Higgs Boson Phenomenology at the LHC

2. Transverse Momentum Distribution

3. All orders Soft Gluon Resummation

4. Role of the Non-perurbative Input at Large Impact Parameter

5. Predictions for Transverse Momentum Distributions of Higgs and Z Bosons at the LHC

6. Summary and Discussion

1. INTRODUCTION

- To establish the Higgs mechanism for electroweak symmetry-breaking, it is necessary to
  - discover the Higgs boson
  - demonstrate mass generation $g_{hxx} \propto m_x$

- The experimental bounds on $m_h$ from the absence of a signal at LEP in $e^+e^- \rightarrow hZ$ are
  - $m_h > 115$ GeV if the branching fraction for decay to $b\bar{b}$ is significant
  - $m_h > 113$ GeV based on the assumption of decay into hadronic jets, without $b$-tagging

- Fits to precise electroweak data suggest that the mass of the scalar SM-like Higgs boson, $m_h < 193$ GeV

- In this work, we consider the broader range $M_Z < m_h < 200$ GeV
  - Interesting to contrast the transverse momentum distributions for Z and Higgs boson production at the same mass
• The Higgs boson is expected to be produced at the LHC through various partonic production processes and observed in its decays to SM particles:
  - $gg \rightarrow hX$, with $h \rightarrow \gamma\gamma$, $h \rightarrow WW^*$, $ZZ^*$;
  - $gg \rightarrow t\bar{t}hX$, with $h \rightarrow b\bar{b}$ or $h \rightarrow \gamma\gamma$;
  - $qq \rightarrow hqqX$ via $W^+W^-(ZZ) \rightarrow hX$, with $h \rightarrow WW^*$, $h \rightarrow \gamma\gamma$, or $h \rightarrow \tau^+\tau^-$

• The fully inclusive gluon-gluon fusion subprocess $gg \rightarrow hX$ is the dominant production mechanism.

\[ \sigma(pp \rightarrow H+X) [pb] \]
\[ \sqrt{s} = 14 \text{ TeV} \]
\[ M_t = 175 \text{ GeV} \]
\[ \text{CTEQ4M} \]
Cross section is smaller than at the LHC by a factor of \( \sim 100 \) to 1000

Combine many channels for the Higgs boson search

Integrated luminosity of at least \( 20 \, \text{fb}^{-1} \) is required for discovery of a Higgs boson with \( m_h = 120 \, \text{GeV} \)

Associated production \( q\bar{q}' \to (W, Z) \to h(W, Z) \) is important for the Tevatron search
GLUE - GLUE FUSION

- lowest order triangle graph
  \[ X = t, b, \hat{q} \]

- In the SM, the top quark \( t \) contribution dominates

- Take the limit \( m_t \to \infty \). The triangle collapses to a point. The predicted cross section agrees within 5% with the triangle cross section for \( m_h < 2m_t \)

- Effective 0th order cross section
  \[
  \sigma_{gg \to hX}^{(0)}(Q) = \sigma_0 \frac{\pi}{S} m_h^2 \delta(Q^2 - m_h^2)
  \]
  \[
  \sigma_0 = \left( \sqrt{2}G_F \right) \frac{\alpha_s^2(\mu_r)}{576\pi}
  \]
  \( G_F \) is the Fermi constant

- The NLO contributions are large, \( K_{NLO} \sim 1.7 \)
  Spira, Djouadi, Graudenz, and Zerwas; Dawson and Kauffman

- NNLO contributions, \( K_{NNLO}(m_h \ll m_t) \sim 2^{1/4} \)
  Harlander and Kilgore PRL 88, 201801 (2002); Anastasiou and Melnikov, hep-ph/0207004

- The inclusive cross section, integrated over transverse momentum, is established; renormalization/factorization scale dependence \( \sim 15\% \)
Total Cross Section at NNLO

- Total inclusive cross sections computed at NNLO
  Harlander and Kilgore

\[
\sigma(pp \rightarrow H+X) \text{ [pb]} \quad \sqrt{s} = 14 \text{ TeV}
\]

- Perturbation theory is well behaved (scale dependence is under control and growth in magnitude from NLO to NNLO is modest)

- Threshold soft gluon resummation \( \left( m_h/\sqrt{s} \rightarrow 1 \right) \)
  Catani, deFlorian, Grazzini, Nason
2. **Cross Section at Finite Transverse Momentum** $Q_T$

- At zero-th order, the triangle diagram produces a $\delta^2(Q_T)$-function transverse momentum distribution.

- Finite Higgs boson transverse momentum is provided at order $\alpha_s$ by $gg$, $qg$, and $q\bar{q}$ subprocesses.

- Also $gg \rightarrow g^* \rightarrow gh$ and $q\bar{q} \rightarrow g^* \rightarrow gh$.

- In the limit $m_t \rightarrow \infty$, the predicted cross section agrees with the full triangle calculation within a few % if $m_h < 2m_t$ and $Q_T < m_t$.

Baur and Glover NP B339, 38 (1990)
CROSS SECTION AT FINITE TRANSVERSE MOMENTUM $Q_T$

- Extraction of a signal for the Higgs boson is aided by an accurate expectation of the $Q_T$ distribution

- Event modeling, kinematical acceptance, and efficiencies all depend on $Q_T$

- Expected shape of $d\sigma/dQ_T$ can affect experimental triggering and analysis strategies

- Selections on $Q_T$ can be used to enhance the signal/background ratio

- In the LHC CMS detector, vertex pointing is not possible with the CMS barrel so that the behavior of $d\sigma/dQ_T$ affects the precision of the determination of the event vertex from which the Higgs boson ($\gamma\gamma$ peak) emerges. Greater $Q_T$ activity associated with Higgs boson production allow a more precise determination of the vertex especially in the case of multiple events per beam crossing
**Differential Cross Section at NLO**

- Differential cross sections computed at NLO
  
  deFlorian, Grazzini, Kunszt PRL 82, 5209 (1999)
  
  
  Glosser, Schmidt hep-ph/0209248

- **gg** subprocess is the largest component

- \( m_h = 120 \text{ GeV} \)

\[
\frac{d\sigma}{dp_T}(pb/GeV)
\]

Ravindran, Smith, van Neerven

- The transverse momentum distribution diverges as \( Q_T \rightarrow 0 \) at fixed-order in perturbation theory
Differential cross section at fixed-order in $\alpha_s$

- At fixed-order in $\alpha_s$, the transverse momentum distribution behaves as
  \[ \frac{\alpha_s}{Q_T^2} \left[ a + b \log\left(\frac{m_h^2}{Q_T^2}\right) \right] \to \infty \quad \text{as} \quad Q_T^2 \to 0 \]
  - $1/Q_T^2$ divergence is related to the gluon propagator
  - The logarithmic term $\log\left(\frac{m_h^2}{Q_T^2}\right)$ remains after the usual cancellation of infra-red divergences and the absorption of collinear divergences into the renormalized parton densities

- In addition
  \[ \sigma_{NLO}^{\text{NLO}} = \mathcal{O}(\alpha_s \log^2\left(\frac{m_h^2}{Q_T^2}\right)) \quad \text{is not small} \]
  \[ (\alpha_s(\mu)/\pi) \ln^2\left(\frac{m_h^2}{Q_T^2}\right) \sim 0.7 \]
  if $\mu = m_h = 125$ GeV and $Q_T = 14$ GeV

- The large logarithmic terms spoil conventional factorization in QCD perturbation theory

- The physical cross section peaks below $Q_T \sim m_h/3$.
  A reliable QCD calculation for small and intermediate $Q_T$ requires that we resum the large logarithmic terms to all orders in $\alpha_s$
Differential Cross Section at Fixed-Order in $\alpha_s$

- Structure of the perturbative expansion in terms of
  $\alpha_s \ln^2 (Q/Q_T)$ instead of $\alpha_s$
  
  $(L = \ln (Q/Q_T))$

- $d\sigma/dQ_T^2 =$
  
  $Q_T^{-2} \left\{ \alpha_s (v'_1 L + v'_0) + \alpha_s^2 (2v'_3 L^3 + 2v'_2 L^2) + \alpha_s^3 (3v'_5 L^5 + 3v'_4 L^4) + \ldots 
  + \alpha_s^2 (2v'_1 L + 2v'_0 L^0) + \alpha_s^3 (3v'_3 L^3 + 3v'_2 L^2) + \alpha_s^3 (\ldots) \right\}$

- In a fixed order calculation (column by column), convergence at small $Q_T$ is compromised by higher order uncalculated logarithmic terms

- In a resummed calculation (line by line), convergence is preserved in each “order” (each line), and higher order corrections are included systematically

- Expand the predictive power of QCD perturbation theory by (re)summing the large logarithmic contributions in an improved calculational scheme
3. All Orders Soft Gluon Resummation

- Resummation in impact parameter $b$-space
  - $\vec{b}$-space = Fourier conjugate of $\vec{Q}_T$-space
  - Fourier transform $\frac{d\sigma}{dydQ_T^2}$ to $b$-space
  - Sum multiple gluon emission to all orders in $\alpha_s$
  - Transverse momentum conservation preserved
  - Fourier transform back to $Q_T$-space
  - Resummation produces a $Q_T$ distribution that is finite as $Q_T \to 0$
  - Note that the perturbative region of large $Q_T$ corresponds to small $b$
THE CSS $b$-SPACE RESUMMATION FORMALISM$^a$

- Resummation of logarithmic terms to all orders in $b$-space

\[
\frac{d\sigma_{AB \to hX}}{dydQ_T^2} = \frac{d\sigma^{(\text{resum})}_{AB \to hX}}{dydQ_T^2} + \frac{d\sigma^{(Y)}_{AB \to hX}}{dydQ_T^2}
\]

- $\sigma^{(\text{resum})}$: resums singular terms that diverge as 
  \[(1/Q_T^2) \ln^n(Q^2/Q_T^2); \; n \geq 0; \; Q = m_h\]
  It dominates in the region of small $Q_T$

- $\sigma^{(Y)}$: This remainder includes all non-singular terms and may include divergences that are less singular at small $Q_T$. May be computed at fixed-order in $\alpha_s$. Tends to dominate at large $Q_T$

\[
\frac{d\sigma^{(\text{resum})}}{dydQ_T^2} = \int \frac{d^2b}{(2\pi)^2} e^{i\vec{Q}_T \cdot \vec{b}} W(b, Q)
\]

\[
= \int \frac{db}{2\pi} J_0(Q_T b) b W(b, Q)
\]

- $b$-space distribution:

\[
W(b, Q) = \sum_{ij} W_{ij}(b, Q) \sigma_{ij \to hX}^{(0)}
\]

$J_0(Q_T b)$ is a Bessel function

---

\[ W(b, Q) = W_{gg}(b, Q)\sigma_{gg\rightarrow hX}^{(0)} \]

satisfies evolution equations in the region of small \( b \):

\[ \frac{\partial}{\partial \ln Q^2} W_{gg}(b, Q) = [K_g(b\mu, \alpha_s) + G_g(Q/\mu, \alpha_s)] W_{gg}(b, Q) \]

\[ \frac{\partial}{\partial \ln \mu^2} K(b\mu, \alpha_s) = -\frac{1}{2} \gamma_g(\alpha_s(\mu)) \]

\[ \frac{\partial}{\partial \ln \mu^2} G(Q/\mu, \alpha_s) = \frac{1}{2} \gamma_g(\alpha_s(\mu)) \]

- The anomalous dimension \( \gamma_g(\alpha_s(\mu)) \) has a perturbative expansion in powers of \( \alpha_s \) without large logarithms.
- Resummation/Solution of the homogeneous evolution equation

\[ W_{gg}(b, Q) = W_{gg}(b, \frac{c}{b}) e^{-S_{gg}(b, Q)} \]

- In the perturbative region \( b \ll 1/\Lambda_{QCD} \), the boundary value \( W_{gg}(b, c/b) \)
  - depends only on one perturbative scale \( \sim 1/b \)
  - contains no large logarithms
- all large logarithms are summed into \( S(b, Q) \)
**Explicit Formulas**

\[
S_g(b, Q) = \int_{c^2/b^2}^{Q^2} \frac{d\mu^2}{\mu^2} \left[ \ln \left( \frac{Q^2}{\mu^2} \right) A_g(\alpha_s(\bar{\mu})) + B_g(\alpha_s(\bar{\mu})) \right]
\]

\[
c = 2e^{-\gamma_E}
\]

- \(A_g\) and \(B_g\) are free of logarithmic dependence and have well-behaved perturbative expansions:

\[
A_g(\alpha_s(\bar{\mu})) = \sum_{n=1}^{\infty} A_g^{(n)} \left( \frac{\alpha_s(\bar{\mu})}{\pi} \right)^n
\]

\[
B_g(\alpha_s(\bar{\mu})) = \sum_{n=1}^{\infty} B_g^{(n)} \left( \frac{\alpha_s(\bar{\mu})}{\pi} \right)^n
\]

\[
A_g^{(1)} = C_A = N_c = 3
\]

\[
A_g^{(2)} = \frac{C_A}{2} \left[ C_A \left( \frac{67}{18} - \frac{\pi^2}{6} \right) - \frac{5}{9} n_F \right]
\]

\[
B_g^{(1)} = -\frac{11C_A - 2n_F}{6}
\]

\[
B_g^{(2)} = C_A^2 \left( \frac{23}{24} + \frac{11}{18} \pi^2 - \frac{3}{2} \zeta(3) \right) + \frac{1}{2} C_F n_F
\]

\[
- C_A n_F \left( \frac{1}{12} + \frac{\pi^2}{9} \right) - \frac{11}{8} C_A C_F
\]

\(\zeta(3)\) is the third Riemann function; \(n_F = 5; C_F = 4/3\)

- \(A_g^{(i)}\) and \(B_g^{(i)}\) are larger than their fermionic counterparts; \(\rightarrow\) more soft gluon radiation in \(gg\) subprocesses
• $W_{gg}(b, c/b, x_A, x_B)$ may be written in factored form:

$$W_{gg}(b, \frac{c}{b}, x_A, x_B) = f_{g/A}(x_A, \mu, \frac{c}{b}) f_{g/B}(x_B, \mu, \frac{c}{b})$$

• $f_{g/A}$ and $f_{g/B}$ are modified gluon parton distributions:

$$f_{g/A}(x_A, \mu, \frac{c}{b}) = \sum_a \int_{x_A}^{1} \frac{d\xi}{\xi} \phi_{a/A}(\xi, \mu) C_{a\to g} \left( \frac{x_A}{\xi}, \mu, \frac{c}{b} \right)$$

$\phi_{a/A}$ is a normal parton density (e.g., CTEQ, MRST)

• The short-distance coefficient functions are expanded in a perturbative series

$$C_{a\to b}(z, \mu, \frac{c}{b}) = \sum_{n=0} C_{a\to b}^{(n)}(z, \mu, b) \left( \frac{\alpha_s(\mu)}{\pi} \right)^n$$

$$C_{g\to g}^{(0)}(z, \mu, \frac{c}{b}) = \delta(1 - z)$$

$$C_{i\to g}^{(0)}(z, \mu, \frac{c}{b}) = 0$$

$$C_{g\to g}^{(1)}(z, \mu, \frac{c}{b}) = \delta(1 - z) \left[ C_A \left( \frac{\pi^2}{4} + \frac{5}{4} \right) - \frac{3}{4} C_F \right] - P_{g\to g}(z) \ln \left( \frac{\mu b}{c} \right)$$

$$C_{i\to g}^{(1)}(z, \mu, c/b) = \frac{1}{2} C_F z - P_{i\to g}(z) \ln \left( \frac{\mu b}{c} \right)$$
The Sudakov function depends only on $Q$ and on the perturbatively calculable functions $A_g$ and $B_g$

The function has a pronounced minimum at very small $b$, $b \sim 0.02 \text{ GeV}^{-1}$

Sudakov factor strongly suppresses the regions of both large and small $b$

Larger Sudakov function at large $b$ at NLO $\rightarrow$ the region of small $Q_T$ is more suppressed; shift of the peak of $d\sigma/dy dQ_T$ to larger $Q_T$ at higher orders
The Sudakov function depends only on $Q$ and on the perturbatively calculable fermionic functions $A_q$ and $B_q$.

The second-order $B_q^{(2)}$ plays a much less significant role in $Z$ production than $B_g^{(2)}$ in Higgs boson production.

Sudakov factor $S_g(b)$ is larger than $S_q(b)$.

Larger Sudakov function at large $b$ for the Higgs boson case $\rightarrow$ the region of small $Q_T$ is more suppressed; the peak of $d\sigma/dy dQ_T$ occurs at larger $Q_T$ for the Higgs boson than for the $Z$ boson.
**Expression for** $bW(b, Q)$

- The expression in impact parameter space that includes resummation of the large logarithmic terms is $W(b, Q)$

$$W(b, Q) = W(b, \frac{c}{b}) e^{-S(b, Q)}$$

- The Sudakov factor $S(b, Q)$ depends on $b$ and $Q$ but not on $\sqrt{S}$

- $W(b, c/b, x_A, x_B)$ may be written in factored form:

$$W(b, \frac{c}{b}, x_A, x_B) = f_{g/A}(x_A, \mu, \frac{c}{b}) f_{g/B}(x_B, \mu, \frac{c}{b})$$

- $f_{g/A}$ and $f_{g/B}$ are modified parton distributions

- $\sqrt{S}$ dependence enters through the parton densities
The function is peaked sharply near \( b \sim 0.05 \text{ GeV}^{-1} \) (c.f., \( Q_T \sim 20 \text{ GeV} \)) well within the region of applicability of perturbative QCD.

The function has essentially no support for \( b > 0.5 \text{ GeV}^{-1} \).

Expect, therefore, that the non-perturbative input at large \( b \) will play a negligible role in Higgs boson production at LHC energies.
The function is peaked sharply near $b \sim 0.12 \text{ GeV}^{-1}$, at about twice the value for Higgs boson production (c.f., $Q_T \sim 8 \text{ GeV}$) but still within the region of applicability of perturbative QCD.

The function spreads into the region $b > 1.0 \text{ GeV}^{-1}$ where non-perturbative physics may become relevant.

Expect that predictions for the $Q_T$ distribution for the Higgs boson will be less sensitive to non-perturbative physics than those for the Z at LHC energies.
RESUMMATION SCHEME

- In the CSS formalism, Sudakov exponent $S(b, Q)$ and coefficient functions $C_{i \rightarrow j}$ are process dependent

- Possible to reorganize the procedure such that these functions are universal

  Catani, deFlorian, Grazzini, NP B596, 299 (2001)

- Introduce an all-orders process-dependent hard part

  \[
  H_{gg}(\alpha_s(Q)) \text{ such that } \qquad
  W_{H}^{\text{pert}}(b, Q, x_A, x_B) \rightarrow \sigma_{gg \rightarrow hX}^{(0)} \times H_{gg}(\alpha_s(Q)) \times \\
  \sum_{a,b} [\phi_{a/A} \otimes C_{a \rightarrow g}] \otimes [\phi_{b/B} \otimes C_{b \rightarrow g}] \times e^{-S(b,Q)}
  \]

  with

  \[
  H_{gg}(\alpha_s(Q)) = \sum_n H_{gg}^{(n)}(\alpha_s/\pi)^n
  \]

  and $H_{gg}^{(0)} = 1$

- Universal $S(b, Q)$ and $C_{i \rightarrow j}$ can be defined by selecting a “resummation scheme”

- Reorganization affects only the perturbative part of $W(b, Q)$. Our approach for extrapolating into the non-perturbative region of large $b$ could also be used in this modified approach
4. **Non-perturbative Region of Large Impact**

**Parameter** $b$

- Typical form for the function $bW(b, Q)$

- Fourier transform

$$ \frac{d\sigma^{(\text{resum})}}{dydQ_T^2} = \int \frac{db}{2\pi} J_0(Q_T b) bW(b, Q) $$

- $W^{\text{pert}}(b, Q)$ is valid for $b < 1/\mu_0 \sim 1 \text{ GeV}^{-1}$

- An expression is required for $bW(b, Q)$ valid for all $b$ in order to perform the integral. Need non-perturbative input at large $b$
\textbf{PREDICTIVE POWER OF THE RESUMMATION FORMALISM}\textsuperscript{a}

- \( b \)-space distribution:
  \[
  \int_0^\infty db \, J_0(Q_T b) \, bW(b, Q)
  \]

- pQCD dominates if \( \int_0^{b_{\text{max}}} db(...) \gg \int_{b_{\text{max}}}^\infty db(...) \)

- or if the saddle point \( b_{sp} \ll b_{\text{max}} \):
  - \( b \)-dep of \( be^{-S(b, Q)} \) \( \rightarrow b_{sp} \propto (\frac{\Lambda_{\text{QCD}}}{Q})^\lambda, \lambda \sim 0.6 \)
  - \( b \)-dep of the parton densities \( \phi(x, \frac{1}{b}) \) from DGLAP evolution
    \[
    \frac{d}{db} \phi(x, \frac{1}{b}) = -\frac{1}{b} \frac{d}{d \ln \frac{1}{b}} \phi(x, \frac{1}{b}) < 0 \text{ for } x < x_c \sim 0.1
    \]

Increase of \( \sqrt{S} \Rightarrow \) smaller \( b_{sp} \) and narrower \( bW(b, Q) \)

Predictive power improves with \( \sqrt{S} \)

\textsuperscript{a} Qiu and Zhang, Phys. Rev. D63, 114011 (2001)
EXTRAPOLATION INTO THE REGION OF LARGE $b$

- To perform the Fourier transform

$$\frac{d\sigma^{(\text{resum})}}{dydQ_T^2} = \int \frac{db}{2\pi} J_0(Q_T b) bW(b, Q)$$

an expression is required for $bW(b, Q)$ valid for all $b$

- In the CSS approach a parameter $b_*$ is introduced

$$W_{\text{CSS}}(b, Q) \equiv W_{\text{pert}}(b_*, Q) F^{NP}(b, Q)$$

- $b_* \equiv b/\sqrt{1 + (b/b_{\text{max}})^2} < b_{\text{max}} = 0.5 \text{ GeV}^{-1}$

- $F^{NP} \sim e^{-\kappa(Q, g_1, g_2, \ldots) b^2}$ a Gaussian with predicted $Q$-dependence; fit parameters, $g_1, g_2, \ldots$

- $F^{NP} < 1$ for all $b$

- The use of $b_*$ modifies $bW(b, Q)$ even in the perturbative region

- Important effect on $\sqrt{S}$ dependence

- $b_* < b$ for all $b \neq 0 \rightarrow$

$$W_{\text{pert}}(b_*, Q) < W_{\text{pert}}(b, Q) \text{ for } b < b_{\text{sp}} \text{ and }$$

$$W_{\text{pert}}(b_*, Q) > W_{\text{pert}}(b, Q) \text{ for } b > b_{\text{sp}}$$

- As $\sqrt{S}$ increases, $b_{\text{sp}}$ shifts down, $W_{\text{pert}}(b, Q)$ becomes narrower and steeper $\rightarrow$ larger deviation of $W_{\text{pert}}(b_*, Q)$ from $W_{\text{pert}}(b, Q)$
Qiu-Zhang Extrapolation to the Large $b$ Region

\[ W(b, Q) = \begin{cases} 
  W_{\text{pert}}(b, Q) & b \leq b_{\text{max}} \\
  W_{\text{pert}}(b_{\text{max}}, Q) F^{NP}(b, Q; b_{\text{max}}) & b > b_{\text{max}} 
\end{cases} \]

- **Virtue:** Preserves perturbative answer for small $b$

- **Functional form of $F^{NP}(b, Q, b_{\text{max}})$?**
  
  - By extrapolating the resummation/evolution equations to large $b$, Qiu and Zhang motivate a term in $F^{NP}(b, Q; b_{\text{max}}) \propto e^{-g(b^2)^{\tilde{\alpha}}}$, with $\tilde{\alpha} < \frac{1}{2}$

  - Parameters $g$ and $\tilde{\alpha}$ are fixed by matching the $b$-dependence of $W(b, Q)$ at $b = b_{\text{max}}$ (1st and 2nd derivatives)

  - Add $g' / \mu^2$ power corrections to evolution equations

  \[ \rightarrow e^{-g'(b^2)} \text{ Gaussian behavior for } F^{NP} \]

  - Parameter $g'$ fixed by fitting Drell-Yan, $W$, $Z$ data

\[
F^{NP}(b, Q; b_{\text{max}}) = \exp \left\{-\ln\left(\frac{Q^2 b_{\text{max}}^2}{\alpha_c^2}\right) \left[ g_1 \left( (b^2)^{\tilde{\alpha}} - (b_{\text{max}}^2)^{\tilde{\alpha}} \right) \right. \right.
\]
\[
\left. \left. \text{(power correction)} + g_2 \left( b^2 - b_{\text{max}}^2 \right) \right] \right. \]
\[
\left. \left. \text{(intrinsic p_T)} - \bar{g}_2 \left( b^2 - b_{\text{max}}^2 \right) \right. \right. \]

---

\textsuperscript{a} Qiu and Zhang, PRL 86, 2724(2001), PRD63, 114011(2001).
Comparison of Different Non-perturbative Forms

- Numerator of the ratio is the form used by Ladinsky and Yuan with the updated parameters of Landry et al.

- Denominator is the form used by Qiu and Zhang, with $g_2 = \bar{g}_2 = 0$

- Even in the small $b$ perturbative region, the CSS/LY form reduces the ratio for $b < 0.2$ and enhances it for $b > 0.2$ → shift to smaller $Q_T$ in the location of the maximum of $d\sigma/dy dQ_T$ and narrowing of the predicted peak.

- Note the strong dependence on $\sqrt{S}$. 
5. Predictions

- For $A_g$ and $B_g$ in the Sudakov factor, use the expansion valid through second order ($n = 2$).
- For $C$ functions, use the expansion through $n = 1$ (Results are therefore consistently at NLL accuracy).
- CTEQ5M parton densities and NLO $\alpha_s(\mu)$
- Parton-level hard-scattering functions valid through first-order in $\alpha_s$
- Central value $\mu = c/b$ in the resummed term, with $c = 2e^{-\gamma_E}$; in the $Y$ function, select a fixed scale $\mu = \kappa \sqrt{m_h^2 + Q_T^2}$, with $\kappa = 0.5$
- Extrapolation into the non-perturbative region of large $b$ with the Qiu-Zhang form (begin with $g_2 = 0$ and $\bar{g}_2 = 0$ in $F^{NP}$ as default choices, and then vary these)
- Integral form for the Bessel function for numerical accuracy $J_0(z) = \frac{1}{\pi} \int_0^\pi \cos \left( z \sin(\theta) \right) \, d\theta$
- Recall

$$
\frac{d\sigma^{\text{total}}_{AB \to hX}}{dydQ_T^2} = \frac{d\sigma^{\text{resum}}_{AB \to hX}}{dydQ_T^2} + \frac{d\sigma^{(Y)}_{AB \to hX}}{dydQ_T^2}
$$
Observe the divergence as $Q_T \to 0$ of the fixed-order perturbative result and the numerical near equality of the perturbative result and its $Q_T \to 0$ asymptotic form at small $Q_T$.

The total prediction is dominated by the all-orders resummed term for $Q_T \leq Q$.

The resummed result makes a smooth transition to the fixed-order perturbative result near or just above $Q_T = Q$, without need of a supplementary matching procedure, even for $d\sigma / dy dQ_T$. 
Higgs boson differential cross section at LHC

- Prediction for $m_h = M_Z$
Z boson differential cross section at LHC

- The peak occurs at a smaller value of $Q_T$ for $Z$ production. At $y = 0$, the peak is at $Q_T \sim 4.8$ GeV for the $Z$, and at $Q_T \sim 11.6$ GeV for the Higgs boson at $m_h = m_Z$

- Narrower distribution for $Z$ production; half-maxima $Q_T \sim 16$ GeV ($Z$), and $Q_T \sim 35$ GeV (Higgs)

- The larger QCD color factors produce more gluonic showering in the $gg$ subprocess that dominates Higgs boson production than in fermionic subprocesses relevant for $Z$ production. After resummation, the enhanced showering suppresses the large-$b$ (small $Q_T$) region more effectively for Higgs boson production
The peak of the $Q_T$ distribution shifts to greater $Q_T$ as $m_h$ grows.

For $Z^*$ masses above $M_Z$, the production model is unchanged except for the difference in mass.

At $y = 0$, predict

<table>
<thead>
<tr>
<th>$m_h$ (GeV)</th>
<th>$M_Z$</th>
<th>$Q_T^{\text{peak}}$ (GeV)</th>
<th>$c.f.$ $Q_T^{\text{peak}}$ $\simeq$ 11 GeV at $m_h = 125$ GeV (Les Houches’01)</th>
</tr>
</thead>
<tbody>
<tr>
<td>125</td>
<td>125</td>
<td>11.6</td>
<td>11.6</td>
</tr>
<tr>
<td>150</td>
<td>150</td>
<td>13.6</td>
<td>13.6</td>
</tr>
<tr>
<td>200</td>
<td>200</td>
<td>14.9</td>
<td>14.9</td>
</tr>
<tr>
<td>225</td>
<td>225</td>
<td>17.2</td>
<td>17.2</td>
</tr>
</tbody>
</table>
Average $< Q_T >$ for Higgs boson production at LHC

- $< Q_T >$ grows from about 41 GeV at $m_h = M_Z$ to about 65 GeV at $m_h = 200$ GeV
- Nearly a straight line over the range shown, with $< Q_T > \simeq 0.21m_h + 22$ GeV
- Since $Q_T \sim 1/b$, the saddle point position suggests $< Q_T > \propto 1/b_{SP} \propto m_h^\lambda$, with fractional power $\lambda$. For large $m_h$, linear fit is a good approximation to fractional power dependence over a limited range in $m_h$.  

$\sqrt{s}=14$ TeV

$y = 0$
Root-mean-square $< Q_T^2 >^{1/2}$ for Higgs boson production

$\sqrt{s} = 14$ TeV
$y = 0$

- $< Q_T^2 >^{1/2}$ grows from about 65 GeV at $m_h = M_Z$ to about 98 GeV at $m_h = 200$ GeV
- Nearly a straight line over the range shown
- For $Z$ production: $< Q_T > = 25$ GeV and $< Q_T^2 >^{1/2} = 38$ GeV. The difference $< Q_T^h > - < Q_T^Z > \simeq 16$ GeV at $m_h = M_Z$ is a manifestation of more significant gluonic radiation in Higgs boson production.
Renormalization/factorization scale dependence

- Default choice $\mu = c/b$ with $c = 2e^{-\gamma_E}$; scale varies with the integration variable $b$. Two other choices are independent of $b$ but proportional to the hard-scale of the collision, $\mu = 0.5\sqrt{m_h^2 + Q_T^2}$ and $\mu = 2\sqrt{m_h^2 + Q_T^2}$.

- Scale dependence can shift the position of the peak by about 1.5 GeV; corresponding changes in the normalization above and below the peak position.
  $d\sigma/dy dQ_T$ at the peak position is shifted by 4 to 5%.

- Anticipate similar level of uncertainty associated with resummation scheme dependence.
Dependence on parameters in the non-perturbative input

\[ R_{G^2} \]

- In \( G^2 = g_2 \ln\left(Q^2b_{\text{max}}^2/c^2\right) + \bar{g}_2 \), the default choice is \( g_2 = \bar{g}_2 = 0 \) for Higgs production.

- \( G^2 = 0.4 \text{ GeV}^2 \) was found to fit FNAL \( W \) and \( Z \) data best.

- Results in the figure for \( G^2 = 0.8 \text{ GeV}^2 \) and \( G^2 = 1.6 \text{ GeV}^2 \) show negligible influence of the non-perturbative contributions for Higgs production. The variations are within numerical uncertainties.

Scale dependence is the principal source of uncertainty. Results are very stable except for \( Q_T \ll Q_T^{\text{peak}} \).
6. CONCLUSIONS AND DISCUSSION

- Subprocess $g + g \rightarrow hX$ dominates inclusive Higgs boson production at LHC with $m_h < 200$ GeV

- The two large scales $m_h$ and $Q_T$ and the fact that the fixed-order QCD contributions are singular as $Q_T \rightarrow 0$, necessitate all-orders resummation of large logarithmic contributions to obtain predictions for $Q_T$ distributions

- At LHC energies, $x_A \sim x_B \sim m_h/\sqrt{S} \sim 0.009$ (for $m_h = 125$ GeV) are small, and the gluon distribution evolves steeply at small $x$. The saddle point in $b$ of the Fourier transform from $b$-space to $Q_T$ space is well into the region of perturbative validity

- Resummed $Q_T$ distributions at LHC determined primarily by the perturbatively calculated $b$-space distributions at small $b$, as long as the assumed form for the non-perturbative input does not modify the resummed distribution in the perturbative region

- Predictions presented for $Q_T$ distributions of Higgs boson and $Z$ production at $\sqrt{S} = 14$ TeV for $m_h = M_Z$ to $m_h = 200$ GeV
• Irreducible backgrounds in the $h \rightarrow \gamma\gamma$ decay channel arise from fermionic subprocesses (e.g., $q\bar{q} \rightarrow \gamma\gamma X$; $qg \rightarrow \gamma\gamma X$) and gluonic subprocesses (e.g., $gg \rightarrow \gamma\gamma X$)

• For $M_{\gamma\gamma} = m_h$, the shape of the $Q_T$ spectrum of the $gg$ box contribution to the irreducible background will be the same after soft gluon resummation as that for the Higgs boson

• $q\bar{q} \rightarrow \gamma\gamma X$ subprocess, has the same initial state structure as $Z$ production. The $Q_T$ spectrum of the $Z$ is softer than that for the Higgs boson because there is less gluon radiation in fermionic subprocesses

• Suggestion a selection of events with large $Q_T^{\gamma\gamma}$ could help to improve $S/B$