STRANGE AND CHARM HYPERON PRODUCTION IN NEUTRINO-NUCLEUS INTERACTION

Joanna Sobczyk
IFIC (Valencia)
28 May 2019

J.E. S., N. Rocco, A. Lovato, J. Nieves
arXiv:1901.10192

CSIC
CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS

IFIC
INSTITUT DE FISICA CORPUSCULAR

VNIVERSITAT ID VALÈNCIA

OUTLINE

- $\Lambda, \Sigma^{\pm}, \Sigma^0$ weak production $\bar{\nu}_l + A \to l^+ + Y + X$

  $Y = \Lambda, \Sigma^{\pm}, \Sigma^0$

  - motivation
  - ground state, interaction vertex, internuclear cascade
  - results
- Λ_c quasi-elastic production $\nu_l + A \to l^- + \Lambda_c + X$
  - interaction vertex (form factors)
  - results

OUTLINE

- $\Lambda, \Sigma^{\pm}, \Sigma^0$ weak production $\bar{\nu}_l + A \rightarrow l^+ + Y + X$

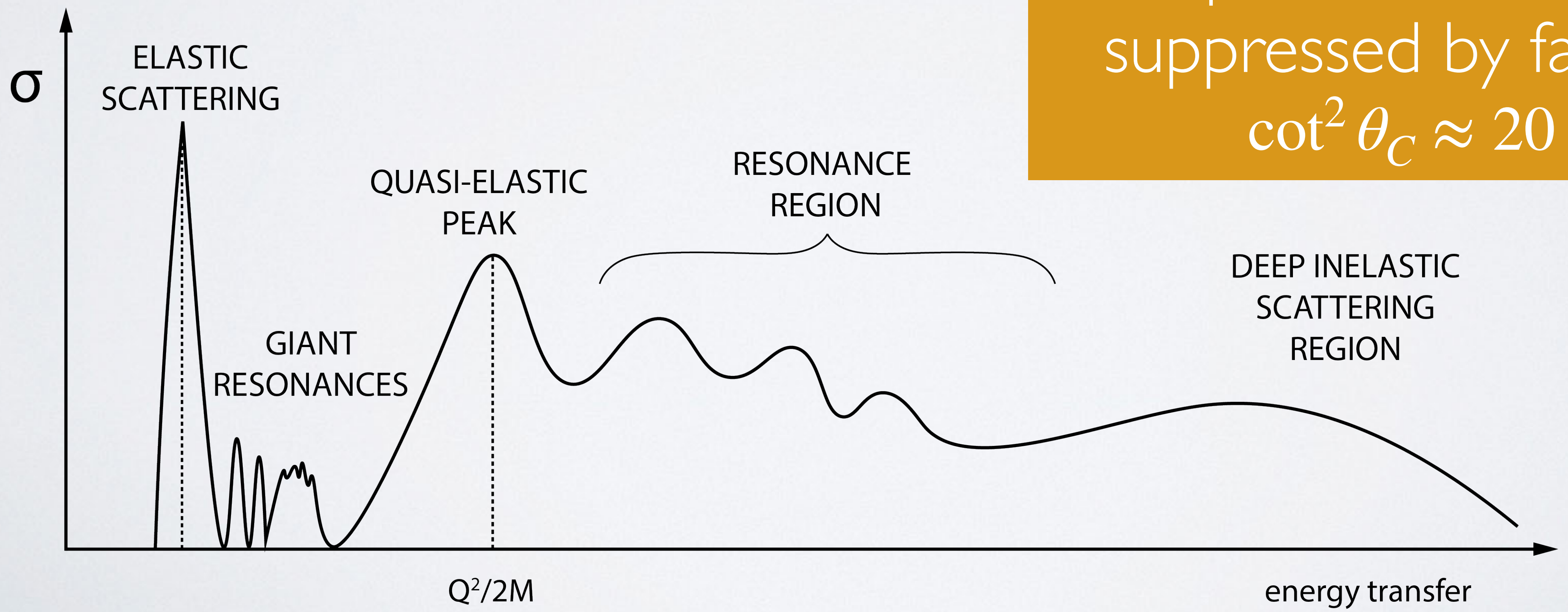
  $Y = \Lambda, \Sigma^{\pm}, \Sigma^0$

  - motivation
  - ground state, interaction vertex, internuclear cascade
  - results

MOTIVATION

- Why is this process important from the point of view of neutrino studies?

Strange production processes are suppressed by factor $\cot^2 \theta_C \approx 20$



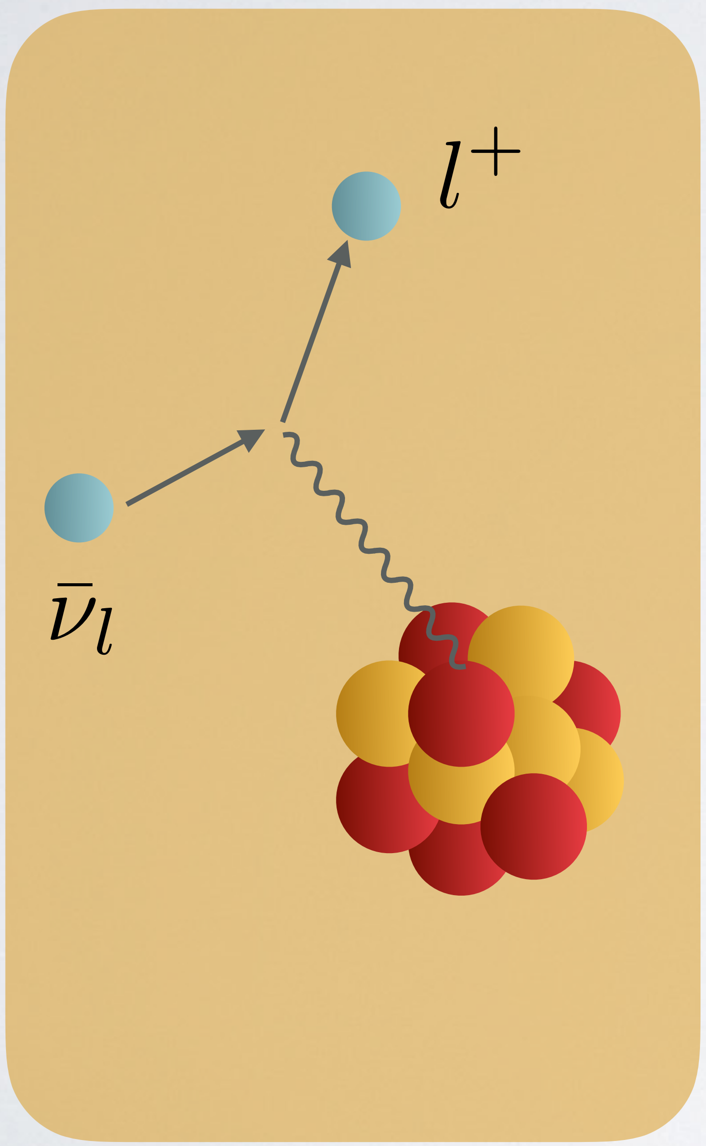
MOTIVATION

- For neutrino oscillation analysis: an important source of pion production (E<600 MeV)
- Estimate the role of nuclear effects in the strange baryon electroweak production
  - ground state (spectral functions vs Fermi gas)
  - internuclear cascade for outgoing hyperons

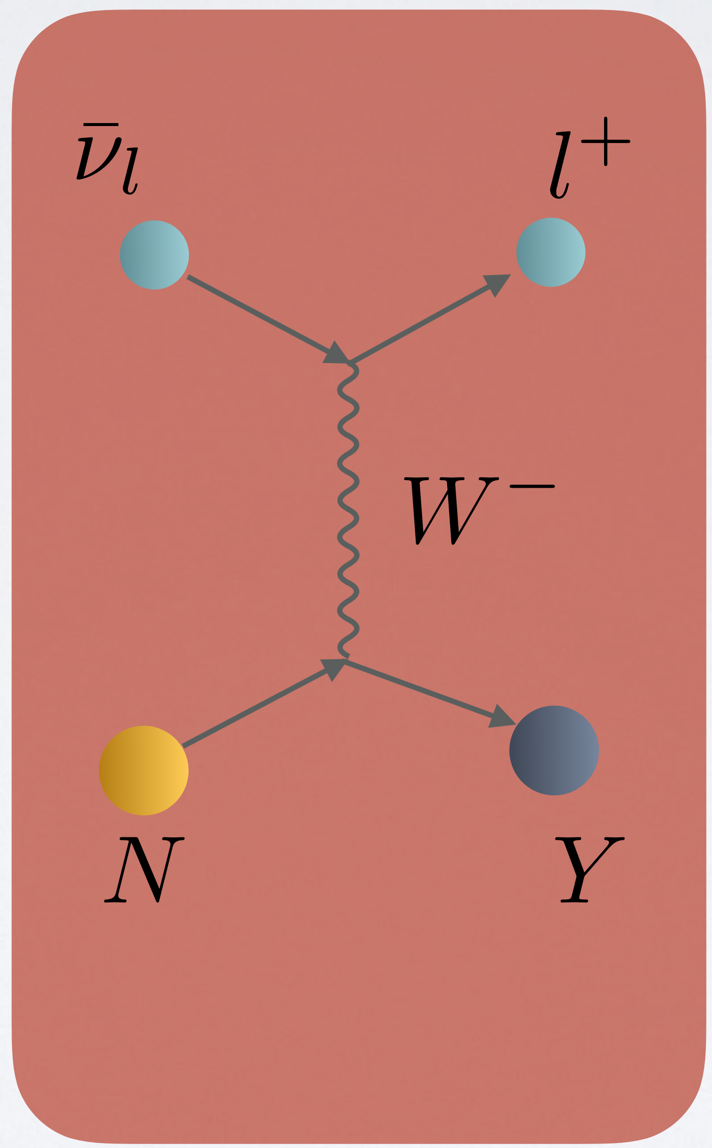
S.K. Singh, M.J. Vicente Vacas
Phys.Rev. D74 (2006) 053009

THREE INGREDIENTS

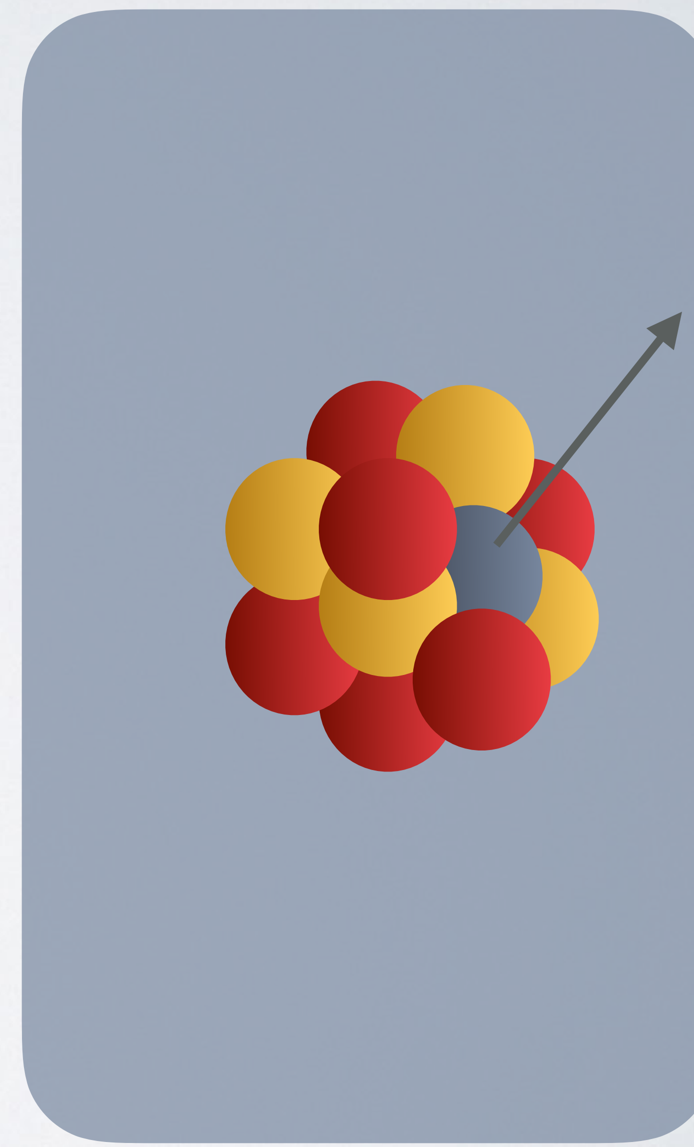
$$\bar{\nu}_l + A \to l^+ + Y + X$$



ground state



Impulse Approximation



internuclear cascade

IMPULSE APPROXIMATION

$$e^- + n \to e^- + n$$

$$e^- + p \to e^- + p$$

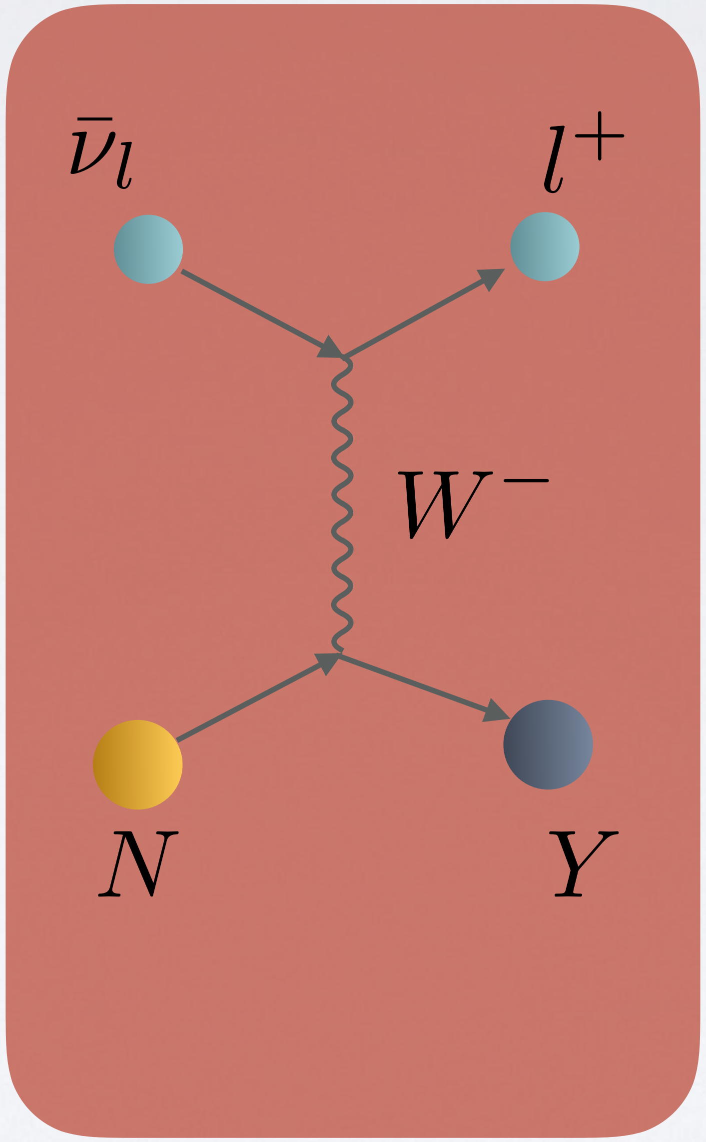
$$\bar{\nu}_l + p \to l^+ + n$$

SU(3)

$$\bar{\nu}_l + p \to l^+ + \Lambda$$

$$\bar{\nu}_l + p \to l^+ + \Sigma^0$$

$$\bar{\nu}_l + n \to l^+ + \Sigma^-$$



FORM FACTORS

Form factors are obtained assuming SU(3) symmetry

$$B = \begin{pmatrix} \frac{1}{\sqrt{2}}\Sigma^0 + \frac{1}{\sqrt{6}}\Lambda & \Sigma^+ & p \\ \Sigma^- & -\frac{1}{\sqrt{2}}\Sigma^0 + \frac{1}{\sqrt{6}}\Lambda & n \\ \Xi^- & \Xi^0 & -\frac{2}{\sqrt{6}}\Lambda \end{pmatrix}$$

octet of hyperons

$$j^\mu_{cc} = \begin{pmatrix} \bar{\Psi}_u & \bar{\Psi}_d & \bar{\Psi}_s \end{pmatrix} \gamma^\mu (1-\gamma_5) \underbrace{\begin{pmatrix} 0 & \cos\theta_C & \sin\theta_C \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}}_{T_{cc}} \begin{pmatrix} \Psi_u \\ \Psi_d \\ \Psi_s \end{pmatrix}$$

charge current

$$\langle H'|j^\mu_{cc}|H\rangle = \bar{u}(p')\Gamma^\mu u(p) \left(D\, \mathrm{Tr}\left(T_{cc}\{H, \bar{H}'\}\right) + F\, \mathrm{Tr}\left(T_{cc}[H, \bar{H}']\right)\right)$$

experimental input

Eckhart-Wigner theorem: the most general SU(3) invariant matrix element build from three octets of SU(3) has 2 possible terms (symmetric and antisymmetric).

FORM FACTORS

$N \rightarrow Y$ vertex has axial-vector structure with 6 form factors

$$\Gamma^\mu_Y = \left[\gamma^\mu f_1(q^2) + i\sigma^{\mu\nu}\frac{q_\nu}{M_Y}f_2(q^2) + \frac{q^\mu}{M_Y}f_3(q^2)\right] - \left[\gamma^\mu g_1(q^2) + i\sigma^{\mu\nu}\frac{q_\nu}{M_Y}g_2(q^2) + \frac{q^\mu}{M_Y}g_3(q^2)\right]\gamma_5$$

FORM FACTORS

$N \to Y$ vertex has axial-vector structure with 6 form factors

$$\Gamma^\mu_Y = \left[\gamma^\mu f_1(q^2) + i\sigma^{\mu\nu}\frac{q_\nu}{M_Y}f_2(q^2) + \frac{q^\mu}{M_Y}f_3(q^2)\right] - \left[\gamma^\mu g_1(q^2) + i\sigma^{\mu\nu}\frac{q_\nu}{M_Y}g_2(q^2) + \frac{q^\mu}{M_Y}g_3(q^2)\right]\gamma_5$$

obtained from $N \to N$ form factors (combination of **F, D** experimental values and Clebsh-Gordan coefficients)

FORM FACTORS

$N \to Y$ vertex has axial-vector structure with 6 form factors

$$\Gamma^\mu_Y = \left[\gamma^\mu f_1(q^2) + i\sigma^{\mu\nu}\frac{q_\nu}{M_Y} f_2(q^2) + \frac{q^\mu}{M_Y} f_3(q^2)\right] - \left[\gamma^\mu g_1(q^2) + i\sigma^{\mu\nu}\frac{q_\nu}{M_Y} g_2(q^2) + \frac{q^\mu}{M_Y} g_3(q^2)\right]\gamma_5$$

small lepton mass

obtained from $N \to N$ form factors (combination of **F, D** experimental values and Clebsh-Gordan coefficients)

FORM FACTORS

$N \to Y$ vertex has axial-vector structure with 6 form factors

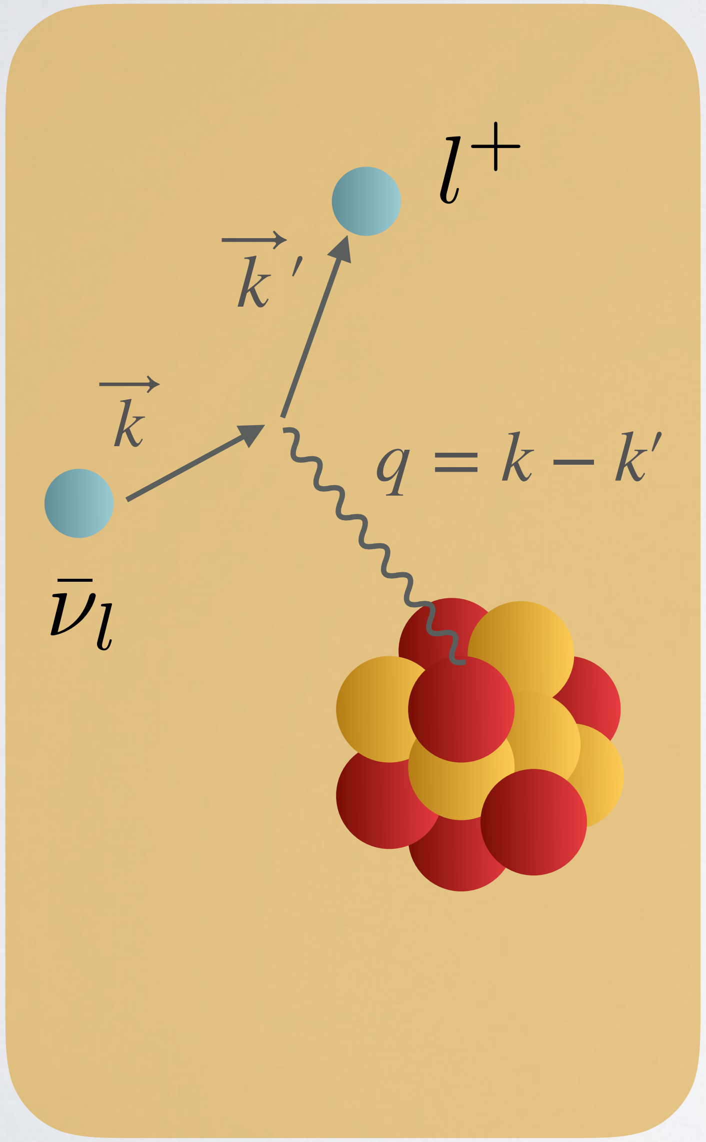
$$\Gamma^{\mu}_{Y} = \left[\gamma^{\mu} f_1(q^2) + i\sigma^{\mu\nu}\frac{q_\nu}{M_Y} f_2(q^2) + \frac{q^\mu}{M_Y} f_3(q^2)\right] - \left[\gamma^{\mu} g_1(q^2) + i\sigma^{\mu\nu}\frac{q_\nu}{M_Y} g_2(q^2) + \frac{q^\mu}{M_Y} g_3(q^2)\right]\gamma_5$$

G-invariance

small lepton mass

obtained from $N \to N$ form factors (combination of **F, D** experimental values and Clebsh-Gordan coefficients)

GROUND STATE



We will use two models for spectral function

P. Fernandez de Cordoba, E. Oset
Phys. Rev. C46 (1992) 1697-1709

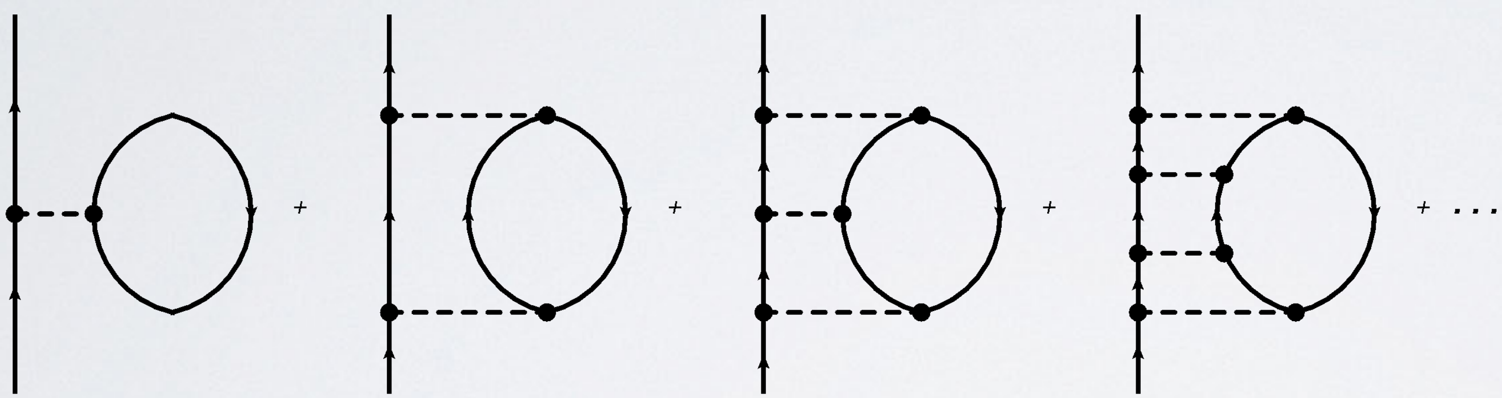
O. Benhar, A. Fabrocini, S. Fantoni, and I. Sick,
Nucl. Phys. A 579, 493

$$\frac{d\sigma}{dE_{k'}d\Omega(\hat{k}')} = \frac{G_F^2 \sin^2\theta_C}{4\pi^2}\frac{|\vec{k}\,'|}{|\vec{k}\,|}L^{(\bar{\nu})}_{\mu\sigma}(k,k')W^{\mu\sigma}(q)$$

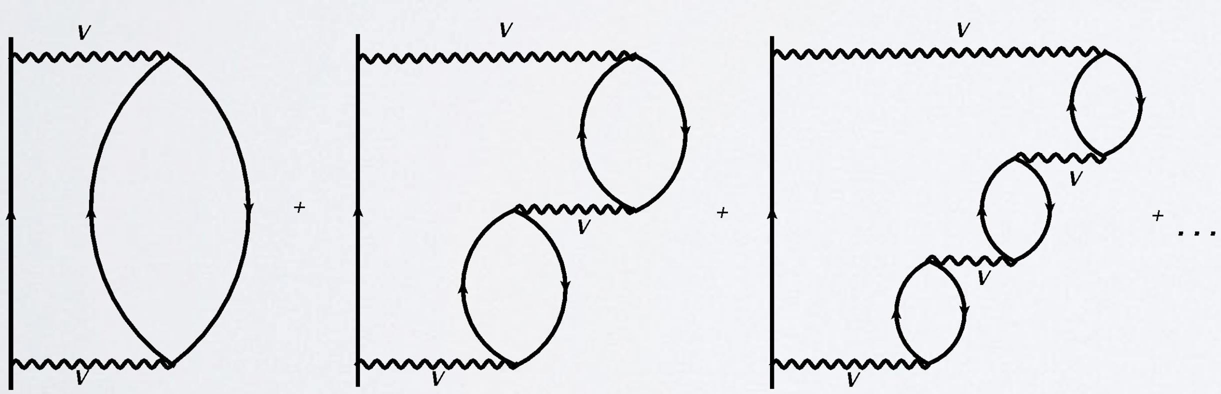
$$L^{(\bar{\nu})}_{\mu\sigma}(k,k') = k_\mu k'_\sigma + k'_\mu k_\sigma - g_{\mu\sigma}k\cdot k' - i\epsilon_{\mu\sigma\alpha\beta}k'^{\alpha}k^{\beta}$$

GROUND STATE (1)

- Semi-phenomenological model for nucleon self-energy $\Sigma(p,E)$ in nuclear medium, satisfying low density theorem.



NN interaction taken from scattering data



polarisation effects using empirical spin-isospin interaction

$$\mathrm{Re}\Sigma(p,E) = -\frac{1}{\pi}\mathscr{P}\int_{E_F}^{\infty} dE' \frac{\mathrm{Im}\Sigma(p,E')}{E-E'} + \frac{1}{\pi}\mathscr{P}\int_{-\infty}^{E_F} dE' \frac{\mathrm{Im}\Sigma(p,E')}{E-E'}$$

P. Fernandez de Cordoba, E. Oset
Phys. Rev. C46 (1992) 1697-1709

GROUND STATE (I)

- Spectral functions:

$$S_{p,h}^{\rm LDA}(\mathbf{p},E) = \mp \frac{1}{\pi} \frac{\mathrm{Im}\Sigma(\mathbf{p},E)}{\left(E - \mathbf{p}^2/2m - \mathrm{Re}\Sigma(\mathbf{p},E)\right)^2 + \mathrm{Im}\Sigma(\mathbf{p},E)^2}$$

- Local density approximation (LDA)

$$W^{\mu\nu}_{LDA}(q) = 2\int d^3r \int \frac{d^3p}{(2\pi)^3} \int dE\, S_h^{\rm LDA}(E,\mathbf{p},\rho) \frac{M}{E_p} \frac{M_Y}{E^Y_{p+q}} \delta(E + q^0 - E^Y_{p+q}(\rho)) A^{\mu\nu}(p,q)$$

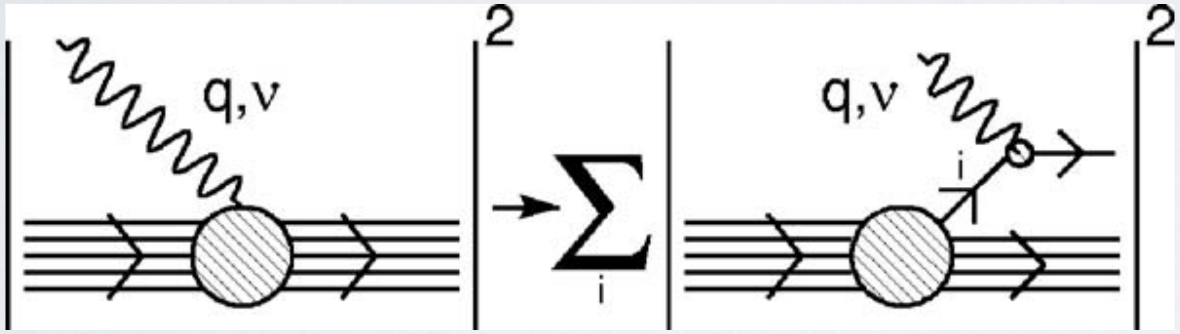
$$A^{\mu\nu}(p,q) = \langle \mathbf{p} \,|\, (j^{\mu}_{cc})^{\dagger} \,|\, \mathbf{p}+\mathbf{q} \rangle \langle \mathbf{p}+\mathbf{q} \,|\, j^{\nu}_{cc} \,|\, \mathbf{p} \rangle$$

matrix element for a single nucleon

GROUND STATE (II)

- Impulse Approximation

$\langle i|$



state factorisation

$|f\rangle = |\mathbf{p}'\rangle \otimes |R\rangle$

$$\langle i|J_\mu|f\rangle \to \sum_k \langle i|[\,|\mathbf{p}\rangle \otimes R\rangle]\langle \mathbf{p}|\sum_i j^i_\mu|\mathbf{p}'\rangle$$

$$S_h^{\mathrm{CBF}}(\mathbf{p},E) = \sum_R |\langle i|\,|[\,|\mathbf{p}\rangle \otimes |R\rangle]\,|^2 \times \delta(E+E_R-E_i)$$

$$W^{\mu\nu}(q) = \int d^3p\,dE\,\frac{M}{E_p} S_h^{\mathrm{CBF}}(\mathbf{p},E) A^{\mu\nu}(p,q)$$

O. Benhar, D. Day and I. Sick, Rev. Mod. Phys. 80, 189

GROUND STATE (II)

- Spectral function has two contributions:

$$S_h^{CBF}(\mathbf{p}, E) = \bar{S}_h^{1h}(\mathbf{p}, E) + \bar{S}_h^{corr}(\mathbf{p}, E)$$

- Modified mean-field scheme:

$$\bar{S}_h^{1h}(\mathbf{p}, E) = \sum_{\alpha \in \{F\}} Z_\alpha \, |\, \phi_\alpha(p) \,|^2 F_\alpha(E - e_\alpha)$$

sum over single particle states

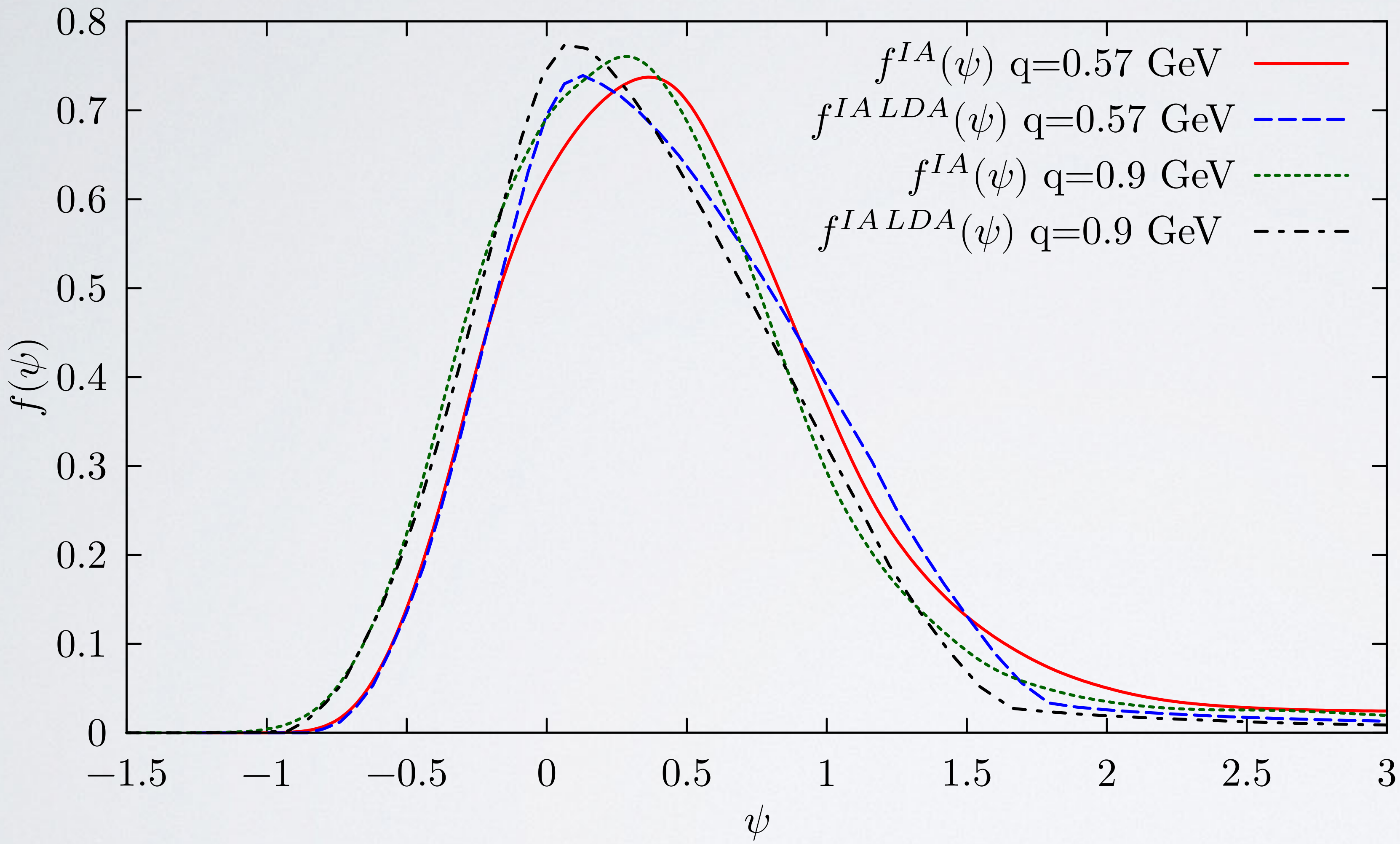
- Correlated Basis Function for nuclear matter (LDA)

$$\bar{S}_h^{corr}(\mathbf{p}, E) = \int dr^3 \, \rho_A(r) \, \bar{S}_{h,\mathrm{NM}}^{corr}(\mathbf{p}, E, \rho_A)$$

high energy and momentum region of the SF

O. Benhar, A. Fabrocini, S. Fantoni, and I. Sick, Nucl. Phys. A 579, 493

COMPARISON OF TWO APPROACHES

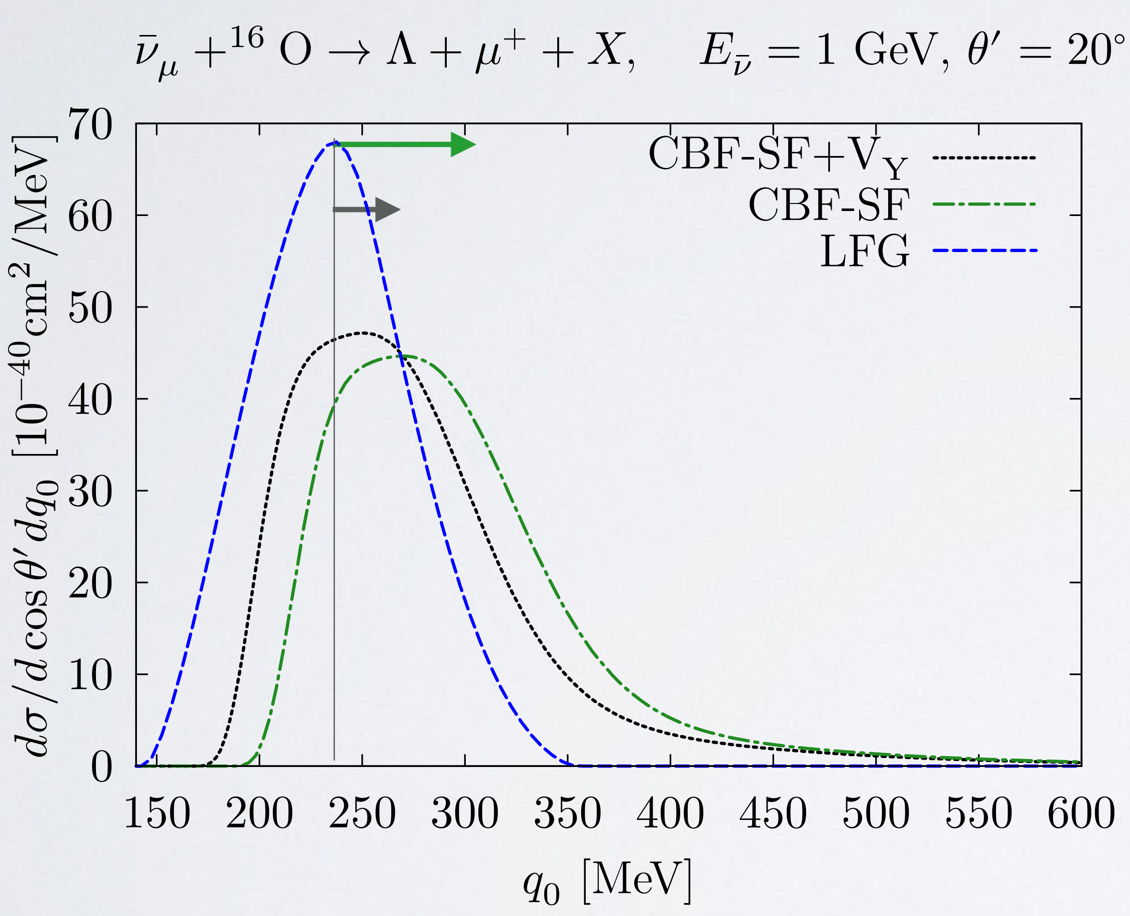


scaling properties of the nuclear responses using both spectral functions

J. E. S., N. Rocco, A. Lovato, and J. Nieves
Phys. Rev. C 97, 035506

COMPARISON OF SPECTRAL FUNCTIONS

$$\frac{d\sigma}{d\cos\theta dq^0}$$



quasi elastic peak position

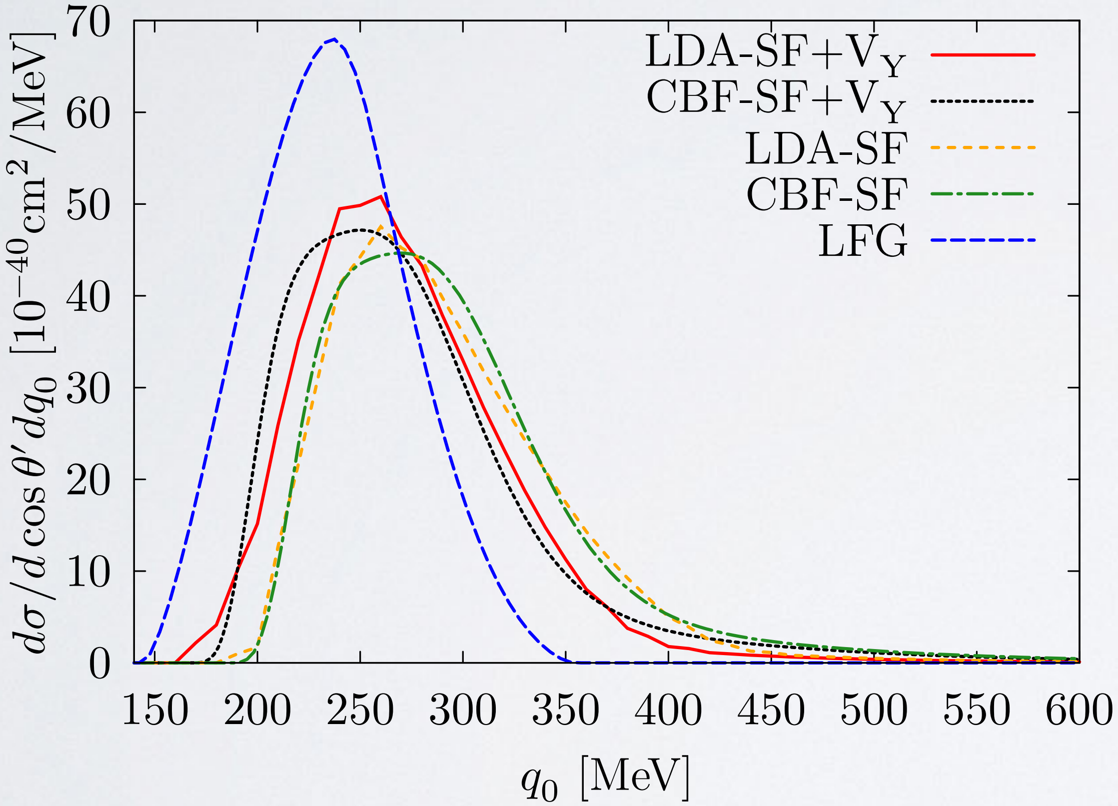
- towards higher q_0 when we "dress" incoming nucleon
- this effect compensated when we include hyperon's potential

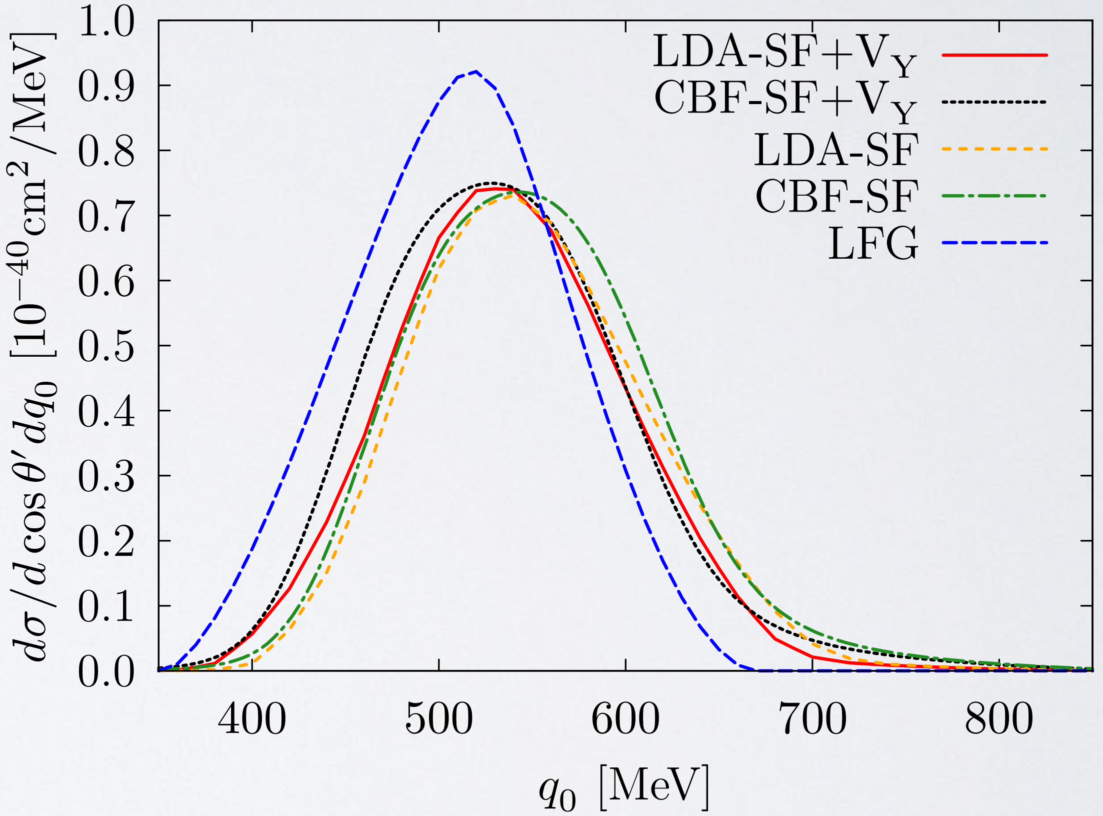
$$V(\rho) = -30\frac{\rho}{\rho_0}\mathrm{MeV}$$

Spectral function v Local Fermi gas

COMPARISON OF SPECTRAL FUNCTIONS

$$\frac{d\sigma}{d\cos\theta dq^0}$$

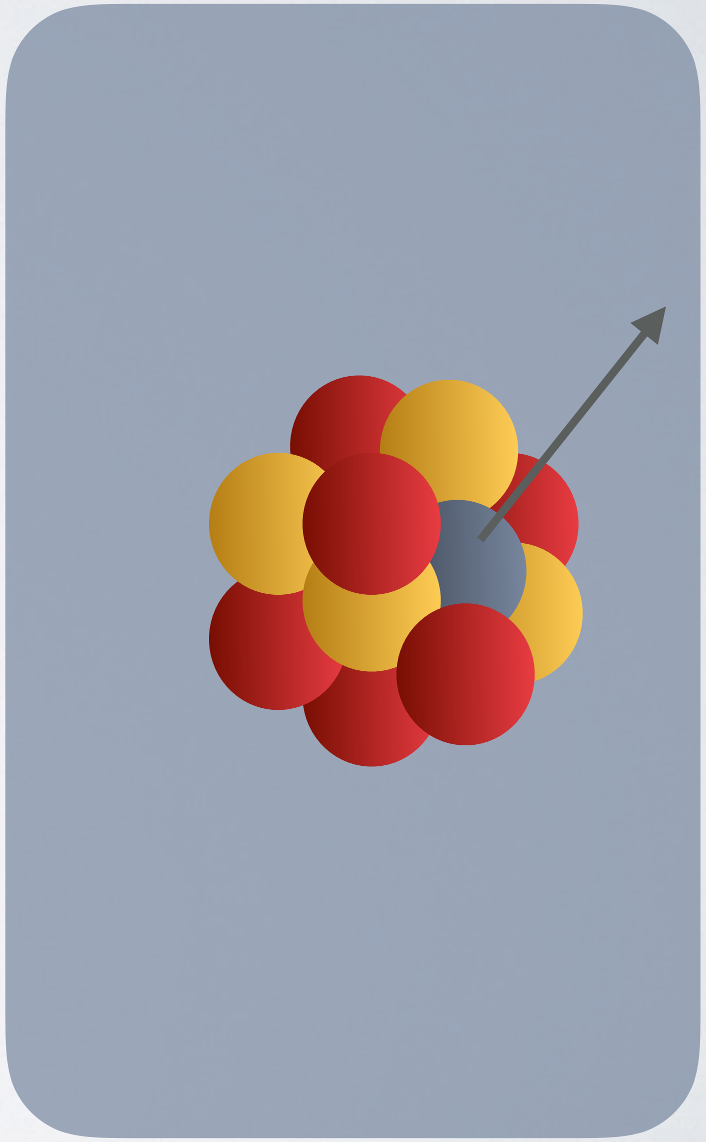




Similar results when we use both spectral functions

INTERNUCLEAR CASCADE

- Monte Carlo cascade (MCC)
  - semi-classical approach to describe final state interactions of outgoing hyperon
  - in this approach, the cascade does not influence kinematics of outgoing lepton
  - generate events according to $\frac{d\sigma}{d\cos\theta dq^0}$



INTERNUCLEAR CASCADE

generate primary vertex ✓

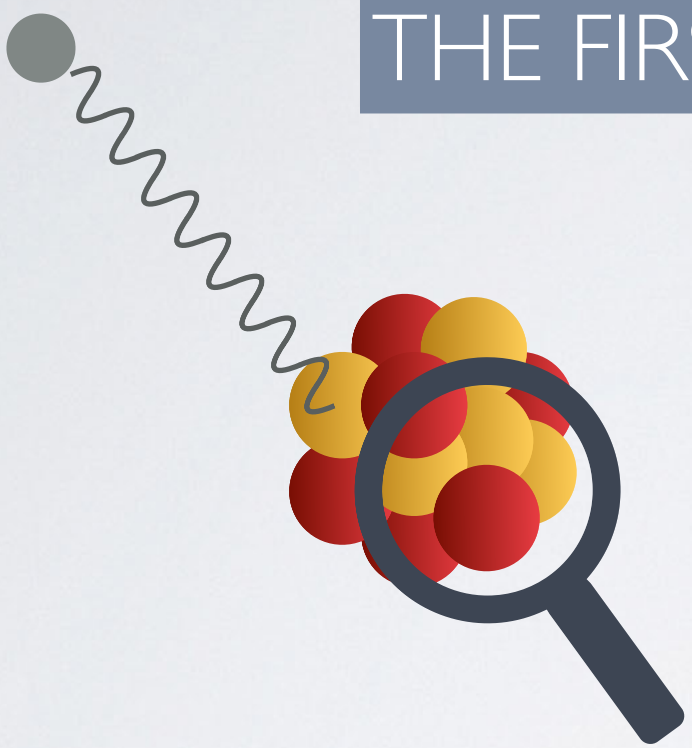
make the first step of outgoing hyperon

repeat steps while hyperon is still inside nucleus

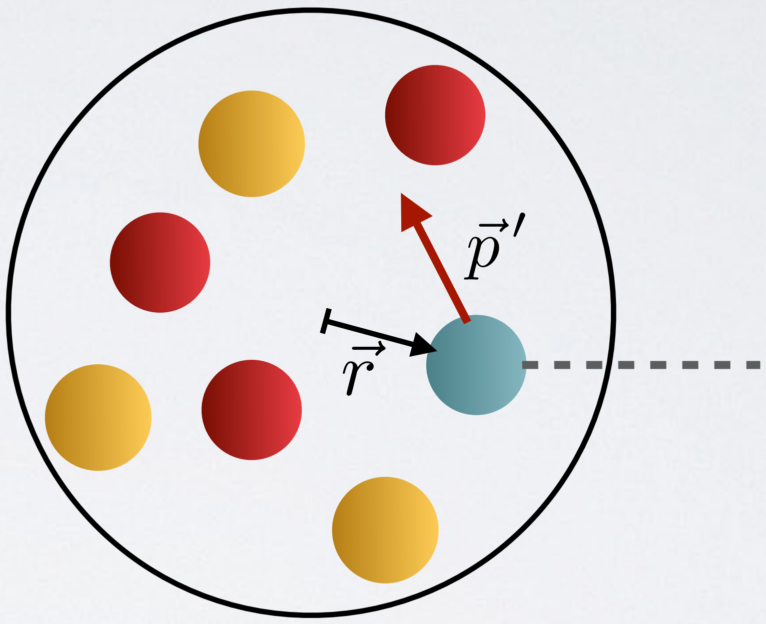
hyperon's kinetic energy below 30 MeV

hyperon gets out of nucleus

INTERNUCLEAR CASCADE



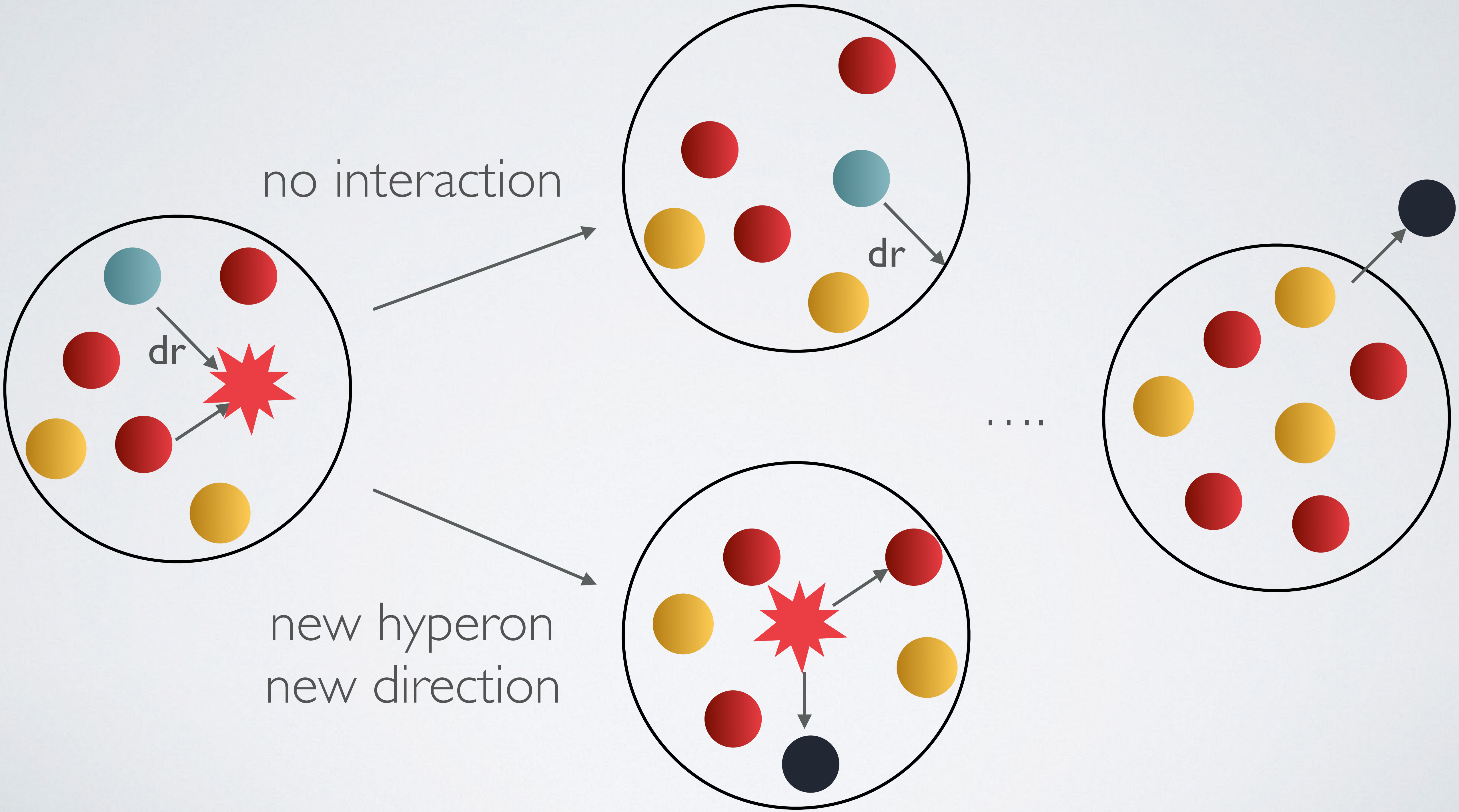
THE FIRST STEP



produced hyperon at distance r with momentum p'

SEMI-CLASSICAL PROCEDURE:
We divide the hyperon's path through the nucleus into small steps.

INTERNUCLEAR CASCADE



INTERNUCLEAR CASCADE ONE STEP

What is the probability of interaction of hyperon Y_1 on the way dl?

Generate a nucleon from the Fermi sea

we calculate $E_{\rm inv}$

For each possible final hyperon Y_i calculate the probability of interaction (per length)

$$\mathcal{P}_i = \left[\rho_p \sigma_{[Y_1+p\to Y_i+N_i]}(E_{\rm inv}) + \rho_n \sigma_{[Y_1+n\to Y_i+N_i]}(E_{\rm inv})\right]$$

σ taken from scattering data

Calculate the total probability of interaction.

$$\mathcal{P} = \sum_i \mathcal{P}_i \, dl$$

INTERNUCLEAR CASCADE ONE STEP

Monte Carlo: generate x and check if interaction took place

$$x \in [0,1] \qquad x > \sum_i \mathcal{P}_i \, dl$$

Randomly choose one interaction channel.

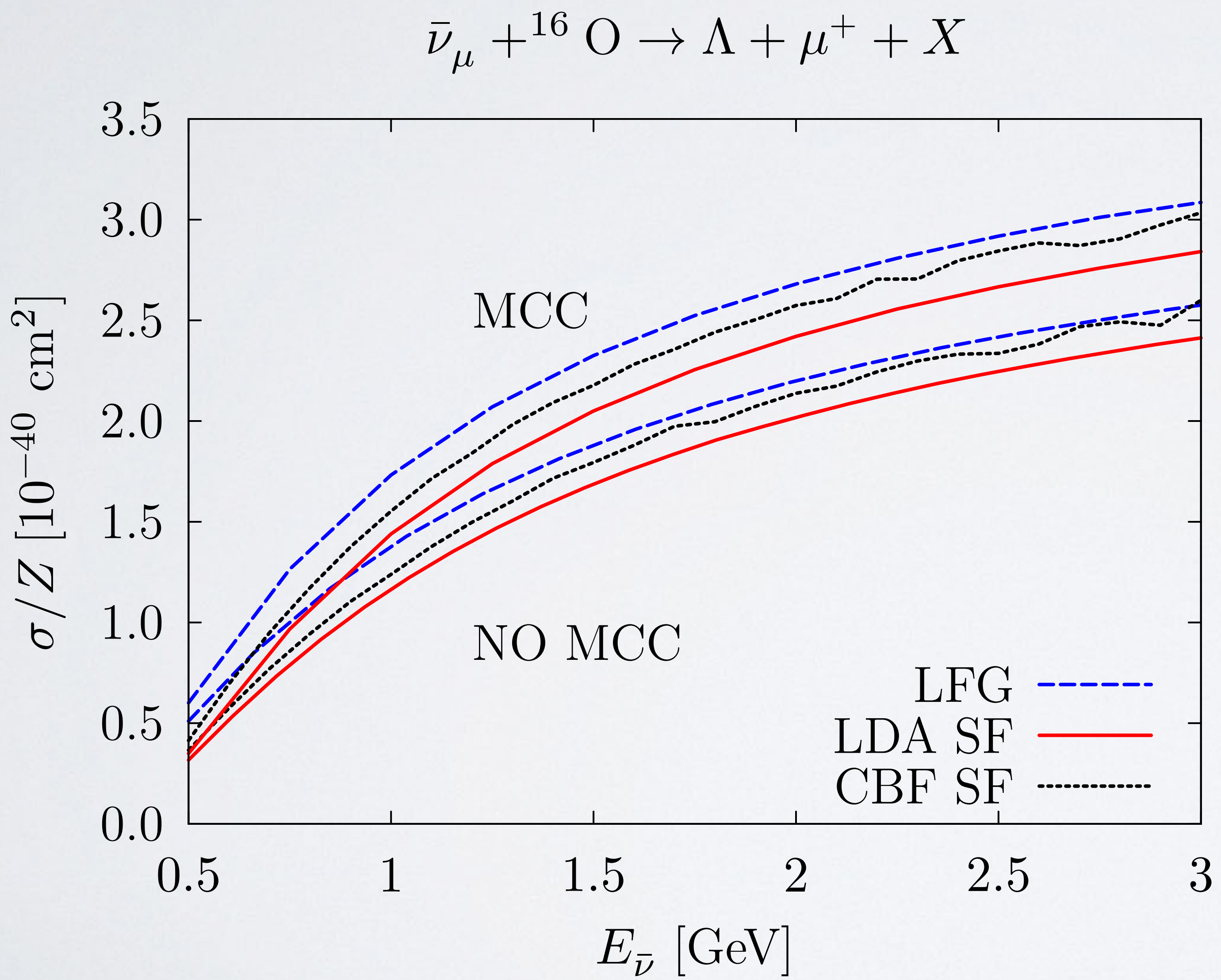
$\mathcal{P}_{\Lambda\to\Lambda}$ $\mathcal{P}_{\Lambda\to\Sigma^0}$

$\mathcal{P}_{\Lambda\to\Sigma^-}$ $\mathcal{P}_{\Lambda\to\Sigma^+}$

Generate direction of new hyperon. Check if outgoing nucleon is above Fermi level.

RESULTS (I)

total cross section

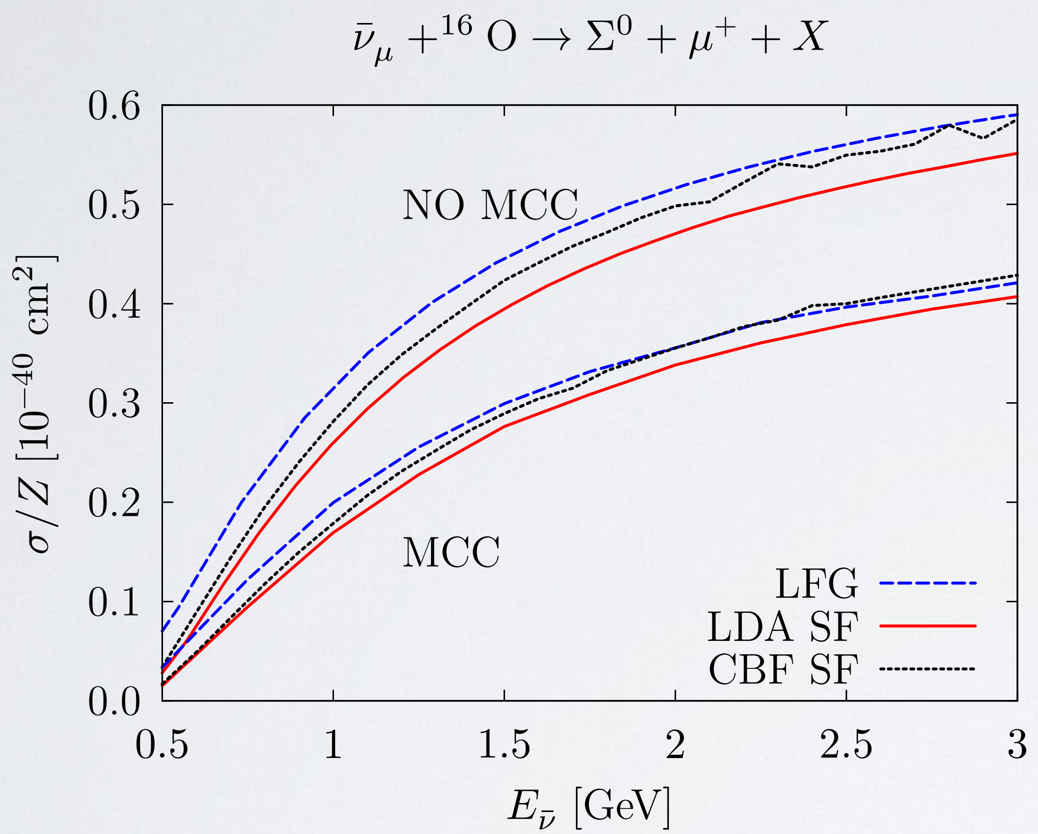


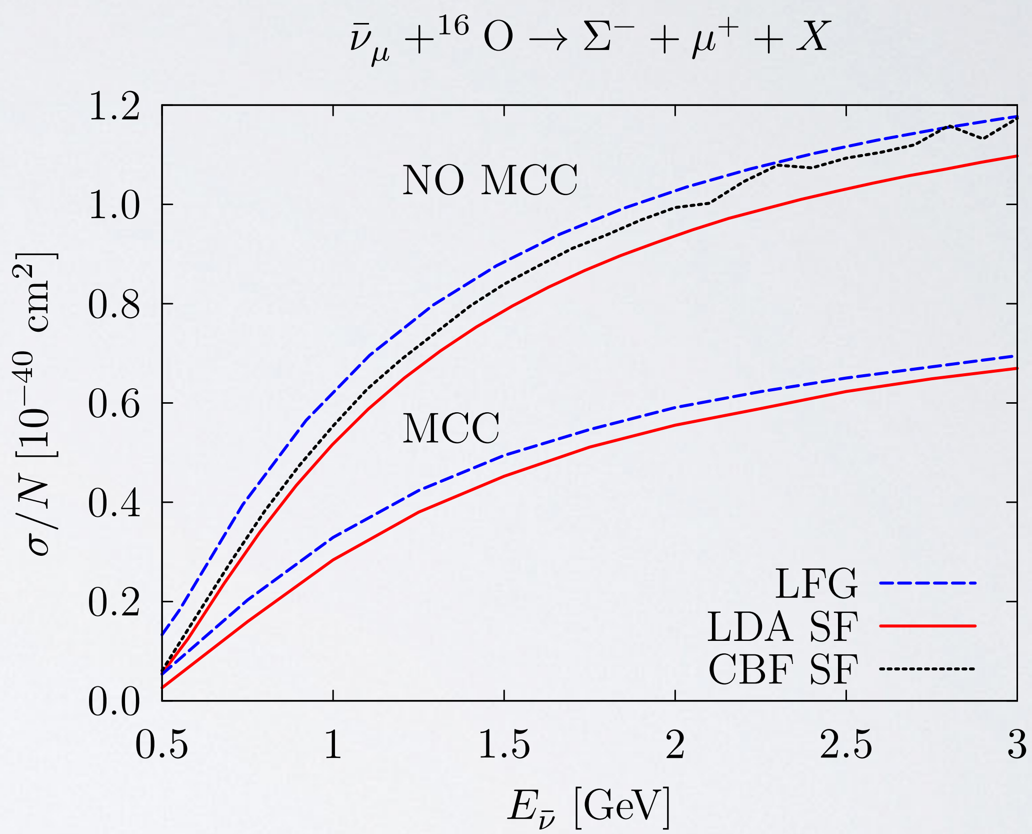
effects of MCC and ground state correlations are comparable

More Λ after MCC is switched on: $\Sigma^\pm, \Sigma^0$ are heavier so $\Sigma \to \Lambda$ has bigger available phase space

RESULTS (I)

total cross section





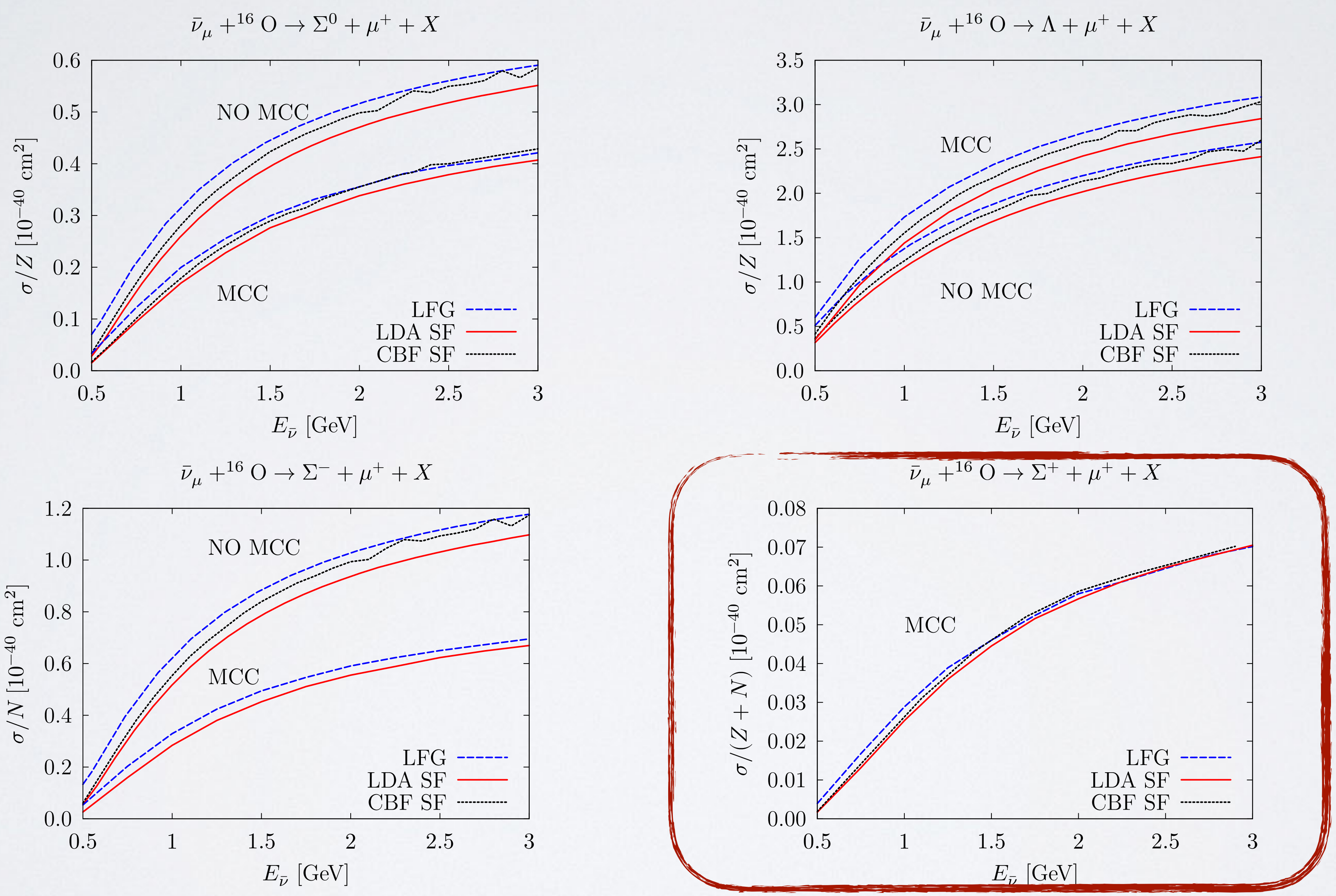
Clebsh-Gordan relation between the form factors

$$\frac{\sigma(\bar{\nu}_\mu + A \to \mu^+ + \Sigma^- + X)}{\sigma(\bar{\nu}_\mu + A \to \mu^+ + \Sigma^0 + X)} = 2$$

(MCC modifies this relation)

RESULTS (I)

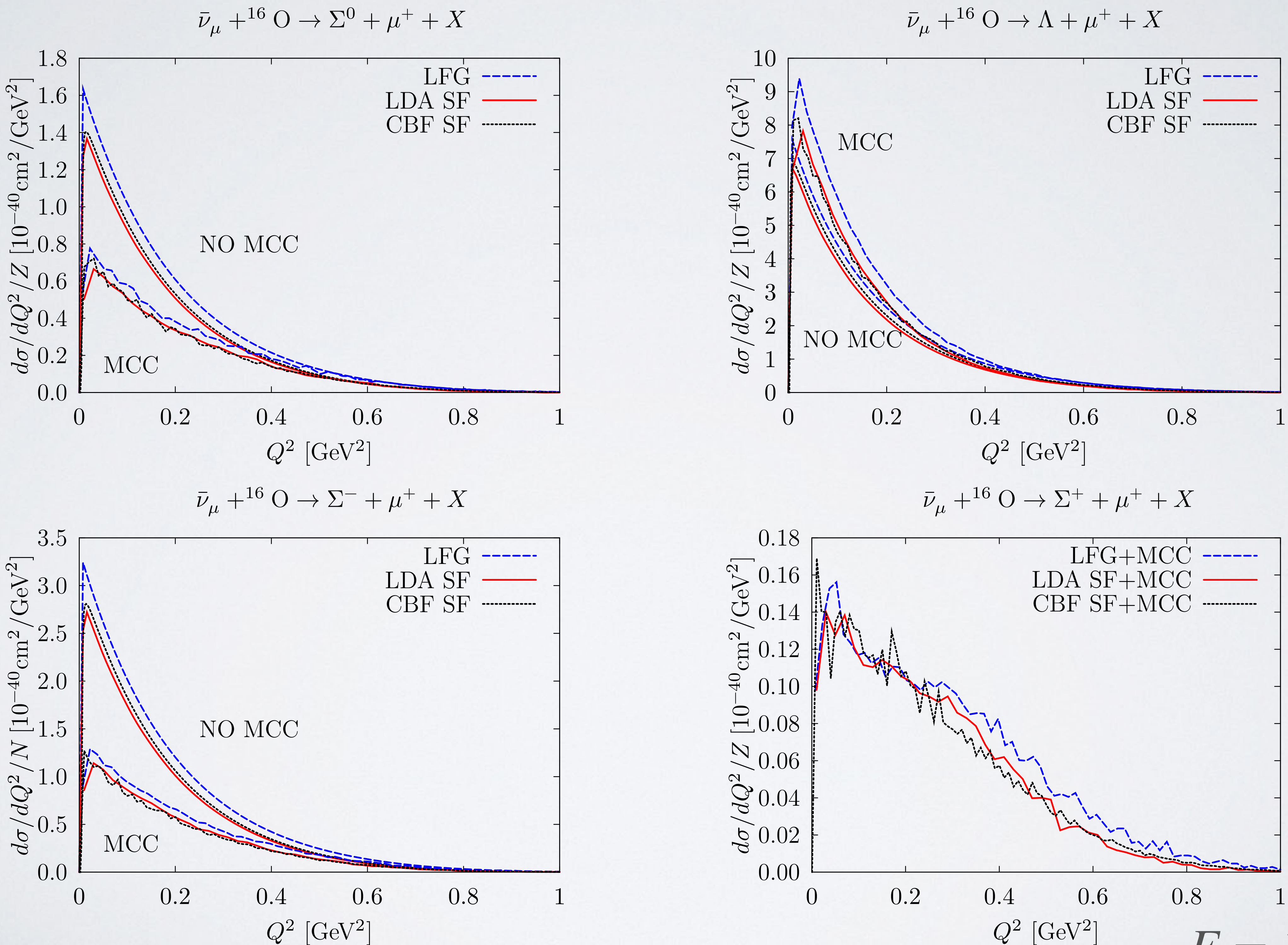
total cross section



produced through MCC

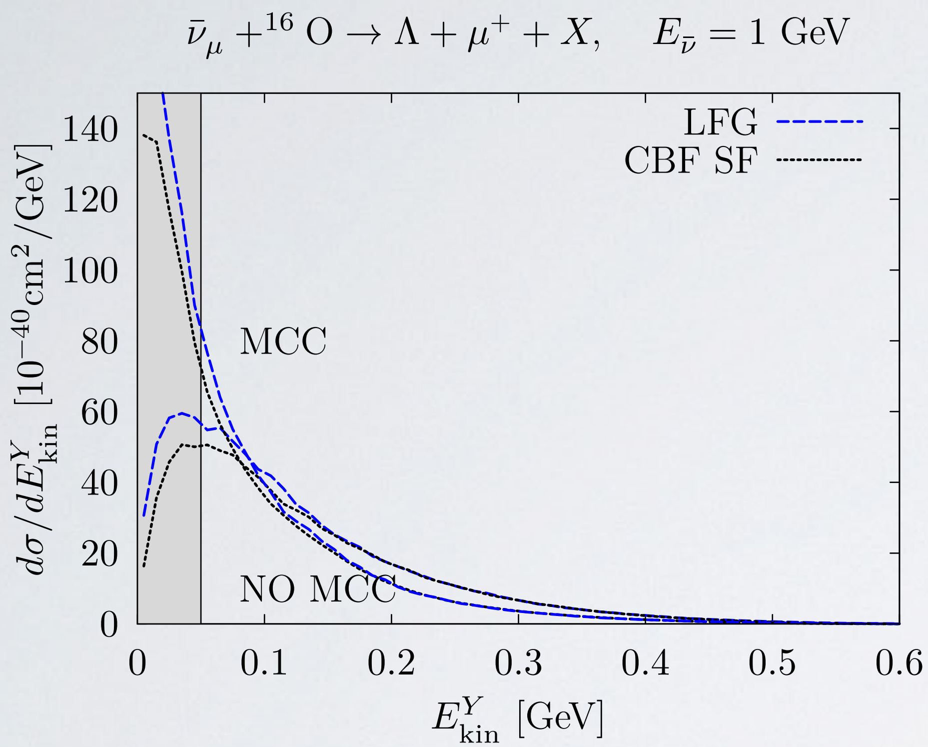
Internuclear cascade does not change the total cross section when summed over all hyperons.

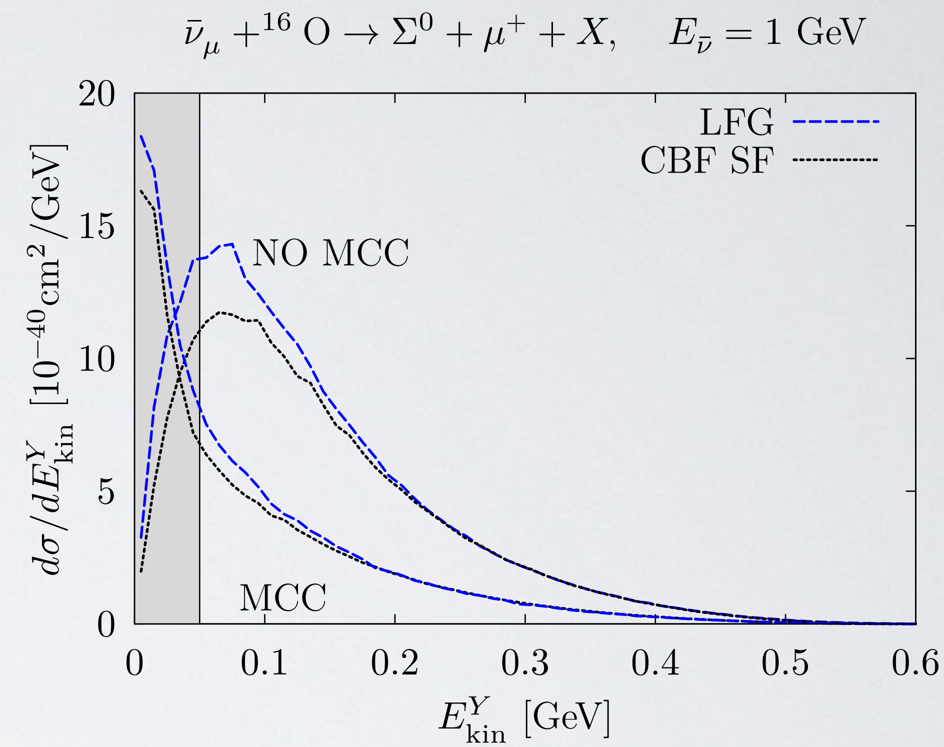
RESULTS (II)



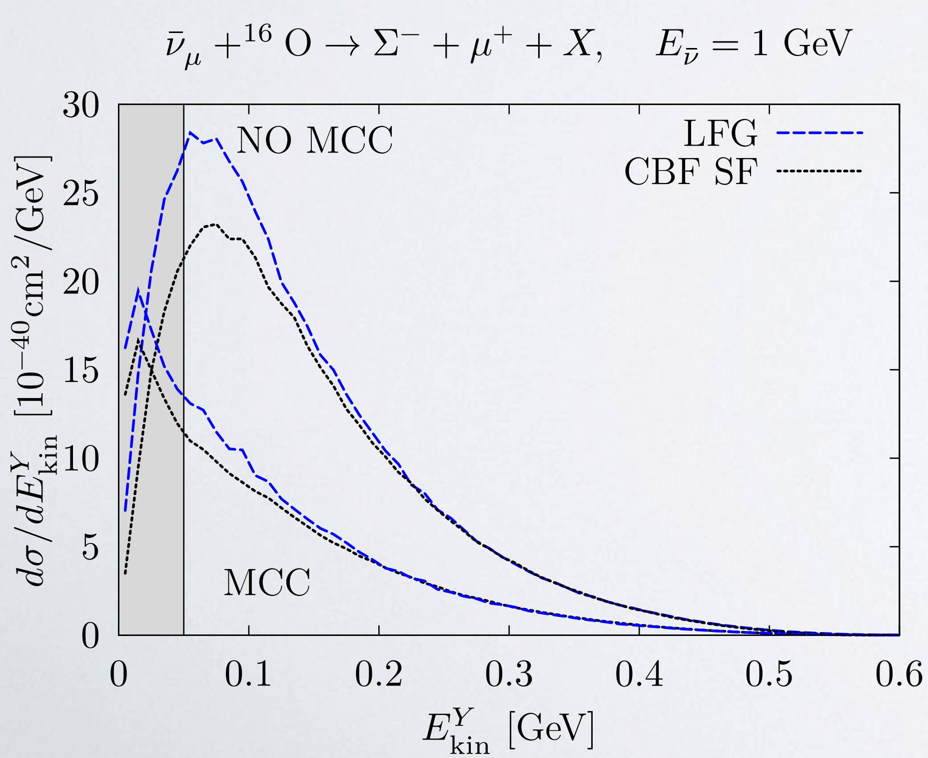
$E = 1$ GeV

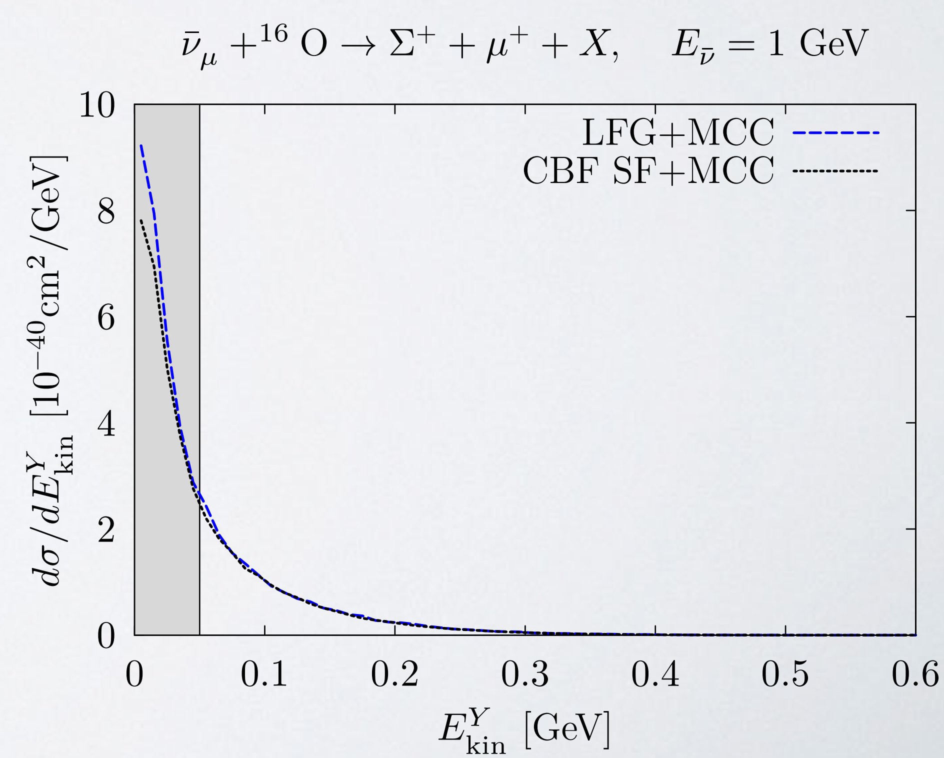
RESULTS (III)





- shaded region: the results are not trustworthy
- MCC redistributes hyperons towards lower energies
- different behaviour for Λ / Σ^-, Σ^0





OUTLINE

- Λ_c quasi-elastic production $\nu_l + A \to l^- + \Lambda_c + X$
  - interaction vertex (form factors)
  - results

MOTIVATION FOR Λ_c WEAK PRODUCTION

- Background for rare processes (e.g. trident processes e.g. $\nu_\mu \rightarrow \nu_\mu l^- l^+$)

- Minerva and DUNE sensitive to charm production

  - Until recently, the form factors could not be well constrained. Recent BESIII results for the decay width $\Lambda_C \rightarrow \Lambda + \bar{\nu}_l + l^-$ made possible some first realistic estimates of the cross section

INPUT DATA

- In the limit of **unbroken SU(3)** we can relate the form-factors for $\Lambda_c \to \Lambda$ and $\Lambda_c \to N$ with a flavour SU(3) rotation (CG coefficient $\sqrt{3/2}$)
- We use form factors from the models consistent with the experimental results of BESIII: $\mathrm{BR} = (3.63 \pm 0.38 \pm 0.20)\ \%$
- Some groups give predictions for both $\Lambda_c \to \Lambda$ and $\Lambda_c \to N$ form factors

MODELS USED IN THE COMPARISON

Lattice QCD **BR: 3.80+/- 0.19%**

S. Meinel, Phys. Rev. D97, 034511 (2018)
S. Meinel, Phys. Rev. Lett. 118, 082001 (2017)

Covariant confined quark model **BR: 2.78%**

T. Gutsche, M. A. Ivanov, J. G. Korner, V. E. Lyubovitskij, and P. Santorelli, Phys. Rev. D90, 114033 (2014)
T. Gutsche, M. A. Ivanov, J. G. Korner, V. E. Lyubovitskij, and P. Santorelli, Phys. Rev. D93, 034008 (2016)

Nonrelativistic quark model (HO basis) **BR: 3.84%**

M. M. Hussain and W. Roberts, Phys. Rev. D95, 053005 (2017)

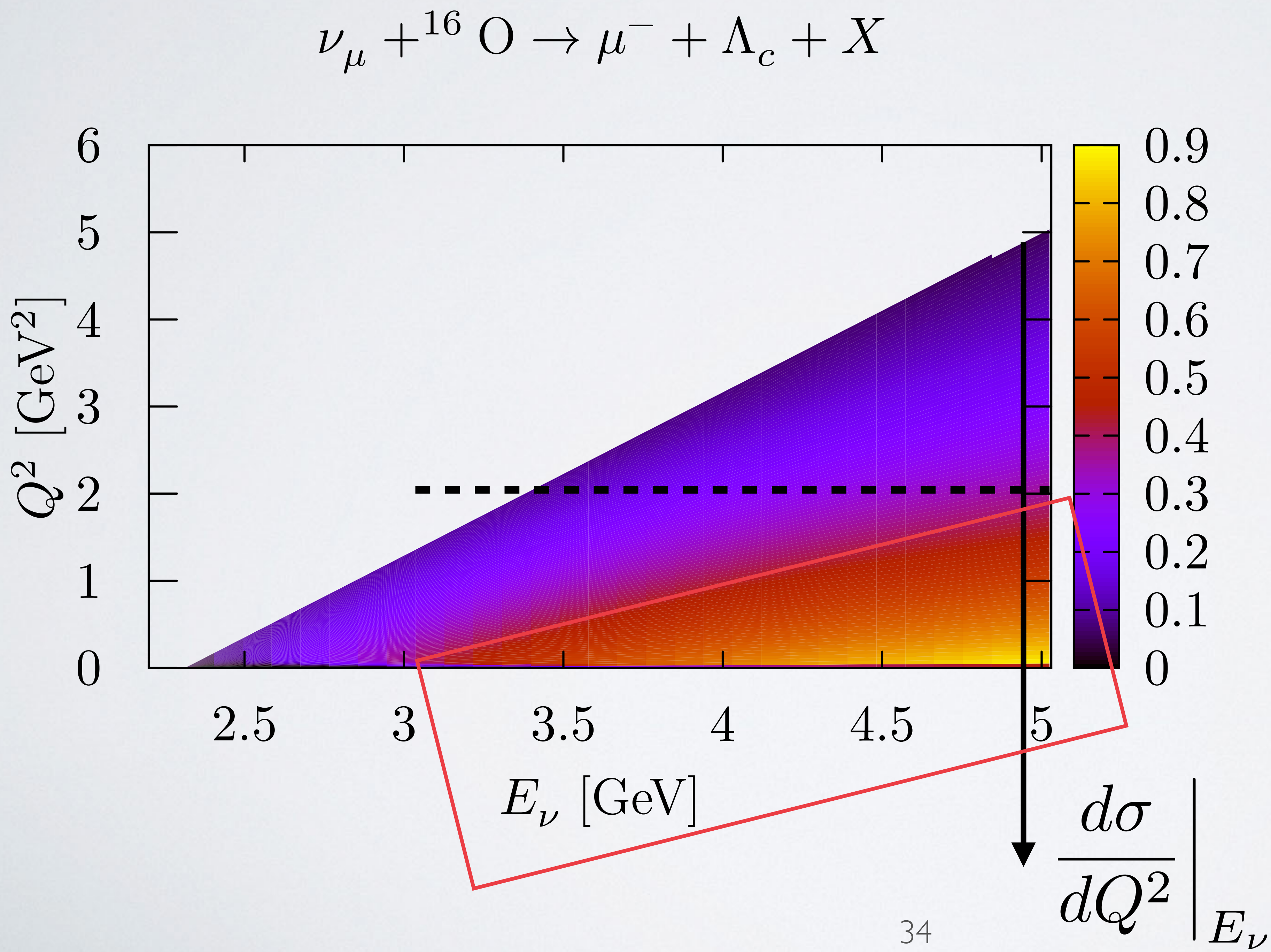
MIT bag model and NRQM **BR: 3.00%, 3.66%**

R. Perez-Marcial, R. Huerta, A. Garcia, and M. Avila-Aoki, Phys. Rev. D40, 2955 (1989)

IMPORTANT REMARKS

- For the decays $Q^2 \in (-1.4, 0)\ \mathrm{GeV}^2$ $\quad (Q^2 = \vec{q}^{\,2} - \omega^2)$
- We extrapolate form-factors to a region of $Q^2 > 0$ taking care that we do not go too high
- We limit our calculation to $E_\nu < 5$ GeV (Minerva, DUNE peak energy)

PHASE SPACE

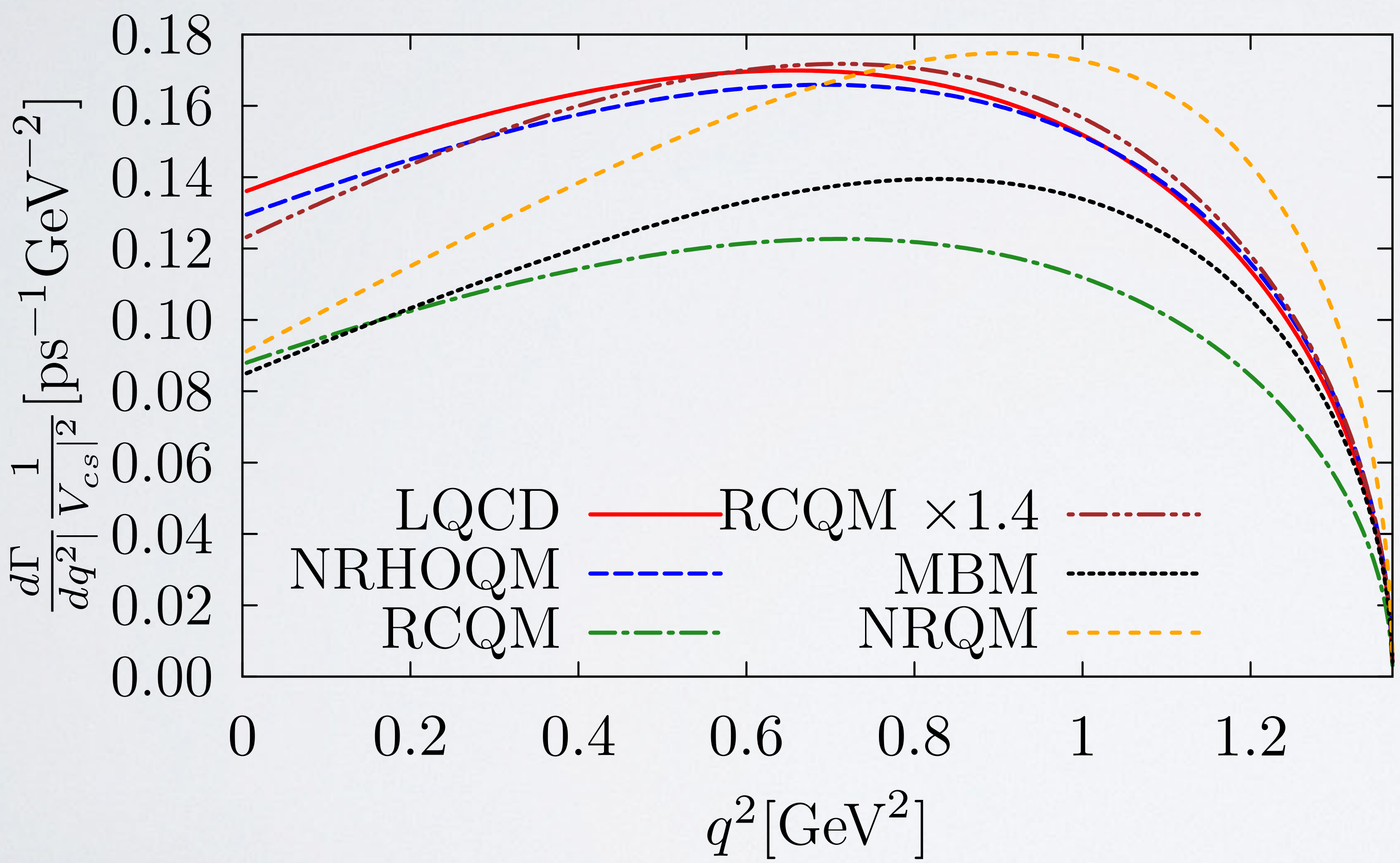


The bulk of cross section lies at low Q[2]

The extrapolation of the form factors to the region of higher Q[2] introduces uncertainties

VARIOUS MODELS FOR FORM FACTORS

$\Lambda_c \to \Lambda \bar{\nu}_e e^-$



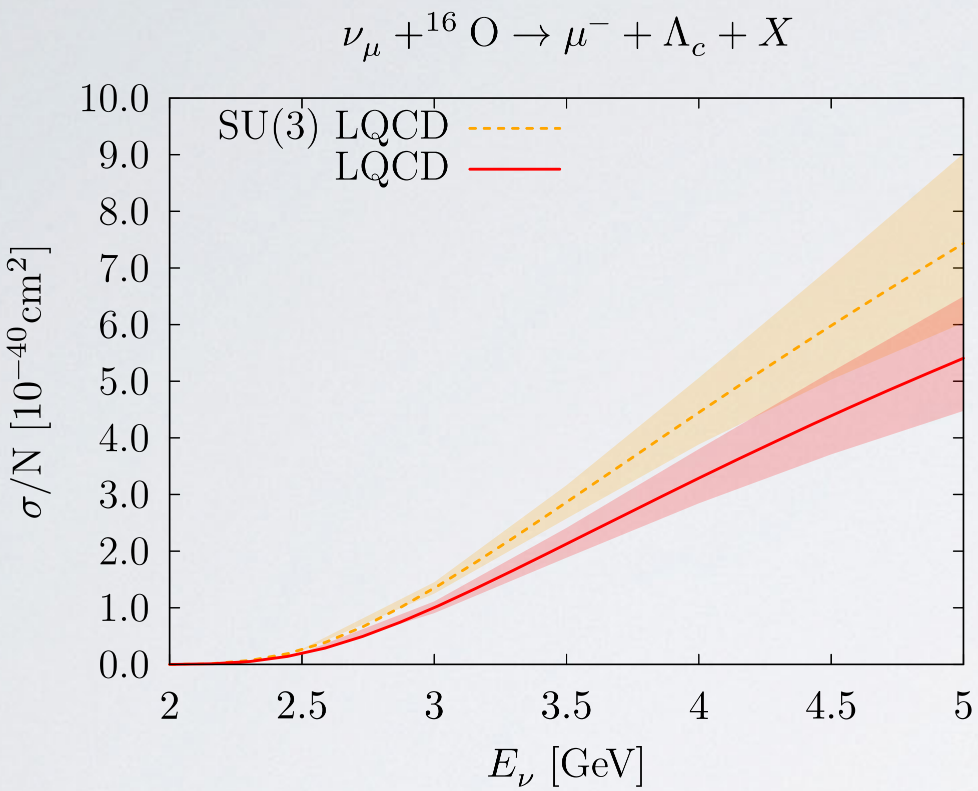
$\frac{d\Gamma}{dq^2}$ in different models: q^2 dependence of the form factors

LQCD, NRHOCM, RCQM have similar q^2 behaviour

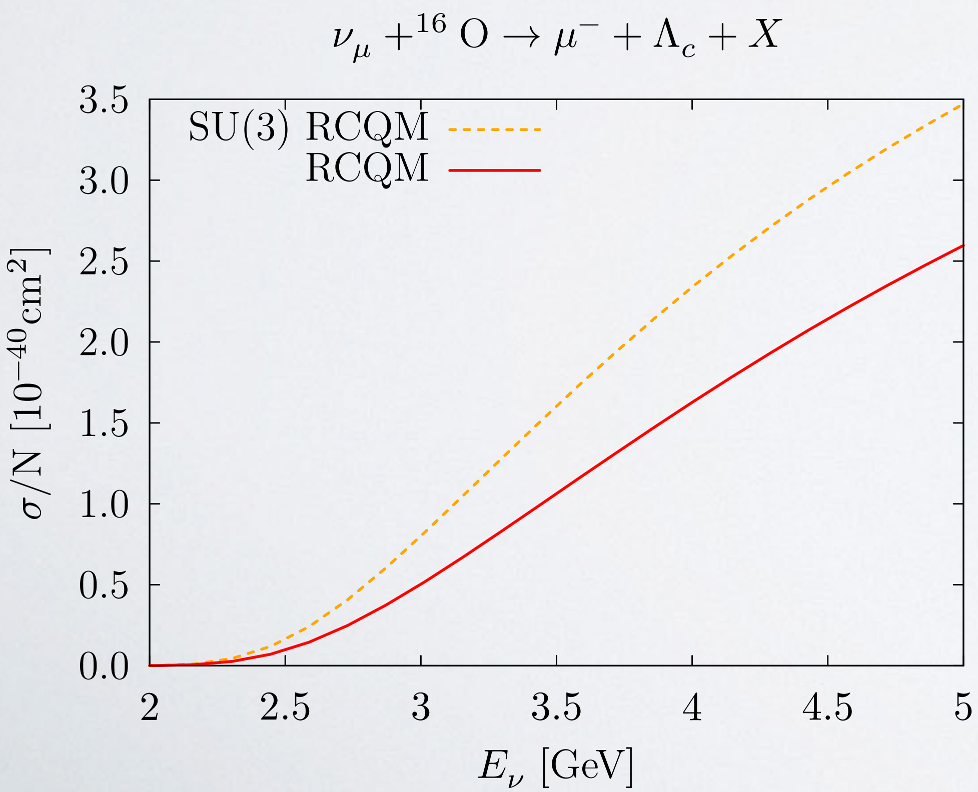
FORM FACTORS

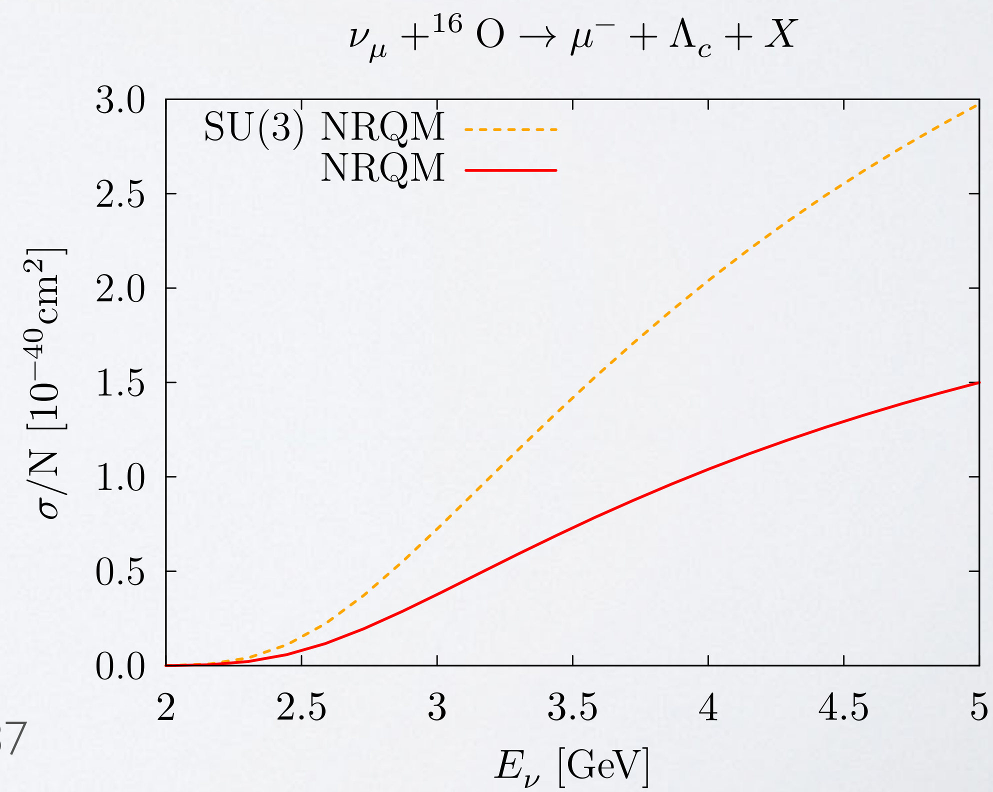
- Restrictions when using the same form factors:
  - fitted to the data at $Q^2<0$ (decay), while used for $Q^2>0$
  - Different contributions coming from distinct form factors in decay processes and cross section (some are not as much constrained)
  - SU(3) breaking effects are on the level of 20-30%

RESULTS

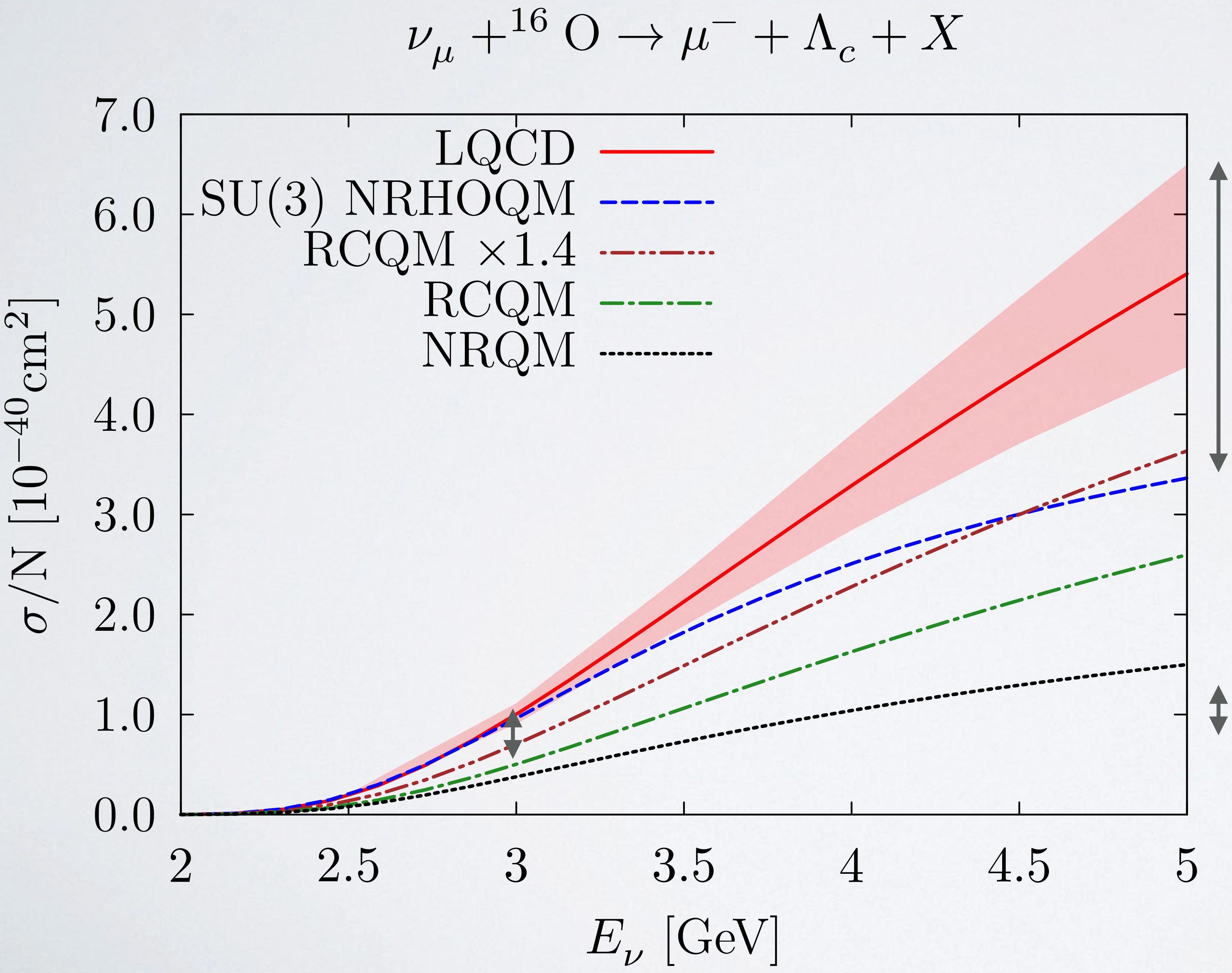


SU(3) breaking effects ~25-50%





RESULTS



DUNE peak

$\sigma(E = 5\ \mathrm{GeV})/N = (4.5^{+2.0}_{-0.9}) \times 10^{-40}\ \mathrm{cm}^2$

Minerva peak

$\sigma(E = 3\ \mathrm{GeV})/N = (0.9^{+0.2}_{-0.1}) \times 10^{-40}\ \mathrm{cm}^2$

CONCLUSIONS

Strange hyperon production

- Large effects of internuclear cascade (total cross section, energy distribution of outgoing hyperons)
- ground state description affects $\frac{d\sigma}{d\cos\theta dq^0}$ does not affect much q^2 distribution
- Two spectral functions give similar predictions

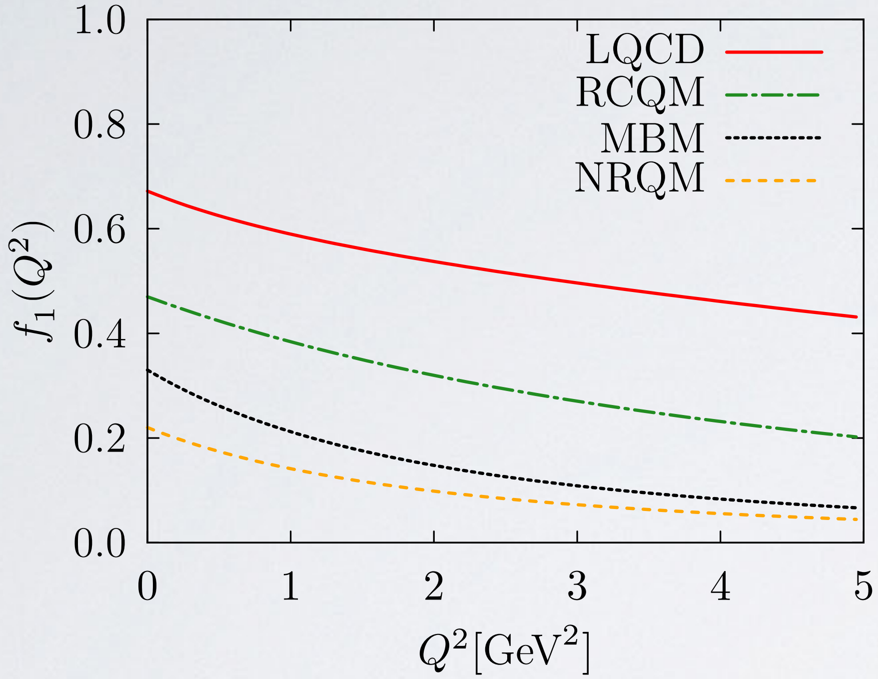
Charm hyperon production

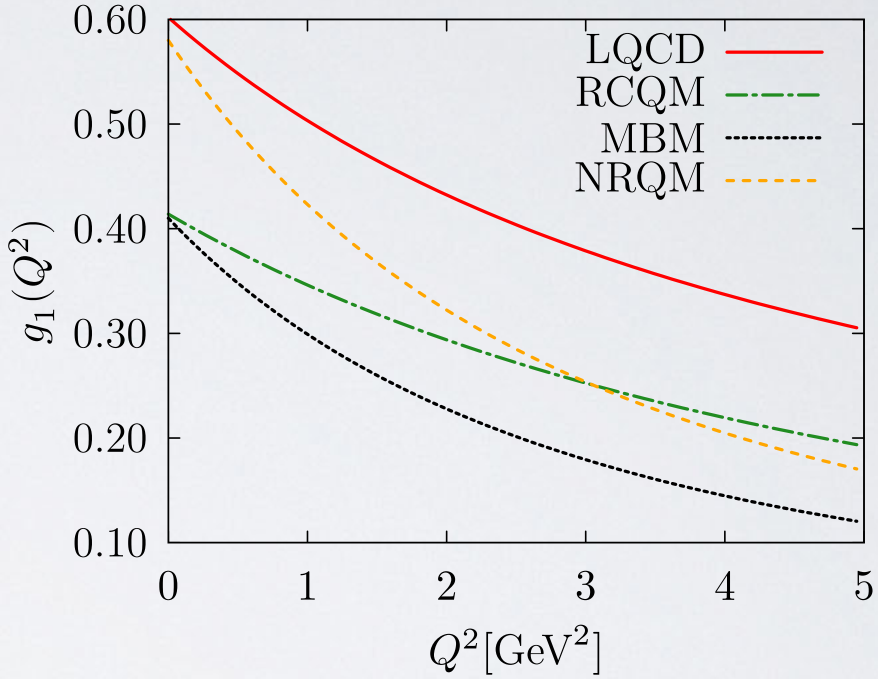
- Experimentally may be measured
- First predictions of Λ_c production with models constrained with BESIII BR measurements
- Large dependence on the form-factors parametrisation (theoretical uncertainty)
- No input data to simulate internuclear cascade

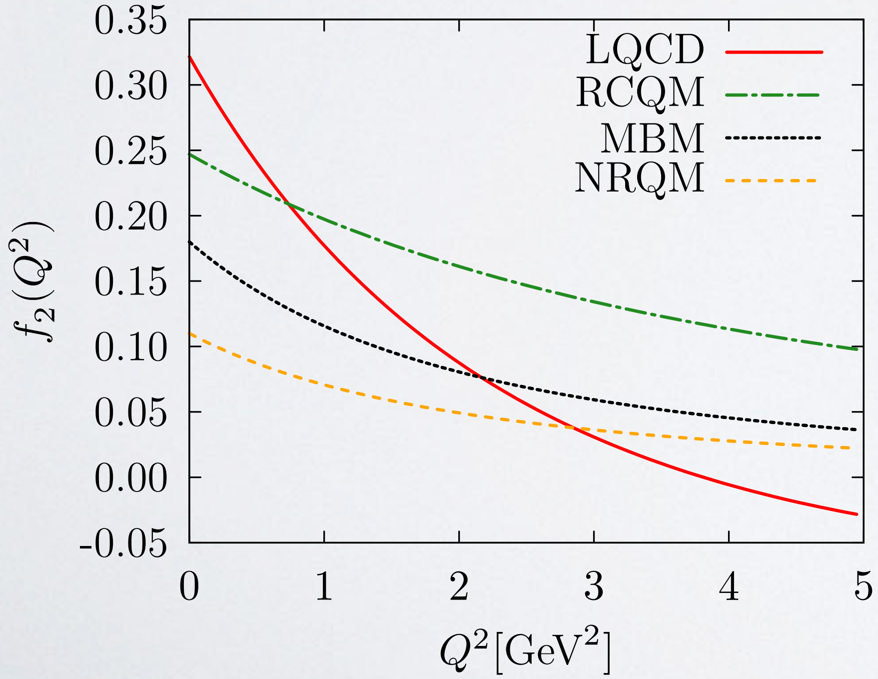
THANK YOU!

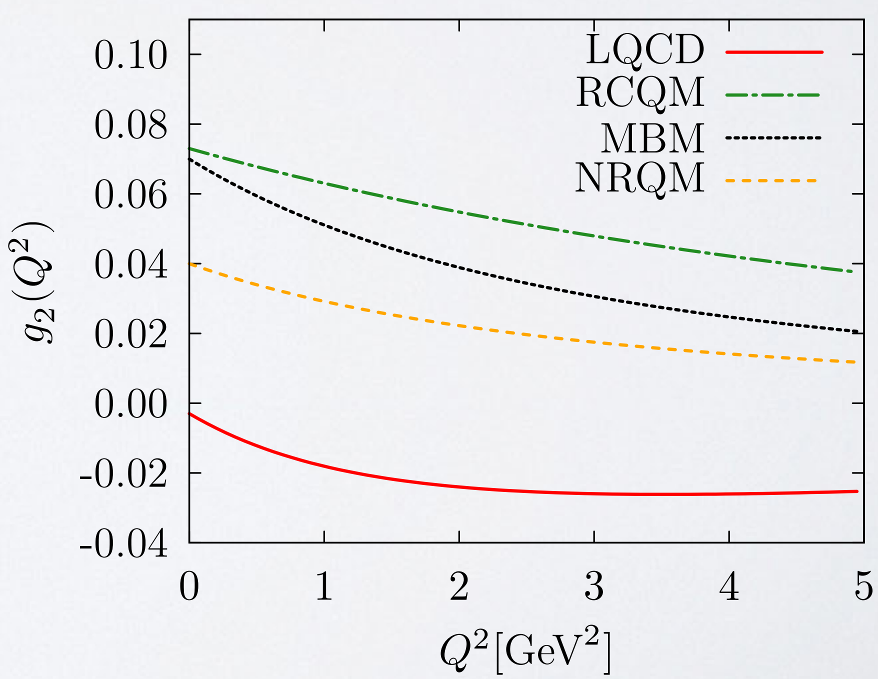
BACKUP

Q^2 DEPENDENCE OF THE FORM FACTORS









CHORUS result for E=27 GeV

$$\frac{\sigma(\Lambda_c)}{\sigma(\mathrm{CC})} = \left(1.54 \pm 0.35(\mathrm{stat}) \pm 0.18(\mathrm{syst})\right) \times 10^{-2}$$

PION PRODUCTION FROM HYPERONS

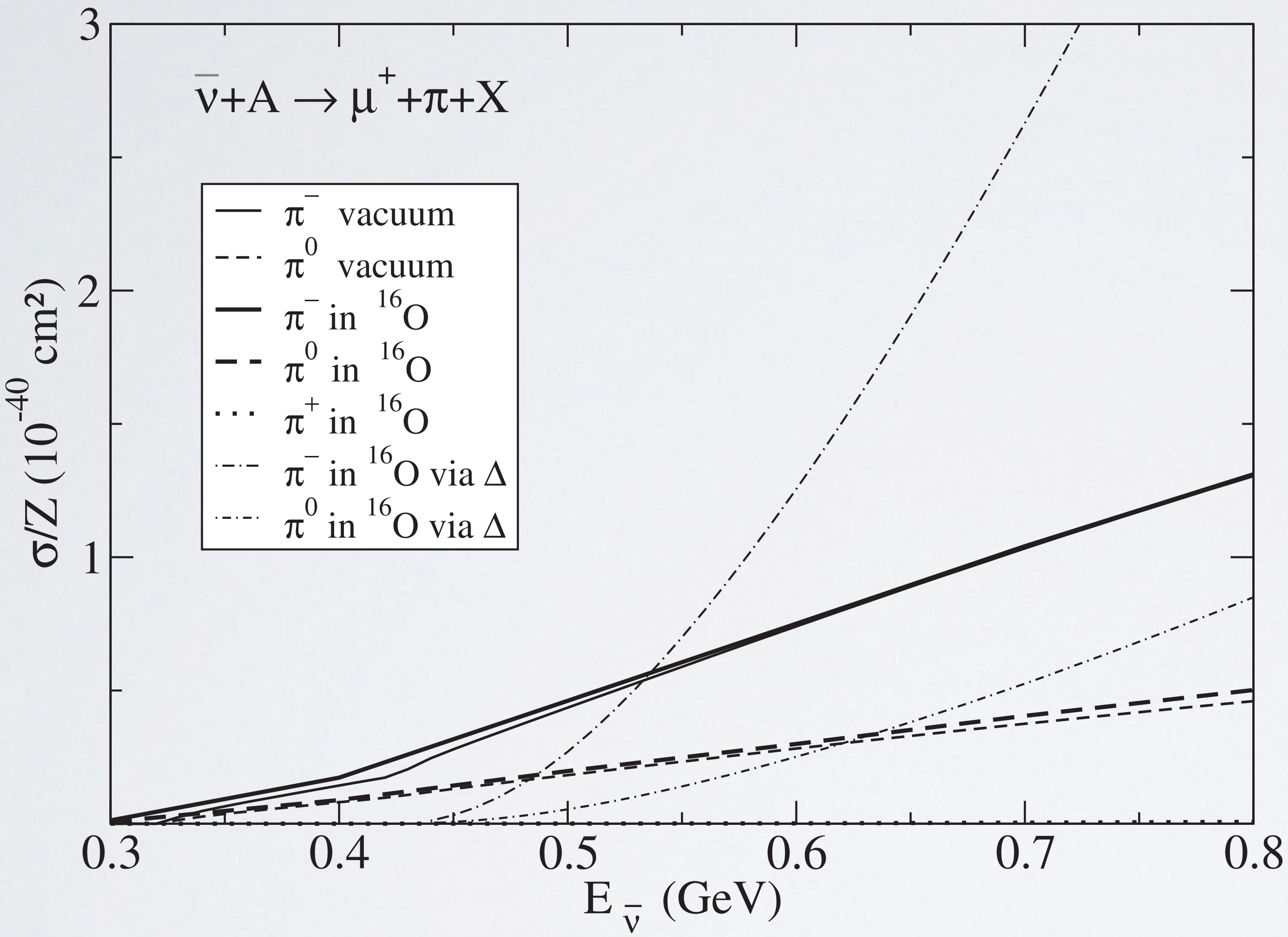


FIG. 10. Cross section for π production via an intermediate hyperon induced by a muonic antineutrino divided by the number of protons as a function of the antineutrino energy. Results compared with pions produced via Δ excitation.

S.K. Singh, M.J. Vicente Vacas
Phys.Rev. D74 (2006) 053009