New multi-nucleon knockout model in NuWro

Hemant Prasad

@WhoAmI

- PhD 3rd year student at University of Wrocław

- I work on NuWro
  - MEC model
  - Reweighting of FSI

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Outline

- Introduction
- Exclusive MEC model (*what do I mean by exclusive?*)
- NuWro implementation of the exclusive MEC model
- Data comparison
- Summary

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...	
	...2%

...(2021) 112008

...ce(NOvA)	
$\sigma_{\nu N}$ and FSI	7.7%
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M. A. Acero *et al.* Phys Rev. D 98 (2018) 032012

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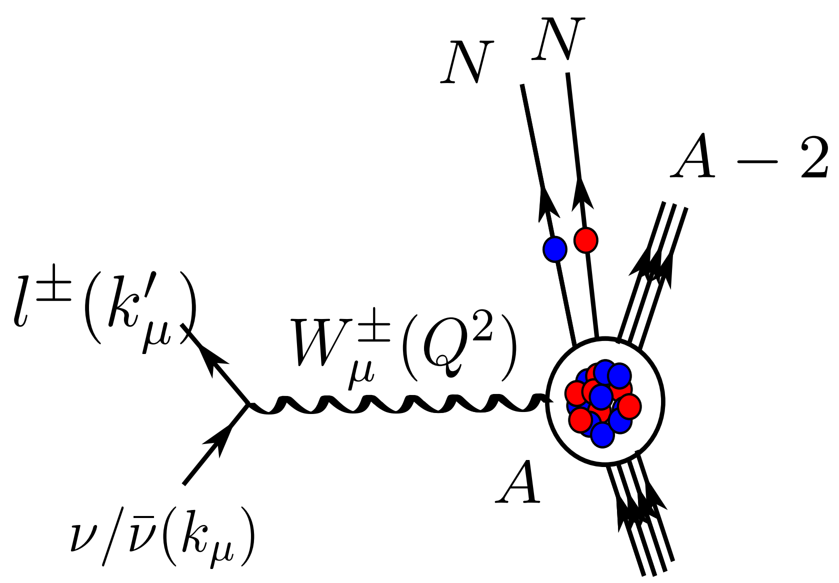
- Expect **1000-2000** for DUNE/HK

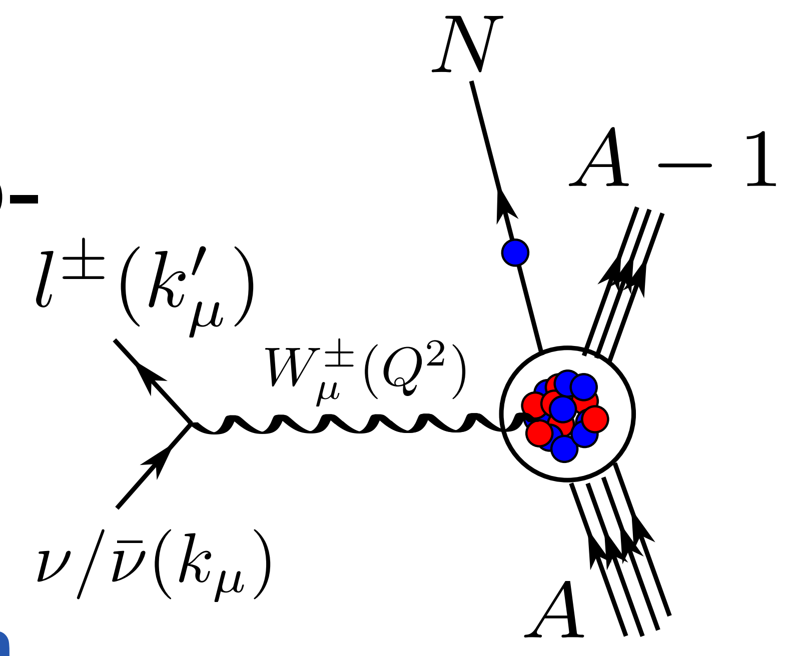
Motivation

Neutrino-nucleus interactions

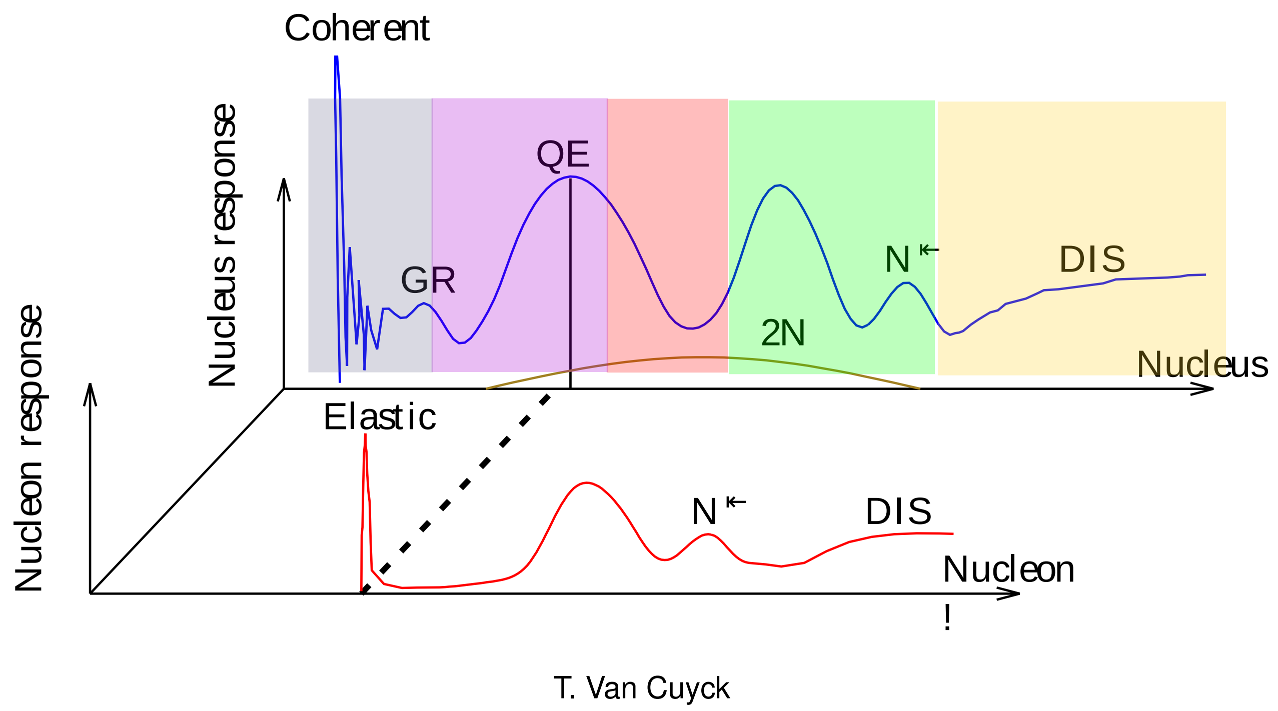
- Accelerated ν-beams have broad spectra of energy.
- Different mechanism emerges on **different energy scales.**
- **Quasi Elastic (QE)** dominates at sub-GeV energies.
- Significant contributions from **meson exchange currents (MEC)** at sub-GeV level.

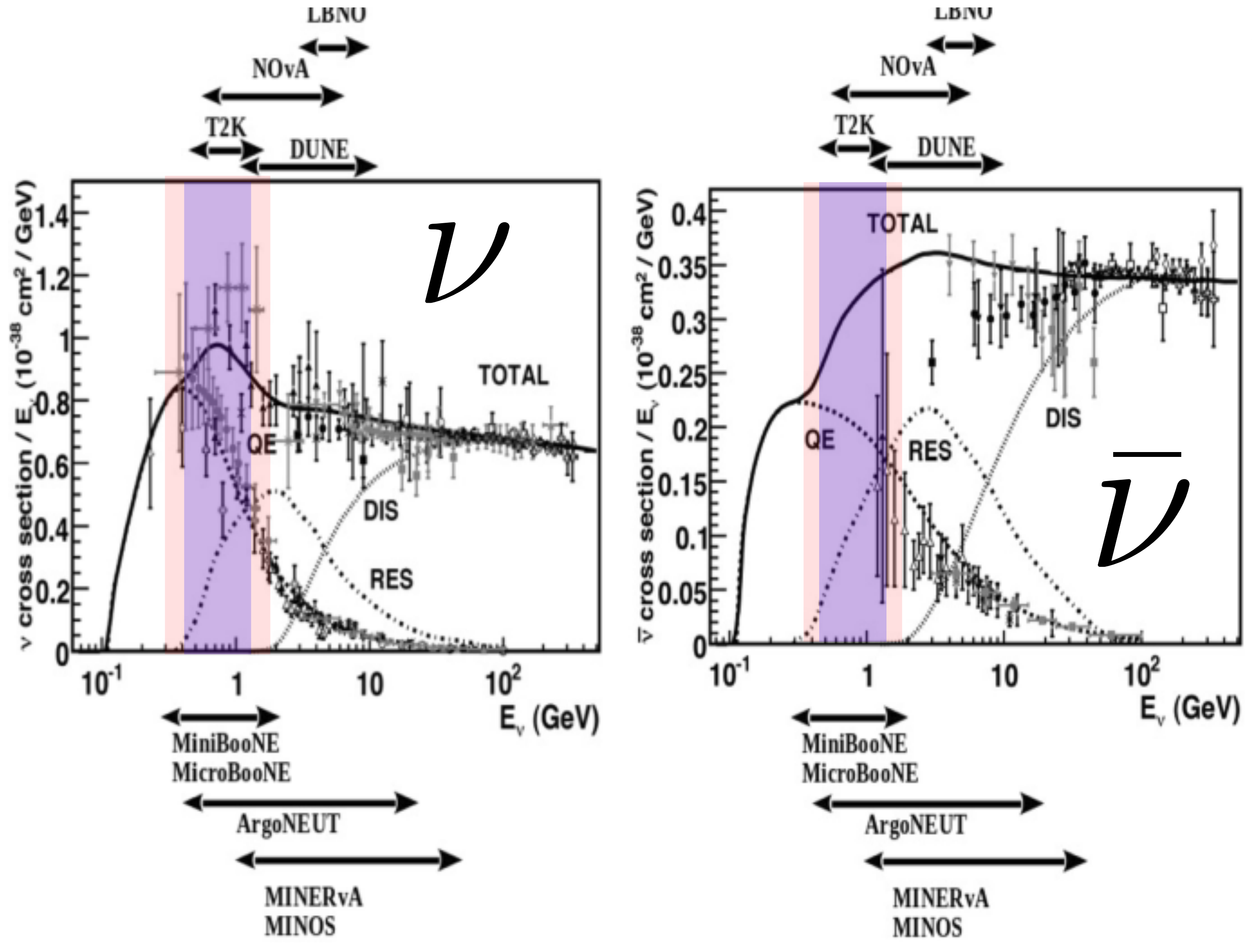


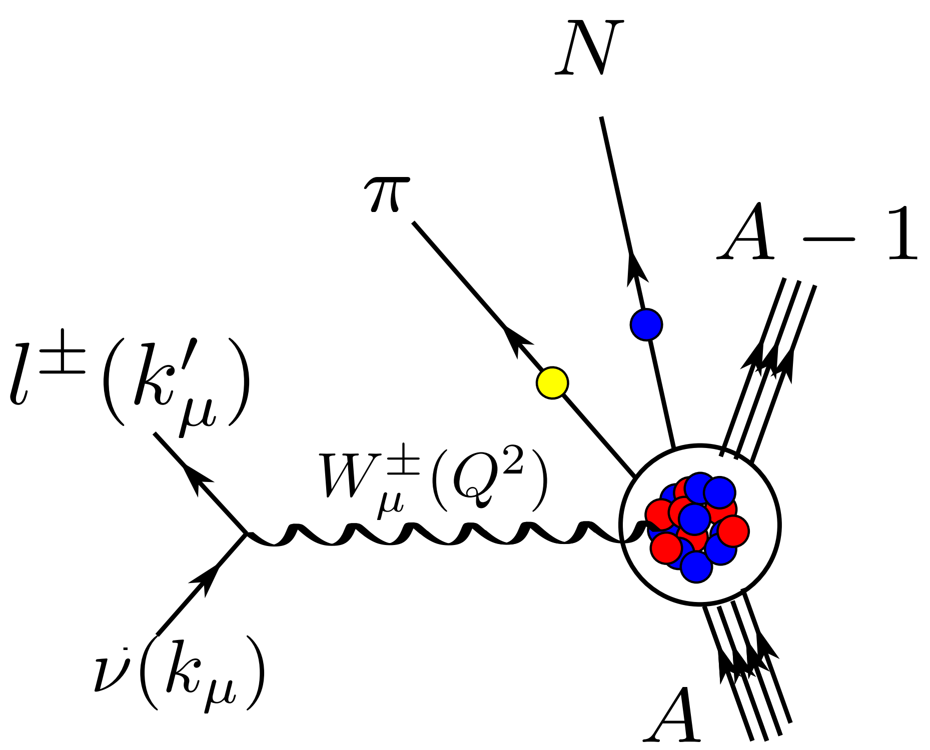
2-Body Current (2p2h)



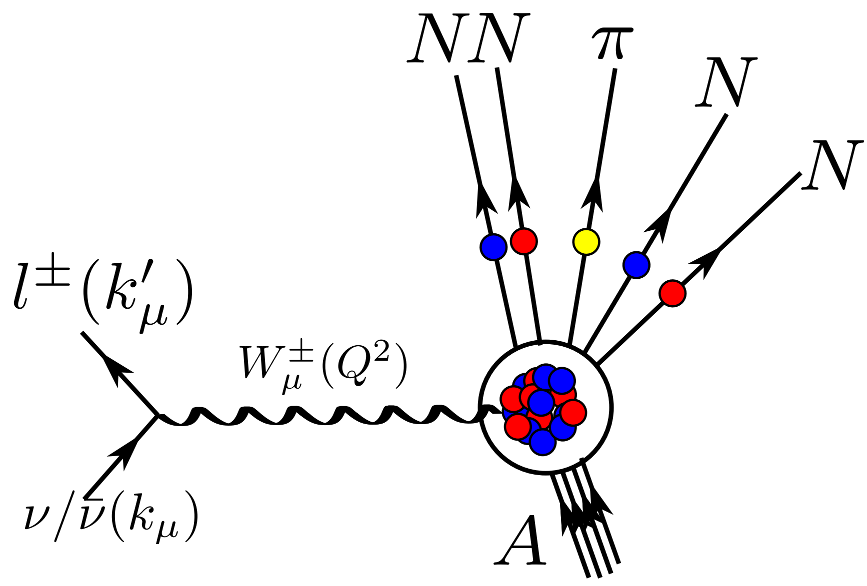
Quasi Elastic Scattering







Resonance Scattering



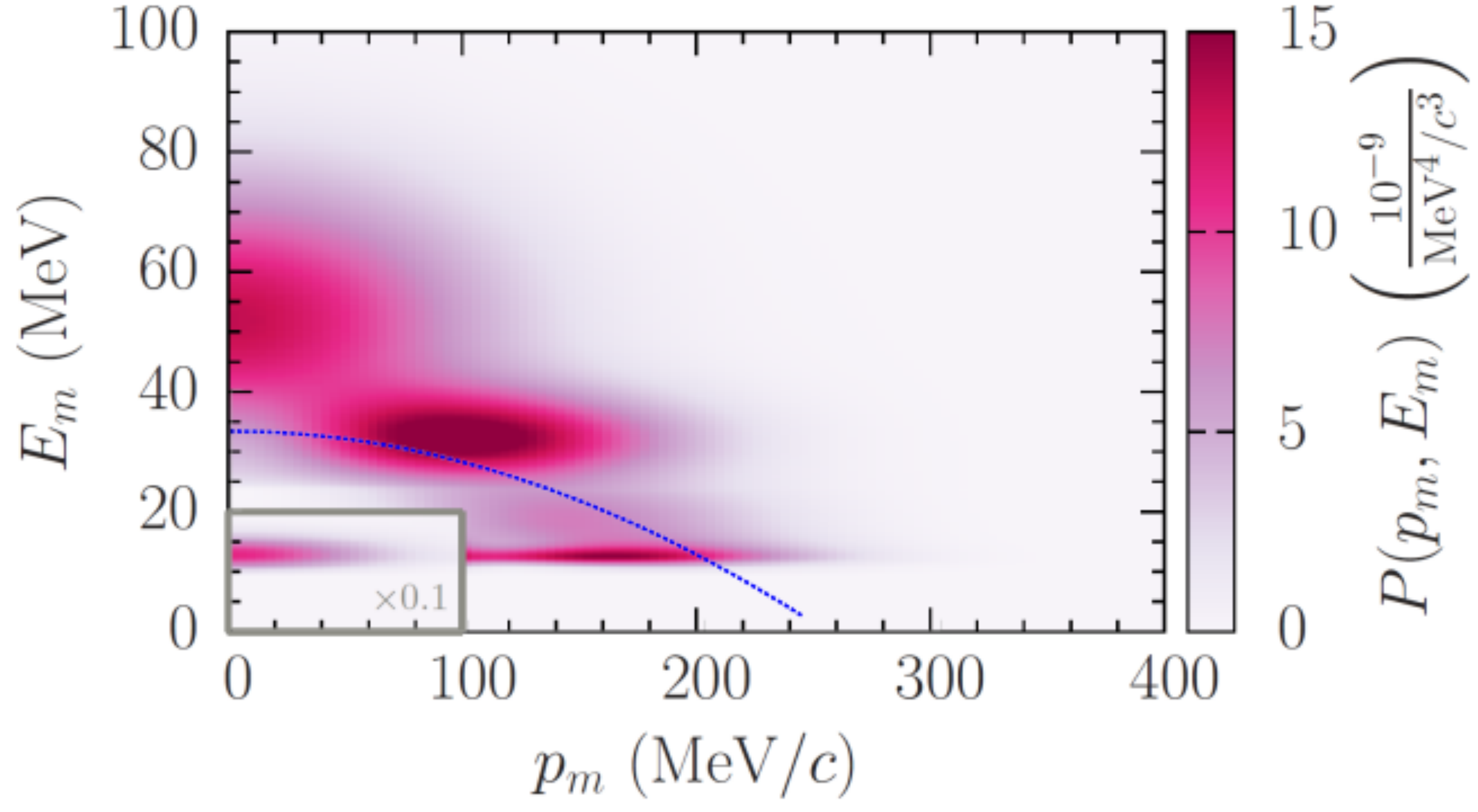
DIS (Deep Inelastic Scattering)

Motivation

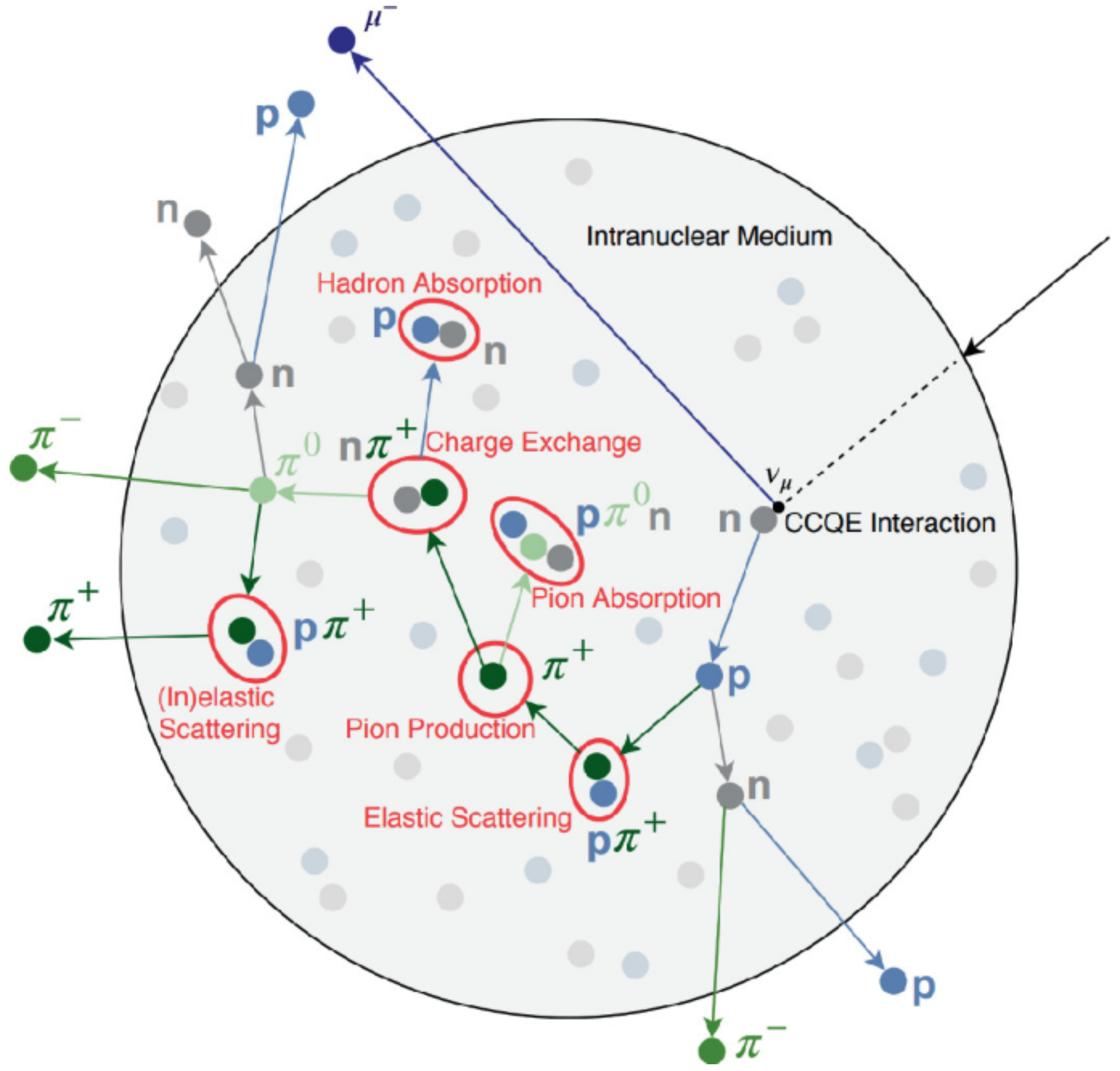
L. Jiang *et al.*, Phys. Rev. D 105 (2022) 112002,

Phys. Rev. D 107 (2023) 012005 (2023)

Nuclear effects



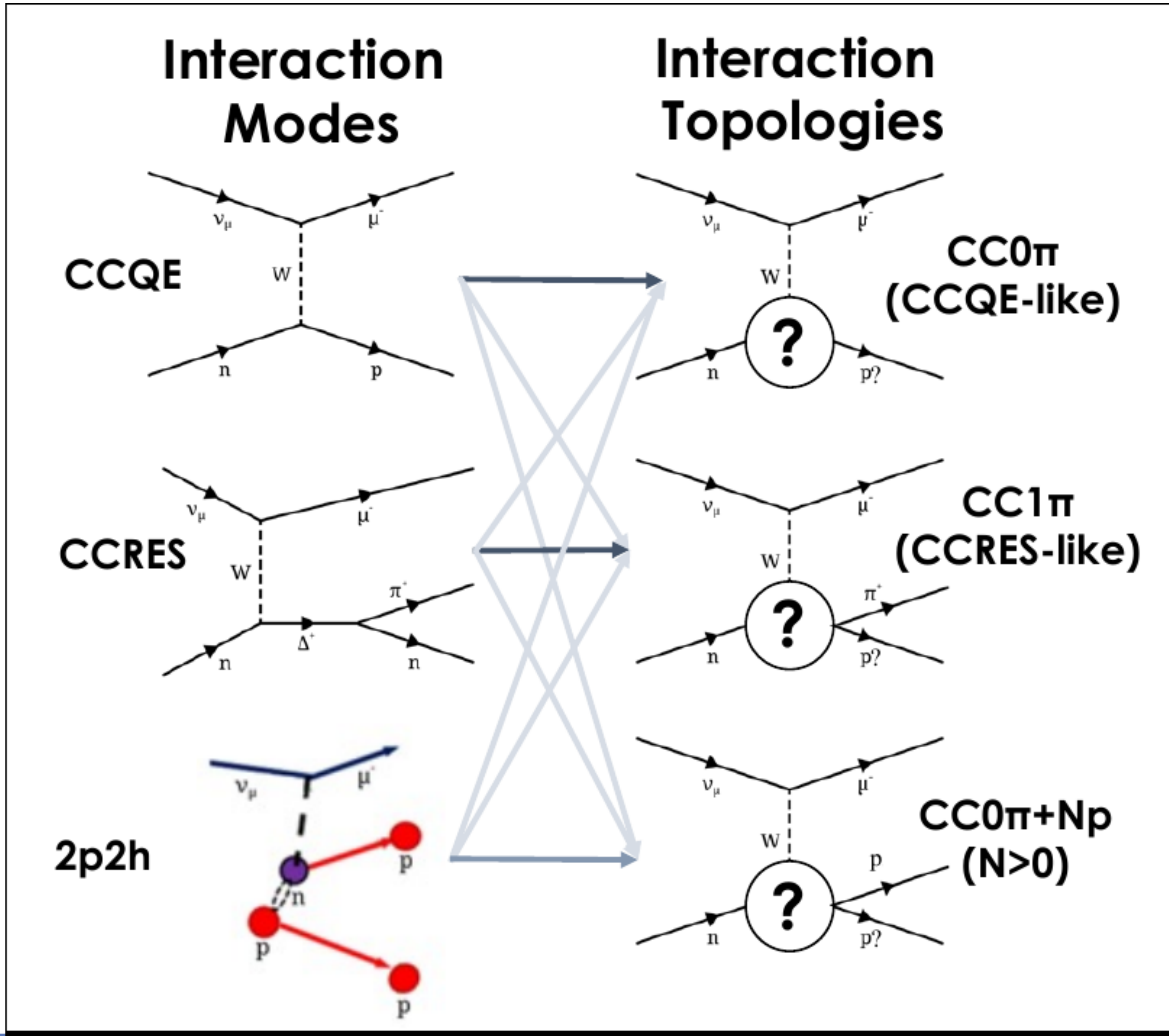
- **Nuclear removal energy and Fermi momentum**
  - Nucleons are moving targets
  - Nucleons are bound inside the nucleus, so some amount of energy is needed to free them
  - Most models predict that removal energy and Fermi motion should be correlated
- **Multi-nucleon interactions**
  - Nucleons interact with each other inside the nucleus (short-range correlations, or meson exchange currents)
  - Multi-nucleon “np-nh” final states
- **Final state interactions (FSI)**
  - Hadrons don’t exit the nucleus cleanly
  - They can re-interact inside the nucleus
  - Distorts kinematics and changes the final state topology
  - Full calculation also changes inclusive cross section



Motivation

Consequences of nuclear effects

- Nuclear effects significantly alter the cross section with respect to the nucleon case
- FSI distort the interaction channel

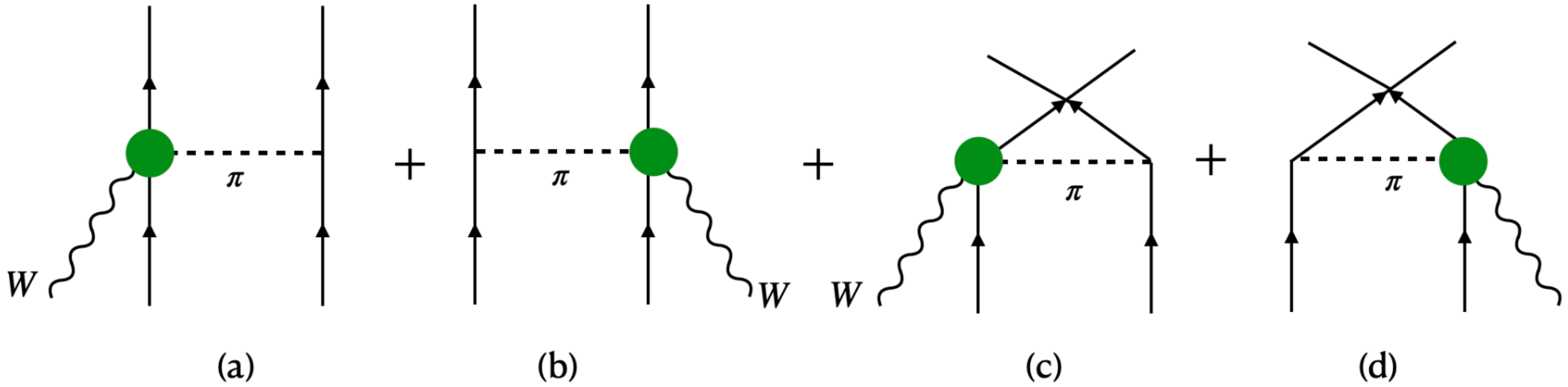


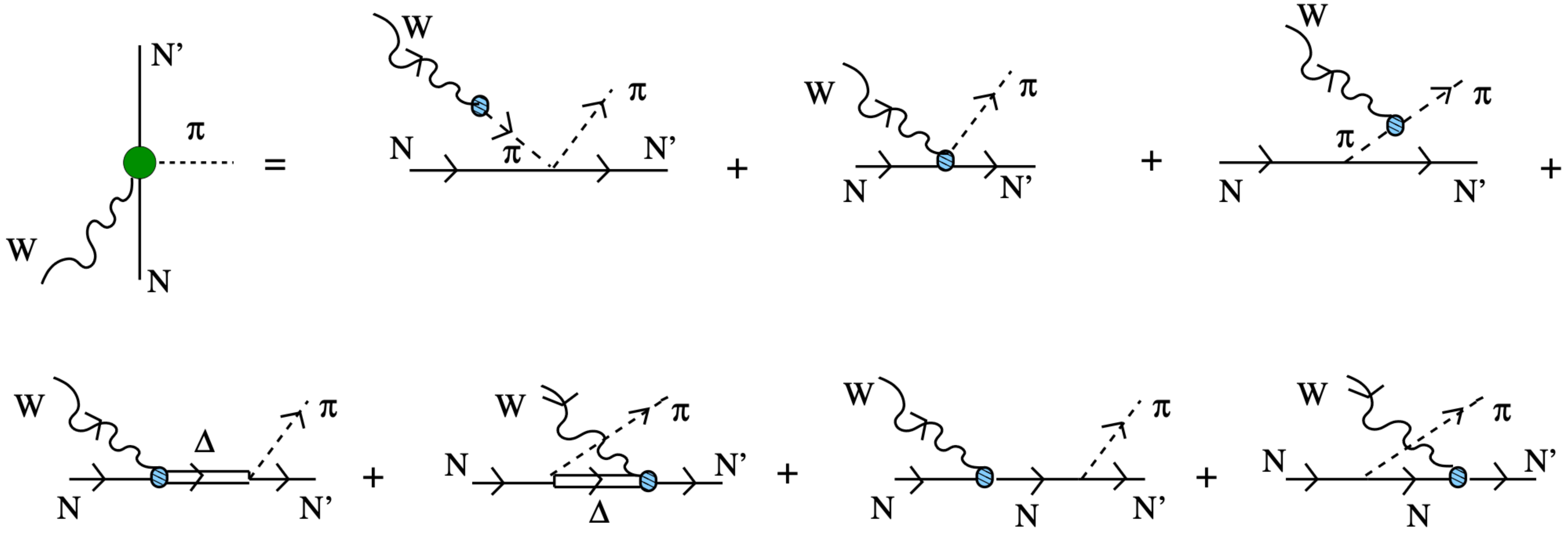
- **I will focus on the “np-nh” interaction mode, which occurs via MEC.**

Motivation

Meson exchange currents

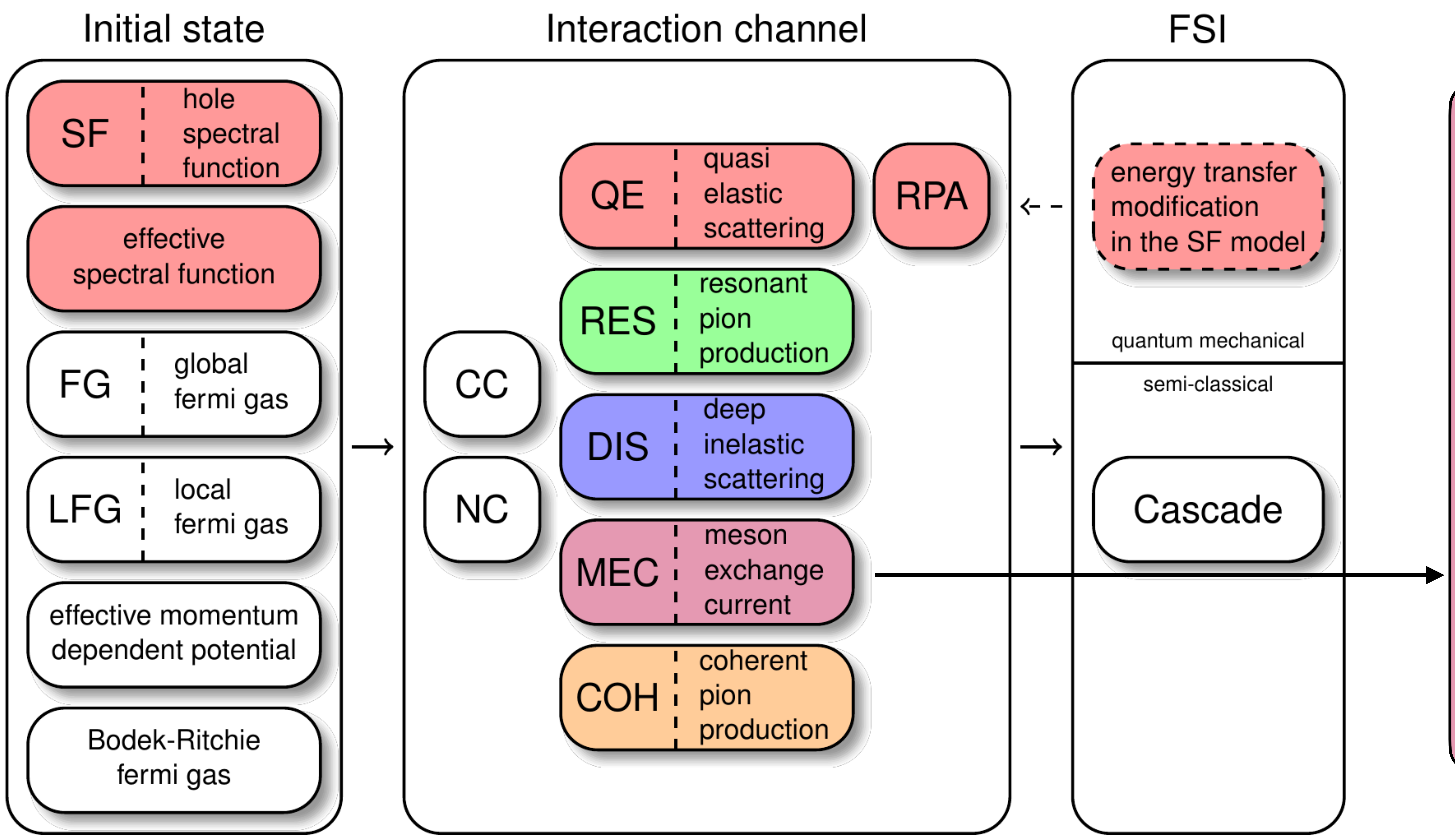
- Motivated by electron-nucleus scattering data.
- A **multi-nucleon knockout** process.
- Energy exchange between nucleons is through in-medium meson production.
- **Significant contribution around ~ 1 GeV.** An important interaction mode for all upcoming neutrino experiments.
- Dominated by two body 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.





NuWro Monte Carlo generator

Schematics



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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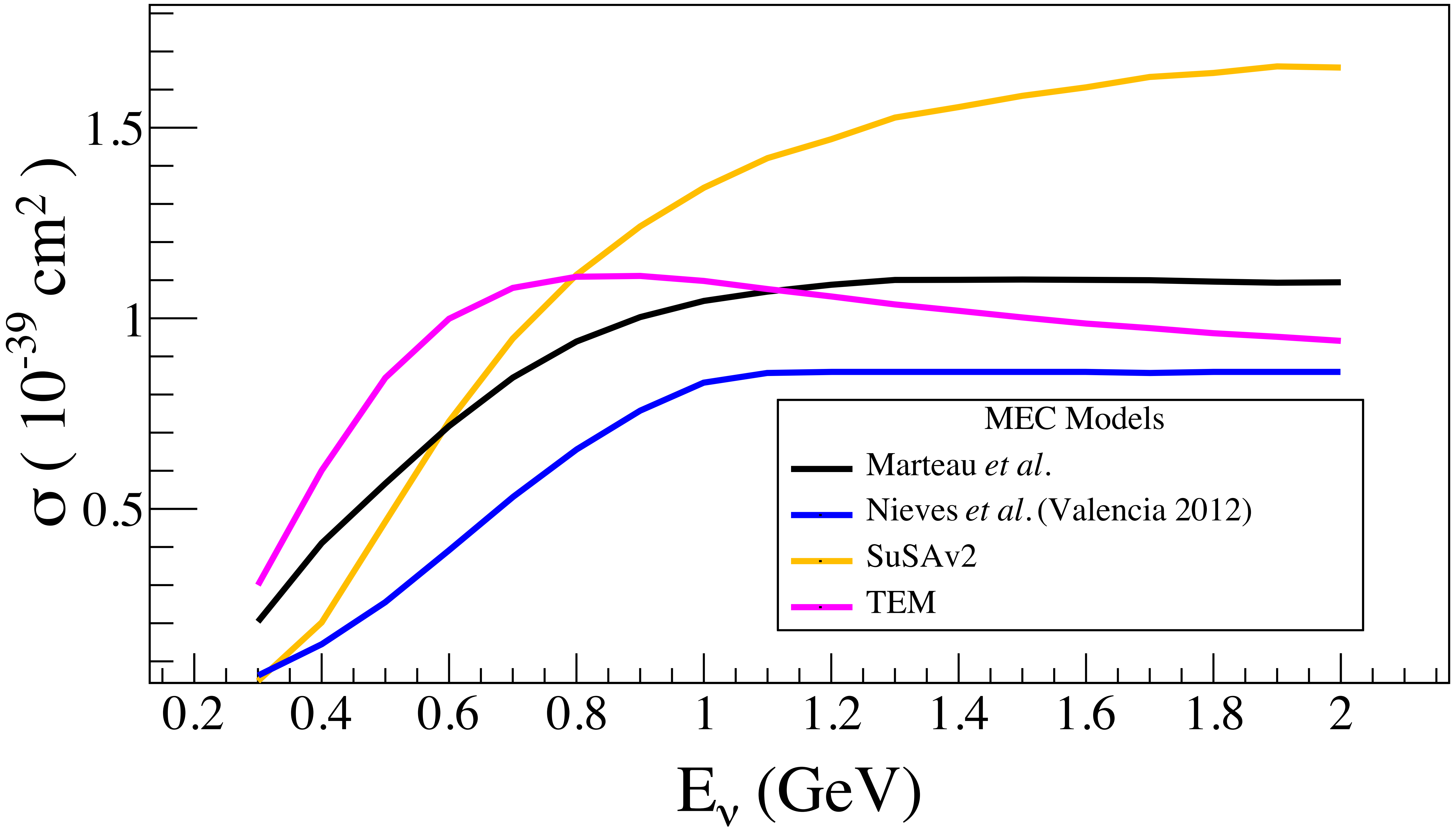

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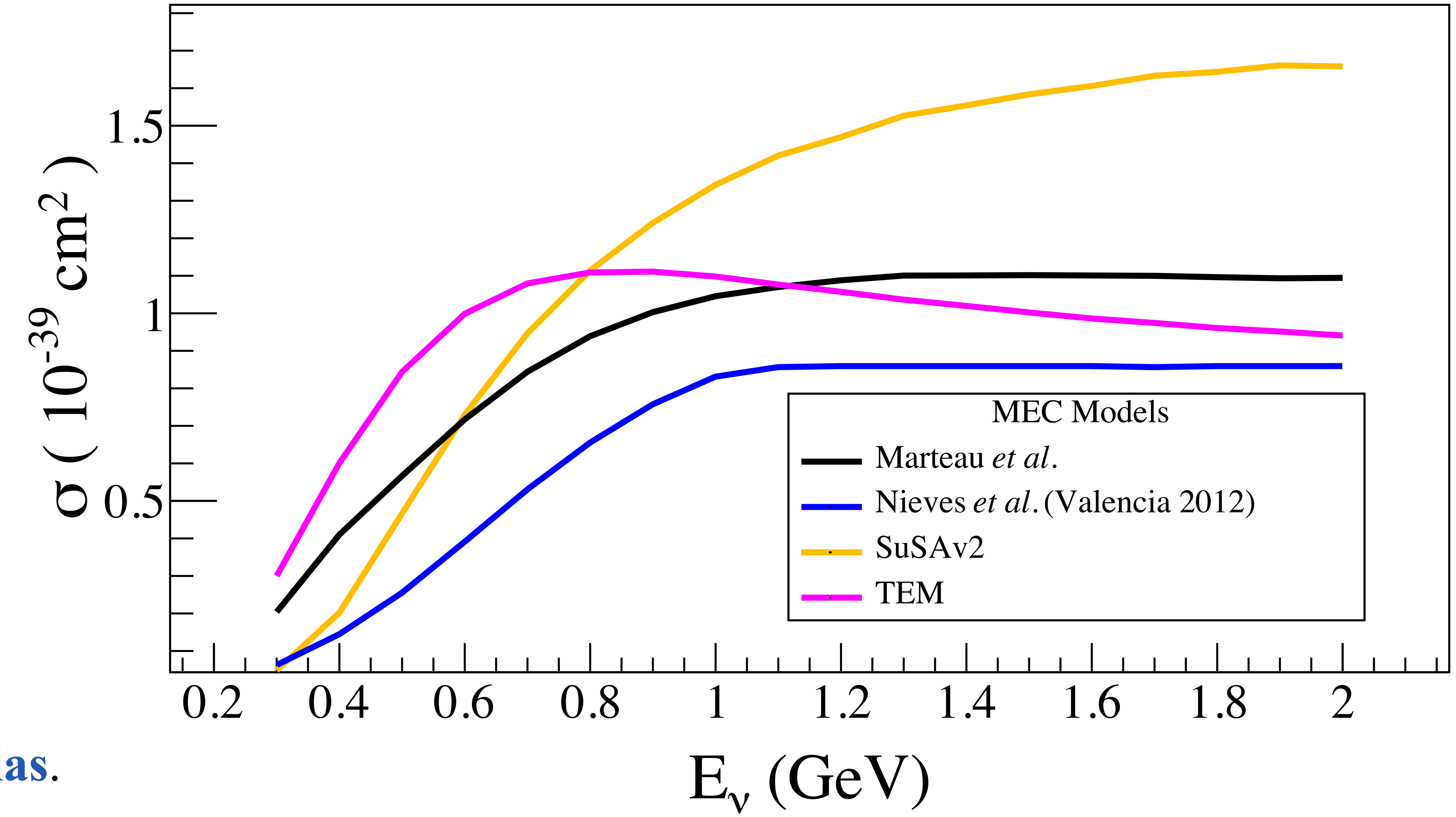


- Their implementation and coverage differs.
  - TE model is implemented with **analytic formulas**.
  - Implementation of Valencia 2012 and SuSav2 models are done using **tabularization of the five response functions** $W^{\mu\nu}(q,\omega)$.
  - Marteau model is implemented in a **hybrid way**.

- 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

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

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

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.

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

Generate outgoing nucleons

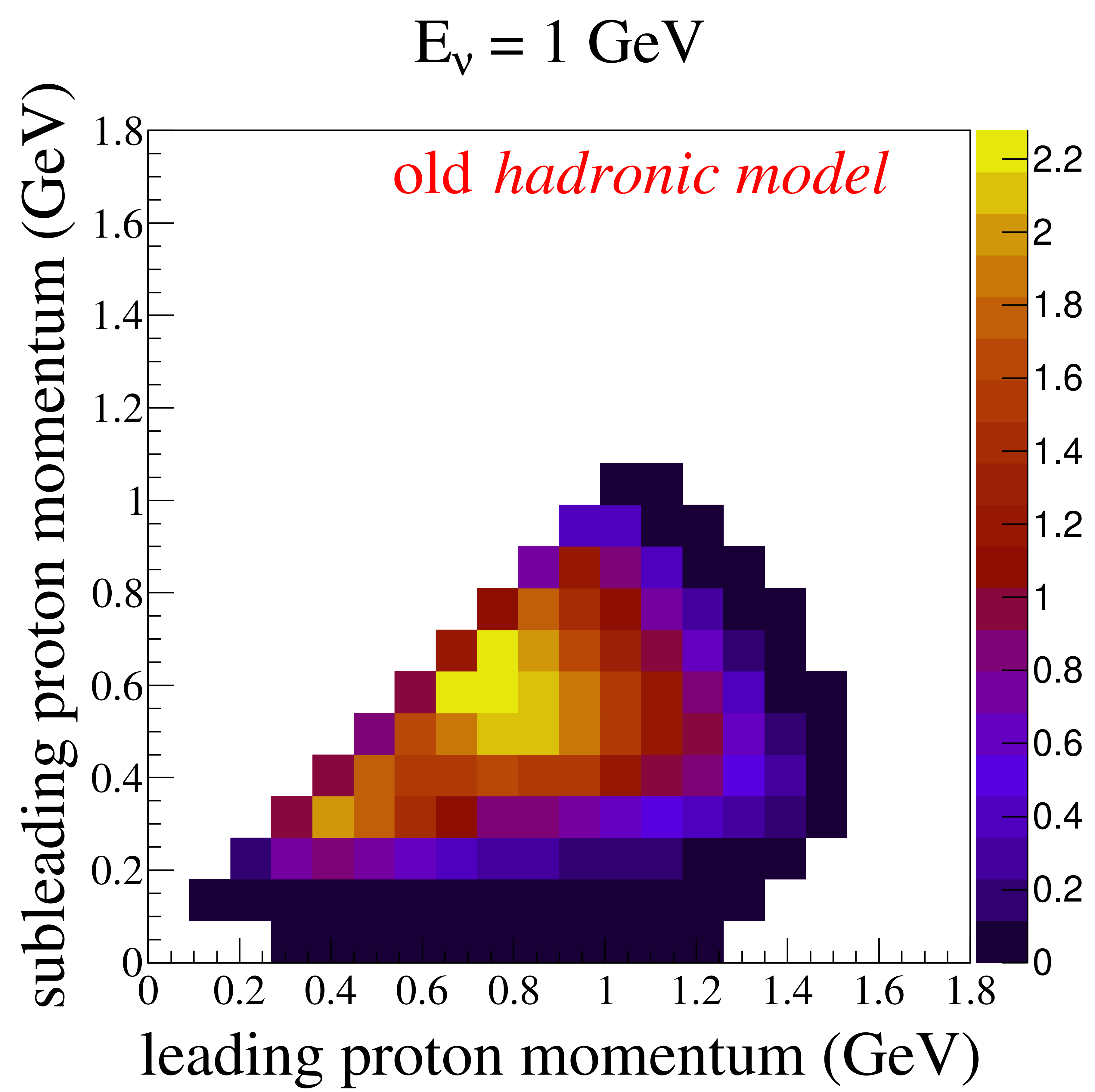
Compute event weight

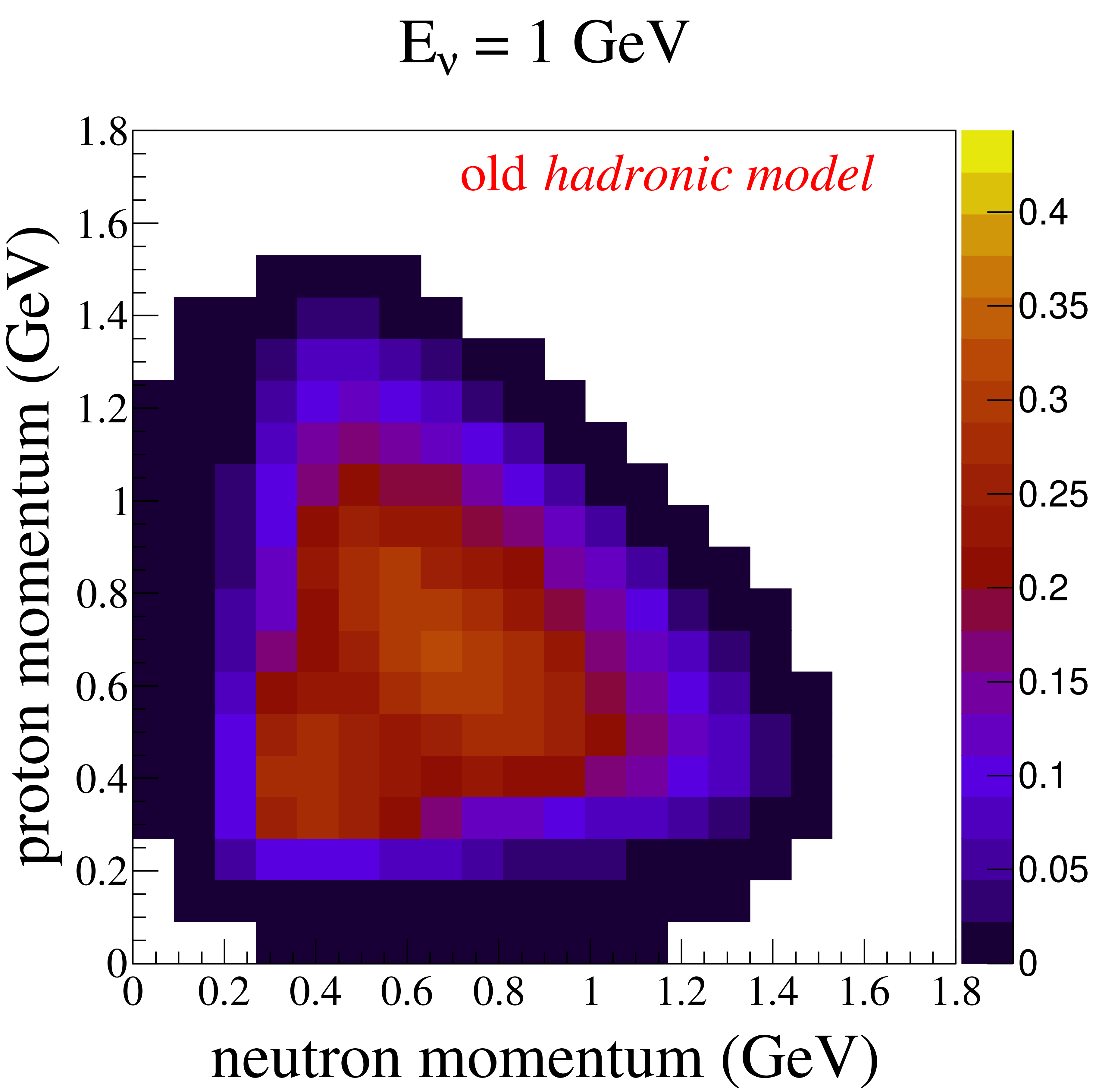
Store the event

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

Implementation of MEC models

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

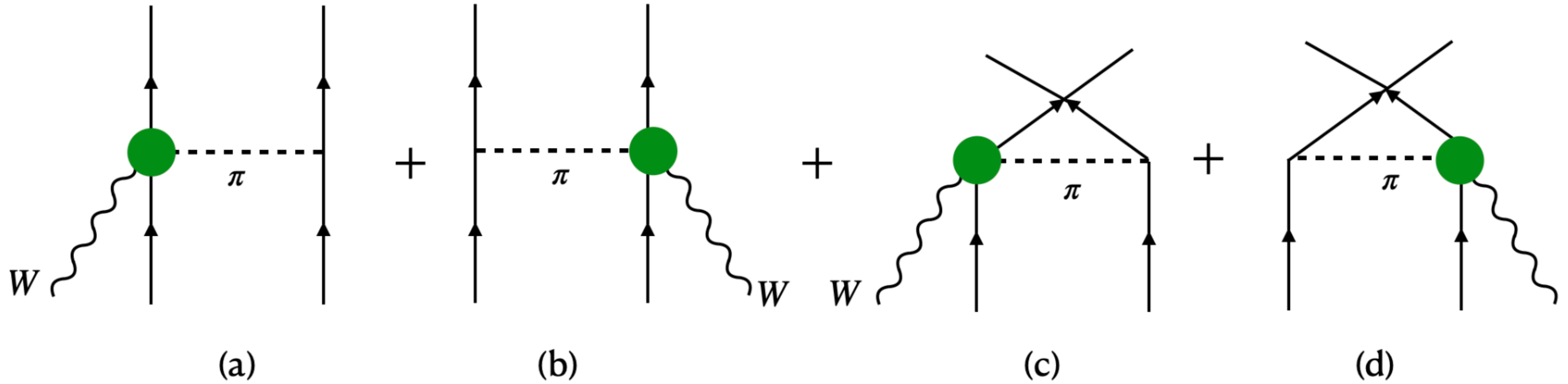




2020 Valencia model

2020 Valencia model

Theoretical model



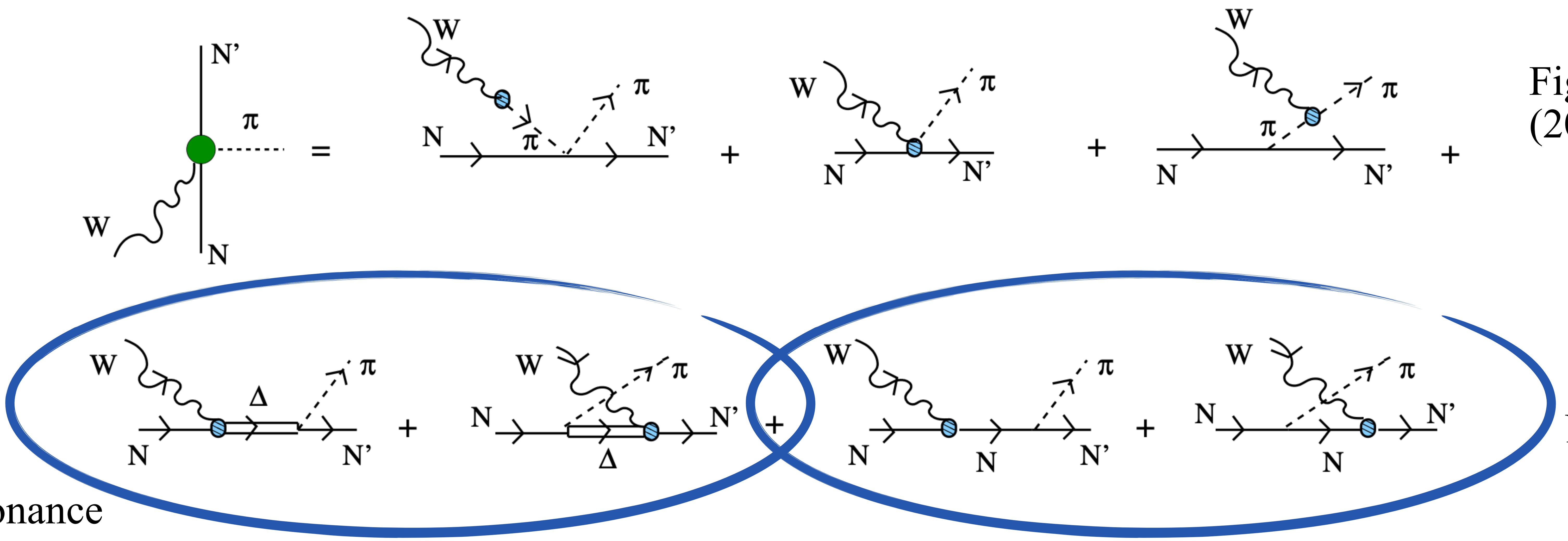


Figure from J.E. Sobczyk *et. al.* Phys. Rev. C. 102 (2020) 024601

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.

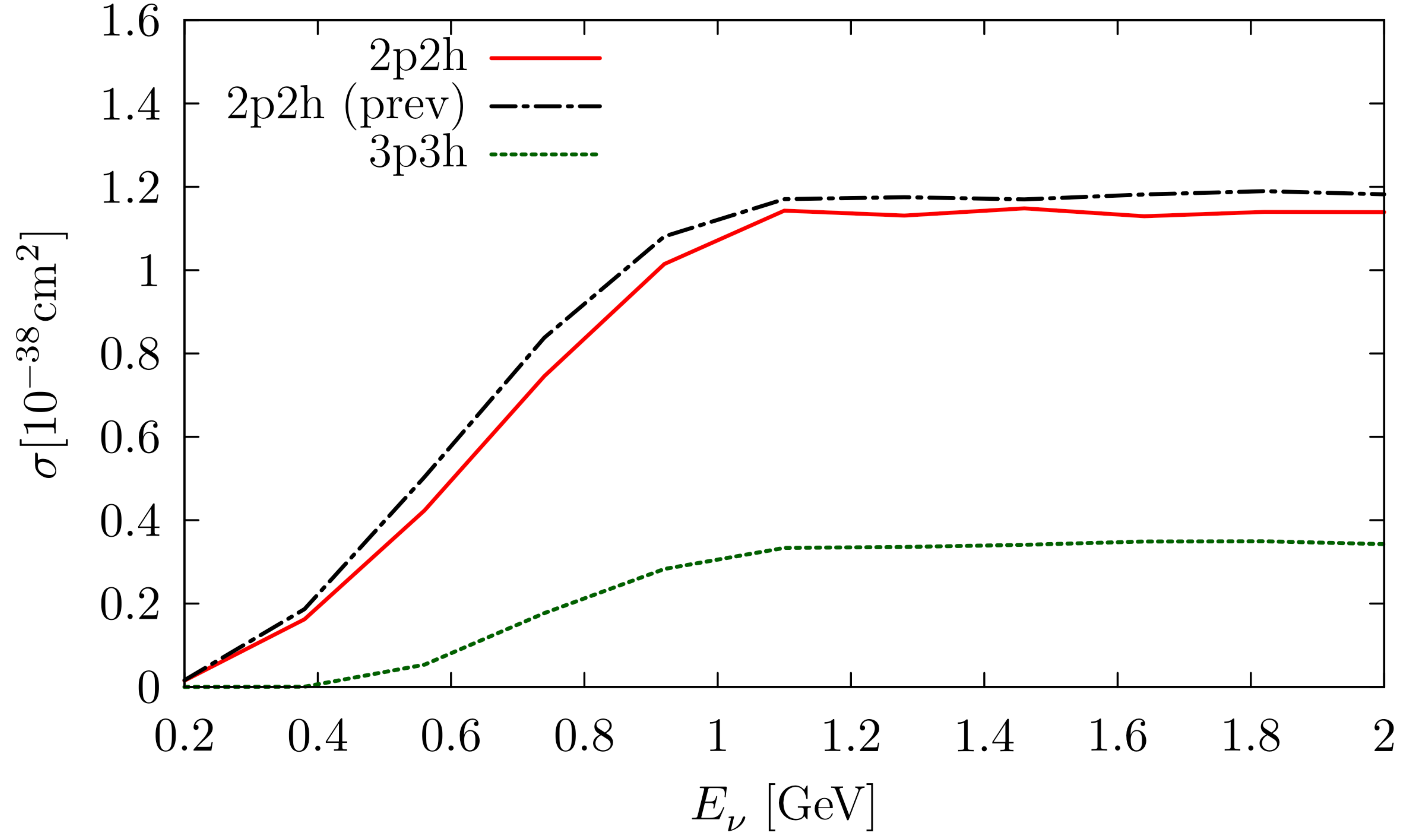
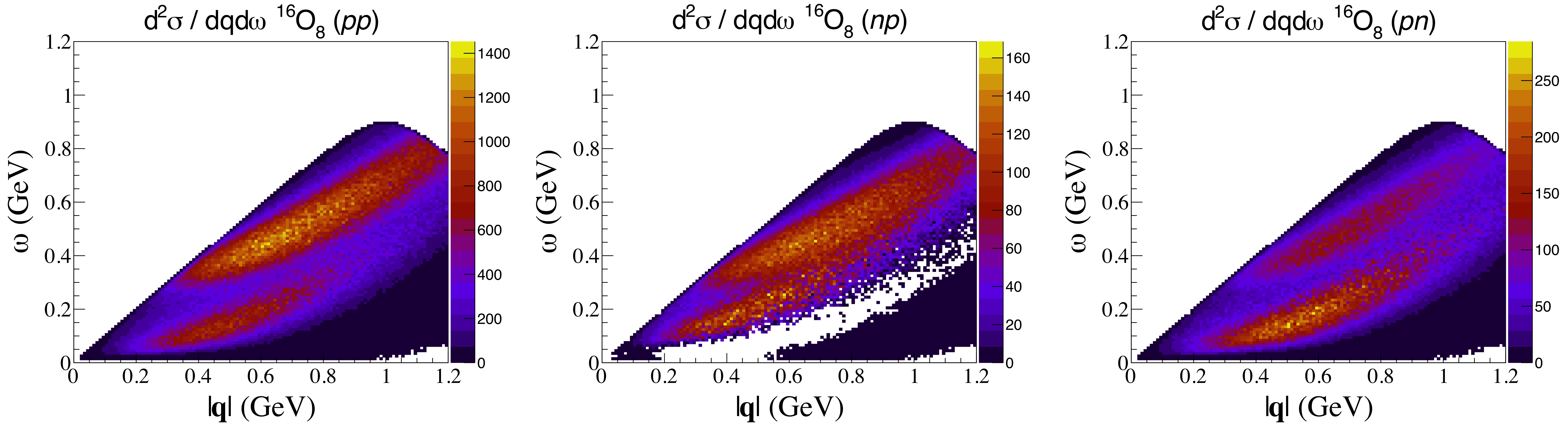


Figure from J.E. Sobczyk *et. al.* Phys. Rev. C. 102 (2020) 024601

2020 Valencia model

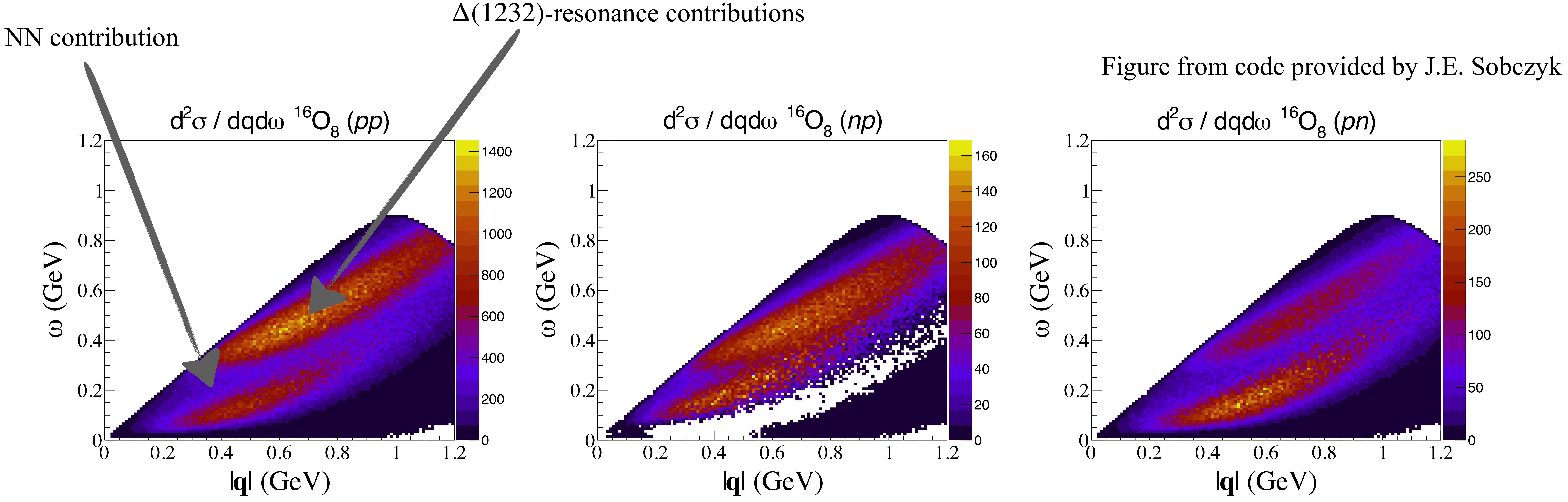
J. E. Sobczyk *et al.* Phys. Rev. C. 102 (2020) 024601

Figure from code provided by J.E. Sobczyk



2020 Valencia model

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



2020 Valencia model

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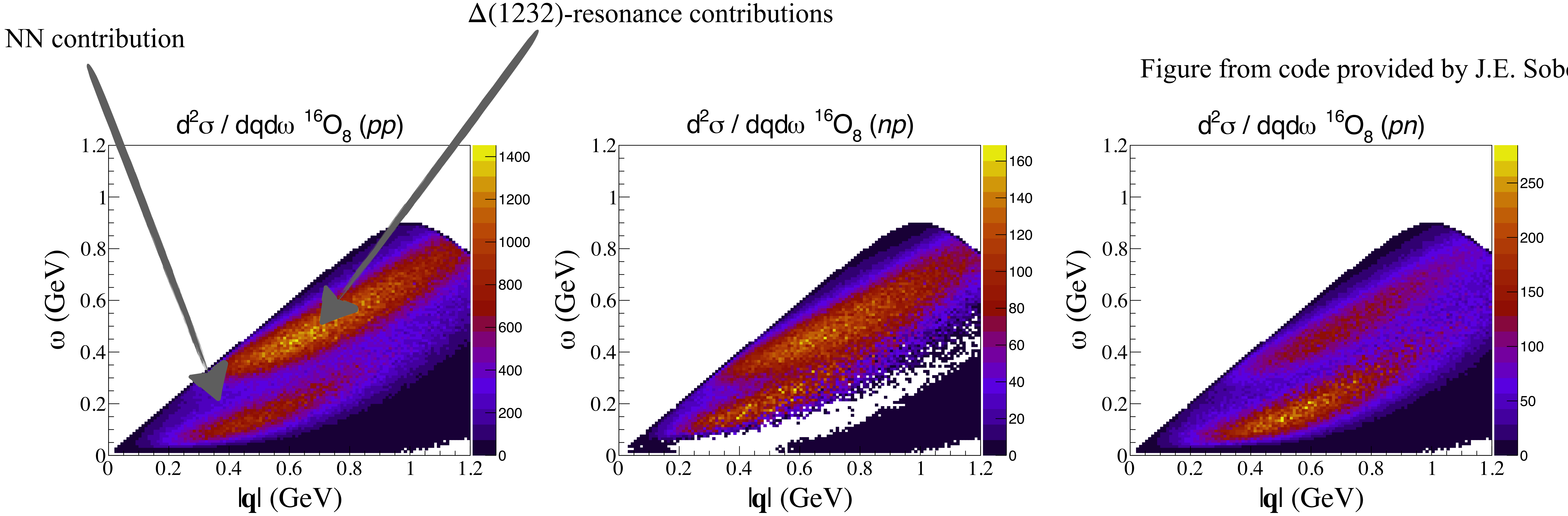


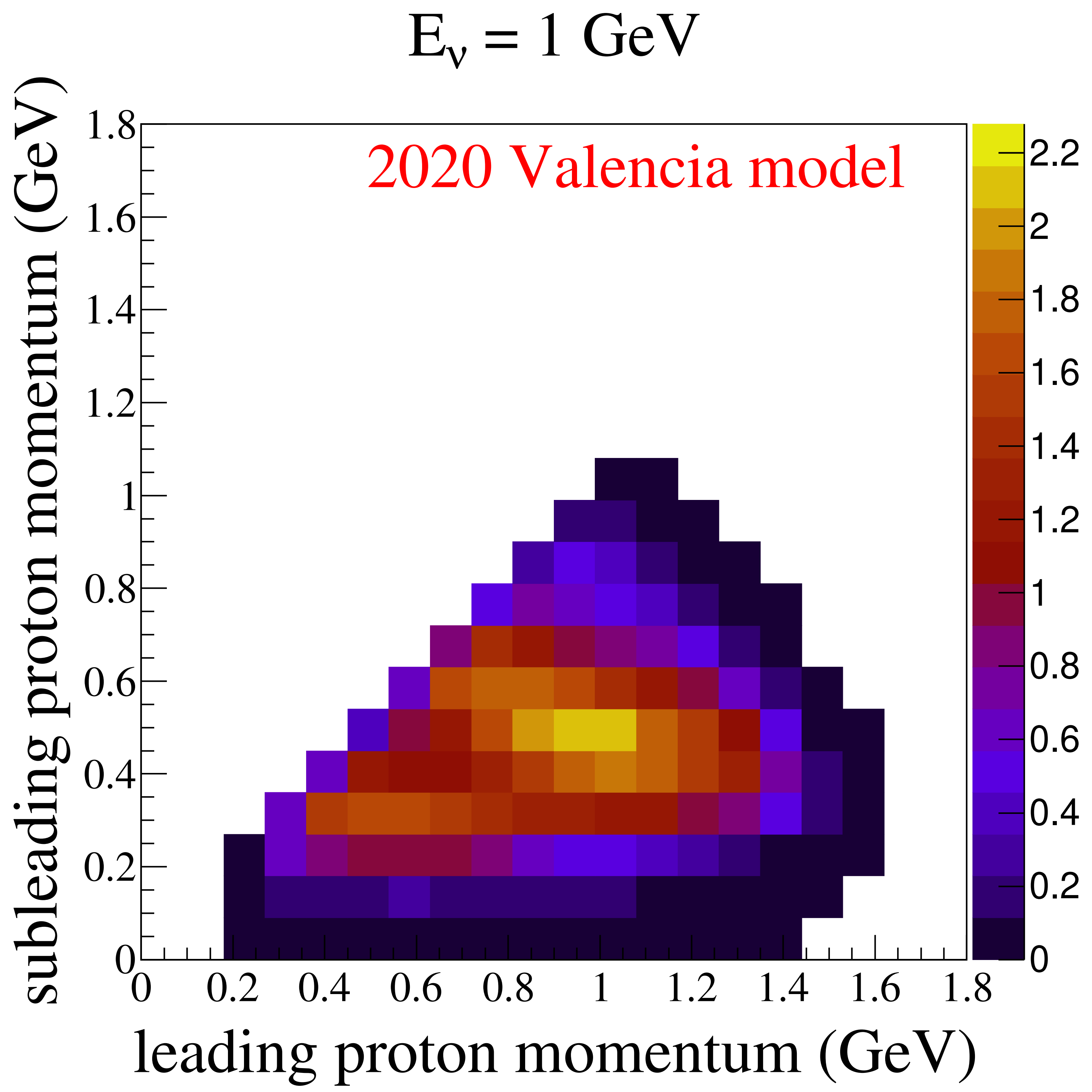
- Correlation strength **differs** based on different outgoing nucleon pair.
- Different outgoing pair **must be treated differently** in Monte Carlo generators !

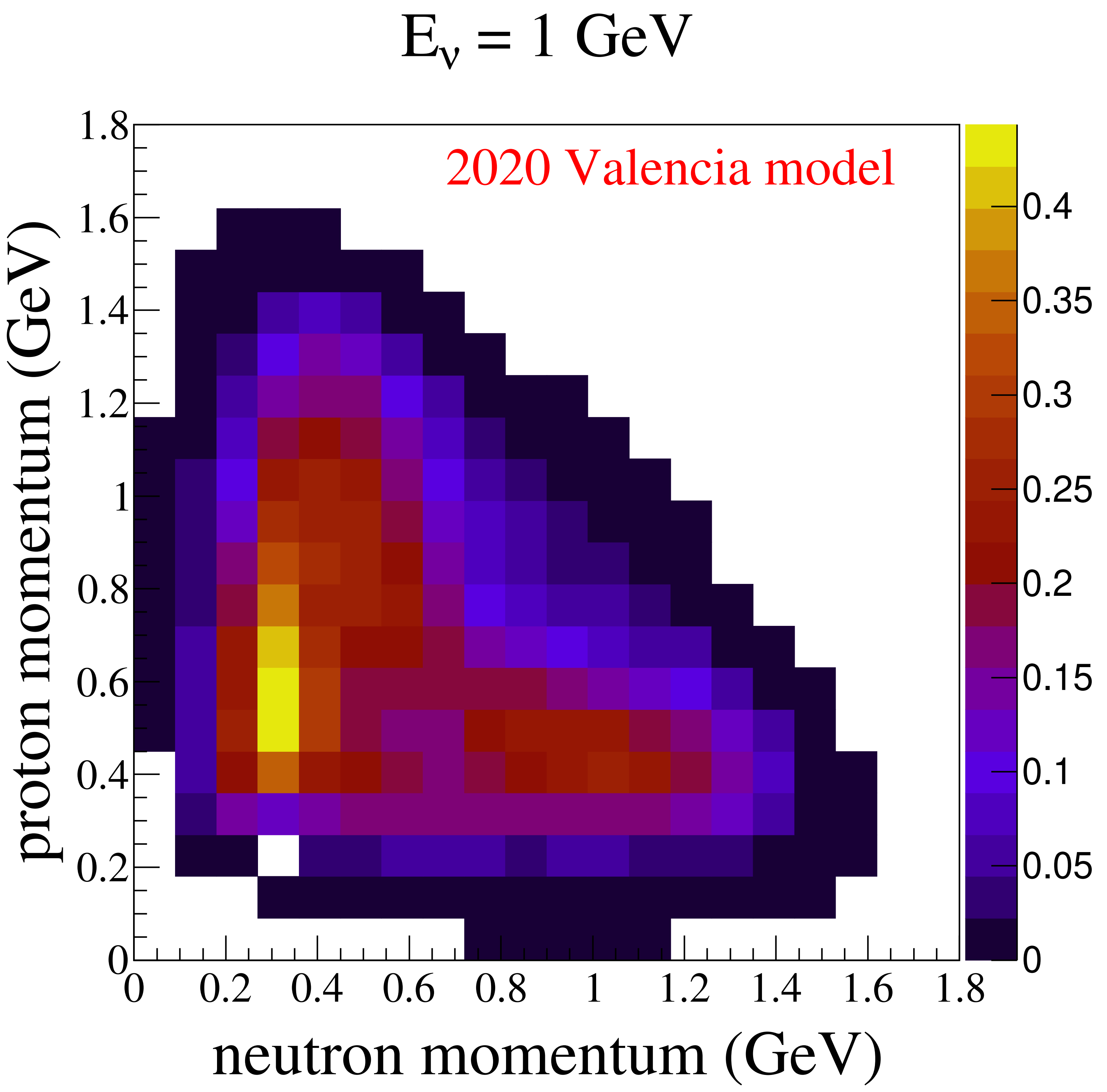
2020 Valencia Model

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

- Predictions on momenta of outgoing nucleons.

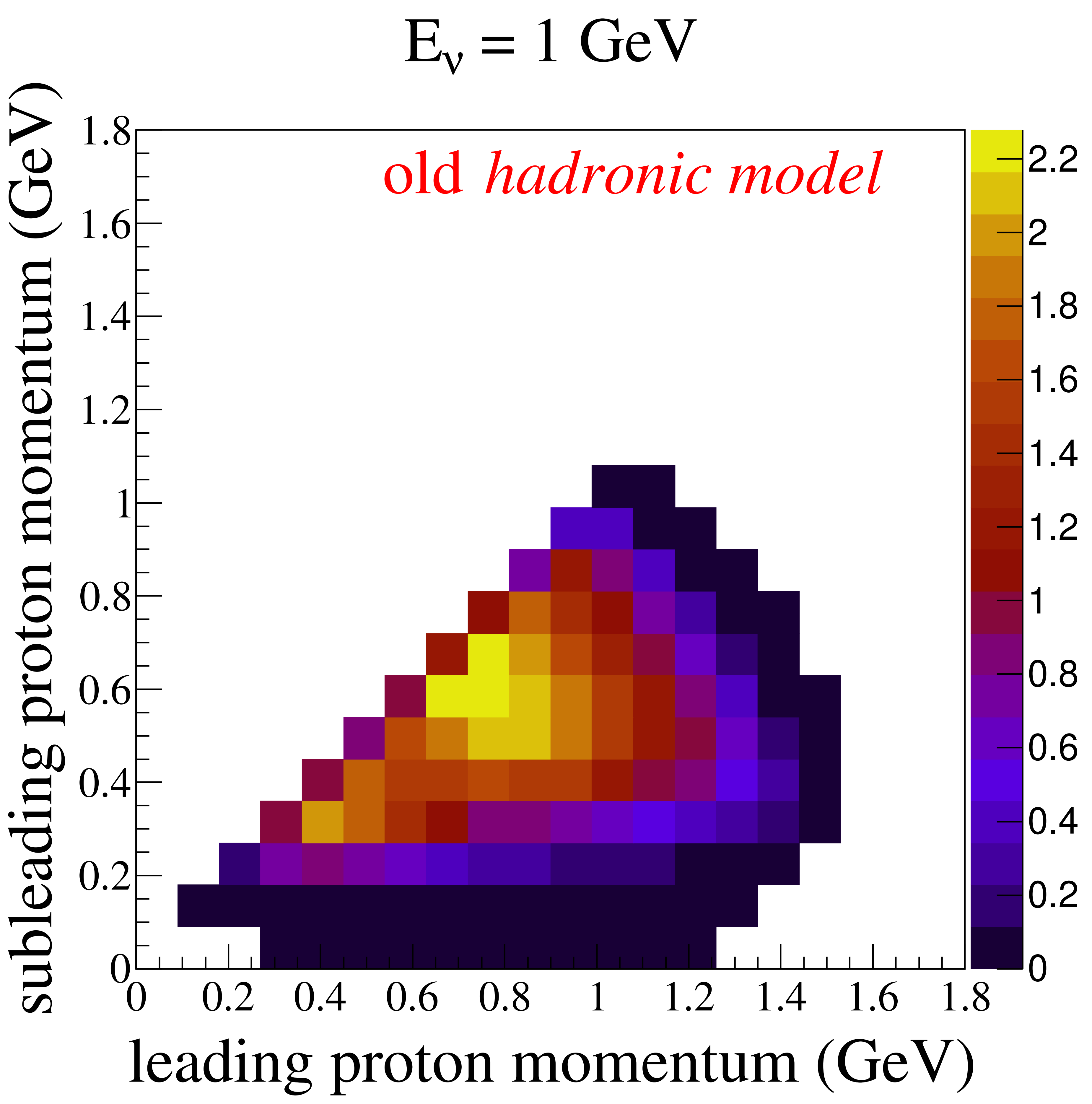
Figure from code provided by J.E. Sobczyk





Modelling Correlations Between Nucleons

Two protons in final state



Modelling Correlations Between Nucleons

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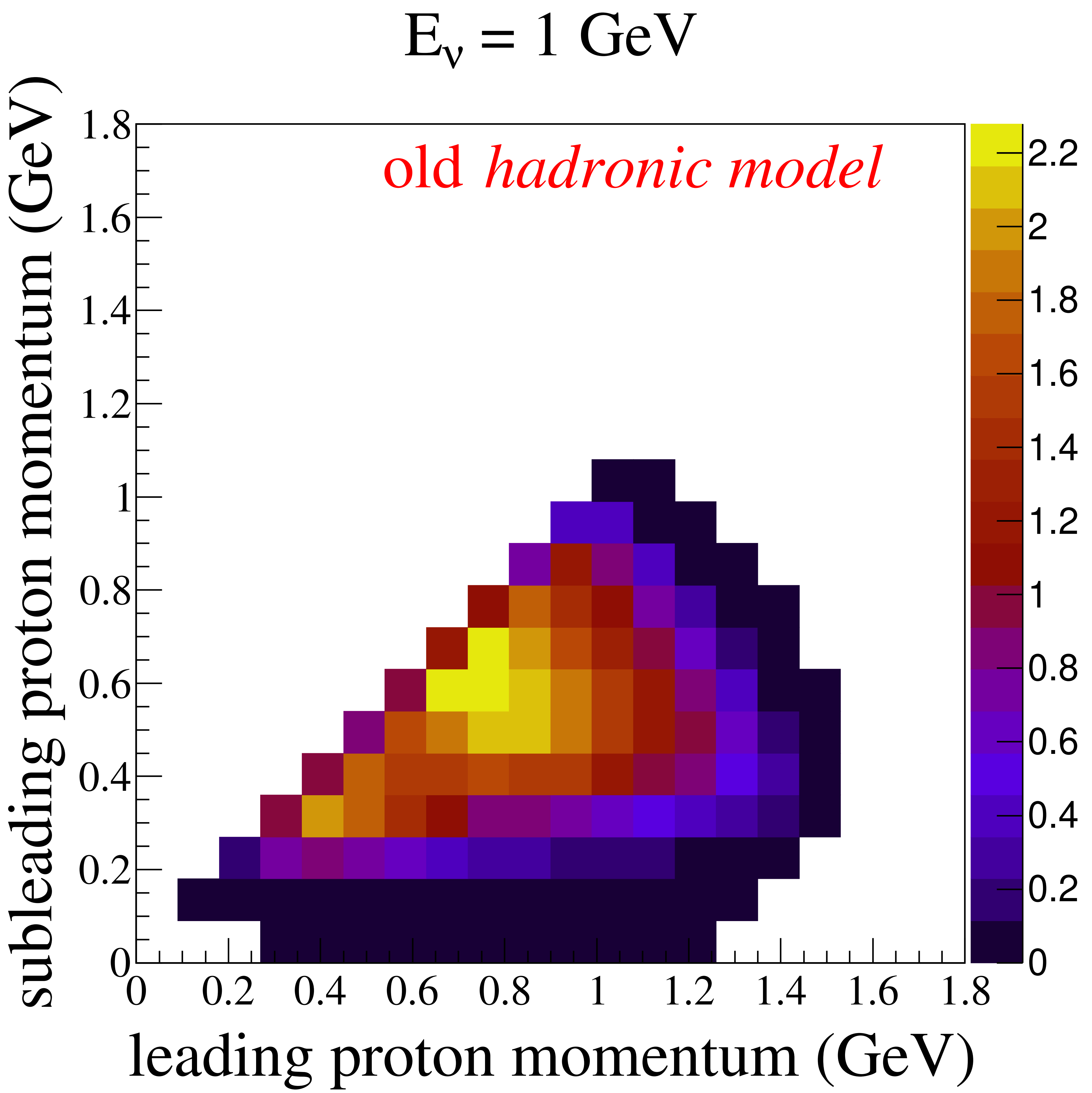

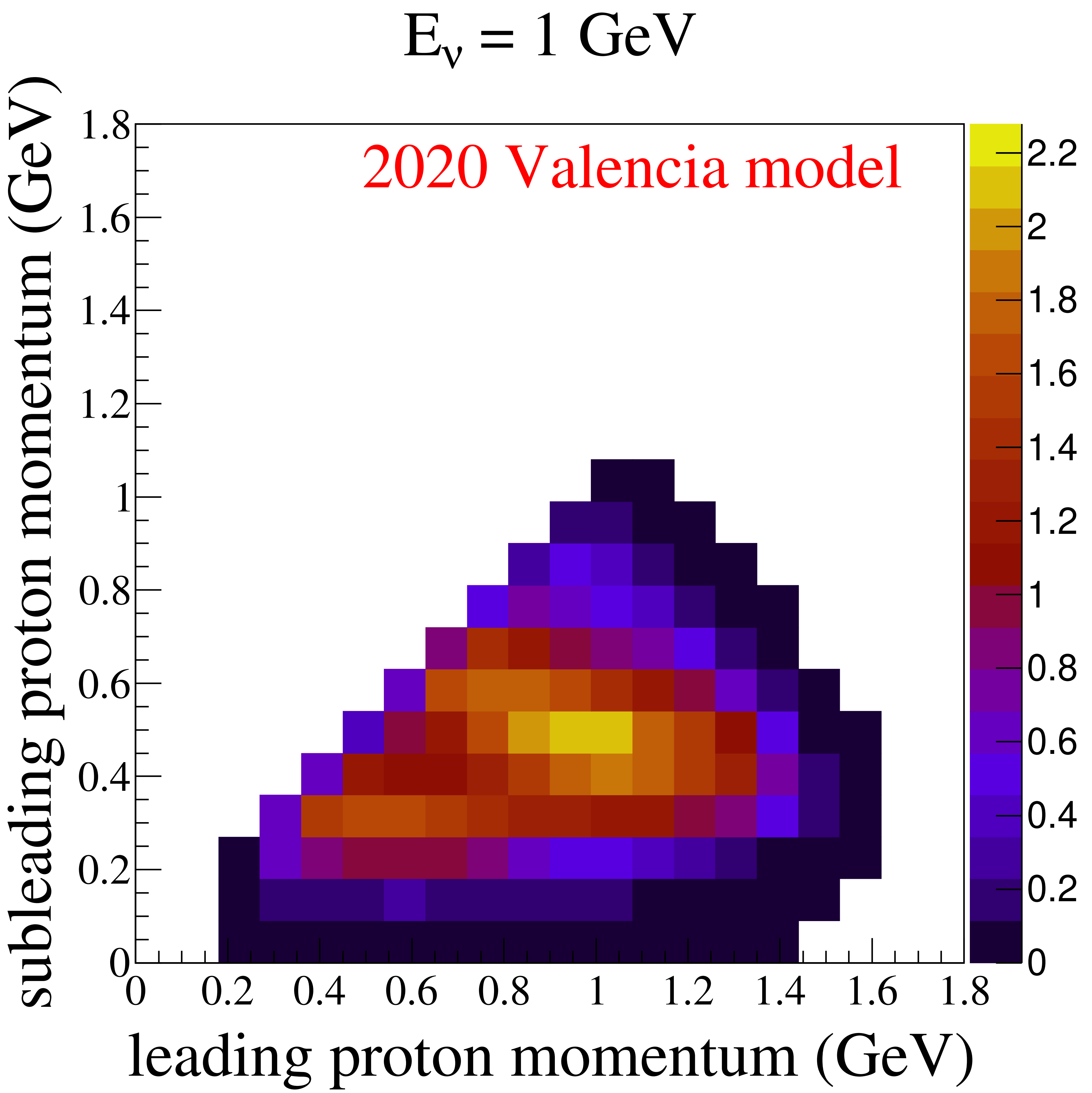

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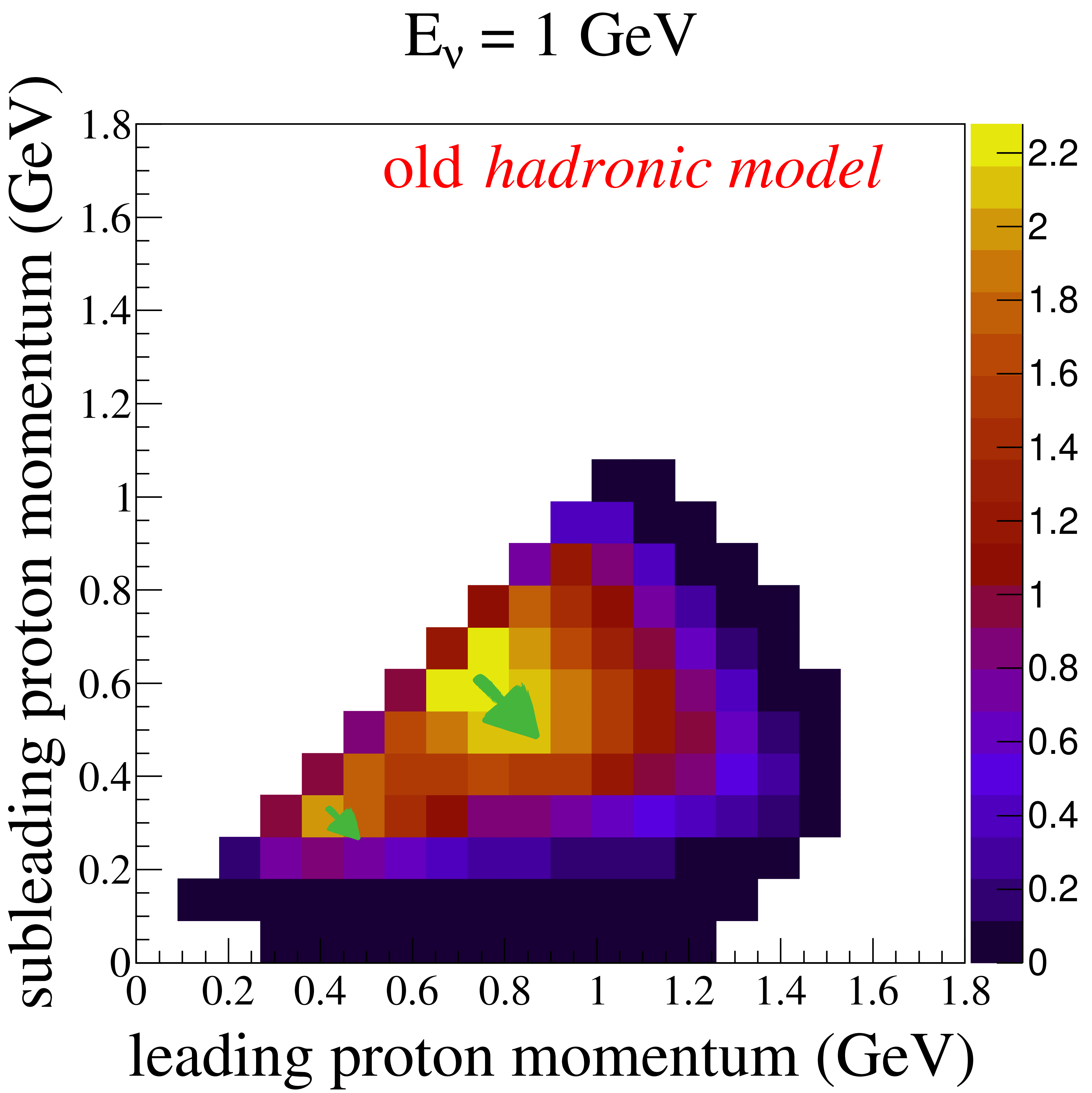

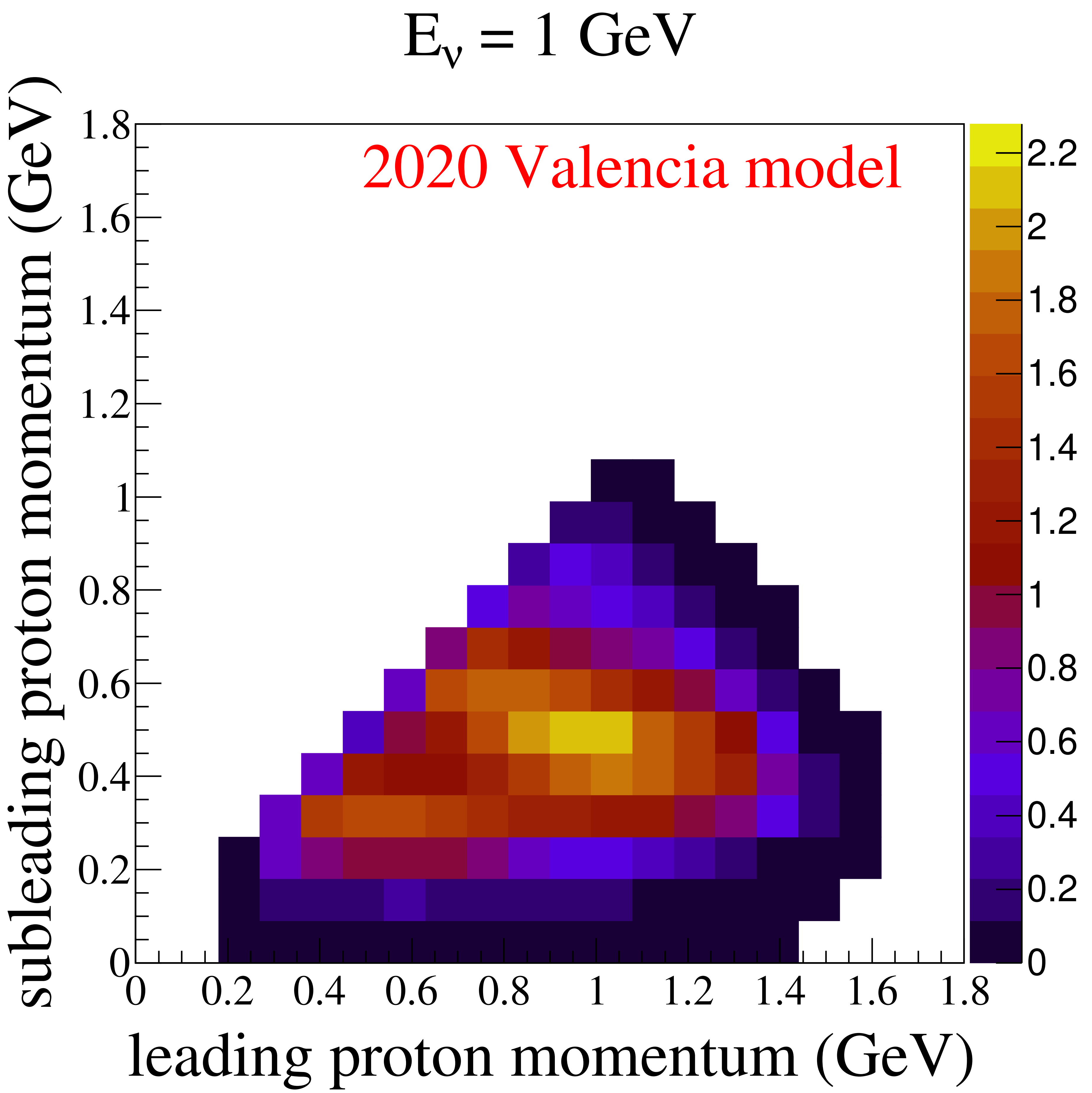

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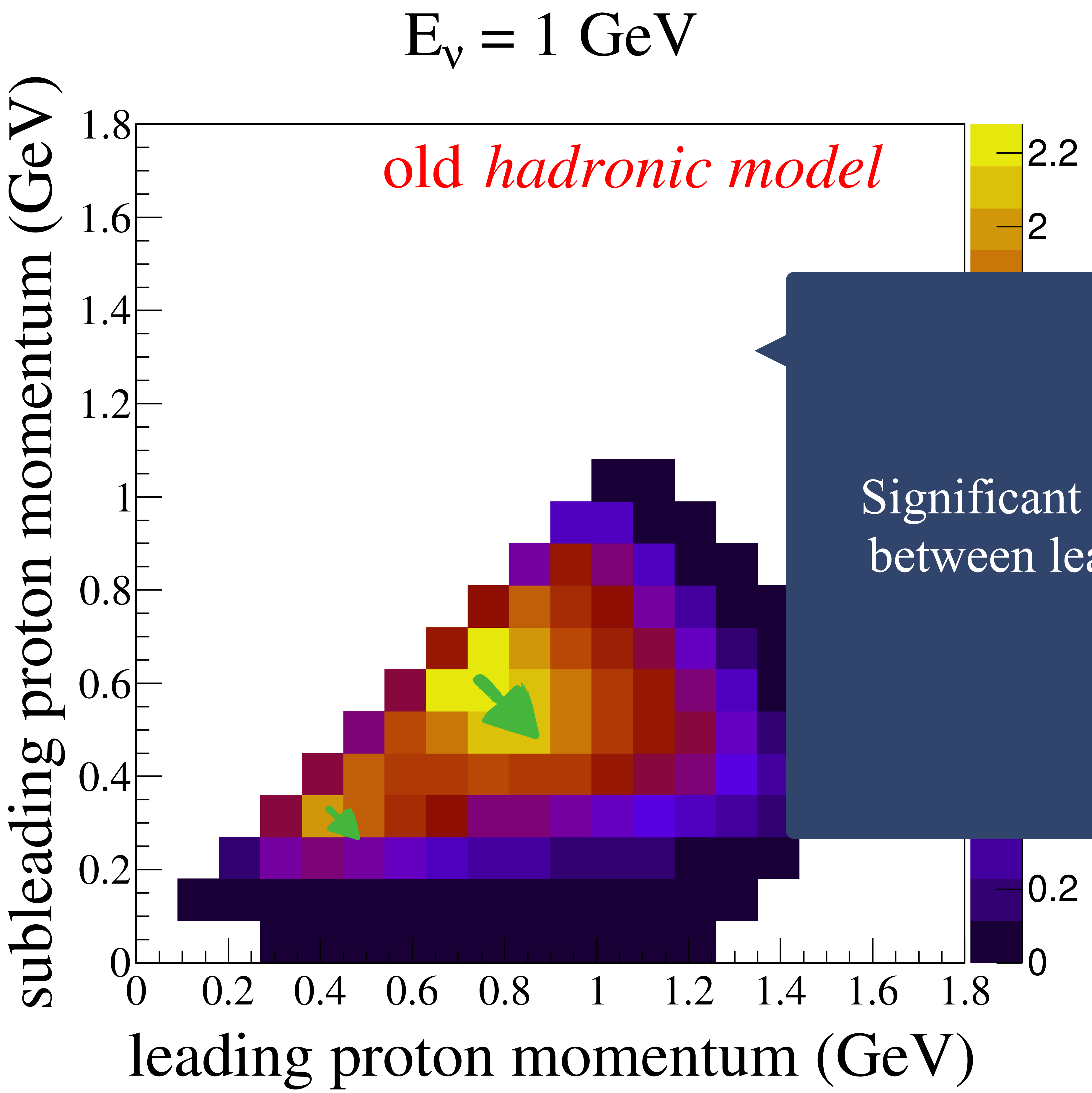
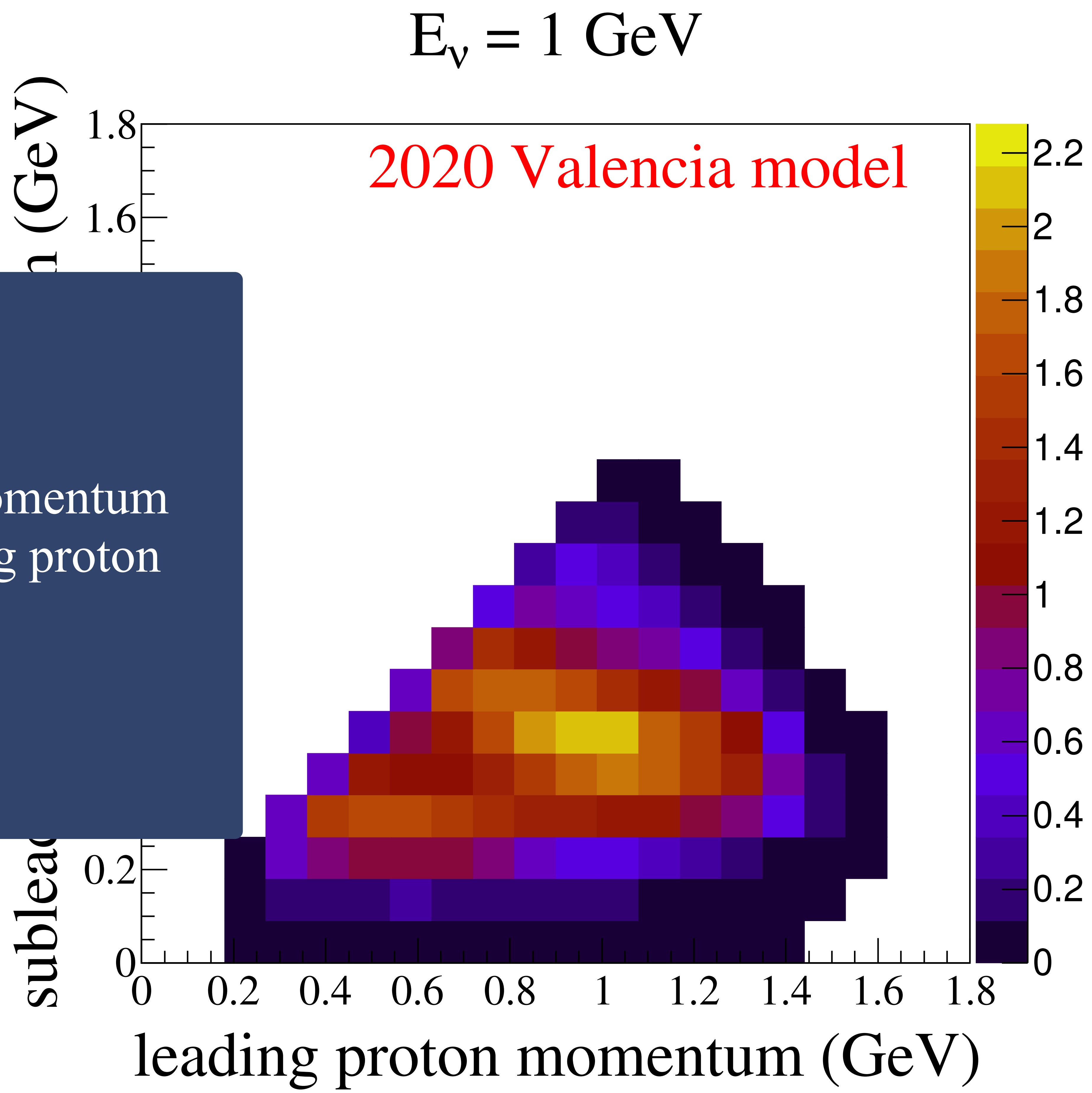
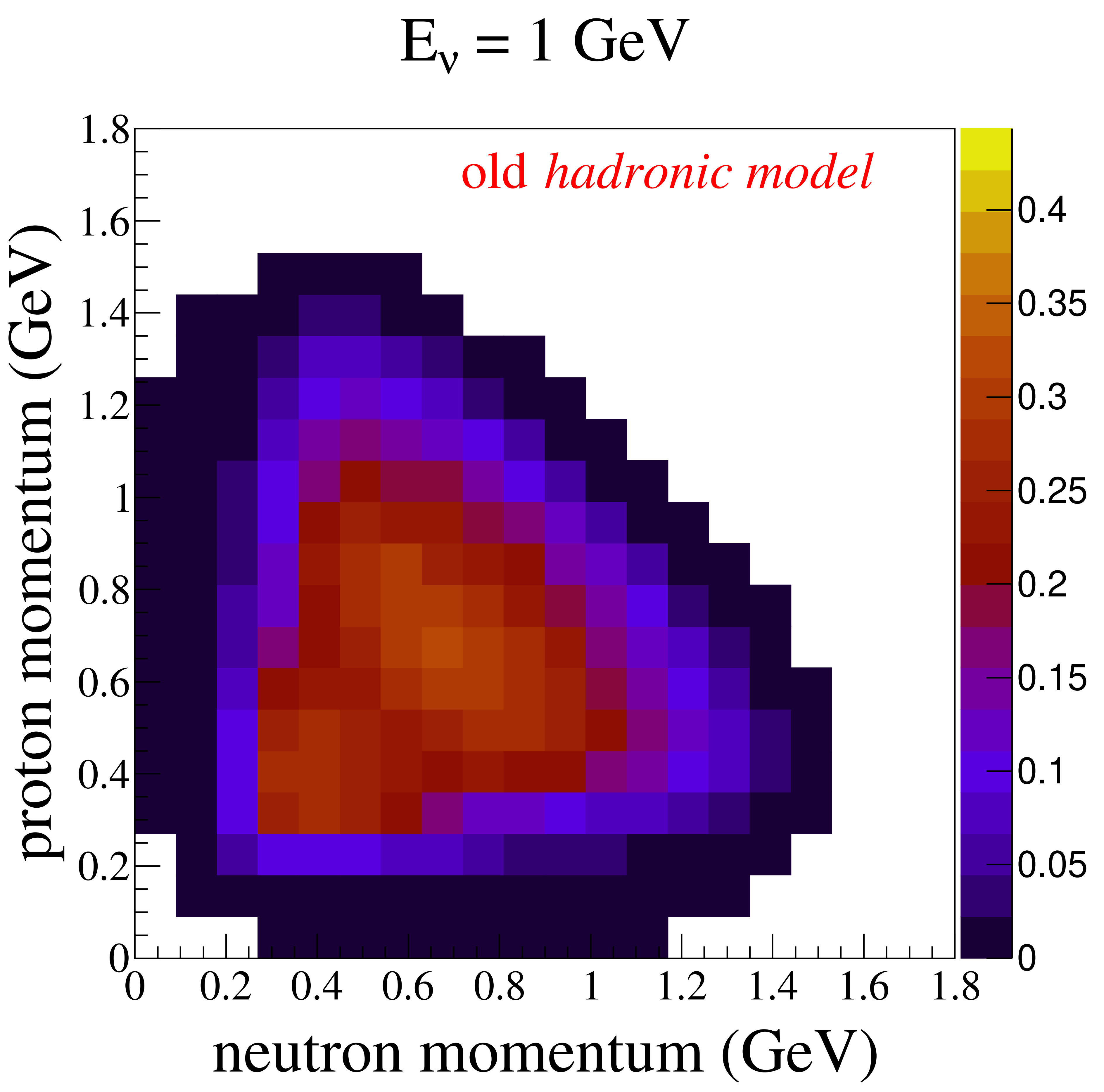


Significant difference in the momentum between leading and subleading proton momentum



Modelling Correlations Between Nucleons

Neutron and a proton in the final state



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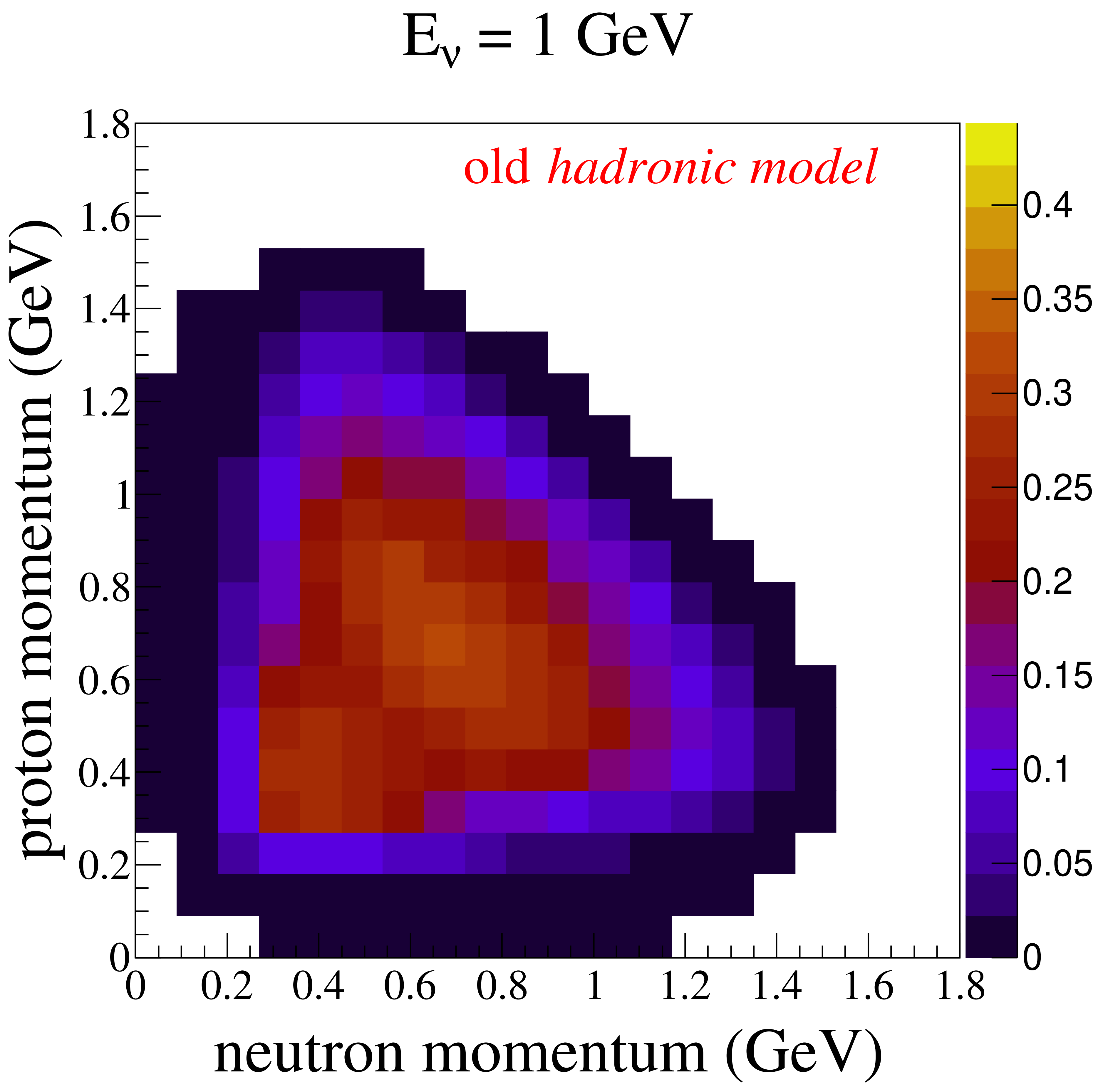

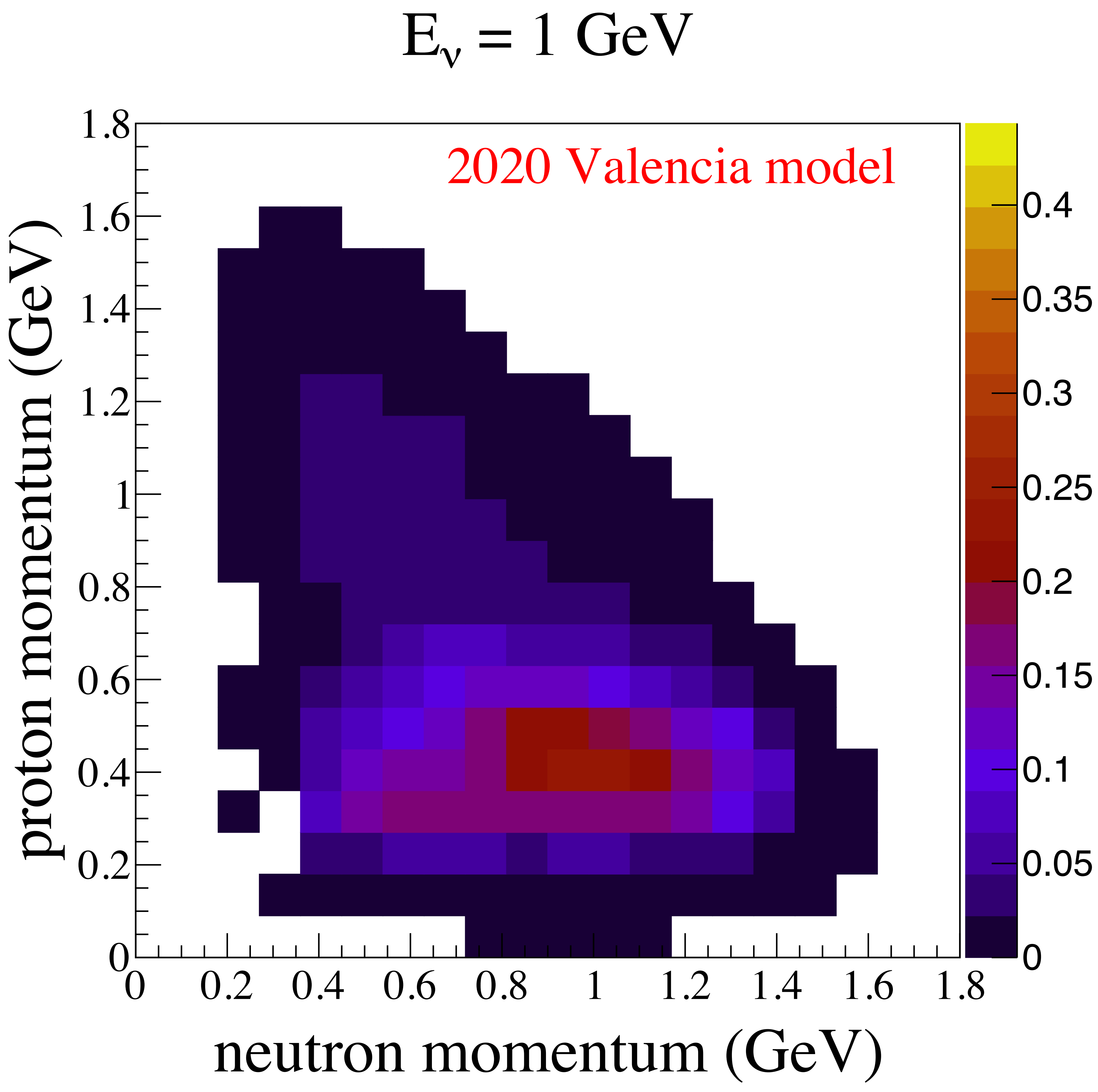

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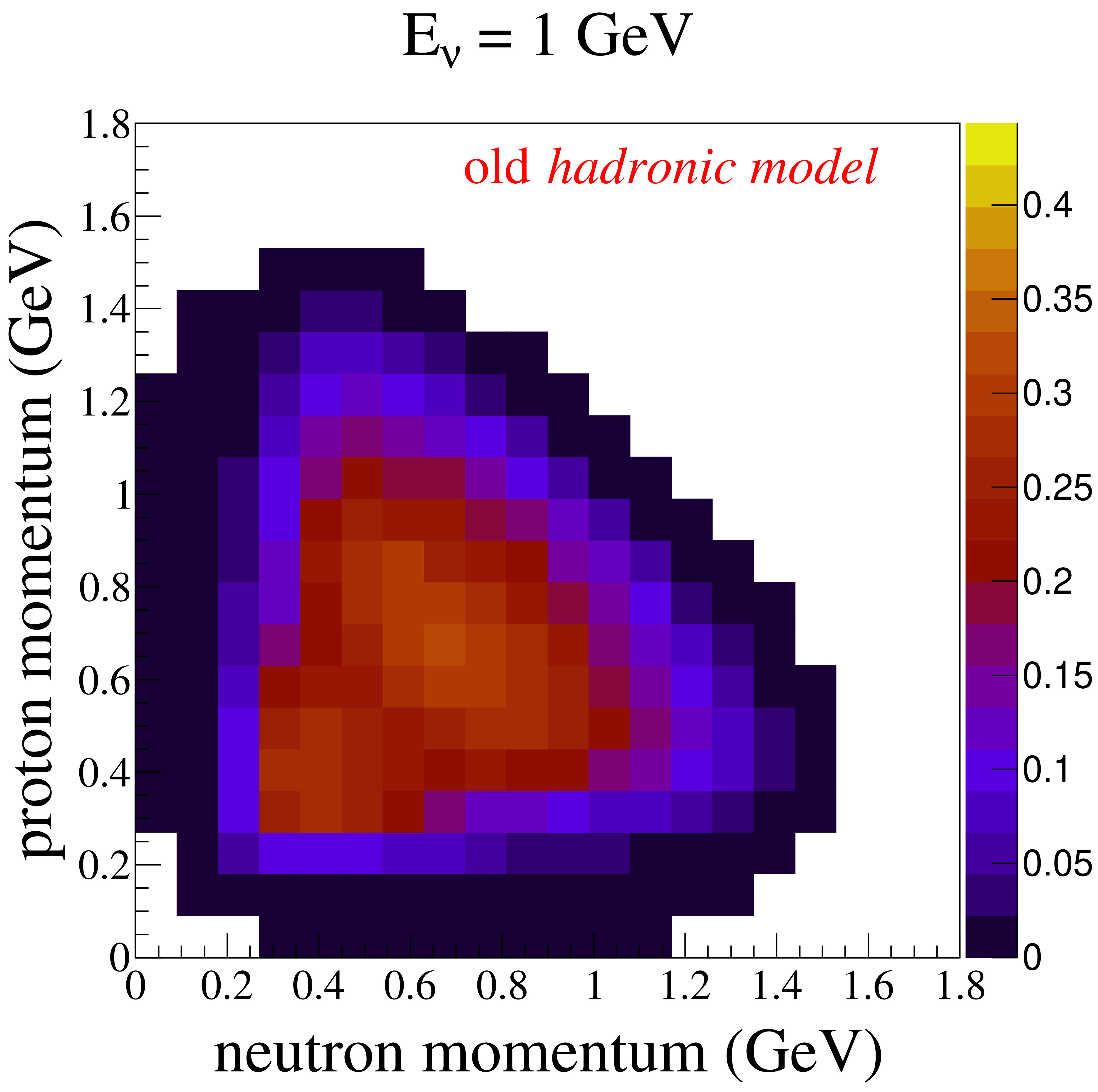

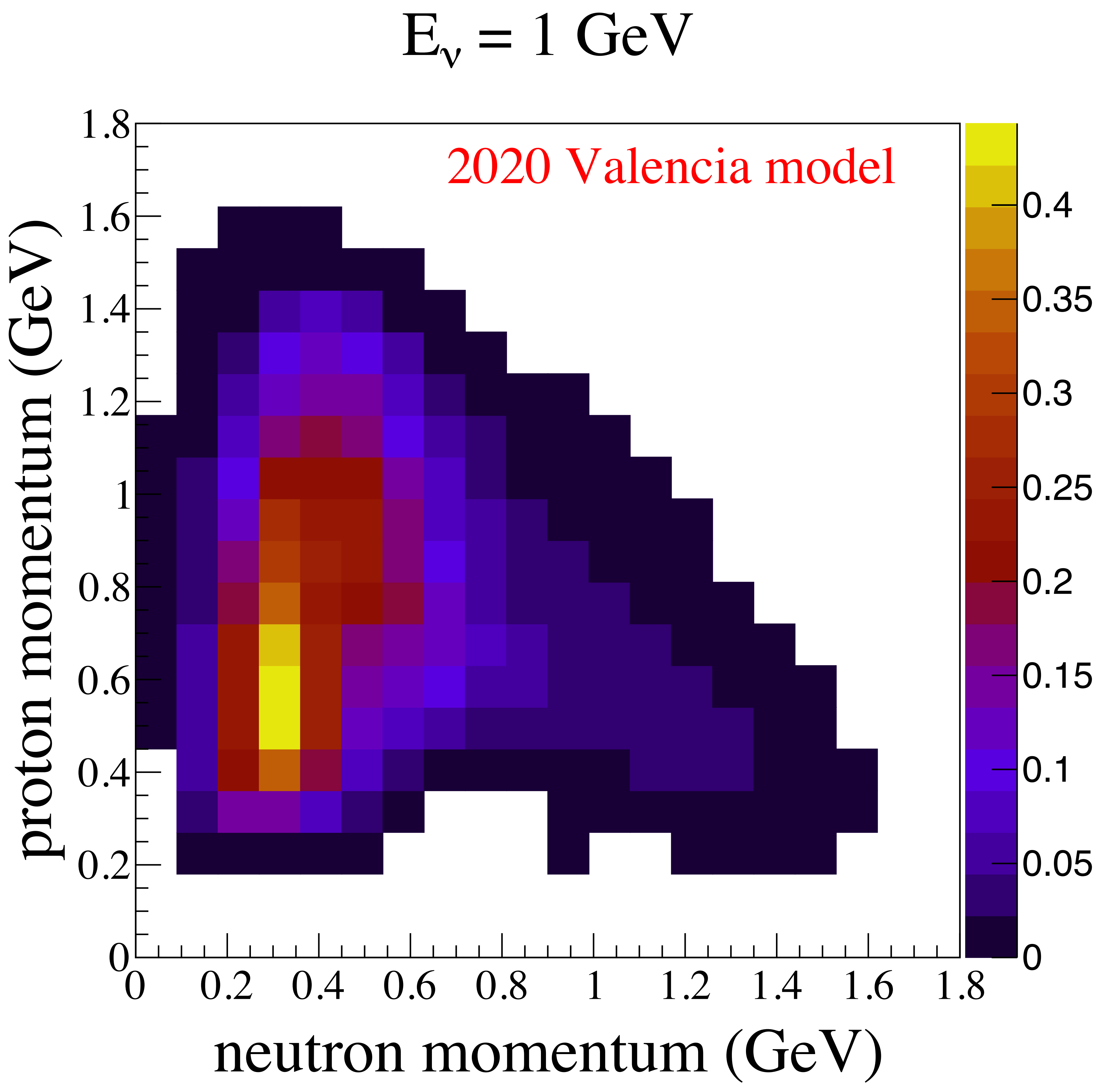

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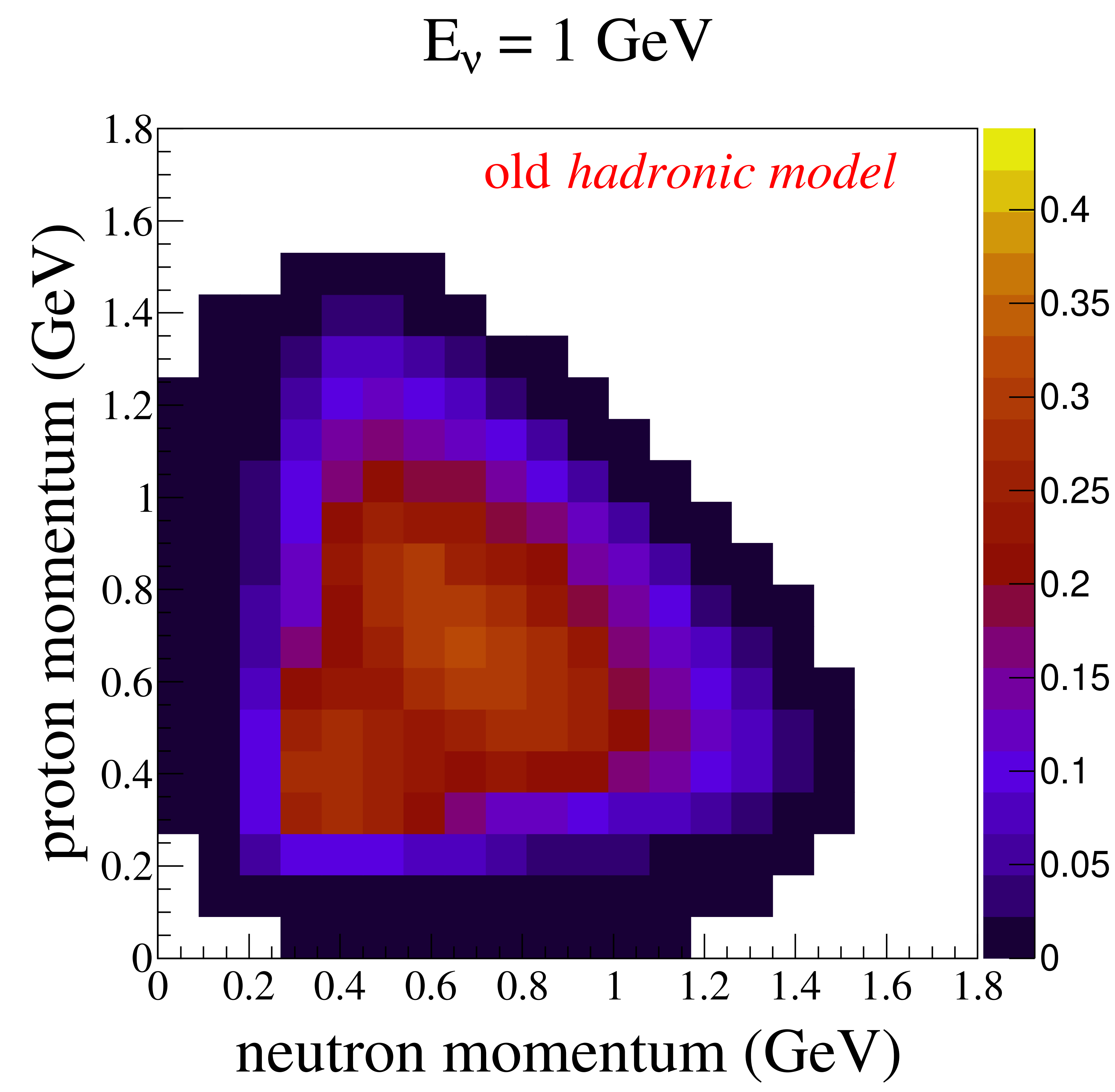

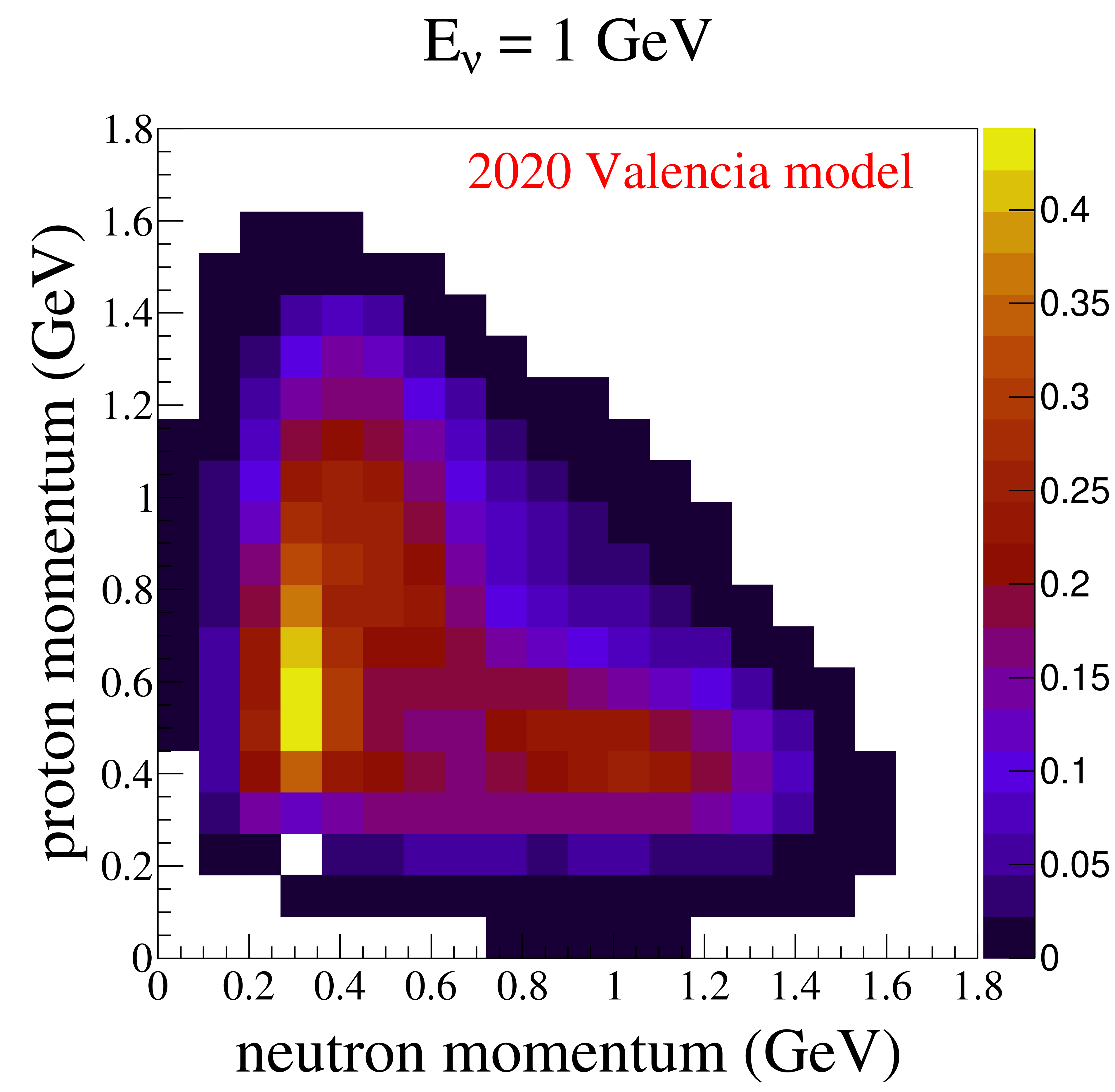

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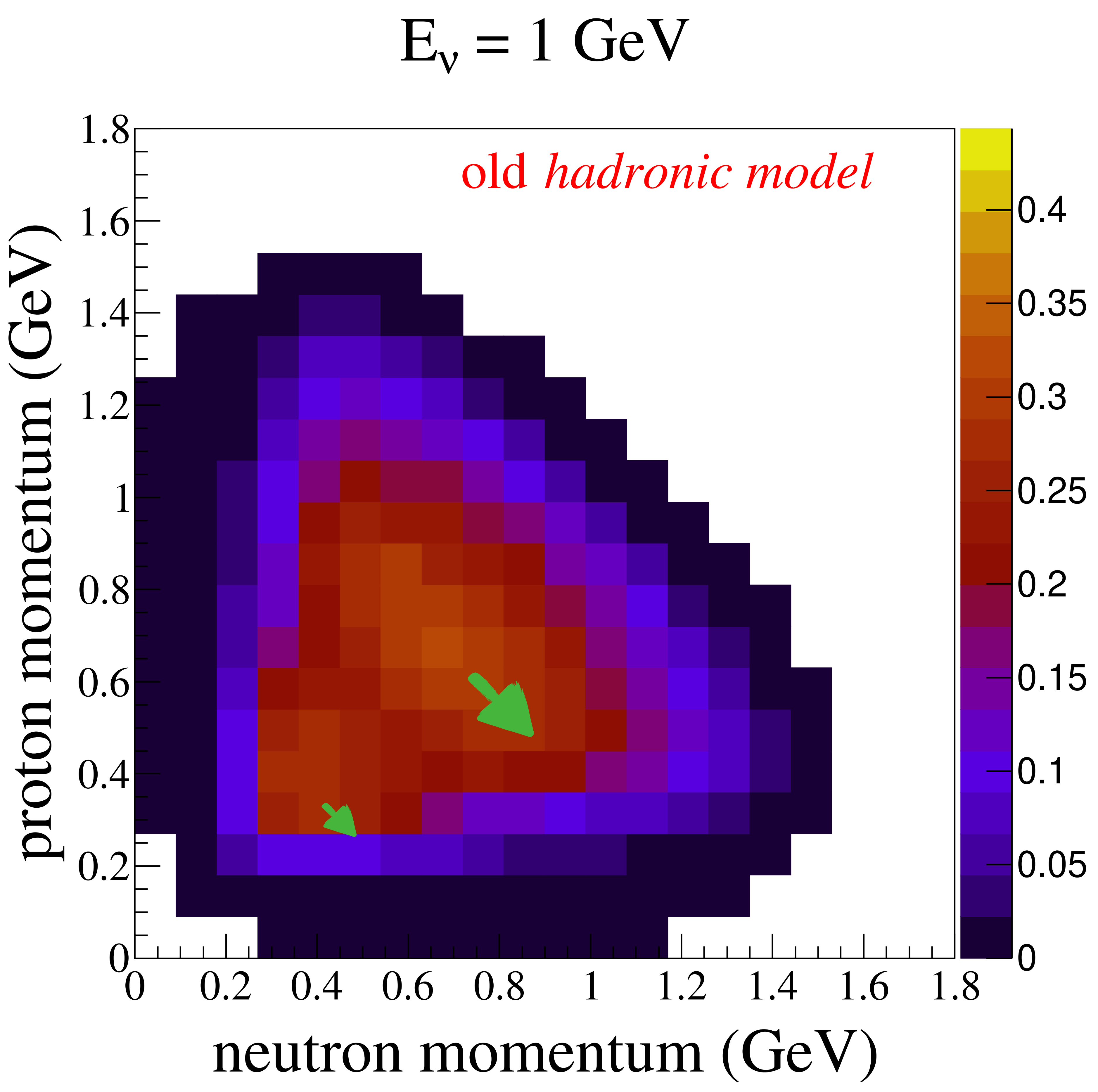

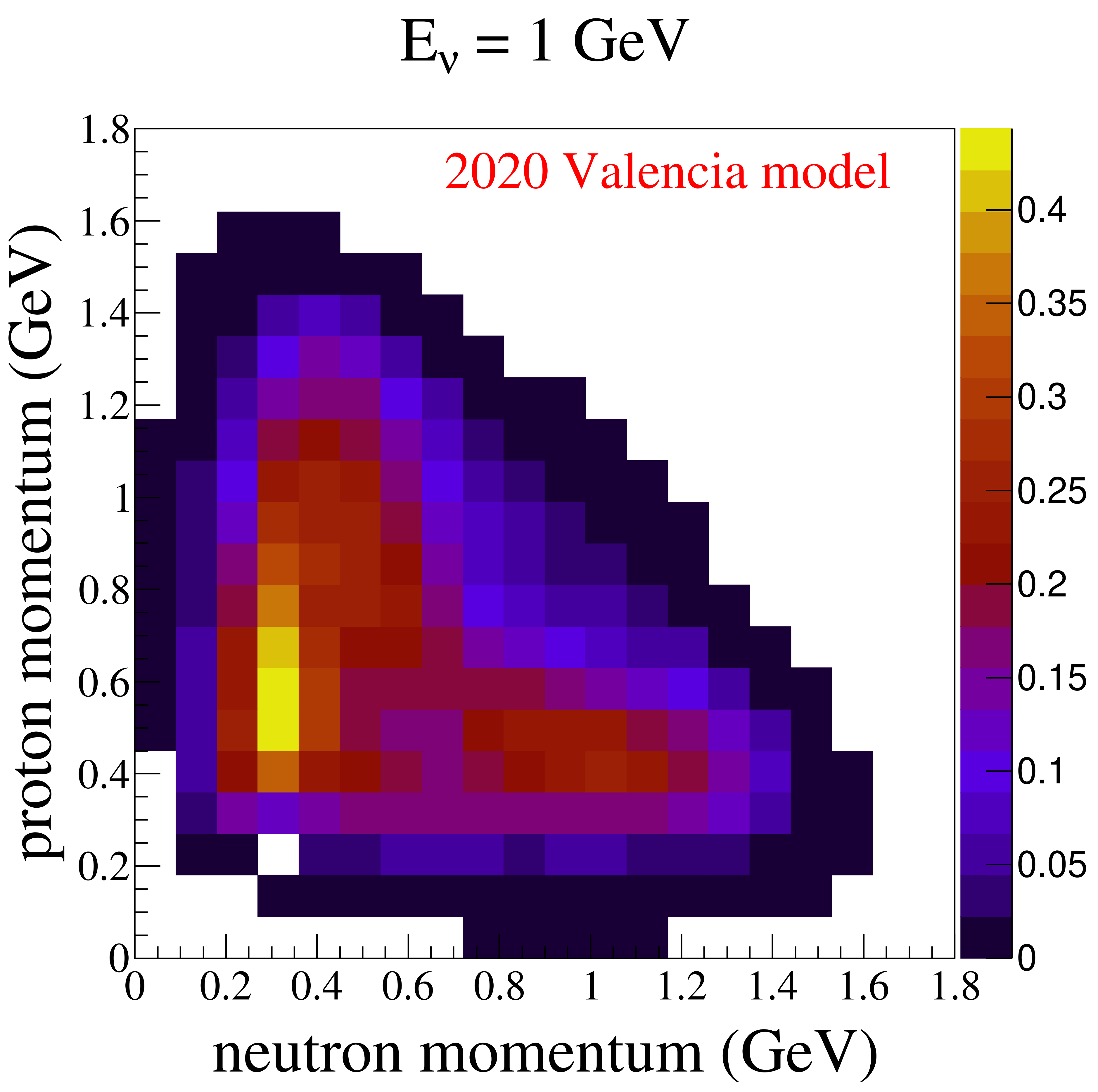

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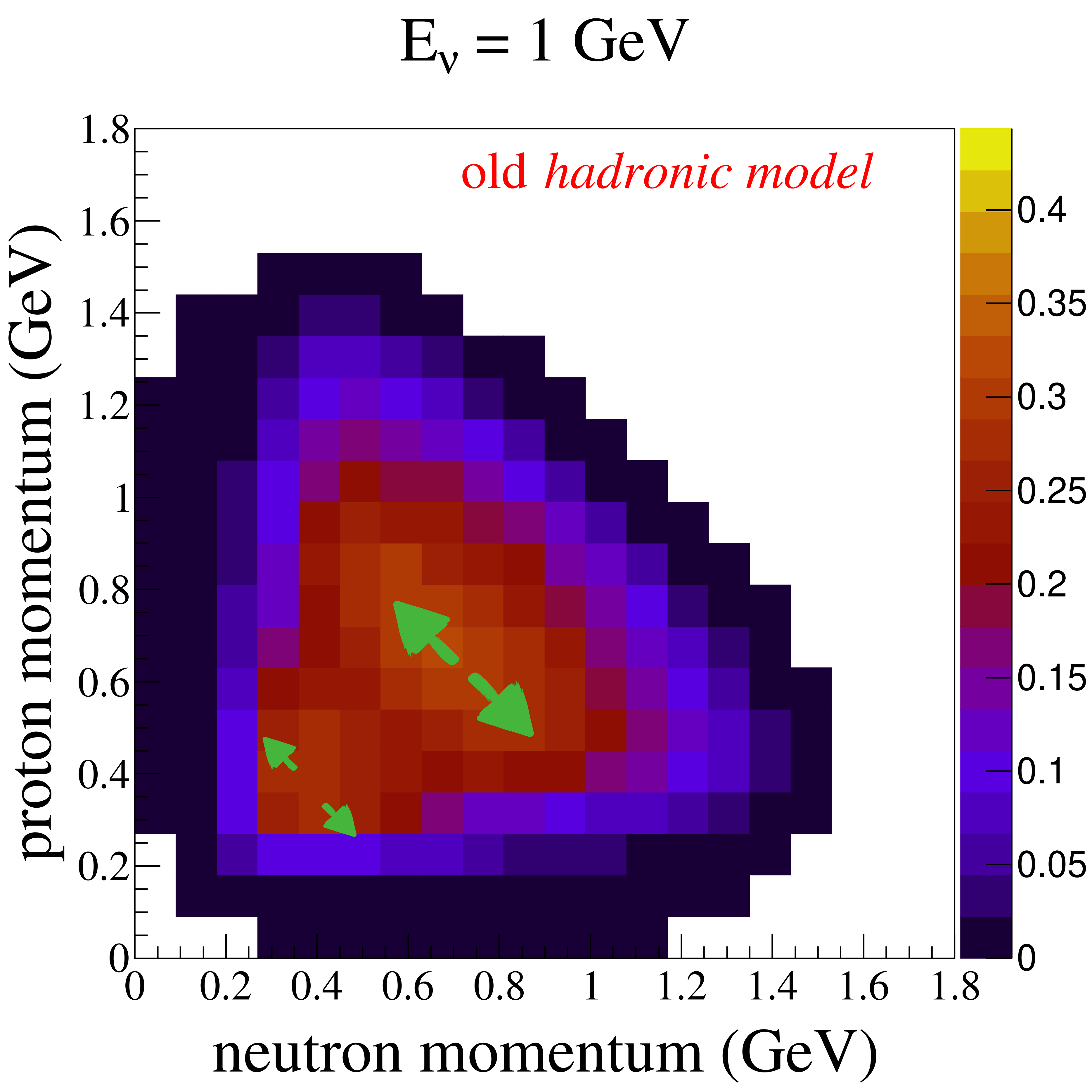

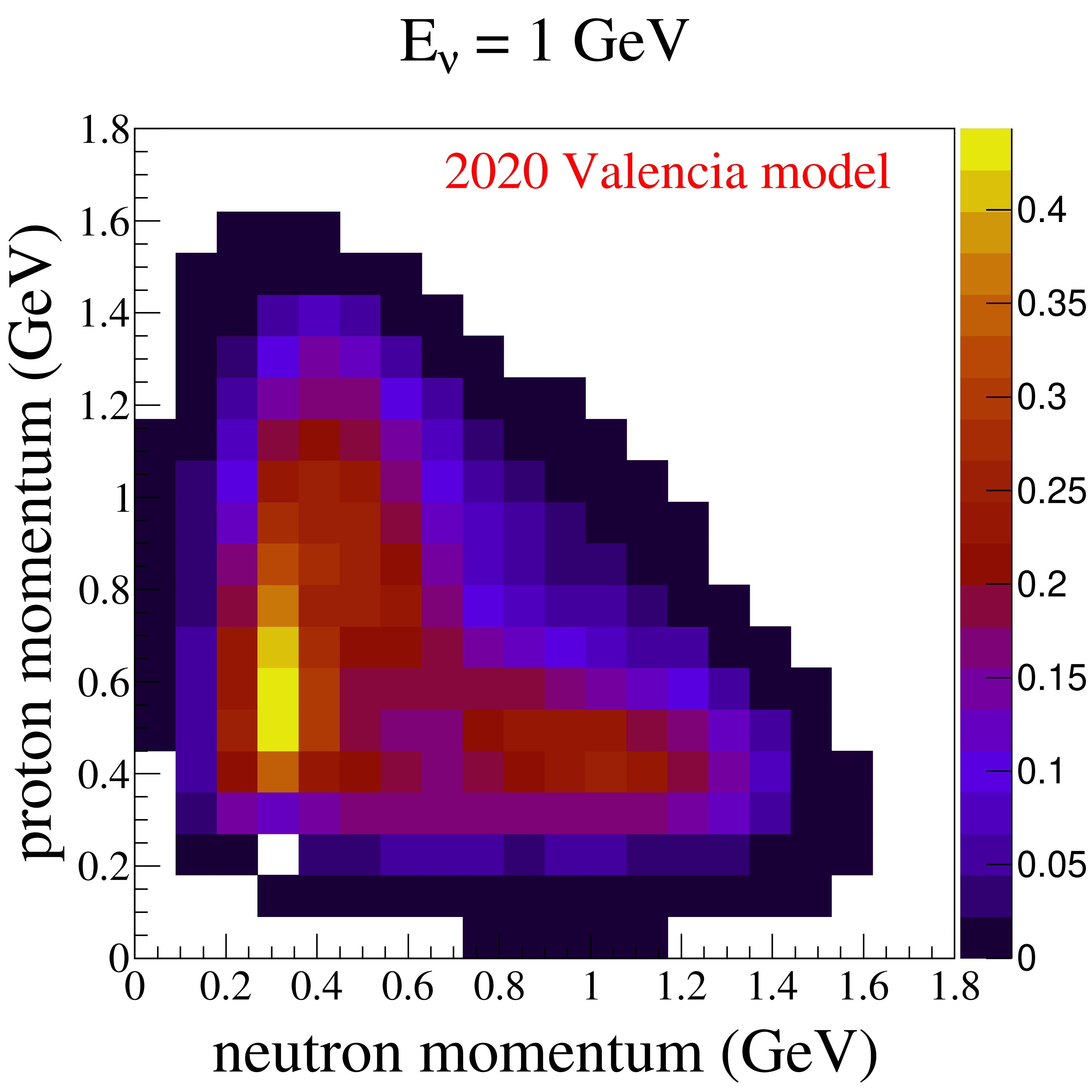

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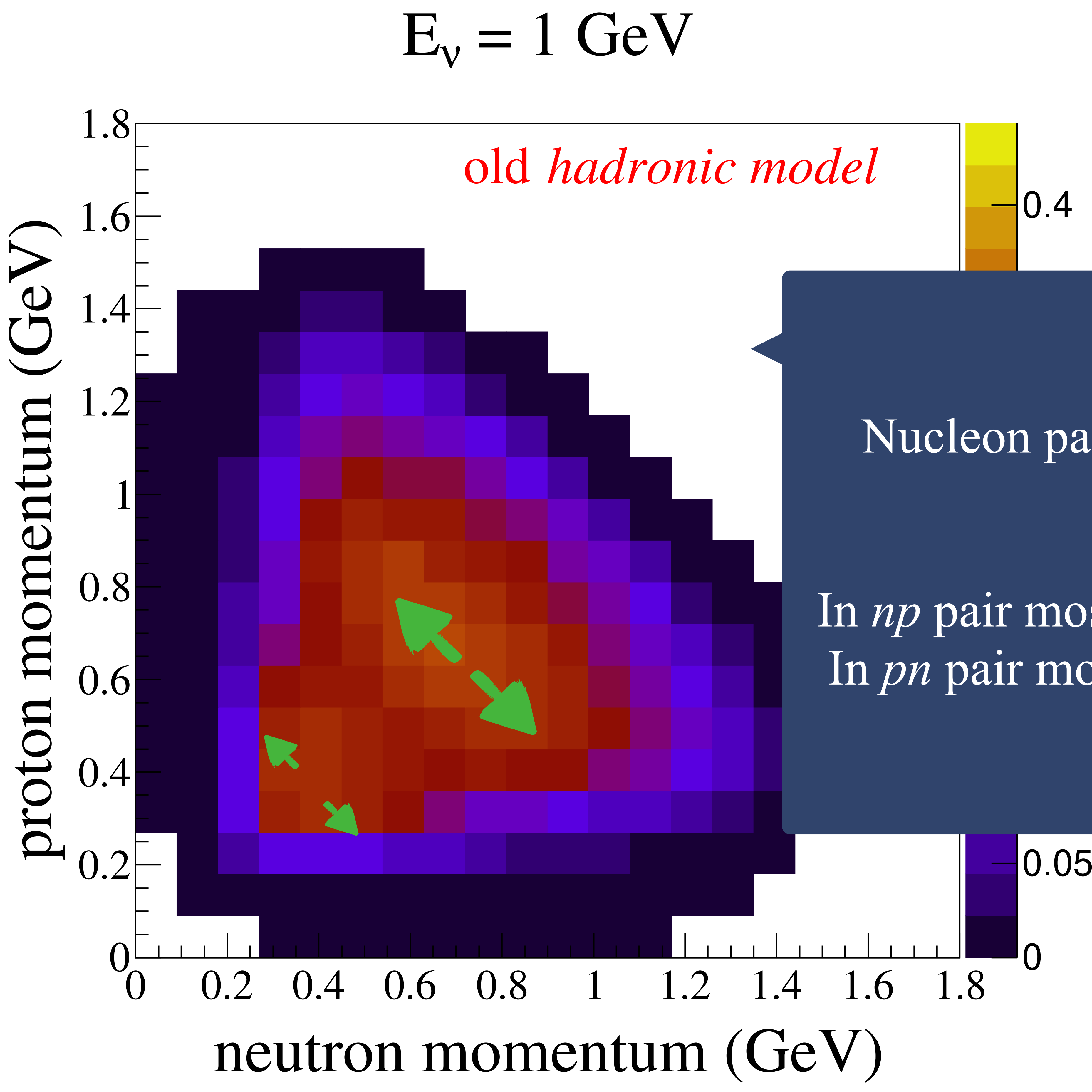
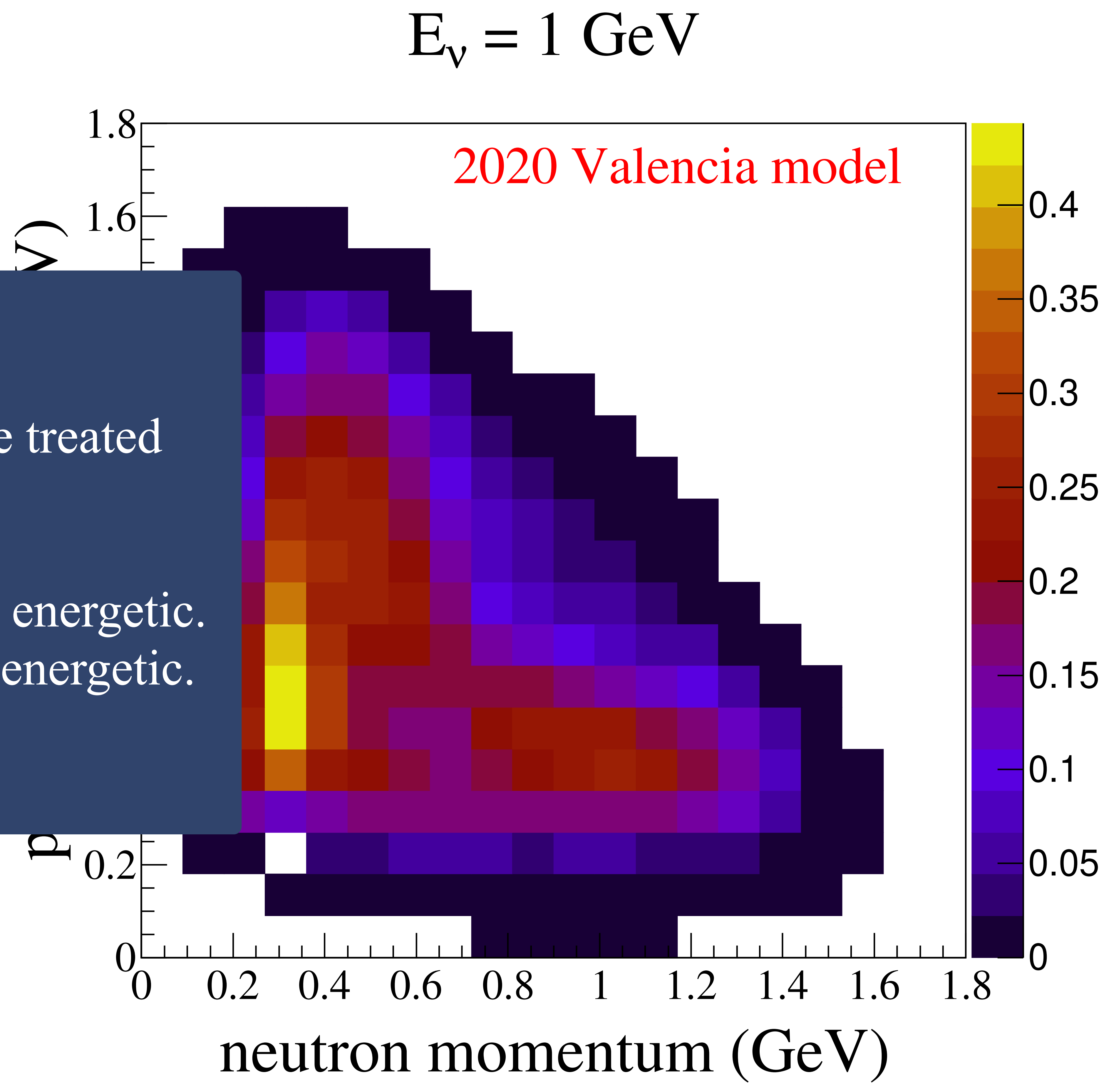


Nucleon pair *np* and *pn* must be treated differently.

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



Modelling Correlations Between Nucleons

Motivation (for 2p2h only)

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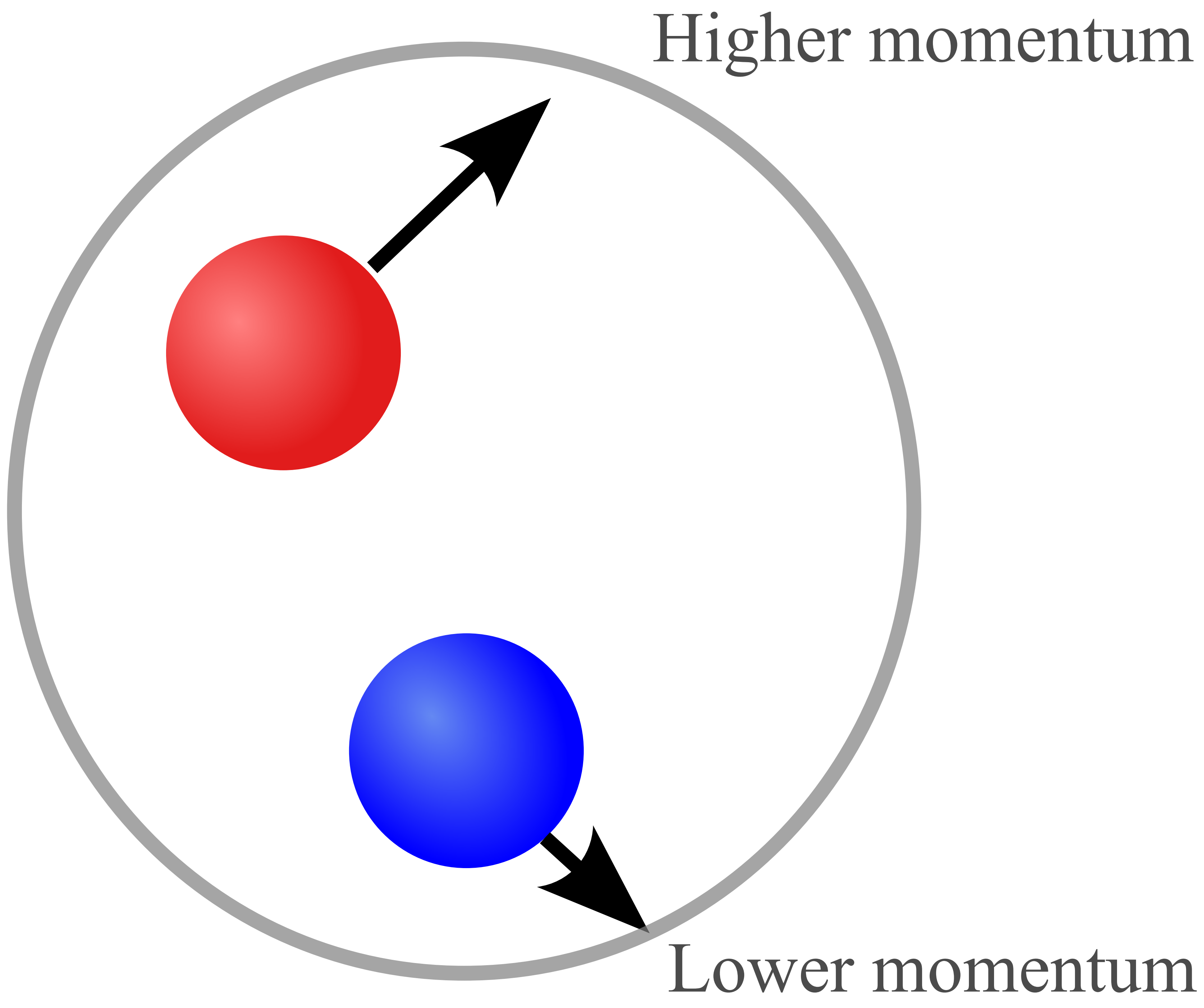
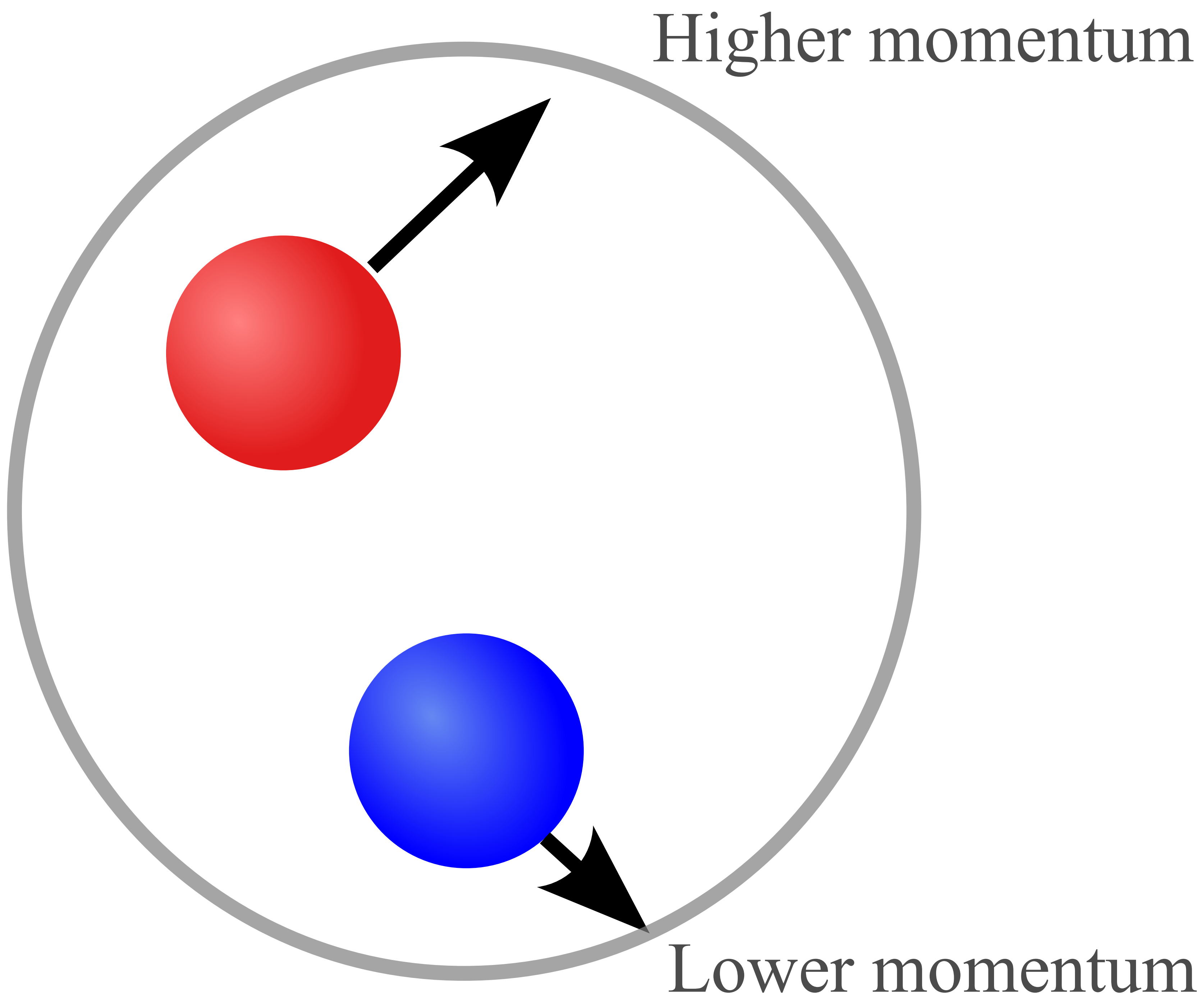


Outgoing nucleons (lab frame)

Modelling Correlations Between Nucleons

Motivation (for 2p2h only)



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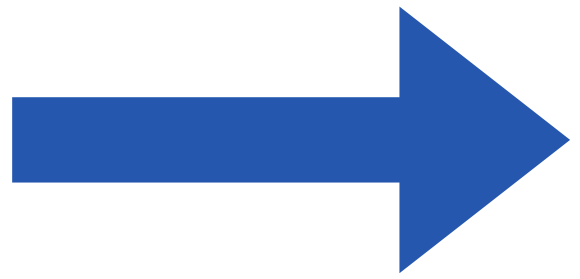

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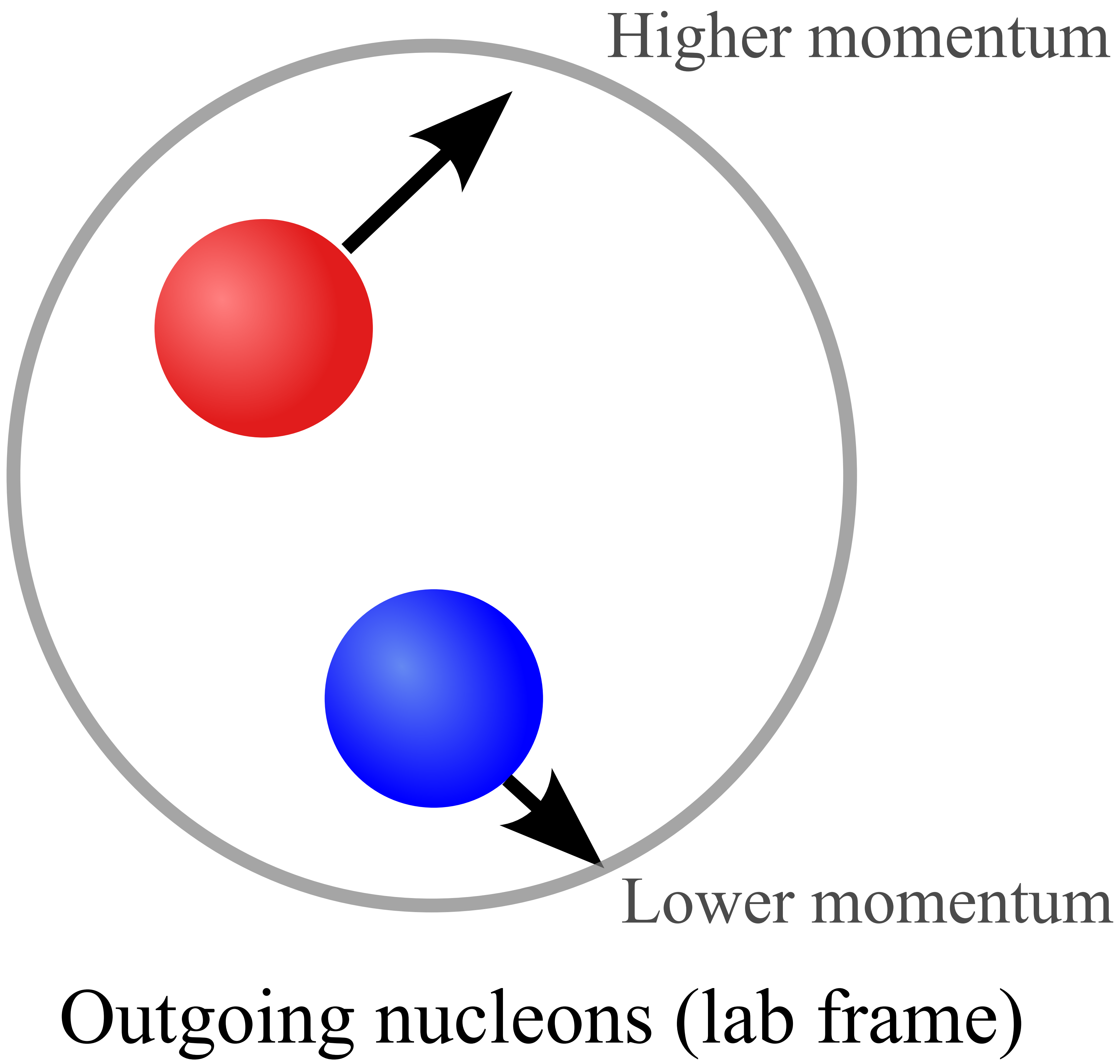
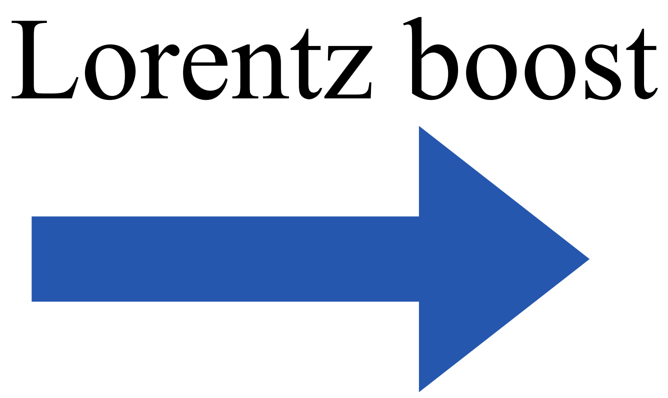
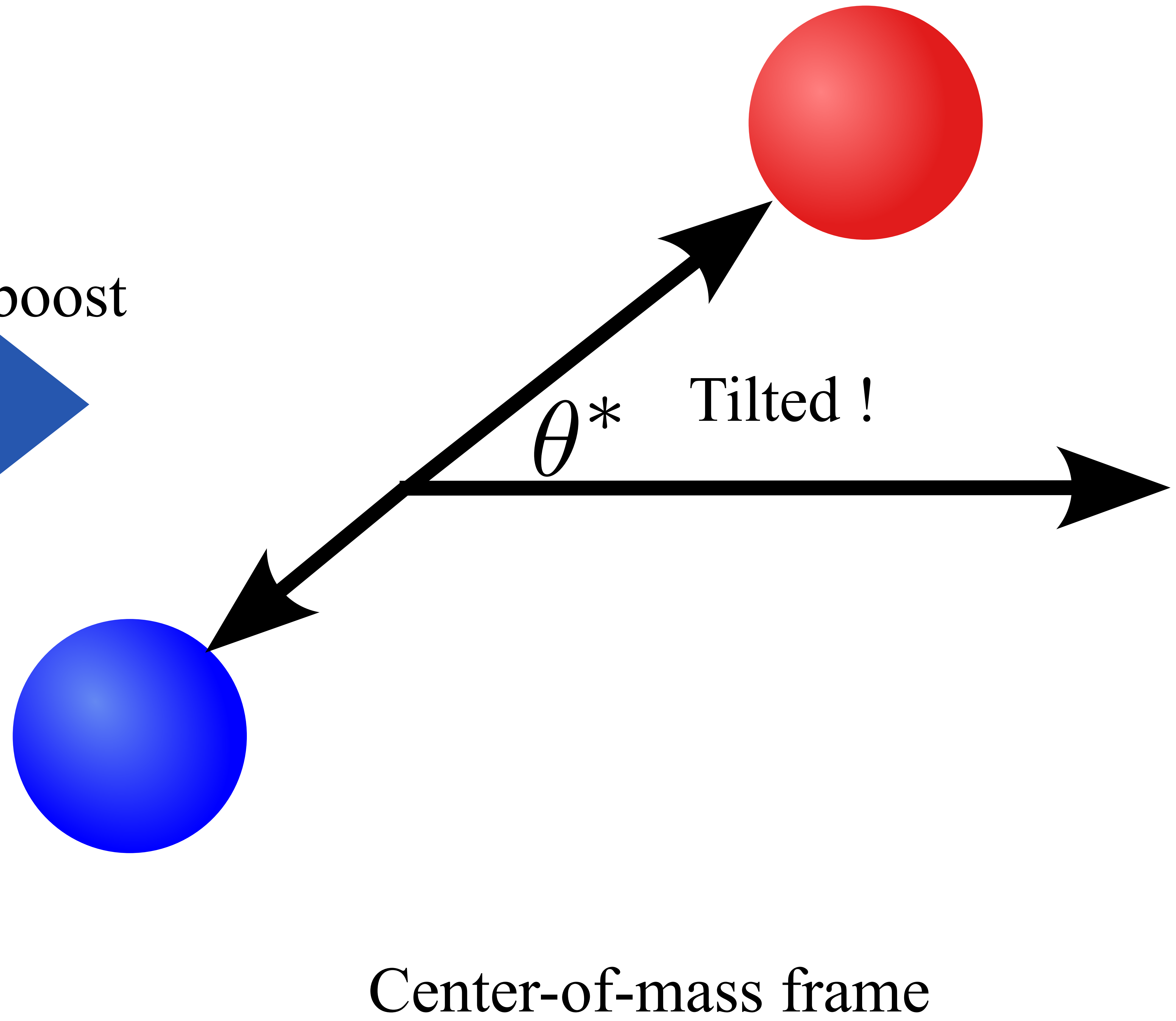




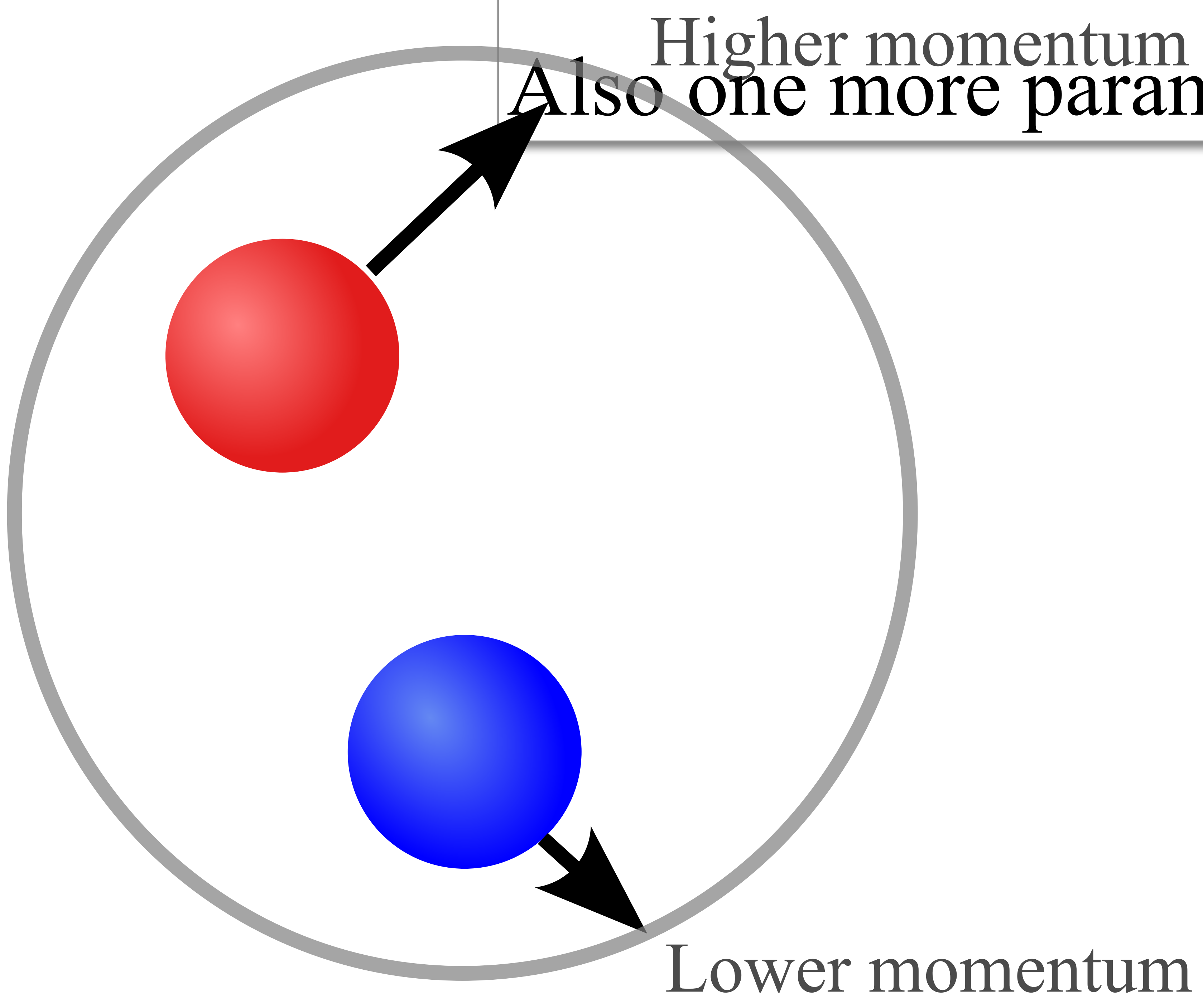


Modelling Correlations Between Nucleons

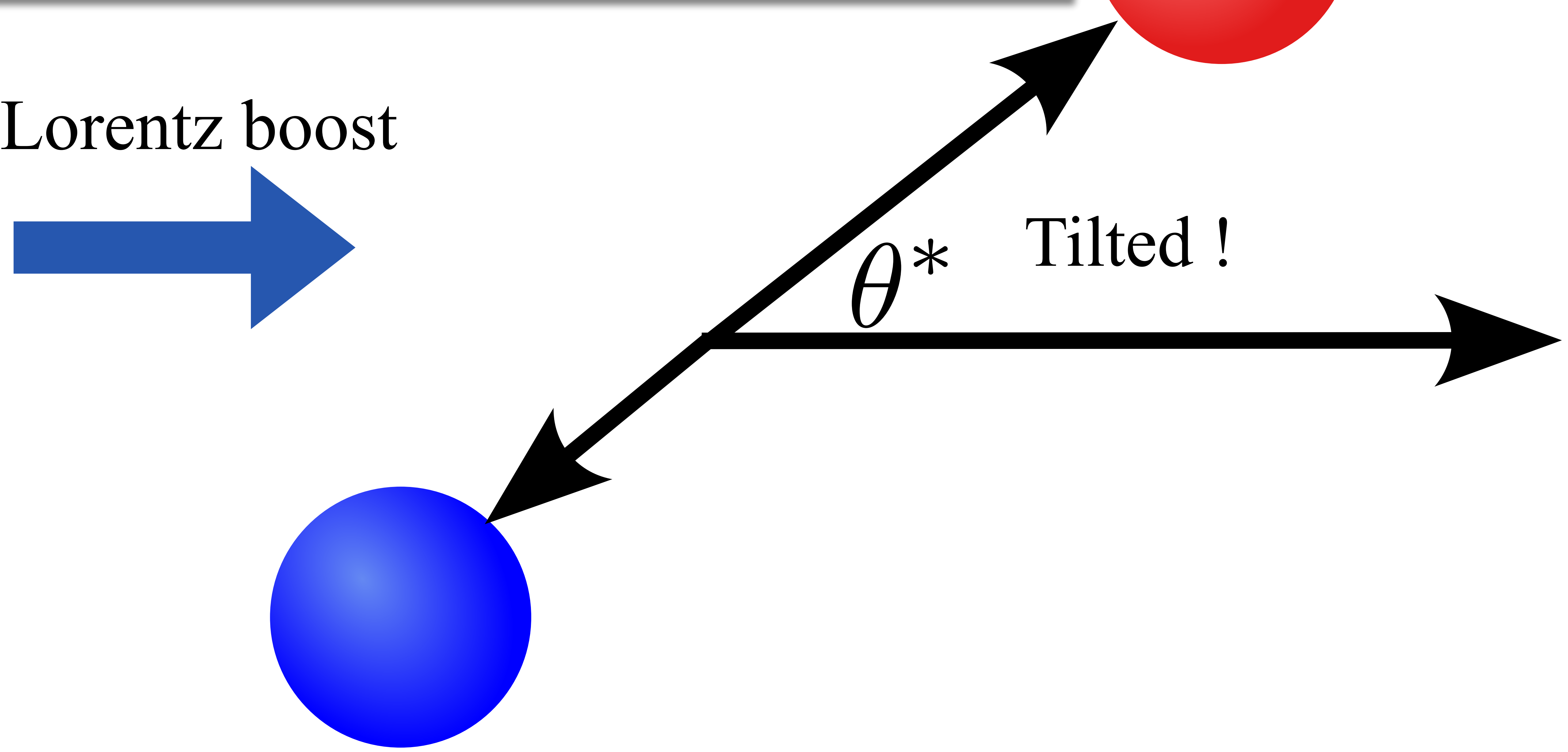
Motivation (for 2p2h only)

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

Also one more parameter to oppose Pauli blocking !!



Outgoing nucleons (lab frame)



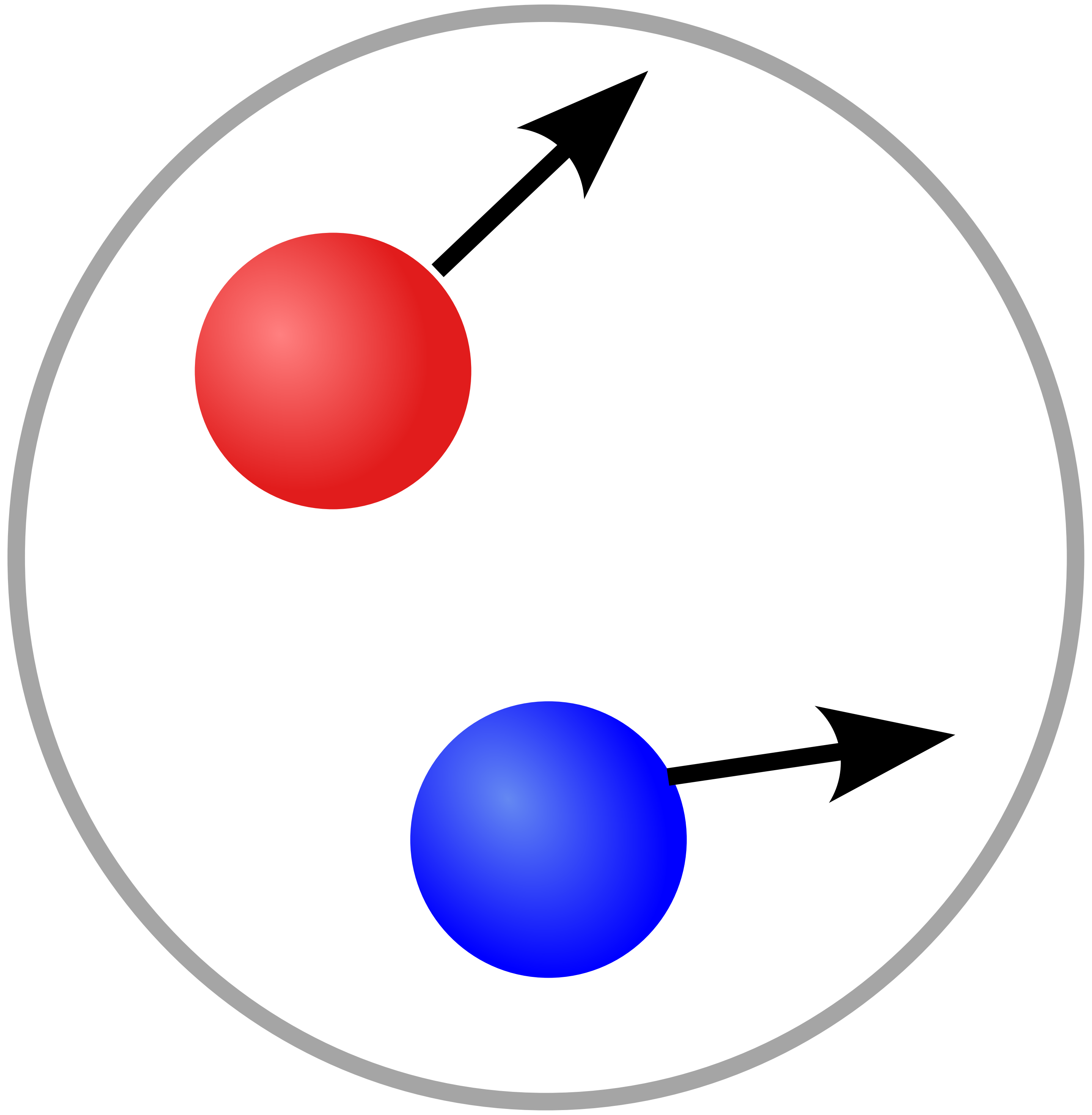
Center-of-mass frame

Modelling Correlations Between Nucleons

Motivation (for 2p2h only)

Modelling Correlations Between Nucleons

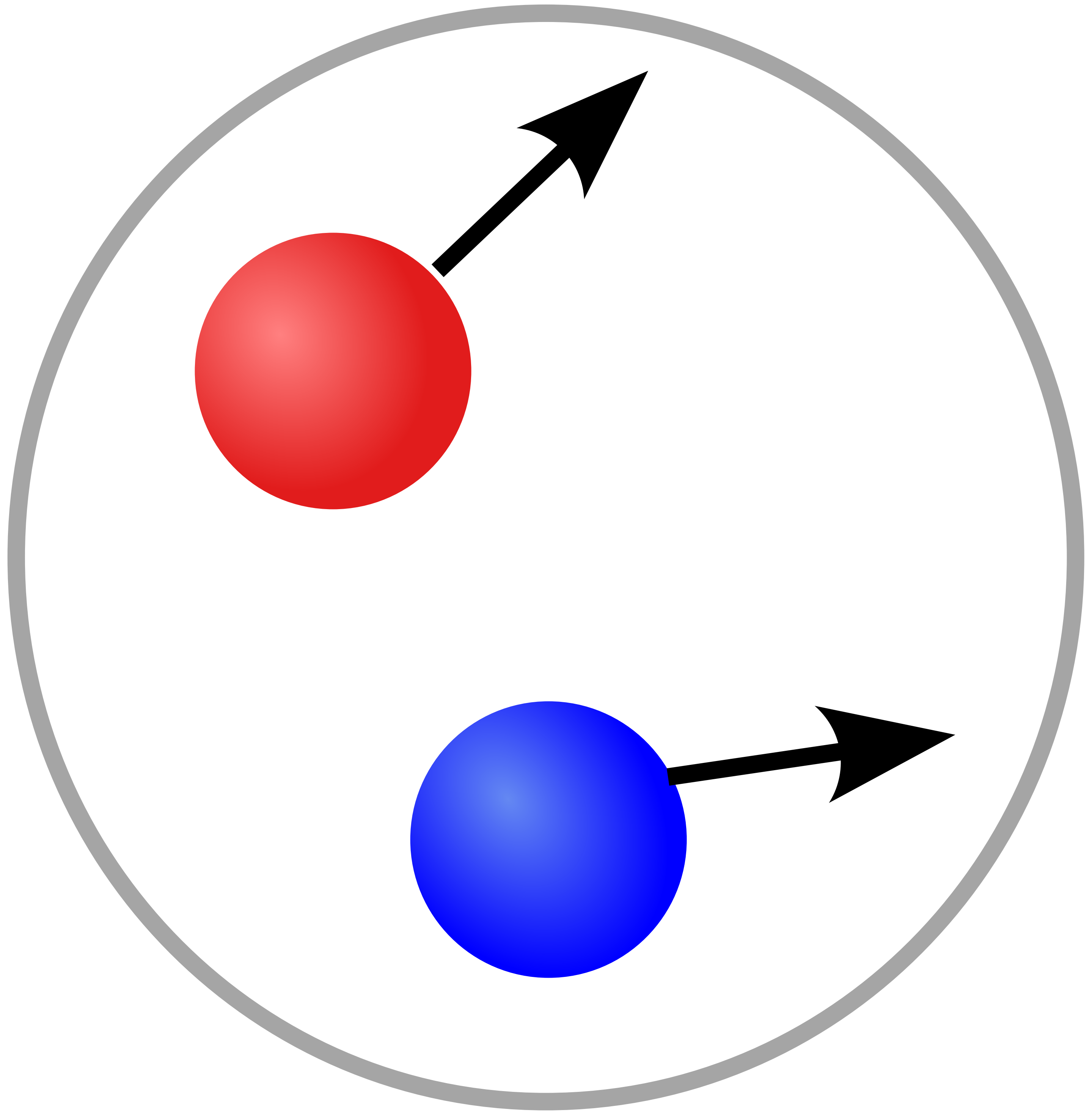
Motivation (for 2p2h only)



Outgoing nucleons (lab frame)

Modelling Correlations Between Nucleons

Motivation (for 2p2h only)

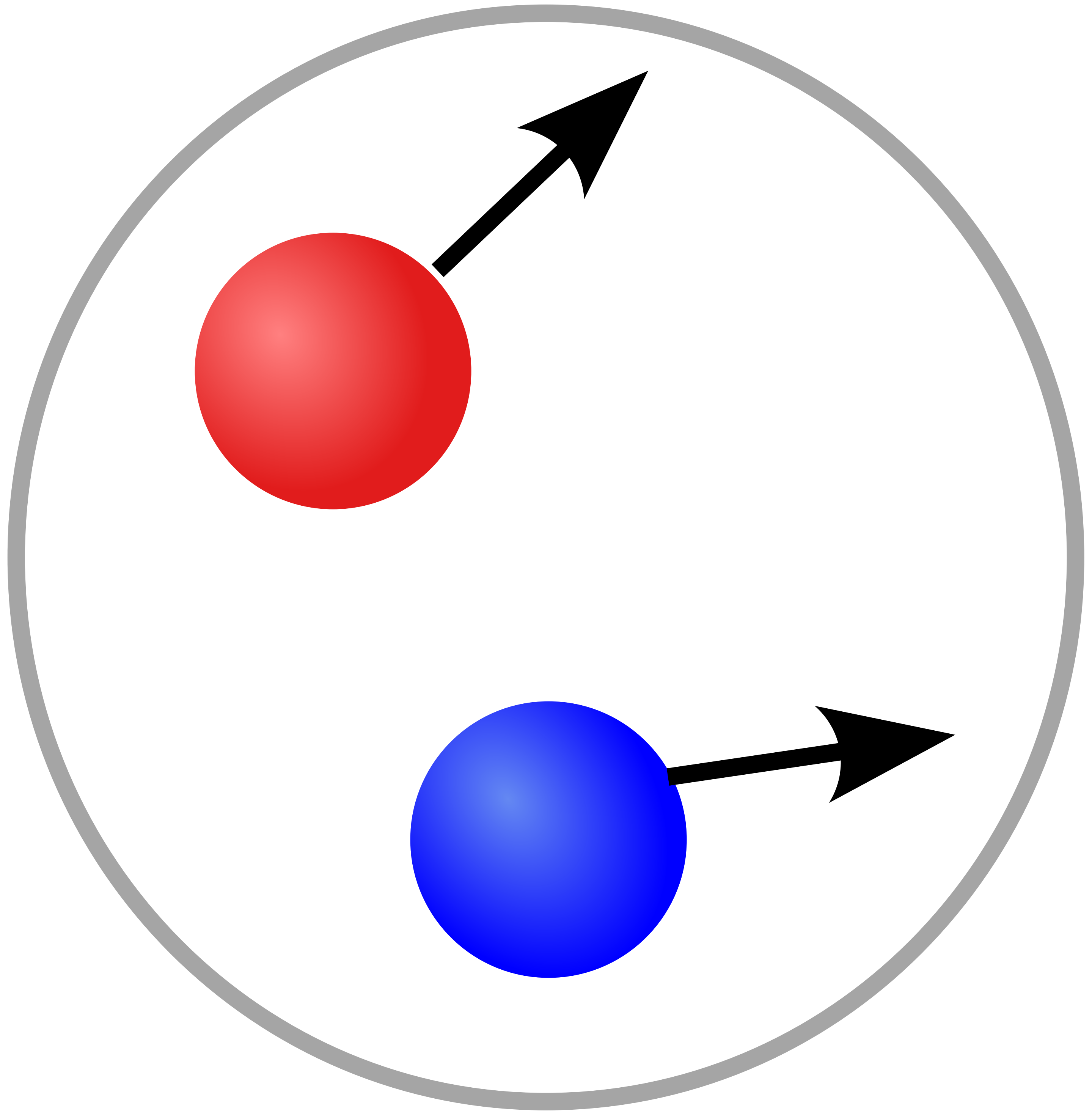


Outgoing nucleons (lab frame)

Lorentz boost

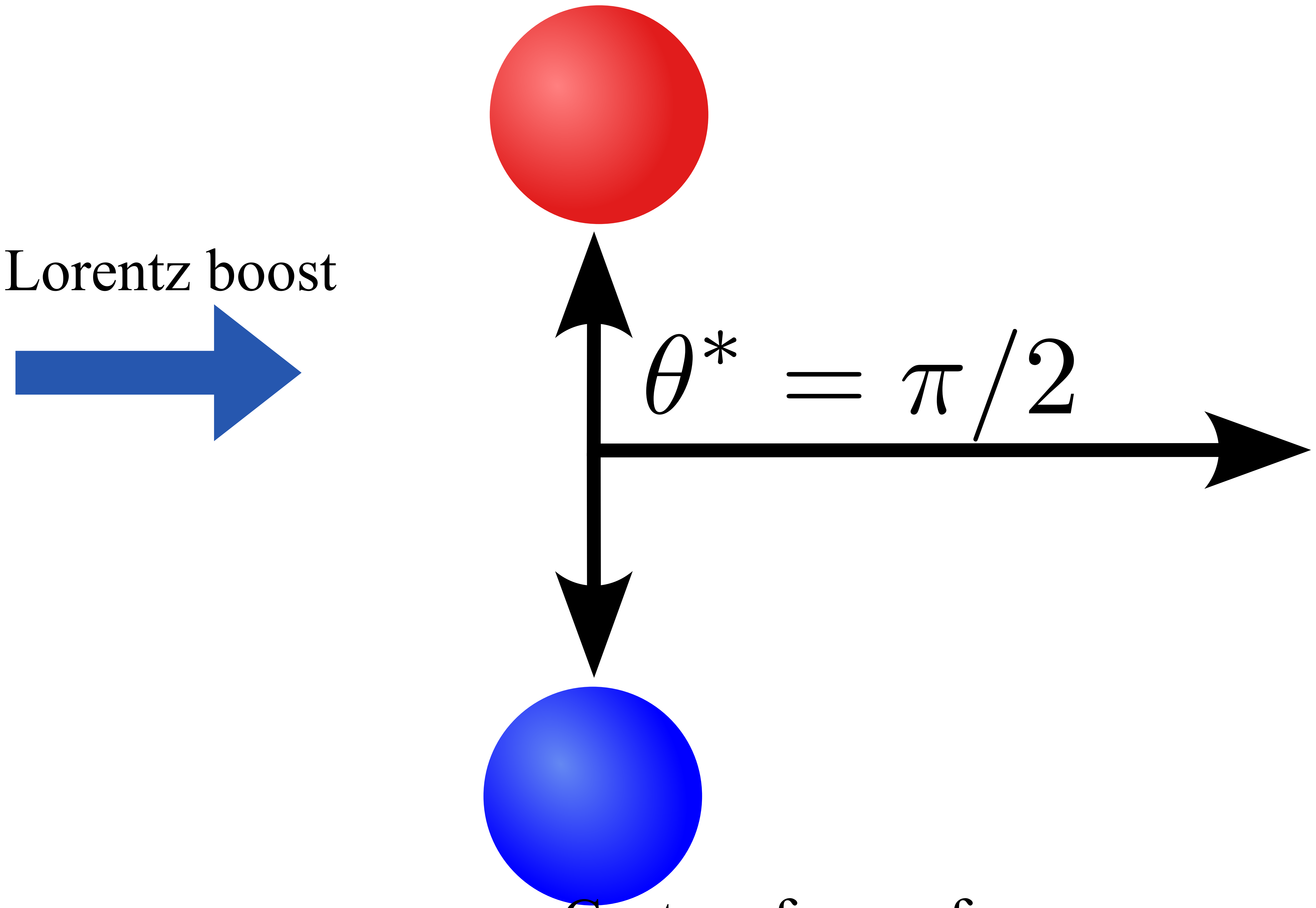
Modelling Correlations Between Nucleons

Motivation (for 2p2h only)



Outgoing nucleons (lab frame)

Lorentz boost

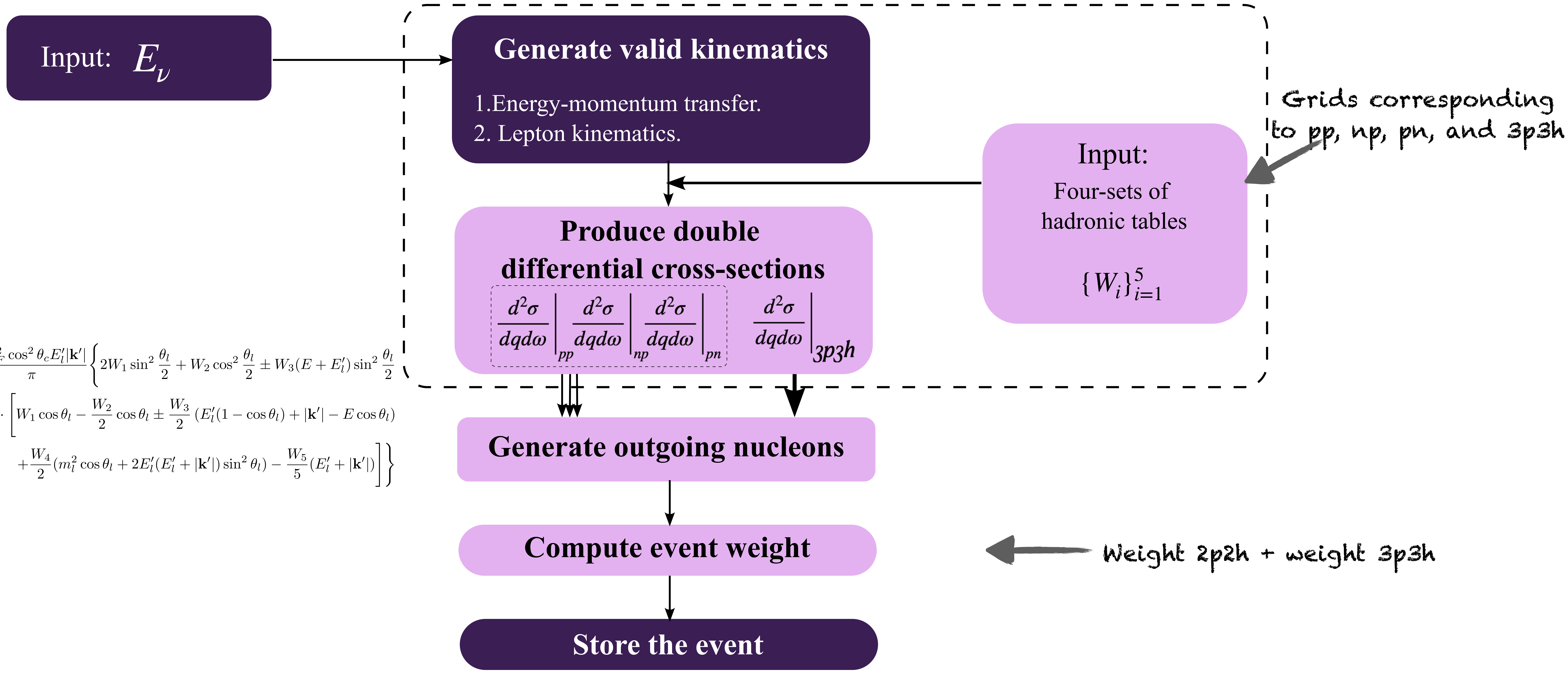


Center-of-mass frame

NuWro implementation of the 2020 Valencia model

New implementation of MEC models

Within the context of 2020 Valencia model

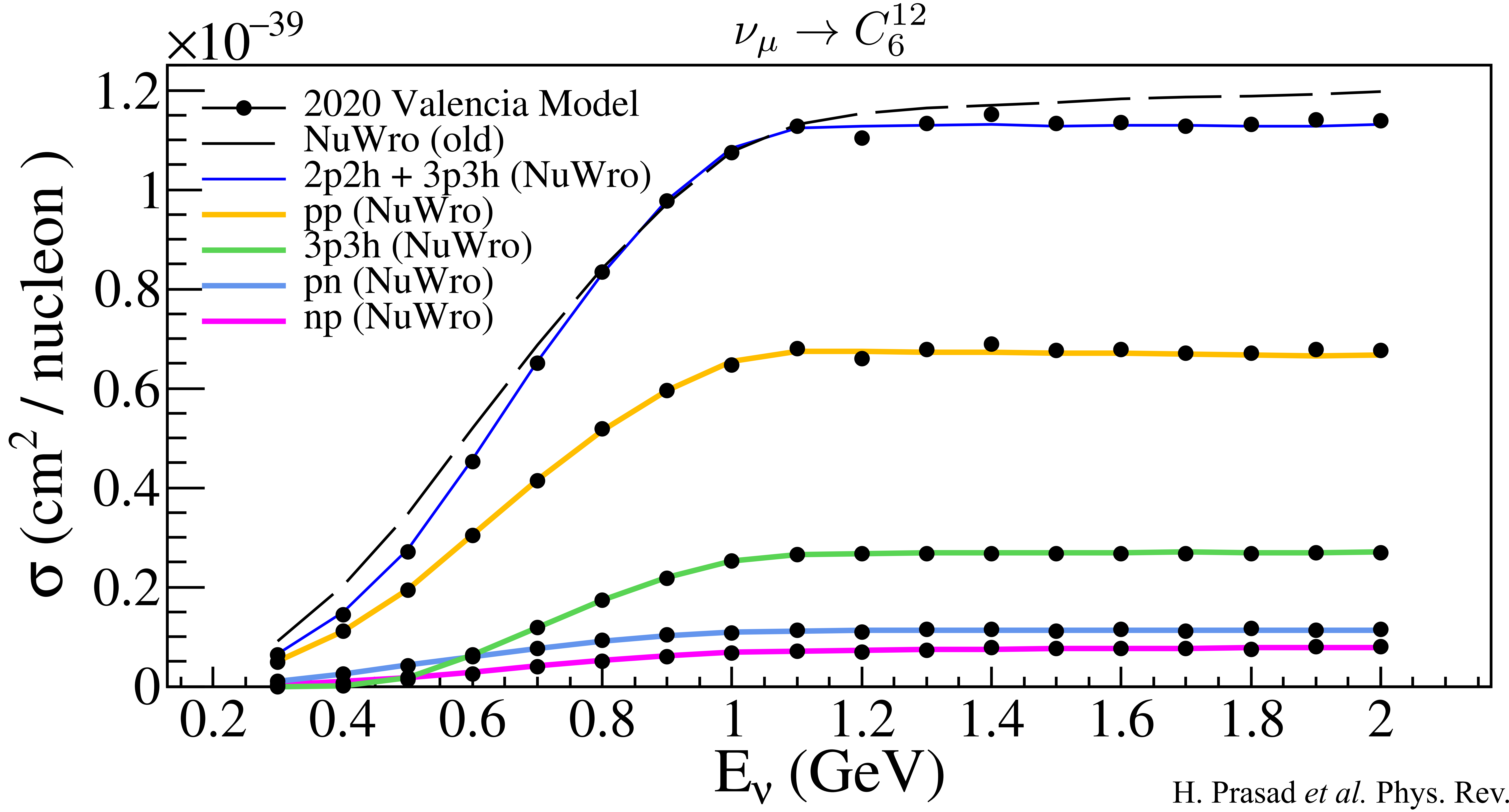


$$
\begin{aligned}
\frac{d^2\sigma}{dE_l'\,d\cos\theta_l} = {} & \frac{2G_F^2\cos^2\theta_c E_l'|\mathbf{k}'|}{\pi}\Big\{2W_1\sin^2\frac{\theta_l}{2} + W_2\cos^2\frac{\theta_l}{2} \pm W_3(E+E_l')\sin^2\frac{\theta_l}{2} \\
& + \frac{m_l^2}{(E_l'+|\mathbf{k}'|)E_l'}\cdot\Big[W_1\cos\theta_l - \frac{W_2}{2}\cos\theta_l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

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

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 outgoing 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

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)

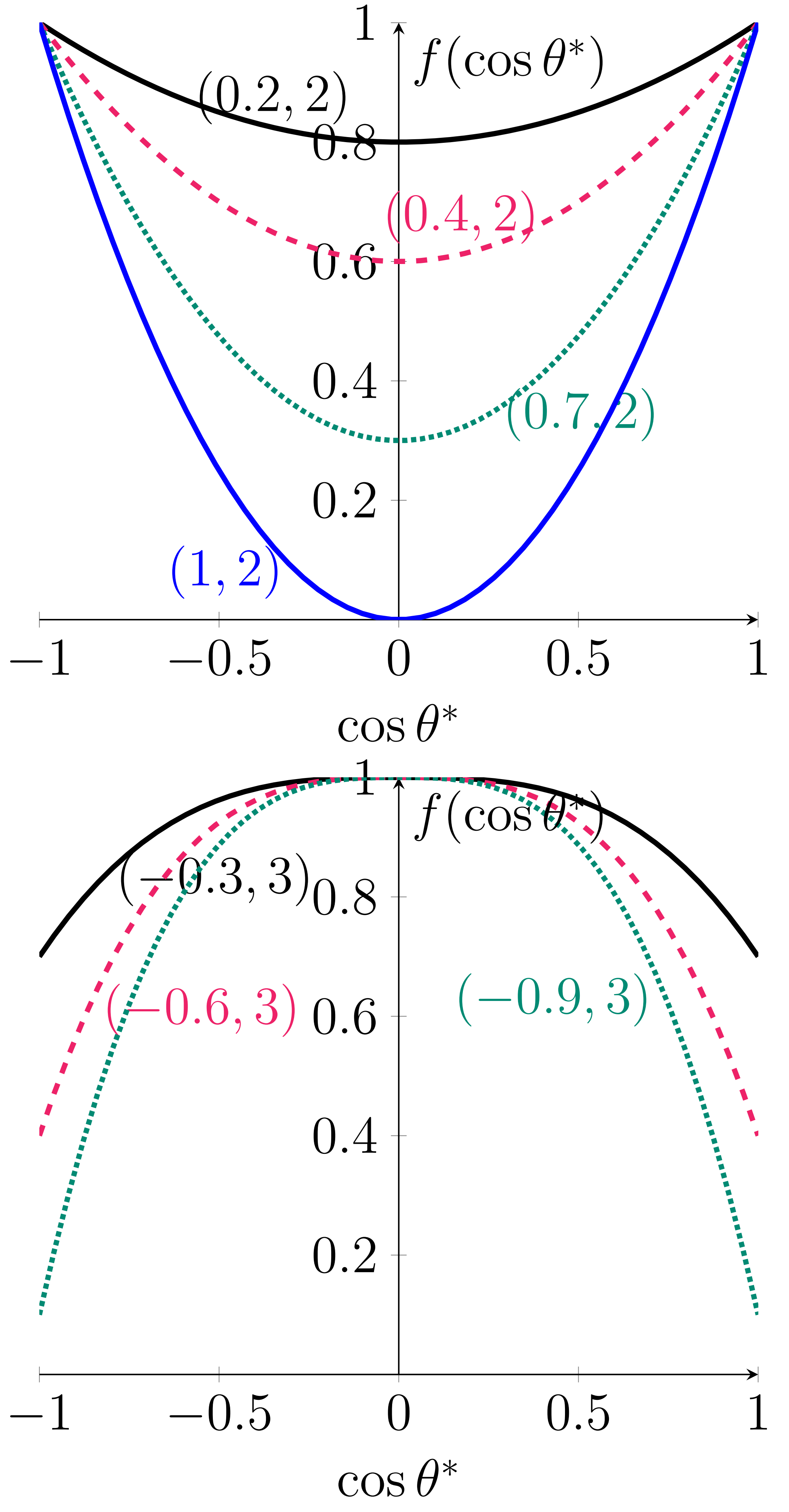
$$f(x; P, l) = \begin{cases} N(\kappa)\left(1 - P + P\left|\dfrac{x}{\kappa}\right|^{l}\right) \\ N'(\kappa)\left(1 + P\left|\dfrac{x}{\kappa}\right|^{l}\right) \end{cases}$$

Normalisation

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

$$l \in \{1, 2, 3, \ldots\}$$
$$P \in [0, 1]$$

$$P \in [-1, 0]$$
$$l \in \{1, 2, 3, \ldots\}$$



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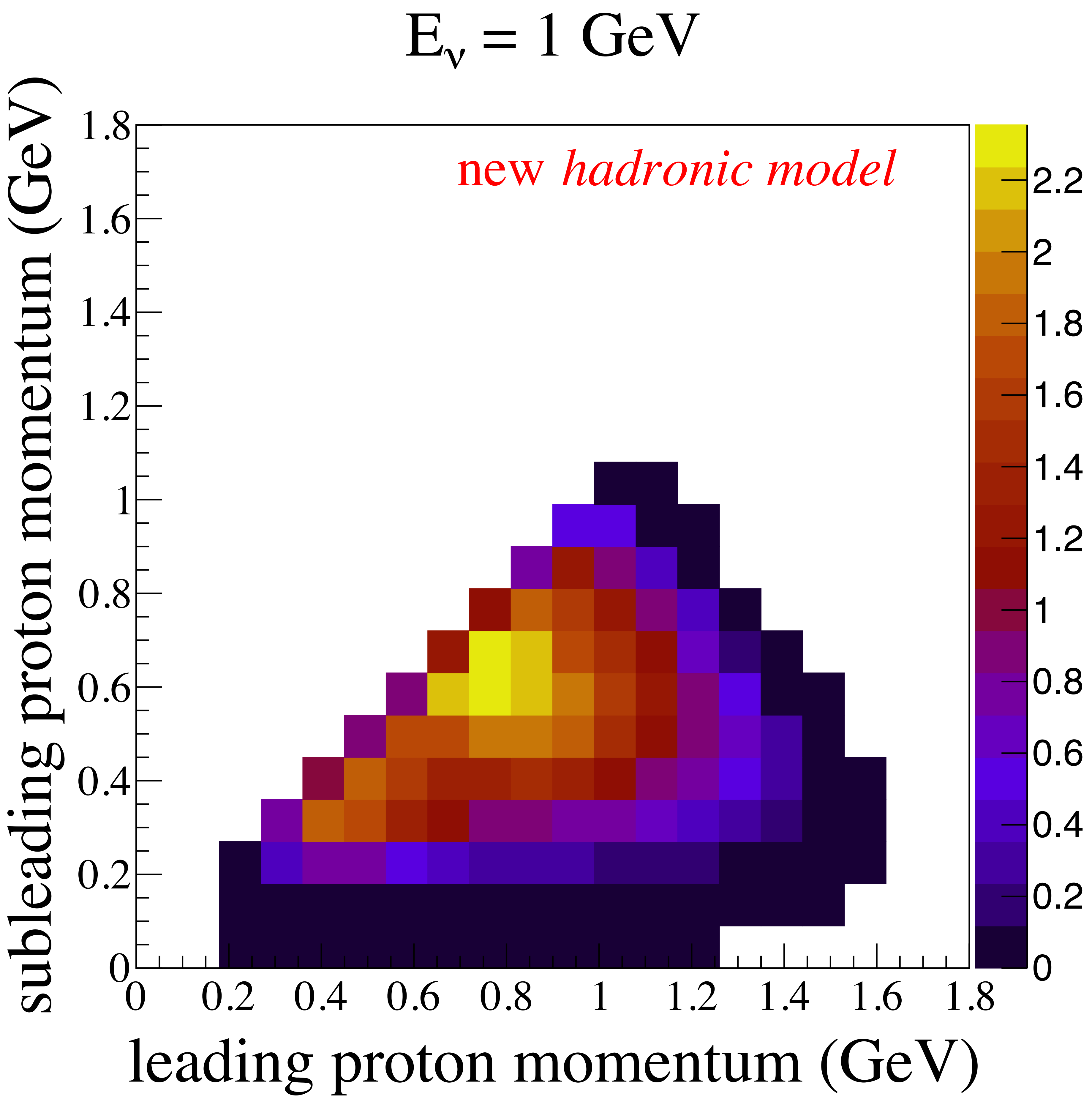
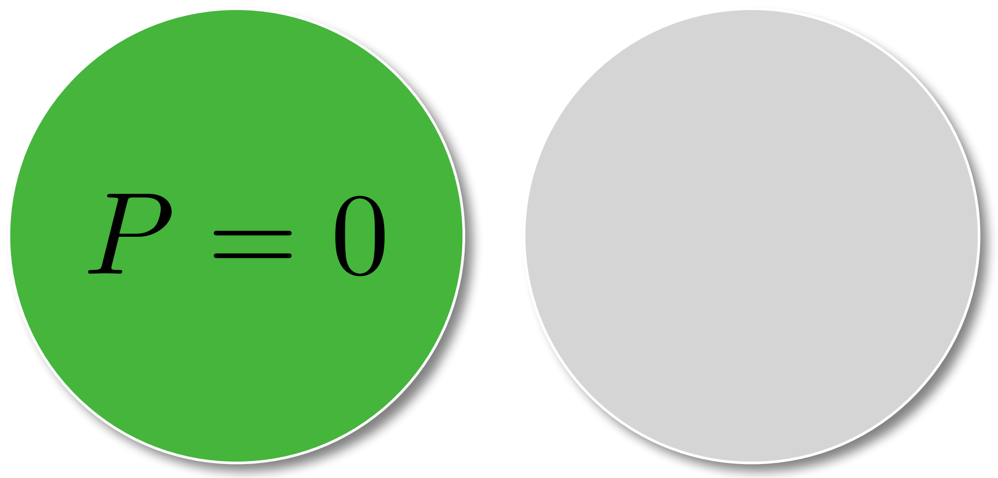
Nucleon sampling function

Caught in action

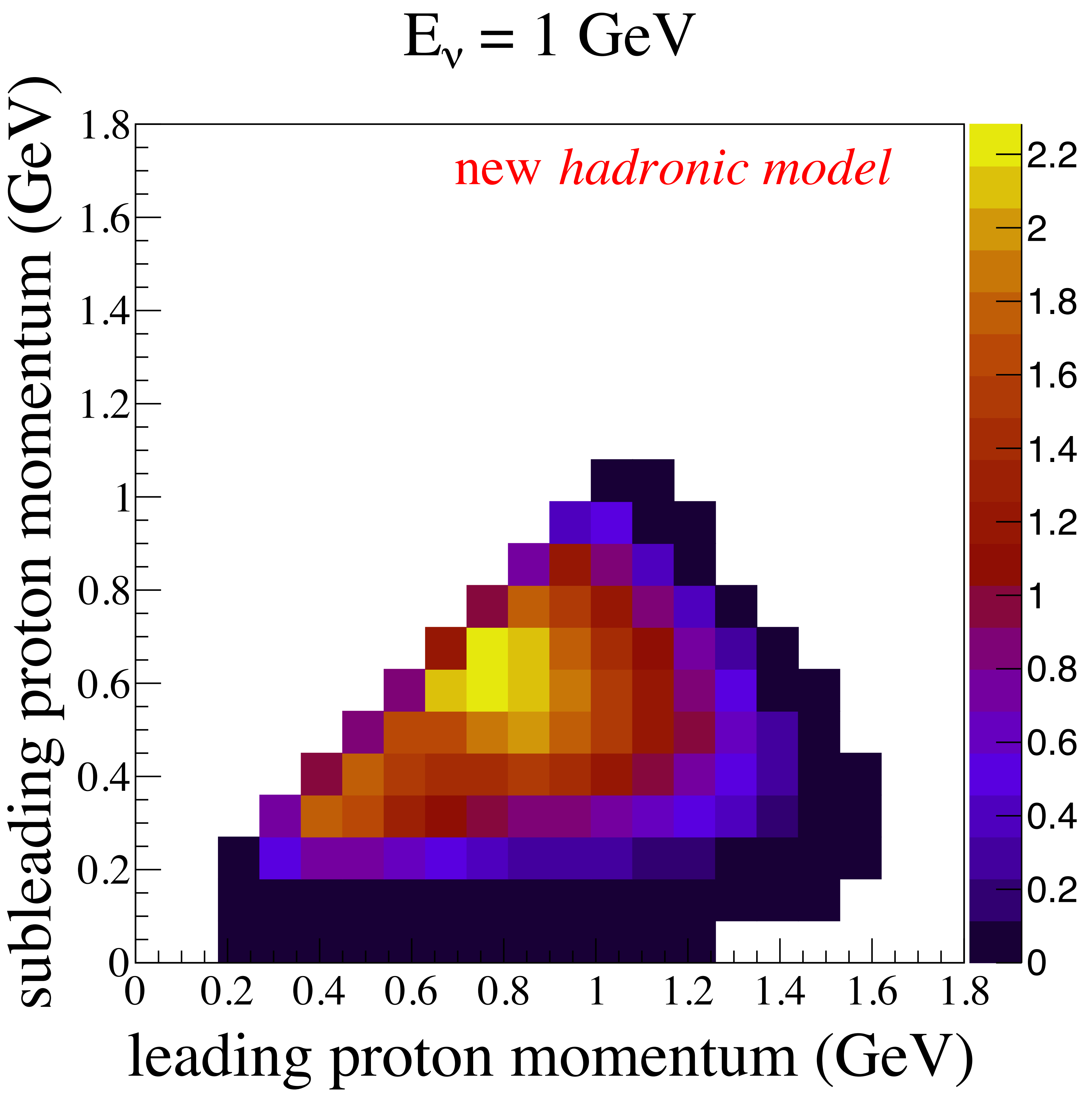




Nucleon sampling function

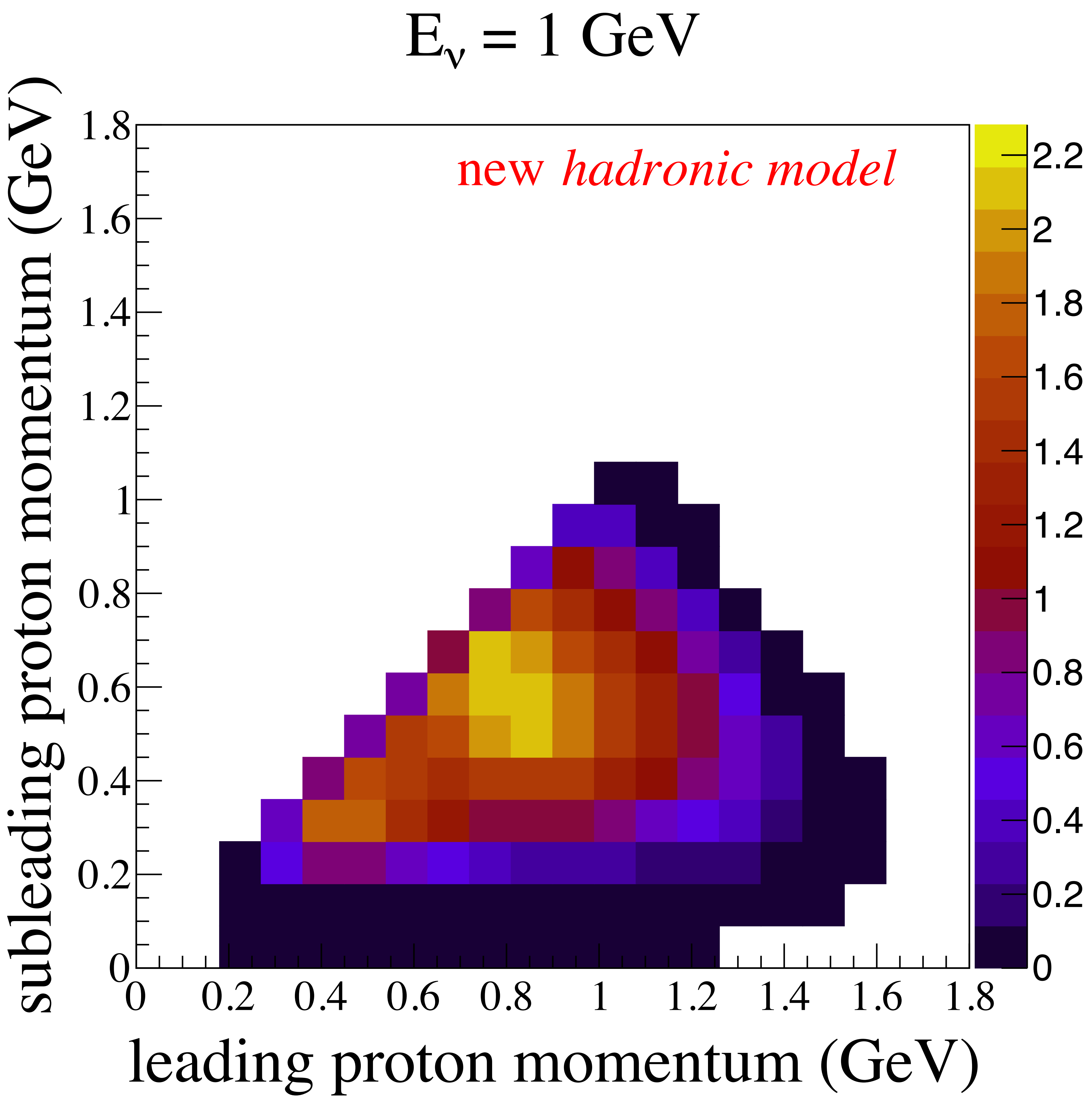
Caught in action

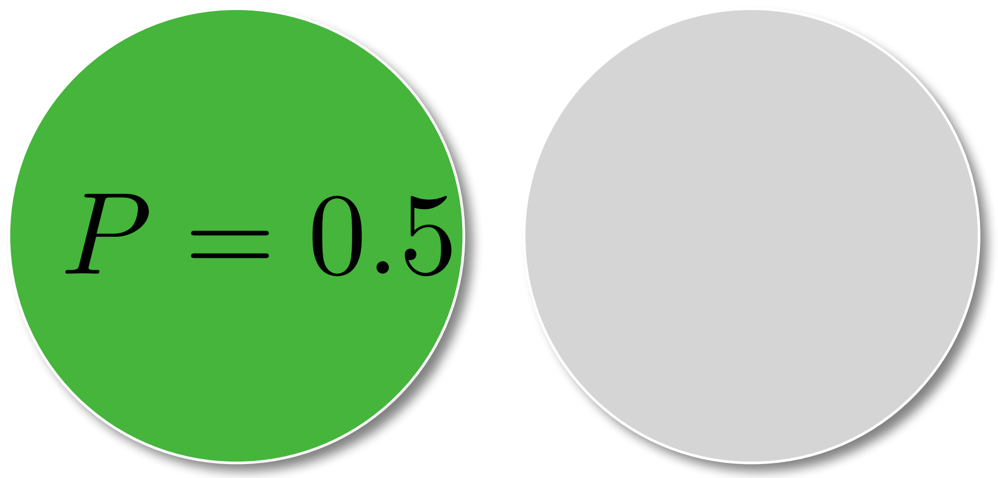
$P = 0.3$



Nucleon sampling function

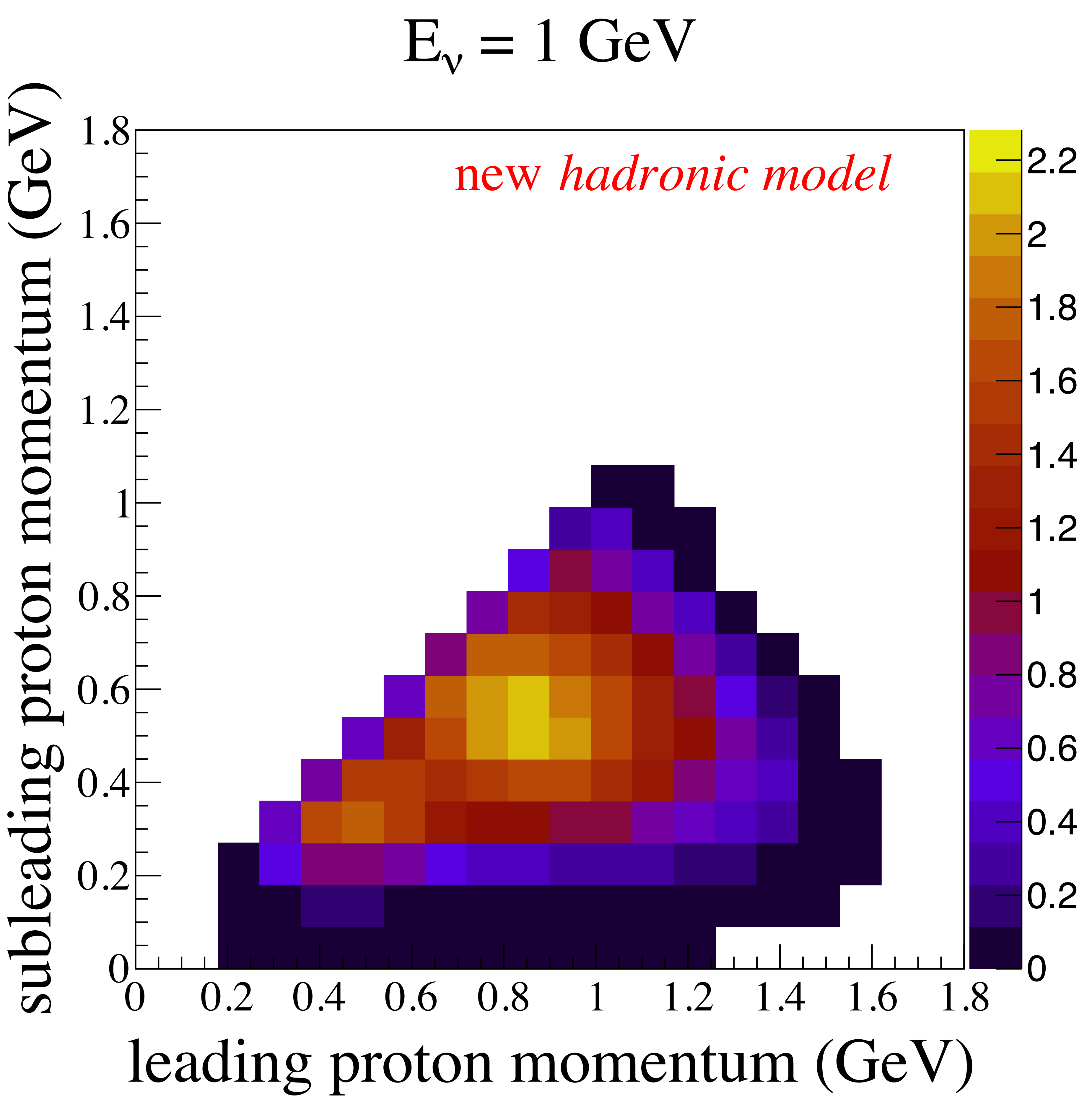
Caught in action

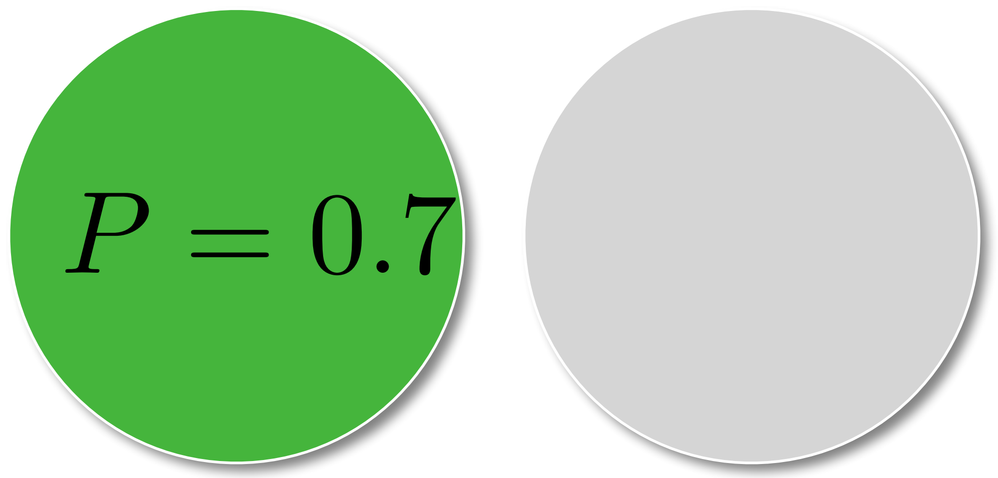




Nucleon sampling function

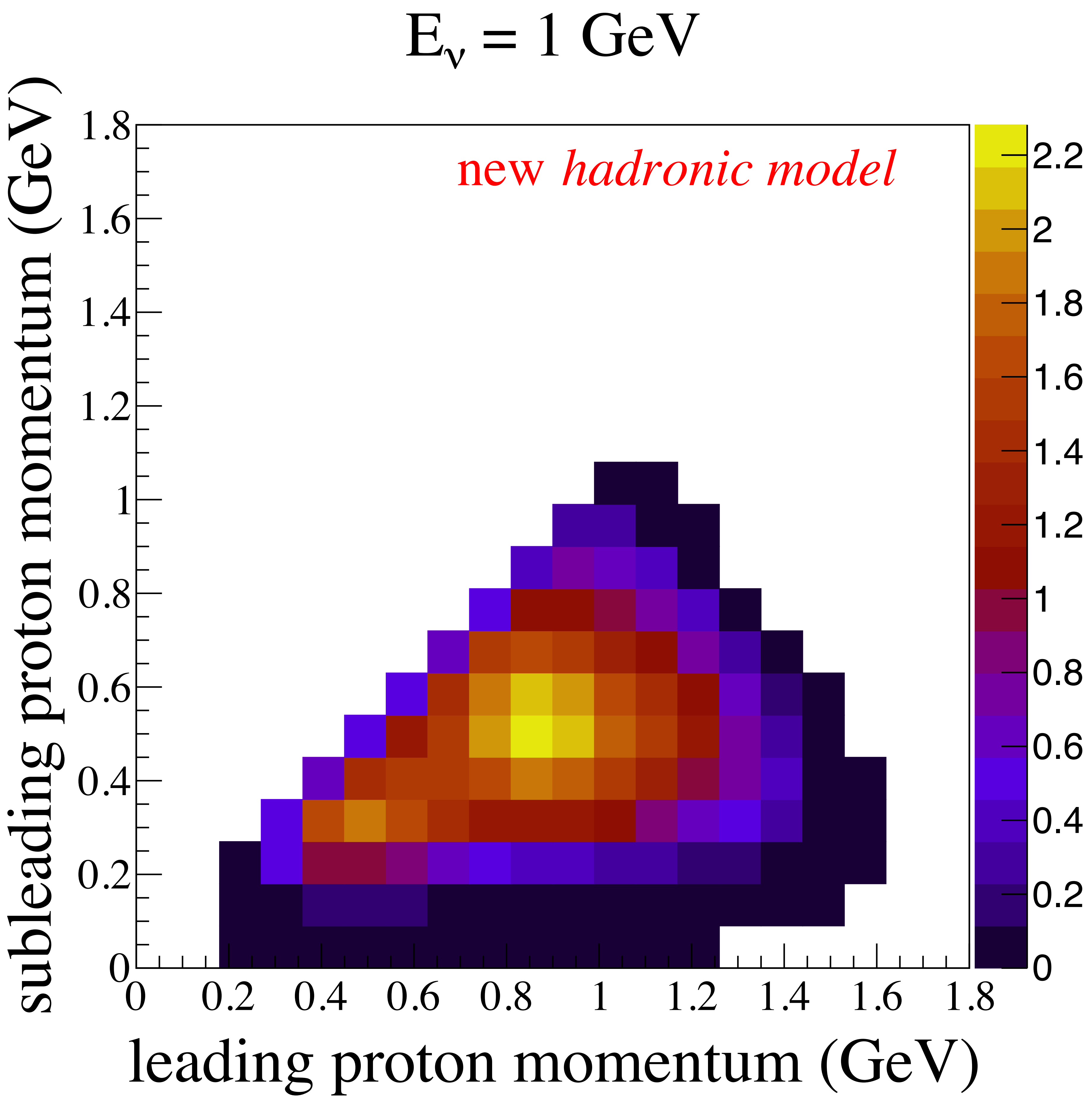
Caught in action

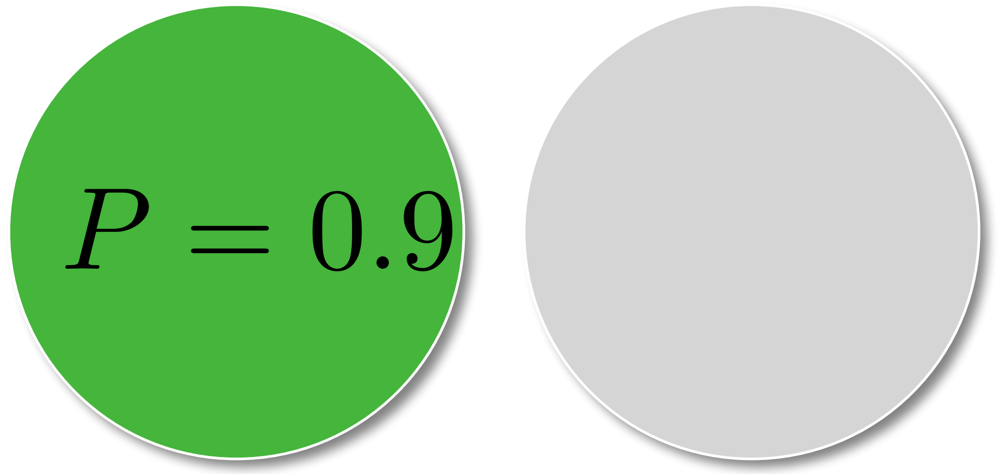




Nucleon sampling function

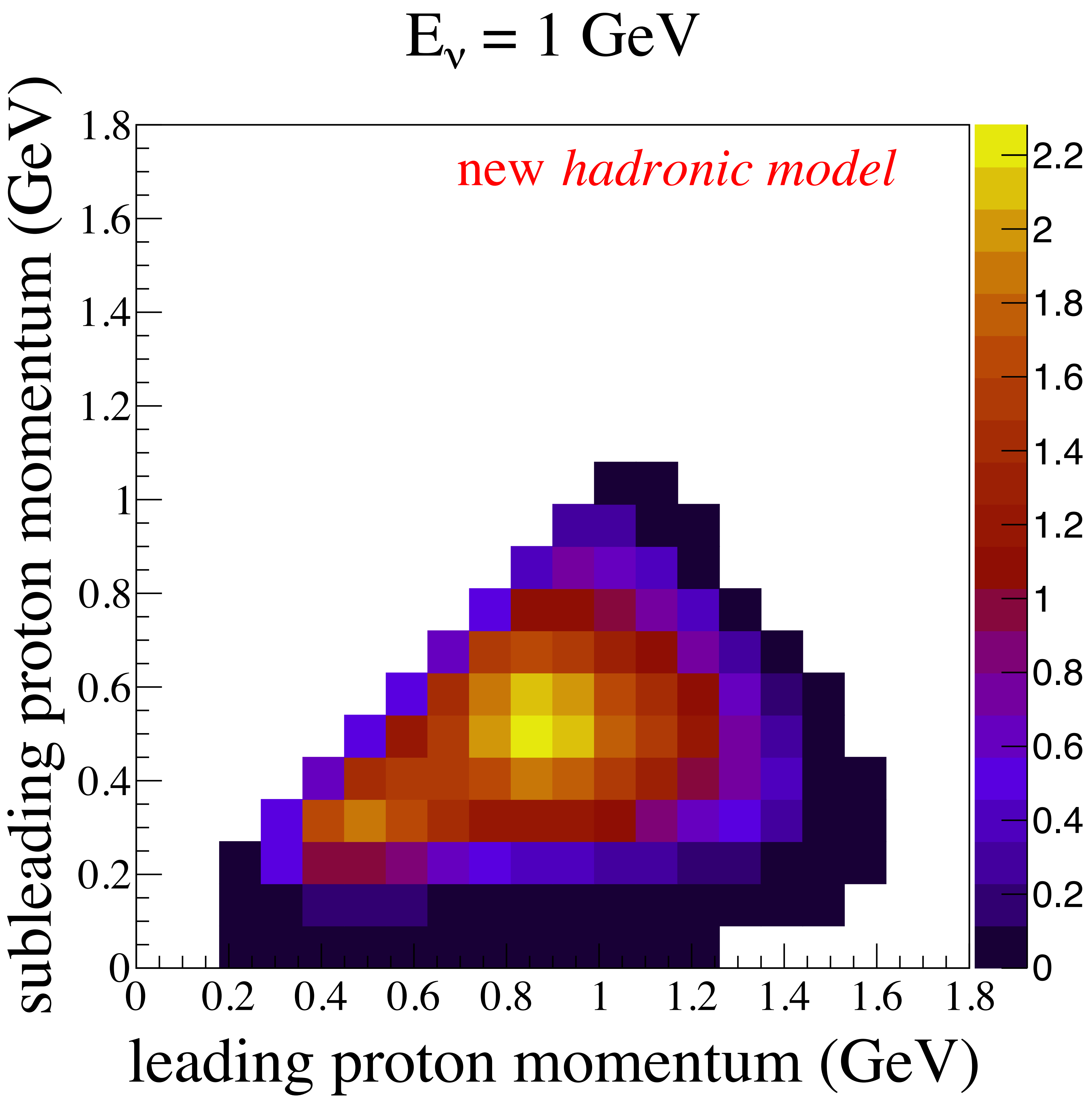
Caught in action





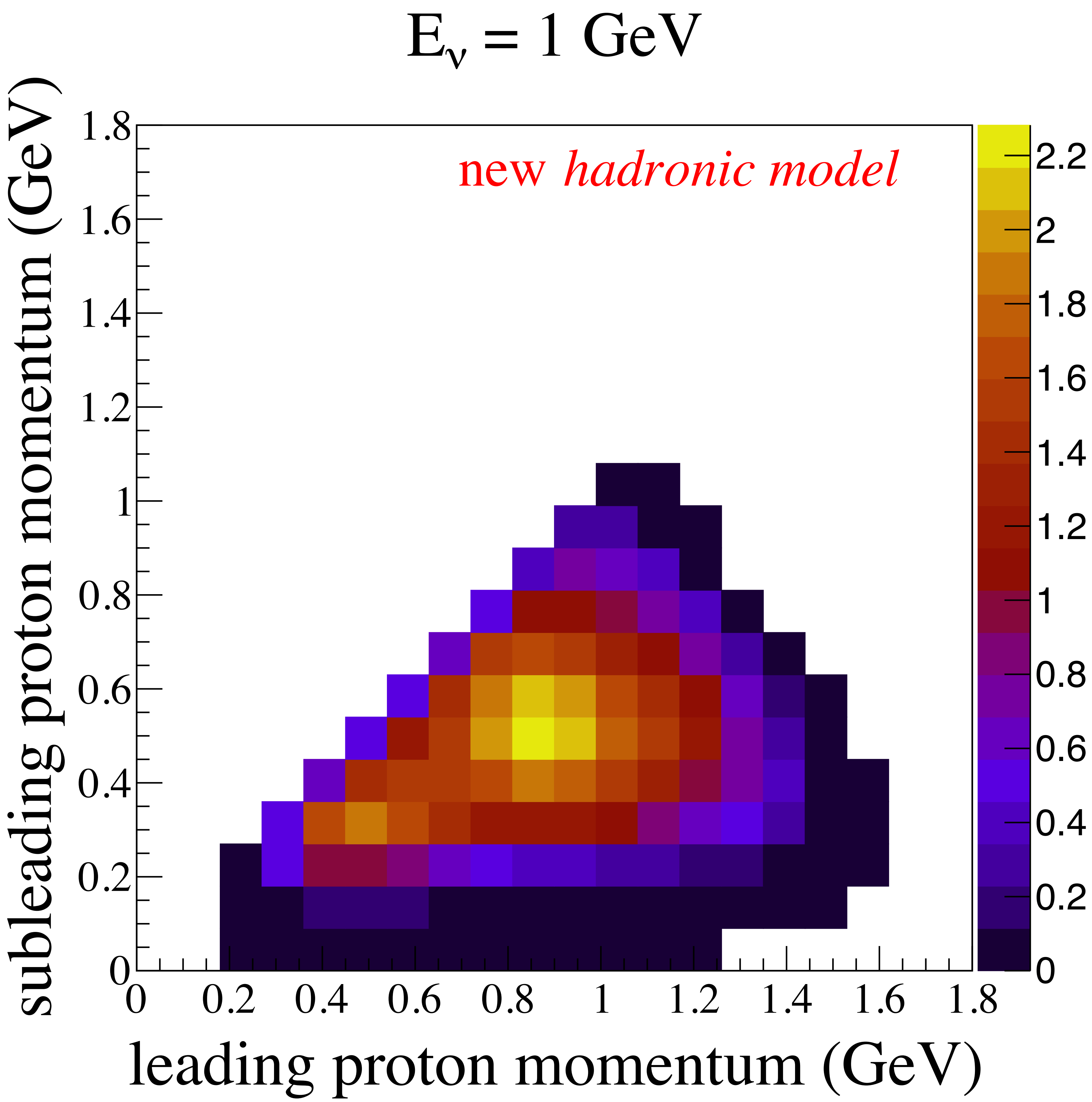
Nucleon sampling function

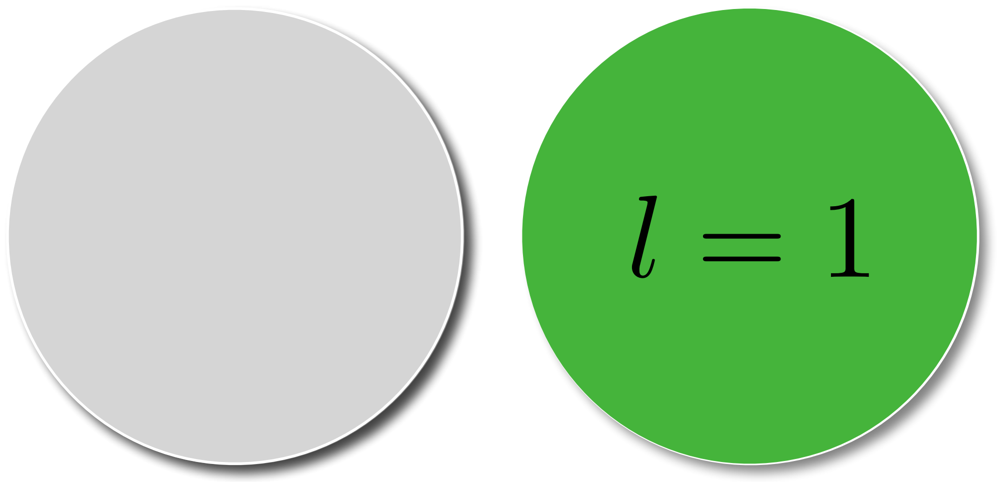
Caught in action



Nucleon sampling function

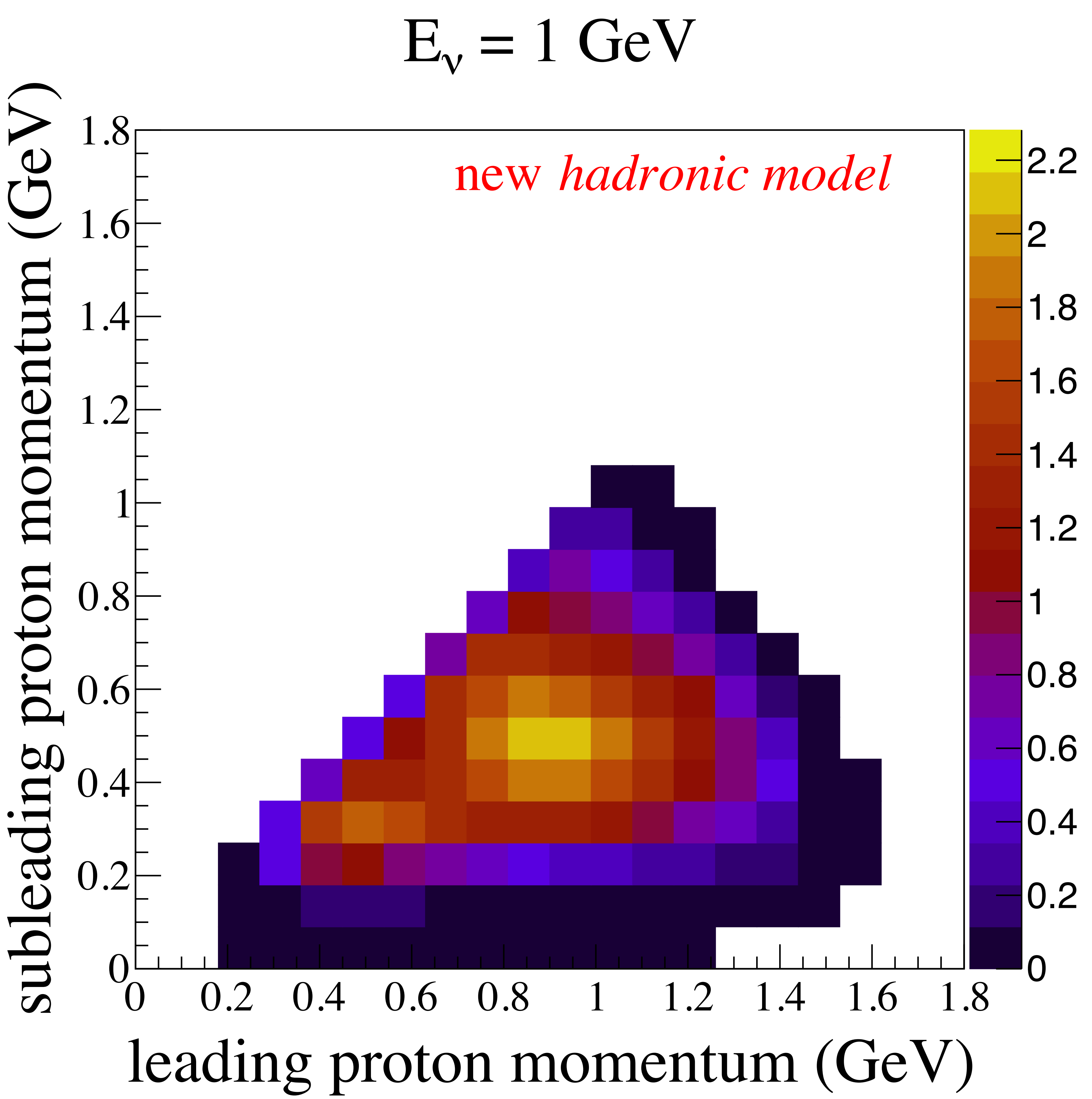
Caught in action





Nucleon sampling function

Caught in action

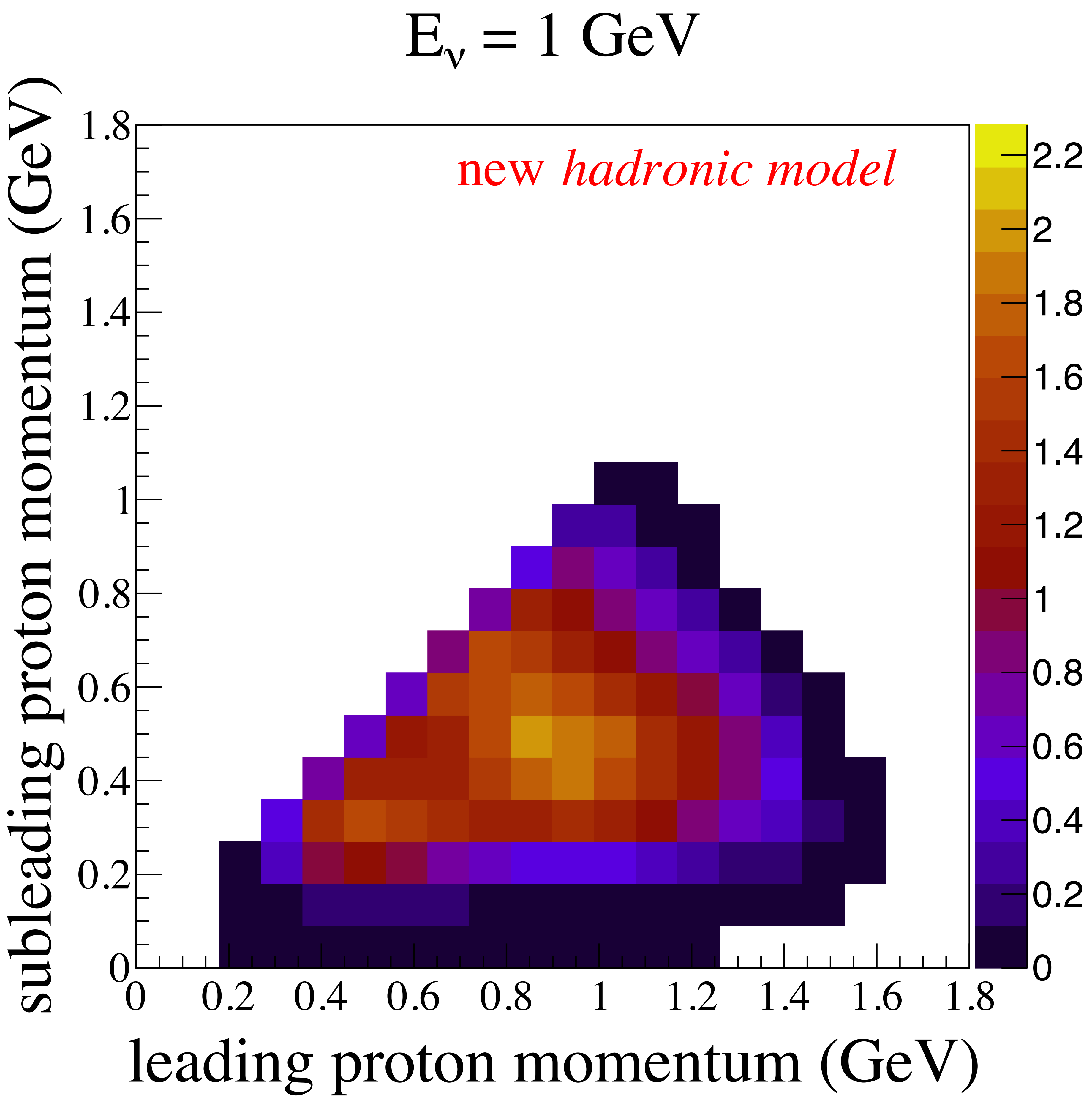


$l = 2$

Nucleon sampling function

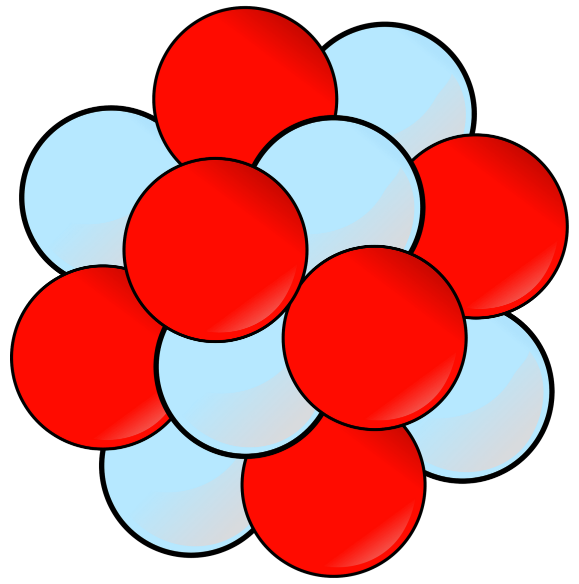
Caught in action

$l = 4$



Implementation results

Hadronic tables



Grids available in NuWro 25.01

- Available for $^{12}_{6}\mathrm{C}$ $^{16}_{8}\mathrm{O}$ $^{40}_{20}\mathrm{Ca}$ $^{208}_{82}\mathrm{Pb}$
- Results I show is for carbon.

Momentum distribution of outgoing nucleons

Two proton in final state (primary vertex)

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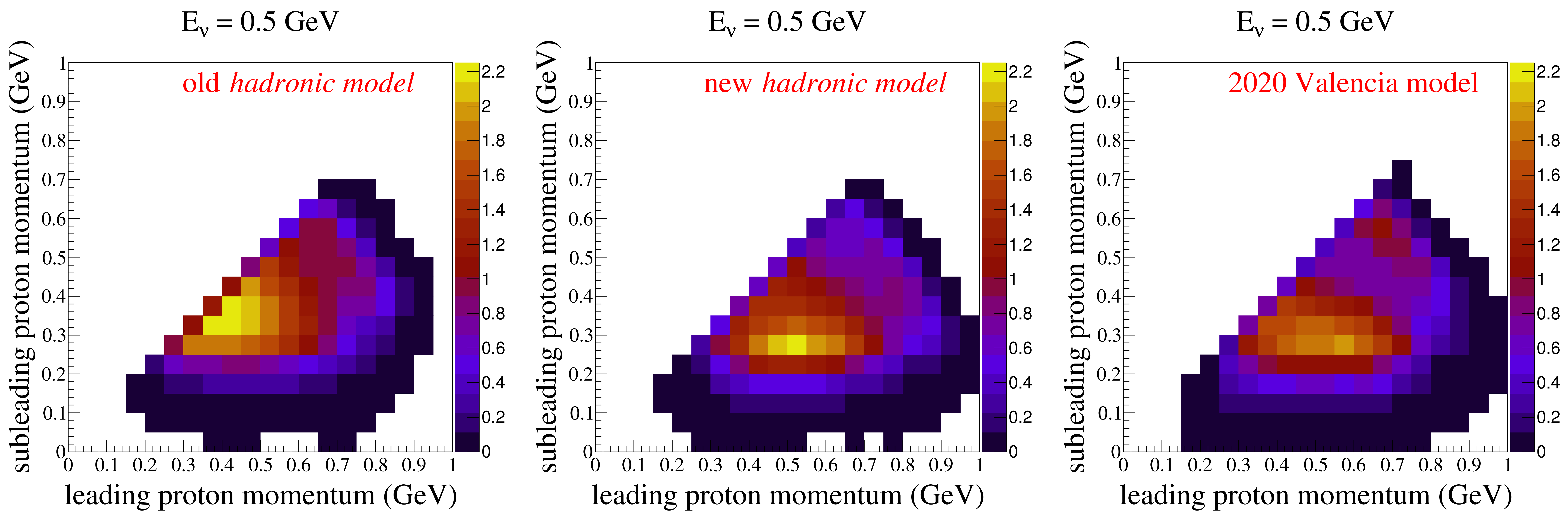
Momentum distribution of outgoing nucleons

Two proton in final state (primary vertex)



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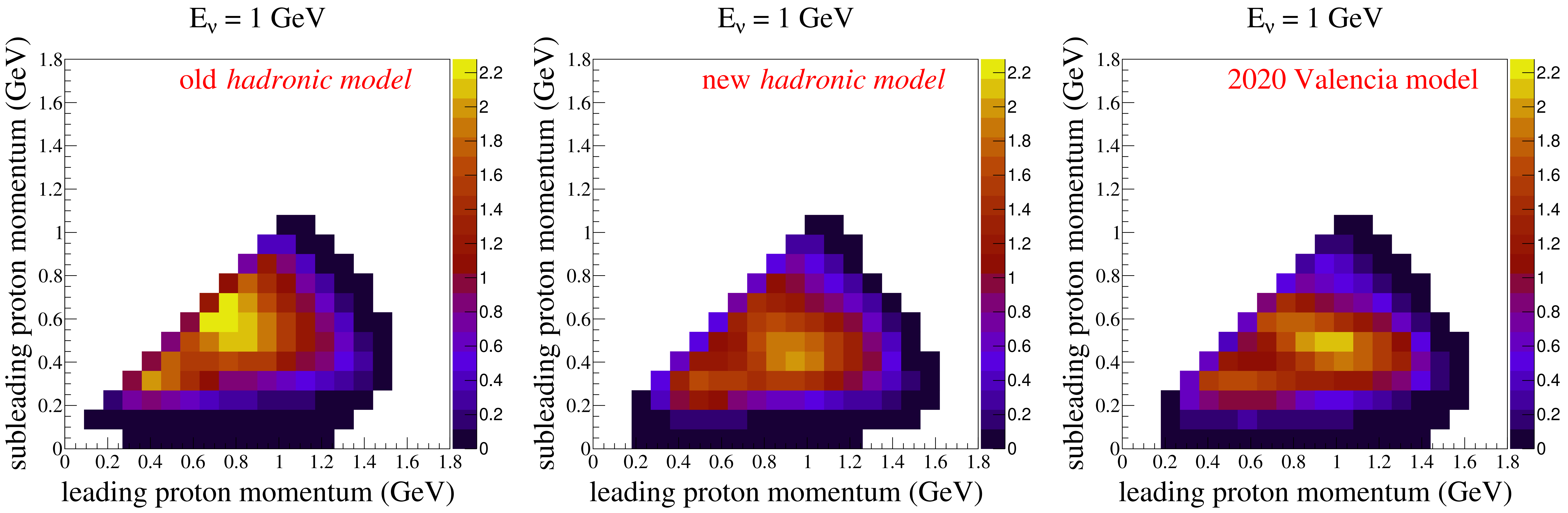

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Momentum distribution of outgoing nucleons

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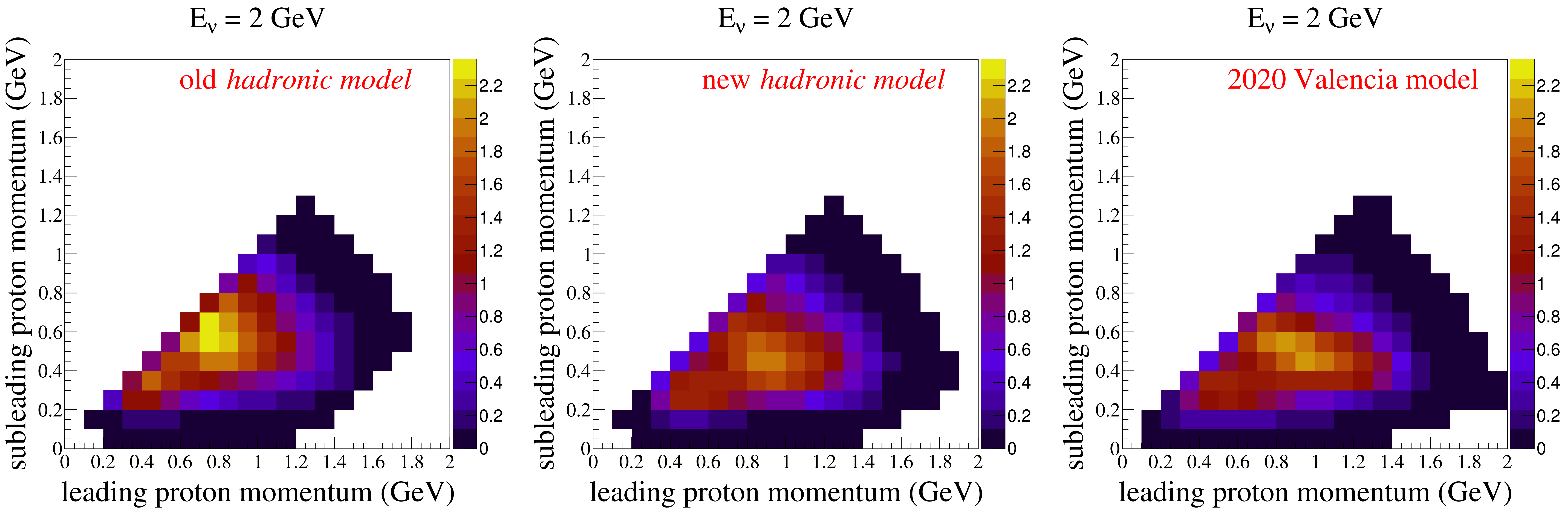

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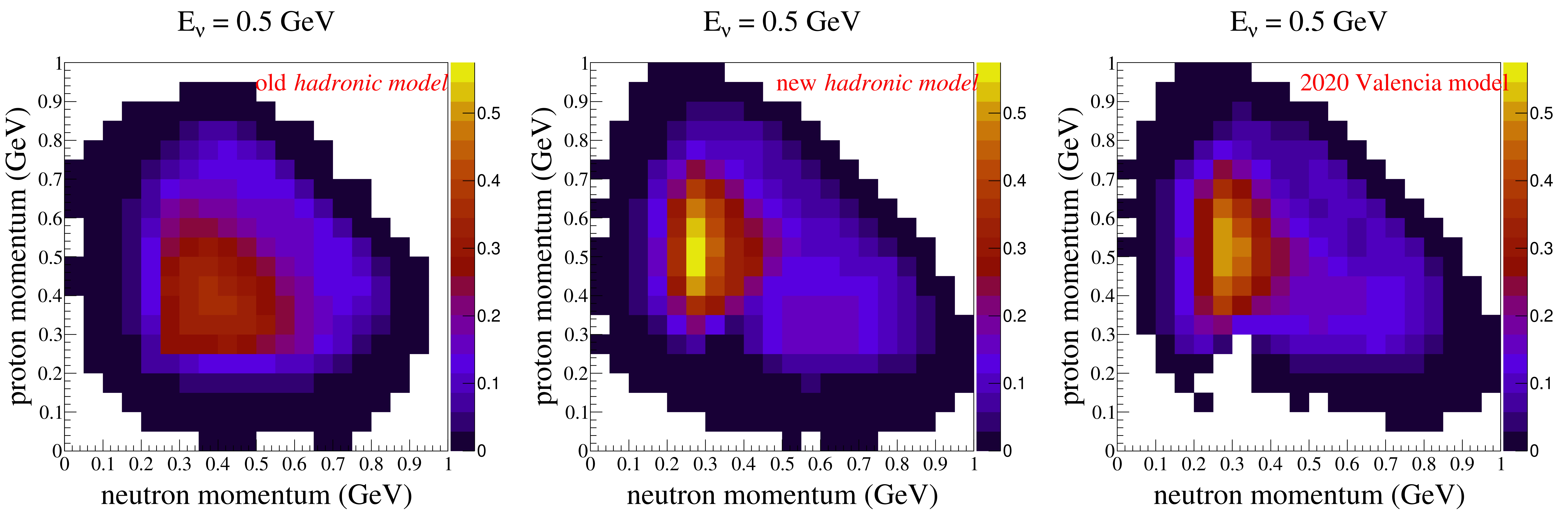
Momentum distribution of outgoing nucleons

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



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Momentum distribution of outgoing nucleons

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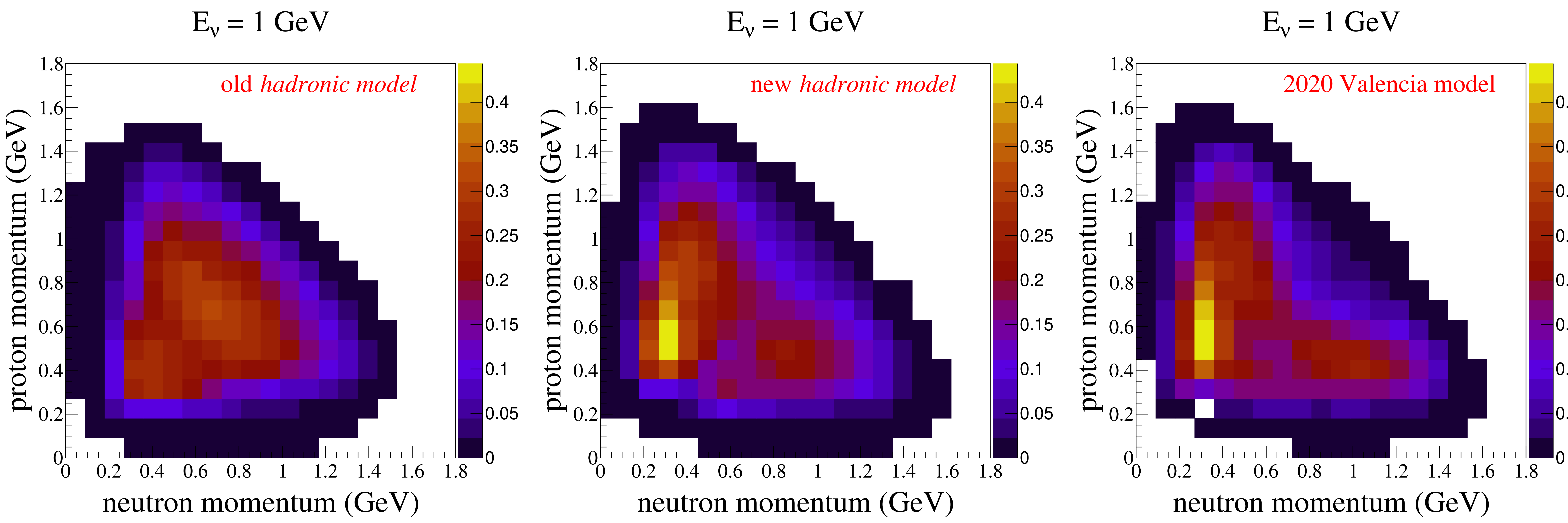

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Momentum distribution of outgoing nucleons

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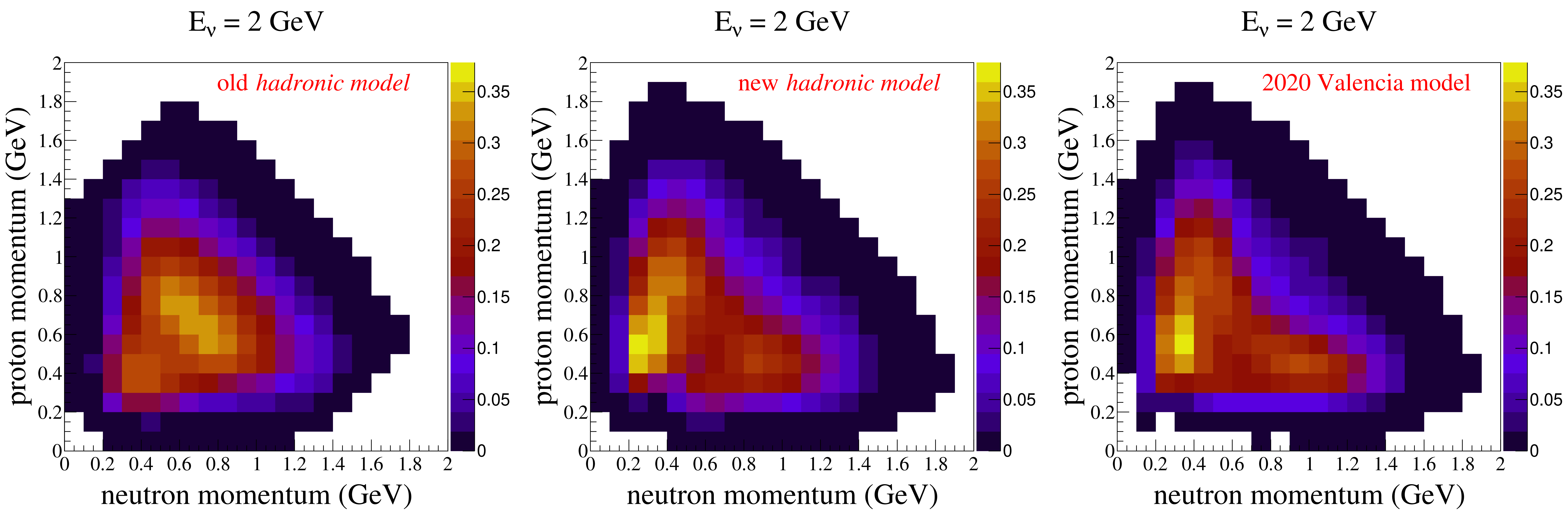

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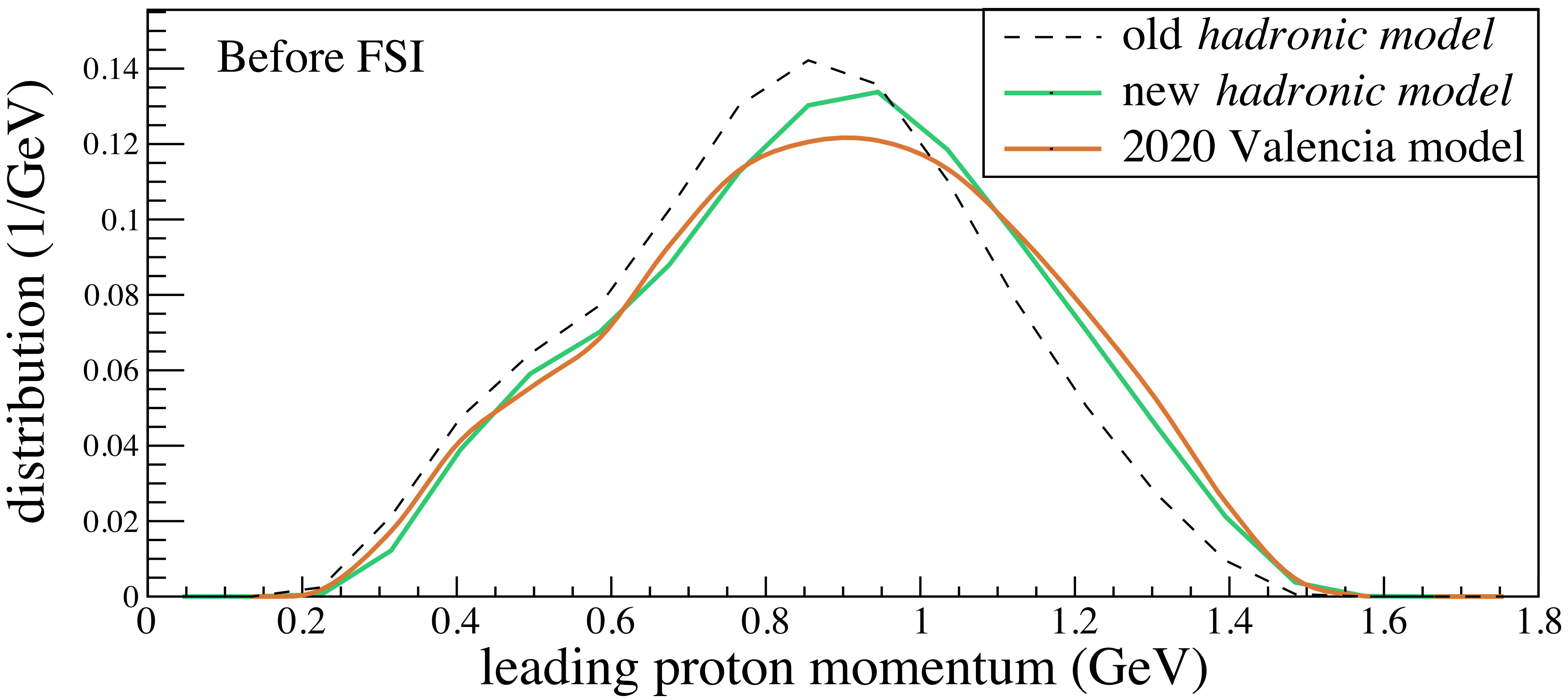
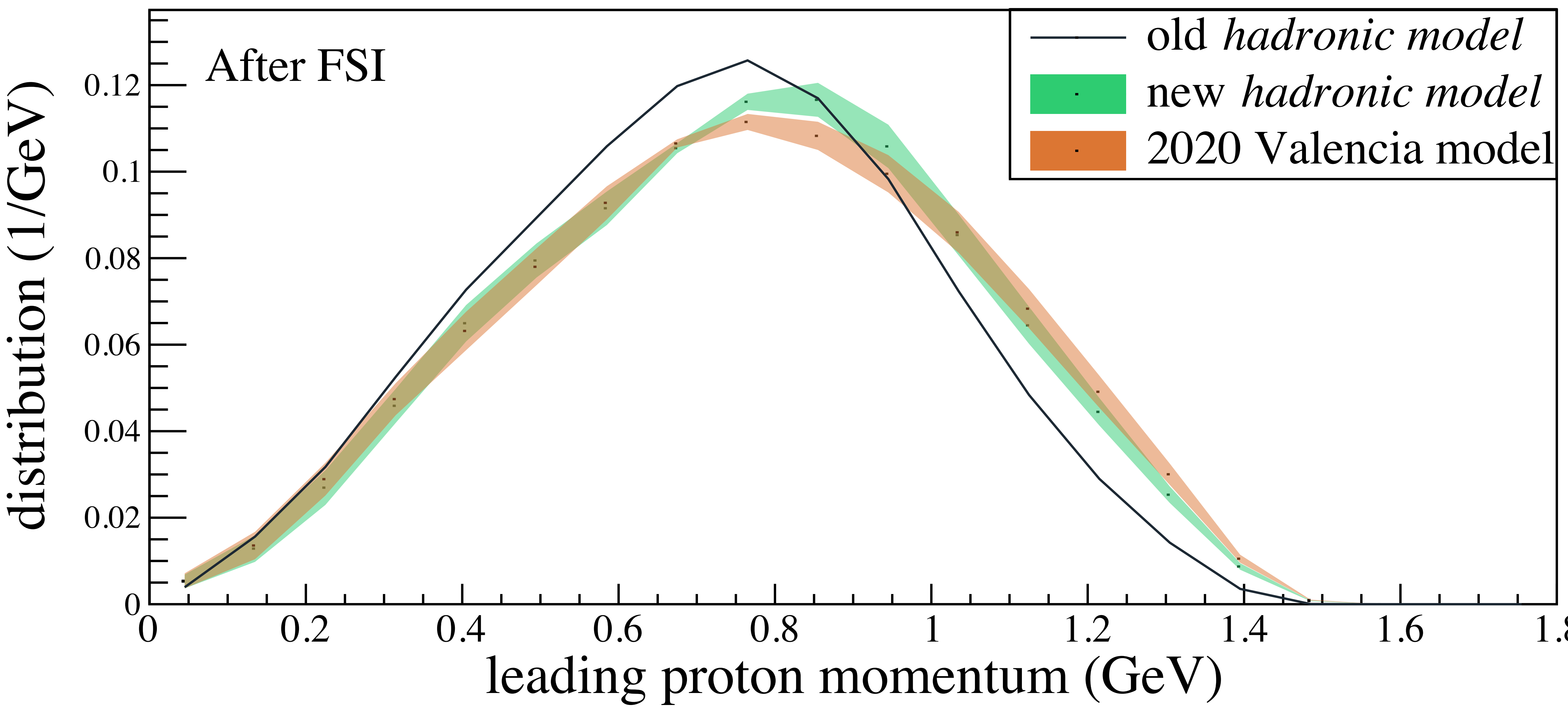
Impact of FSI

A distribution of momentum of the maximal proton





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

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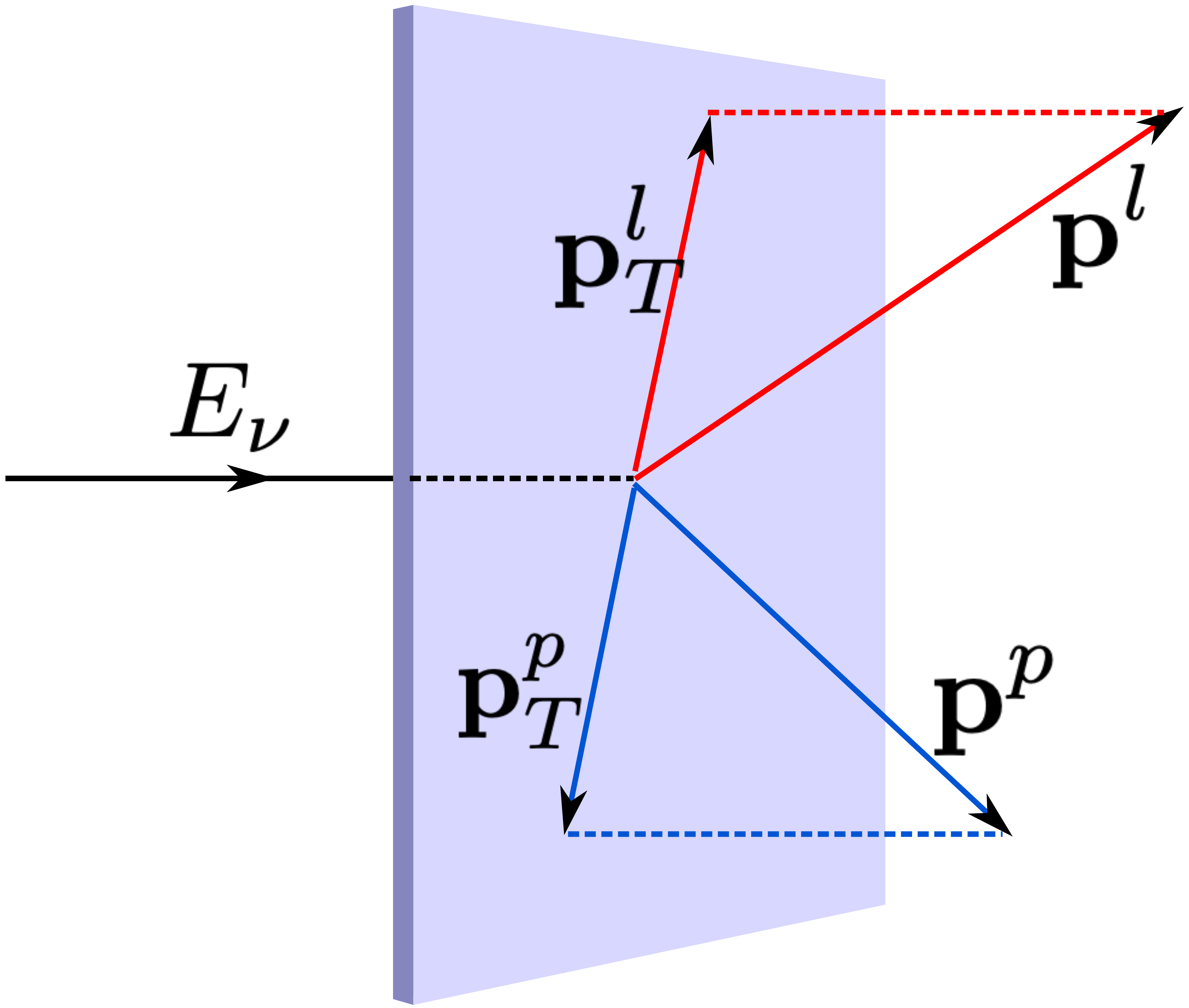
Transverse kinematic imbalance

Impact of nuclear effects

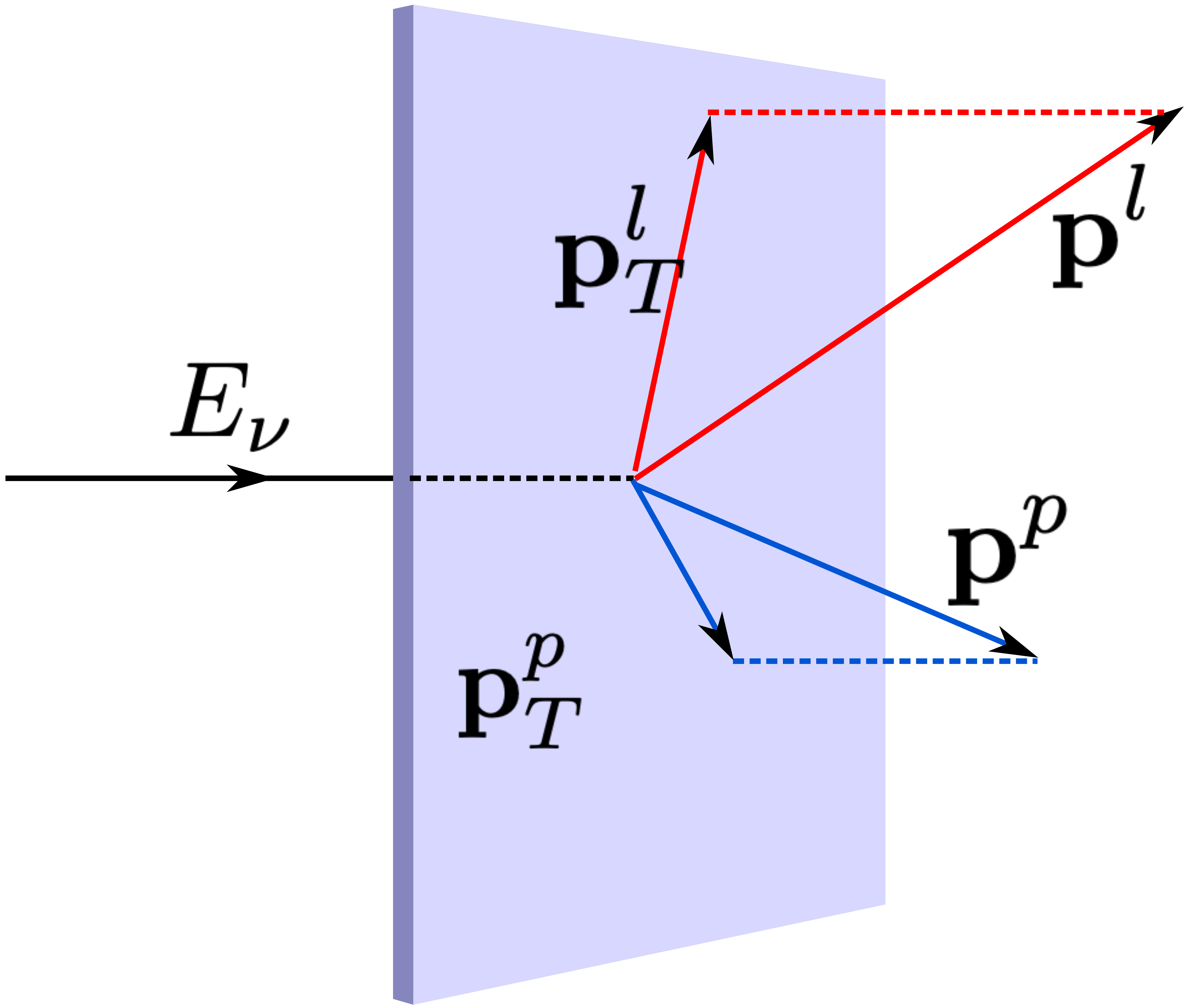


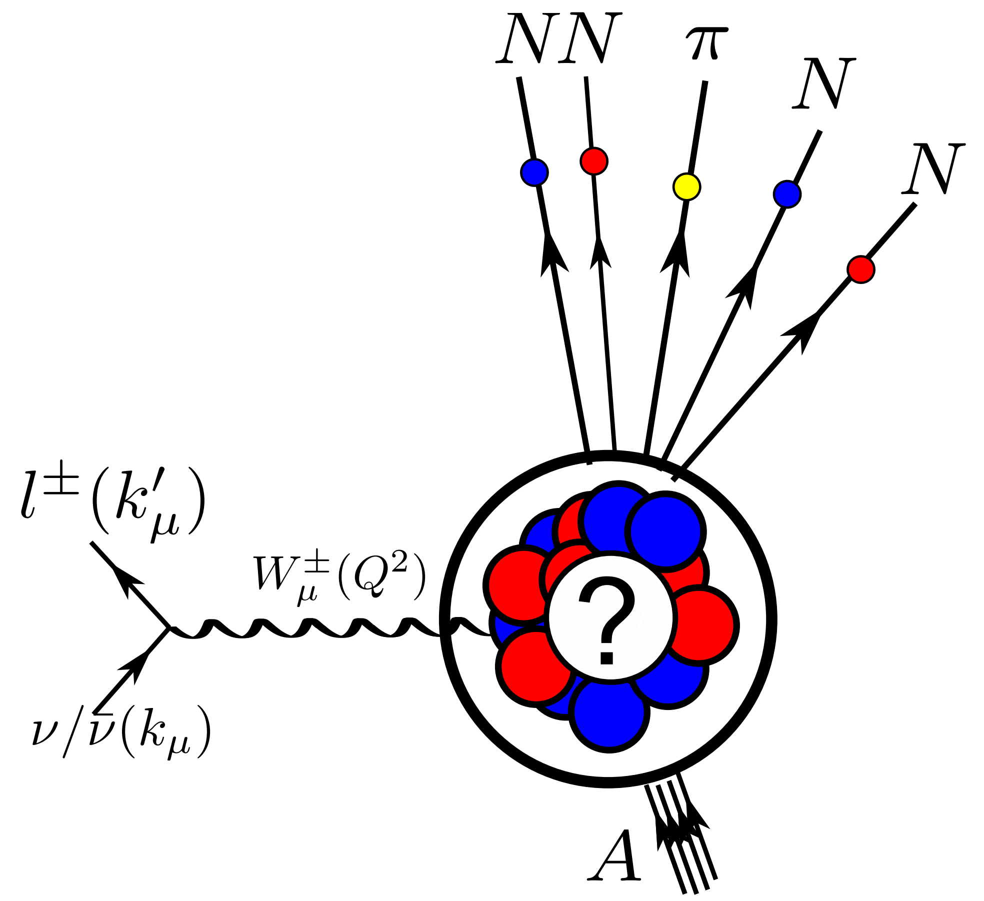
$$\mathbf{p}_T^l + \mathbf{p}_T^p = 0$$

For a static and free electron

Transverse kinematic imbalance

Impact of nuclear effects



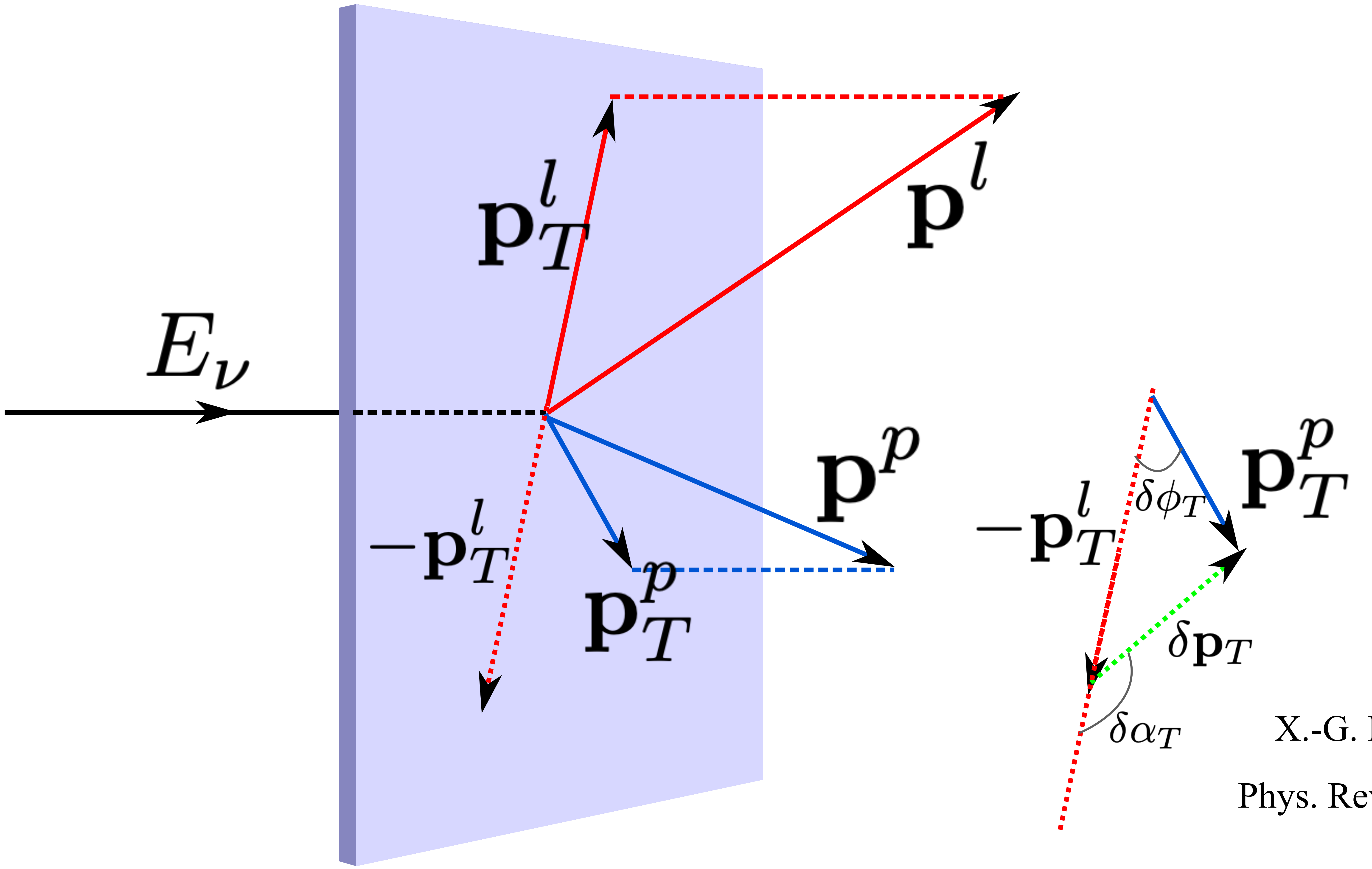


$$\mathbf{p}_T^l + \mathbf{p}_T^p \neq 0$$

With nuclear effects !

Transverse kinematic imbalance

Impact of nuclear effects

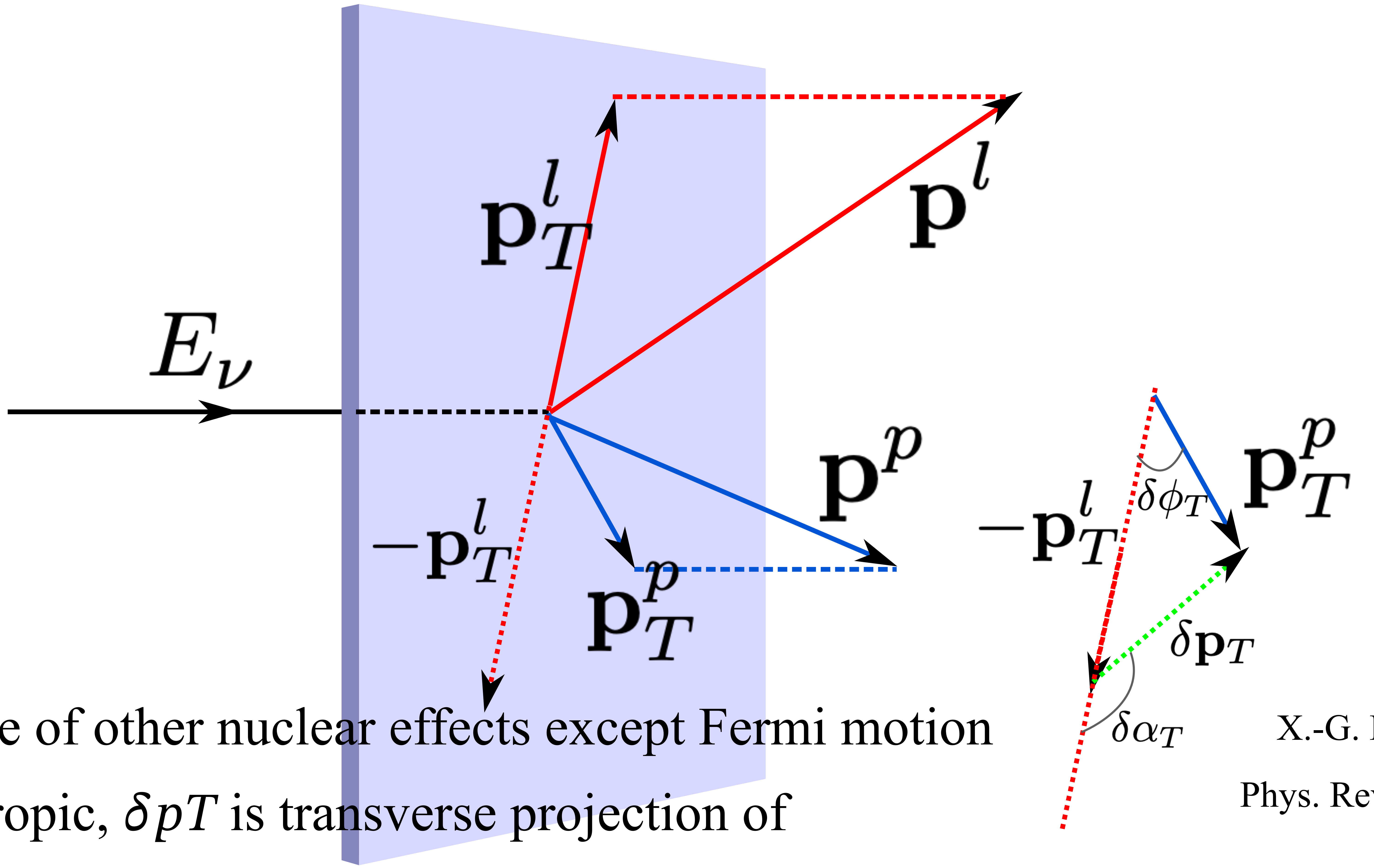


X.-G. Lu *et al.*

Phys. Rev. C 94 (2016), 015503

Transverse kinematic imbalance

Impact of nuclear effects

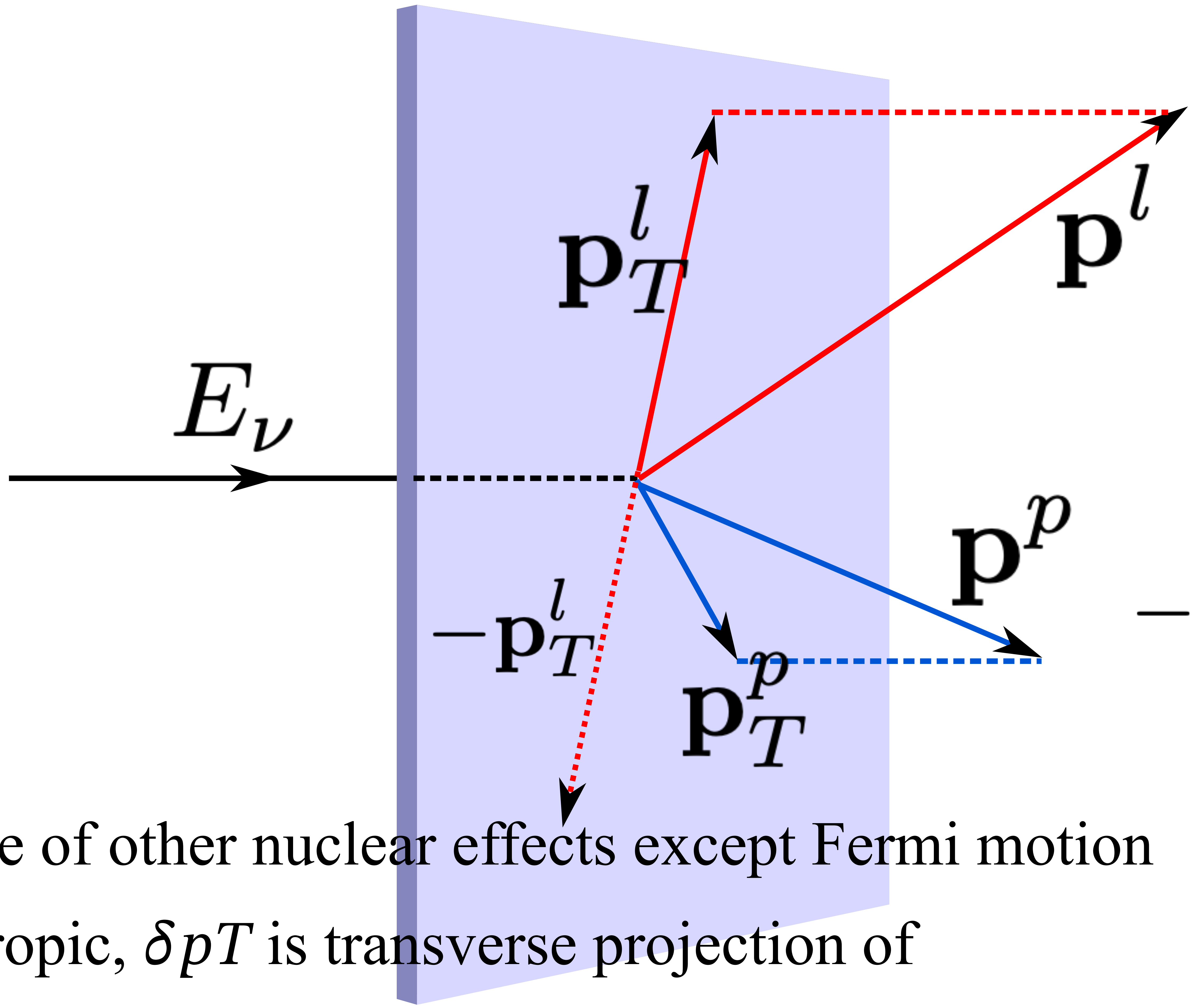


In the absence of other nuclear effects except Fermi motion which is isotropic, δpT is transverse projection of Fermi motion.

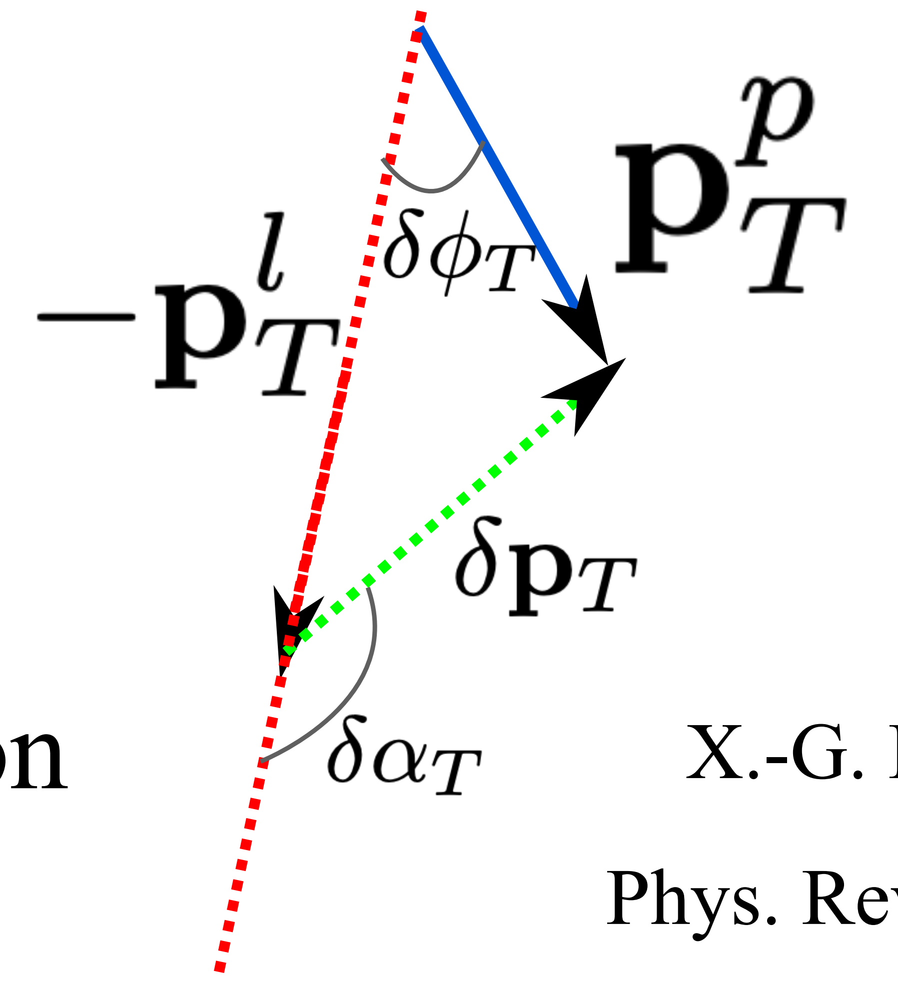
X.-G. Lu *et al.*
Phys. Rev. C 94 (2016), 015503

Transverse kinematic imbalance

Impact of nuclear effects



$\delta\alpha_T \rightarrow$ A uniform distribution!!



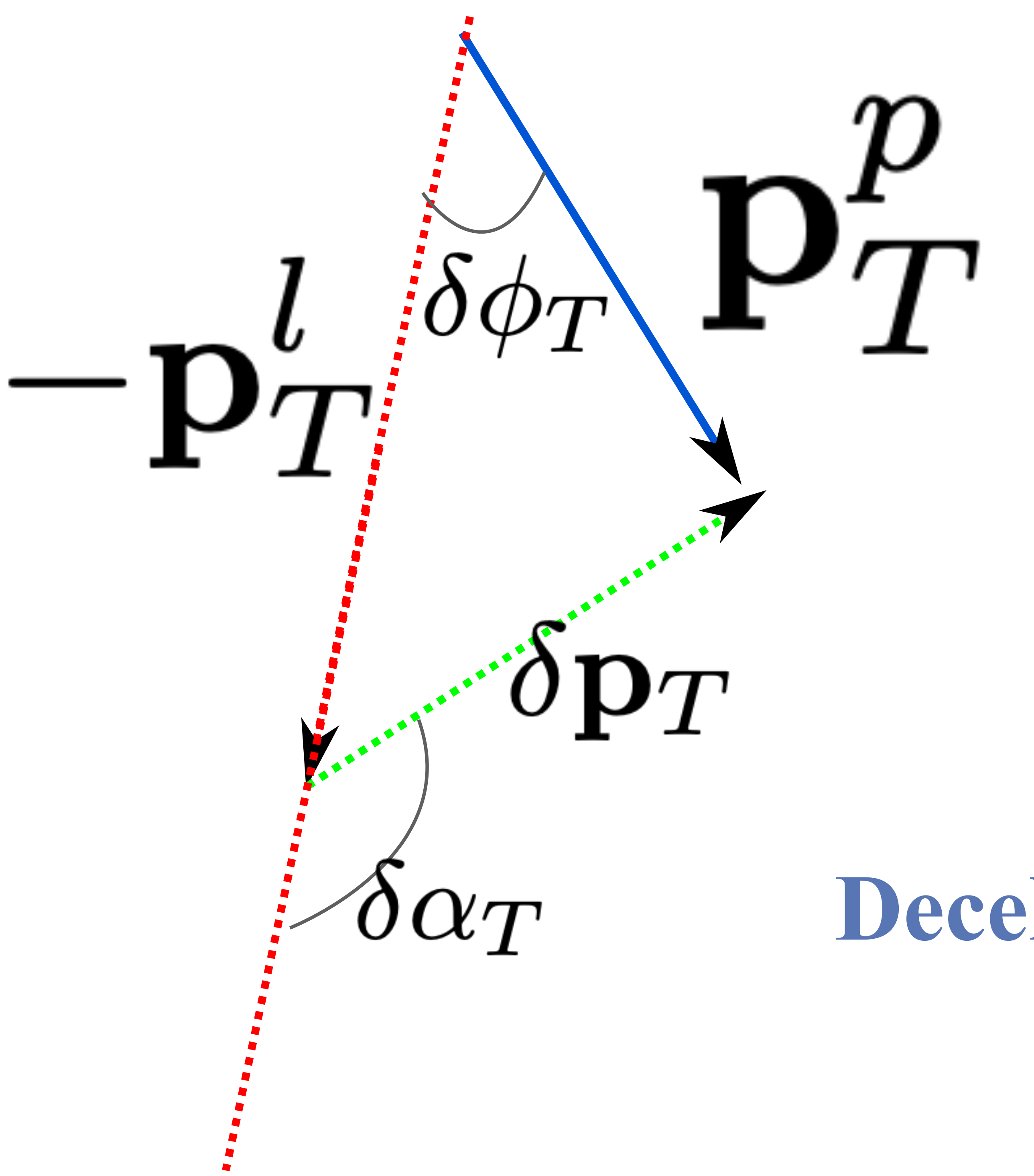
X.-G. Lu *et al.*

Phys. Rev. C 94 (2016), 015503

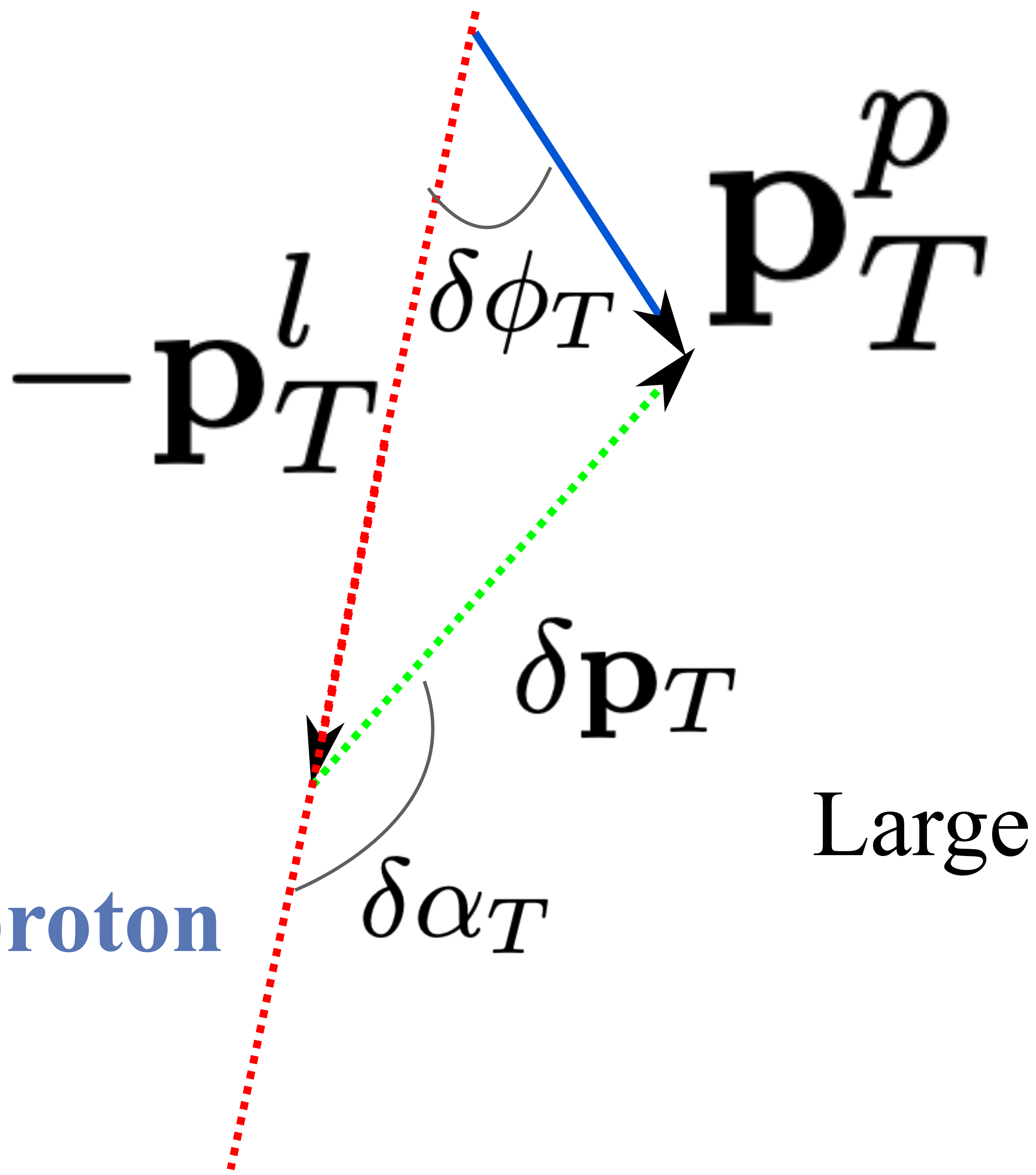
In the absence of other nuclear effects except Fermi motion which is isotropic, δpT is transverse projection of Fermi motion.

Transverse kinematic imbalance

Impact of FSI



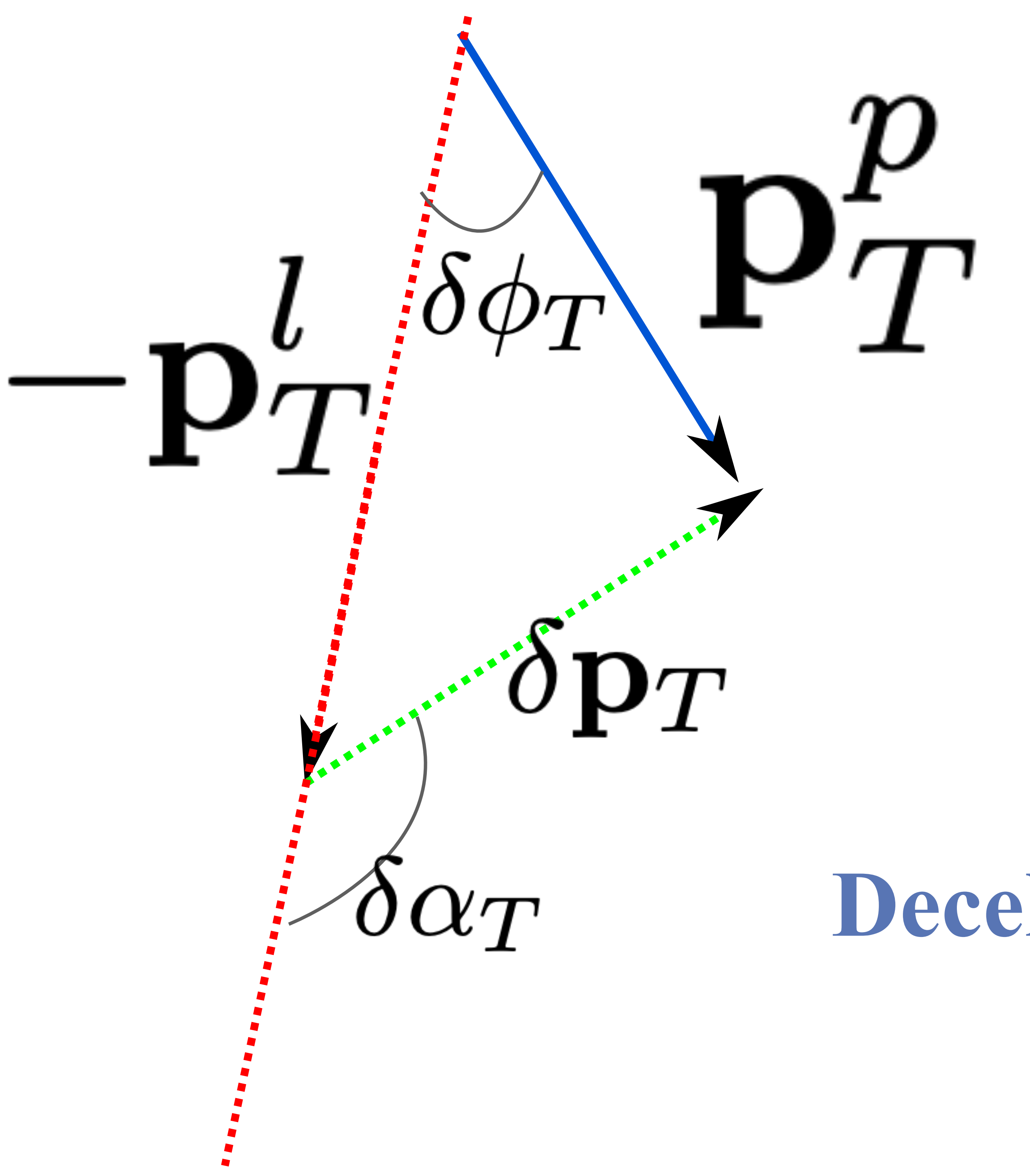
Deceleration of proton from FSI !!



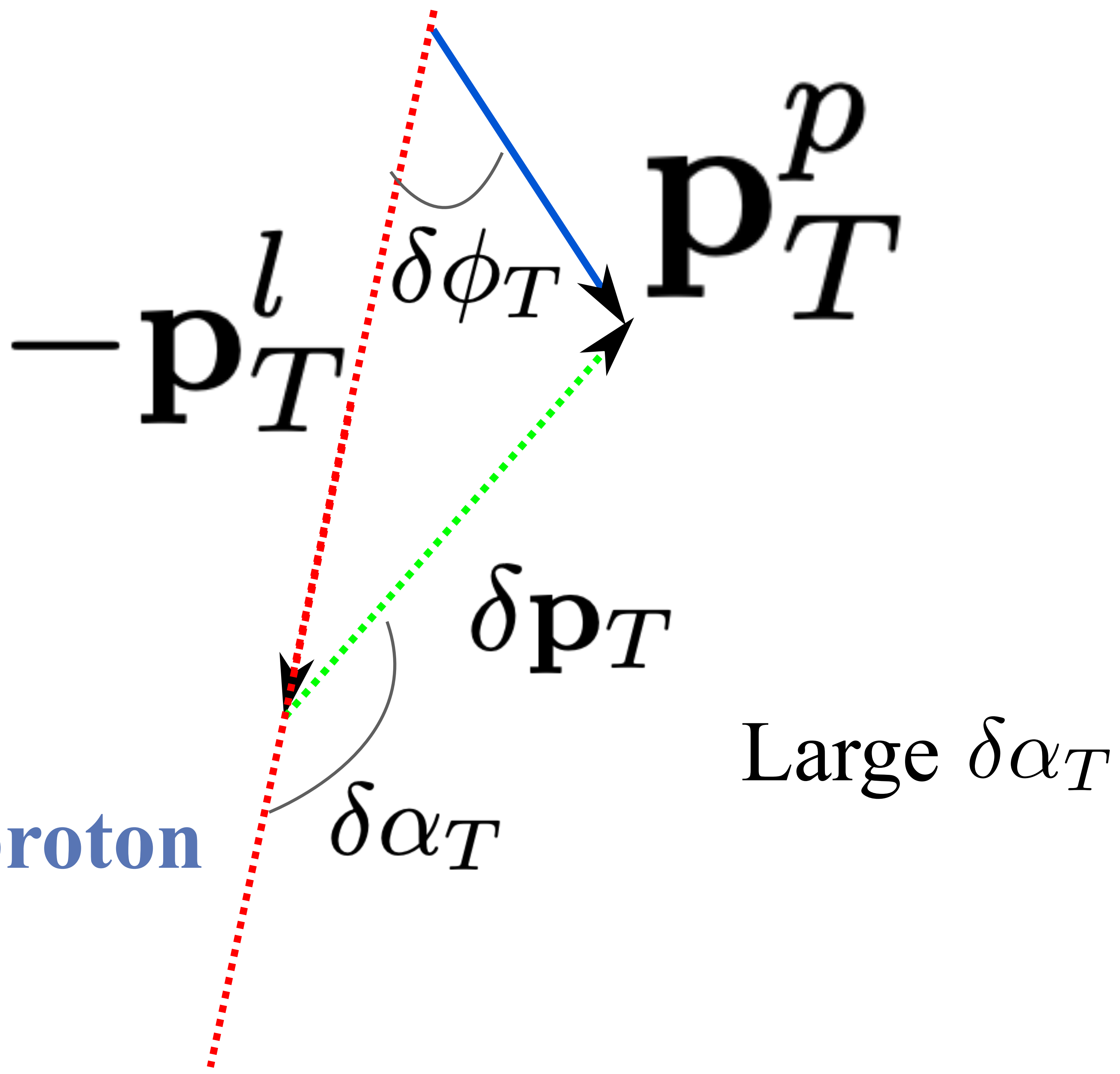
Large $\delta\alpha_T$

Transverse kinematic imbalance

Impact of FSI



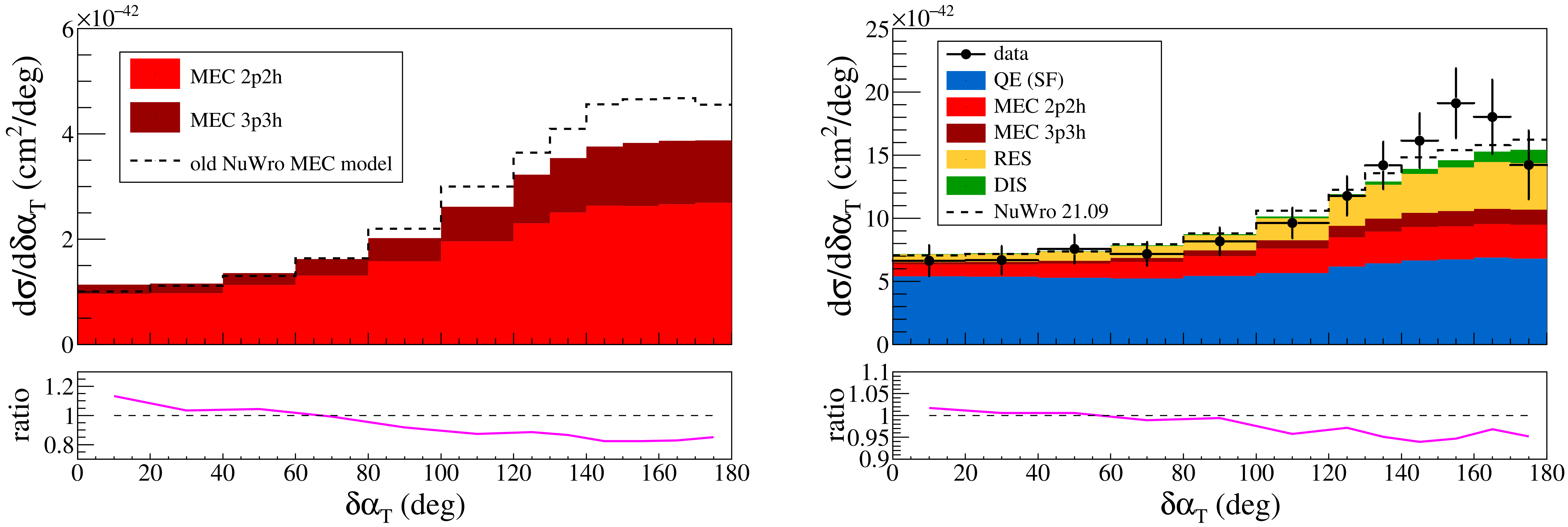
Deceleration of proton from FSI !!



One must expect a deviation from uniform distribution of $\delta\alpha_T$, to a distribution favouring higher $\delta\alpha_T$ angles !

MINERνA CC1p0π data*

Comparison : old vs new MEC model



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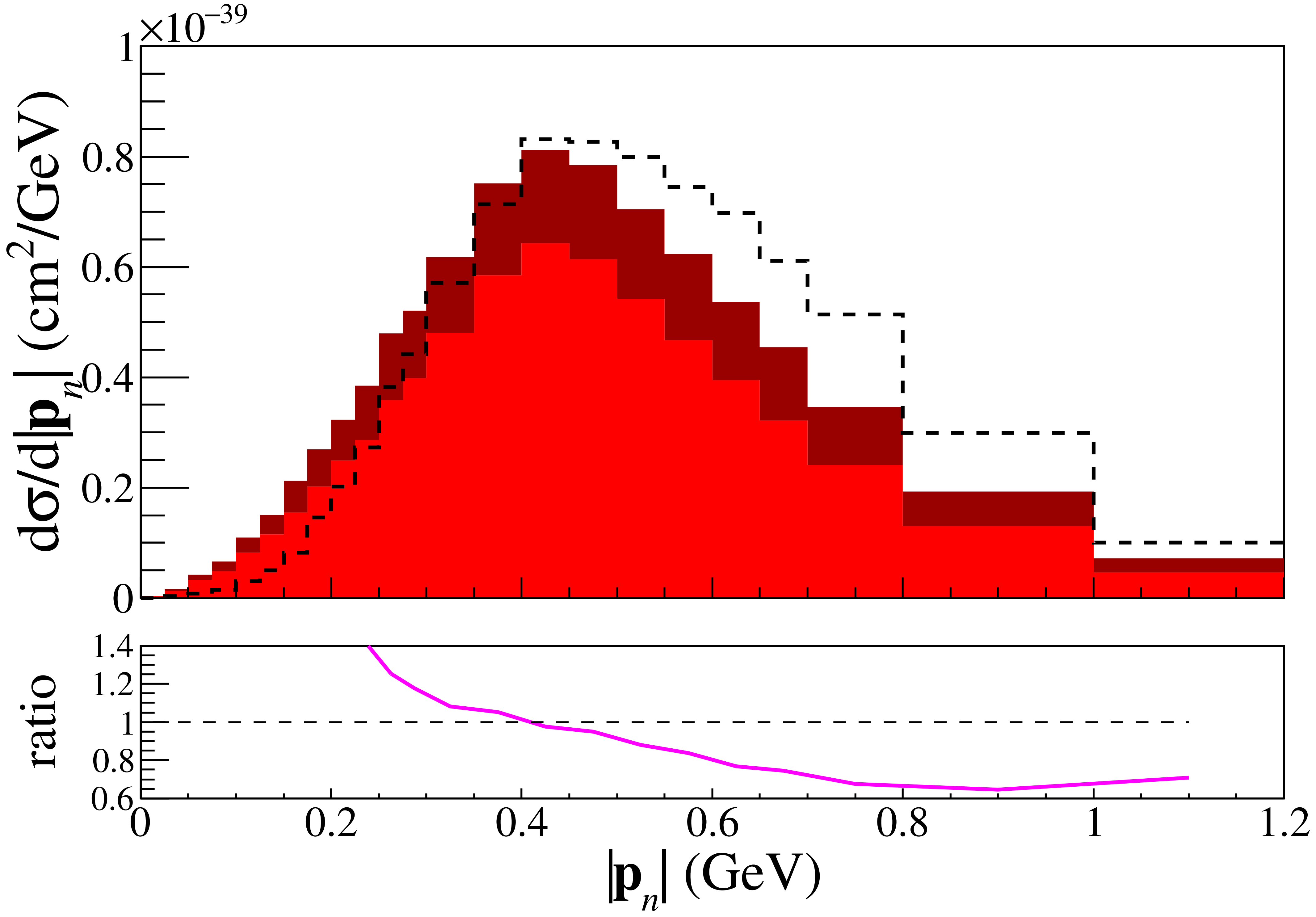
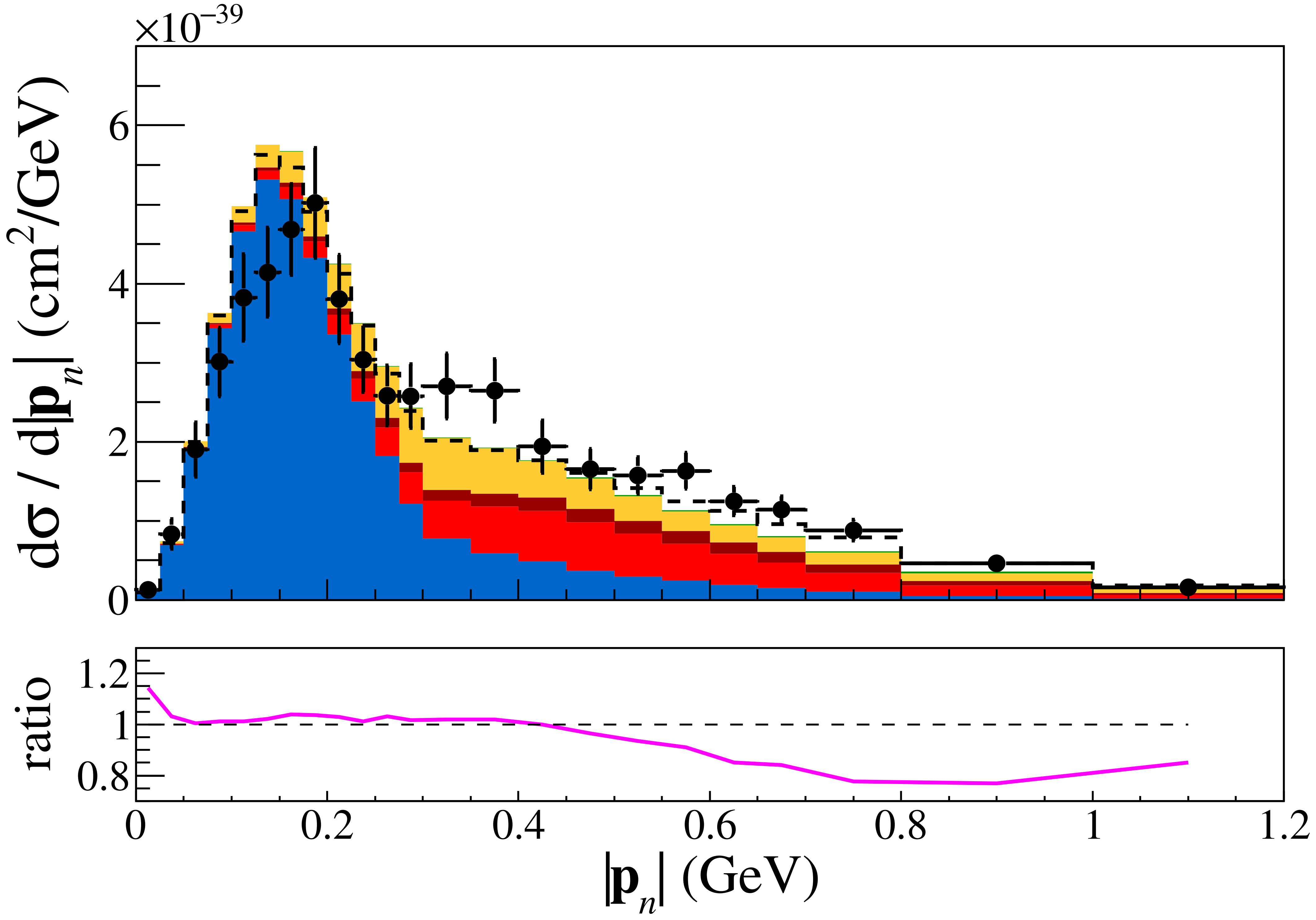
*X.-G. Lu *et al.* Phys. Rev. D 101, (2020) 092001

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

MINERνA CC1p0π data*

Comparison : old vs new MEC model





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

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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

- Studying nuclear effects is crucial for understanding neutrino-nucleus interactions, which are essential for the next generation of oscillation experiments.
  - Probes of these effects can only come from measurements of lepton and hadron kinematics in exclusive processes

- Neutrino experiments have made interesting measurements with clear sensitivity to these effects, but no models have yet described such data effectively.
  - New fully-exclusive MEC models and CCQE models (*Rwik Banerjee's talk on 18th, Sept 2025*) are being added to neutrino interaction generators, but this is just the start of what is necessary.

- Development of a generalised hadronic model in NuWro Monte Carlo generator
  - 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.

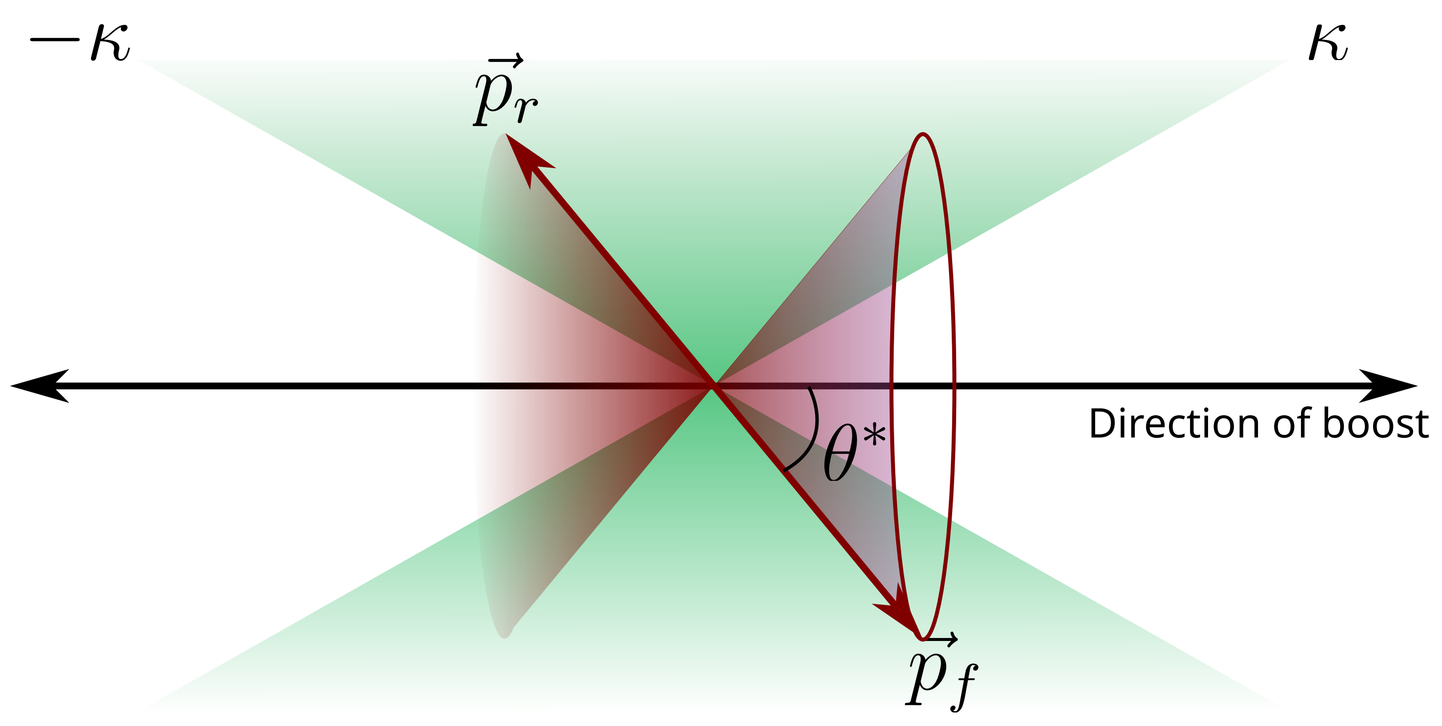
Thank you for your attention

Backup Slides

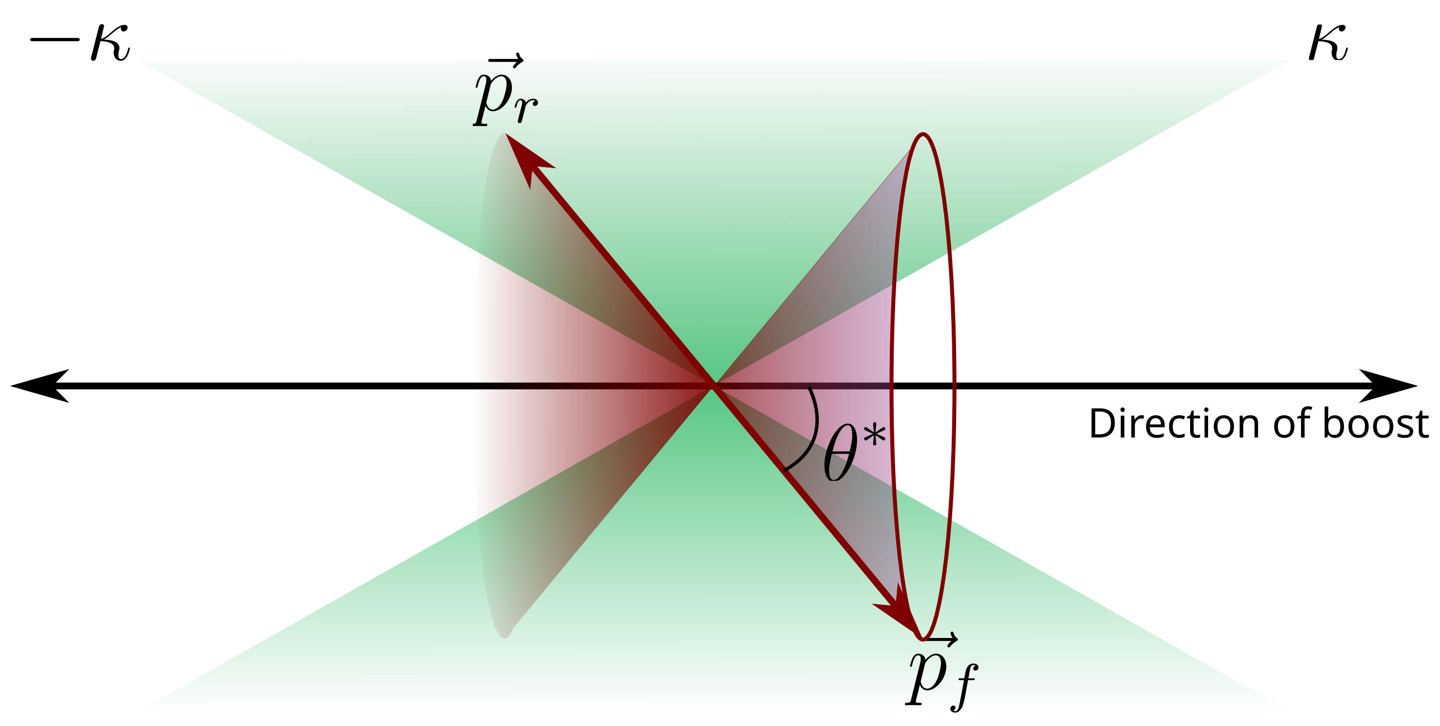
Fitting adjustable parameters

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

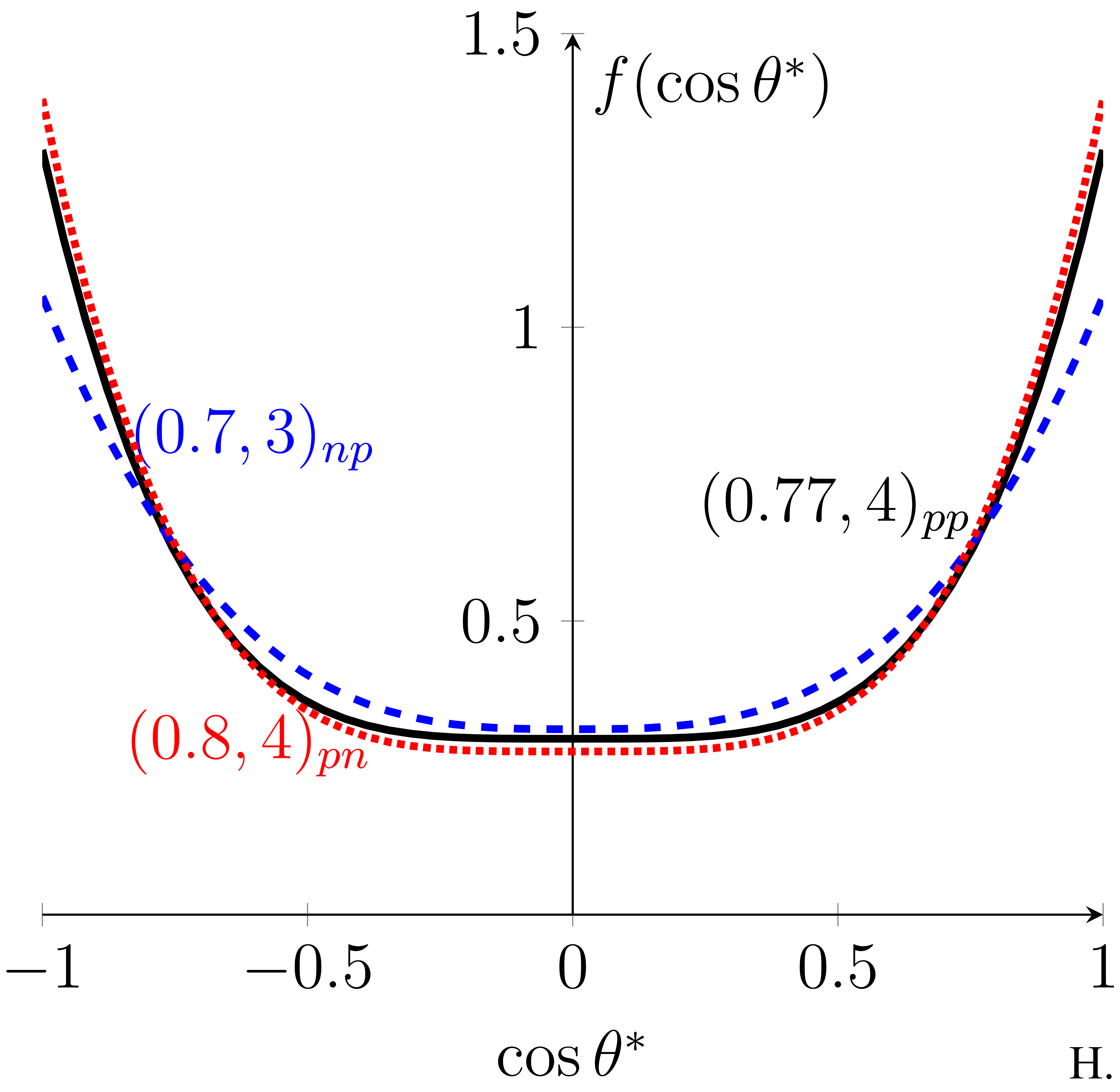
$$\tilde{\chi}^2 = \frac{1}{2N_{\text{bins}}} \sum_{i,j}^{N_{\text{bins}}} \frac{(N_{ij}^{\text{NuWro}} - N_{ij}^{\text{Valencia}})^2}{(N_{ij}^{\text{NuWro}} + N_{ij}^{\text{Valencia}})}$$

- 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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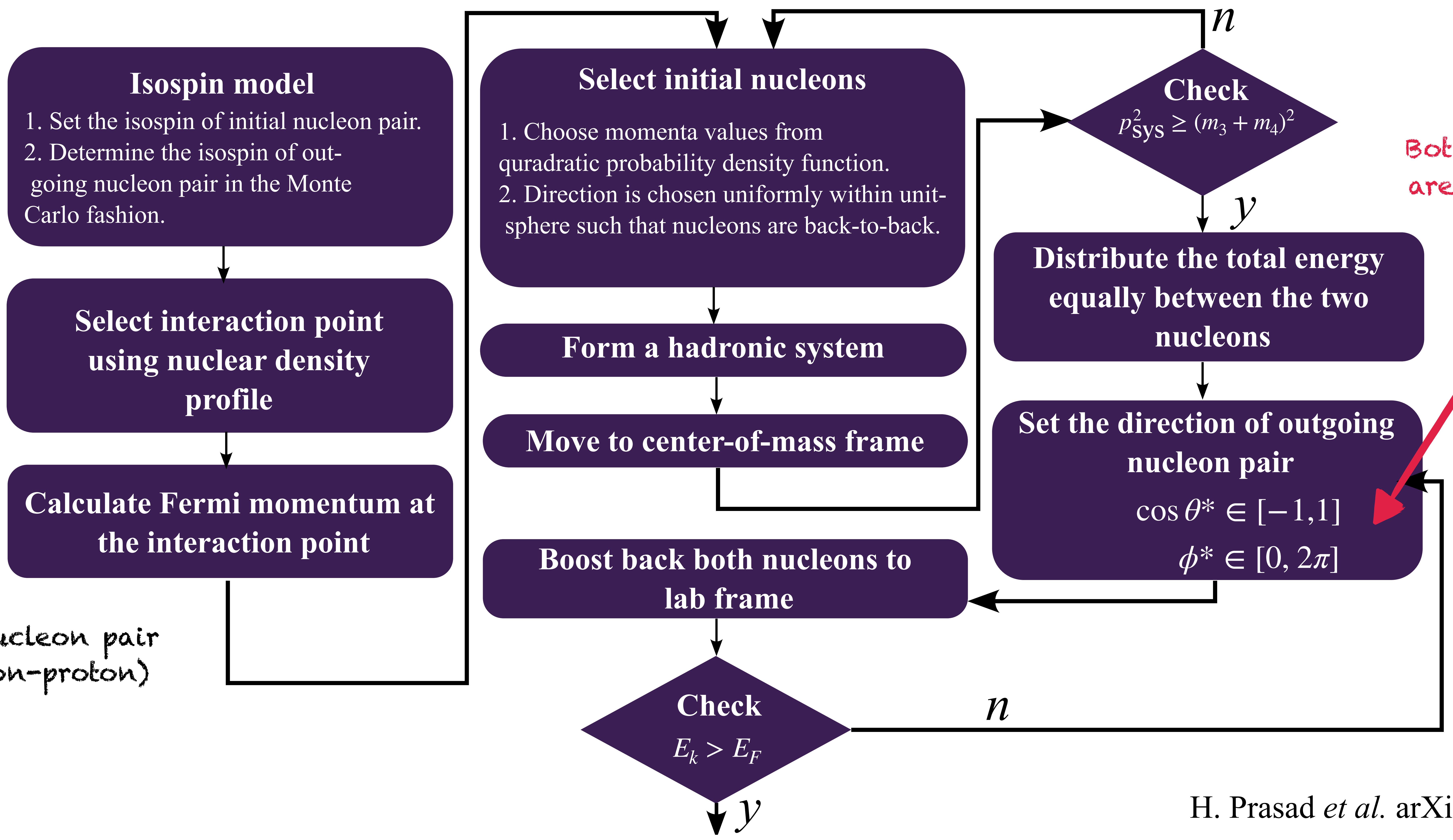
Implementation of MEC models

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



Both the angles θ^*, ϕ^* are chosen uniformly

85% of outgoing nucleon pair are set as pp (proton-proton)

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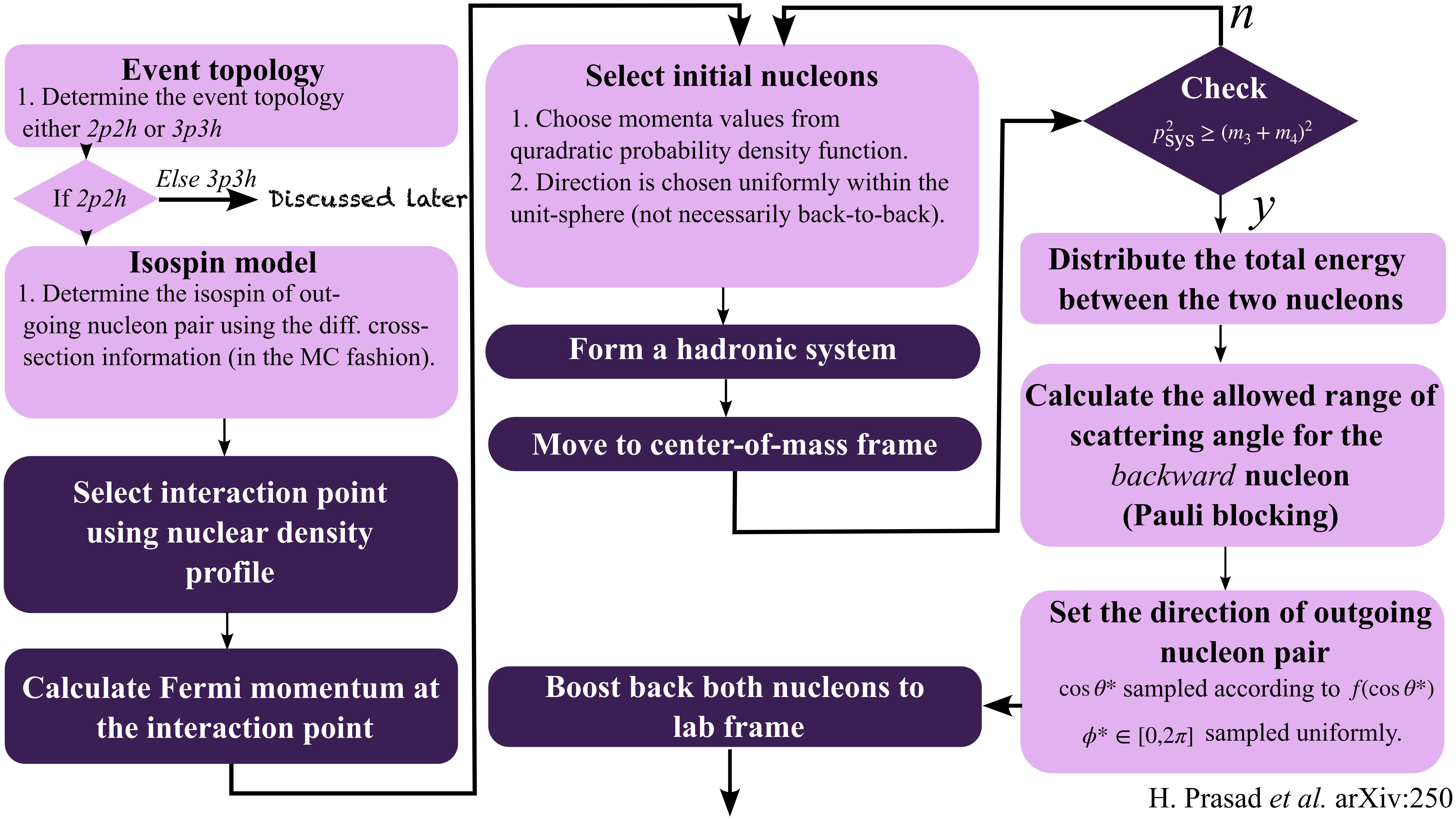
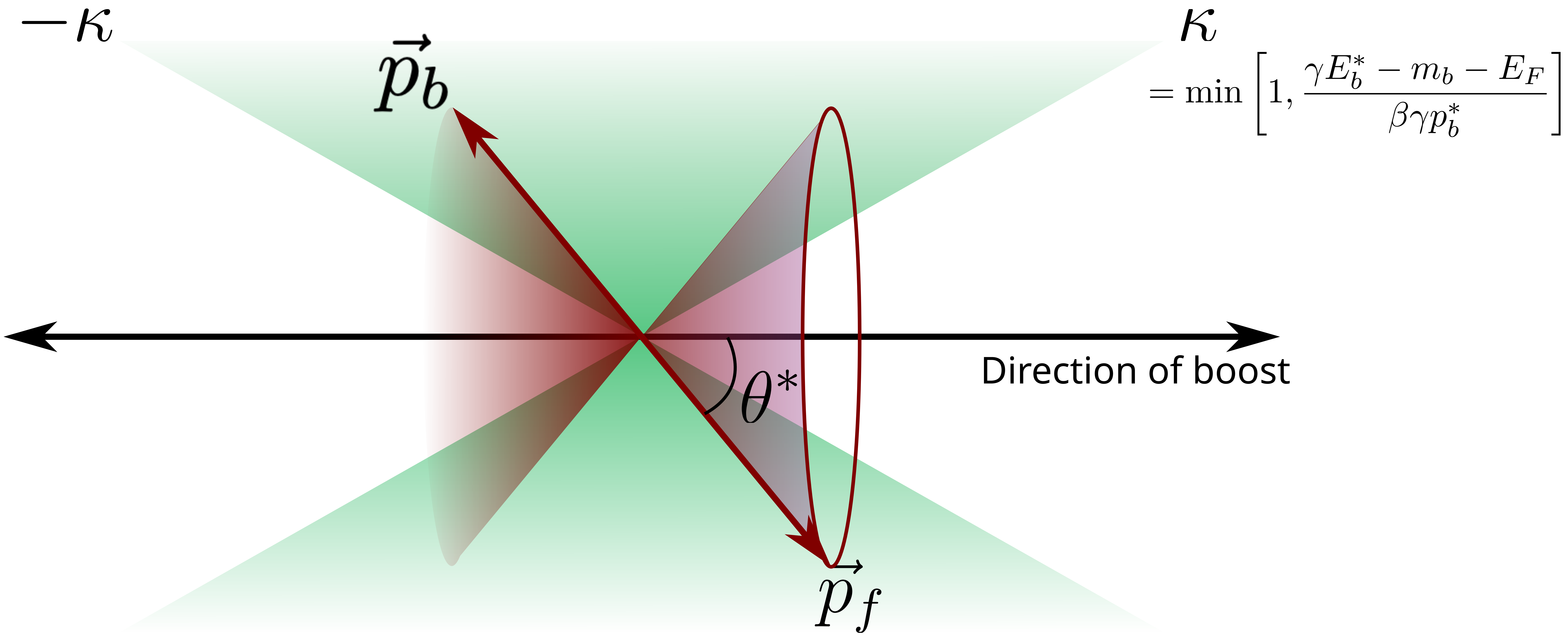
New implementation of MEC models



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

Pauli blocking in center-of-mass frame

Schematics



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