Meson Exchange Current (MEC) model in Neutrino Interaction Generator

outline

1. Introduction
2. Leptonic simulation in GENIE
3. Hadronic simulation in GENIE
4. Comparisons
5. Discussion

Teppei Katori
Massachusetts Institute of Technology
(and Cordão de Ouro Chicago)
NuInt12, CBPF, Rio de Janeiro, Brazil, Oct. 22, 2012

1. Introduction

2. Leptonic simulation in GENIE

3. hadronic simulation in GENIE

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Benhar, Day, Sick
Rev.Mod.Phys80(2008)189

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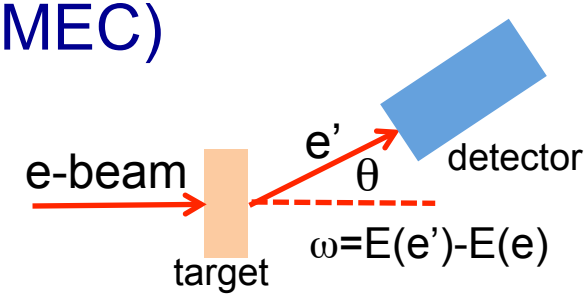
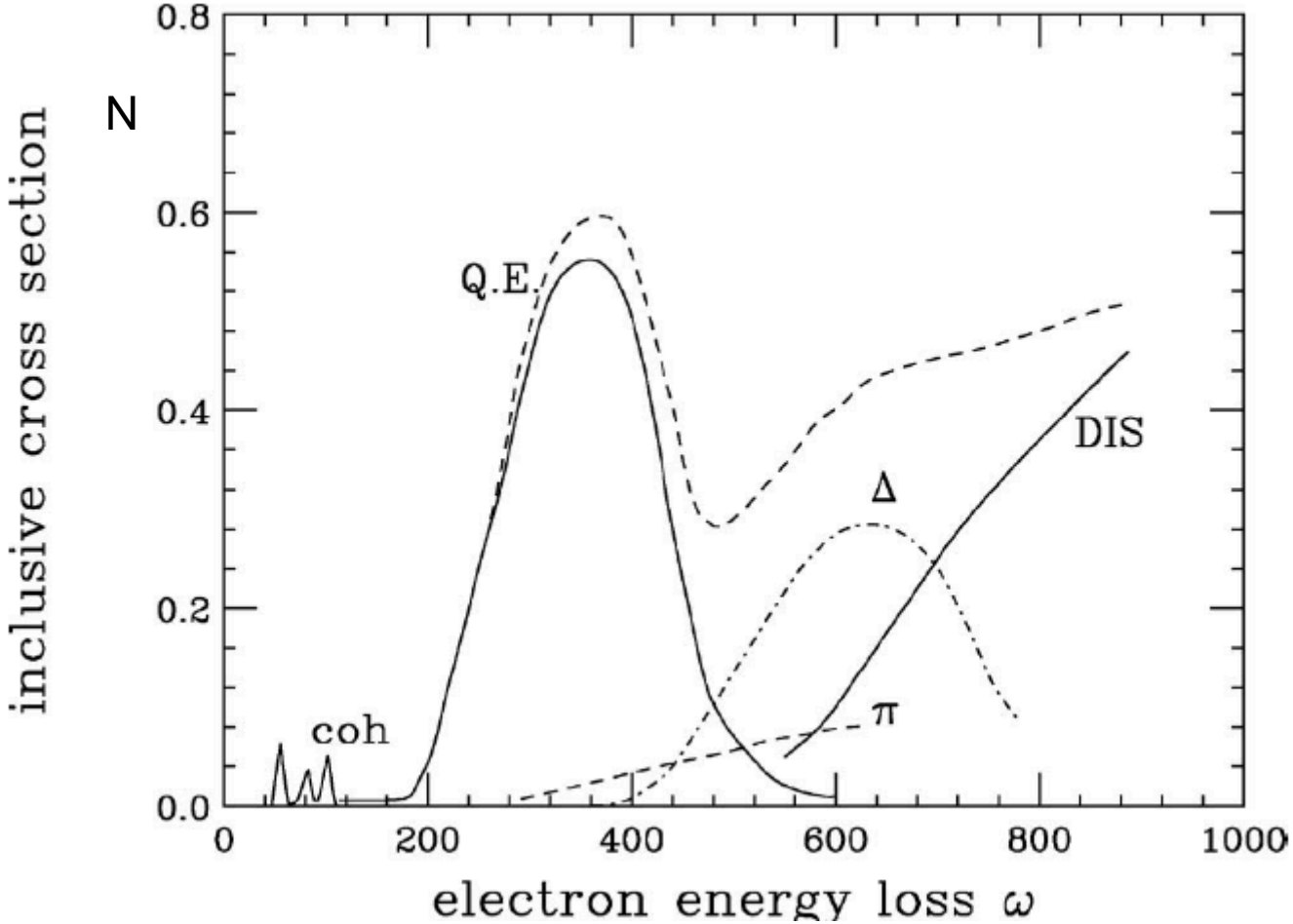


Inclusive electron scattering with function of energy loss



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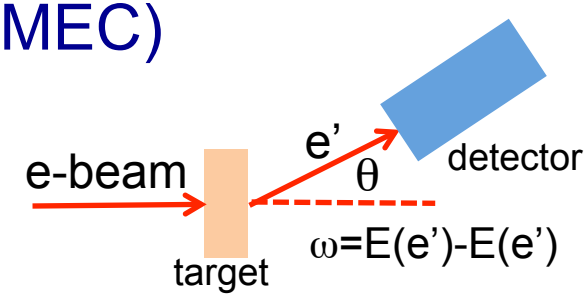

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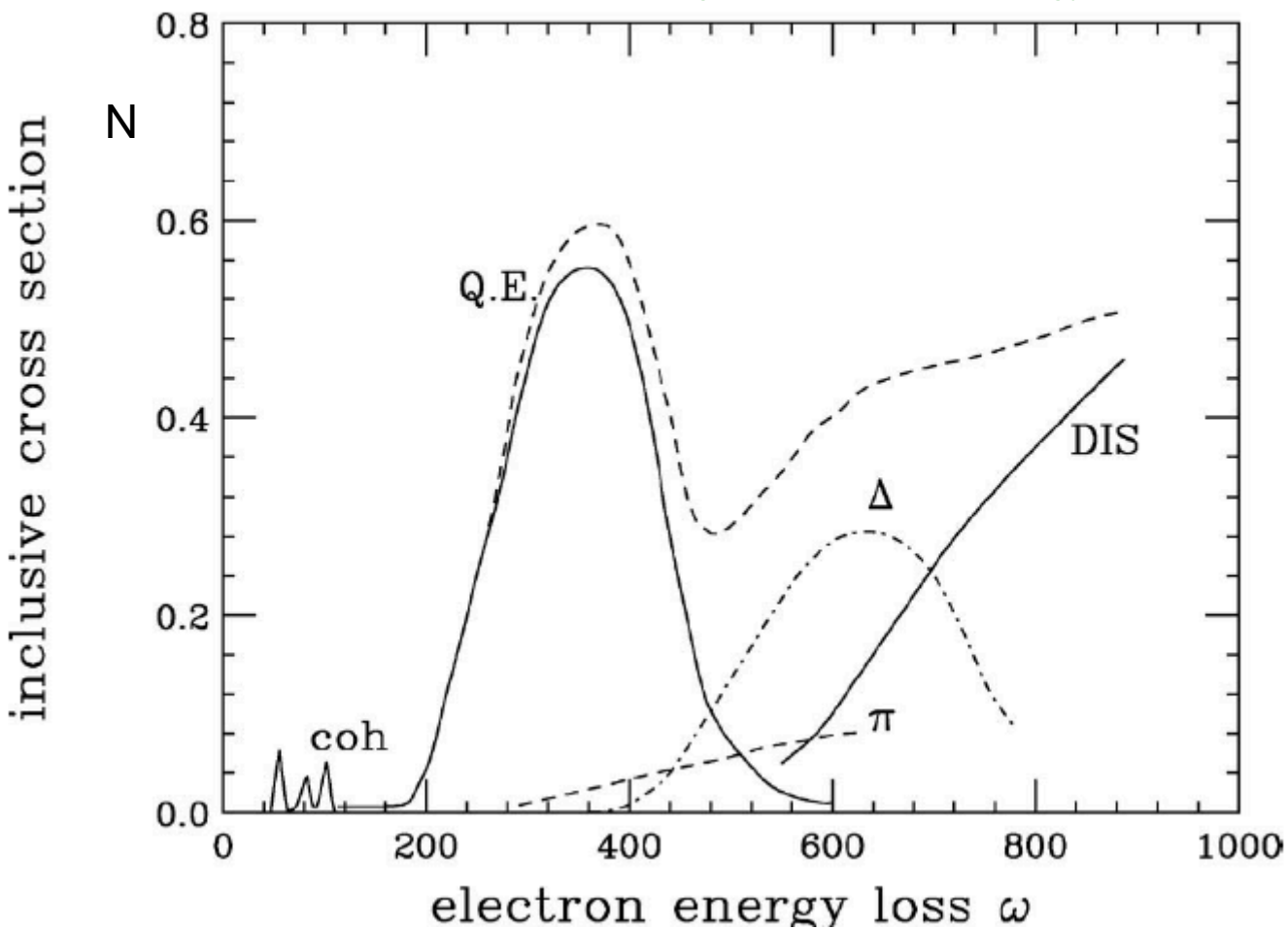

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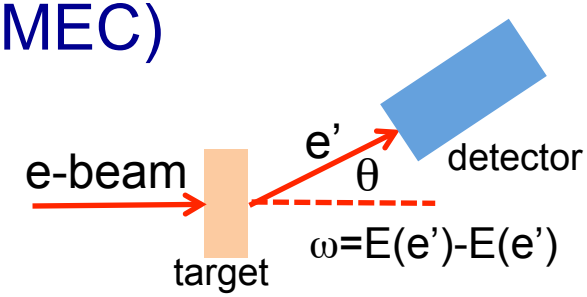

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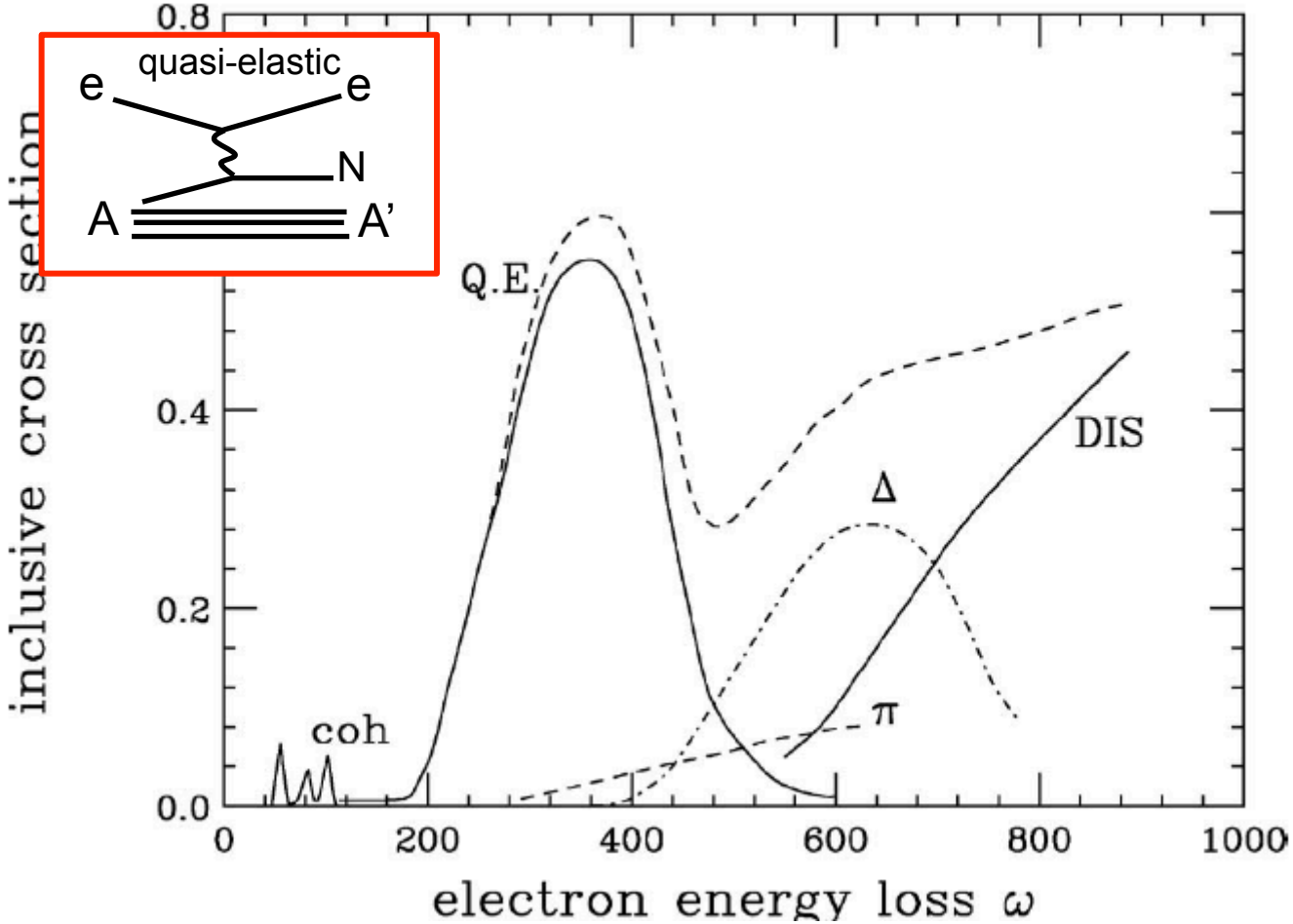

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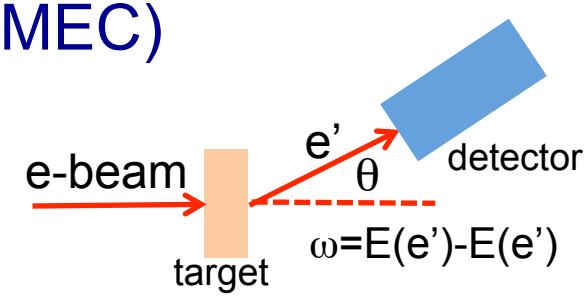

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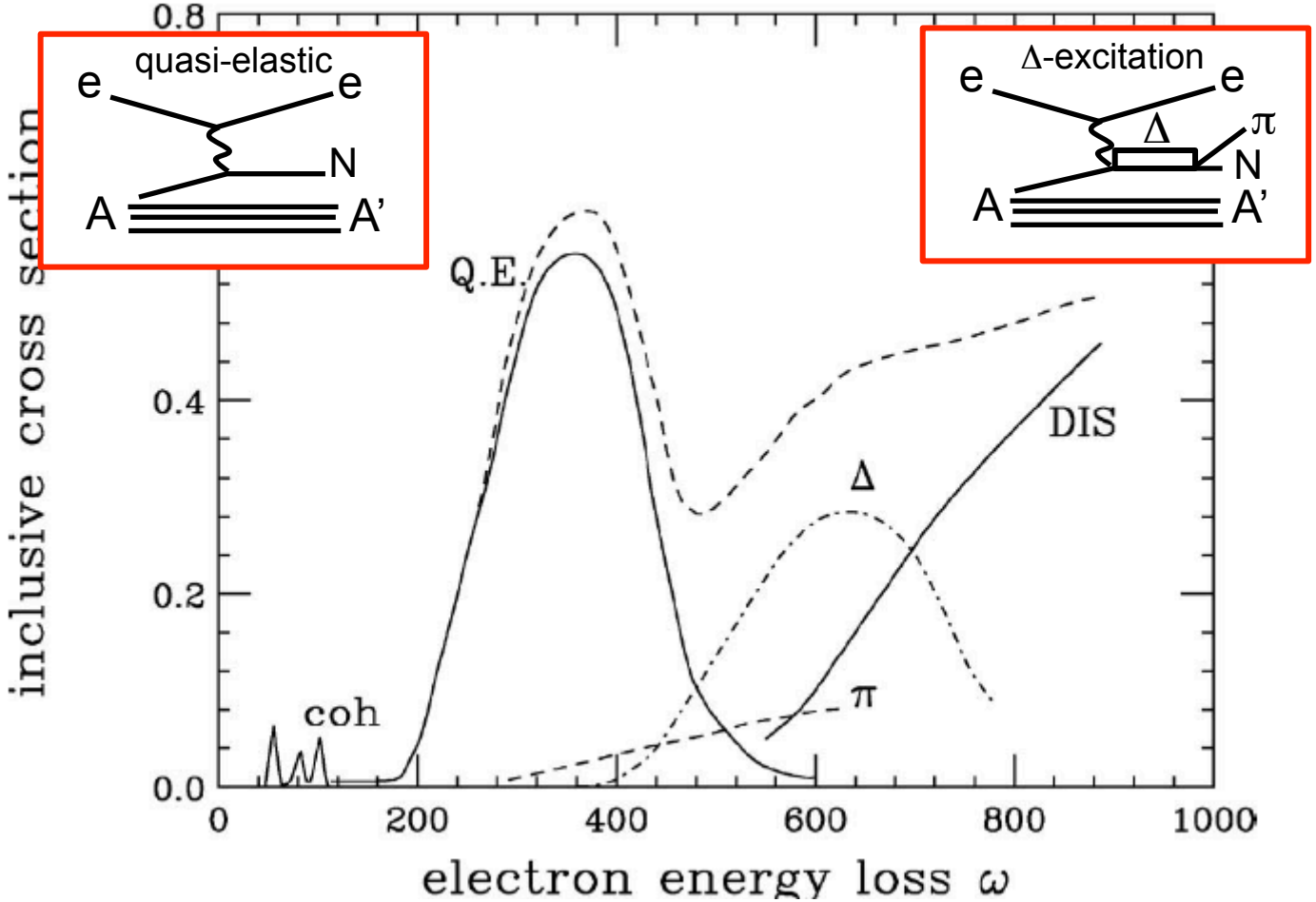

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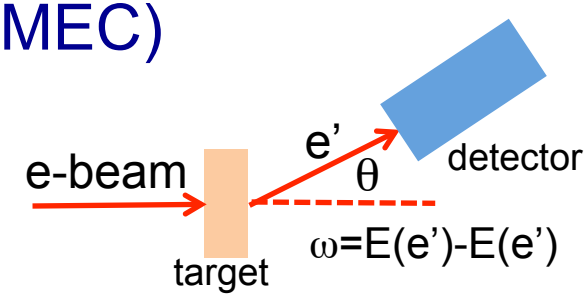

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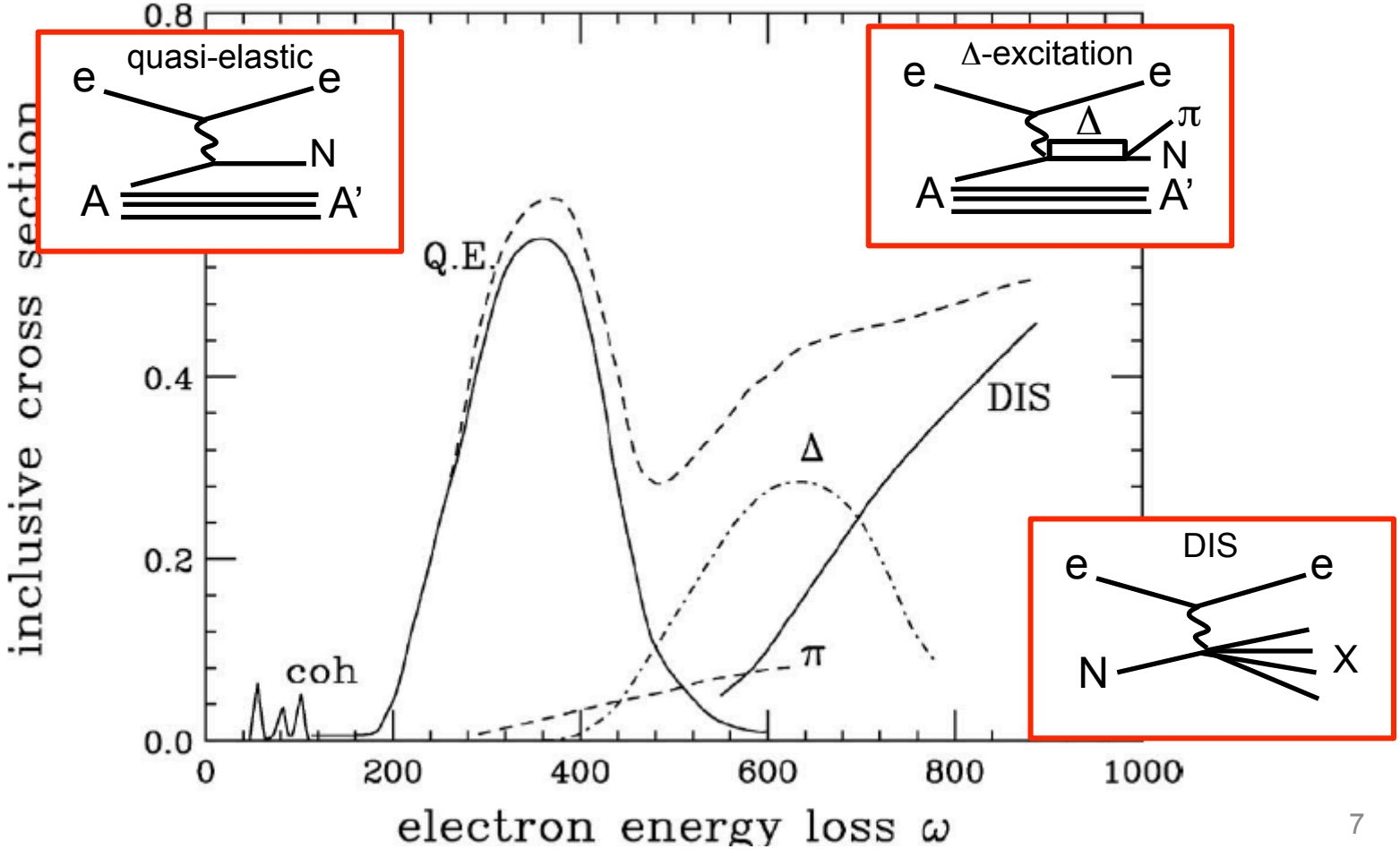

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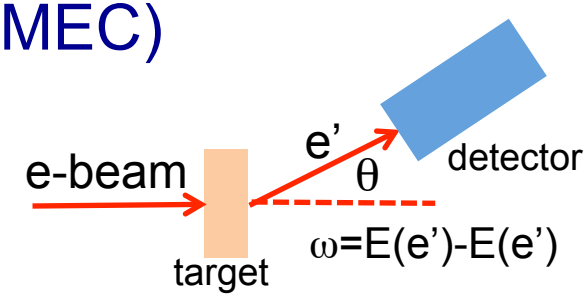

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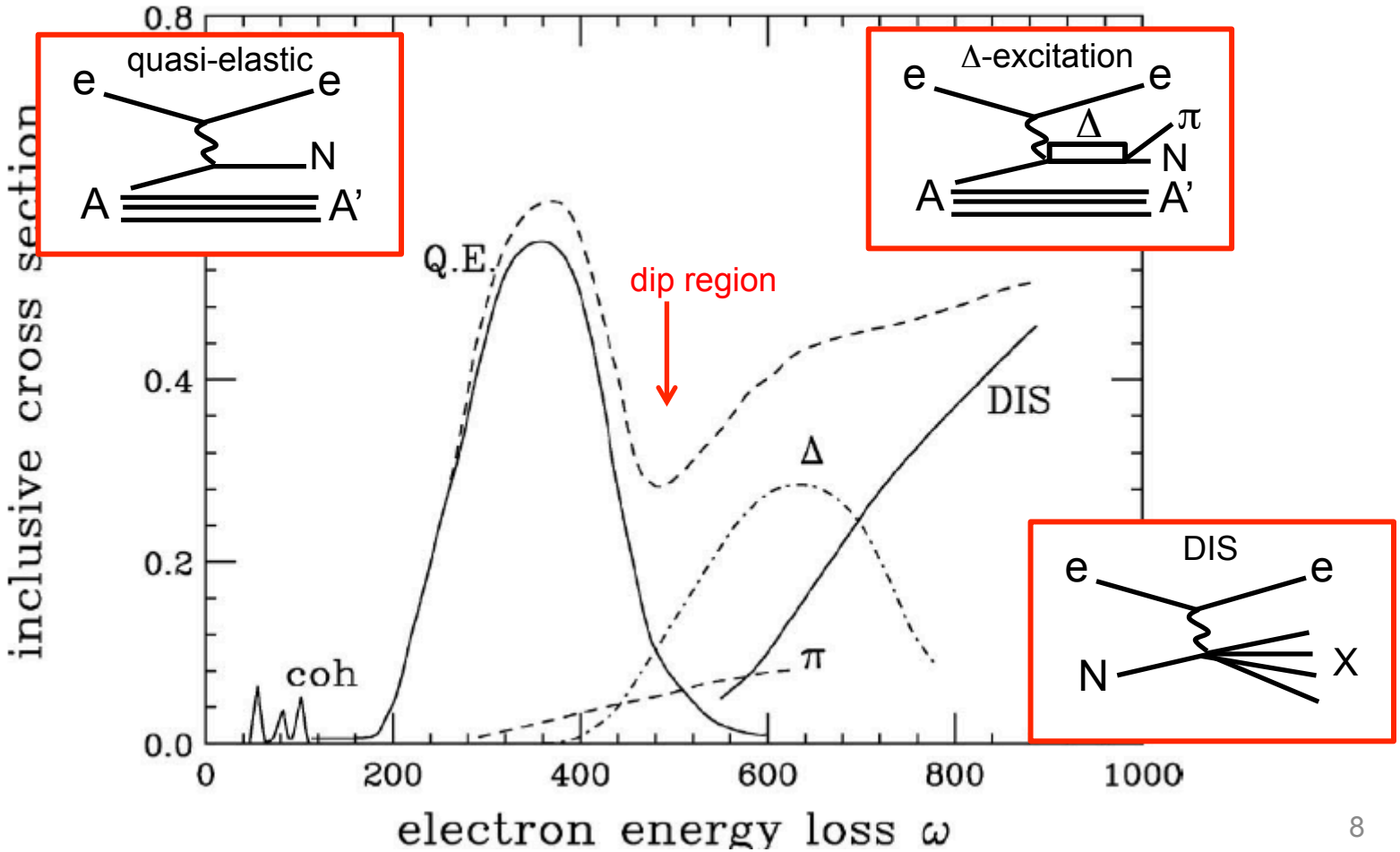

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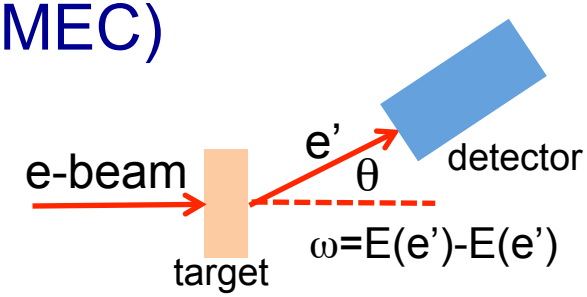

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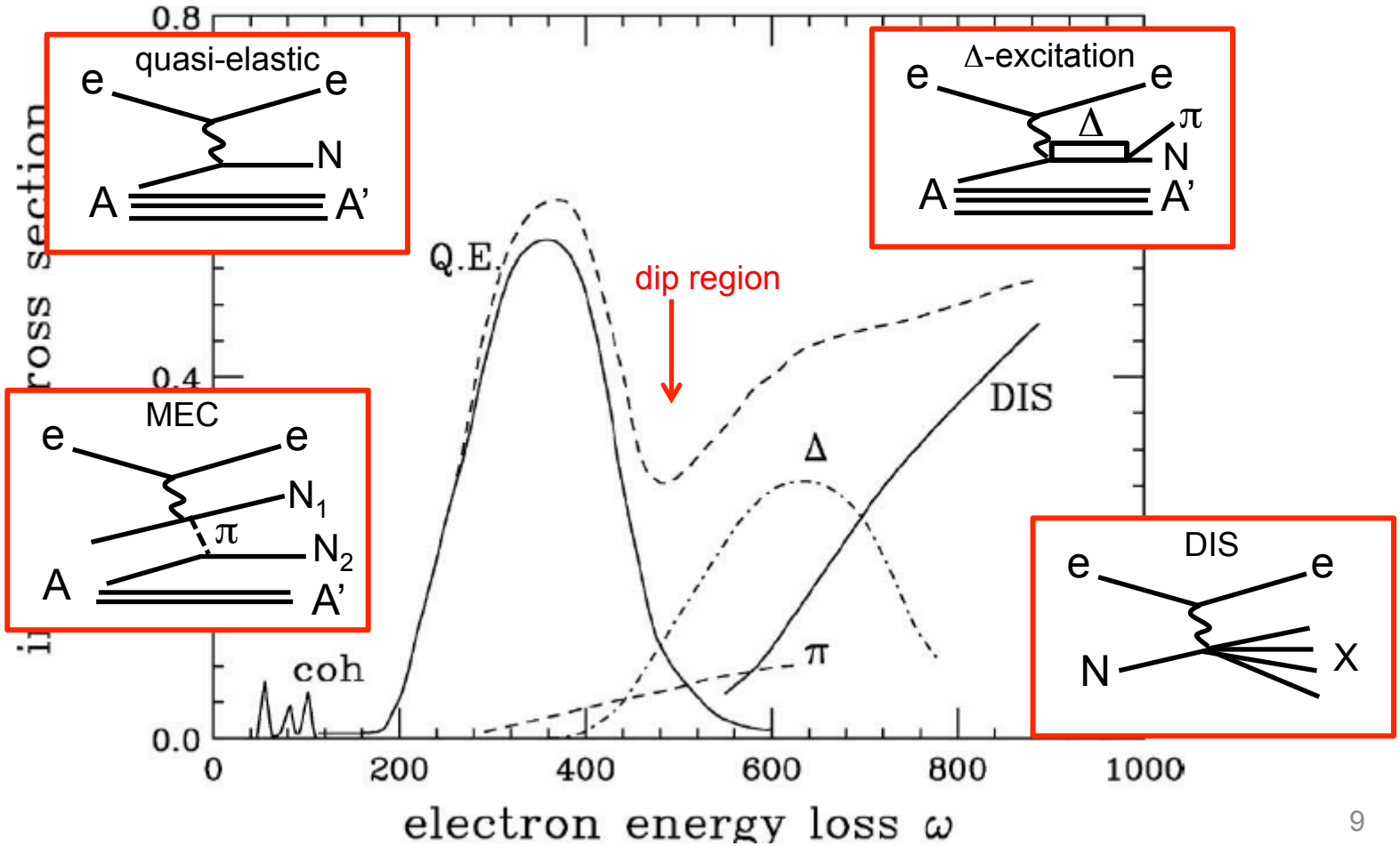

Van Orden and Donnelly
Annals.Phys.131(1981)451

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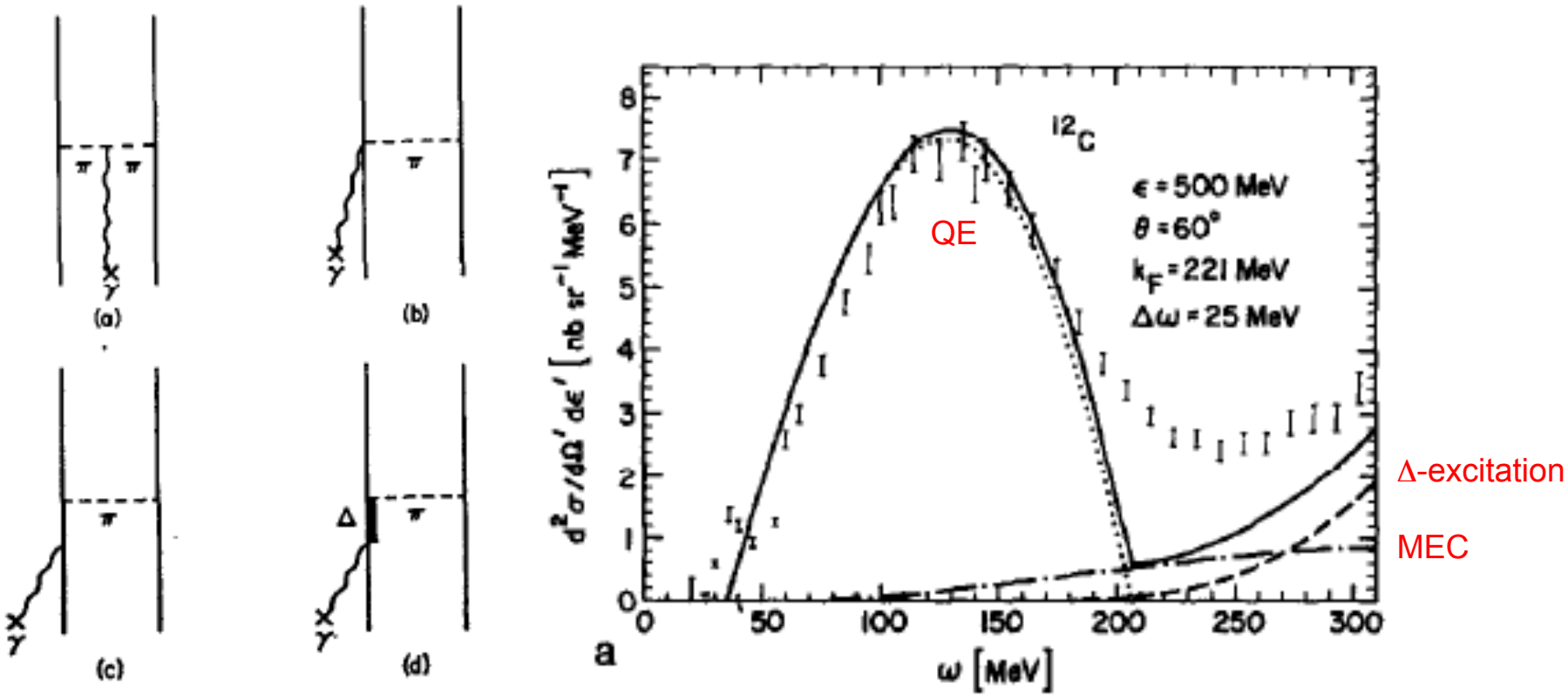
- MEC also contributes to QE peak (~10%)



Carlson et al,
PRC65(2002)024002

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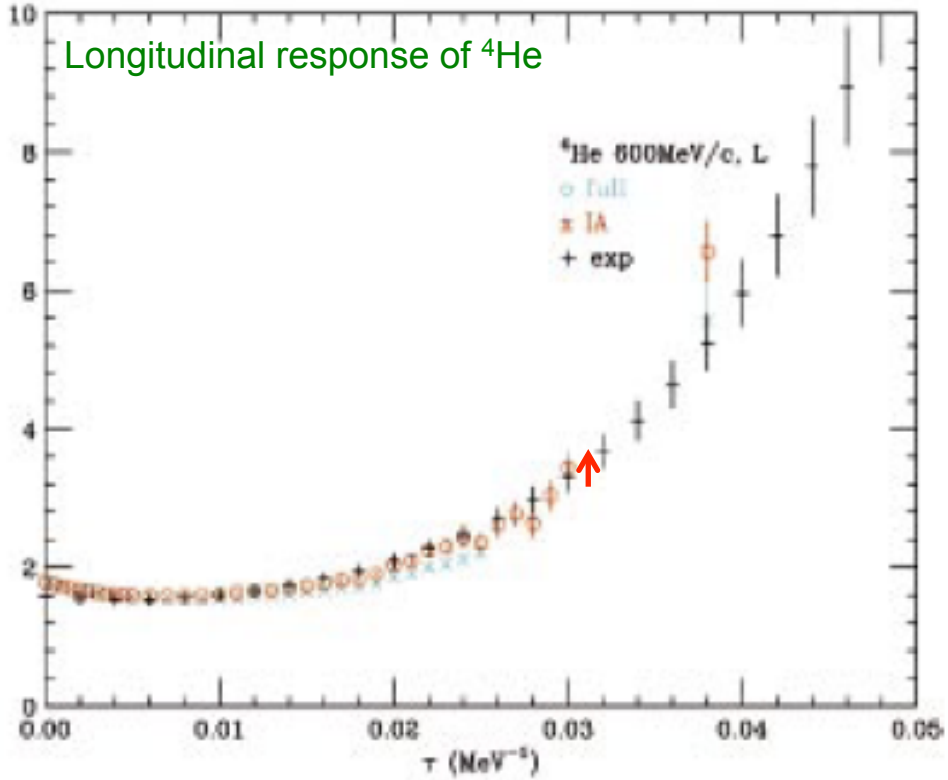
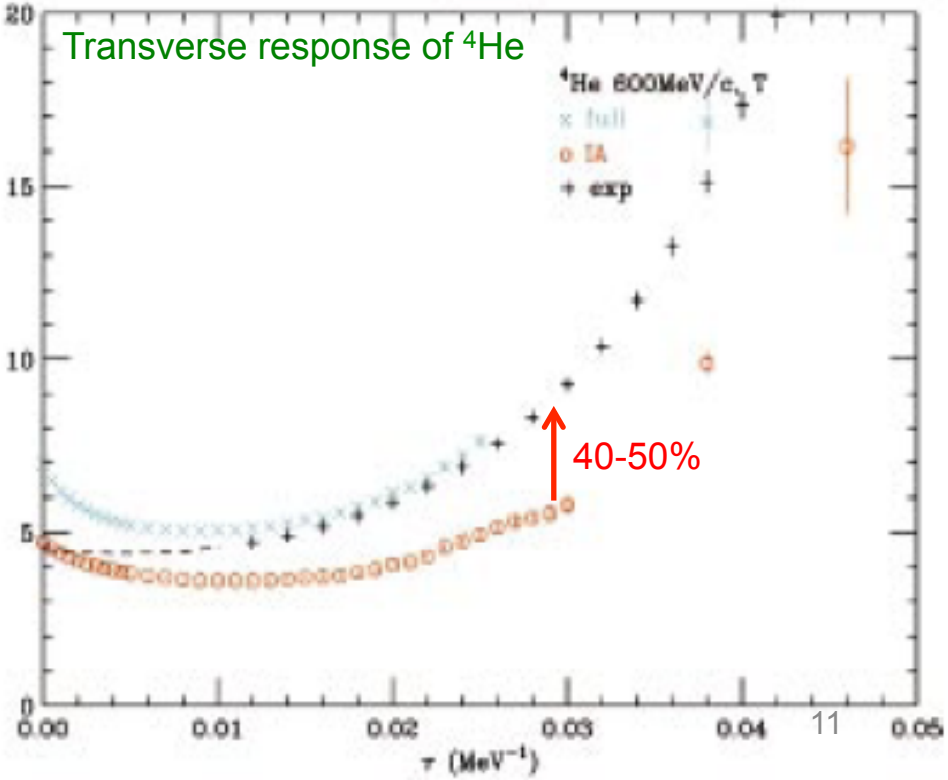
- MEC may contribute more than we thought

Note:
Calculation with good NN potential – has correlations
Light nuclei only
Non-relativistic





Martini et al,
PRC80(2009)065501

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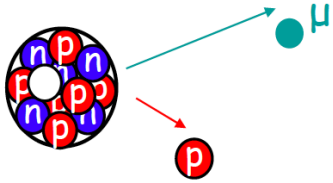
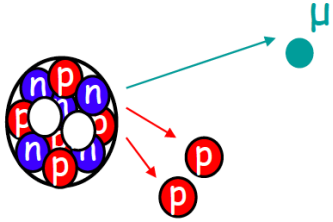
- This process may be needed to describe recent QE ν-xs data

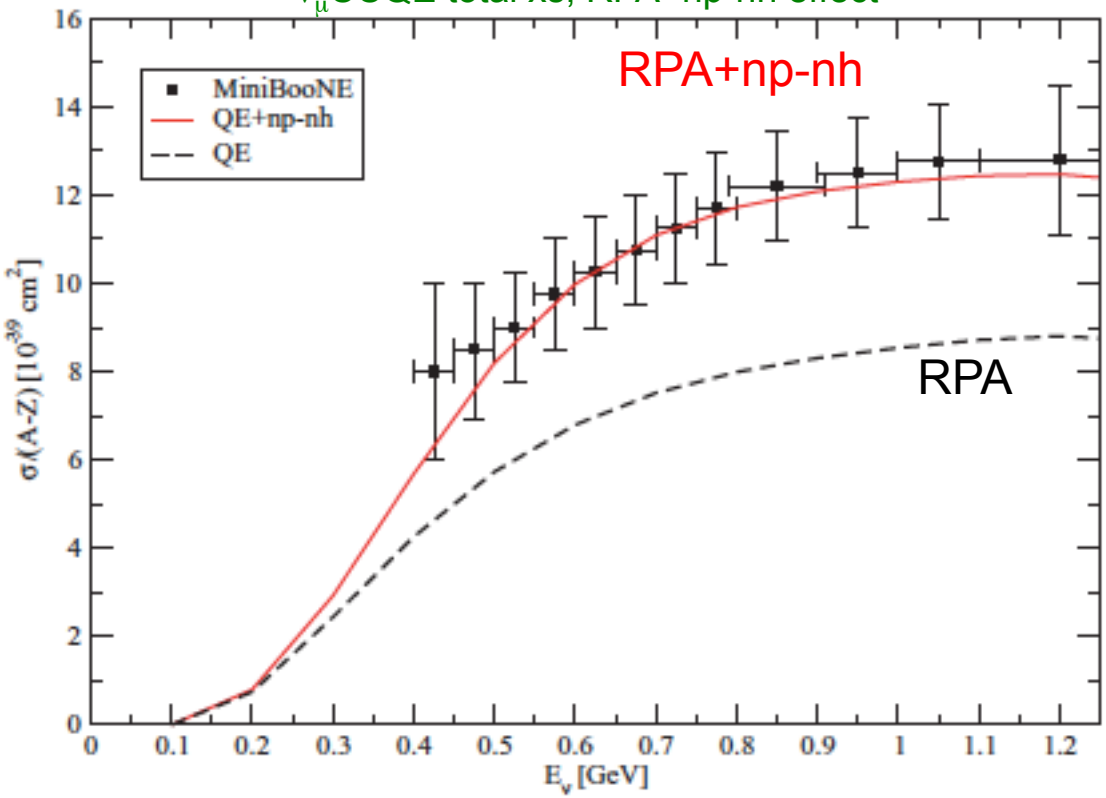
Quasielastic (QE)



Two Nucleons knock-out (2p-2h)



ν_μCCQE total xs, RPA+np-nh effect



Nieves et al,
Nucl.Phys.A627(1997)543
PRC83(2011)045501

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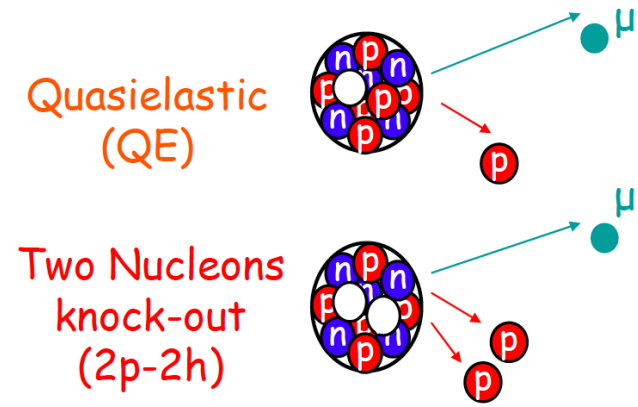
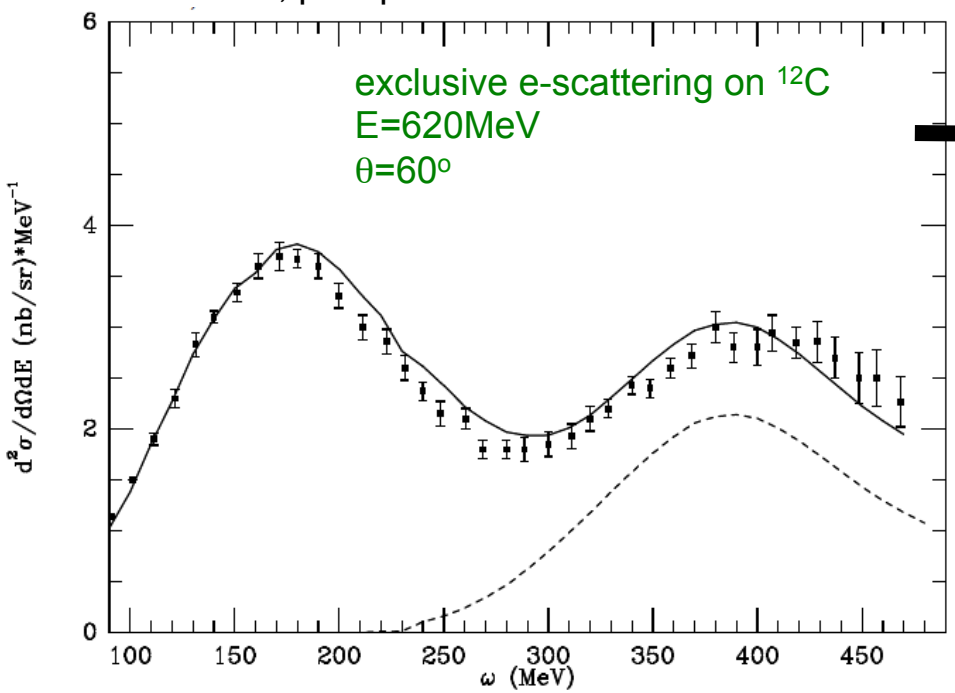
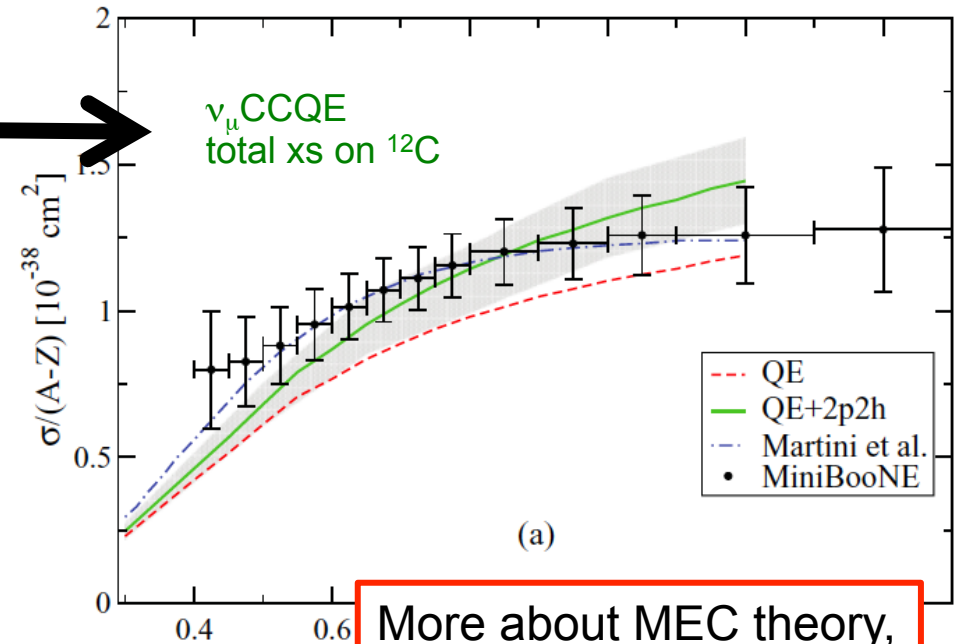
- MEC verified in e-scattering agrees with ν-scattering



Note,
Local Fermi gas with extra correlations,
MEC, pion production





More about MEC theory,
see all talks on Friday

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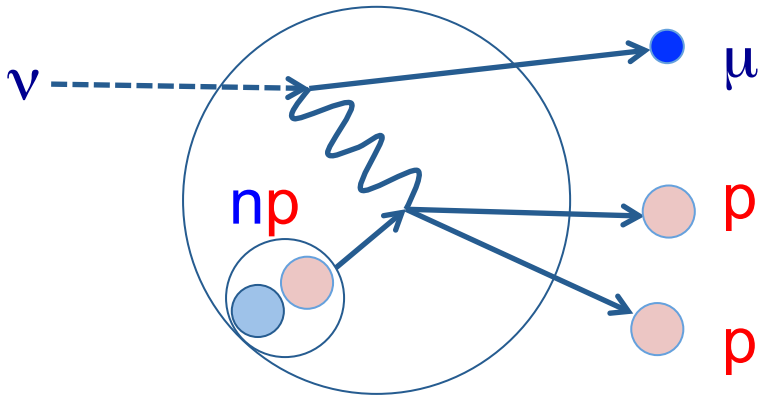
Goal of this program
- Build the model consistent with both e-scattering and ν-scattering experiments
- Implement such model in MC generator to simulate neutrino experiments
- Predict realistic signal of MEC in neutrino experiments



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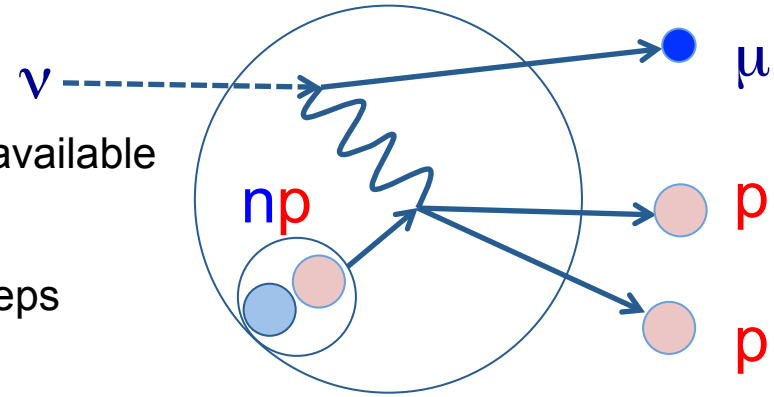


Currently, hadronic kinematic distributions are not available from any models in the market

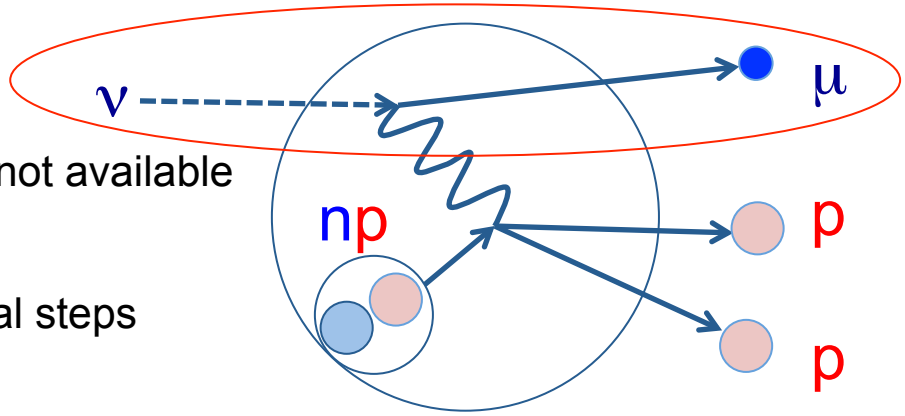
Therefore implementation of MEC takes several steps

(1) specify leptonic model
- Choose a model to generate lepton differential cross section
- Energy-momentum transfer is specified from the model
- Verify the model using e-scattering data

(2) specify hadronic model
- Model how to pick up 2 nucleons
- Model how to share the energy-momentum transfer, to knock-out 2 nucleons

(3) specify FSI model
- Outgoing lepton and nucleons undertake standard FSI model in GENIE

2. MEC simulation in GENIE



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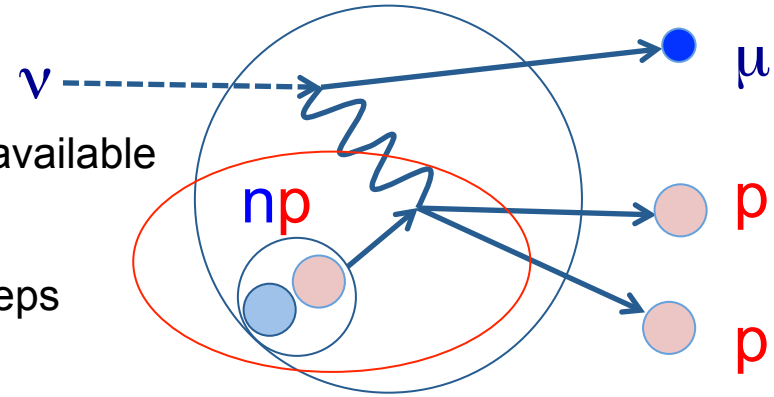

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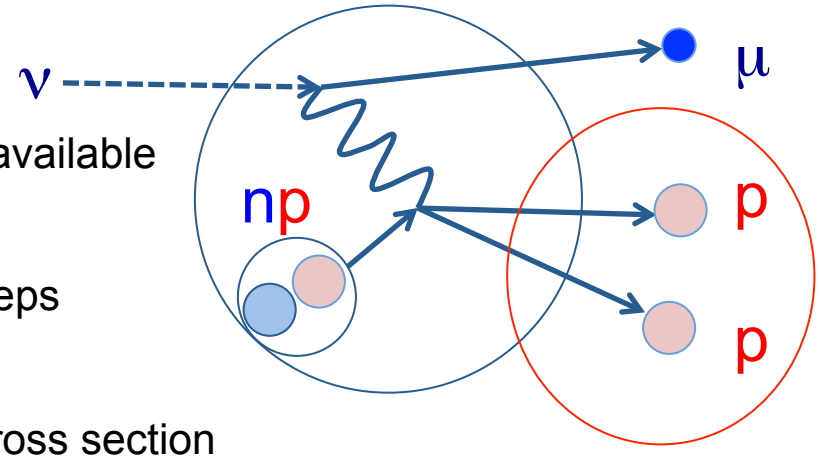

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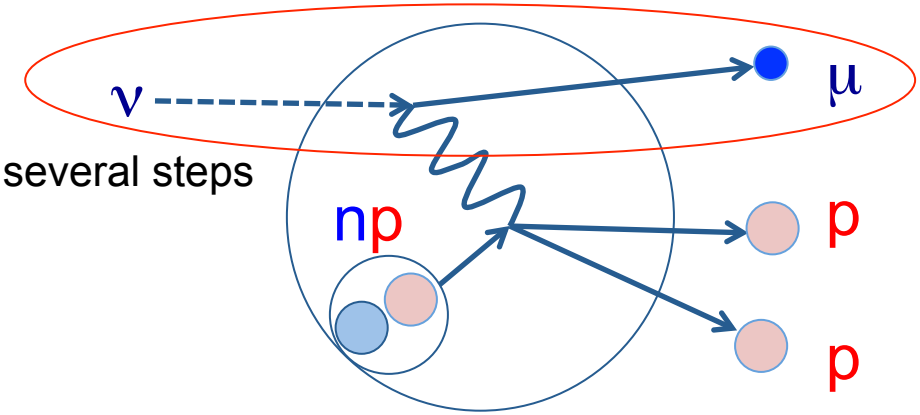
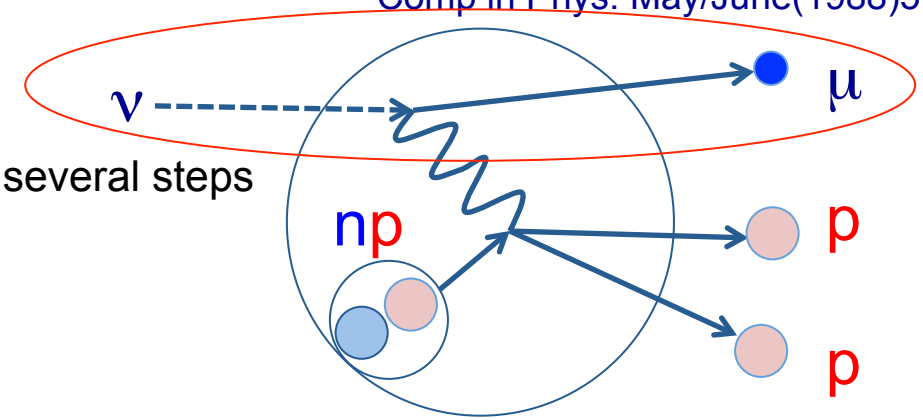


In GENIE, Neutrino interaction is simulated in several steps
(1) specify leptonic model
(2) specify hadronic model
(3) specify FSI model

MEC model requirement
- It enhances total neutrino cross section ~30%
- It enhances more high angle scattering due to transverse nature
- It reproduces inclusive e-scattering data

2. Leptonic simulation in GENIE

Lightbody and O'Connell
Comp in Phys. May/June(1988)57



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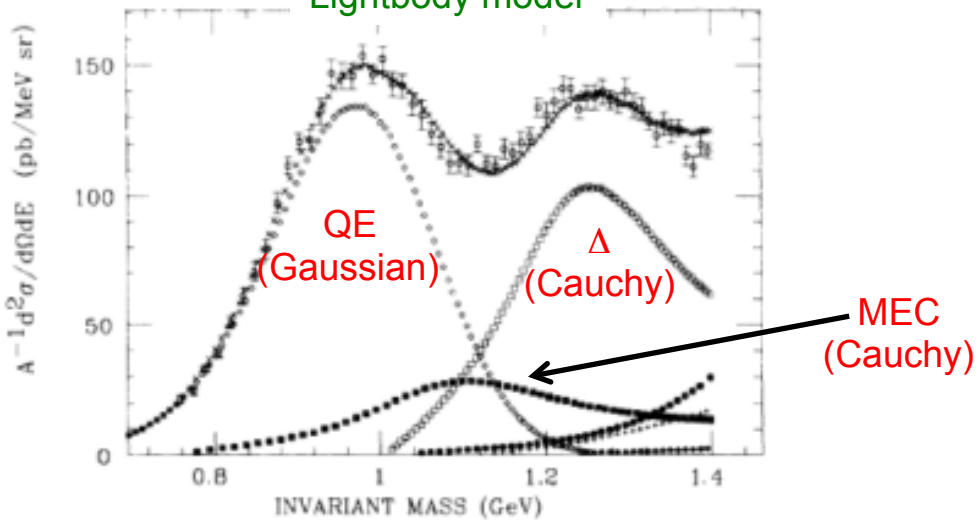
Dytman model
- First MEC model in GENIE
- Based on early work by Lightbody and O'Connell
- Easy to implement, easy to tune

Feature
- New MEC channel has only magnetic form factor (Pauli form factor)
- MEC channel is Gaussian (mean~ 1.9 GeV width~150 MeV)
- Linear A dependence to match previous studies

Lightbody model



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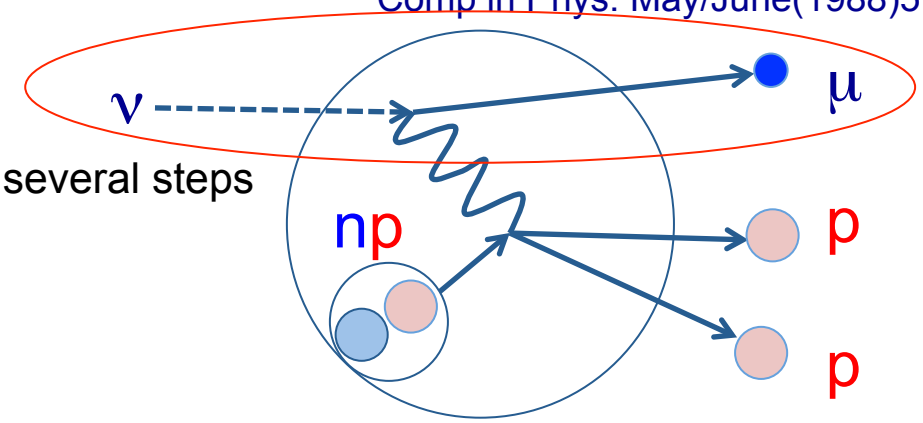

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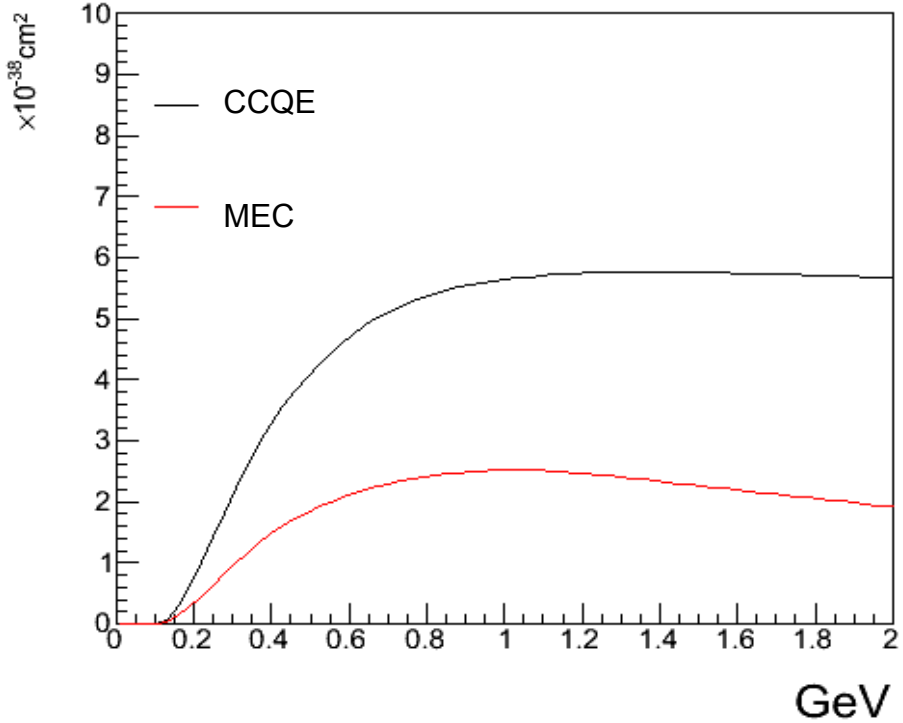
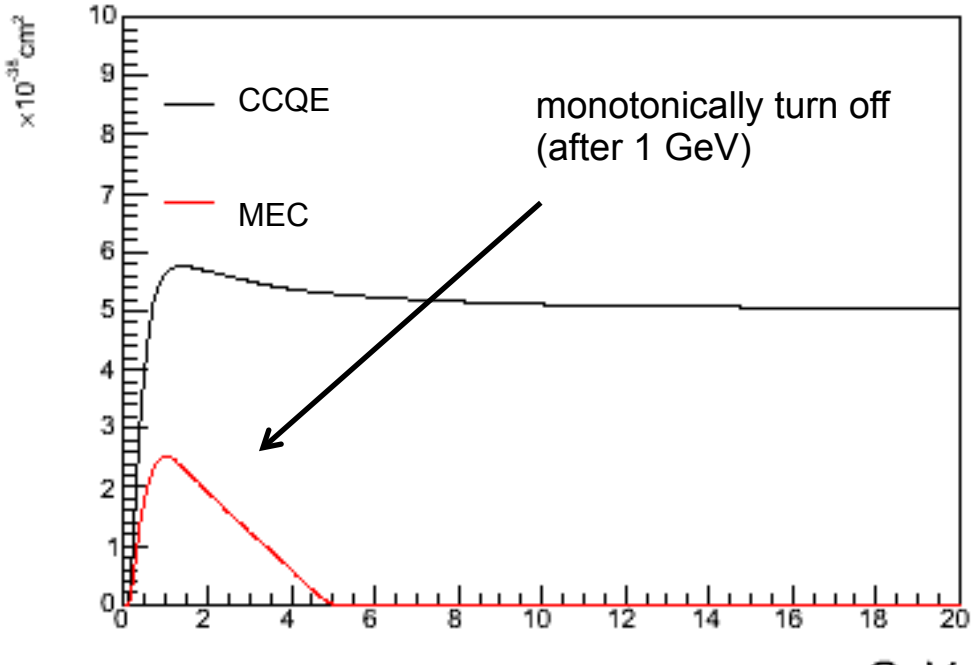
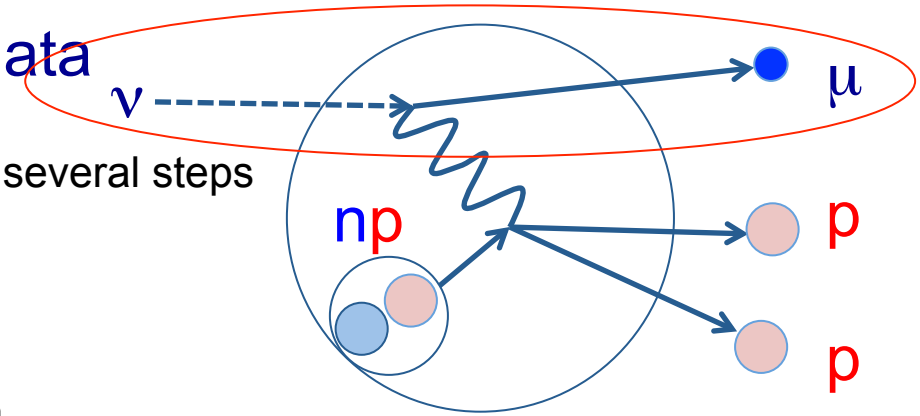
ν_μ-^{12}C total cross section





2. Comparison with e-scattering data



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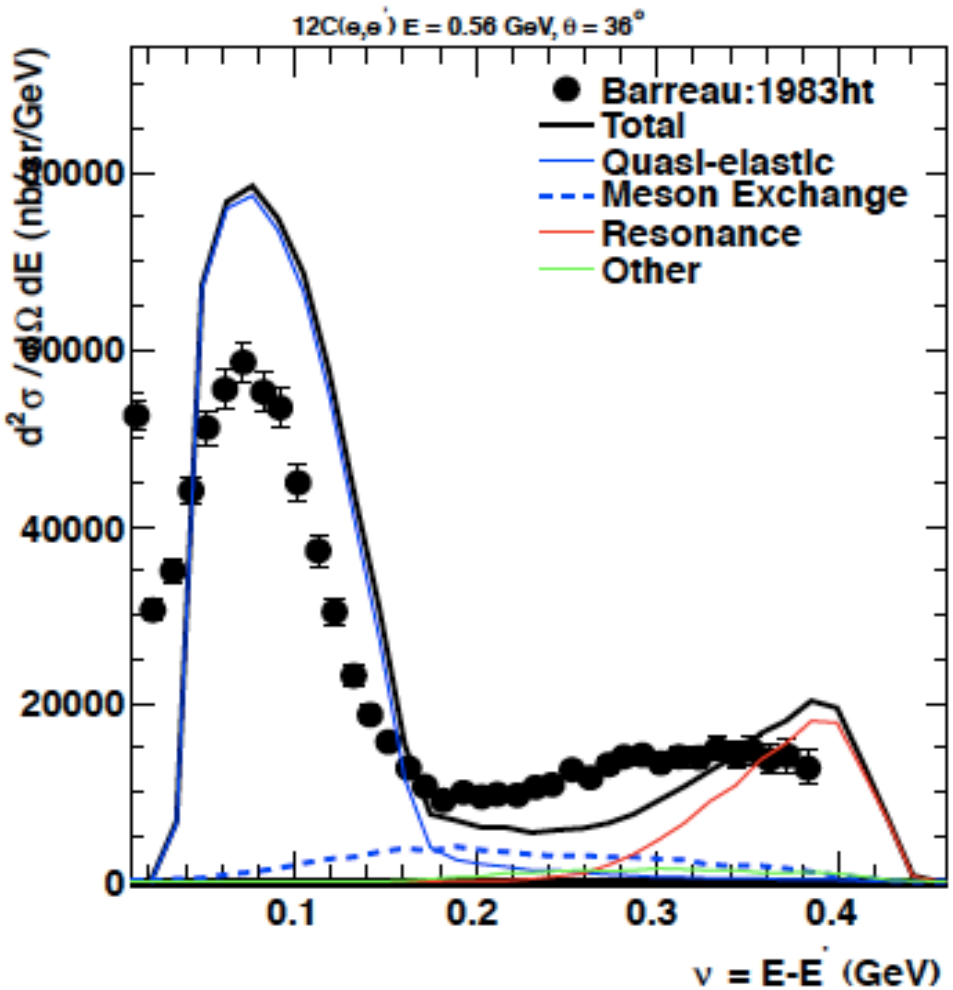
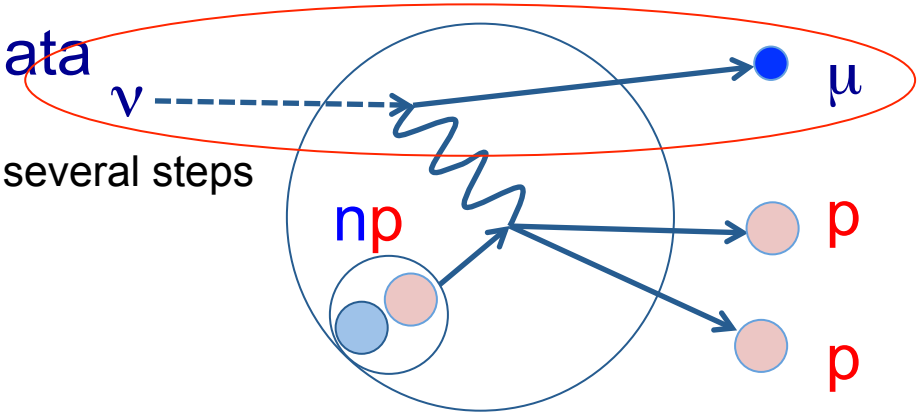


Carbon target, 560MeV, 36° (Q^2~0.1GeV^2)

At low angle, RFG model overestimate QE peak

MEC is small contribution at low angle

2. Comparison with e-scattering data



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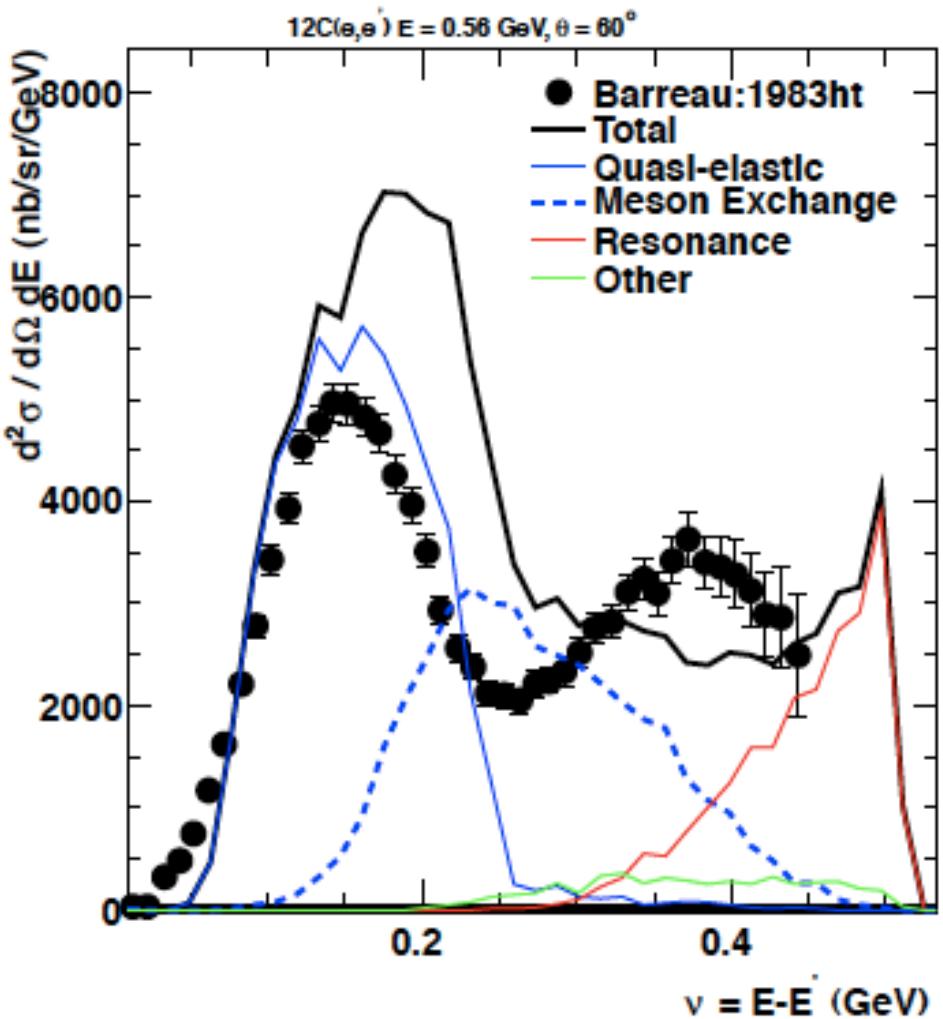


Carbon target, 560MeV, 60° (Q^2~0.2GeV^2)

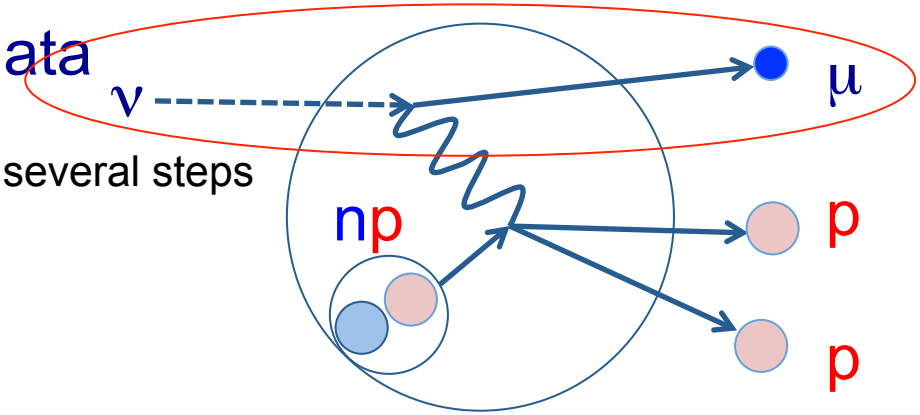
MEC is related to transverse response function

↓

More important at larger scattering angle

Pion production model is under development

2. Comparison with e-scattering data



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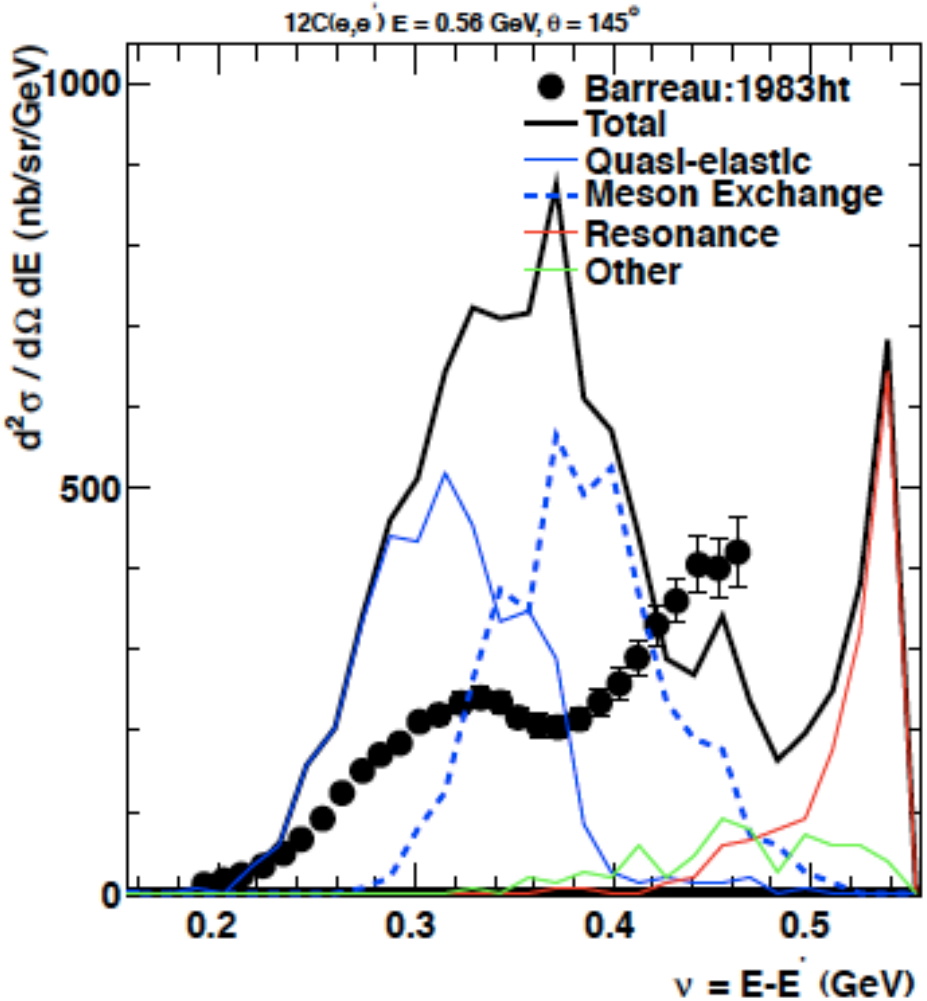

Carbon target, 560MeV, 145° (Q^2~0.5GeV^2)

MEC is related to transverse response function

↓

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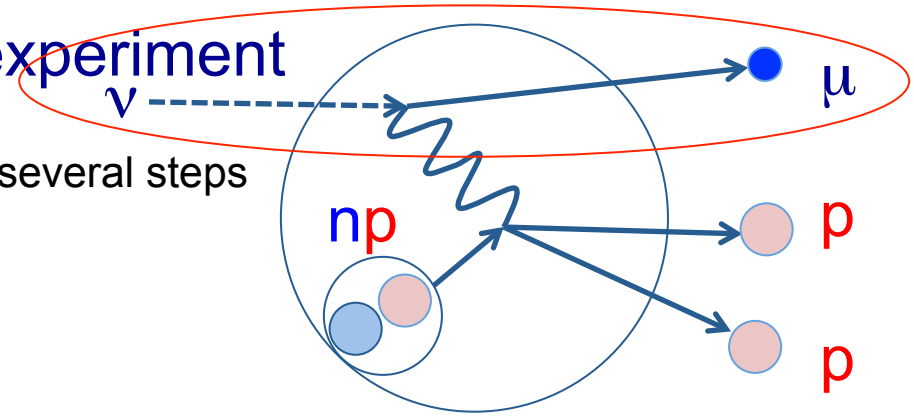
2. GENIE prediction for neutrino experiment



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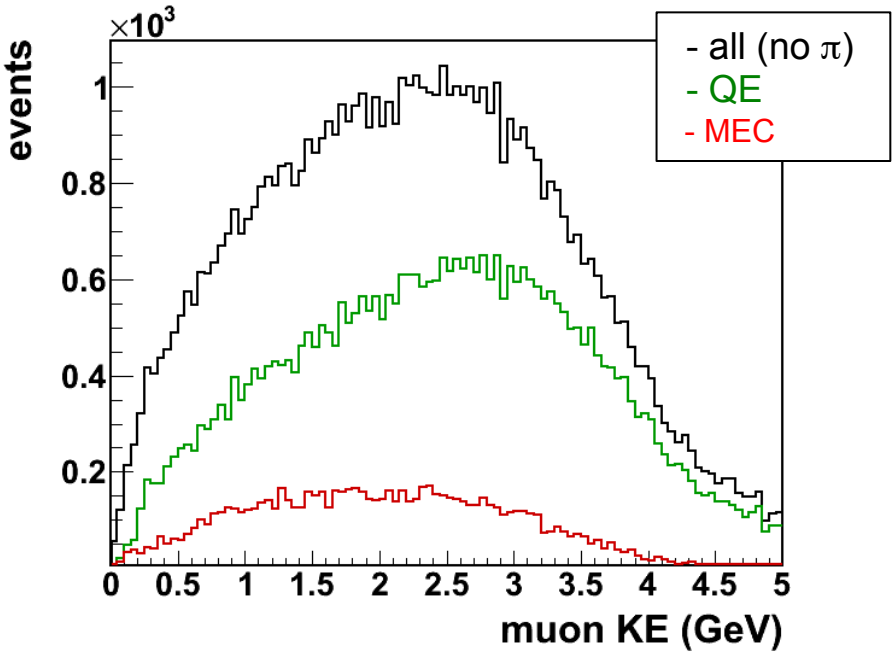
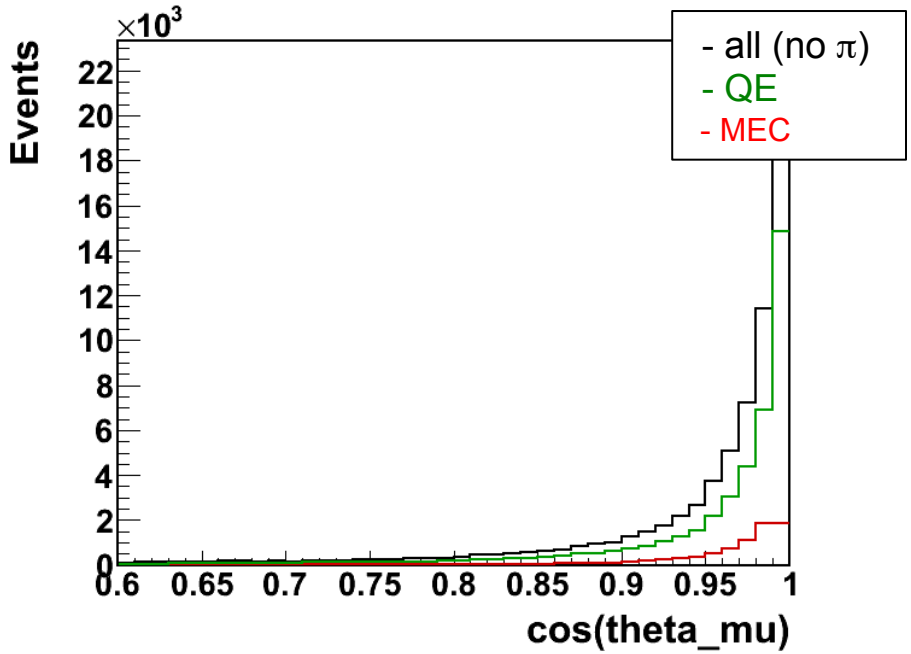
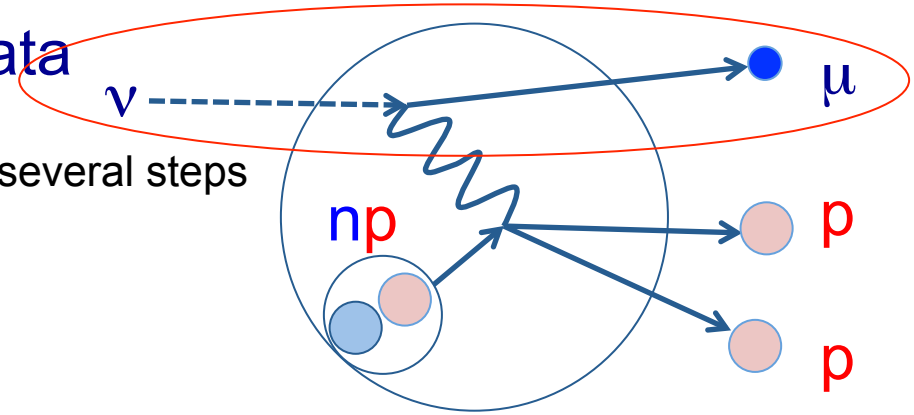
Neutrino interaction kinematics
- with NuMI low energy configuration
- matches MINERvA





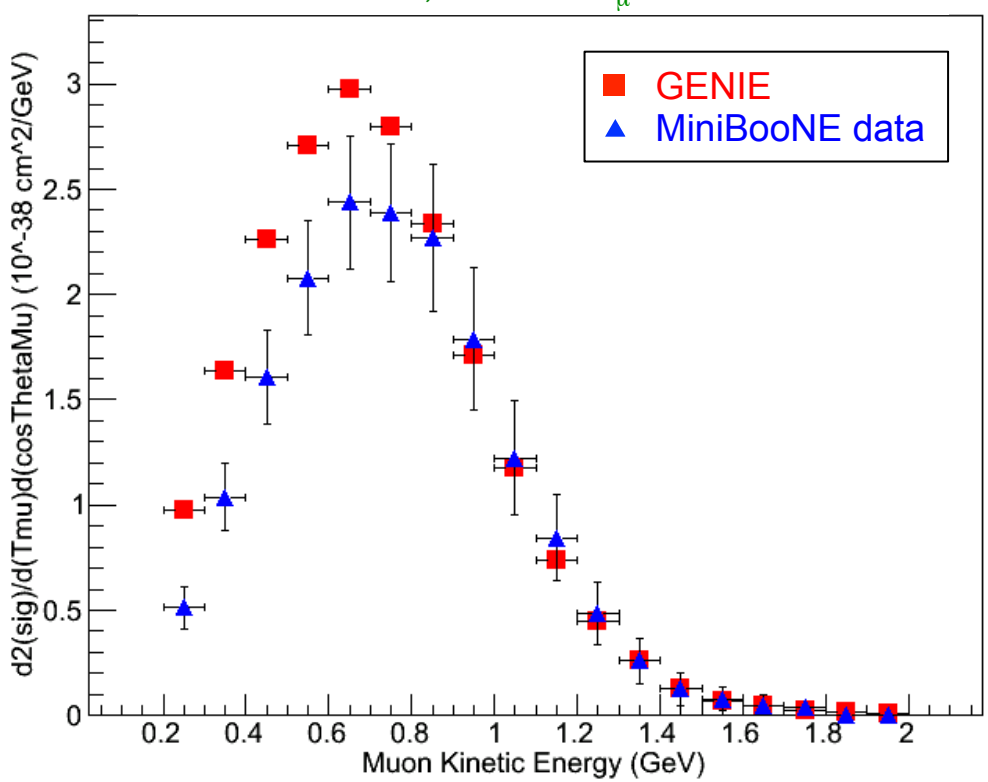
MiniBooNE collaboration,
PRD81(2010)092005

2. Comparison with MiniBooNE data



In GENIE, Neutrino interaction is simulated in several steps
(1) specify leptonic model
(2) specify hadronic model
(3) specify FSI model

Comparison with MiniBooNE flux-folded
ν_μCCQE double differential cross section data
Tmu distribution, $0.8 < \cos\theta_\mu < 0.9$



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MiniBooNE collaboration,
PRD81(2010)092005

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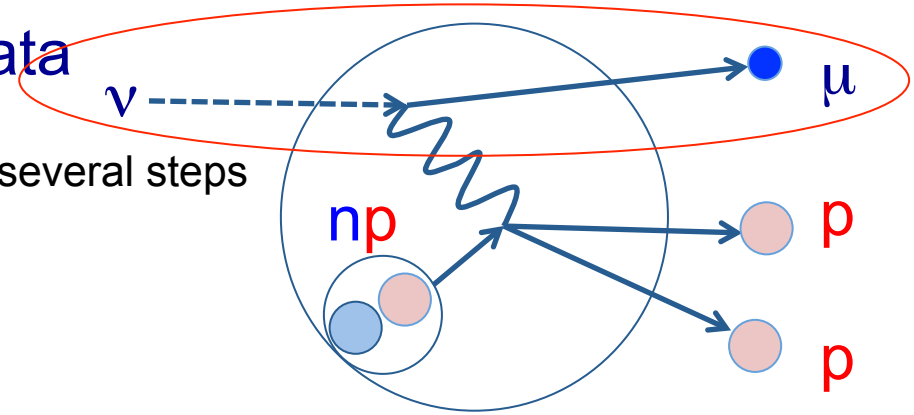

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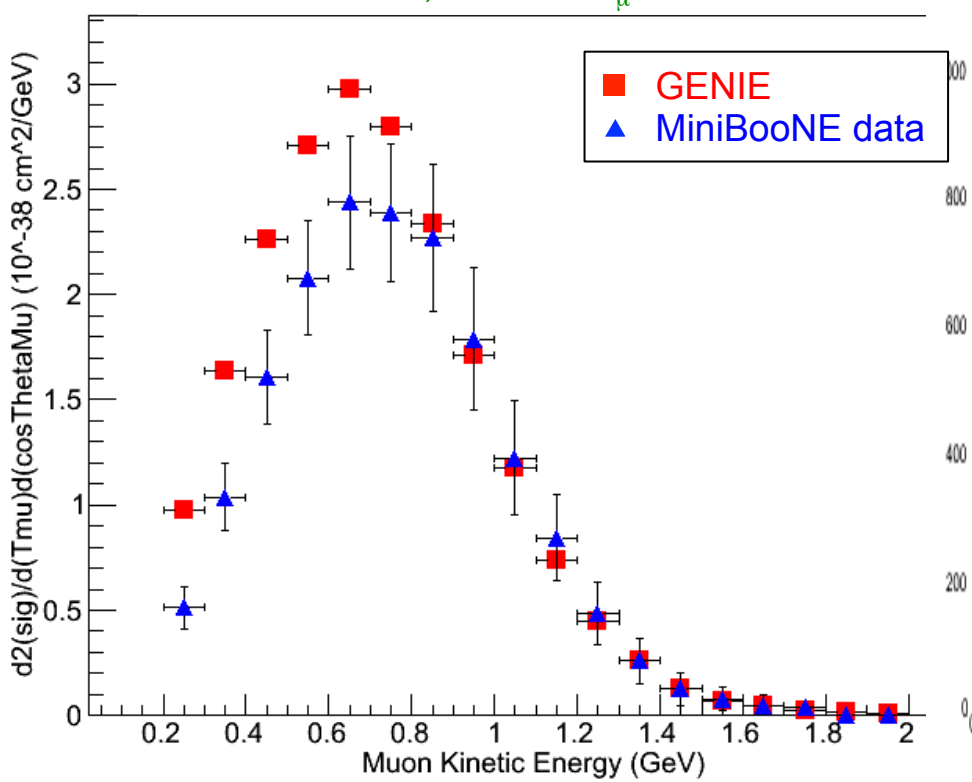
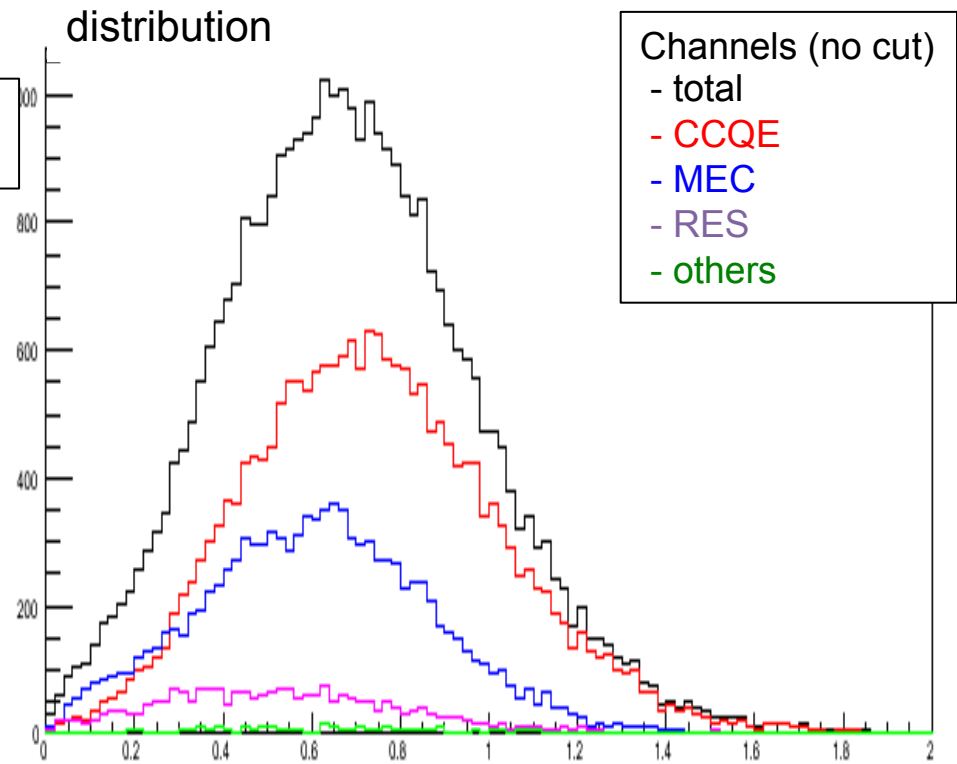


Decomposition of GENIE prediction
- it shows complicated mix due to flux distribution



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PRD81(2010)092005

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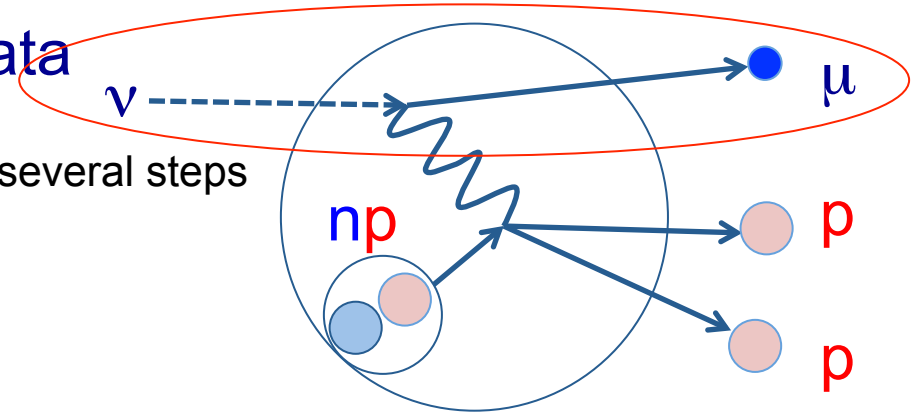

In GENIE, Neutrino interaction is simulated in several steps
(1) specify leptonic model
(2) specify hadronic model
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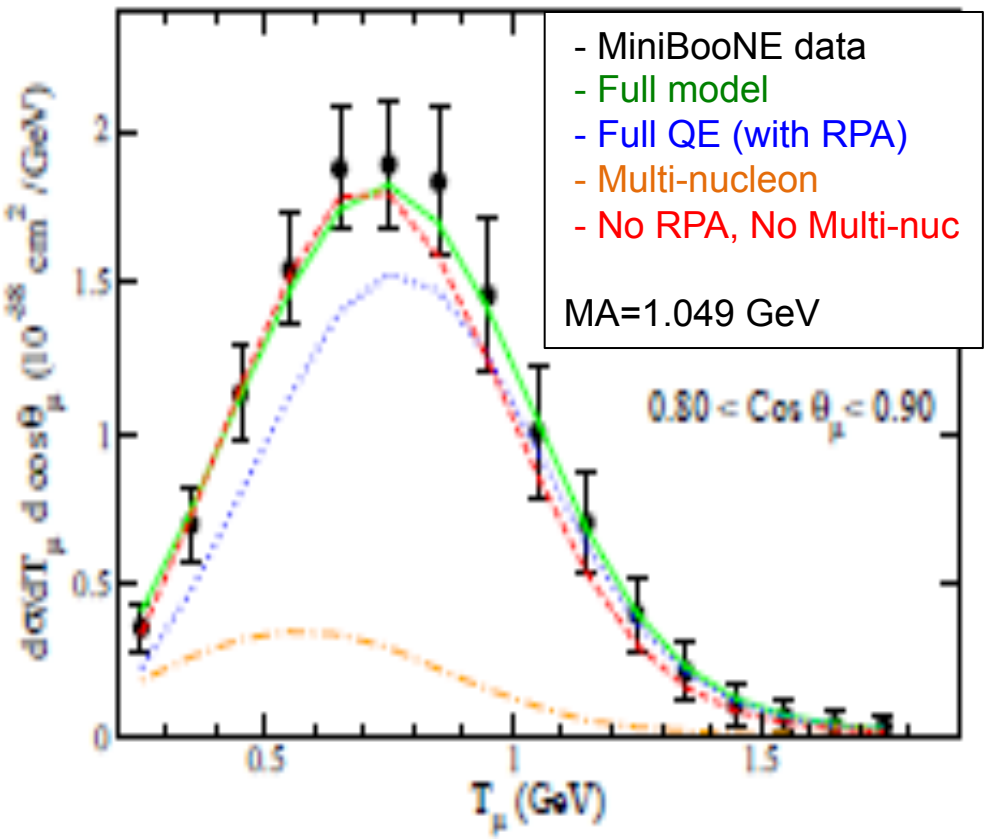
Decomposition of Valencia model
- theory-based model is somewhat different



Decomposition of GENIE prediction
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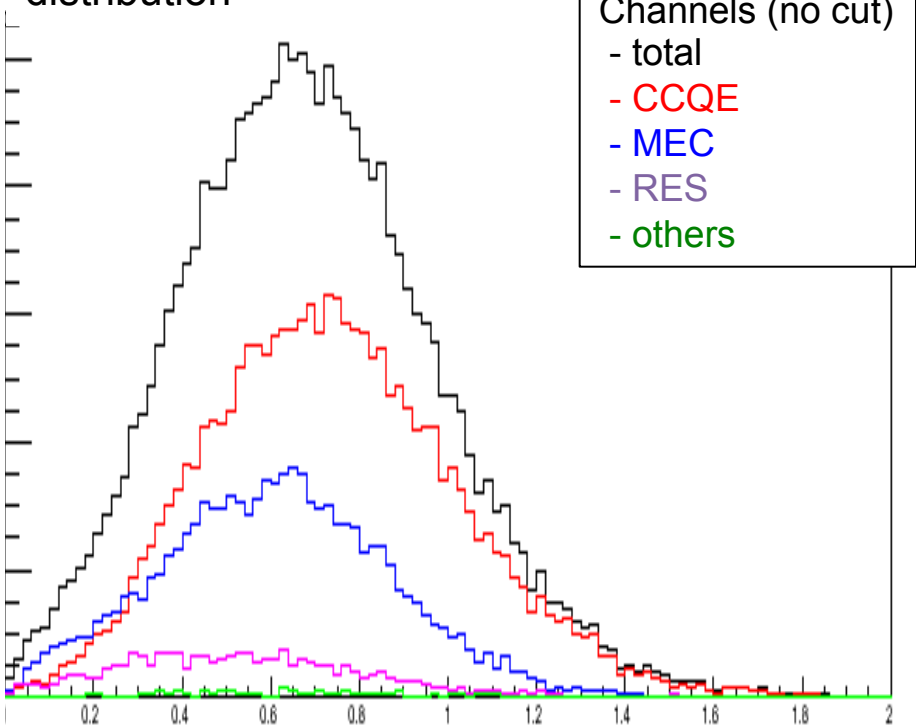

MiniBooNE collaboration,
PRD81(2010)092005

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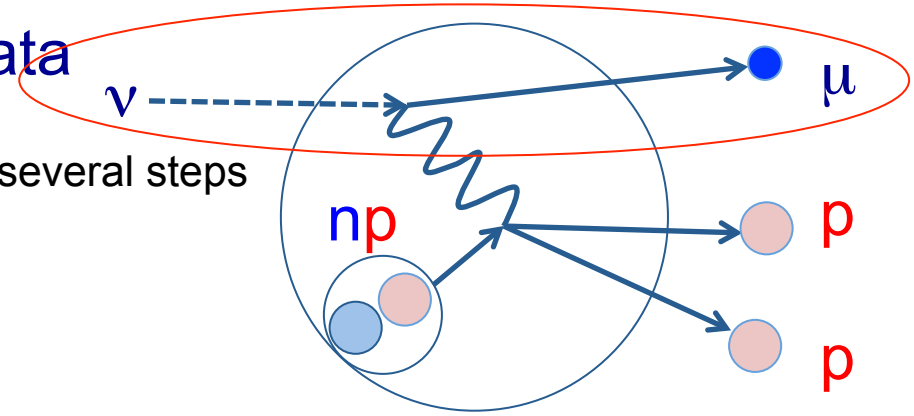

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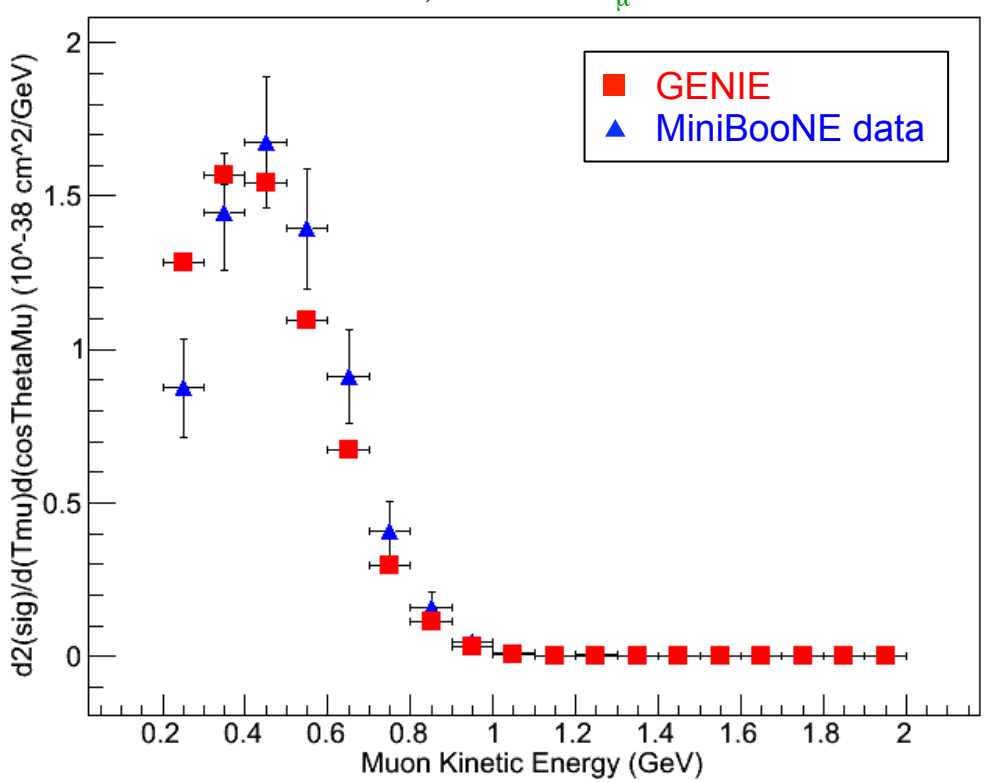
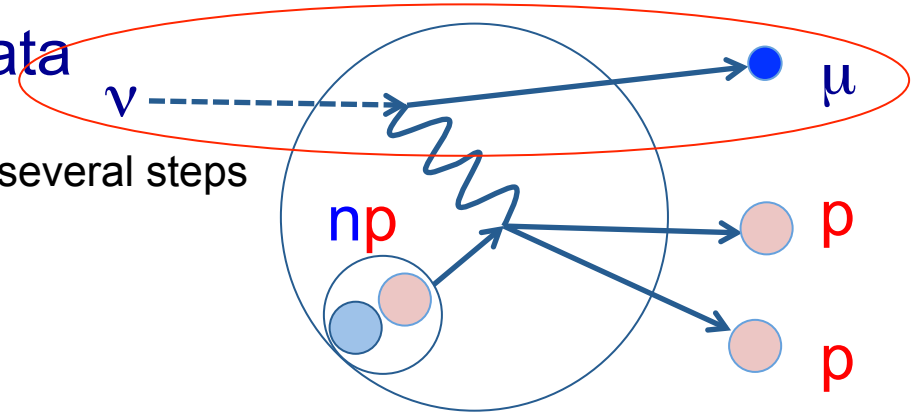


Tmu distribution, $0.8 < \cos\theta_\mu < 0.9$
- Slight over estimation at low angle muons

Tmu distribution, $0.5 < \cos\theta_\mu < 0.6$
- MC agrees with data at mild angle

MiniBooNE collaboration,
PRD81(2010)092005

2. Comparison with MiniBooNE data



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Comparison with MiniBooNE flux-folded
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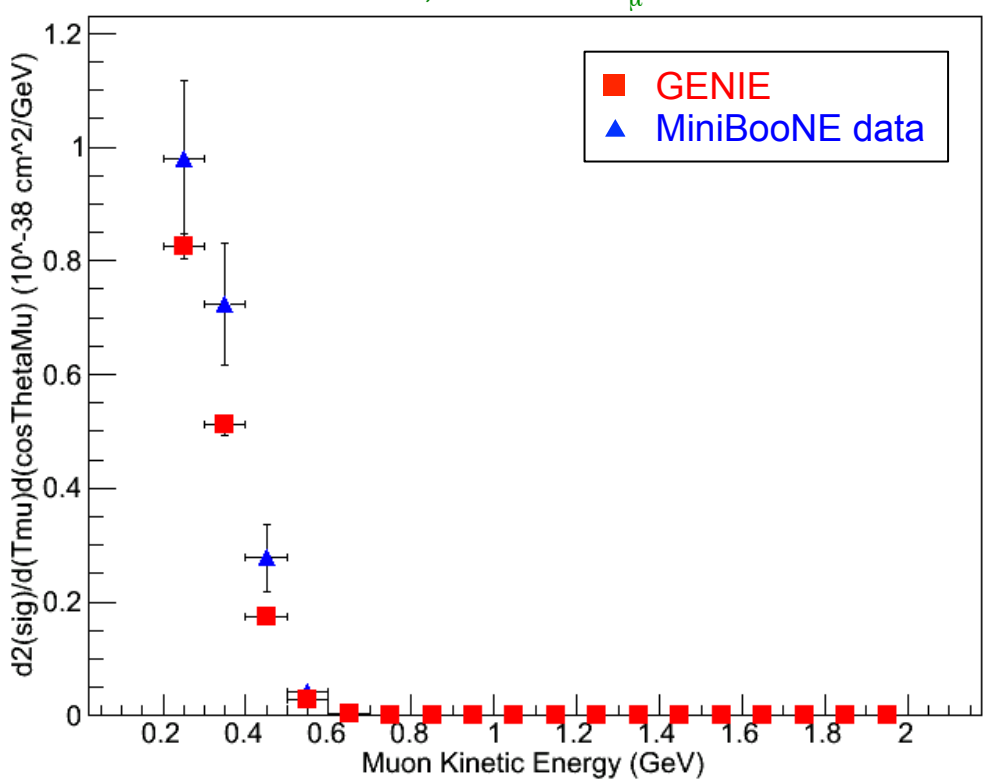
Tmu distribution, $-0.1 < \cos\theta_\mu < 0.0$



Tmu distribution, $0.8 < \cos\theta_\mu < 0.9$
- Slight over estimation at low angle muons

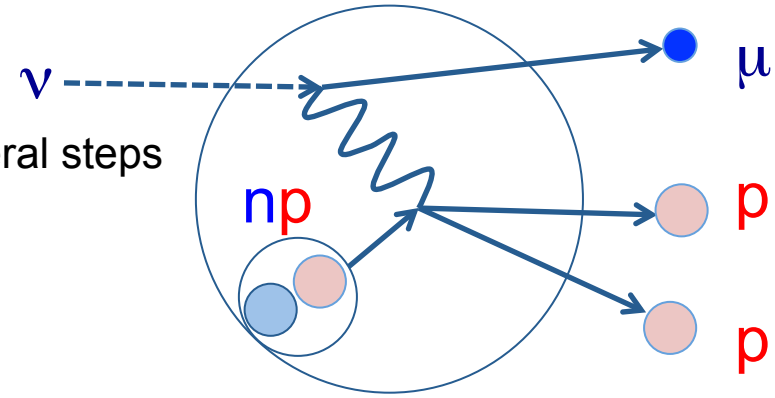
Tmu distribution, $0.5 < \cos\theta_\mu < 0.6$
- MC agrees with data at mild angle

Tmu distribution, $-0.1 < \cos\theta_\mu < 0.0$
- Slight under estimation at high angle

But remember the model is tested with electron data only!

Ankowski et al,
PRD82(2010)013002

2. Leptonic simulation in GENIE



In GENIE, Neutrino interaction is simulated in several steps
(1) specify leptonic model
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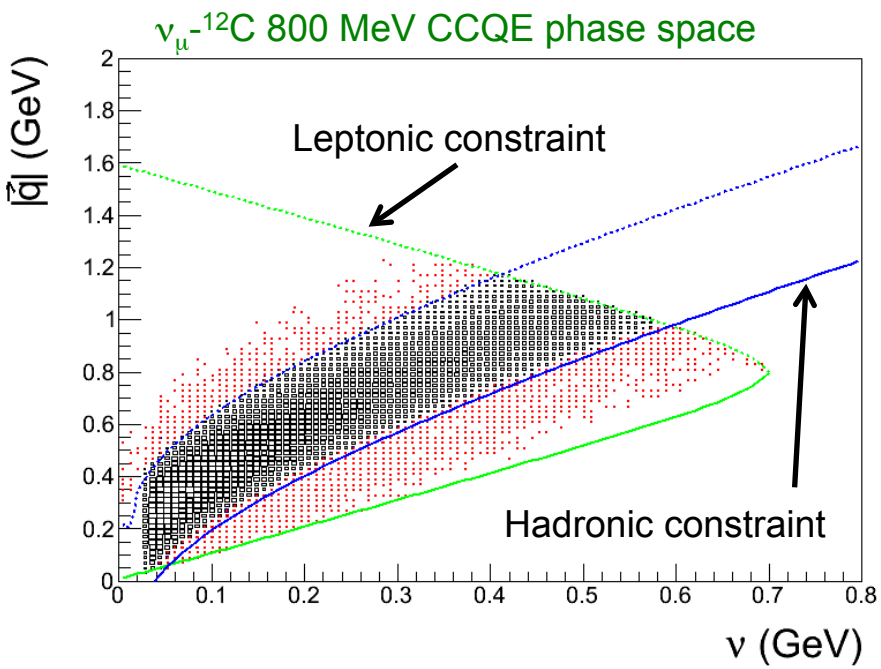
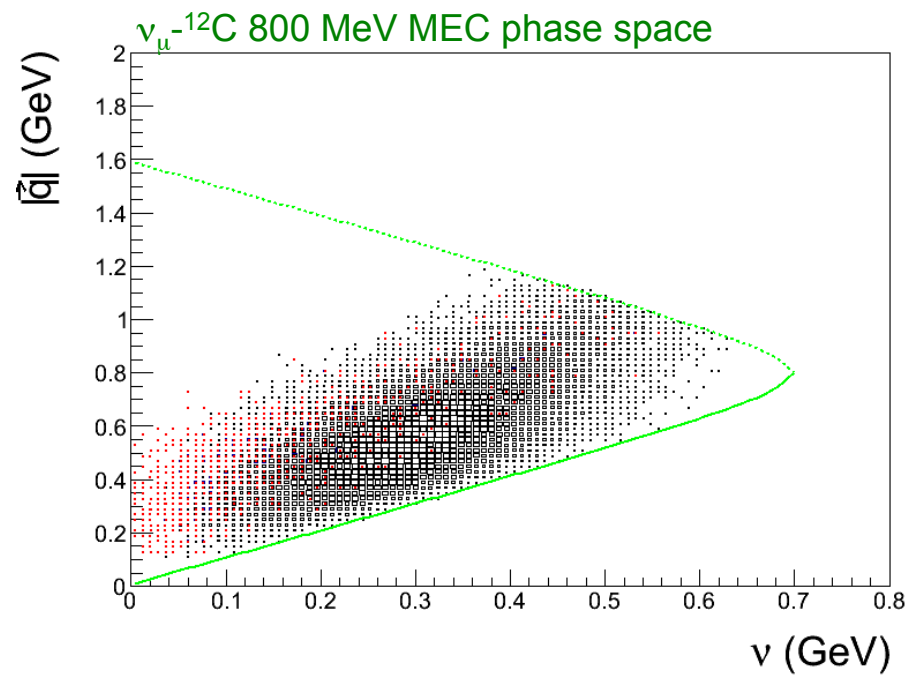
Kinematic constraint
- Leptonic constraint (energy-momentum conservation)
- Hadronic constraint (model dependent kinematic constraint)
- Both CCQE and MEC show ~2% Hadronic constraint violation





1. Introduction

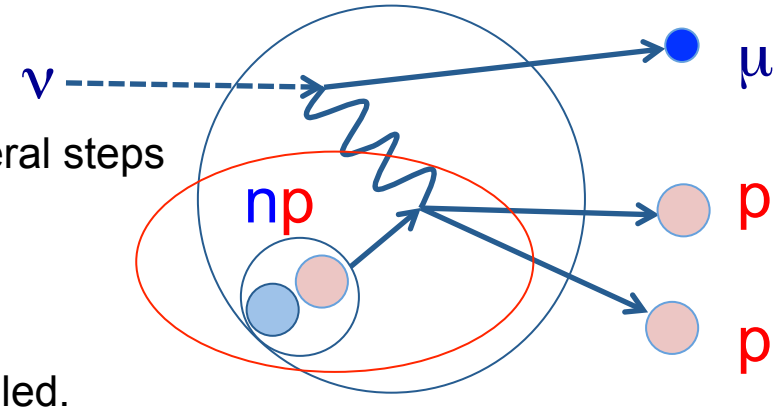
2. Leptonic simulation in GENIE

3. hadronic simulation in GENIE

4. Comparisons

5. Discussion

3. Hadron simulation in GENIE



In GENIE, Neutrino interaction is simulated in several steps
(1) specify leptonic model
(2) specify hadronic model
(3) specify FSI model

Kinematic distribution of nucleon need to be modelled.
MEC model defines lepton kinematics, and
Hadron model defines nucleon kinematics.

Nucleon cluster model
- Simple but reasonable model (GENIE, NuWro)
- it has enough flexibility to add more features later

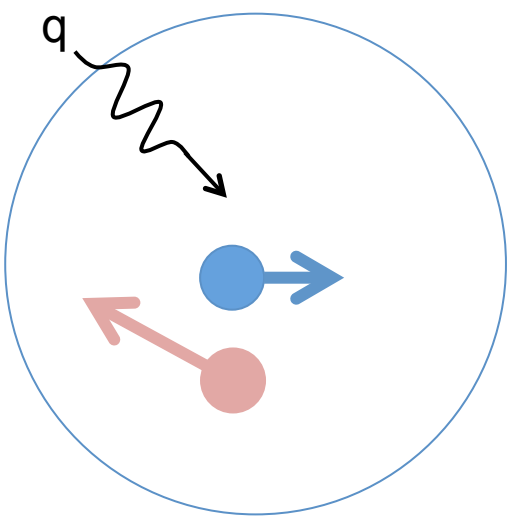
3. Nucleon cluster model in GENIE

For a given Energy-Momentum transfer...
1. Choose 2 nucleons from specified kinematics (e.g., Fermi gas)

Fermi gas
- nucleon kinematics are randomly chosen from Fermi sea (GENIE, GiBUU, NuWro)

Spectral function
- nucleon kinematics can be chosen from spectral function

Phase space density
- cross section is weighted with nucleon phase space density (GiBUU)

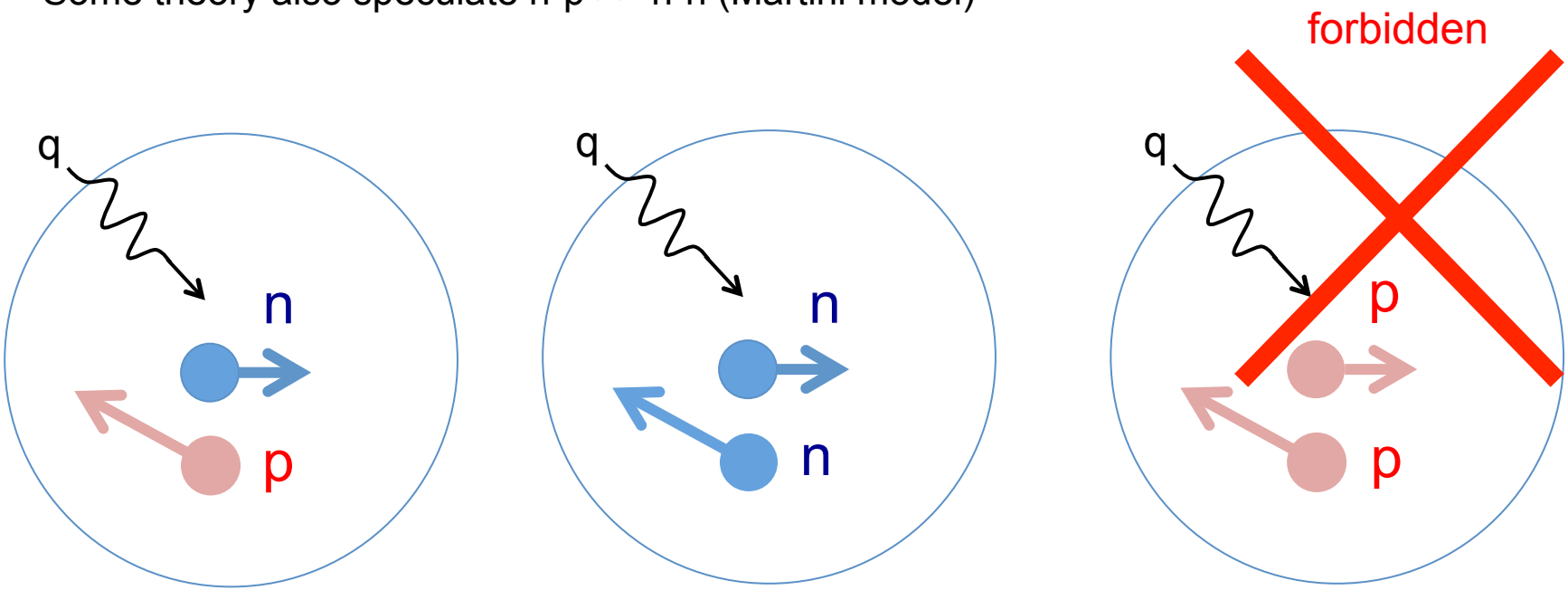


3. Nucleon cluster model in GENIE

For a given Energy-Momentum transfer...
1. Choose 2 nucleons from specified kinematics (e.g., Fermi gas)
2. All n-n, n-p, p-p pairs are allowed, if interaction is allowed

e.g.) ν_μ-^{12}C CC MEC interaction
- It requires at least one neutron (p-p pair is forbidden)
- based on random choice, n-p : n-n ~ 3 : 1 (NuWro, GiBUU)
- based on isospin conjecture, n-p : n-n ~ 1 : 4 (GENIE)
- based on short range correlation n-p : n-n ~ 90 : 5

Some theory also speculate n-p >> n-n (Martini model)



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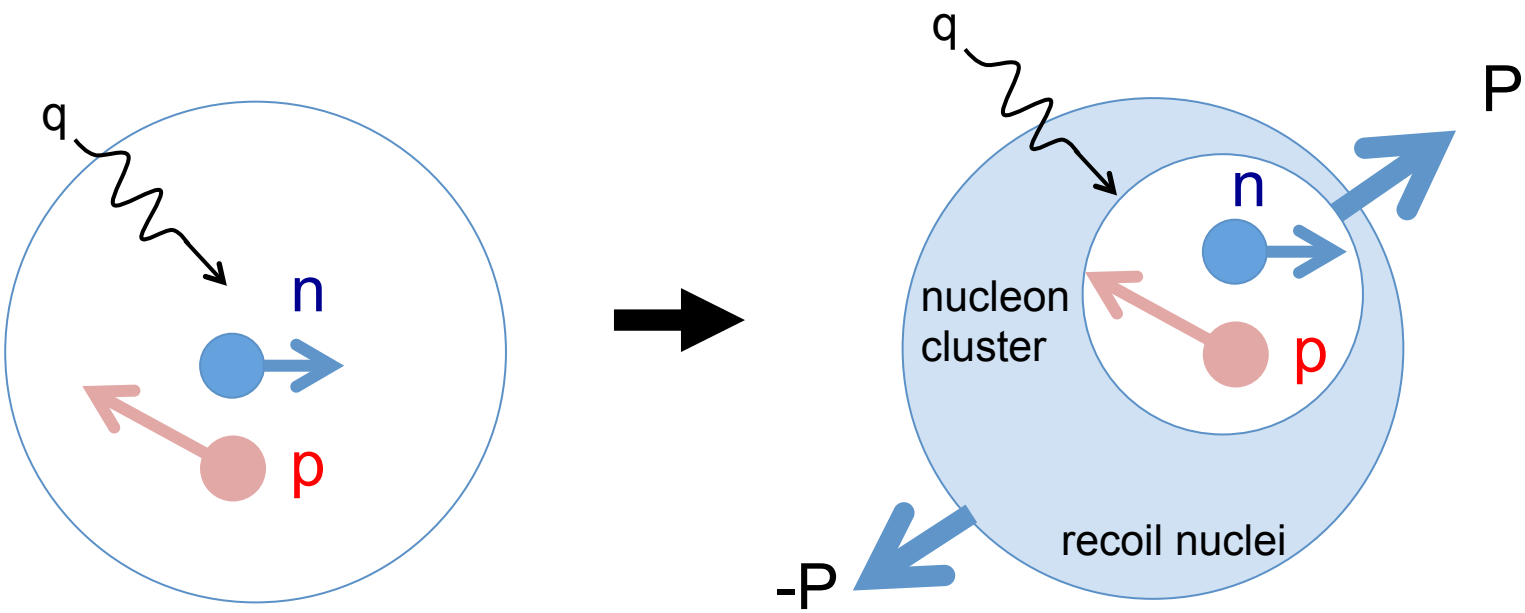
3. Energy-momentum conservation

e.g.) GENIE
- 2 nucleons make a on-shell cluster



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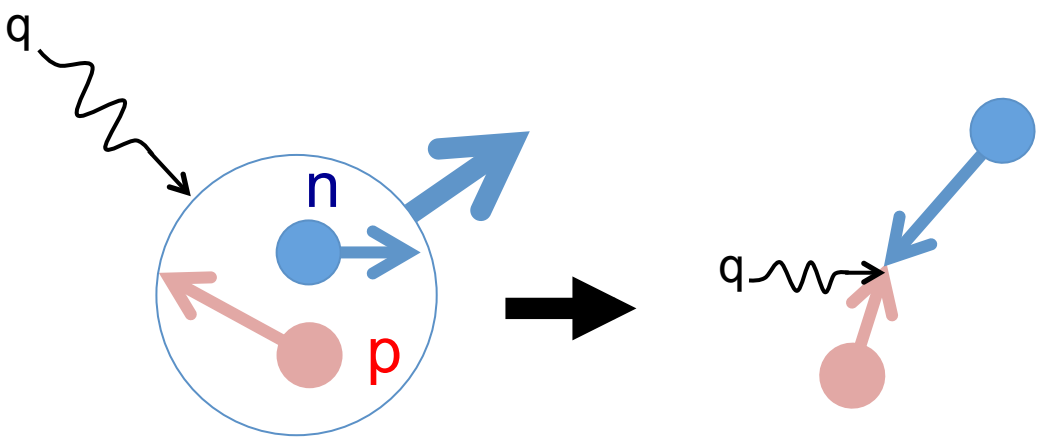
e.g.) GENIE
- 2 nucleons make a on-shell cluster
- Energy-momentum transfer and nucleon cluster makes CM system (hadronic system)



3. Nucleon cluster model in GENIE

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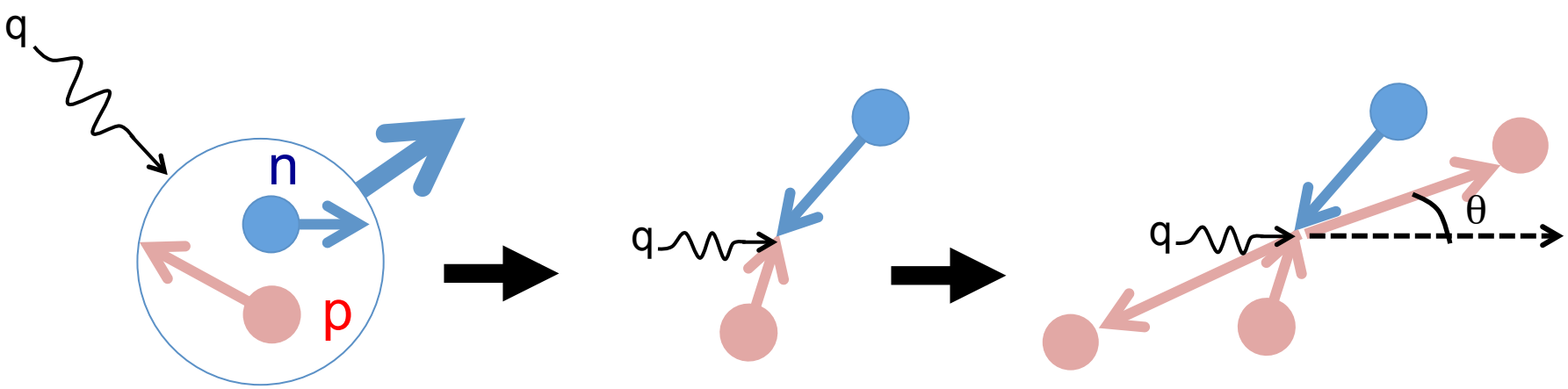

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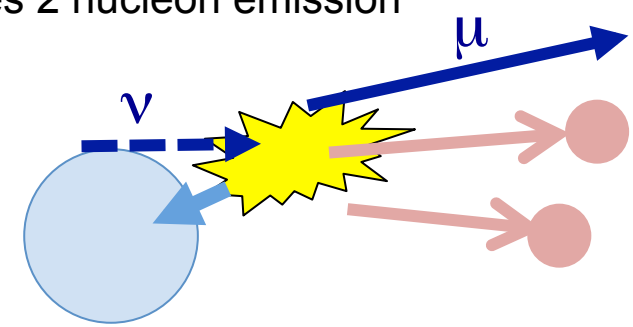

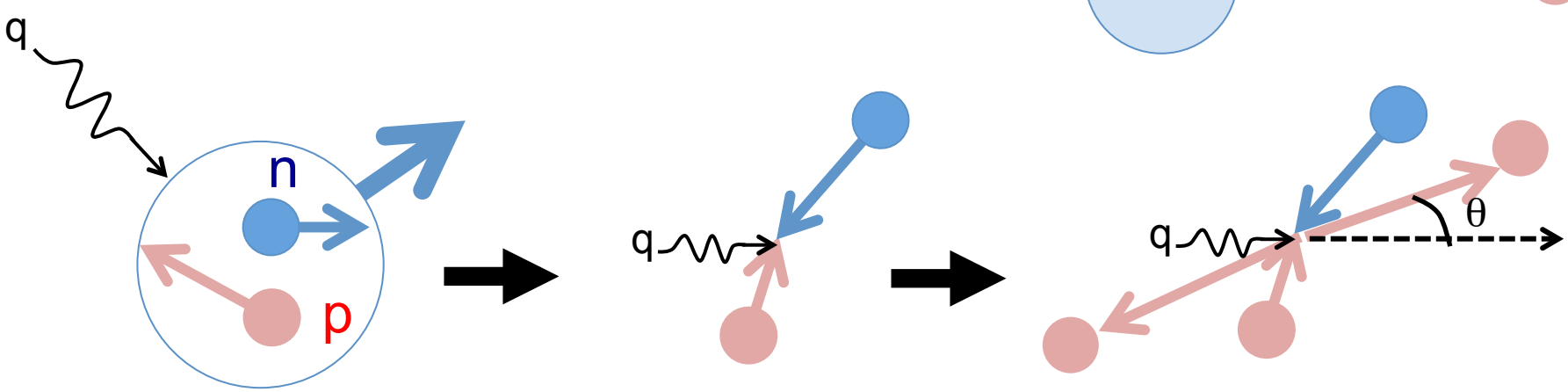

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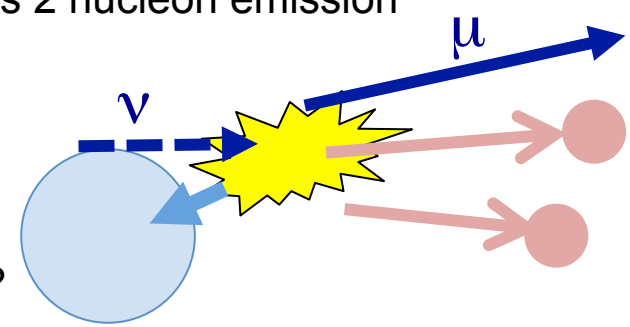
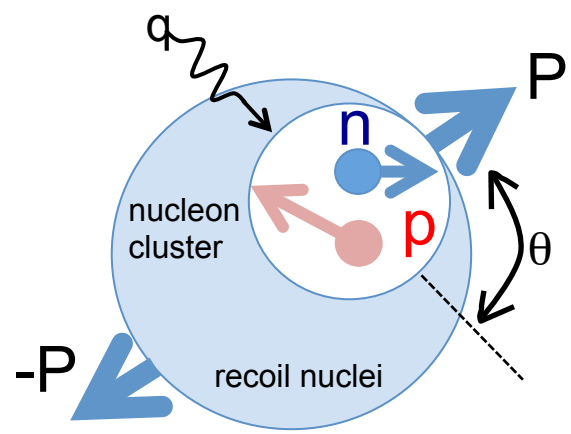


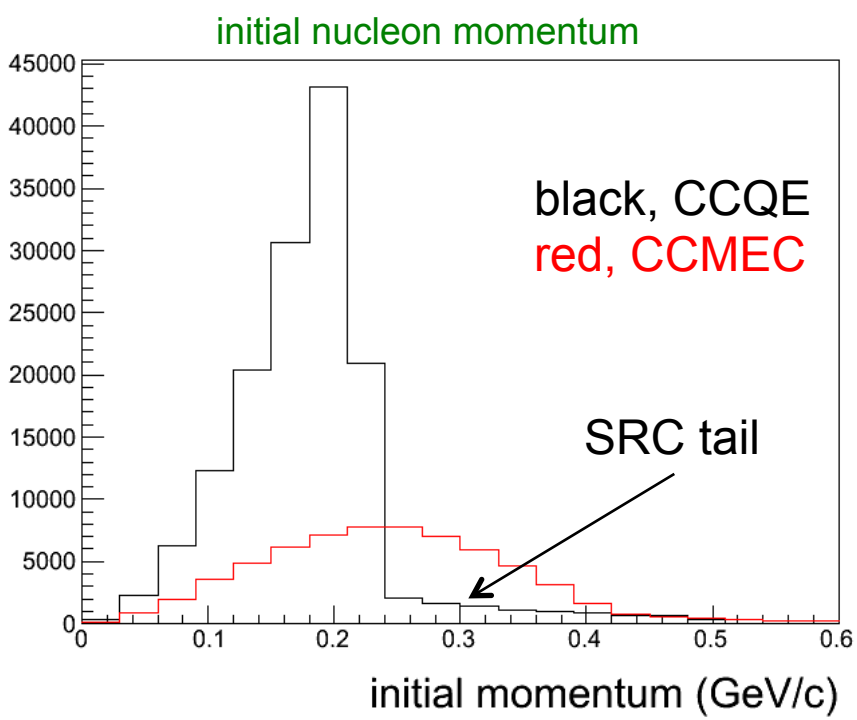
Issues:
- correlations may exist in initial 2 nucleons, any models?
- certain pairs may be favoured, any models?
- separation energy, binding energy, etc, any measurements?

The model can be extended to include these feature later

3. Nucleon cluster kinematics

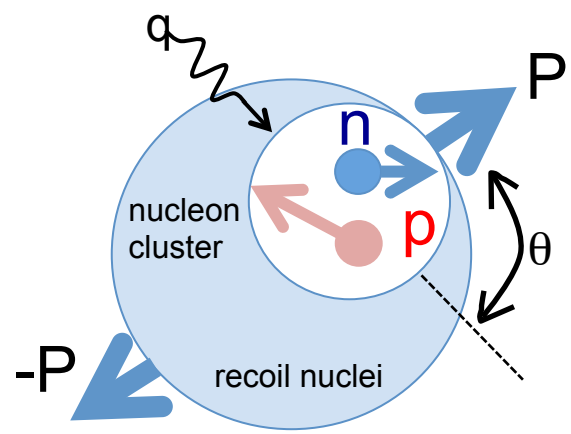
Nucleon cluster kinematic distribution
- Isotropic momentum distribution
- Nucleon cluster has more symmetric momentum distribution than CCQE, extends to higher energy



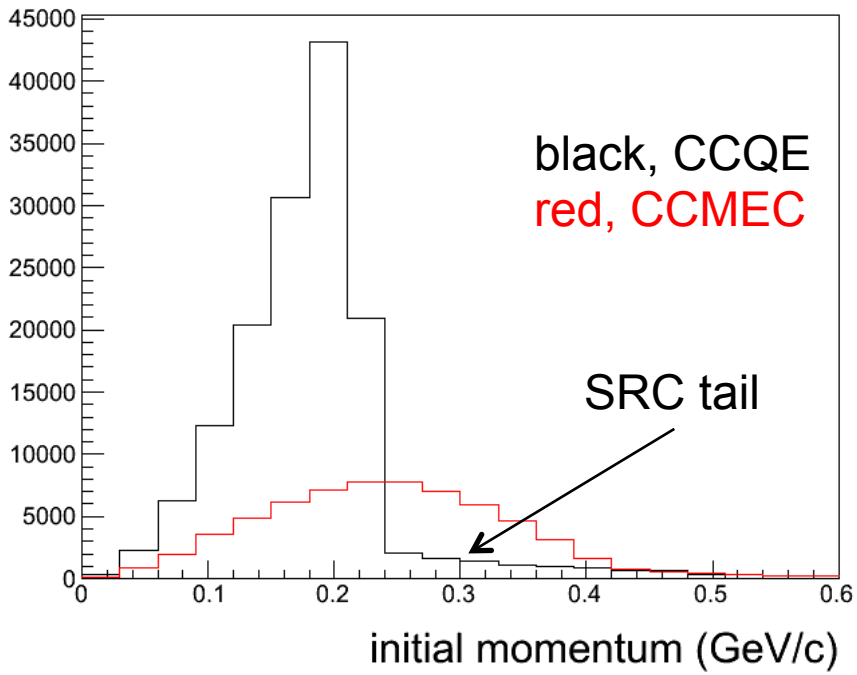


3. Nucleon cluster kinematics

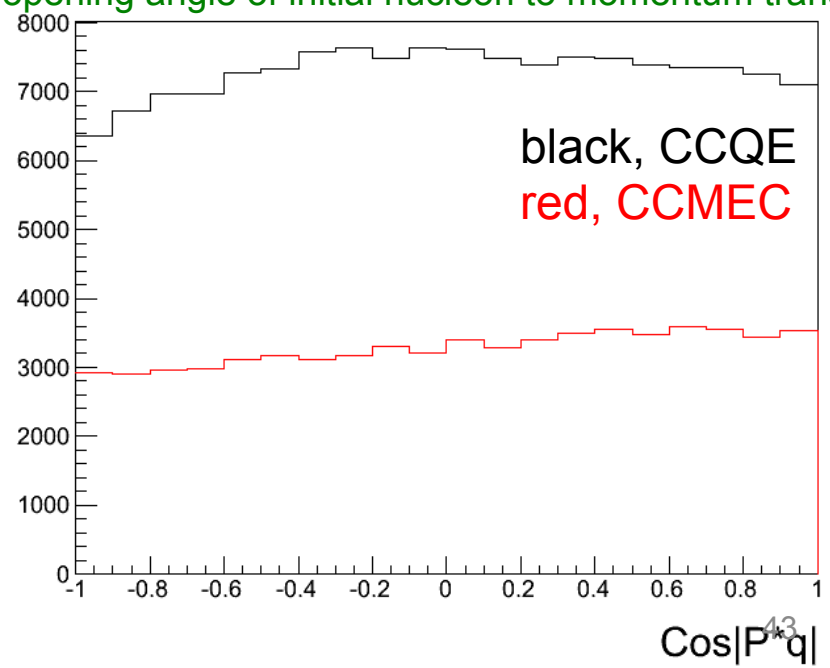
Nucleon cluster kinematic distribution
- Isotropic momentum distribution
- Nucleon cluster has more symmetric momentum distribution than CCQE, extends to higher energy
- Isotropic angular distribution
- Nucleon cluster has no preferred direction against momentum transfer



initial nucleon momentum

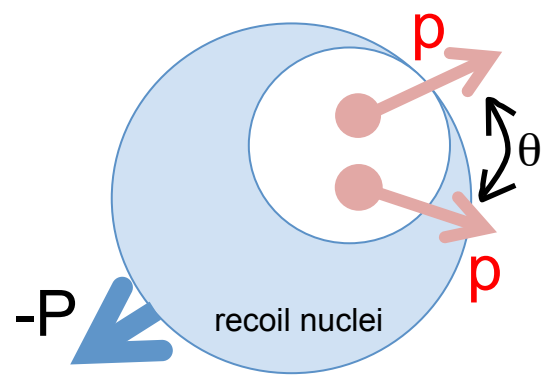


opening angle of initial nucleon to momentum transfer

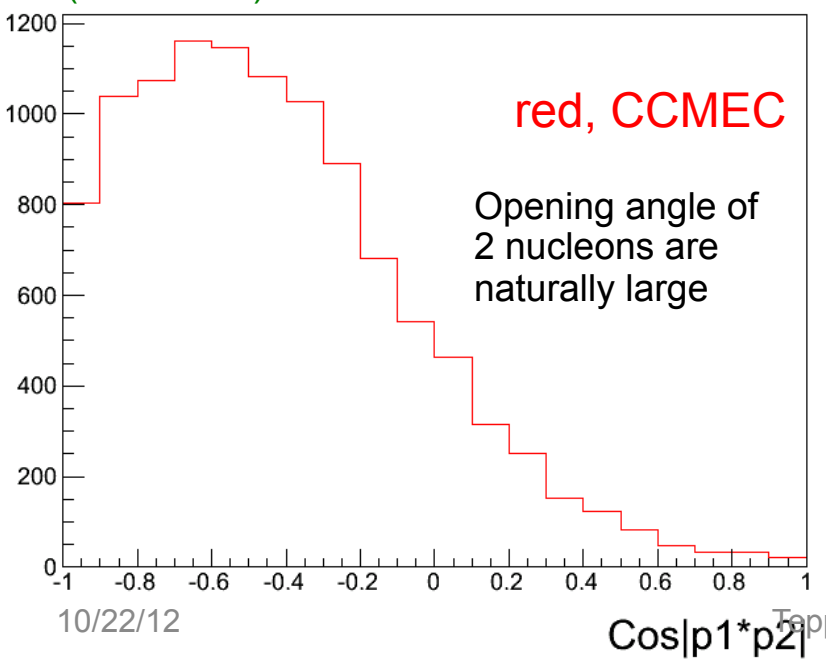


3. Nucleon cluster model kinematics for 800 MeV ν_μ on ^{12}C

2 outgoing nucleon kinematics
- 2 outgoing nucleons tend to be back-to-back (model dependent feature)



opening angle of 2 outgoing nucleons (before FSI)



3. Nucleon cluster model kinematics for 800 MeV ν_μ on ^{12}C

In GENIE, Neutrino interaction is simulated in several steps
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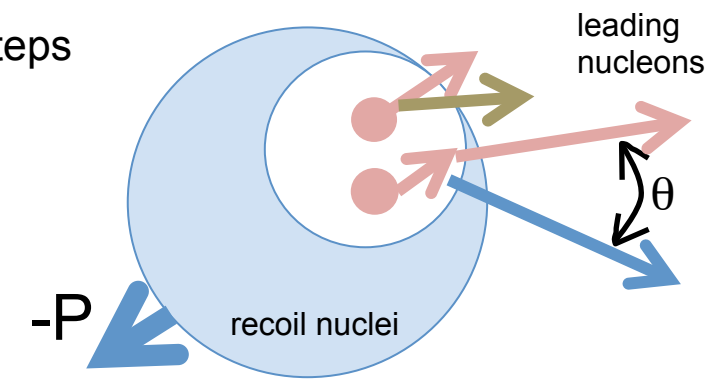
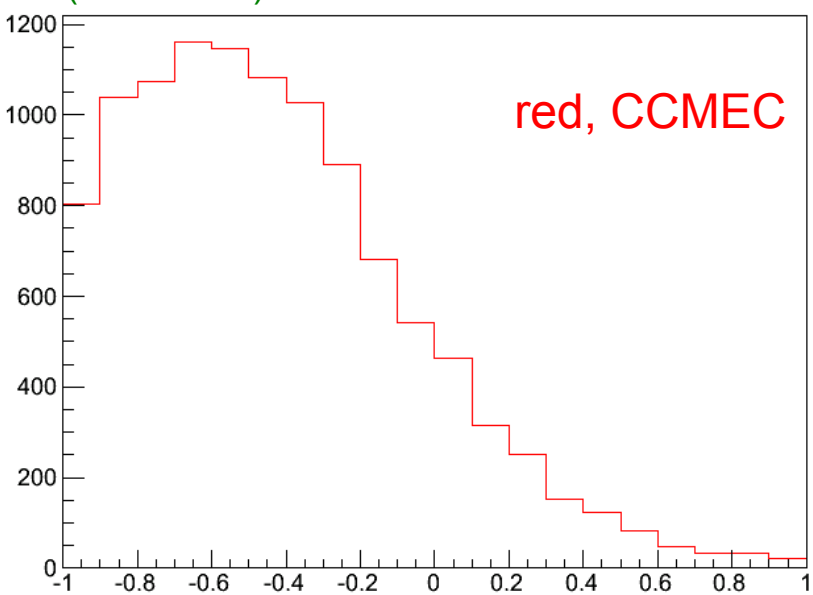
GENIE FSI model (hA FSI model)
- After FSI, MEC still has larger opening angle for 2 nucleons than CCQE

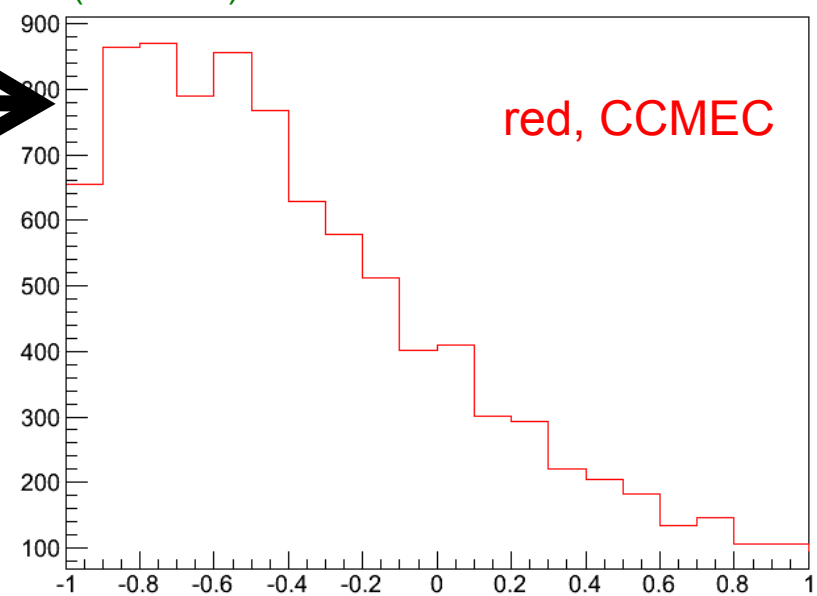


opening angle of 2 outgoing nucleons (before FSI)



Cos|p1*p2|

opening angle of 2 leading outgoing nucleons (after FSI)



opening angle of leading nucleons after FSI

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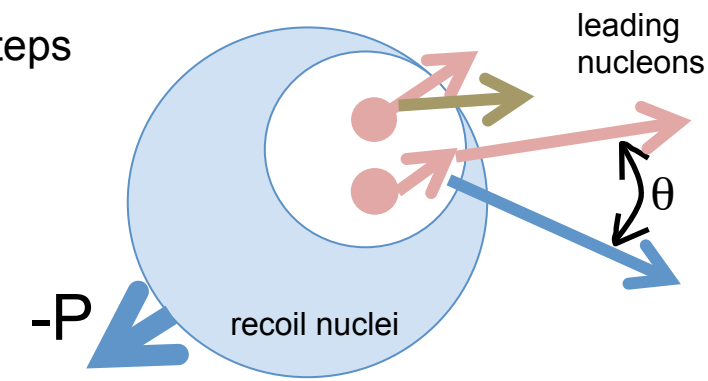
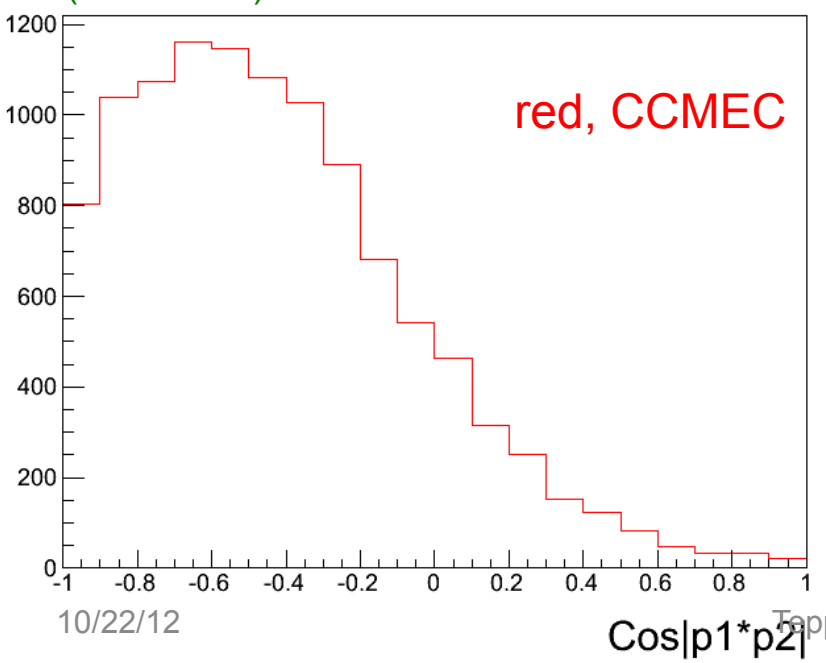
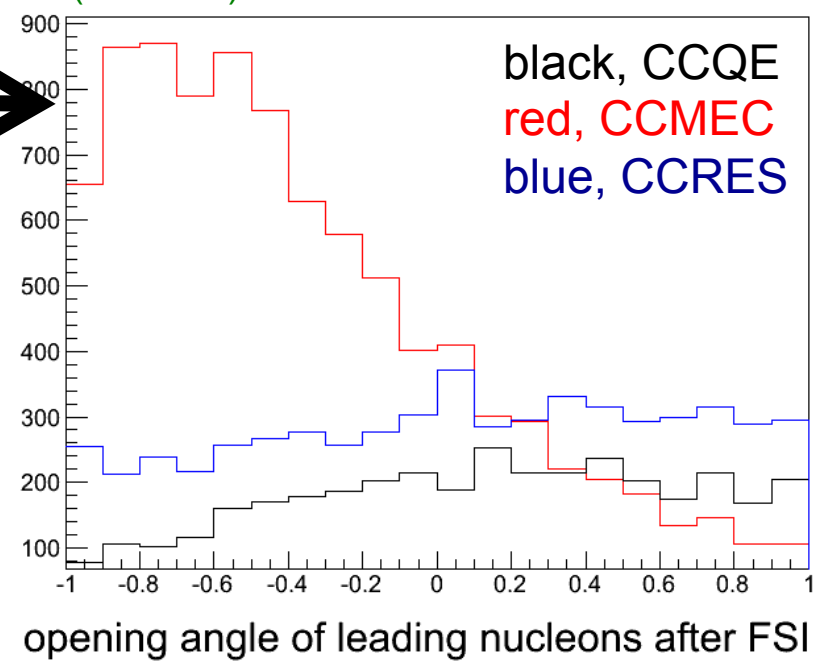


GENIE FSI model (hA FSI model)
- After FSI, MEC still has larger opening angle for 2 nucleons than CCQE
- This is rare configuration for CCQE and resonance

opening angle of 2 outgoing nucleons
(before FSI)



opening angle of 2 leading outgoing nucleons
(after FSI)



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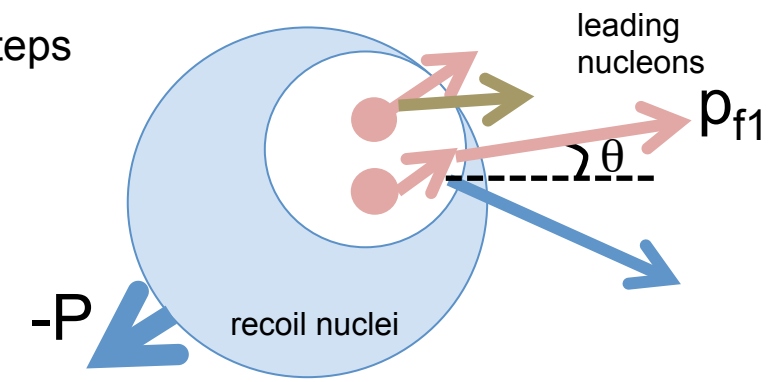
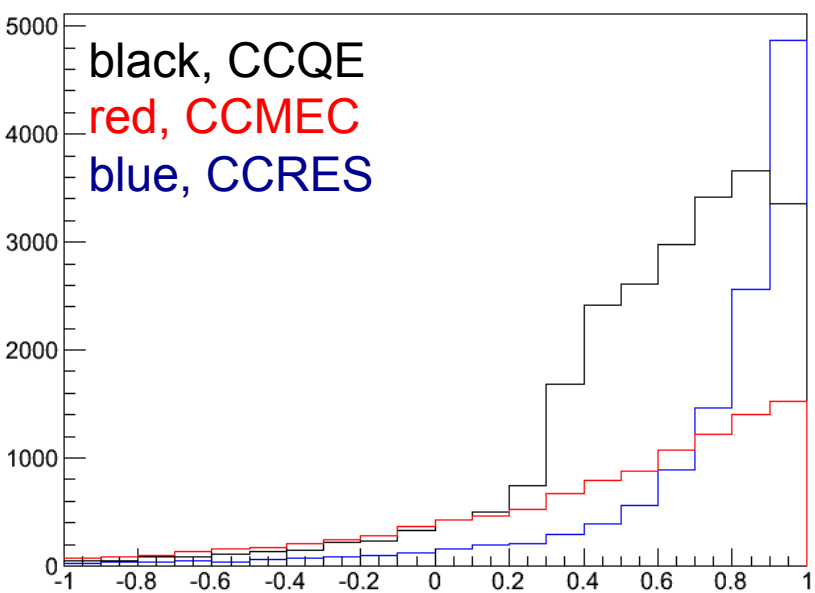
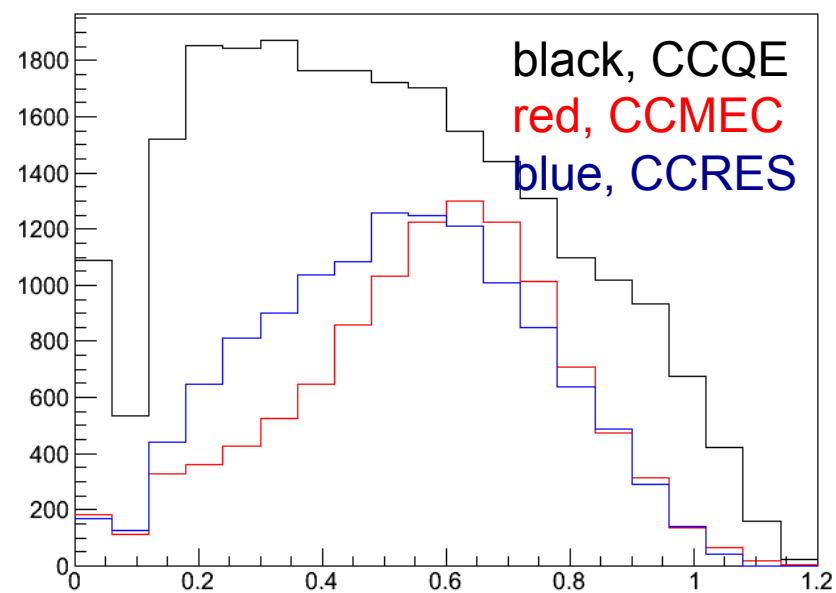
GENIE FSI model (hA FSI model)
- leading outgoing nucleon momentum
- leading outgoing nucleon angle



Nucleon cluster model may predict interesting event topologies



scattering angle of leading nucleon after FSI

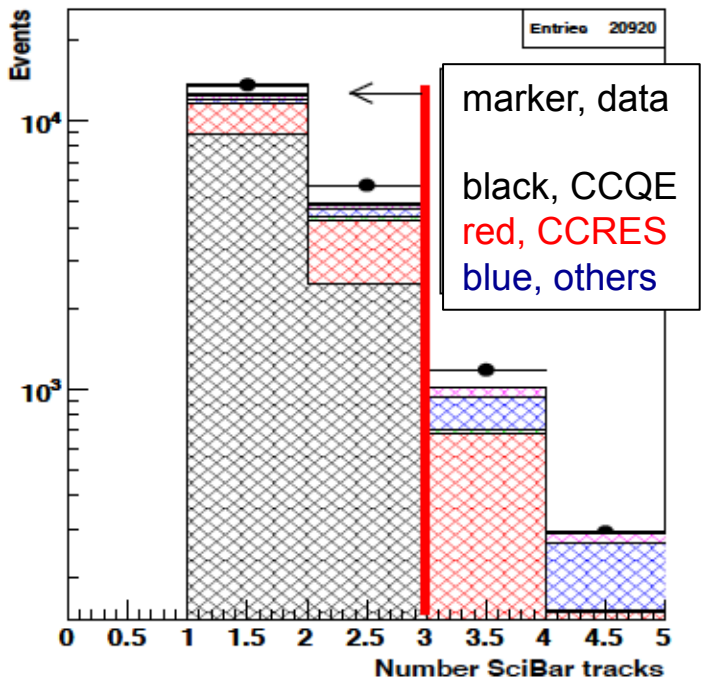


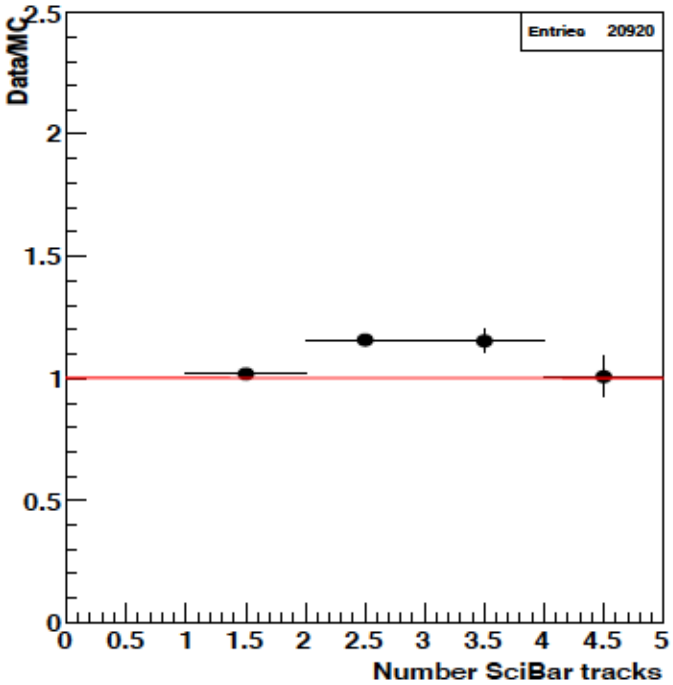
max nucleon momentum after FSI (GeV/c)

3. SciBooNE multi-track analysis

SciBooNE CC analysis
- total rate is normalized to CC inclusive measurement
- data is compared with NeuT prediction
- 3 track data shows excess, this can be explained by many ways
  - Resonance channel xs is underestimated?
  - FSI is not modelled correctly?
  - Indication of multi-nucleon emission?

SciBooNE CC track number





1. Introduction

2. Leptonic simulation in GENIE

3. hadronic simulation in GENIE

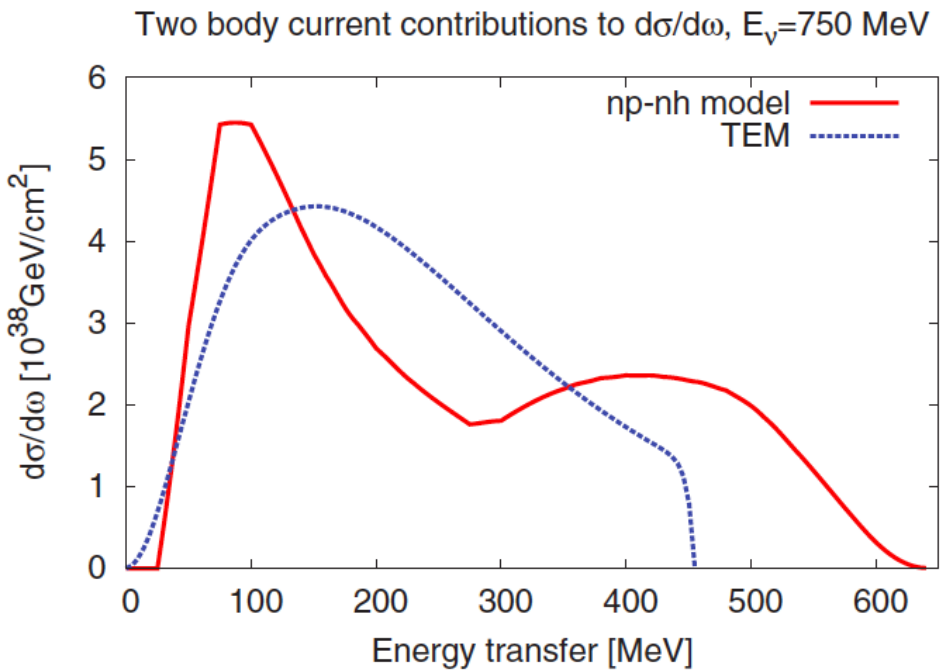
4. Comparisons

5. Discussion

4. MEC model in NuWro

Sobczyk, PRD86(2012)015504
Martini et al, PRC80(2009)065501
Bodek et al, EUJC71(2011)1726

NuWro
- 2 choices of MEC model
  - np-nh model (based on Marteau model)
  - TEM (Transverse enhancement model)
- Nucleon cluster model similar to GENIE (more attention to energy balance)

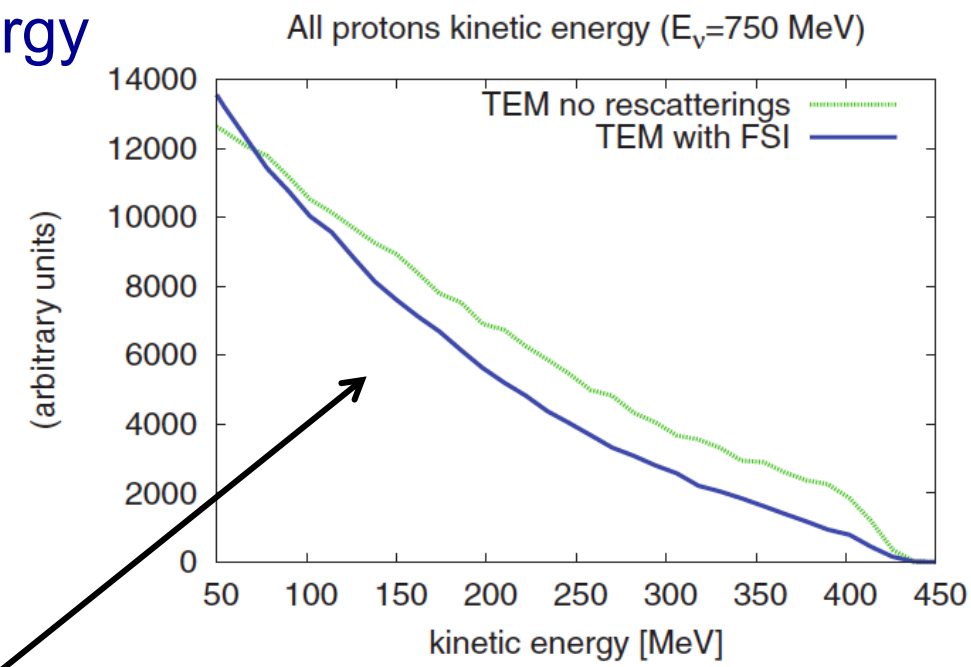


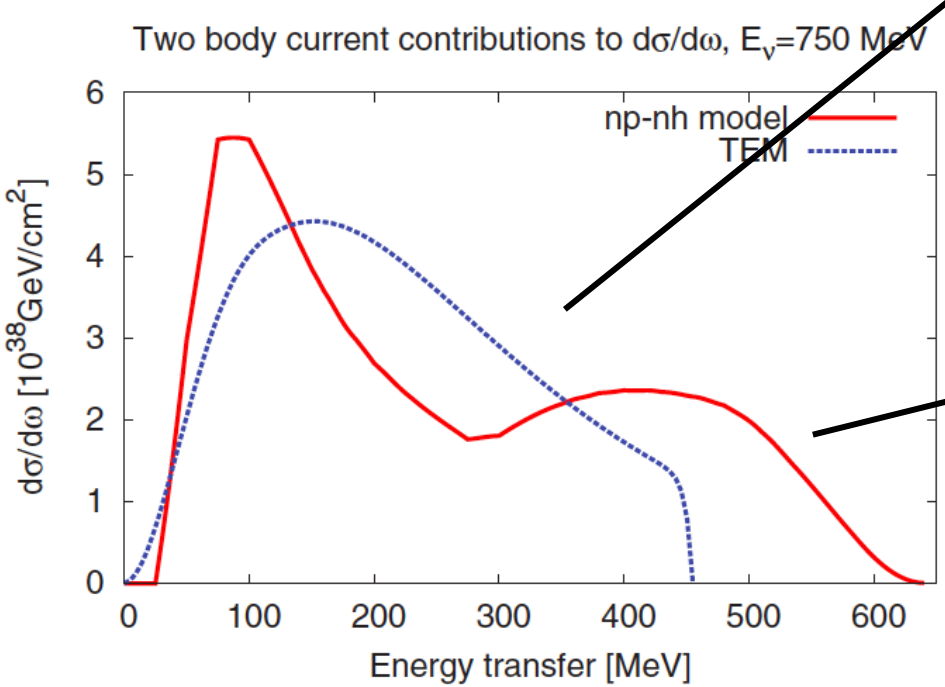
Sobczyk, PRD86(2012)015504

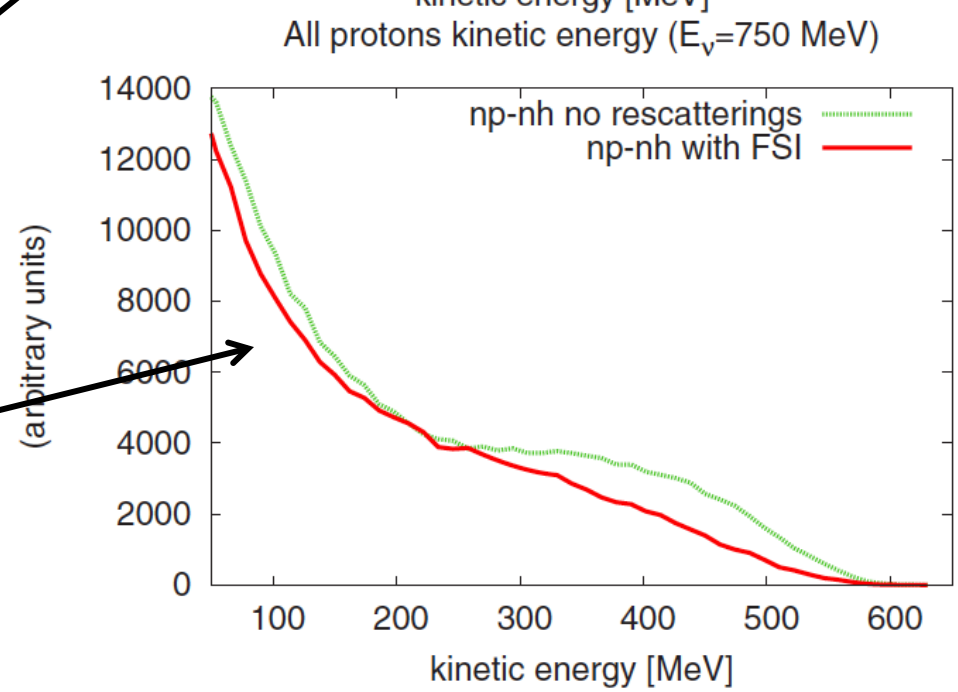
4. Sum of all nucleon kinetic energy

NuWro
- 2 choices of MEC model
  - np-nh model (based on Marteau model)
  - TEM (Transverse enhancement model)
- Nucleon cluster model similar to GENIE (more attention to energy balance)

Different predictions on energy transfer provide different predictions on total kinetic energy, but after FSI, most of structure is gone







Sobczyk, PRD86(2012)015504

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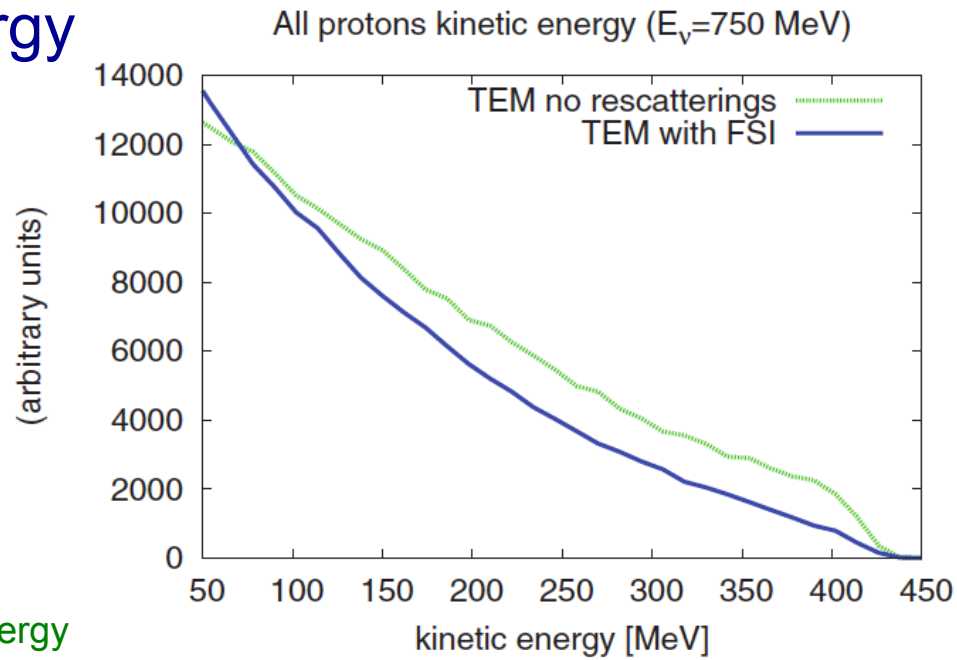
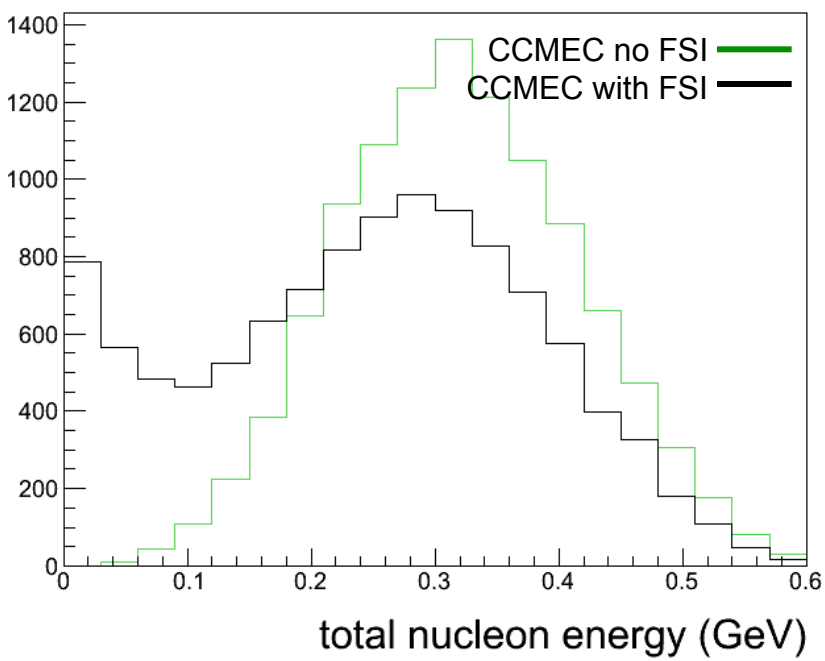
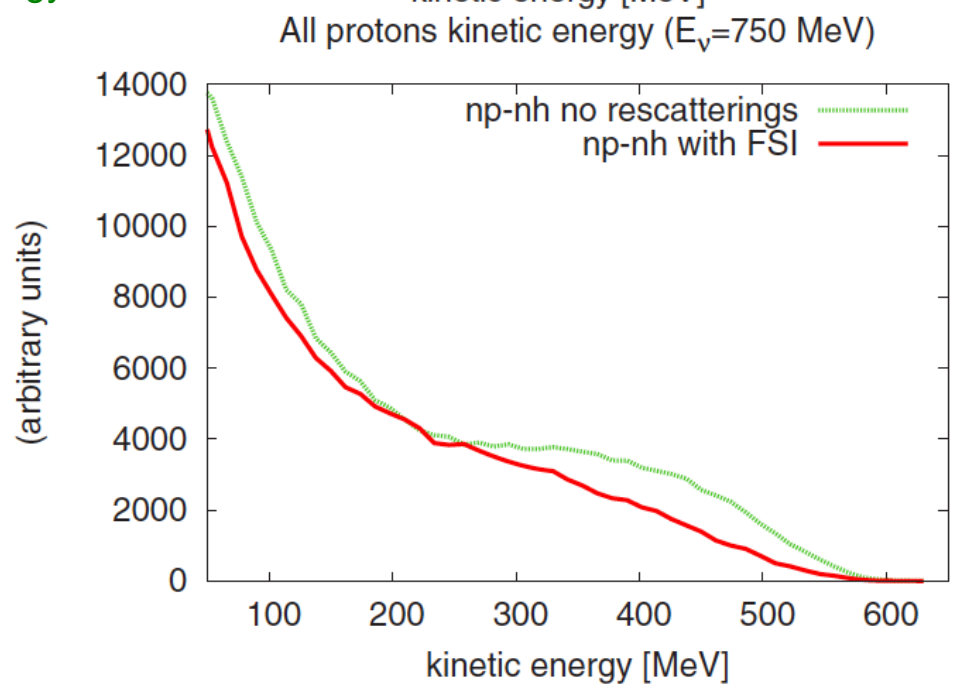
For GENIE, Dytman model has Gaussian energy transfer, therefore has symmetric kinetic energy distribution.



GENIE ν_μ-^{12}C 800 MeV total outgoing nucleon kinetic energy





Sobczyk, PRD86(2012)015504

4. Max nucleon momentum

NuWro
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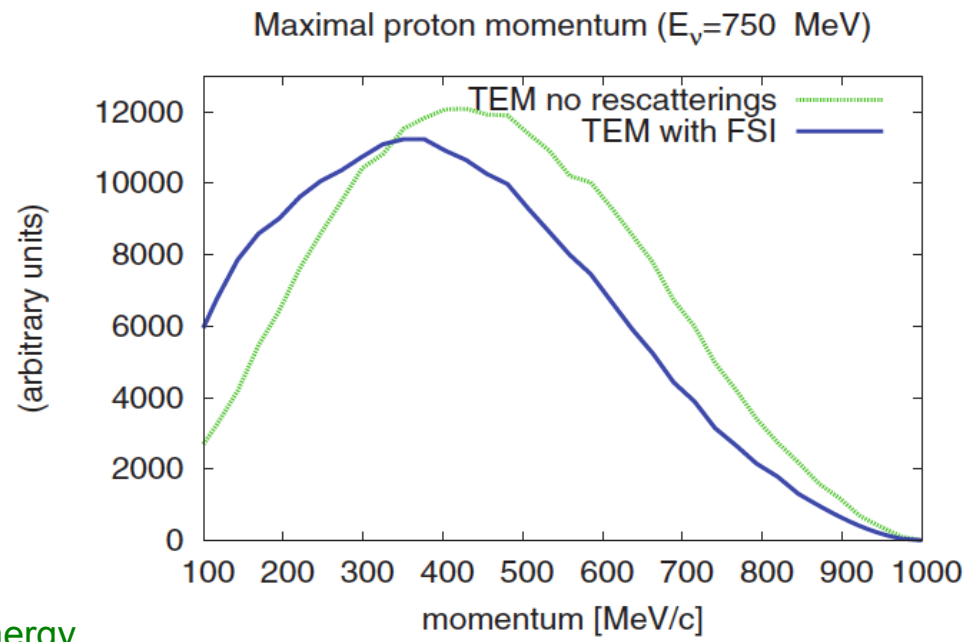

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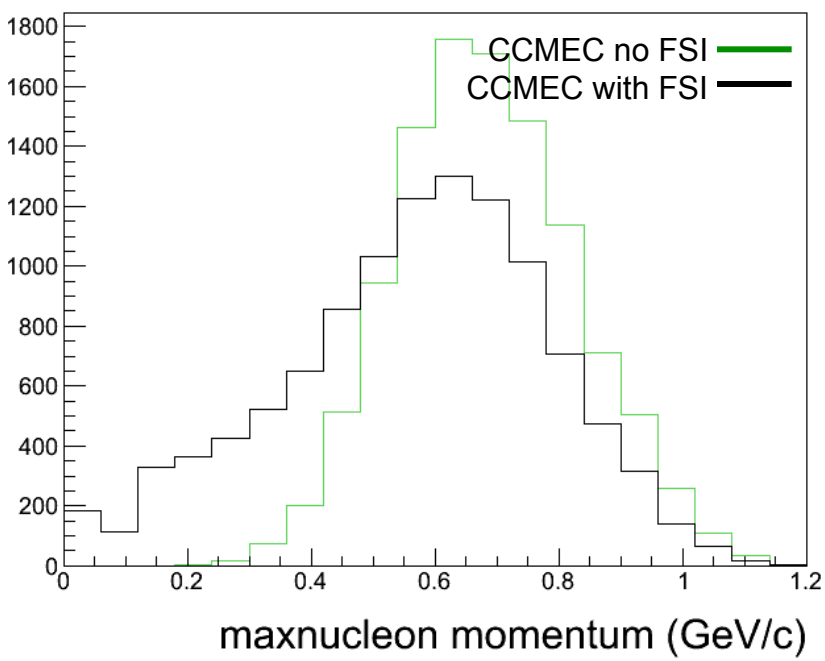
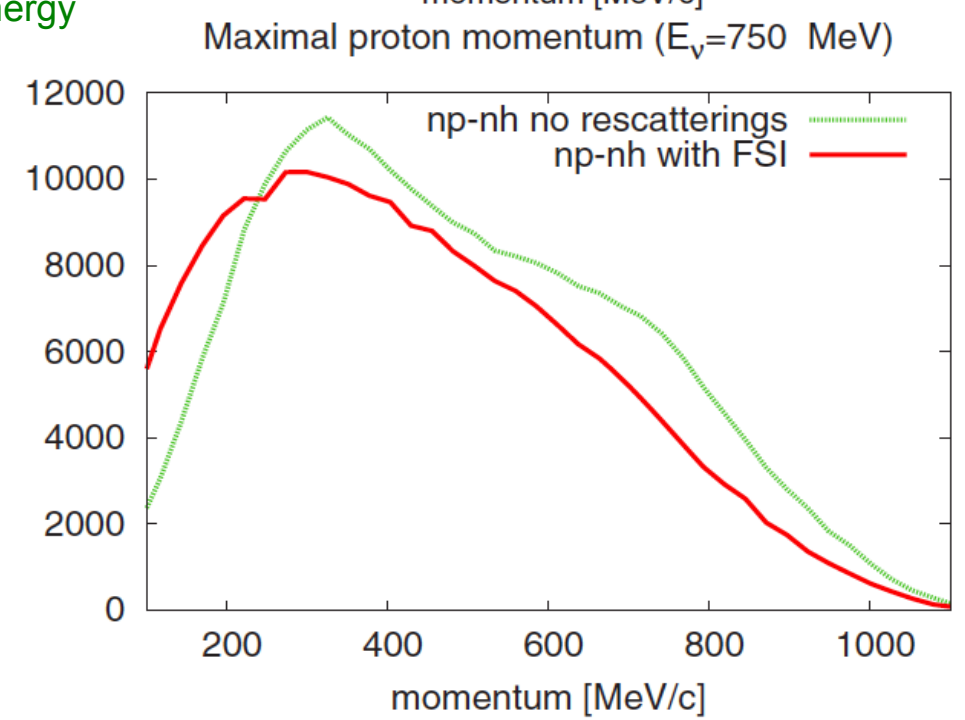




Lalakulich et al,
PRC86(2012)014614

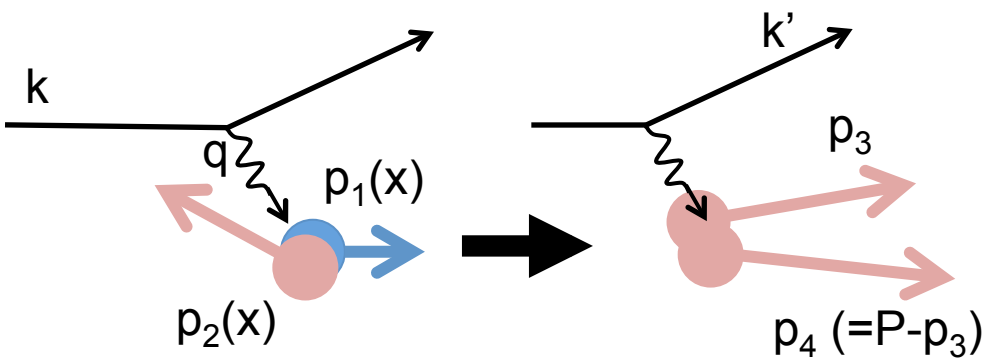
4. MEC model in GiBUU

One-particle phase space density
(solution of coupled Kadanoff-Baym eqn.)

Triple differential cross section
- A special care is paid for the phase space
- 2 nucleons start from same location (effect of nuclear density is squared)

Symmetry factor
(n-n, p-p pair=1/2, n-p pair=1)

$$\frac{d^3\sigma^{(3)}}{d\Omega' dE'} = \frac{|\mathbf{k}'|}{|\mathbf{k}|} g_1 g_2 \mathcal{S}_{34}\mathcal{S}_{12} \frac{1}{(2\pi)^4 8} \int d^3x \int \frac{d^3p_1}{(2\pi)^3 2E_1} \int \frac{d^3p_2}{(2\pi)^3 2E_2} f_1(x,p_1) f_2(x,p_2)$$
$$\times \int \frac{d\Omega_3}{4\pi} \overline{|\mathcal{M}_{\nu 12\to l' 34}|^2} \frac{\tilde{\mathbf{p}}_3^2}{(P_0-\tilde{E}_3)|\tilde{\mathbf{p}}_3| + \tilde{E}_3|\mathbf{P}-\tilde{\mathbf{p}}_3|},$$



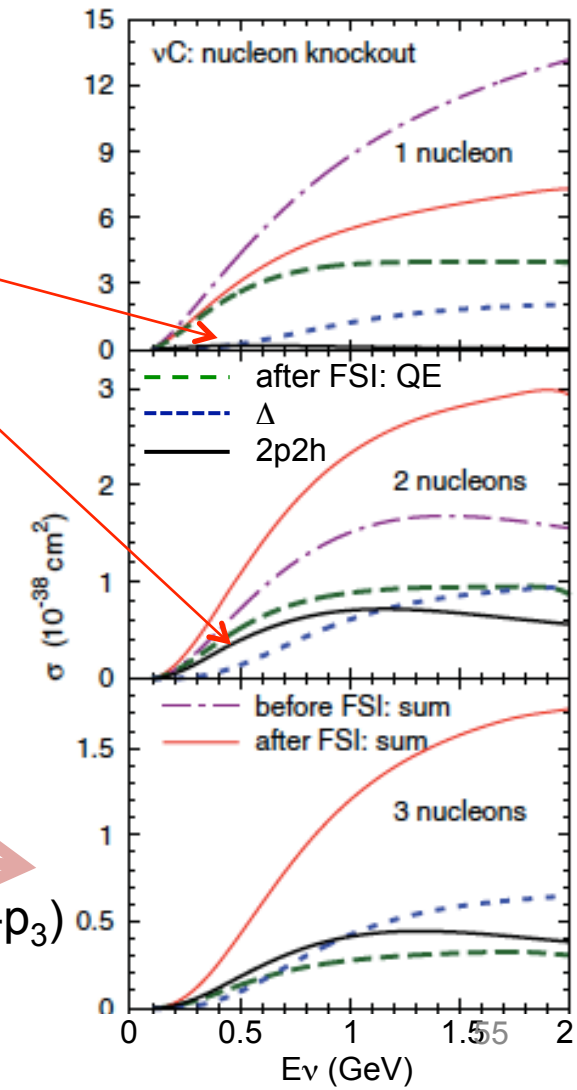
Lalakulich et al,
PRC86(2012)014614

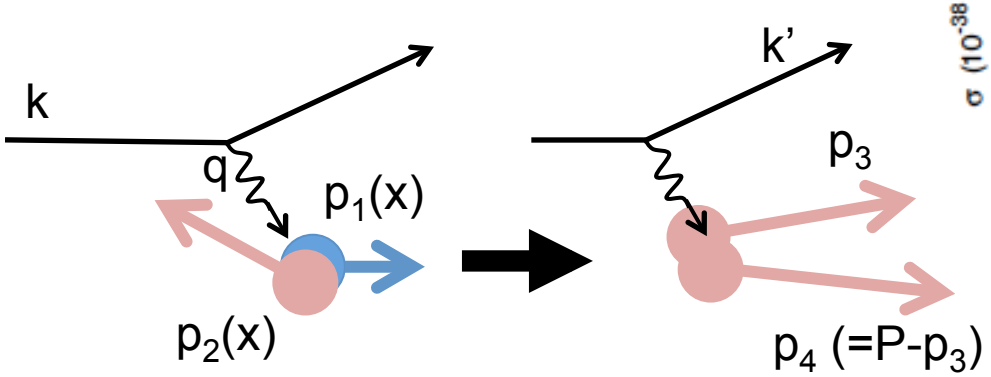
4. Total cross section, with N-nucleons

GiBUU
- A special care is paid for the phase space
- 2 nucleons start from same location)
- hadronic tensor is transverse projector (model II)
- FSI controls final state particles

2p-2h doesn't contribute to 1 nucleon knockout
- MEC model shouldn't enhance 1-nucleon knock out

GiBUU ν_μ-^{12}C total cross section for multi-nucleon knockout (after FSI)





Lalakulich et al,
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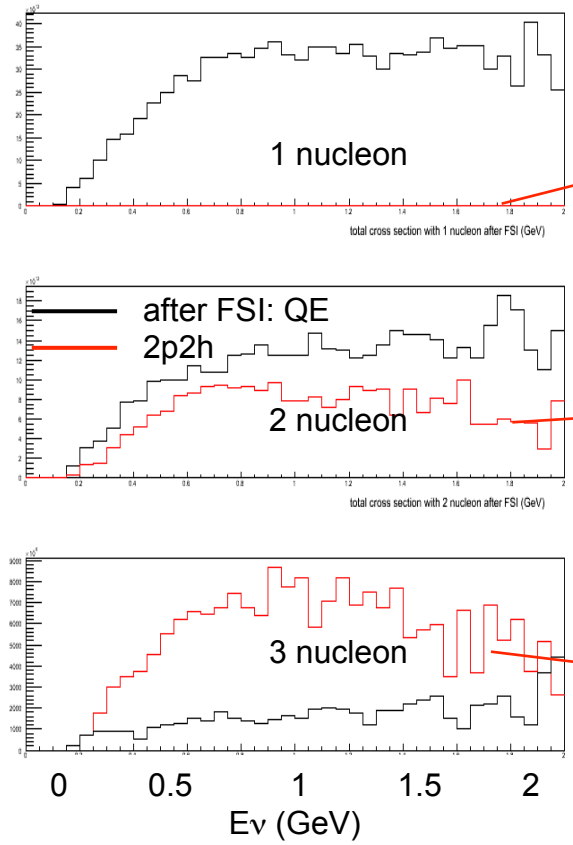
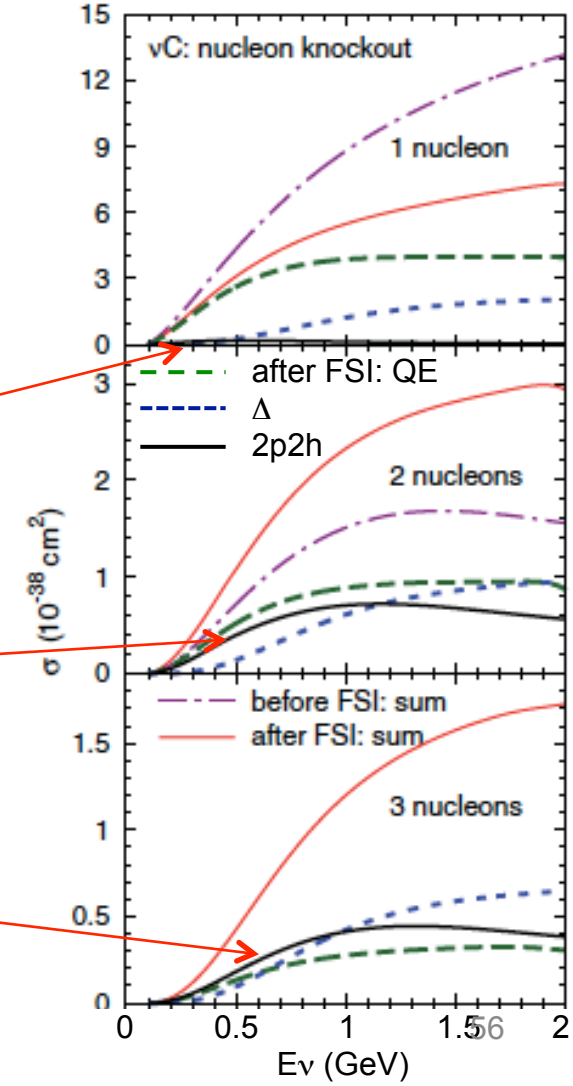
GENIE ν_μ-^{12}C total xs for multi-nucleon knockout (after FSI)



GiBUU ν_μ-^{12}C total cross section for multi-nucleon knockout (after FSI)



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5. Discussion

The effort to implement MEC model in MC is just started..., with many open questions
- How to choose 2 initial nucleon kinematics?
- How to implement 2 final nucleon FSI?
- What kind of pairs are preferred, n-n, or n-p, or p-p?
- Where are 2 nucleons generated?
- Do we assume any correlation of initial nucleon? (momentum and location)

Some of them may be described in theoretical models, but what is best way to implement in MC? (can have significant effect on predictions!)

e.g.) Short Range Correlations (SRC)
- Initial nucleons can be off-shell
- from hadron experiments, n-p pair is preferred
- 2 nucleons are close
- initial momenta are correlated (back-to-back)

We need more input for a realistic prediction

5. Discussion

GENIE v2.7.2
- First tagged version with MEC
- Lepton kinematic is based on Dytman model, tests are ongoing with e-scattering data
- Hadron kinematic is based on GENIE nucleon cluster model
- Will be available Mar. 2013

Acknowledgement
- Costas Andreopoulos
- Steve Dytman
- Hugh Gallagher
- Ulrich Mosel
- Jan Sobczyk

Muito obrigado!

Backup