

Production of Hyperons, Charmed Baryons, and Hadronic Molecule Candidates in Neutrino-Proton Reaction

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- 3 Numerical Results
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Pentaquark States: Recent Progress

Experimental milestones:

- **2015:** LHCb observed $P_c(4380)^+$ and $P_c(4450)^+$ in $J/\psi p$ spectrum
- **2019:** Refined structures revealed three narrow states: $P_c(4312)^+$, $P_c(4440)^+$, $P_c(4457)^+$
- Located near $\Sigma_c \bar{D}^{(*)}$ thresholds \rightarrow hadronic molecule picture
- **2020:** Evidence for $P_{cs}(4459)$ in $J/\psi \Lambda$ channel

Theoretical interpretation:

- Hadronic molecules
- Compact pentaquarks

Why Neutrino–Proton Reactions?

Unique advantages:

- **Clean environment:** Clean initial and final states

Experimental facilities:

- NOMAD (CERN)
- MINER ν A (Fermilab)
- Future high-intensity neutrino beams

Physics goals:

- Hyperon production
- Charm production
- Search for exotic states

Our Research Goals

Main objectives

Estimate exclusive production of:

- 1 **Hyperons:** $\bar{\nu}_\mu p \rightarrow \mu^+ K^0 \Lambda$
- 2 **Charmed baryons:** $\bar{\nu}_\mu p \rightarrow \mu^+ \bar{D}^0 \Lambda$
- 3 **Charm with nucleon:** $\bar{\nu}_\mu p \rightarrow \mu^+ \bar{D}^0 n$
- 4 **Hadronic molecules:** $\bar{\nu}_\mu p \rightarrow \mu^+ (\bar{D} N)$

Theoretical framework

- Effective Lagrangian approach
- Chiral perturbation theory (ChPT)
- Hadronic molecular model
- Phenomenological form factors + lattice QCD inputs

Feynman Diagrams: Tree-Level Processes

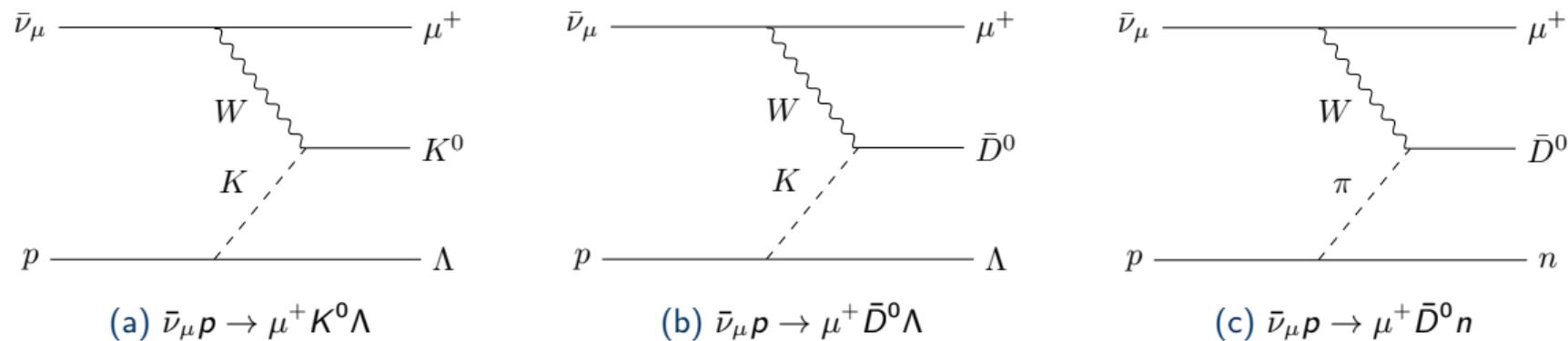


Figure: Tree-level diagrams for three-body final states

- Panel (a): W couples to u and d quarks (strange production)
- Panel (b): W couples to c and s quarks (charm production)
- Panel (c): W couples to c and d quarks (charm production)
- CKM suppression: $V_{cd}/V_{cs} \approx 0.23$

Effective Lagrangians (1): Electroweak Sector

Charged current interaction:

$$\mathcal{L}_c = -\frac{g}{\sqrt{2}} \left(\bar{\nu}_l \gamma^\mu \frac{1 - \gamma^5}{2} l \right) W_\mu^+ + \text{h.c.} \quad (1)$$

where $g = e/\sin\theta_w$ and $\frac{G_F}{\sqrt{2}} = \frac{g^2}{8M_W^2}$

Chiral Lagrangian for W -hadron coupling:

$$\mathcal{L}_2 = i\frac{F_0^2}{2} \text{Tr} \left(l_\mu \partial^\mu U^\dagger U \right) + \dots \quad (2)$$

with $l_\mu = -\frac{g}{\sqrt{2}}(W_\mu^+ T_+ + \text{h.c.})$ and $T_+ = \begin{pmatrix} 0 & V_{ud} & V_{us} \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$

- F_0 : decay constant in three-flavor chiral limit ($F_\pi = 92.4$ MeV)
- $U = \exp(i\phi/F_0)$: contains pseudoscalar Goldstone bosons

Effective Lagrangians (2): Meson-Baryon Interactions

Baryon-pseudoscalar meson coupling (ChPT):

$$\mathcal{L}_{\phi BB} = -\frac{D}{2F_0} \text{Tr}(\bar{B}\gamma^\mu\gamma_5\{\partial_\mu\phi, B\}) - \frac{F}{2F_0} \text{Tr}(\bar{B}\gamma^\mu\gamma_5[\partial_\mu\phi, B]) \quad (3)$$

with $D = 0.80$, $F = 0.50$ at tree level

Specific examples:

$$\mathcal{L}_{pK\Lambda} = \frac{D + 3F}{2\sqrt{3}} (\bar{\Lambda}\gamma^\mu\gamma_5 p \partial_\mu K^-) + \text{h.c.} \quad (4)$$

$$\mathcal{L}_{WKK} = -\frac{g}{2\sqrt{2}} V_{ud} W_\mu^+ (\partial^\mu K^0 K^- - K^0 \partial^\mu K^-) + \text{h.c.} \quad (5)$$

$$\mathcal{L}_{K^0\pi W} = -\frac{g}{2\sqrt{2}} V_{us} W_\mu^+ (\partial^\mu \bar{K}^0 \pi^- - \bar{K}^0 \partial^\mu \pi^-) + \text{h.c.} \quad (6)$$

Form Factors (1): Semileptonic Vertices

D meson semileptonic form factors:

$$\langle P|V_\mu|D\rangle = f_+(q^2) \left(p_{D\mu} + p_{P\mu} - \frac{m_D^2 - m_P^2}{q^2} q_\mu \right) + f_0(q^2) \frac{m_D^2 - m_P^2}{q^2} q_\mu \quad (7)$$

$$f_0(z) = \frac{1}{1 - q^2(z)/M_{0+}^2} \sum_{n=0}^{M-1} b_n z^n, \quad (8)$$

$$f_+(z) = \frac{1}{1 - q^2(z)/M_{1-}^2} \sum_{n=0}^{N-1} a_n \left(z^n - \frac{n}{N} (-1)^{n-N} z^N \right) \quad (9)$$

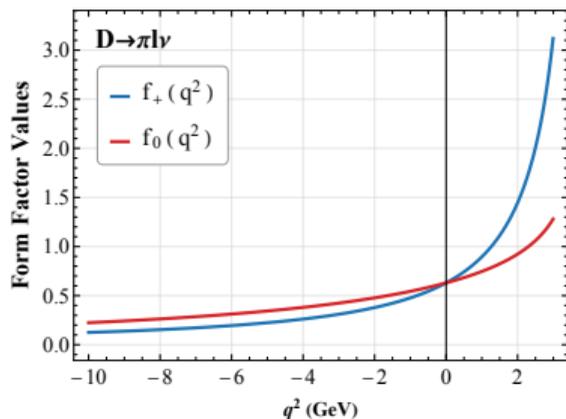


Figure: $D \rightarrow \pi l \nu$ form factors

- BCL parameterization with lattice QCD inputs
- Extended to $q^2 < 0$ region (spacelike)

K meson semileptonic form factor:

$$F_V(q^2) = \frac{M_\rho^2}{M_\rho^2 - q^2} \quad (10)$$

Hadronic Molecule Production

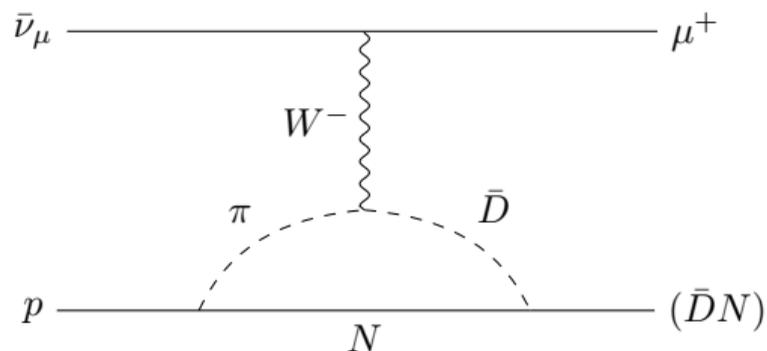


Figure: Loop diagram for $(\bar{D}N)$ molecule production

Isospin configurations:

$$|(\bar{D}N), I = 0\rangle = \frac{1}{\sqrt{2}}(|D^- p\rangle - |\bar{D}^0 n\rangle)$$

$$|(\bar{D}N), I = 1\rangle = \frac{1}{\sqrt{2}}(|D^- p\rangle + |\bar{D}^0 n\rangle)$$

Key features:

- Triangle loop with π exchange
- Molecular state $(\bar{D}N)$ with $J^P = 1/2^-$
- Coupling constants from our previous work:
 - $g_{\bar{D}N}^{I=0} = 1.68$
 - $g_{\bar{D}N}^{I=1} = 2.62$
- Much smaller cross section than tree-level

Effective Lagrangians (3): Hadronic Molecule Vertex

Molecular state vertex:

$$\mathcal{L}_{(\bar{D}N)}(x) = ig_{\bar{D}N} \bar{P}_{\bar{c}}(x) \int d^4y \Phi(y^2) N(x + w_{\bar{D}N}y) \bar{D}(x - w_{N\bar{D}}y) + \text{h.c.} \quad (11)$$

- $P_{\bar{c}}$: $(\bar{D}N)$ molecular state with $J^P = 1/2^-$
- $\omega_{ij} = m_i/(m_i + m_j)$: kinematic weight factor
- $\Phi(y^2)$: correlation function (Gaussian form in momentum space)

Effective $W-p-(\bar{D}N)$ vertex after loop integration:

$$\mathcal{L}_{B'BV} = \bar{B}'_1 \left(g_{B'BV} \gamma_5 \gamma^\mu + \frac{f_{B'BV}}{m_1 - m_2} \gamma_5 \sigma^{\mu\nu} \partial_\nu \right) V_\mu B_2 + \text{h.c.} \quad (12)$$

where $g_{B'BV}$ and $f_{B'BV}$ incorporate the loop-induced form factor

Form Factors (2): Loop Vertex and Cutoff Dependence

Exchanged meson form factors:

$$f_1(q^2) = \frac{\Lambda_1^4}{\Lambda_1^4 + (q^2 - m_{\text{ex}}^2)^2} \quad (13)$$

$$f_2(q^2) = \left(\frac{\Lambda_2^2 - m_{\text{ex}}^2}{\Lambda_2^2 - q^2} \right)^2 \quad (14)$$

- f_1 : triangle loop diagram
- f_2 : tree-level diagrams(t-channel)

Molecule vertex:

$$\tilde{\Phi}(p_E^2) \doteq \exp\left(-\frac{p_E^2}{\Lambda^2}\right) \quad (15)$$

- $\tilde{\Phi}$: Gaussian form to model this vertex function
- $\Lambda_1, \Lambda_2, \Lambda$: cutoff parameters

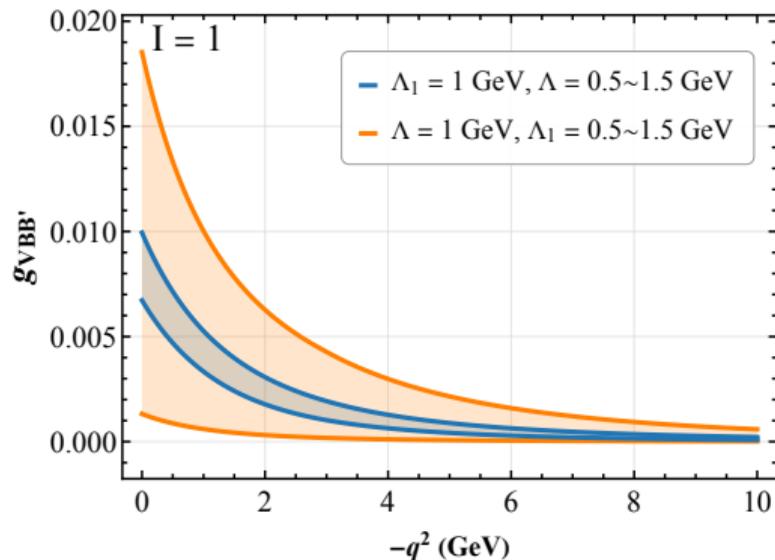


Figure: Coupling constant $g_{pP_{\bar{\epsilon}}W}$ vs cutoff parameters ($I=1$ case)

Result: Moderate dependence on cutoffs
 \Rightarrow Set $\Lambda = \Lambda_1 = 1$ GeV

Form Factors (3): Isospin Dependence

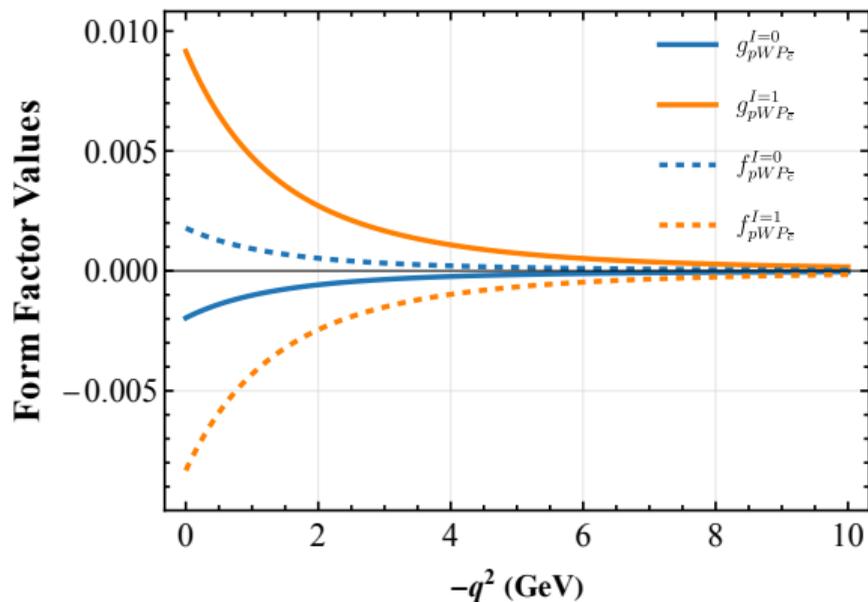


Figure: Coupling constants for different isospin configurations

- $I = 0$ and $I = 1$ states have opposite signs
- $I = 1$ coupling slightly larger in magnitude

Dalitz Plots for $\bar{\nu}_\mu p \rightarrow \mu^+ \bar{D}^0 \Lambda$

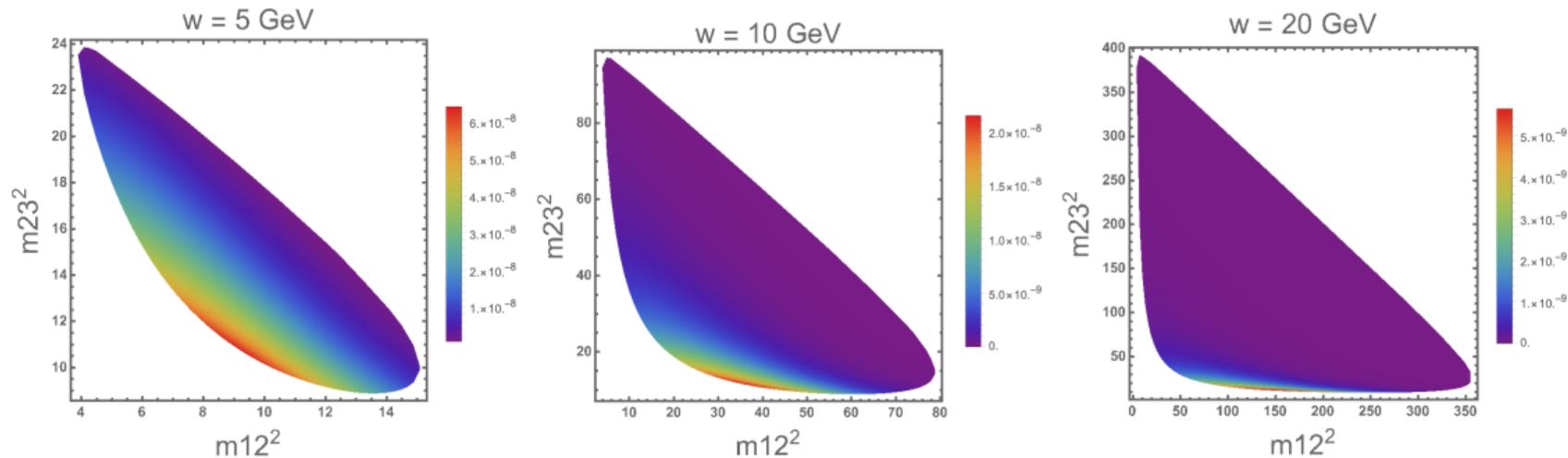


Figure: Dalitz plots for $\bar{\nu}_\mu p \rightarrow \mu^+ \bar{D}^0 \Lambda$ at $w = 5, 10, 20$ GeV, where particles 1, 2, 3 correspond to μ^+ , \bar{D}^0 , and Λ , respectively. Events concentrate in the low- m_{23}^2 region (low $\bar{D}^0 \Lambda$ invariant mass).

Key observations:

- Events dominated by low m_{23}^2 (low $\bar{D}^0 \Lambda$ invariant mass)
- Feature arises from DKW vertex form factor
- Width in m_{23}^2 broadens with energy, then saturates

Invariant Mass Spectrum

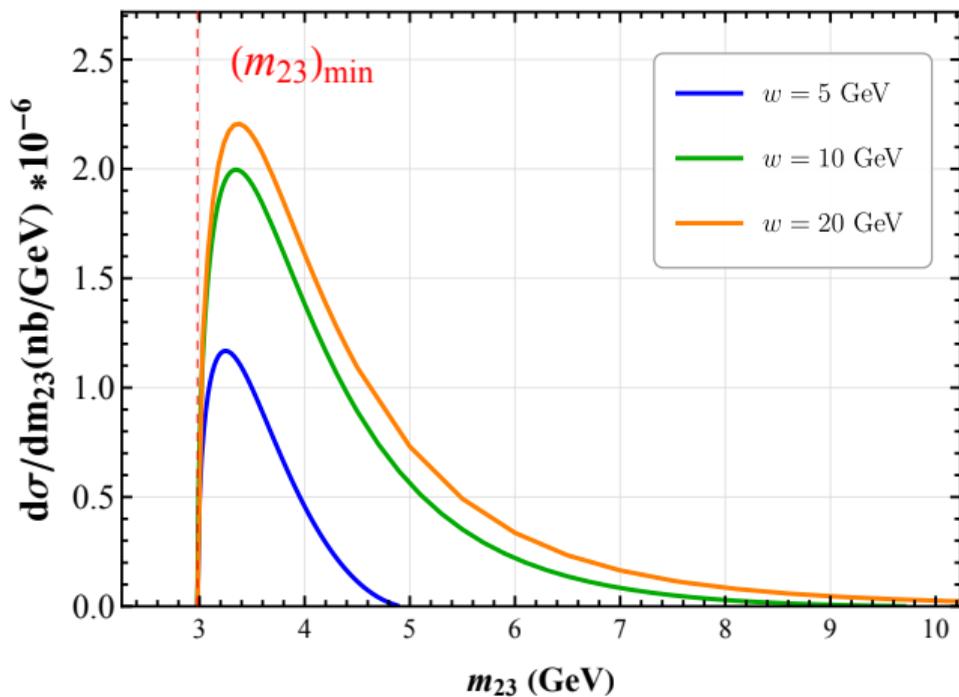


Figure: $\bar{D}\Lambda$ invariant mass spectra

Physical implications:

- Width increases with total energy
- Broadening rate slows at high energies

Total Cross Sections: Tree-Level Processes

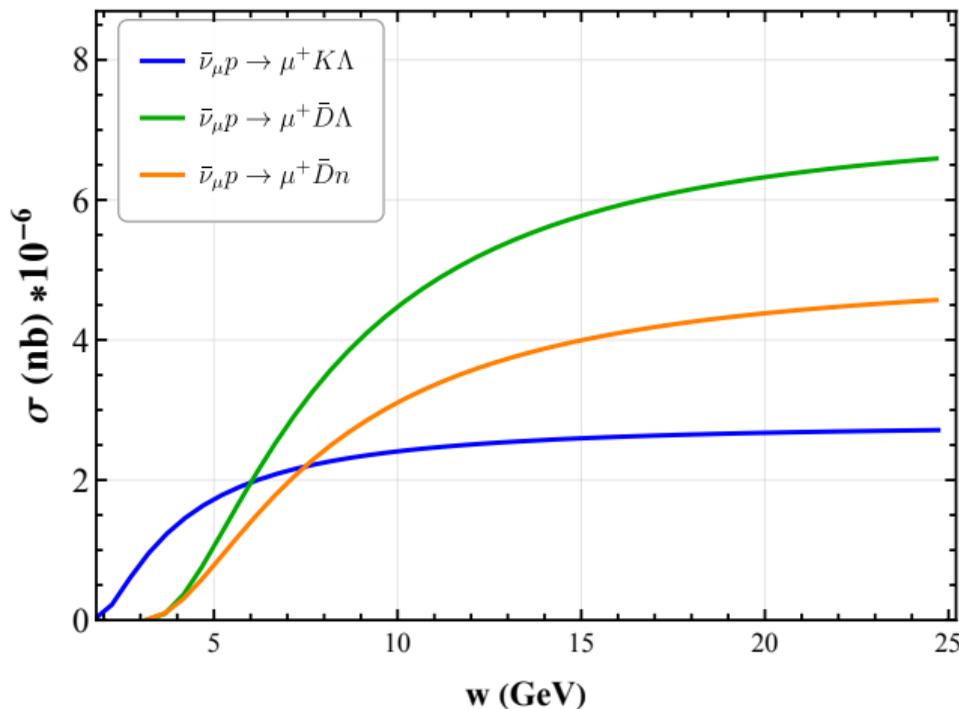


Figure: Cross sections up to $w = 25$ GeV with $\Lambda_2 = 1$ GeV

All three processes have comparable magnitudes!

Why is $\sigma(\bar{\nu}_\mu p \rightarrow \mu^+ K^0 \Lambda)$ smaller?

- KKW form factor decreases more rapidly than DKW

Why is $\sigma(\bar{\nu}_\mu p \rightarrow \mu^+ \bar{D}^0 n)$ large despite CKM?

- $V_{cd}/V_{cs} \approx 0.23$ suppression
- BUT: larger $D\pi W$ form factor
- Larger $p n \pi$ coupling
- Compensates CKM factor!

Cutoff Dependence

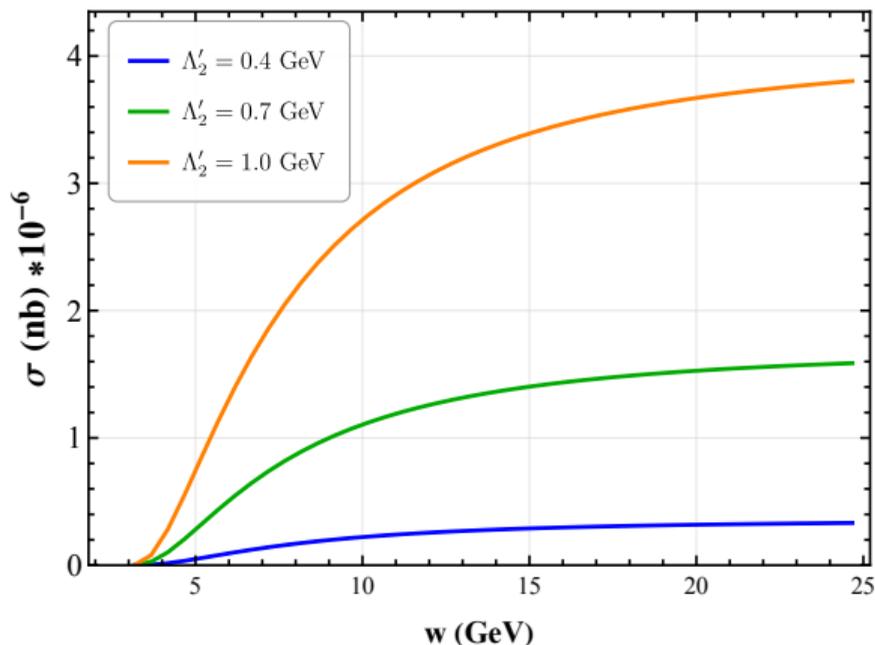


Figure: Effect of cutoff parameter $\Lambda'_2 = \Lambda_2 - m_\pi$

Cutoff variation:

- Typical range: $\Lambda'_2 = 0.4\text{--}1.0$ GeV
- Changes cross section by ~ 1 order of magnitude
- Modest impact on overall scale

Our choice:

- $\Lambda_2 = 1$ GeV for all calculations
- Reasonable physical scale
- $\sim 0.4\text{--}0.5$ GeV above meson mass

Molecular State Production

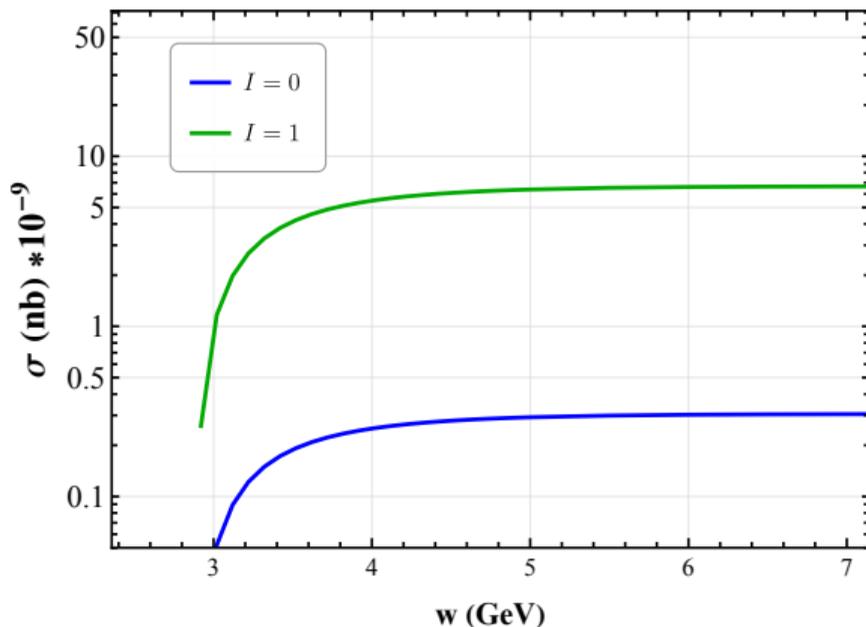


Figure: Cross section for $\bar{\nu}_\mu p \rightarrow \mu^+(\bar{D}N)$ from threshold up to $\sqrt{s} = 7$ GeV

Key features:

- Much smaller than tree-level ($\sim 10^{-9}$ nb vs 10^{-6} nb)
- Due to small coupling constants in loop vertices
- $I = 1$ channel larger than $I = 0$

Experimental prospects:

- Challenging but potentially measurable
- Requires high-statistics neutrino facilities

Differential Cross Sections (1): Three-Body Final State

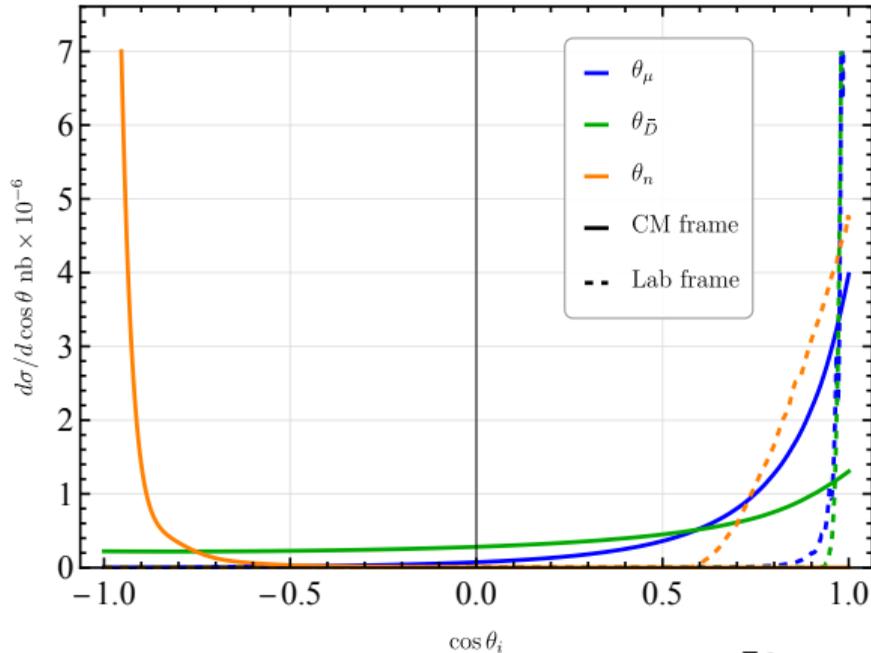


Figure: Angular distributions for $\bar{\nu}_\mu p \rightarrow \mu^+ \bar{D}^0 n$ at $\sqrt{s} = 5$ GeV

- Solid: center-of-mass frame; Dashed: laboratory frame
- Lab frame strongly forward-biased (massless $\bar{\nu}_\mu$)
- Reflects kinematic constraints

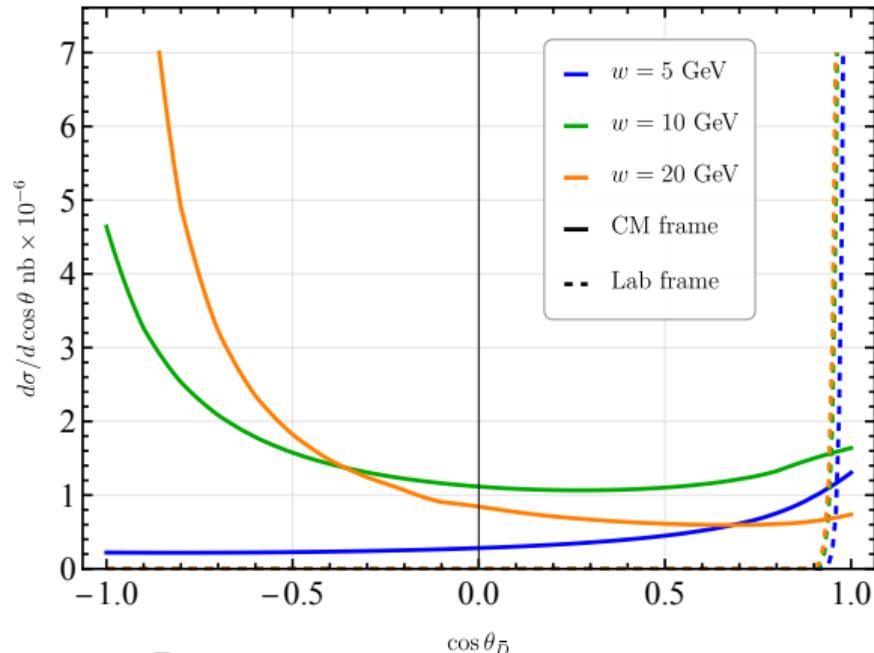
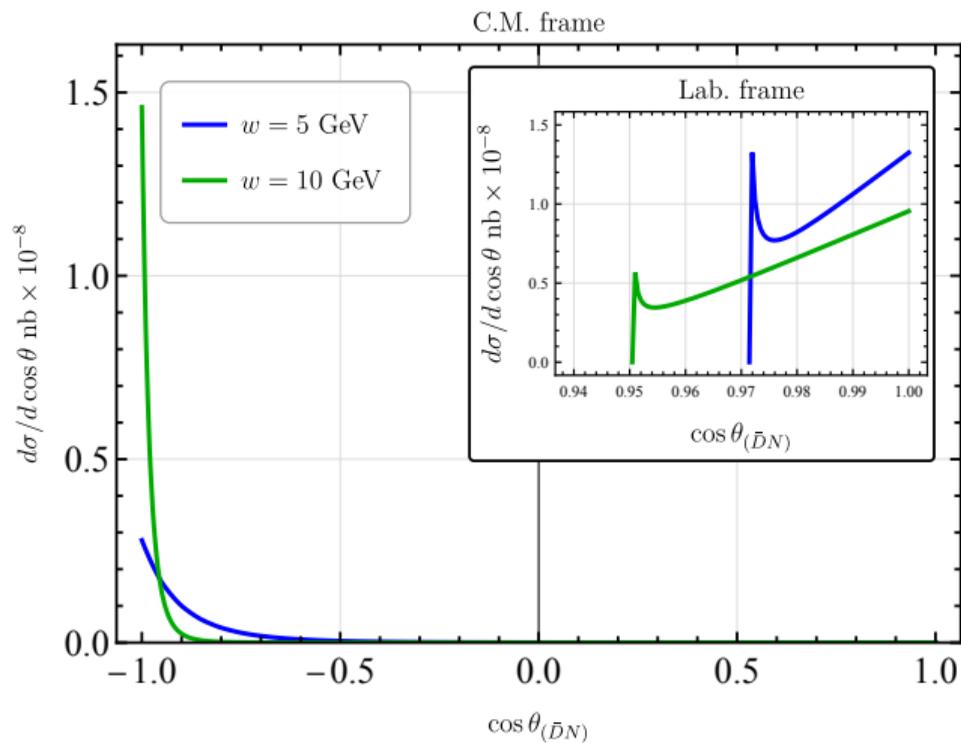


Figure: \bar{D}^0 angular distribution at different energies

Differential Cross Sections (2): Molecular State



Two-body kinematics:

- C.M. frame: ($\bar{D}N$) predominantly backward scattered
- Lab frame: Strong forward focusing (Lorentz boost)

Figure: Angular distribution for $\bar{\nu}_\mu p \rightarrow \mu^+(\bar{D}N)$ with $l = 0$

Theoretical Framework:

- Effective Lagrangian approach + Chiral perturbation theory (ChPT)
- Hadronic molecular model with Gaussian correlation function
- Form factors from lattice QCD (semileptonic vertices) and VMD model
- Tree-level and loop diagrams for hyperon, charm, and molecular production

Key Results — Cross Sections:

- **Tree-level processes** ($\Lambda_2 = 1$ GeV): $\sigma \sim 10^{-6}$ nb at $w = 10$ GeV
 - $\bar{\nu}_\mu p \rightarrow \mu^+ K^0 \Lambda$: $\sim 2 \times 10^{-6}$ nb
 - $\bar{\nu}_\mu p \rightarrow \mu^+ \bar{D}^0 \Lambda$: $\sim 4 \times 10^{-6}$ nb
 - $\bar{\nu}_\mu p \rightarrow \mu^+ \bar{D}^0 n$: $\sim 6 \times 10^{-6}$ nb
 - Events dominated by low m_{23}^2 in Dalitz plots
- **Molecular production**: $\sigma(\bar{\nu}_\mu p \rightarrow \mu^+(\bar{D}N)) \sim 10^{-9}$ nb
 - $l = 1$ channel: $\sim 5 \times 10^{-9}$ nb; $l = 0$ channel: $\sim 3 \times 10^{-9}$ nb
- Kinematic distributions show strong forward boosting in lab frame