Hadro- and Photoproduction of Heavy Quarks in Longitudinally Polarised Collisions at NLO

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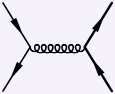
Outlines

Leading order diagrams

In LO: Heavy quark hadroproduction proceeds through two subprocesses:

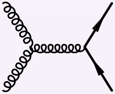
- quark–antiquark annihilation,

$$q\bar{q} \rightarrow Q\bar{Q}$$

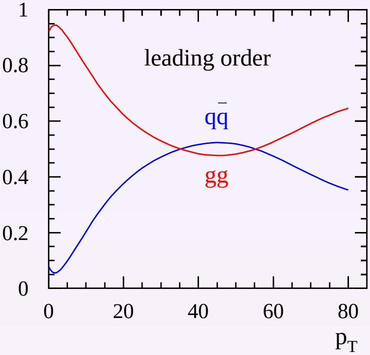


- gluon–gluon fusion,

$$gg \rightarrow Q\bar{Q}$$



Relative amounts of these subprocesses for RHIC, $\sqrt{S} = 200$ GeV (CTEQ6):



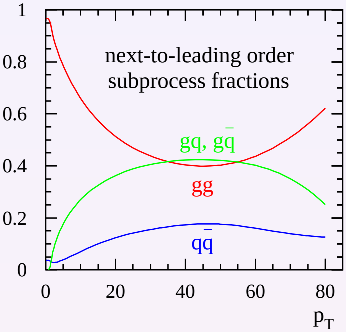
Heavy quark production at NLO

NLO corrections

- Lots of real and virtual corrections to the LO subprocesses
- Genuine new subprocess of gluon–(anti-)quark fusion: $g + q(\bar{q}) \rightarrow Q + \bar{Q} + q(\bar{q})$

The need for NLO corrections:

- Large corrections in unpolarised case known (Nason et al., Beenakker et al.)
- Reduced dependence on unphysical (renormalisation and factorisation) scales



Determination of Δg

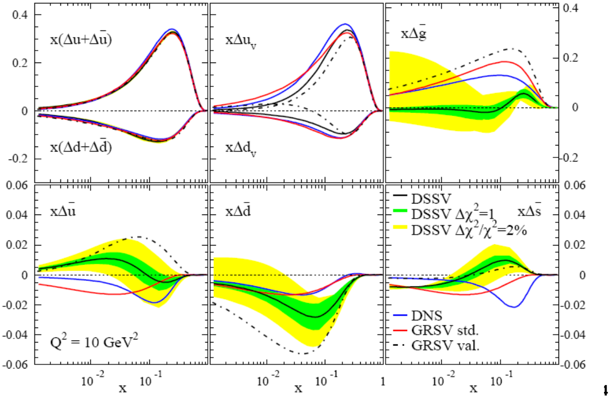
Heavy quark production in longitudinally polarised collisions:

- Sensitivity to Δg through gluon–gluon fusion
- Provides determination of Δg, completely independent of single-inclusive pion/jet production studied so far
- In pQCD: less partonic subprocesses than for pion/jet production
- However, experimentally very challenging
- Δg suggested to be small (e.g., DSSV)
  $\Longrightarrow$ expect very small spin asymmetries

summary of DSSV distributions:

- robust pattern of flavor-**asymmetric** light quark-sea (even within uncertainties)
- $\Delta u + \Delta\bar{u}$ and $\Delta d + \Delta\bar{d}$ very similar to GRSV/DNS results
- small Δg, perhaps with a node
- Δs positive at large x
- $\Delta\bar{u} > 0$, $\Delta\bar{d} < 0$ predicted in some models

  Diakonov et al.; Goeke et al.; Gluck, Reya; Bourrely, Soffer, ...



Structure of the calculation

- Complication: one has to match calculation on the parton level with the detection of heavy quarks in experiment
- Heavy quarks are usually detected through their decay products

General structure of a pQCD calculation for HQ cross sections

$$pp \xrightarrow{(1)} Q \xrightarrow{(2)} Mesons \xrightarrow{(3)} decay\,(e^{\pm}, \mu^{\pm})$$

- (1): calculable in pQCD (making use of the factorisation theorem);
  NLO state of the art:
  - unpolarised: Nason et al.; van Neerven et al.
  - polarised: Bojak, Stratmann; Riedl, Stratmann, Schäfer

  FONLL: + resummation of quasi-collinear logs at NLL (unpol.): Cacciari et al.
- (2): non-perturbative fragmentation (from data): Cacciari et al.
- (3): leptonic decay spectrum from e^+e^- data (CLEO, BaBar, . . .)

Monte-Carlo phase space integration

Simple Example:

$$I = \lim_{\epsilon \to 0+} \left\{ \int_0^1 \frac{dx}{x} x^{\epsilon} F(x) - \frac{1}{\epsilon} F(0) \right\}$$

Subtraction method:

$$I = \lim_{\epsilon \to 0+} \left\{ \int_0^1 \frac{dx}{x} x^{\epsilon} [F(x) - F(0) + F(0)] - \frac{1}{\epsilon} F(0) \right\} = \int_0^1 \frac{dx}{x} [F(x) - F(0)]$$

Phase space slicing method:

$$I = \lim_{\epsilon \to 0+} \left\{ \int_0^{\delta} \frac{dx}{x} x^{\epsilon} F(x) + \int_{\delta}^1 \frac{dx}{x} x^{\epsilon} F(x) - \frac{1}{\epsilon} F(0) \right\} = \int_{\delta}^1 \frac{dx}{x} F(x) + F(0) \ln \delta + \mathcal{O}(\delta)$$

▸ Details

Phase space for Monte-Carlo integration

Start with $a(k_1) + b(k_2) \rightarrow C(p_1) + D(p_2) + e(k_3)$. $x = \frac{s_2}{s}$ where $s_2 = (p_1 + p_2)^2$
y: cosine of the angle between $\mathbf{p_1}$ and $\mathbf{k_1}$ in the c.m.s. of the incoming partons
In the c.m.s. of the $Q\bar{Q}$ system (z axis e.g. choosen $\parallel$ $\mathbf{k_1}$):

$$p_1 = \frac{1}{2}\sqrt{s_2}(1, \beta_x \sin\theta_2 \sin\theta_1, \beta_x cos\theta_2 \sin\theta_1, \beta_x \cos\theta_1)$$

Write in $d = 4 - 2\epsilon$:

$$d\Phi_3 = HNd\Phi_2^{(x)} \frac{s^{1-\epsilon}}{2\pi}(1-x)^{1-2\epsilon}(1-y^2)^{-\epsilon} dy \sin^{-2\epsilon}\theta_2 d\theta_2$$

$$d\Phi_2^{(x)} = \frac{2^{2\epsilon}}{\Gamma(1-\epsilon)}\left(\frac{4\pi}{sx}\right)^{\epsilon}\frac{1}{16\pi}\beta_x^{1-2\epsilon}\sin^{-2\epsilon}\theta_1 d\cos\theta_1 dx$$

$$H = \frac{\Gamma(1-\epsilon)}{\Gamma(1+\epsilon)\Gamma(1-2\epsilon)} = 1 - \frac{\pi^2}{3}\epsilon^2 + \mathcal{O}(\epsilon^2)$$

$$N = (4\pi)^{\epsilon-2}\Gamma(1+\epsilon)$$

Subtraction method for heavy quarks in detail

Extract poles from matrix element:

$$f(x,y,\theta_1,\theta_2) := s^2(1-x)^2(1-y^2)M_{2\to3}(s,x,y,\theta_1,\theta_2)$$

is finite

$$d\sigma^{(r)} = HNd\Phi_2^{(x)}\frac{s^{-1-\epsilon}}{2\pi}dy\sin^{-2\epsilon}\theta_2 d\theta_2(1-x)^{(-1-2\epsilon)}(1-y^2)^{-1-\epsilon}f(x,y,\theta_1,\theta_2).$$

Expansions

Use for the $(1-x)^{-1-2\epsilon}$ term

$$(1-x)^{-1-2\epsilon} = -\frac{\tilde{\beta}^{-4\epsilon}}{2\epsilon}\delta(1-x) + \left(\frac{1}{1-x}\right)_{\tilde{\rho}} - 2\epsilon\left(\frac{\log(1-x)}{1-x}\right)_{\tilde{\rho}} + \mathcal{O}(\epsilon^2)$$

where

$$\int_{\tilde{\rho}}^{1} h(x)\left(\frac{1}{1-x}\right)_{\tilde{\rho}} dx = \int_{\tilde{\rho}}^{1} \frac{h(x)-h(1)}{1-x} dx$$

and

$$\int_{\tilde{\rho}}^{1} h(x)\left(\frac{\log(1-x)}{1-x}\right)_{\tilde{\rho}} dx = \int_{\tilde{\rho}}^{1} [h(x)-h(1)]\frac{\log(1-x)}{1-x} dx$$

with

$$\tilde{\beta} = \sqrt{1-\tilde{\rho}}$$

▸ Generic formula

Altogether . . .

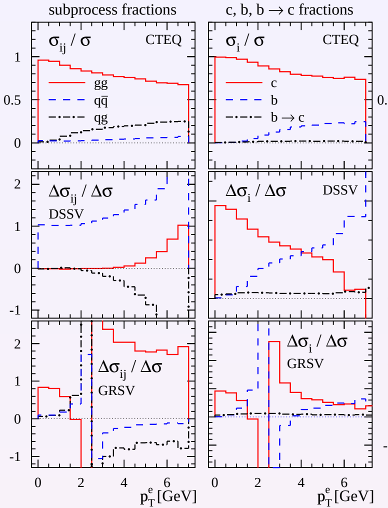
One finally arrives at:

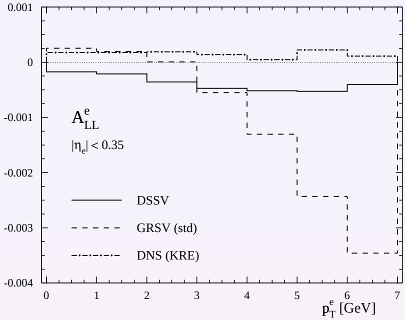
$$d\hat{\sigma} = d\sigma^{(b)} + d\hat{\sigma}^{(c+)} + d\hat{\sigma}^{(c-)} + d\hat{\sigma}^{(s)} + d\sigma^{(v)} + d\sigma^{(f)}$$

where:

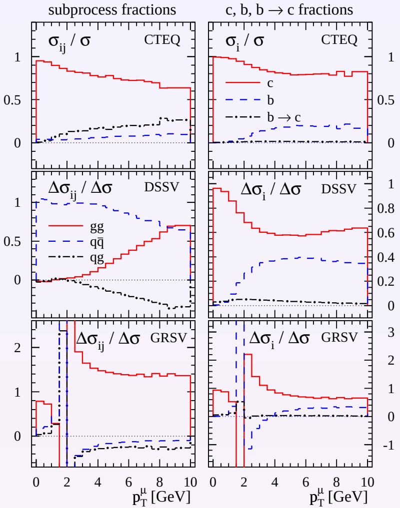
- $d\sigma^{(b)}$: Born cross section
- $d\hat{\sigma}^{(c\pm)}$: collinear parts (including mass factorisation)
- $d\hat{\sigma}^{(s)}$: soft part (including mass factorisation)
- $d\sigma^{(v)}$: virtual contributions
- $d\sigma^{(f)}$: finite/regular real NLO corrections

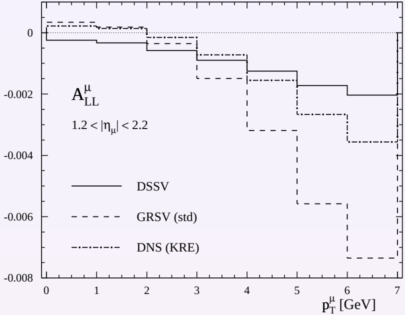
Single electrons at RHIC (PHENIX)



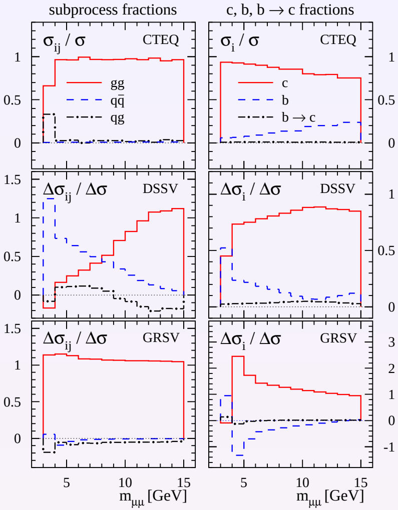


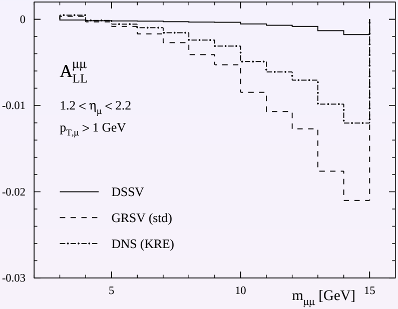
Single muons at RHIC (PHENIX)



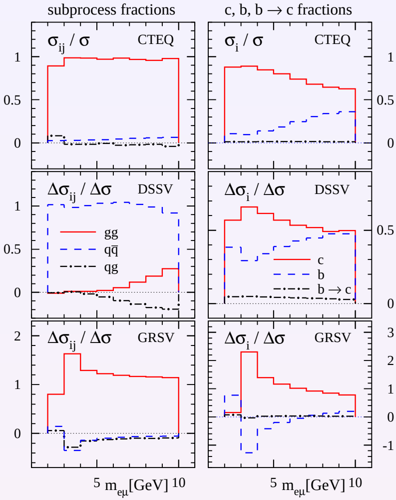


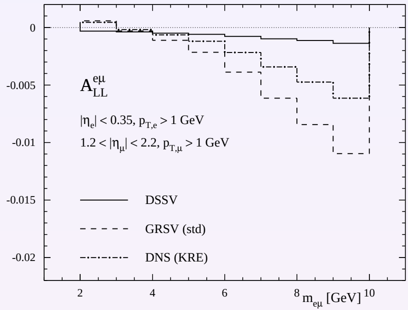
Muon-muon correlations at RHIC (PHENIX)



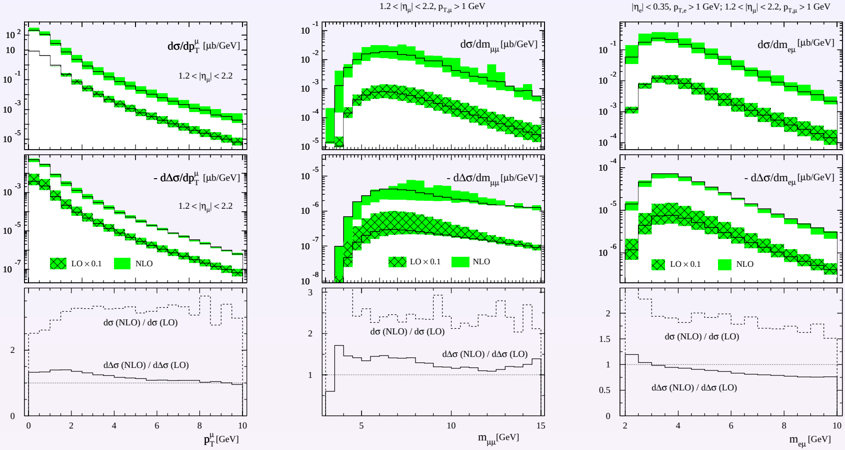


Electron-muon correlations at RHIC (PHENIX)





The theoretical uncertainties at RHIC (PHENIX)

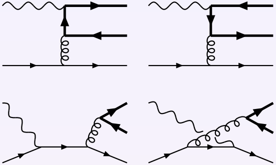


$1.2 < |\eta_\mu| < 2.2$, $p_{T,\mu} > 1$ GeV

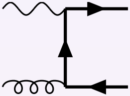
$|\eta_e| < 0.35$, $p_{T,e} > 1$ GeV; $1.2 < |\eta_\mu| < 2.2$, $p_{T,\mu} > 1$ GeV

Contributing processes

- calculation analogous to hadroproduction
- contributions arise from
  - $\gamma q(\bar{q})$ here no LO diagrams



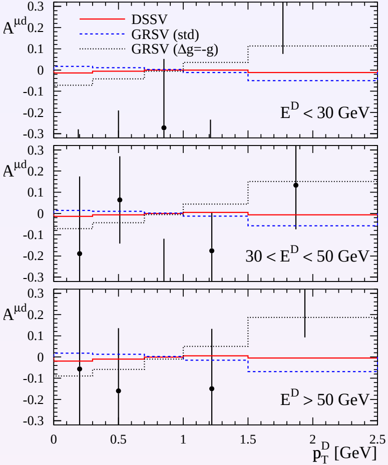
  - γg : leading order diagram:

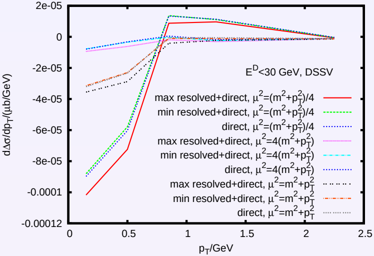


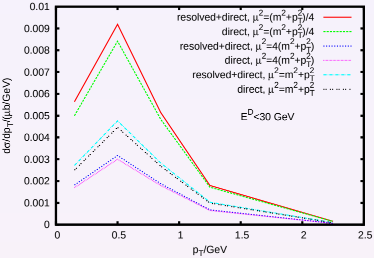
(e.g. Bojak, Stratmann; Contogouris et al.)

- also “resolved” contributions
- is measured at COMPASS

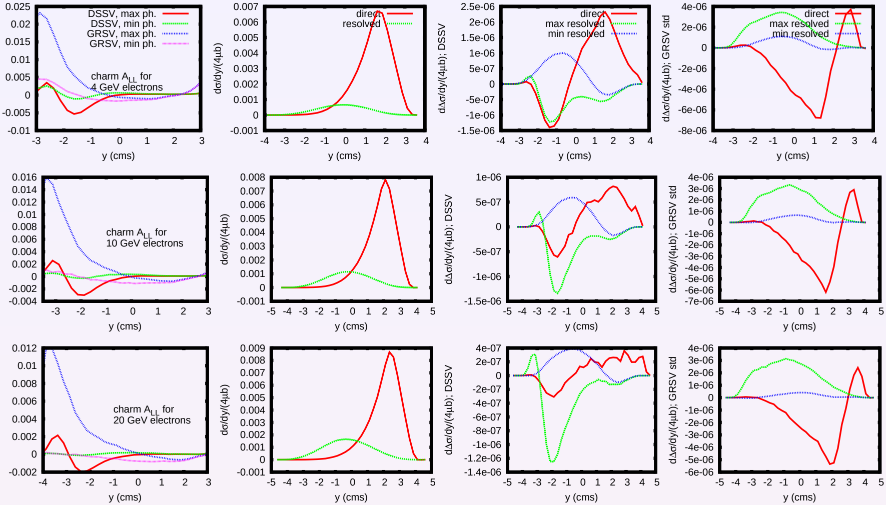
Compass $p_T(D)$


DSSV
GRSV (std)
GRSV (Δg=-g)
A^μd
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
E^D < 30 GeV
30 < E^D < 50 GeV
E^D > 50 GeV
0
0.5
1
1.5
2
2.5
p_T^D [GeV]

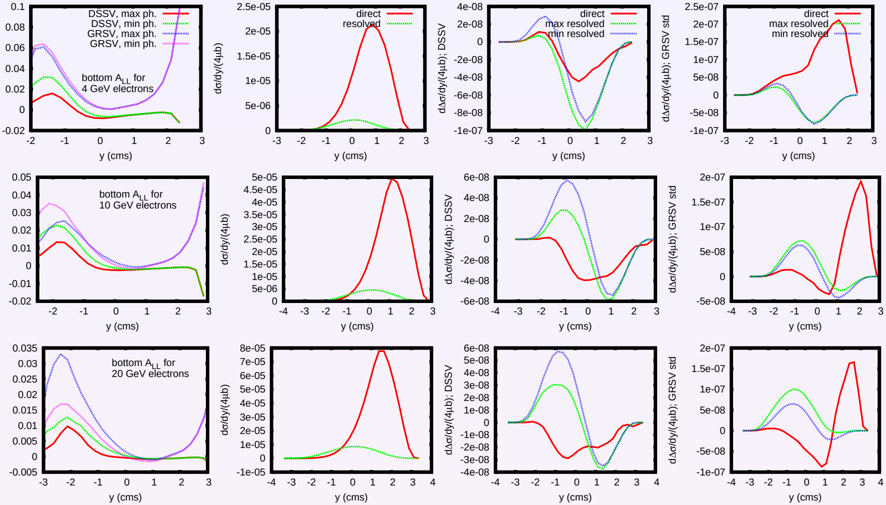

dΔσ/dp_T/(μb/GeV)
2e-05
0
-2e-05
-4e-05
-6e-05
-8e-05
-0.0001
-0.00012
0
0.5
1
1.5
2
2.5
p_T/GeV
E^D<30 GeV, DSSV
max resolved+direct, μ²=(m²+p_T²)/4
min resolved+direct, μ²=(m²+p_T²)/4
direct, μ²=(m²+p_T²)/4
max resolved+direct, μ²=4(m²+p_T²)
min resolved+direct, μ²=4(m²+p_T²)
direct, μ²=4(m²+p_T²)
max resolved+direct, μ²=m²+p_T²
min resolved+direct, μ²=m²+p_T²
direct, μ²=m²+p_T²


dσ/dp_T/(μb/GeV)
0.01
0.009
0.008
0.007
0.006
0.005
0.004
0.003
0.002
0.001
0
0
0.5
1
1.5
2
2.5
p_T/GeV
resolved+direct, μ²=(m²+p_T²)/4
direct, μ²=(m²+p_T²)/4
resolved+direct, μ²=4(m²+p_T²)
direct, μ²=4(m²+p_T²)
resolved+direct, μ²=m²+p_T²
direct, μ²=m²+p_T²
E^D<30 GeV

D mesons at eRHIC (preliminary)



B mesons at eRHIC (preliminary)



Summary and Outlook

New flexible MC code for polarised HQ production

- allows to study single-inclusive HQ production and $Q\bar{Q}$ correlations
- includes decay to lepton level
- available for hadro- and photoproduction (both for direct and resolved part)
- at the moment experimentally relevant at RHIC (HQ hadroproduction) and at COMPASS (HQ photoproduction)
- can be used for more detailed studies concerning HQ photoproduction at EIC
- might be relevant for other projects in the future (e.g, GSI FAIR, J-PARC)

Thank you for your attention