Implementation of the new MEC model in NuWro

Hemant Prasad

Outline

- Introduction
- 2020 Valencia MEC Model
- NuWro implementation of MEC models
- Data comparison
- Summary

@WhoAmI

- PhD 3rd year student at University of Wrocław
  - Under Jan T. Sobczyk

- NuWro dev
  - MEC models
  - Reweighting of FSI

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Introduction

Motivation

Precision era of ν-oscillation experiments

Uncertainties Source (T2K)	
$\sigma_{\nu N}$ and FSI	3.8%
Total Syst.	5.2%

K. Abe *et al.* Phys Rev. D 103 (2021) 112008

Uncertainties Source(NOvA)	
$\sigma_{\nu N}$ and FSI	7.7%
Total Syst.	9.2%

M. A. Acero *et al.* Phys Rev. D 98 (2018) 032012

- Statistics (NOvA) :
  - 126 (66) events for $\nu_{\mu}(\nu_{e})$ disappearance (appearance)
- Expect **1000-2000** for DUNE/HK

Motivation

Precision era of ν-oscillation experiments

Systematic uncertainty must be reduced for future experiments

Uncertai... S...	
	...2%

...(2021) 112008

...es ...ce(NOvA)	
$\sigma_{\nu N}$ and FSI	7.7%
Total Syst.	9.2%

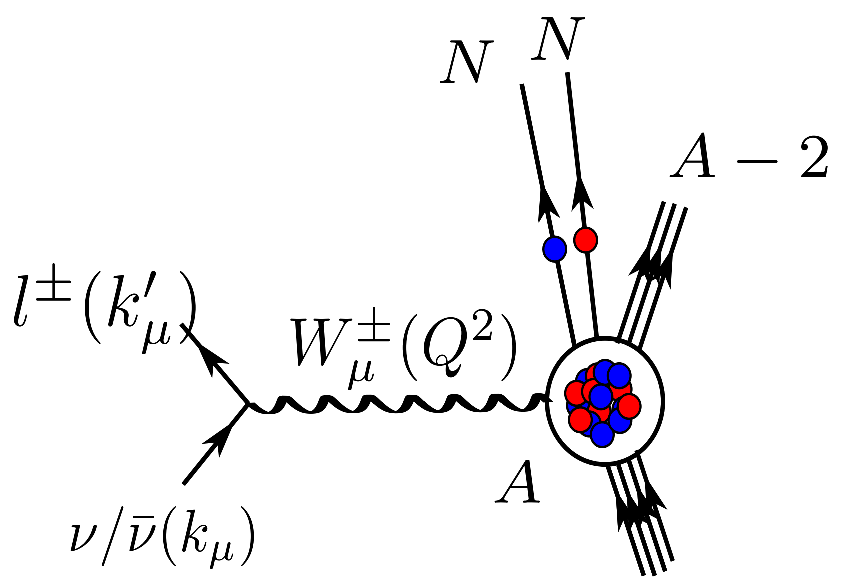
M. A. Acero *et al.* Phys Rev. D 98 (2018) 032012

- Statistics (NOvA) :
  - 126 (66) events for $\nu_\mu(\nu_e)$ disappearance (appearance)
- Expect **1000-2000** for DUNE/HK

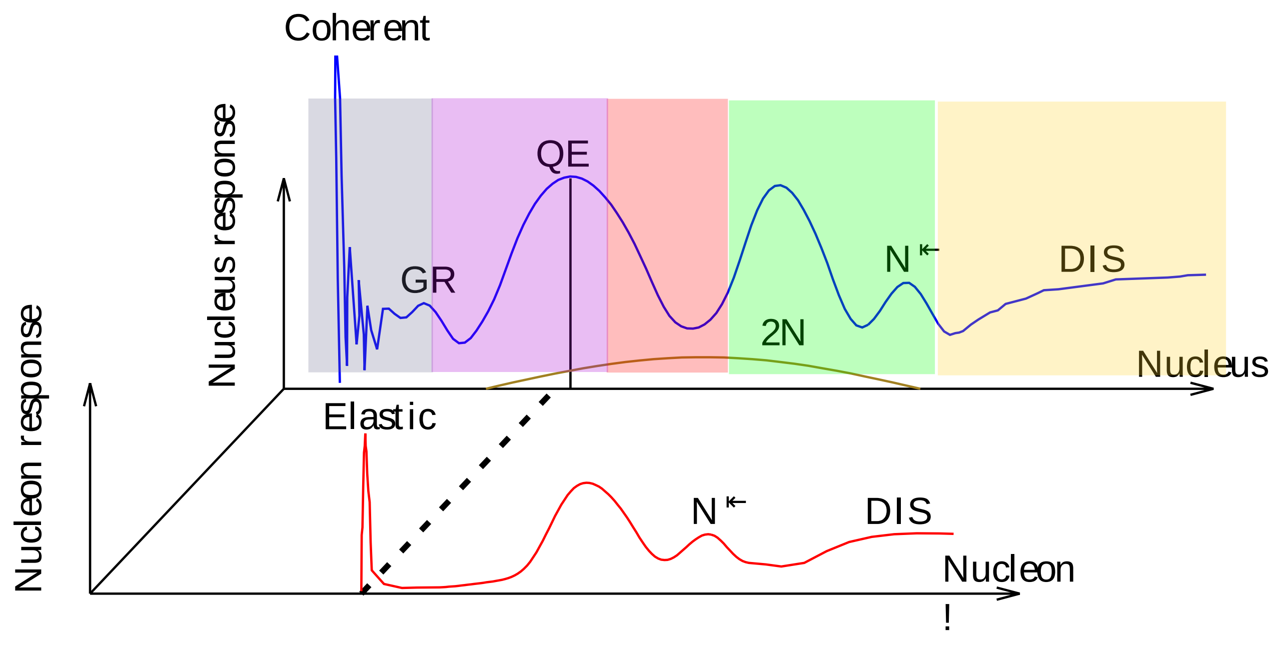
Motivation

Neutrino-nucleus interactions

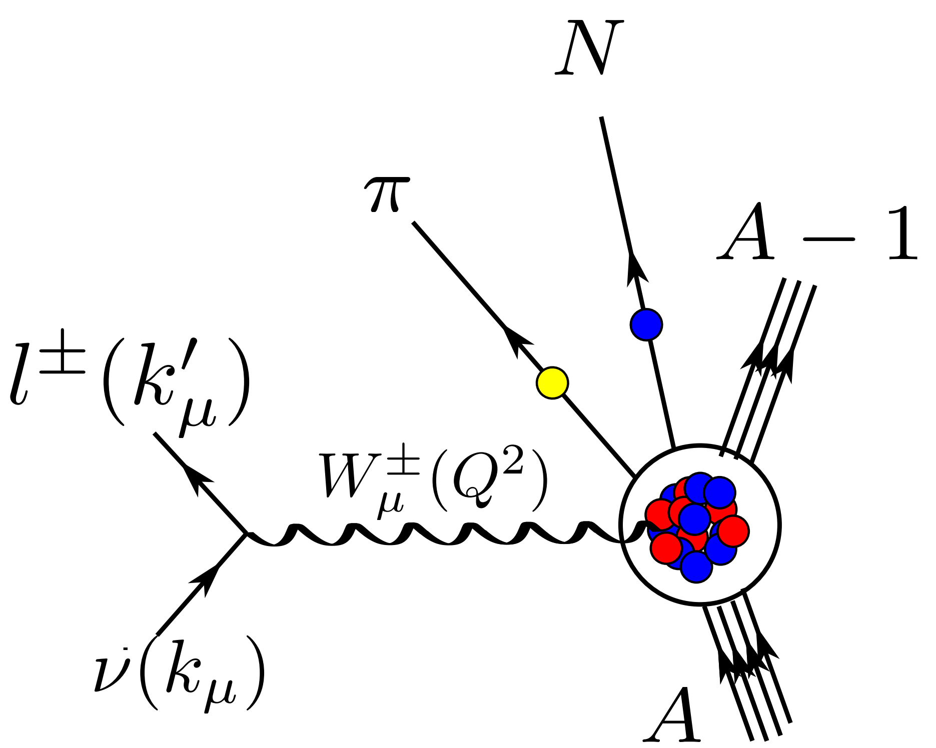
- Accelerated ν-beams have broad spectra of energy.
- Different mechanism emerges on **different energy scales.**
- **Quasi Elastic (QE)** dominates at sub-GeV energies.
- Significant contributions from **meson exchange currents (MEC)** at sub-GeV level.



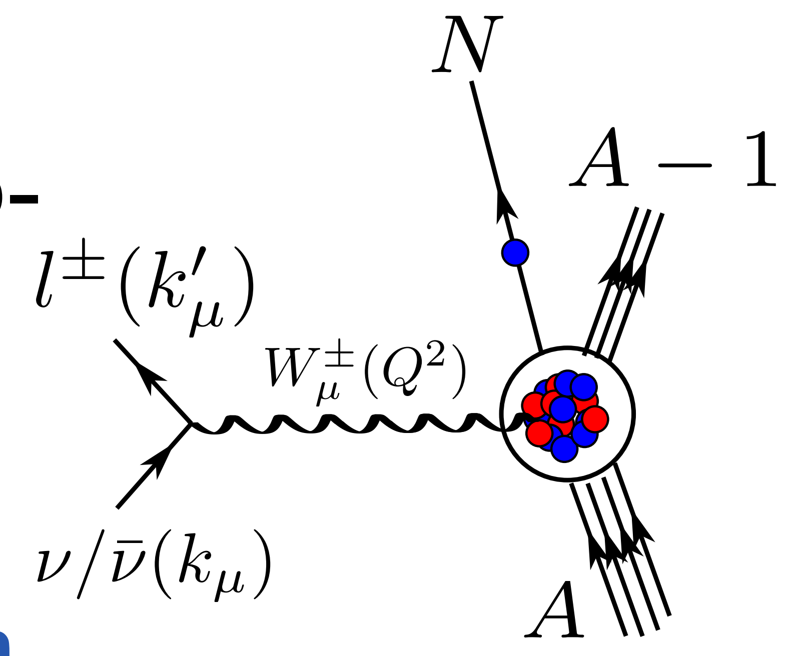
2-Body Current (2p2h)



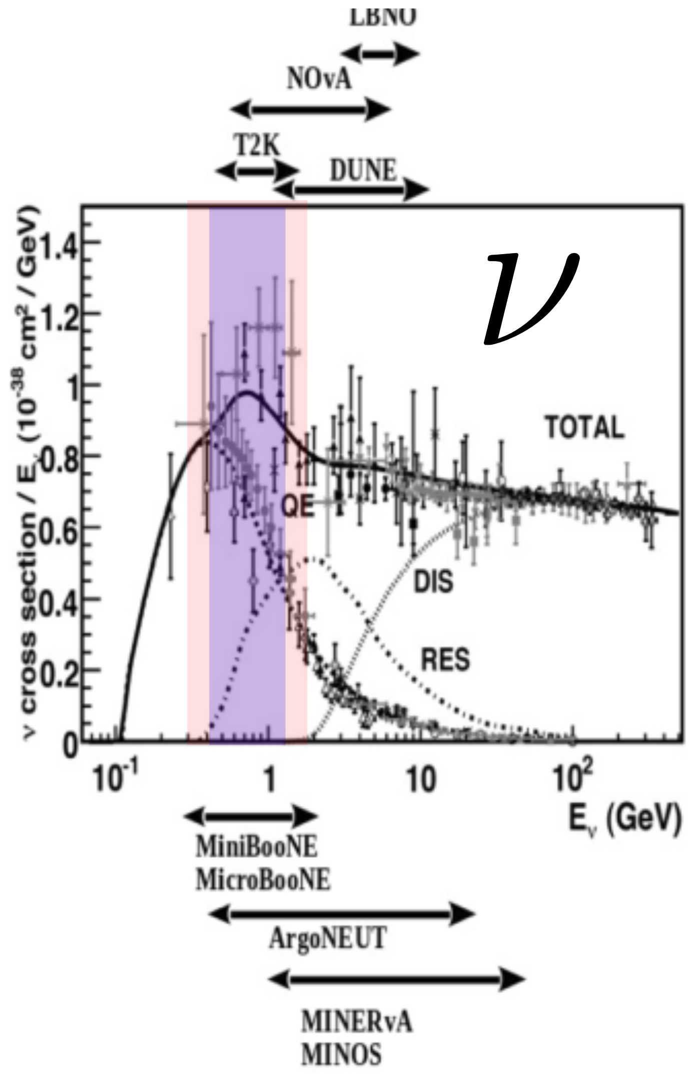
T. Van Cuyck

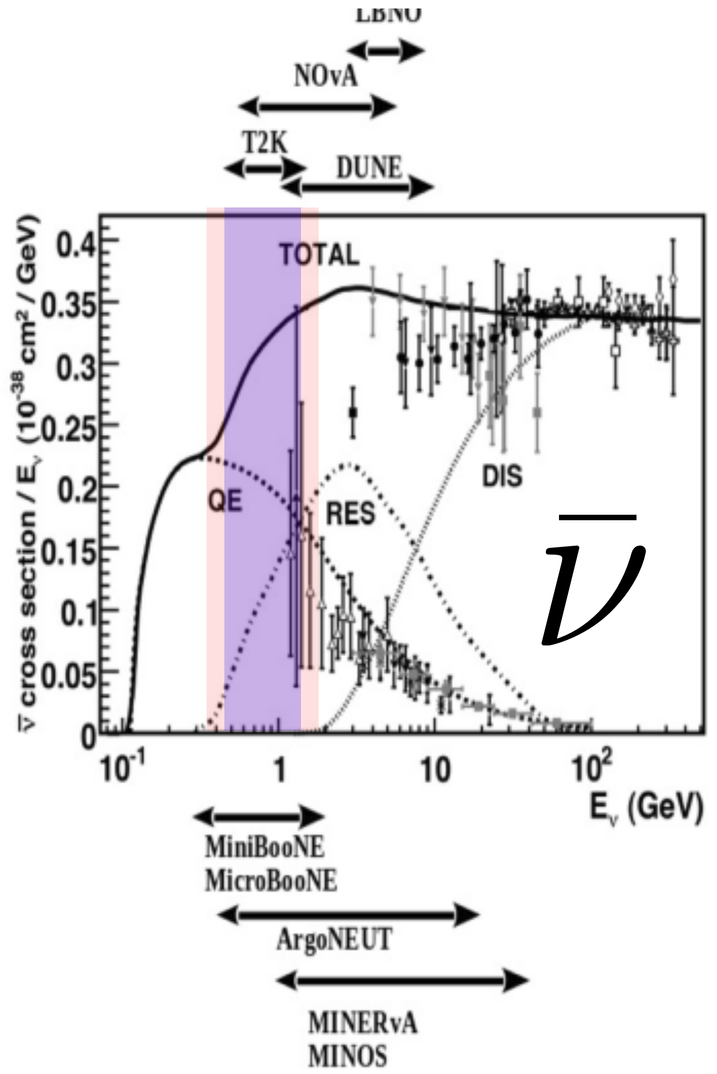


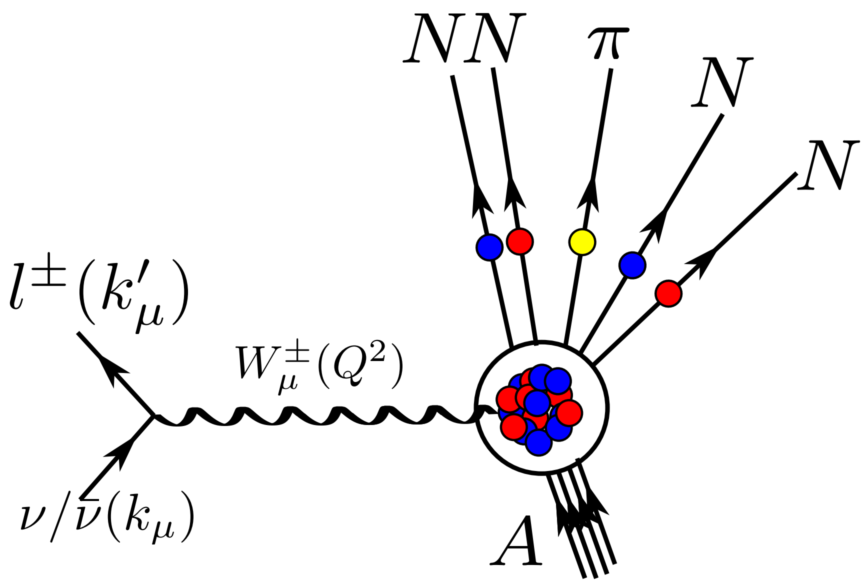
Resonance Scattering



Quasi Elastic Scattering







DIS (Deep Inelastic Scattering)

Motivation

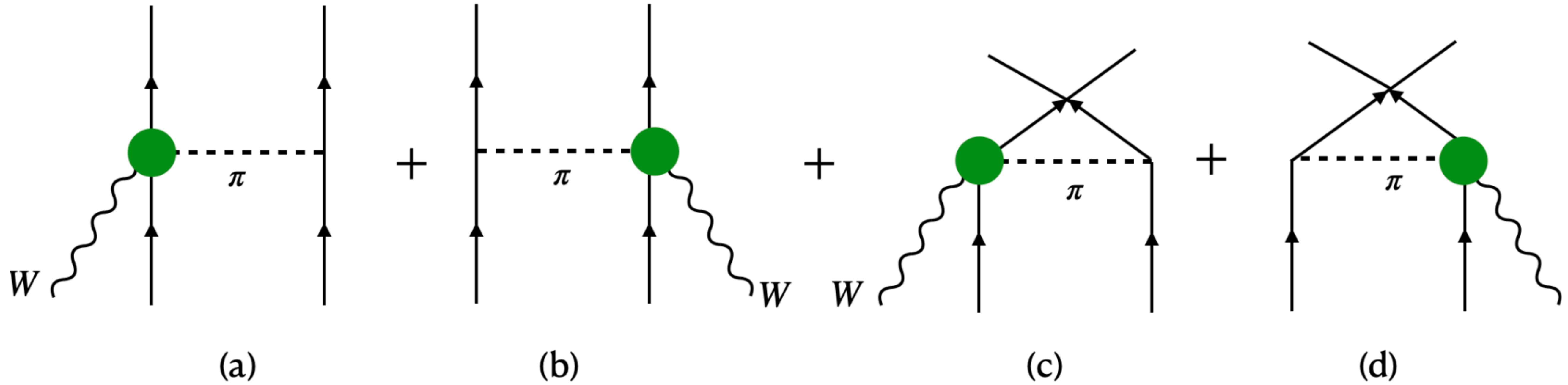
Meson exchange currents

- Motivated by electron-nucleus scattering data.
- A **multi-nucleon knockout** process.
- Energy exchange between nucleons is through in-medium meson production.
- **Significant contribution around ~ 1 GeV.** An important interaction mode for all upcoming neutrino experiments.
- Dominated by two body current interactions (2p2h). Small contribution coming from three body current interactions as well (3p3h) before FSI !!
- Highly model dependent (*will be shown in the upcoming slides !*). Various models are present in the market. Must be implemented in Monte Carlo generators as well.

2020 Valencia model

2020 Valencia model

Theoretical background $W^{\pm}N \rightarrow N'\pi$



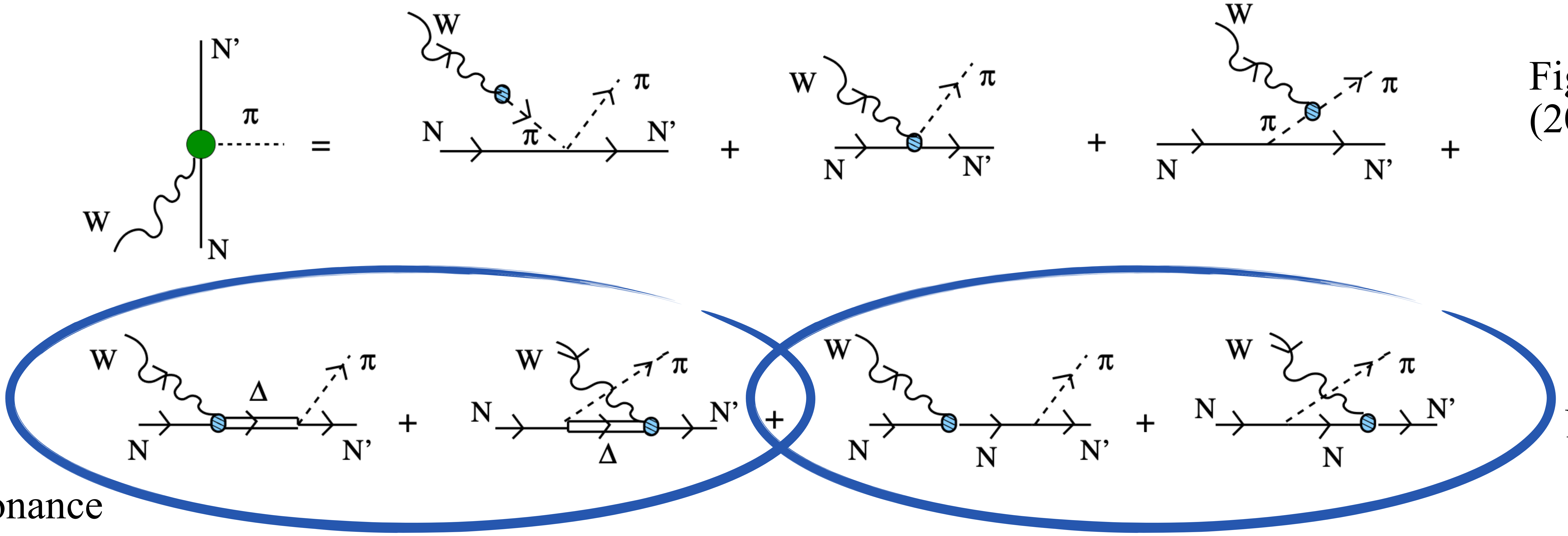


Figure from J.E. Sobczyk *et. al.* Phys. Rev. C. 102 (2020) 024601

NN contribution

Δ(1232)-resonance

2020 Valencia model

J. E. Sobczyk *et al.* Phys. Rev. C. 102 (2020) 024601

- Separation of 2p2h and 3p3h contribution from the total MEC cross section.

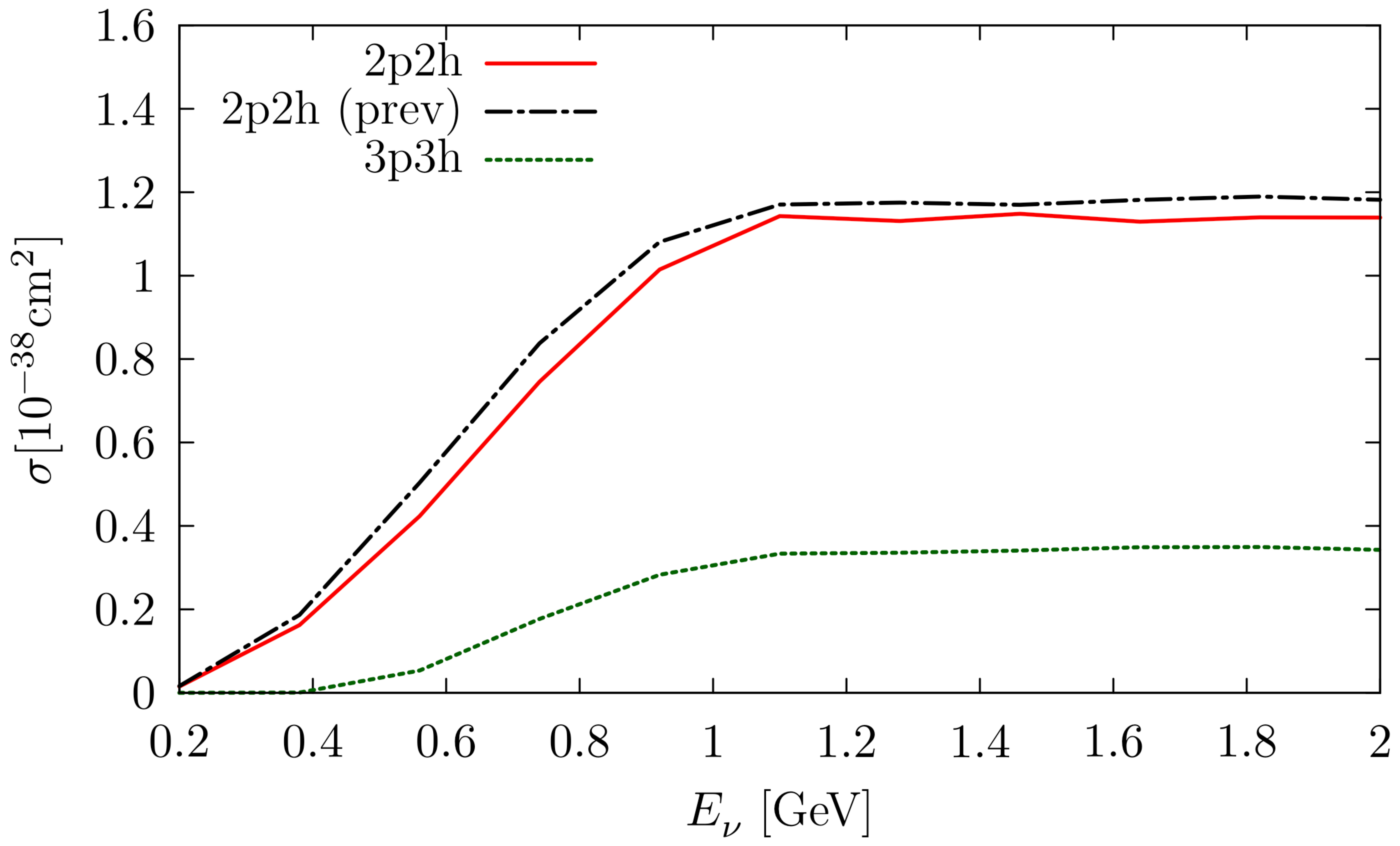


Figure from J.E. Sobczyk *et. al.* Phys. Rev. C. 102 (2020) 024601

2020 Valencia model

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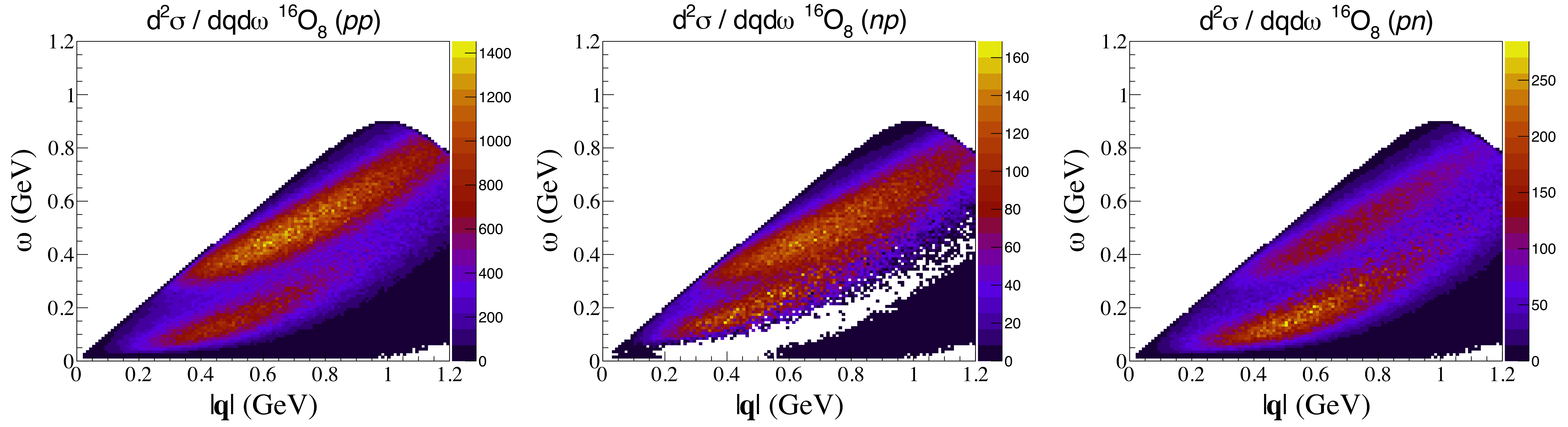
Figure from code provided by J.E. Sobczyk



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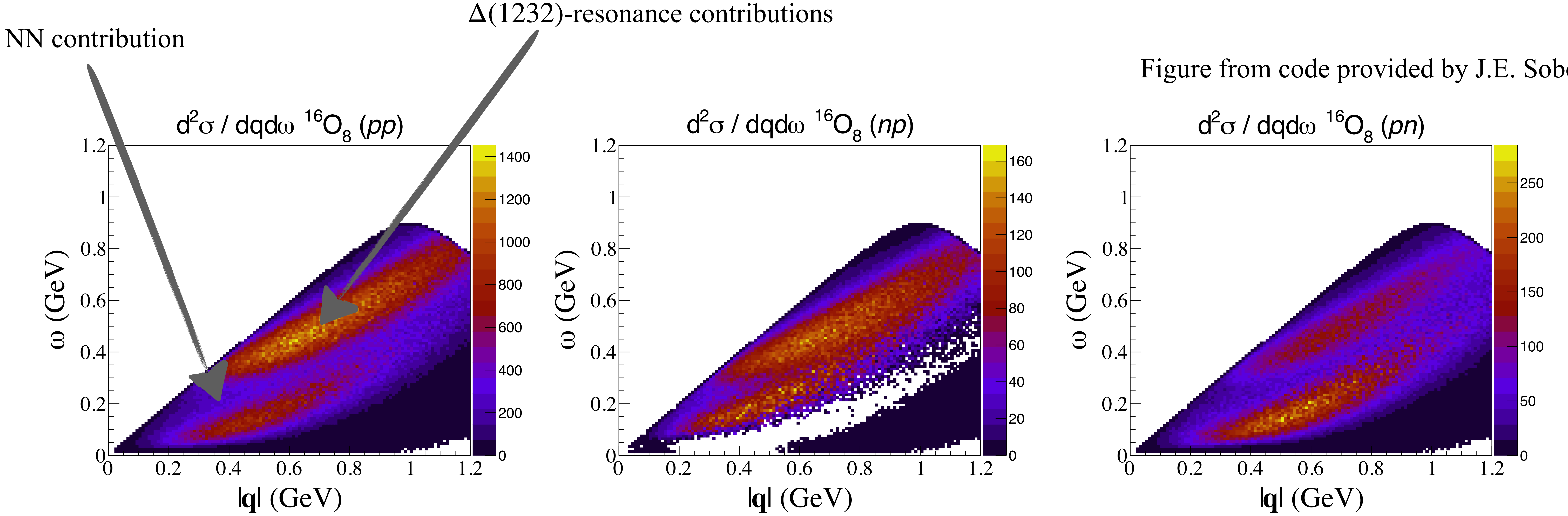

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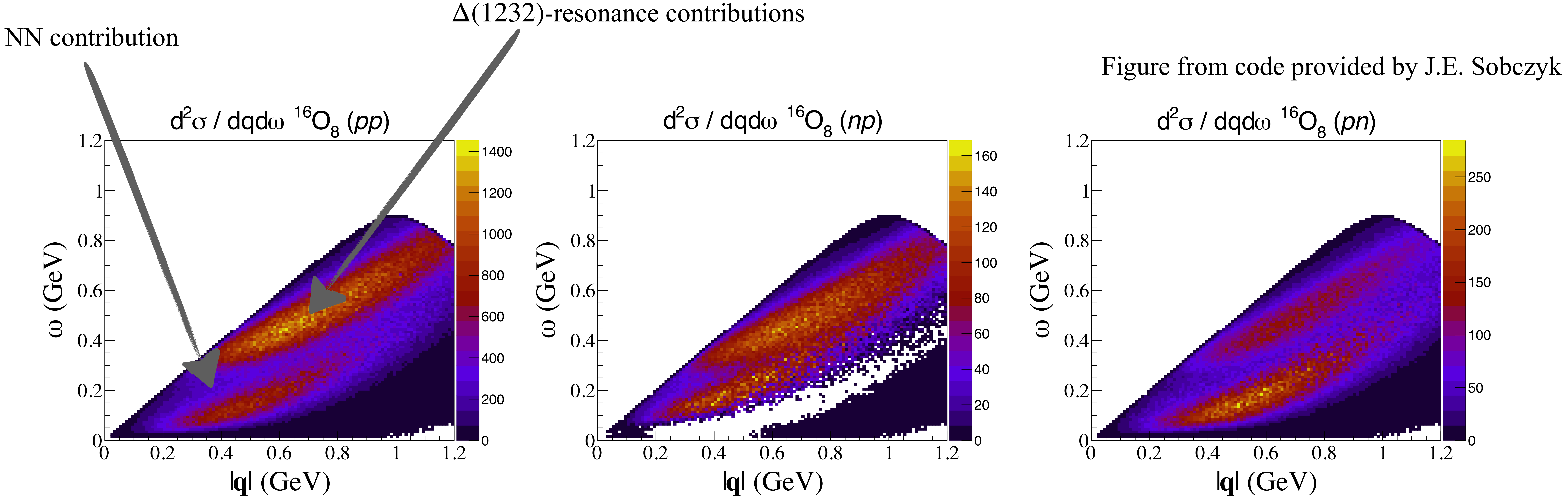


- Correlation strength **differs** based on different outgoing nucleon pair.
- Different outgoing pair **must be treated differently** in Monte Carlo generators !

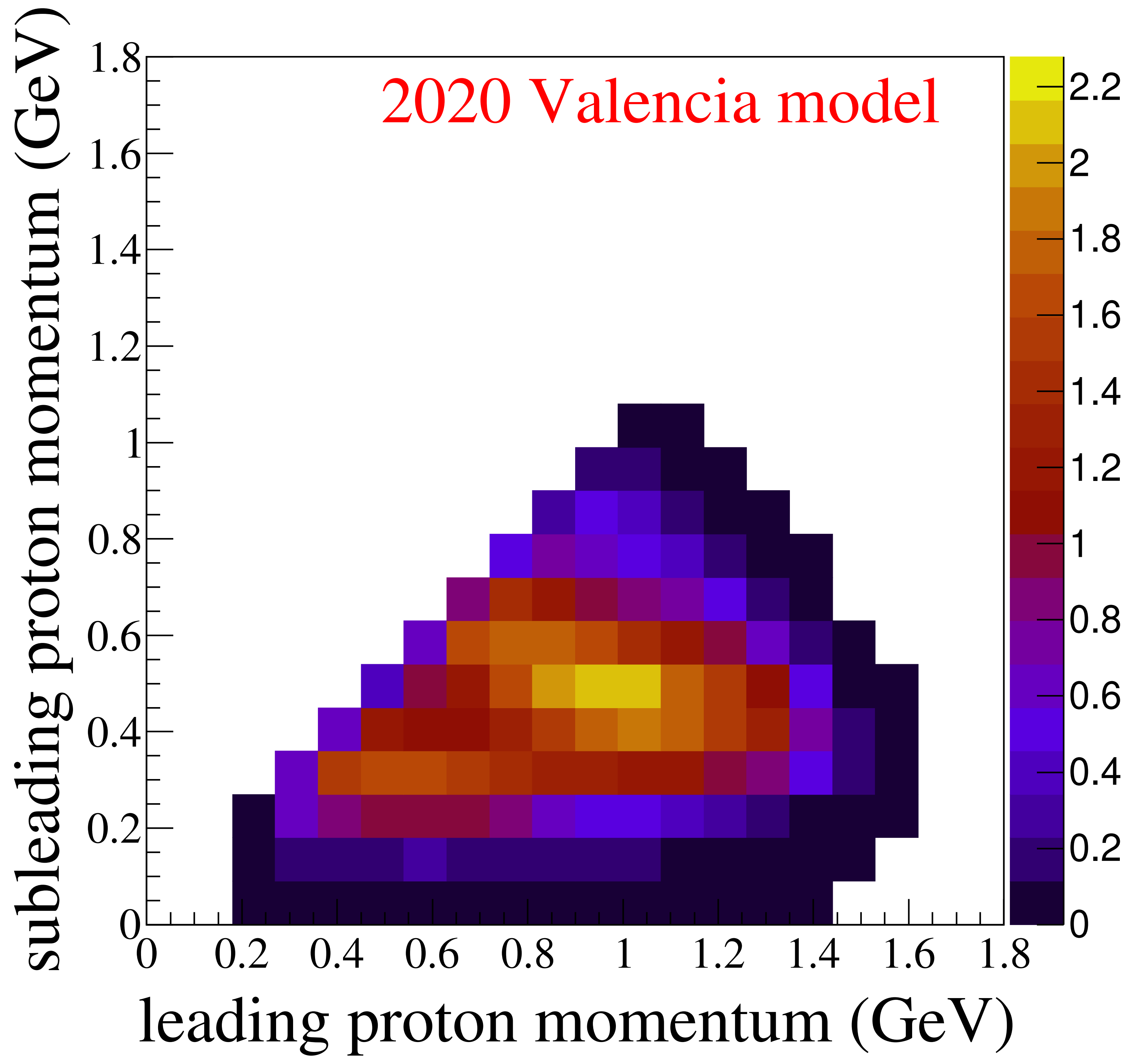
2020 Valencia Model

J. E. Sobczyk *et al.* Phys. Rev. C. 102 (2020) 024601

- Predictions on momenta of outgoing nucleons.

Figure from code provided by J.E. Sobczyk

E_ν = 1 GeV



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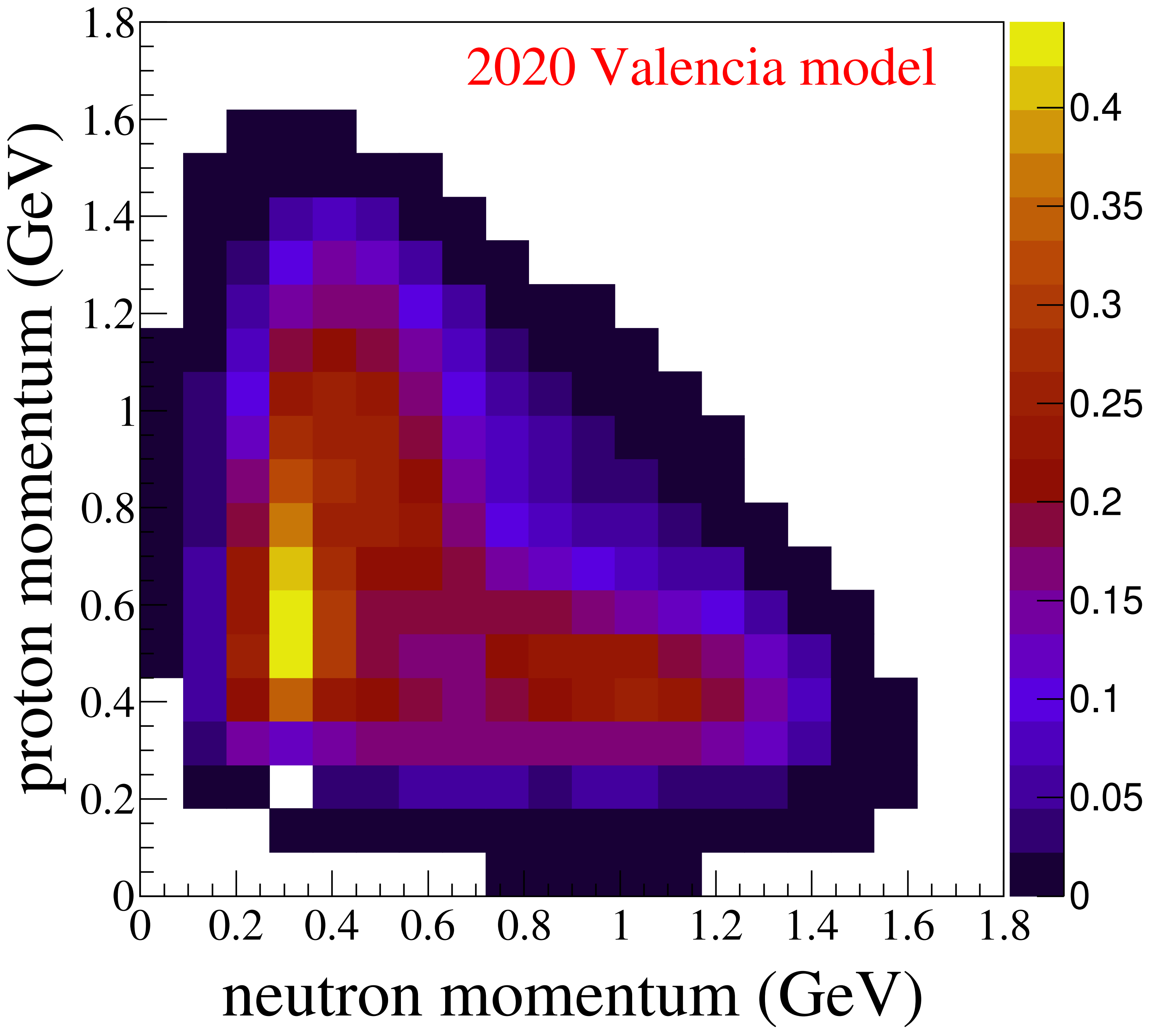
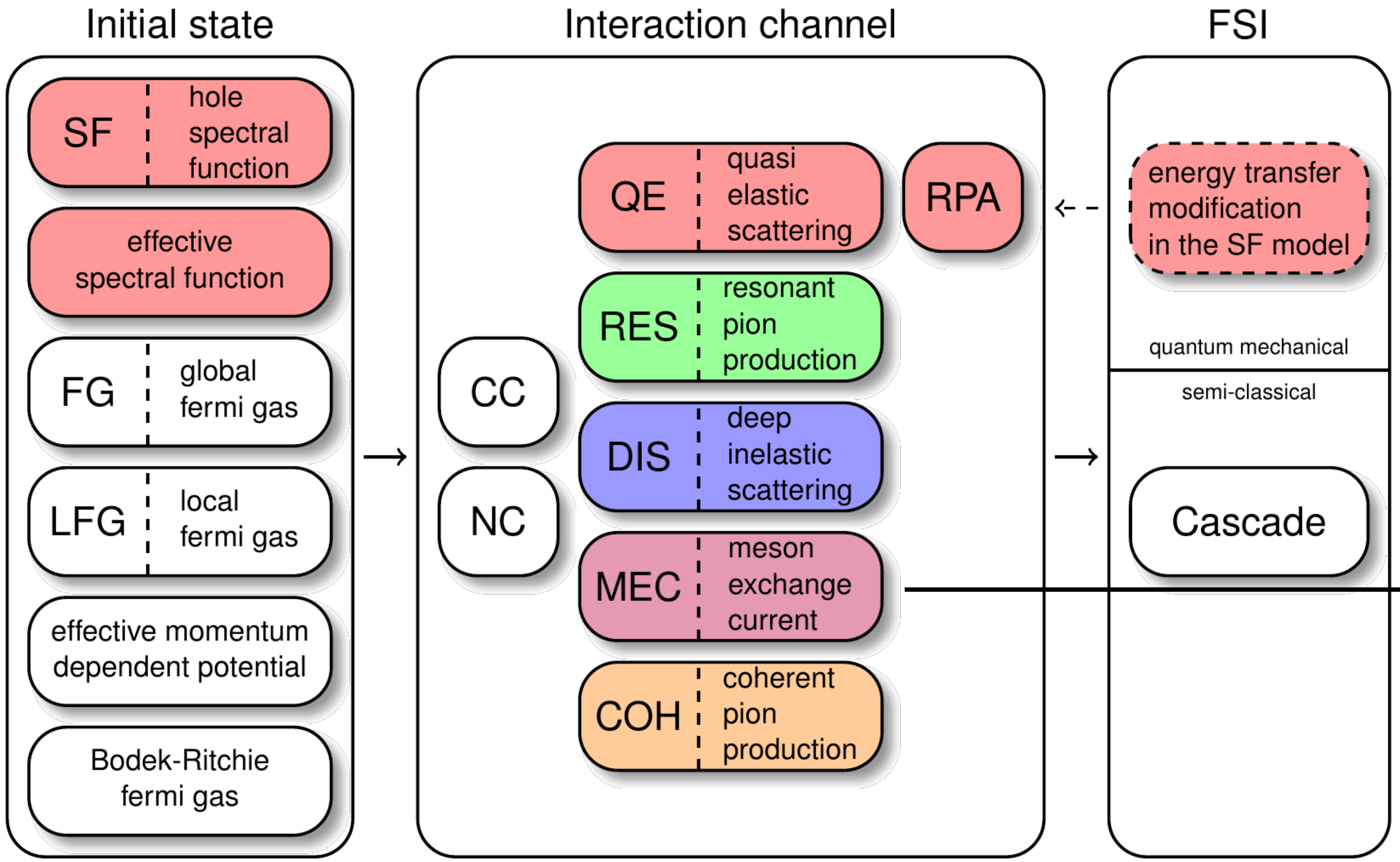


NuWro implementation of MEC models

Schematics of NuWro

Within the context of MEC model



Credit: Kajetan Niewczas

MEC

1. Inclusive part

   computation of lepton kinematics and double differential cross section in (q, ω).

2. Exclusive part

   a. *Deciding the isospins of outgoing nucleons.*

   b. *Simulation of momenta of outgoing nucleons.*

MEC models in NuWro

- Four MEC models are featured in NuWro :
    - Nieves *et al.* model (also referred as Valencia 2012 model).
    - Marteau *et al.* model.
    - SuSAv2 model.
    - Transverse enhancement (TE) model.

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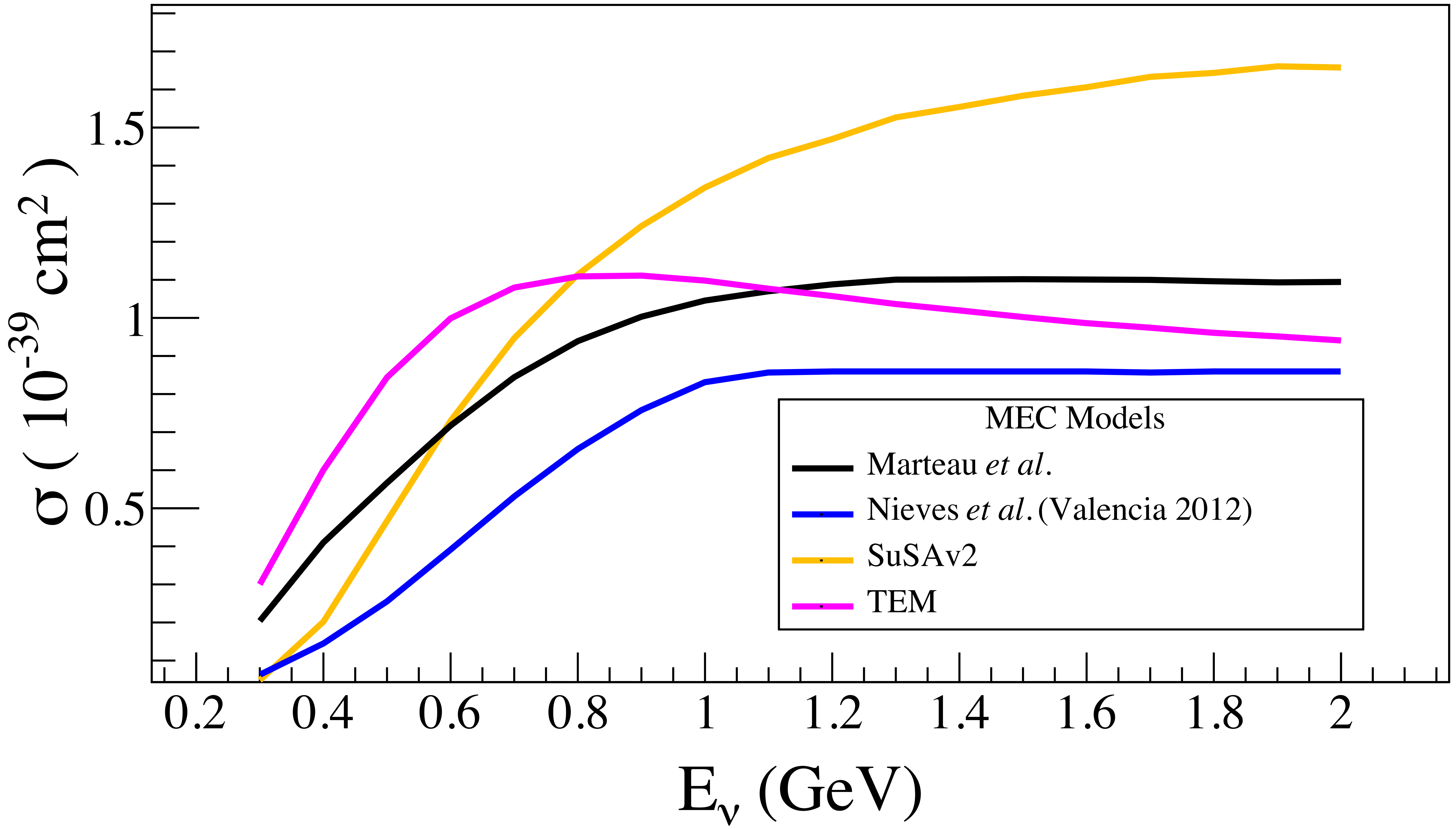

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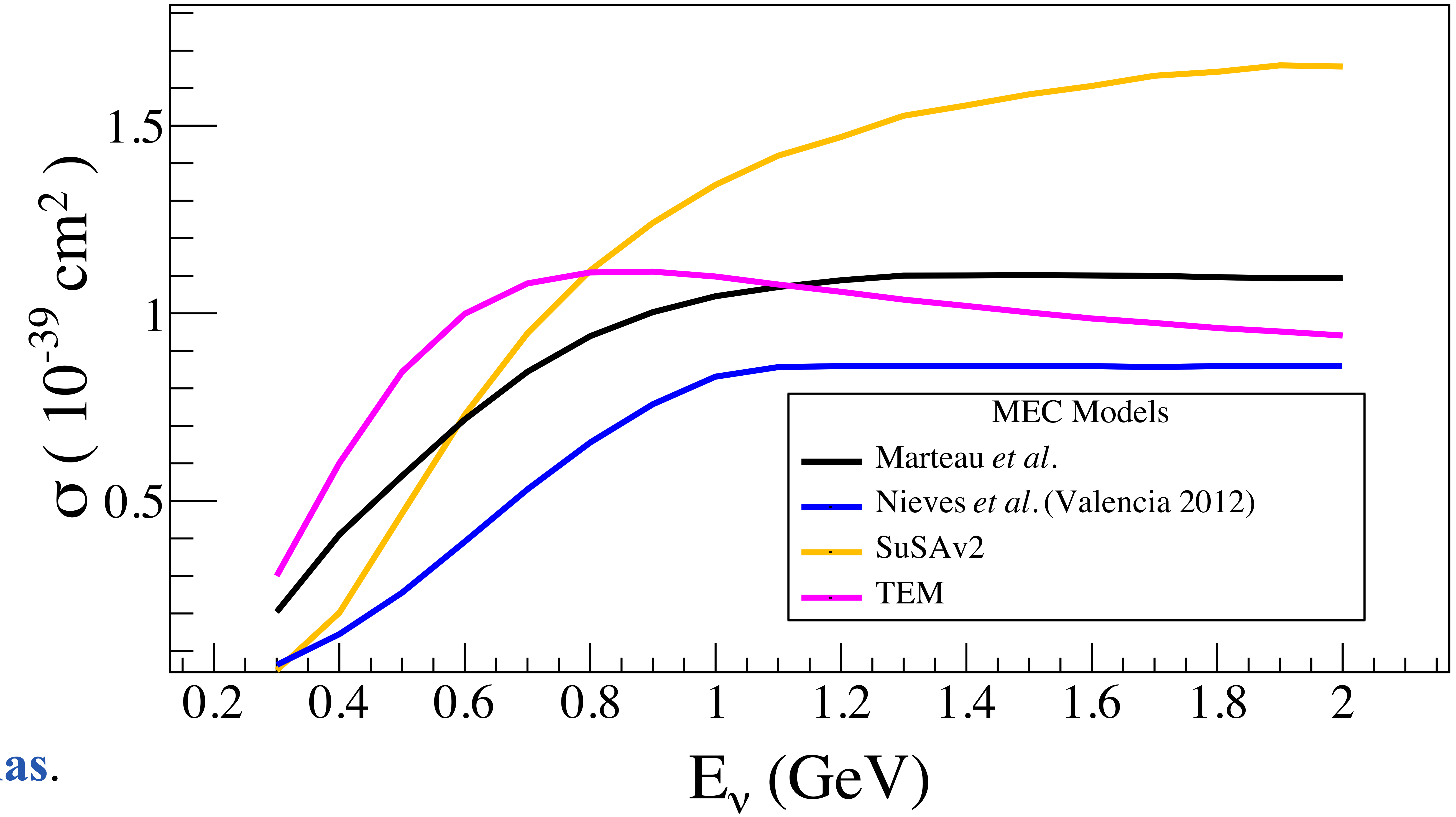

- Their implementation and coverage differs.
  - TE model is implemented with **analytic formulas**.
  - Implementation of Valencia 2012 and SuSav2 models are done using **tabularization of the five response functions** $W^{\mu\nu}(q,\omega)$.
  - Marteau model is implemented in a **hybrid way**.

- The exclusive parts of different MEC models are modelled identically, referred to as the "**old hadronic model**".

Implementation of MEC models

Within the context of Nieves *et al.* (Valencia 2012) model

What we need is : $$\frac{d^8\sigma}{dE_l' d\Omega(\hat{\mathbf{k}}) d\mathbf{p}_1 d\mathbf{p}_2}$$

Theoretical MEC models only predicts : $$\frac{d^2\sigma}{dE_l' d\Omega(\hat{\mathbf{k}})}$$

So it is then necessary to develop tools to produce complete events for given values for specific energy-momentum transfer by **assigning outgoing nucleons ispospin and momentum.**

Implementation of MEC models

Within the context of Nieves *et al.* (Valencia 2012) model

Input:

Generate valid kinematics

1. Energy-momentum transfer.
2. Lepton kinematics.

Grids corresponding to 2p2h only

Input:

$\{W_i\}_{i=1}^{5}$

Produce double differential cross-section

$$\frac{d^2\sigma}{dq\,d\omega}$$

Differential cross section Corresponding to 2p2h.

$$\begin{aligned}\frac{d^2\sigma}{dE_l'\,d\cos\theta_l} = {} & \frac{2G_F^2\cos^2\theta_c E_l'|\mathbf{k}'|}{\pi}\Bigg\{2W_1\sin^2\frac{\theta_l}{2} + W_2\cos^2\frac{\theta_l}{2} \pm W_3(E+E_l')\sin^2\frac{\theta_l}{2} \\ & + \frac{m_l^2}{(E_l'+|\mathbf{k}'|)E_l'}\cdot\Bigg[W_1\cos\theta_l - \frac{W_2}{2}\cos\theta_l \pm \frac{W_3}{2}\left(E_l'(1-\cos\theta_l)+|\mathbf{k}'|-E\cos\theta_l\right) \\ & + \frac{W_4}{2}\left(m_l^2\cos\theta_l + 2E_l'(E_l'+|\mathbf{k}'|)\sin^2\theta_l\right) - \frac{W_5}{5}(E_l'+|\mathbf{k}'|)\Bigg]\Bigg\}\end{aligned}$$

Generate outgoing nucleons

Compute event weight

Store the event

H. Prasad *et al.* arXiv:2501.11470v1

Implementation of MEC models

Within the context of Nieves *et al.* (Valencia 2012) model

H. Prasad *et al.* arXiv:2501.11470v1

Implementation of MEC models

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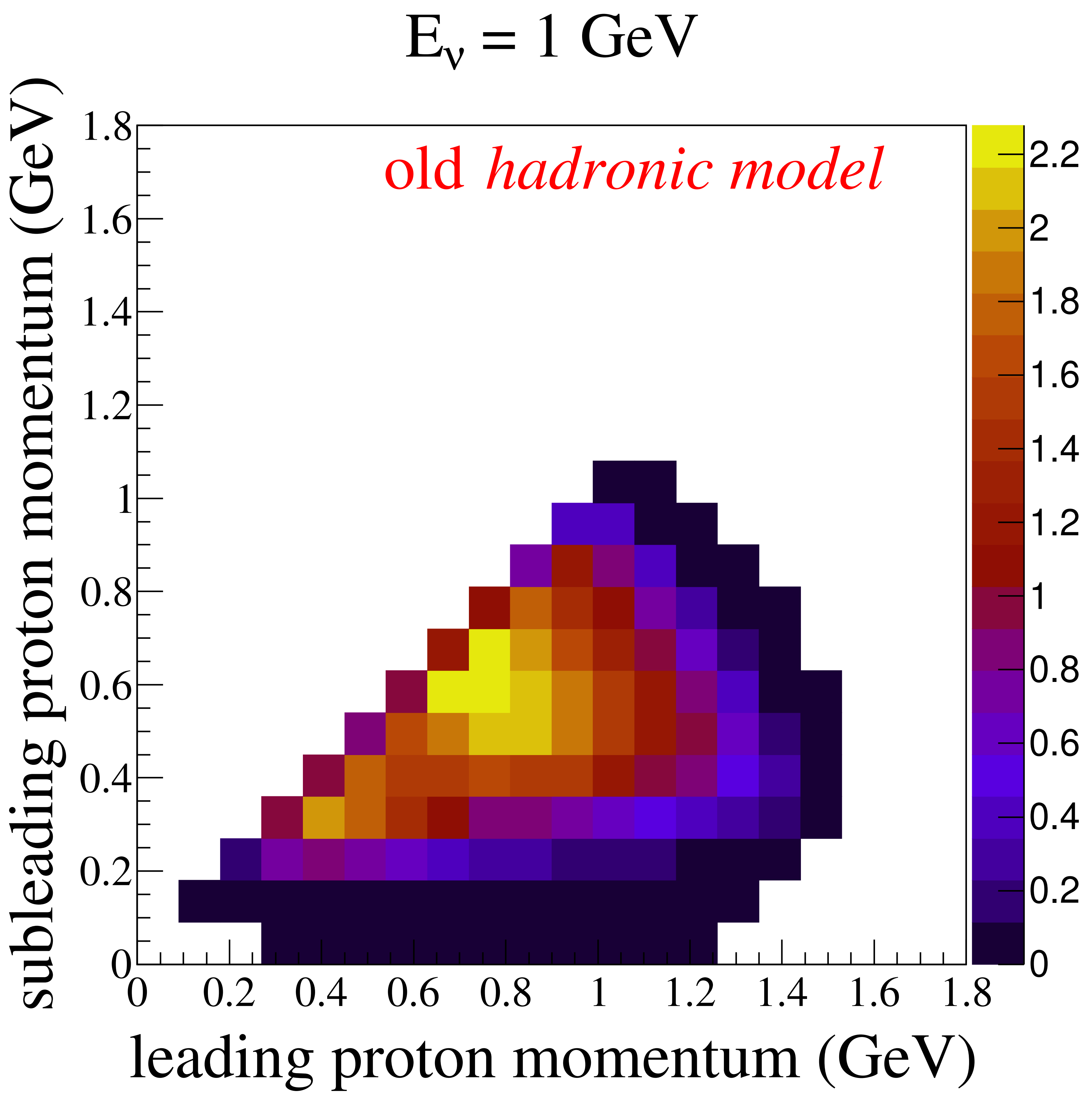
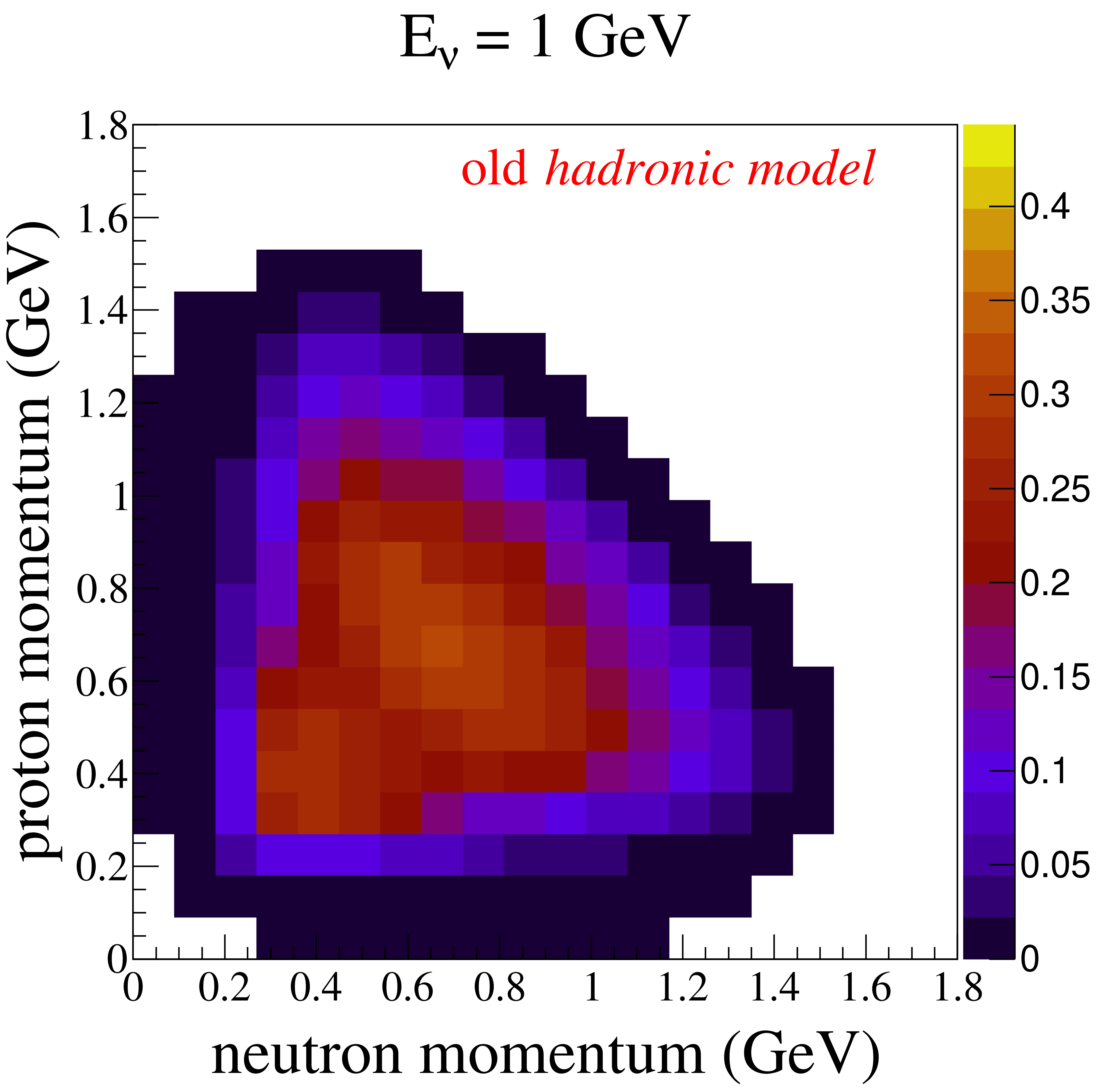




New implementation of MEC models

Within the context of 2020 Valencia model

Input: E_ν

Generate valid kinematics

1. Energy-momentum transfer.
2. Lepton kinematics.

Input:
Four-sets of hadronic tables
$\{W_i\}_{i=1}^{5}$

Grids corresponding to pp, np, pn, and 3p3h

Produce double differential cross-sections

$$\left.\frac{d^2\sigma}{dq\,d\omega}\right|_{pp} \quad \left.\frac{d^2\sigma}{dq\,d\omega}\right|_{np} \quad \left.\frac{d^2\sigma}{dq\,d\omega}\right|_{pn} \qquad \left.\frac{d^2\sigma}{dq\,d\omega}\right|_{3p3h}$$

$$\frac{d^2\sigma}{dE_l'\,d\cos\theta_l} = \frac{2G_F^2\cos^2\theta_c E_l'|\mathbf{k}'|}{\pi}\Bigg\{2W_1\sin^2\frac{\theta_l}{2} + W_2\cos^2\frac{\theta_l}{2} \pm W_3(E+E_l')\sin^2\frac{\theta_l}{2} + \frac{m_l^2}{(E_l'+|\mathbf{k}'|)E_l'}\cdot\Bigg[W_1\cos\theta_l - \frac{W_2}{2}\cos\theta_l \pm \frac{W_3}{2}\left(E_l'(1-\cos\theta_l)+|\mathbf{k}'|-E\cos\theta_l\right) + \frac{W_4}{2}(m_l^2\cos\theta_l + 2E_l'(E_l'+|\mathbf{k}'|)\sin^2\theta_l) - \frac{W_5}{5}(E_l'+|\mathbf{k}'|)\Bigg]\Bigg\}$$

Generate outgoing nucleons

Compute event weight

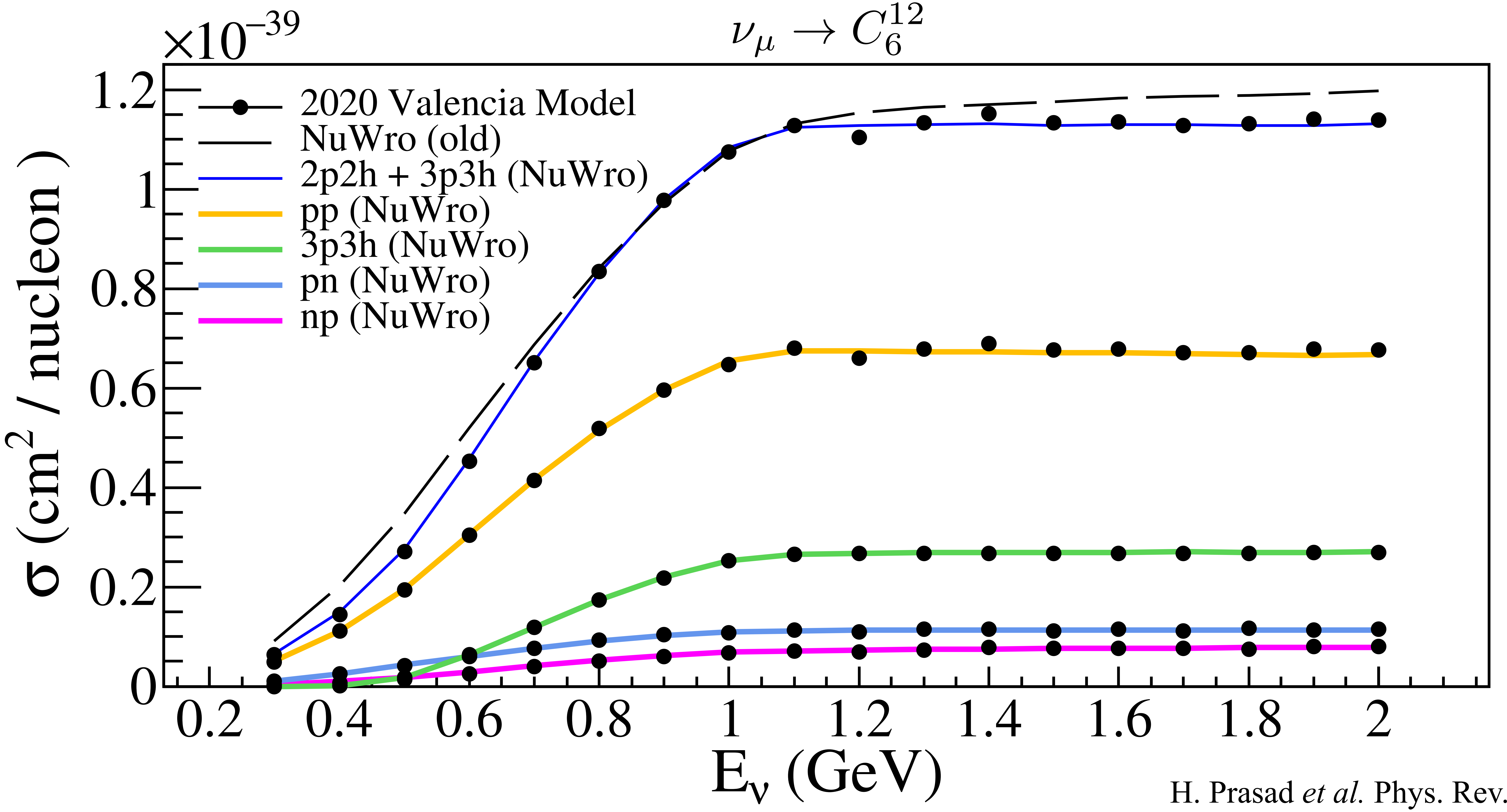
Weight 2p2h + weight 3p3h

Store the event

H. Prasad *et al.* arXiv:2501.11470v1

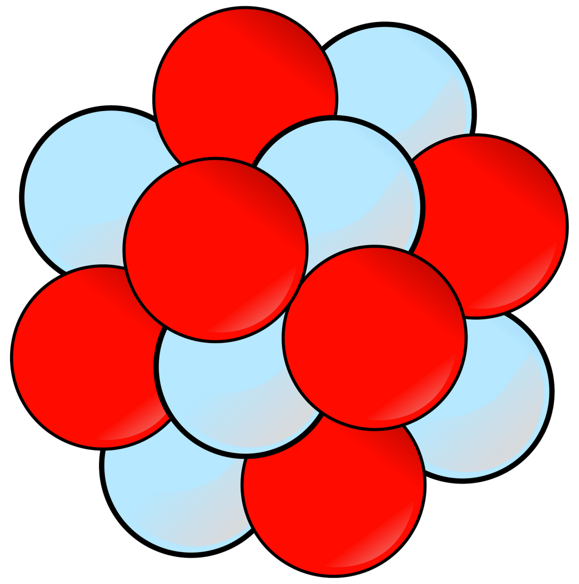
Inclusive part

Nuwro implementation of the 2020 Valencia model



H. Prasad *et al.* Phys. Rev. D 111 (2025) 036032

Hadronic tables



Grids available in NuWro 25.01

- Available hadronic grids for `mec_kind=6`

$$ {}^{12}_{6}\mathrm{C} \quad {}^{16}_{8}\mathrm{O} \quad {}^{40}_{20}\mathrm{Ca} \quad {}^{208}_{82}\mathrm{Pb} $$

- Results I show is for carbon.

New implementation of MEC models

Event topology
1. Determine the event topology either *2p2h* or *3p3h*

If *2p2h*

Else 3p3h → Discussed later

Isospin model
1. Determine the isospin of out-going nucleon pair using the diff. cross-section information (in the MC fashion).

Select interaction point using nuclear density profile

Calculate Fermi momentum at the interaction point

Select initial nucleons
1. Choose momenta values from quradratic probability density function.
2. Direction is chosen uniformly within the unit-sphere (not necessarily back-to-back).

Form a hadronic system

Move to center-of-mass frame

Check
$p^2_{\text{sys}} \geq (m_3 + m_4)^2$

n

y

Distribute the total energy between the two nucleons

Calculate the allowed range of scattering angle for the *backward* nucleon (Pauli blocking)

Set the direction of outgoing nucleon pair
$\cos\theta^*$ sampled according to $f(\cos\theta^*)$
$\phi^* \in [0,2\pi]$ sampled uniformly.

Boost back both nucleons to lab frame

H. Prasad *et al.* arXiv:2501.11470v1

New implementation of MEC models

Within the context of 2020 Valencia model

Event topology

1. Determine the event topology either *2p2h* or *3p3h*

If *3p3h*

Isospin model

1. Determine the isospin of out-going nucleon pair using simple combinatorics

$\binom{Z'}{3}$ ppn $\binom{Z'}{1}\binom{A-Z'}{2}$

ppp $\binom{Z'}{2}\binom{A-Z'}{1}$ pnn

Use phase space model for three-body interaction

$$Z' = Z \pm 1$$

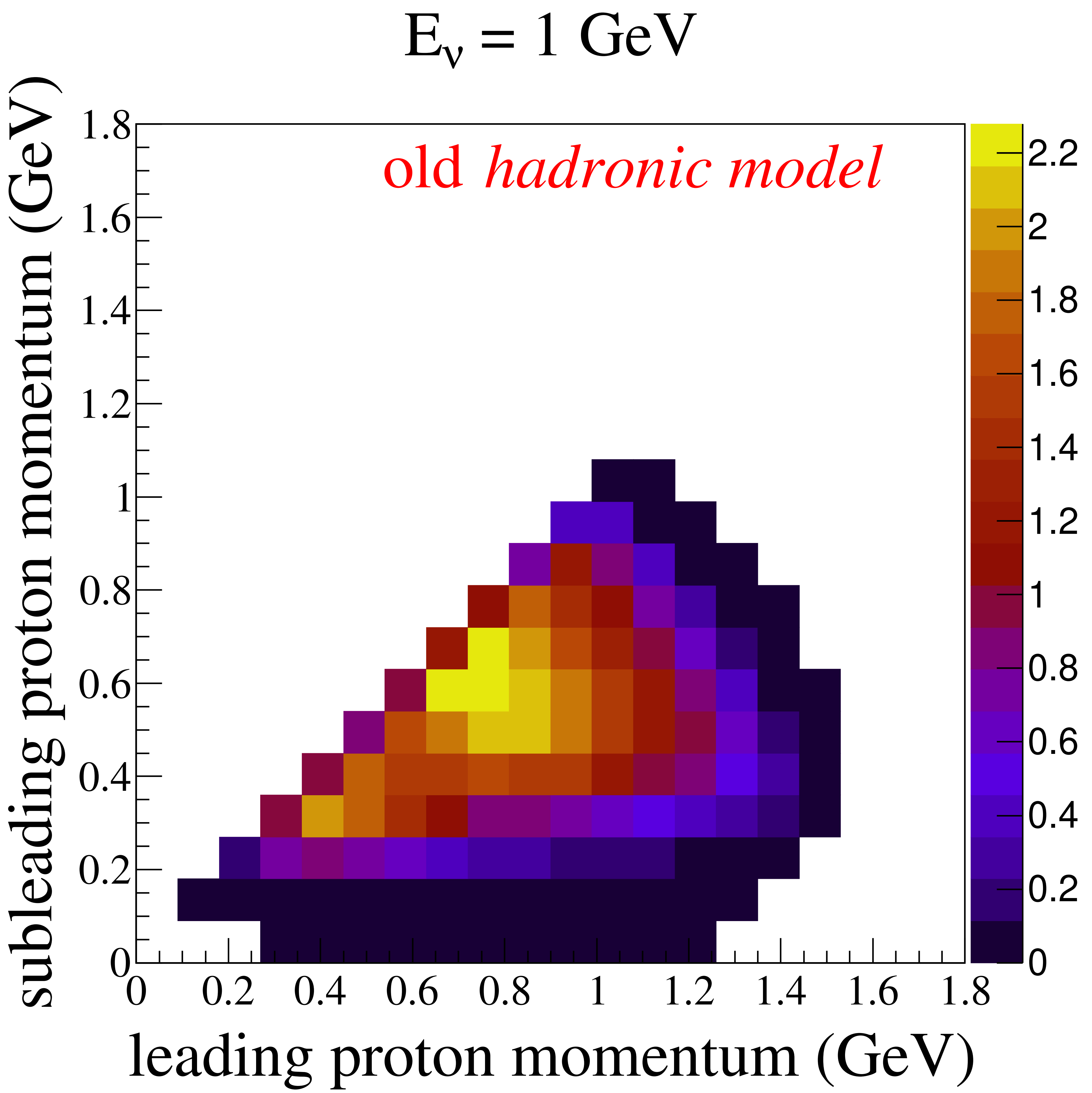
Depending on (anti) neutrino - nucleus interaction

Theory gives no hints so we choose combinatorics for isospin and phase space for momenta !!

H. Prasad *et al.* arXiv:2501.11470v1

Modelling Correlations Between Nucleons

Two protons in final state



Modelling Correlations Between Nucleons

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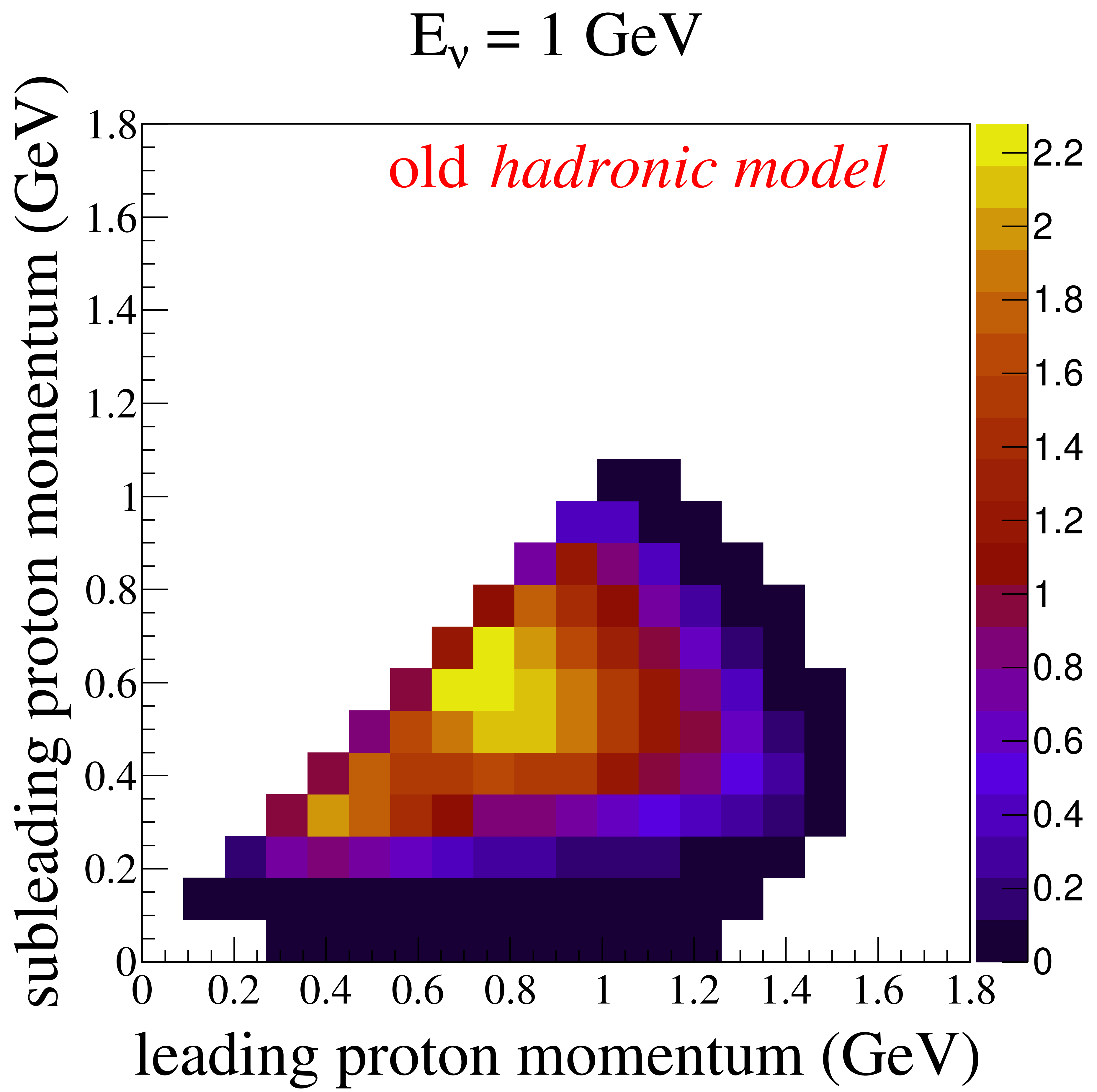

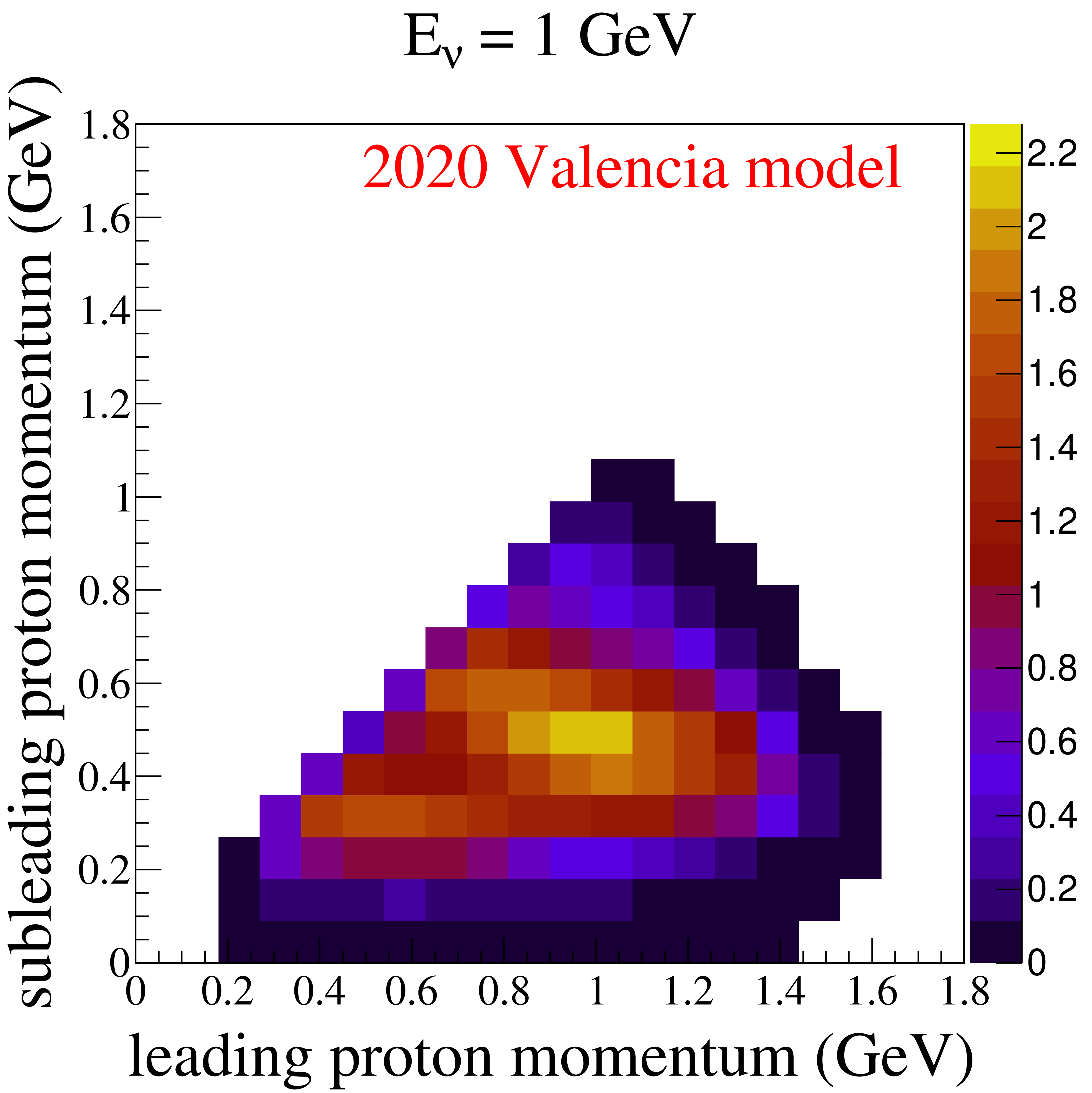

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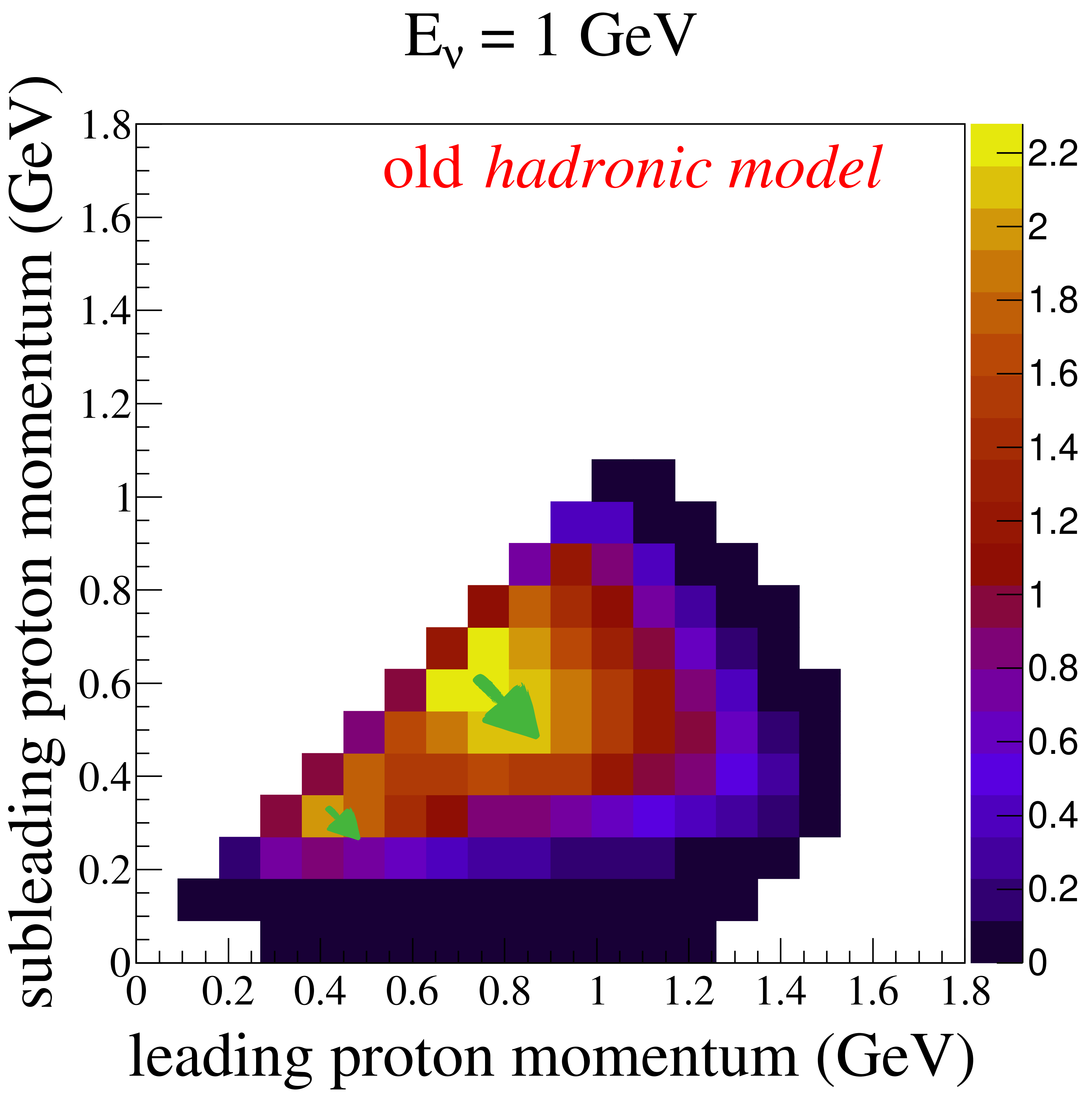

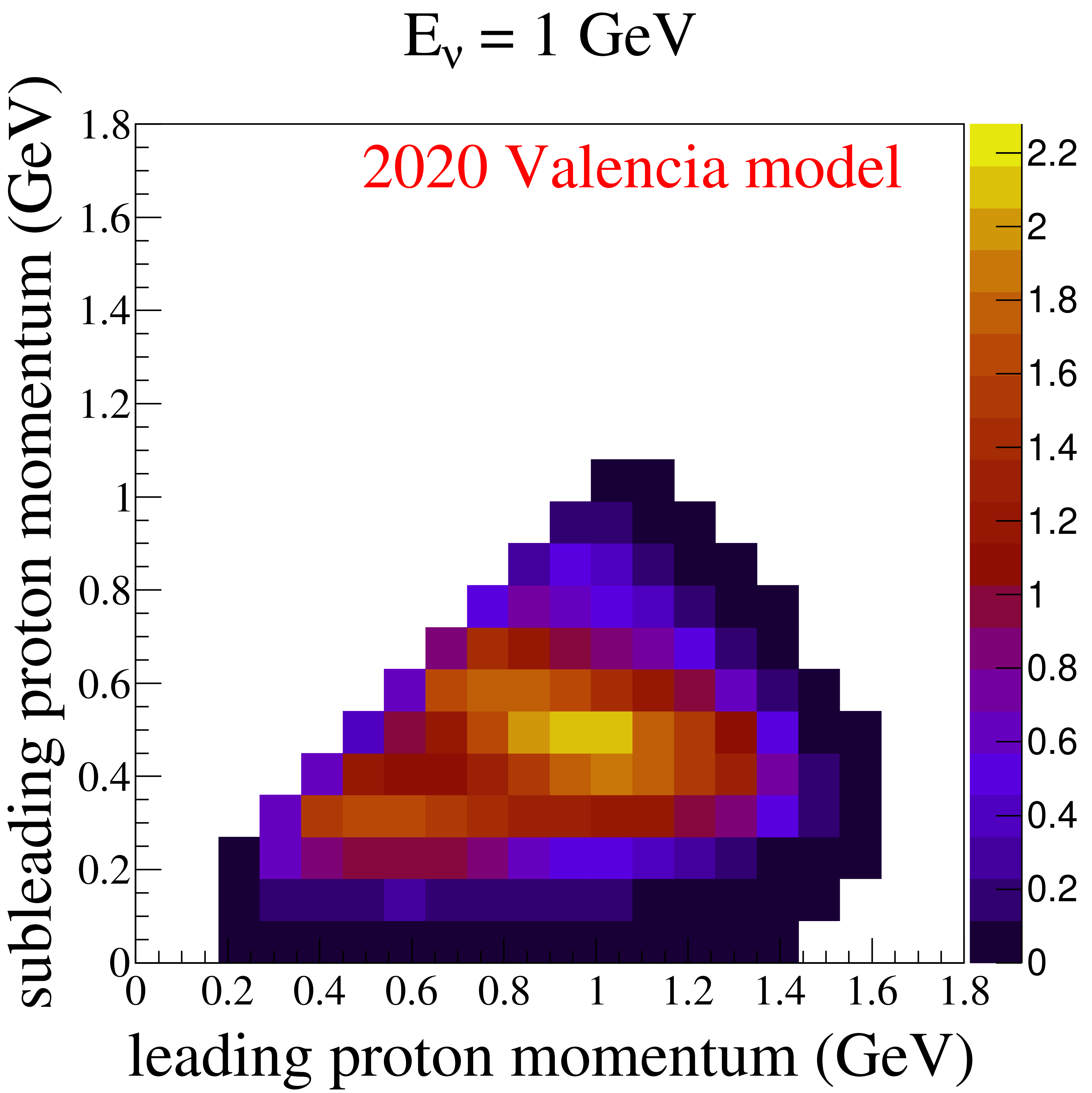

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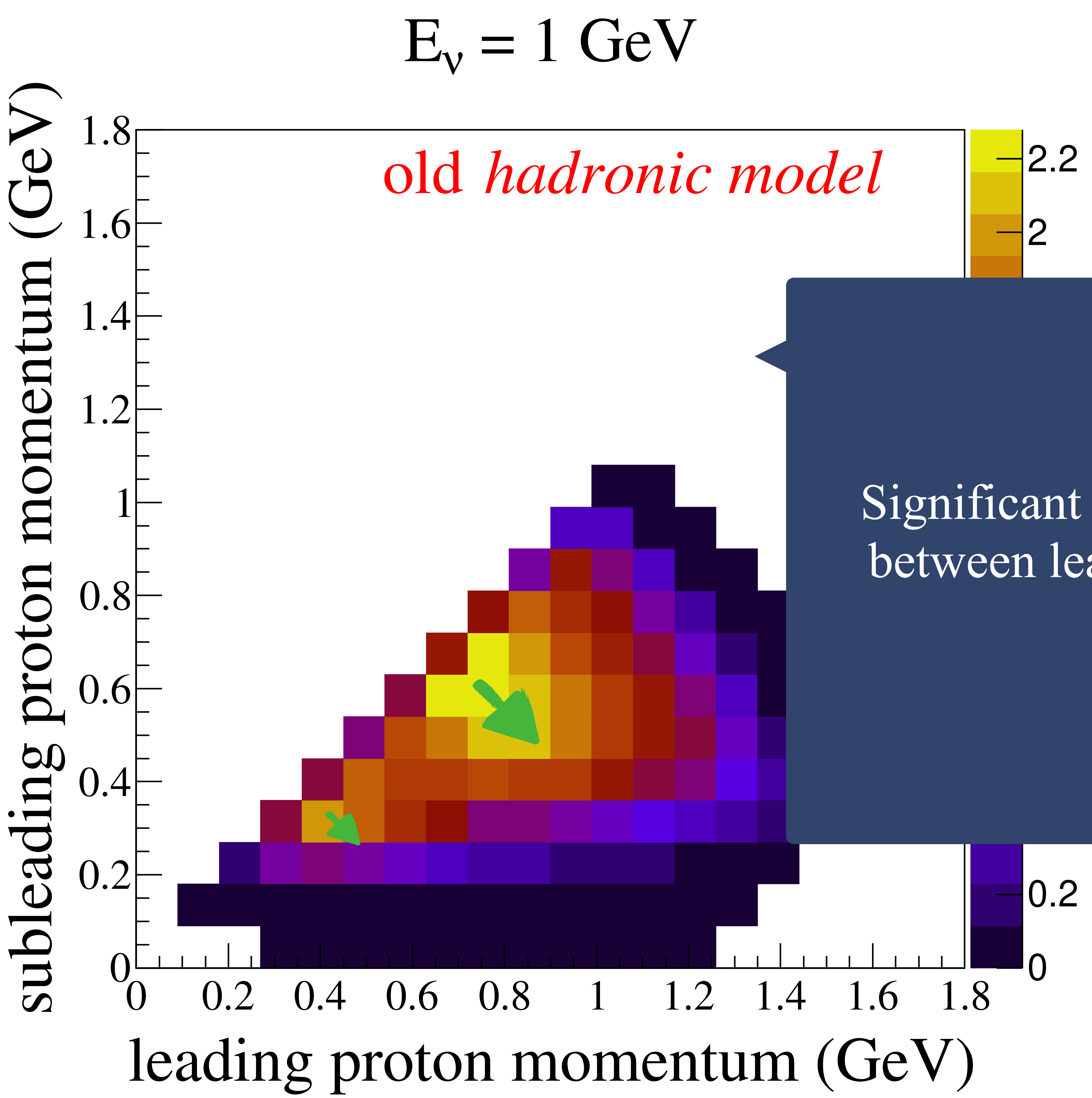
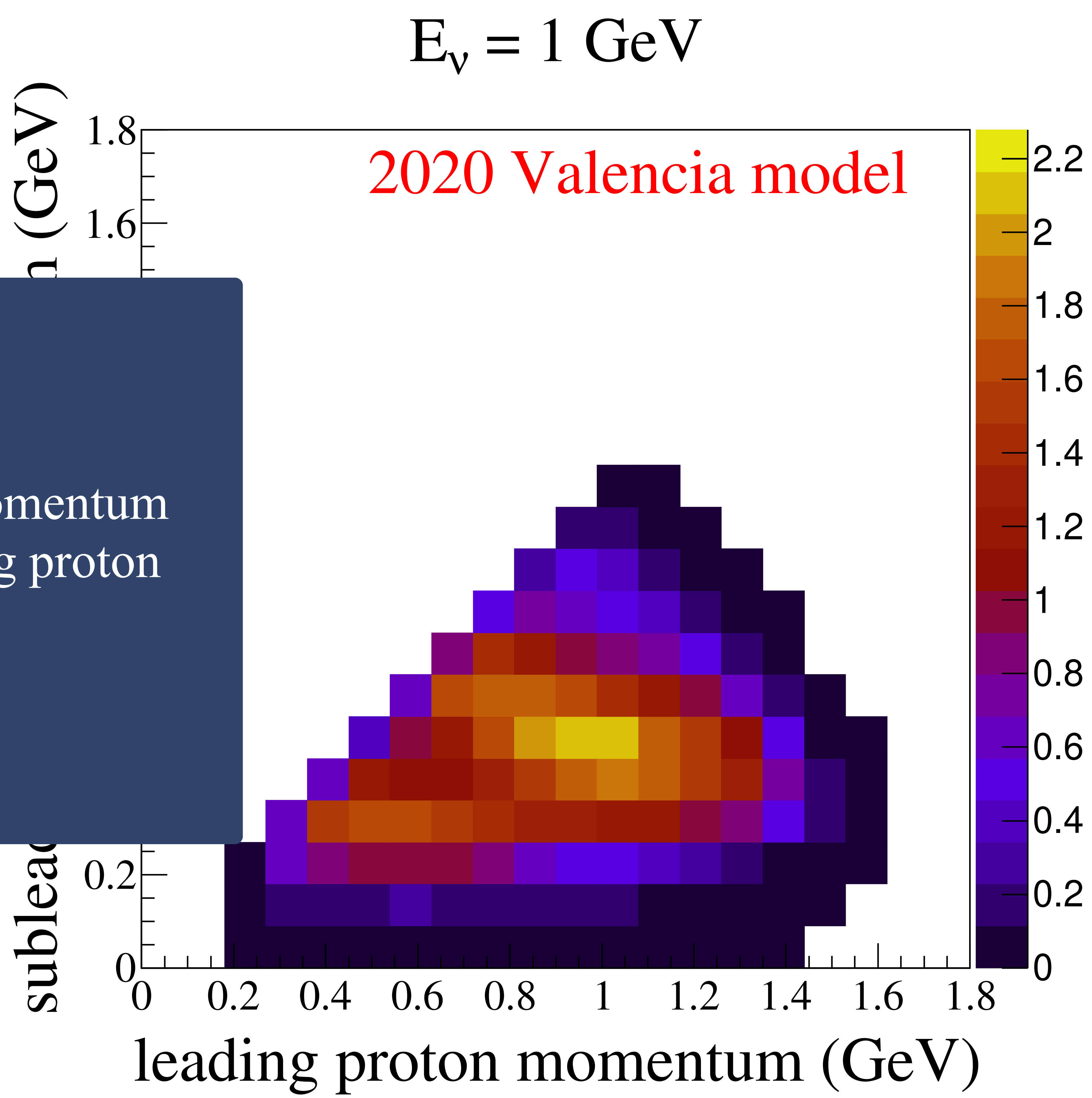


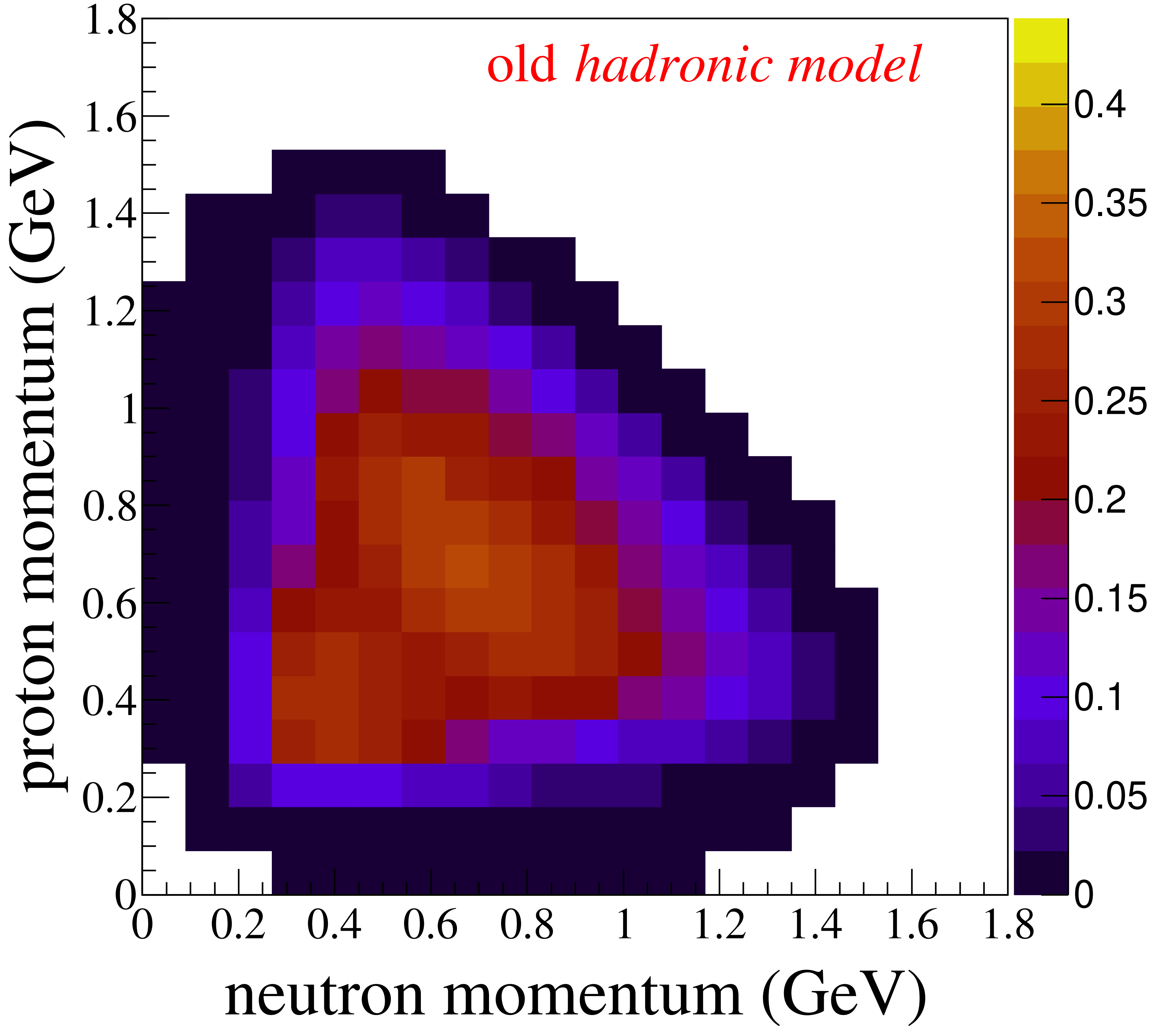
Significant difference in the momentum between leading and subleading proton momentum



Modelling Correlations Between Nucleons

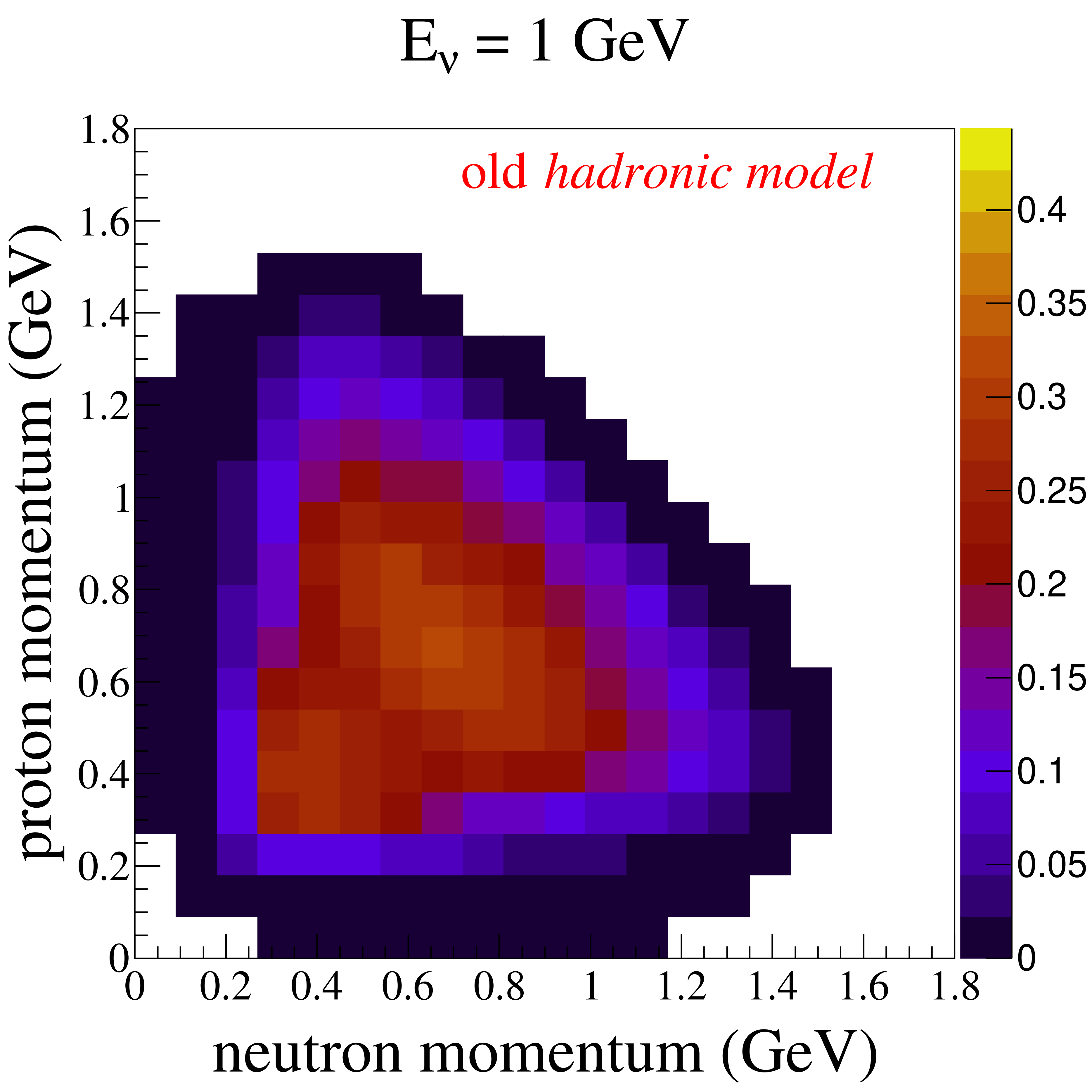
Neutron and a proton in the final state

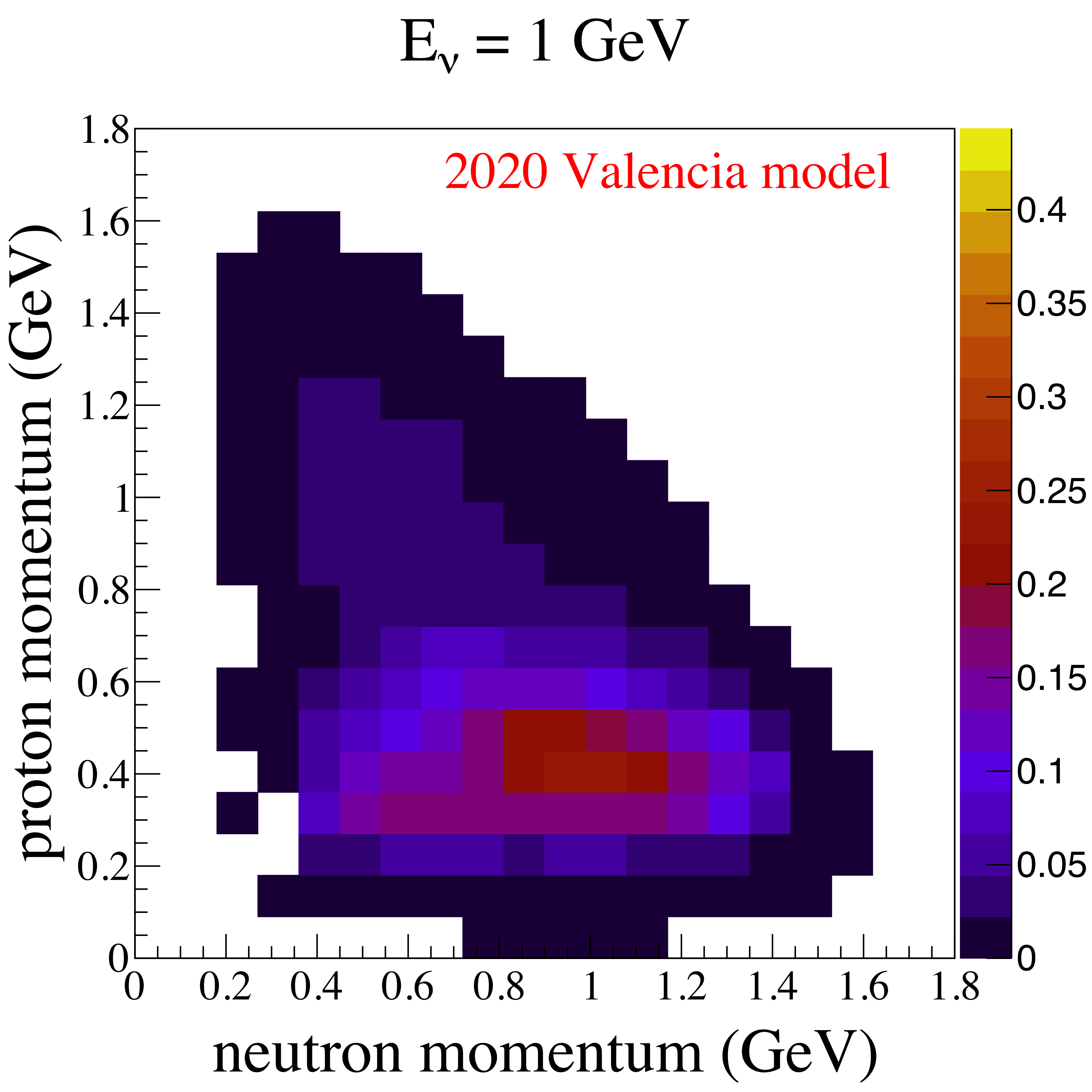
$E_\nu = 1$ GeV



Modelling Correlations Between Nucleons

Neutron and a proton in the final state





Modelling Correlations Between Nucleons

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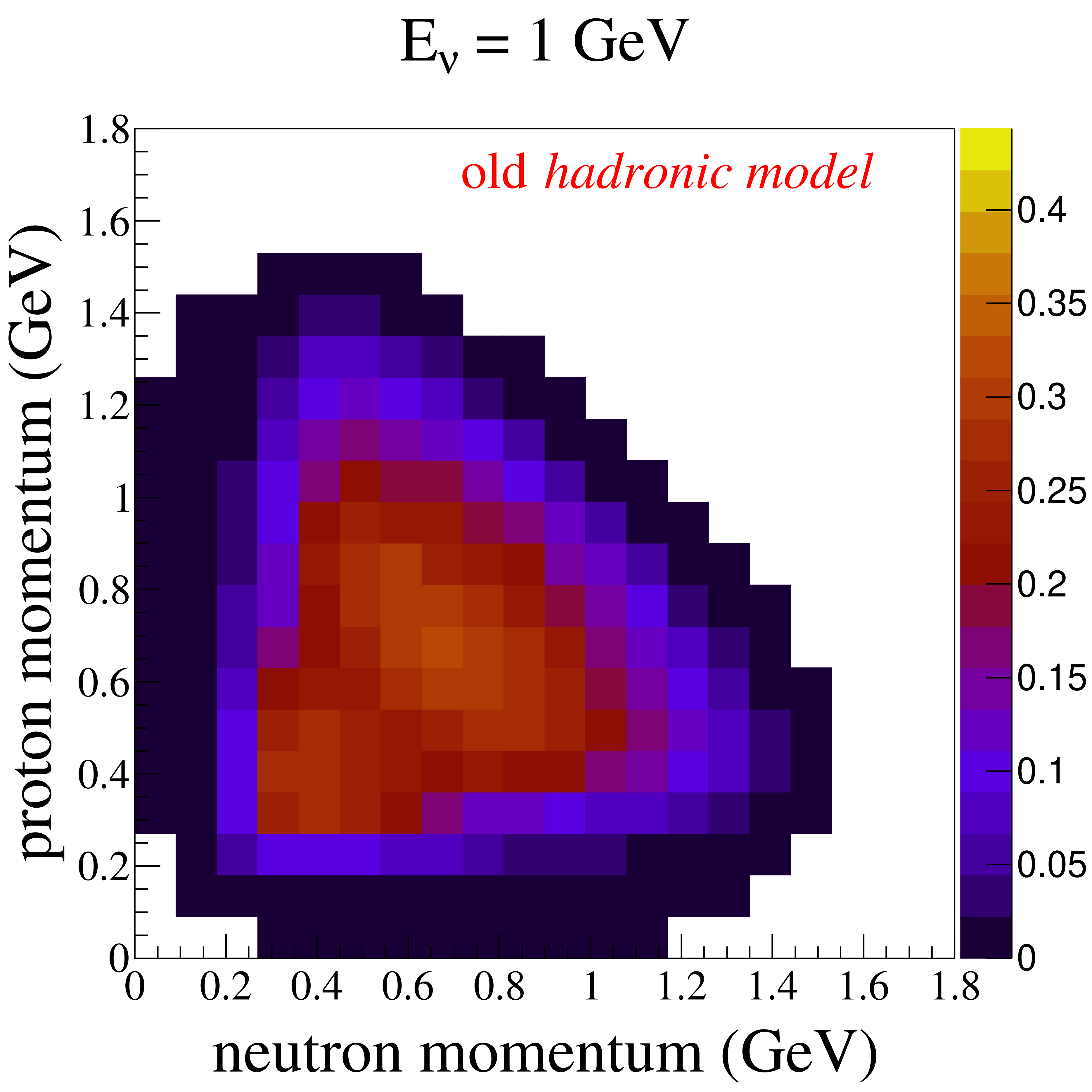

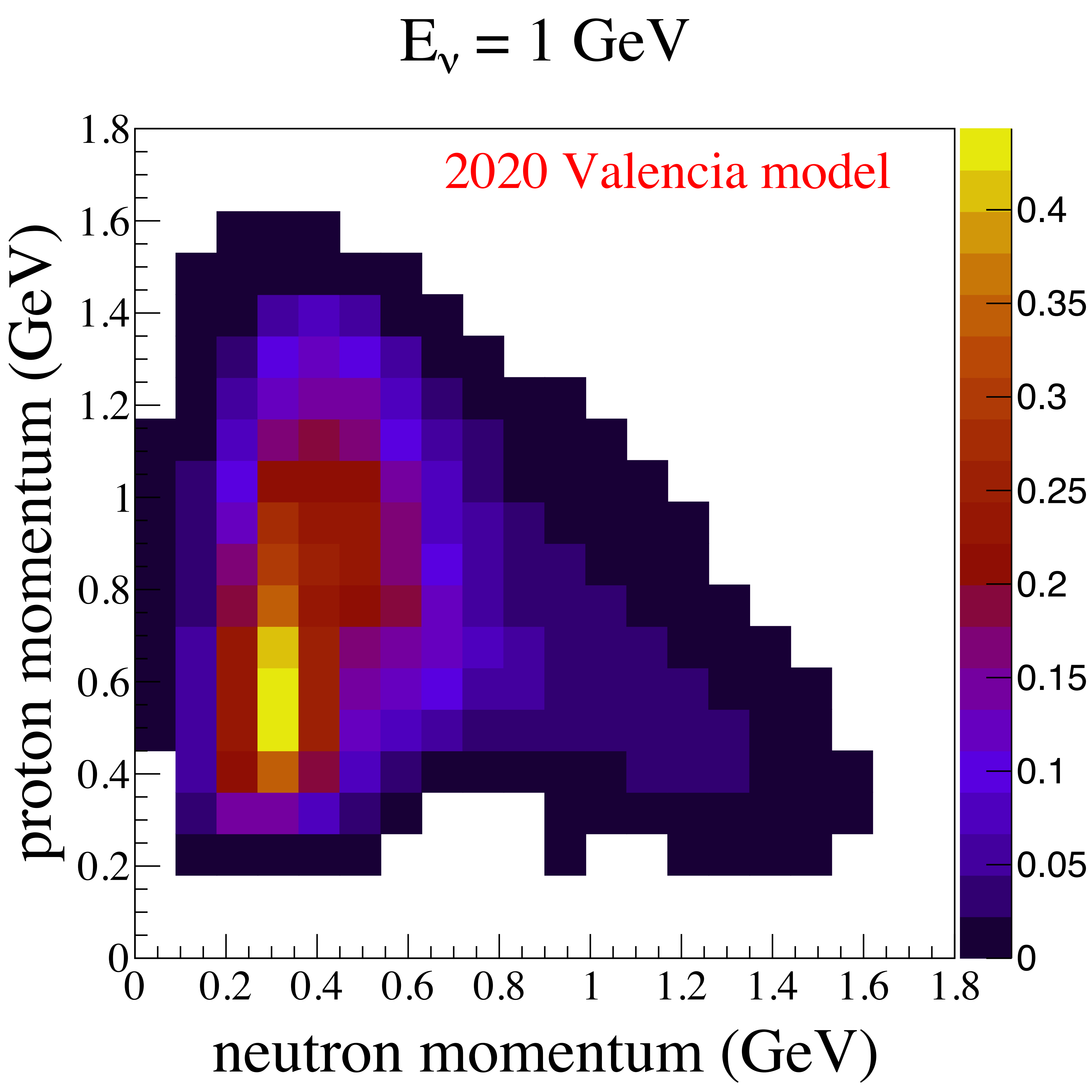

Modelling Correlations Between Nucleons

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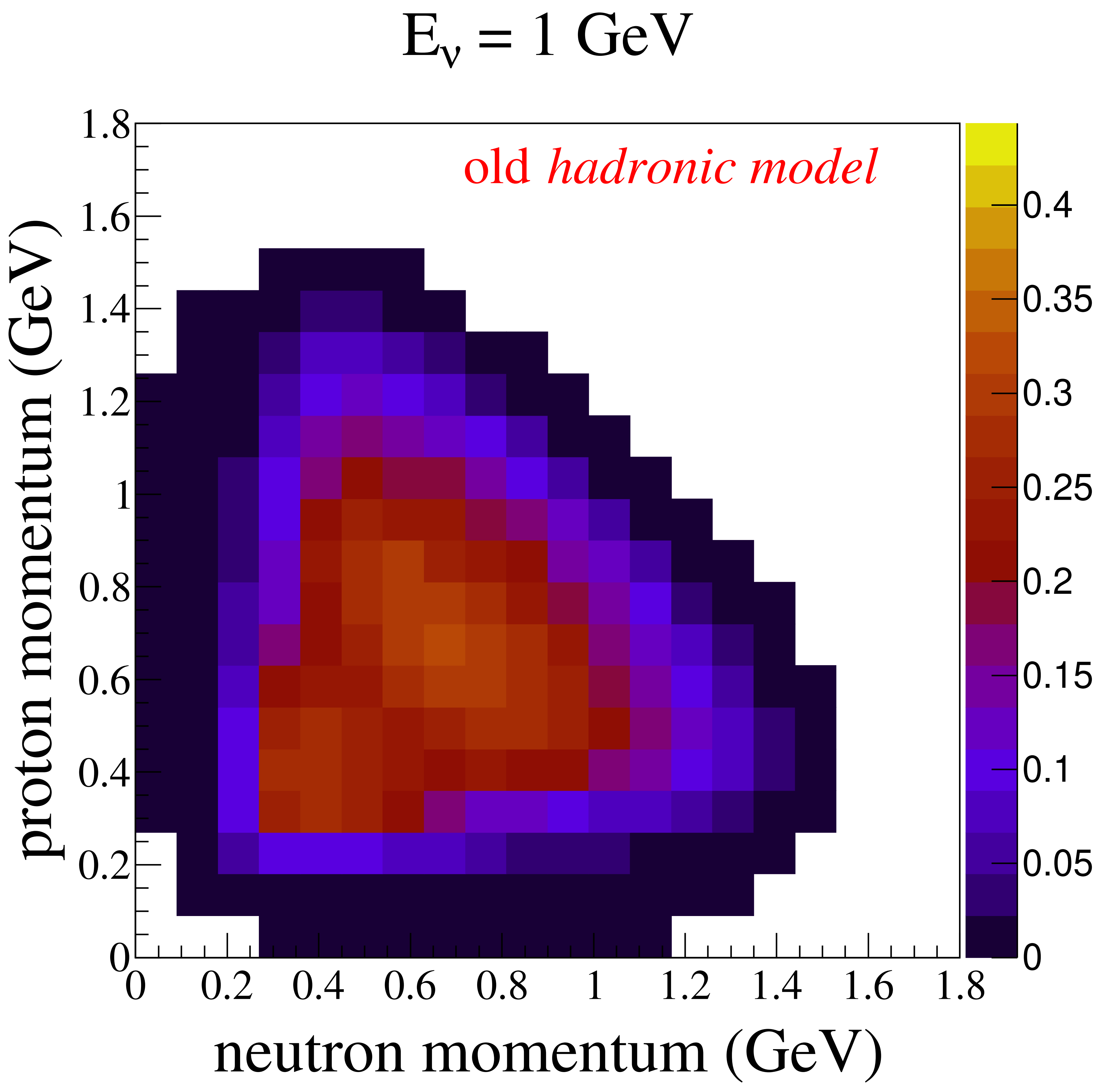

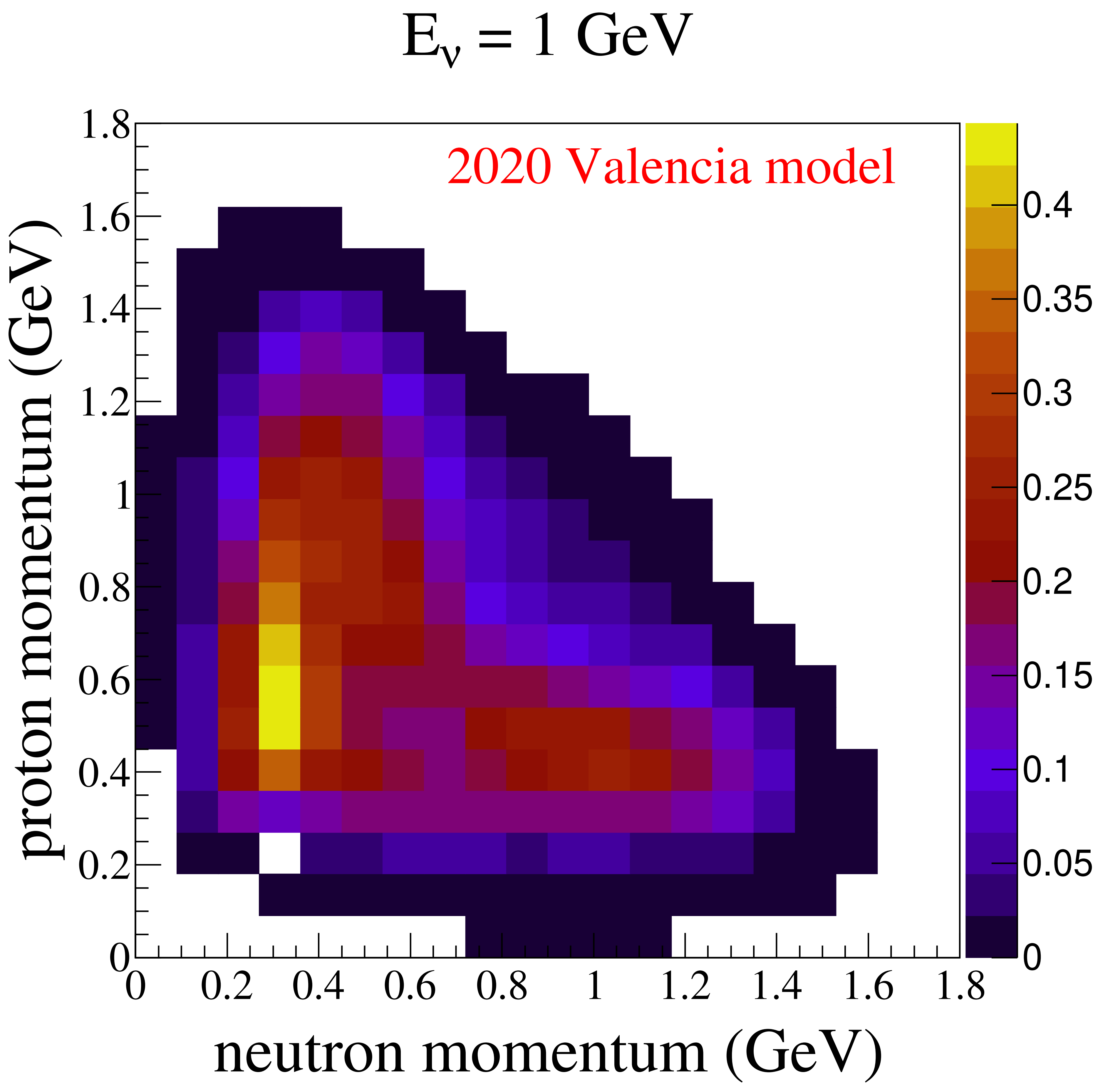

Modelling Correlations Between Nucleons

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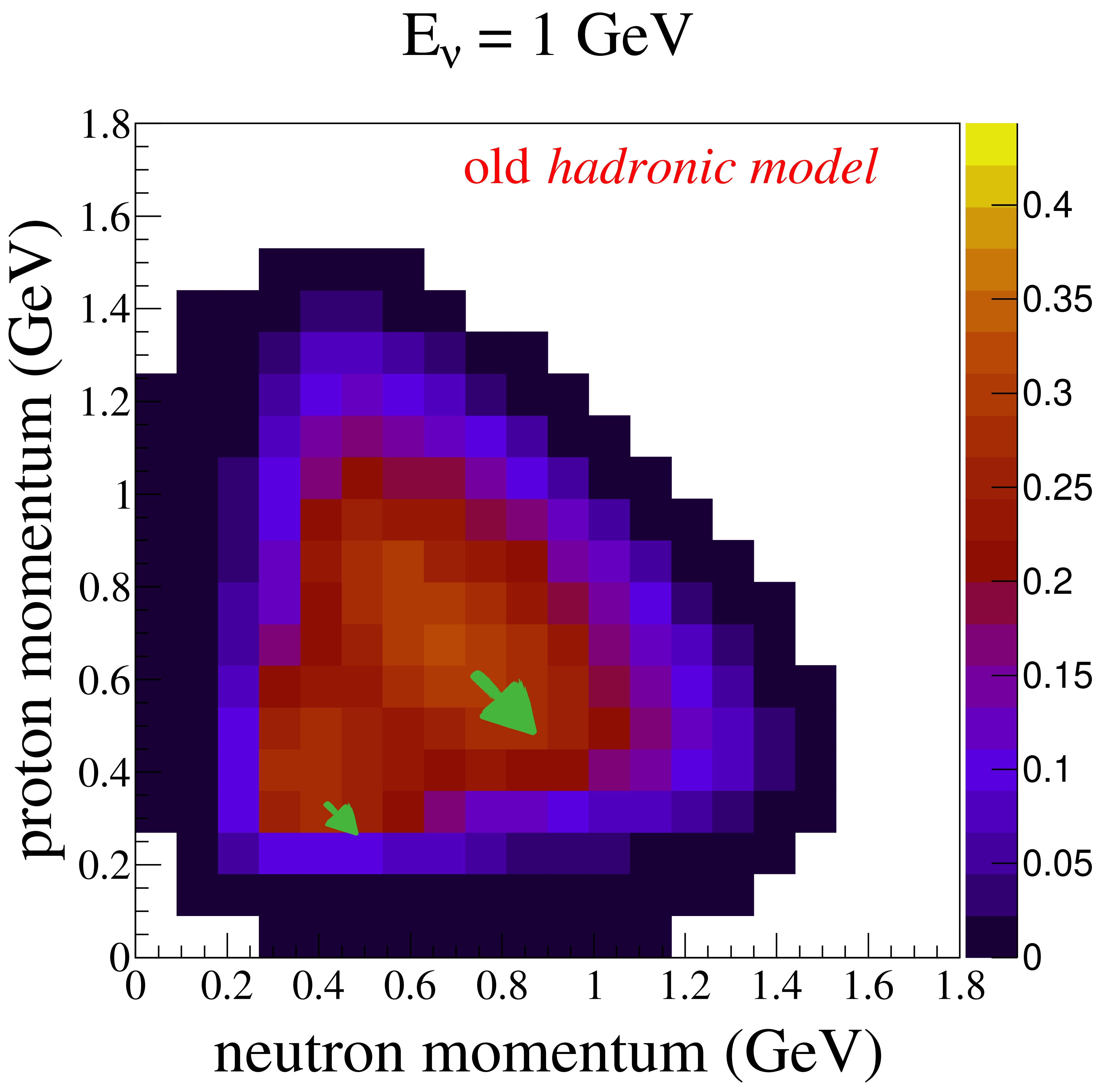

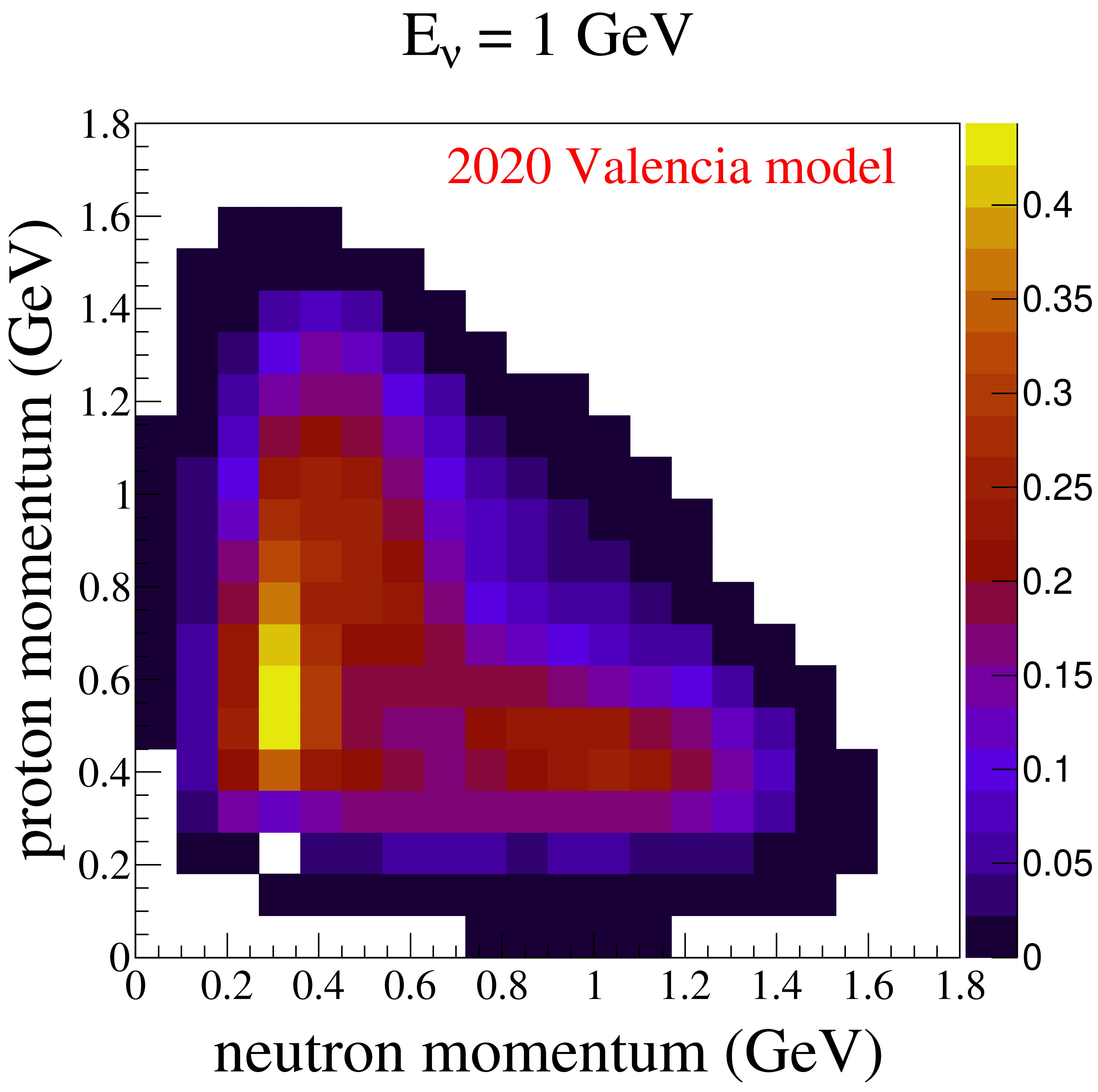

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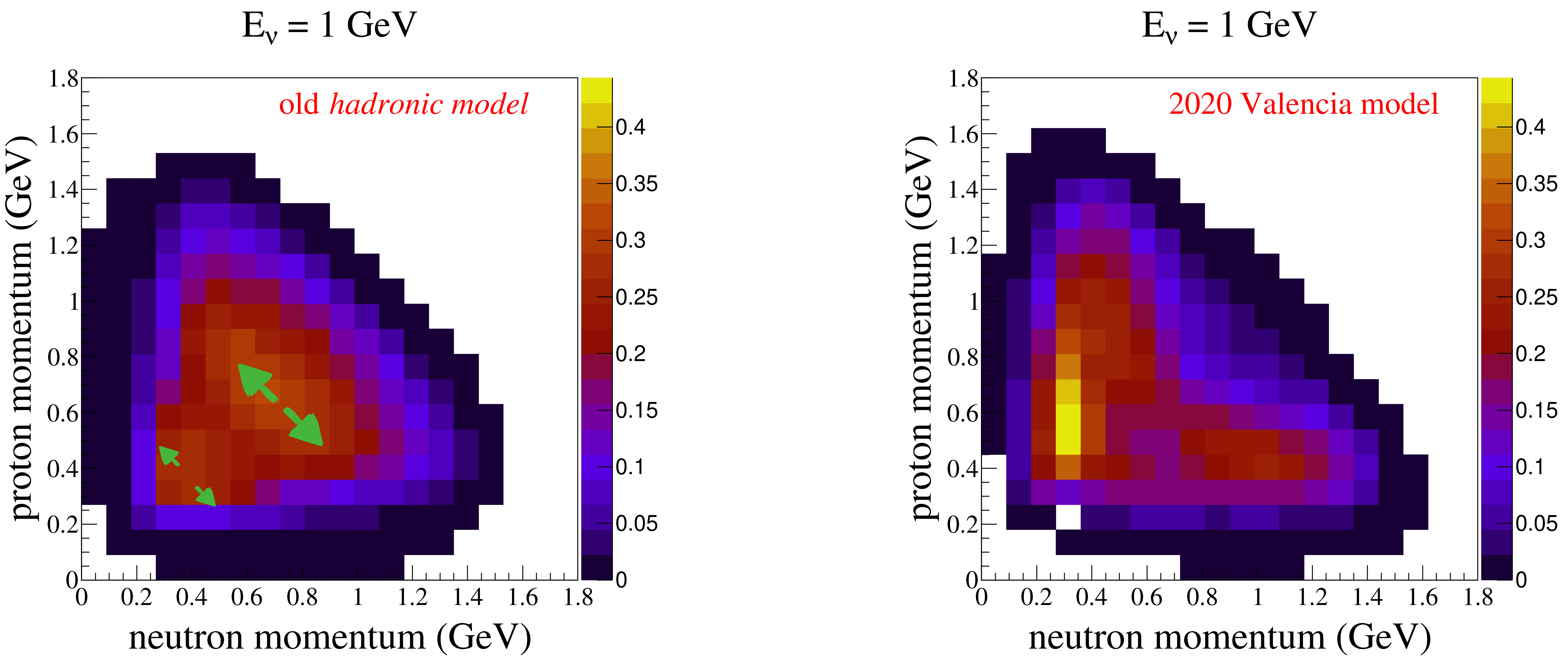

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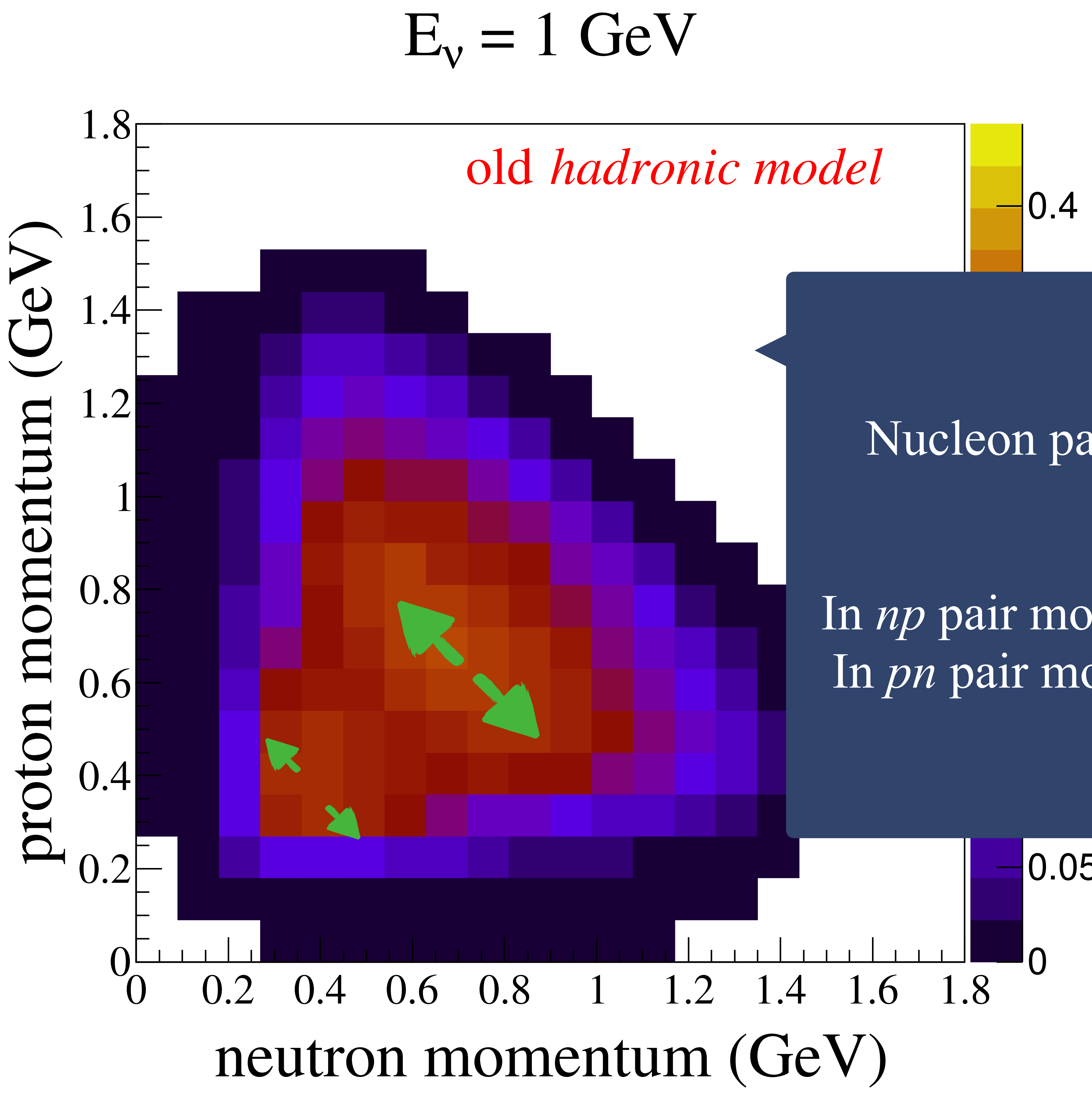
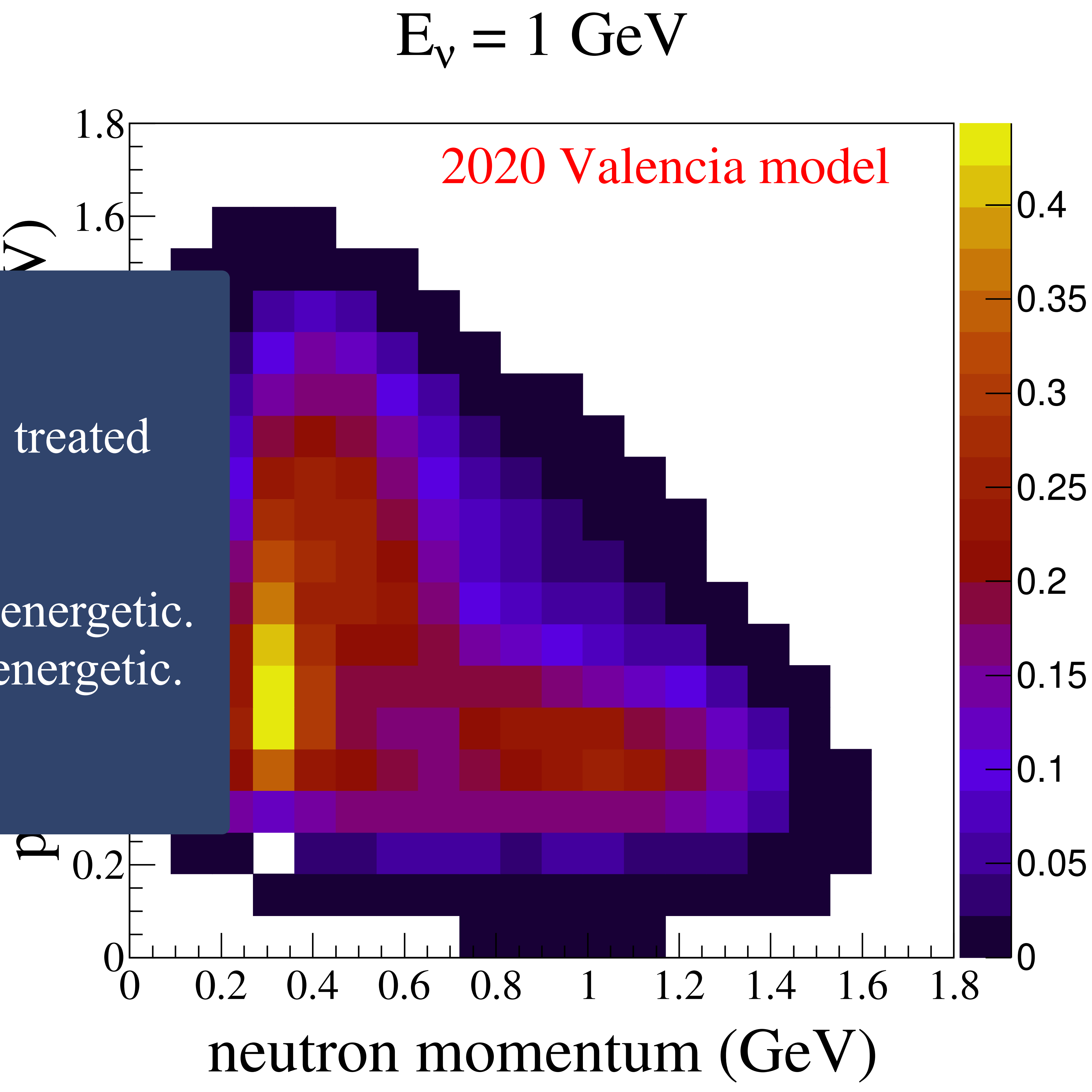




Nucleon pair *np* and *pn* must be treated differently.

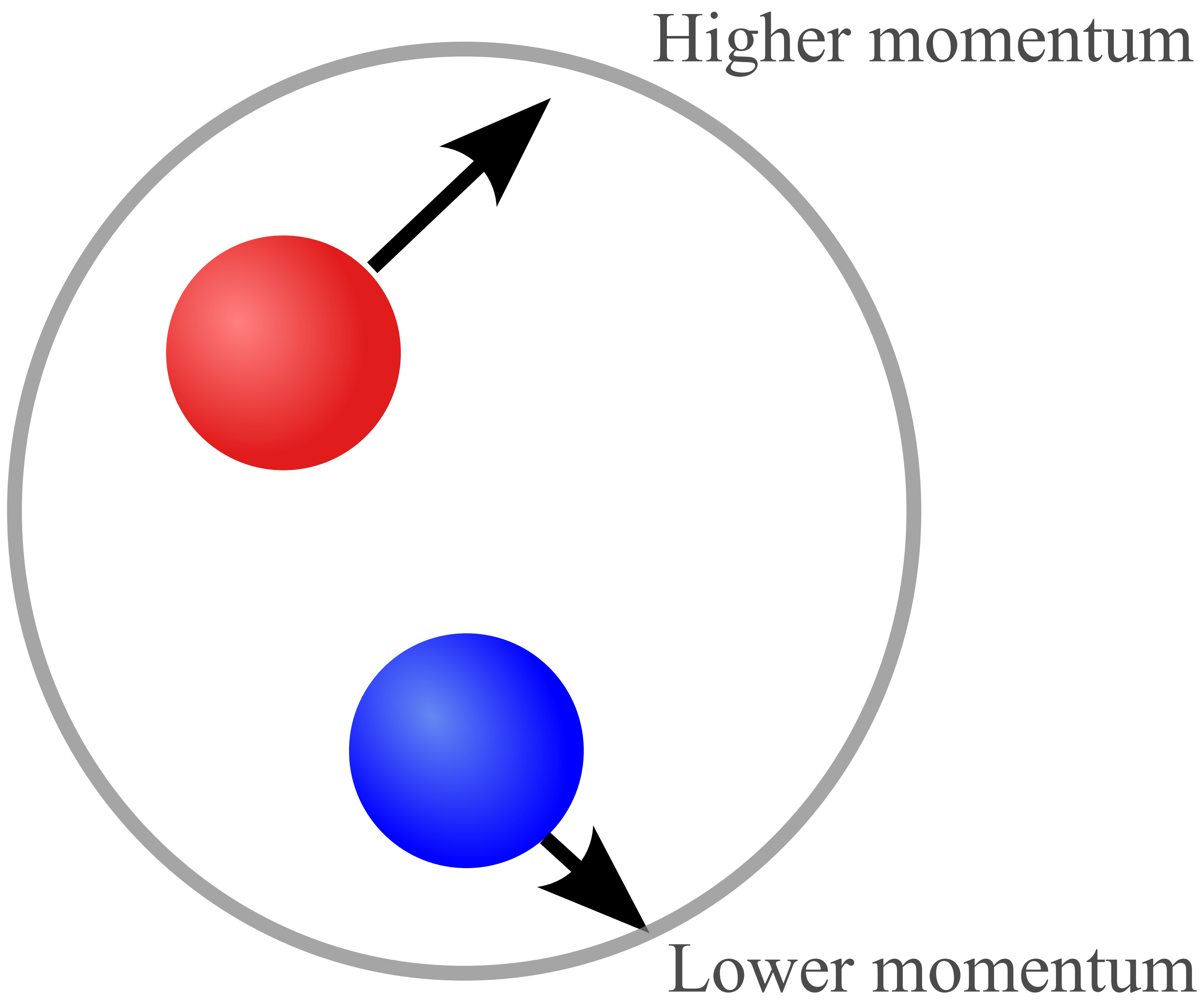
In *np* pair mostly neutron is more energetic.
In *pn* pair mostly proton is more energetic.

Modelling Correlations Between Nucleons

Motivation (for 2p2h only)

Modelling Correlations Between Nucleons

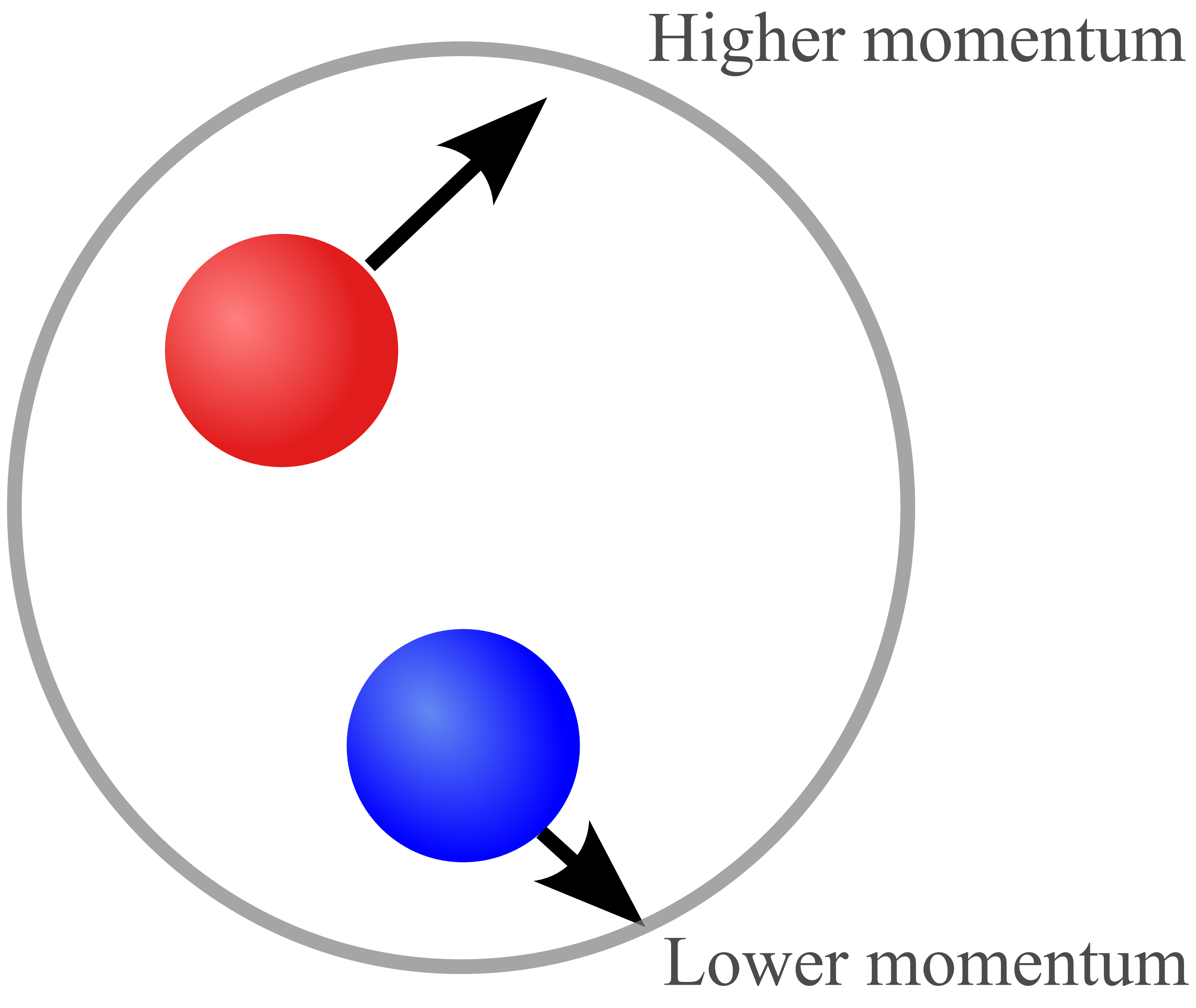
Motivation (for 2p2h only)



Outgoing nucleons (lab frame)

Modelling Correlations Between Nucleons

Motivation (for 2p2h only)

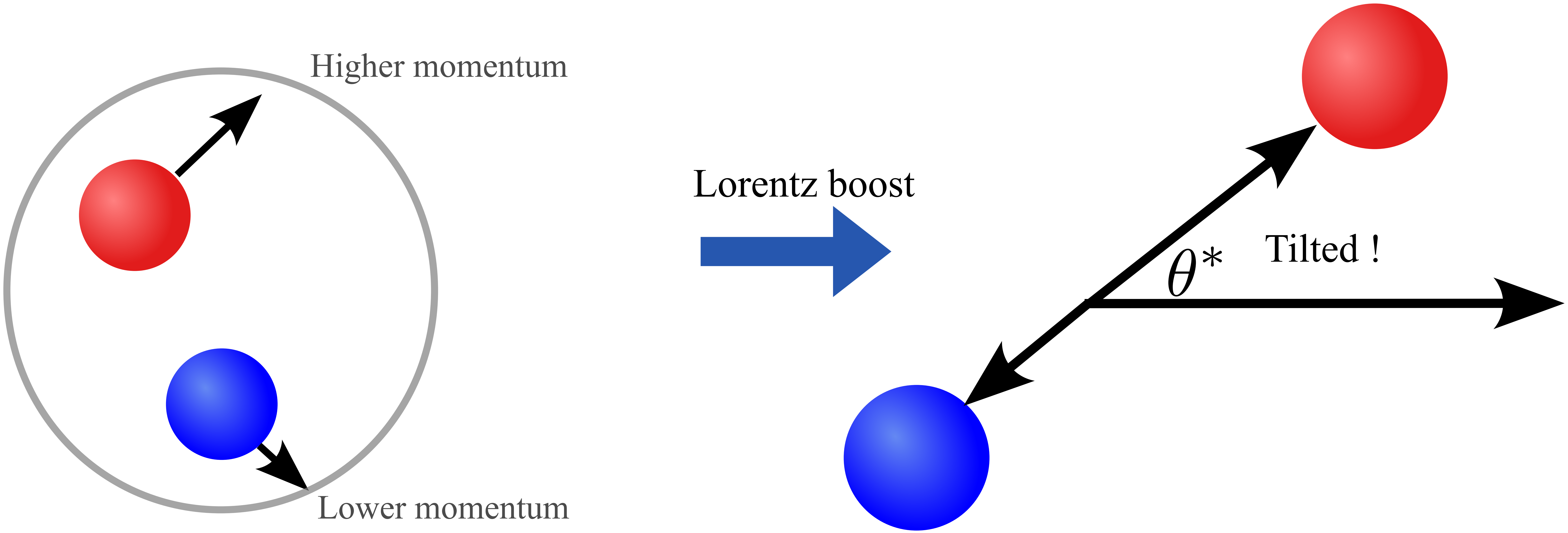


Outgoing nucleons (lab frame)

Lorentz boost

Modelling Correlations Between Nucleons

Motivation (for 2p2h only)



Outgoing nucleons (lab frame)

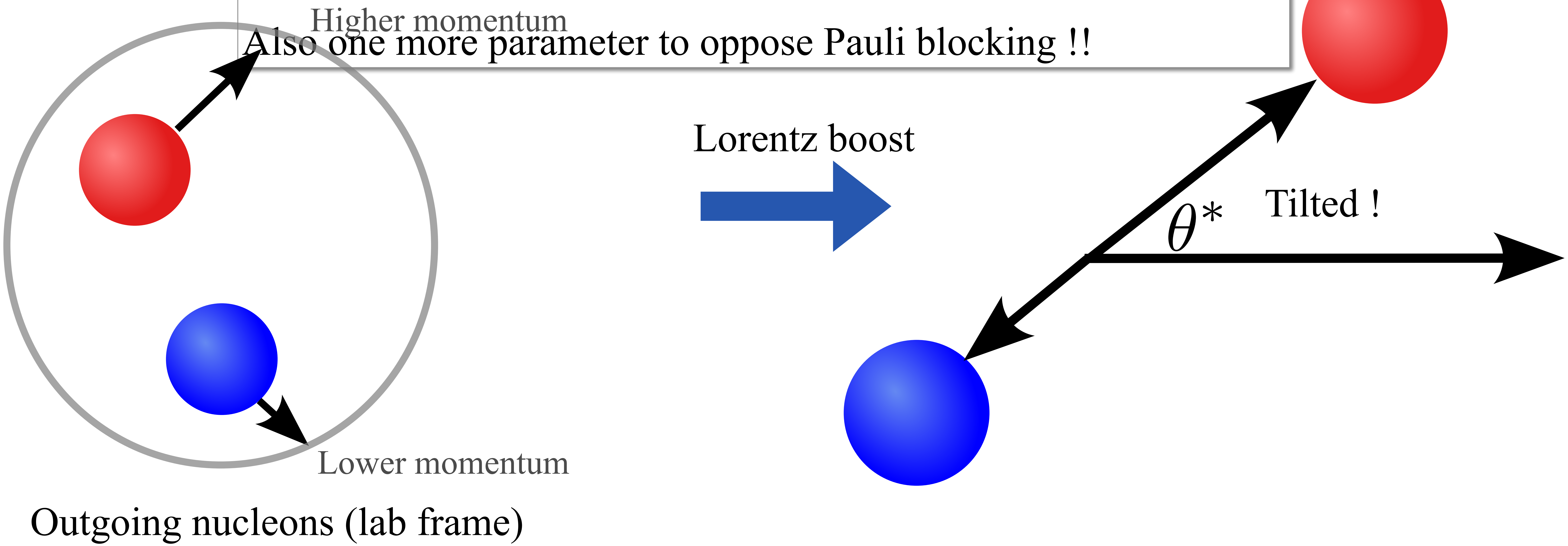
Center-of-mass frame

Modelling Correlations Between Nucleons

Motivation (for 2p2h only)

One must add one parameter to tilt the nucleon pair in CM frame

Also one more parameter to oppose Pauli blocking !!



Modelling Correlations Between Nucleons

Motivation (for 2p2h only)

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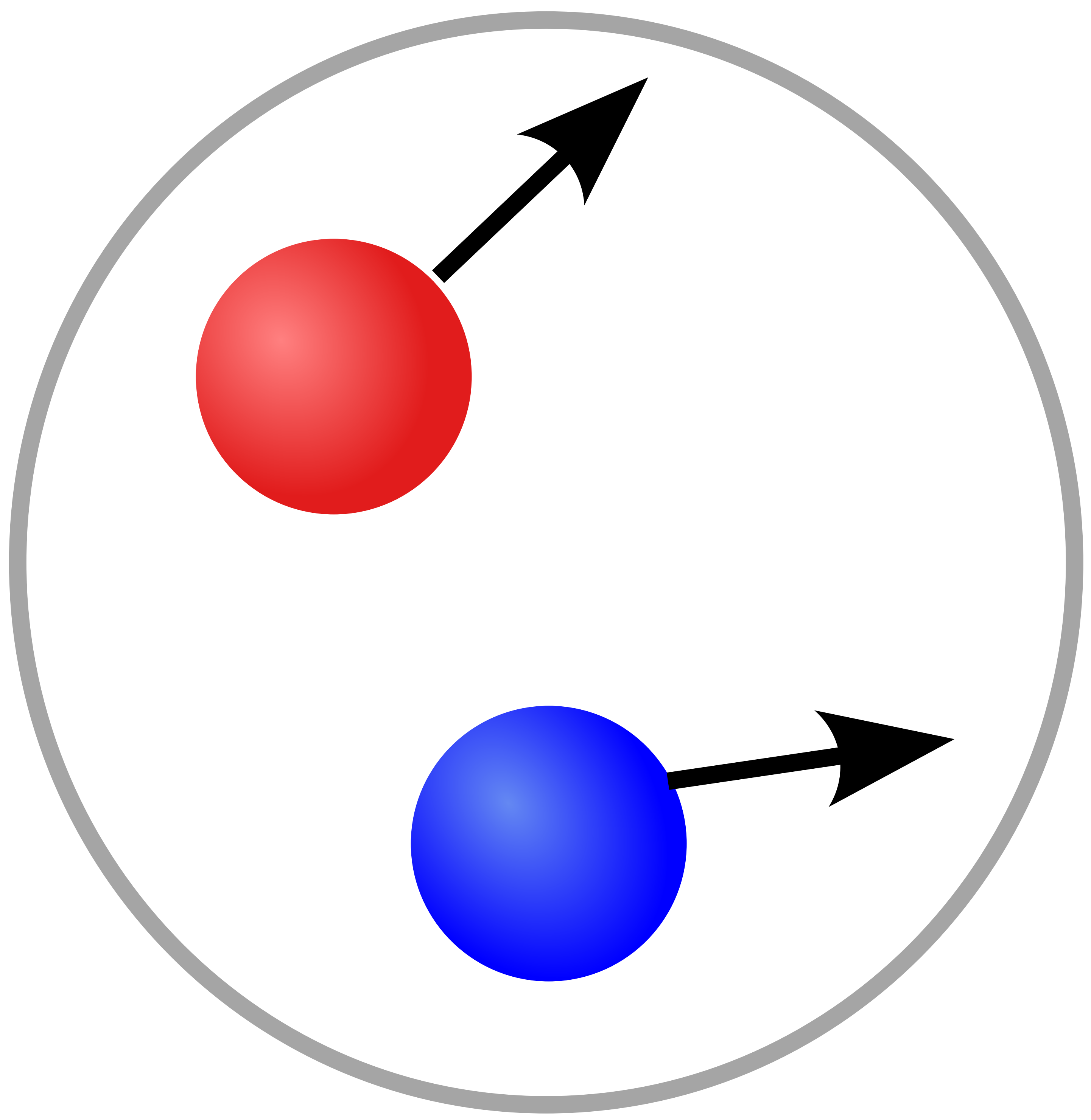
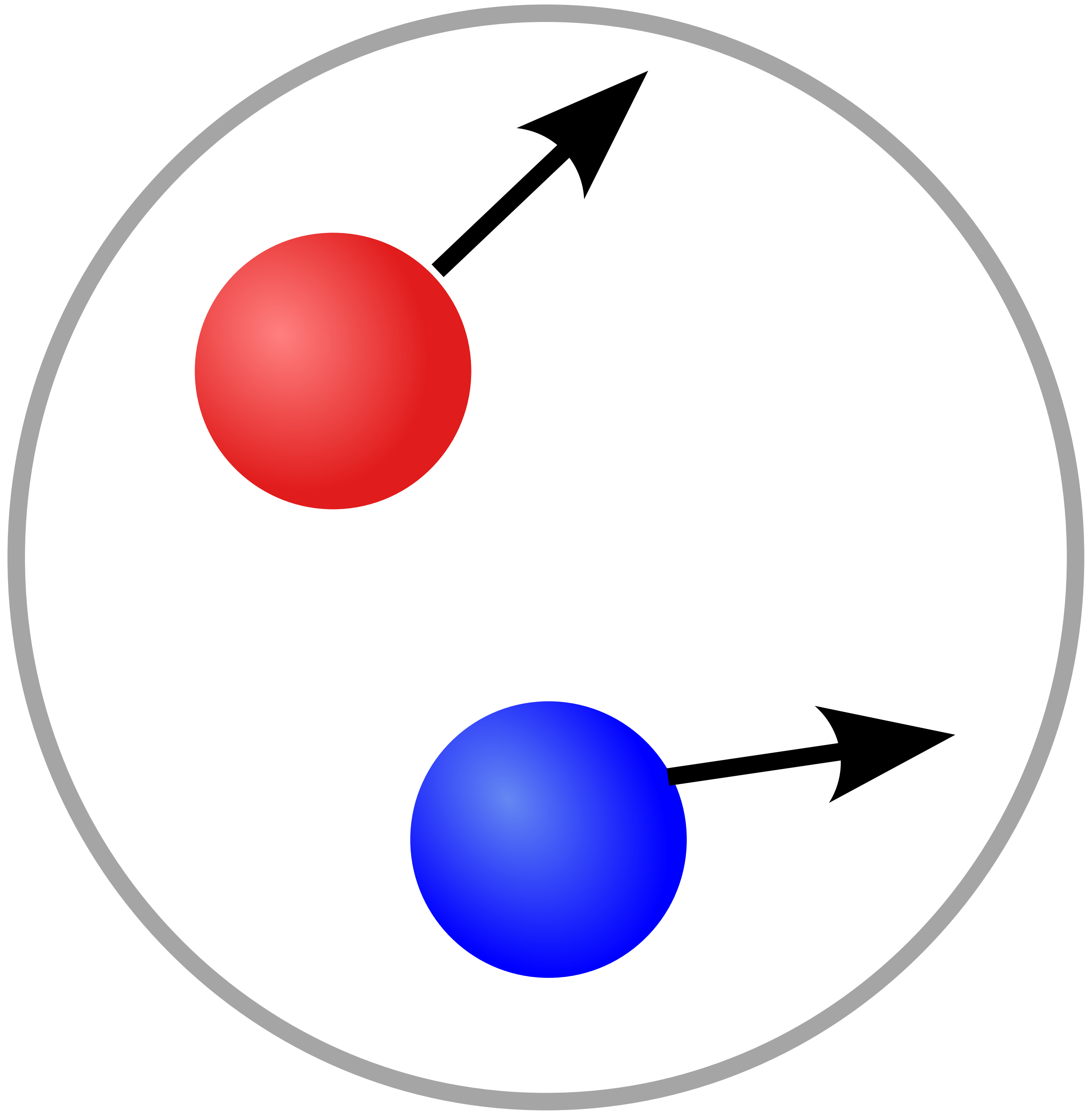


Outgoing nucleons (lab frame)

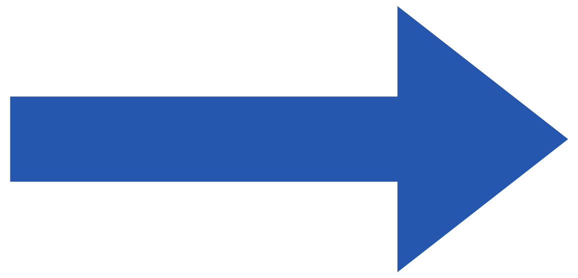
Modelling Correlations Between Nucleons

Motivation (for 2p2h only)



Outgoing nucleons (lab frame)

Lorentz boost



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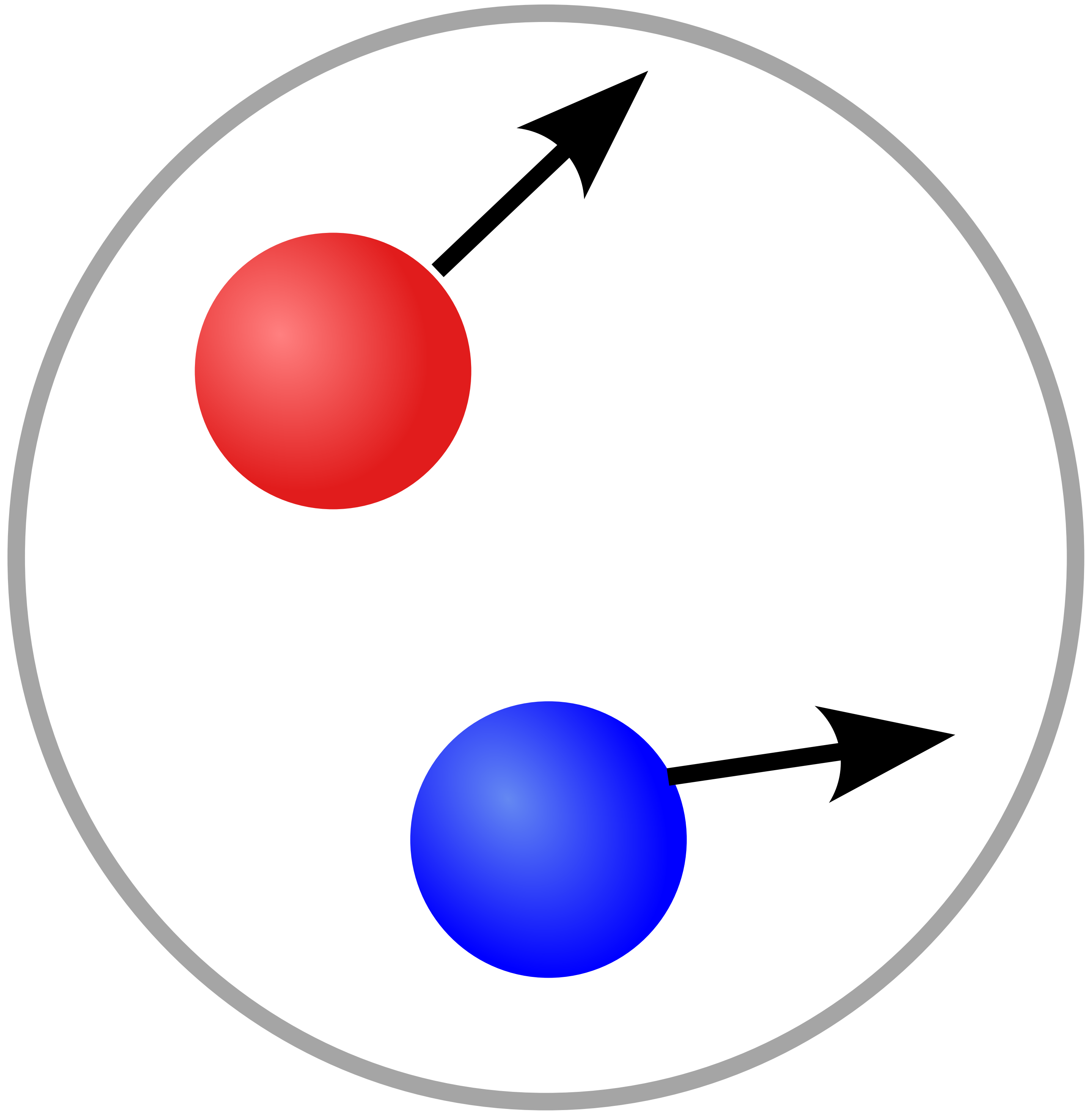
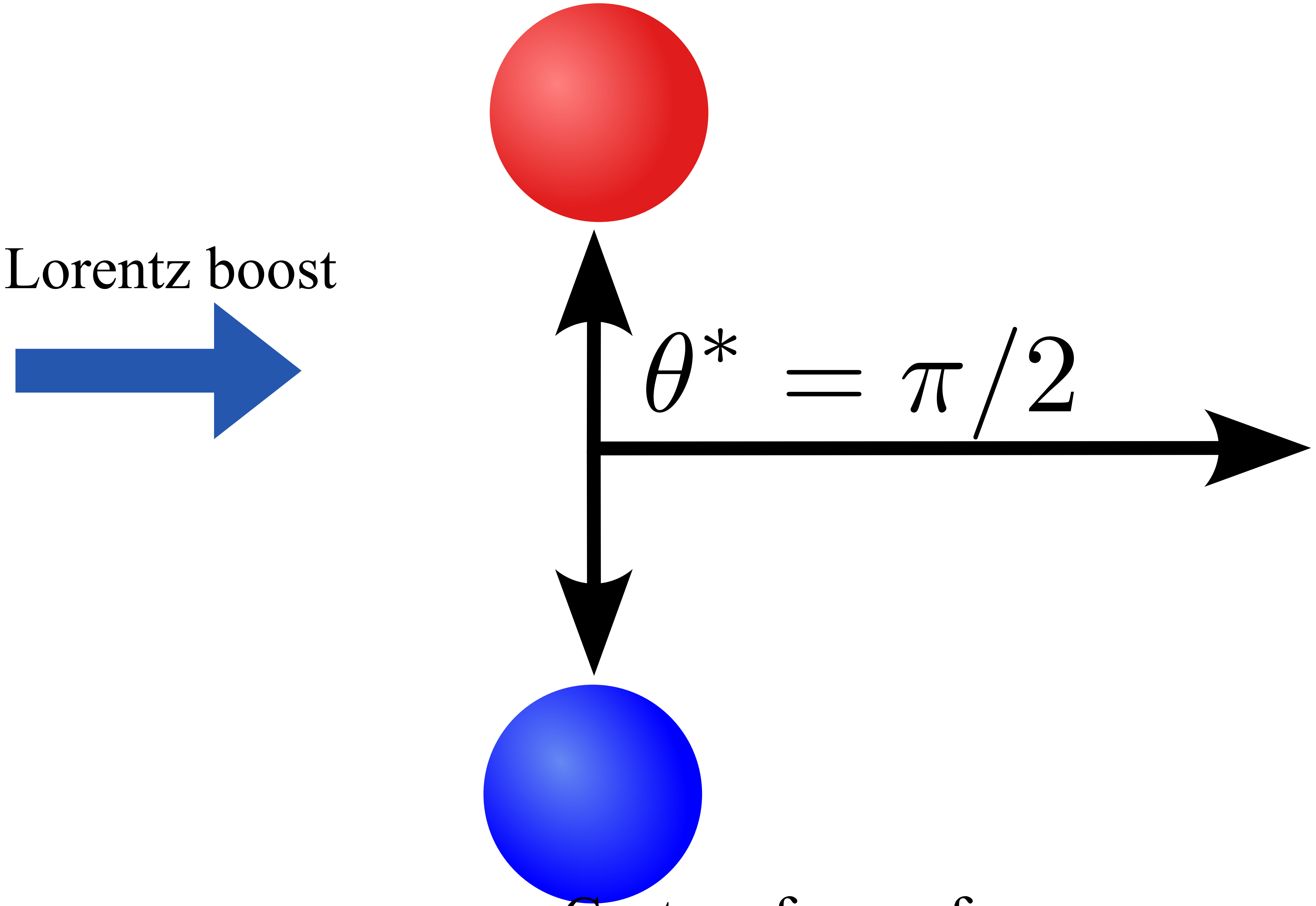
Motivation (for 2p2h only)



Outgoing nucleons (lab frame)

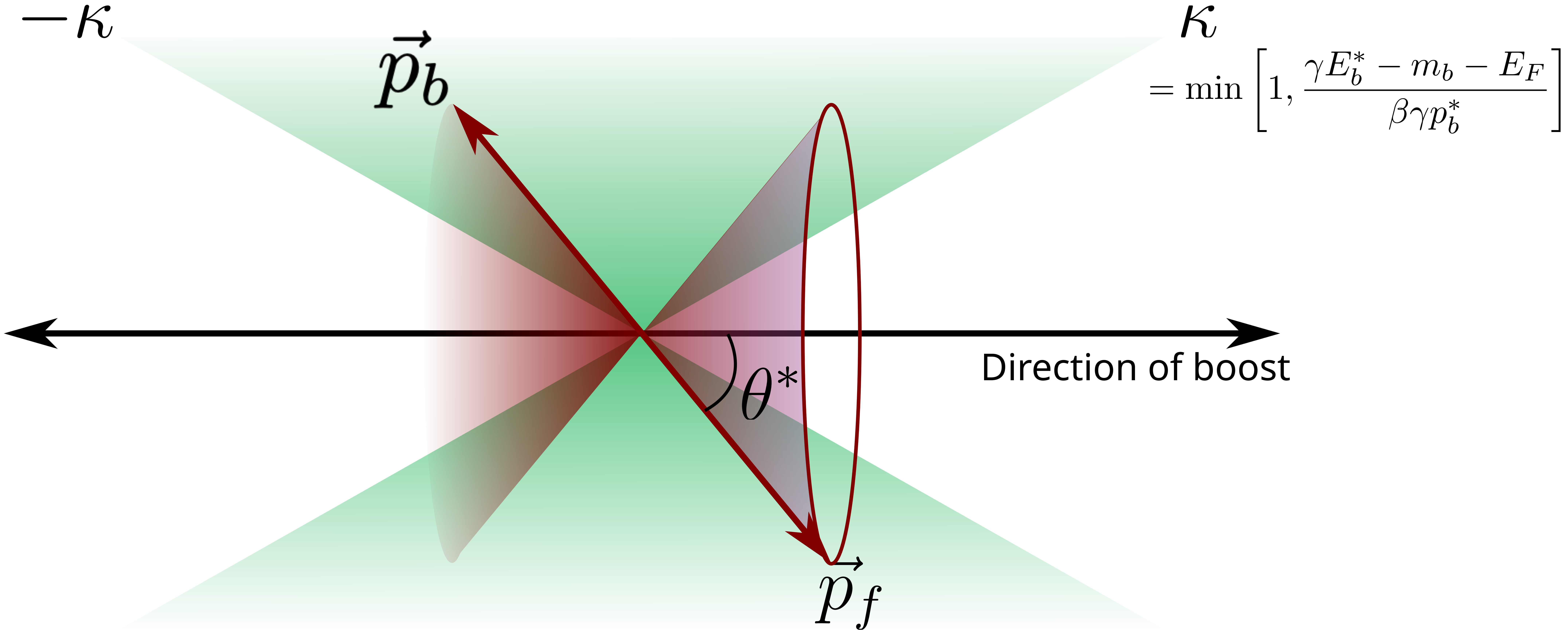
Lorentz boost



Center-of-mass frame

Pauli blocking in center-of-mass frame

Schematics



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Modelling Correlations Between Nucleons

Nucleons Sampling Function (for 2p2h only)

Assumption

There exists a **universal nucleon sampling function** with finite parameters which contains information about the direction of outgoing nucleon pair in centre-of-mass frame which can **replicate the correlations** between outgoing nucleons in the lab frame

Modelling Correlations Between Nucleons

Nucleons Sampling Function (for 2p2h only)

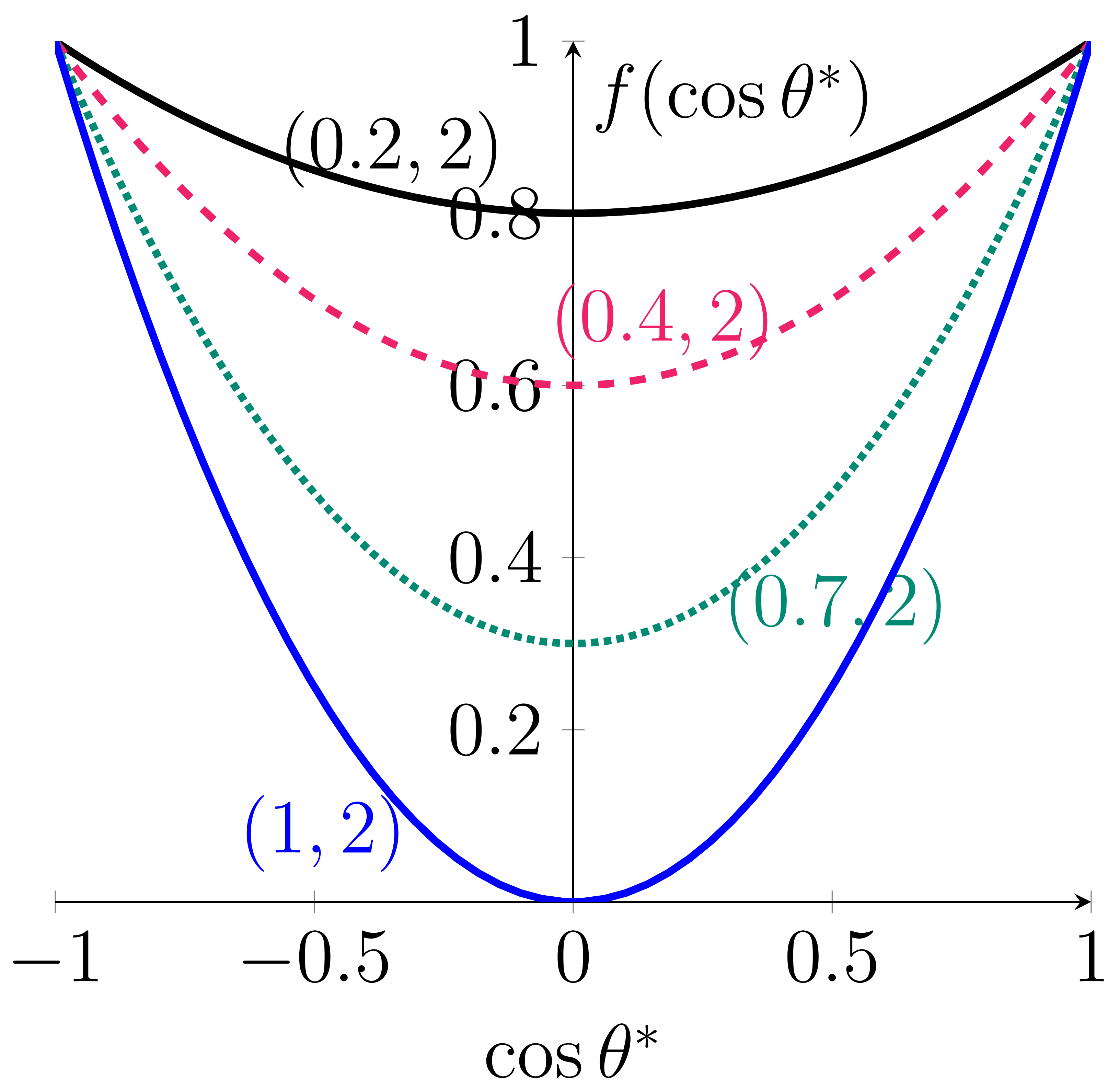
$$f(x;P,l)=\begin{cases} N(\kappa)\left(1-P+P\left|\frac{x}{\kappa}\right|^{l}\right) & l\in\{1,2,3,\dots\},\ P\in[0,1] \\ N'(\kappa)\left(1+P\left|\frac{x}{\kappa}\right|^{l}\right) & P\in[-1,0],\ l\in\{1,2,3,\dots\} \end{cases}$$

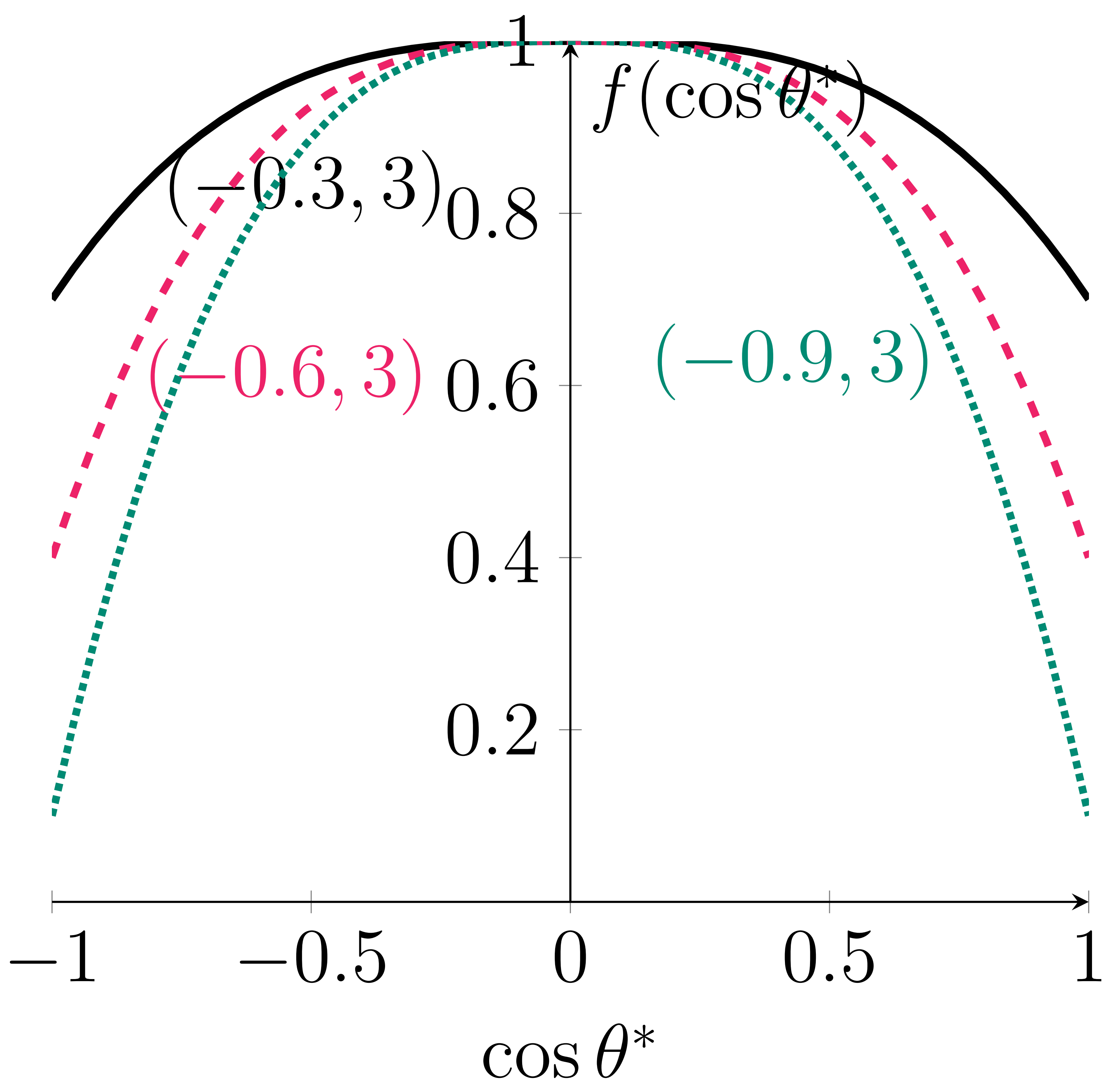
Normalisation factor

$$\kappa=\min\left[1,\frac{\gamma E_b^*-m_b-E_F}{\beta\gamma p_b^*}\right]$$

Nucleon sampling function

Shape





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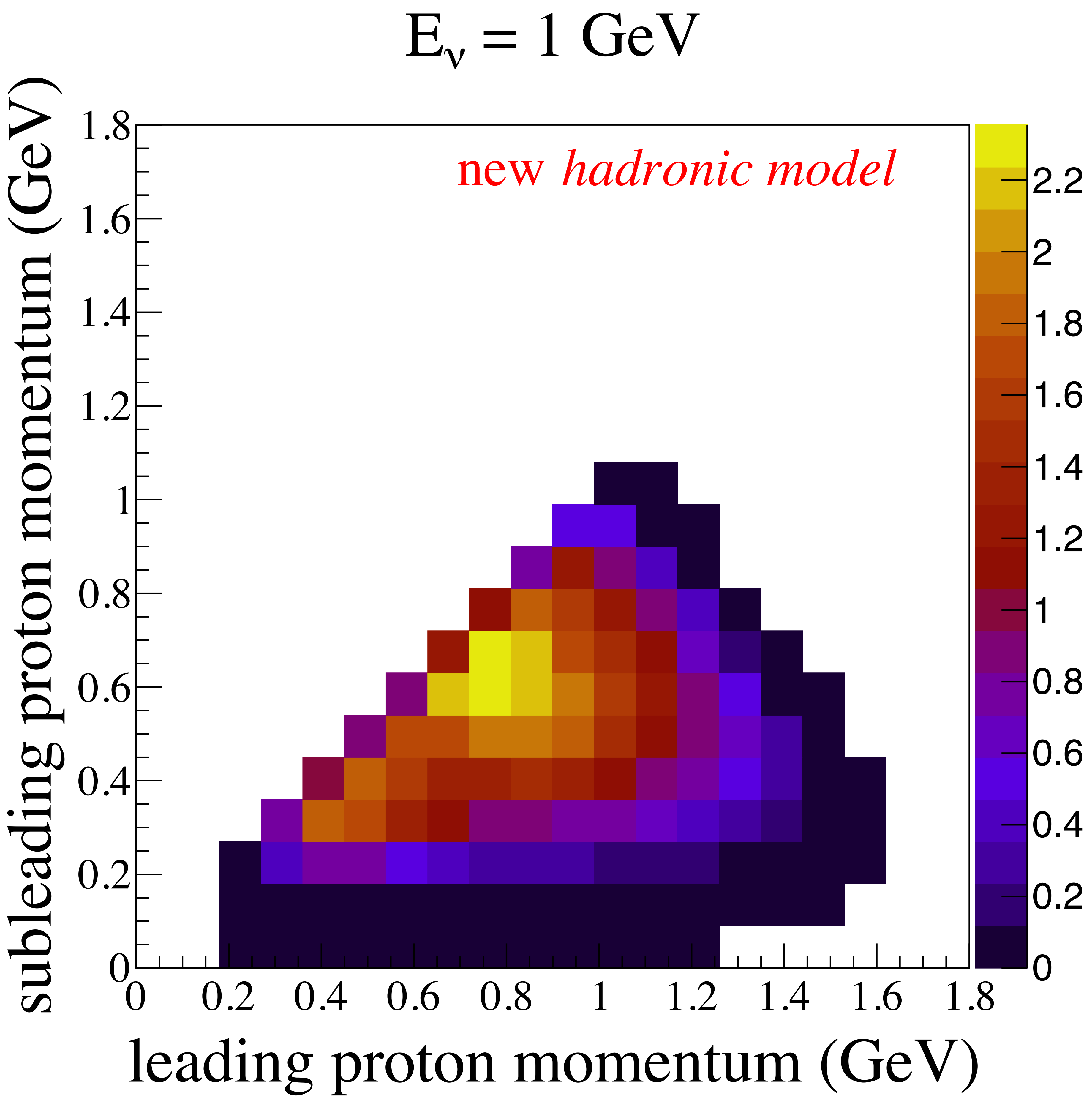
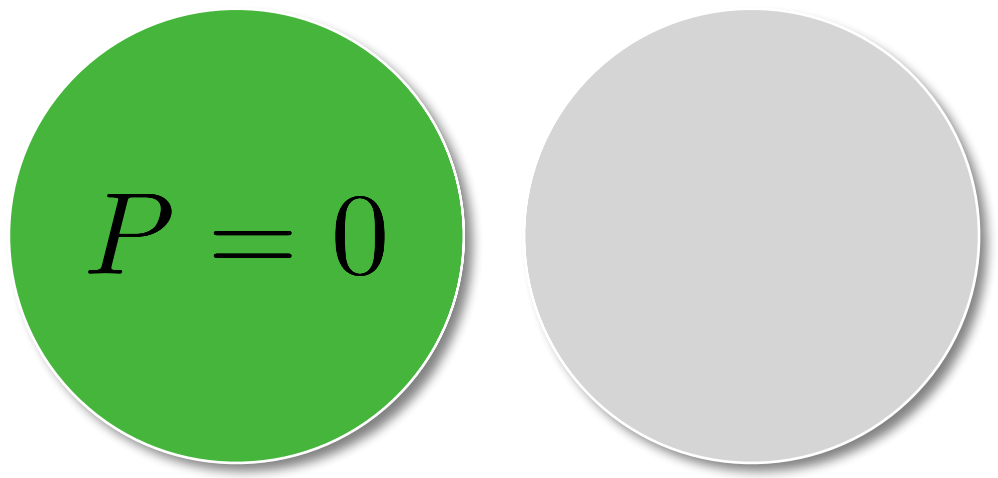
Nucleon sampling function

Caught in action





Nucleon sampling function

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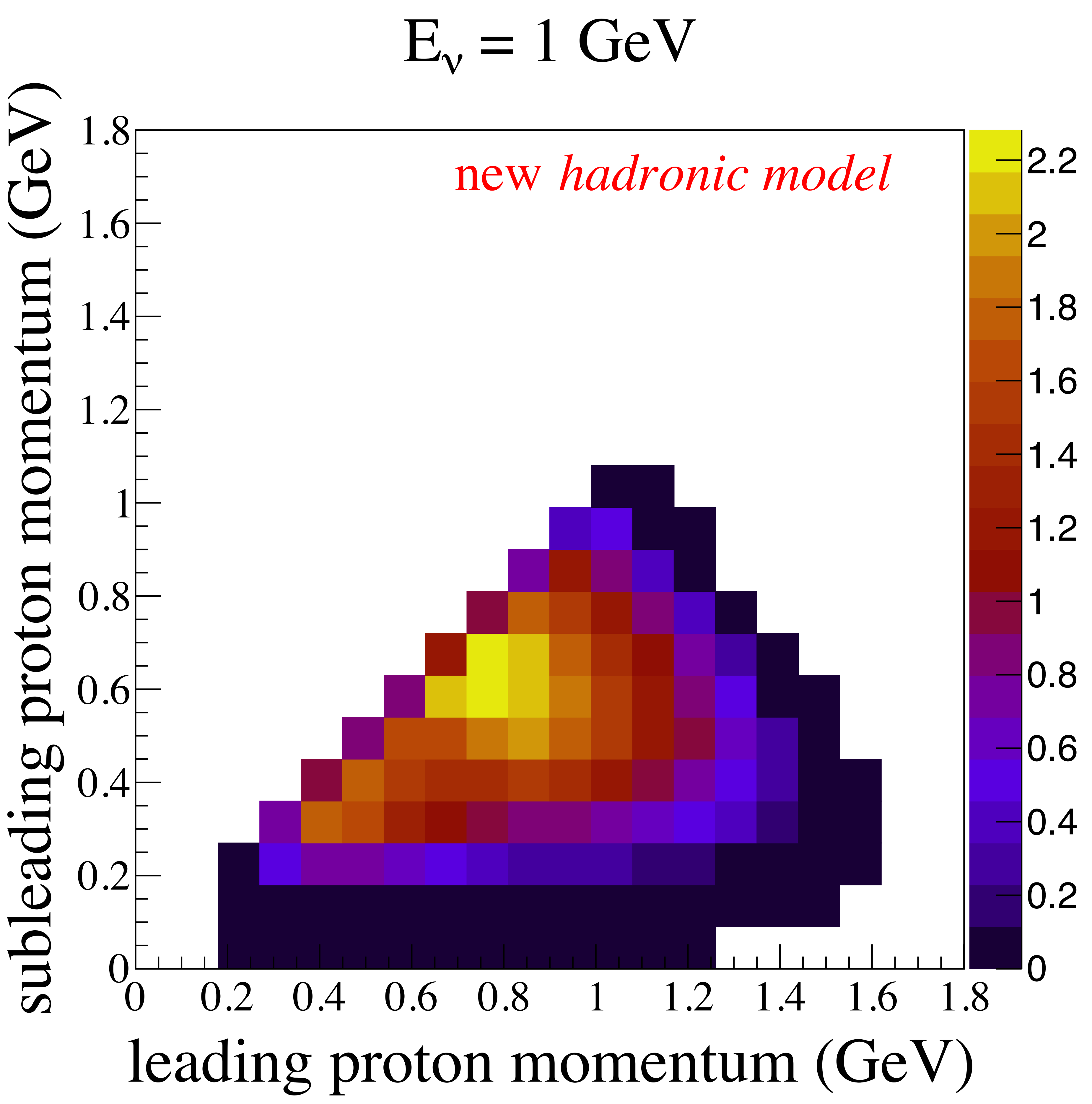
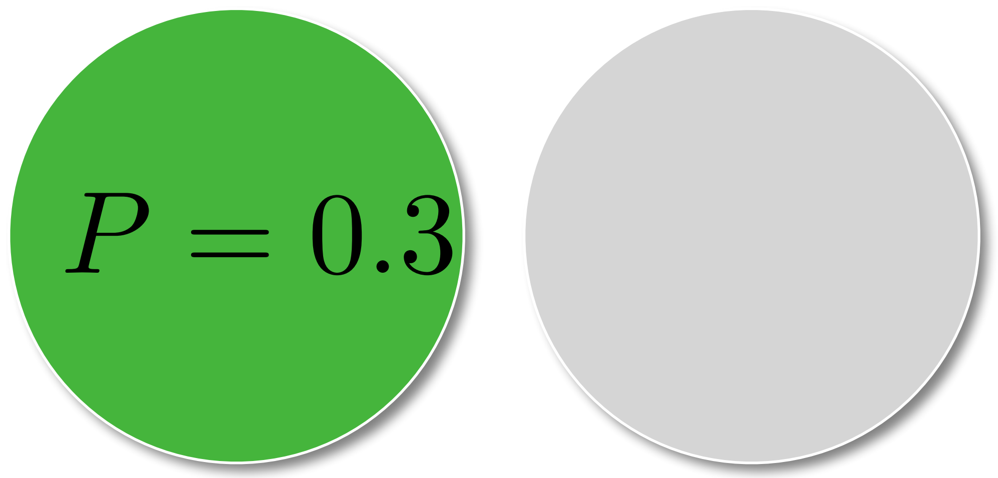
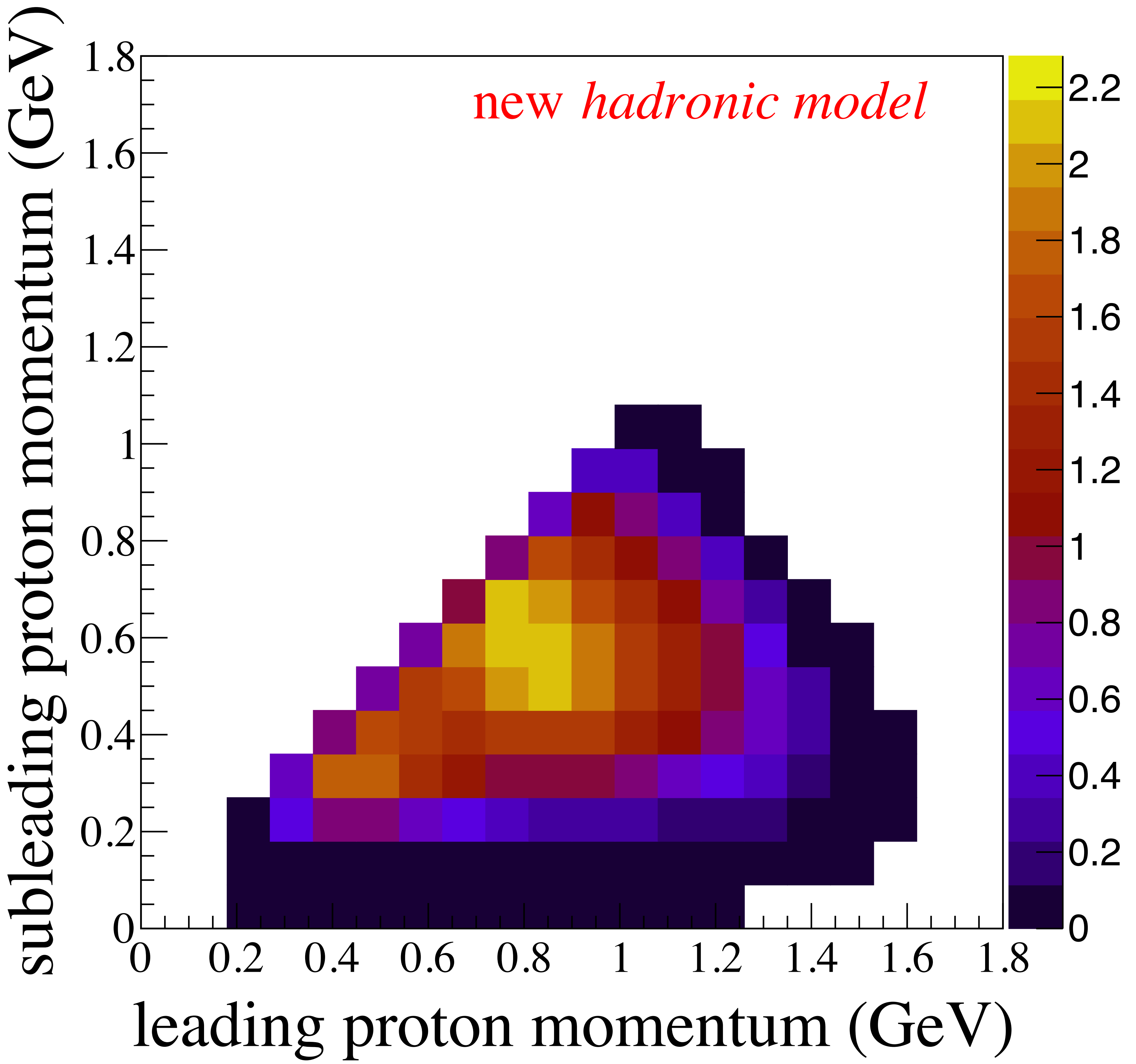


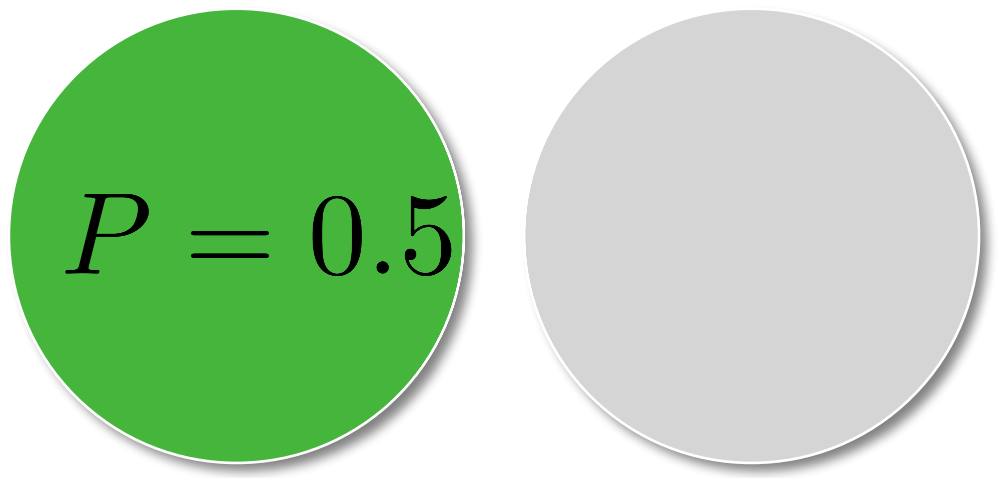


Nucleon sampling function

Caught in action

E_ν = 1 GeV

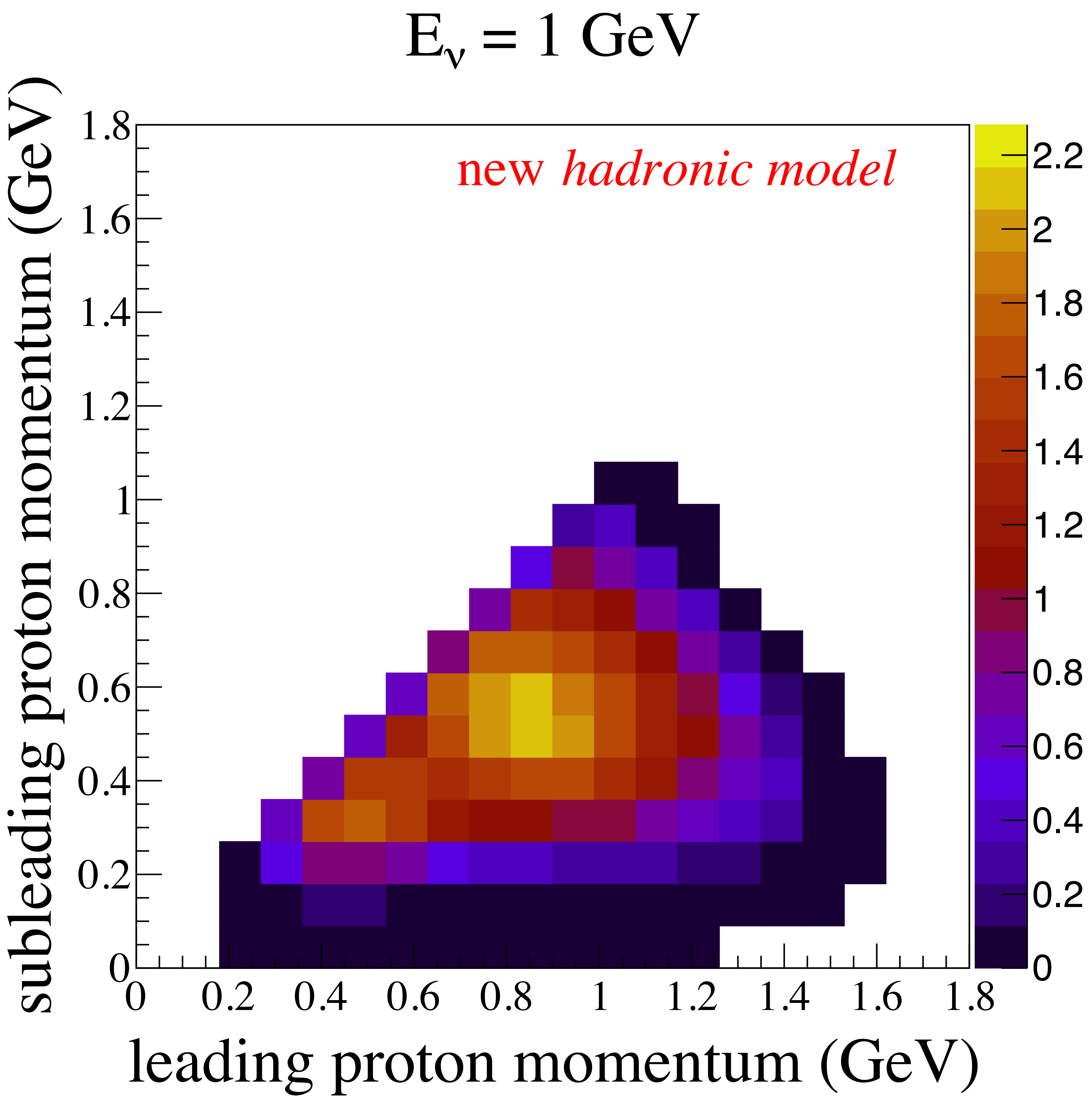




Nucleon sampling function

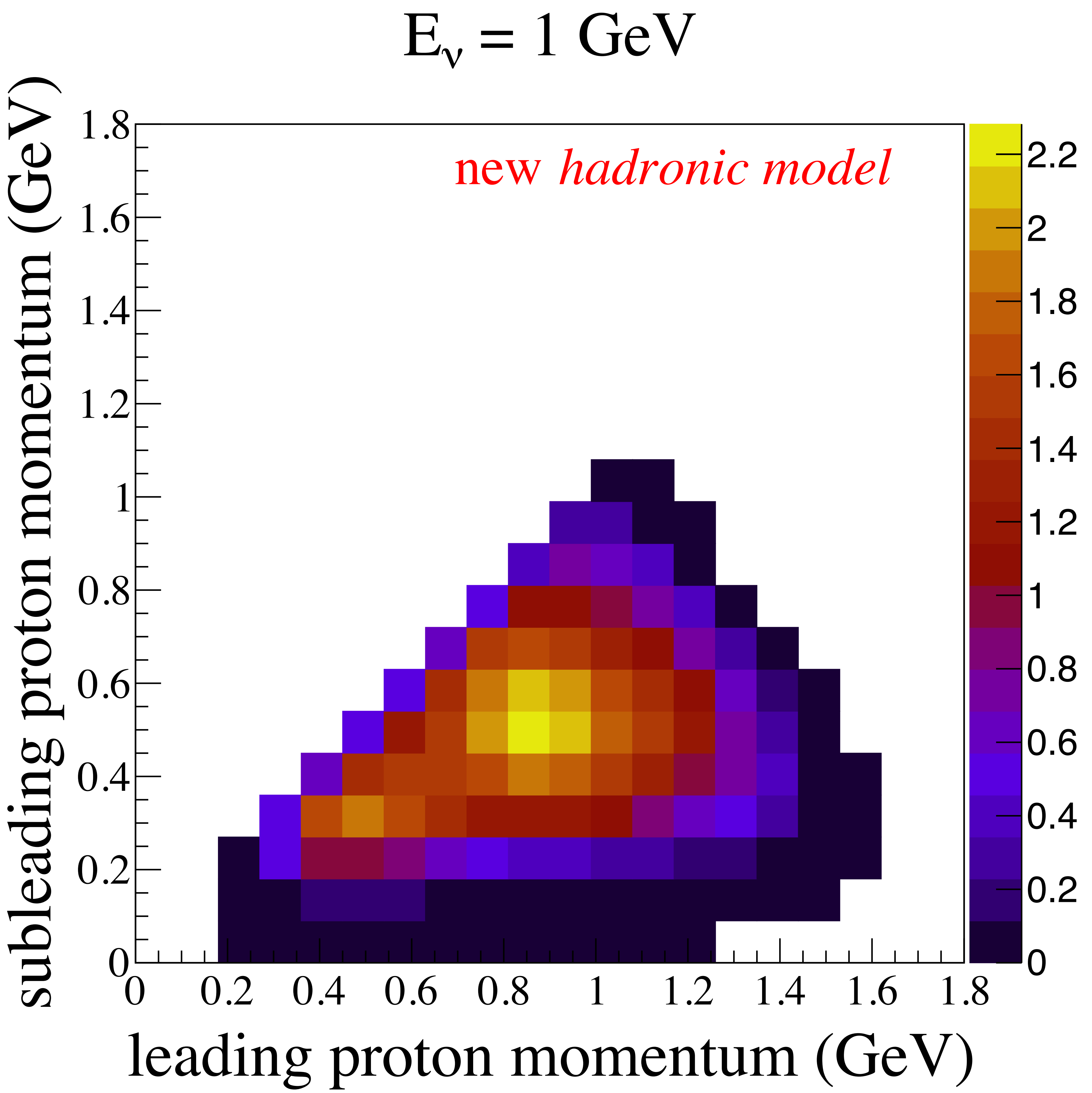
Caught in action

$P = 0.7$



Nucleon sampling function

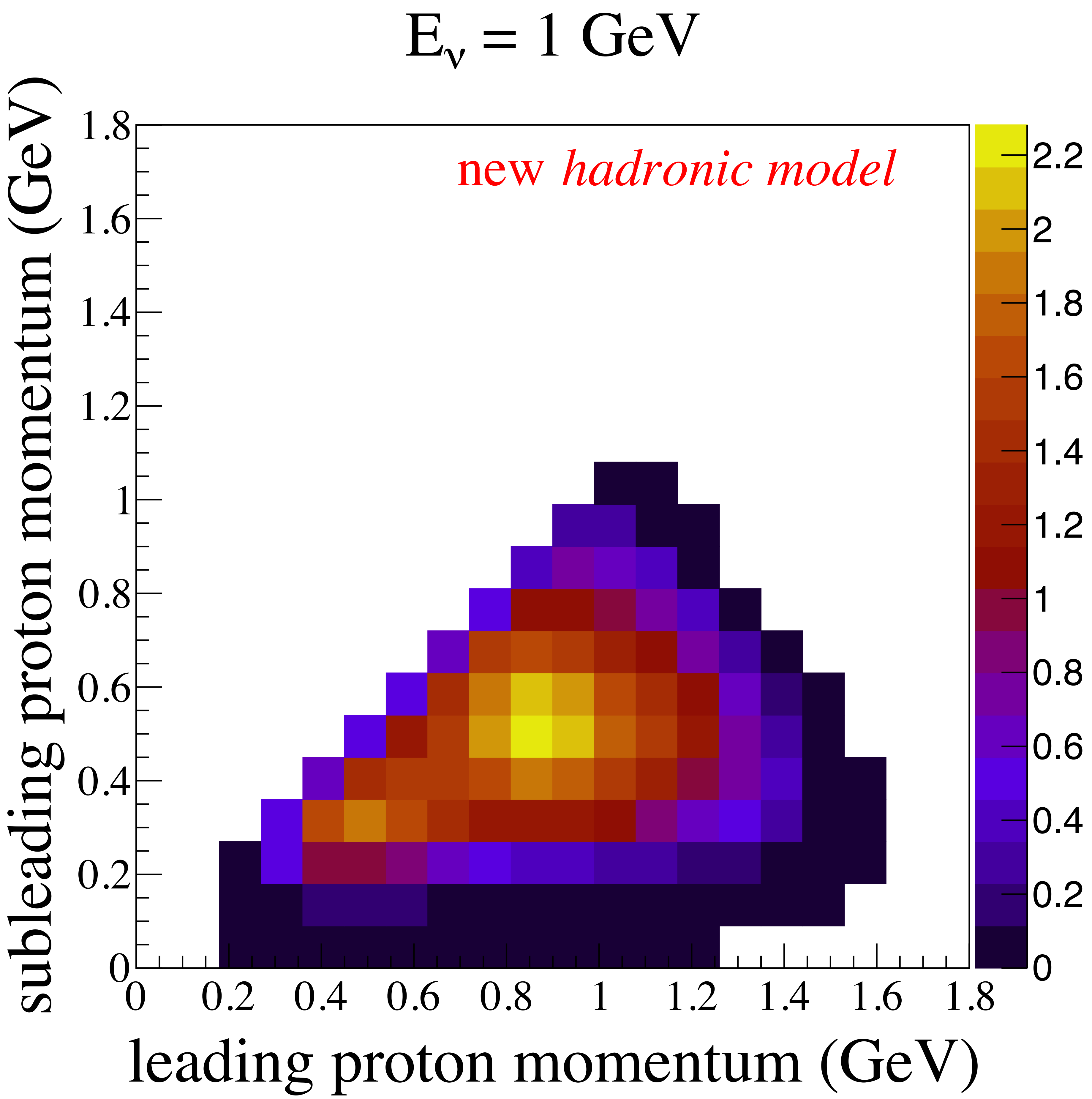
Caught in action



$P = 0.9$

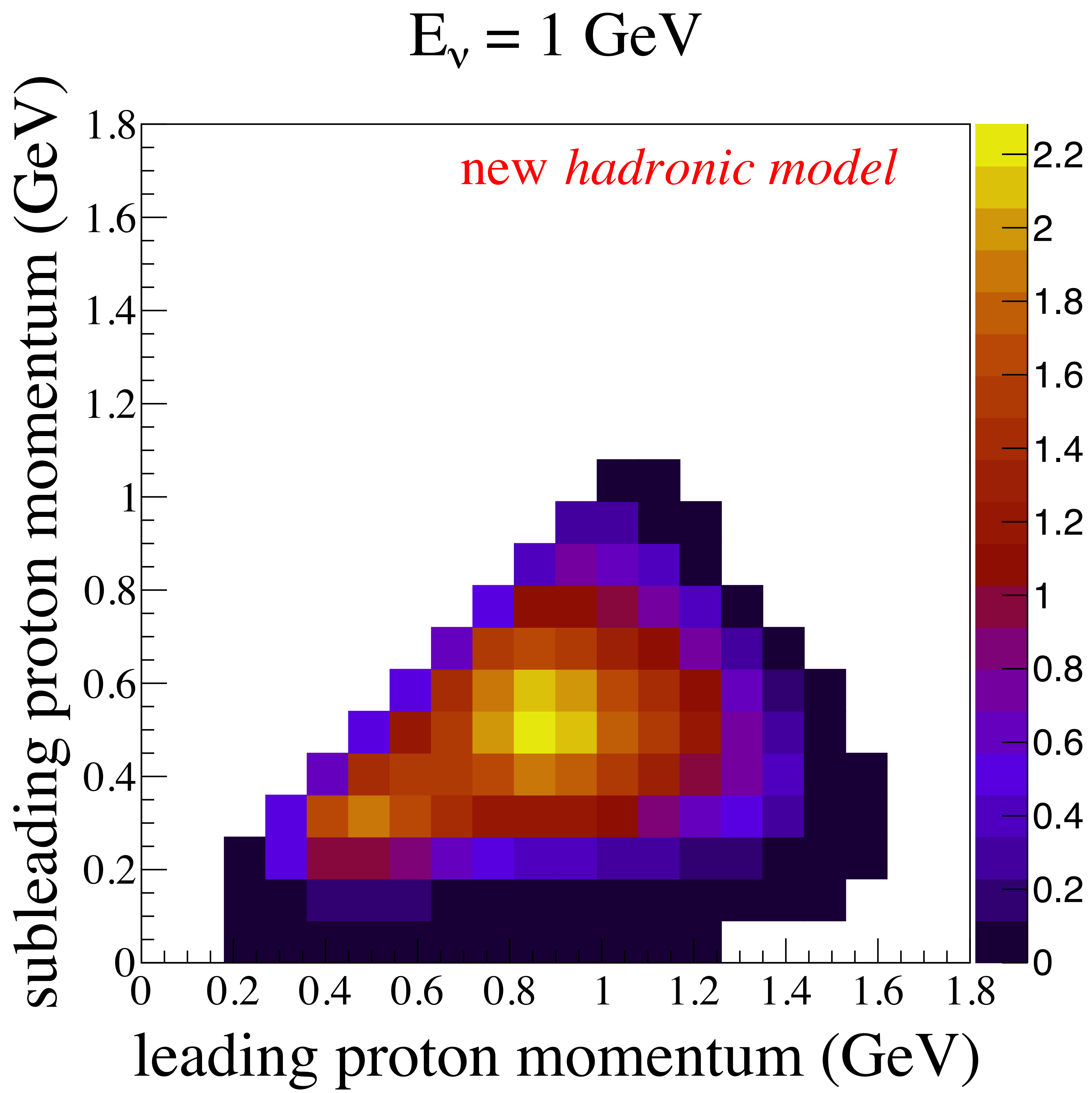
Nucleon sampling function

Caught in action



Nucleon sampling function

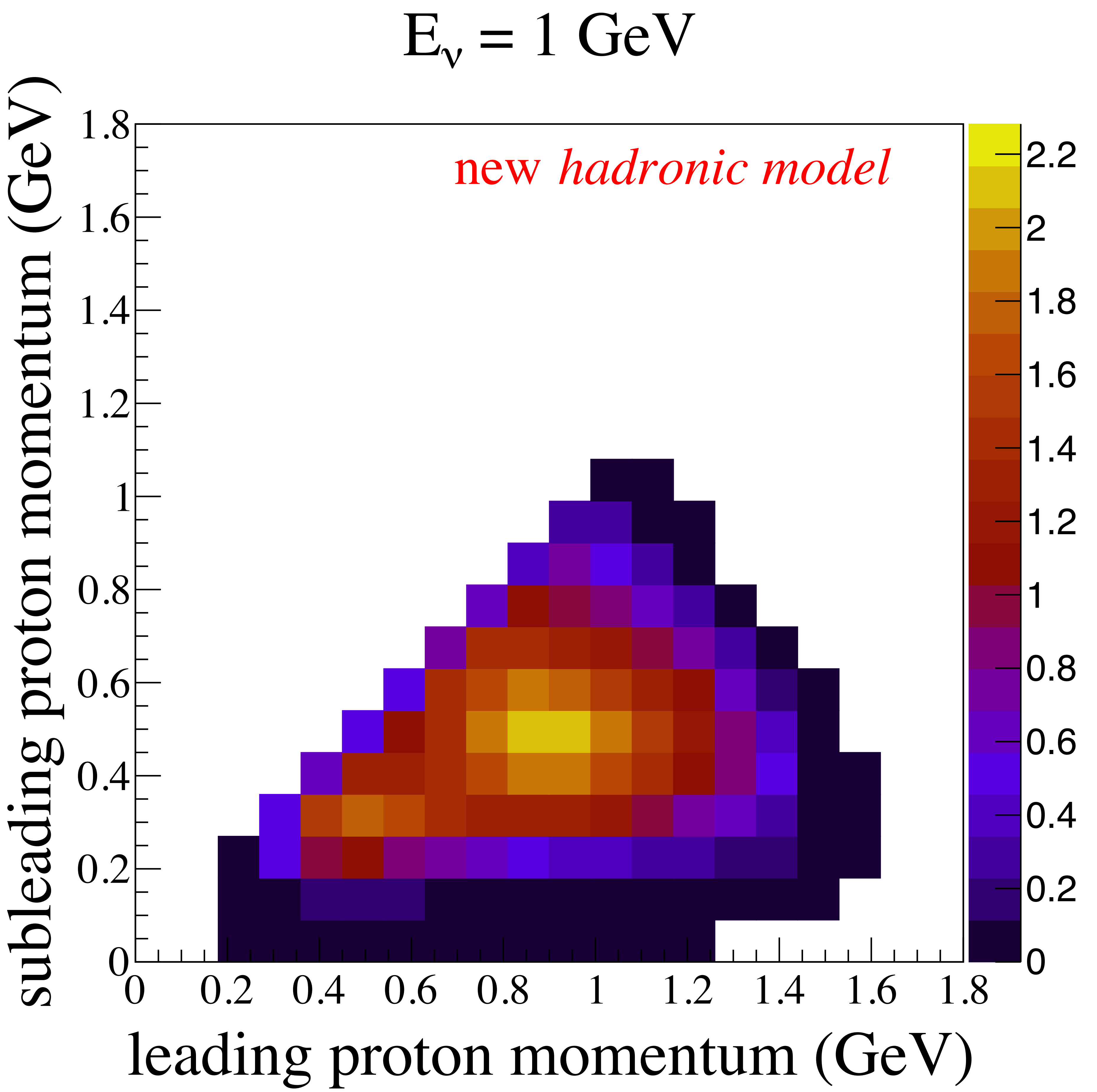
Caught in action

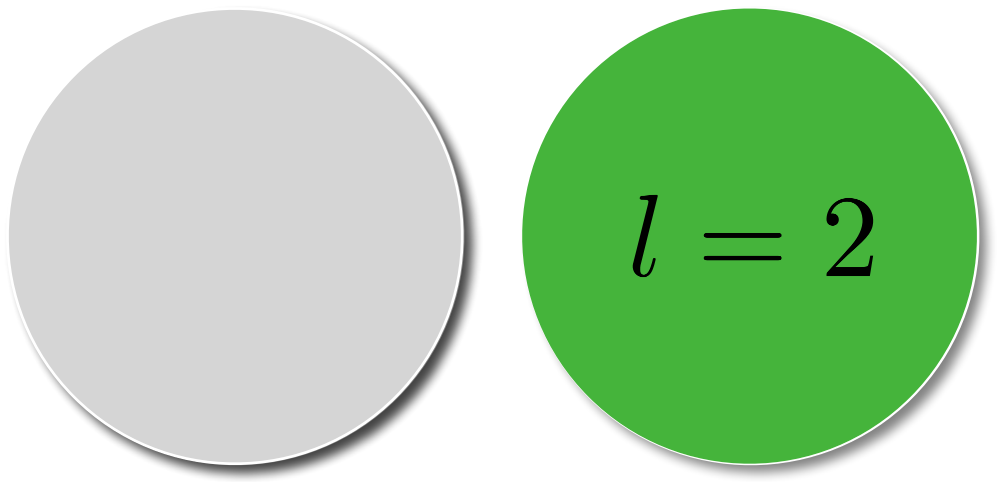


$l = 1$

Nucleon sampling function

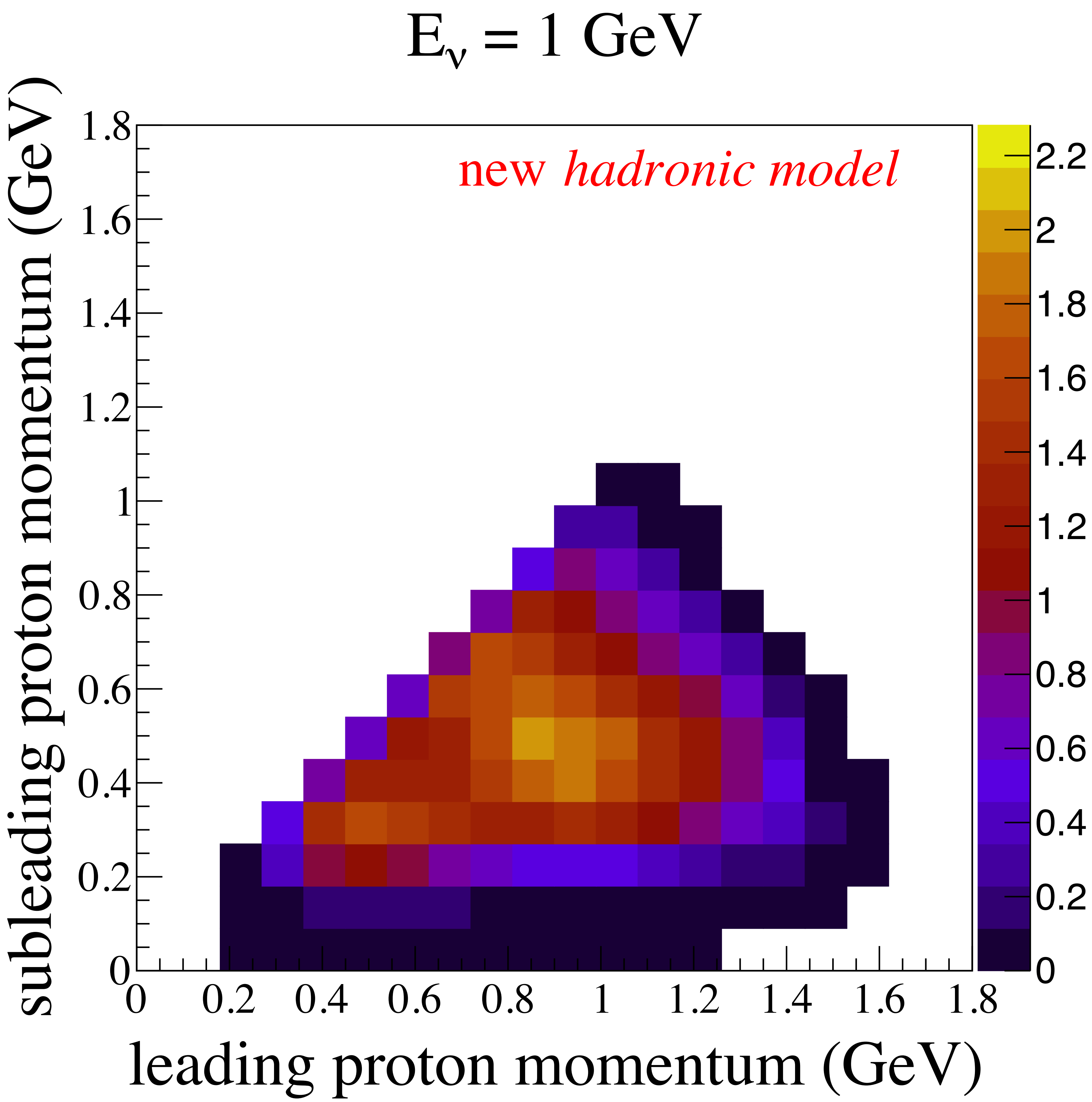
Caught in action





Nucleon sampling function

Caught in action



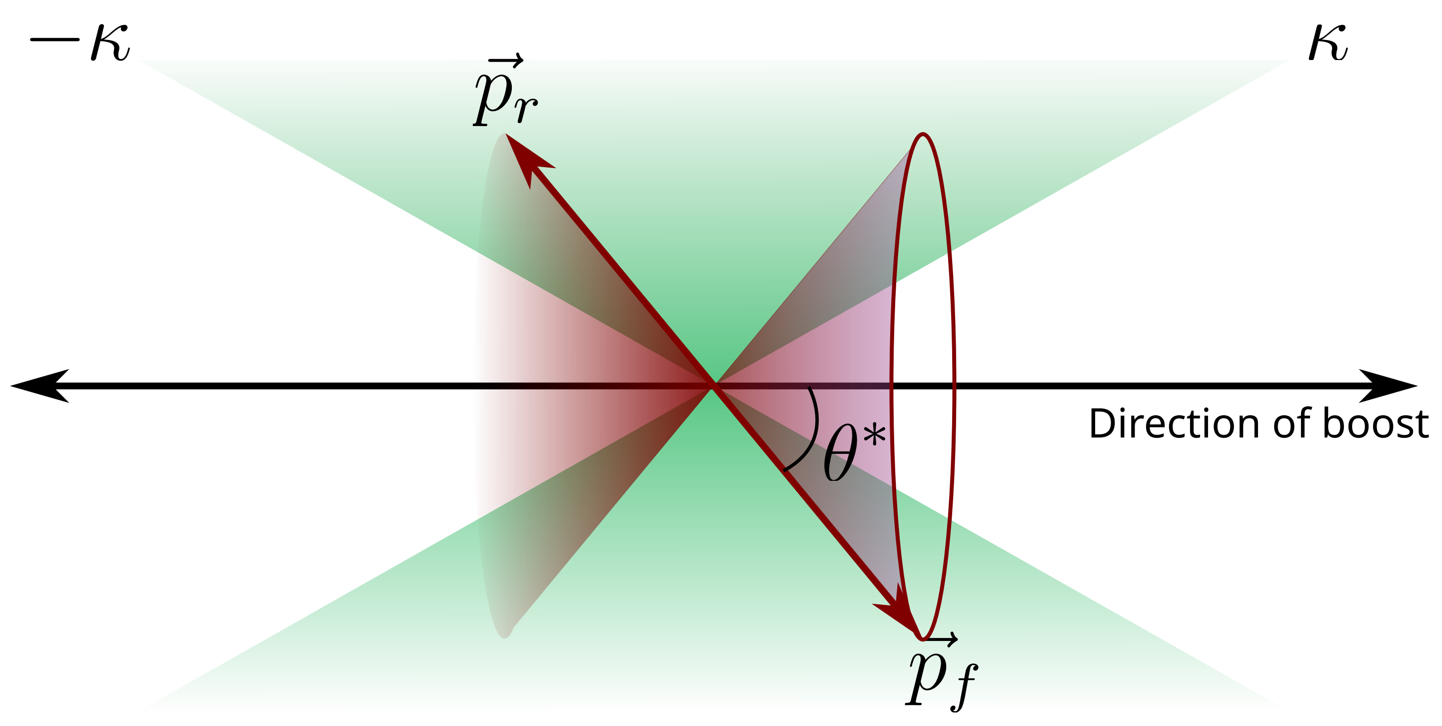
$l = 4$

Implementation results

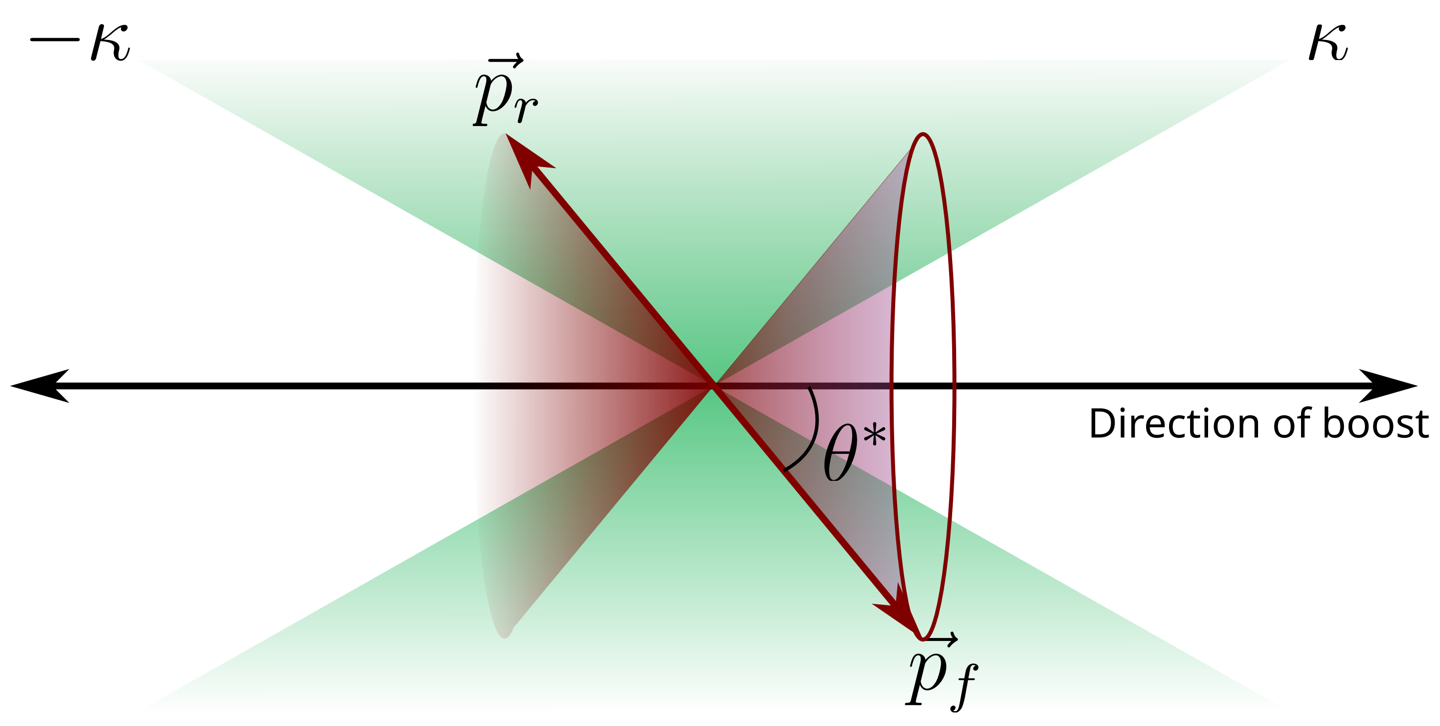
Fitting adjustable parameters

Optimal parameters obtained after fit

- We first assume the following:
  - In np (pn) configuration neutron (proton) is a forward nucleon.



Forward nucleon -> neutron



Forward nucleon -> proton

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Fitting adjustable parameters

Optimal parameters obtained after fit

- Each outgoing nucleon pair is provided with a separate parameter set .
- The momentum distributions of the outgoing nucleons, and , are fit separately.
  - has 2 parameters to fit.
  - has 4 parameters to fit.
- Optimal values $(\hat{P}, \hat{l})_{\{pp,np,pn\}}$ are found after **minimisation procedure**.
- These optimal values work sufficiently good for all neutrino energies. Hence they are called "global fit values"

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Minimisation procedure

Optimising the nucleon phase space

- Specify parameter space $P \in [-1,1] \quad n \in \{1,2,..,10\}$ $\Delta P = 0.01 \quad \Delta n = 1$

- Choose neutrino energy values GeV
- For any given (P,n), produce outgoing nucleon distribution
- Choose only those bins in 2020 Valencia model where
- Compare the differences between two distributions using

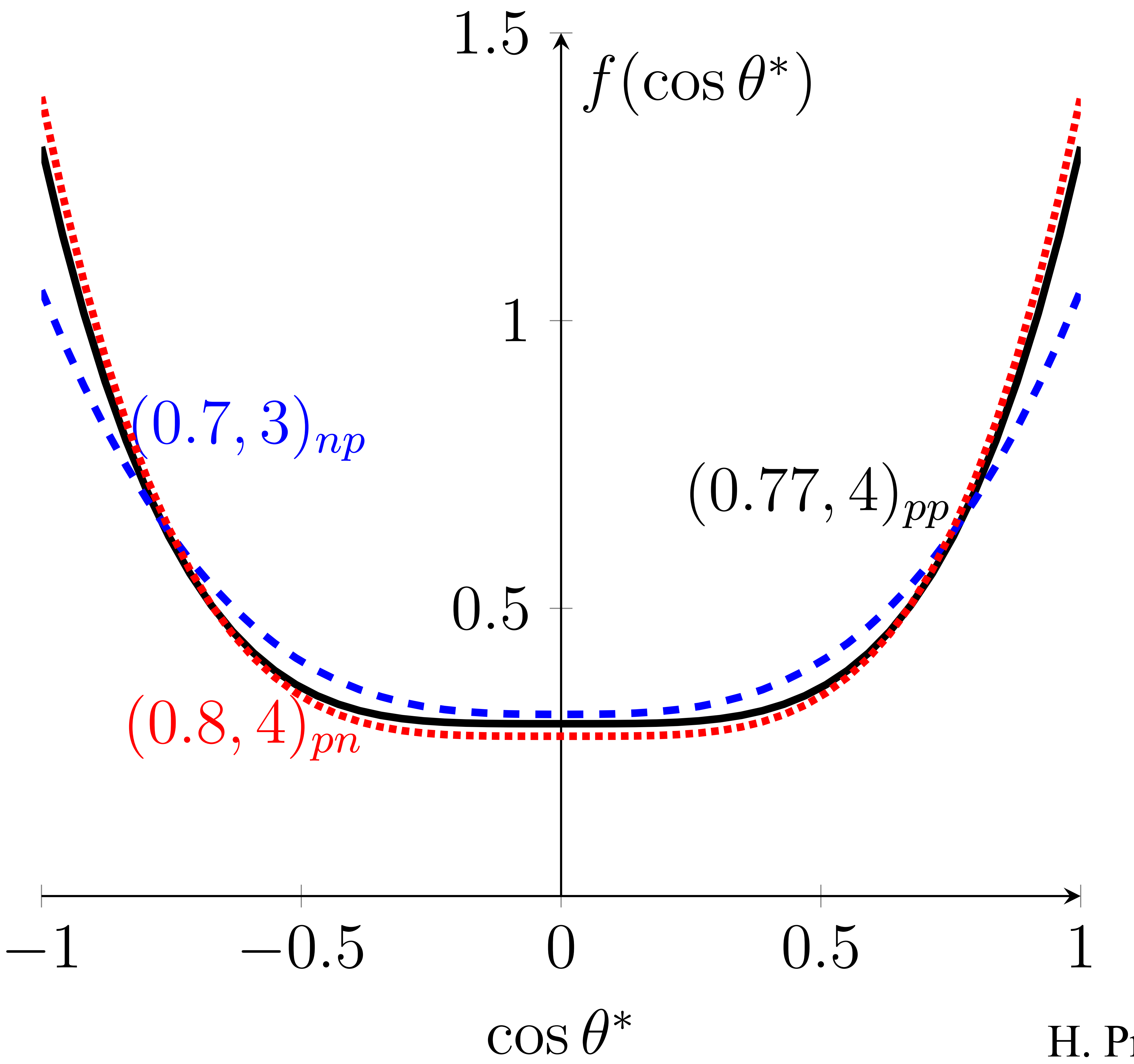
$$\tilde{\chi}^2 = \frac{1}{2N_{\text{bins}}} \sum_{i,j}^{N_{\text{bins}}} \frac{(N_{ij}^{\text{NuWro}} - N_{ij}^{\text{Valencia}})^2}{(N_{ij}^{\text{NuWro}} + N_{ij}^{\text{Valencia}})}$$

- Find the minimum $\tilde{\chi}^2$ within the parameter space

- Find the global minimum $\tilde{\tilde{\chi}}^2_{pp} = \min_{\tilde{\chi}^2} \left\{ \sum_{E_\nu} \tilde{\chi}^2_{pp}(P, l)_{pp} \right\}$

Fitting adjustable parameters

Optimal parameters obtained after fit



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Momentum distribution of outgoing nucleons

Two proton in final state (primary vertex)

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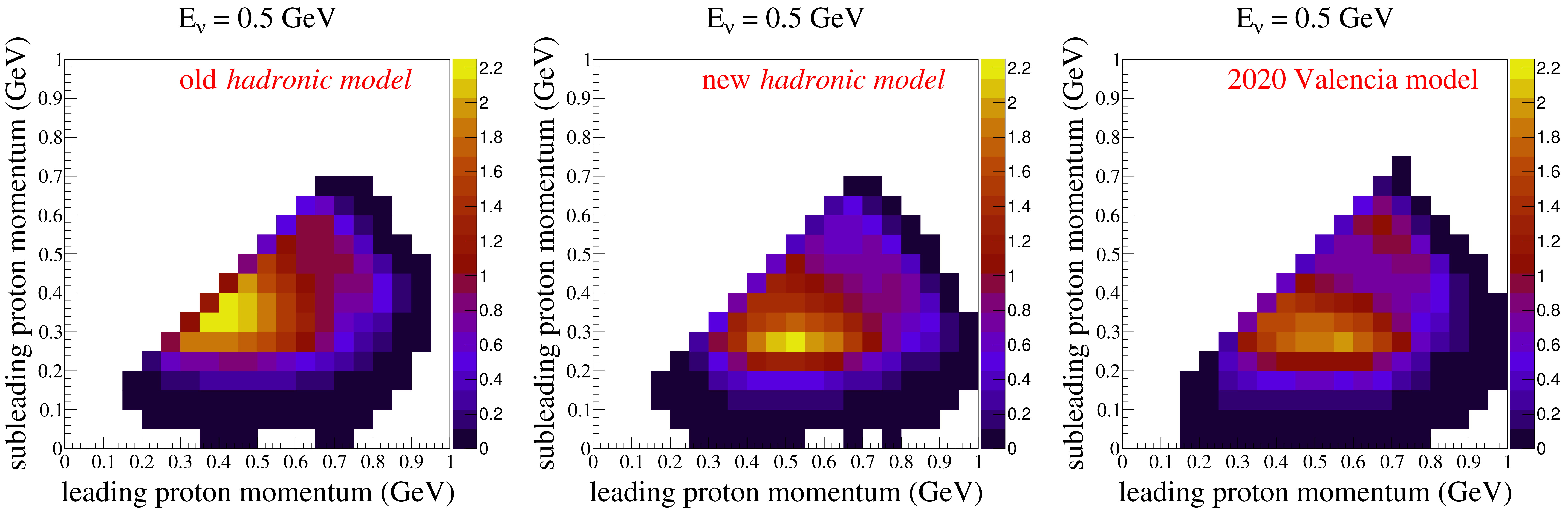

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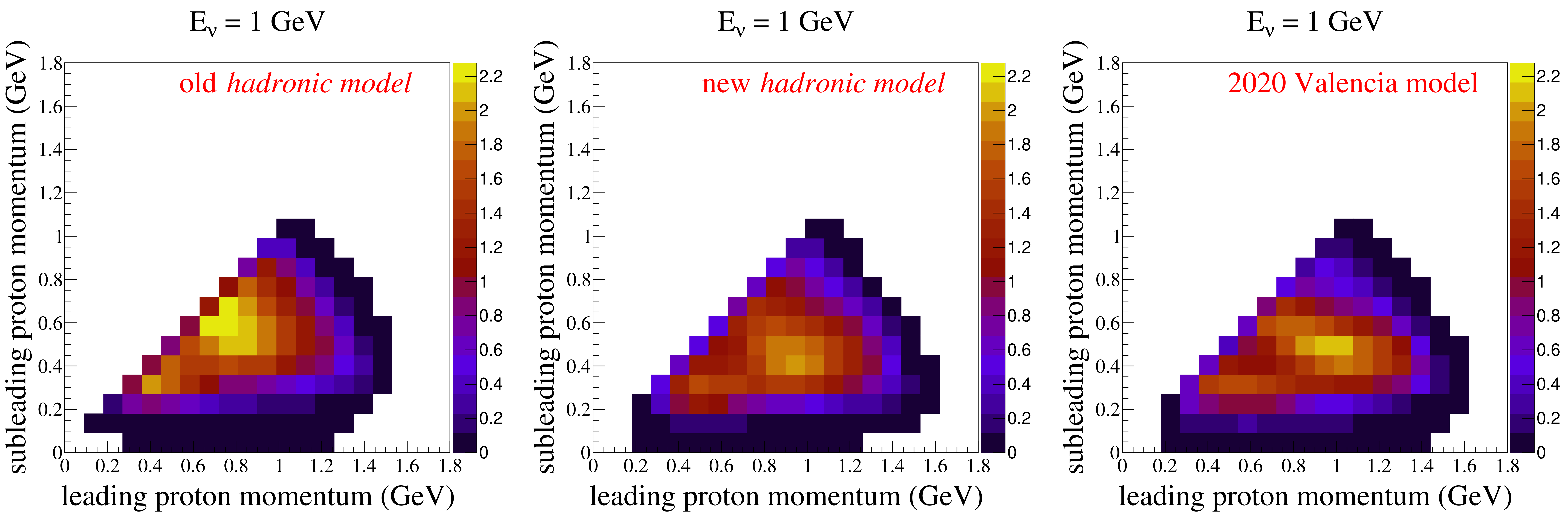

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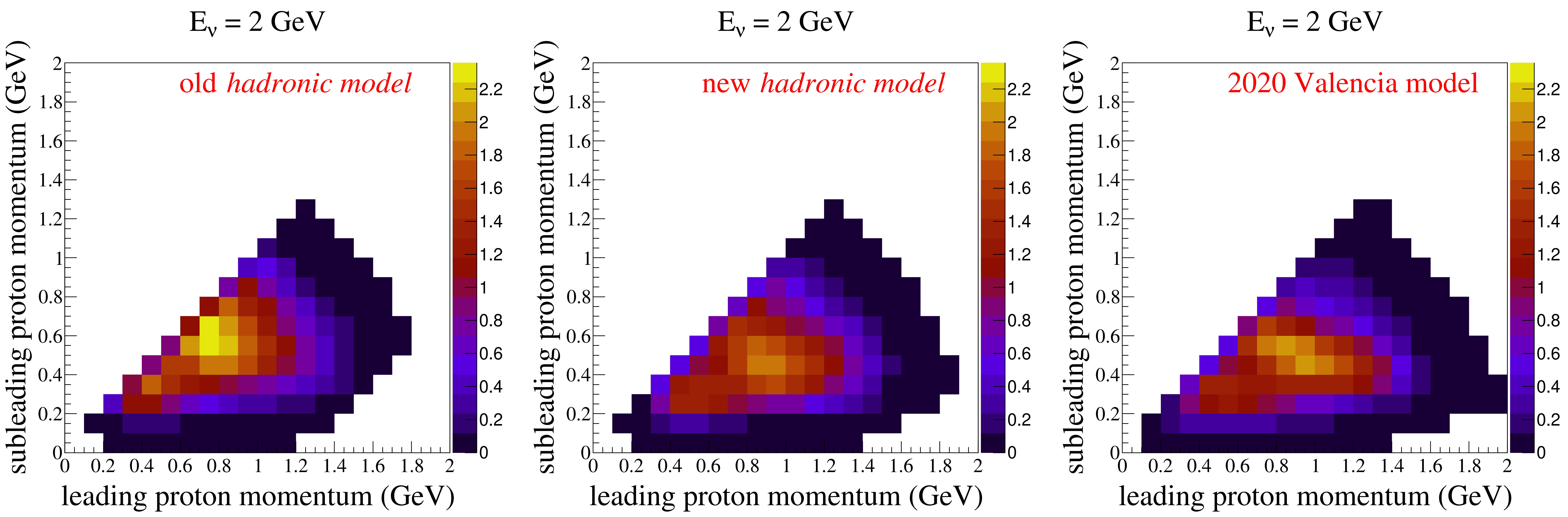

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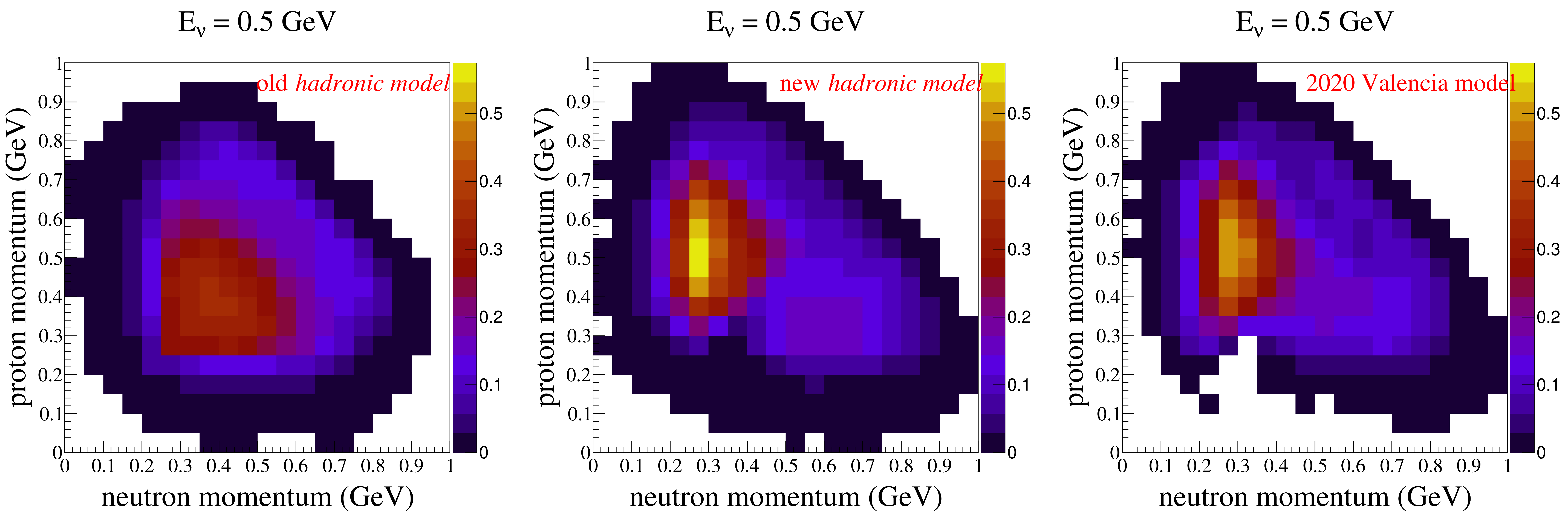
Momentum distribution of outgoing nucleons

A neutron and a proton in the final state (primary vertex)



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Momentum distribution of outgoing nucleons

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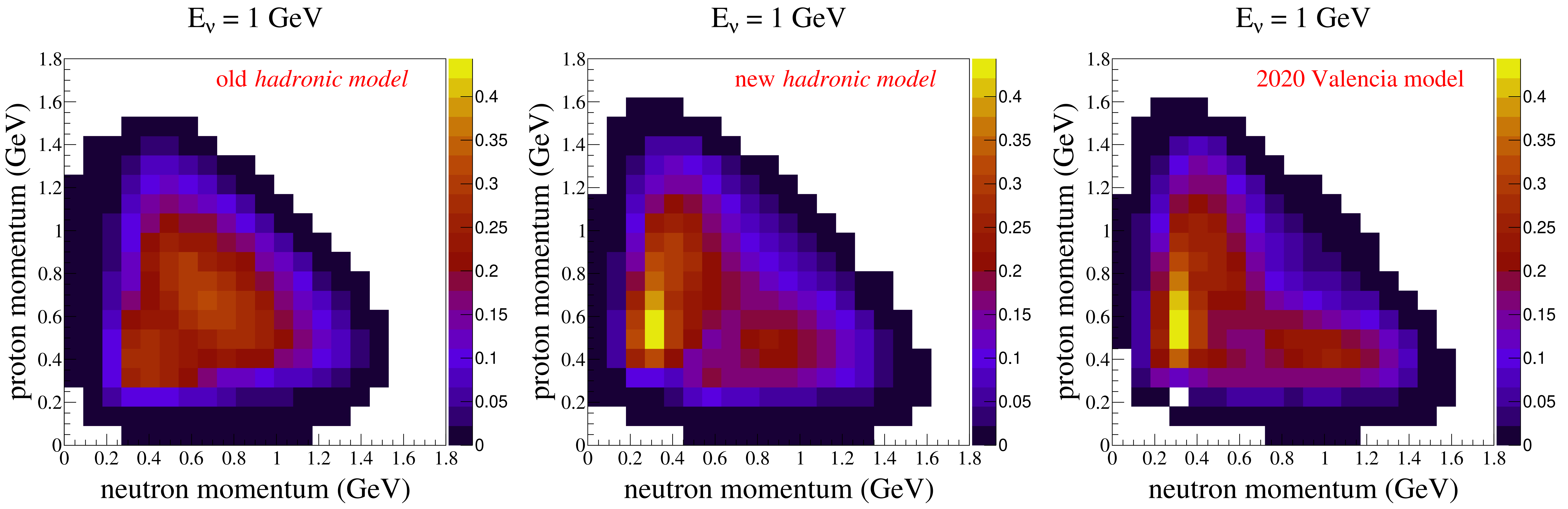

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Momentum distribution of outgoing nucleons

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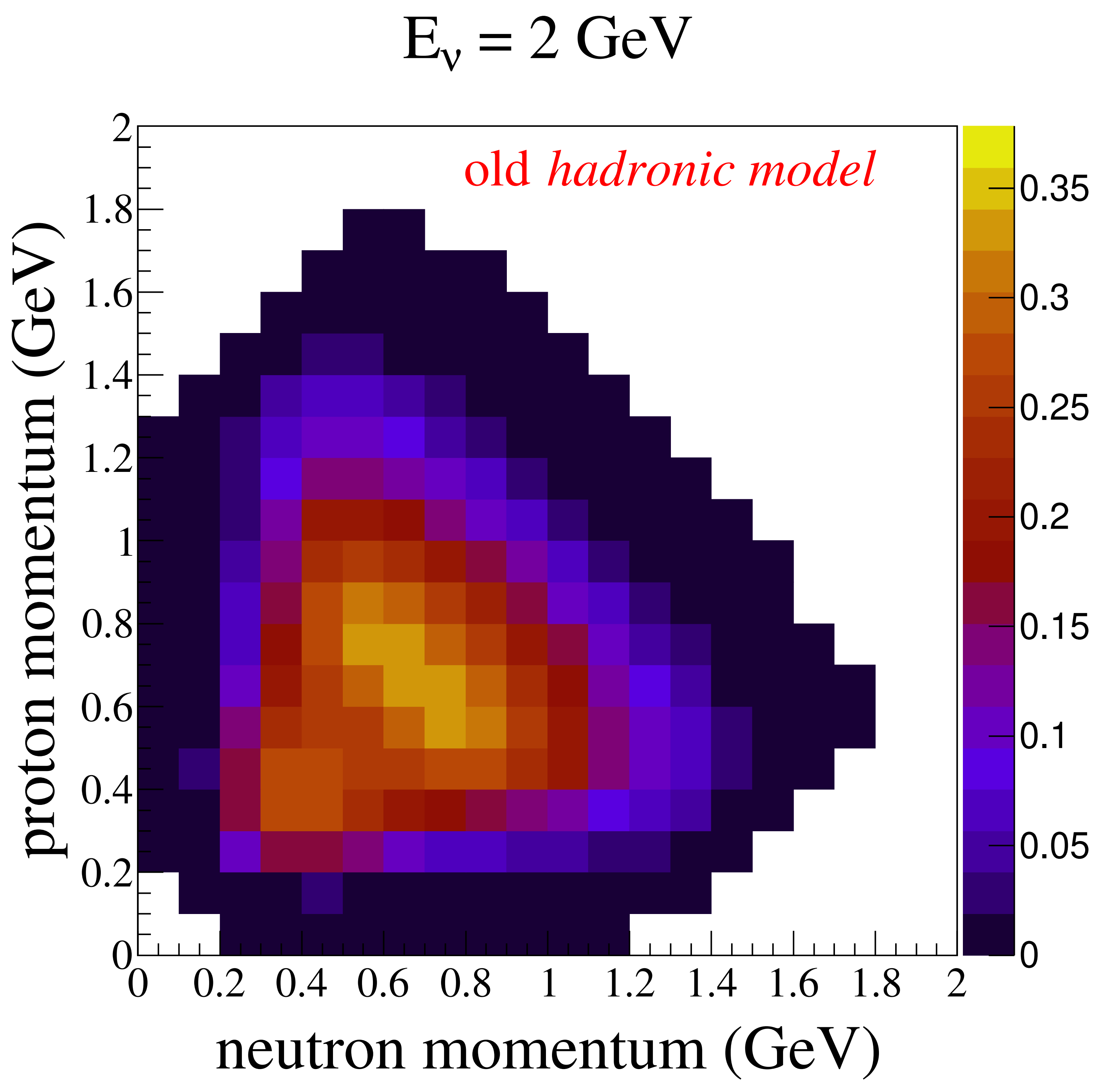

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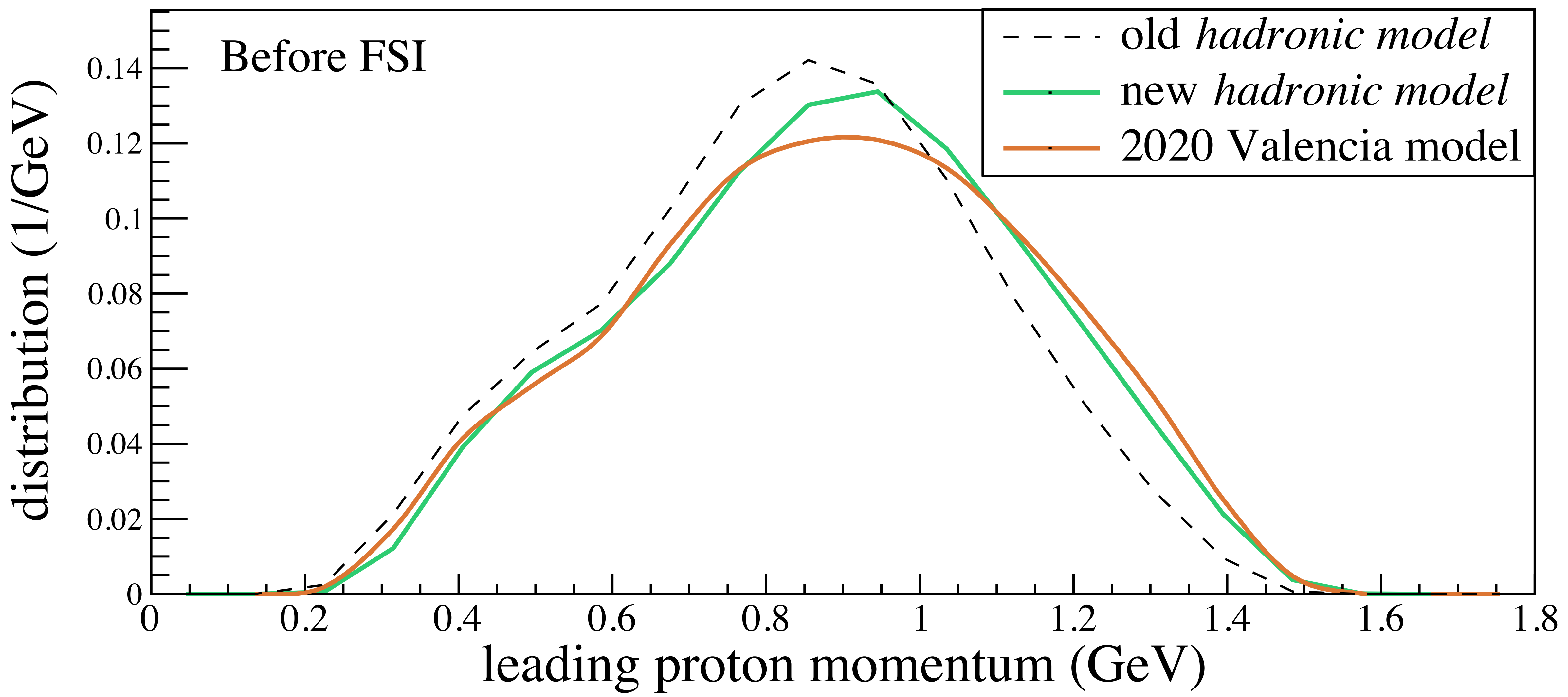
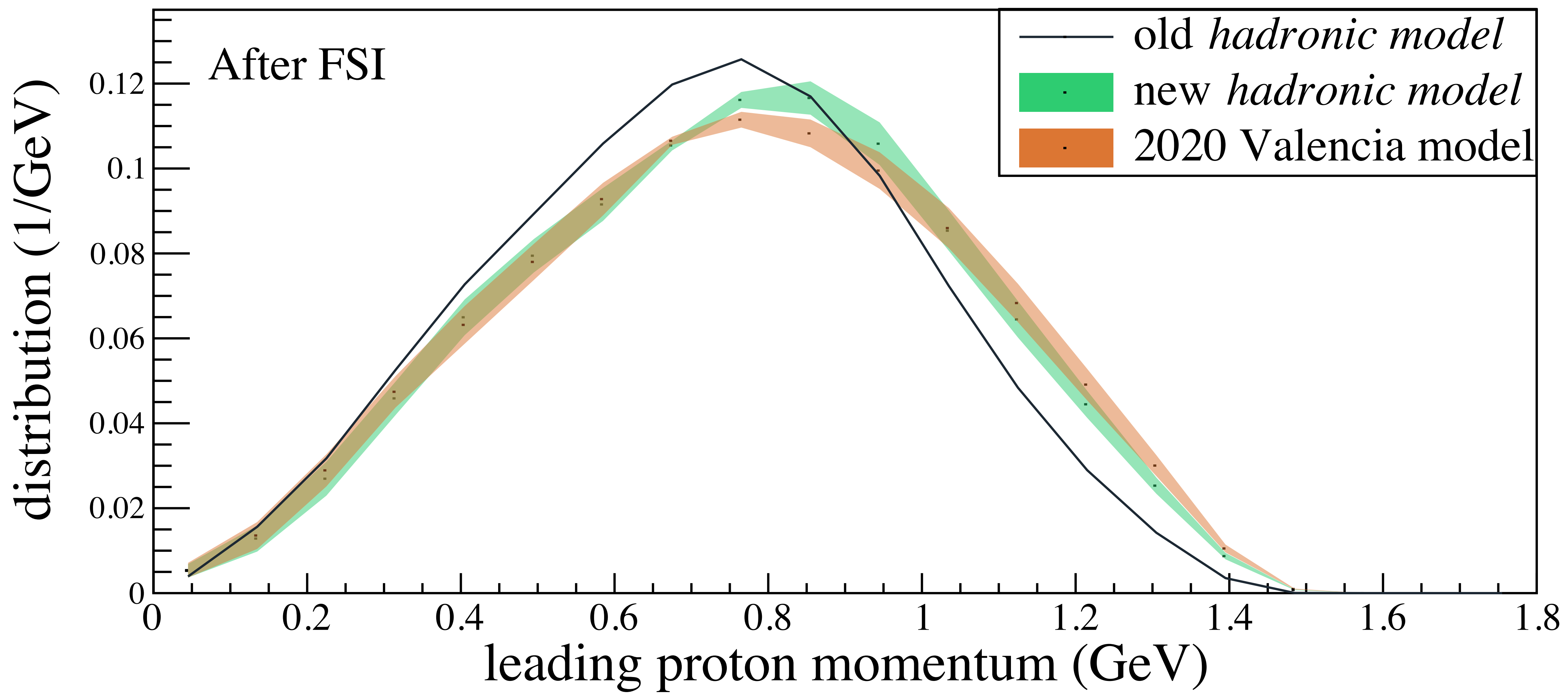
Impact of FSI

A distribution of momentum of the maximal proton





We claim that the difference is smaller than uncertainty of FSI !!

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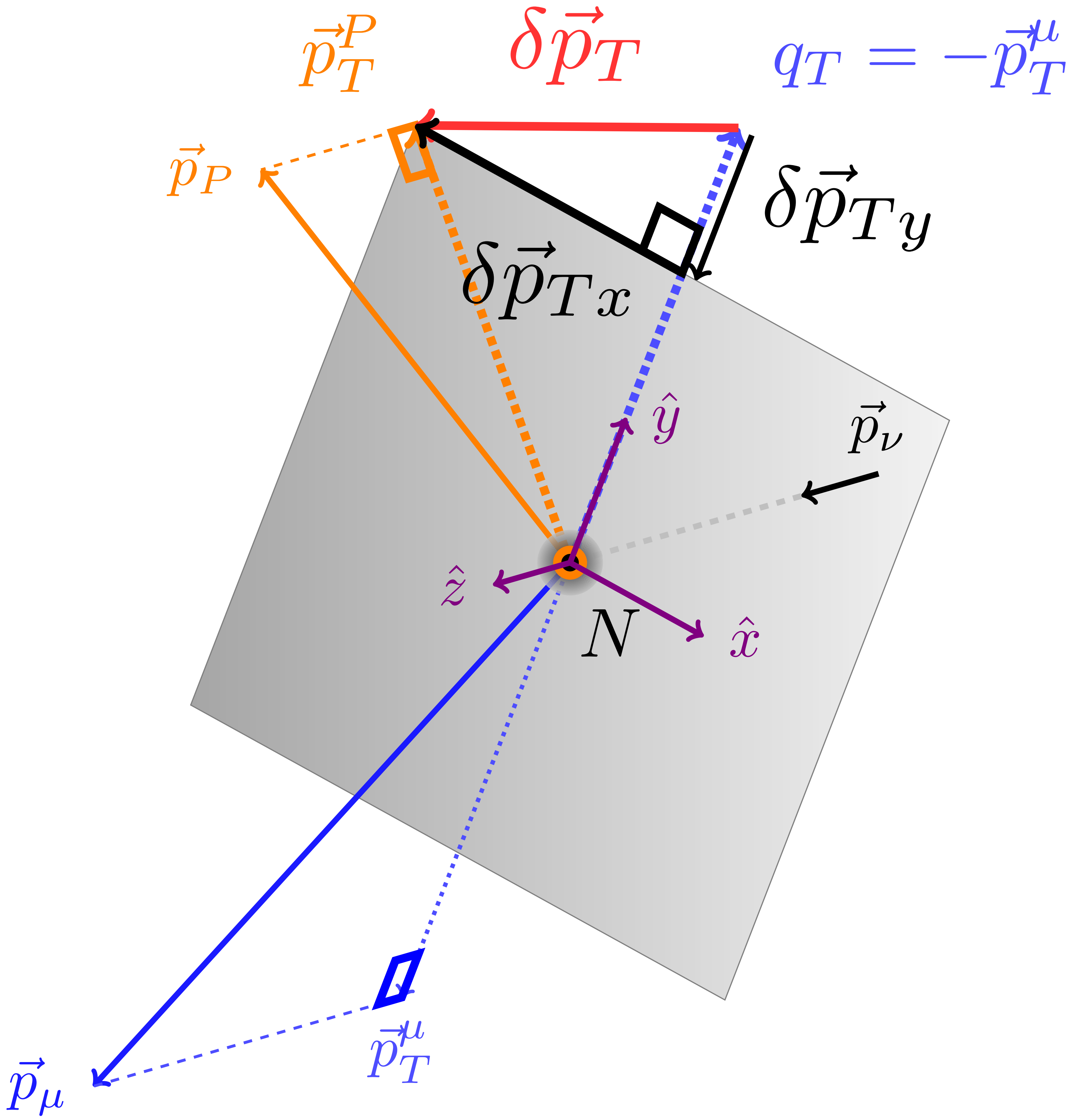
Transverse kinematic imbalance

Impact of nuclear effects



$\delta \mathbf{p}_T = 0$

For static and free nucleon !!

$\delta\alpha_T$

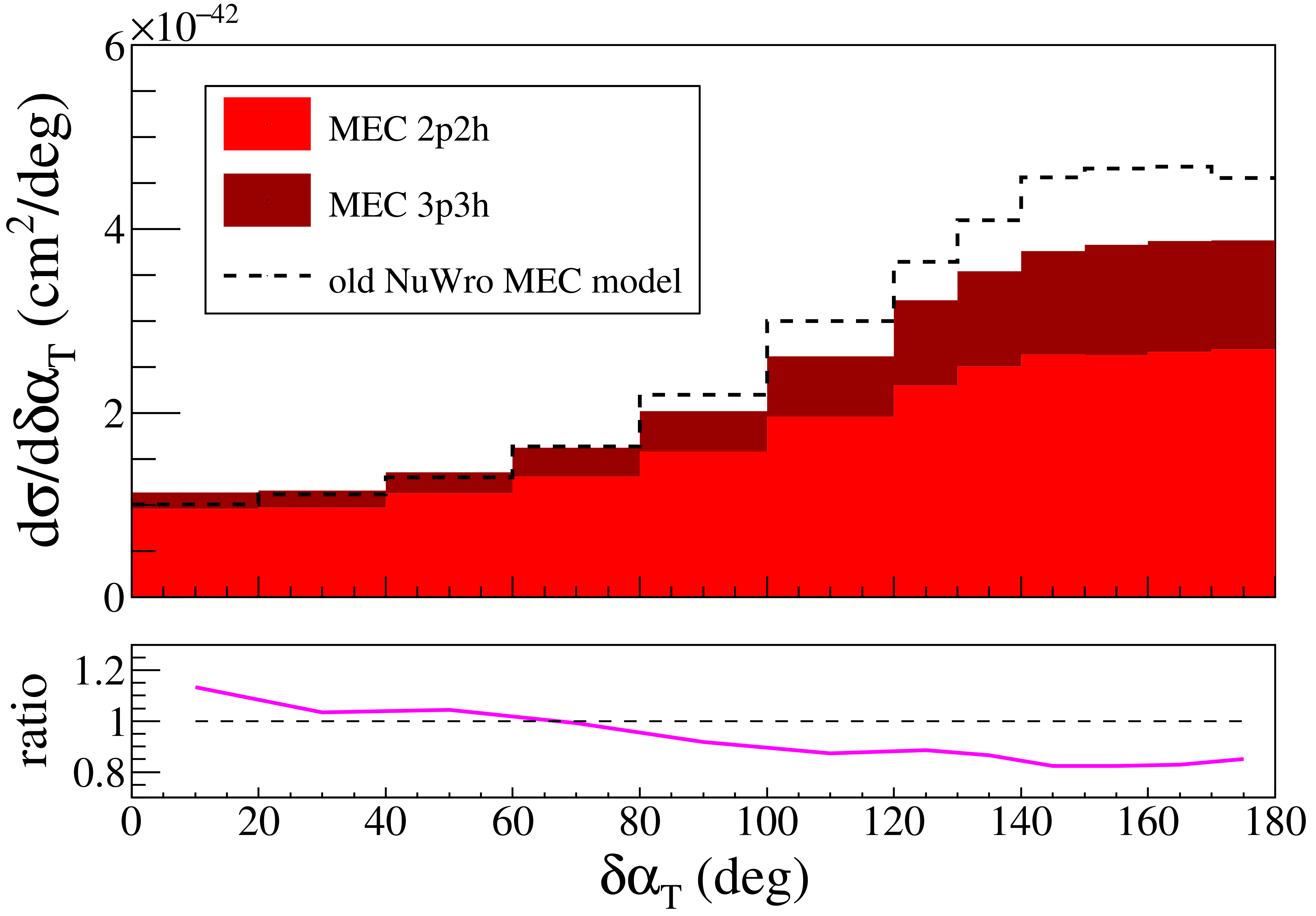
Uniform for Fermi motion !!

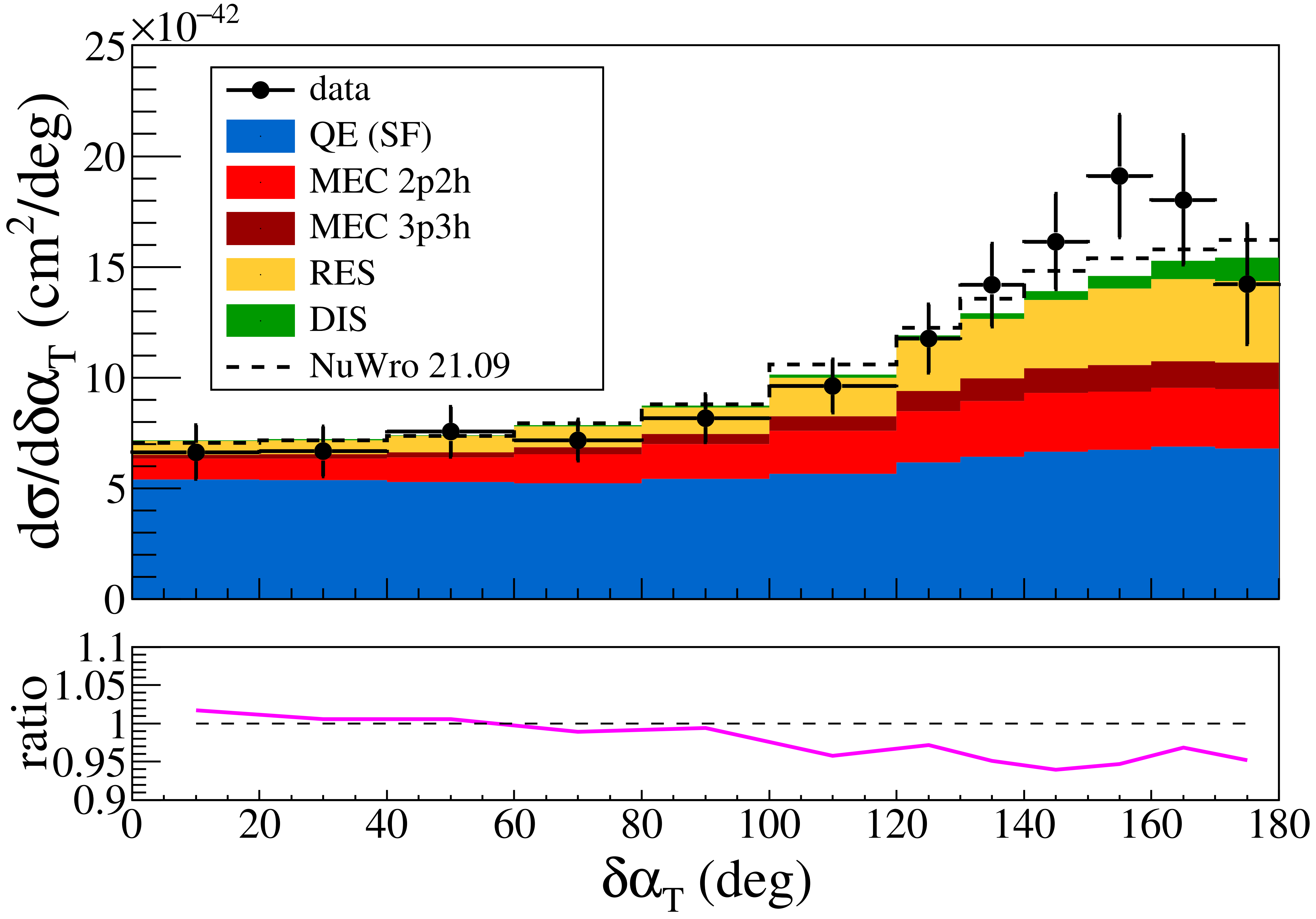
X.-G. Lu *et al.* Phys. Rev. D 101, (2020) 092001

T. Cai *et al.* Phys. Rev. Lett. 121, (2018) 022504

MINERνA CC1p0π data*

Comparison : old vs new MEC model





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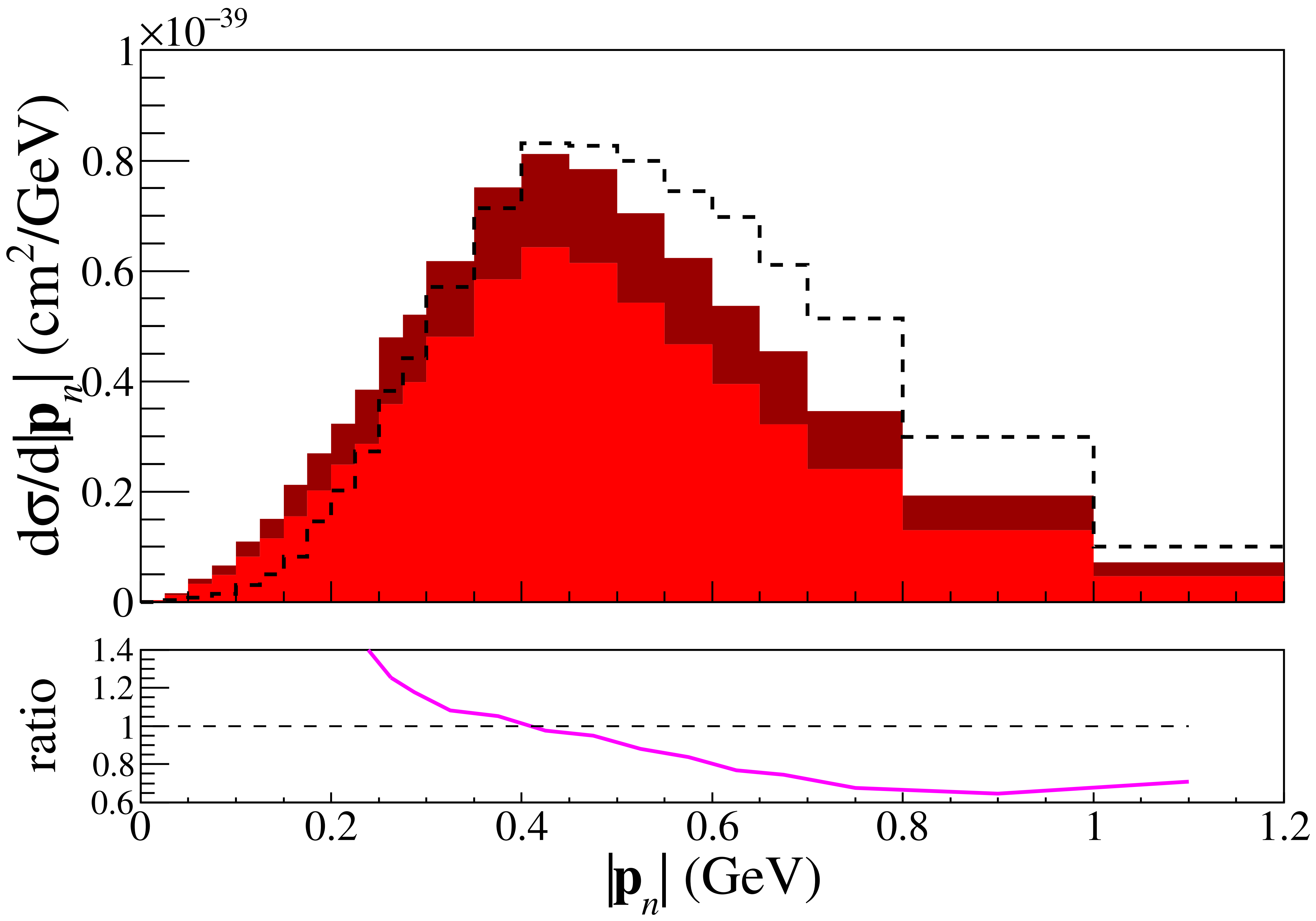

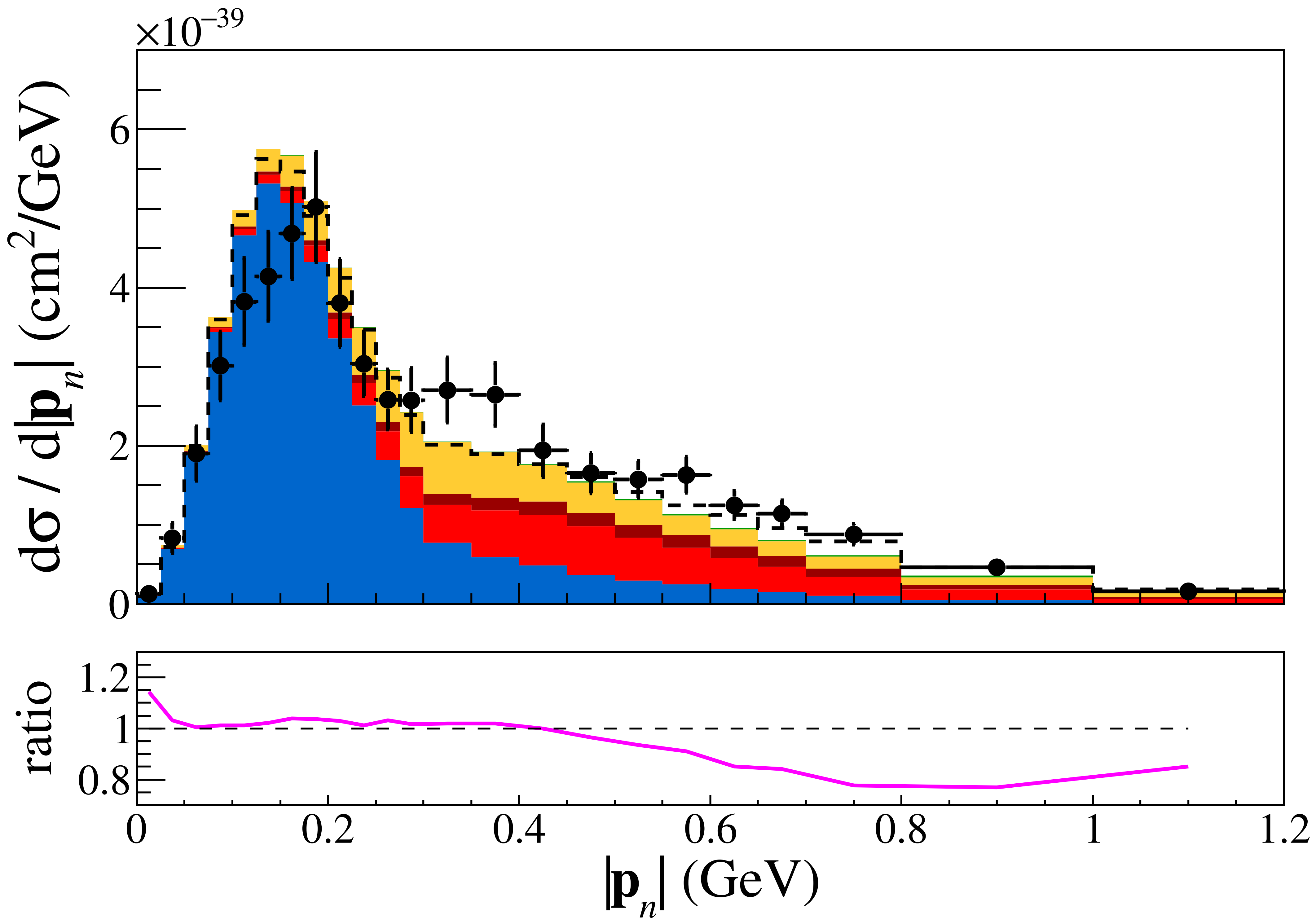

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X.-G. Lu *et al.* Phys. Rev. D 101, (2020) 092001

T. Cai *et al.* Phys. Rev. Lett. 121, (2018) 022504

MINERνA CC1p0π data*

χ^2/d.o.f comparison : old vs new MEC model

	Old MEC model	New MEC model
$d\sigma/d\lvert\mathbf{p}_p\rvert$	0.99 (24.76/25)	0.79 (19.72/25)
$d\sigma/d\theta_p$	1.73 (44.88/26)	1.62 (42.08/26)
$d\sigma/d\delta\Phi_T$	2.69 (63.78/23)	1.95 (44.82/23)
$d\sigma/d\delta\lvert\mathbf{p}_T\rvert$	3.05 (73.10/24)	2.82 (67.68/24)
$d\sigma/d\delta\alpha_T$	1.76 (21.13/12)	1.63 (19.52/12)
$d\sigma/d\lvert\mathbf{p}_n\rvert$	2.70 (64.85/24)	3.21 (77.09/24)

	Old MEC model		New MEC model	
	-0.2 - 0.2 (GeV)	-0.7 - 0.7 (GeV)	-0.2 - 0.2 (GeV)	-0.7 - 0.7 (GeV)
$\delta\mathbf{p}_{T_x}$	2.21 (17.69/8)	2.29 (64.25/28)	2.85 (22.77/8)	1.95 (54.49/28)
$\delta\mathbf{p}_{T_y}$	0.44 (3.51/8)	3.23 (90.44/28)	0.58 (4.63/8)	2.05 (57.55/28)

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Summary

- Development of a generalised hadronic model
  - The addition of new adjustable parameters to approximate correlations between the momenta of outgoing nucleons.
  - Any future MEC model, including the **upcoming Valencia 2024 model**, can also be incorporated into NuWro using the same hadronic model.
- Implementation of Valencia 2020 model
  - The nucleon phase space of the Valencia 2020 model can now be reproduced in NuWro.
- **Effect on hadronic observables**
  - We observe that hadronic observables are sensitive to how we model the correlations between momenta of outgoing nucleons.


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Thank you for your attention

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