Heavy Flavour Production, QCD, and the Quark-Photon Coupling

Achim Geiser, DESY Hamburg

Achim.Geiser@desy.de

Photon2007

Paris, France, 11 July 2007

- Introduction: Heavy Quark photoproduction
- Choice of renormalization/factorization scales in QCD:
Phenomenological considerations and cross checks with data
Plea for a change of default QCD scale for NLO calculations
- Speculation on photon-quark coupling
- Conclusions

Photoproduction of Open Heavy Flavour

Dominant production process in ep -collisions: Boson-Gluon -Fusion

- Driven by **gluons** in the proton

- Relevant scales:

$$m_b \sim 5 \text{ GeV}, \quad m_c \sim 1.5 \text{ GeV}$$

$$Q^2 \lesssim 1 \text{ GeV}^2 \rightarrow \gamma p$$

$$> 2 \text{ GeV}^2 \rightarrow \text{DIS}$$

$$p_T^{b,c} \quad \text{Event selection: } p_t^{jet} > 6 \text{ or } 7 \text{ GeV}$$

multiscale problem

-> terms $[\alpha_s \ln (Q^2/m_Q^2)]^n$, $[\alpha_s \ln (p_T^2/m_Q^2)]^n$, etc.

in perturbative expansion -> potentially large th. errors

Beauty in photoproduction: summary

details→talk J. Loizides

b quark

HERA

data/QCD:

reasonable agreement,

but tendency
data > QCD

at low p_T

theory uncertainty
underestimated?

scale choice often dominant theoretical error

How well do we understand choice of
QCD scales?

(issue also raised e.g. in talk G. Grindhammer)

remarks on QCD scale dependence

- Ideally (calculation to all orders) QCD predictions should not depend on the choice of renormalization and factorization scales μ_r , μ_f
=> **not physical parameters** => can not be determined from data
- In practice, finite order calculations **do** depend on choice of these scales
= reference points for perturbative expansion (Taylor expansion)
- Choice of scale is to large extent arbitrary.
Best solution is case by case evaluation of sensible scales, and detailed study of behaviour of cross section with respect to variation of these scales.
- In practice often replaced by **simple recipes**. Overinterpretation might lead to premature conclusions that data/QCD predictions do not agree.
- If recipes at all, at least try to use the "best"
=> try to evaluate performance

Common recipes for scale choice

Common sense criterion/try to minimize occurrence of large logs:

- $\Rightarrow$ 1. choose "natural" scale of process involved ($m, Q^2, E_T, \dots$)
but subscales (e.g. subdominant gluon radiation) often lower

nowadays often only criterion used

Two other textbook criteria from the late 80ies: **time for a revival?**

- principle of fastest apparent convergence: choice of scales such that, ideally, cross sections will not change when higher order corrections are included
 $\Rightarrow$ 2. best bet: $NLO = LO$ $\Rightarrow$ hope: $NNLO = NLO$ **check!**
- principle of minimal sensitivity: minimize sensitivity to scale variations
 $\Rightarrow$ 3. best bet: $d\sigma/d\mu = 0$ $\Rightarrow$ hope: minimize NLO corrections
- range of variation of scale is supposed to be a measure of theoretical error for uncalculated higher orders
- evaluate all three criteria to determine a "reasonable" choice

example: total b cross section at HERA-B

Bonciani, Catani, Mangano, Nason
Nucl. Phys. B 529 (1998) 424

NLO stability:

- $NLO = LO$
- $d\sigma_{NLO}/d\mu = 0$

NLO+NLL stability:

- $NLO+NLL = LO$
- $NLO+NLL = NLO$
- $d\sigma_{NLO+NLL}/d\mu = 0$

— "natural" scale

in many cases, such
solutions do not exist
 $\Rightarrow$ consider those cases
where they do

example: Higgs production at LHC

S. Moch, A. Vogt, Phys.Lett. B631 (2005) 48

NNLO stability:

- NNLO = NLO
- $d\sigma_{\text{NNLO}}/d\mu = 0$

N³LO stability:

- N³LO = NLO
- N³LO = NNLO
- $d\sigma_{\text{NLO+NLL}}/d\mu = 0$

— "natural" scale

NNLO/N³LO calculations, where available, support validity of scheme!

"optimal" ren./fact. scale from theory

$$\mu_0/2 < \mu < 2\mu_0$$

$$\mu_0/4 < \mu < \mu_0$$

"standard" scale range
proposed new default

NLO (NNLO) QCD

survey of:

- beauty at Sp $\bar{p}$ S, Tevatron, HERA-B
- top at Tevatron
- Z, H at LHC
- jets in γp and at Tevatron

$$\mu_0^2 = m^2 (+ p_T^2)$$

$$\mu_0^2 = E_T^2$$

cross check with data: c and b at Tevatron

standard scale

CDF II Preliminary 740 pb⁻¹

cross check with data: c and b at Tevatron

new scale

CDF II Preliminary 740 pb⁻¹

beauty at $\text{Sp}\bar{\text{p}}\text{S}$,

$b+c$ at RHIC

standard scale

beauty at $\text{Sp}\bar{\text{p}}\text{S}$,

$\text{b}+\text{c}$ at RHIC

new scale

top at Tevatron,

charm at HERA

standard scale

top at Tevatron,

charm at HERA

new scale

standard scale

DIS

new scale

DIS

approximate
estimate (A.G.),
to be calculated
exactly

Beauty in photoproduction: standard

HERA

standard scale
 $\mu_0^2 = m^2 + p_T^2$

Beauty in PHP: new reference scale

HERA

new scale
 $\mu_0 \rightarrow \mu_0/2$

thanks to
E. Nuncio-
Quiroz

Conclusion/**Plea**: either dedicated study, or

- propose, from now on, to use default QCD scale $\mu_0/2$ for **all** heavy flavour (and other?) NLO cross section predictions at HERA and elsewhere, including LHC
- scale variation by factor 2 seems reasonable

some people are doing this already:

also at HERA

see also talk G. Grindhammer

EPJ C44 (2005) 183: Multijet-Production in DIS

ZEUS

BUT: Heavy Flavours in $\gamma\gamma$ at LEP ?

details on data: talk Finch

mainly

predictions adapted from
Drees et al., PLB 306 (1993) 371

changing scale $\mu_0 \rightarrow \mu_0/2$
helps, but not much
(LO process is pure QED)

How well do we understand the
quark/photon coupling?

investigate *very* tentative idea:

Interference of QED with nonperturbative QCD??

Amplitudes (HERA):

$$\begin{aligned} & -1/3\sqrt{\alpha} \quad (Q=b) \\ & +2/3\sqrt{\alpha} \quad (Q=c) \end{aligned}$$

$$\begin{aligned} & \begin{matrix} u & d \\ (+2/3-1/3)\sqrt{\alpha} \\ = 1/3\sqrt{\alpha} \end{matrix} \end{aligned}$$

colourless system of
3 quasi-real gluons

$$(C_F\alpha_s(\mu^2))^{3/2}$$

quasi-real
($Q^2 \sim 10^{-3} \text{ GeV}^2$)

Interference of QED with nonperturbative QCD?

amplitudes for effective photon coupling:

$$b \sim -1/3 \left(1 + \underbrace{\mathcal{K} (C_F \alpha_s(\mu^2))}_{\sim 0.14} \right)^{3/2} \quad \mu^2 \sim m_Q^2 + p_T^2 \sim 2m_Q^2$$

cancellation $\nearrow$

$$\alpha_s(2m_b^2) \approx 0.20$$

$$c \sim 2/3 \left(1 - \underbrace{\frac{1}{2}\mathcal{K} (C_F \alpha_s(\mu^2))}_{\sim 0.22} \right)^{3/2}$$

$(\sim 0.15 \text{ for } p_{Tc} \sim m_b)$

$$\alpha_s(2m_c^2) \approx 0.27$$

where $\mathcal{K}$ = unknown complex factor of non-perturbative origin (of order 1)

example: arbitrarily **assume** $\mathcal{K} \approx 1$ (real)

$\Rightarrow$ effective γb coupling enhanced by factor $(1+0.14)^2 = 1.30$

$\Rightarrow$ effective γc coupling reduced by factor $(1-\frac{1}{2} \times 0.22)^2 = 0.79$

Heavy Flavours in $\gamma\gamma$ at LEP, revisited

scale $\uparrow$ and
coupling $\downarrow$ changes
cancel

standard predictions ($\kappa=0$) from
Drees et al., PLB 306 (1993) 371

scale $\uparrow$ and
coupling $\uparrow$ changes
add

Beauty in photoproduction: standard

reminder:

HERA

$$\mu_0^2 = m^2 + p_T^2$$

standard photon coupling

Beauty in photoproduction: new scale

reminder:

HERA

$$\mu_0 \rightarrow \mu_0/2$$

standard photon coupling

Beauty in photoproduction: non-standard

HERA

$$\mu_0 \rightarrow \mu_0/2$$

non-standard photon coupling

still consistent -> not excluded

compatibility with other measurements?

- purely hadronic processes (Tevatron, LHC) unaffected
- purely weak processes (W/Z at Tevatron, CC at HERA) unaffected
- change of coupling only relevant for (quasi-)real photons
($Q^2 > 1 \text{ GeV}^2 \rightarrow$ perturbative $\rightarrow \kappa \ll 1 \rightarrow$ very small/negligible)
 $\Rightarrow$ no significant change for DIS at HERA, $e^+e^- \rightarrow q\bar{q}X$
- reduction of charm photoproduction at HERA, qualitatively
compensated by increase due to $\mu \rightarrow \mu/2$ (to be checked quantitatively)
- for hard scale $\mu \gg m_q$, modifications for up and down quark
contributions cancel exactly in leading order $\Rightarrow u, d; s, c$ cancel
 $\Rightarrow$ no net effect for 2,4,6 final state flavours (e.g. $N_F=4$ γp fixed target)
 $\Rightarrow$ some increase ($\sim 2\%$) in PHP high E_T jet production at HERA,
high E_T single photon production at Tevatron (5=3-2 flavours, b only) !
- should affect e.m. branching ratios, e.g. $D^* \rightarrow D\gamma$ (but not
electroweak ones like $b \rightarrow s\gamma$, since $W\gamma$ coupling unaffected) !
- other processes ?

Summary and conclusions

Beauty cross sections at HERA and elsewhere in reasonable agreement with perturbative QCD predictions (but often above “central” prediction).

Phenomenological arguments (independent of data) suggest shift in choice of “optimal” renormalization/factorization scales to ~half their “standard” values
⇒ good agreement with many different data sets

Plea to make this the new default, whenever a dedicated study is absent, in particular before claiming disagreement between data and NLO QCD.
up/down scale variation by factor 2 looks OK.

(theorists who do not like this: please provide NNLO calculations!)

b “excess” of $\gamma\gamma$ at LEP? ⇒ investigate modification of photon-quark coupling from interference with non-perturbative QCD? ⇒ compatible with HERA beauty data.
Compatibility with other measurements and theoretical constraints to be checked
Important e.g. for α_s from PHP jets at HERA → hopefully exclude (confirm??) soon.

Backup slides

pQCD approximations

assume one dominant hard scale:

Massive scheme: $\rightarrow m_b$

- **b massive** p_T^2
- **neglects** $[\alpha_s \ln(Q^2/m_b^2)]^n$

$\rightarrow$ **Perturbative production:**

NLO

=FFNS

alternative: kt-factorization

Massless scheme: $\rightarrow p_T, Q^2$

- **b massless!** p_T^2
- **Resums** $[\alpha_s \ln(Q^2/m_b^2)]^n$

$\rightarrow$ **b also in Proton and Photon!**

FONLL

(GM)-VFNS

NLL

=ZM-VFNS

Variable schemes (VFNS):

$\rightarrow$ at small Q^2 massive, at large Q^2 massless

FONLL

(GM)-VFNS

Beauty in photoproduction: summary

b quark

HERA

data/QCD:

reasonable agreement,
 but tendency
 data > QCD
 at low p_T

k_T factoriz.
 and NLO
 predictions
 agree

theory uncert.
 underestimated?

FONLL (VFNS) prediction not yet available, should it help?

famous b cross sections at the Tevatron

(a bit of history)

combination of appropriate fragmentation,
NLL corrections, + many smaller experimental
and theoretical issues (Cacciari et al.)

problem also for HERA? could one have done better?

b cross sections at UA1 (630 GeV p $\bar{p}$)

NLO (1992) and FONLL (2004) agree with each other and with data (1991/94)

(fragm. and decay spectra, br. ratios, ... were all consistently tuned in MC to measured data)

FONLL (2004) agrees with data (1991) at b quark, B hadron, and muon level

UA1, PLB 256 (1991) 112
 UA1, Z.Phys.C 61 (1994) 41
 MNR, Nucl.Phys.B 373 (1992) 295
 Cacciari et al., JHEP 0407 (2004) 33

Charm in photoproduction at HERA

QCD calculations using

CTEQ5M1 + AFG structure functions

$$m_c = 1.5 \pm 0.2 \text{ GeV}, \quad \mu_0^2 = m_c^2 + p_T^2,$$

$$\mu_r = \mu_f = \mu, \quad \mu_0/2 < \mu < 2\mu_0$$

$$f(c \rightarrow D^*) = 0.235$$

$$e_{\text{Peterson}} = 0.035 \text{ (FO NLO)}, 0.02 \text{ (FONLL)}$$

update?

NLO (FMNR)

reasonable agreement
some differences at forward η

FONNL

(Cacciari et al.)

similar, not better at large p_T

=> Do not expect major change
for b at HERA from
NLO (no resummation)
-> FONLL (with resummation)
but would be nice to have