Precision Measurements and Parton Distribution Functions

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I thank my collaborators for providing many useful slides. Special thanks to Qing-Hong Cao, Chuan-Ren Chen, Joey Huston, Hung-Liang Lai, Jon Pumplin, Pavel Nadolsky, and Wu-Ki Tung.
Wu-Ki Tung
1939-2009

- passed away on March 30, 2009
- the founder of “The Coordinated Theoretical-Experimental Project on Quantum Chromodynamics” (CTEQ) Collaboration.
- a founding member of Overseas Chinese Physics Association (OCPA)
- The last publication by himself is an invited article on Bjorken scaling in the new on-line “Scholarpedia” web site, sent in less than a month before his death.

http://www.scholarpedia.org/article/Bjorken_scaling
Remembering Wu-Ki

Reminded by my colleague Chih-Yung Chien (at JHU)

Two most famous sentences from Wu-Ki:

**Of Course**

**How do I know**

I will tell you some of those stories (O and H) in this talk.
Timeline of CTEQ PDFs

- Each study is well motivated by experimental data.

- What will the upcoming LHC data tell us about the yet-to-be explored PDFs?
Most precise measurement of W boson mass was done at Tevatron.

Most precise measurement of Top quark mass was done at Tevatron.
Outlines

- Precision measurements at Tevatron Run-2 and LHC:
  - W/Z Physics

- Impact of New CTEQ Parton Distribution Functions to LHC Phenomenology:
  - W/Z, Top and Higgs Physics
$W$-boson physics

1. W-boson production and decay at hadron collider
2. How to measure $W$-boson mass and width?
3. High order radiative corrections:
   - QCD (NLO, NNLO, Resummation)
   - EW (QED-like, NLO)
4. ResBos-A and its predictions
Theory requirements for Tevatron Run-II and LHC:

- Theory framework for Tevatron Run-I
  - \( O(\alpha_s) \) (NLO-QCD) corrections
  - \( O(\alpha) \) (QED) corrections

- Run-II experimental targets:
  \[ \frac{\delta \sigma_{tot}}{\sigma_{tot}} \sim 2 - 3\% \]
  \[ \delta M_W \sim 30 \text{ MeV} \]

- Many factors contribute at a percent level:
  - \( O(\alpha_s^2) \) (NNLO-QCD) corrections
  - \( O(\alpha) \) (NLO-EW) corrections
  - uncertainties of parton distributions
  - power corrections to resummed cross sections

}\{ Adequate for comparison to Run-I data

\{ Task: consistent and efficient implementation of these effects
Theory Calculations

There are a variety of programs available for comparison of data to theory and/or predictions.

- Tree level (Alpgen, CompHEP, Grace, Madgraph…)
  - Les Houches accord
- Parton shower Monte Carlos (Herwig, Pythia,…)
  - MC@NLO
- $N^n$LO (EKS, Jetrad, Dyrad, Wgrad, Zgrad,…)
  - recover NLO (NNLO?) normalization
- Resummed (ResBos)

Important to know strengths/weaknesses of each.
NLO Electroweak Calculations

- $\mathcal{O}(\alpha)$ QED corrections to $W/Z$ lepton decays
  F.A. Berends et al., Z. Physik C27 (1985) 155,365

- Electroweak corrections to $W$ production
  - Pole approximation ($\sqrt{s} = M_W$)
  - Complete $\mathcal{O}(\alpha)$ corrections
    C.M. Carloni Calame et al., JHEP 12 (2006) 016

- Electroweak corrections to $Z$ production
  - $\mathcal{O}(\alpha)$ photonic corrections
  - Complete $\mathcal{O}(\alpha)$ corrections
Multiple Photon Emissions

- Higher-order (real+virtual) QED corrections to $W/Z$ production
  → **HORACE** (Pavia): QED Parton Shower + NLO electroweak corrections to $W/Z$ production ($Z$ production available soon)
    
  
  → **WINHAC** (Cracow): YFS exponentiation + electroweak corrections to $W$ decay
    

- Perfect agreement between **HORACE** and **WINHAC** on multiphoton corrections to all $W$ observables
  

- Recent effort to improve the treatment of multiphoton radiation in **HERWIG** (with **SOPHTY** via YFS) and **PHOTOS** (via QED Parton Shower)
  
  K. Hamilton and P. Richardson, JHEP 0607 (2006) 010

- **$W$-mass shift due to multiphoton radiation is about 10% of that caused by one photon emission → non-negligible for precision $W$ mass measurements!**
  
Higher Order QCD Corrections

• NLO/NNLO corrections to $W/Z$ total production rate

• NLO calculations for $W$, $Z + 1$, 2 jets (DYRAD, MCFM ...)  

• resummation of leading/next-to-leading $p_T/W$ logs (ResBos)  

• NLO corrections merged with HERWIG Parton Shower (MC@NLO)  
  S. Frixione and B.R. Webber, JHEP 0206 (2002) 029

• Multi-parton matrix elements Monte Carlos (ALPGEN, SHERPA...) 
  matched with vetoed Parton Showers  
  M.L. Mangano et al., JHEP 0307 (2003) 001
  F. Krauss et al., JHEP 0507 (2005) 018

• fully differential NNLO corrections to $W/Z$ production (FEWZ)  
Combine QCD and Electroweak

- First attempt: combination of soft-gluon resummation with NLO final-state QED corrections

- Electroweak and QCD corrections can be combined in factorized form to arrive at

\[
\left[ \frac{d\sigma}{d\mathcal{O}} \right]_{\text{QCD} \times \text{EW}} = \left\{ \left[ \frac{d\sigma}{d\mathcal{O}} \right]_{\text{QCD}} \right\} + \left\{ \left[ \frac{d\sigma}{d\mathcal{O}} \right]_{\text{EW}} - \left[ \frac{d\sigma}{d\mathcal{O}} \right]_{\text{LO}} \right\}_{\text{HERWIG PS}}
\]

- QCD \Rightarrow \text{ResBos, MC@NLO, ALPGEN (with CKKW-MLM Parton Shower matching and standard matching parameters), FEWZ, ...}

- EW \Rightarrow \text{Electroweak + multiphoton corrections from HORACE convoluted with HERWIG QCD Parton Shower}

  - NLO electroweak corrections are interfaced to QCD Parton Shower evolution \( O(\alpha \alpha_s) \) corrections not reliable when hard non-collinear QCD radiation is important
  - Beyond this approximation, a full two-loop \( O(\alpha \alpha_s) \) calculation is needed (unavailable yet)

J.H. Kühn et al., hep-ph/0703283
NLO/NNLO\_EW to pp \rightarrow Wj
Shortcoming in fixed order pQCD calculations

- Cannot describe data with small $q_T$ of W-boson.
- Cannot precisely determine $m_W$ at hadron colliders without knowing the transverse momentum of W-boson. Most events fall in the small $q_T$ region.

(at NLO)

Transverse momentum

$$q_T(W)$$
To describe data → Resummation is needed

Dashed: CSS (1,1,1)
Solid: CSS (2,2,1)
Perturbaative

Resummation

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

Dotted: Pert (\(\alpha_s\))
Dot-dashed: Pert (\(\alpha_s^2\))
Resummation effects agree with data very well

\[ P\bar{P} \rightarrow Z \ @ \ Tevatron \]
What is QCD resummation?

- All order quantum corrections

\[
\frac{d\sigma}{dq_T^2} \sim \frac{1}{q_T^2} \sum_{n=1}^{\infty} \sum_{m=0}^{2n-1} \alpha_s^{(n)} \ln^{(m)} \left( \frac{Q^2}{q_T^2} \right) \\
\sim \frac{1}{q_T^2} \left\{ \alpha_s \left( \frac{L}{L+1} \right) + \alpha_s^2 \left( \frac{L^3 + L^2 + L + 1}{L} \right) + \alpha_s^3 \left( \frac{L^5 + L^4 + L^3 + L^2 + L + 1}{L^2 + L + 1} \right) + \cdots \right\}
\]

Resummation is to reorganize the results in terms of the large Log’s.
What is QCD resummation?

- reorganization of logs

\[
\frac{d\sigma}{dq_T^2} \sim \frac{1}{q_T^2} \left\{ [\alpha_s (L+1)] + \alpha_s^2 \left( L^3 + L^2 \right) + \alpha_s^3 \left( L^5 + L^4 \right) + \cdots \right\}
\]

+ [ \alpha_s^2 (L+1) + \alpha_s^3 \left( L^3 + L^2 \right) + \cdots ]

+ [ \alpha_s^3 (L+1) + \cdots ]

+ [ + \cdots ]

Renormalization Group Technique
CSS resummation formalism

\[
\frac{d\sigma}{dq_T^2 dy dQ^2} = \frac{\pi}{S} \sigma_0 \delta \left( Q^2 - M_W^2 \right). \\
\left\{ \frac{1}{(2\pi)^2} \int d^2 b \ e^{i\vec{q}_T \cdot \vec{b}} \tilde{W}(b, Q, x_A, x_B) \cdot [\text{Non-perturbative functions}] \right\} + Y(q_T, y, Q) \\
\tilde{W} = e^{-S(b)} \cdot C \otimes f(x_A) \cdot C \otimes f(x_B) \\
= \sum_j \int_{x_A}^1 \frac{d\xi_A}{\xi_A} C_j \left( \frac{x_A}{\xi_A}, b, \mu \right) \cdot f_{j/\Lambda}(\xi_A, \mu) \\
= \sum_k \int_{x_B}^1 \frac{d\xi_B}{\xi_B} C_k \left( \frac{x_B}{\xi_B}, b, \mu \right) \cdot f_{k/\Lambda}(\xi_B, \mu)
\]

Sudakov form factor

\[ S(b) = \int_{(\frac{b}{\mu})^2}^{Q^2} \frac{d\bar{\mu}^2}{\mu^2} \left[ \ln \left( \frac{Q^2}{\bar{\mu}^2} \right) A(\bar{\mu}) + B(\bar{\mu}) \right] \]

[Non-perturbative functions] are functions of \( (b, Q, x_A, x_B) \) which include QCD effects beyond Leading Twist.
Resummation effects agree with data very well

$P\bar{P} \rightarrow Z \ @$ Tevatron

Predicted by ResBos:

A fortran program that includes the effect of multiple soft gluon emission on the production of $W$ and $Z$ bosons in hadron collisions.
W Charge Asymmetry: A Monitor of DFs

- Difference between u(x) and d(x) in proton cause \( u\bar{d} \rightarrow W^+ \) and \( \bar{u}d \rightarrow W^- \) to be boosted in opposite directions.

\[
A(y_w) = \frac{d \sigma(W^+)/dy_w - d \sigma(W^-)/dy_w}{d \sigma(W^+)/dy_w + d \sigma(W^-)/dy_w}
\]

\[
A(y_w) \approx \frac{u(x_1)d(x_2) - d(x_1)u(x_2)}{u(x_1)d(x_2) + d(x_1)u(x_2)}
\]

Rapidity charge asymmetry is sensitive to \( d(x)/u(x) \) ratio at high-\( x \) → primary interest of PDF fitters.

- cannot reconstruct \( y_w \) directly
- measure charged lepton only

\[
A(\eta_l) = \frac{d \sigma(l^+)/d \eta_l - d \sigma(l^-)/d \eta_l}{d \sigma(l^+)/d \eta_l + d \sigma(l^-)/d \eta_l}
\]
All recent CTEQ and MSTW PDF fits include the effects of soft gluon resummation predicted by ResBos.
The complete NLO EW correction to W and Z boson production in hadron collisions are known.

The NLO QED corrections to the decay of W and Z bosons can be factored out from the complete NLO EW corrections in a gauge invariant way.
Precision measurements require accurate theoretical predictions.

- **ResBos-A:** improved ResBos by including final state NLO QED corrections to $W$ and $Z$ production and decay.

*hep-ph/0401026*
Qing-Hong Cao and CPY

- **Resum+Born**

- **Resum+NLO**

  - and denote FQED radiation corrections, which dominates the W mass shift.
Transverse momentum distribution of charged lepton

$p_T^e$ is sensitive to $q_T^W$

Cuts:

$p_T^{e^+} > 25$ GeV
$E_T > 25$ GeV
$|\eta^{e^+}| < 1.2$
W Boson $q_T$ @ D0 Run-2

Figure: Phys. Rev. Lett. 100, 102002 (2008)
Z-boson physics

1. Help to improve the measurement of W-boson
   - calibrate detector
   - indirect measurement of W-boson width

2. ResBos-A and its predictions
   - effective Born approximation
   - various kinematical distributions
Precision measurement of Z-boson

help to calibrate detector

Mass information comes primarily from lepton $p_T$

- Run 2 goal: calibrate $p_T$ to $\sim 0.01\%$

Use $Z$ decays to model boson $p_T$ distribution, detector response to hadronic recoil energy

Combine lepton and neutrino $p_T$ to form transverse mass ($m_T$) for best statistical power

Additional information from $\nu p_T$

(inferred through measurement of hadronic recoil energy)
1. We are entering the era of precision measurement at hadron colliders.

2. For precision measurement of \( W \) mass, it is needed to include both QCD and EW corrections consistently and efficiently.
   As the first step toward this goal, ResBos-A includes both the initial state multiple soft gluon resummation effect and final state QED corrections (which dominates the \( W \) mass shift).

3. Precision measurement of \( Z \) boson, via the ratio method, can improve \( W \)-boson mass measurement and provide indirect measurement of \( W \)-boson width.

**Precision Electroweak Physics at Hadron Colliders**

http://hep.pa.msu.edu/resum/
Include Initial state QCD soft gluon resummation and Final state QED corrections

For Drell-Yan, W, Z, Higgs, di-photon pairs, etc.

In collaboration with
Csaba Balazs, Pavel Nadolsky, Qing-Hong Cao, Jian-Wei Qiu
(Michigan State, Iowa State)

ResBos: http://hep.pa.msu.edu/resum/
ResBos-A: including final state QED corrections
Plotter: on-line plotting package (by P. Nadolsky)

hep-ph/9505203
hep-ph/9704258
hep-ph/0401026
Impact of New CTEQ Parton Distribution Functions to LHC Phenomenology:

W/Z, Top and Higgs Physics
New Physics signal found?

Excitement at 10 years ago

CDF Run 1A Data (1992-93)


High-x gluon not well known

...can be accommodated in the Standard Model
LHC Parton Kinematics

Sensitive to new region of x and Q values.

Need better determination of PDFs

Need new kind of global analysis, such as “The Combined PDF and P_T Fits”
Recent CTEQ activities

- Preliminary CT09 fit (P.N.)
  - effect of the Tevatron Run-2 jet and $W$ asymmetry data on CT09 PDF's
  - CT09 strangeness at small $x$

- Combined fit of PDF's and Drell-Yan $p_T$ distributions (H.-L. Lai)

- PDF's for leading-order Monte-Carlo programs (H.-L. Lai)
Figure 1: Gluon distributions and uncertainties: CT09G (solid red); fit using CDF run II jets only (short dash blue); fit using D0 run II jets only (long dash green). (A larger weight factor $x^4$ is used in the right-hand figure to accentuate the large-$x$ behavior.)

hep-ph/0904.2424
Comparison of CT09 and CTEQ6.6 gluon PDF uncertainties at $Q=2$ GeV. MSTW08 central fit is also shown.
Comparison of CT09 and CTEQ6.6 gluon PDF uncertainties at $Q=85$ GeV. MSTW08 central fit is also shown.
Combined PDF+ $p_T$ Global Analysis

Precision measurement and combined global analysis of PDF including $P_T$ resummation theory and data

In collaboration with

Hung-Liang Lai, Pavel Nadolsky, and Jon Pumplin
Combined PDF+ $p_T$ Global Analysis

New Inputs:

- Experimentally: include not only rapidity ($y$) but also $p_T$ of Drell-Yan pairs and $Z$ bosons
- Theoretically: include $p_T$ Resummation formalism to account for the soft physics that entangle with multi-scale measurements

New Outputs:

- $F_{NP}$ of non-perturbative function is simultaneously determined, In addition to the PDF $f_a(x,\mu)$. 
Preliminary results
Measurement of g2 from D0

A Study of $Z \rightarrow e^+e^-$ and $Z \rightarrow \mu^+\mu^-$ Events Produced at Low Transverse Momentum Using a Novel Technique

The $Z$ boson transverse momentum, $p_T^Z$, can be decomposed into two components, $a_T$ and $a_L$, that are transverse and parallel, respectively, to the di-lepton thrust axis. Using the $a_T$ distribution of $Z$ decays observed with the DØ detector, we measure $g_2$, a phenomenological parameter in the BLNY non-perturbative form factor. In a combined measurement with di-muon and di-electron decay channels, using approximately 2 fb$^{-1}$ of data, we measure $g_2 = 0.63 \pm 0.02 \pm 0.04$ GeV$^2$. The first uncertainty is experimental and the second uncertainty is due to the PDF dependence of the theoretical prediction.

Translated to $F_{NP}$: $F_{NP}(M_Z)/b^2 = 2.51 \pm 0.15$
Preliminary results

<table>
<thead>
<tr>
<th></th>
<th>CTEQ66 (BLNY)</th>
<th>CTEQ66 (refit g’s)</th>
<th>g2c</th>
<th>g2l</th>
<th>g2h</th>
</tr>
</thead>
<tbody>
<tr>
<td>$g_1$</td>
<td>.210</td>
<td>.234</td>
<td>.294</td>
<td>.409</td>
<td>.219</td>
</tr>
<tr>
<td>$g_2$</td>
<td>.680</td>
<td>.600</td>
<td>.566</td>
<td>.415</td>
<td>.660</td>
</tr>
<tr>
<td>$g_1 g_3$</td>
<td>-.126</td>
<td>-.174</td>
<td>-.194</td>
<td>-.194</td>
<td>-.194</td>
</tr>
<tr>
<td>$F_{NP}(M_Z)/b^2$</td>
<td>2.68</td>
<td>2.51</td>
<td>2.49</td>
<td>2.10</td>
<td>2.73</td>
</tr>
<tr>
<td>$\chi^2_{pt}$ (111 Pts)</td>
<td>403</td>
<td>165</td>
<td>135</td>
<td>155</td>
<td>155</td>
</tr>
<tr>
<td>$\Delta \chi^2_{pt}$</td>
<td>267</td>
<td>30</td>
<td>0</td>
<td>20</td>
<td>20</td>
</tr>
</tbody>
</table>

(This range of 2.10 to 2.75 shall be compared to D0’s 2.36 to 2.66.)
Impact of New CTEQ Parton Distribution Functions to LHC Phenomenology:

W/Z, Top and Higgs Physics
CTEQ6.6 PDFs

CTEQ6.6 PDF’s, heavy flavors and PDF induced correlations between LHC observables

hep-ph/0802.0007

In collaboration with

Pavel Nadolsky, Hung-Liang Lai, Qing-Hong Cao, Joey Huston, Jon Pumplin, Dan Stump, Wu-Ki Tung
NLO calculations using ResBos, WTTOT, MCFM

CTEQ6.5 and CTEQ6.6 cross sections are qualitatively same

At LHC, $\sigma_{W,Z}^{CTEQ6.6M} \approx 1.06 \sigma_{W,Z}^{CTEQ6.1M}$

- reflects a 6% increase in light quark luminosities
  $\mathcal{L}_{q_i\bar{q}_j}(x_1, x_2, Q) = q_i(x_1, Q)\bar{q}_j(x_2, Q)$ at relevant $x$ and $Q$

finer differences with CTEQ6.5 in precision predictions for $W$, $Z$ production, strange-quark scattering
Correlation analysis for collider observables

A technique based on the Hessian method

For $2N$ PDF eigensets and two cross sections $X$ and $Y$:

$$
\Delta X = \frac{1}{2} \sqrt{\sum_{i=1}^{N} (X^{(+)}_i - X^{(-)}_i)^2}
$$

$$
\cos \varphi = \frac{1}{4\Delta X \Delta Y} \sum_{i=1}^{N} (X^{(+)}_i - X^{(-)}_i) (Y^{(+)}_i - Y^{(-)}_i)
$$

$X^{(\pm)}_i$ are maximal (minimal) values of $X_i$ tolerated along the $i$-th PDF eigenvector direction; $N = 22$ for the CTEQ6.6 set

For CT09 PDFs, $N=24$. 
Correlation analysis for collider observables

Correlation angle \( \varphi \)

Determines the parametric form of the \( X - Y \) correlation ellipse

\[
X = X_0 + \Delta X \cos \theta \\
Y = Y_0 + \Delta Y \cos(\theta + \varphi)
\]

- \( \cos \varphi \approx 1 \): \( \delta Y \) and \( \delta X \) are nearly in the same direction.
- \( \cos \varphi \approx 0 \): \( \delta Y \) and \( \delta X \) are nearly perpendicular.
- \( \cos \varphi \approx -1 \): \( \delta Y \) and \( \delta X \) are nearly in opposite directions.

\( X_0, Y_0 \): best-fit values

\( \Delta X, \Delta Y \): PDF errors

Measurement of \( X \) imposes tight constraints on \( Y \). Measurement of \( Y \) imposes loose constraints on \( X \).
Correlations (CT09 PDFs) @ LHC_10

For cross section of $Z$ boson at the LHC_10 TeV

For cross section of $W^+$ boson at the LHC_10 TeV
Correlations (CT09 PDFs) @ LHC_10

For cross section of \( W^- \) boson at the LHC_10 TeV

\[
\text{CT09: } W^- \sigma_{\text{tot}} (Q=85. \text{ GeV})
\]

\[
\begin{array}{c}
\text{Correlation cos(\phi)} \\
10^{-5} \quad 10^{-4} \quad 10^{-3} \quad 10^{-2} \quad 10^{-1} \quad 1 \n\end{array}
\]

\[
\begin{array}{c}
d \quad u \quad g \quad c \quad s 
\end{array}
\]

\[
\text{W^+/W^- vs u/d (x,Q=85. GeV)}
\]

\[
\begin{array}{c}
\text{Correlation cos(\phi)} \\
10^{-5} \quad 10^{-4} \quad 10^{-3} \quad 10^{-2} \quad 10^{-1} \quad 1 
\end{array}
\]

W+/W- vs. u/d at the LHC_10 TeV
Comparison of CT09 and CTEQ6.6 u and d PDF uncertainties at Q=85 GeV. MSTW08 central fit is also shown.
Correlations (CT09 PDFs) @ LHC_10

Cross section of a 500 GeV Higgs boson at the LHC_10 TeV

Top quark pair cross section at the LHC_10 TeV
Correlations (CT09 PDFs) @ LHC_10

Higgs (500 GeV) vs top quark pair

W+ vs Z
Correlation of Z Rapidity distribution at LHC_10 TeV to CT09 PDFs

Sensitive to different parton flavors at different rapidity.
Correlations (CT09 PDFs) for Higgs (120 GeV)

At Tevatron

At LHC 10 TeV

Different sensitivity to partons at various x values lead to different PDF induced uncertainty in cross sections.
Top Quark Pair production rates

At Tevatron Run-2, uncertainty induced by PDFs is sizable.

Uncertainty induced by factorization (and renormalization) scale dependence is large at the LHC. Hence, NNLO calculation is needed.
Use top quark pair production rate to determine the mass of top quark.

Need NNLO result (A. Mitov, et al.)
What’s top mass?

What’s the top mass in a full event generator, such as PYTHIA?

NOBODY KNOWS

Parton showers generate some higher order corrections in the event shape, but with approximations.
Effect of pQCD Resummation:

Higgs Signal and Background
Resummation: effects of different pdf and higher order @ high $p_T$

- new pdf : cteq 6.6M
- matching NNLO ($\alpha_s^4$) in high $p_T$ region

Including K factors in $\frac{d\sigma}{dQ^2dydQ_T}$ grids:

$$k_{pert} = \frac{pert(\alpha_s^3) + pert(\alpha_s^4)}{pert(\alpha_s^3)}$$

$$k_Y = \frac{Y(\alpha_s^3) + Y(\alpha_s^4)}{Y(\alpha_s^3)}$$

Total cross section of $gg \rightarrow H \rightarrow WW \rightarrow \ell^+\ell^-\nu\nu$

$M_H=160$ GeV

<table>
<thead>
<tr>
<th></th>
<th>cteq 6.1M ($\alpha_s^3$)</th>
<th>cteq 6.6M ($\alpha_s^3$)</th>
<th>cteq 6.6M ($\alpha_s^4$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>@Tevatron</td>
<td>2.37 fb</td>
<td>2.26 fb</td>
<td>2.60 fb</td>
</tr>
<tr>
<td>@LHC</td>
<td>174 fb</td>
<td>172 fb</td>
<td>205 fb</td>
</tr>
</tbody>
</table>

Transverse momentum and rapidity of H

\[ gg \rightarrow H \rightarrow WW \rightarrow \ell^+\ell^-\nu\nu \]
The search for Higgs resonance relies on good understanding of the large QCD background.

- It is useful to apply the likelihood analysis to fully differential distributions of the signal and background.
- Resummation is needed for logarithmic corrections of several types from all orders in $\alpha_s$.
  - e.g., $\alpha_s^n \ln^k(Q_T/Q)$ at $Q_T \ll Q$.

Global aspects, such as calibration of collider luminosity and detectors, will affect precision of the measurement of Higgs cross sections.
pQCD Resummation Calculation

NNLL/NLO distributions for Higgs → γγ signal and background (ResBos, normalized: $M_H = 130$ GeV, $128 < Q < 132$ GeV)

$Q_T$ and $\gamma_{\gamma_1} - \gamma_{\gamma_2}$ in the lab frame

Decay angles $\theta_*, \phi_*$ in the $\gamma\gamma$ rest frame

no singularities, in contrast to the fixed-order rate
Direct diphotons

The dominant production mode; evaluated up to NLO in $\alpha_s$

Balazs, Berger, Nadolsky, Yuan, 2006

$q\bar{q} + qg$ channel

- NLO matrix elements: Aurencche et al.; Bailey, Owens, Ohnemus
- $q\bar{q}$ scattering dominates at the Tevatron
- $qg$ scattering is strongly enhanced at the LHC by photon radiation off final-state quarks
Effect of initial state heavy parton

\[ \mathcal{O}(\alpha_S) \] resummed cross section

Simplified ACOT scheme was used

\[ \therefore M_H \neq 0 \text{ only in the gluon-initiated channels} \]

\[ S_{pert}(b, Q) \text{ and functions } C_{ijq}^{in}(x, b\mu_F), C_{bj}^{out}(z, b\mu_F) \text{ do not depend on the mass} \]

Only \[ C_{ijq}^{in}(x, b, M, \mu_F) \text{ retains mass} \]

The effect from initial state heavy parton mass is included in perturbative Wilson coefficient function, using CSS resummation fromalism in the general-mass variable-flavor number scheme.

This effect has been included in the ResBos code.
Figure 2: Transverse momentum distribution of on-shell Higgs bosons in the $b\bar{b} \rightarrow \mathcal{H}$ channel at (a) the Tevatron and (b) LHC. The solid (red) lines show the $q_T$ distribution in the massive (S-ACOT) scheme. The dashed (black) lines show the distribution in the massless ("ZM-VFN") scheme. The numerical calculation was performed using the programs Legacy and ResBos [29, 30] with the CTEQ5HQ1 parton distribution functions [31]. The bottom quark mass is taken to be $m_b = 4.5$ GeV.
Conclusion

- Precision measurements demand higher order calculations
  - NLO, NNLO, Resummation

- PDFs need to be refined using the early LHC (W, Z and top) data
  - to reliably predict New Physics signal.
Backup Slides
Run-2 W Lepton Asymmetry Data
Run-2 W Lepton Asymmetry Data