Centre of Excellence in Quark Matter

Dimuon production in DIS with charm mass and NNLO corrections

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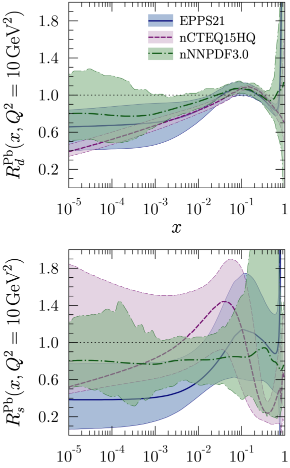
Introduction

Strange-quark distribution

- Still quite poorly known, even for free protons
- Relevant for
  - W and Z production at the LHC
  - electroweak parameters
- Mostly constrained by neutrino-nucleus data
  - nuclear target for sufficient statistics
  - correlation between proton and nuclear PDFs



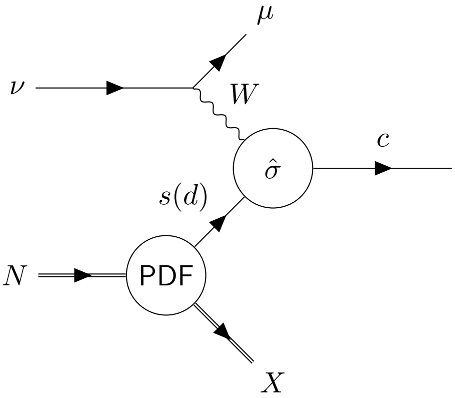
M. Klasen, H. Paukkunen; Ann. Rev. Nucl. Part. Sci. 2023

Dimuon production in νN collisions

- Probe s with charm production
  $\rightarrow$ dimuon production
- Usually computed with

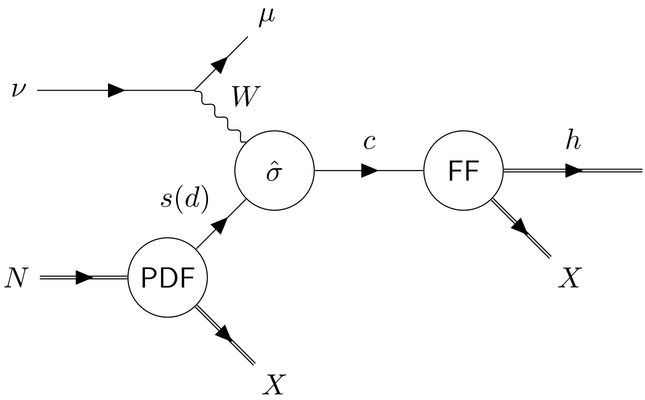
  $$\mathrm{d}\sigma(\nu N \rightarrow \mu\mu X) \simeq \mathcal{A}\mathcal{B}_\mu \mathrm{d}\sigma(\nu N \rightarrow \mu c X)$$

- Holds only at LO
- Needs additional input
  - external acceptance $\mathcal{A}$
  - semileptonic branching fraction $\mathcal{B}_\mu$



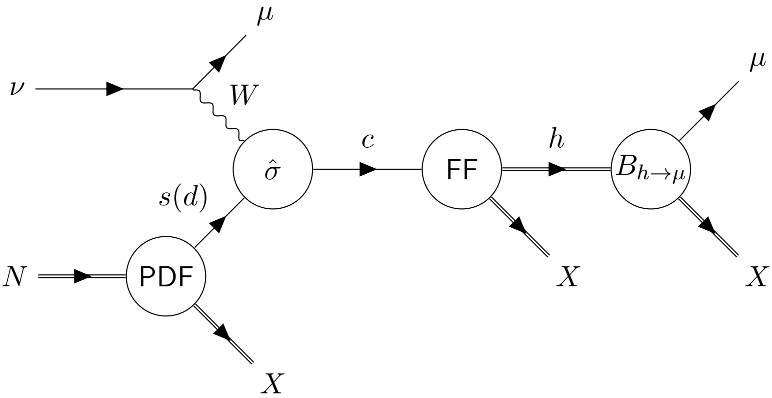
- SIDIS: charm fragmentation
- DGLAP-evolved NLO FFs
  - kkks08 for D^0 and D^+
  - bkk05 for D_s and Λ_c
- Leading charm mass effects

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



Dimuon production in νN collisions - the SIDIS approach

- Use SIDIS to produce a charmed hadron → well-known
- Decay of charmed hadron to a muon → how?



Decay of charmed hadrons

General formalism

- Assume production of hadron h and its decay factorizes:

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

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

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

- 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

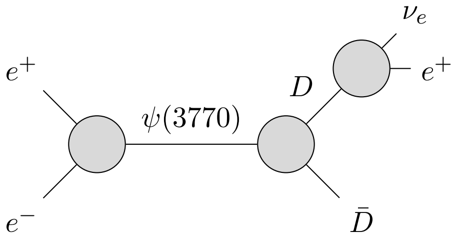
- Decay function parametrization

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

- Fit the function

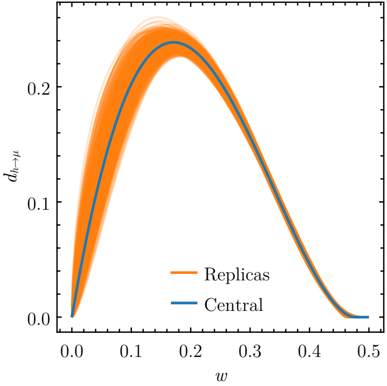
$$\frac{\mathrm{d}\Gamma(D)}{\mathrm{d}\,|\mathbf{P}_e|} = \frac{\pi}{m_D} |\mathbf{P}_e| \int \mathrm{d}(\cos\theta) d_{D\to\mu}(w)$$

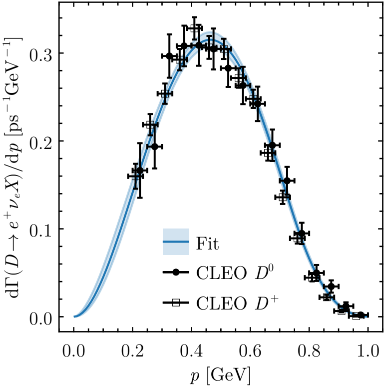
to CLEO data [PRL 97 (2006) 251801]



Fit uncertainty

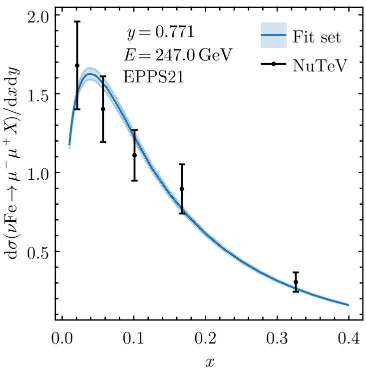
- Fit parameters N, α, β, and γ are highly correlated
- Use 1000 Monte-Carlo replicas to estimate uncertainty

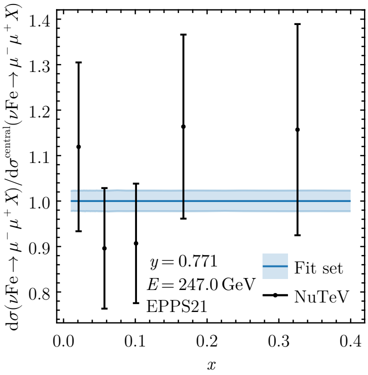




Application to dimuon production

$$\frac{\mathrm{d}\sigma(\nu N \to \mu\mu X)}{\mathrm{d}x\,\mathrm{d}y} = \sum_h \int \mathrm{d}z\, \frac{\mathrm{d}\sigma(\nu N \to \mu h X)}{\mathrm{d}z\,\mathrm{d}x\,\mathrm{d}y} \frac{1}{\Gamma^h_{\text{tot}}} \Gamma_{h\to\mu}(E_h = zyE_\nu, E_\mu^{\text{min}})$$



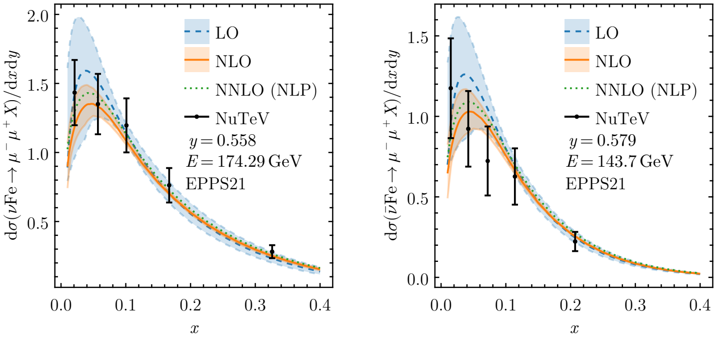


Results

Scale uncertainty

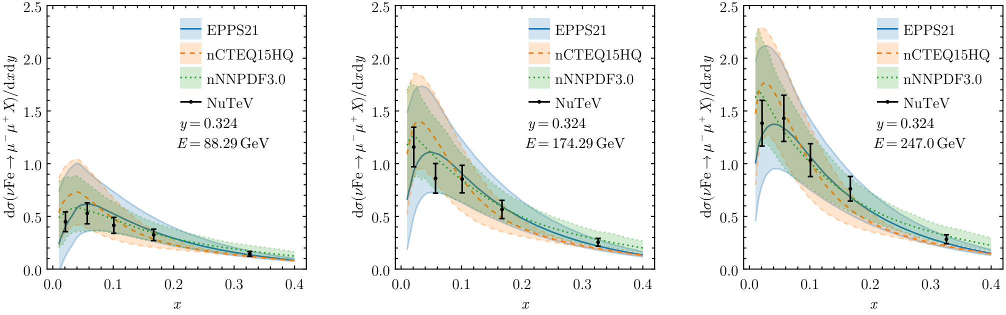
- Vary renormalization, factorization, and fragmentation scales
- Approximative quark-to-quark next-to-leading power NNLO contribution

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



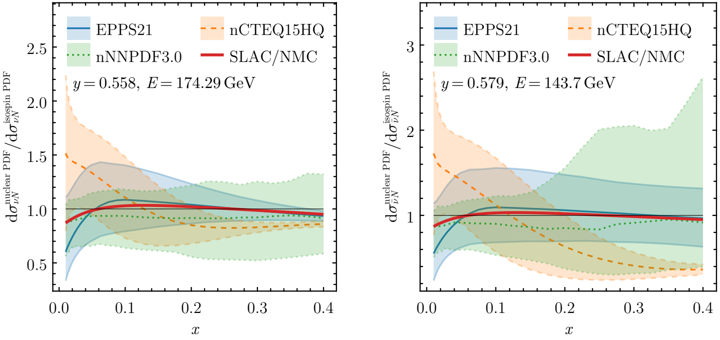
PDF comparison

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



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



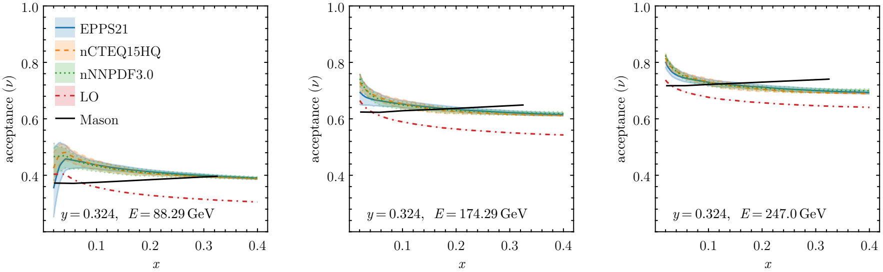
Acceptance correction

- Muon energy cut is now built-in $\rightarrow$ can compute acceptance from

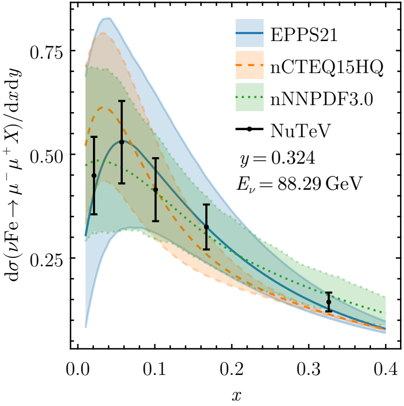
$$\mathcal{A} = \frac{\mathrm{d}\sigma(\nu N \to \mu\mu X)}{\mathcal{B}_\mu \mathrm{d}\sigma(\nu N \to \mu c X)}$$

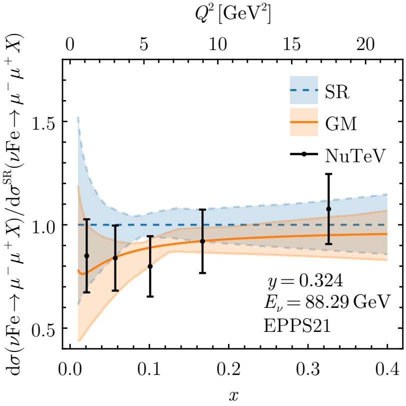
- Compare against existing Monte-Carlo calculation, used e.g. by NNPDF4.0

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



- Full charm mass dependence [Phys. Lett. B 398 (1997), 381-386]
- Subleading effects relevant at low Q^2

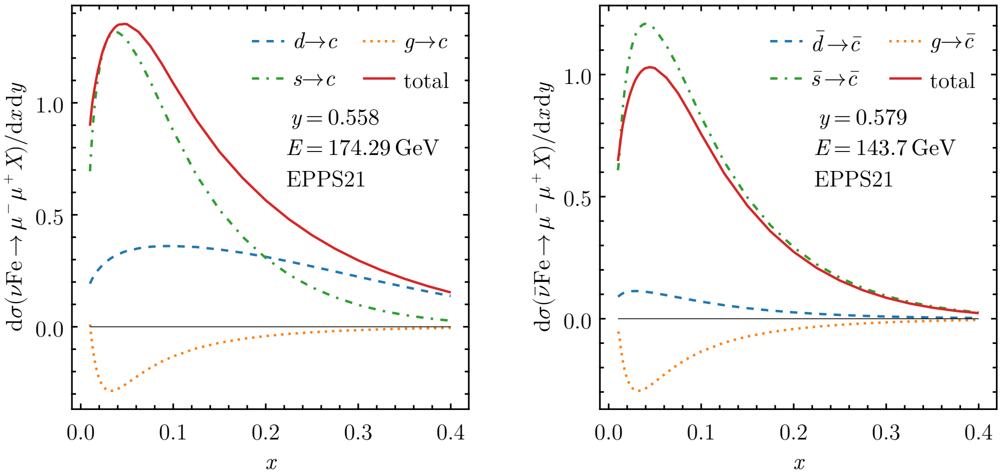




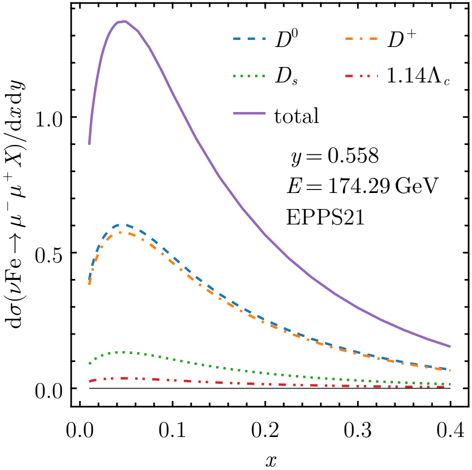
Conclusions

- 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



Decay formalism (1/2)

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

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

- Narrow-width approximation

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

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

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

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

- With these, the cross section becomes

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