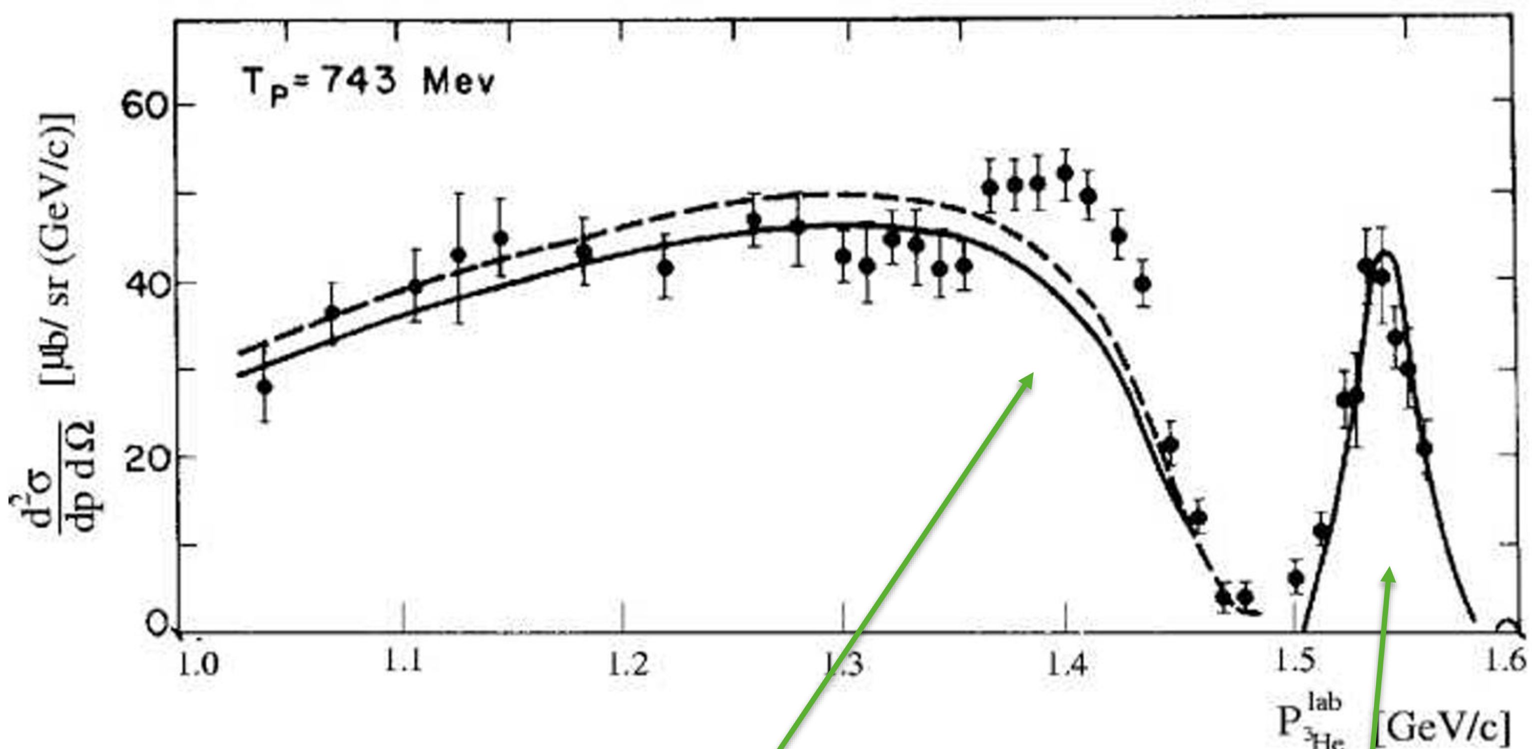
It began with the forging of the great rings.

It began with the ~~forging of the great rings.~~ ABC

It began with the ABC effect, 1960

Alexander Abashian, Norman E. Booth and Kenneth M. Crowe

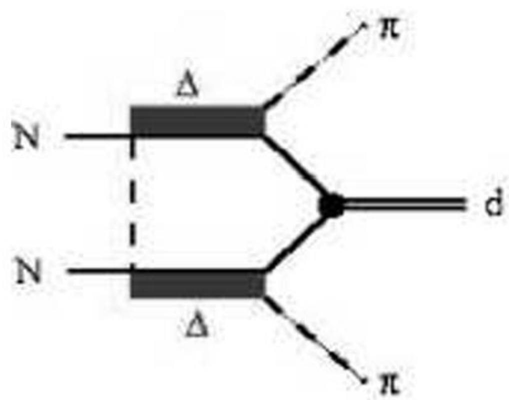
$pd \rightarrow^3 He + X$ at 0 degree

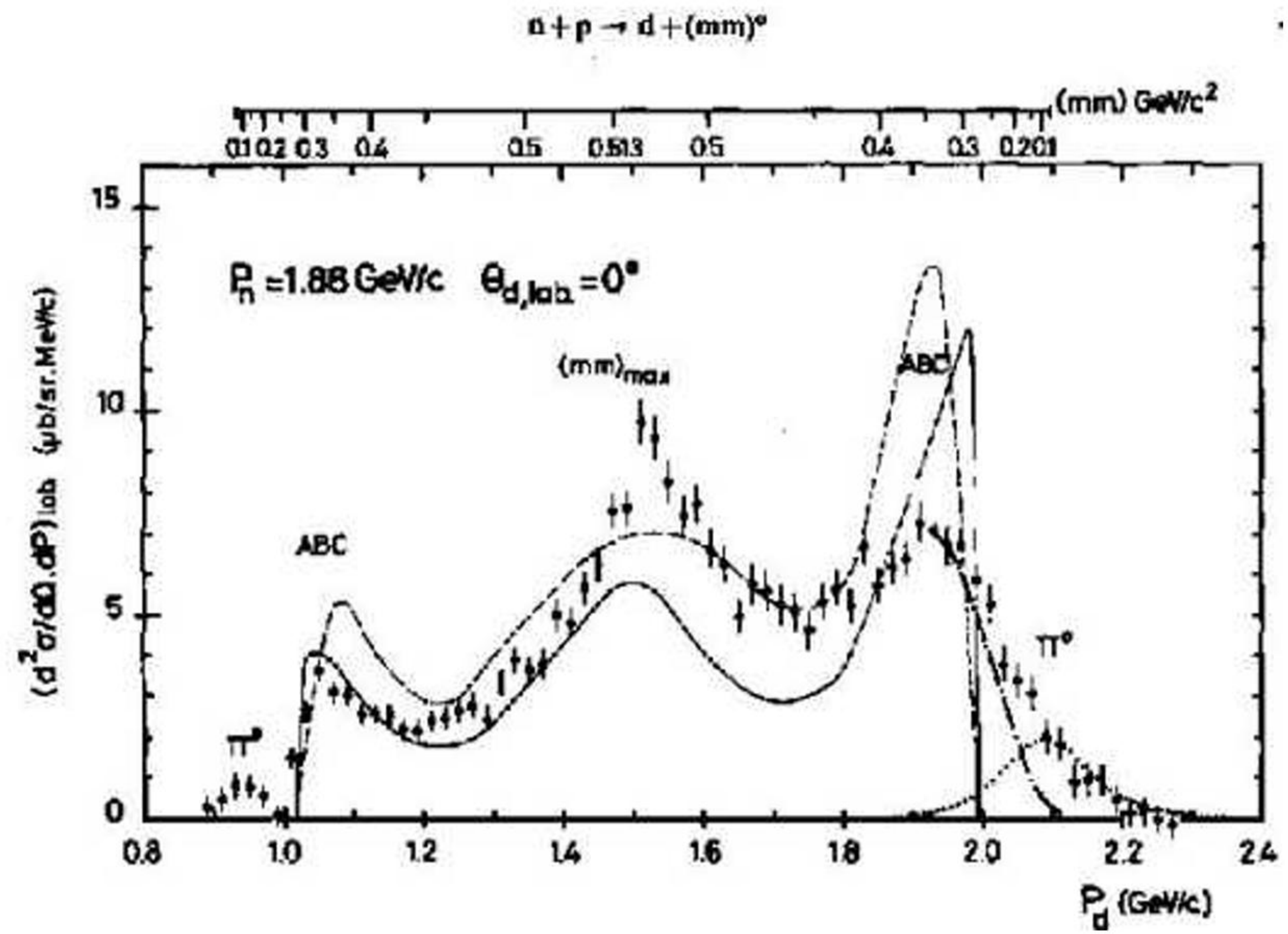


$X = \pi\pi$

$X = \pi$

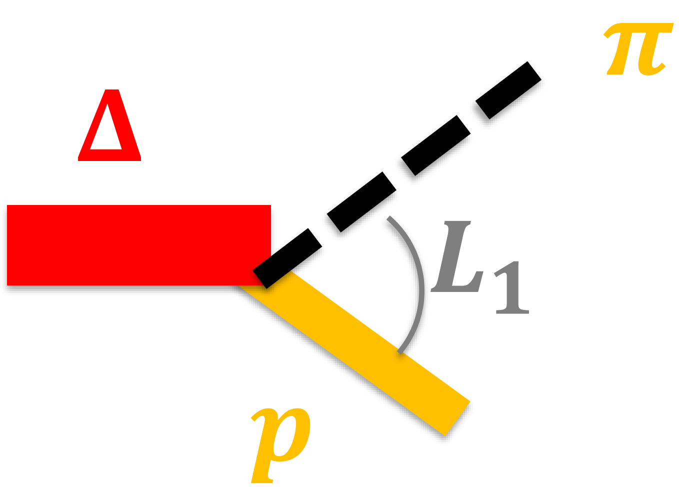
Saclay





$pn \rightarrow d + X$ at 0 degree

Total angular momentum



J – total angular momentum
L – angular momentum
S – spin
P – Parity
(S and J might be interchangeable)
Angular momentum – vector additive
Parity - multiplicative

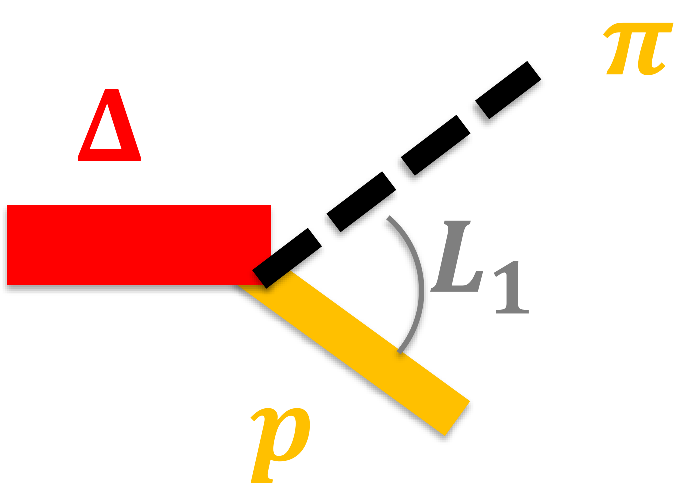
$$\overrightarrow{J_A} = \overrightarrow{S_{b_1}} + \overrightarrow{S_{b_2}} + \overrightarrow{L_1} \qquad P_A = P_{b_1} \cdot P_{b_2} \cdot (-1)^{L_1}$$

$$J^p(\Delta) = \frac{3}{2}^+ \qquad J^p(\mathrm{p}) = \frac{1}{2}^+ \qquad J^p(\pi) = 0^-$$

$$P_\Delta = P_p \cdot P_\pi \cdot (-1)^{L_1} = ?$$

$$L_1 = ?$$

Total angular momentum



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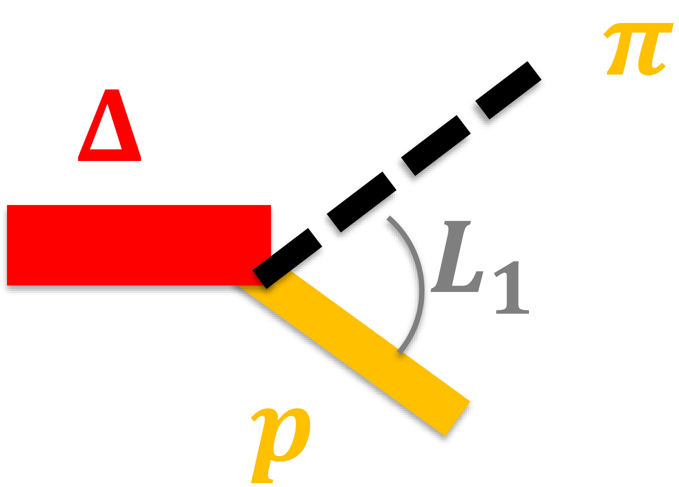
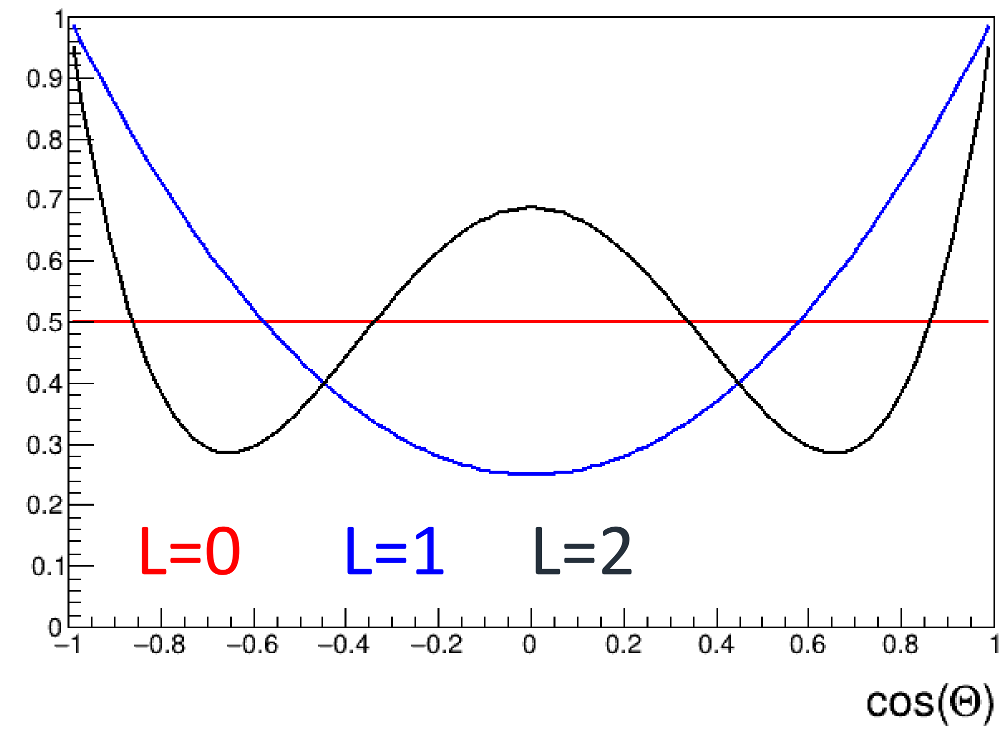
$$P_\Delta = P_p \cdot P_\pi \cdot (-1)^{L_1} = (+1) \cdot (-1) \cdot (-1)^{L_1} \text{-} \ L_1 - odd$$

$$L_1 = 1$$

Total angular momentum





$\overrightarrow{J_A} = \overrightarrow{S_{b_1}} + \overrightarrow{S_{b_2}} + \overrightarrow{L_1}$ $\qquad$ $P_A = P_{b_1} \cdot P_{b_2} \cdot (-1)^{L_1}$

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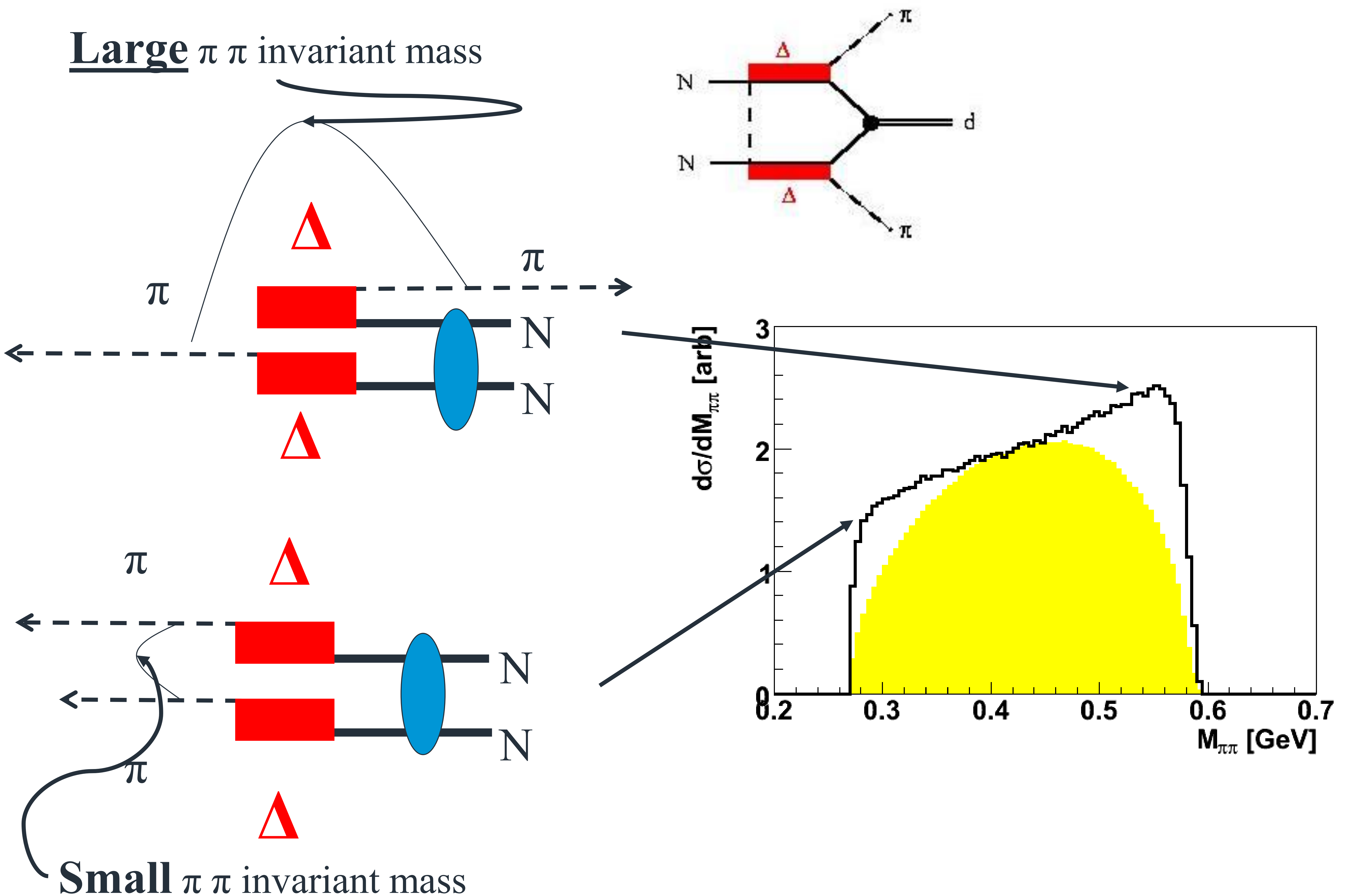
$P_\Delta = P_p \cdot P_\pi \cdot (-1)^{L_1} = (+1) \cdot (-1) \cdot (-1)^{L_1}$- $L_1 - odd$

$$L_1 = 1$$

Historical expectations



History became legend, legend became myth,

and for ~~two and a half thousand~~ forty years,

the ~~Ring~~ effect passed out of all knowledge.

Until, when chance came, it ensnared a new bearer.

History beca … *came myth,*

and for ~~two~~ … *years,*

effect

the ~~Ring~~ pas … *edge.*

Until, when … *ared a new*

bearer.

The ABC effect

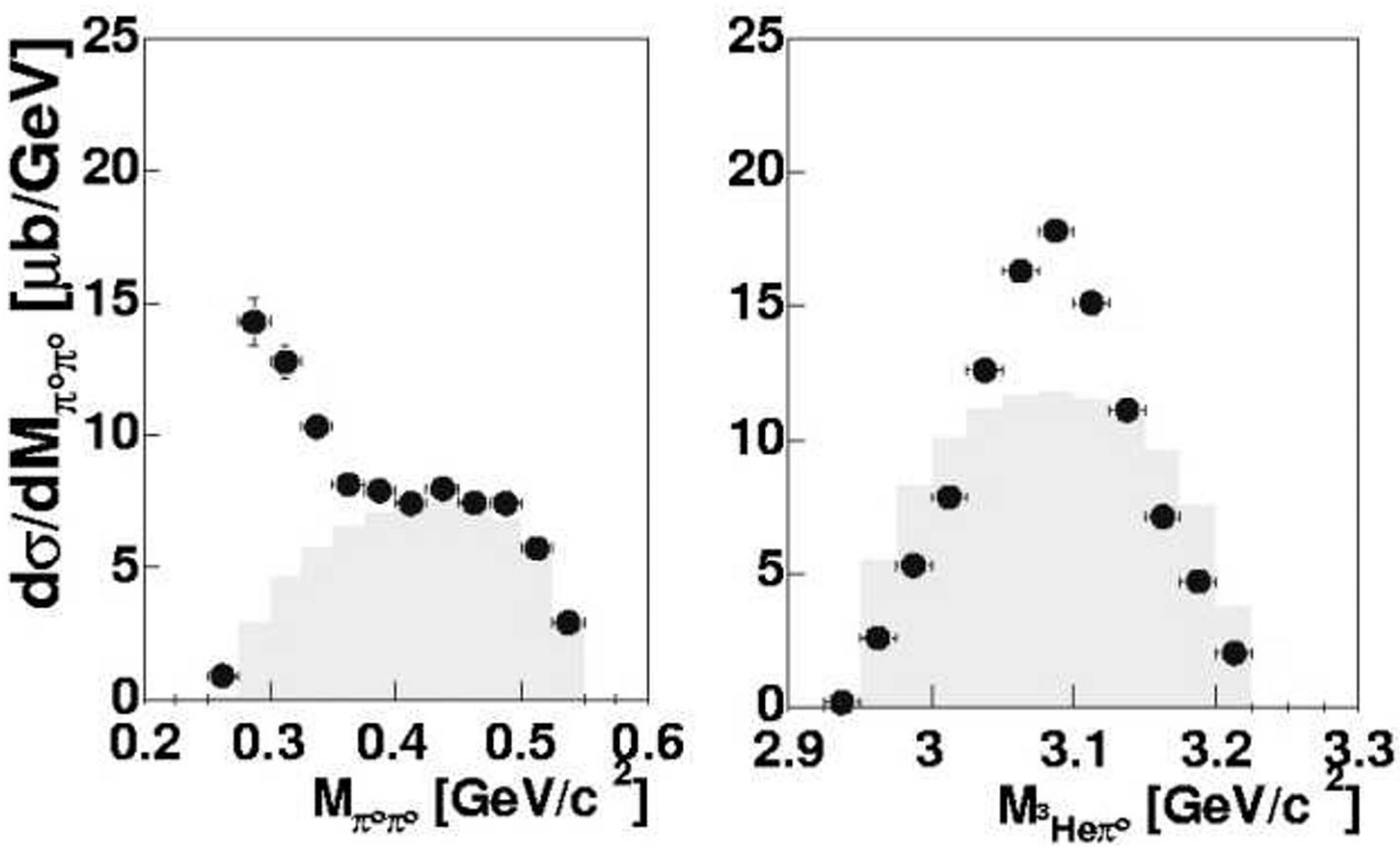
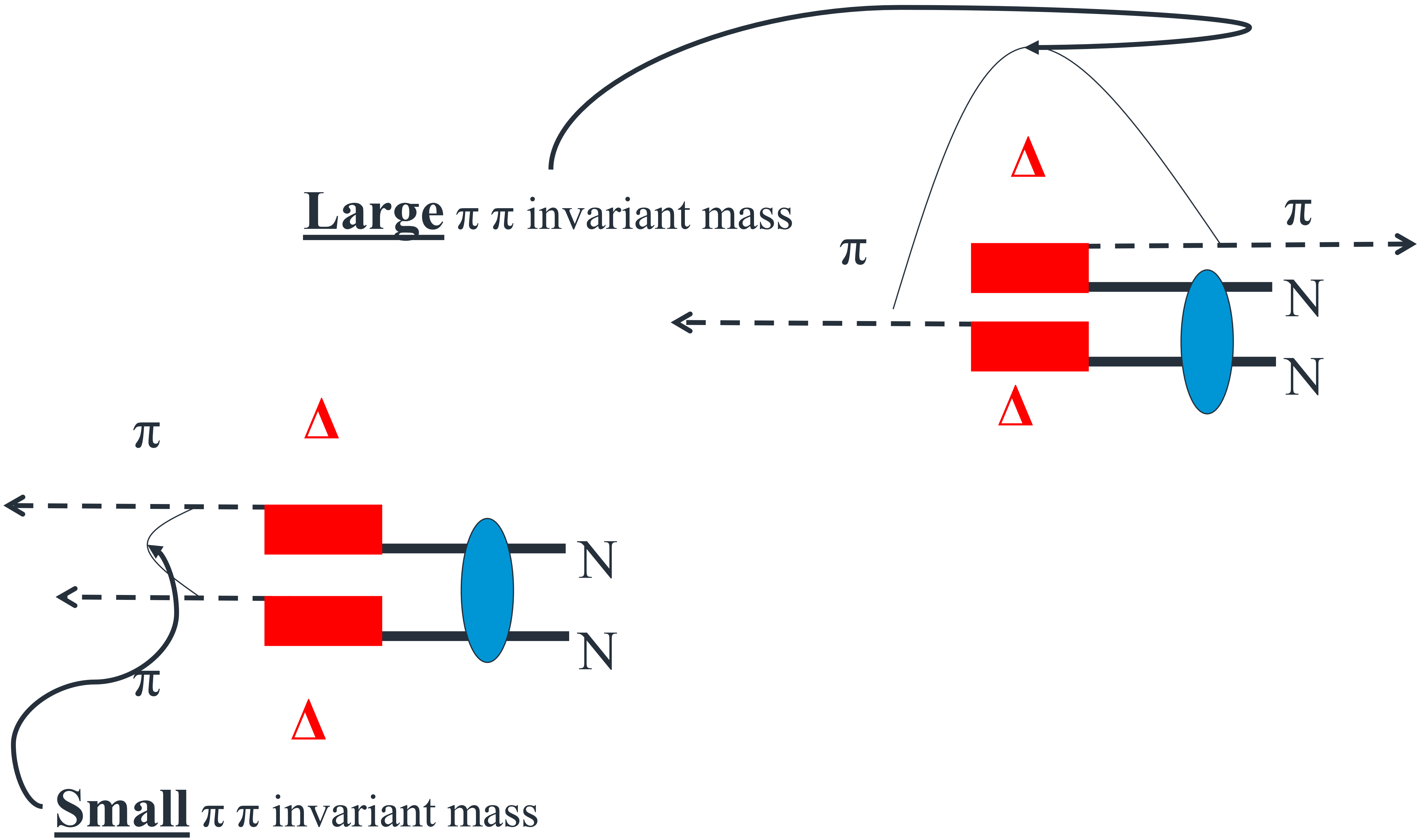


Fig. 5—5 Differential cross-section in dependence of $M_{\pi^0\pi^0}$ *(left) and* $M_{^3He\pi^0}$ *(right) for the reaction* $pd \rightarrow {}^3He\pi^0\pi^0$. *Shaded areas represent phase space distributions, in the left histogram phase space is normalized to touch the data, in the right one to equal the integral cross-section*

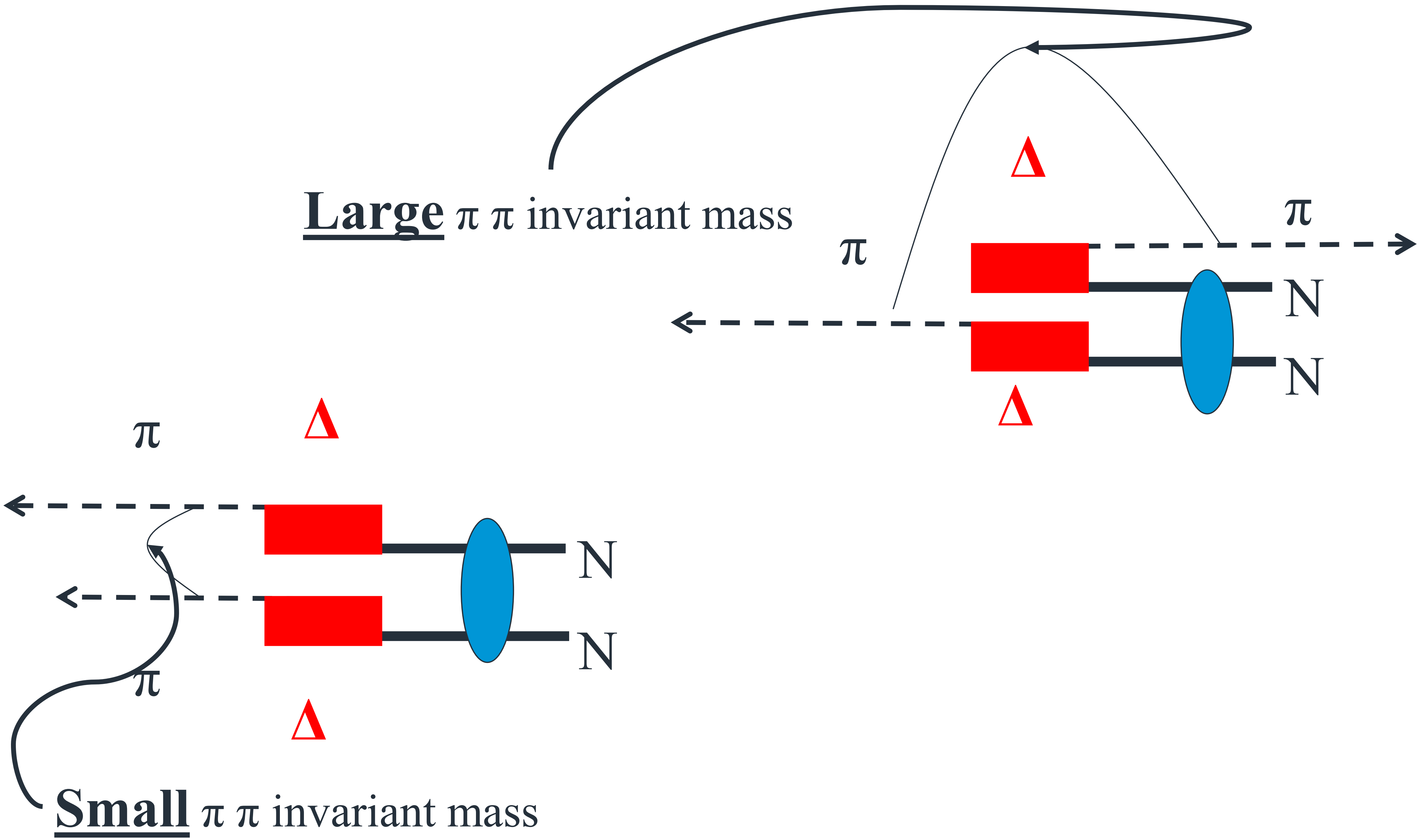
New particle

Bound ΔΔ



$$q_{\Delta\Delta} = \underline{(\vec{p}_{N_1}} + \vec{p}_{\pi_1}) - \underline{(\vec{p}_{N_2}} + \vec{p}_{\pi_2}) \approx \vec{p}_{\pi_1} - \vec{p}_{\pi_2} = q_{\pi\pi}$$

Bound ΔΔ

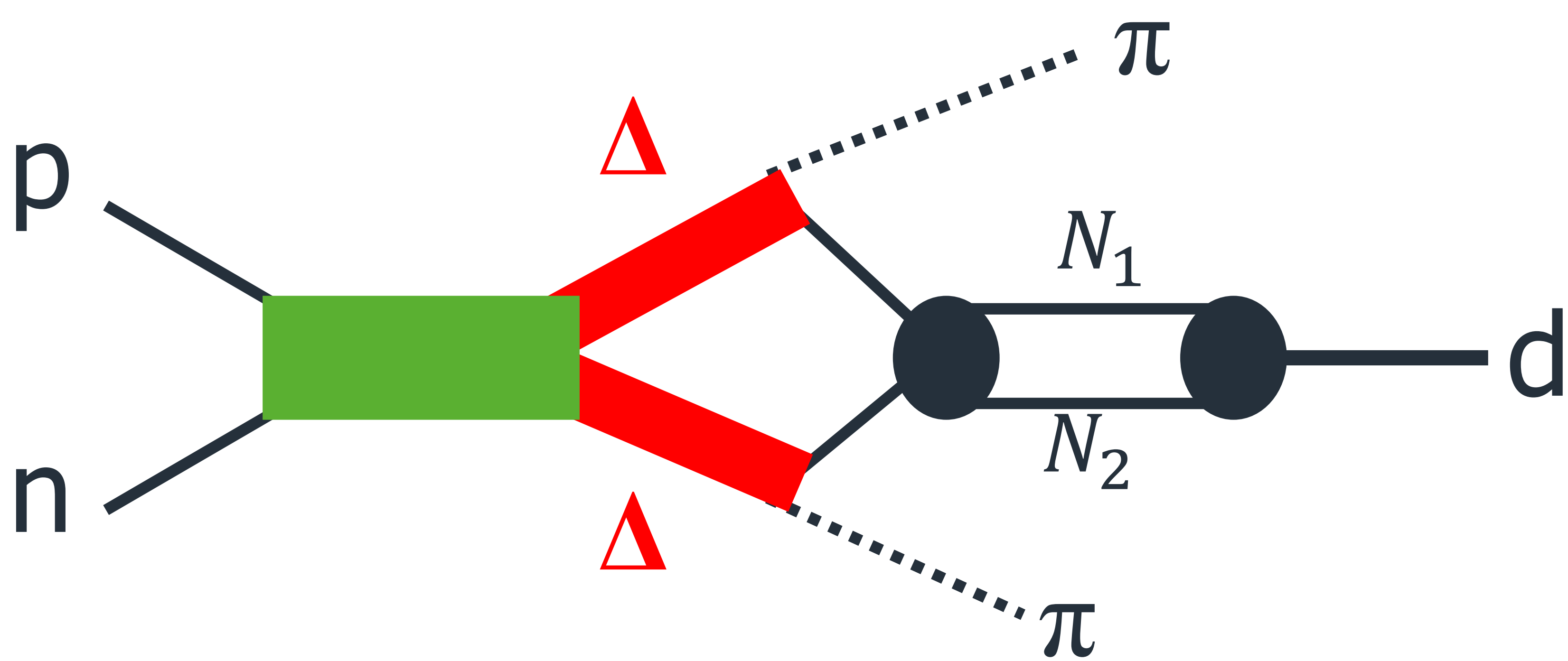


$$q_{\Delta\Delta} = (\vec{p}_{N_1} + \vec{p}_{\pi_1}) - (\vec{p}_{N_2} + \vec{p}_{\pi_2}) \approx \vec{p}_{\pi_1} - \vec{p}_{\pi_2} = q_{\pi\pi}$$

$d^* \to d\pi\pi$ decay

- pn → d* → ΔΔ → dππ

$$FF = \frac{1}{1 + \frac{q_{\Delta\Delta}^2}{\Lambda^2}}$$

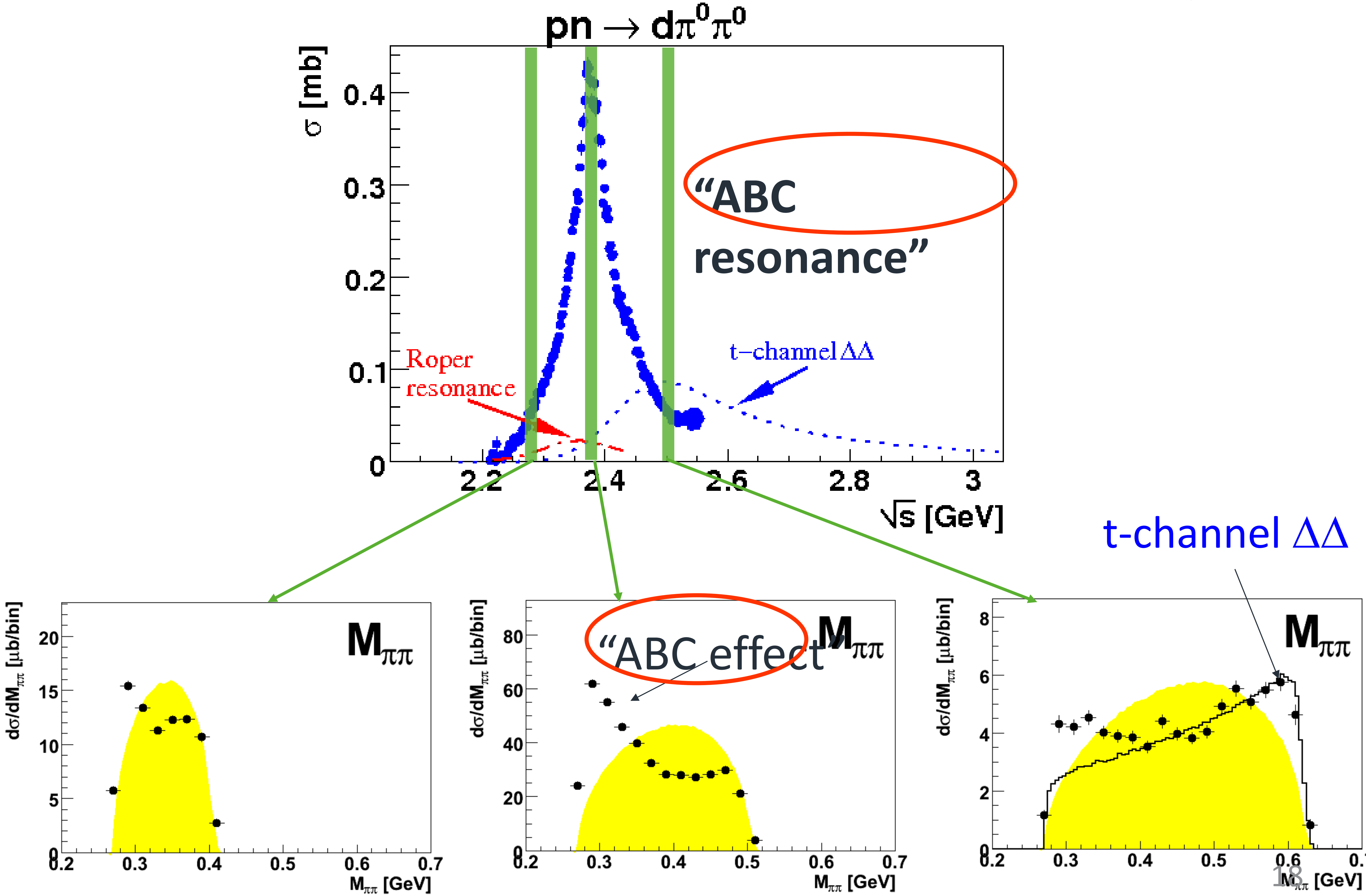


$$\overrightarrow{p_{\Delta_2}} - \overrightarrow{p_{\Delta_2}} = \left(\overrightarrow{p_{N_1}} + \overrightarrow{p_{\pi_1}}\right) - \left(\overrightarrow{p_{N_2}} + \overrightarrow{p_{\pi_2}}\right) = \left(\overrightarrow{p_{N_1}} - \overrightarrow{p_{N_2}}\right) + \left(\overrightarrow{p_{\pi_1}} - \overrightarrow{p_{\pi_2}}\right) \approx \left(\overrightarrow{p_{\pi_1}} - \overrightarrow{p_{\pi_2}}\right)$$

$$\overrightarrow{p_{N_1}} \approx \overrightarrow{p_{N_1}}$$

$$\overrightarrow{p_{\Delta_2}} - \overrightarrow{p_{\Delta_2}} \approx \left(\overrightarrow{p_{\pi_1}} - \overrightarrow{p_{\pi_2}}\right) \leftrightarrow M_{\pi\pi}$$

ΔΔ resonance



Quantum numbers of the structure

$pn \rightarrow R \rightarrow d\ \pi^0\pi^0$

Antisymmetrization: $J^p=1^+$ or 3^+ : if $L_{\Delta\Delta}=0$

$$\sigma(\cos\Theta_d^*) = \overbrace{\underbrace{D_0P_0 + D_2P_2}_{1^+} + D_4P_4 + D_6P_6}^{}$$

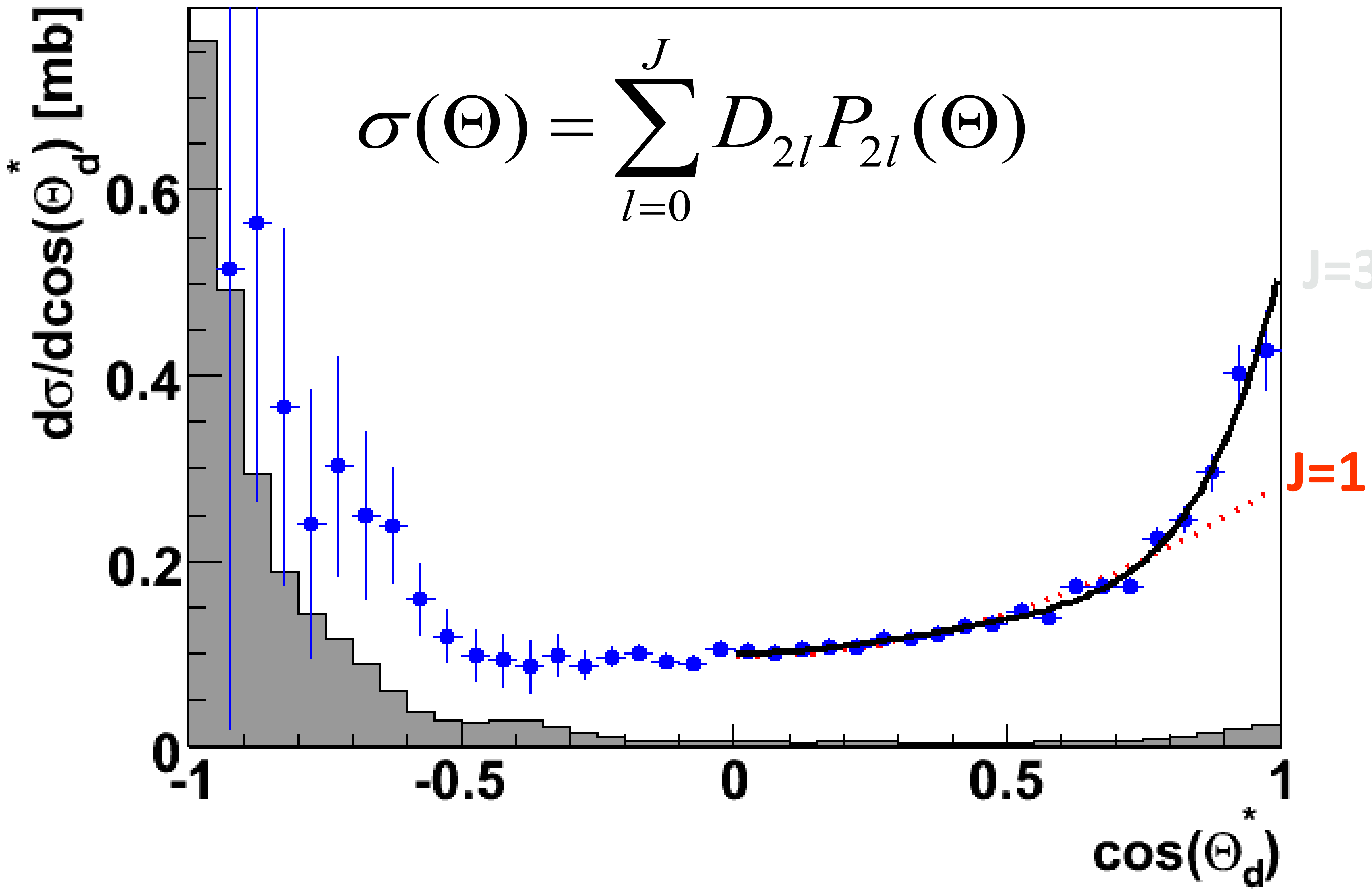
$$\underbrace{D_0P_0 + D_2P_2 + D_4P_4 + D_6P_6}_{\boxed{3^+}}$$

1^+ excluded by $\sigma(\Theta)$.

3^+ assigned

$$\left.\underbrace{pn}_{I=0,1} \rightarrow \underbrace{d}_{I=0}\ \underbrace{\pi^0\pi^0}_{I=0,2}\right\} \Rightarrow \boxed{I=0}$$

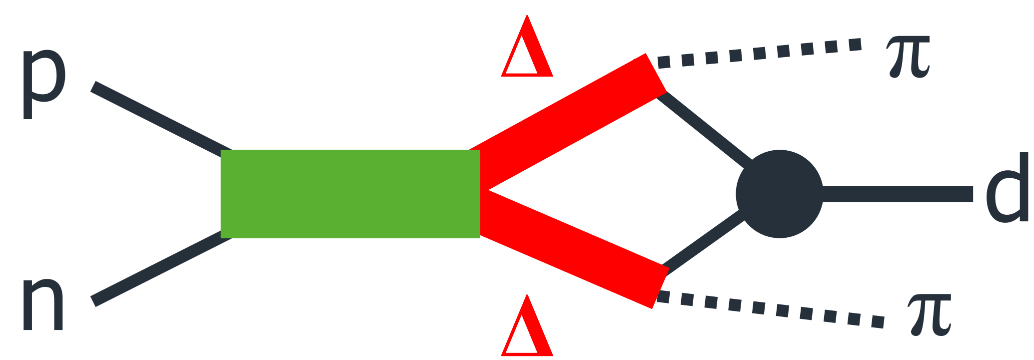
Angular distribution in the peak



The new particle

$d^*(2380)$

pn → **dibaryon** → ΔΔ → $d\pi^0\pi^0$



I(J^p) = 0(3^+)

$$M_{d^*} = 2.38\,GeV \approx 2M_\Delta - 80\,MeV$$

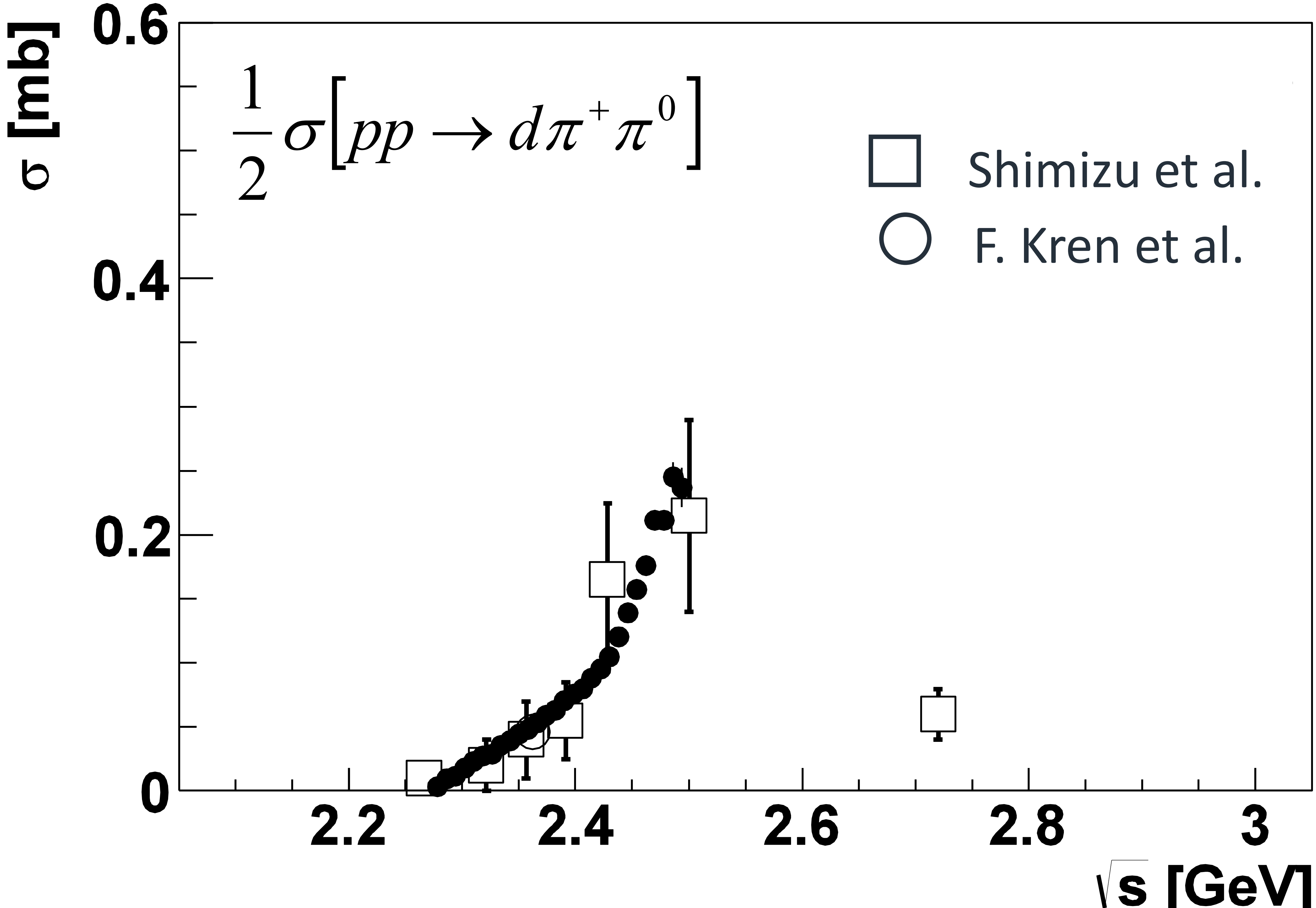
$$\Gamma_{d^*} = 70\text{ MeV} \ll \Gamma_{\Delta\Delta} = 240\,MeV$$

Enemies: **“probably effect of $\pi^0\pi^0$ - should not be in $\pi^+\pi^-$”**

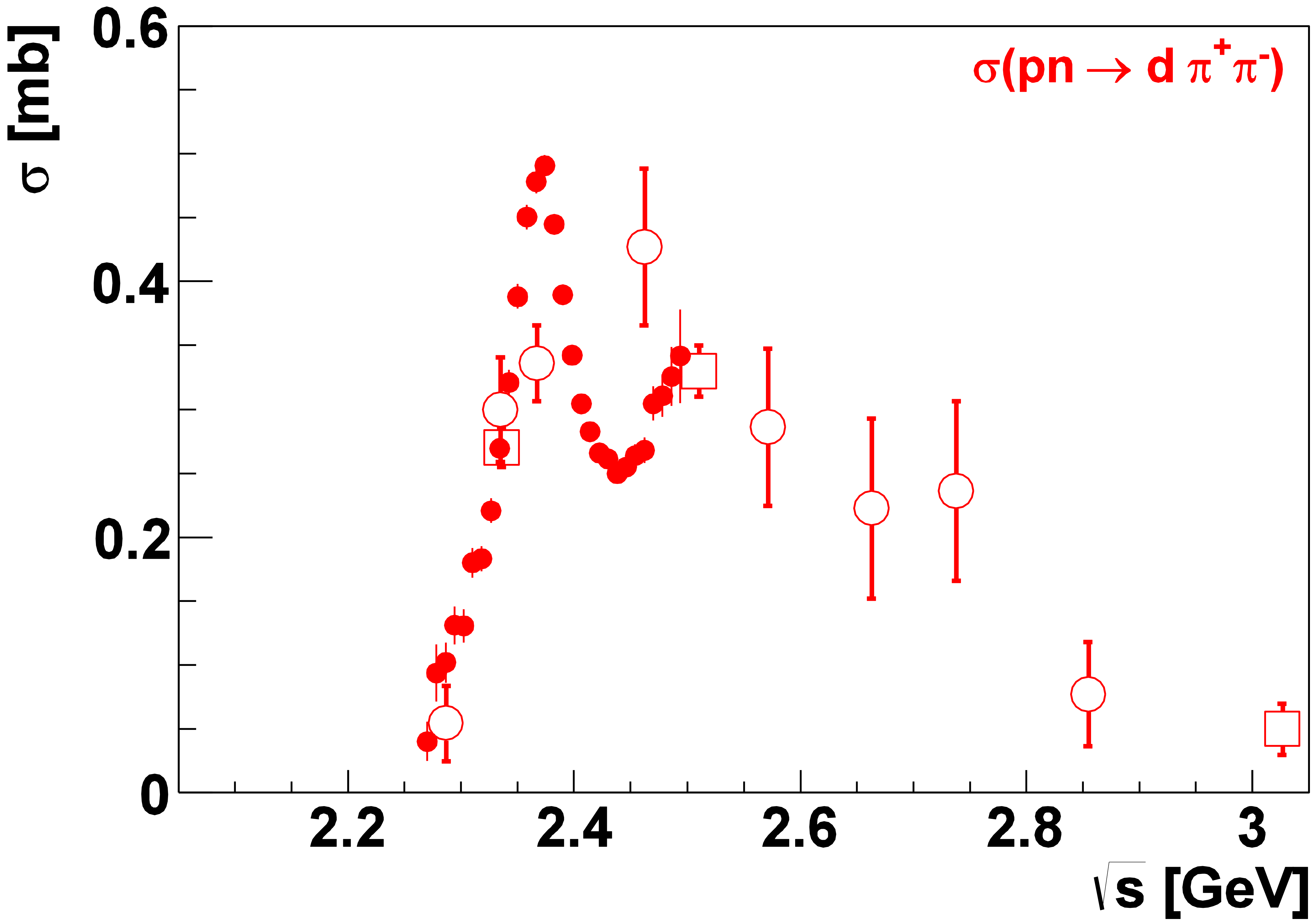
Isospin relations

$$\sigma[pn \to d\pi^+\pi^-] = \overbrace{\frac{1}{2}\sigma[pp \to d\pi^+\pi^0]}^{I=1} \underbrace{+2\sigma[pn \to d\pi^0\pi^0]}_{I=0}$$

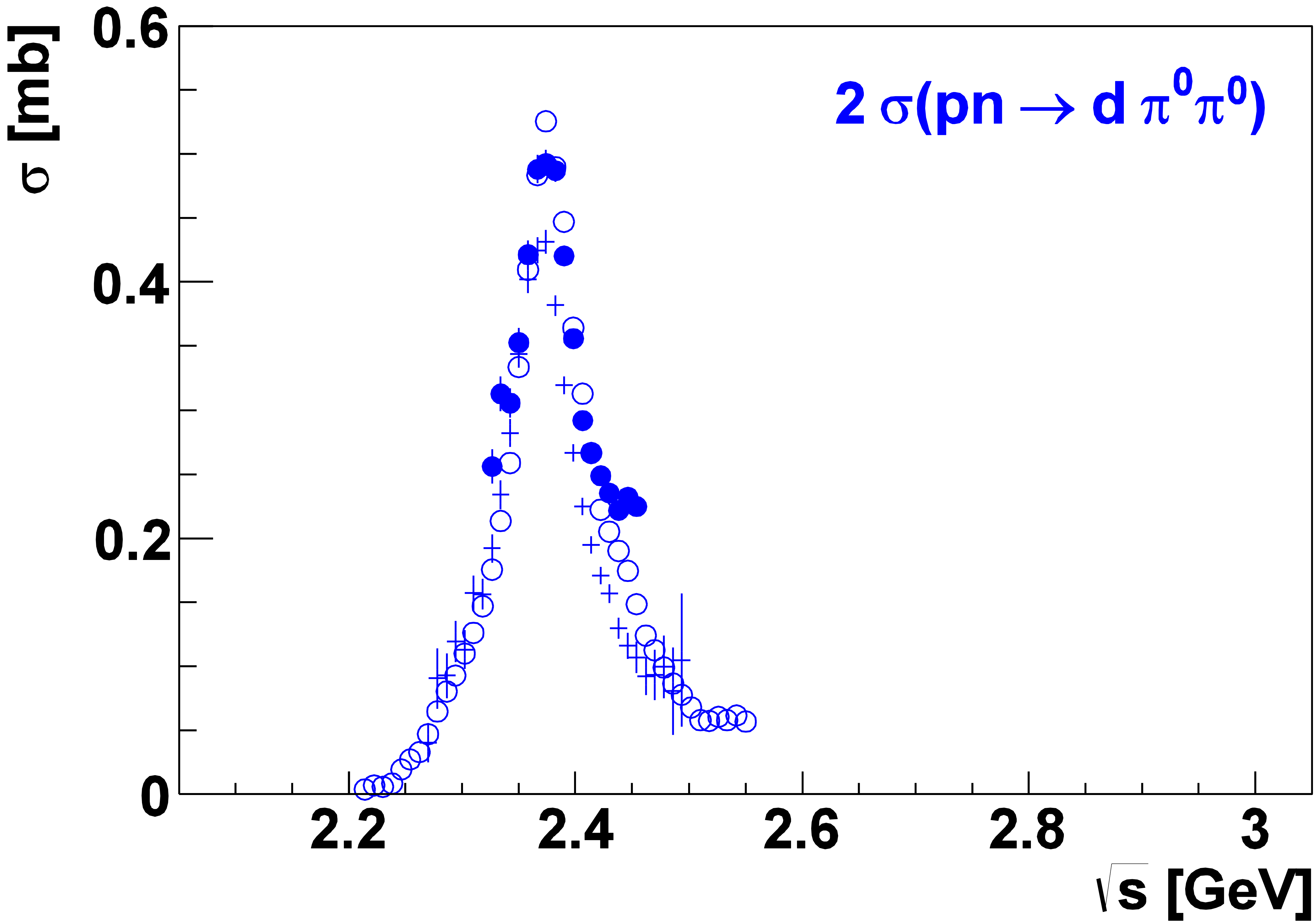
Total cross section pp → $d\pi^+\pi^0$



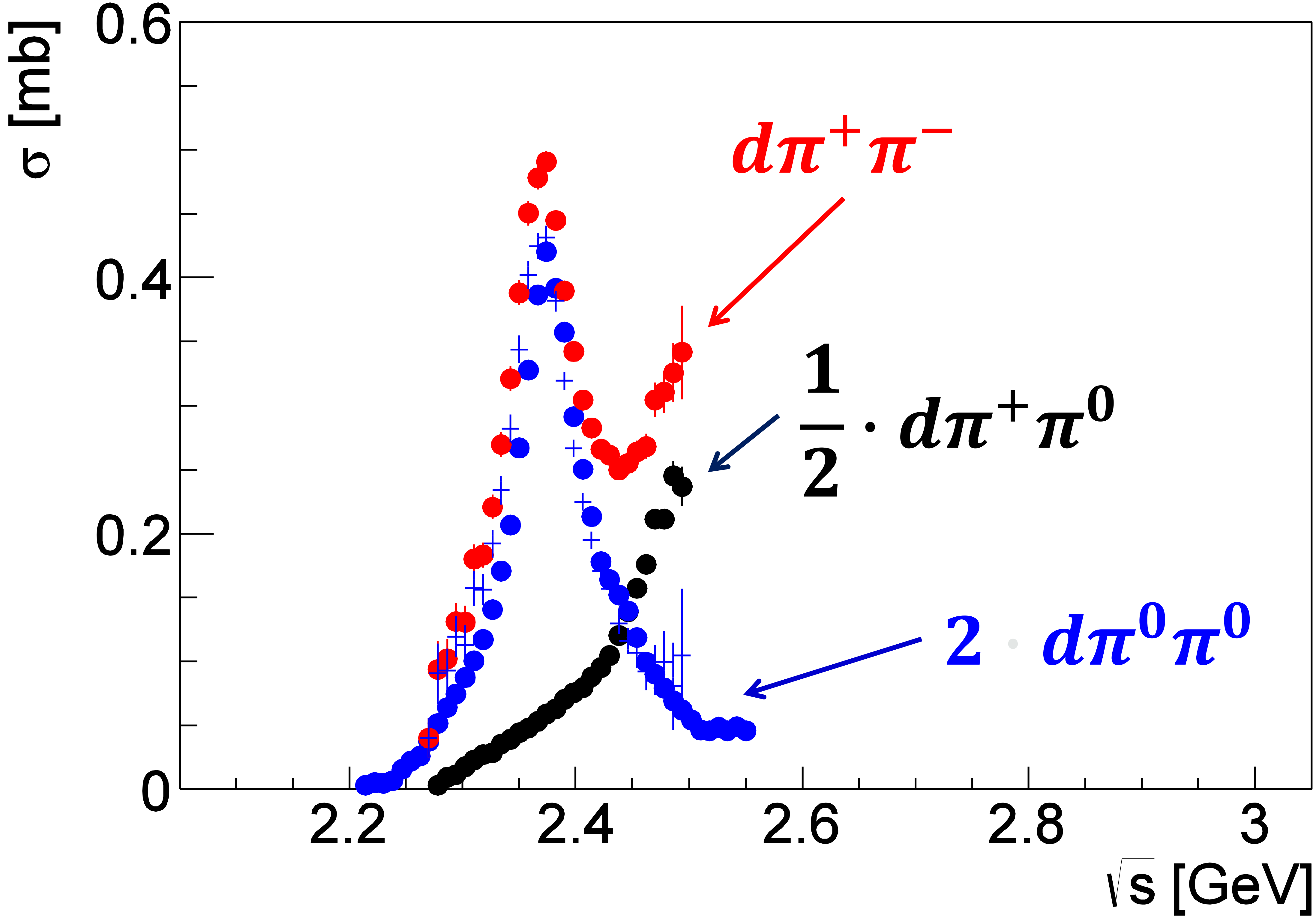
Total cross section $pn \to d\pi^+\pi^-$



Total cross section $pn \rightarrow d\pi^0\pi^0$

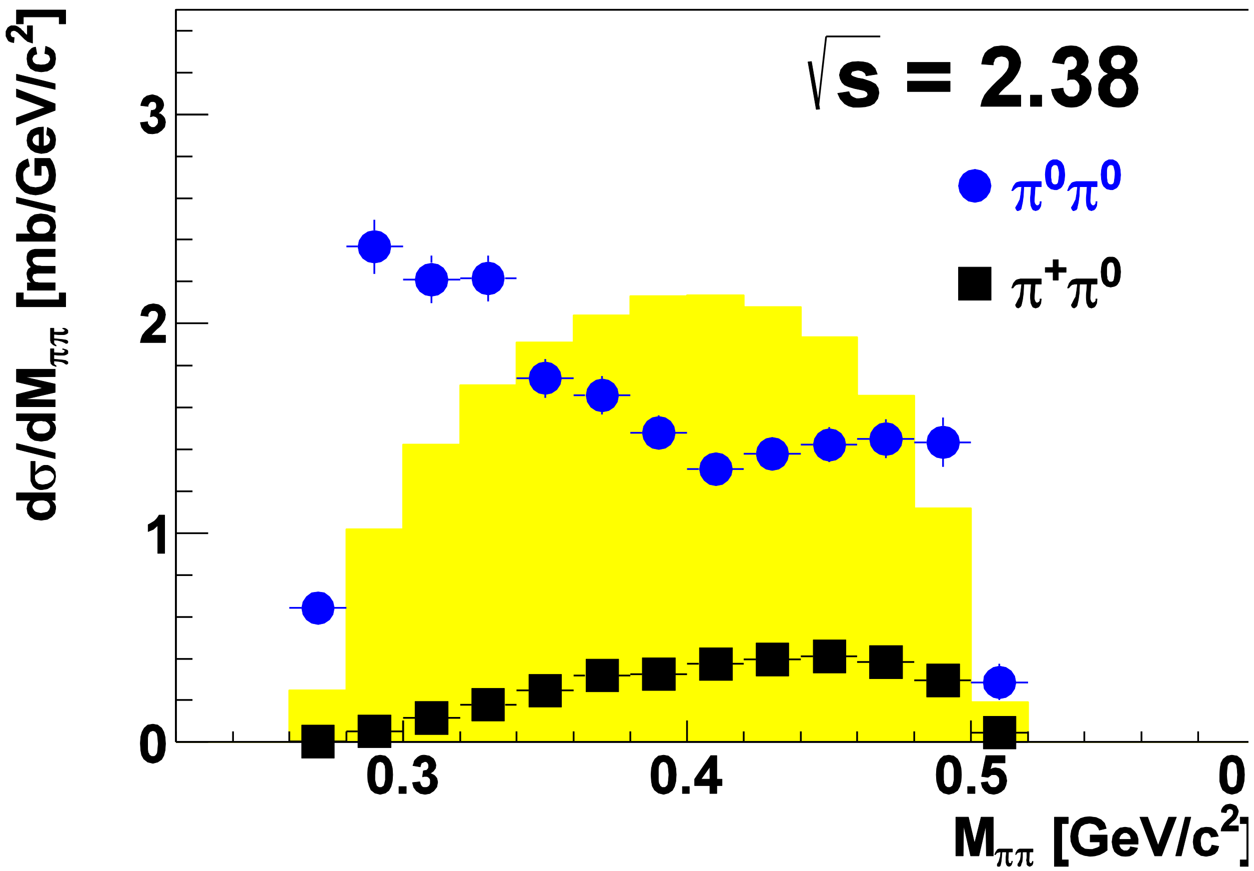


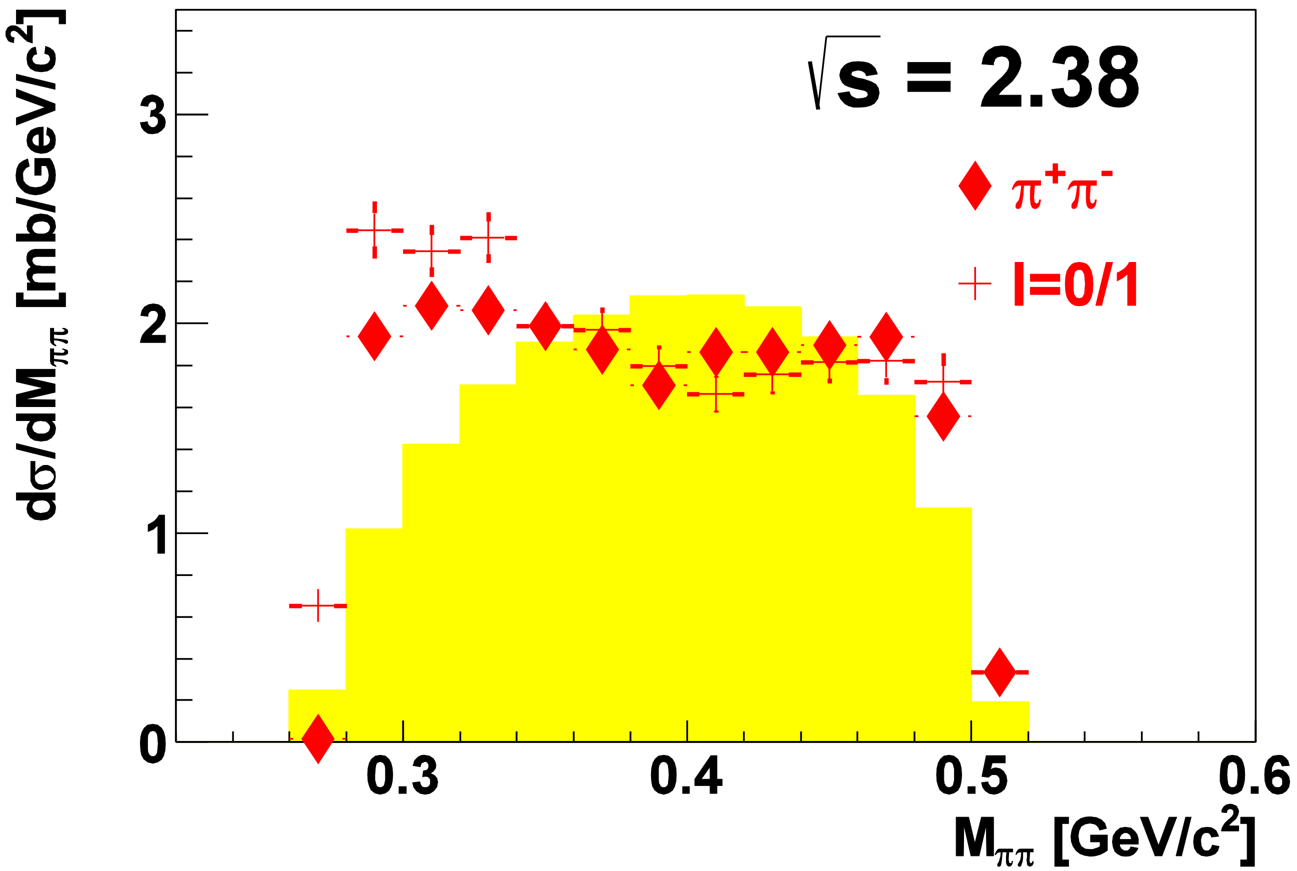
Total cross section $pN \rightarrow d\pi\pi$



P. Adlarson et. Al arXiv:1212.2881

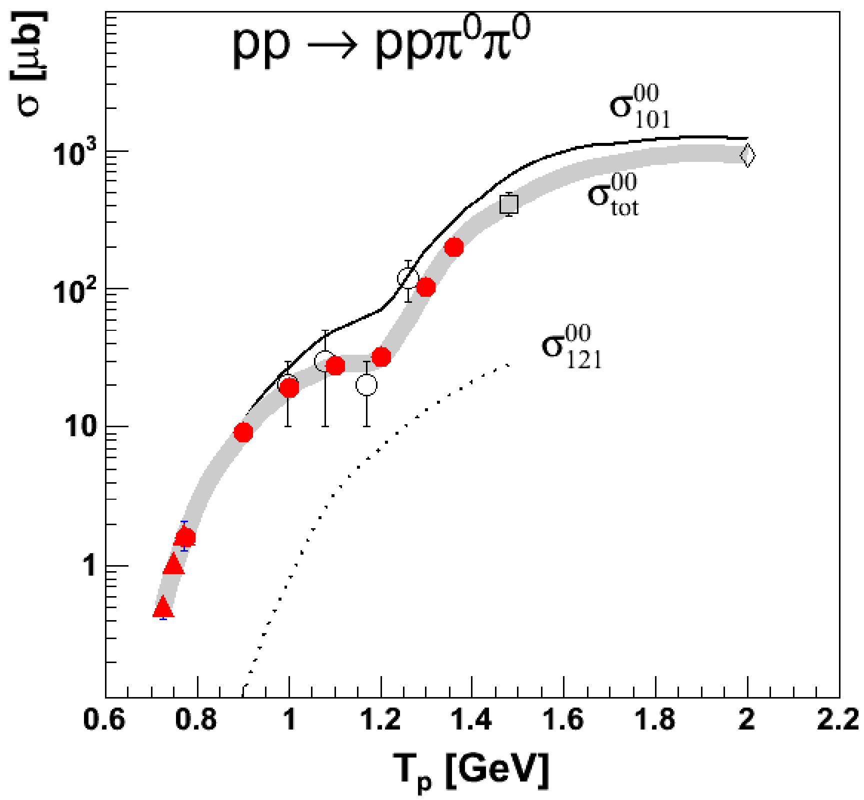
$\mathcal{M}_{\pi\pi}$ in pN $\rightarrow$ d$\pi\pi$

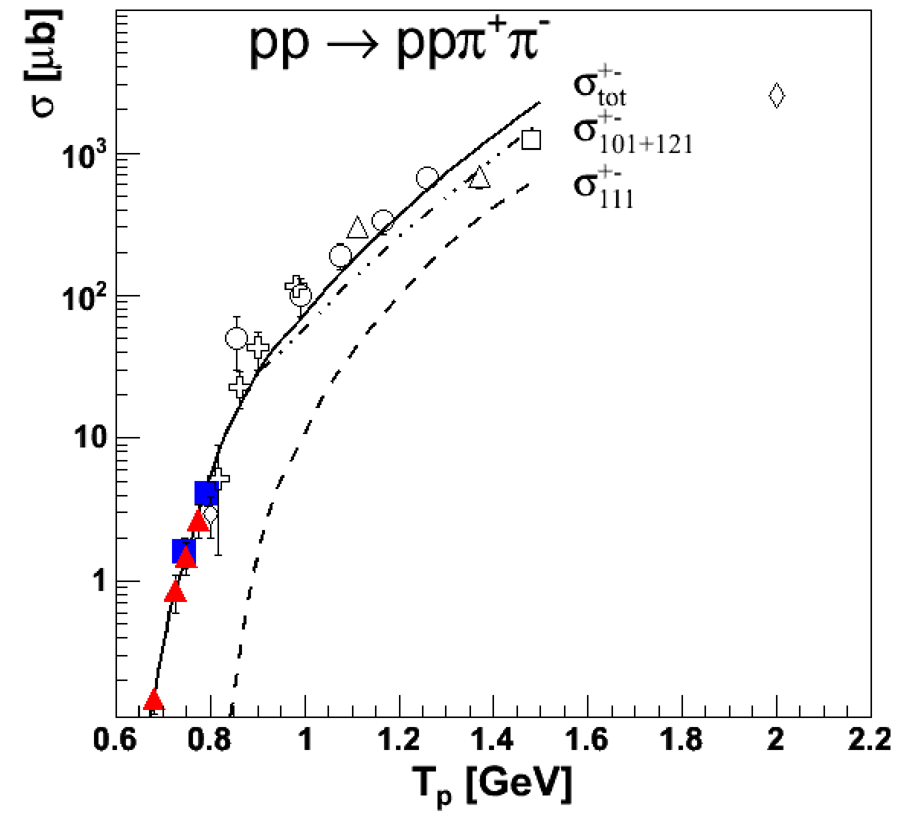




Enemies: **“probably effect deuteron - should not be in open channel”**

Isospin Decomposition

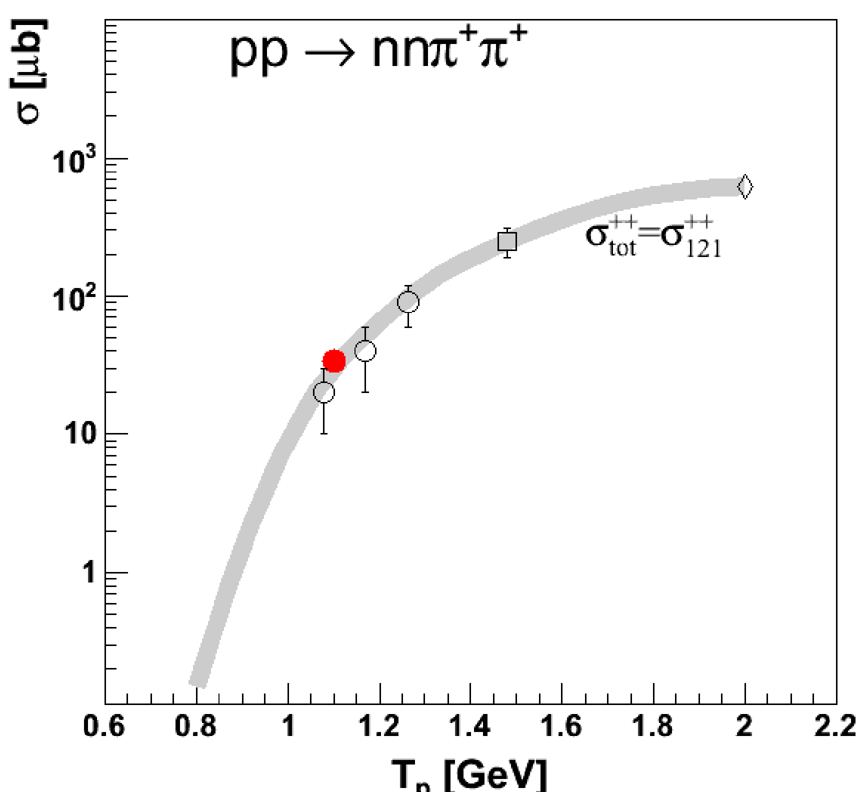


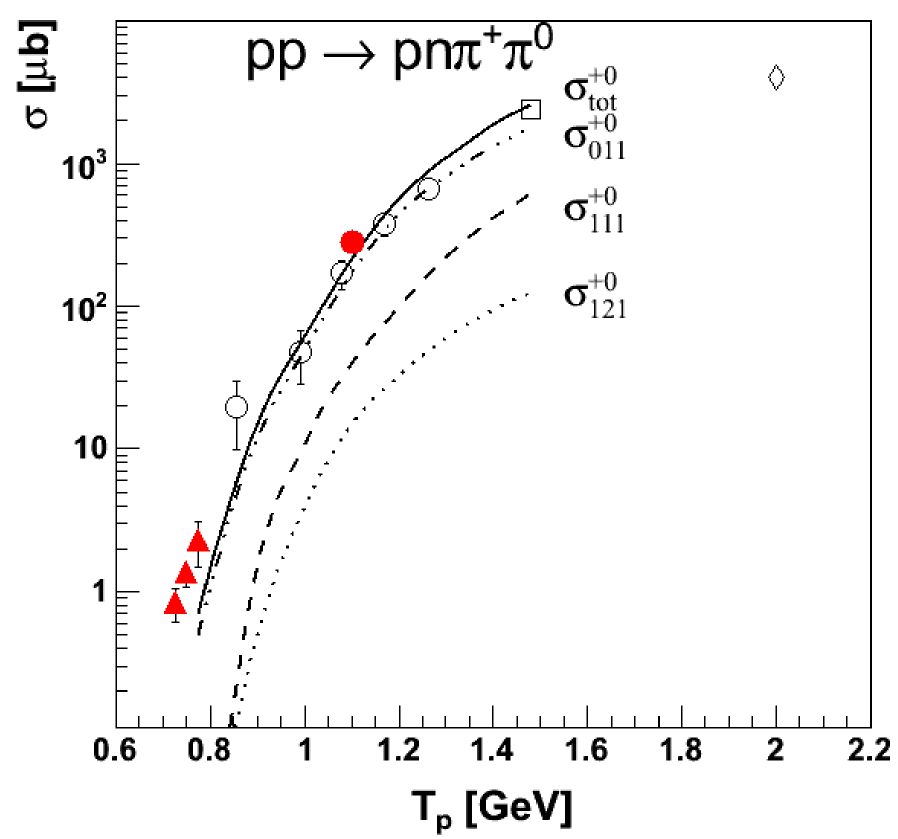


N*(1440)

ΔΔ

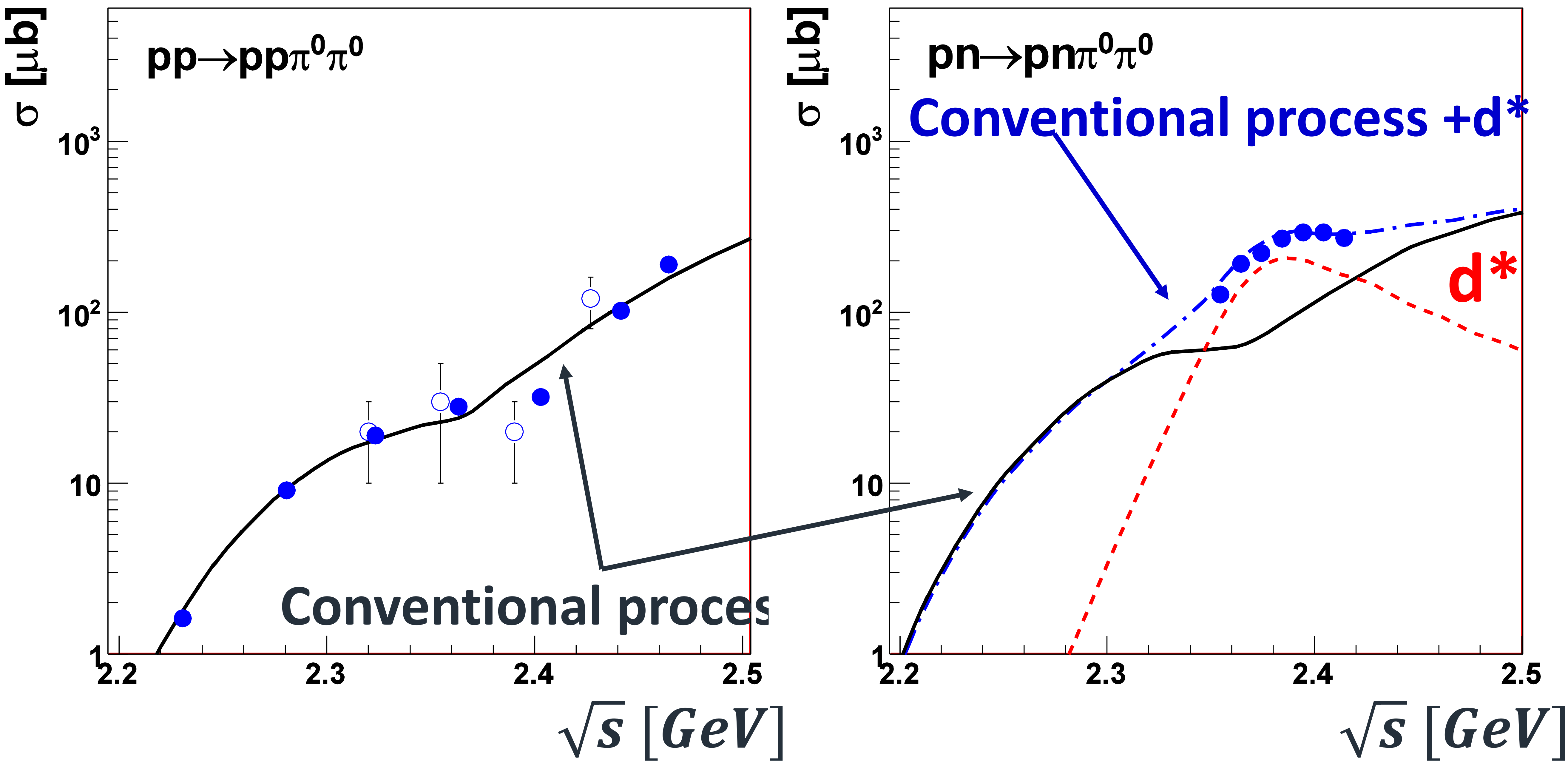
[Δ(1600)]





Skorodko at al., Phys. Lett. B**679** (2009) 30

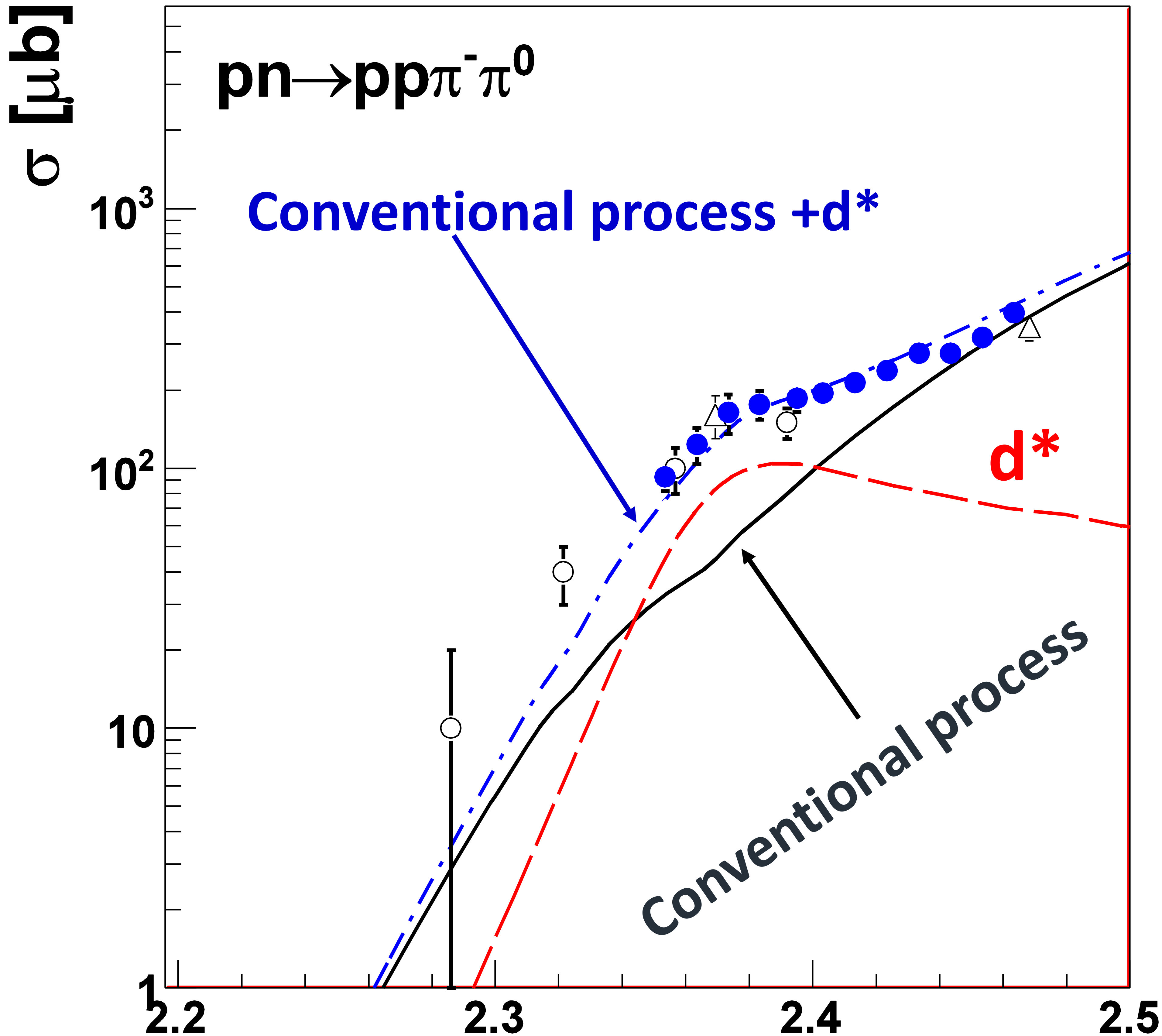
$pn \rightarrow pn\pi^0\pi^0$



P. Adlarson et al., arXiv:1409.2659

Enemies: **“not a proof – it’s just broken deuteron”**

$pn \to pp\pi^-\pi^0$



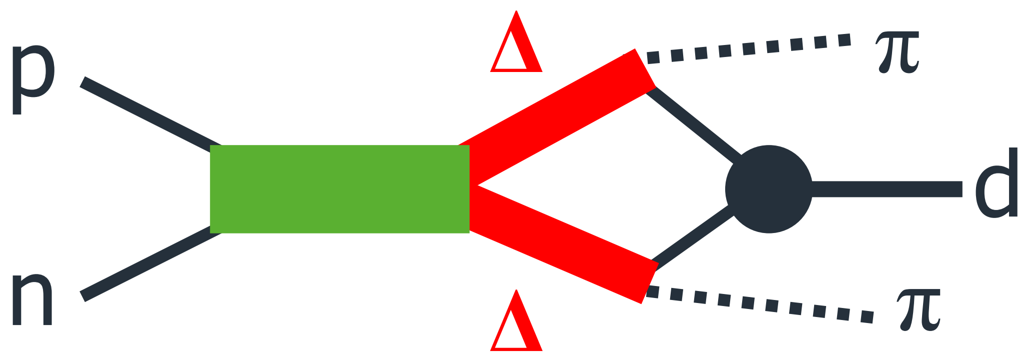
$\sqrt{s}\ [GeV]$

P. Adlarson et al., Phys. Rev. C 88, 055208 (2013).

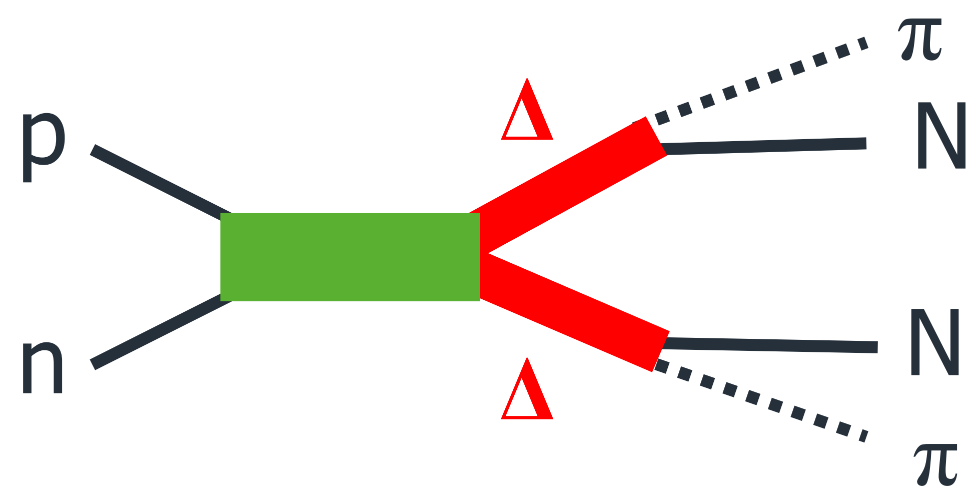
Enemies: **“probably related to $\pi\pi$ dynamics – nobody saw it in elastic”**

From ΔΔ to pn decay

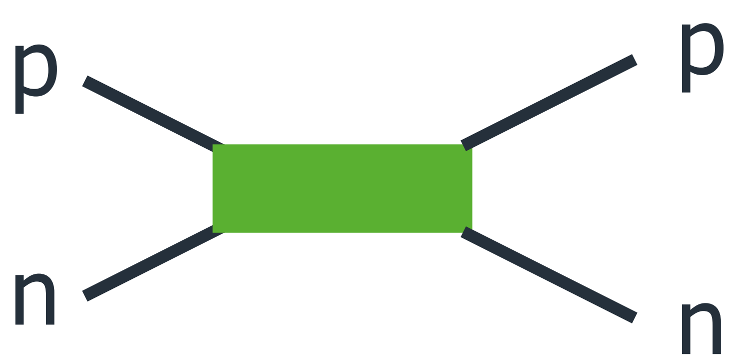
$pn \to d^* \to \Delta\Delta \to d\pi\pi$



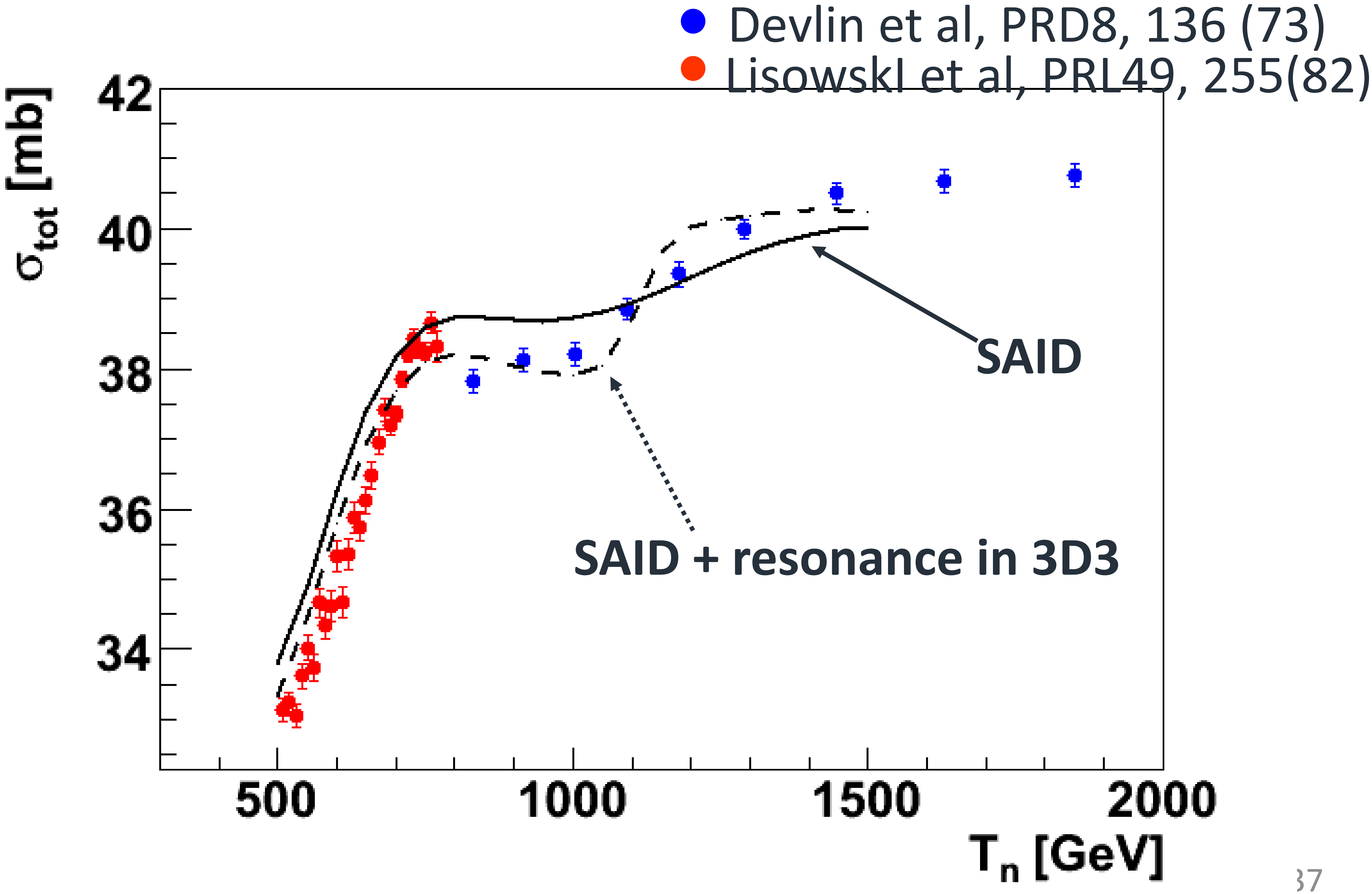
- $pn \to d^* \to \Delta\Delta \to NN\pi\pi$



- $pn \to d^* \to pn$

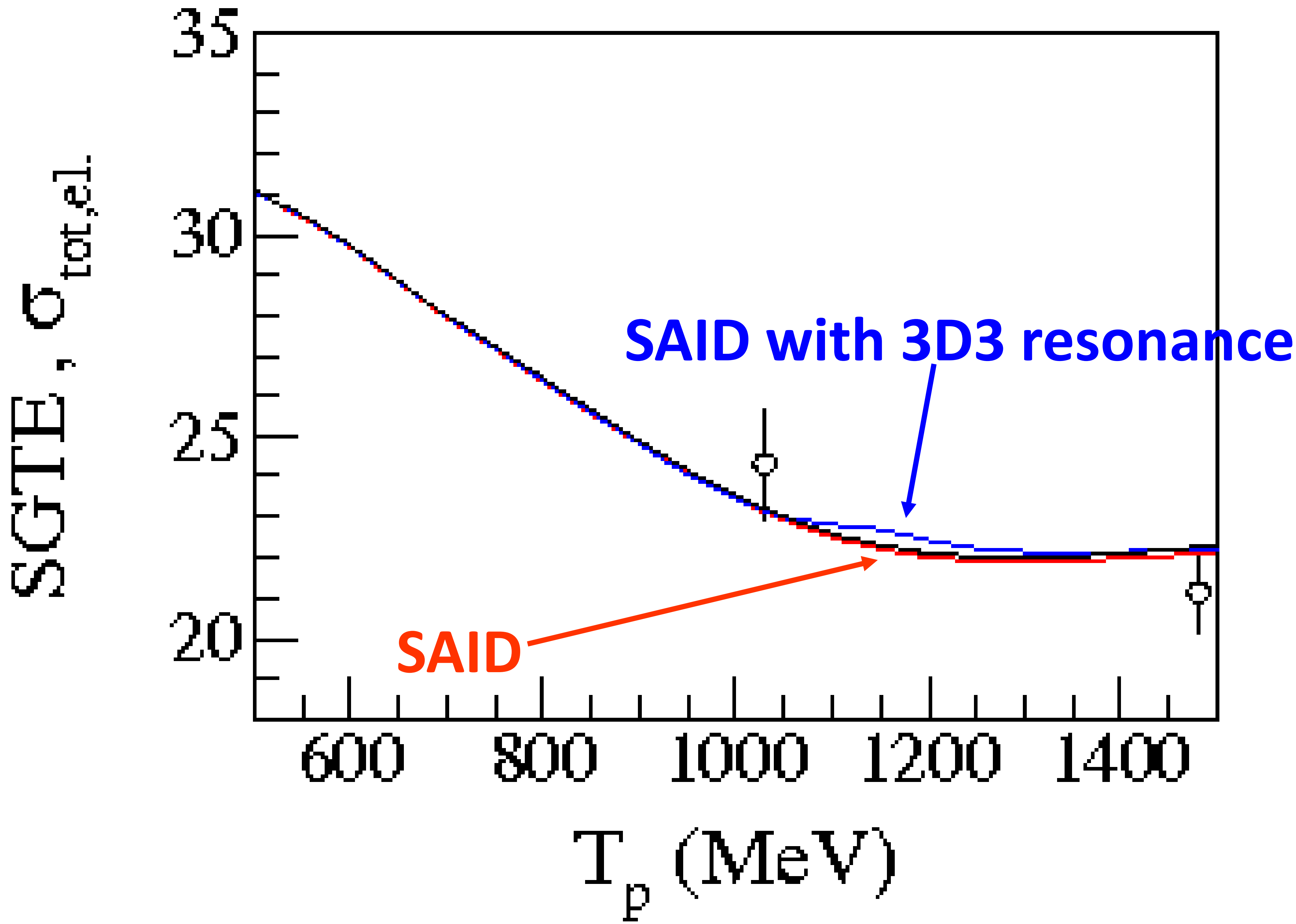


Total pn cross-section



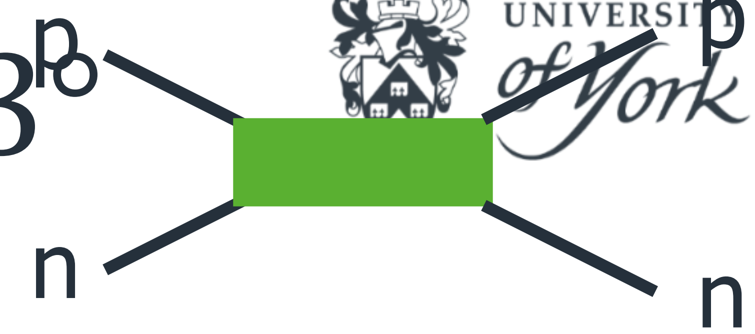
Expectations

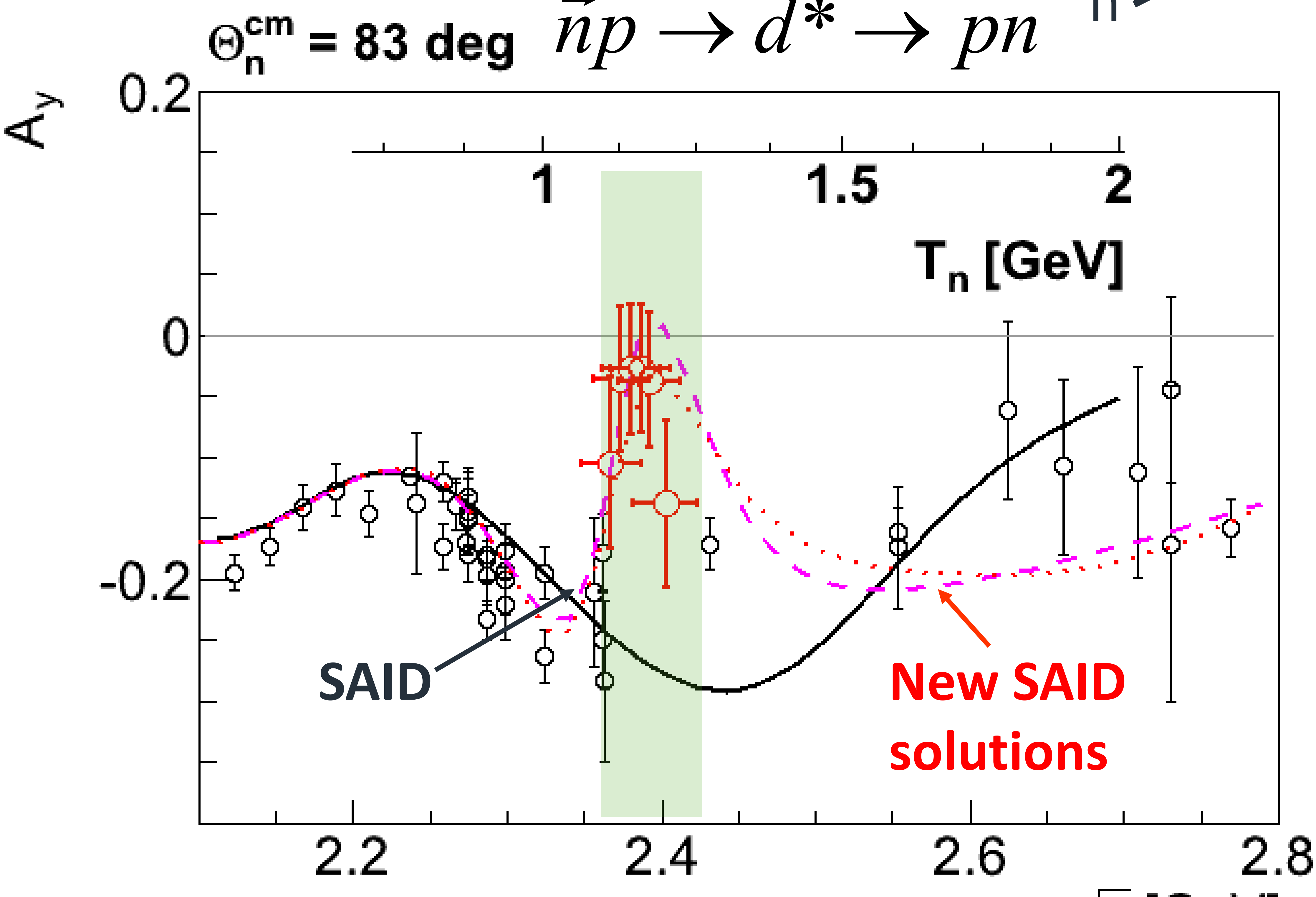
$$pn \to R \to pn$$



A_y energy dependence at 83°

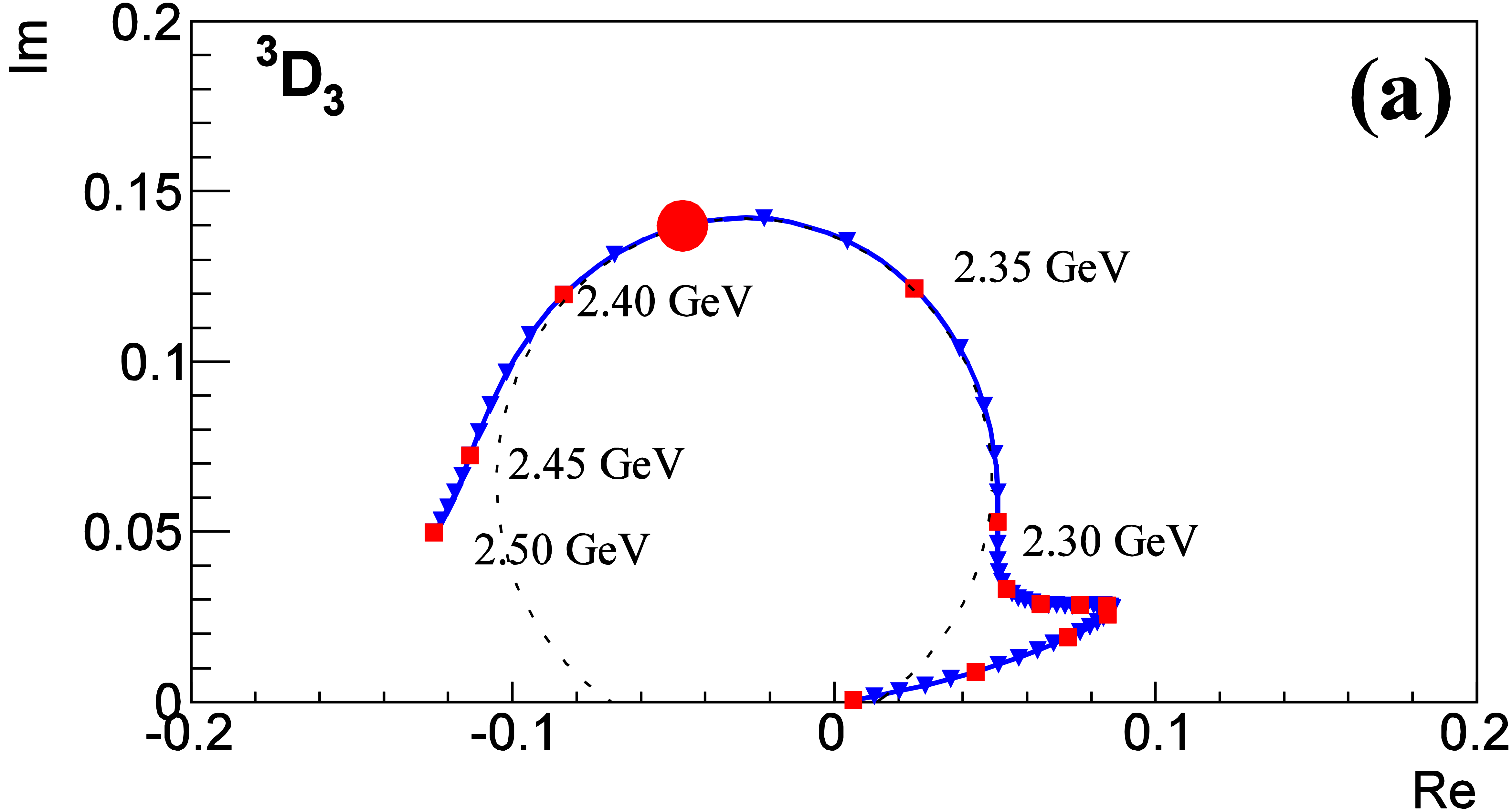
$\vec{n}p \rightarrow d^* \rightarrow pn$





P. Adlarson et al. Phys. Rev. Lett. **112**, 202301 (2014)

Argand plot

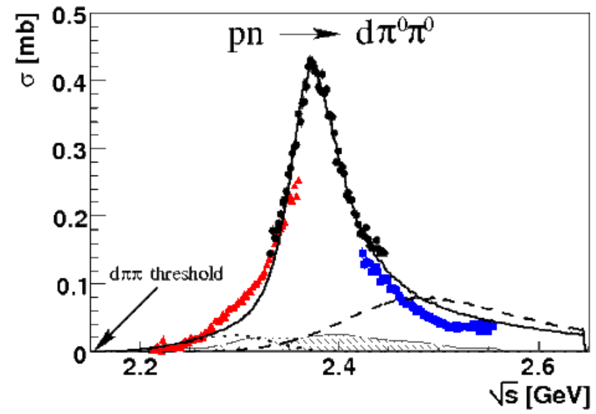


P. Adlarson et al. Phys. Rev. Lett. **112**, 202301, (2014)

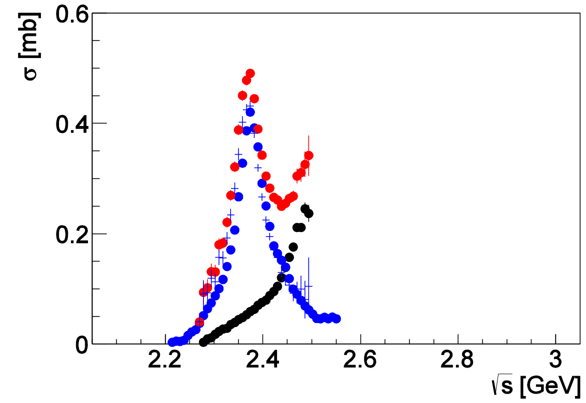
P. Adlarson et al. Phys. Rev. C **90**, 035204 , (2014)

Dibaryon hadronic decays

PRL 106 (2011) 242302



●●● WASA data



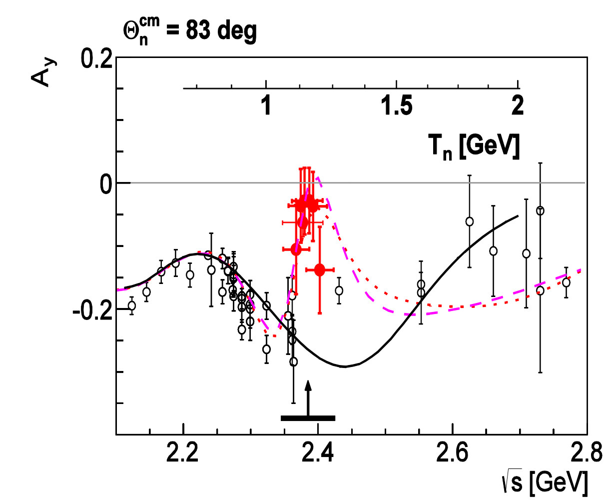
PLB 721 (2013) 229

$d\pi^0\pi^0$

$d\pi^+\pi^-$

pn → **d*(2380)**

pn

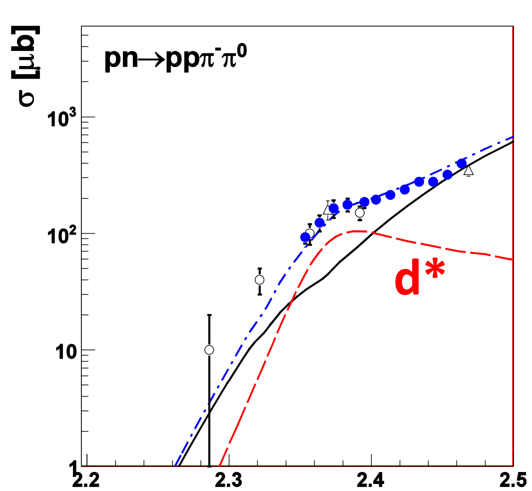


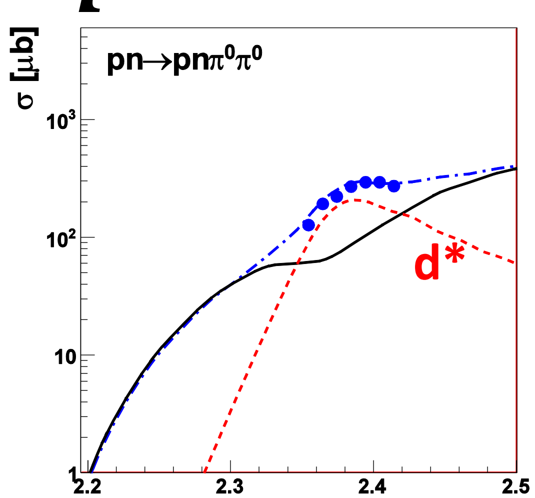
PRL 112 (2014) 202301
PRC **90**, (2014) 035204

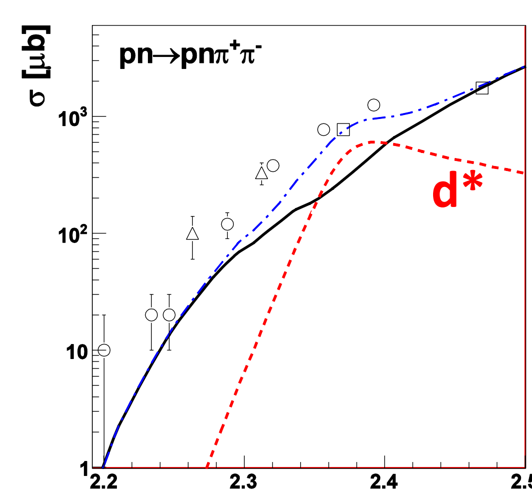
$pp\pi^-\pi^0$

$pn\pi^0\pi^0$

$pn\pi^+\pi^-$







PRC 88 (2013) 055208
PLB 743 (2015) 325

$d^*(2380)$ decay branches

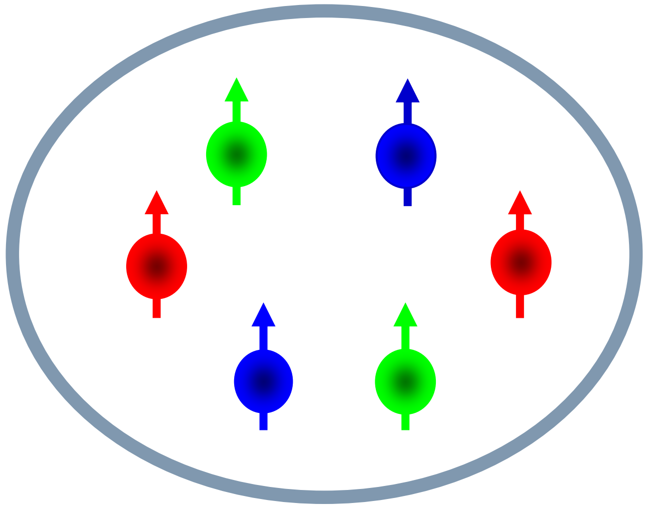
d^* decay channel	Branching ratio, %
pn	12(3)
$d\pi^0\pi^0$	14(1)
$d\pi^+\pi^-$	23(2)
$pn\pi^+\pi^-$	30(5)
$pn\pi^0\pi^0$	12(2)
$pp\pi^0\pi^-$	6(1)
$nn\pi^0\pi^+$	6(1)
$NN\pi$	0(<9)

Eur.Phys.J. A51 (2015) 7, 87

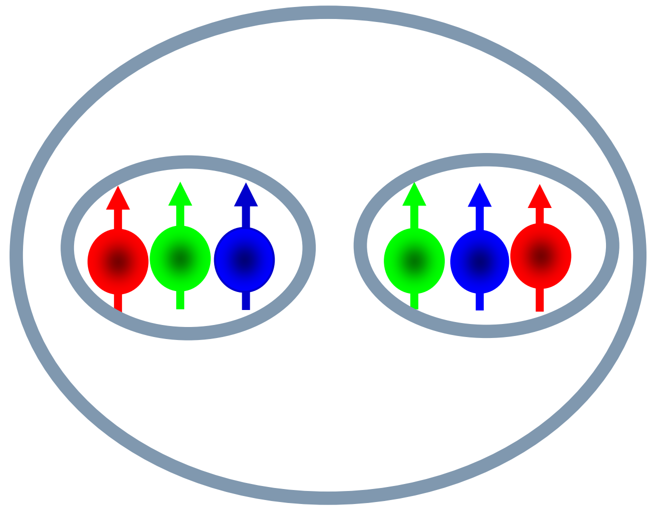
Internal structure

d* internal structure

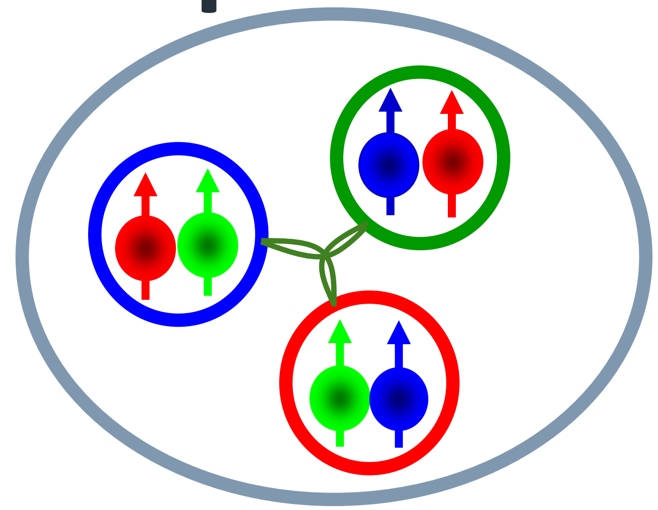
Hexaquark



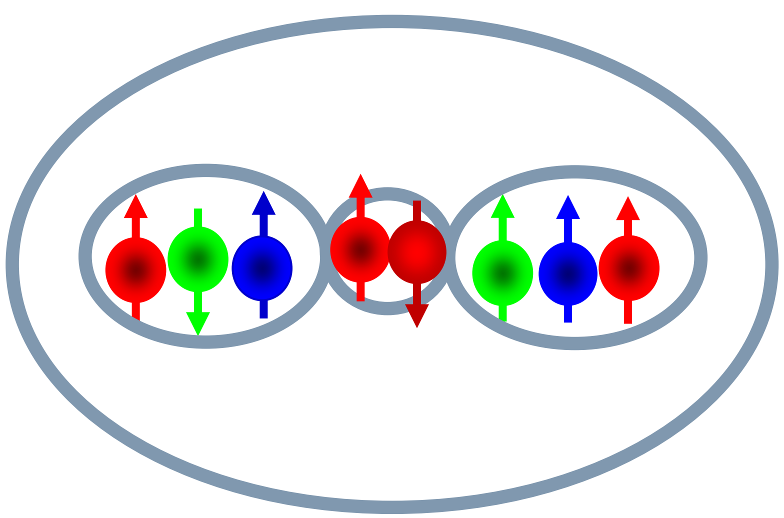
Molecule



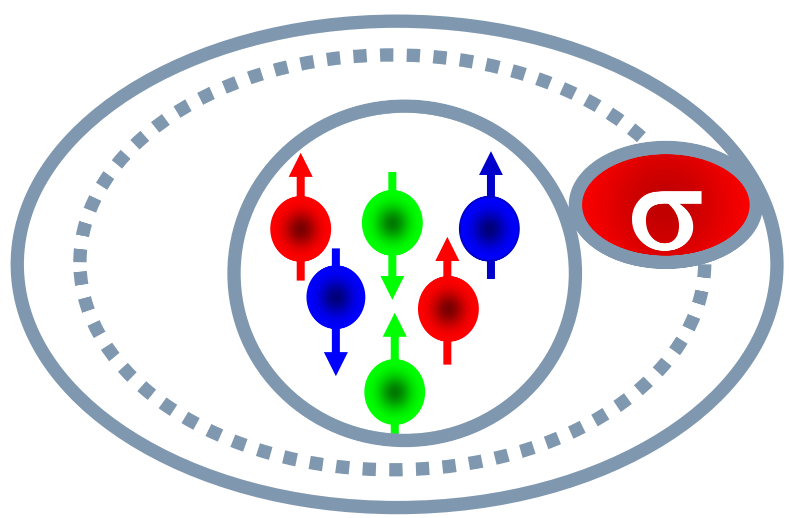
Diquark dominated



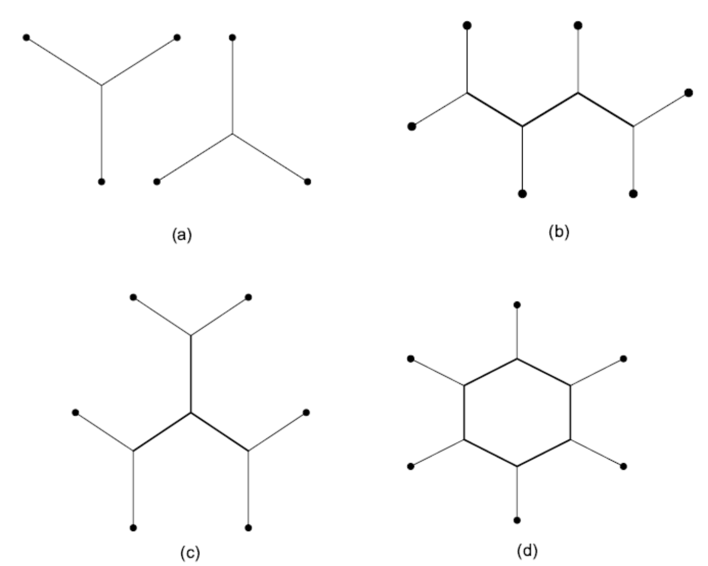
Meson assisted



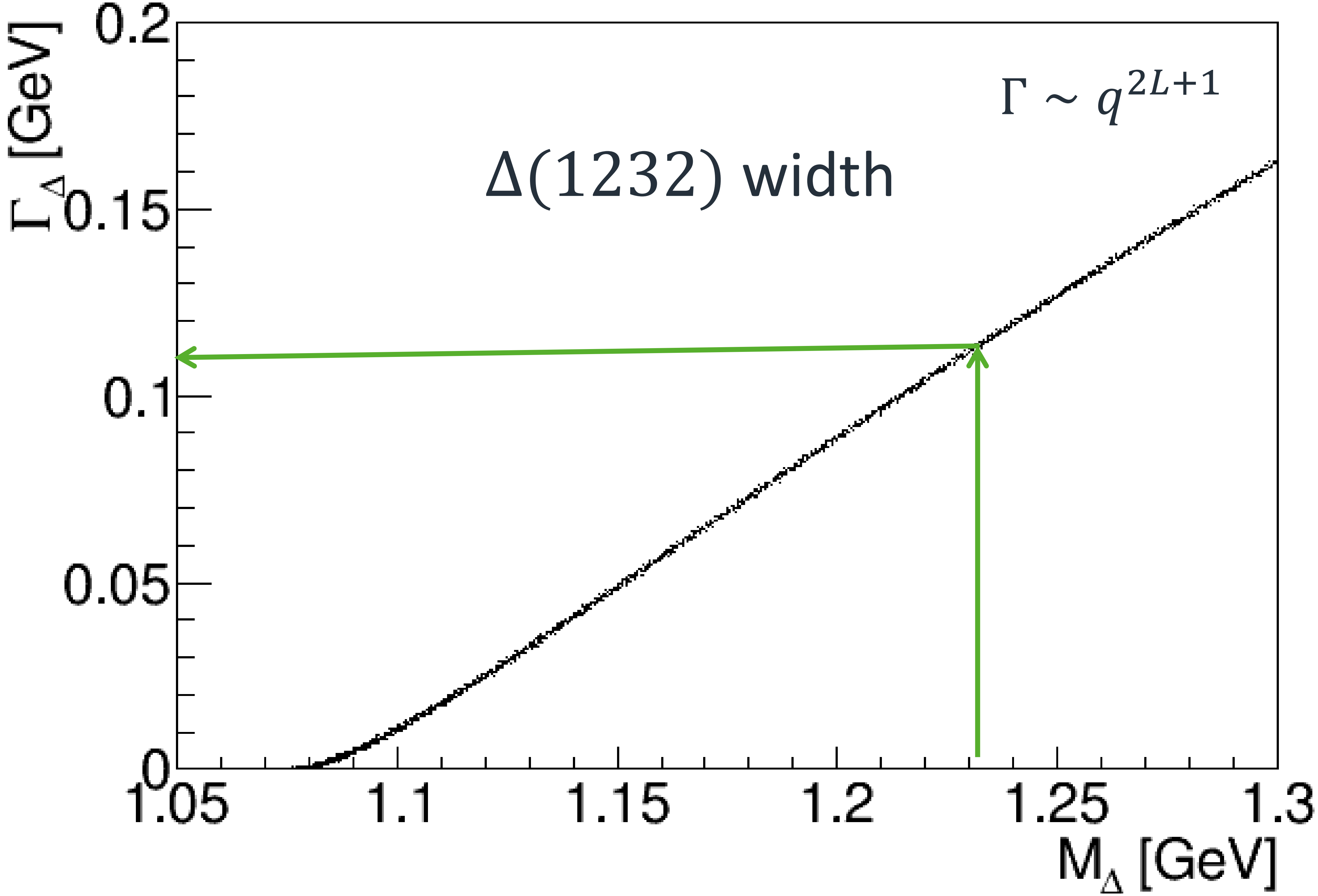
σ-dressed



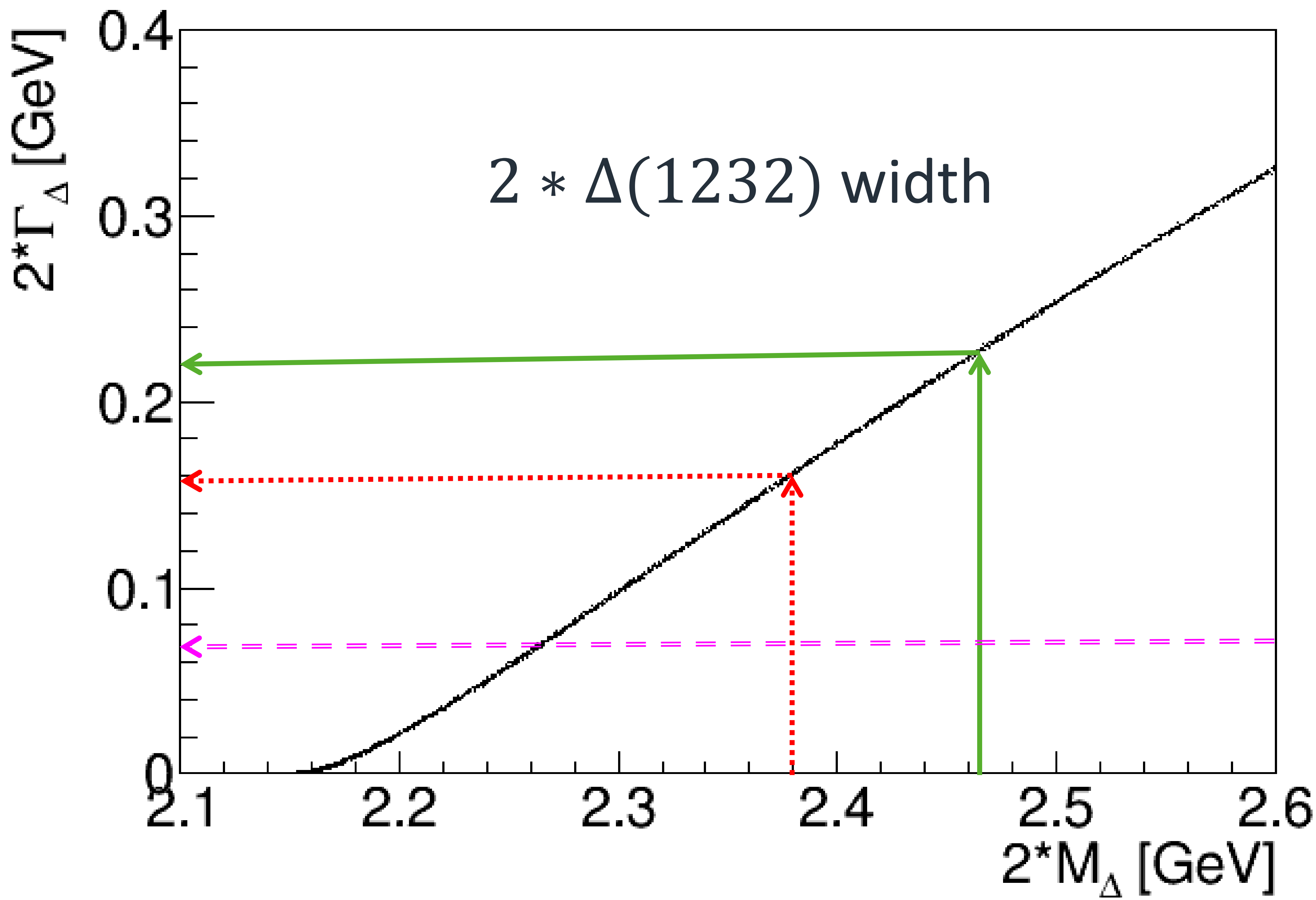
6q configurations



Deltaron: the width quest



Deltaron: the with quest



Deltaron: the with quest

$$M_\Delta = \sqrt{\left(\frac{M_{d^*}}{2}\right)^2 - q_\Delta^2}$$

The mass of the bound Δ in the Deltaron

Δ momentum in the Deltaron

$M_\Delta = \dfrac{M_{d^*}}{2}$ only if $q_\Delta = 0$

$q_\Delta = 0$ only if the size of the Deltaron is ∞

For $R_{d^*} = 0.9 fm$, $\Gamma_{d^*} = 2\Gamma_\Delta = 70\ MeV$

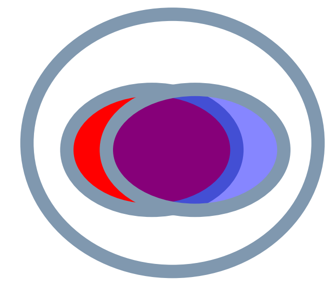
see A. Gal, Phys.Lett. B769 (2017) 436 for details

$d^*(2380)$ size

UNIVERSITY of York

Deuteron

Deltaron



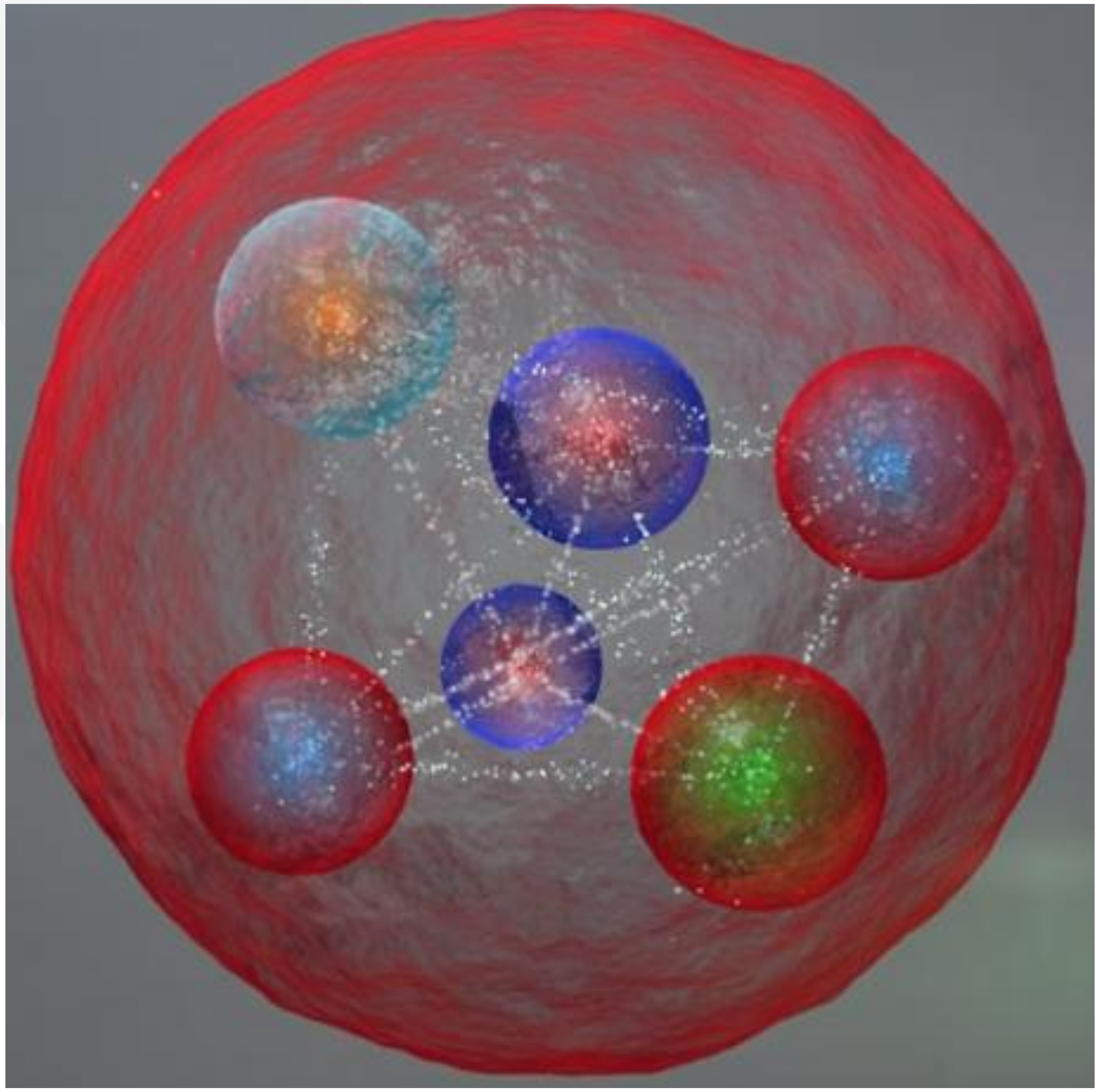
$$\text{size} \sim \frac{1}{\sqrt{mE_B}}$$

$$\frac{Deltaron}{Deuteron} = \frac{\sqrt{m_N E_{Deuteron}}}{\sqrt{m_\Delta E_{d^*}}} \sim \frac{1}{7}$$

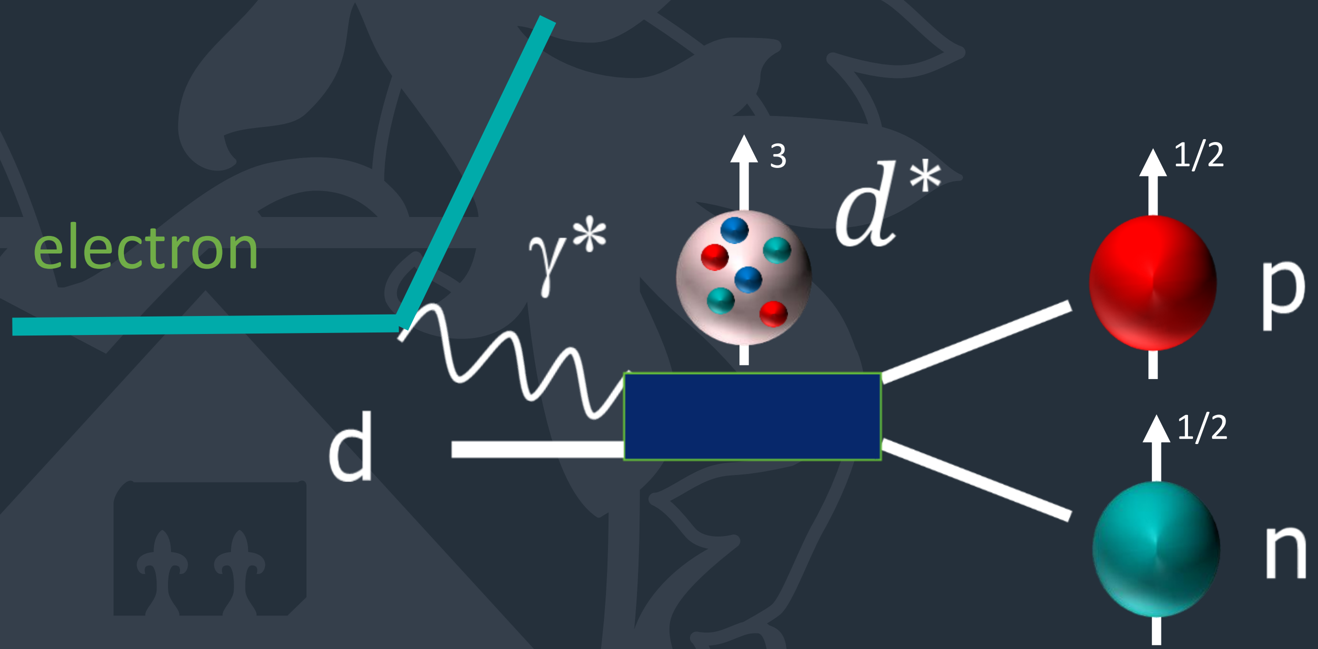
$$R_{deuteron} \sim 2.2\ fm \Rightarrow R_{\Delta\Delta} \sim 0.3\ fm$$

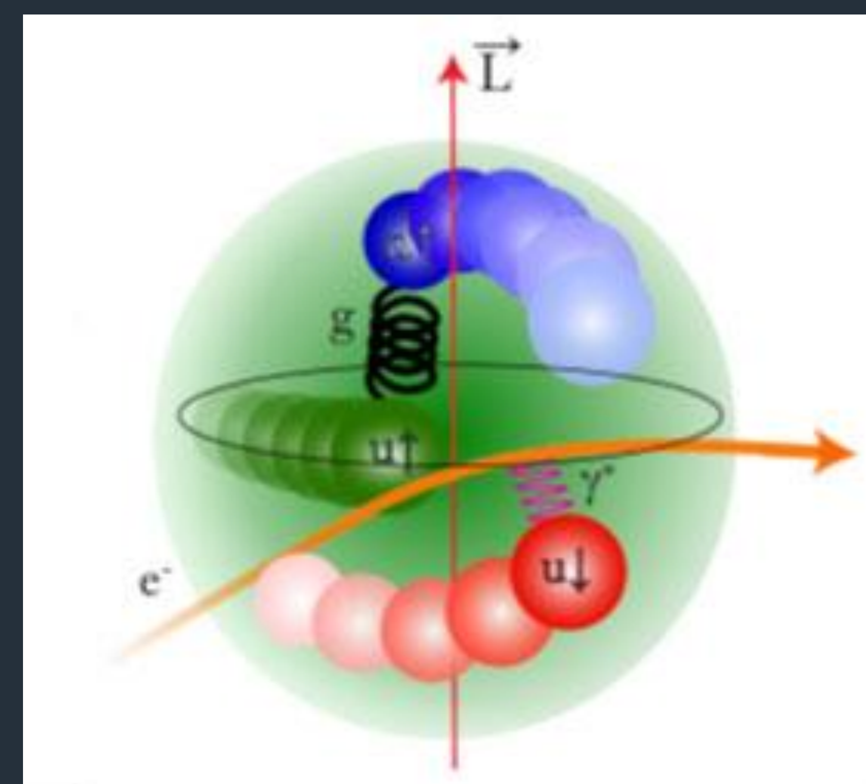
Nearly complete overlap

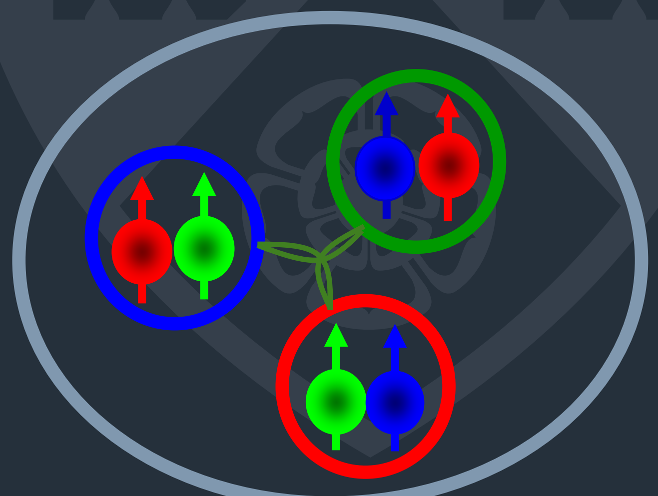
Hexaquark/Dibaryon $d^*(2380)$

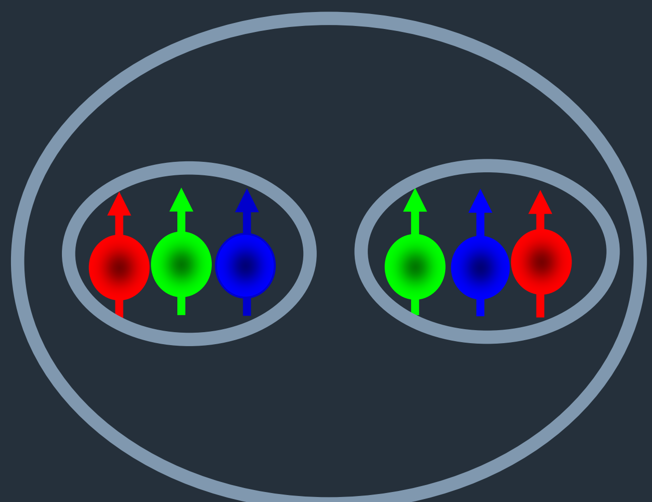


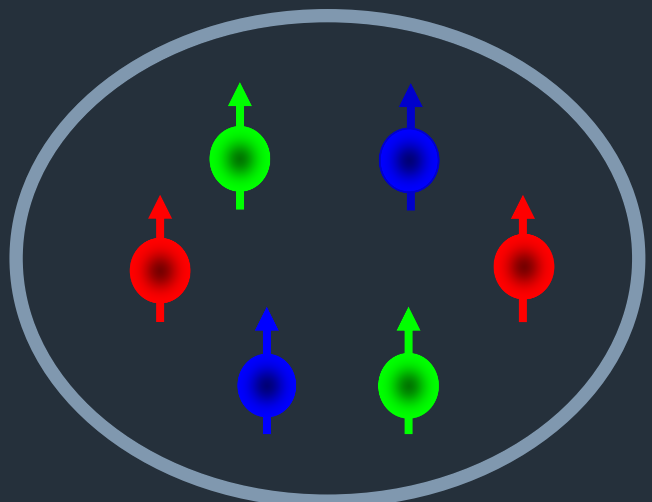
Hexaquark Autopsy











$d \to d^*(2380)$ transitions

0.15% Deuteron: $|6q\rangle$

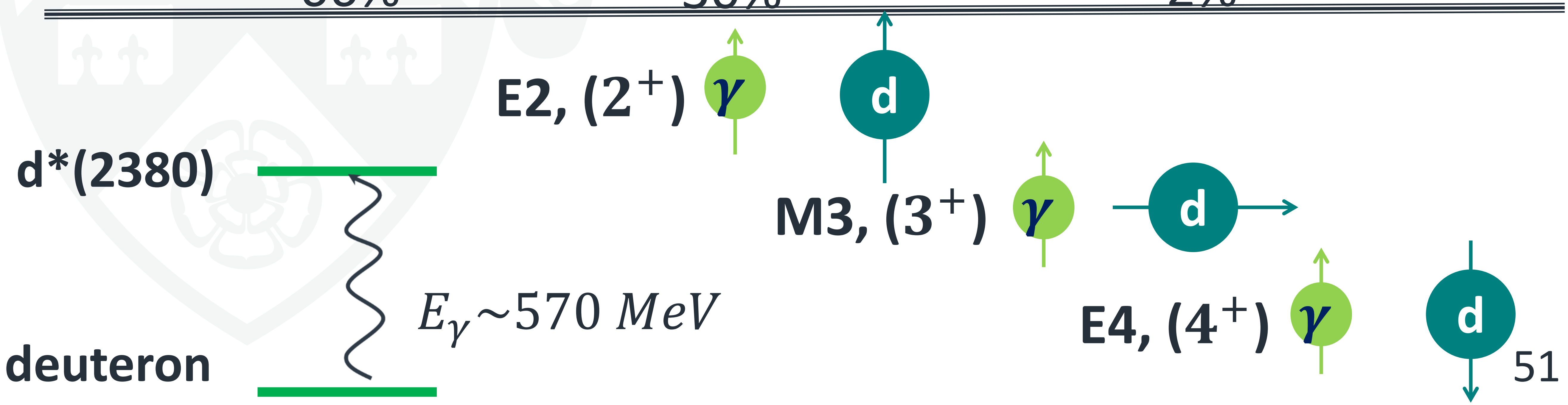
5% $|pn_{S-wave}\rangle$ $|pn_{D-wave}\rangle$

γ

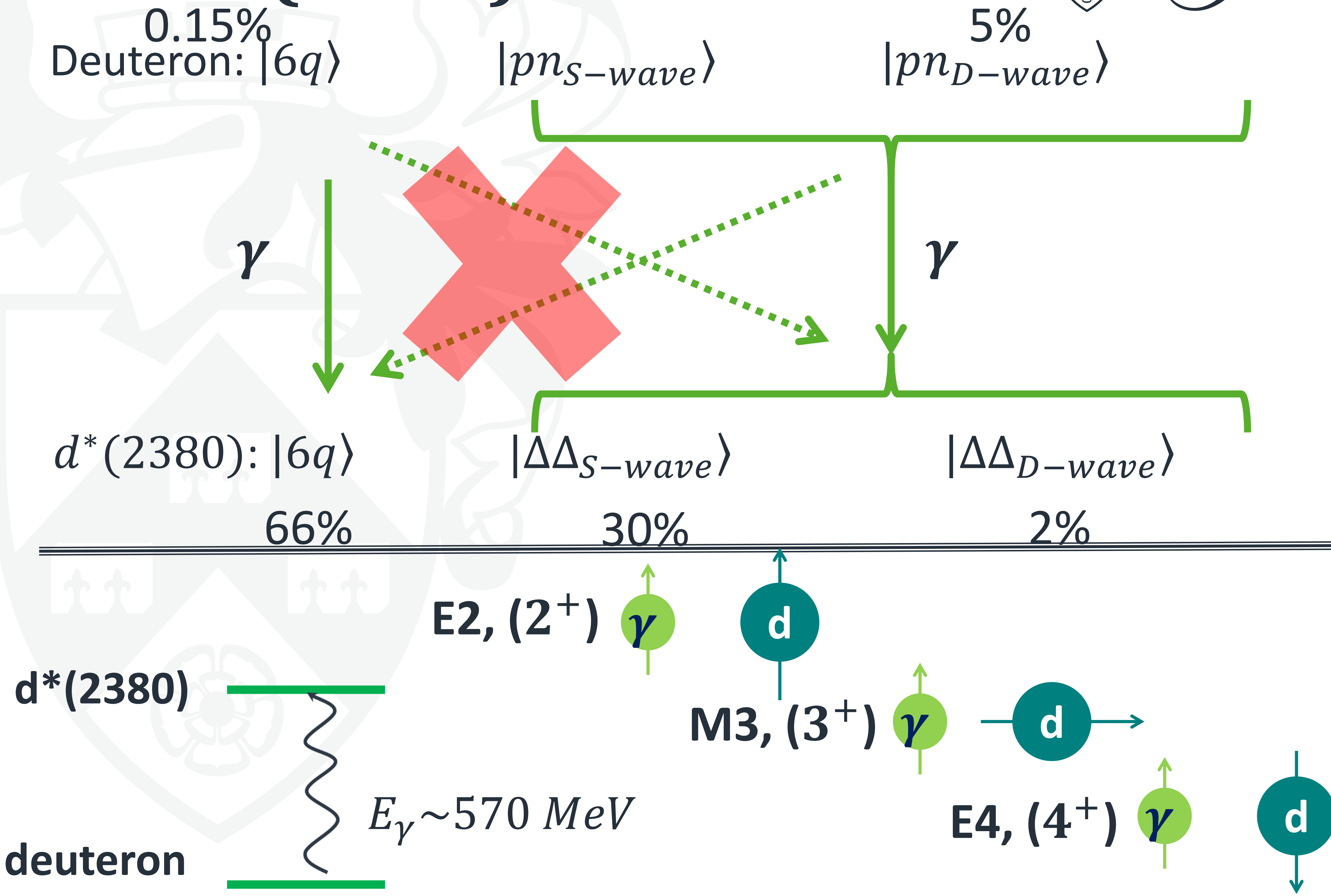
γ

$d^*(2380)$: $|6q\rangle$ $|\Delta\Delta_{S-wave}\rangle$ $|\Delta\Delta_{D-wave}\rangle$

66% 30% 2%



$d \rightarrow d^*(2380)$ transitions

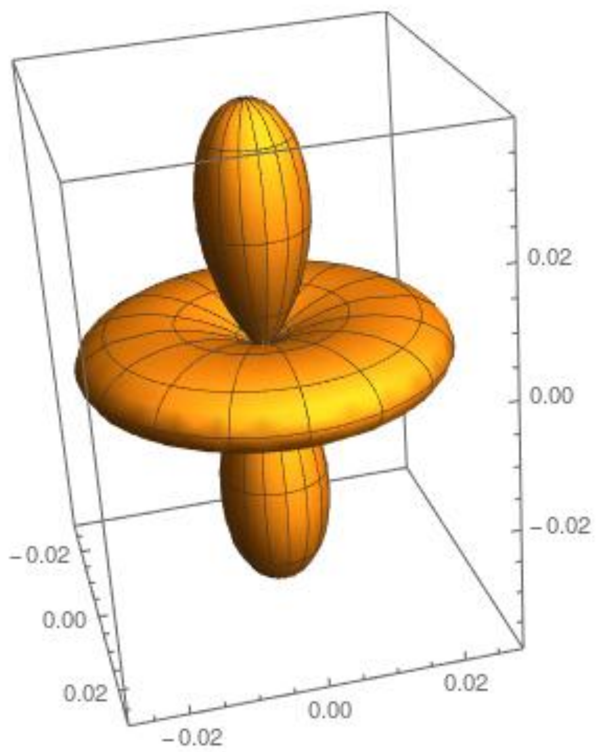


Is $d^*(2380)$ compact?

Small E2 transition $\rightarrow$ compact

Not necessary

Pion cloud configurations in $d^*(2380)$



- Cancellation effects
- $d^*(2380)$ Electric Quadrupole moment is small
- $d^*(2380)$ Magnetic Octupole moment is large!!!

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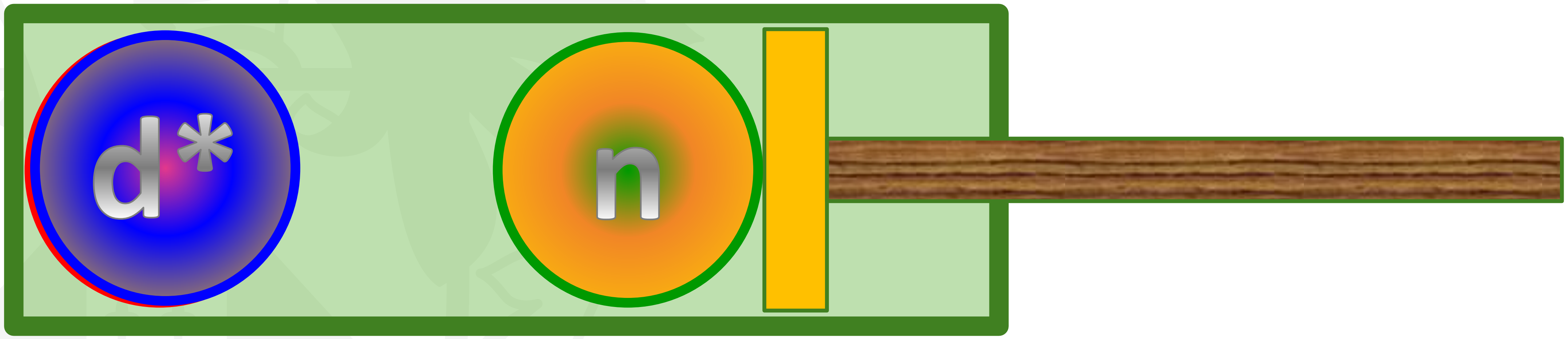
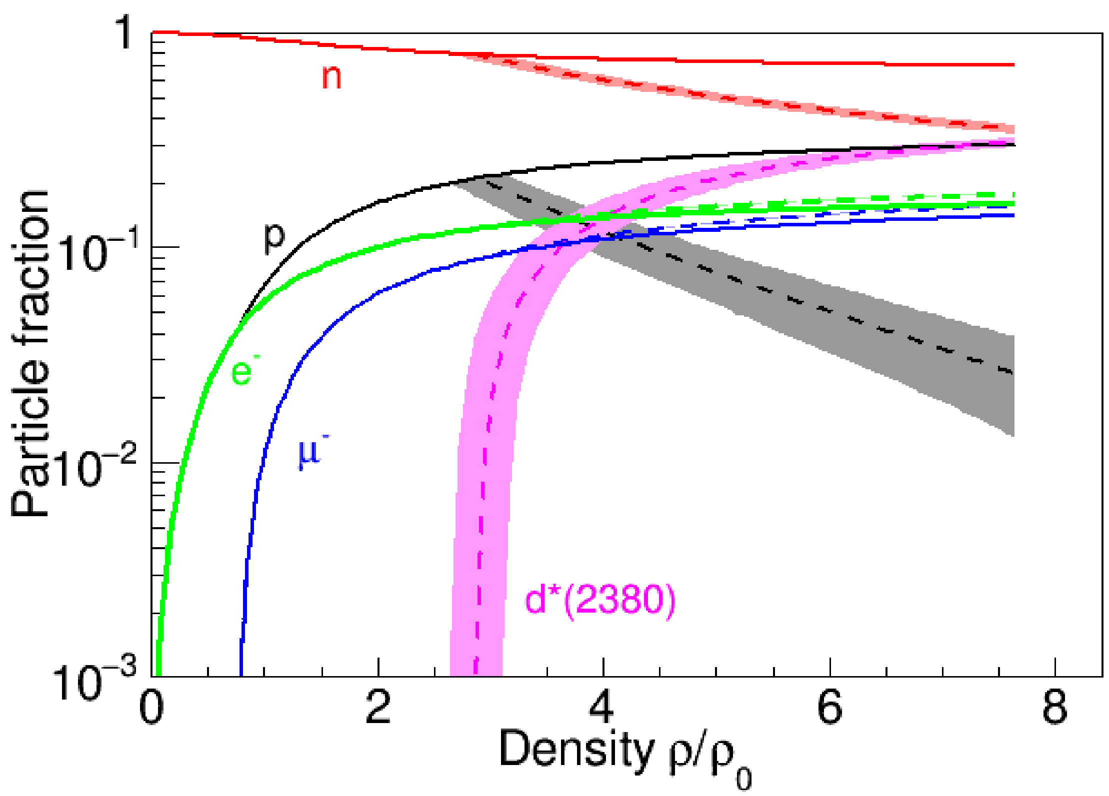
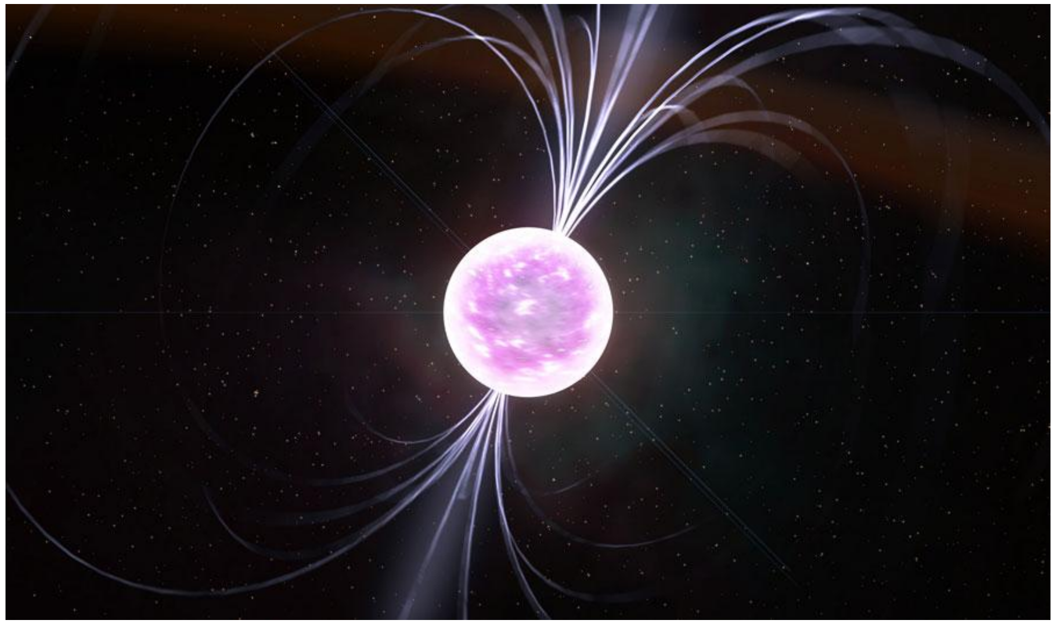
Nuclear matter at high density

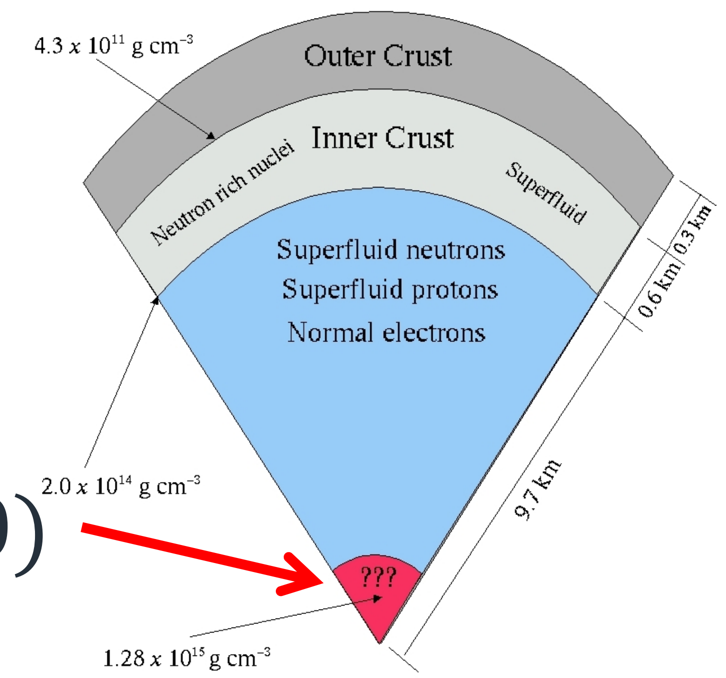


Hidden interior





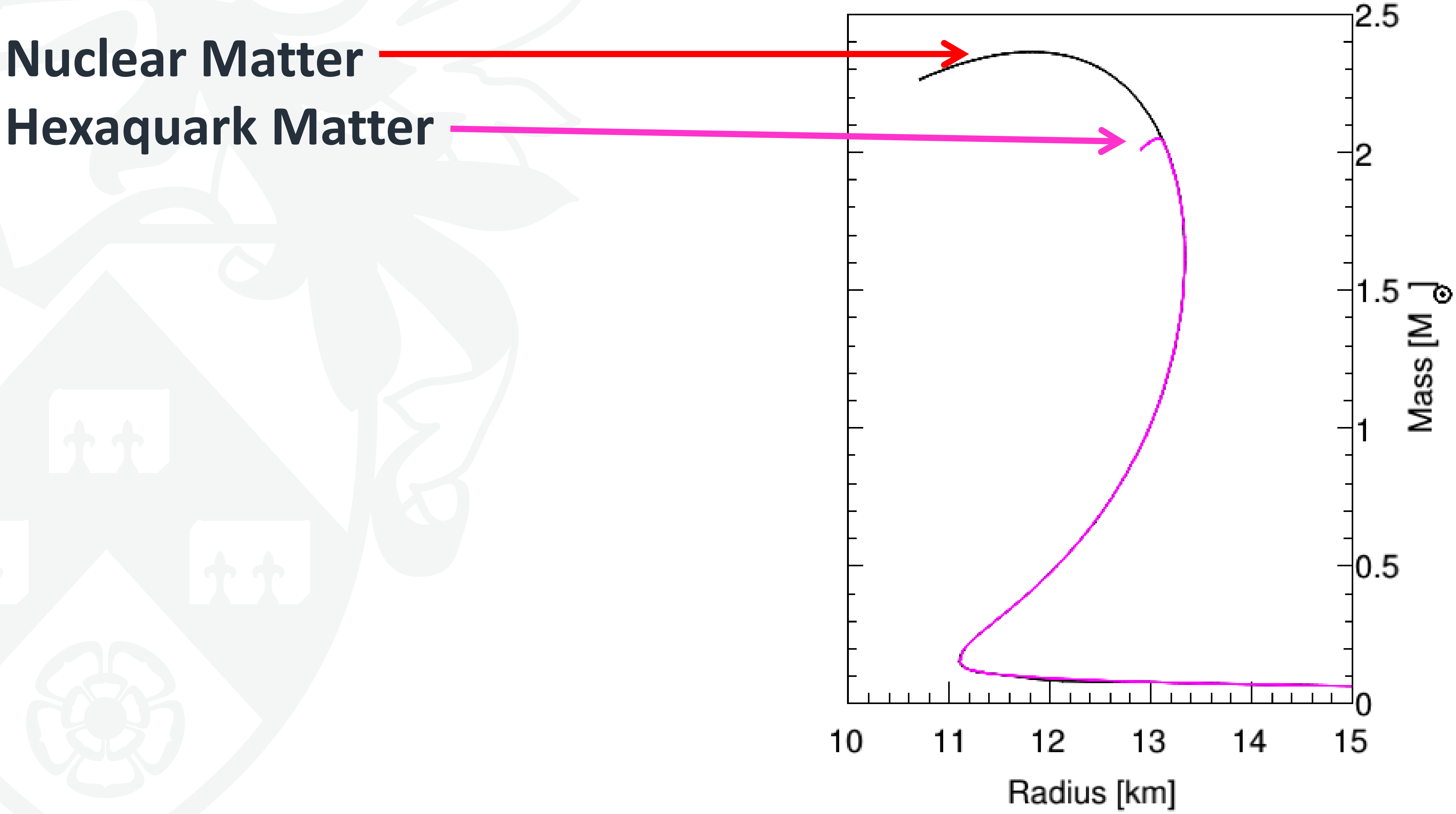
$d^*(2380)$



Neutron Star Pizza

I. Vidaña, M. Bashkanov, D.P. Watts, A. Pastore
Phys.Lett. B781 (2018) 112-116

Hexaquarks in Neutron Stars

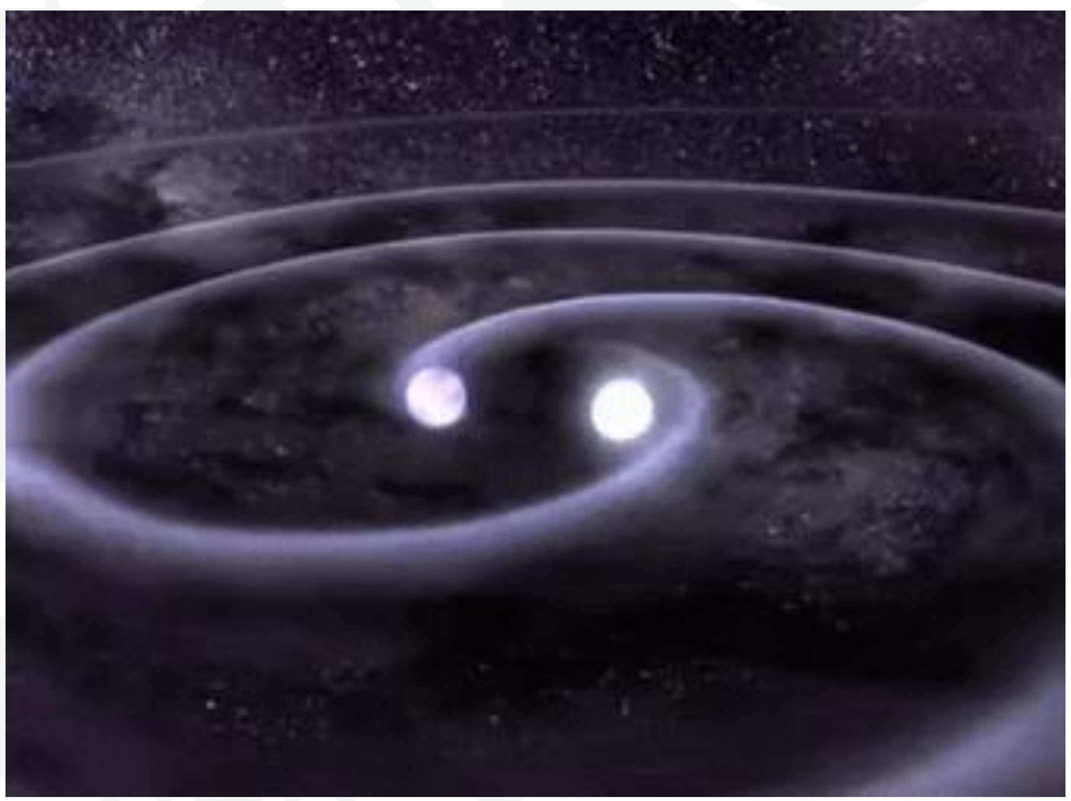


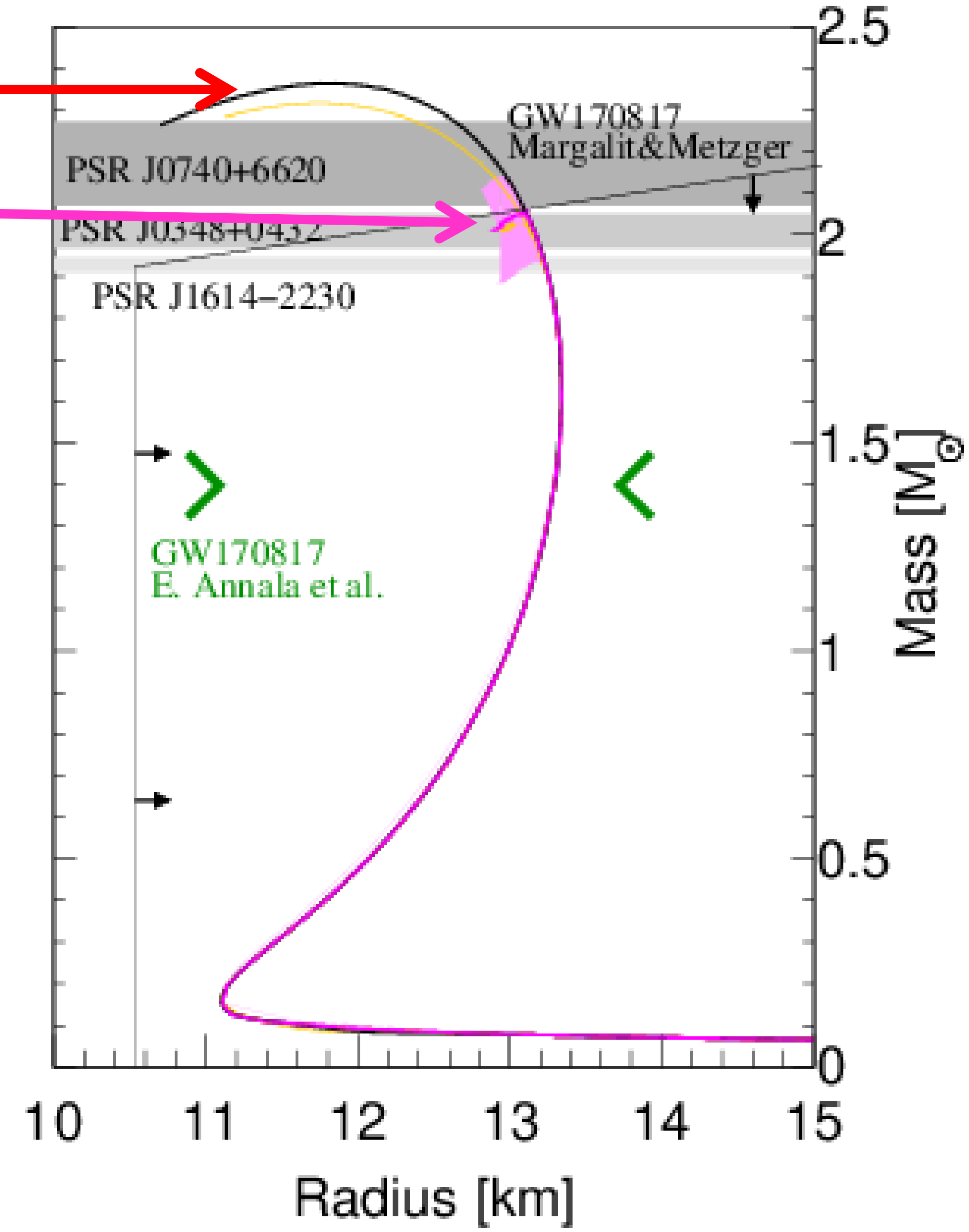
I. Vidaña, M. Bashkanov, D.P. Watts, A. Pastore
Phys.Lett. B781 (2018) 112-116

Hexaquarks in Neutron Stars

Nuclear Matter

Hexaquark Matter

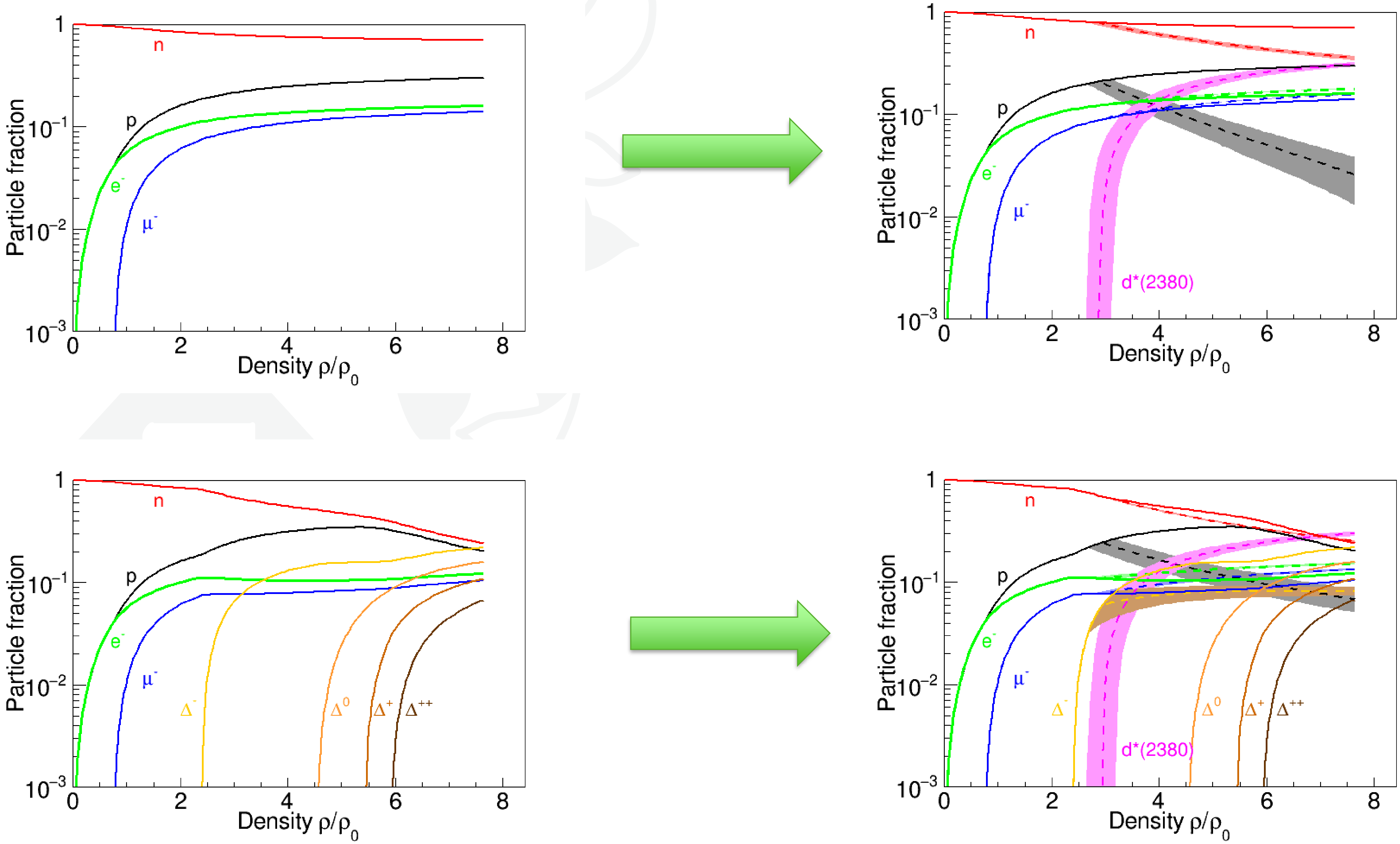




I. Vidaña, M. Bashkanov, D.P. Watts, A. Pastore

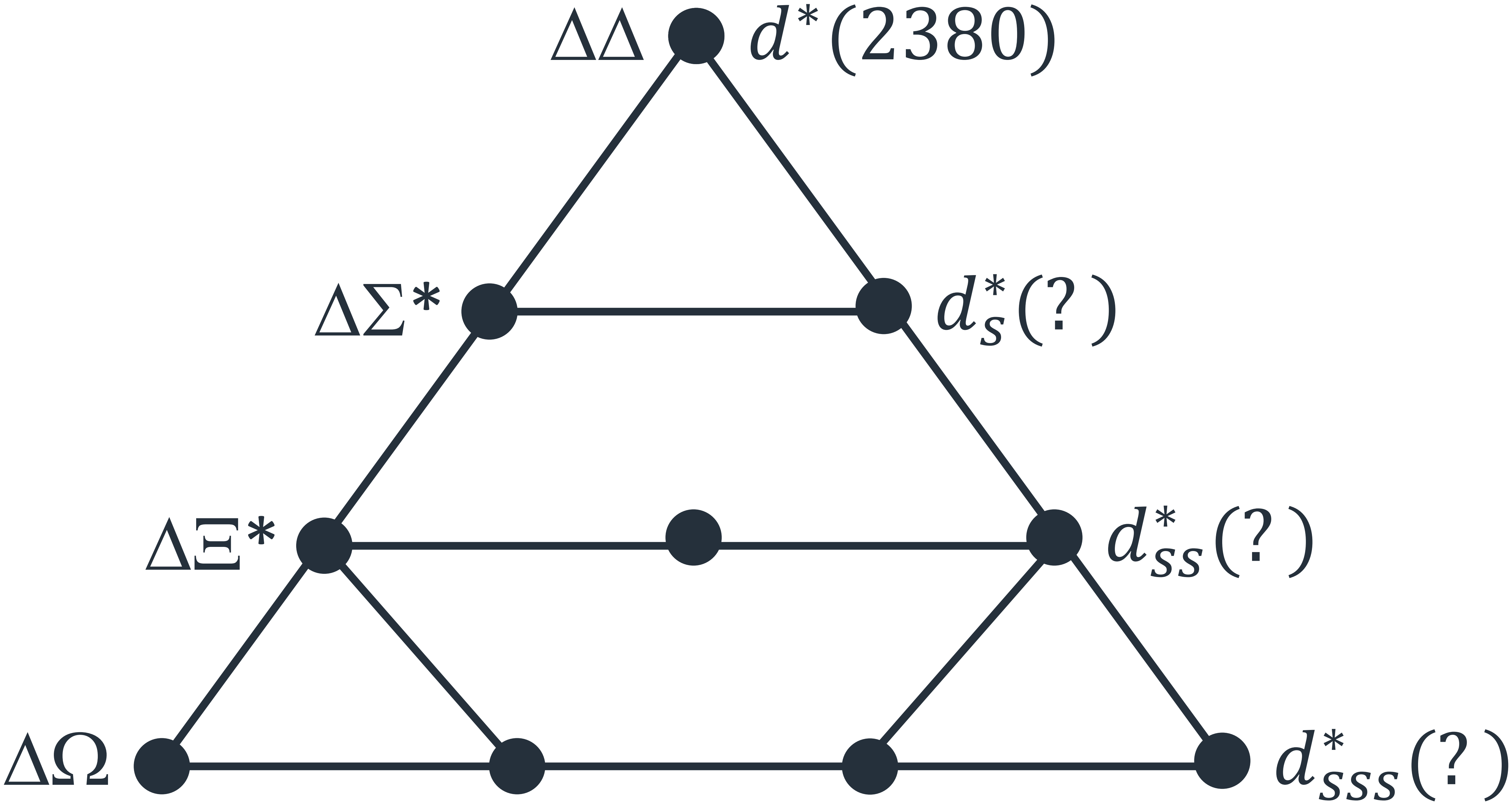
Phys.Lett. B781 (2018) 112-116 Submitted to arXiv: 28.06.2017

Hexaquarks EoS



I. Vidaña, M. Bashkanov, D.P. Watts, A. Pastore **Phys.Lett. B781**

d*(2380) SU(3) multiplet



Conclusion

- To discover something, you need to
  - Live long
  - Work hard
  - Do not listen to the experts

Questions

1. $d^*(2380)$ has quantum numbers $I(J^P) = 0(3^+), M = 2380\ MeV, \Gamma = 70\ MeV$:

   1. what decay channels could it have?

2. NN has two states $0(1^+)$ - deuteron and $1(0^+)$ - "demon deuteron", unbound by 66keV

   1. What would be the analogue in the d* case?
   2. How would you produce a mirror-d* state?

3. What magnetic moment would you expect for d*

4. Consider photo/electro-production of the d*

   1. What amplitudes do you expect to dominate
   2. What could be the possible obstacles?