Drell-Yan process
and
heavy boson production
at hadron colliders

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June 4, 2007
Some references

- My slides are available from the CTEQ webpage or http://hep.pa.msu.edu/nadolsky/tmp/cteqX.pdf

- Feynman rules for tree helicity amplitudes involving massive quarks and bosons
  Schwinn, Weinzierl, hep-th/0503015

- Gluon PDF in a pion (depends on theory assumptions)

- Multiple parton interactions in Pythia
  Sjostrand, Mrenna, Skands, hep-ph/0603175, chapters 11.2-11.4
Outline

Saturday

- low-$Q$ lepton pair production
- heavy electroweak bosons
- kinematics
- leading-order (LO) cross sections
- NLO/NNLO results

Monday

- modern applications
- QCD factorization and resummation of large logarithms
- new physics searches
Typical parton momentum fractions

\[ x_{A,B} \equiv \frac{Q}{\sqrt{s}} e^{\pm y} \]

Born level:
\[ p_\mu^a = x_A p_\mu^A, \]
\[ p_\mu^b = x_B p_\mu_B \]

Typical rapidities in the experiment: \(|y| \lesssim 2\)

- Experiments at higher energies are sensitive to PDF’s at smaller \(x\)
Particle states probed by Drell-Yan-like processes
Particle states probed by Drell-Yan-like processes

\[ pN \rightarrow \gamma^* \rightarrow \ell^+\ell^- X \text{ at } Q < 20 \text{ GeV} \]

- Continuous $\gamma^*$ cross section
- Multiple quarkonium resonances (neglected in the PDF fit)
  - $J/\psi (c\bar{c})$– found in $e^+e^-$ scattering (1974)
  - $\Upsilon (b\bar{b})$– found in $pN \rightarrow \mu^+\mu^- X$ (FNAL-E288, 1977)
Particle states probed by Drell-Yan-like processes

$J/\psi$, $\Upsilon$ resonances shown with better resolution (FNAL-E866)
Constraints on quark sea from $pN \rightarrow \ell^+ \ell^- X$

$(N = p, d, Fe, Cu, ..)$

\[
\frac{d\sigma_{pp}}{dQ^2 dy} \sim \left( \frac{2}{3} \right)^2 \left[ u_A \bar{u}_B + \bar{u}_A u_B \right] + \left( -\frac{1}{3} \right)^2 \left[ d_A \bar{d}_B + \bar{d}_A d_B \right] + \text{smaller terms}
\]

\[\Rightarrow\] sensitivity to $\bar{q}(x, Q)$

Assuming charge symmetry between protons and neutrons

$(u_p = d_n, u_n = d_p)$:

\[
\frac{d\sigma_{pn}}{dQ^2 dy} \sim \left( \frac{2}{3} \right)^2 \left[ u_A \bar{d}_B + \bar{u}_A d_B \right] + \left( -\frac{1}{3} \right)^2 \left[ d_A \bar{u}_B + \bar{d}_A u_B \right] + \text{smaller terms}
\]

If deuterium binding corrections are neglected:

$q_d(x) \approx q_p(x) + q_n(x)$

At $x_A \gg x_B$ (large $y$): $\bar{q}(x_A) \sim 0$ and $4u(x_A) \gg d(x_A)$

\[
\frac{\sigma_{pd}}{2\sigma_{pp}} \approx \frac{1}{2} \left( 1 + \frac{d_A}{4u_A} \right) \left[ 1 + r \right] \approx \frac{1}{2} (1 + r), \text{ where } r \equiv \frac{\bar{d}(x_B)}{\bar{u}(x_B)}
\]

$\therefore \sigma_{pd}/(2\sigma_{pp})$ constrains $\bar{d}(x, Q)/\bar{u}(x, Q)$ at moderate $x$
Constraints on quark sea from $pN \to \ell^+ \ell^- X$

\((N = p, d, Fe, Cu, ..)\)

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\(\therefore\) \(\sigma_{pd}/(2\sigma_{pp})\) constrains \(\bar{d}(x, Q)/\bar{u}(x, Q)\) at moderate \(x\)
Constraints on quark sea from \( pN \to \ell^+ \ell^- X \) 

\( (N = p, d, Fe, Cu, \ldots) \)

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\]

\( \Rightarrow \) sensitivity to \( \bar{q}(x, Q) \)

Assuming charge symmetry between protons and neutrons 

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\]

\( \therefore \frac{\sigma_{pd}}{(2\sigma_{pp})} \) constrains \( \frac{\bar{d}(x, Q)}{\bar{u}(x, Q)} \) at moderate \( x \)
Theory vs. experiment

Cross section at $Q = 4 - 17$ GeV

$\sigma_{pd}/(2\sigma_{pp})$ at large $x_F = x_A - x_B$

The recent PDF fits (e.g., CTEQ5M) quantitatively account for the violation of $SU(2)$ symmetry in the quark sea
Particle states probed by Drell-Yan-like processes

\[ \gamma^*, J/\psi, Y, W, Z, H, Z', G_{\text{RS}}, \ldots \]

Particle mass (GeV)

1, 10, 100, 1000

c, b, t

\( W \) and \( Z \) boson production

- good convergence of the \( \alpha_s \) series
- small backgrounds
- separation of PDF flavors (via the CKM matrix)
- sensitivity to new physics

Fig. 9.5. The lepton pair cross section in pp collisions at \( \sqrt{s} = 1.8 \) TeV, with CDF data from ref. [12] (open circles) and ref. [13] (solid circles). The curve is the next-to-leading-order QCD prediction using the parton distributions from ref. [9]
Leptonic vs. hadronic decay modes

The $W$ and $Z$ branching ratios $\text{Br}_i \equiv \Gamma_i / \Gamma$ are

- $\text{Br} [W \to \ell \nu_\ell] \approx 3 \times 11\%$, $\text{Br} [W \to \text{jets}] \approx 68\%$
- $\text{Br} [Z \to \ell^+ \ell^-] = 3 \times 3.36\%$, $\text{Br} [Z \to \nu_\ell \bar{\nu}_\ell] = 3 \times 6.67\%$, $\text{Br} [Z \to \text{jets}] \approx 70\%$

At $\sqrt{s}$ of a few TeV, hadronic $W, Z$ decays cannot be observed because of the large background (mostly $qq, gg \to \text{jets}$)

Despite small branching ratios, the only viable decay modes are

- $Z \to e^+ e^-, Z \to \mu^+ \mu^-$
- $W \to e + \nu_e, W \to \mu + \nu_\mu$, with neutrinos identified by missing transverse energy $E_T$
A quiz on $W$ boson kinematics

Consider $AB \rightarrow (W^+ \rightarrow e^+\nu_e)X$ decay in the lab frame. The most probable transverse momentum $Q_T$ of the $W$ boson is

a) $Q_T = \sqrt{s}/2$

b) $Q_T = |\vec{p}_T^e| + E_T$

c) $Q_T = 0$

d) $Q_T = 2 - 5$ GeV, depending on $\sqrt{s}$.
A quiz on $W$ boson kinematics

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a) $Q_T = \sqrt{s}/2$

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c) $Q_T = 0$

d) $Q_T = 2 - 5$ GeV, depending on $\sqrt{s}$

The LO condition $Q_T = 0$ (corresponding to no QCD radiation) is never realized because of self-suppression of very soft QCD contributions (Sudakov suppression). To predict $d\sigma/dQ_T$ at $Q_T \ll Q \sim M_W$, one needs to resum such soft contributions to all orders in $\alpha_S$. 
A quiz on $W$ boson kinematics

Consider $AB \rightarrow (W^+ \rightarrow e^+ \nu_e)X$ decay in the lab frame. The most probable transverse momentum $p_T^e$ of the positron is

a) $p_T^e = 0 - 5$ GeV  
b) $p_T^e \approx 40$ GeV  
c) $p_T^e \approx 80$ GeV  
d) $p_T^e = Q_T/2$
A quiz on $W$ boson kinematics

Consider $AB \rightarrow (W^+ \rightarrow e^+\nu_e)X$ decay in the lab frame. The most probable transverse momentum $p_T^e$ of the positron is

a) $p_T^e = 0 - 5$ GeV
b) $p_T^e \approx 40$ GeV = $M_W/2$
c) $p_T^e \approx 80$ GeV
d) $p_T^e = Q_T/2$

$d\sigma/dp_T^e$ has a kinematical (Jacobian) peak,

- located exactly at $p_T^e = M_W/2$ if $Q_T = 0$ and $Q = M_W$
- smeared by higher-order EW and soft QCD corrections
The origin of the Jacobian peak

In the Collins-Soper $W$ rest frame, for $Q = M_W$:

$$p_T^e = |\vec{p}_1| \sin \theta_* = \frac{M_W}{2} \sin \theta_*$$

$$\frac{d\sigma}{d \cos \theta_*} = \sum_j F_j(Q, Q_T, y) a_j(\theta_*, \varphi_*)$$

$$a_1 = 1 + \cos^2 \theta_*, \quad a_2 = 2 \cos \theta_*, \text{ etc. (smooth functions)}$$

$$\frac{d\sigma}{dp_T^e} = \left| \frac{d \cos \theta_*}{dp_T^e} \right| \frac{d\sigma}{d \cos \theta_*} = \frac{1}{\sqrt{1 - \left(\frac{2p_T^e}{M_W}\right)^2}} \frac{4p_T^e}{M_W^2} \frac{d\sigma}{d \cos \theta_*}$$

$$\frac{d\sigma}{dp_T^e} \to \infty \text{ if } p_T^e \to M_W/2 \ (!)$$
The origin of the Jacobian peak

If \( Q_T = 0 \): \((p_T^e)_{\text{lab frame}} = (p_T^e)_{\text{CS frame}}\)

(the boost from the CS frame to the lab frame is along the \( z \)-axis)

Corrections to \( d\sigma/dp_T^e \) are of order

- \( \mathcal{O}(\Gamma_W^2/M_W^2) \) due to the non-zero \( W \) width \( \Gamma_W \) \((Q \neq M_W)\)

- \( \mathcal{O}(Q_T/Q) \) due to the boost \( \Rightarrow \) sensitivity to the shape of \( d\sigma/dQ_T \) (soft radiation) at \( Q_T \ll Q \)

A similar Jacobian peak is present in \( d\sigma/dp_T^{\nu} \)
Lepton transverse mass

Definition

\[ M_T^{\ell\nu} \equiv 2(p_T^e p_T^\nu - \vec{p}_T^e \cdot \vec{p}_T^\nu) \] in the lab frame (Smith, van Neerven, Vermaseren, 1983)

Exercise

Assuming \( Q_T = 0 \), verify that there is a Jacobian peak in \( d\sigma / dM_T^{\ell\nu} \) at \( M_T^{\ell\nu} = M_W \)

- Corrections to \( d\sigma / dM_T^{\ell\nu} \) are of order \( \mathcal{O}(Q_T^2/Q^2) \) ⇒ reduced sensitivity to small-\( Q_T \) soft contributions

- \( d\sigma / dM_T^{\ell\nu} \), \( d\sigma / dp_T^e \), and \( d\sigma / dp_T^\nu \) are important observables. They are commonly used to measure \( M_W \). \( \Gamma_W \) is found from \( d\sigma / dM_T^{\ell\nu} \) at large \( M_T^{\ell\nu} \)
$W$ and $Z$ production as a “luminosity monitor”

(Dittmar, Pauss, Zurcher; Khoze, Martin, Orava, Ryskin; Giele, Keller’;...)

- Cross sections for $pp \rightarrow W^\pm X$, $pp \rightarrow Z^0 X$ at the LHC can be measured with accuracy $\delta\sigma/\sigma \sim 1\%$ (tens of millions of events even at low luminosity)

- These measurements can be employed to
  - measure all other LHC cross sections in units of $\sigma_{LHC}^{W, Z}$
  - measure magnitudes of $\sigma_{LHC}^{W, Z}$; use them to monitor the LHC luminosity in real time
  - precisely measure PDF’s (parton luminosities); reduce theory uncertainties for tiny new physics signals and huge SM backgrounds

The accuracy of luminosity monitoring in $pp$ elastic scattering at the Tevatron is of order 5\%
Theoretical aspects of luminosity monitoring

Several factors contribute to $W$ & $Z$ cross sections at a percent level, including

- $\mathcal{O}(\alpha_s^2)$, or NNLO, QCD corrections
- $\mathcal{O}(\alpha)$, or NLO, EW corrections
- PDF uncertainties
- Experimental acceptance
- QCD and EW showering (all-orders resummations)

Sometimes, these effects (e.g., PDF dependence or constant $K$-factors) may cancel in ratios, but in many cases they do not...
Ratios of $W$ and $Z$ cross sections

Radiative contributions, PDF dependence have similar structure in $W$, $Z$, and alike cross sections; cancel well in Xsection ratios
$\sigma_Z$ vs. $\sigma_W$ at NLO for various PDF sets

However, the PDF errors for cross sections themselves are still very appreciable

CTEQ6.5/CTEQ6.1 $\sim 1.07$

- reflects a 7% increase in parton luminosities
  \[ \mathcal{L}_{q_i\bar{q}_j}(x_1, x_2, Q) = q_i(x_1, Q)\bar{q}_j(x_2, Q) \]
  in the relevant $x$ and $Q$ ranges for $u, d, s$ quarks (consequence of improved treatment of heavy-flavor masses in DIS at HERA)
Charged lepton asymmetry at the Tevatron

\[ A_{ch}(y_e) \equiv \frac{d\sigma^{W^+}}{dy_e} - \frac{d\sigma^{W^-}}{dy_e} - \frac{d\sigma^{W^+}}{dy_e} + \frac{d\sigma^{W^-}}{dy_e} \]

- related to the boson Born-level asymmetry when \( y_e \) is large

\[ A_{ch}(y) \xrightarrow{y \to y_{\text{max}}} \frac{r(x_B) - r(x_A)}{r(x_B) + r(x_A)}, \quad r(x) \equiv \frac{d(x, M_W)}{u(x, M_W)} \]

- constrains the PDF ratio \( d(x, M_W)/u(x, M_W) \) at \( x \to 1 \)

- In experimental analyses, a selection cut \( p_{T_e} > p_{T_e}^{\text{min}} \) is imposed
Charge asymmetry in $p_T^e$ bins (CDF Run-2)

With $p_T e$ cuts imposed, $A_{ch}(y_e)$ is sensitive to small-$Q_T$ resummation.
Factorization for inclusive cross sections

Scale dependence of the renormalized QCD charge $g(\mu)$ and fermion masses $m_f(\mu)$:

$$
\mu \frac{dg(\mu)}{d\mu} = \beta(g(\mu)), \quad \mu \frac{dm_f(\mu)}{d\mu} = -\gamma_m(g(\mu))m_f(\mu)
$$

The RG equations predict that $\alpha_s(\mu) \to 0$ and $m_f(\mu) \to 0$ as $\mu \to \infty$

These features are employed to prove factorization for inclusive Drell-Yan cross sections (Bodwin, PRD 31, 2616 (1985); Collins, Soper, Sterman, NPB 261, 104 (1985); B308, 833 (1988)):

$$
\frac{d\sigma(Q, \{m_f\})}{d\tau} = \sum_{a,b} \int_{x_A}^1 dx_A \int_{x_B}^1 dx_B \frac{d\tilde{\sigma}}{d\tau} \left( \frac{Q}{\mu}, \frac{\tau}{\xi_A \xi_B}, \{m_f = 0\} \right) f_{a/A}(\xi_A, \mu) f_{b/B}(\xi_B, \mu) + O \left( \left\{ \frac{m_f^2}{\mu^2} \right\} \right)
$$

assuming $\mu \sim Q \sim \sqrt{s} \gg \{m_f\}, \Lambda_{QCD}$
Factorization for inclusive cross sections

\[
\frac{d\sigma(Q, \{m_f\})}{d\tau} = \sum_{a,b} \int_{x_A}^{1} d\xi_A \int_{x_B}^{1} d\xi_B \frac{d\tilde{\sigma} \left( \frac{Q}{\mu}, \frac{\tau}{\xi_A \xi_B}, \{m_f = 0\} \right)}{d\tau} f_{a/A}(\xi_A, \mu) f_{b/B}(\xi_B, \mu) + \mathcal{O} \left( \left\{ \frac{m_f^2}{\mu^2} \right\} \right)
\]

\begin{itemize}
    \item The hard cross section \( \tilde{\sigma} \) is infrared-safe: \( \lim_{\{m_f \to 0\}} \tilde{\sigma}(\{m_f\}) \) is finite and can be computed as a series in \( \alpha_s(\mu) \)
    
    \item Collinear logarithms are subtracted from \( \tilde{\sigma} \) and resummed in \( f(\xi, \mu) \) using DGLAP equations
    
    \item Soft-gluon singularities in \( \tilde{\sigma} \) vanish when the sum of all Feynman diagrams is integrated over all phase space (Kinoshita-Lee-Nauenberg theorem)
\end{itemize}
Differential distributions may still contain integrable soft singularities of the type $\alpha_s^k \ln^m (Q^2 / p_i \cdot p_j)$, e.g., $L \equiv \ln (Q^2 / Q_T^2) \gg 1$:

$$\frac{d\sigma}{dQ_T^2} \bigg|_{Q_T \to 0} \approx \frac{1}{Q_T^2} \left\{ \alpha_s (L + 1) + \alpha_s^2 (L^3 + L^2 + L + 1) + \alpha_s^3 (L^5 + L^4 + L^3 + L^2 + L + 1) + \ldots \right\}.$$

The purpose of $Q_T$ resummation is to reorganize this series as

$$\frac{d\sigma}{dQ_T^2} \bigg|_{Q_T \to 0} \approx \frac{1}{Q_T^2} \left\{ \alpha_s Z_1 + \alpha_s^2 Z_2 + \ldots \right\},$$

where $\alpha_s^{n+1} Z_{n+1} \ll \alpha_s^n Z_n$:

$$\alpha_s Z_1 \sim \alpha_s (L + 1) + \alpha_s^2 (L^3 + L^2) + \alpha_s^3 (L^5 + L^4) + \ldots \quad | A_1, B_1, C_0 ;$$

$$\alpha_s^2 Z_2 \sim \alpha_s^2 (L + 1) + \alpha_s^3 (L^3 + L^2) + \ldots \quad | A_2, B_2, C_1 ;$$

$$\alpha_s^3 Z_3 \sim \alpha_s^3 (L + 1) + \ldots \quad | A_3, B_3, C_2 .$$
QCD factorization at large and small $Q_T$

 Finite-order (FO) factorization

\[ \Lambda_{QCD}^2 \ll q_T^2 \sim Q^2 \]

Small-$q_T$ factorization

\[ \Lambda_{QCD}^2 \ll q_T^2 \ll Q^2 \]

Solution for all $q_T$: 

\[ + \quad \text{FO} \quad - \]
Factorization at $Q_T \ll Q$
(Collins, Soper, Sterman, 1985)

Realized in space of the impact parameter $b$

$$\left. \frac{d\sigma_{AB\to VX}}{dQ^2 dy dq_T^2} \right|_{q_T^2 \ll Q^2} = \sum_{\text{flavors}} \int \frac{d^2 b}{(2\pi)^2} e^{-i\vec{q}_T \cdot \vec{b}} \bar{W}_{ab}(b, Q, x_A, x_B)$$

$$\bar{W}_{ab}(b, Q, x_A, x_B) = |\mathcal{H}_{ab}|^2 \ e^{-S(b, Q)} \bar{P}_a(x_A, b) \bar{P}_b(x_B, b)$$

$\mathcal{H}_{ab}$ is the hard vertex, $S$ is the soft (Sudakov) factor, $\bar{P}_a(x, b)$ is the unintegrated PDF

For $b \ll 1 \text{ GeV}^{-1}$, $\bar{W}_{ab}(b, Q, x_A, x_B)$ is calculable in perturbative QCD; at $Q \sim M_Z$, this region dominates the resummed cross section.
Nonperturbative contributions at large $b$

At $b \gtrsim 1 \text{ GeV}^{-1}$, the leading nonperturbative contribution is approximated as $\exp(-a(Q)b^2)$, where $a(Q)$ is an effective “nonperturbative parton $\langle k_T^2 \rangle/4$” inside the proton.

The RG invariance suggests that

$$a(Q) \approx a_1 + a_2 \ln Q,$$

where $a_{1,2} \sim \Lambda_{QCD}^2$, and $a_2$ is process-independent.

The $\ln Q$ growth of $a(Q)$ is indeed observed in the Drell-Yan and $Z p_T$ data.
An example of the resummed cross section

$Z$ production at the Tevatron vs. resummed NLO (Balazs, Ladinsky, PN, Yuan)

In this case, precise predictions for $\frac{d\sigma}{dQ_T}$ are needed to measure $M_W$ with accuracy better than 0.03%
Particle states probed by Drell-Yan-like processes

New physics at $Q > 100$ GeV

- Indirect constraints from electroweak precision measurements
- Direct new physics searches

Electron $E_T$

Low-Q Drell-Yan  W & Z  Resummation  New physics

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Search for heavy states at DO

$$W' \rightarrow \ell \nu$$

Pavel Nadolsky (ANL)
Search for heavy states at DO

Leptoquark $\rightarrow \mu\mu$
Search for heavy states at DO

Contact interactions: $p\bar{p} \rightarrow e(e^* \rightarrow e\gamma)X$
Search for heavy states at DO

Randall-Sundrum graviton $\rightarrow ee, \gamma\gamma$
Higgs sector in Standard Model & supersymmetry

**SM: 1 Higgs doublet, one boson $H$**

- **Direct search:** $m_H > 114$ GeV at 95% c.l.
- **Indirect:** $M_H = 80^{+39}_{-28}$ GeV at 68% c.l.

**MSSM: 2 Higgs doublets; $h^0$, $H^0$, $A^0$, $H^\pm$**

$m_h \leq m_Z |\cos 2\beta| + \text{rad. corr.} \lesssim 135$ GeV

- In these models, expect one or more Higgs bosons with mass below 140 GeV
- Many other possibilities for EW symmetry breaking exist!
Higgs sector in Standard Model & supersymmetry

- the goal of direct and indirect measurements is to over-constrain SM, greatly constrain SUSY
- indirect constraints strongly depend on $M_W$, $m_t$ values, hence require accurate QCD predictions for $W$ and $t$ production

For example, in SM

$$
M_W = 80.3827 - 0.0579 \ln \left( \frac{M_H}{100 \text{ GeV}} \right) - 0.008 \ln^2 \left( \frac{M_H}{100 \text{ GeV}} \right) \\
+ 0.543 \left( \left( \frac{m_t}{175 \text{ GeV}} \right)^2 - 1 \right) - 0.517 \left( \frac{\Delta \alpha_{\text{had}}(M_Z)}{0.0280} - 1 \right) - 0.085 \left( \frac{\alpha_s(M_Z)}{0.118} - 1 \right)
$$

Pavel Nadolsky (ANL)  
CTEQ summer school Lecture 2  
June 4, 2007
Let's concentrate on $gg \rightarrow H \rightarrow \gamma\gamma$, the leading search mode for $M_H < 140$ GeV (besides vector boson fusion and $tt\bar{t}H$ production)
The scattering proceeds via a top quark loop, which can be replaced by an effective point vertex under the assumption $m_t^2 \gg m_H^2$ (works well for $m_H \lesssim 350$ GeV). This trick greatly simplifies calculations, which can be carried out up to two gluon loops (as in the Drell-Yan process). Many techniques developed for the Drell-Yan process also apply to Higgs production.
However, $gg \rightarrow \text{Higgs}$ is characterized by slower convergence of the series in $\alpha_s$ than $q\bar{q} \rightarrow W, Z$. 

$$\sqrt{s} = 14 \text{ TeV}$$

$$m_h = 120 \text{ GeV}$$

$\mu_{h/2} \leq \mu \leq 2m_h$
$Q_T$ resummation for Higgs bosons has been carried out by several groups, and they are in a reasonable agreement (Balazs, Yuan; Berger, Qiu; Bozzi et al.; Kulesza, Stirling; Kulesza, Sterman, Vogelsang).
Resummed distributions for Higgs \(\rightarrow \gamma\gamma\) signal and background (ResBos, normalized; \(M_H = 130\) GeV, \(128 < Q < 132\) GeV)

\(Q_T\) and \(y_{\gamma_1} - y_{\gamma_2}\) in the lab frame

Decay angles \(\theta_*\), \(\varphi_*\) in the \(\gamma\gamma\) rest frame

no singularities, in contrast to the fixed-order rate
Summary

Essential applications of Drell-Yan-like processes

- clean tests of QCD factorization
- studies of the nucleon structure (quark sea, flavor separation, ...)
- “standard candle” processes (luminosity monitors, ...)
- electroweak precision measurements
- searches for new physics

Many interesting topics were not covered

- Polarized Drell-Yan-like processes (measurements of new nucleon structure functions)
- Connections to $k_T$ factorization in semi-inclusive DIS
- Various resummations (small $x$, threshold, heavy-quark, ...)
- Higher-twist and nuclear effects in low-$Q$ Drell-Yan and heavy-ion scattering
Many exciting studies still remain to be done!
Backup slides
$W$ and $Z$ signal in the hadron decay mode at SPS and Tevatron

$pp \to \text{jets at } \sqrt{s} = 630 \text{ GeV};$ background/signal$\sim 20$

$pp \to \text{jets at } \sqrt{s} = 1.8 \text{ TeV};$ background/signal$\sim 255$ (J. Pumplin, PRD45, 806 (1992))

Pavel Nadolsky (ANL)  
CTEQ summer school Lecture 2  
June 4, 2007
Impact of charm contributions to DIS at HERA

CTEQ6.5 employs a more accurate calculation of charm mass effects (general-mass factorization scheme) in DIS structure functions $F_i(x, Q^2)$ at HERA.

- $W, Z$ production at the LHC: $x \sim 10^{-3} - 10^{-2}$

- Suppression of charm contribution to $F_2(x, Q^2)$ in CTEQ6.5 results in larger $^{\bar{u}}(x)$, $^\bar{d}(x)$ at small $x \Rightarrow$ larger $\sigma_{W,Z}^{LHC}$

\[
\dfrac{\delta \bar{q}_{\text{light}}(x)}{\bar{q}_{\text{light}}(x)} = 3 - 4\% \Rightarrow \dfrac{\delta L_{q_i\bar{q}_j}}{L_{q_i\bar{q}_j}} = 2(\dfrac{\delta \bar{q}_{\text{light}}}{\bar{q}_{\text{light}}}) = 6 - 8\%
\]
Heavy Quark Loops

Somewhat surprisingly, gluon fusion via a virtual top-quark loop dominates Higgs production at hadron colliders.

$$\sigma_{1.0}(gg \rightarrow H) = \frac{\pi G_F}{128\sqrt{2}} \left( \frac{\alpha_s(\mu)}{\pi} \right)^2 \tau^2 |1 + (1 - \tau)f(\tau)|^2 \delta \left( 1 - \frac{M_H^2}{\hat{s}} \right)$$

$$f(\tau) = \begin{cases} \arcsin^2 \frac{1}{\sqrt{\tau}}, & \tau \geq 1, \\ -\frac{1}{4} \left[ \ln \frac{1 - \sqrt{1 - \tau}}{1 + \sqrt{1 - \tau}} - i\pi \right]^2, & \tau < 1, \end{cases}$$

$$\tau = 4M_t^2/M_H^2.$$
Light Higgs boson search at the LHC

- $gg \rightarrow h \rightarrow \gamma\gamma$ (via a $t$-quark loop) is the leading search mode for $115 \lesssim M_H \lesssim 140$ GeV
- A $5\sigma$ discovery of SM Higgs boson is possible with $\mathcal{L} = 10 - 30$ fb$^{-1}$
- $\delta M_H \lesssim 1$ GeV, $\delta\sigma(H \rightarrow \gamma\gamma) \sim 20\%$ within the experimental reach at later stages?
Light Higgs boson search at the LHC

- $gg \rightarrow h \rightarrow \gamma\gamma$ (via a $t$-quark loop) is the leading search mode for $115 \lesssim M_H \lesssim 140$ GeV
- A 5$\sigma$ discovery of SM Higgs boson is possible with $L = 10 - 30$ fb$^{-1}$
- $\delta M_H \lesssim 1$ GeV, $\delta \sigma(H \rightarrow \gamma\gamma) \sim 20\%$ within the experimental reach at later stages?
- Statistical significance depends on the (new) physics model, QCD contributions, etc.

A challenging measurement!