

Next-to-Leading Order QCD Corrections to Inclusive Heavy-Flavor Production in Polarized Deep-Inelastic Scattering

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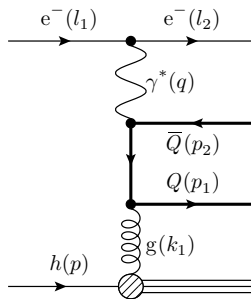
- 1 Introduction
- 2 Computation Review
- 3 Partonic Results
- 4 Hadronic Results
- 5 Outlook

- Heavy Quarks (HQ): $c(m_c = 1.5 \text{ GeV})$, $b(m_b = 4.75 \text{ GeV})$, $t(m_t = 175 \text{ GeV})$
- EIC will reach region with HQ relevant to structure functions
- compare unpolarized case @HERA: at small $x \sim 30\%$ charm contributions
- dominated by PGF \rightarrow measure Δg
- scheme for massive quarks in polarized PDFs?
- first NLO computation of process
- need improved charm tagging
- full inclusive cross section is complicated to reconstruct
- no hadronization here

- scale of hard process in a perturbative regime
 $m > \Lambda_{QCD}$
- finite mass m^2 ensures full inclusive cross sections
- full m^2 dependence makes computations complicated: phase space + matrix elements
- 2-scale problem: encounter $\ln\left(\frac{s-4m^2}{4m^2}\right)$ and/or $\ln(Q^2/m^2)$
- keep analytic expressions

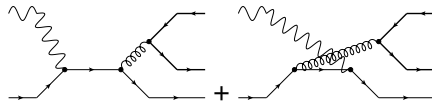


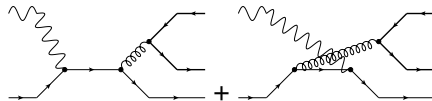
$$e^-(l_1) + h(p) \rightarrow e^-(l_2) + \bar{Q}(p_2) + X[Q]$$



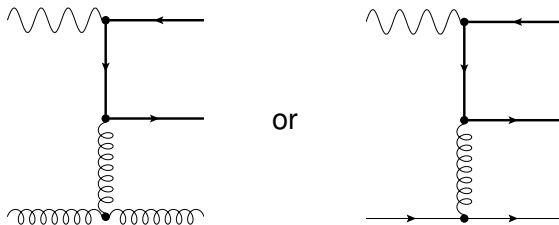
- $S_h = (p + l_1)^2 = x y Q^2$, x, y ,
 $Q^2 = -q^2 = -(l_1 - l_2)^2 \ll M_Z^2$
- unpolarized cross section:
 $\frac{d^2\sigma}{dx dy} = \frac{2\pi\alpha^2}{xyQ^2} \left(Y_+ F_2(x, Q^2) - y^2 F_L(x, Q^2) \right)$
 $2x F_1(x, Q^2) = F_2(x, Q^2) - F_L(x, Q^2)$
- polarized cross section:
 $\frac{d^2\Delta\sigma}{dx dy} = \frac{4\pi\alpha^2}{xyQ^2} Y_- \cdot 2x g_1(x, Q^2)$
- with $Y_{\pm} = 1 \pm (1 - y)^2$
- $[k = T] \rightarrow 2x F_1$, $[k = L] \rightarrow F_L$ and $[k = P] \rightarrow 2x g_1$

- use factorisation theorem: $s \rightarrow \xi S_h + \text{PDF}$
- $g(k_1) + \gamma^*(q) \rightarrow \bar{Q}(p_2) + Q(p_1)$
- three massive particles: $2 \cdot m^2 > 0, q^2 = -Q^2 < 0$
- compute 2-to-3-phase space: e.g. $dPS_3 \sim dt_1 ds_4 d\Omega_n$



- compute diagrams: 
- $\Rightarrow 2xg_1(x) \sim e_u^2 \cdot \xi \Delta u(\xi) \otimes d_{P,q}^{(1)}(\chi, \chi')$
- $d_{P,q}^{(1)}(\chi, \chi') = c_1(\chi, \chi') \ln(\chi) + c_2(\chi, \chi') \text{Li}_2\left(\frac{1+\chi'}{1+\chi}\right) + \dots \checkmark$
- $\frac{m^2}{s} = \frac{\chi}{(1+\chi)^2}$ and $\frac{m^2}{s+Q^2} = \frac{m^2}{s'} = \frac{\chi'}{(1+\chi')^2}$ and $\frac{m^2}{Q^2} = \frac{\chi q}{(1-\chi q)^2}$
- γ_5 and $\varepsilon_{\mu\nu\rho\sigma}$ in n -dimension? \rightarrow HVBM

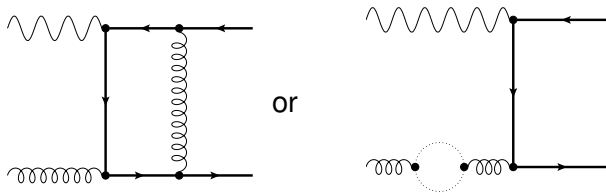
collinear poles appear in, e.g.,



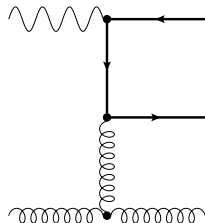
- remove by mass factorization $\rightarrow \overline{\text{MS}}$
- $\Rightarrow 2xg_1(x) \sim e_H^2 \cdot \xi \Delta g(\xi) \otimes \ln(\mu_F^2/m^2) \bar{c}_{P,g}^{F,(1)}(\chi, \chi_q)$
- $\bar{c}_{P,g}^{F,(1)}(\chi, \chi_q) = c_1(\chi, \chi_q) \ln(\chi) + c_2(\chi, \chi_q) \text{Li}_2\left(\frac{1-\chi_q}{1+\chi}\right) + \dots$ (\checkmark for $Q^2 \gg m^2$)

Computation Review - UV and IR Poles

virtual diagrams are, e.g.,



soft poles appear in the limit of a soft gluon $k_2 \rightarrow 0$, e.g.,



soft + virtual + renormalization ($\overline{\text{MS}}_m$) + factorization is finite!

$$\begin{aligned}
 D_0(m^2, 0, q^2, m^2, t, s, 0, m^2, m^2, m^2) &= \frac{iC_\epsilon}{\beta st_1} \times \left[-\frac{2}{\epsilon} \ln(\chi) - 2 \ln(\chi) \ln\left(\frac{-t_1}{m^2}\right) \right. \\
 &+ \text{Li}_2(1 - \chi^2) - 4\zeta(2) + \ln^2(\chi_q) + 2 \text{Li}_2(-\chi\chi_q) + 2 \text{Li}_2\left(\frac{-\chi}{\chi_q}\right) \\
 &+ 2 \ln(\chi\chi_q) \ln(1 + \chi\chi_q) + 2 \ln\left(\frac{\chi}{\chi_q}\right) \ln\left(1 + \frac{\chi}{\chi_q}\right) \left. \right] \\
 \int \frac{d\Omega_n}{t' u_7^2} &\sim -\frac{2\pi(m^2 + s_4)(s' + t_1)}{s_4 t_1^2 u_1^2} \left[-2 + \frac{t_1 u_1 (-q^2 s_4 + (2m^2 + s_4)(s' + u_1))}{(s' + t_1) (q^2 s_4 t_1 + m^2 (s' + u_1)^2)} \right. \\
 &+ \frac{2}{\epsilon} + \ln\left(\frac{t_1^2 u_1^2 (m^2 + s_4)}{(s' + t_1)^2 (m^2 (s' + u_1)^2 + q^2 t_1 s_4)}\right) \left. \right]
 \end{aligned}$$

$$D_0(m^2, 0, q^2, m^2, t, s, 0, m^2, m^2, m^2) = \frac{iC_\epsilon}{\beta s t_1} \times \left[-\frac{2}{\epsilon} \right]$$

$$+ \text{Li}_2(1 - \chi^2) - 4\zeta(2) + \ln^2(\chi q) + 2\text{Li}_2(-\chi\chi_q) + 2\text{Li}$$

$$+ 2\ln(\chi\chi_q)\ln(1 + \chi\chi_q) + 2\ln\left(\frac{\chi}{\chi_q}\right)\ln\left(1 + \frac{\chi}{\chi_q}\right) \Big]$$

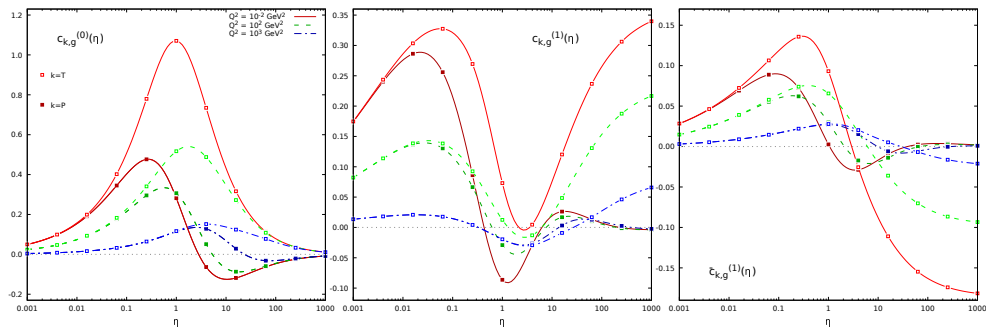
$$\int \frac{d\Omega_n}{t' u_7^2} \sim -\frac{2\pi(m^2 + s_4)(s' + t_1)}{s_4 t_1^2 u_1^2} \left[-2 + \frac{t_1 u_1(-q^2 s_4)}{(s' + t_1)(c} \right.$$

$$\left. + \frac{2}{\epsilon} + \ln\left(\frac{t_1^2 u_1^2(m^2 + s_4)}{(s' + t_1)^2(m^2(s' + u_1)^2 + q^2 t_1 s_4)}\right) \right]$$



OOO, I'VE THOUGHT OF A NEW ONE!
TWO SQUIGGLES AND A BACKWARDS Θ!

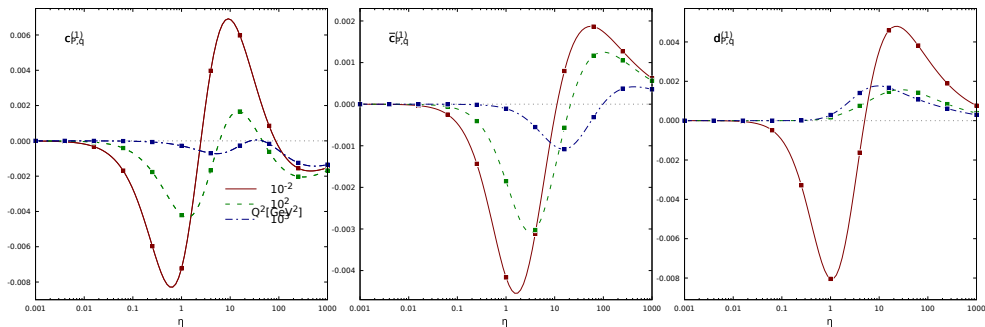
$$2xg_1 \sim \alpha_s \cdot \xi \Delta g(\xi) \otimes \left(c_{P,g}^{(0)} + 4\pi\alpha_s \left[c_{P,g}^{(1)} + \ln \left(\frac{\mu^2}{m^2} \right) \bar{c}_{P,g}^{(1)} \right] \right)$$



$$\eta = \frac{s - 4m^2}{4m^2}, \quad m = m_b = 4.75 \text{ GeV}$$

Partonic Results - Light Quark Channel

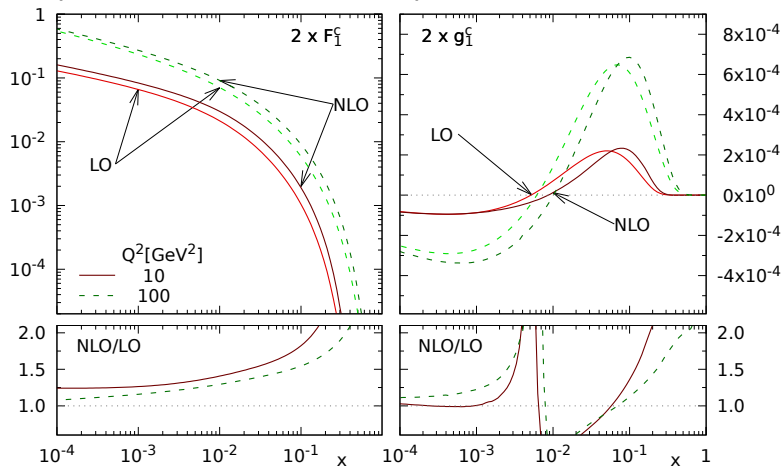
$$2xg_1 \sim \alpha_s^2 \sum_{q \in \{u,d,s\}} \xi (\Delta q(\xi) + \Delta \bar{q}(\xi)) \otimes \left(e_H^2 \left[c_{P,q}^{(1)} + \ln \left(\frac{\mu^2}{m^2} \right) \bar{c}_{P,q}^{(1)} \right] + e_q^2 d_{P,q}^{(1)} \right)$$



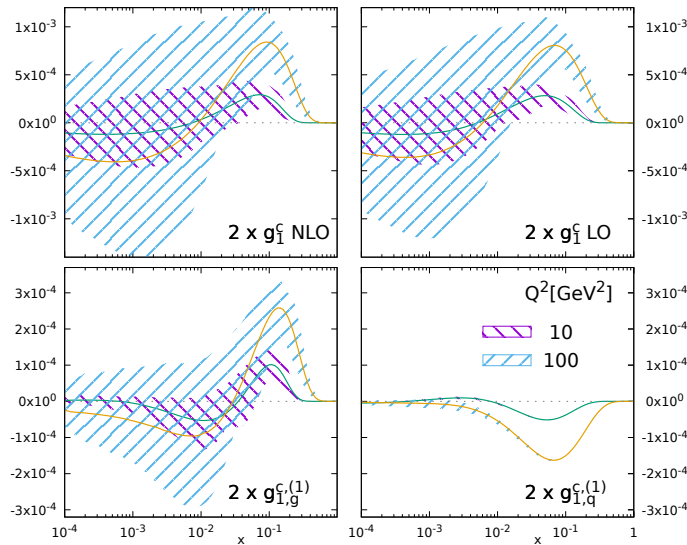
$$\eta = \frac{s - 4m^2}{4m^2}, \quad m = m_b = 4.75 \text{ GeV}$$

Hadronic Results - Unpolarized vs. Polarized

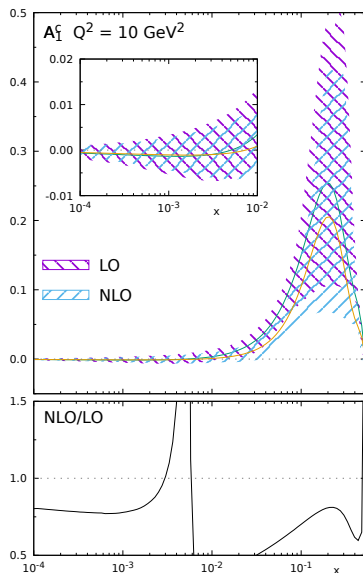
unpolarized \sim MSTW2008 \leftrightarrow polarized \sim DSSV2014



Hadronic Results - PDF Uncertainties DSSV (I)

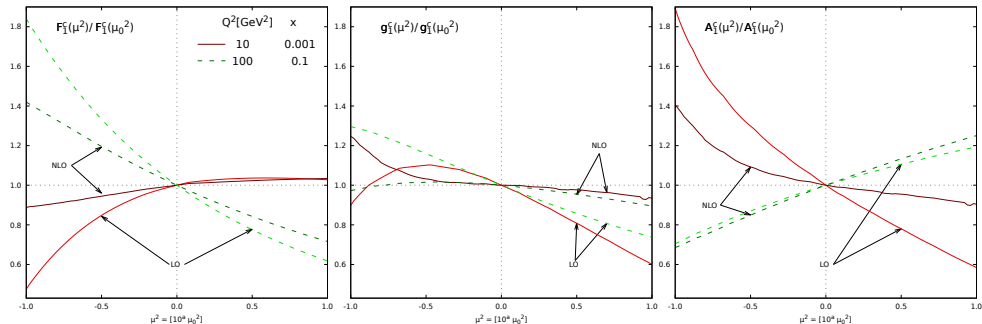


Hadronic Results - PDF Uncertainties DSSV (II)



- $A_1^c(x, Q^2) = \frac{g_1^c(x, Q^2)}{F_1^c(x, Q^2)}$
- error band are only due to DSSV uncertainties (no correlations!)
- sign unclear
- need measurement of $\mathcal{O}(10^{-3})$
- $NLO \lesssim LO$

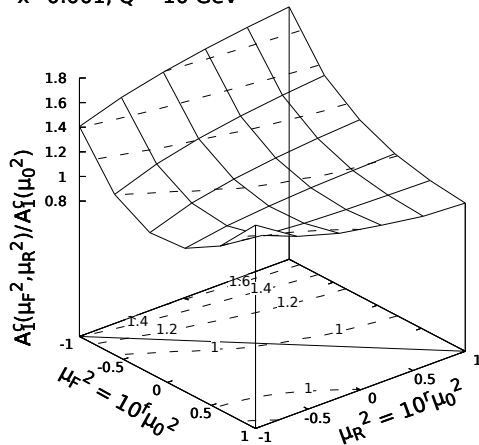
Hadronic Results - Scale Uncertainties (I)



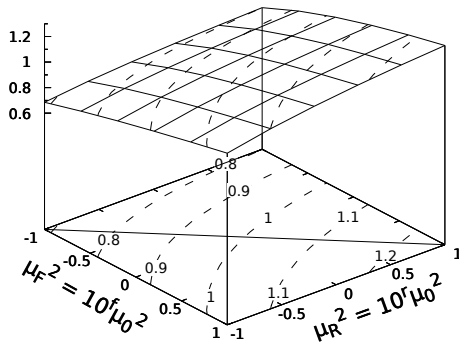
$$\mu^2 = 10^a \mu_0^2 \text{ with } \mu_0^2 = 4m^2 + Q^2 \quad (1)$$

Hadronic Results - Scale Uncertainties (II)

$x=0.001, Q^2=10 \text{ GeV}^2$



$x=0.1, Q^2=100 \text{ GeV}^2$



- inclusive distributions: $\frac{dg_1}{dp_{T,\bar{Q}}}, \frac{dg_1}{dy_{\bar{Q}}}$
- correlated distributions: $\frac{dg_1}{dM_{Q\bar{Q}}^2}, \frac{dg_1}{d\phi_{Q\bar{Q}}}$
- full neutral current (NC) contributions: $F_3^{Z\gamma}, g_4^{Z\gamma}, g_5^{Z\gamma}$ and F_2^Z, F_L^Z, g_1^Z
- distributions of full NC structure functions: $\frac{dg_1^{NC}}{dp_{T,\bar{Q}}}, \frac{dg_1^{NC}}{dM_{Q\bar{Q}}^2}$

Thank you for your attention!