Universität Münster

Neutrino DIS in Nuclear PDF Fits

Herbstschule HEP 2026

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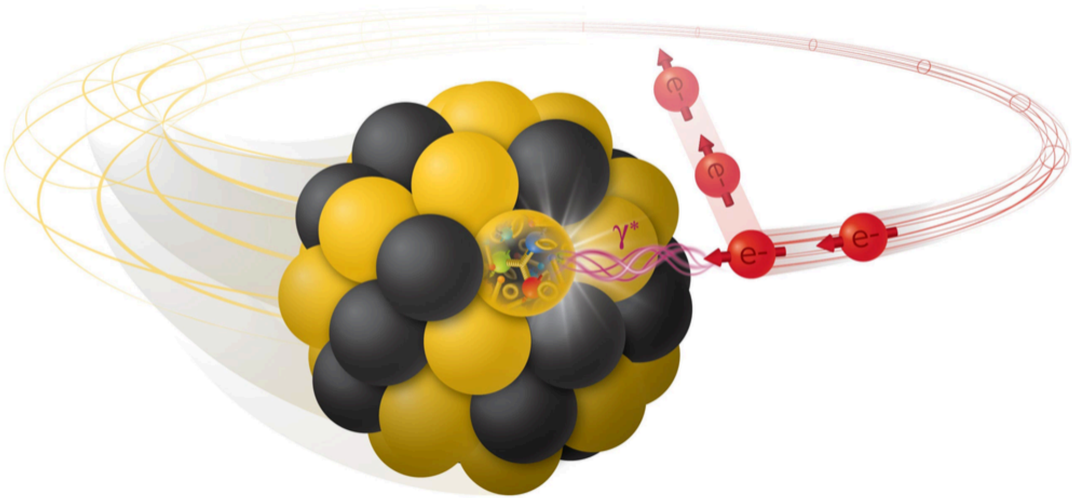
nCTEQ

nuclear parton distribution functions

September, 2026

Probing the Structure of Nuclei



[ePIC Collaboration]

$$\mathrm{d}\sigma \sim \sum_I a_I F_I, \quad F_I = \sum_i C_{Ii} \otimes f_i$$

- F_I : structure functions - encode the hardonic response
- C_{Ii}: perturbative short-distance scattering
- f_i: partonic structure of the target

PDF Framework

Factorization:

$$F_I\left(x, Q^2\right) = \sum_i \int_x^1 \frac{\mathrm{d}\xi}{\xi} C_{Ii}\left(\frac{x}{\xi}, \frac{Q^2}{\mu^2}, \alpha_s\right) f_i\left(\xi, \mu^2\right) + \mathcal{O}\left(\frac{\Lambda^2}{Q^2}\right)$$

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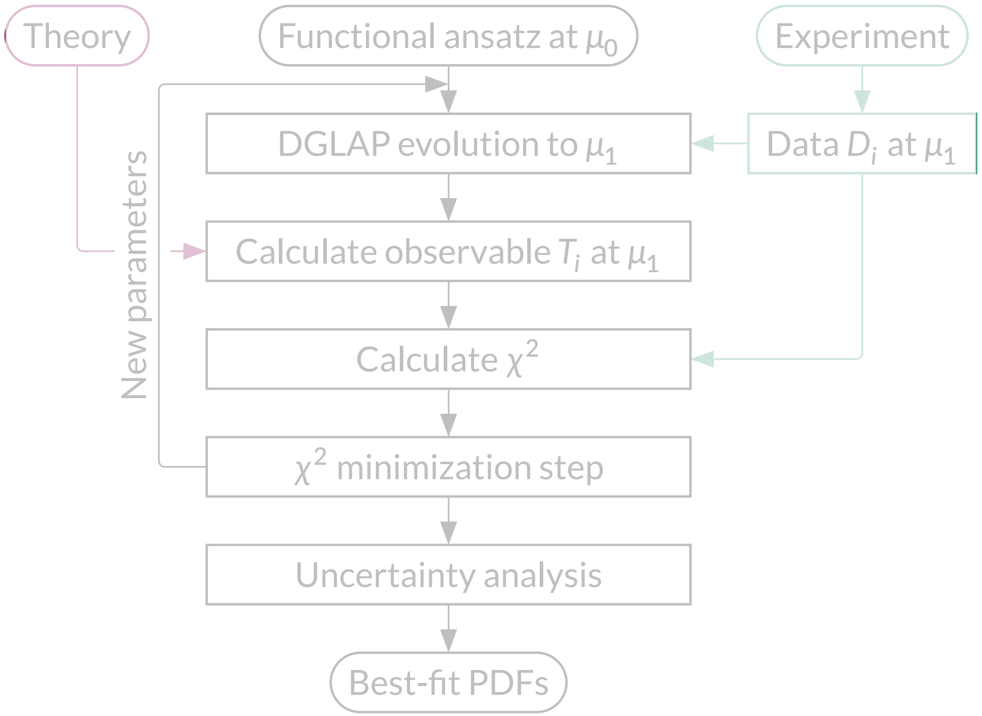
- f: distribution of parton i carrying momentum fraction ξ at factorization scale μ
- PDF x dependence not calculable in pQCD: Assume parametrization at chosen input scale μ_0

$$x f_i(x,\mu_0) = N(1-x)^{c_{i,1}} x^{c_{i,2}} P(x, c_{i,3}, \ldots)$$

- perturbatively evolved with DGLAP equations



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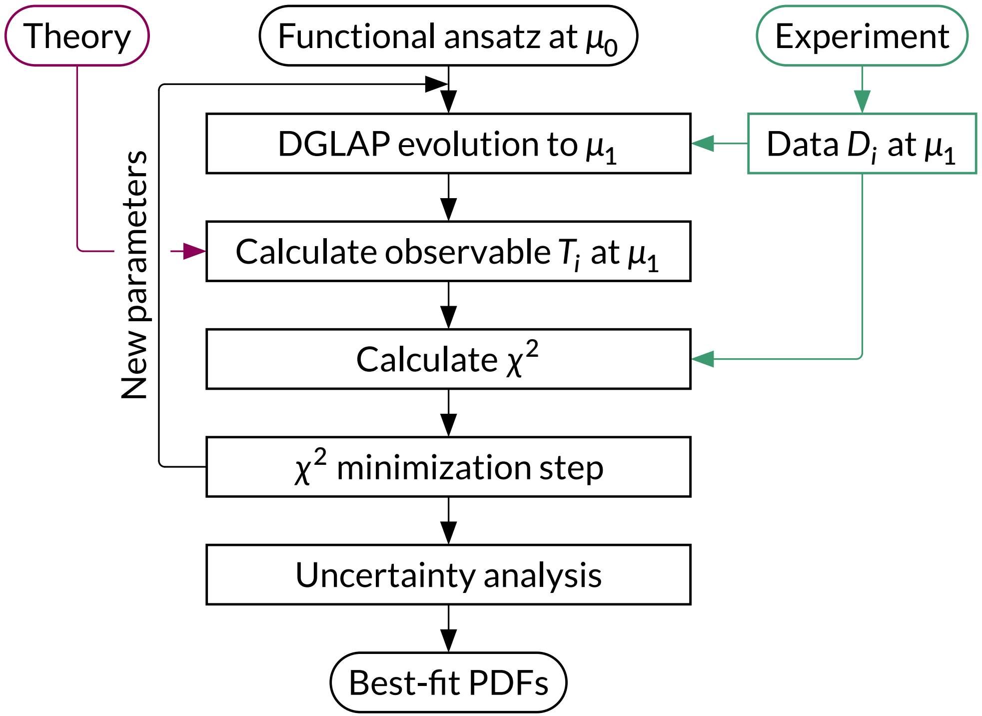
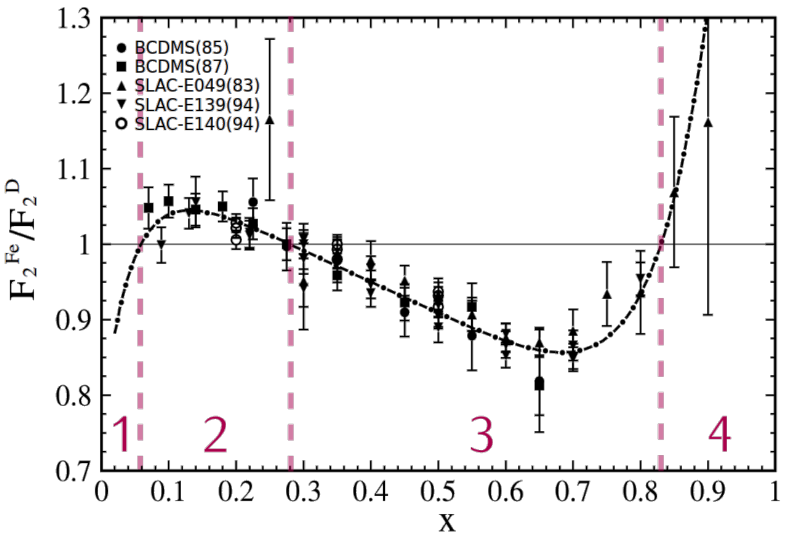


Why do we need nuclear PDFs?

Nuclear modifications: $F_2^A(x) \neq ZF_2^p(x) + NF_2^n(x)$



1. shadowing
2. anti-shadowing
3. EMC effect
4. Fermi motion

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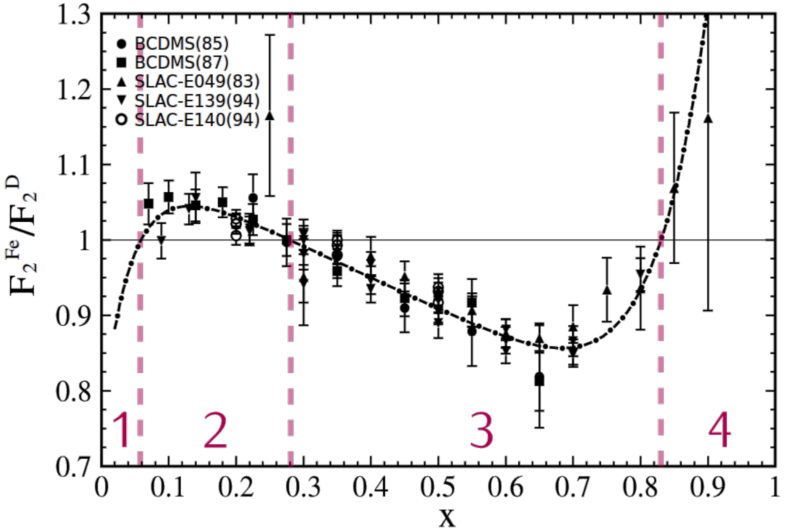

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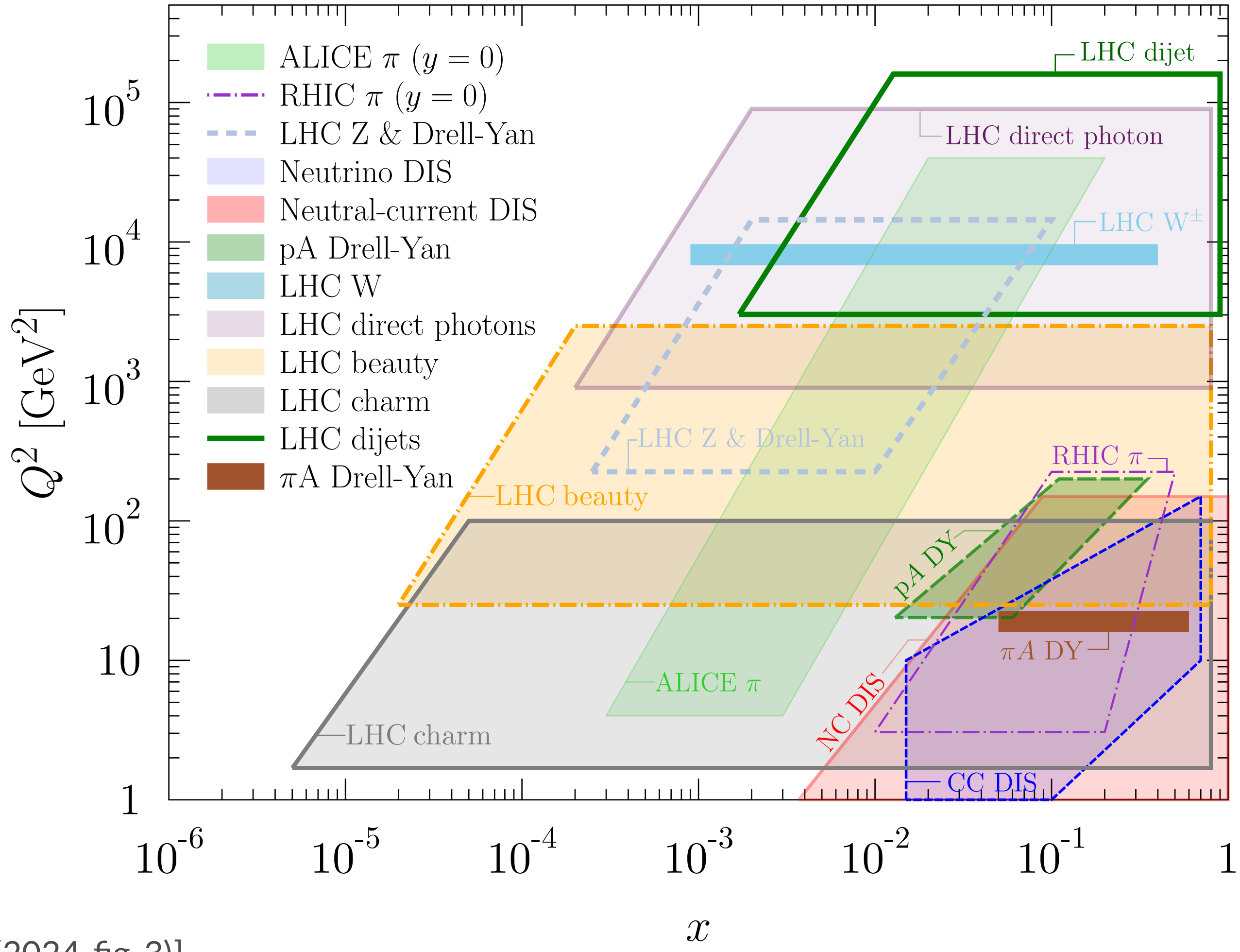
$\rightarrow$ Construct n(uclear)PDFs that include these modifications w.r.t to the free proton

proton bound in nucleus A		nuclear PDF per nucleon		free proton
$c_i \rightarrow c_i(A)$: $f^{p/A}$	$\Longleftrightarrow$	$f^A = \frac{Z}{A} f^{p/A} + \frac{N}{A} f^{n/A}$	$\xrightarrow{A=1}$	f^p

Kinematic Landscape



[Klasen and Paukkunen (2024, fig. 3)]

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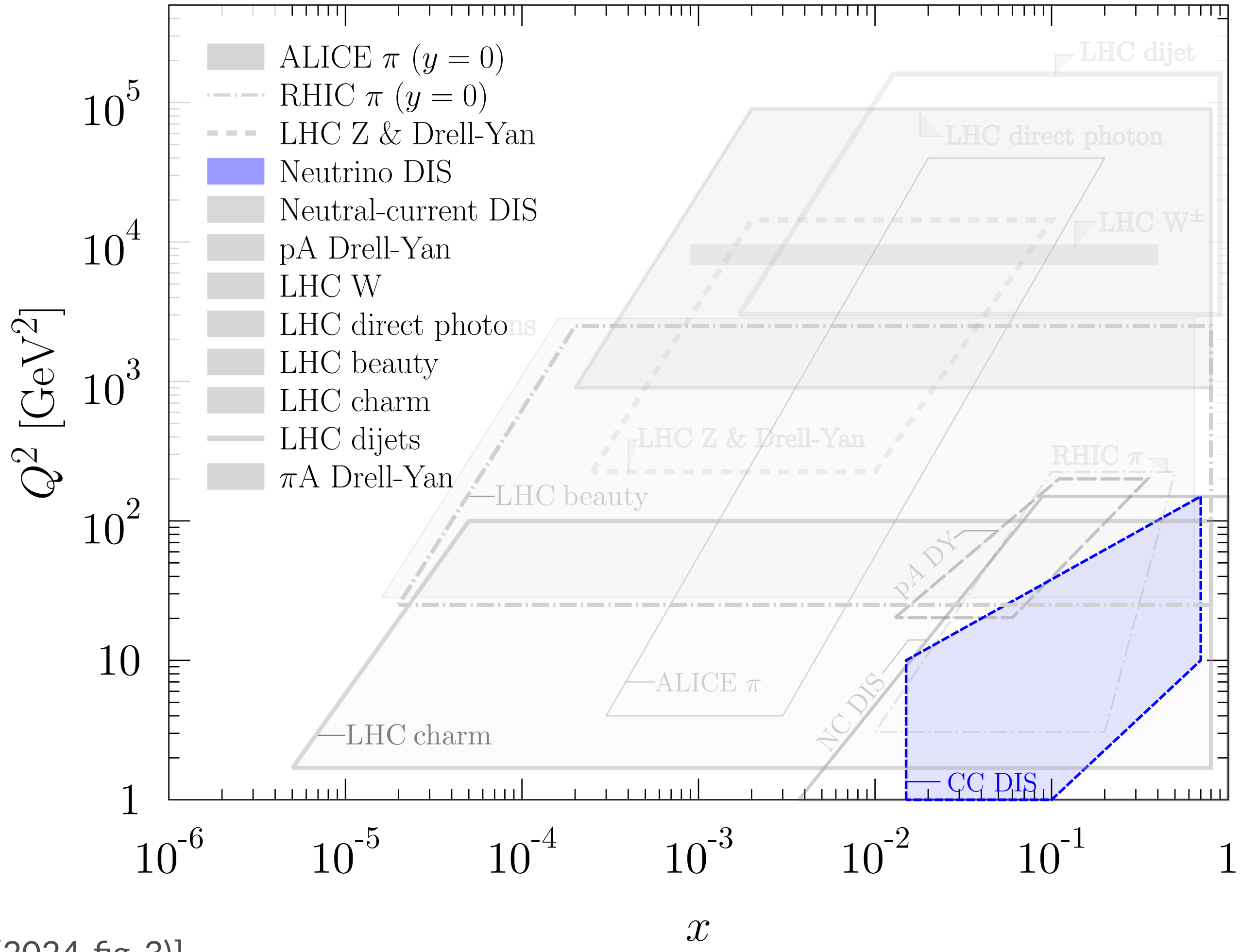

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Neutrino DIS

- Measure $\nu A \to lX$ collisions due to low interaction rate of neutrinos

$$\frac{\mathrm{d}^2\sigma^{\nu A}}{\mathrm{d}x\,\mathrm{d}y} \propto Y_+F_2 - y^2F_L \pm Y\_xF_3, \quad Y_\pm = 1 \pm (1-y)^2$$

- CC DIS provides flavour sensititvy (LO, high Q^2)

$$\frac{\mathrm{d}^2\sigma^{\nu A}}{\mathrm{d}x\,\mathrm{d}y} \propto \left(d^A + s^A\right) + (1-y)^2\left(\overline{u}^A + \overline{c}^A\right)$$

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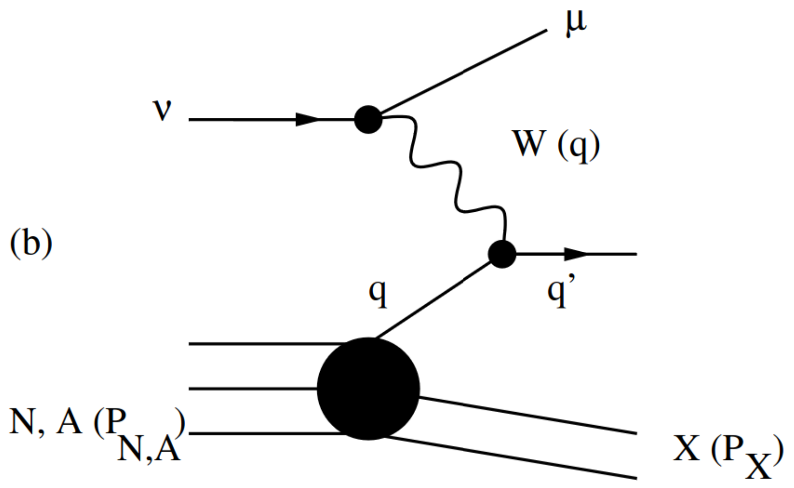

[Klasen and Paukkunen (2024, fig. 3)]

$$q = k - k', \quad Q^2 = -q^2, \quad x = \frac{Q^2}{2P\cdot q}, \quad y = \frac{P\cdot q}{P\cdot k}$$

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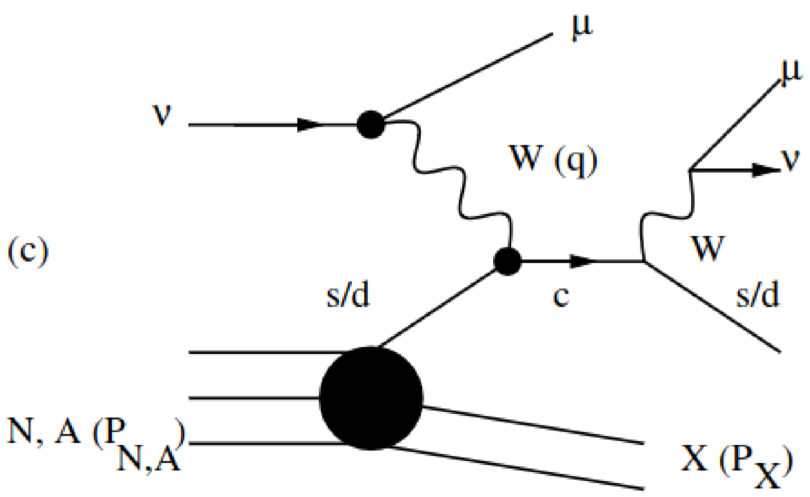
- Semi-inclusive charm production probes $s, \bar{s}$

$$\nu_\mu + s \to \mu^- + c, \quad \bar{\nu}_\mu + \bar{s} \to \mu^+ + \bar{c}$$



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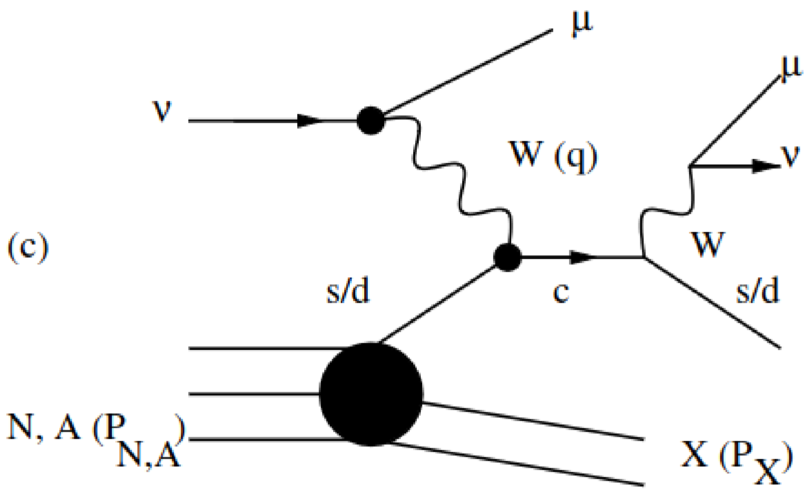
νDIS puts important constraints on nPDFs!



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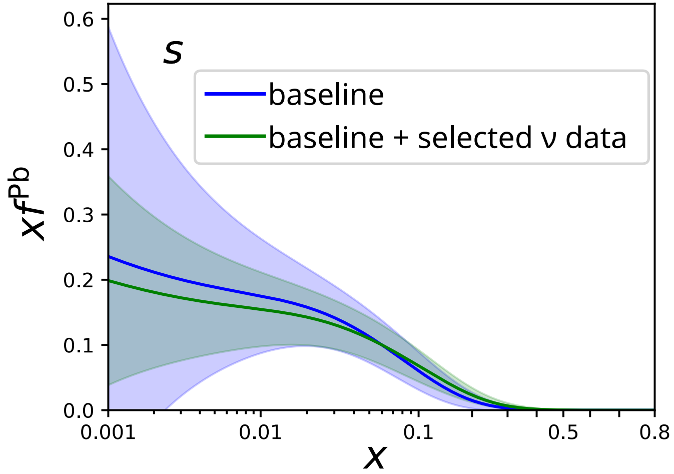
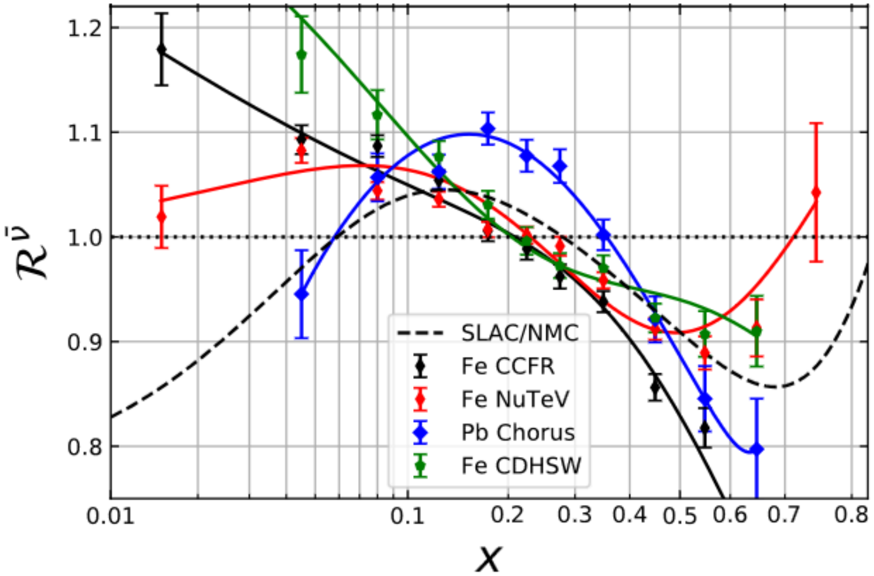


Neutrino Data in Global nPDF Fits

Nuclear corrections:



[Muzakka et al. (2022, fig. 4)]

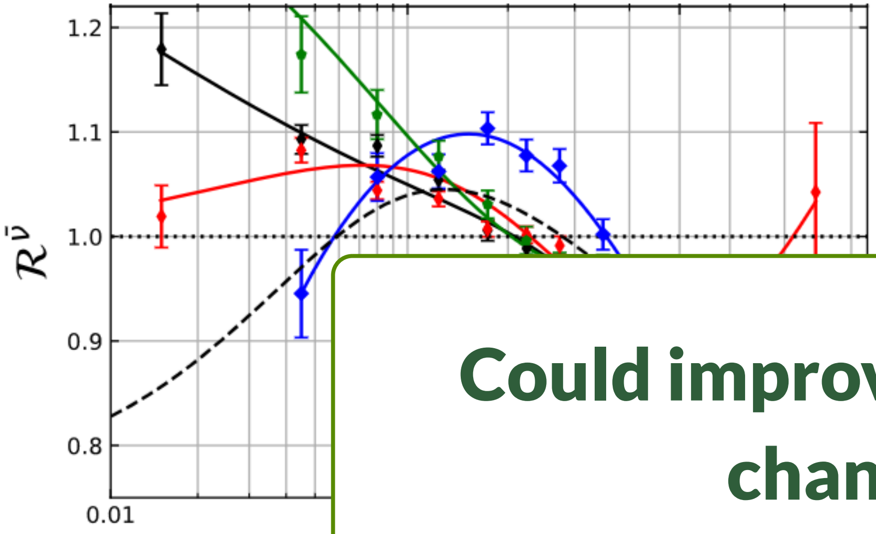
Where is the tension?

- Tension with the charged-lepton/LHC baseline and within parts of the neutrino data
- Different neutrino data sets prefer different nuclear corrections in some regions

What has been tried?

- Alternative treatment of normalization/systematic uncertainties
- Kinematic cuts and inclusion of only mutually compatible data sets

Nuclear corrections:



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Where is the tension?

- Tension with the charged-lepton/LHC baseline and within parts of the neutrino data
- Different neutrino data sets prefer different nuclear corrections in some regions

Could improved heavy-quark theory change this picture?

n/systematic

nutually compatible data sets

Flavor Number Schemes

FFNS Fixed-flavor-number scheme

- active flavors n_f fixed, eg. u, d, s
- charm is massive, **but not an active parton**
- valid in threshold region ($Q \sim m_c$)
  - in asymptotic region: large $\ln\left(\frac{Q^2}{m_c^2}\right)$

ZM-VFNS Zero-mass variable-flavor-number scheme

- active flavors variable: $n_\mathrm{f} \to n_\mathrm{f}(\mu)$
- **charm becomes an active parton**
  - active quarks treated as massless: $m \to 0$
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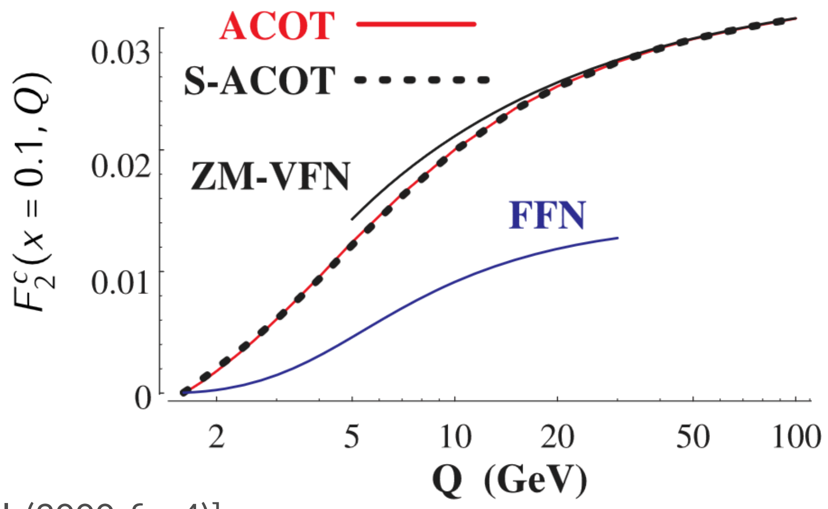
GM-VFNS General-mass variable-flavor-number scheme

- charm becomes **an active parton**, while m_c is retained
- active flavors variable: $n_\mathrm{f} \to n_\mathrm{f}(\mu)$
- valid over whole kinematic range
  - include mass effects
  - resum large logs via DGLAP

Heavy-quark effects in charged-current DIS

- ACOT prescription interpolates between ZM-VFNS prescription for $m_c \ll Q$ and the FFNS prescription near $m_c \sim Q$



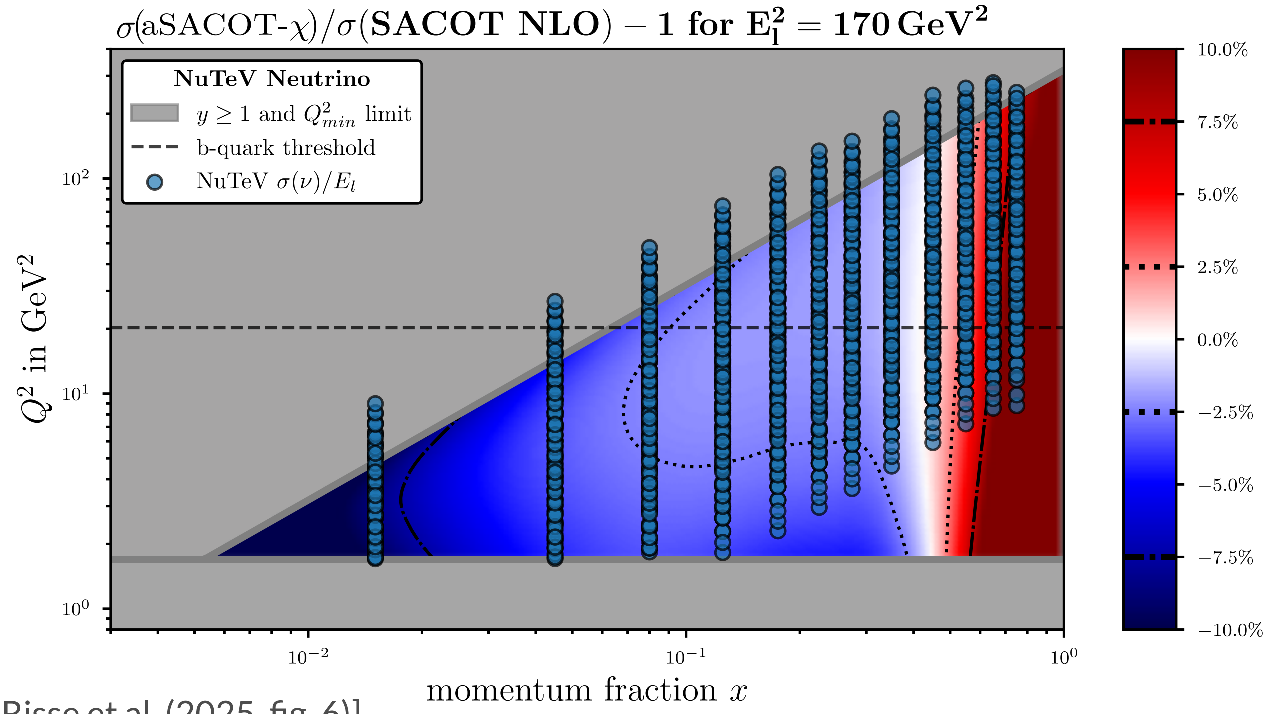
[Krämer et al. (2000, fig. 4)]

- Approximate NNLO contributions to quark mass effects [Stavreva et al. (2012)]

$$ACOT\left[\mathcal{O}\left(\alpha_s^{0+1+2}\right)\right] \simeq ACOT\left[\mathcal{O}\left(\alpha_s^{0+1}\right)\right] + \text{ZM-VFNS}\left[\mathcal{O}\left(\alpha_s^{2}\right)\right]|_\chi, \quad x \to \chi = x \underbrace{\left[1 + \left(\frac{m_c}{Q}\right)^2\right]}_{\text{suppression}}$$

Impact on Neutrino Data

- νDIS probes relatively low Q^2
- **Mass effects can significantly modify the prediction**
- Fast implementation in APFEL++
  → suitable for repeated evaluations in PDF analyses



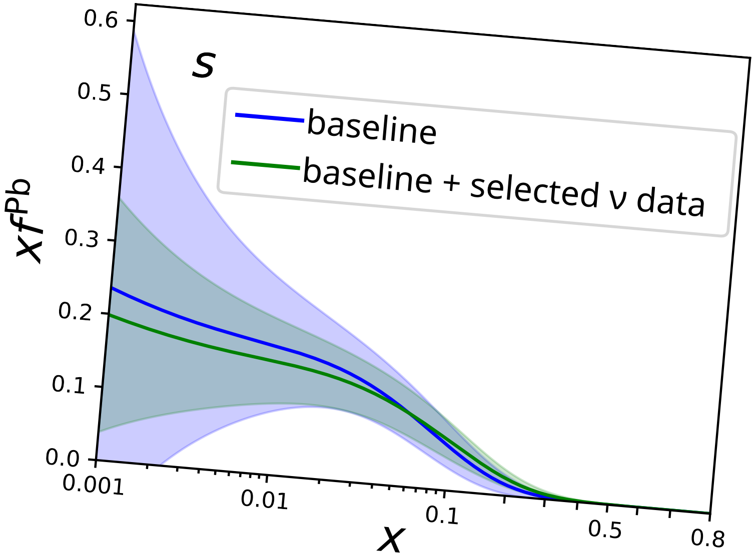
[Risse et al. (2025, fig. 6)]

Enables a systematic re-analysis of νDIS in nPDF fits at approximate NNLO

- approximate NNLO → full massive ACOT at NNLO? [Caola et al. (2026)]

Summary

- νDIS provides **complementary flavor information for nPDFs**
  - consistent inclusion in global fits remains challenging
- PhD project: investigate NNLO heavy quark mass effects in νDIS in a **dedicated nCTEQ fit**
- Towards **NNLO precision in nPDF phenomenology**



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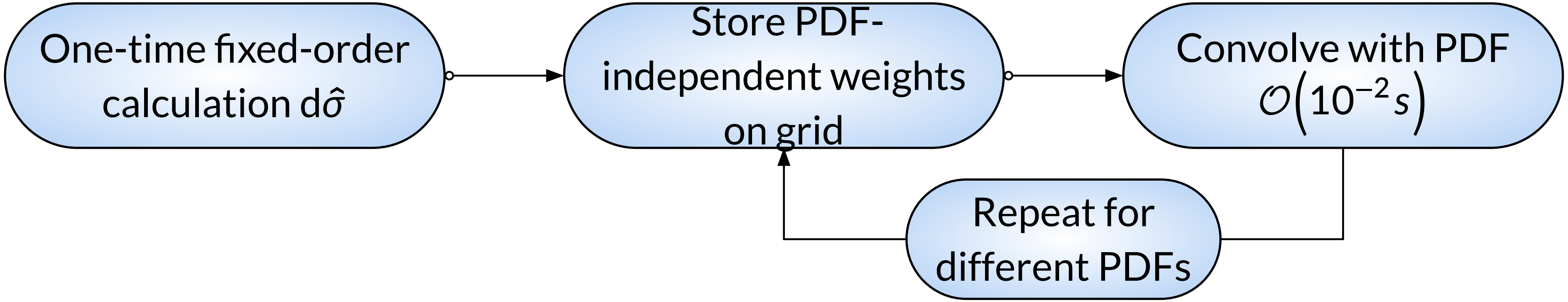
Backup

Interpolation Grids

Parton-level Monte Carlo prediciton for hardon collider observables are computationally expensive.

PDF fits: Re-evaluate the same observable for many choices of PDFs, μ_F, μ_R, and $\alpha_{\mathrm{EW},s}$.

Solution: Interpolation grids



Expand cross section in couplings and logarithms of the scale:

$$\frac{\mathrm{d}\hat{\sigma}_{ab}}{d\mathcal{O}}(x_1, x_2, \mathcal{O}, \mu_R, \mu_F) = \sum_{k,l,m,n} \alpha_s^k\left(\mu_R^2\right)\alpha^l \log^m\left(\frac{\mu_R^2}{Q^2}\right)\log^n\left(\frac{\mu_F^2}{Q^2}\right)W_{ab}^{k,l,m,n}\left(x_1, x_2, Q^2, \mathcal{O}\right)$$

PineAPPL Grids

Naive Approach:

- Store phase space weight at the event level in terms of 4-tuples $\left\{x_1^i, x_2^i, Q_i^2, w_{ab,i}\right\}$ at phase point i

$\rightarrow$ Event files $\mathcal{O}(1)$ TB

PineAPPL Approach [Carrazza et al. (2020)][1]

- Approximate the weights by using Lagrange-Interpolation:
  $f(x) \approx \sum_i f(x_i) L_i(x) \Rightarrow \mathrm{d}\sigma = \sum_i f(x_i) \int \mathrm{d}x L_i(x) d\hat{\sigma}(x)$

- Map $\left(x_1, x_2, Q^2\right) \rightarrow (y_1, y_2, \tau)$ via:
  $y(x) = 5(1-x) - \log x, \quad \tau\left(Q^2\right) = \log\log \frac{Q^2}{(0.25\ \mathrm{GeV})^2}$
- Update grid points :
  $a_{i,j} \leftarrow a_{i,j} + L_i(u(y(x_1)))L_j(u(y(x_2)))w(x_1, x_2)$
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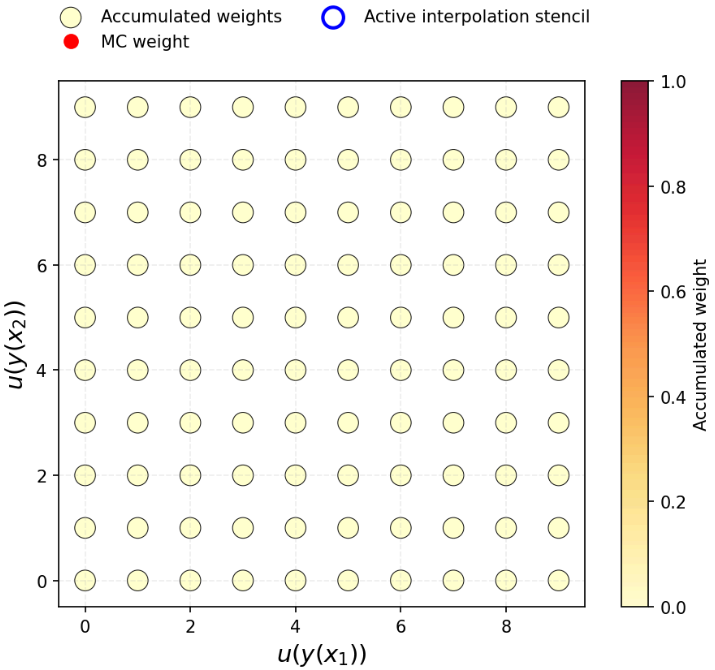

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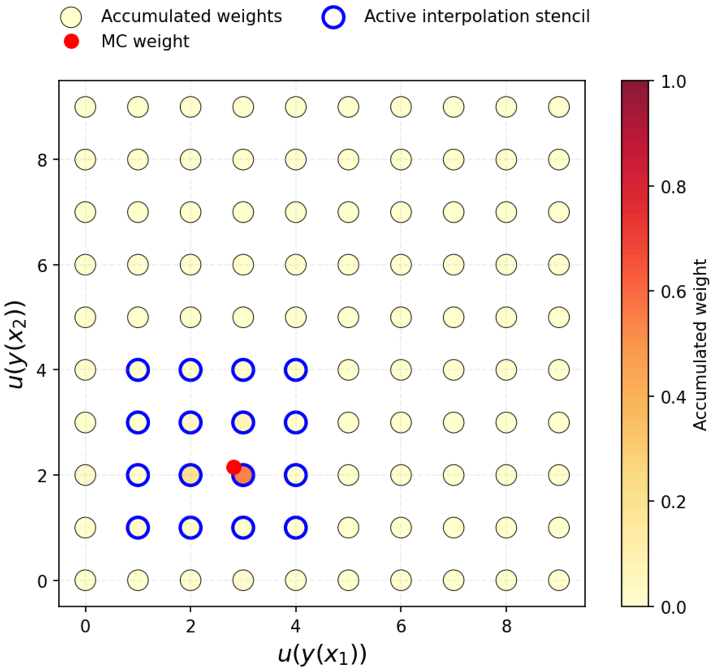

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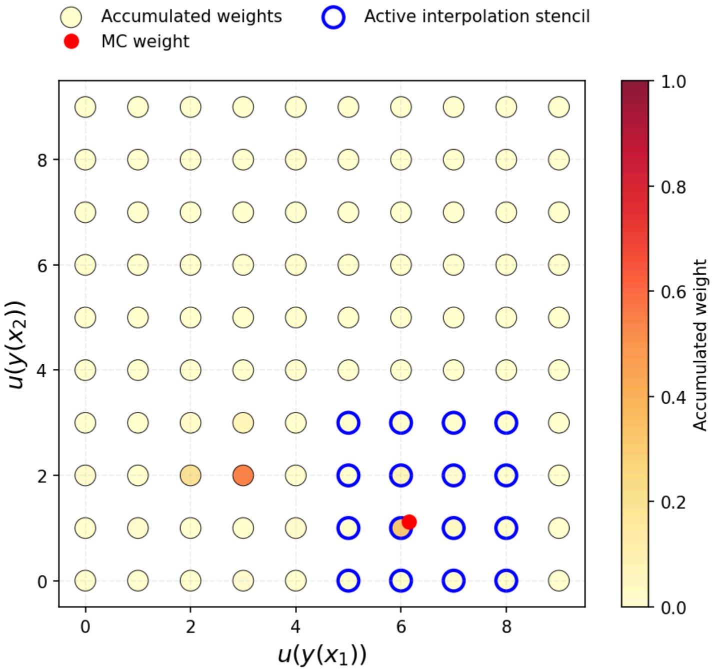

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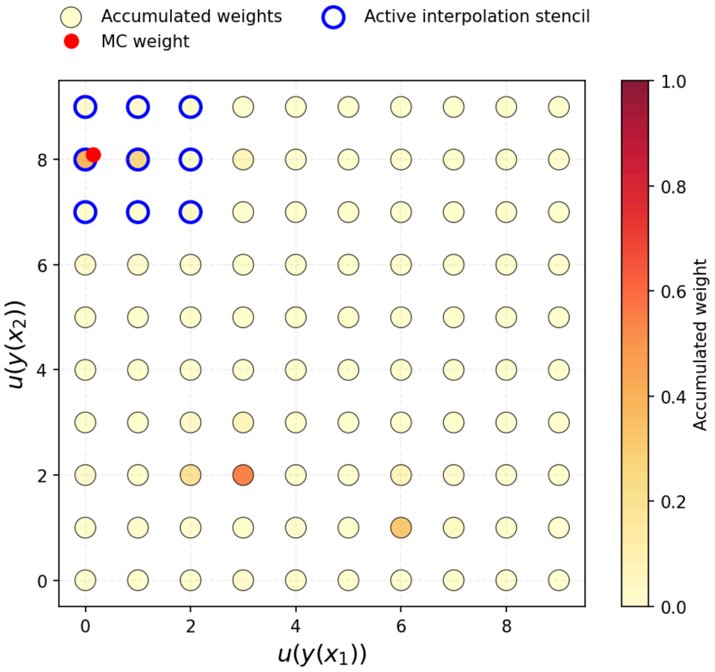

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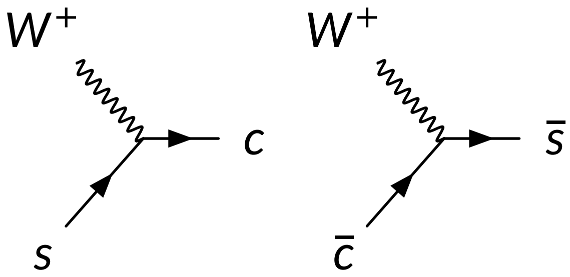
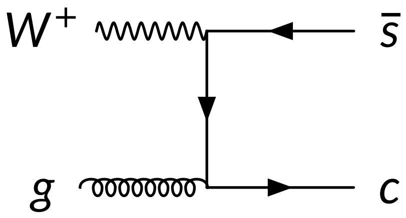
Quark Scattering



Gluon Fusion



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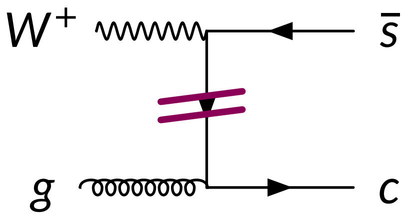

In collinear limit:

$$C^{\mathrm{GF}} \sim C^{\mathrm{QS}} \otimes P_{qg} \ln \frac{Q^2}{m_c^2} + C^{\mathrm{finite}}$$

$$F_i^{\mathrm{ACOT}} = F_i^{\mathrm{QS}} + F_i^{\mathrm{GF}} - F_i^{\mathrm{SUB}} \quad \text{with} \quad F^{\mathrm{SUB}} = F^{\mathrm{QS}} \otimes \left(\alpha_s P_{qg} \ln \frac{\mu^2}{m_c^2} \right)$$