Neutrino reactions in the resonance region

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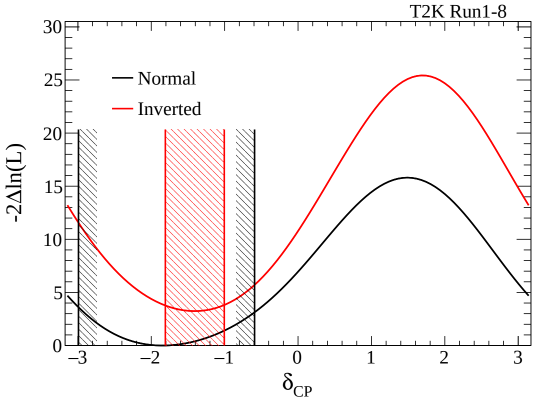
Motivation

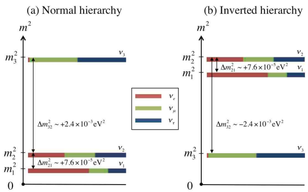
CP violation in lepton sector, Mass hierarchy ...

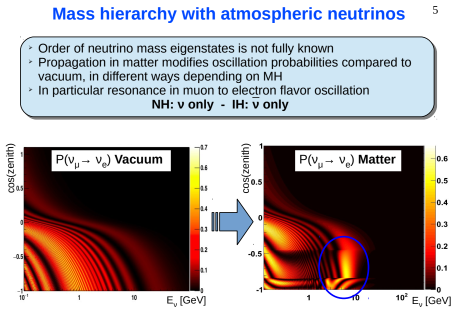


T2K Collaboration PRL121(2018) 171802
2σ confidence interval for δ_{CP} does not contain

$$\delta_{CP} = 0, \pi$$

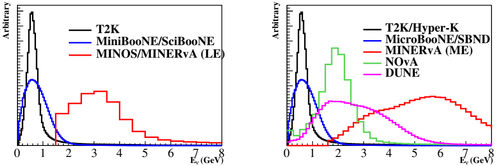
Atmospheric Neutrino:Matter effects depends on MH





C. Bronner(Workshop on Shallow and DIS Scattering 2018)

Neutrino flux of current and future LBL experiments
(T. Katori, M. Martini arXiv 1611.0770)

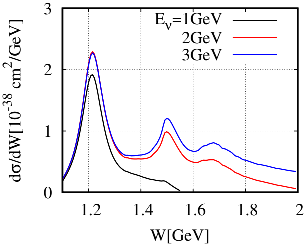


- Neutrino energy of LBL and Atmospheric neutrino experiments $\sim$ GeV
- Importance of neutrino reaction in N^*, Δ resonance region in neutrino detection through ν-nucleus reaction.

CC Neutrino-nucleon reaction (as building block to describe neutrino-nucleus reaction)

$$
\begin{aligned}
\nu + N \quad \rightarrow \quad & l + N \\
& l + N + \pi \\
& l + N + \eta \\
& l + Y + K \\
& l + N + \pi + \pi \\
& .... \\
& l + Y \\
& l + N + K \\
& ....
\end{aligned}
$$

$\nu_\mu n \rightarrow \mu^- X$ (ANL-Osaka model)



- Model of neutrino reaction in resonance region
- Pion production in $\Delta(1232)$ region
- Pion production in N^*, Δ region
- Model of axial vector current
- Summary

Models of Neutrino reaction in resonance region

model dependence of single pion production

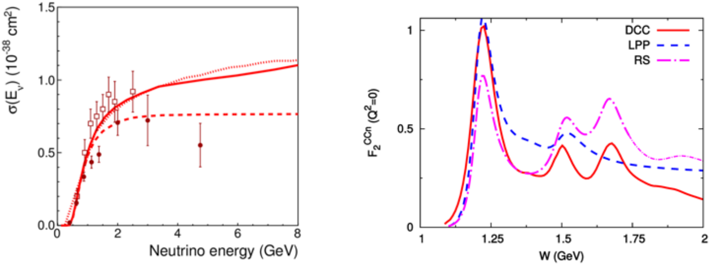
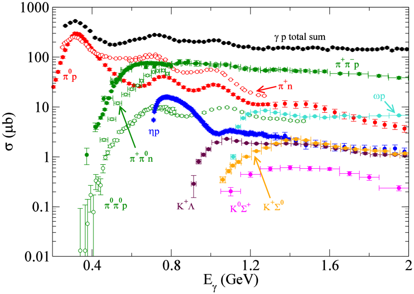


Figure 11: (left) Various data with generator fits for $\nu_\mu p \to \mu^- \pi^+ p$ as of 2015 (P. Rodrigues, private communication). Data are shown as open squares for BNL [286] and closed circles for ANL [287]. Calculations are shown as solid lines (GENIE), dashed lines (NEUT), and dotted lines (NuWRO). (right) Comparison of theoretical calculations for $\nu_\mu n$ CC 1π [305]. RS is Rein-Sehgal [296]; LPP is an isobar-model calculation [298], and DCC is full coupled channel calculation [305].

- Neutrino Generator RES+DIS bg, RES=Rein-Sehgal model

Alvarez-Ruso, L. and others, NuSTEC White Paper

	$\Delta(1232)$ region	Beyond $\Delta(1232)$ region($W < 2GeV$)
Resonane	Δ only	several overlaping resonances
Non-resonant	smaller than Res, Chiral L	comparable to Res
Channels	πN only	πN and $\pi\pi N$ are comparable $\eta N, K\Lambda, K\Sigma$ also



Total cross section of γp

ANL-Osaka DCC model

Model developed for N^* physics: spectrum of nucleon excited states,transition form factors

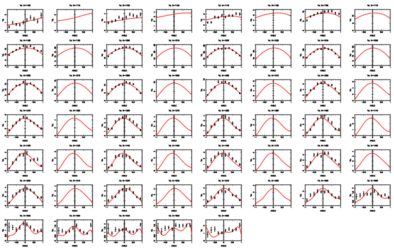
- Fock-Space:isobar(N^*, Δ) , Meson-Baryon ($\pi N, \eta N, K\Lambda, K\Sigma, \pi\pi N(\pi\Delta, \rho N, \sigma N)$)
- Interaction:isobar excitation and non-resonant meson-baryon interaction
- Coupled-channel(Lippmann-Schwinger)equation is solved numerically.

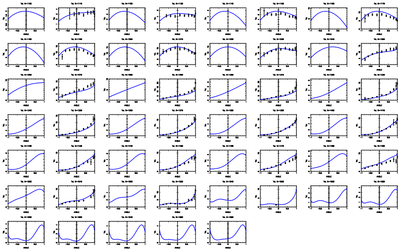
$$T = V + VG_0T$$

- The model is constructed by fitting available data on pion, photon, electron induced meson production reaction(two-body final state). (Recent model: H. Kamano,S.X. Nakamura, T.-S. H. Lee, TS, PRC88,035209(2013)
- the model is extended for neutron and axial vector current.
  Axial vector current: $g_A^{NN^*}$ from $g_\pi^{NN^*}$ assuming PCAC and dipole form factor.

  Neutron: H. Kamano,S.X. Nakamura,T.-S. H. Lee,TS, PRC94 015291 (2016)
  Neutrino:S. X. Nakamura,H. Kamano, TS,PRD92 07402(2015)

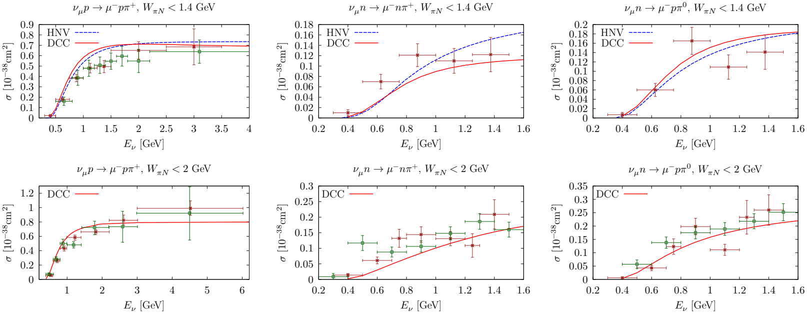
π^0, π^+ electroproduction on proton
($\sigma_T + \epsilon\sigma_L$ for $W = 1.1 - 1.68 GeV$ at $Q^2 = 0.4 (GeV/c)^2$





electromagnetic NN^* transition form factors are extracted by analyzing $(e, e'\pi)$.

Neutrino induced pion production in $\Delta(1232)$ region

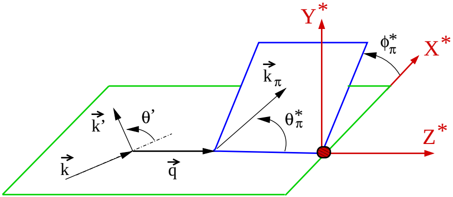


J. Sobczyk,E. Hernandez,S.X. Nakamura, J. Nieves,T. Sato PRD98(2018)073001

- Re-analyzed ANL/BNL data, C. Wilkinson et al. PRD90
- ANL-Osaka DCC,PRD92, Hernandez,Nieves,Valverde PRD76
- Recently FSI effects($10 \sim 30\%$) found by S.X.Nakamura et al.

Angular distribution of pion

$$\frac{d\sigma^{CC}}{dW_{\pi N}dQ^2d\Omega^*_\pi} = \frac{G_F^2 W_{\pi N}}{4\pi M k^2}[A^* + B^*\cos\phi_\pi + C^*\cos 2\phi_\pi + D^*\sin\phi_\pi + E^*\sin 2\phi_\pi]$$



PV: $\sin\phi_\pi \sim \boldsymbol{k}\times\boldsymbol{k}'\cdot\boldsymbol{k}_\pi$

- angular distribution is sensitive to reaction dynamics. (phase, res. and non-res.)
- parity violating T-odd angular distributions(D^*, E^*): due to final-state-interaction
- (D^*, E^*) are sensitive to interference among partial waves.

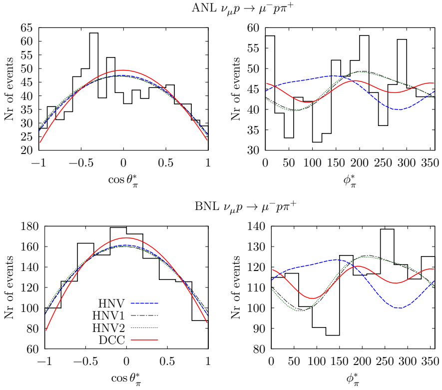
In Δ resonance region, $l_\pi \leq 1$

$$E^* \propto \sin^2\theta_\pi \sin(\delta_{P_{33}} - \delta_{P_{31}})[|M^V_{1+}||E^A_{1-}| + |M^V_{1-}|(4|M^A_{1+}| + 2|E^A_{1+}|)].$$

$M_{1+}, E_{1+} : p3/2$, $M_{1-}, E_{1-} : p1/2$

Pion angular distribution in $\Delta(1232)$ region

Flux averaged angular distribution of pion: Comparison with ANL/BNL data

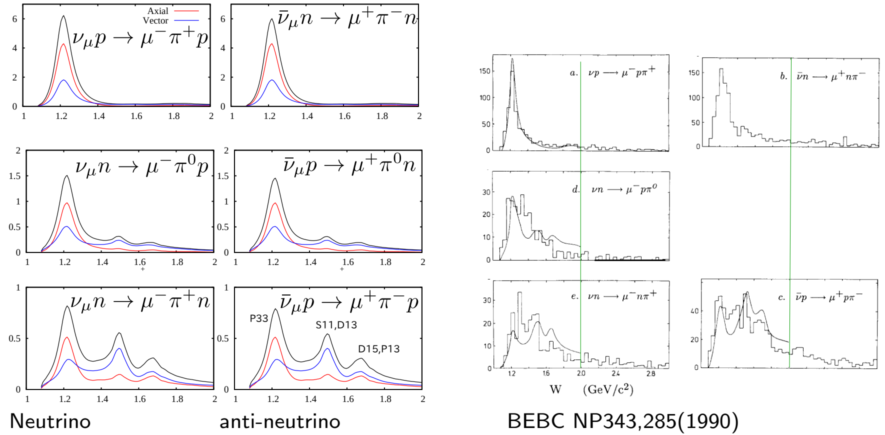


$d\sigma/d\cos\theta_\pi$ $\quad$ $d\sigma/d\phi_\pi$

J. E. Sobczyk, E. Hernandez, S.X. Nakamura, J. Nieves, T. Sato, PRD98 073001(2018)

Pion production cross section in N^*, Δ region

$d\sigma/dW_{\pi N}$ of single pion production $E_\nu = 40GeV$



BEBC NP343,285(1990)

- νp: $\Delta(1232)$
- νn:$\Delta(1232)$ + higher resonance region

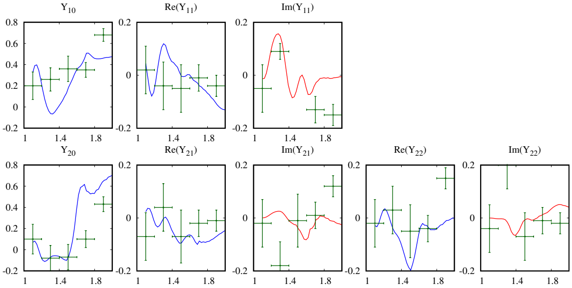
Pion angular distribution in N^*, Δ region

$$< Y_{lm} >= \frac{\int d\Omega_\pi Y^*_{lm} \frac{d\sigma}{dW d\Omega_\pi}}{\int d\Omega_\pi Y^*_{00} \frac{d\sigma}{dW d\Omega_\pi}}$$

Data:NPB343 (1990)D. Allasia et al.

ANL-Osaka Model (preliminary) ($\bar{\nu} p \to \mu^+ p \pi^-$, $E_\nu = 20 GeV$)

$$\frac{d\sigma}{dW d\Omega_\pi} = \sigma_0 + \sigma_c \cos\phi_\pi + \sigma_s \sin\phi_\pi + \sigma_{2c} \cos 2\phi_\pi + \sigma_{2s} \sin 2\phi_\pi$$



- Angular distribution depends on W, Q^2. Need to examine models of neutrino event generators.

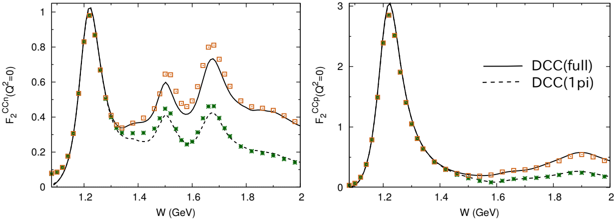
Axial Vector current of ANL-Osaka Model

Axial Vector current F_2^{CC} (total cross section) at $Q^2 = 0$

DCC model : 1π dash, a Total solid

πN cross section data: 1π green, a Total brown

$$F_2^{CC}(Q^2 = 0) = \frac{2f_\pi^2}{\pi}\sigma(\pi + N)$$



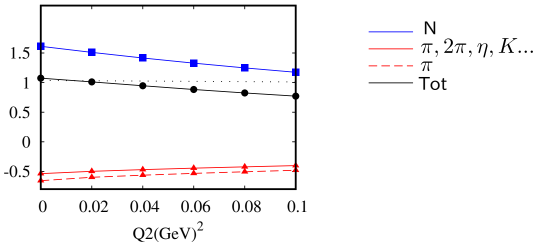
Neutron Proton

- Description of axial vector current at $Q^2 = 0$ is consistent with pion scattering data.

Adler's sum rule (Q^2 Dependence of axial vector current)preliminary

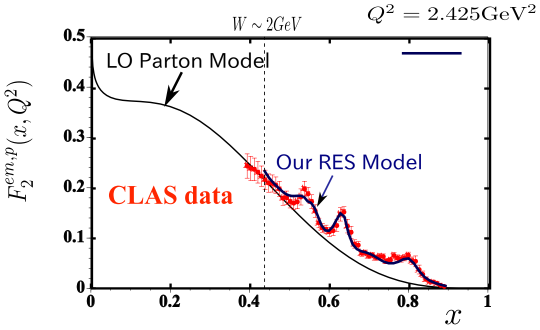
$$1 = [g_A(Q^2)]^2 + \int_{\nu_{th}}^{\infty} [W^A_{2,n}(\nu, Q^2) - W^A_{2,p}(\nu, Q^2)] d\nu$$

- $W^A_{2,n} - W^A_{2,p} = 2(W^A_{2,I=1/2} - W^A_{2,I=3/2})/3$
- $g_A(Q^2)$: $g_A = 1.27, M_A = 1.1 GeV$
- $W^A_{2,n/p}$: DCC model. ν integration: from threshold up to $W = 2GeV$



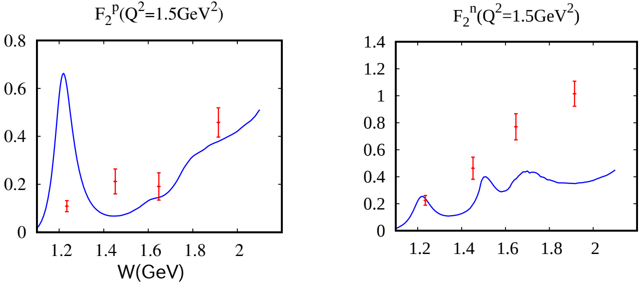
S.L. Adler,PR143(1965)1144,arXiv:0905.2923, E. A. Paschos, D. Schalla, PRD84(2011),013004.

$F_2(x, Q^2)$ of electromagnetic current



- DIS region $W > 2GeV$, $Q^2 > 1GeV^2$.
- Reasonable description of transition region in terms of hadron picture(ANL-Osaka Model).

$F_2(x,Q^2)$ of charged current(CC)



Data: Z. Phys. C28 (1985) Allasia et al.

- $F_2^p(CC) = F_{2,I=3/2}(CC) \quad F_{2,n}(CC) = \dfrac{F_{2,I=3/2}(CC) + 2F_{2,I=1/2}(CC)}{3}$
- $F_2^V(CC) = F_2^A(CC)$ in LO parton model
- $F_2^V(CC) >> F_2^A(CC)$ at large W, Q^2 in DCC model
- task: construct model of meson production reaction with $F_2^V \sim F_2^A$ around $W \sim 2GeV, Q^2 \sim 1-2GeV^2$

Summary

- ANL-OSAKA DCC model is extended to describe weak meson production reaction up to $W < 2GeV$.
- Neutrino induced single pion production in N^*, Δ resonance region is studied using ANL-Osaka model.
  Phase among partial waves/ interplay between non-resonant and resonant mechanism are important for angular distribution of pion.
  Feature of data can be understood within ANL-Osaka model.
  Comparison with Neutrino event generators(NEUT, GENIE,NuWro,..) and other models will be very useful.
- Model of axial vector current is examined.
  At $Q^2 = 0$, DCC model reproduce πN data.
  Adler sum rule provides a consistency test on description of axial current in resonance region with finite Q^2.
  in progress: improve Q^2-dependence of axial current
- needs new data on νd and νp with improved statistics.

Back up

Summary of models for neutrino reaction in RES

	Res	Non-res	Unit.	1pi	2pi	Tot
RS	Delta,N*	-	X	O		O
LPP	Delta,N*	X	X	O		O
HVM	Delta(1232)	chiral	O	O		
	Delta(1232)+N(1440)	chiral	X	O	O	
Giessen	Delta, N*	phen.	X	O		O
ANL-Osaka	Delta, N*	O	O	O	O	O

RS: D. Rein, L. M. Sehgal AP133(81), LPP: O. Lalakulich,E.A. Paschos,G. Piranlshvili,PRD74(2006)
HNV: E. Hernandez,J. Nieves,M. Valverde PRD76(2007) Giessen: T. Leitner,O.Buss,L.Alvarez-Ruso,U. Mosel,PRC79(2009)

ANL-Osaka DCC:S.X.Nakamura,H. Kamano,TS,PRD92(2015) ,TS,D. Uno,T.-S.H.Lee PRC67(2003)

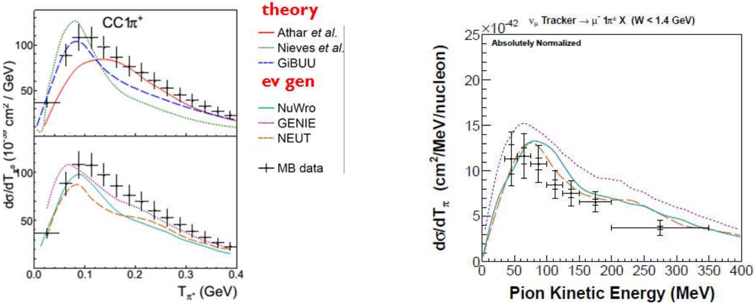
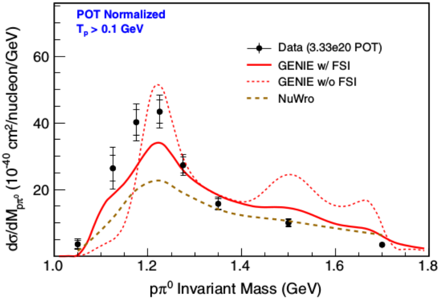


Figure 12: (left) Comparison of theoretical and event generator calculations available in 2014 with MiniBooNE $\nu_\mu CH_2$ CC π^+ production data [332] (right) Comparison of event generator calculations with MINERνA $\nu_\mu CH$ CC π^+ data [289]. Calculations are from NEUT (solid line), GENIE (dotted line), and NuWro (dashed line).

Alvarez-Ruso, L. and others, NuSTEC White Paper

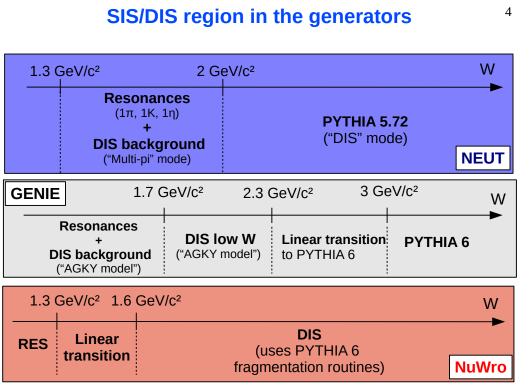


$$\nu_\mu + CH \to \mu^- \pi^0 X \;\; E_\nu \sim 3GeV$$

O. Altinok et al. PRD96(2018)072003

Model of neutrino reaction in resonance region

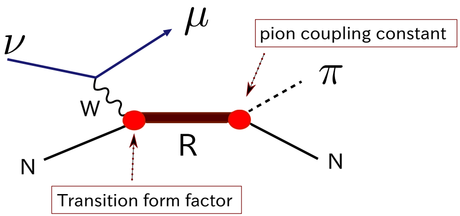
Generator



C. Bronner (Workshop on Shallow and DIS Scattering 2018)

- resonance model (Isobar model: Rein-Sehgal Model)

Isobar model



Breit-Wigner formula for partial wave $(J^\pi I)$

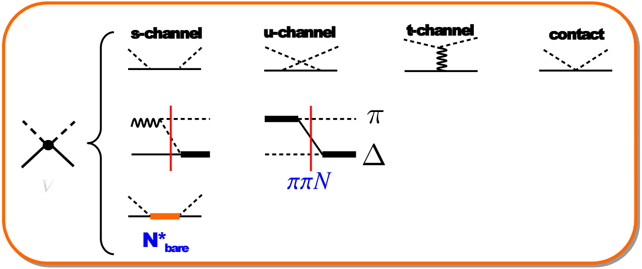
$$\frac{g_{\pi NR} \quad g_{JNR}}{W - M_R + i\Gamma_R/2}$$

(Rein-Shegal, O. Lalakulich, E. A. Paschos,

- Mass(M_R), Width(Γ_R) of resonance R from PDG.
- $g_{\pi NR} = \sqrt{\frac{\Gamma}{2}B_\pi}, \quad g_{VNR} = \sqrt{\frac{\Gamma}{2}B_\gamma} \quad g_{ANR} =$ PCAC or Quark model
- No control of relative phases (non-res vs res, (J^π, I) channels.)

Brief explanation of Coupled-channel model($\pi N, \eta N, K\Lambda, K\Sigma, \pi\pi N$)

Physics included inside V



- Differential cross section and polarization data analyzed within the ANL-Osaka Model

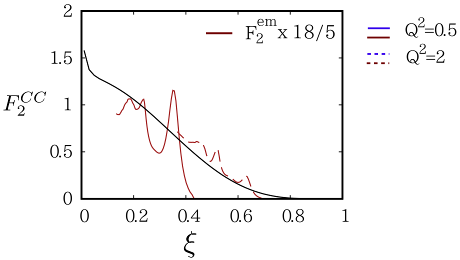
$$
\begin{aligned}
\pi p &\rightarrow \pi N, \eta N, K\Lambda, K\Sigma \\
\gamma p &\rightarrow \pi N, \eta N, K\Lambda, K\Sigma \\
ep &\rightarrow e'\pi N
\end{aligned}
$$

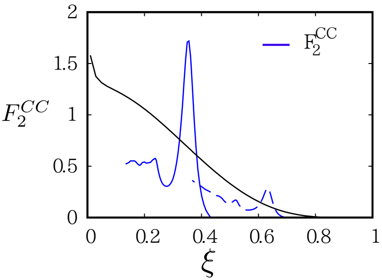
- γn: needed for CC, NC to separate iso-vector from iso-scalar component.
- Axial vector current: $g_A^{NN^*}$ from $g_\pi^{NN^*}$ assuming PCAC and dipole form factor. (Only in Δ region, the model can tested by data.)

High Q^2 region ($F_2^{CC} = \dfrac{F_{2,p}^{CC} + F_{2,n}^{CC}}{2}$)

- (Left) $F_2^{em} \times 18/5$ of ANL-Osaka Model.

$$F_2^{CC} \approx \frac{18}{5} F_2^{em} \sim x(u + \bar{u} + d + \bar{d}) \quad \text{PDF}$$





- (Right)F_2^{CC} of ANL-Osaka Model $\quad F_2^{CC} \propto |V_{IV}|^2 + |A_{IV}|^2 \quad$ DCC

Possibility to study A_μ^{CC}: Parity violating asymmetry $N(\vec{e}, e')X$

$$
\begin{aligned}
A_{PV} &= \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} \\
&= -\frac{Q^2 G_F}{\sqrt{2}4\pi\alpha} \frac{\cos^2\frac{\theta}{2} W_2^{\gamma Z} + \sin^2\frac{\theta}{2}[2W_1^{\gamma Z} + (1 - 4\sin^2\theta_W)\frac{E_e + E_e'}{M_N} W_3^{\gamma Z}]}{\cos^2\frac{\theta}{2} W_2^{em} + \sin^2\frac{\theta}{2} W_1^{em}}
\end{aligned}
$$

$d(\vec{e}, e')X$,$E_e = 4.867 GeV, \theta = 12.9^o$ (PVDIS PRC91 045506 (2015))