Multi-pion Resonances and the Continuum

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★ Dynamical coupled-channels (DCC) model

Analysis of $\gamma^{(*)}N,\ \pi N \rightarrow \pi N,\ \pi\pi N,\ \eta N,\ K\Lambda,\ K\Sigma$

Extension to $\nu N \rightarrow l^- X$ $(X = \pi N,\ \pi\pi N,\ \eta N,\ K\Lambda,\ K\Sigma)$

★ New results for $\nu N \rightarrow l^- X$

Introduction

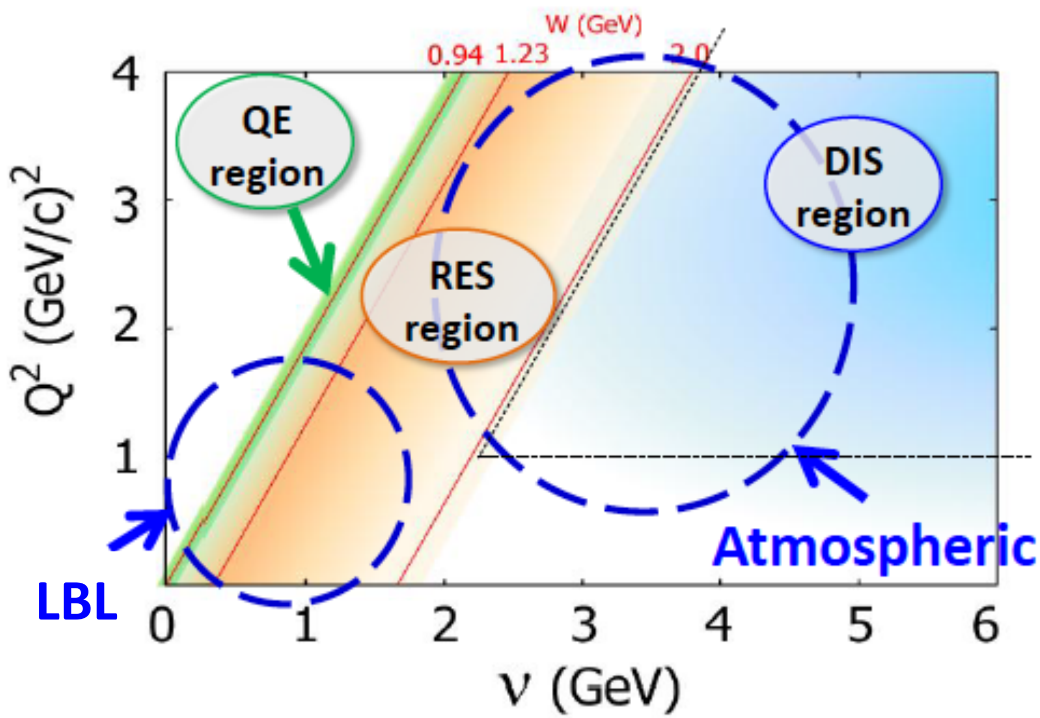
Neutrino-nucleus scattering for ν-oscillation experiments

Next-generation exp. ➔ leptonic $\not{CP}$, mass hierarchy

ν−nucleus scattering needs to be understood more precisely

Neutrino-nucleus scattering for ν-oscillation experiments

Next-generation exp. ➔ leptonic C̸P, mass hierarchy

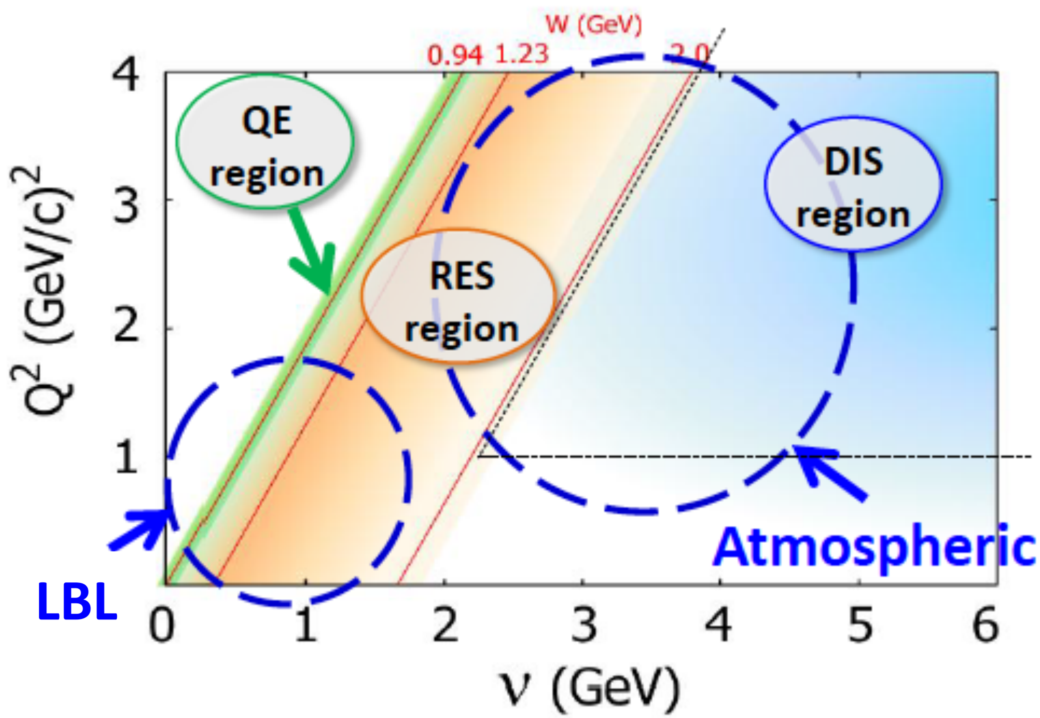


Wide kinematical region with different characteristic

➔ Combination of different expertise is necessary

Neutrino-nucleus scattering for ν-oscillation experiments

Next-generation exp. ➔ leptonic $\not{CP}$, mass hierarchy

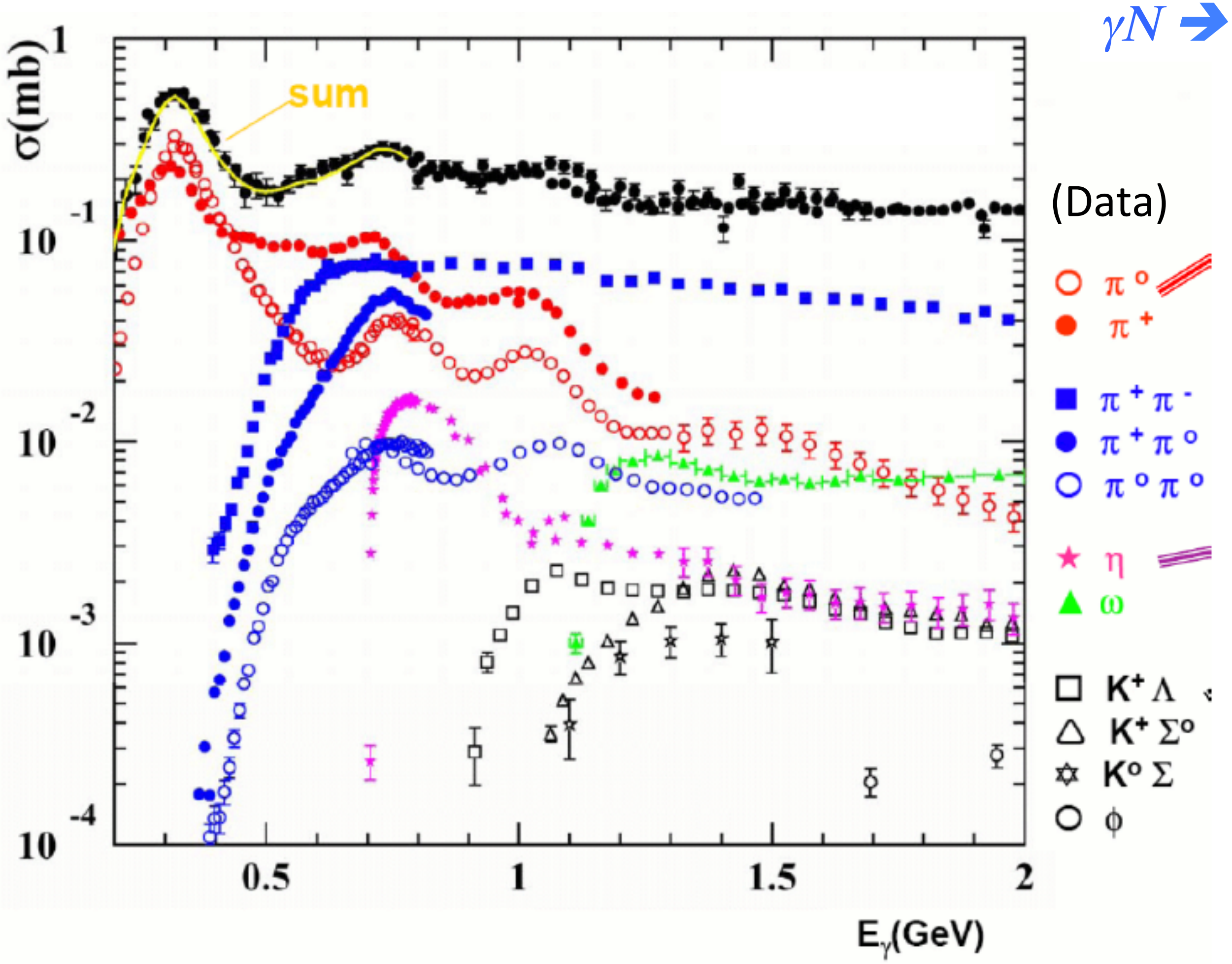


Collaboration at J-PARC Branch of KEK Theory Center

http://j-parc-th.kek.jp/html/English/e-index.html

Resonance region

$\gamma N \rightarrow X$



Multi-channel reaction

- 2π production is comparable to 1π
- η, K productions (background of proton decay exp.)

GOAL : Develop νN-interaction model in resonance region

Problems in previous models

- (multi-channel) Unitarity is missing
- Important 2 π production model is missing

Our strategy to overcome the problems…

We develop a Unitary coupled-channels model

★ Dynamical coupled-channels (DCC) model for $\gamma N, \pi N \rightarrow \pi N, \pi\pi N, \eta N, K\Lambda, K\Sigma$

★ Extension to $\nu N \rightarrow l^- X$ ($X = \pi N, \pi\pi N, \eta N, K\Lambda, K\Sigma$) (← THIS WORK)

Dynamical Coupled-Channels model for meson productions

DCC (Dynamical Coupled-Channel) model

Matsuyama et al., Phys. Rep. **439**, 193 (2007)

Kamano et al., PRC 88, 035209 (2013)

Coupled-channel Lippmann-Schwinger equation

$$T_{ab} = V_{ab} + \sum_c V_{ac} G_c T_{cb}$$

$$\{a, b, c\} = \gamma^* N,\ \pi N,\ \eta N,\ \pi\pi N\,(\pi\Delta, \sigma N, \rho N),\ K\Lambda,\ K\Sigma\ \ AN$$

Coupled-channel unitarity is fully taken into account

DCC (Dynamical Coupled-Channel) model

Matsuyama et al., Phys. Rep. **439**, 193 (2007)

Kamano et al., PRC 88, 035209 (2013)

Coupled-channel Lippmann-Schwinger equation

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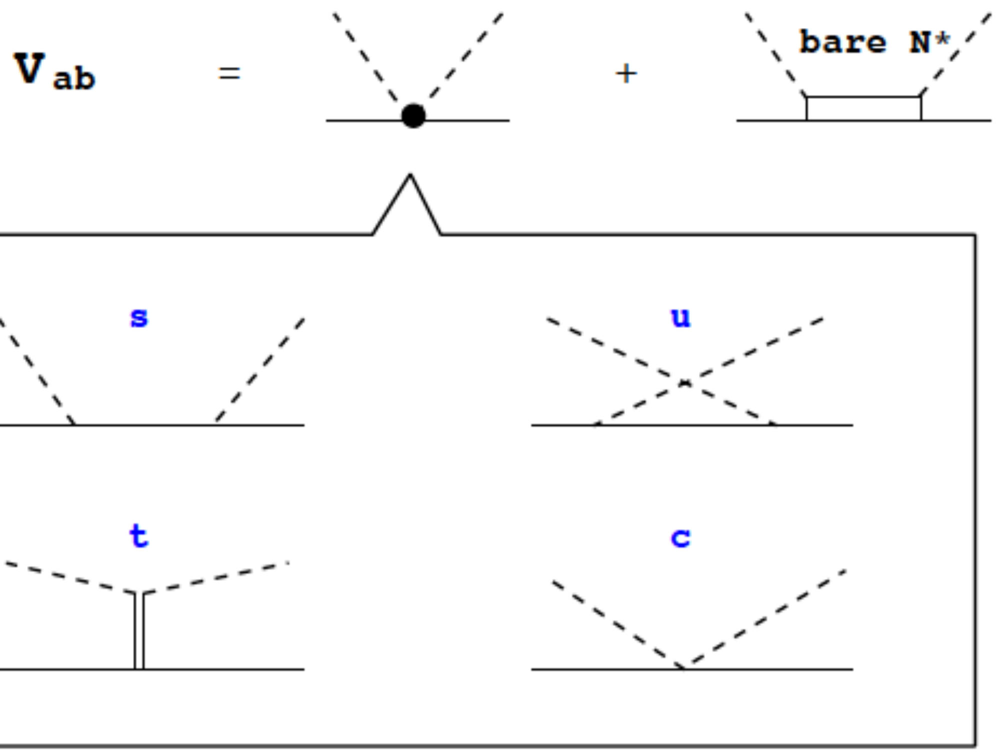


Quality of describing data with DCC model

Kamano, Nakamura, Lee, Sato, PRC 88 (2013)

Model is extensively tested by

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

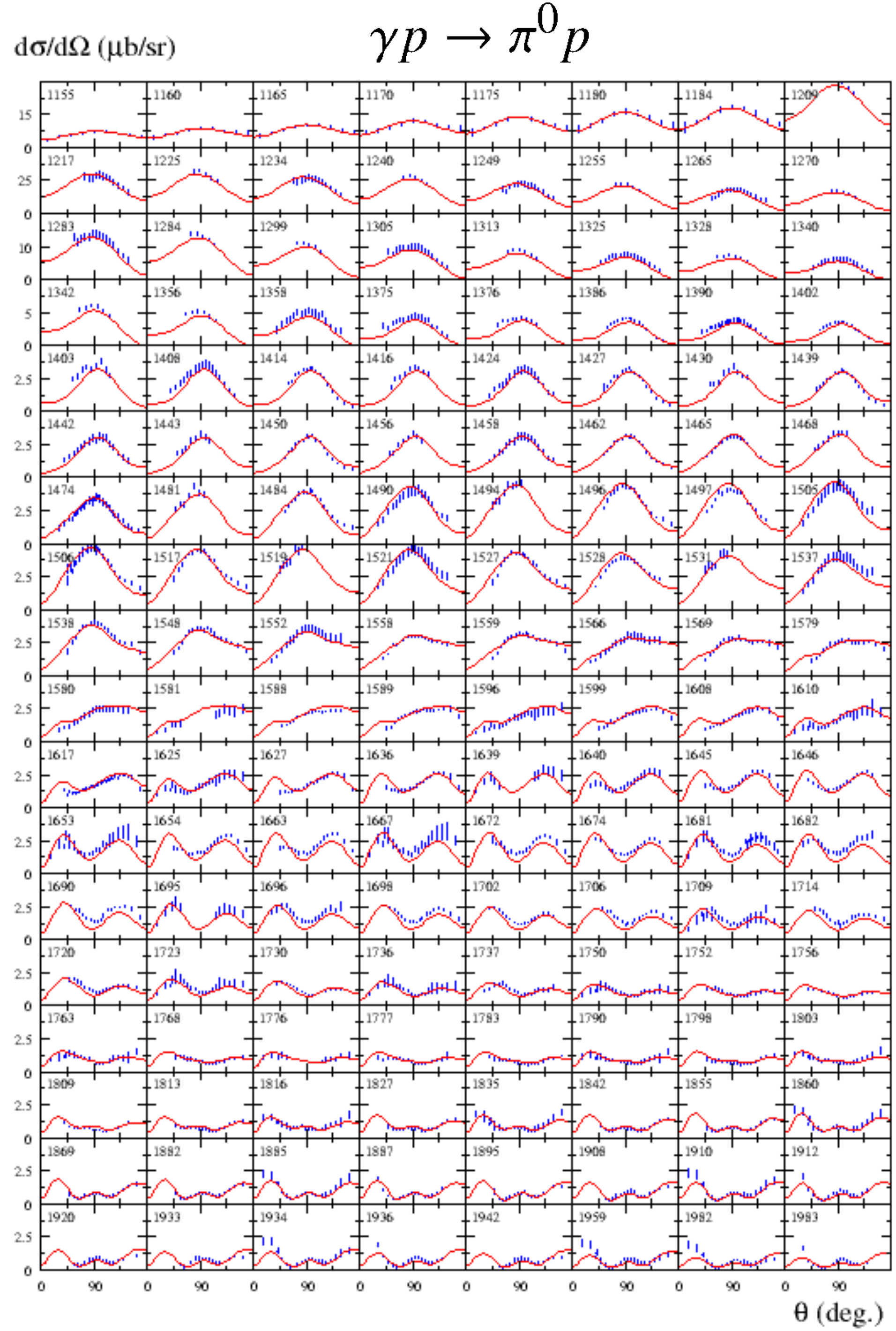
($W \leq 2.1$ GeV, ~ 20,000 data points)

↓

application to ν-scattering

reliable vector current ($Q^2 = 0$)

$\pi N \rightarrow X$ model combined with PCAC

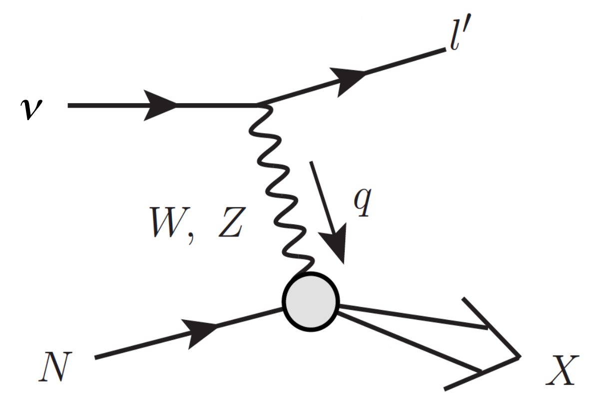


DCC model for neutrino interaction

$\nu N \rightarrow l\, X \quad (X = \pi N, \pi\pi N, \eta N, K\Lambda, K\Sigma)$

at forward limit $Q^2=0$

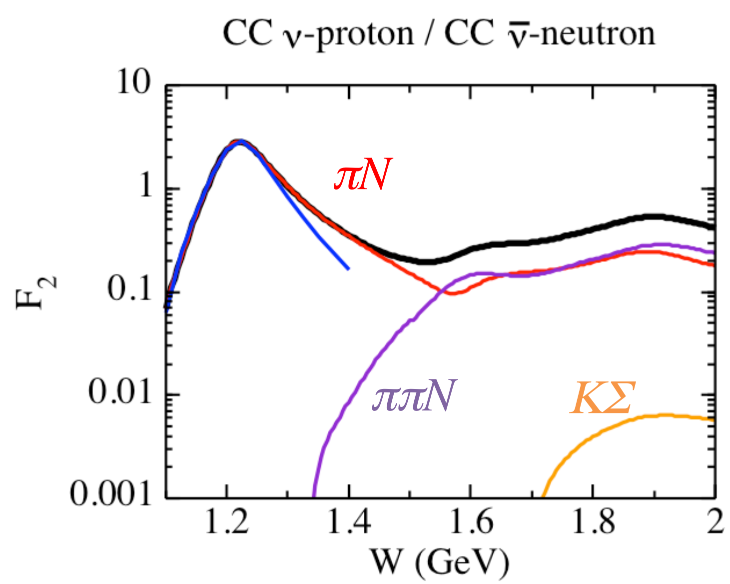
Kamano, Nakamura, Lee, Sato, PRD 86 (2012)



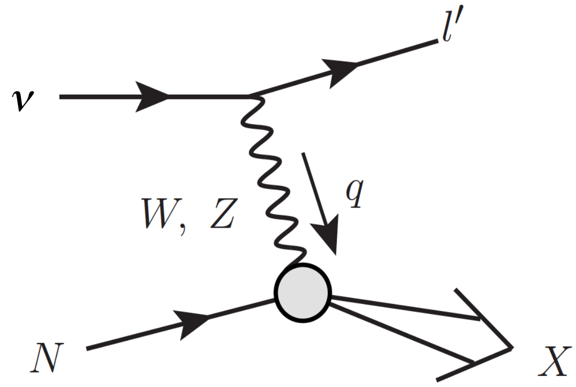
$$\frac{d\sigma}{dE_\ell d\Omega_\ell} = \frac{G_F^2}{2\pi^2} E_\ell^2\, W_2$$

via PCAC $\quad F_2 \equiv \omega W_2 = \frac{2 f_\pi^2}{\pi} \sigma_{\pi N \to X}$

$\sigma_{\pi N \rightarrow X}$ is from our DCC model



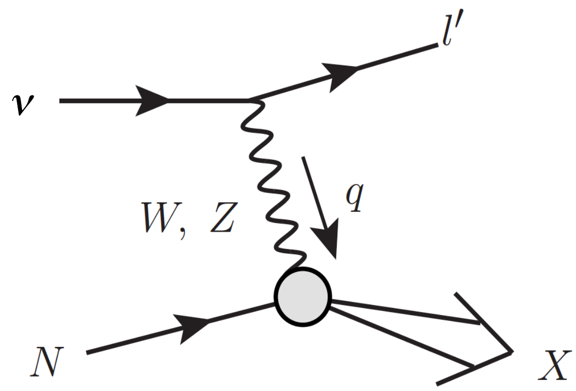
DCC model for neutrino interaction



Extension to full kinematical region $Q^2 \neq 0$

➔ Model for vector & axial currents is necessary

DCC model for neutrino interaction



Vector current

Q^2=0

γp ➔ MB

γn ➔ πN ➔ isospin separation

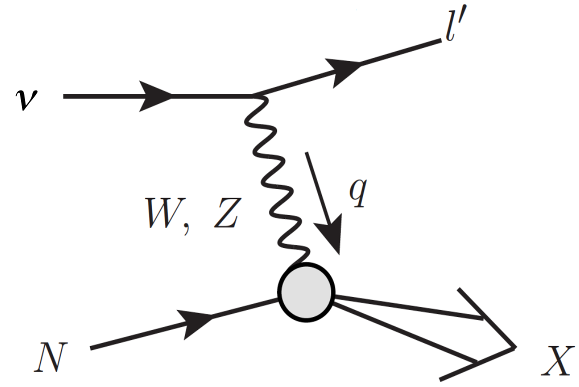
necessary for calculating ν-interaction

Q^2≠0 (electromagnetic form factors for VNN^* couplings)

obtainable from $(e,e'\ \pi)$, $(e,e'\ X)$ data analysis

We've done first analysis of all these reactions ➔ $VNN^*(Q^2)$ fixed ➔ neutrino reactions

DCC model for neutrino interaction

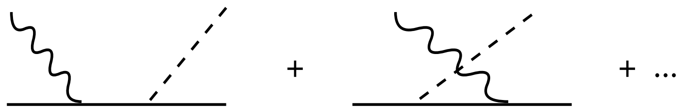


Axial current

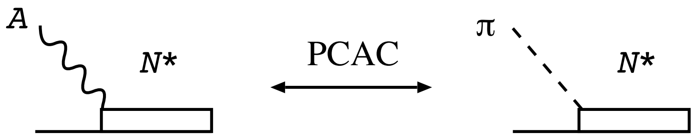
Q^2=0

non-resonant mechanisms

$$\partial_\mu \pi \rightarrow f_\pi A_\mu^{external}$$



resonant mechanisms



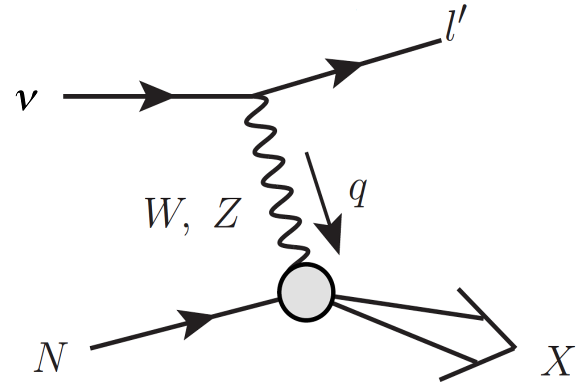
Interference among resonances and background can be made under control within DCC model

Caveat for this presentation : phenomenological axial currents are added to maintain PCAC relation

$$q \cdot A_{AN\rightarrow\pi N} \sim i\, f_\pi T_{\pi N\rightarrow\pi N}$$

to be improved in future

DCC model for neutrino interaction



Axial current

$Q^2 \neq 0$ axial form factors

non-resonant mechanisms $\left(\frac{1}{1+Q^2/M_A^2}\right)^2$ M_A=1.02 GeV

resonant mechanisms $(1+aQ^2)\exp(-bQ^2)\left(\frac{1}{1+Q^2/M_A^2}\right)^2$ Sato et al. PRC 67 (2003)

More neutrino data are necessary to fix axial form factors for ANN^*

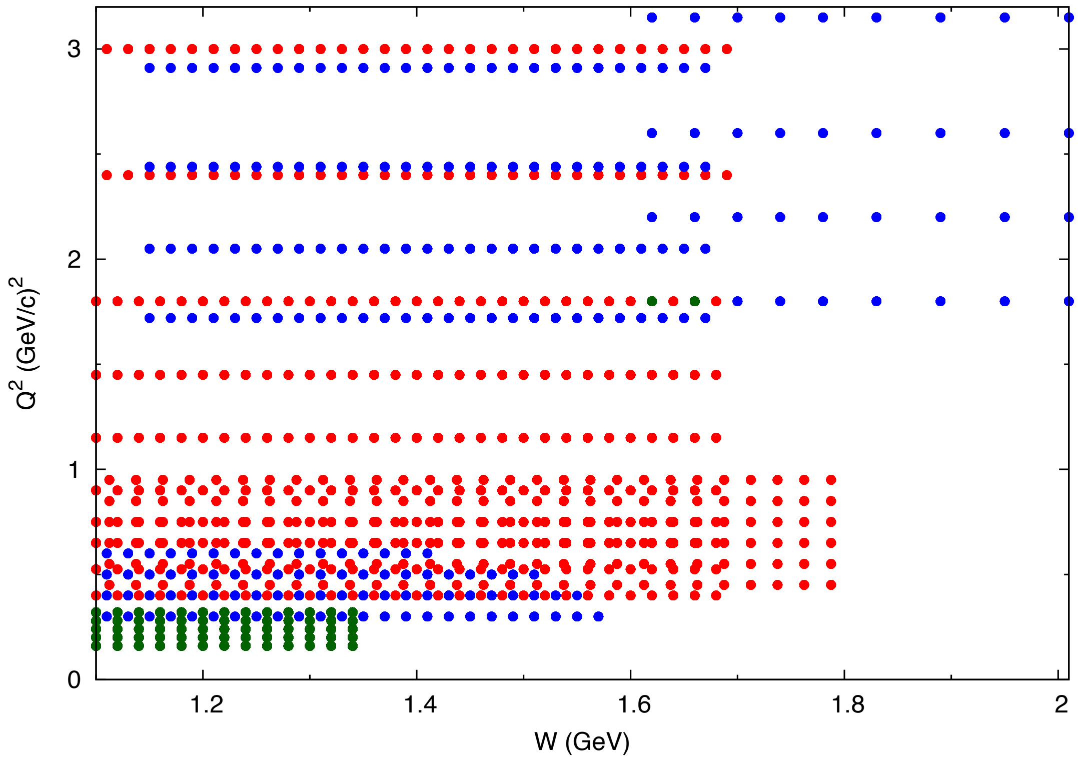
Neutrino cross sections will be predicted with this axial current for this presentation

Analysis of electron scattering data

Analysis of electron-proton scattering data

Purpose : Determine Q^2 –dependence of vector coupling of p-N^* : $VpN^*(Q^2)$

Data : * 1π electroproduction



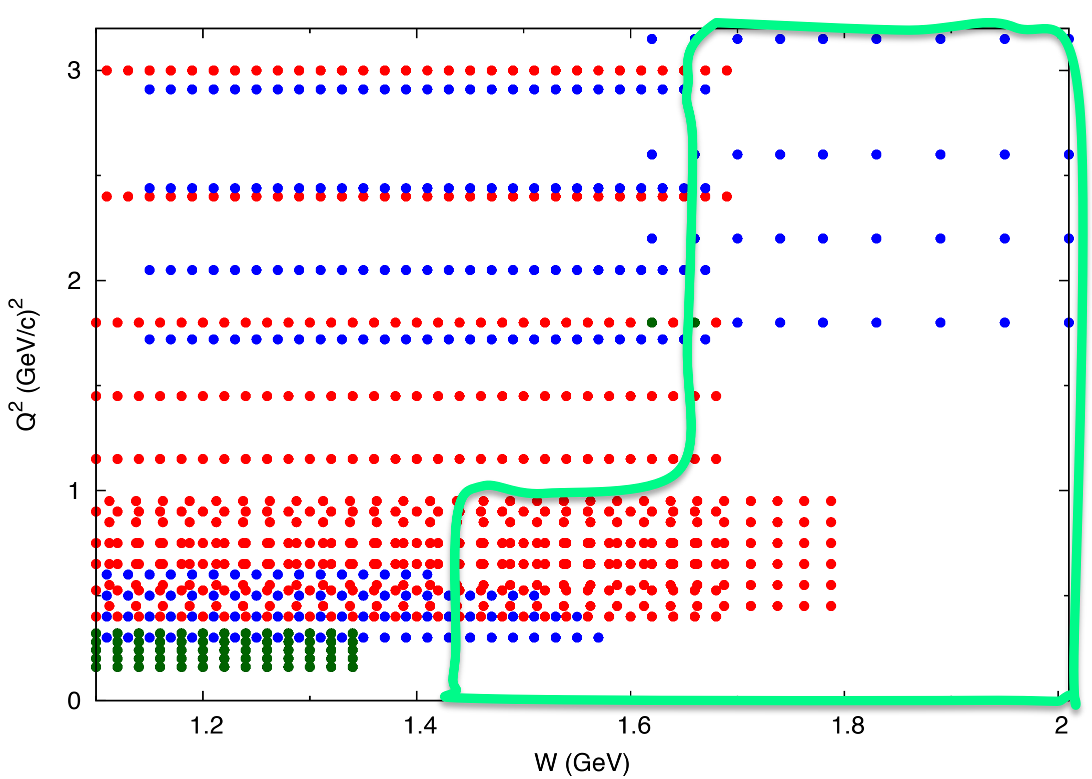
Database

- $p(e,e'\pi^0)p$
- $p(e,e'\pi^+)n$
- both

Analysis of electron-proton scattering data

Purpose : Determine Q^2–dependence of vector coupling of p-N^* : $VpN^*(Q^2)$

Data : * 1π electroproduction



Database

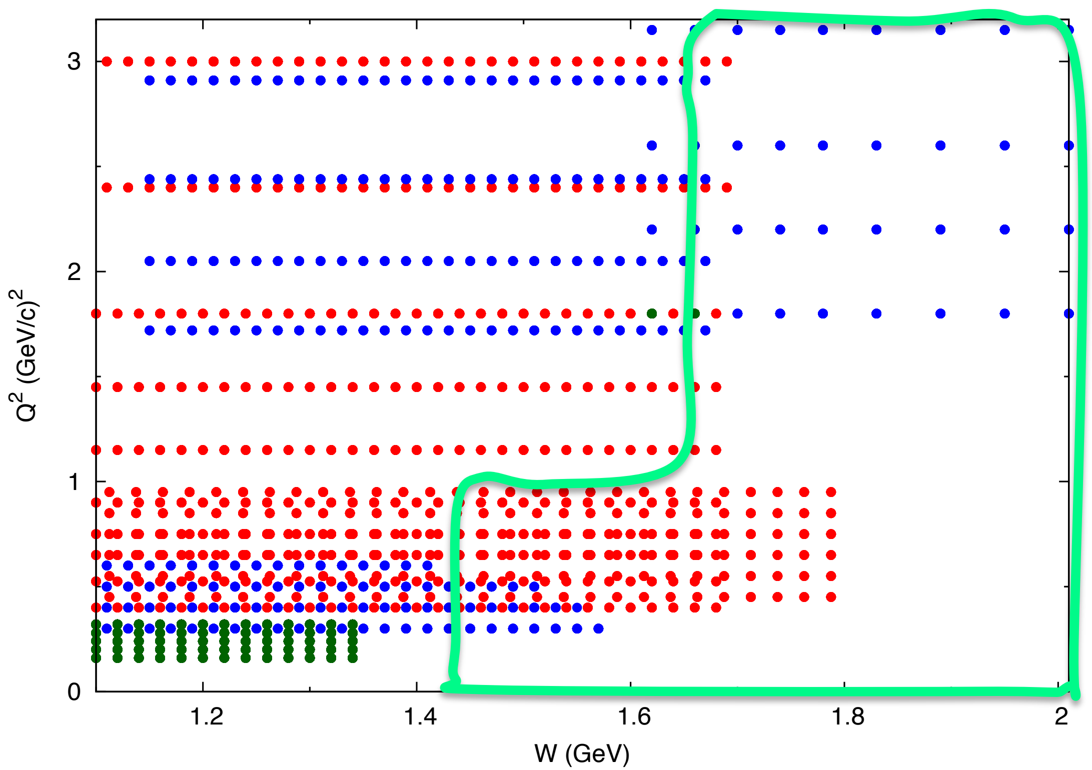
- $p(e,e'\pi^0)p$
- $p(e,e'\pi^+)n$
- both

Analysis of electron-proton scattering data

Purpose : Determine Q^2–dependence of vector coupling of p-N^* : $VpN^*(Q^2)$

Data : * 1π electroproduction

* Empirical inclusive inelastic structure functions σ_T, σ_L ← Christy et al, PRC 81 (2010)



Database

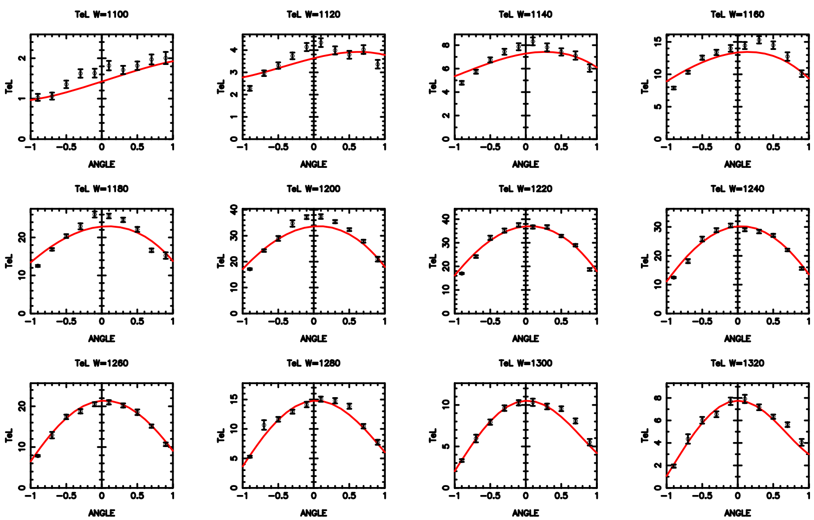
- $p(e,e'\pi^0)p$
- $p(e,e'\pi^+)n$
- both
- region where inclusive σ_T & σ_L are fitted

Analysis result

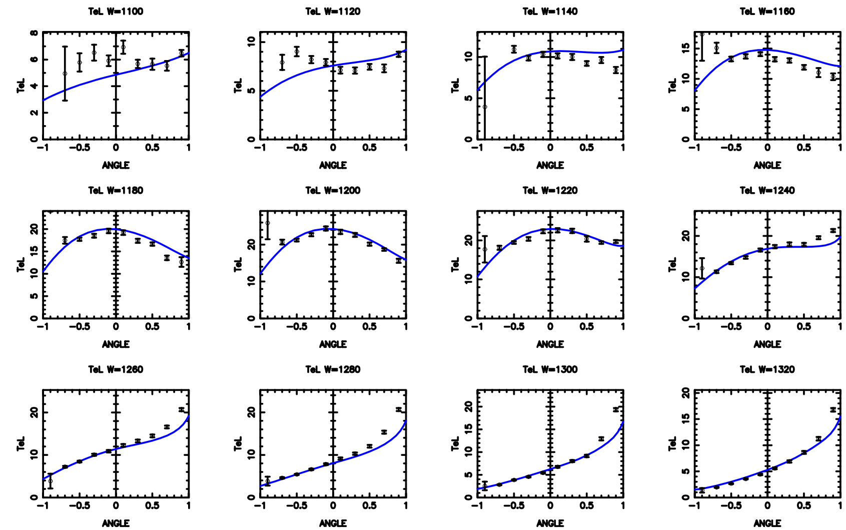
Q^2=0.16 (GeV/c)^2

$\sigma_T + \varepsilon\, \sigma_L$ for W=1.1 - 1.32 GeV

$p(e,e'\pi^0)p$



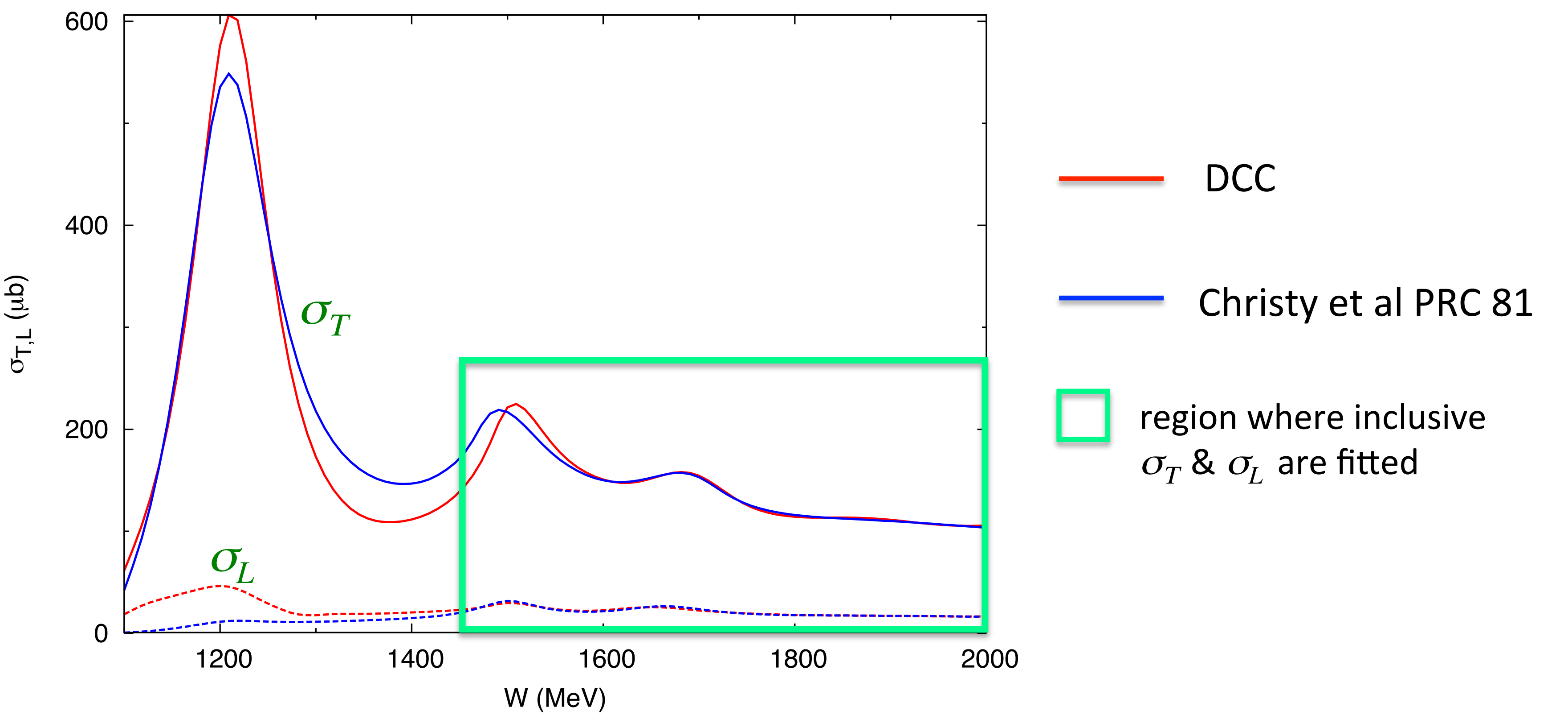
$p(e,e'\pi^+)n$



Analysis result

Q^2=0.16 (GeV/c)^2

σ_T & σ_L (inclusive inelastic)

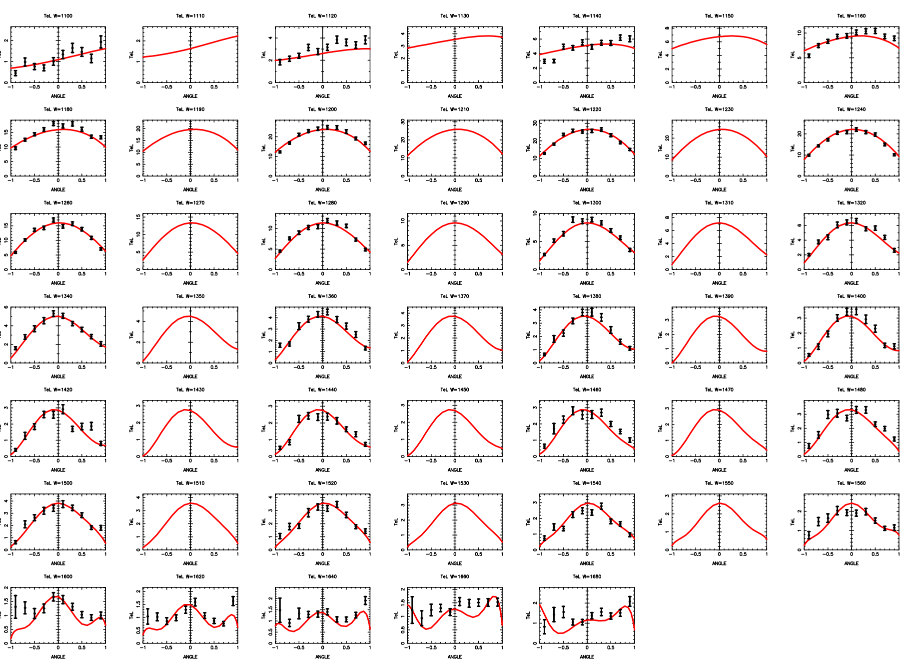


Analysis result

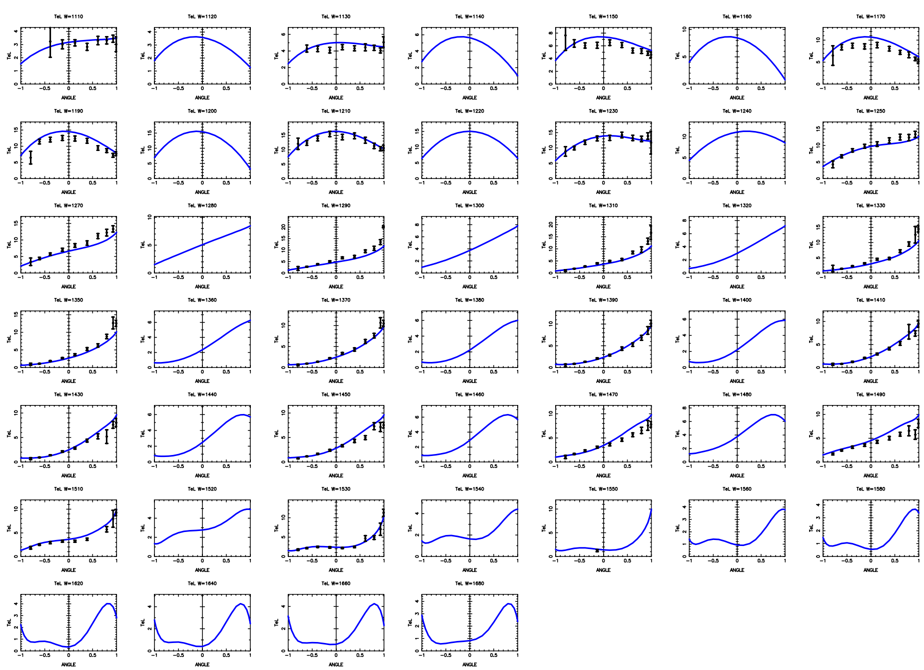
Q^2=0.40 (GeV/c)^2

$\sigma_T + \varepsilon\,\sigma_L$ for W=1.1 – 1.68 GeV

$p(e,e'\pi^0)p$



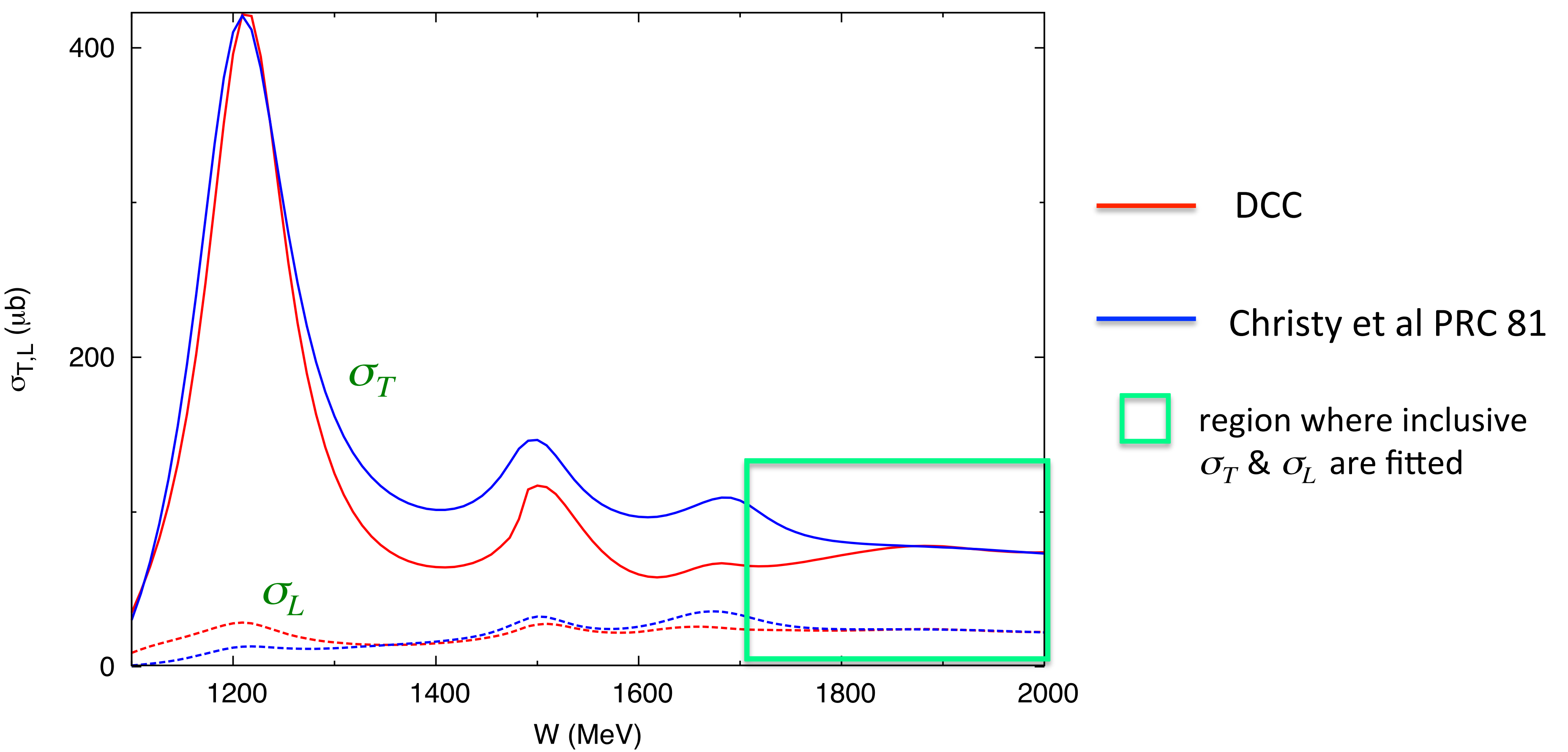
$p(e,e'\pi^+)n$



Analysis result

Q^2=0.40 (GeV/c)^2

σ_T & σ_L (inclusive inelastic)

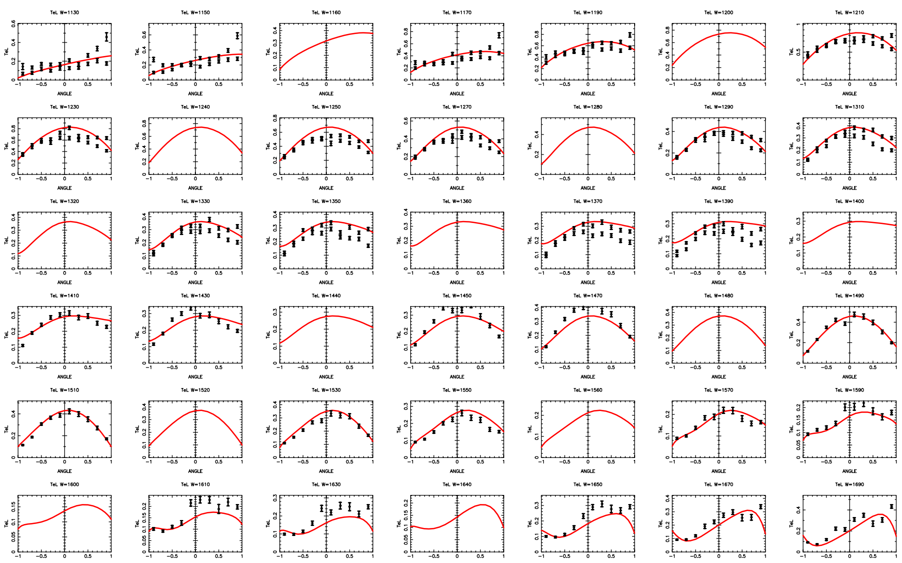


Analysis result

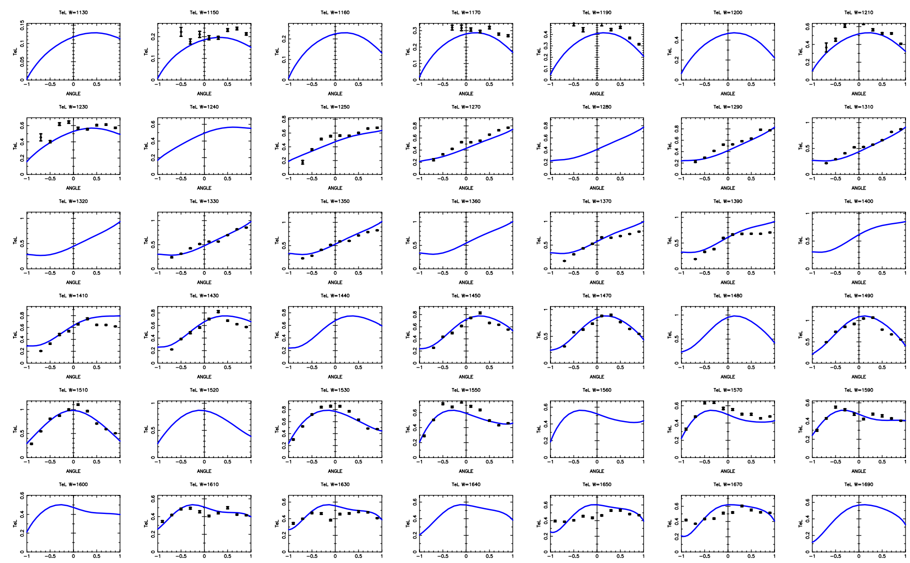
Q^2=2.95 (GeV/c)^2

$\sigma_T + \varepsilon\, \sigma_L$ for W=1.11 – 1.69 GeV

$p(e,e'\pi^0)p$



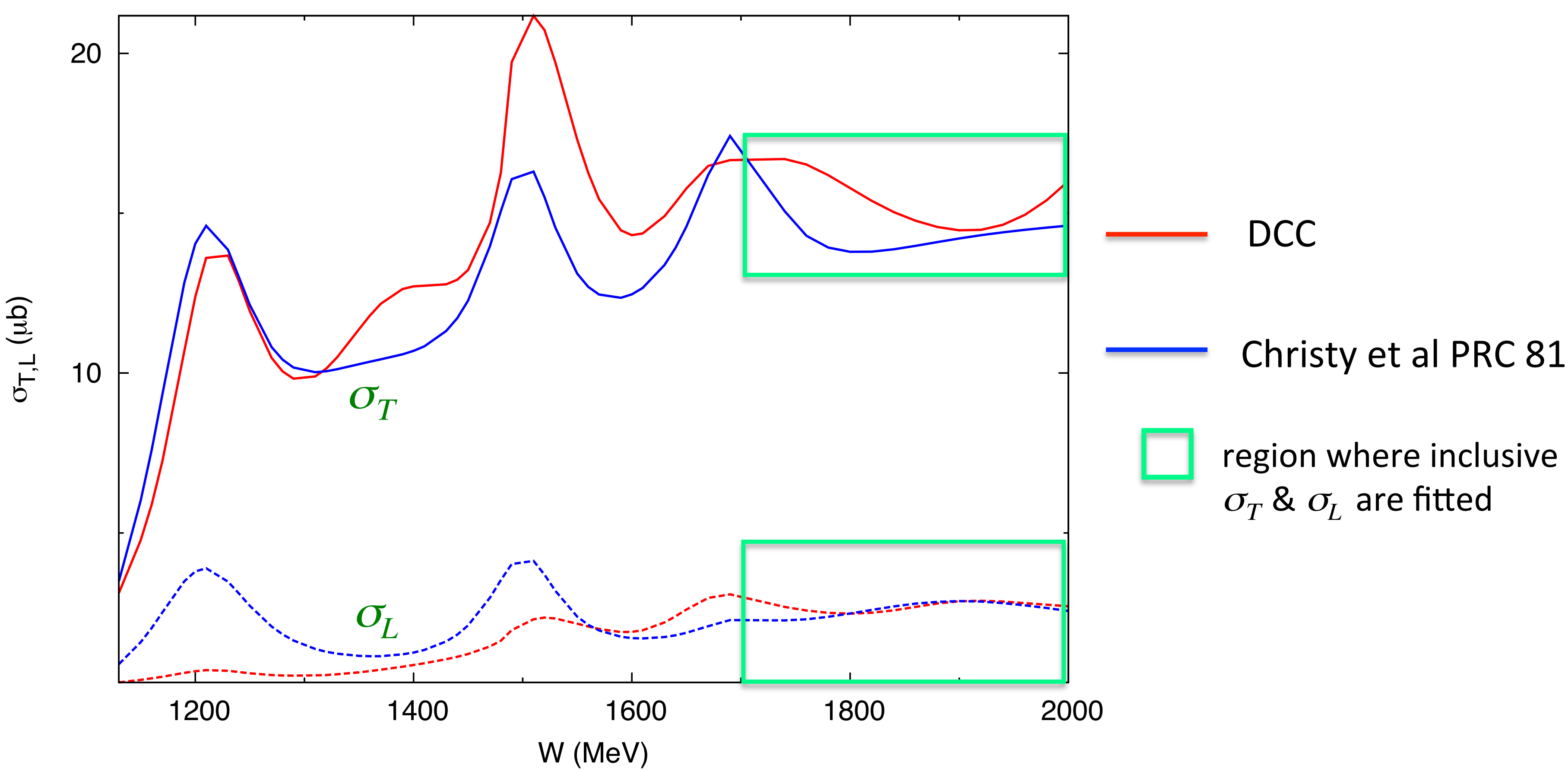
$p(e,e'\pi^+)n$



Analysis result

Q^2=2.95 (GeV/c)^2

σ_T & σ_L (inclusive inelastic)



Analysis of electron-'neutron' scattering data

Purpose : Vector coupling of neutron-N^* and its Q^2 –dependence : $VnN^*(Q^2)$ $(I=1/2)$

$I=3/2$ part has been fixed by proton target data

Data : * 1π photoproduction (Q^2=0)

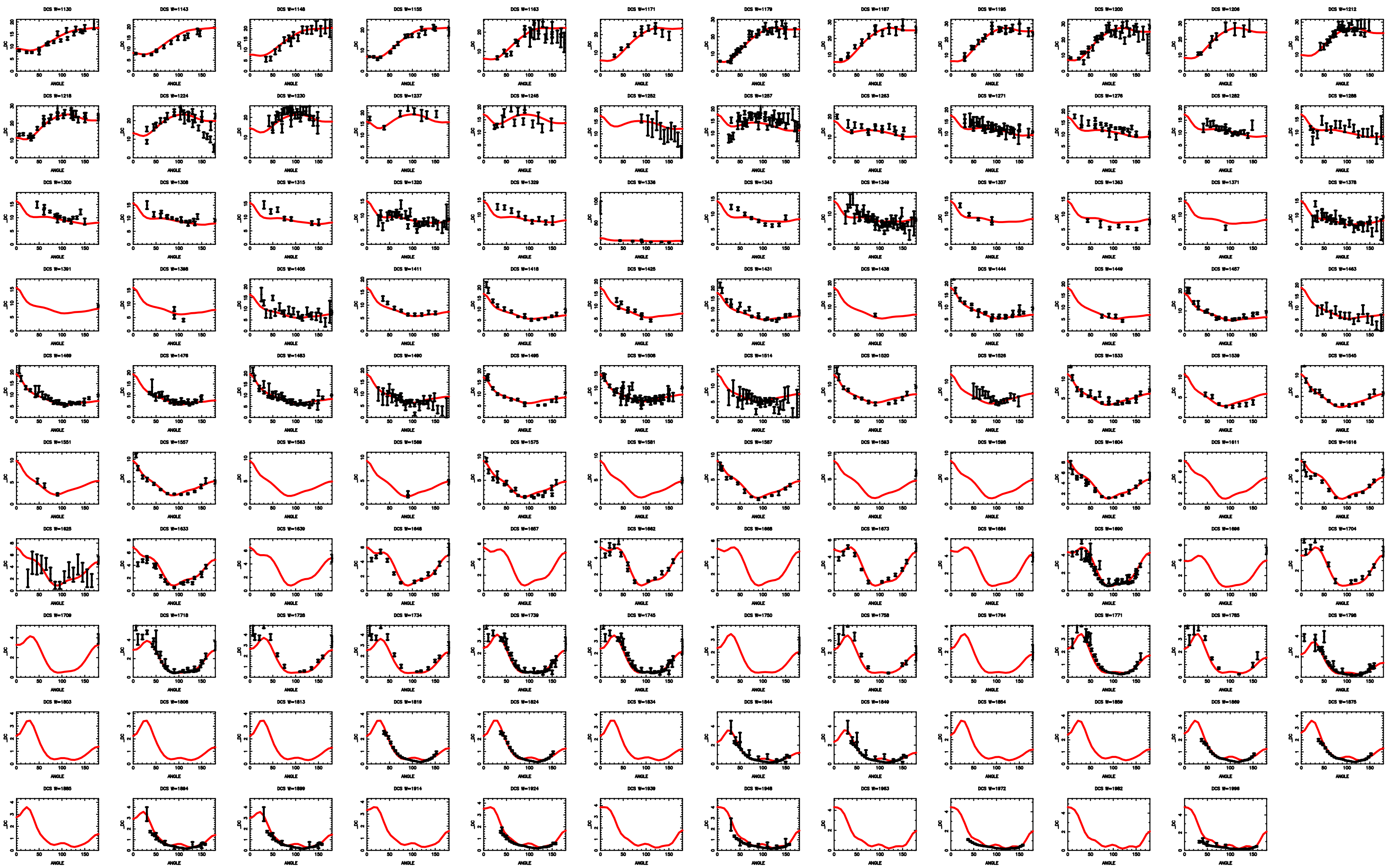
* Empirical inclusive inelastic structure functions σ_T, σ_L ($Q^2 \neq 0$)

← Christy and Bosted, PRC 77 (2010), 81 (2010)

Analysis result

Q^2=0

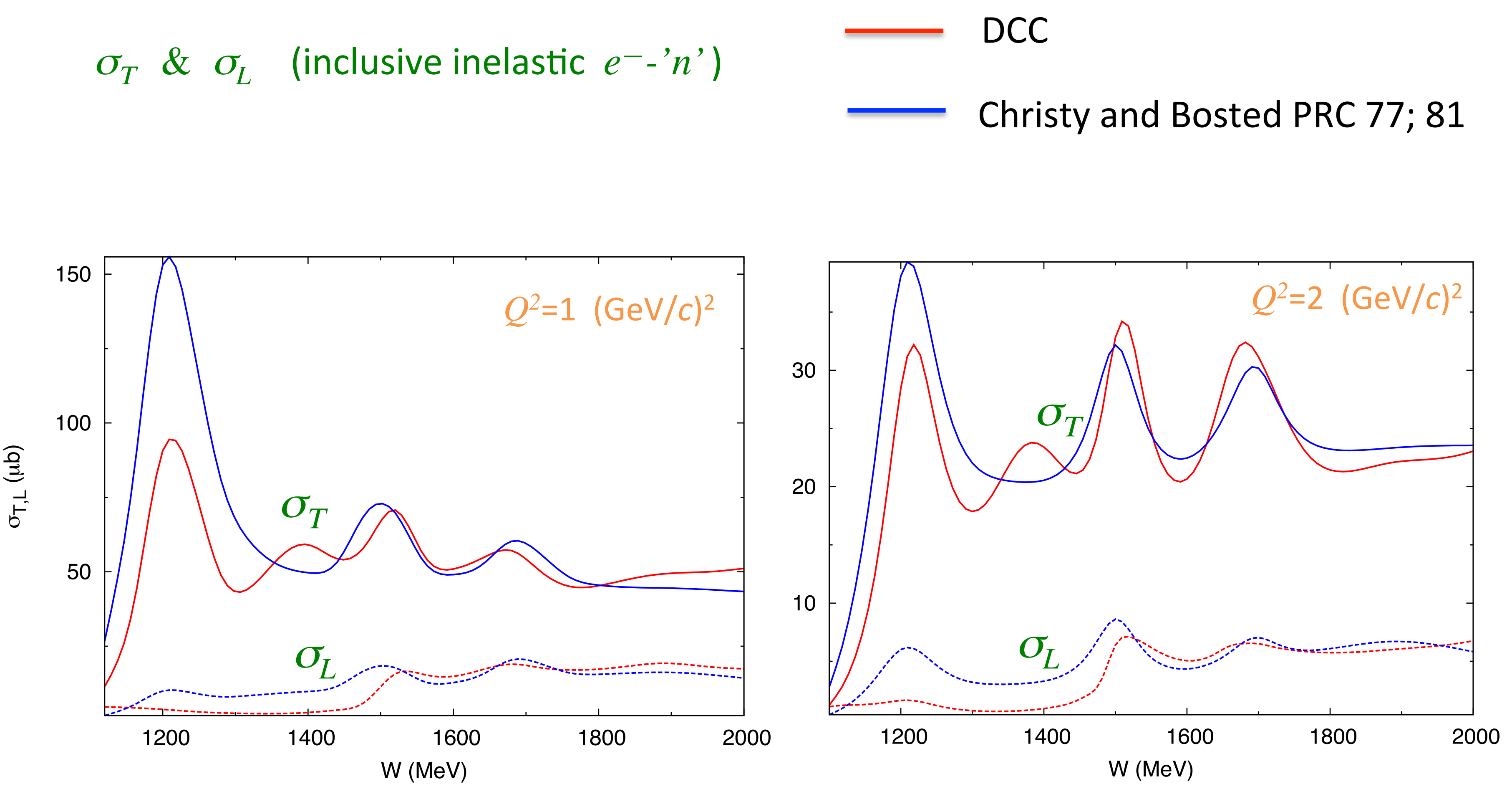
$d\sigma / d\Omega$ $(\gamma n \rightarrow \pi^- p)$ for W=1.1 – 2.0 GeV



Analysis result

$Q^2 \neq 0$

σ_T & σ_L (inclusive inelastic e^--'n')



For application to neutrino interactions

Analysis of electron scattering data

➔ $VpN^*(Q^2)$ & $VnN^*(Q^2)$ fixed for several Q^2 values

➔ Parameterize $VpN^*(Q^2)$ & $VnN^*(Q^2)$ with simple analytic function of Q^2

I=3/2	:	$VpN^*(Q^2) = VnN^*(Q^2)$	➔ CC, NC
I=1/2 isovector part	:	$(\ VpN^*(Q^2) - VnN^*(Q^2)\ )\ /\ 2$	➔ CC, NC
I=1/2 isoscalar part	:	$(\ VpN^*(Q^2) + VnN^*(Q^2)\ )\ /\ 2$	➔ NC

DCC vector currents has been tested by data for whole kinematical region

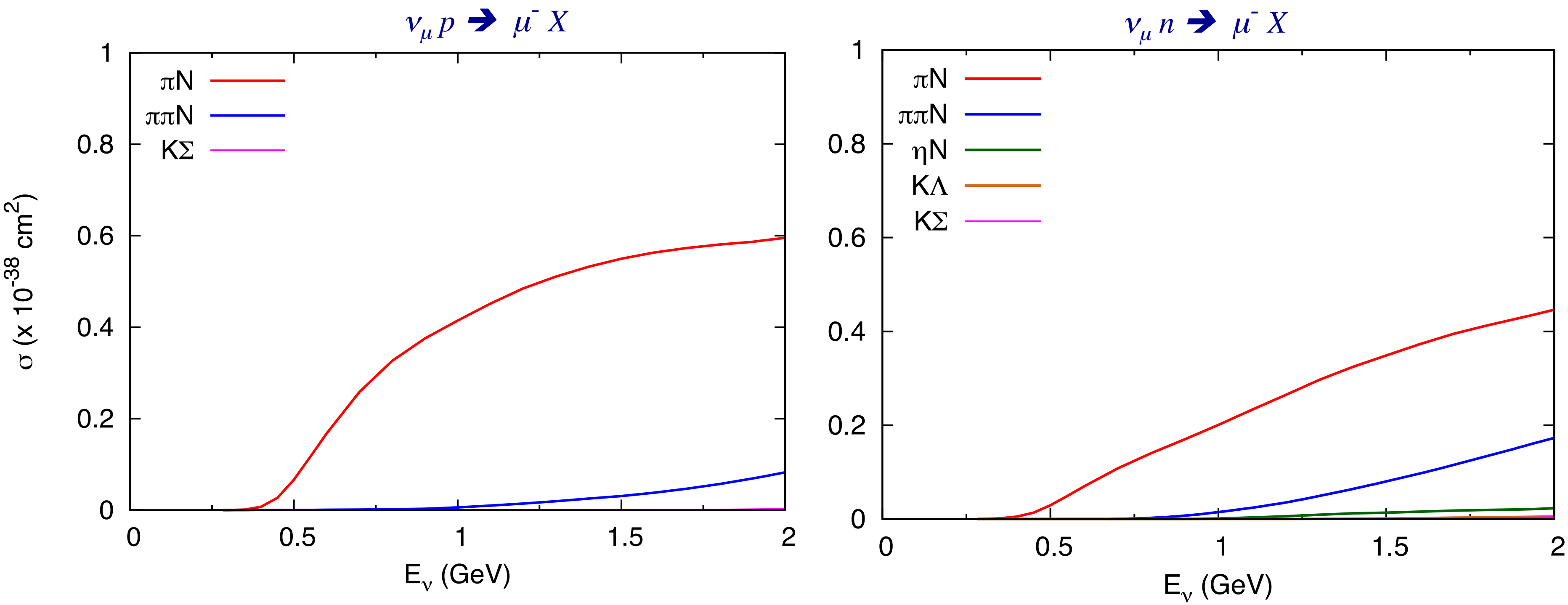
relevant to neutrino interactions of $E_\nu \leq 2$ GeV

Neutrino Results

Caveat repeated

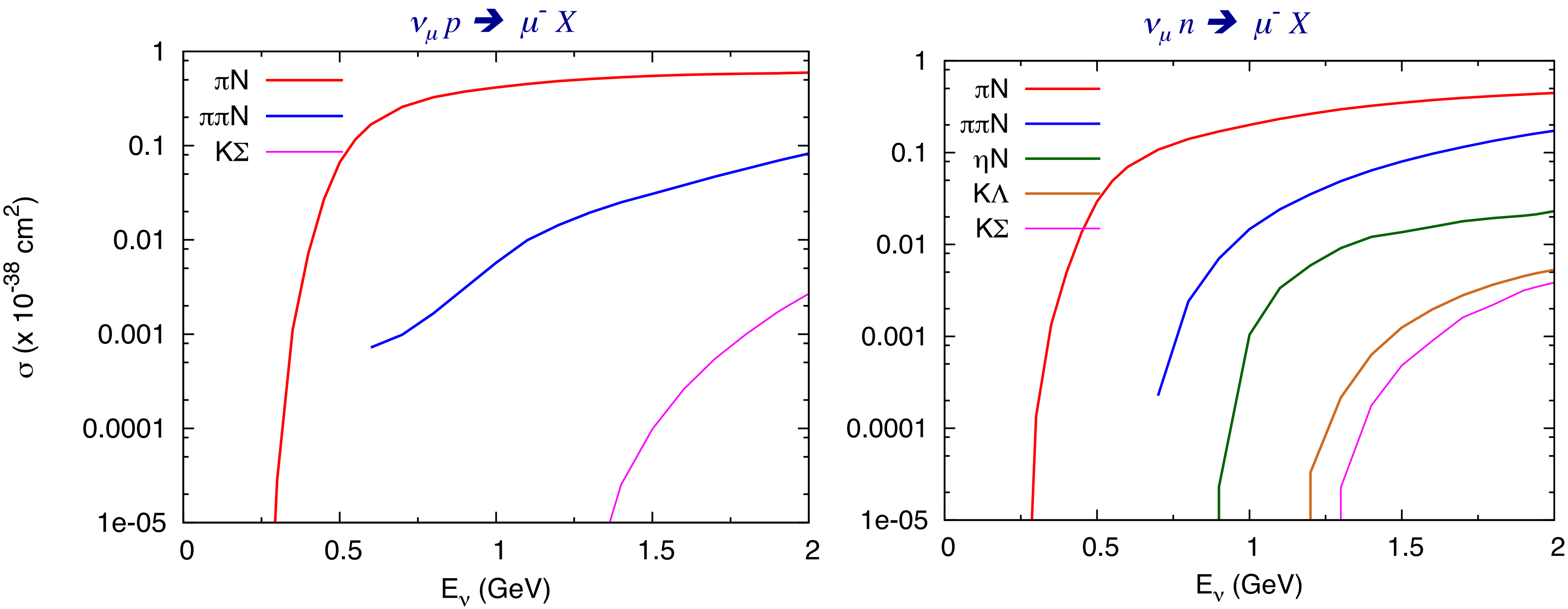
- Axial current used here is not fully consistent with πN interaction of DCC model
- PCAC relation is maintained to some extent
- Results presented here are from first exploratory attempt
- Careful examination needs to be made to obtain a final result

Cross section for $\nu_\mu N \rightarrow \mu^- X$



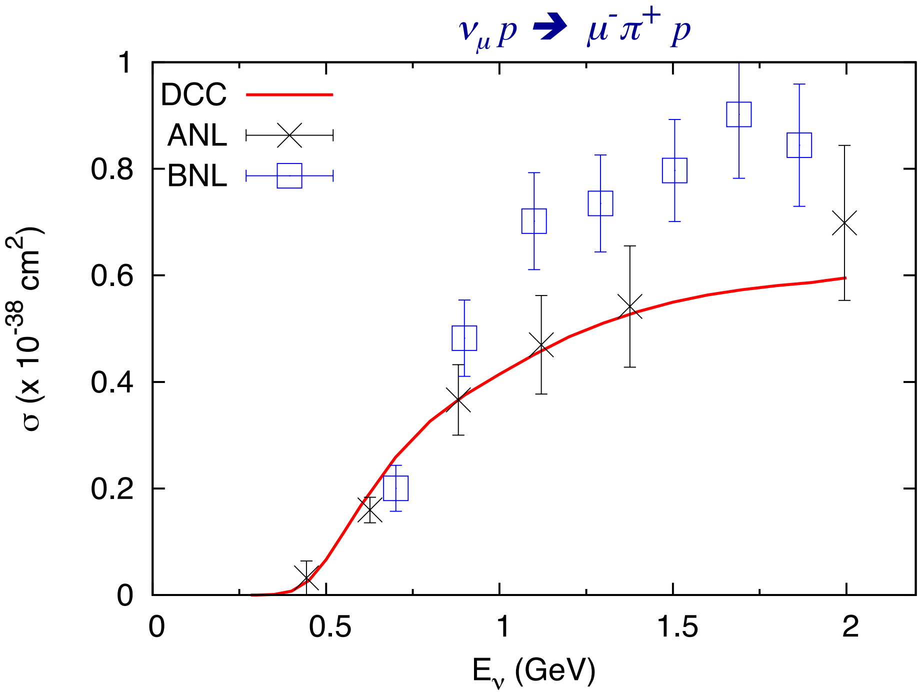
- πN & $\pi\pi N$ are main channels in few-GeV region
- ηN, KY cross sections are $10^{-1} - 10^{-2}$ smaller

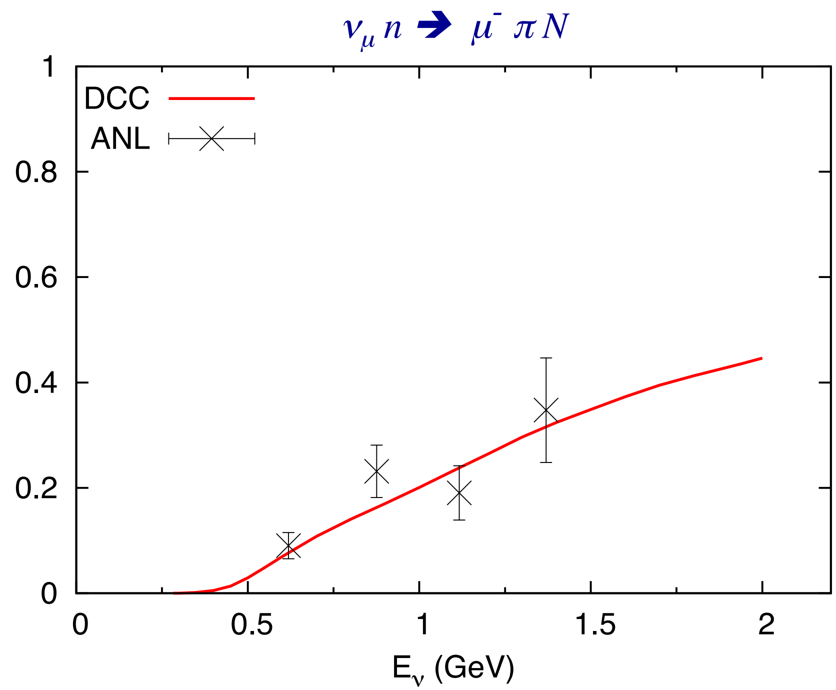
Cross section for $\nu_\mu N \rightarrow \mu^- X$



- πN & $\pi\pi N$ are main channels in few-GeV region
- ηN, KY cross sections are $10^{-1} - 10^{-2}$ smaller

Comparison with $\nu_\mu N \rightarrow \mu^- \pi N$ data



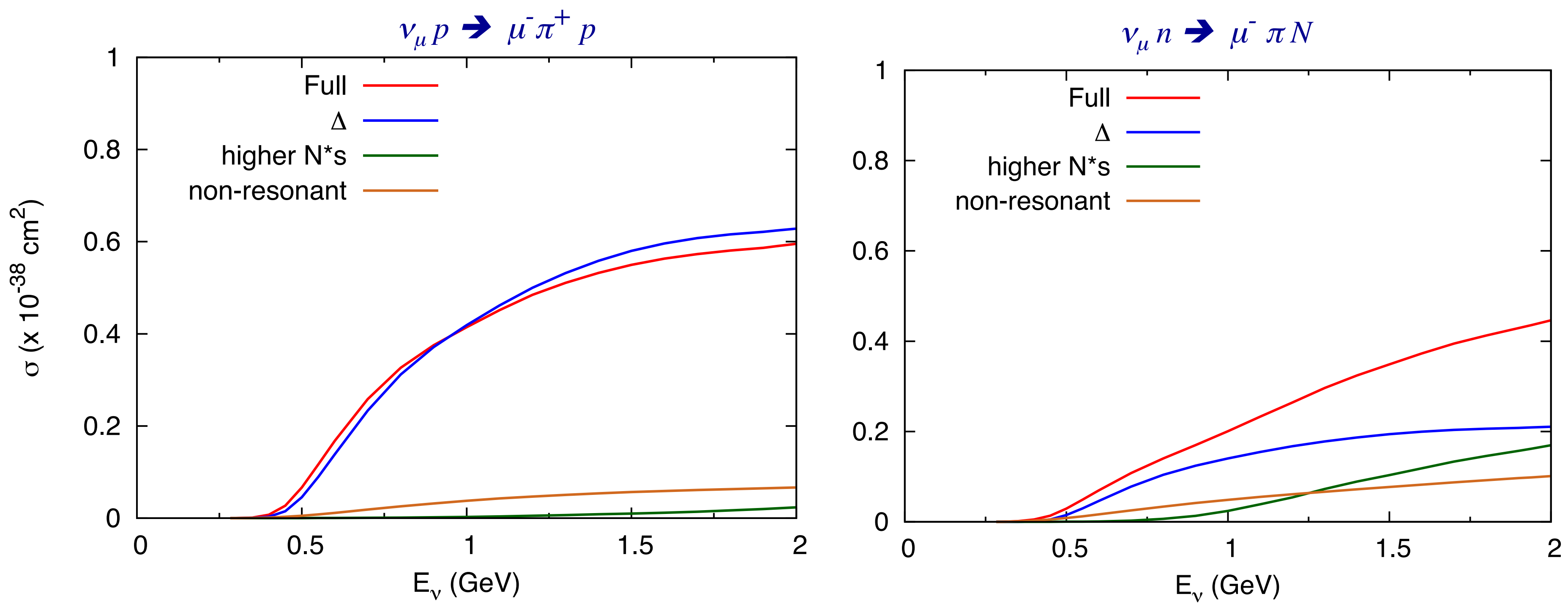


DCC model prediction is consistent with ANL data

ANL Data : PRD **19**, 2521 (1979)
BNL Data : PRD **34**, 2554 (1986)

- DCC model has flexibility to fit data ($ANN^*(Q^2)$)
- Data should be analyzed with nuclear effects

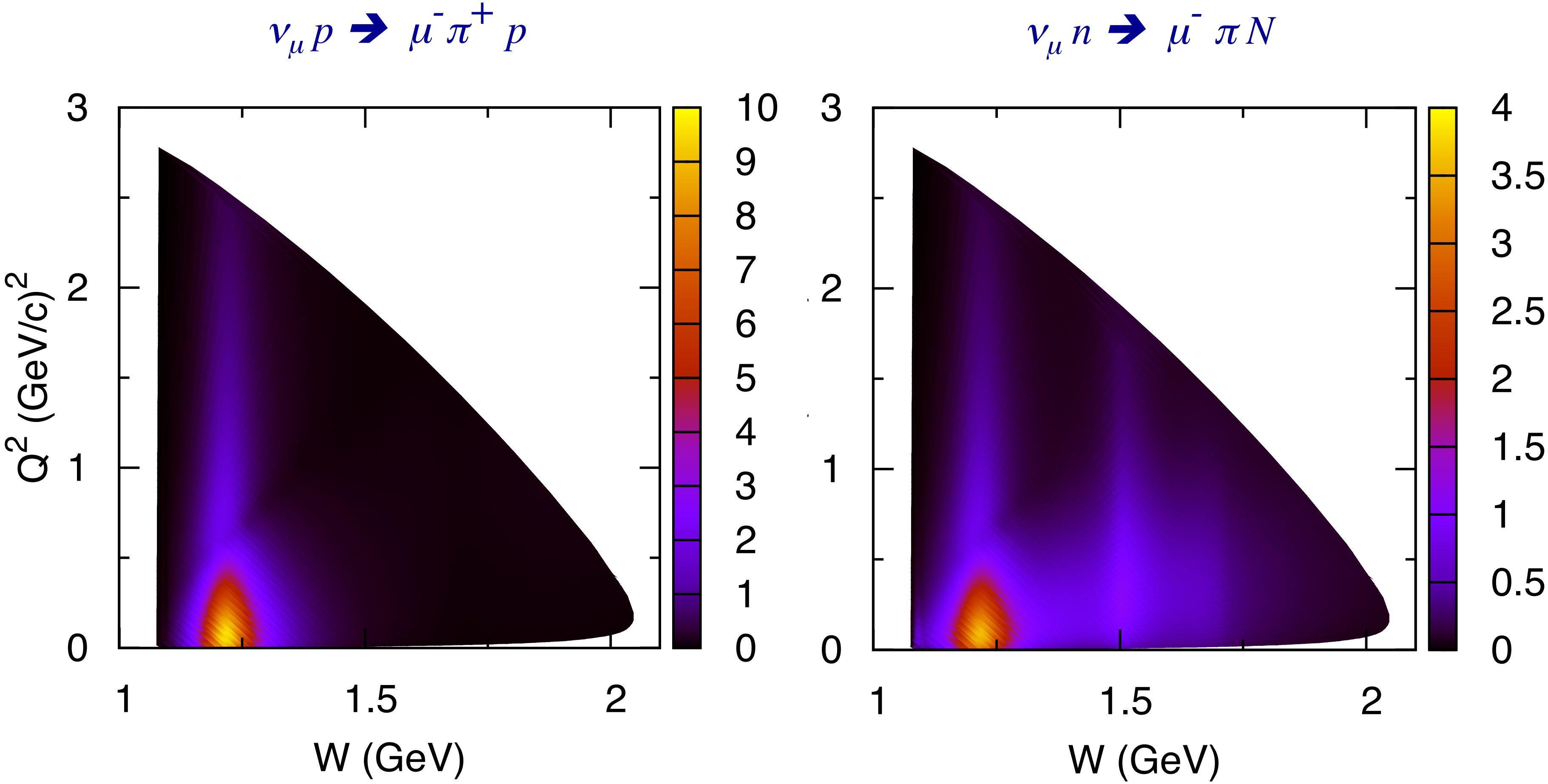
Mechanisms for $\nu_\mu N \rightarrow \mu^- \pi N$



- Δ dominates for $\nu_\mu p \rightarrow \mu^- \pi^+ p$ $(I=3/2)$ for $E_\nu \leq 2$ GeV
- Non-resonant mechanisms contribute significantly
- Higher N^*s becomes important towards $E_\nu \approx 2$ GeV for $\nu_\mu n \rightarrow \mu^- \pi N$

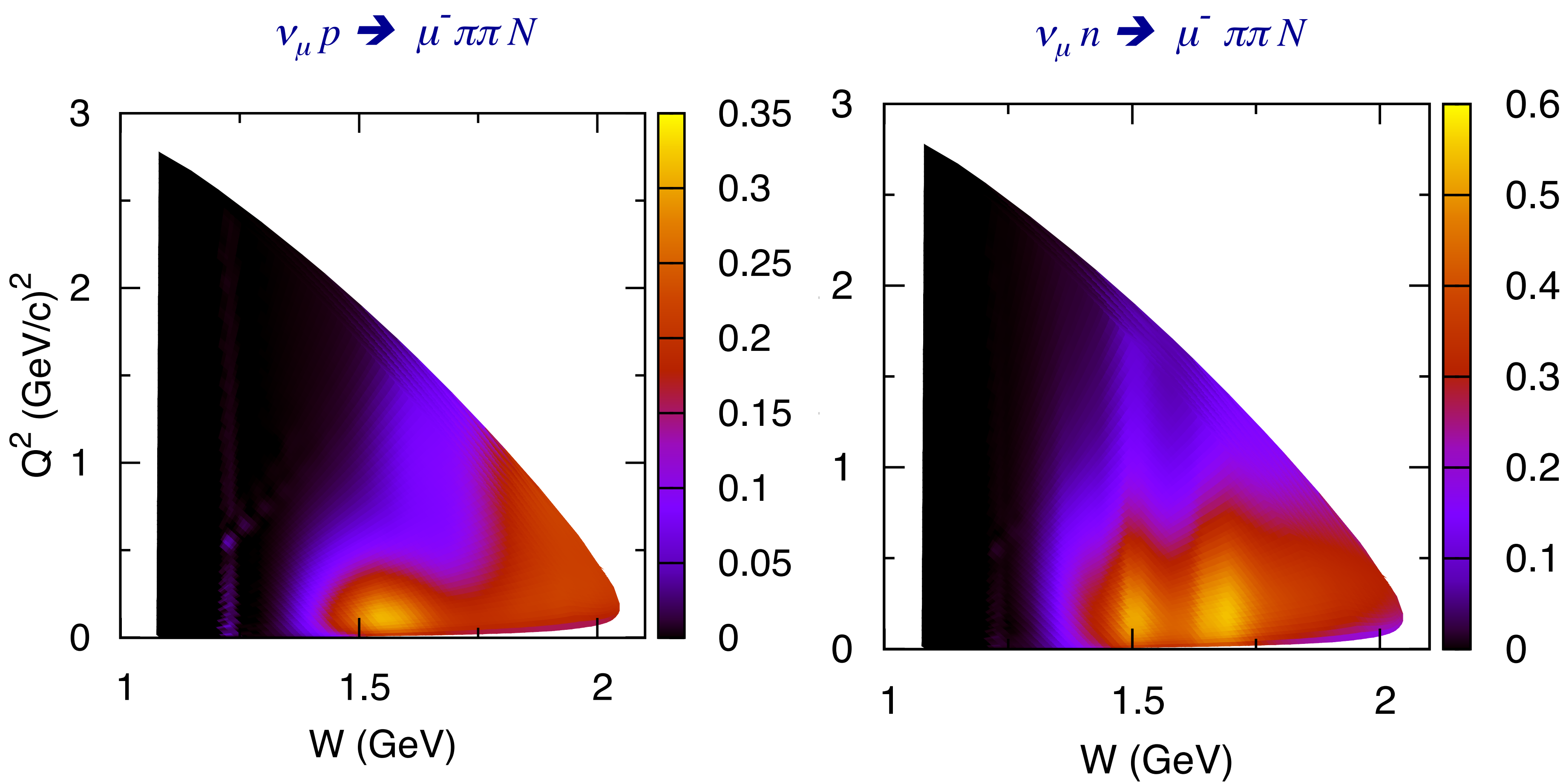
$$d\sigma / dW\, dQ^2 \ (\times 10^{-38}\, \mathrm{cm}^2 / \mathrm{GeV}^2)$$

E_ν = 2 GeV



$d\sigma / dW\, dQ^2$ ($\times 10^{-38}$ cm^2 / GeV^2)

E_ν = 2 GeV



Conclusion

Development of DCC model for νN interaction in resonance region

Start with DCC model for γN, πN ➔ πN, $\pi\pi N$, ηN, $K\Lambda$, $K\Sigma$

➔ extension of vector current to $Q^2 \neq 0$ region, isospin separation

through analysis of $e^- - p$ & $e^- -$'n' data for $W \leq 2$ GeV , $Q^2 \leq 3$ (GeV/c)^2

➔ Development of axial current for νN interaction; more study needed

Conclusion

- πN & $\pi\pi N$ are main channels in few-GeV region
- DCC model prediction is consistent with ANL data
- Δ, N^*s, non-resonant are all important in few-GeV region (for $\nu_\mu n$ ➔ $\mu^- X$)

➔ essential to understand interference pattern among them

➔ DCC model can do this; consistency between π interaction and axial current

BACKUP

Formalism

Cross section for $\nu N \rightarrow l\, X$ ($X = \pi N, \pi\pi N, \eta N, K\Lambda, K\Sigma$)

$\theta \rightarrow 0$

$$\frac{d\sigma}{dE_\ell d\Omega_\ell} = \frac{G_F^2}{2\pi^2} E_\ell^2 \left(2W_1 \sin^2\frac{\theta}{2} + W_2 \cos^2\frac{\theta}{2} \pm W_3 \frac{E_\nu + E_\ell}{m_N} \sin^2\frac{\theta}{2} \right)$$

$Q^2 \rightarrow 0$

$$W_2 = \frac{Q^2}{\vec{q}^2} \sum \left[\frac{1}{2}\left(|\langle J^x \rangle|^2 + |\langle J^y \rangle|^2\right) + \frac{Q^2}{\vec{q}_c^2} \left| \left\langle J^0 + \frac{\omega_c}{Q^2} q \cdot J \right\rangle \right|^2 \right]$$

CVC & PCAC

$$\langle q \cdot J \rangle = \langle q \cdot V \rangle - \langle q \cdot A \rangle = i f_\pi m_\pi^2 \langle \hat{\pi} \rangle$$

LSZ & smoothness

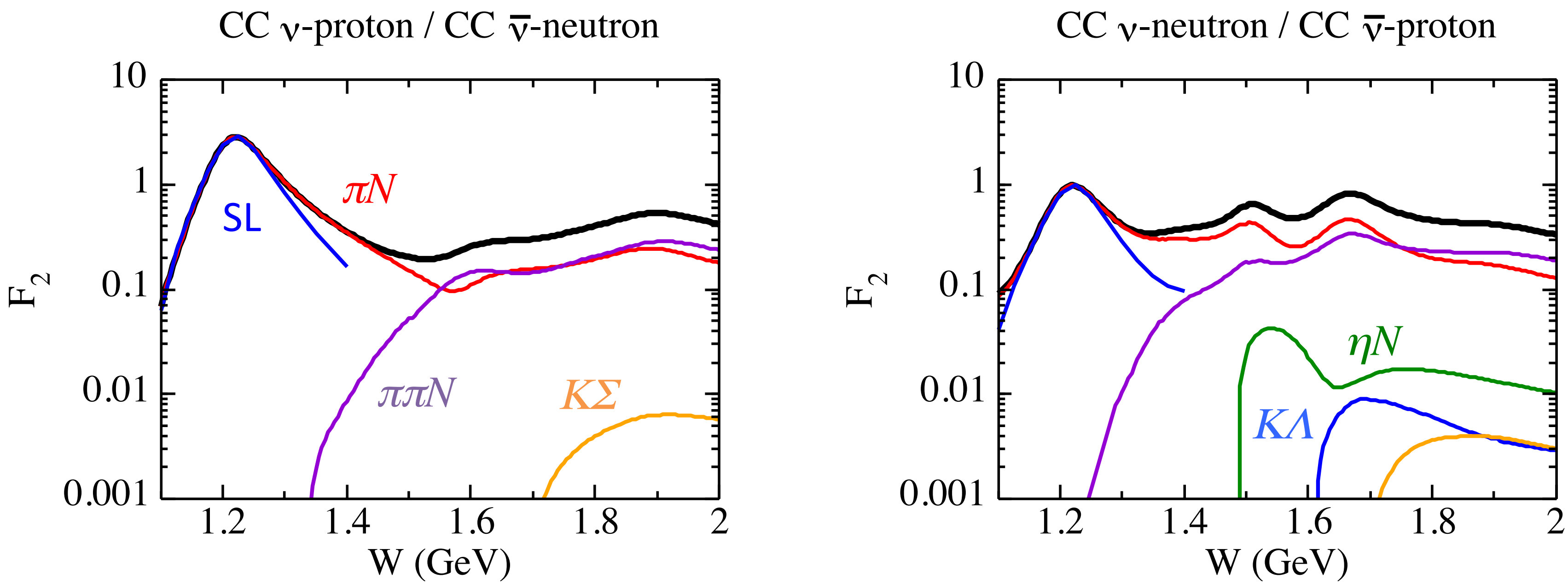
$$\langle X | \hat{\pi} | N \rangle = \frac{\sqrt{2\omega_c}}{m_\pi^2} \mathcal{T}_{\pi N \to X}(0) \sim \frac{\sqrt{2\omega_c}}{m_\pi^2} \mathcal{T}_{\pi N \to X}(m_\pi^2)$$

Finally

$$F_2 \equiv \omega W_2 = \frac{2 f_\pi^2}{\pi} \sigma_{\pi N \to X}$$

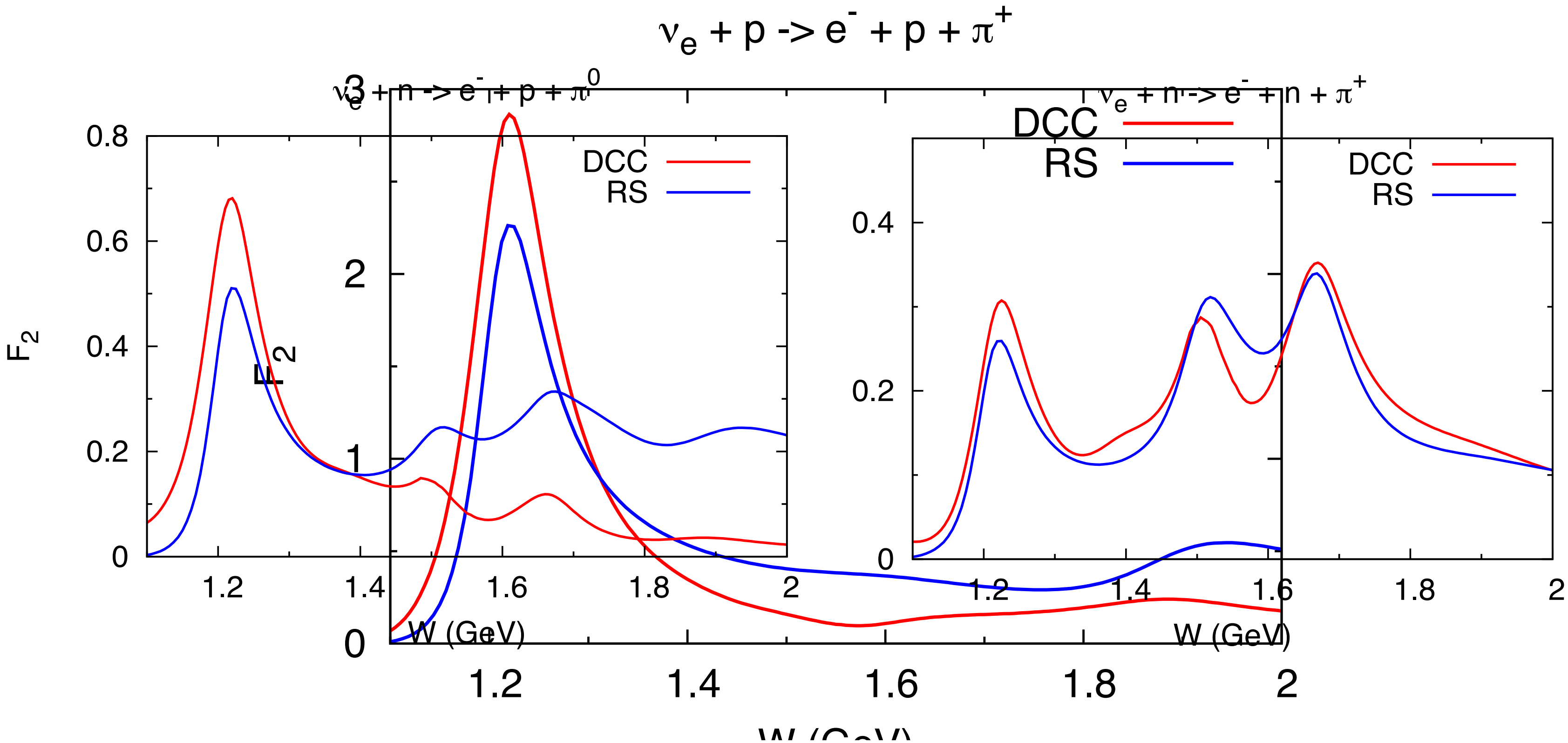
$\sigma_{\pi N \rightarrow X}$ is from our DCC model

Results



- Prediction based on model well tested by data (first $\nu N \rightarrow \pi\pi N$)
- πN dominates for $W \leq 1.5$ GeV
- $\pi\pi N$ becomes comparable to πN for $W \geq 1.5$ GeV
- Smaller contribution from ηN and KY $O(10^{-1})$ - $O(10^{-2})$
- Agreement with SL (no PCAC) in Δ region

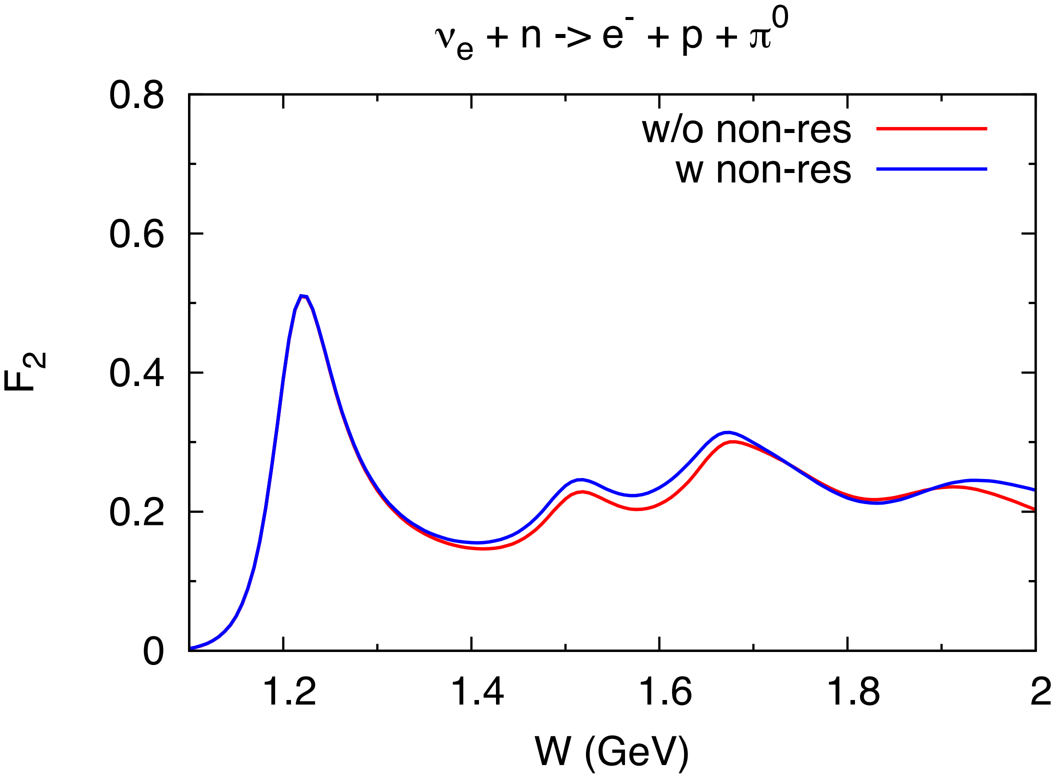
Comparison with Rein-Sehgal model



Comparison in whole kinematical region will be done

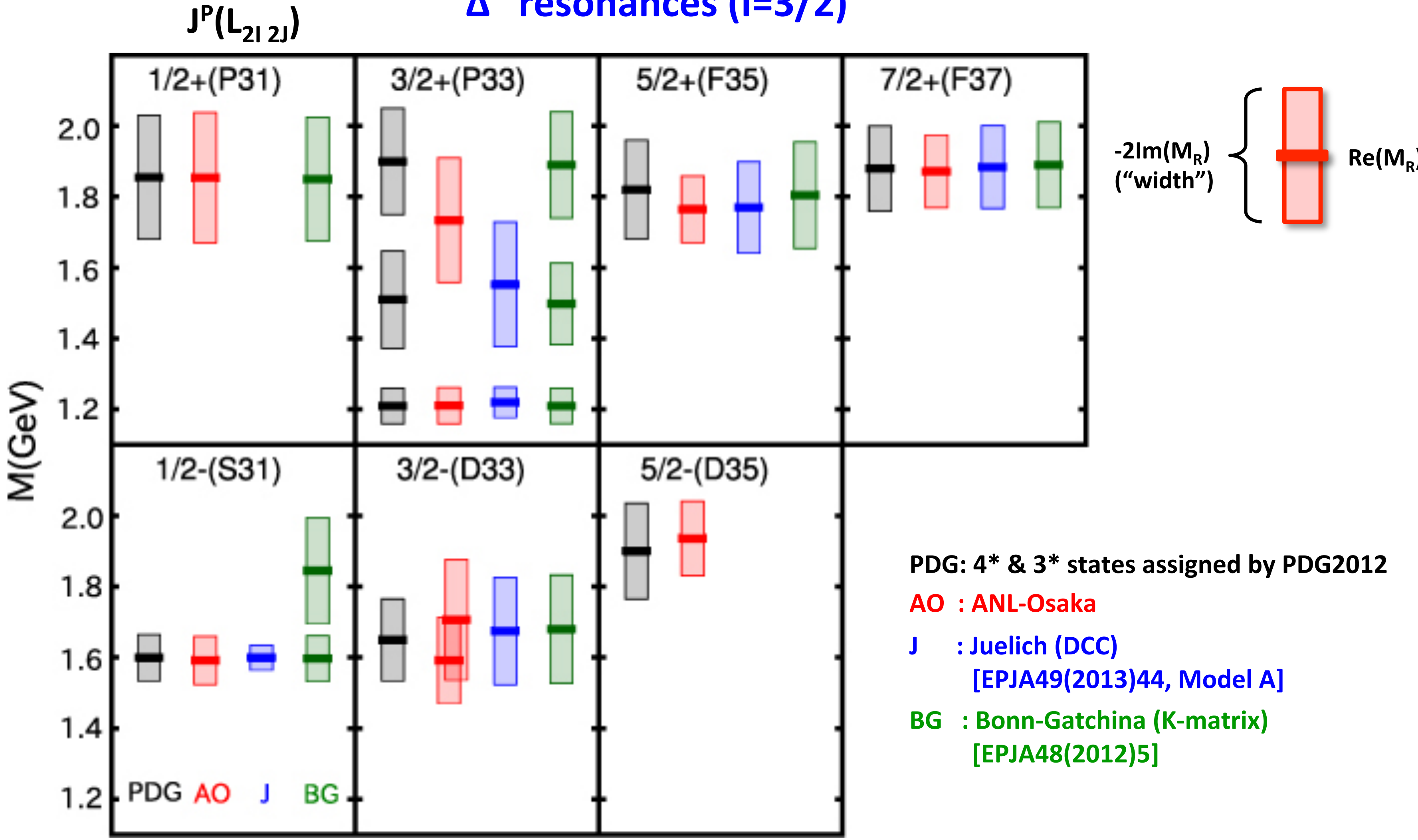
after axial current model is developed

F_2 from RS model



Kamano, Nakamura, Lee, Sato, arXiv:1305.4351

"Δ" resonances (I=3/2)



PDG: 4* & 3* states assigned by PDG2012

AO : ANL-Osaka

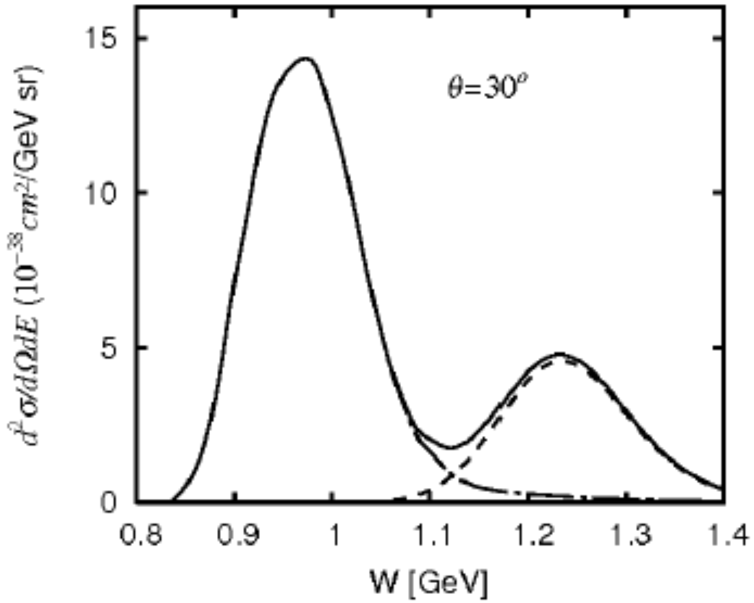
J : Juelich (DCC) [EPJA49(2013)44, Model A]

BG : Bonn-Gatchina (K-matrix) [EPJA48(2012)5]

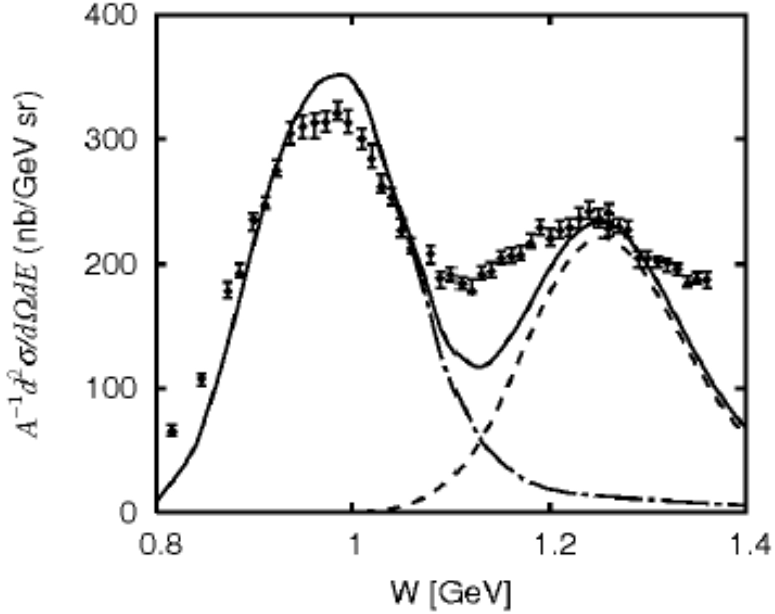
SL model applied to ν−nucleus scattering

1 π production

$\nu_e + {}^{12}\mathrm{C} \to e^- + X \ (E_\nu = 1 \text{ GeV})$



$e^- + {}^{12}\mathrm{C} \to e^- + X \ (E_e = 1.1 \text{ GeV})$



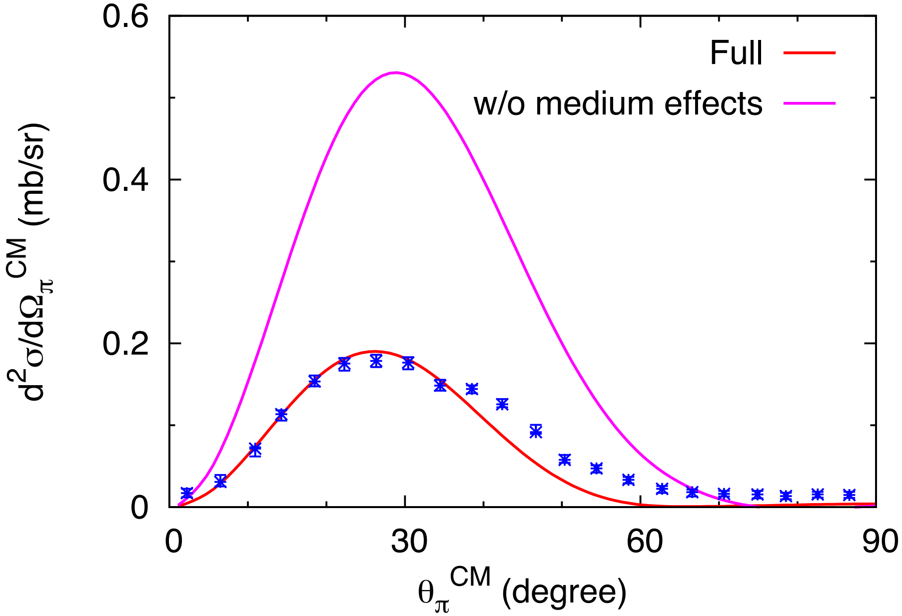
Szczerbinska et al. (2007)

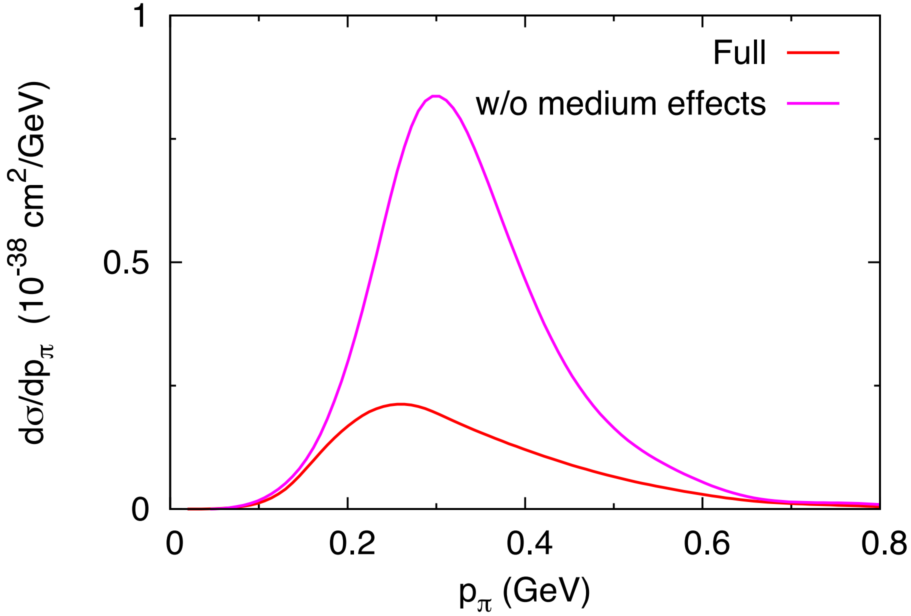
SL model applied to ν−nucleus scattering

coherent π production

$\gamma + {}^{12}\mathrm{C} \rightarrow \pi^0 + {}^{12}\mathrm{C}$

$\nu_\mu + {}^{12}\mathrm{C} \rightarrow \mu^- + \pi^0 + {}^{12}\mathrm{C}$





Nakamura et al. (2010)

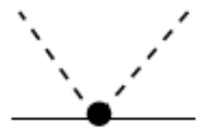
DCC (Dynamical Coupled-Channel) model

Matsuyama et al., Phys. Rep. **439**, 193 (2007)

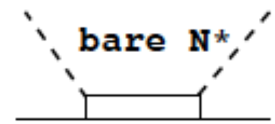
Coupled-channel Lippmann-Schwinger equation

$$T_{ab} = V_{ab} + \sum_c V_{ac}\, G_c\, T_{cb}$$

$\mathbf{V_{ab}}$ =



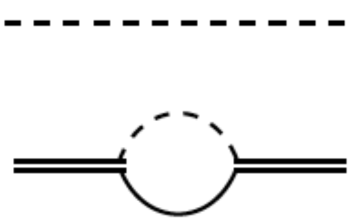
+



\+ **Z**

G_c =

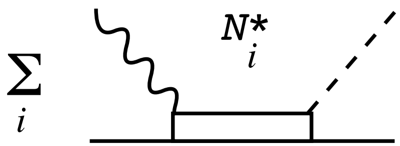
for stable channels



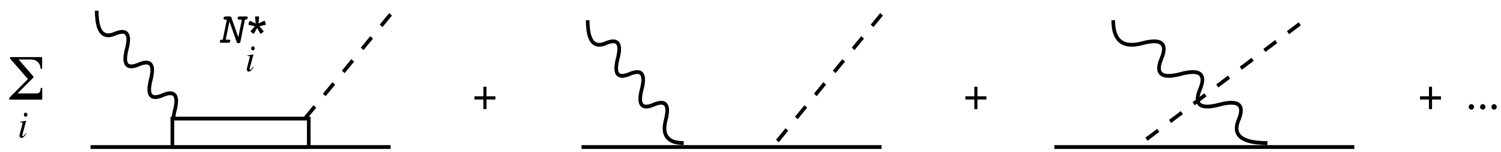
for unstable channels

Previous models for ν–induced 1π production in resonance region

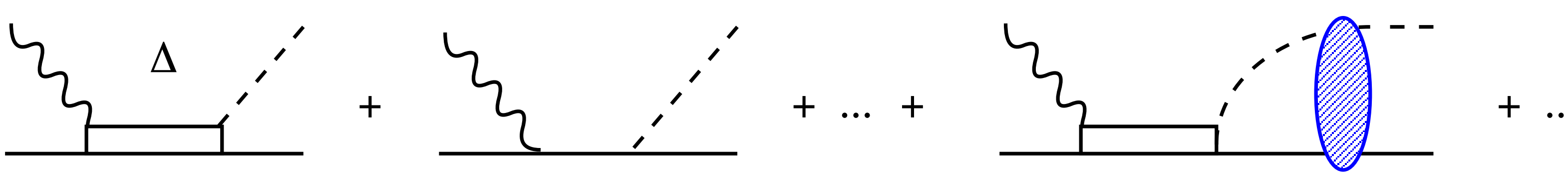
resonant only Rein et al. (1981), (1987) ; Lalalulich et al. (2005), (2006)



+ non-resonant (tree-level) Hernandez et al. (2007), (2010) ; Lalakulich et al. (2010)

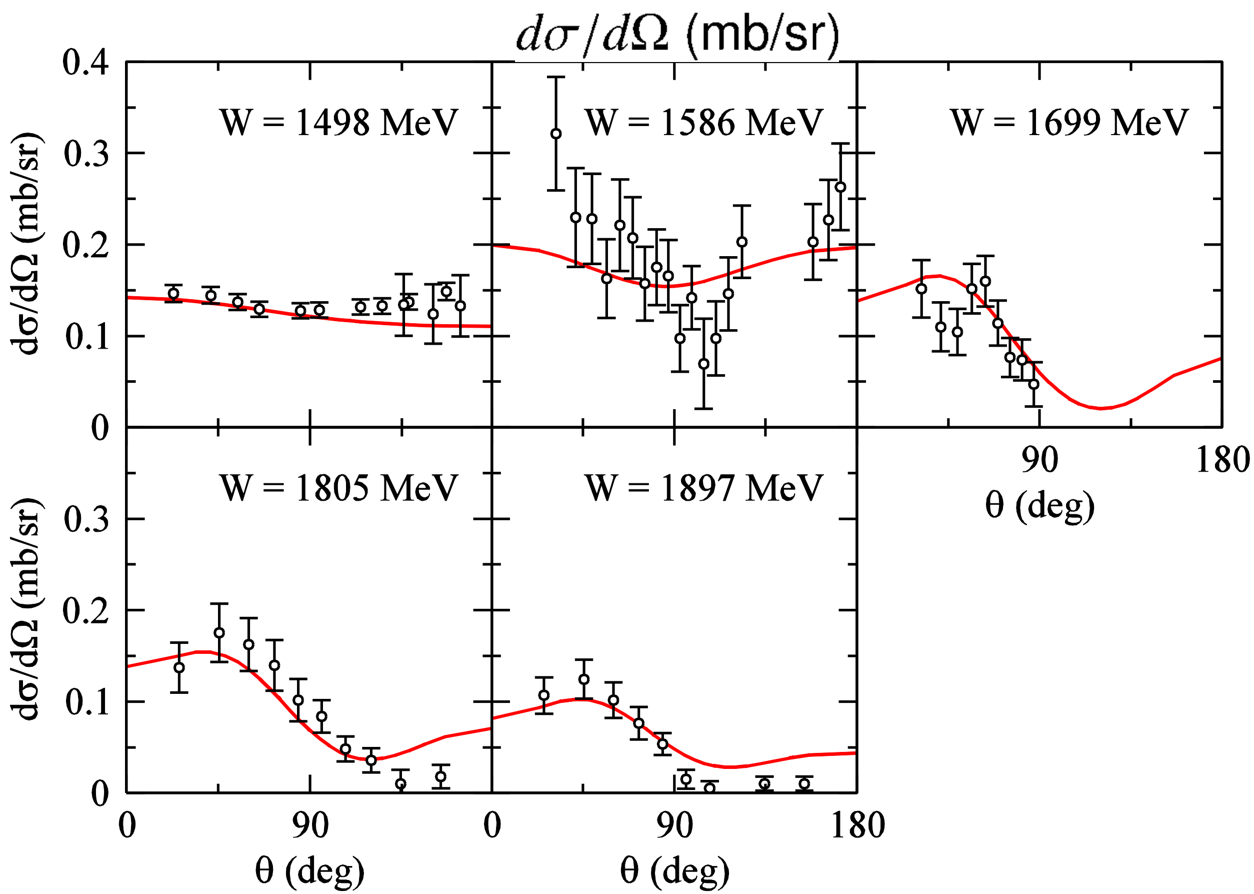


+ rescattering (πN unitarity) Sato, Lee (2003), (2005)

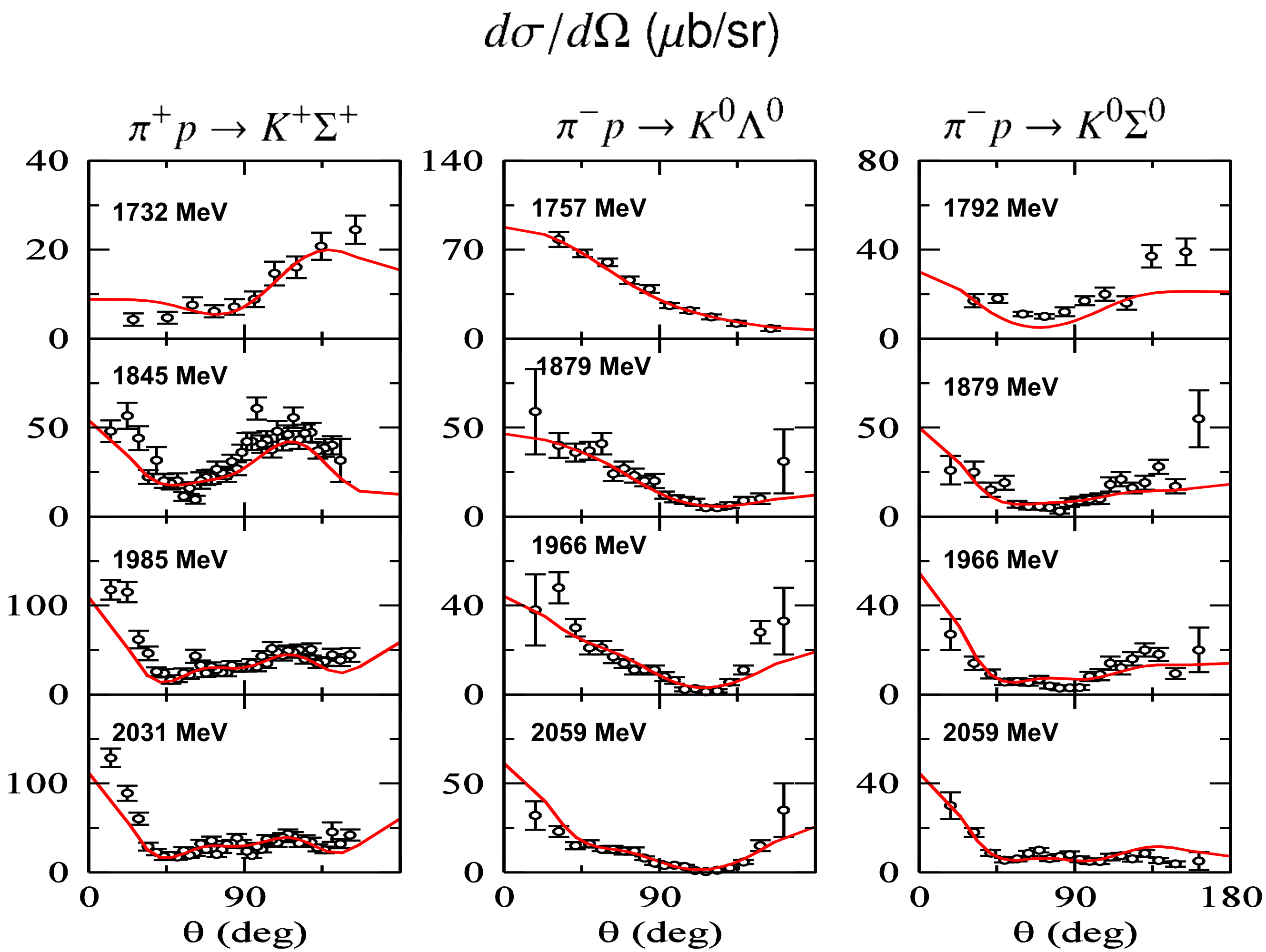


Eta production reactions

$$\pi^- p \to \eta n$$



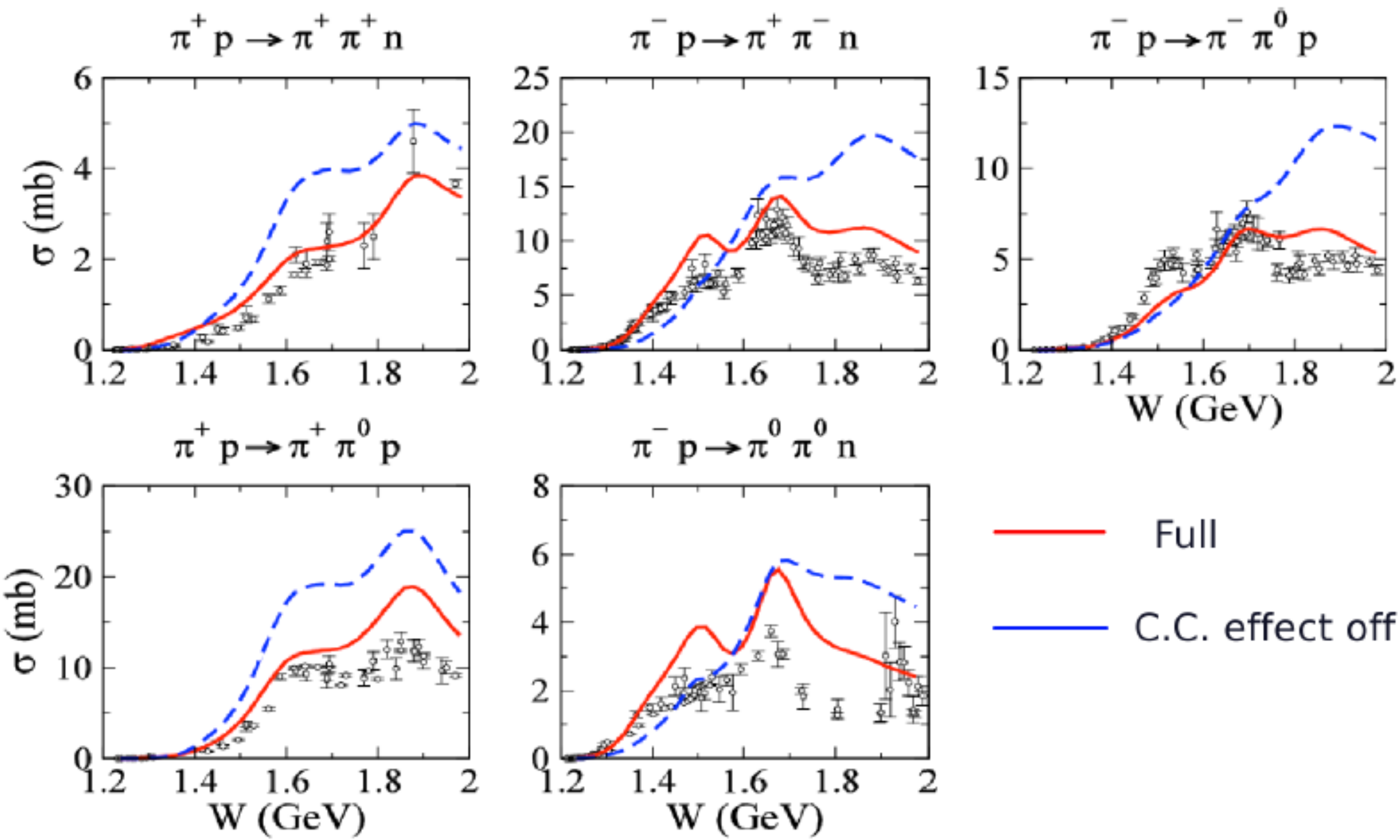
KY production reactions



$\pi N \rightarrow \pi\pi N$

(parameters had been fitted to $\pi N \rightarrow \pi N$)

Kamano, Julia-Diaz, Lee, Matsuyama, Sato, PRC79 025206 (2009)



DCC analysis of meson production data

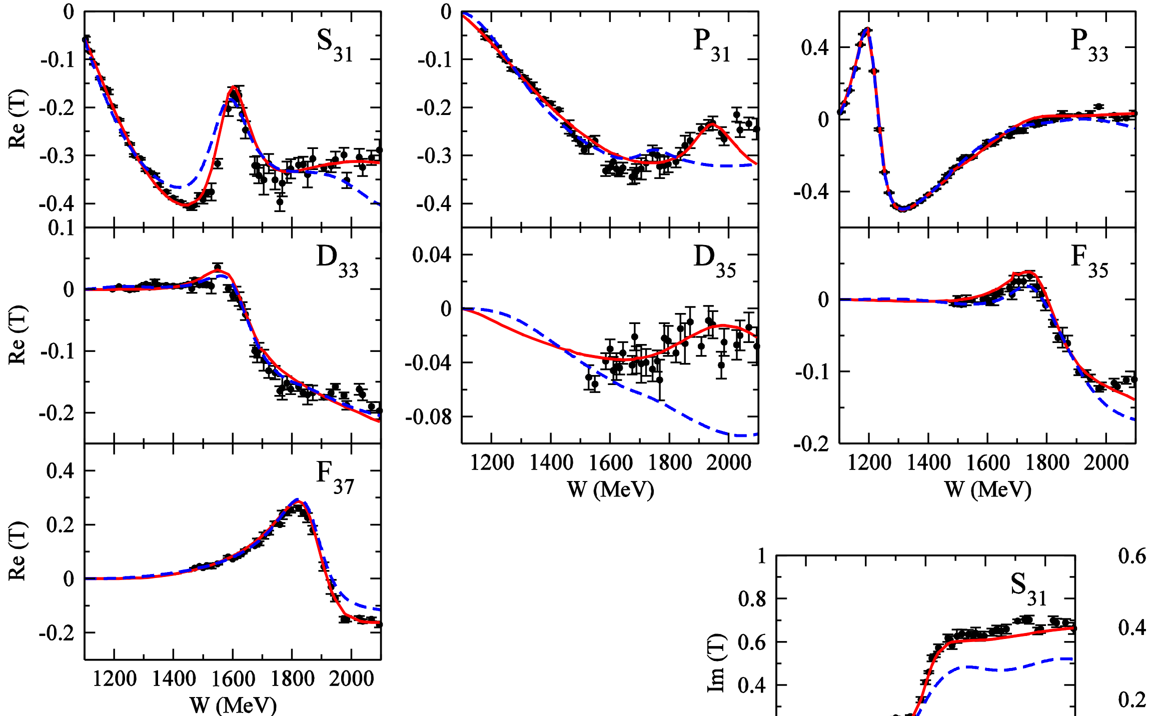
Fully combined analysis of γN, πN ➔ πN, ηN, $K\Lambda$, $K\Sigma$

(W ≤ 2.1 GeV)

~380 parameters (N^* mass, N^* ➔ MB couplings, cutoffs)

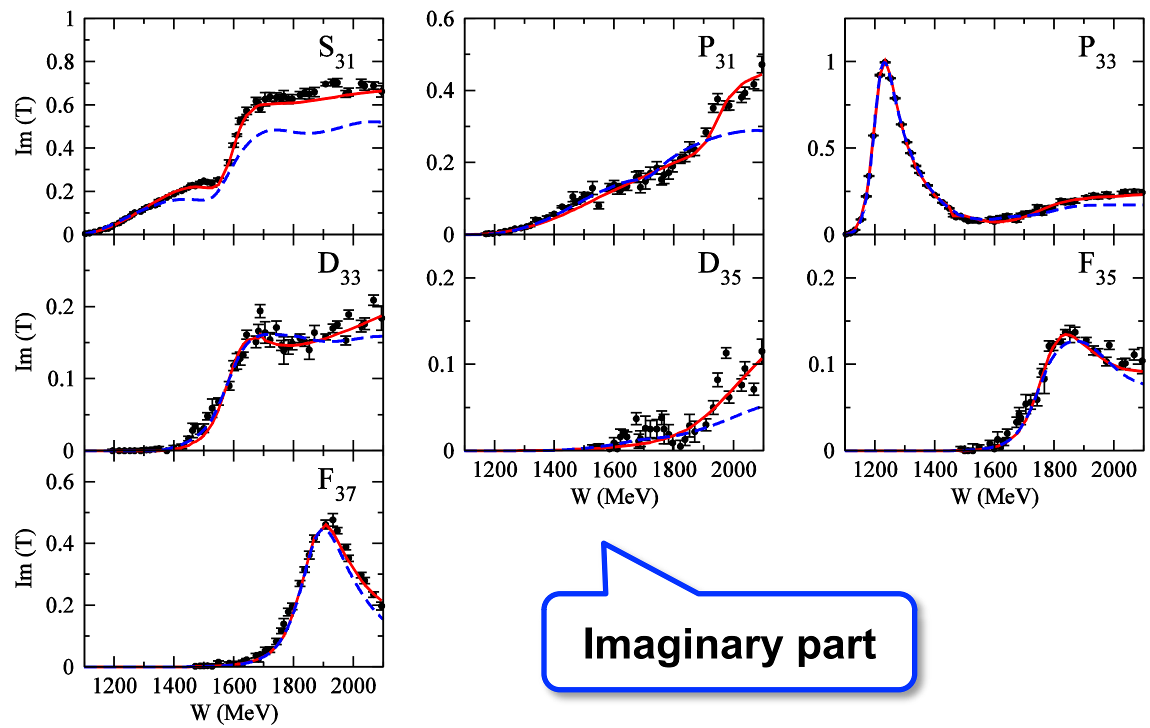
to fit ~ 20,000 data points

Partial wave amplitudes of pi N scattering



Real part

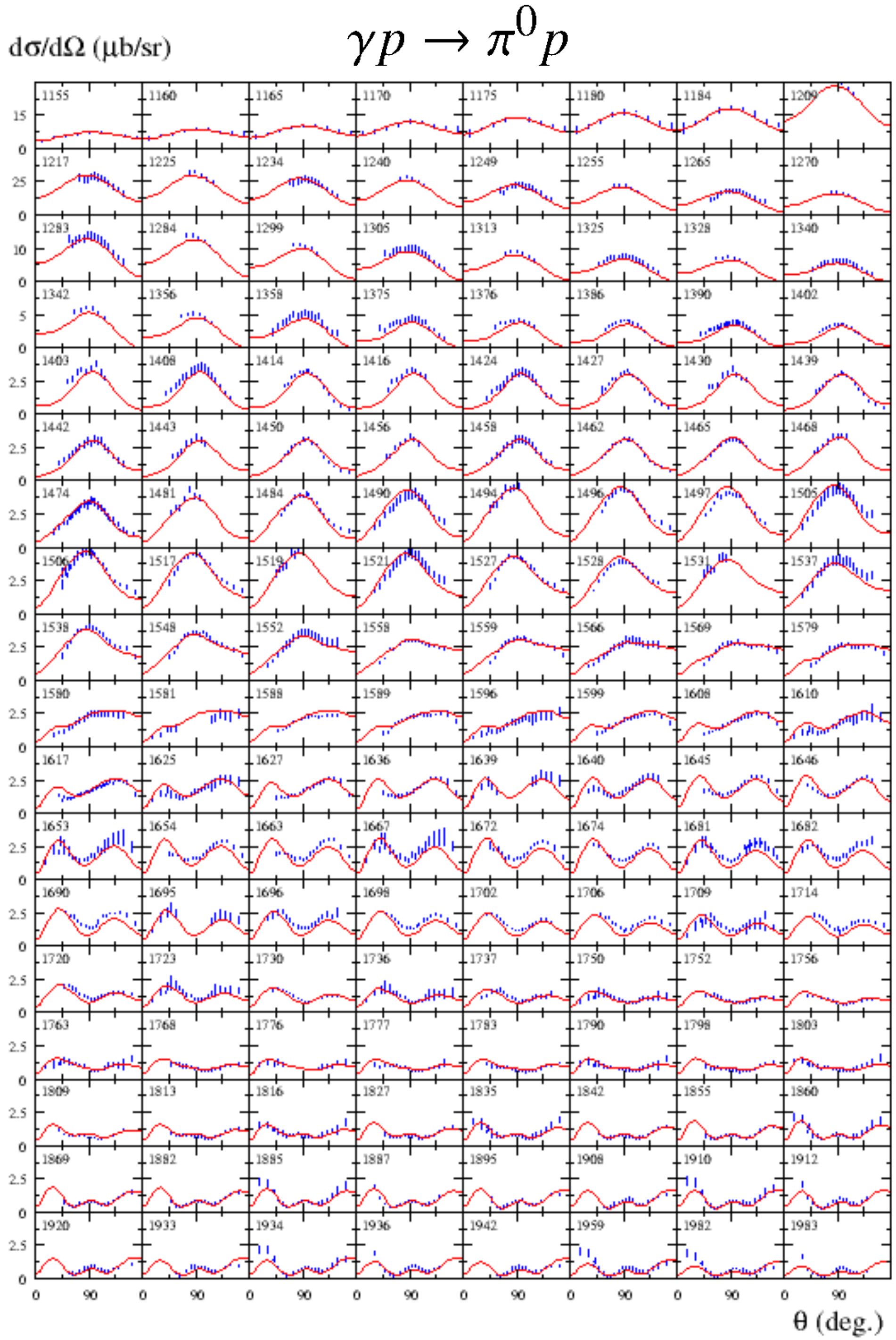
$$I = \frac{3}{2}$$



Imaginary part

Kamano, Nakamura, Lee, Sato, arXiv:1305.4351

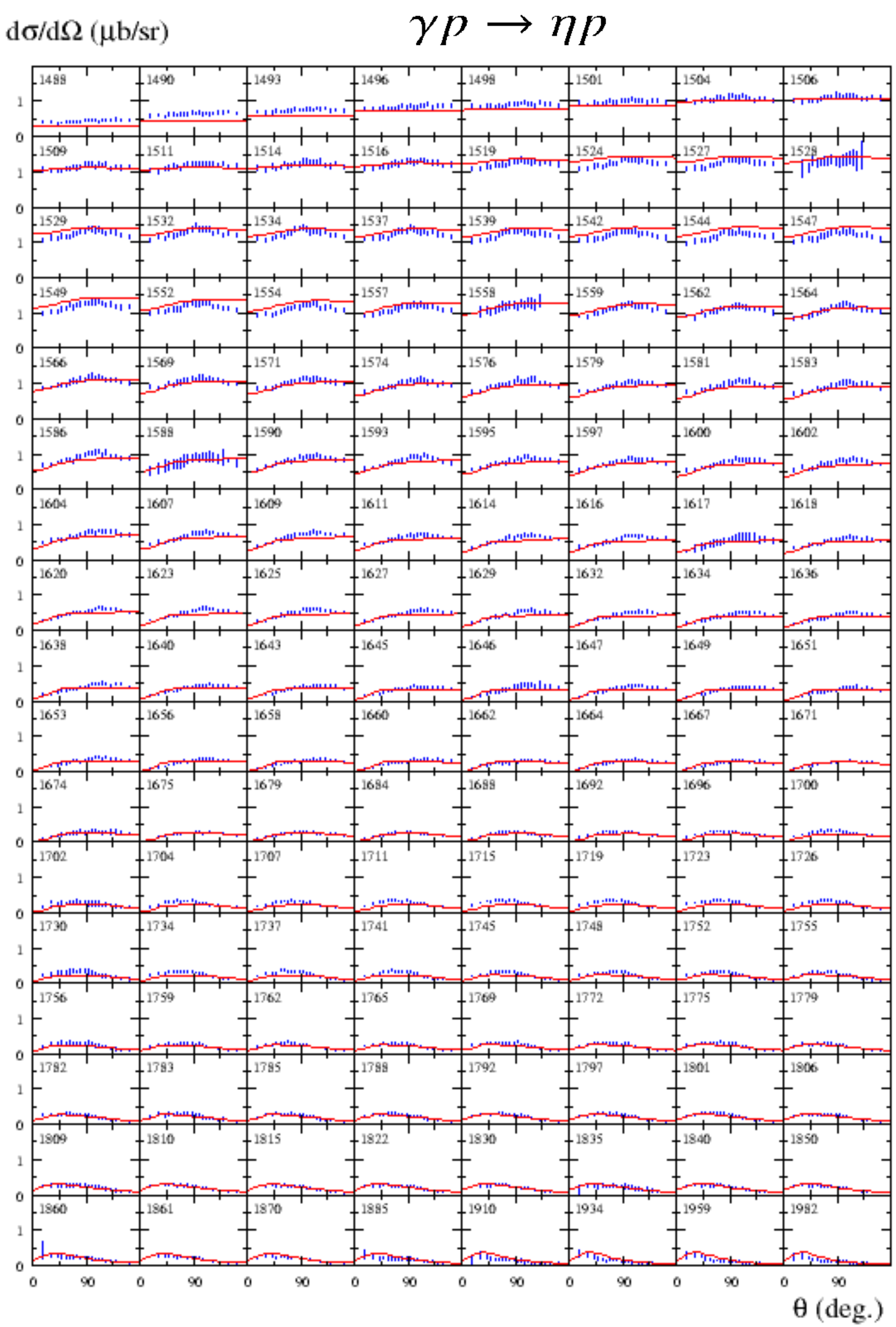
Previous model
(fitted to $\pi N \rightarrow \pi N$ data only)
[PRC76 065201 (2007)]



Kamano, Nakamura, Lee, Sato, arXiv:1305.4351

Vector current (Q^2=0) for 1π

Production is well-tested by data

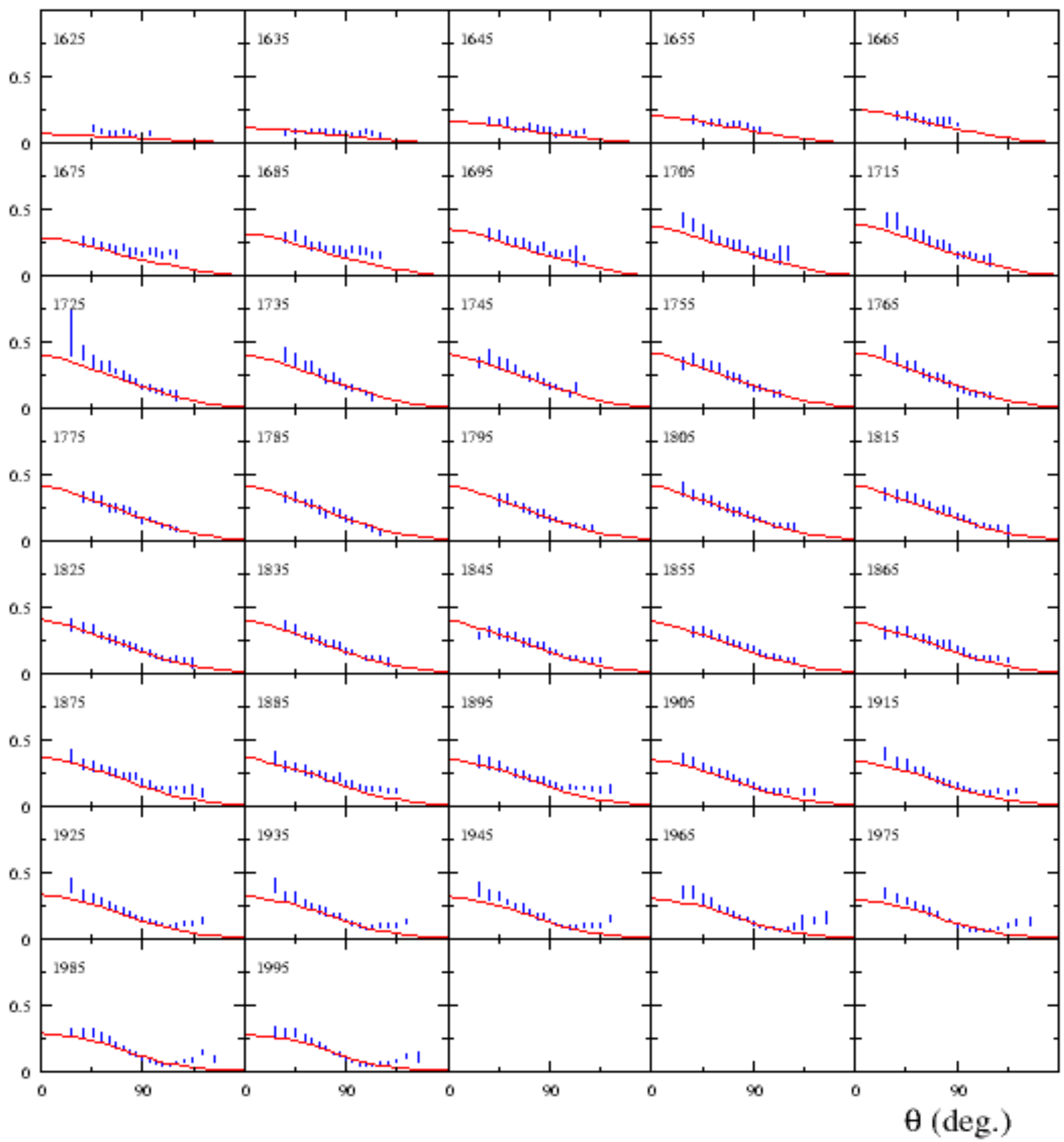


Kamano, Nakamura, Lee, Sato, arXiv:1305.4351

Vector current (Q^2=0) for η
Production is well-tested by data

$\gamma p \rightarrow K^+ \Lambda$

Kamano, Nakamura, Lee, Sato, arXiv:1305.4351



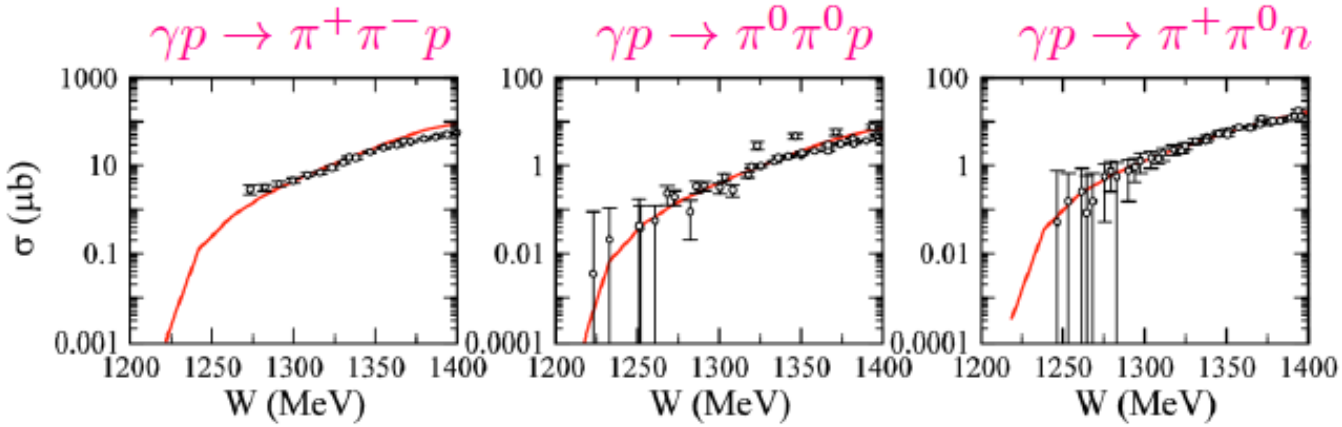
Vector current (Q^2=0) for K

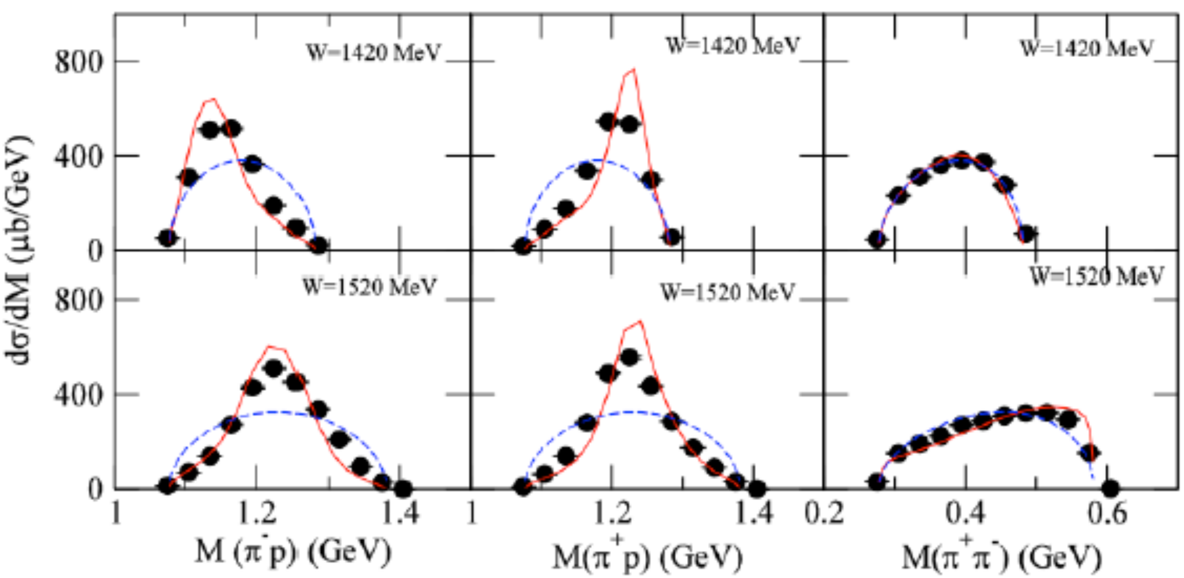
Production is well-tested by data

$\gamma N \rightarrow \pi\pi N$

(parameters had been fitted to $\pi N, \gamma N \rightarrow \pi N$)

Kamano, Julia-Diaz, Lee, Matsuyama, Sato, PRC80 065203 (2009)





- * Good description near threshold
- * Good shape of invariant mass distribution
- * Total cross sections overestimate data for $W \geq 1.5$ GeV