Dimuon production in neutrino-nucleus collisions - the SIDIS approach

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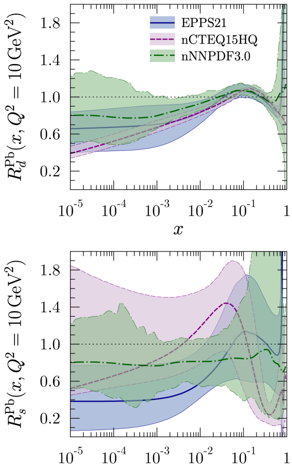
Centre of Excellence in Quark Matter

Strange-quark distribution

- Still quite poorly known, even for free protons
- Relevant for
  - W and Z production at the LHC
  - precision determination of electroweak parameters such as W mass and weak mixing angle
- Mostly constrained by neutrino-nucleus data
  - Nuclear target needed for sufficient statistics
  - Plays an important role in free-proton fits $\rightarrow$ correlation between proton and nuclear PDFs



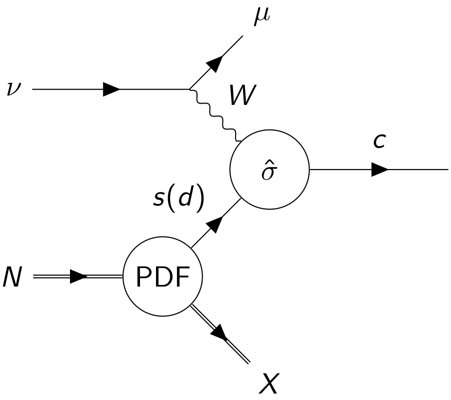
M. Klasen, H. Paukkunen; Ann. Rev. Nucl. Part. Sci. 2023

Dimuon production in νN collisions

- Charm production probes the strange-quark distribution
- Can't detect charm directly, so dimuons instead
- Usually computed by assuming factorization:

$$d\sigma(\nu N \to \mu\mu X) \simeq \mathcal{A}\mathcal{B}_\mu d\sigma(\nu N \to \mu c X)$$

  - True at LO, but breaks down at NLO
  - Requires external acceptance $\mathcal{A}$
  - Semileptonic branching fraction $\mathcal{B}_\mu$ averaged over charm mesons is an effective quantity

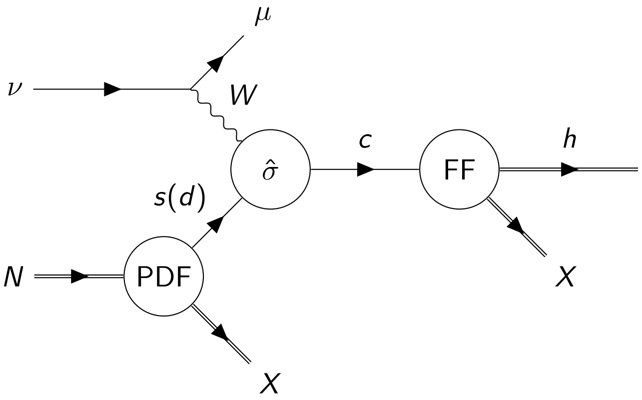


SIDIS

- SIDIS: fragmentation of charm quark
- DGLAP-evolved NLO FFs
  - kkks08 for D^0 and D^+
  - bkk05 for D_s and Λ_c
- Slow rescaling variable

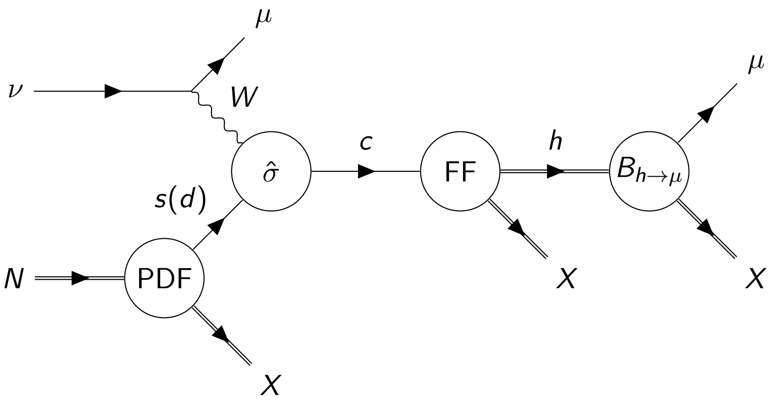
$$\chi = x\left(1 + \frac{m^2}{Q^2}\right)$$

takes leading quark-mass effects into account



Dimuon production in νN collisions - the SIDIS approach

- Use SIDIS to produce a charmed hadron $\rightarrow$ well-known
- Decay of charmed hadron to a muon $\rightarrow$ how?



General formalism

- Assuming production of hadron h and its decay factorizes, the cross section can be written as

$$\sigma(\nu N \to \mu\mu X) = \int \mathrm{d}\sigma(\nu N \to \mu h X) \frac{\Gamma_{h\to\mu}}{\Gamma_{\text{tot}}}$$

- Write the decay width as $[w = (P_\mu \cdot P_h)/m_h^2]$

$$\Gamma_{h\to\mu} = \frac{1}{2m_h} \int \frac{\mathrm{d}^3\mathbf{P}_\mu}{E_\mu} d_{h\to\mu}(w) \implies \frac{\mathrm{d}\Gamma_{h\to\mu}}{\mathrm{d}\left|\mathbf{P}_\mu\right|} = \frac{\pi}{m_h} \frac{\left|\mathbf{P}_\mu\right|^2}{E_\mu} \int \mathrm{d}(\cos\theta) d_{h\to\mu}(w)$$

- Introduce cut on muon energy

$$\Gamma_{h\to\mu}(E_h, E_\mu^{\text{min}}) = \frac{\pi}{m_h} \int \mathrm{d}\rho\, \rho E_h^2 \int \mathrm{d}(\cos\theta) d_{h\to\mu}(w) \Big|_{E_\mu = \rho E_h \geq E_\mu^{\text{min}}}$$

Fitting the decay function

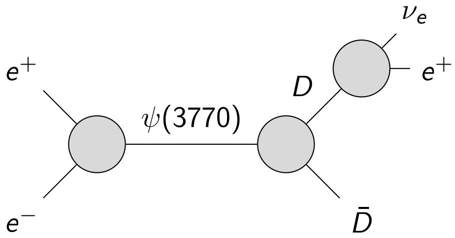
- Decay function parametrization

$$d_{D\to\mu}(w) = N w^{\alpha}(1-\gamma w)^{\beta}\theta(0 \leq w \leq 1/\gamma)$$

- Fit the function

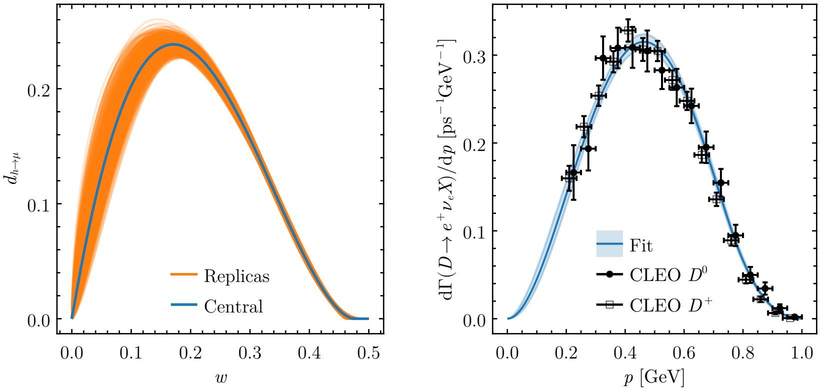
$$\frac{\mathrm{d}\Gamma(D)}{\mathrm{d}\left|\mathbf{P}_e\right|} = \frac{\pi}{m_D}\left|\mathbf{P}_e\right| \int \mathrm{d}(\cos\theta) d_{D\to\mu}(w)$$

to CLEO data [PRL 97 (2006) 251801]



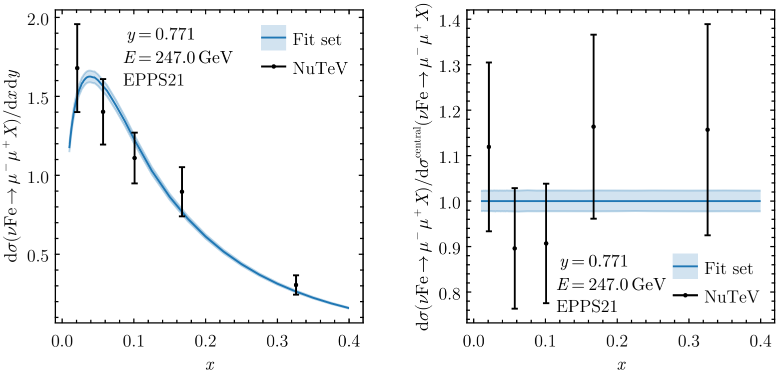
Fit uncertainty

- Fit parameters N, α, β, and γ are highly correlated
- Use 1000 Monte-Carlo replicas to estimate uncertainty



Application to dimuon production

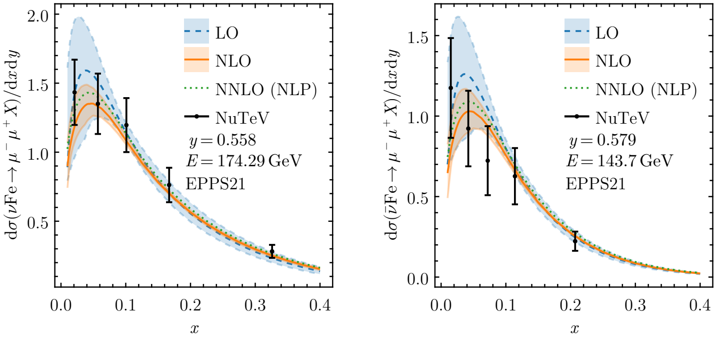
$$\frac{d\sigma(\nu N \to \mu\mu X)}{dx\,dy} = \sum_h \int dz \, \frac{d\sigma(\nu N \to \mu h X)}{dz\,dx\,dy} \frac{1}{\Gamma^h_{\rm tot}} \Gamma_{h\to\mu}(E_h = zyE_\nu, E_\mu^{\rm min})$$



Scale uncertainty

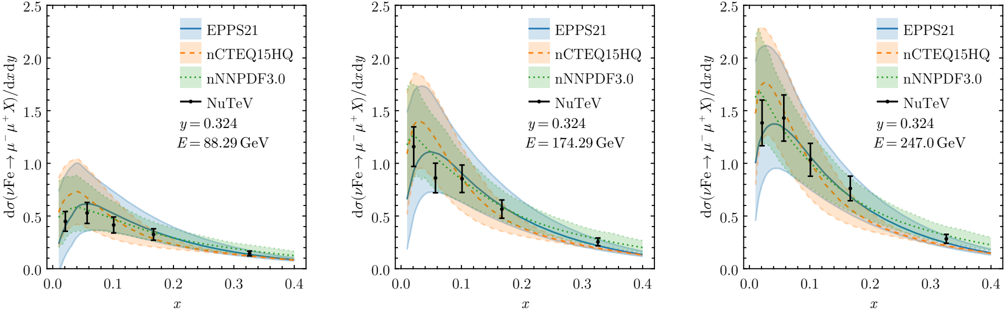
- Vary renormalization, factorization, and fragmentation scales
- Approximative quark-to-quark next-to-leading power NNLO contribution

[Abele et al; Phys.Rev.D 104 (2021) 9, 094046]



PDF comparison

- Good agreement with NuTeV data [PRL 99 (2007) 192001]
- PDFs agree within uncertainty bands, but overall shapes differ → reflects the shape of the strange-quark distribution



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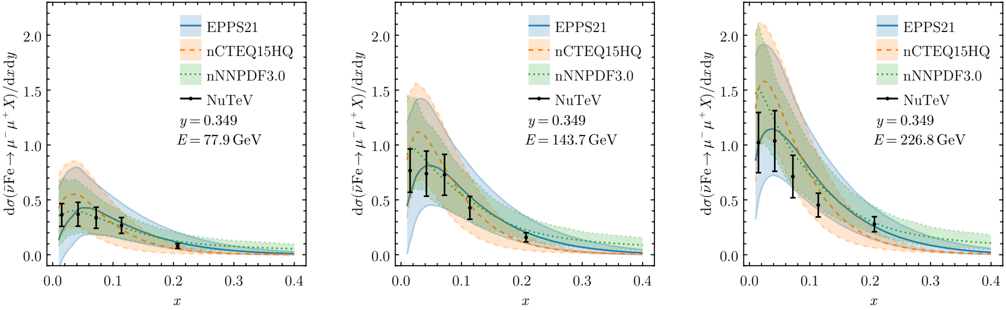
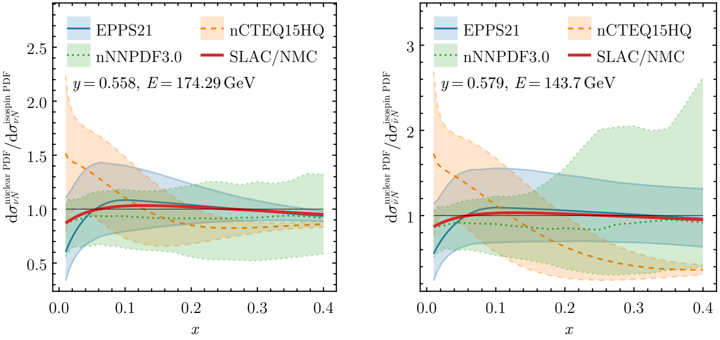


Nuclear modification

- Multiplicative nuclear modification factor $\mathrm{d}\sigma_{\nu N}^{\mathrm{nPDF}}/\mathrm{d}\sigma_{\nu N}^{\mathrm{isospin\ PDF}}$
- Isospin-corrected PDFs $(u_A^p, d_A^p) = \frac{Z}{A}(u^p, d^p) + \frac{N}{A}(d^p, u^p)$
- SLAC/NMC form for reference [Seligman, PhD thesis, Columbia U. 1997]
- Significant uncertainties from nPDF uncertainties



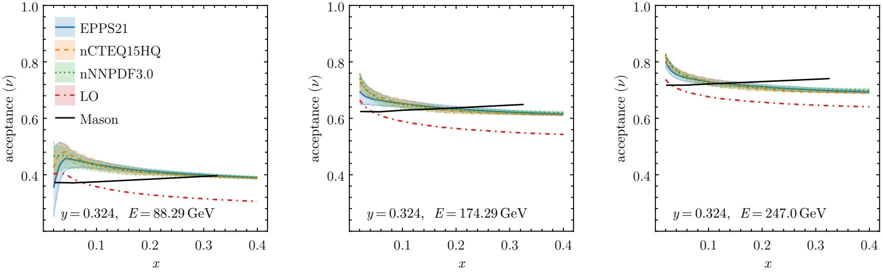
Acceptance correction

- Dimuon cross section now has muon energy cut built-in → can compute acceptance from

$$\mathcal{A} = \frac{\mathrm{d}\sigma(\nu N \to \mu\mu X)}{\mathcal{B}_\mu \mathrm{d}\sigma(\nu N \to \mu c X)}$$

- Compare against existing Monte-Carlo calculation, used e.g. by NNPDF4.0

[D. A. Mason, PhD thesis, Oregon U. 2006]



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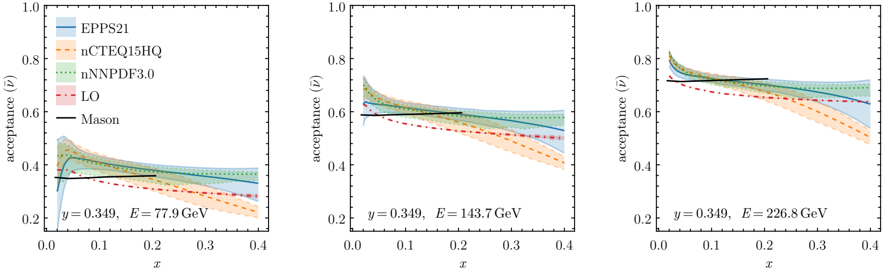
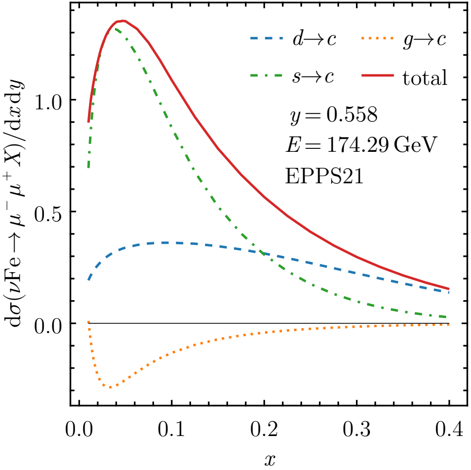
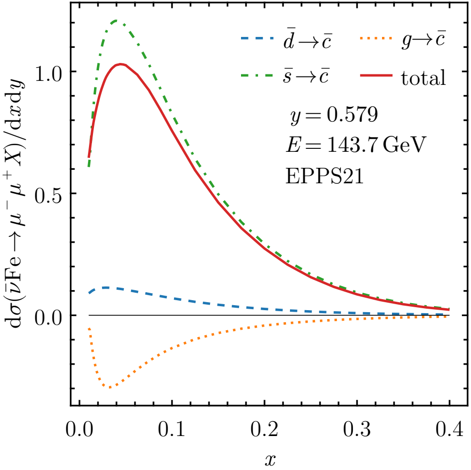


Conclusions

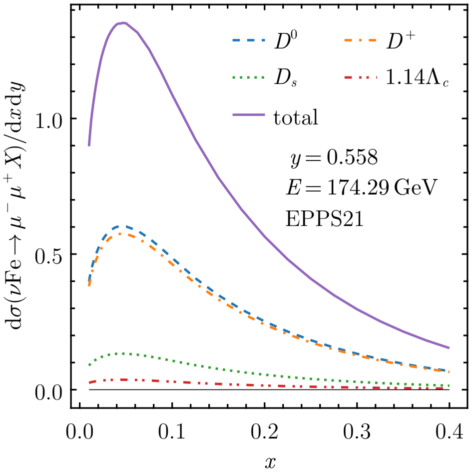
- We have computed dimuon production in neutrino-nucleus collisions directly using SIDIS and a decay function
  - Decay function can be obtained by fitting to independent data
  - Assumption that dimuon production is proportional to charm production is not necessary
  - Effective acceptance correction shows systematic differences to a commonly used calculation
- Good agreement with NuTeV (and CCFR) dimuon data
- **The SIDIS approach provides a consistent and self-contained calculation of dimuon production without the need for an external acceptance correction**

Channel decomposition





Fragmentation



Quark-mass effects

- Leading quark-mass effects can be included with the slow rescaling variable

$$\chi = x\left(1 + \frac{m^2}{Q^2}\right)$$

- The slow rescaling variable captures all mass effects at LO, and leading mass effects at NLO
- Relevant effects: shrinks the phase space, shifts the argument of PDFs

Decay formalism (1/2)

- Assume that the production of a hadron h and its decay factorizes in $AB \to h \to CX$

$$\sigma(AB \to CX) = \frac{1}{2s} \int \mathrm{d(PS)} (2\pi)^4 \delta^{(4)}(P_A + P_B - P_C - P_{X_1} - P_{X_2}) \\ \times (\text{production}) \frac{1}{(P_h^2 - m_h^2)^2 + m_h^2 \Gamma_{\text{tot}}^2} (\text{decay})$$

- Narrow-width approximation

$$\frac{1}{(P_h^2 - m_h^2)^2 + m_h^2 \Gamma_{\text{tot}}^2} \simeq \frac{\pi}{m_h \Gamma_{\text{tot}}} \delta(P_h^2 - m_h^2)$$

Decay formalism (2/2)

- Insert unity as

$$1 = \int \frac{\mathrm{d}P_h^2}{2\pi} \int \frac{\mathrm{d}^3\mathbf{P}_h}{(2\pi)^3 2E_h} (2\pi)^4 \delta^{(4)}(P_h - P_C - P_{X_2})$$

- Identify production cross section and decay width

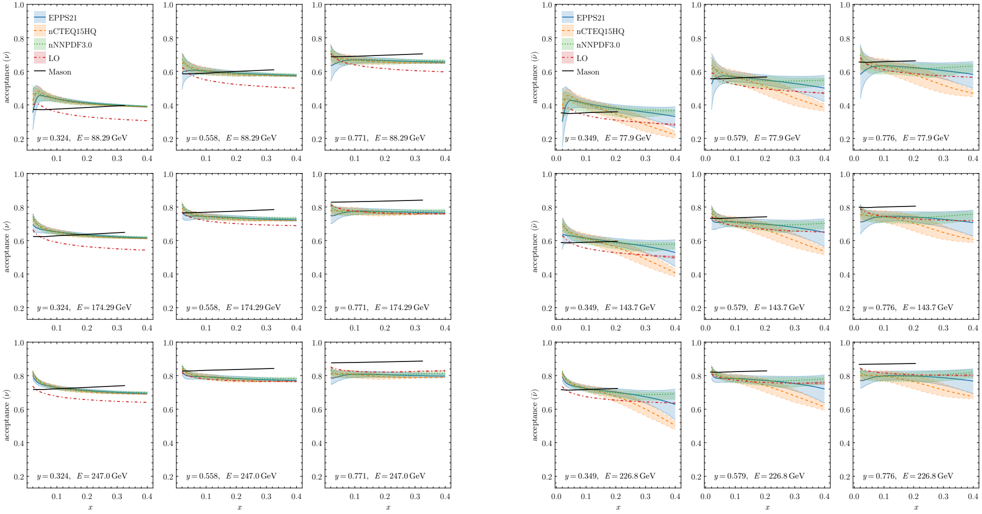
$$\mathrm{d}\sigma(AB \to hX) = \frac{1}{2s} \int \mathrm{d(PS)(production)}\delta^{(4)}(P_A + P_B - P_{X_1} - P_h - P_C)$$

$$\Gamma_{h\to C} = \frac{1}{2m_h} \int \mathrm{d(PS)(decay)}\delta^{(4)}(P_h - P_{X_2} - P_C)$$

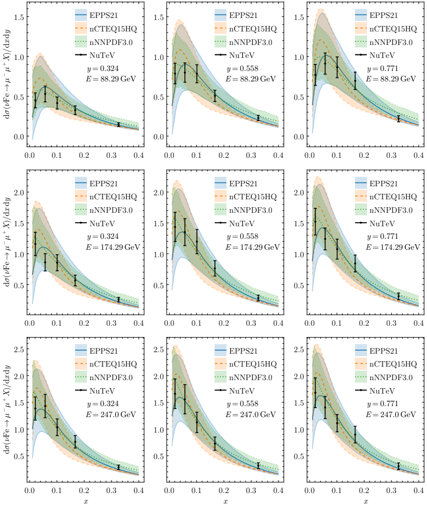
- With these, the cross section becomes

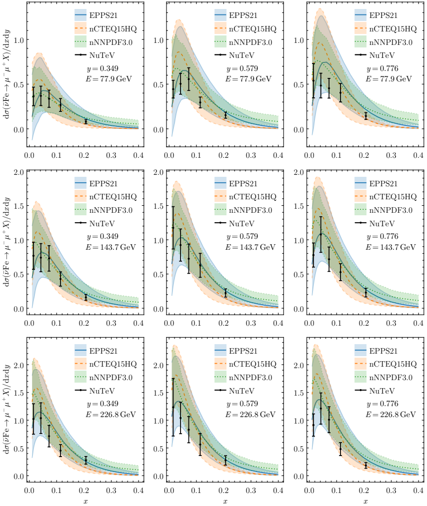
$$\sigma(AB \to CX) = \int \mathrm{d(PS)}\mathrm{d}\sigma(AB \to hX)\frac{\Gamma_{h\to C}}{\Gamma_{\mathrm{tot}}}$$

Acceptance systematics



PDF comparison systematics (NuTeV)





PDF comparison systematics (CCFR)