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

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Outline

Introduction - Heavy Quarks (HQ)

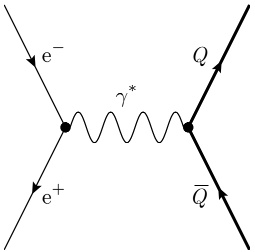
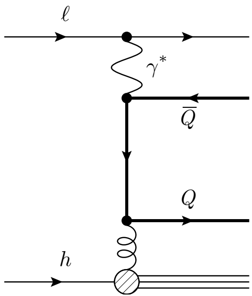
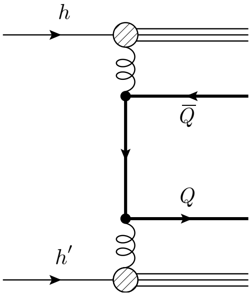
- Heavy Quarks (HQ): $c(m_c = 1.5\,\mathrm{GeV})$, $b(m_b = 4.75\,\mathrm{GeV})$, $t(m_t = 175\,\mathrm{GeV})$
- EIC will reach region with HQ relevant to structure functions
- compare unpolarized case @HERA: at small $x \sim 30\%$ charm contributions
- dominated by PGF $\rightarrow$ measure Δg
- scheme 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

Introduction - Heavy Quarks (HQ)

- scale of hard process in a pertubative 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

Introduction - Experimental Setups

e^--e^+-annihilation (SIA)	deep inelastic scattering (DIS)	Drell-Yan process (DY)
$e^- + e^+ \to \overline{Q} + X[Q]$	$\ell + h \to \ell' + \overline{Q} + X[Q]$	$h + h' \to \overline{Q} + X[Q]$
		
LEP, ILC	HERA, COMPASS, EIC	Tevatron, LHC
gluon	factorization	top, Higgs

Introduction - Structure Functions

cross section (xs):
$$\frac{d^2\sigma}{dxdy} = \frac{2\pi y\alpha^2}{Q^4} L^{\mu\nu} W_{\mu\nu} \tag{1}$$

hadronic tensor:
$$W_{\mu\nu} = \left(-g_{\mu\nu} + \frac{q_\mu q_\nu}{q^2}\right) F_1(x,Q^2) + \frac{P_\mu P_\nu}{P\cdot q} F_2(x,Q^2) + i\epsilon_{\mu\nu\alpha\beta}\frac{q^\alpha S^\beta}{P\cdot q} g_1(x,Q^2) \tag{2}$$

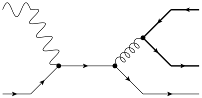
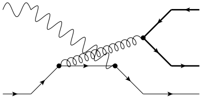
$$F_L(x,Q^2) = F_2(x,Q^2) - 2xF_1(x,Q^2) \tag{3}$$

unpolarized xs:
$$\frac{d^2\sigma}{dxdy} = \frac{2\pi\alpha^2}{xyQ^2}\left(Y_+ F_2(x,Q^2) - y^2 F_L(x,Q^2)\right) \tag{4}$$

polarized xs:
$$\frac{d^2\Delta\sigma}{dxdy} = \frac{4\pi\alpha^2}{xyQ^2} Y_- \cdot 2xg_1(x,Q^2) \tag{5}$$

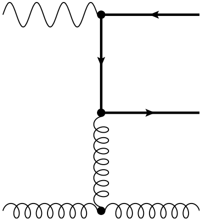
$$Y_\pm = 1 \pm (1-y)^2 \tag{6}$$

Computation Review

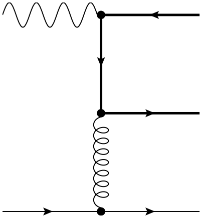
- use factorisation theorem: $s \to \xi S_h$ + PDF
- $\mathrm{g}(k_1) + \gamma^*(q) \to \bar{Q}(p_2) + Q(p_1)$
- three massive particles: $2 \cdot m^2 > 0, q^2 = -Q^2 < 0$
- compute 2-to-3-phase space: e.g. $dPS_3 \sim dt_1 ds_4 d\Omega_n$
- compute diagrams:  + 
- $\Rightarrow 2xg_1(x) \sim e_u^2 \cdot \xi\Delta u(\xi) \otimes d_{P,q}^{(1)}(\chi,\chi')$
- $d_{P,q}^{(1)}(\chi,\chi') = c_1(\chi,\chi')\ln(\chi) + c_2(\chi,\chi')\,\mathrm{Li}_2\left(\frac{1+\chi'}{1+\chi}\right) + \ldots$ ✓
- $\frac{m^2}{s} = \frac{\chi}{(1+\chi)^2}$ and $\frac{m^2}{s+Q^2} = \frac{m^2}{s'} = \frac{\chi'}{(1+\chi')^2}$ and $\frac{m^2}{Q^2} = \frac{\chi_q}{(1-\chi_q)^2}$

Computation Review - Collinear Poles

collinear poles appear in, e.g.,



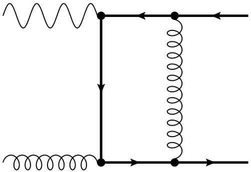
or



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

Computation Review - UV and IR Poles

virtual diagrams are, e.g.,



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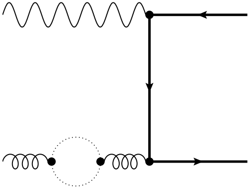
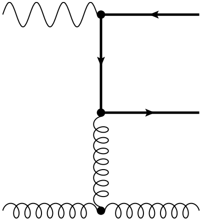


soft poles appear in the limit of a soft gluon $k_2 \to 0$, e.g.,



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

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

$$+ \mathrm{Li}_2(1-\chi^2) - 4\zeta(2) + \ln^2(\chi_q) + 2\,\mathrm{Li}_2(-\chi\chi_q) + 2\,\mathrm{Li}_2\left(\frac{-\chi}{\chi_q}\right)$$

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

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

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

Computation Review - Analytic Expressions

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

$$+ \mathrm{Li}_2(1-\chi^2) - 4\zeta(2) + \ln^2(\chi_q) + 2\,\mathrm{Li}_2(-\chi\chi_q) + 2\,\mathrm{Li} \ldots$$

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

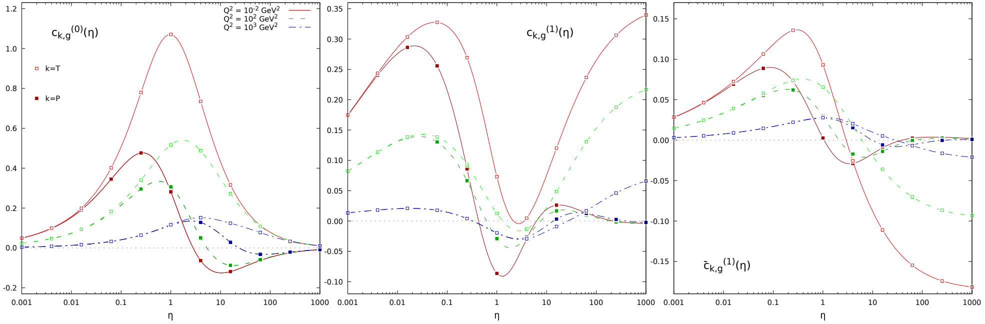
$$\int \frac{d\Omega_n}{t' {u_7}^2} \sim -\frac{2\pi(m^2+s_4)(s'+t_1)}{s_4 {t_1}^2 {u_1}^2}\Bigg[-2 + \frac{t_1 u_1(-q^2 s_4 \ldots}{(s'+t_1)\,(q \ldots}$$

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

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

Partonic Results - Gluon Channel

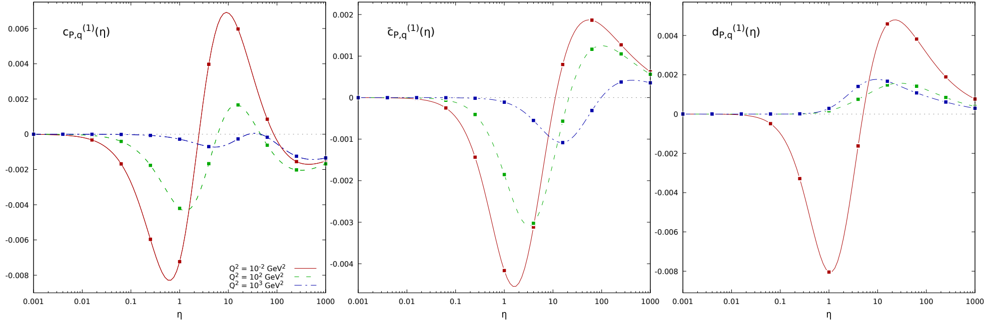
$$2xg_1(x) \sim \xi\Delta g(\xi) \otimes \left(c^{(0)}_{P,g} + 4\pi\alpha_s \left[c^{(1)}_{P,g} + \ln\left(\frac{\mu^2}{m^2}\right) \bar{c}^{(1)}_{P,g} \right] \right) \qquad (7)$$



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

Partonic Results - Light Quark Channel

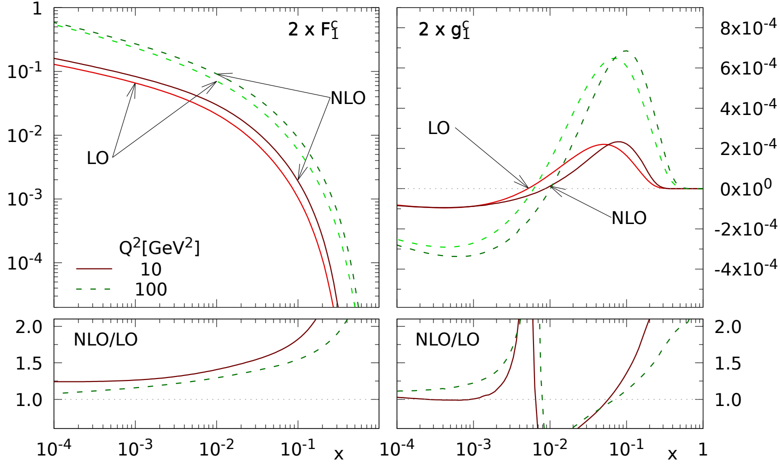
$$2xg_1(x) \sim \sum_{q\in\{u,d,s\}} \xi\left(\Delta q(\xi) + \Delta\bar{q}(\xi)\right) \otimes \left(e_H^2\left[c_{P,q}^{(1)} + \ln\left(\frac{\mu^2}{m^2}\right)\bar{c}_{P,q}^{(1)}\right] + e_q^2 d_{P,q}^{(1)}\right) \tag{8}$$



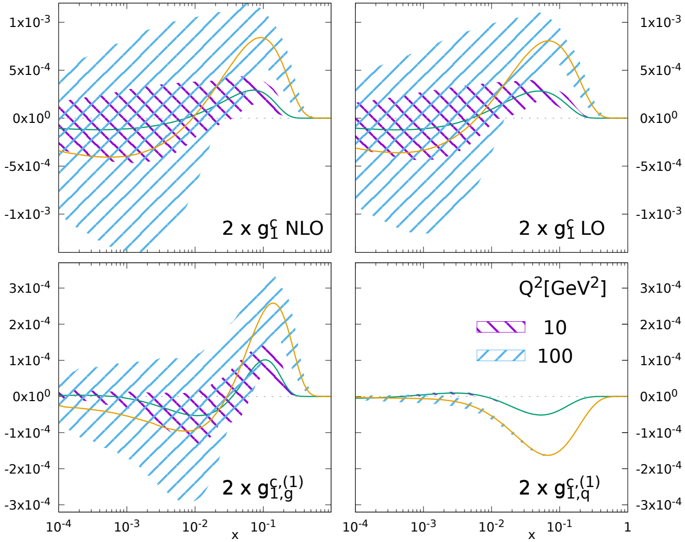
$$\eta = \frac{s-4m^2}{4m^2}, \quad m = m_b = 4.75\,\mathrm{GeV}$$

Hadronic Results - Unpolarized vs. Polarized

unpolarized $\sim$ MSTW2008 $\leftrightarrow$ polarized $\sim$ DSSV2014

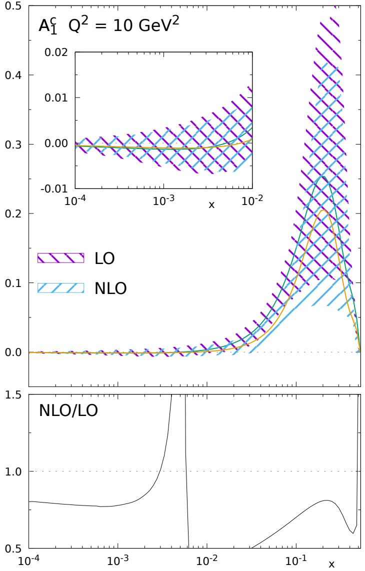


Hadronic Results - PDF Uncertainties DSSV (I)



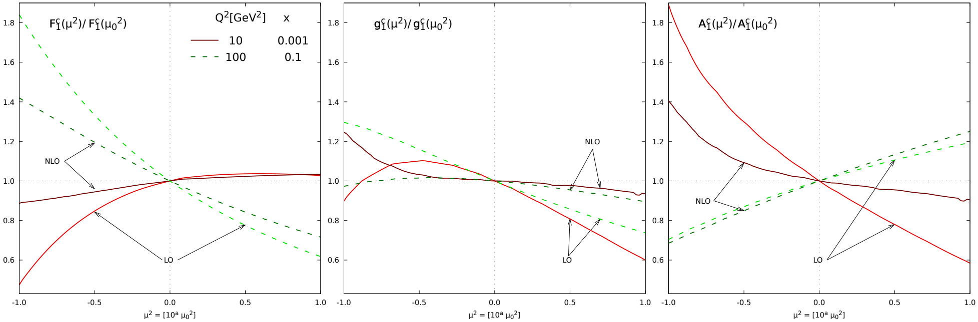
- gluon dominates
- quarks only make small contributions
- sign unclear
- quark band small
- default gluon is small

Hadronic Results - PDF Uncertainties DSSV (II)



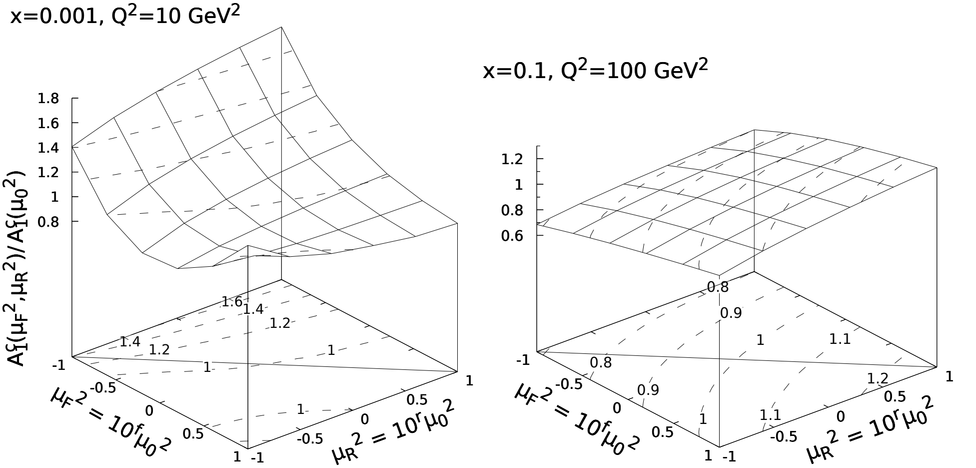
- $A_1^c(x,Q^2) = \frac{g_1^c(x,Q^2)}{F_1^c(x,Q^2)}$
- error band are only due to DSSV uncertainties (no correlations!)
- sign unclear
- need measurement of $\mathcal{O}(10^{-3})$
- NLO $\lesssim$ LO

Hadronic Results - Scale Uncertainties (I)



$$\mu^2 = 10^a \mu_0^2 \text{ with } \mu_0^2 = 4m^2 + Q^2 \tag{9}$$

Hadronic Results - Scale Uncertainties (II)



Outlook

- inclusive distributions: $\frac{dg_1}{dp_{T,\bar{Q}}}$, $\frac{dg_1}{dy_{\bar{Q}}}$
- correlated distributions: $\frac{dg_1}{dM^2_{Q\bar{Q}}}$, $\frac{dg_1}{d\phi_{Q\bar{Q}}}$
- 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: $\frac{dg_1^{NC}}{dp_{T,\bar{Q}}}$, $\frac{dg_1^{NC}}{dM^2_{Q\bar{Q}}}$