Predictions for dimuon production in high-energy neutrino-proton collisions using the color dipole model

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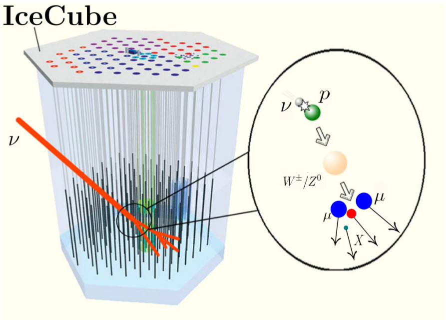
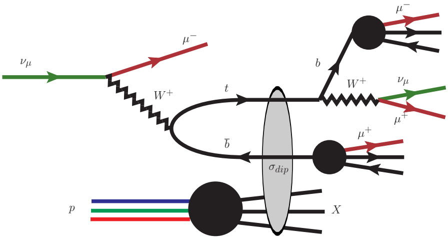
Introduction



- Measuring neutrino-proton cross sections providing crucial insights into small-x parton distribution functions

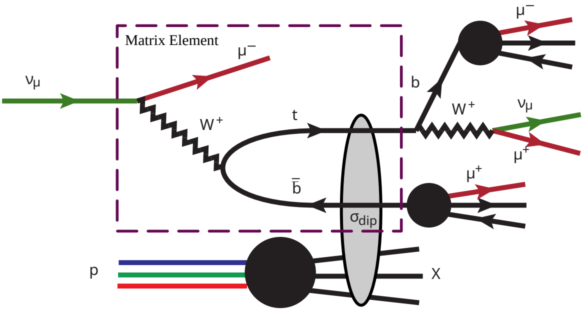
In neutrino-proton interactions we observed:

- High-energy **multimuon** production.
- **Angular separation** between muons.
- The heavy quarks production generates multiple muons through their decays and hadronization.



Objective

νp Interaction (Color dipole model) + Pythia8



Theoretical background

Differential cross section for the production of a heavy quark in parton model to neutrino–proton charged-current DIS is given by Deep inelastic scattering, Oxford University; Quantum Chromodynamics at High Energy, Oxford University; Particle Data Group:

$$\frac{d^2\sigma^{\nu p\to q\bar{q}'}}{dxdy} = \frac{s}{4\pi}\frac{G_F^2 M_W^4}{(M_W^2+Q^2)^2}\left[(1-y)^2F_+^{q\bar{q}'} + 2(1-y)F_0^{q\bar{q}'} + F_-^{q\bar{q}'}\right] \qquad (1)$$

- $s = 2m_p E_\nu$,
- m_p, proton mass,
- E_ν, energy of the neutrino
- Q^2, virtuality of the vector boson,
- $x = Q^2/2p\cdot q$, standard Bjorken variable,
- $y = (E_\nu - E_l)/E_\nu$, inelasticity parameter from $y = Q^2/xs$.

For the W boson interaction with the proton, the structure functions with $\lambda = +1, 0, -1$ are proportional to the boson–proton cross sections:

$$F_\lambda^{W,Z}(x,Q^2) \propto \frac{Q^2}{4\pi^2}\sigma_\lambda^{Wp}, \qquad (2)$$

OBS: when we considere neutral corrent $\bar{q}^{'} = \bar{q}$ and used M_Z rather M_W

Theoretical background

The vector boson–proton differential cross section is given by (eq. 81 of Ref. Nucl. Phys. A 710, 180-217 (2002)):

$$\frac{d\sigma^{Vp}}{d^2p_t dz} = \int d^2r_1 d^2r_2 \frac{e^{i\vec{p}_t\cdot(\vec{r}_1-\vec{r}_2)}}{(2\pi)^2}\Psi^\dagger\Psi(z,\vec{r}_1,\vec{r}_2)\sigma_{\rm dip}(x,z,\vec{r}_1,\vec{r}_2). \qquad (3)$$

The structure functions are convolutions over the dipole size r of wave functions and the proton–dipole cross section Z. Phys. C 49, 607-618 (1991), Eur. Phys. J. C 29, 521 (2003), JETP Lett. 82, 385-389 (2005), JETP Lett. 95, 55-60 (2012).

$$F_\lambda = \frac{Q^2}{4\pi^2}\int d^2r \int_0^1 dz \Psi^\dagger\Psi_\lambda(z,r)\sigma_{\rm dip}(\xi,r),$$

For heavy quarks, the kinematic shift in the momentum fraction is explicitly:

$$\xi = x\left(1+\frac{(m_q+m_{\bar{q}'})^2}{Q^2}\right),$$

The $W \to q\bar{q}'$ wave functions, calculated in the proton rest frame, are given by

$$\Psi^\dagger\Psi_+^{q\bar{q}'}(z,r) = \frac{2N_cV_{q\bar{q}'}^2}{\pi^2}(1-z)^2\left\{\varepsilon^2K_1(\varepsilon r)^2 + m_q^2K_0(\varepsilon r)^2\right\},$$

$$\Psi^\dagger\Psi_-^{q\bar{q}'}(z,r) = \frac{2N_cV_{q\bar{q}'}^2}{\pi^2}z^2\left\{\varepsilon^2K_1(\varepsilon r)^2 + m_{\bar{q}'}^2K_0(\varepsilon r)^2\right\}$$

$$\Psi^\dagger\Psi_0^{q\bar{q}'}(z,r) = \frac{N_cV_{q\bar{q}'}^2}{\pi^2Q^2}\Big\{(m_q^2+m_{\bar{q}'}^2)\varepsilon^2K_1(\varepsilon r)^2,$$

$$+\left(\left(\varepsilon^2+z(1-z)Q^2\right)^2+m_q^2m_{\bar{q}'}^2\right)K_0(\varepsilon r)^2\Big\}.$$

with:

$$\varepsilon^2 = z(1-z)Q^2+(1-z)m_q^2+zm_{\bar{q}'}^2.$$

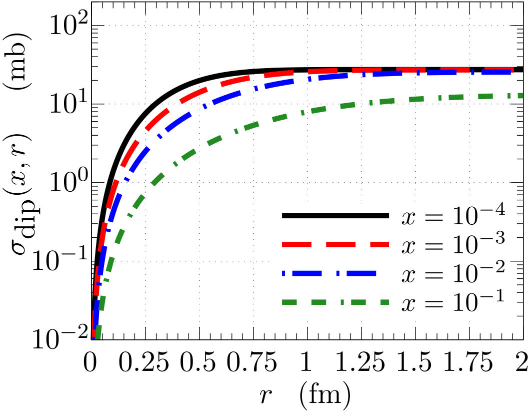
Theoretical background

Golec-Biernat-Wusthoff (GBW) parameterization Phys. Rev. D 59 (1998), Phys. Rev. D 60 (1999):

$$\sigma_{\rm dip}(x,r) = \sigma_0\left(1-\exp\left(-\frac{r^2 Q_s^2(x)}{4}\right)\right),$$

$$Q_s^2(x) = Q_0^2\left(\frac{x_0}{x}\right)^{\lambda}$$

The GBW parametrization has the advantage of being a analytical function, making it easy to Fourier transform. Phys. Rev. D 98, 036002 (2018)



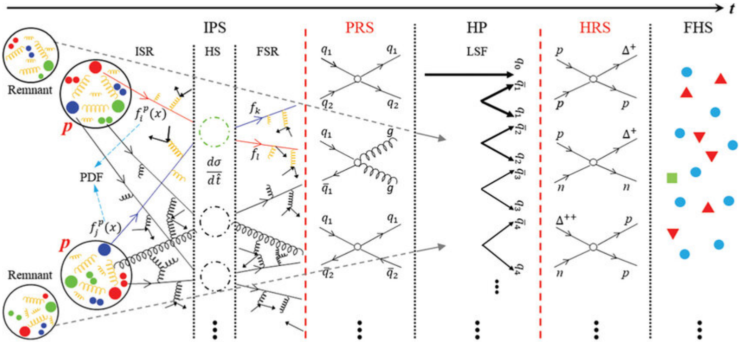
The most recent fit of HERA data to the GBW model parameters is presented in Ref. JHEP 03 (2018), 102:

$$\sigma_0 = 27.43\,\text{mb},\ \lambda = 0.248,\ Q_0^2 = 1.0\,\text{GeV}^2,\ x_0 = 4\times10^{-5}.$$

We use the same quark masses as in the fit, namely, $m_u = m_d = m_s = 0.14\,\text{GeV}$, $m_c = 1.4\,\text{GeV}$, and $m_b = 4.6\,\text{GeV}$. We also use $m_t = 173\,\text{GeV}$.

Theoretical background

Pythia simulation



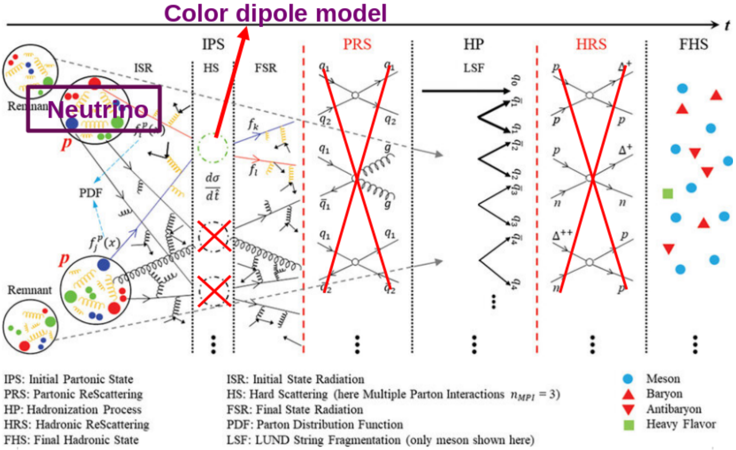
IPS: Initial Partonic State
PRS: Partonic ReScattering
HP: Hadronization Process
HRS: Hadronic ReScattering
FHS: Final Hadronic State

ISR: Initial State Radiation
HS: Hard Scattering (here Multiple Parton Interactions $n_{MPI} = 3$)
FSR: Final State Radiation
PDF: Parton Distribution Function
LSF: LUND String Fragmentation (only meson shown here)

● Meson
▲ Baryon
▼ Antibaryon
■ Heavy Flavor

Theoretical background

Pythia simulation



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🟩 Heavy Flavor

- **LHA interface.**

Results

$$\frac{d\sigma^{Vp}}{d^2p_t dz} \propto V^2_{q\bar{q}'}$$

Matriz CKM (Cabibbo–Kobayashi–Maskawa matrix)

$$\begin{bmatrix} |V_{ud}| & |V_{us}| & |V_{ub}| \\ |V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}| & |V_{ts}| & |V_{tb}| \end{bmatrix} = \begin{bmatrix} 0.97435 \pm 0.00016 & 0.22500 \pm 0.00067 & 0.00369 \pm 0.00011 \\ 0.22486 \pm 0.00067 & 0.97349 \pm 0.00016 & 0.04182^{+0.00085}_{-0.00074} \\ 0.00857^{+0.00020}_{-0.00018} & 0.04110^{+0.00083}_{-0.00072} & 0.999118^{+0.000031}_{-0.000036} \end{bmatrix}$$

Excluding small values (marked by the red line) and disregarding the production of light quarks, because the production of energetic muons remains low (marked by the blue line).

$$\begin{bmatrix} \cancel{|V_{ud}|} & \cancel{|V_{us}|} & \cancel{|V_{ub}|} \\ |V_{cd}| & |V_{cs}| & \cancel{|V_{cb}|} \\ \cancel{|V_{td}|} & \cancel{|V_{ts}|} & |V_{tb}| \end{bmatrix} = \begin{bmatrix} \cancel{0.97435 \pm 0.00016} & \cancel{0.22500 \pm 0.00067} & \cancel{0.00369 \pm 0.00011} \\ 0.22486 \pm 0.00067 & 0.97349 \pm 0.00016 & \cancel{0.04182^{+0.00085}_{-0.00074}} \\ \cancel{0.00857^{+0.00020}_{-0.00018}} & \cancel{0.04110^{+0.00083}_{-0.00072}} & 0.999118^{+0.000031}_{-0.000036} \end{bmatrix}$$

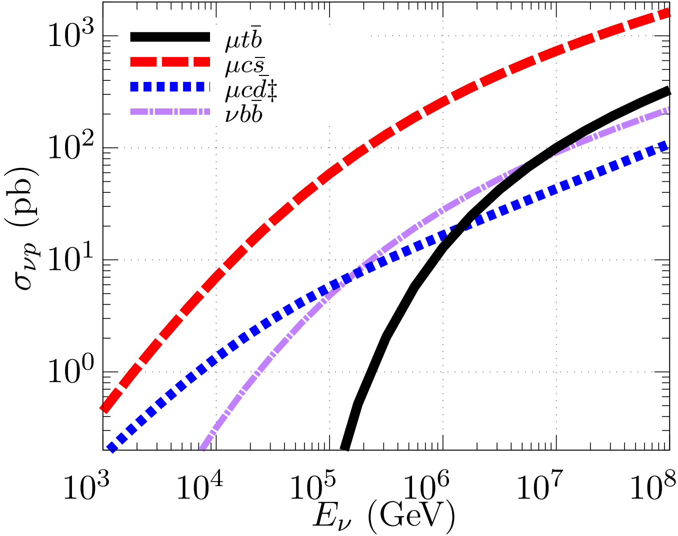


Figure: Inclusive cross section for heavy quark production in muon neutrino–proton collisions, shown as a function of neutrino energy and calculated using the color dipole event generator. In the case of the $\mu c\bar{d}$ final state, the large valence quark contribution necessitates the use of standard Pythia (without the color dipole model event generator) as indicated by the ‡ symbol.

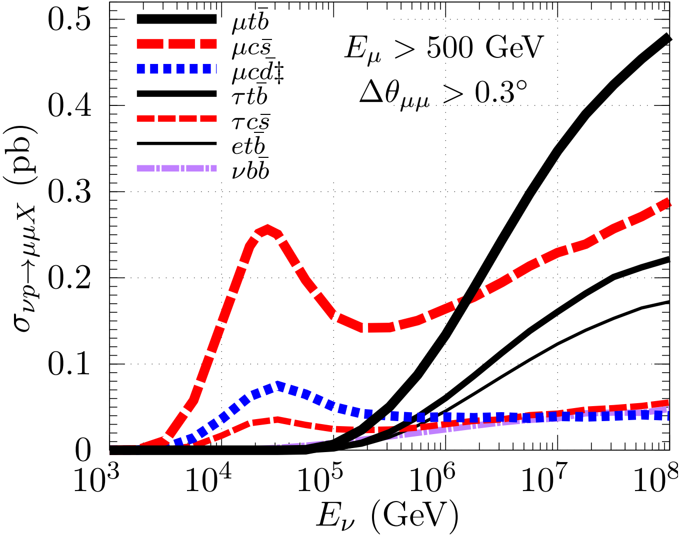


Figure: The cross section as a function neutrino energy for the production of pairs of muons with energy larger than 500 GeV and with angular separation larger than 0.3°. The main channels are shown, the labels specify the three particles in the final state of the matrix element.

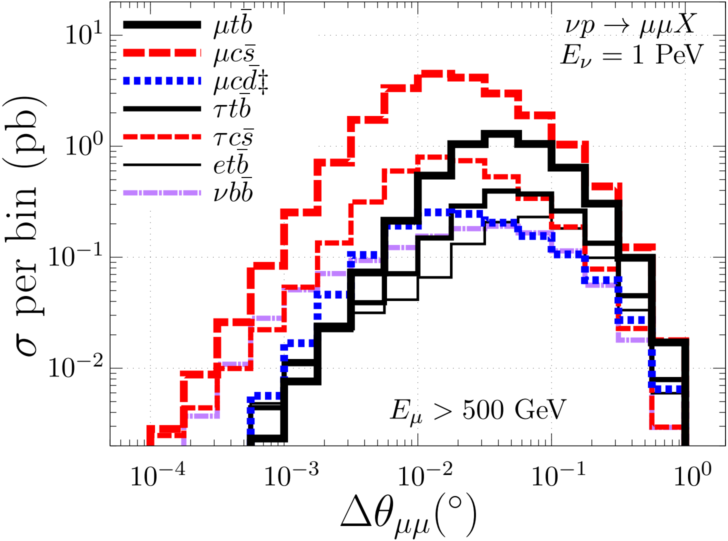


Figure: The cross section is presented as a histogram on the largest angular separation between muons

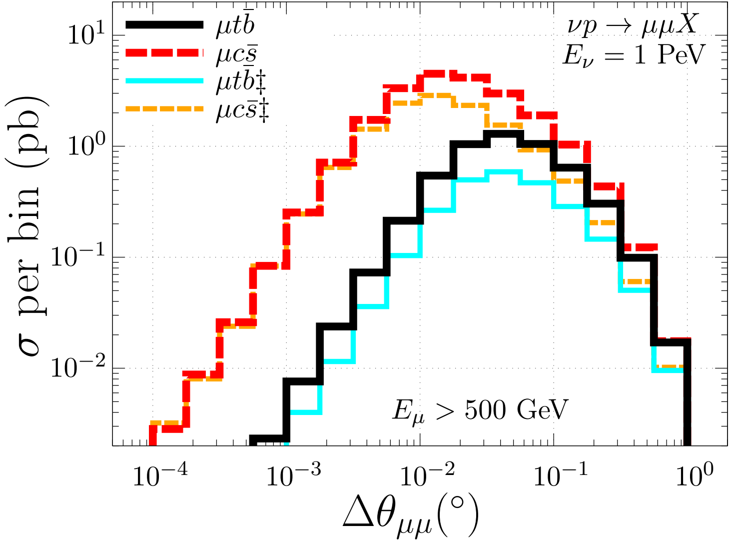


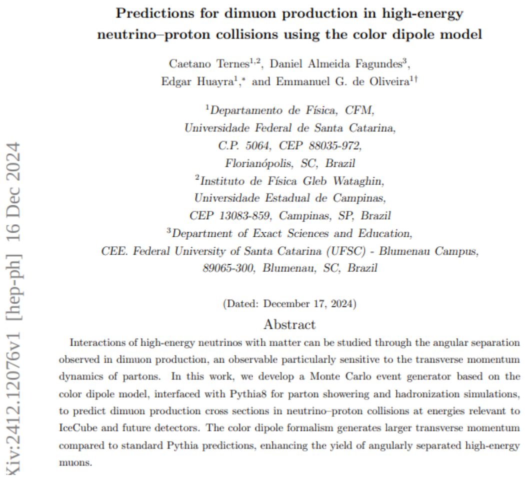
Figure: We compare the color dipole model event generator combined with Pythia for showering and hadronization to the standard Pythia ($\mu c\bar{s}‡$) or Pythia plus MadGraph ($\mu t\bar{b}‡$).

Conclusion

- We have predicted the cross sections for high-energy dimuon production in interactions between high-energy neutrinos and protons.
- We are using the color dipole model in conjunction with Pythia8 Monte Carlo to obtain these predictions.
- The main channels identified are $W^+ \to c\bar{s}$ and $W^+ \to t\bar{b}$, at lower and higher energies respectively.
- Our predictions include the dependence on the angle between the muons, as this observable is particularly sensitive to transverse momentum generated in the hard matrix element.
- The color dipole formalism predicts a nonzero transverse momentum at the matrix element, resulting in dimouns with larger angular separation compared to default LO Pythia8 predictions, as observed in the $c\bar{s}$ case.

Conclusion

- These results are available at Arxiv, https://arxiv.org/pdf/2412.12076



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Abstract

Interactions of high-energy neutrinos with matter can be studied through the angular separation observed in dimuon production, an observable particularly sensitive to the transverse momentum dynamics of partons. In this work, we develop a Monte Carlo event generator based on the color dipole model, interfaced with Pythia8 for parton showering and hadronization simulations, to predict dimuon production cross sections in neutrino–proton collisions at energies relevant to IceCube and future detectors. The color dipole formalism generates larger transverse momentum compared to standard Pythia predictions, enhancing the yield of angularly separated high-energy muons.

Acknowledgments

HIGH ENERGY PHYSICS
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CAPES

THANK YOU FOR YOUR ATTENTION