C T E Q

Precision Measurements and Parton Distribution Functions

C.-P. Yuan

Michigan State University

May 8, 2009 @ Berkeley Workshop

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.

C T E Q

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

CTEQ

Remembering Wu-Ki

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

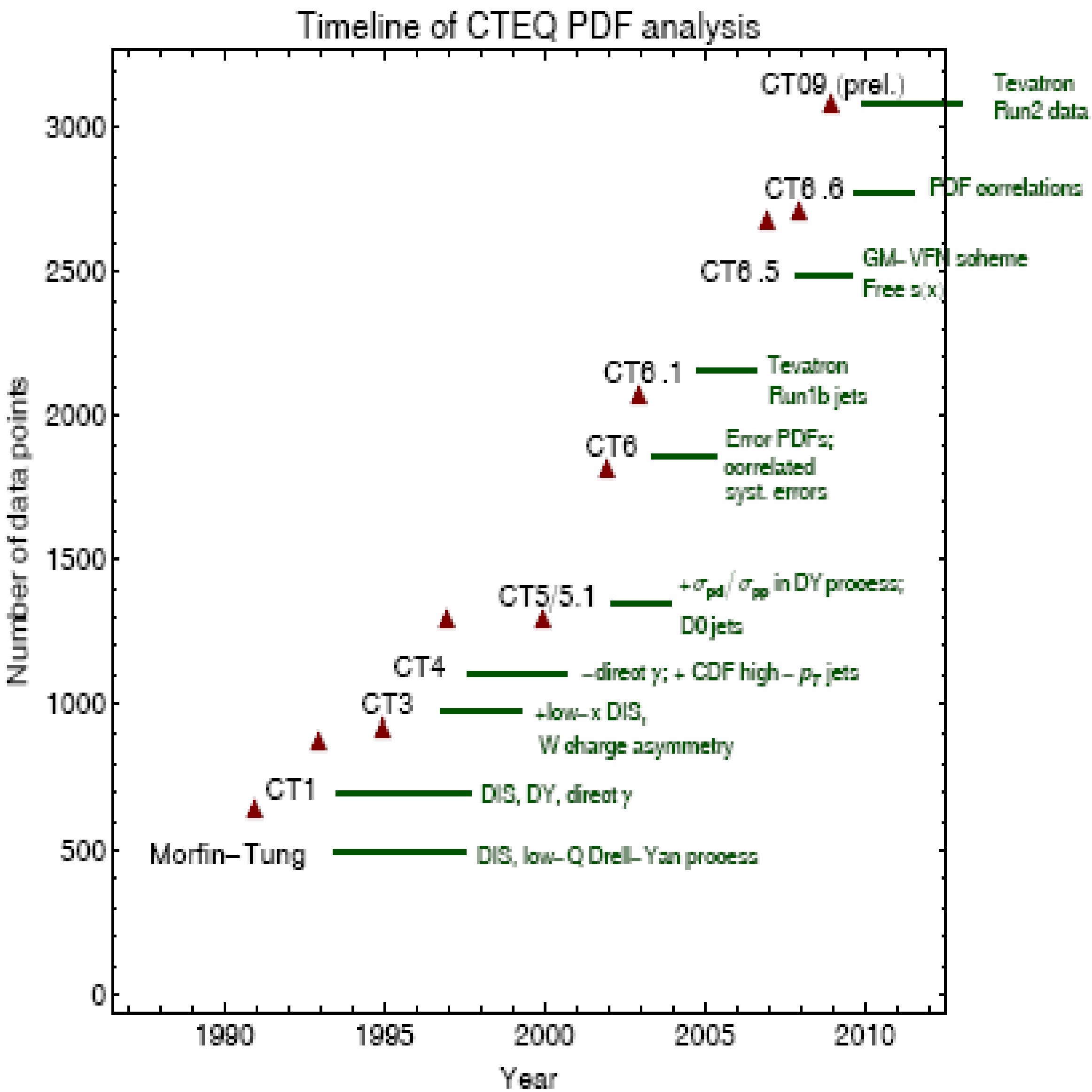
Two most famous sentences from Wu-Ki:

Of Course

How do I know

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

Timeline of CTEQ PDFs



O:

Each study is well motivated by experimental data

H:

What will the upcoming LHC data tell us about the yet-to-be explored PDFs?

Precision Data

- Most precise measurement of W boson mass was done at Tevatron.

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

CTEQ

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

❶ W-boson production and decay at hadron collider

❷ How to measure W-boson mass and width?

❸ High order radiative corrections:

- ☞ QCD (NLO, NNLO, Resummation)
- ☞ EW (QED-like, NLO)

❹ ResBos-A and its predictions

CTEQ

Theory requirements for Tevatron Run-II and LHC:

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

  } Adequate for comparison to Run-I data

- Run-II experimental targets:

$$\delta\sigma_{tot}/\sigma_{tot} \sim 2\ -\ 3\%$$

$$\delta M_W \sim 30 \text{ MeV}$$

- 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

  } 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^nLO (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 ($\sqrt{\hat{s}} = M_W$)

    D. Wackeroth and W. Hollik, Phys. Rev. **D55** (1997) 6788

    U. Baur, S. Keller, D. Wackeroth, Phys. Rev. **D59** (1999) 013002 WGRAD
  - ⋆ Complete $\mathcal{O}(\alpha)$ corrections

    V.A. Zykunov, Eur. P. J. **C3** (2001) 9, Phys. Atom. Nucl. **69** (2006) 1522

    S. Dittmaier and M. Krämer, Phys. Rev. **D65** (2002) 073007 DK

    U. Baur and D. Wackeroth, Phys. Rev. **D70** (2004) 073015 WGRAD2

    A. Arbuzov *et al.*, Eur. Phys. J. **C46** (2006) 407 SANC

    C.M. Carloni Calame *et al.*, JHEP **12** (2006) 016 HORACE

- Electroweak corrections to Z production
  - ⋆ $\mathcal{O}(\alpha)$ photonic corrections

    U. Baur, S. Keller, W.K. Sakumoto, Phys. Rev. **D57** (1998) 199 ZGRAD
  - ⋆ Complete $\mathcal{O}(\alpha)$ corrections

    U. Baur *et al.*, Phys. Rev. **D65** (2002) 033007 ZGRAD2

Multiple Photon Emissions

- Higher-order (real+virtual) QED corrections to W/Z production
  - $\longrightarrow$ HORACE (Pavia): QED Parton Shower + NLO electroweak corrections to W/Z production (Z production available soon)

    C.M. Carloni Calame *et al.*, Phys. Rev. **D69** (2004) 037301

    C.M. Carloni Calame *et al.*, JHEP **05** (2005) 019; JHEP **12** (2006) 016
  - $\longrightarrow$ WINHAC (Cracow): YFS exponentiation + electroweak corrections to W decay

    S. Jadach and W. Placzek, Eur. Phys. J. **C29** (2003) 325
- Perfect agreement between HORACE and WINHAC on multiphoton corrections to all W observables

  C.M. Carloni Calame *et al.*, Acta Phys. Pol. **B35** (2004) 1643
- 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

  P. Golonka and Z. Was, Eur. Phys. J. **C45** (2006) 97

★ W-mass shift due to multiphoton radiation is about 10% of that caused by one photon emission $\longrightarrow$ non-negligible for precision W mass measurements!

C.M. Carloni Calame *et al.*, Phys. Rev. **D69** (2004) 037301

Higher Order QCD Corrections

- NLO/NNLO corrections to W/Z total production rate

  G. Altarelli, R.K. Ellis, M. Greco and G. Martinelli, Nucl. Phys. **B246** (1984) 12

  R. Hamberg, W.L. van Neerven, T. Matsuura, Nucl. Phys. **B359** (1991) 343

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

  W.T. Giele, E.W.N. Glover and D.A. Kosower, Nucl. Phys. **B403** (1993) 633

  J.M. Campbell and R.K. Ellis, Phys. Rev. **D65** (2002) 113007

- resummation of leading/next-to-leading $p_\perp^W/M_W$ logs (ResBos)

  C. Balazs and C.P. Yuan, Phys. Rev. **D56** (1997) 5558

- 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)

  C. Anastasiou *et al.* , Phys. Rev. **D69** (2004) 094008

  K. Melnikov and F. Petriello, Phys. Rev. Lett. **96** (2006) 231803, Phys. Rev. **D74** (2006) 114017

Combine QCD and Electroweak

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

  Q.-H. Cao and C.-P. Yuan, Phys. Rev. Lett. **93** (2004) 042001
  ResBos−A

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

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

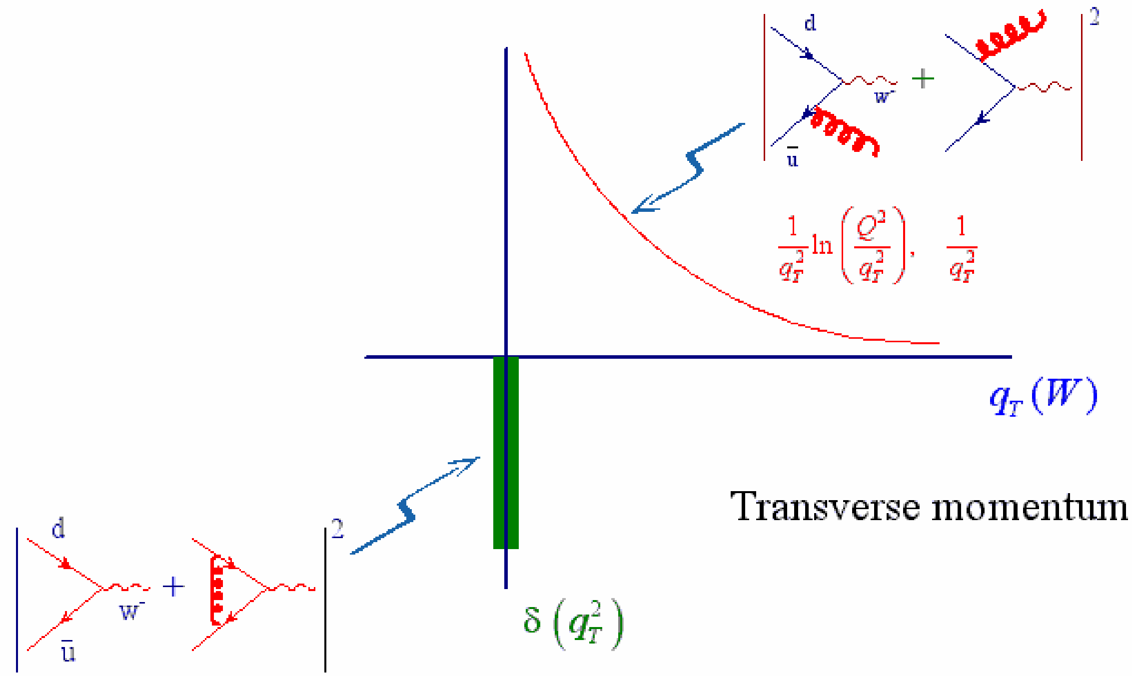
- QCD ⇒ ResBos, MC@NLO, ALPGEN (with CKKW-MLM Parton Shower matching and standard matching parameters), FEWZ, ...
- EW ⇒ Electroweak + multiphoton corrections from HORACE convoluted with HERWIG QCD Parton Shower
  - ⋆ NLO electroweak corrections are interfaced to QCD Parton Shower evolution ⇒ $\mathcal{O}(\alpha\alpha_s)$ corrections not reliable when hard non-collinear QCD radiation is important
  - ⋆ Beyond this approximation, a full two-loop $\mathcal{O}(\alpha\alpha_s)$ calculation is needed (unavailable yet)

    J.H. Kühn *et al.*, hep-ph/0703283
    $\text{NLO/NNLO}_{\text{EW}}$ to $pp \to Wj$

C T E Q

Shortcoming in fixed order pQCD calculations

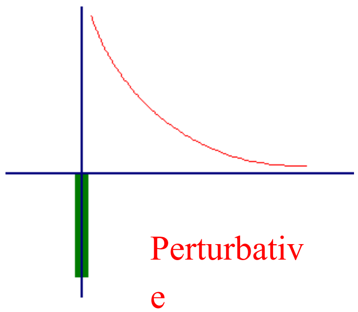
- Cannot describe data with small q_T of W-boson.
- Cannot precisely determine m_W at hadron colliders without knowing the transverse momentum of W-boson. Most events fall in the small q_T region.

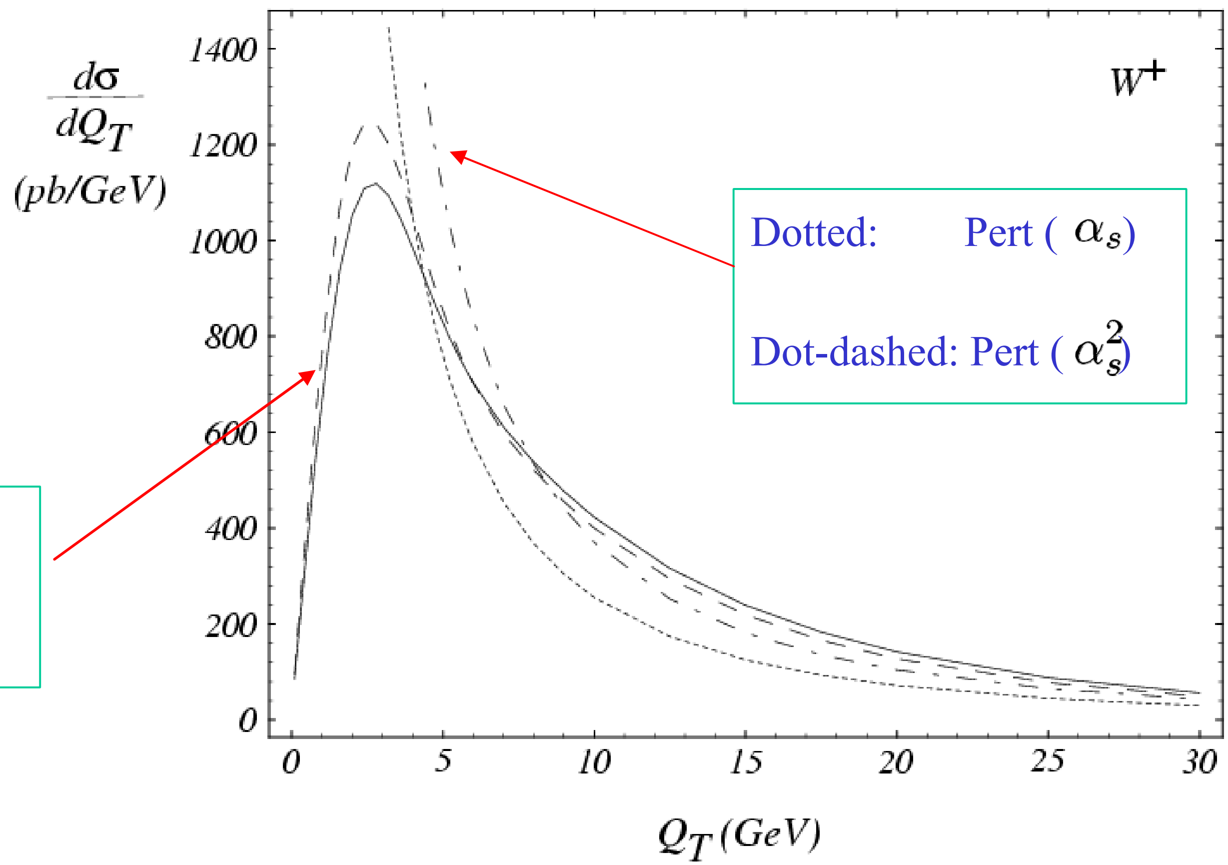


(at NLO)

C T E Q

To describe data ⇒ Resummation is needed





Dotted: Pert (α_s)

Dot-dashed: Pert (α_s^2)

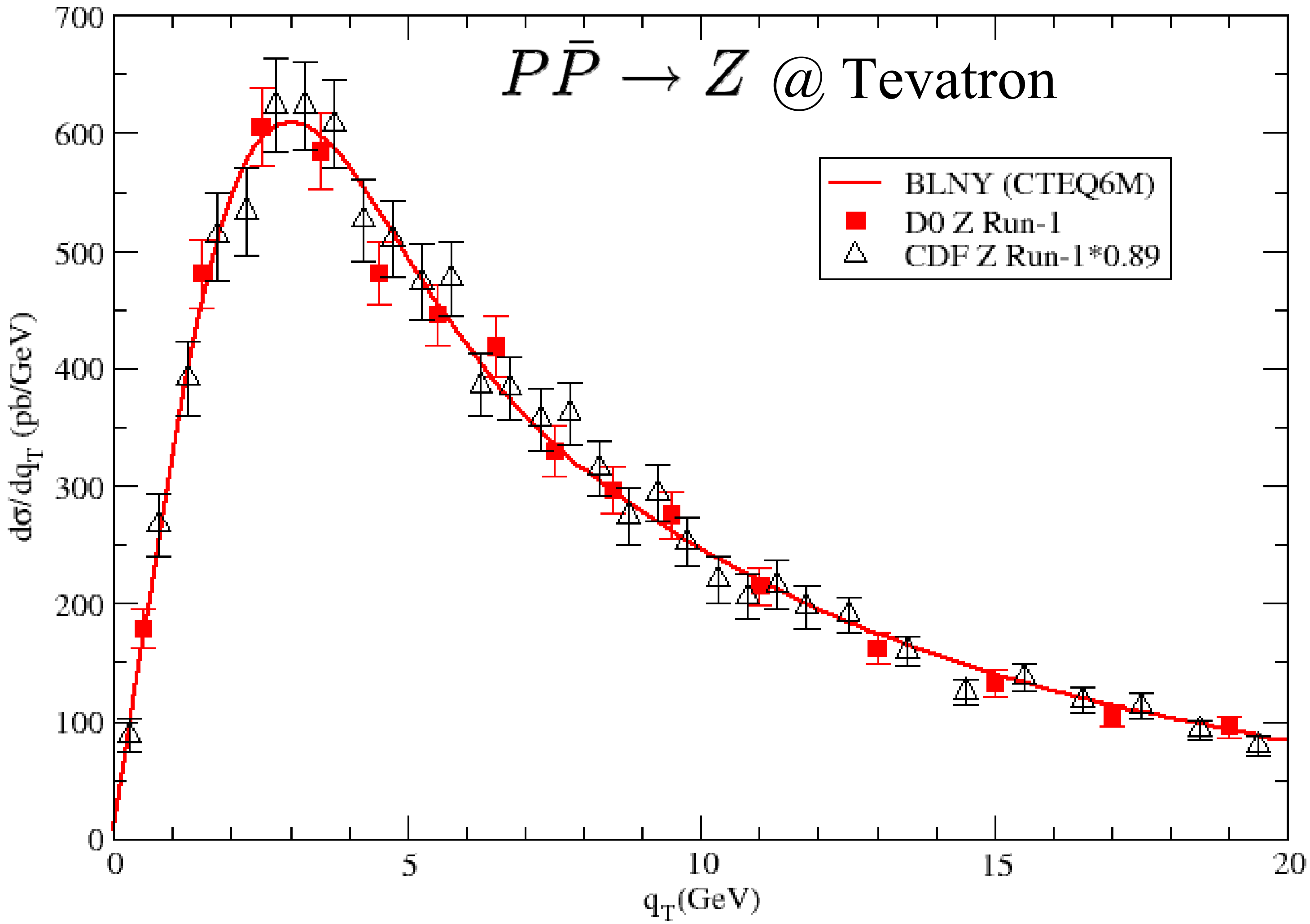
Dashed: CSS (1,1,1)

Solid: CSS (2,2,1)

Resummation

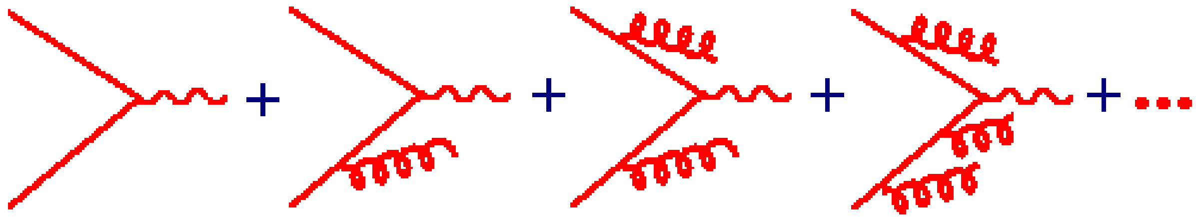
C T E Q

Resummation effects agree with data very well



What is QCD resummation ?

- All order quantum corrections



$$\frac{d\hat{\sigma}}{dq_T^2} \sim \frac{1}{q_T^2} \sum_{n=1}^{\infty} \sum_{m=0}^{2n-1} \alpha_S^{(n)} \ln^{(m)} \left(\frac{Q^2}{q_T^2} \right) \qquad L \equiv \ln \left(\frac{Q^2}{q_T^2} \right)$$

$$\sim \frac{1}{q_T^2} \{ \quad \alpha_S \left(\underline{L+1} \right)$$

$$+\alpha_S^2 \left(\underline{L^3 + L^2} + \underline{L+1} \right)$$

$$+\alpha_S^3 \left(\underline{L^5 + L^4} + \underline{L^3 + L^2} + \underline{L+1} \right)$$

$$+ \cdots \quad \}$$

Resummation is to reorganize the results in terms of the large Log's.

What is QCD resummation ?

- reorganization of logs

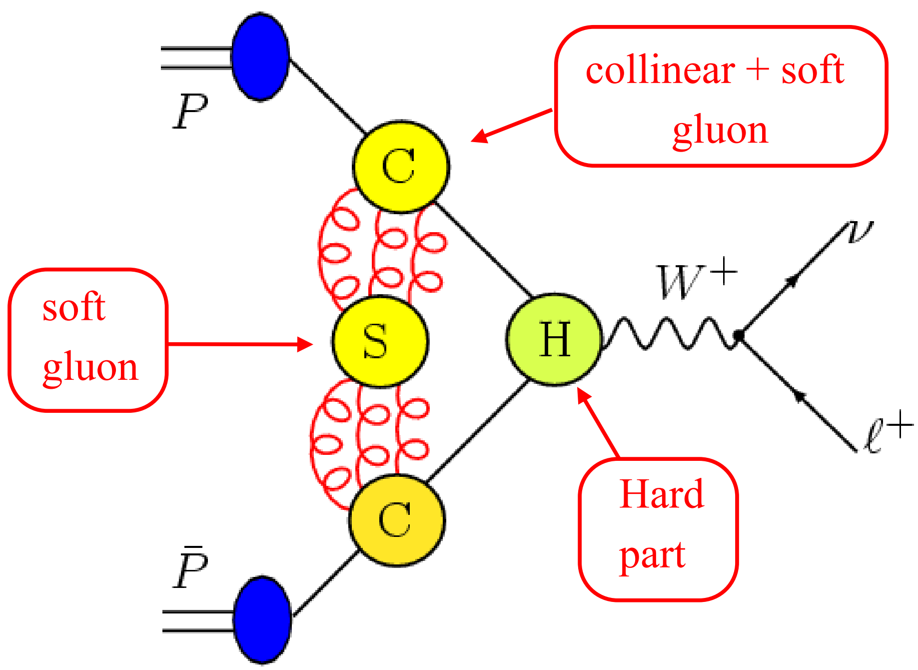
$$\frac{d\sigma}{dq_T^2} \sim \frac{1}{q_T^2}\Big\{ \quad [\alpha_S(L+1) \quad +\alpha_S^2(L^3+L^2) + \alpha_S^3(L^5+L^4) \quad +\cdots \;]$$

$$+[\qquad +\alpha_S^2(L+1) \quad +\alpha_S^3(L^3+L^2) \quad +\cdots \;]$$

$$+[\qquad +\alpha_S^3(L+1) \quad +\cdots \;]$$

$$+\cdots \;\Big\}$$

Renormalization Group Technique



CSS resummation formalism

Collins-Soper-Sterman

$$\frac{d\sigma}{dq_T^2\, dy\, dQ^2} = \frac{\pi}{S}\sigma_0 \delta\left(Q^2 - M_W^2\right)\cdot$$

$$\left\{\frac{1}{(2\pi)^2}\int d^2b \quad e^{i\vec{q}_T\cdot\vec{b}}\tilde{W}\left(b,Q,x_A,x_B\right)\cdot \text{[Non-perturbative functions]}\right.$$

$$\left. + Y\left(q_T, y, Q\right)\right\}$$

$$\tilde{W} = e^{-S(b)}\cdot C\otimes f\left(x_A\right)\cdot C\otimes f\left(x_B\right)$$

$$C\otimes f(x_A) \rightarrow \sum_j \int_{x_A}^1 \frac{d\xi_A}{\xi_A} C_{\bar{q}j}\left(\frac{x_A}{\xi_A}, b, \mu\right)\cdot f_{j/A}\left(\xi_A, \mu\right)$$

$$C\otimes f(x_B) \rightarrow \sum_k \int_{x_B}^1 \frac{d\xi_B}{\xi_B} C_{qk}\left(\frac{x_A}{\xi_A}, b, \mu\right)\cdot f_{k/B}\left(\xi_B, \mu\right)$$

$e^{-S(b)} \rightarrow$ Sudakov form factor

$$S(b) = \int_{\left(\frac{b_0}{b}\right)^2}^{Q^2} \frac{d\bar{\mu}^2}{\bar{\mu}^2}\left[\ln\left(\frac{Q^2}{\bar{\mu}^2}\right)A(\bar{\mu}) + B(\bar{\mu})\right]$$

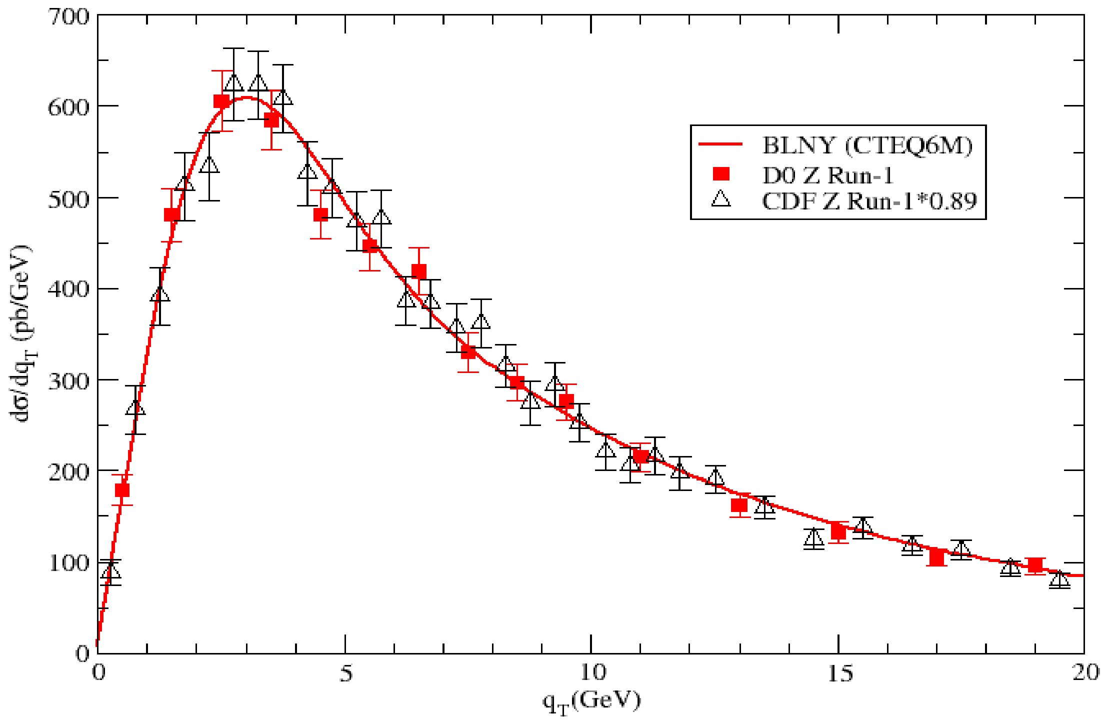
[Non-perturbative functions] are functions of (b,Q,x_A,x_B) which include QCD effects beyond Leading Twist.

Resummation effects agree with data very well

$P\bar{P} \to Z$ @ 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.



C T E Q

W Charge Asymmetry: A Monitor of DFs

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

$$A(y_W) = \frac{d\sigma(W^+)/dy_W - d\sigma(W^-)/dy_W}{d\sigma(W^+)/dy_W + d\sigma(W^-)/dy_W}$$

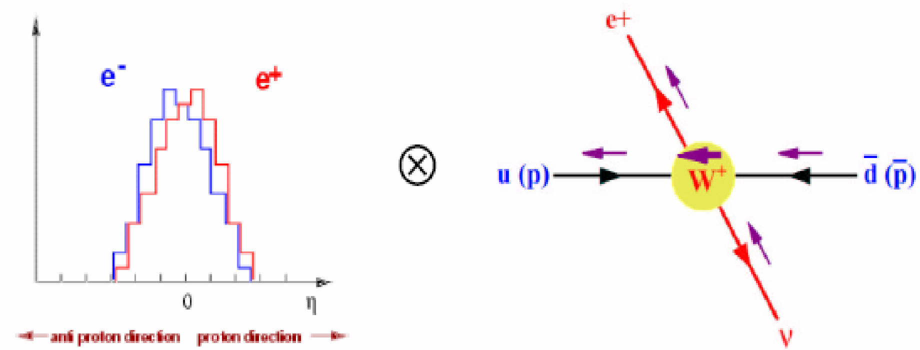
$$A(y_W) \approx \frac{u(x_1)d(x_2) - d(x_1)u(x_2)}{u(x_1)d(x_2) + d(x_1)u(x_2)}$$

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

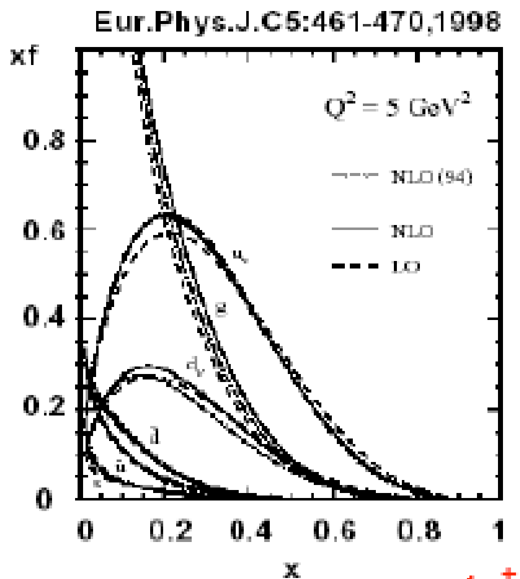
- cannot reconstruct y_W directly
- measure charged lepton only

$$A(\eta_l) = \frac{d\sigma(l^+)/d\eta_l - d\sigma(l^-)/d\eta_l}{d\sigma(l^+)/d\eta_l + d\sigma(l^-)/d\eta_l}$$

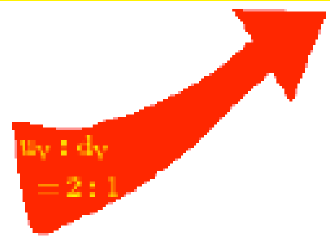
$A(\eta_l) =$

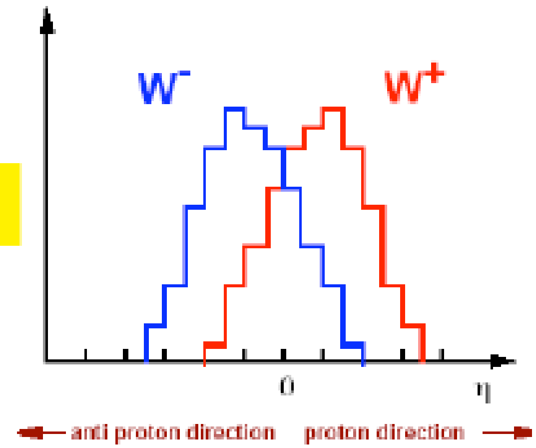


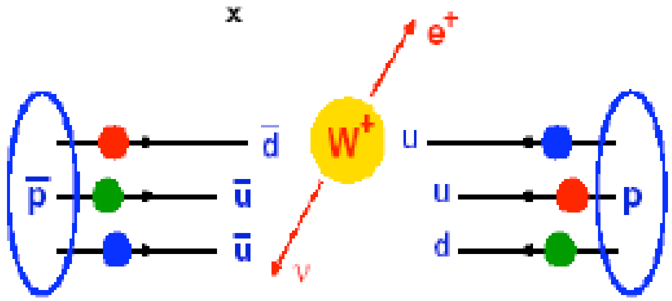
Rapidity Distribution



u higher momentum





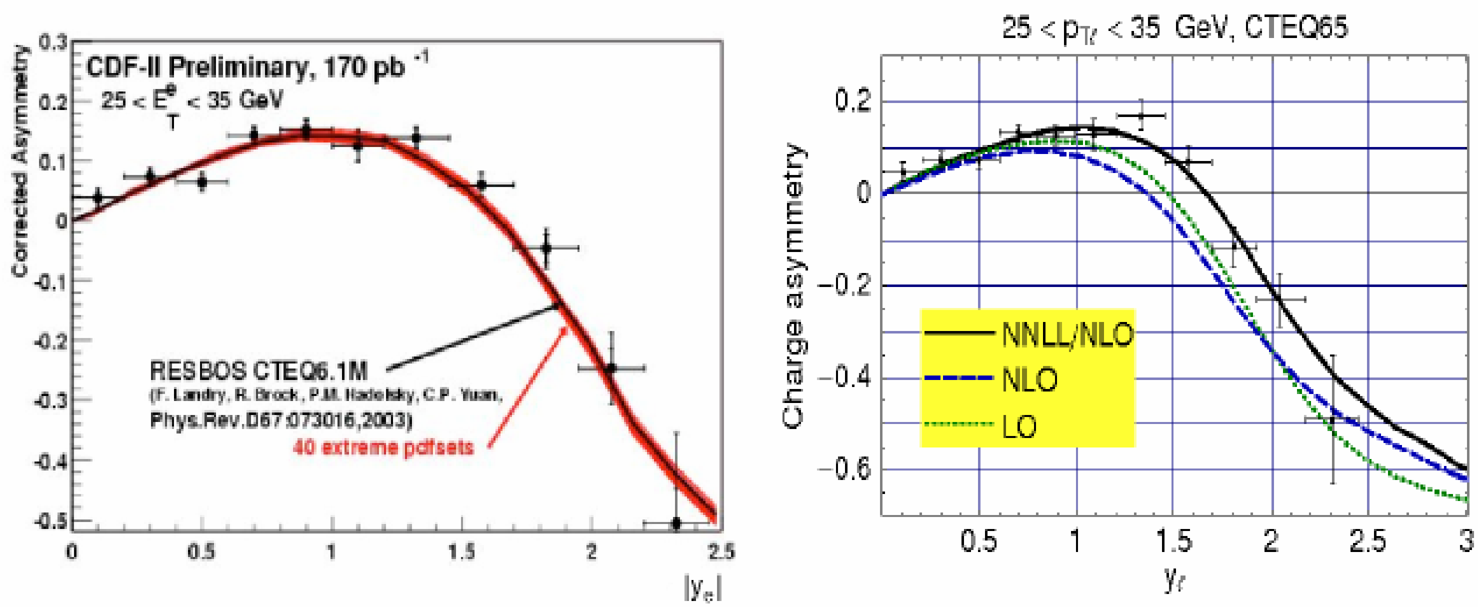


W^+ boosted in p direction
W^- boosted in $\bar{p}$ direction

CTEQ

ResBos needed for Rapidity

Charged lepton asymmetry (from *W* decay)



All recent CTEQ and MSTW PDF fits include the effects of soft gluon resummation predicted by ResBos.

NLO EW corrections

- The complete NLO EW correction to W and Z boson production in hadron collisions are known.

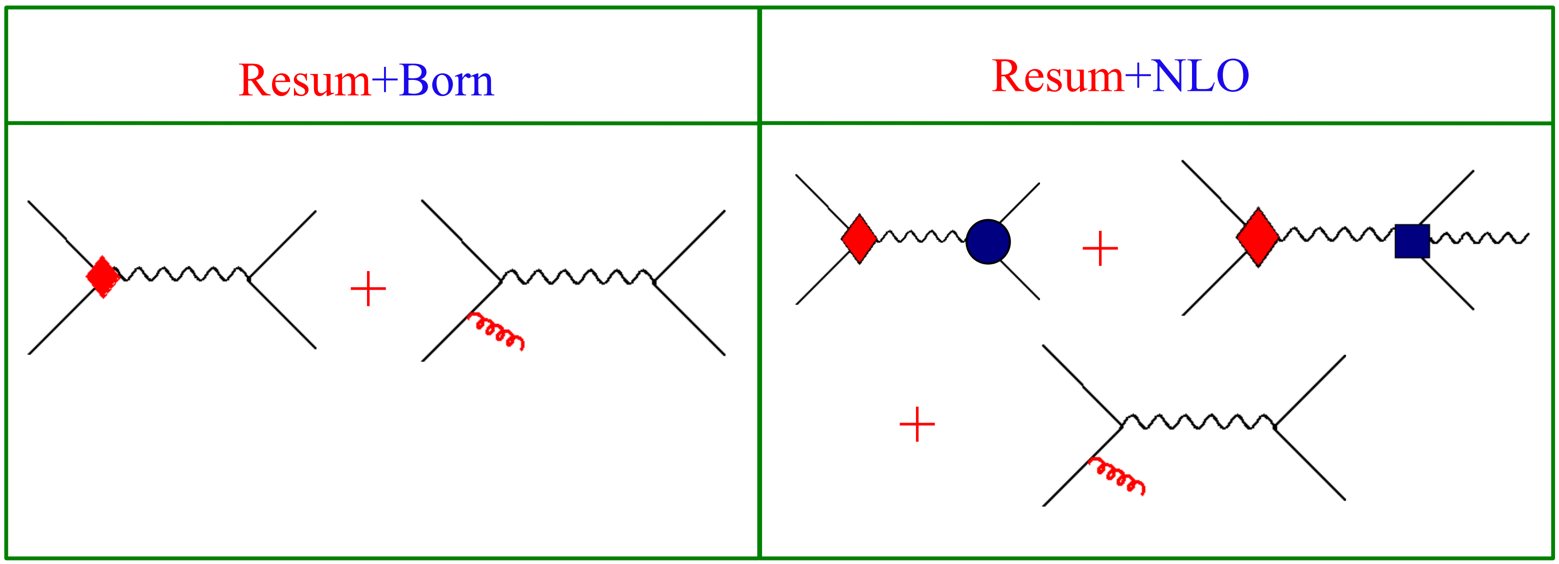
- The NLO QED corrections to the decay of W and Z bosons can be factored out from the complete NLO EW corrections in a gauge invariant way.

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



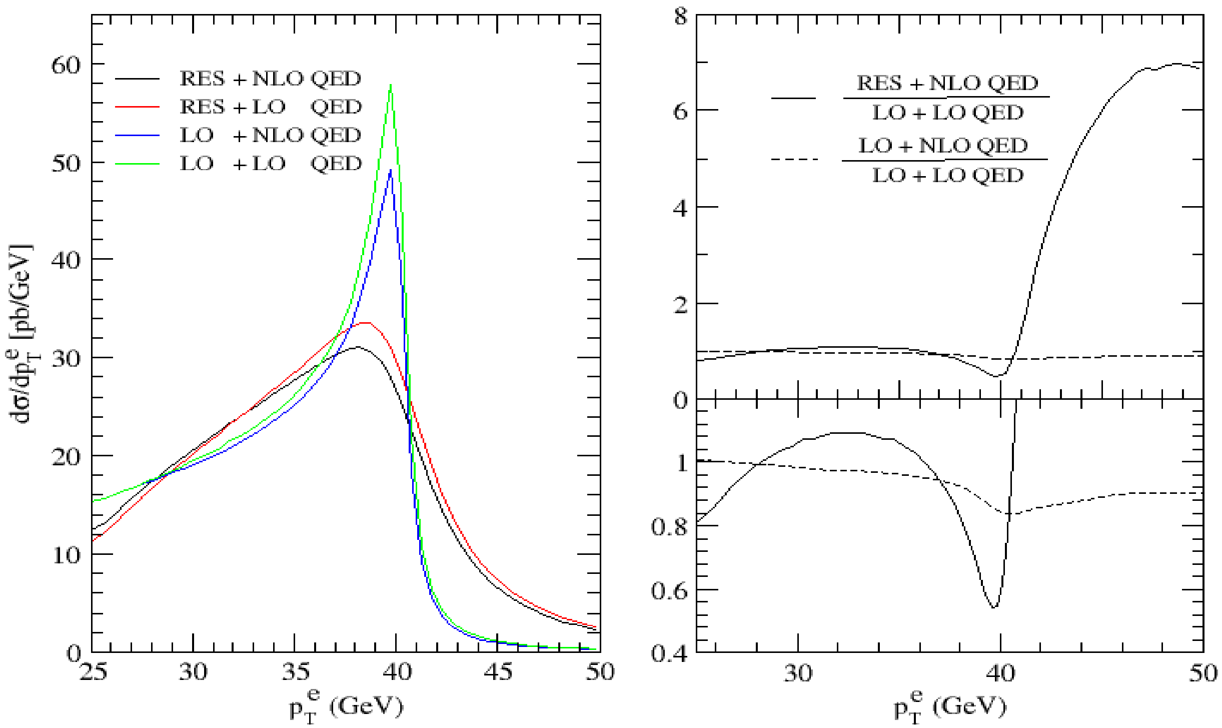
● and ■ denote FQED radiation corrections, which dominates the W mass shift.

C T E Q

Transverse momentum distribution of charged lepton

p_T^e is sensitive to q_T^W

INIT FINAL



Cuts:

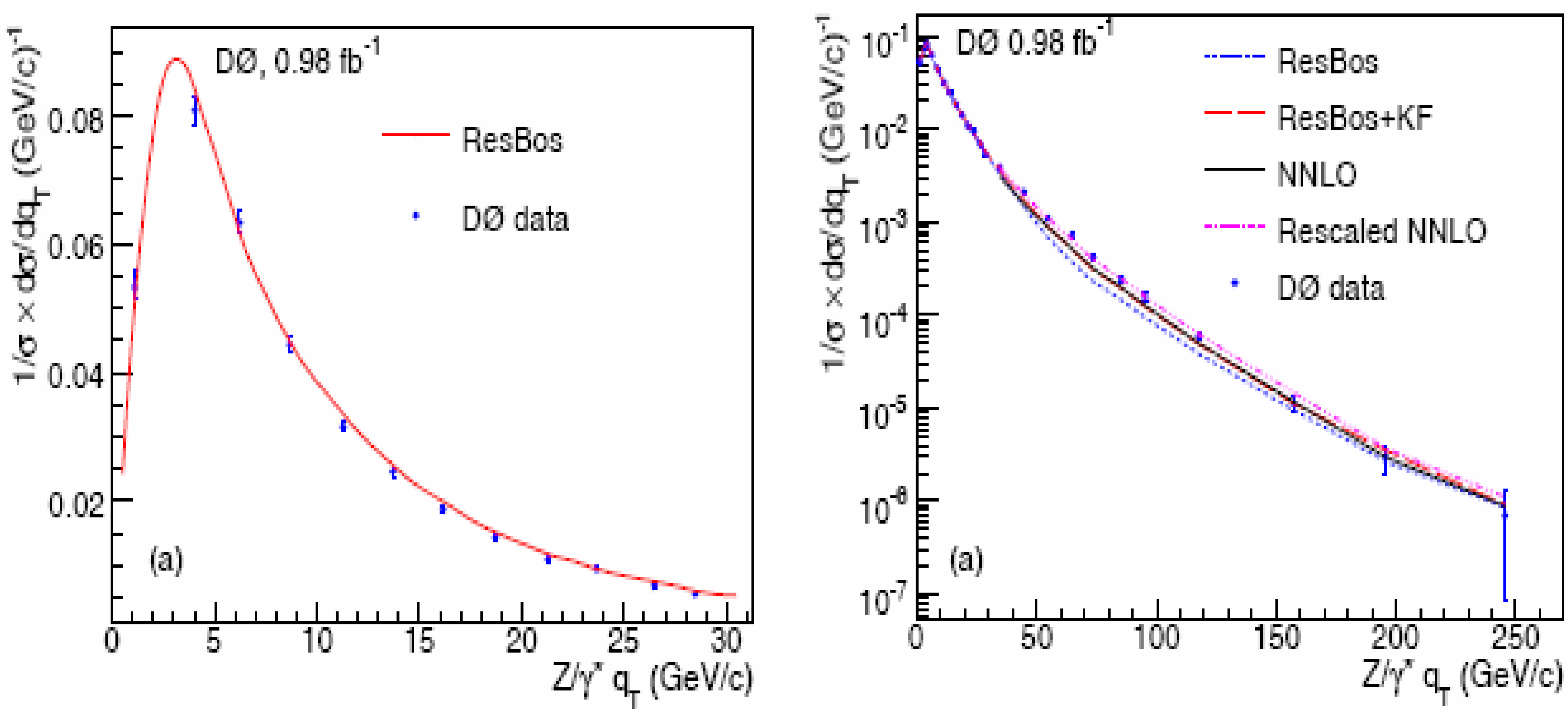
$p_T^{e^+} > 25$ GeV

$\not{E}_T > 25$ GeV

$|\eta^{e^+}| < 1.2$

C T E Q

W Boson q_T @ D0 Run-2



low q_T region

Figure: Phys. Rev. Lett. 100 , 102002 (2008)

Z-boson physics

❶ Help to improve the measurement of W-boson

- calibrate detector
- indirect measurement of W-boson width

❷ ResBos-A and its predictions

- effective Born approximation
- various kinematical distributions

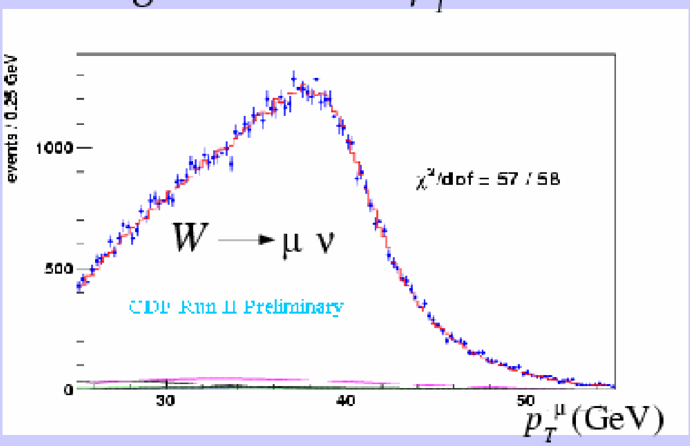
C T E Q

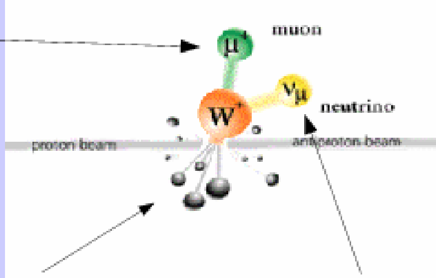
Precision measurement of Z-boson

☞ help to calibrate detector

Mass information comes primarily from lepton p_T

- Run 2 goal: calibrate p_T to ~0.01%

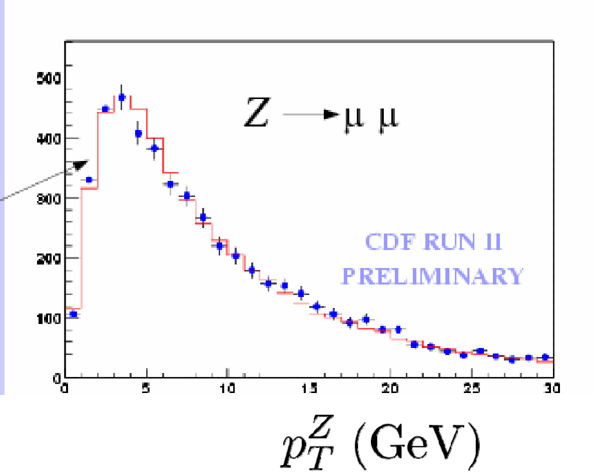




Additional information from ν p_T

(inferred through measurement of hadronic recoil energy)

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

C T E Q

First part of Conclusion and outlook

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/

ResBos **ResBos-A**

Include Initial state QCD soft gluon resummation
and Final state QED corrections

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

hep-ph/9505203

In collaboration with

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

ResBos: http://hep.pa.msu.edu/resum/ hep-ph/9704258
ResBos-A: including final state QED corrections hep-ph/0401026
Plotter: on-line plotting package (by P. Nadolsky)

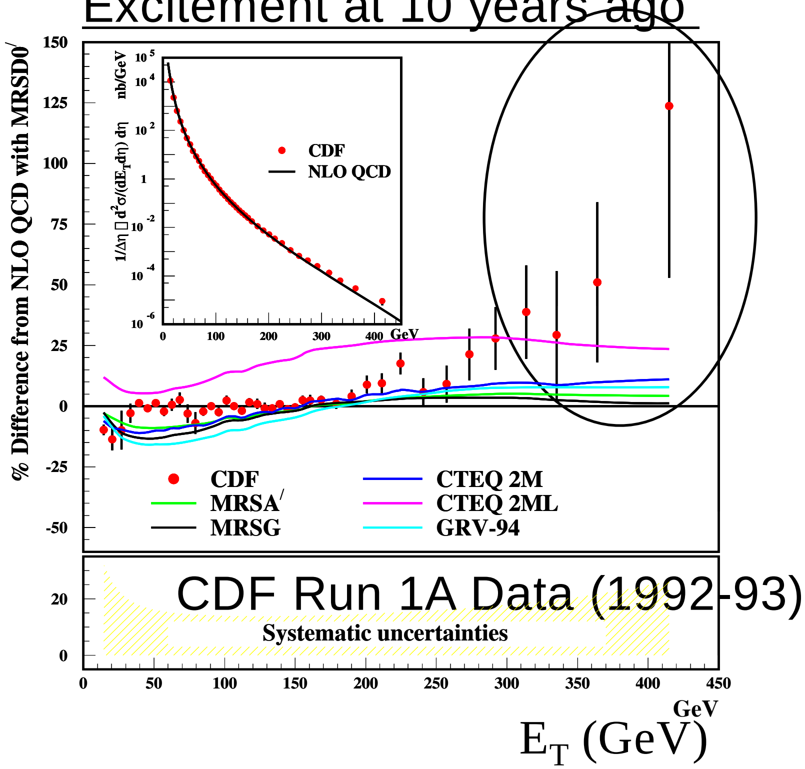
CTEQ

Impact of New CTEQ Parton Distribution Functions to LHC Phenomenology:

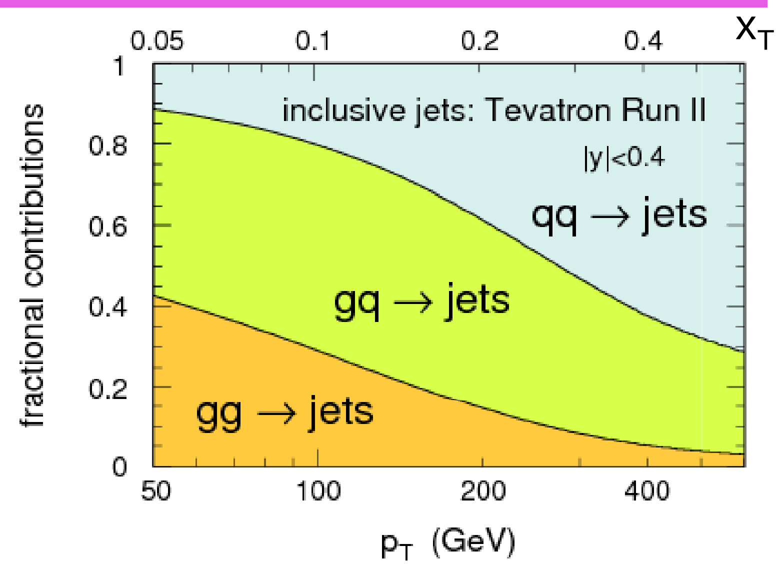
W/Z, Top and Higgs Physics

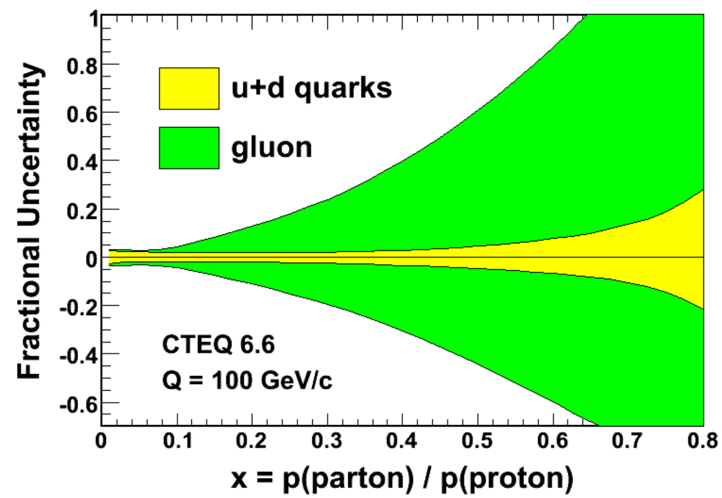
New Physics signal found?

Excitement at 10 years ago



Phys. Rev. Lett. 77, 438 (1996)

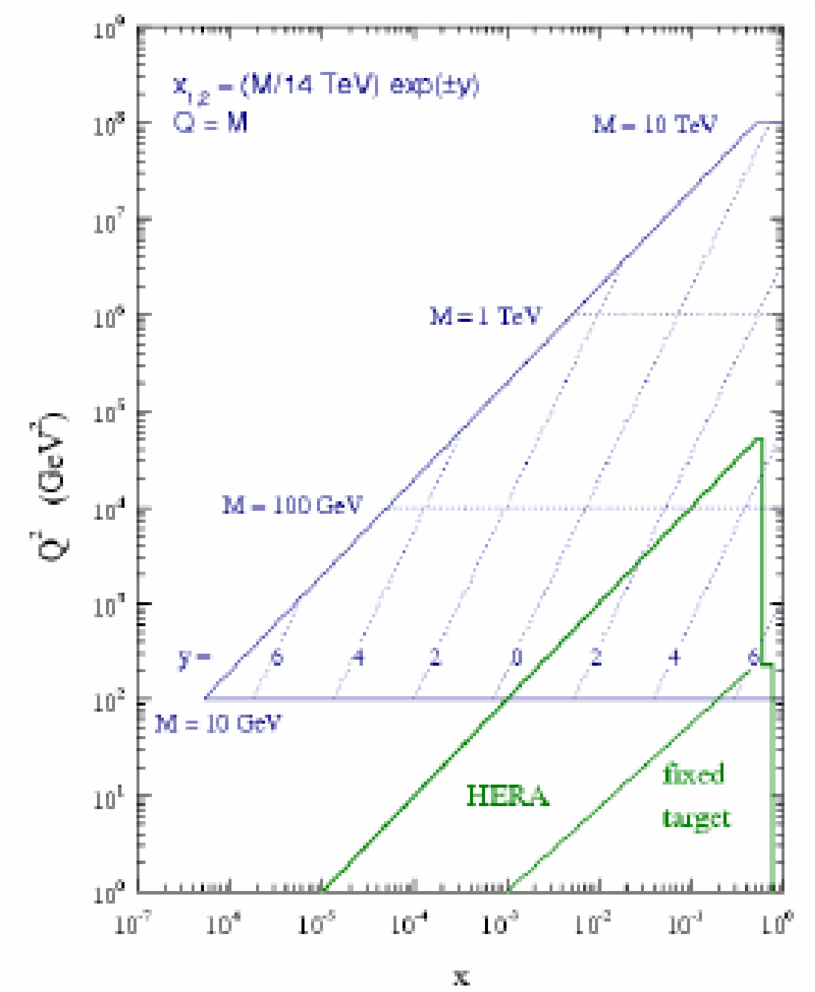




High-x gluon not well known

…can be accommodated in the Standard Model

LHC Parton Kinematics



Sensitive to new region of x and Q values.

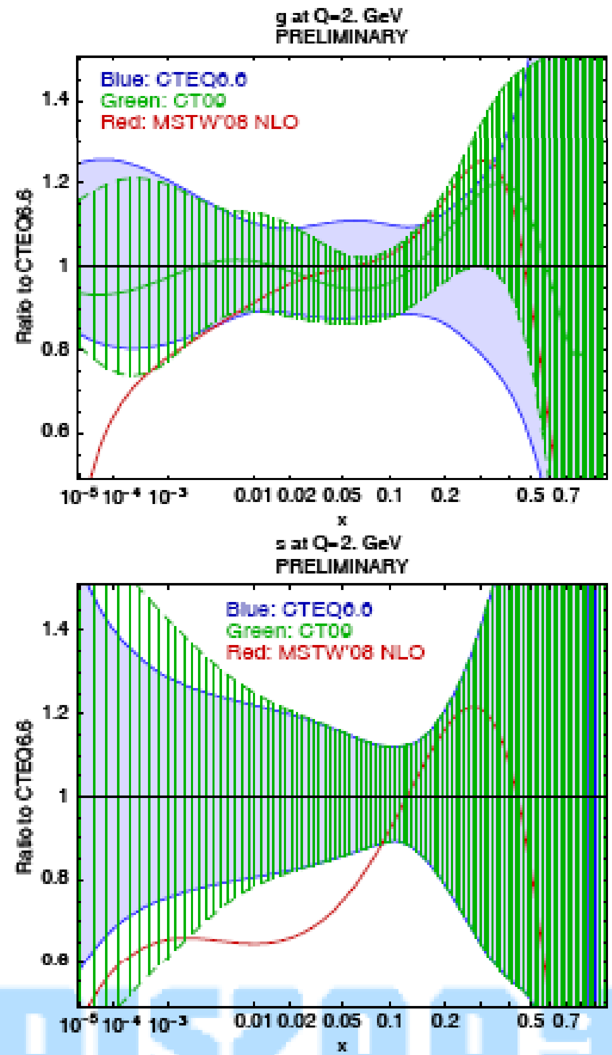
Need better determination of PDFs

Need new kind of global analysis, such as "The Combined PDF and P_T Fits"

C T E Q Wu-Ki's O and H will be continued

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)*



CTEQ

CT09: Impact of Run-2 Jet Data

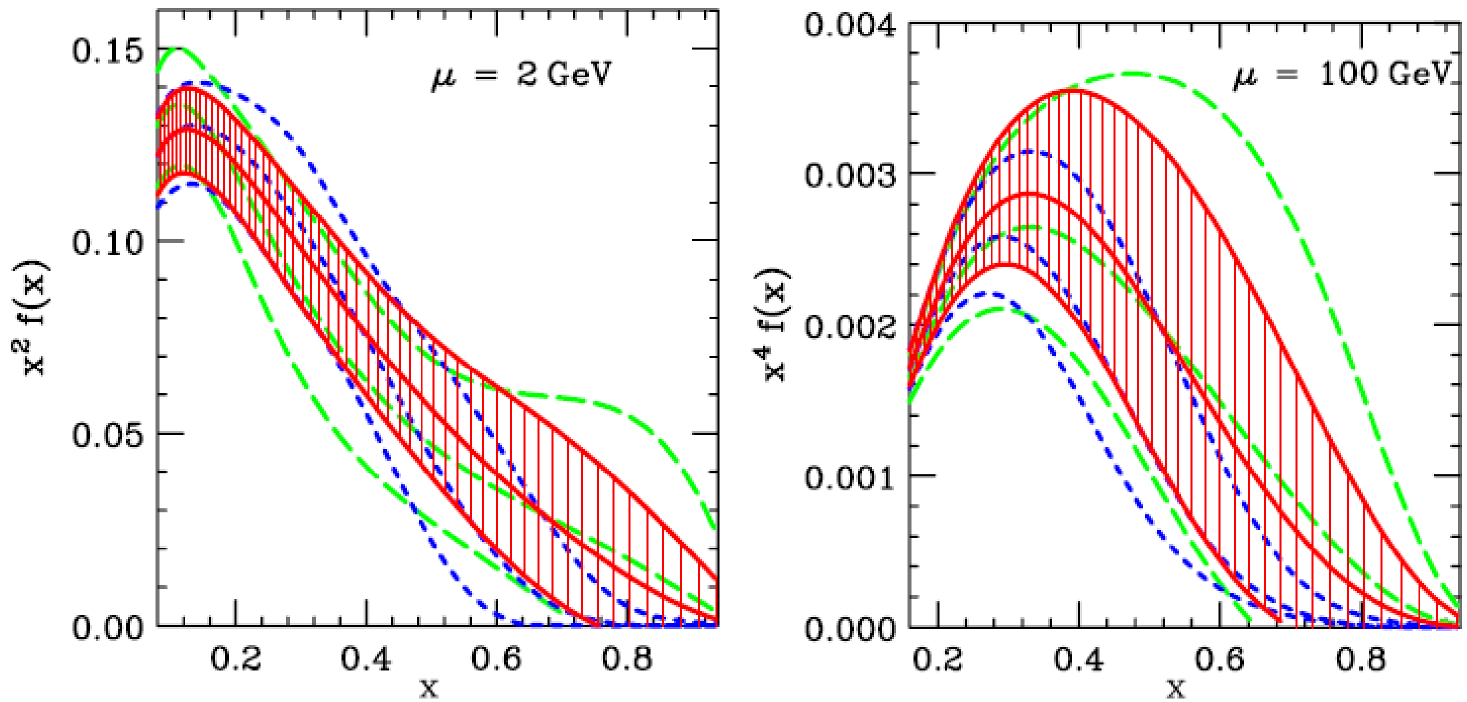
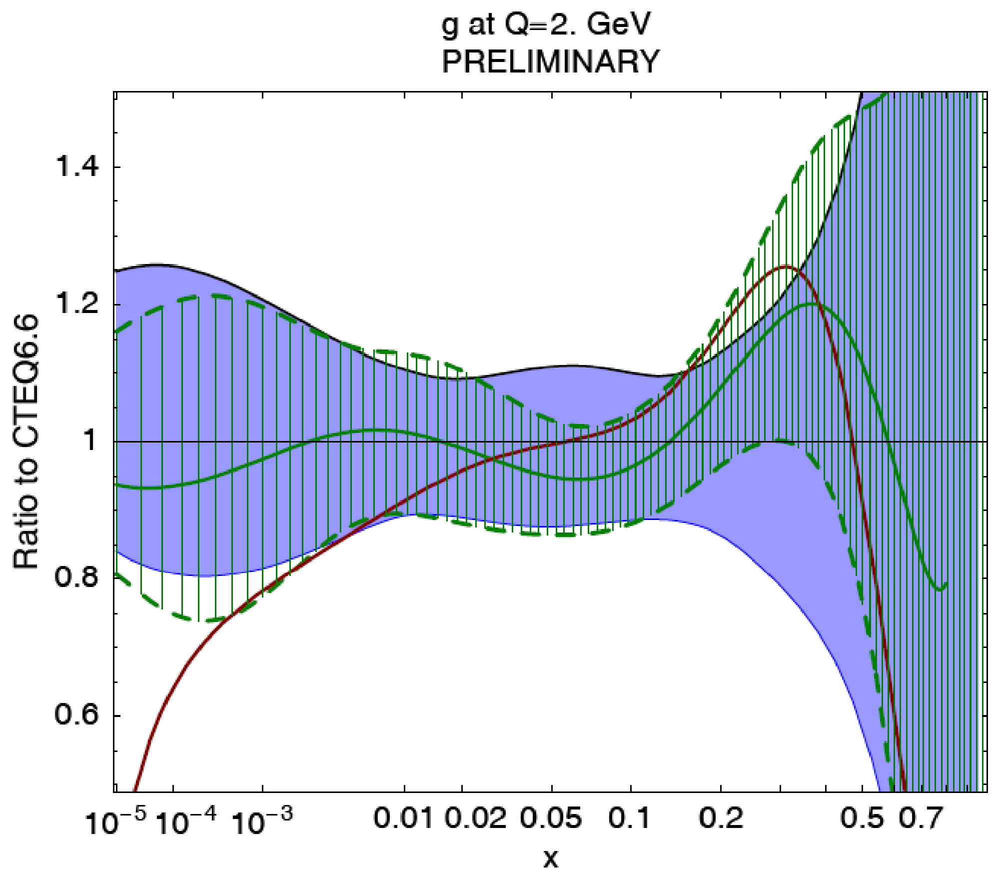


Figure 1: Gluon distributions and uncertainties: CT09G (solid red); fit using CDF run II jets only (short dash blue); fit using D0 run II jets only (long dash green). (A larger weight factor x^4 is used in the right-hand figure to accentuate the large-x behavior.)

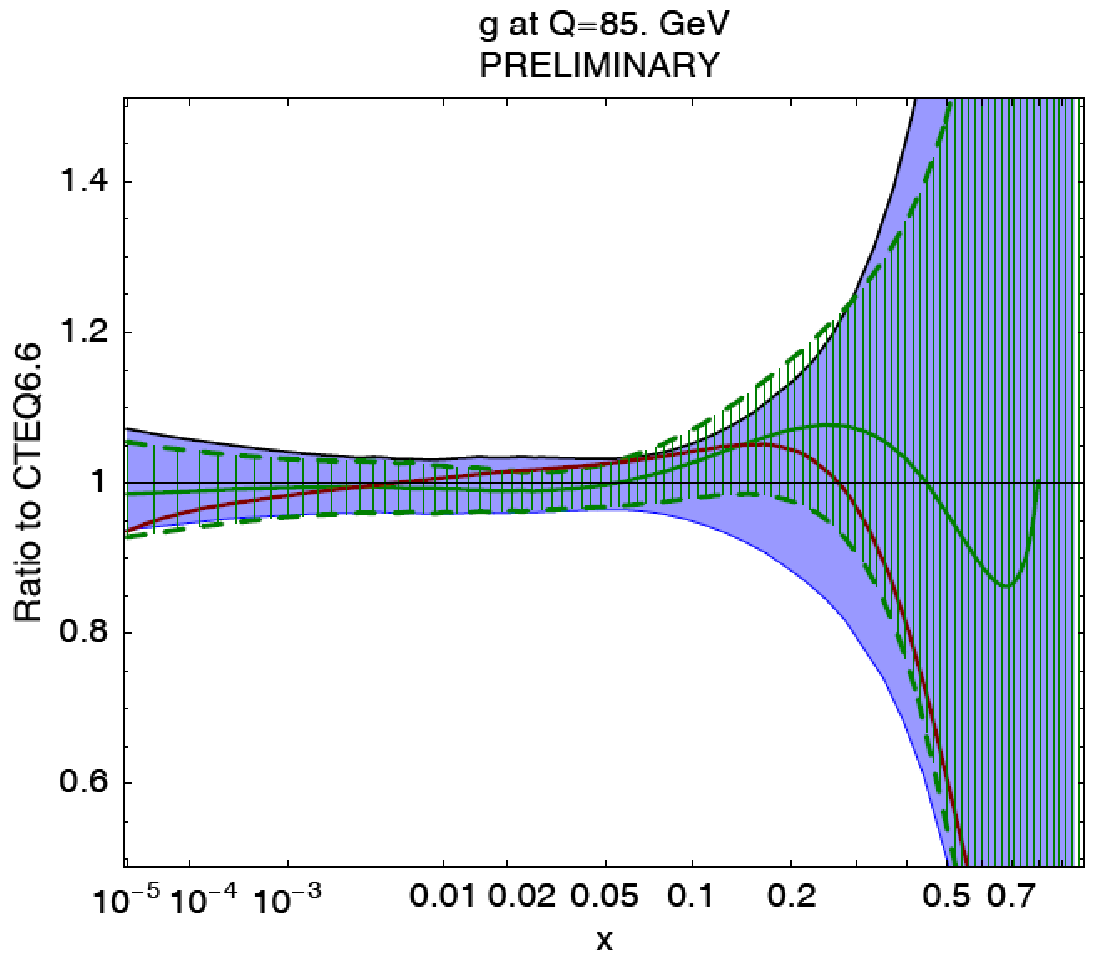
hep-ph/0904.2424

CT09 vs CTEQ6.6



Comparison of CT09 and CTEQ6.6 gluon PDF uncertainties at Q=2 GeV. MSTW08 central fit is also shown.

CT09 vs CTEQ6.6



Comparison of CT09 and CTEQ6.6 gluon PDF uncertainties at Q=85 GeV. MSTW08 central fit is also shown.

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

CTEQ

Combined PDF+ p_T Global Analysis

New Inputs:

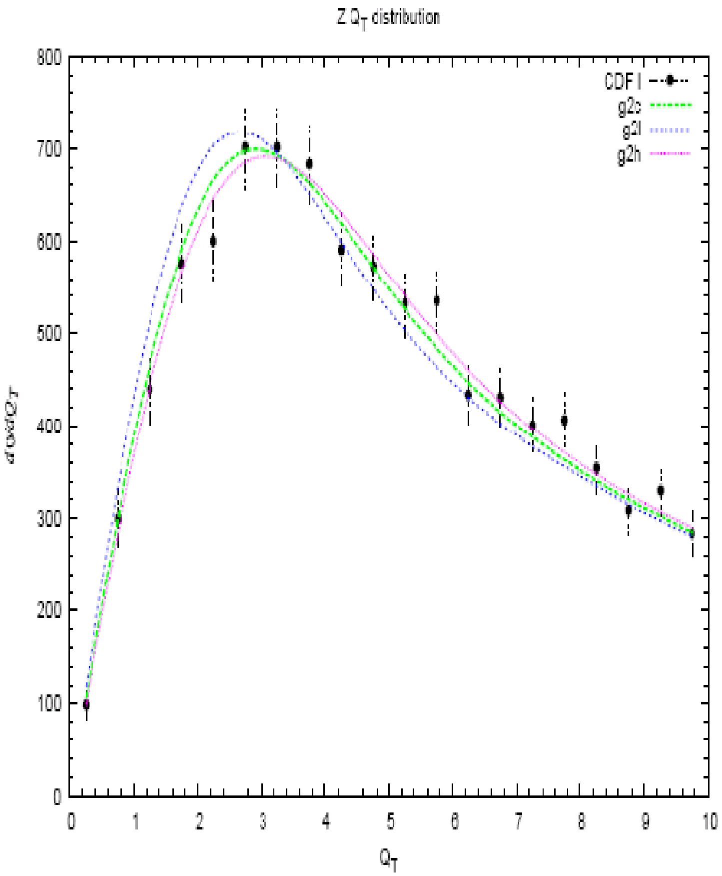
- Experimentally: include not only rapidity (y) but also p_T of Drell-Yan pairs and Z bosons
- Theoretically: include p_T Resummation formalism to account for the soft physics that entangle with multi-scale measurements

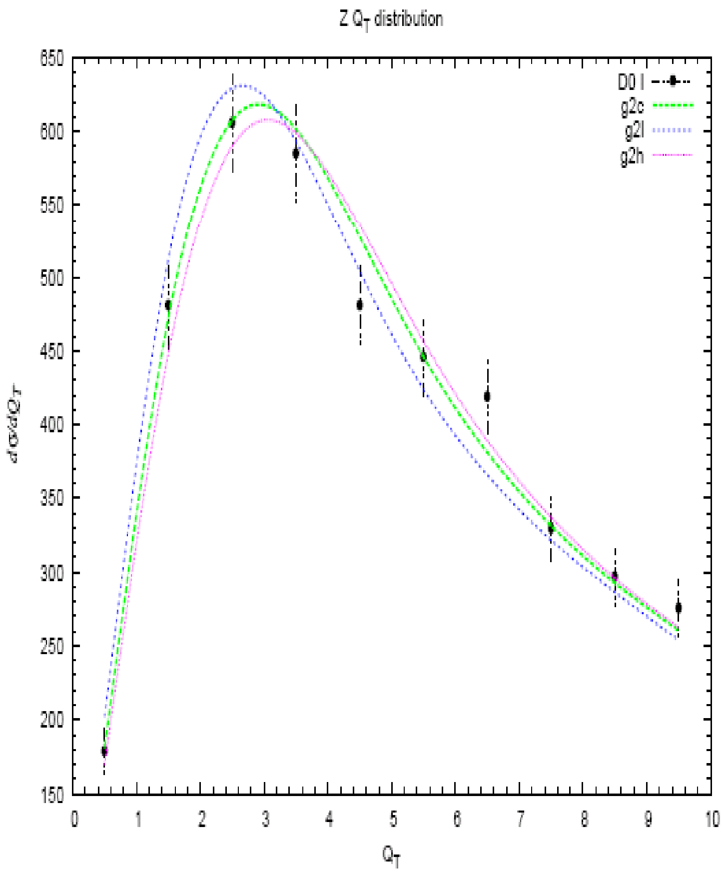
New Outputs:

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

C T E Q

Preliminary results





CTEQ

Measurement of g2 from D0

DØ Note 5755-CONF

Version: 1.5

A Study of $Z \to e^+e^-$ and $Z \to \mu^+\mu^-$ 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} : $F_{NP}(M_Z)/b^2 = 2.51 \pm 0.15$

C T E Q

Preliminary results

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

(This range of 2.10 to 2.75 shall be compared to D0's 2.36 to 2.66.)

CTEQ

Impact of New CTEQ Parton Distribution Functions to LHC Phenomenology:

W/Z, Top and Higgs Physics

CTEQ

CTEQ6.6 PDFs

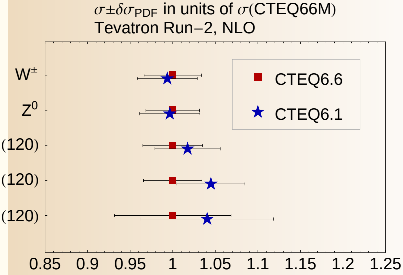
CTEQ6.6 PDF's, heavy flavors and PDF induced correlations between LHC observables

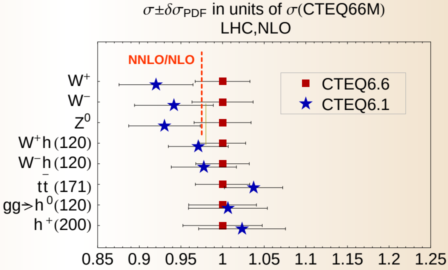
hep-ph/0802.0007

In collaboration with

Pavel Nadolsky, Hung-Liang Lai, Qing-Hong Cao, Joey Huston,
Jon Pumplin, Dan Stump, Wu-Ki Tung

Tevatron and LHC cross sections





- 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

CTEQ

Correlation analysis for collider observables

A technique based on the Hessian method

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

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

$$\cos\varphi = \frac{1}{4\Delta X\,\Delta Y}\sum_{i=1}^{N}\left(X_i^{(+)} - X_i^{(-)}\right)\left(Y_i^{(+)} - Y_i^{(-)}\right)$$

$X_i^{(\pm)}$ 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.

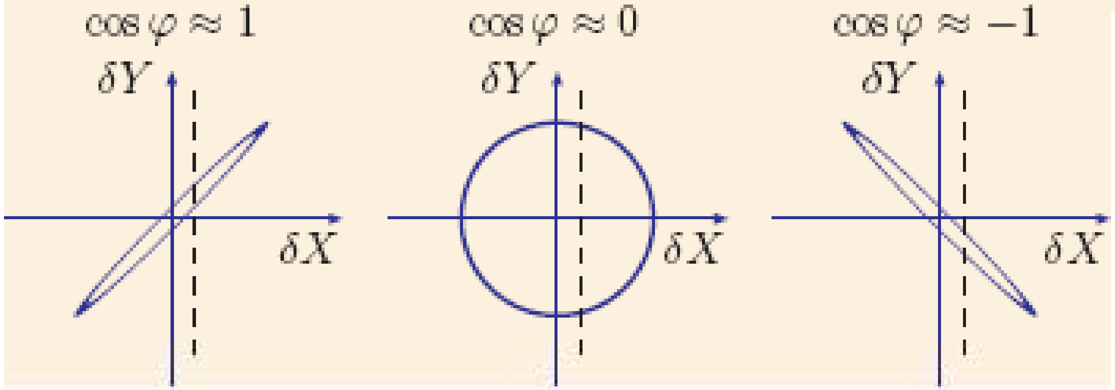
CTEQ

Correlation analysis for collider observables

Correlation angle φ

Determines the parametric form of the $X-Y$ correlation ellipse

$$
\begin{aligned}
X &= X_0 + \Delta X \cos\theta \\
Y &= Y_0 + \Delta Y \cos(\theta + \varphi)
\end{aligned}
$$



X_0, Y_0: best-fit values

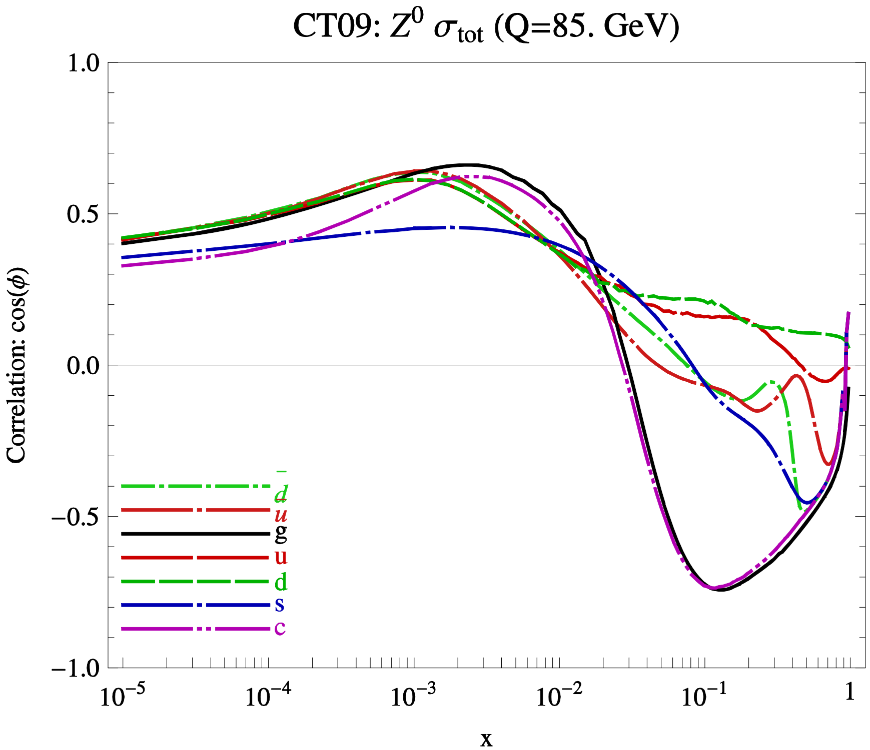
$\Delta X, \Delta Y$: PDF errors

$\cos\varphi \approx \pm 1$: Measurement of X imposes tight constraints on Y

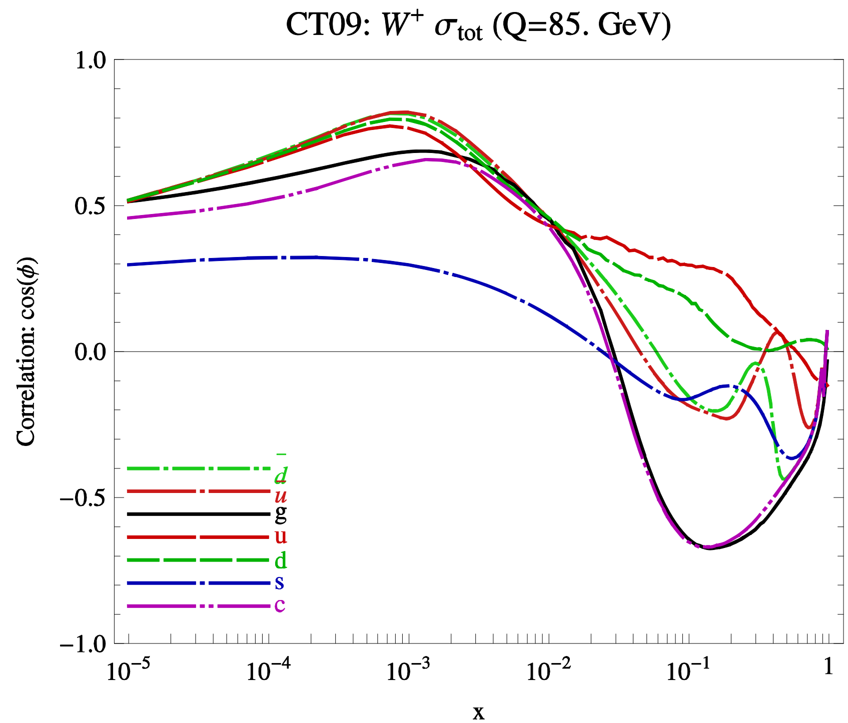
$\cos\varphi \approx 0$: Measurement of X imposes loose constraints on Y

C T E Q

Correlations (CT09 PDFs) @ LHC_10

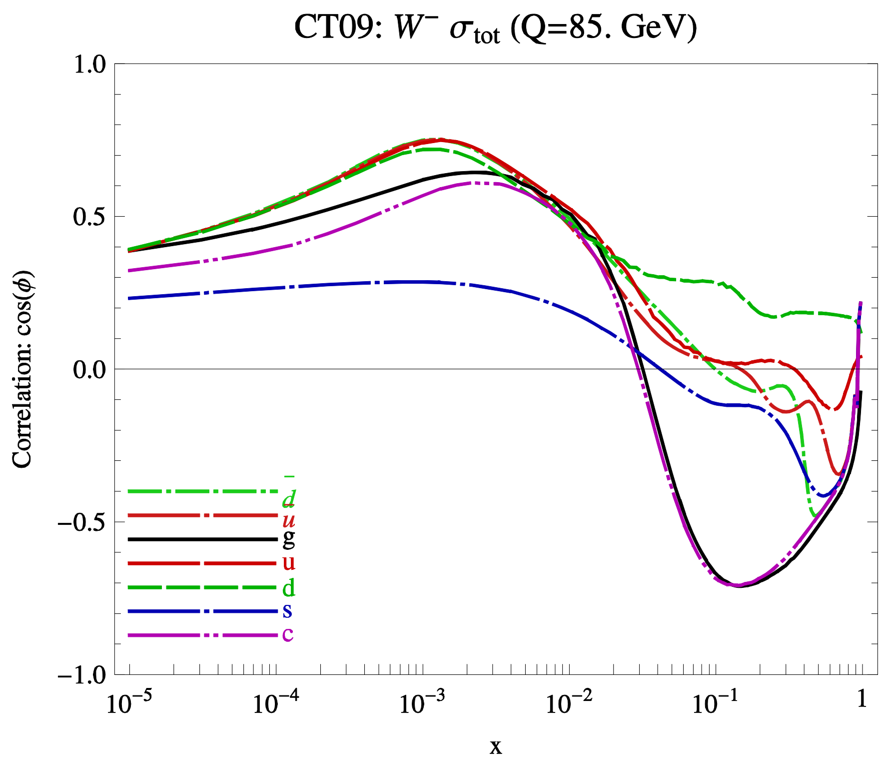


For cross section of Z boson at the LHC_10 TeV

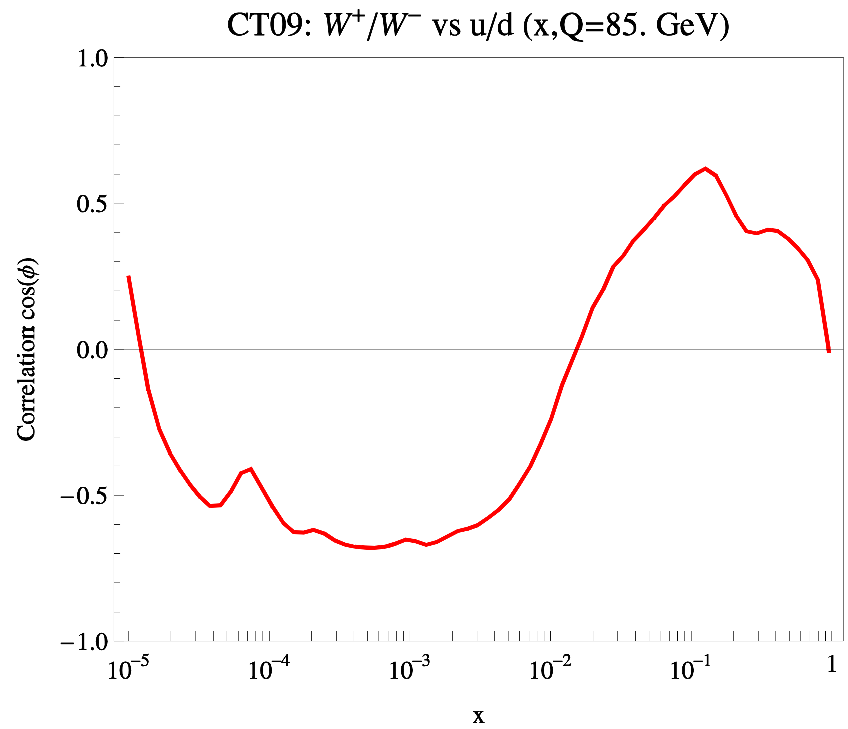


For cross section of W+ boson at the LHC_10 TeV

Correlations (CT09 PDFs) @ LHC_10



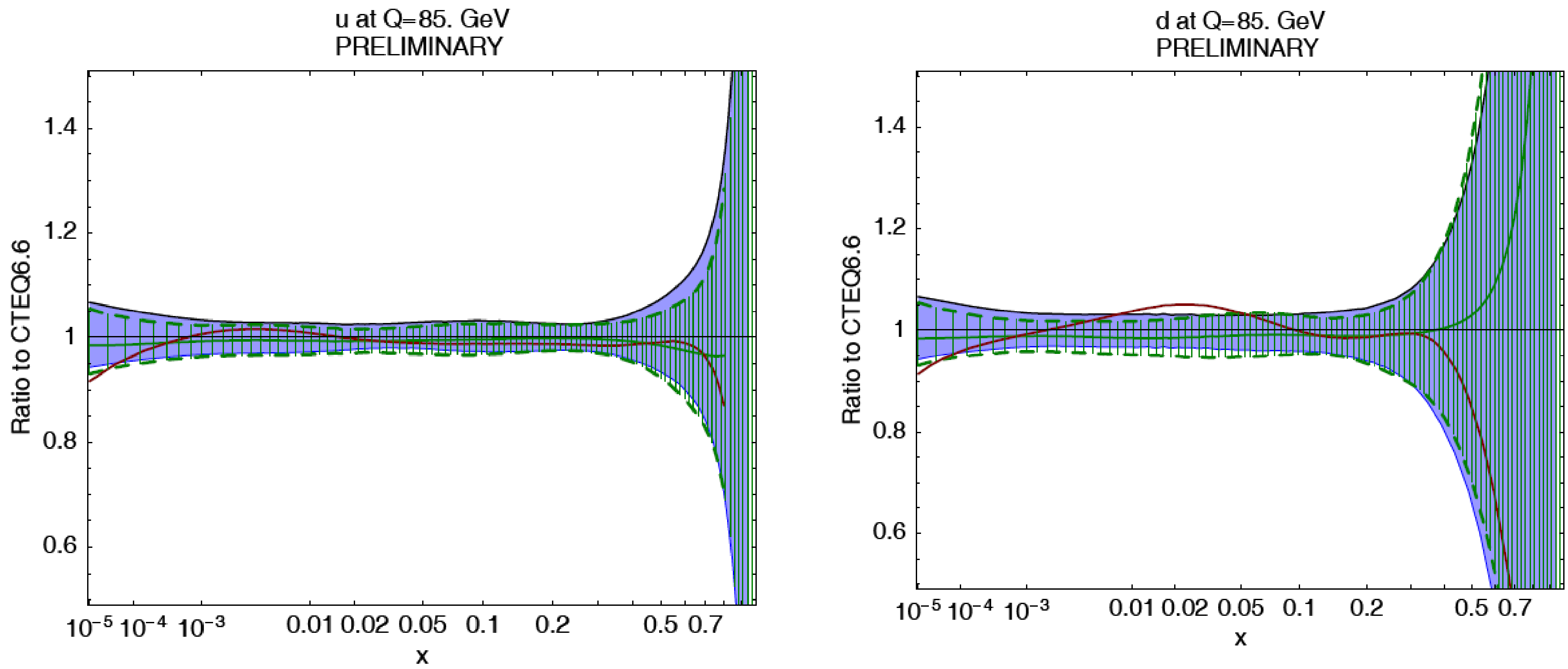
For cross section of W- boson
at the LHC_10 TeV



W+/W- vs. u/d
at the LHC_10 TeV

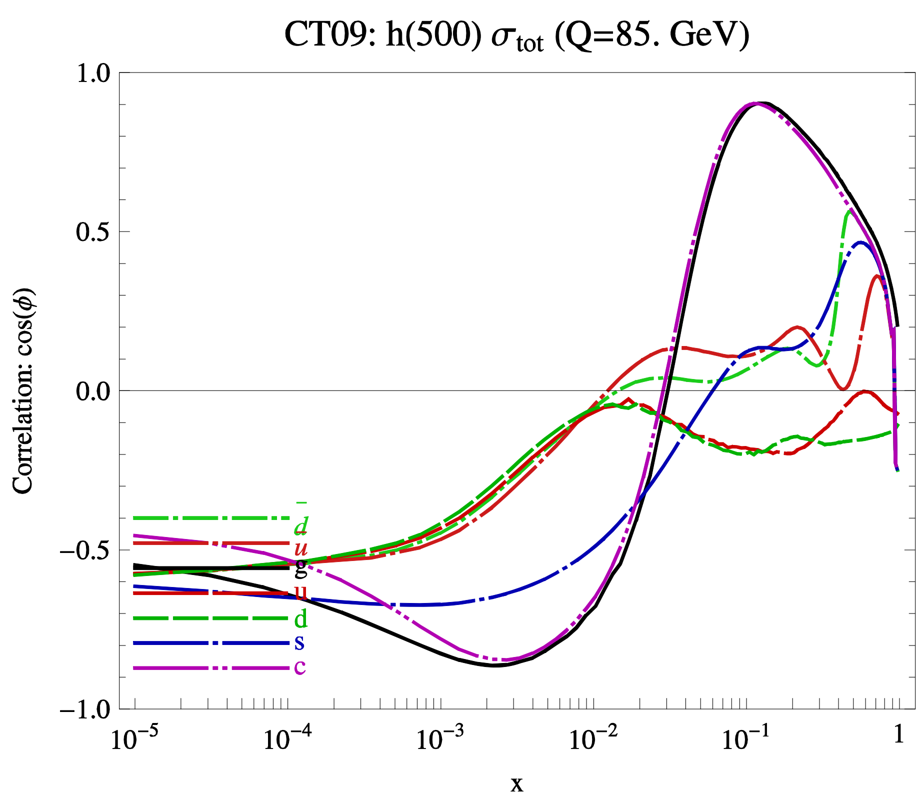
CTEQ

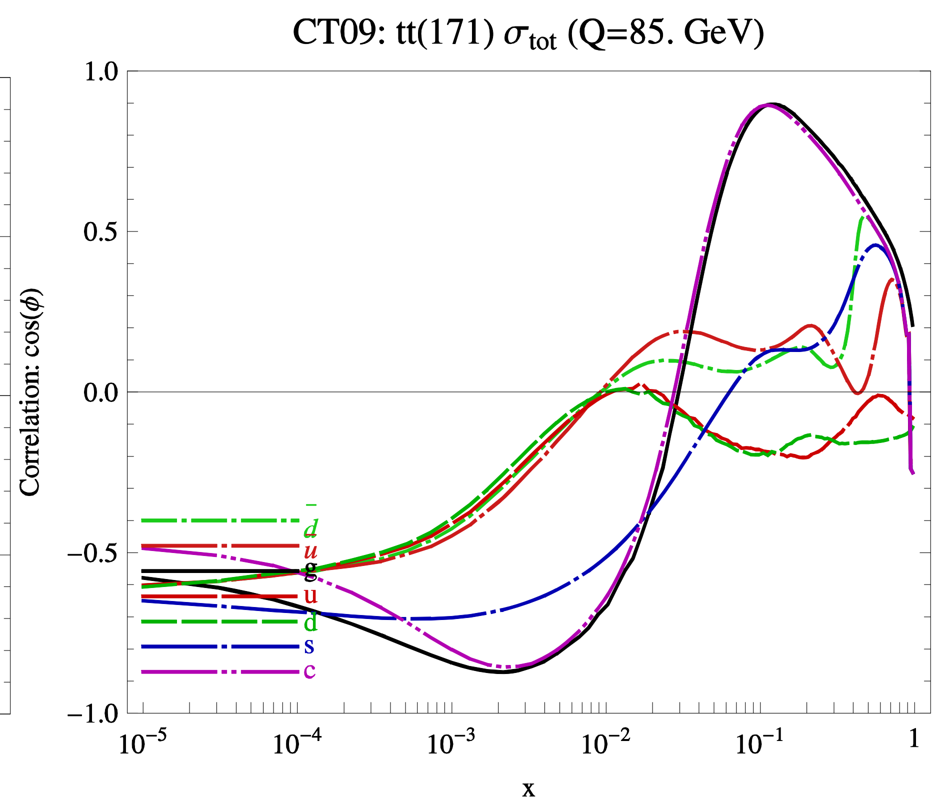
CT09 vs CTEQ6.6



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

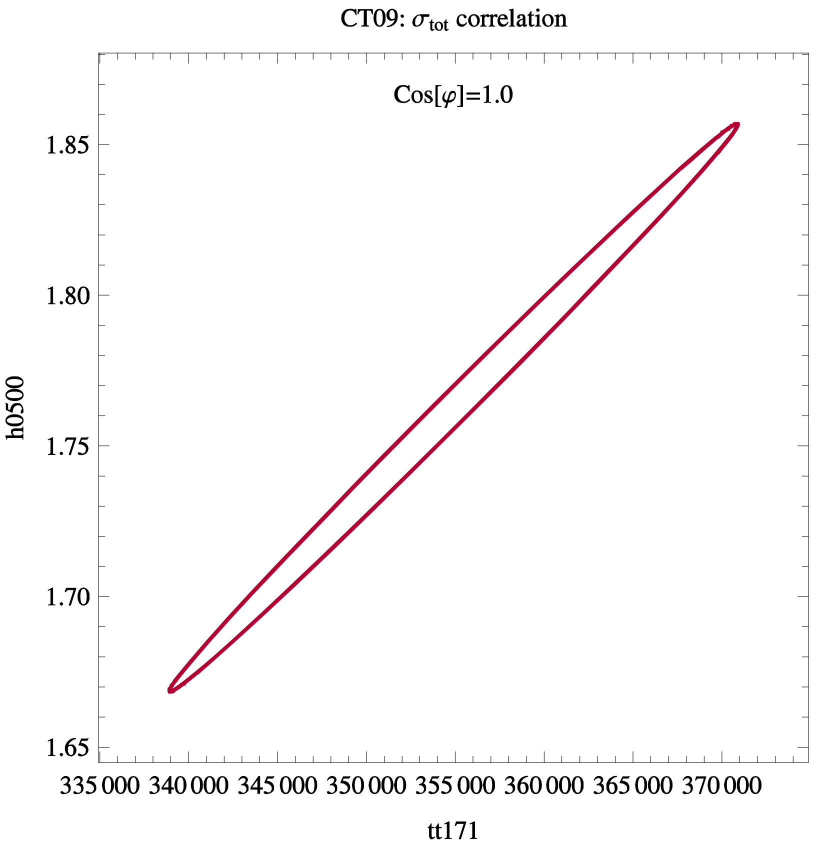




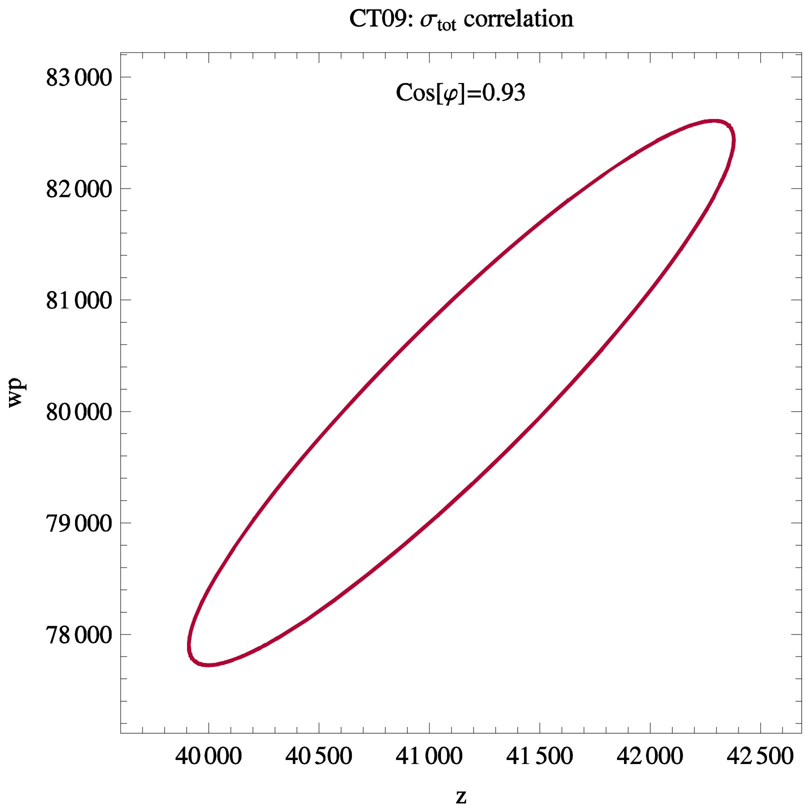
Cross section of a
500 GeV Higgs boson
at the LHC_10 TeV

Top quark pair cross section
at the LHC_10 TeV

Correlations (CT09 PDFs) @ LHC_10



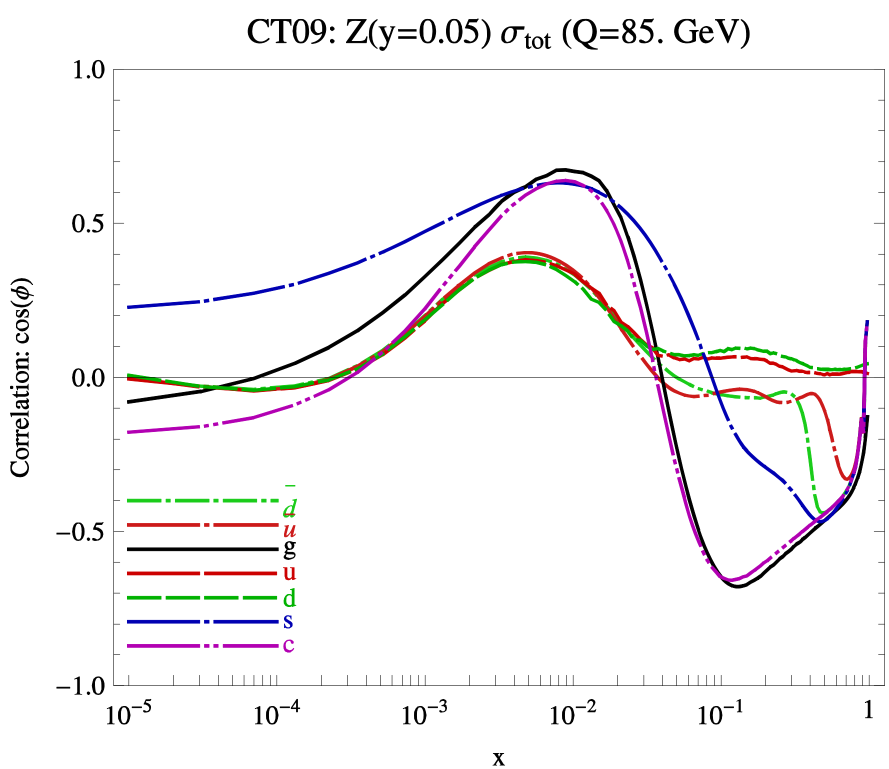
Higgs (500 GeV) vs top quark pair

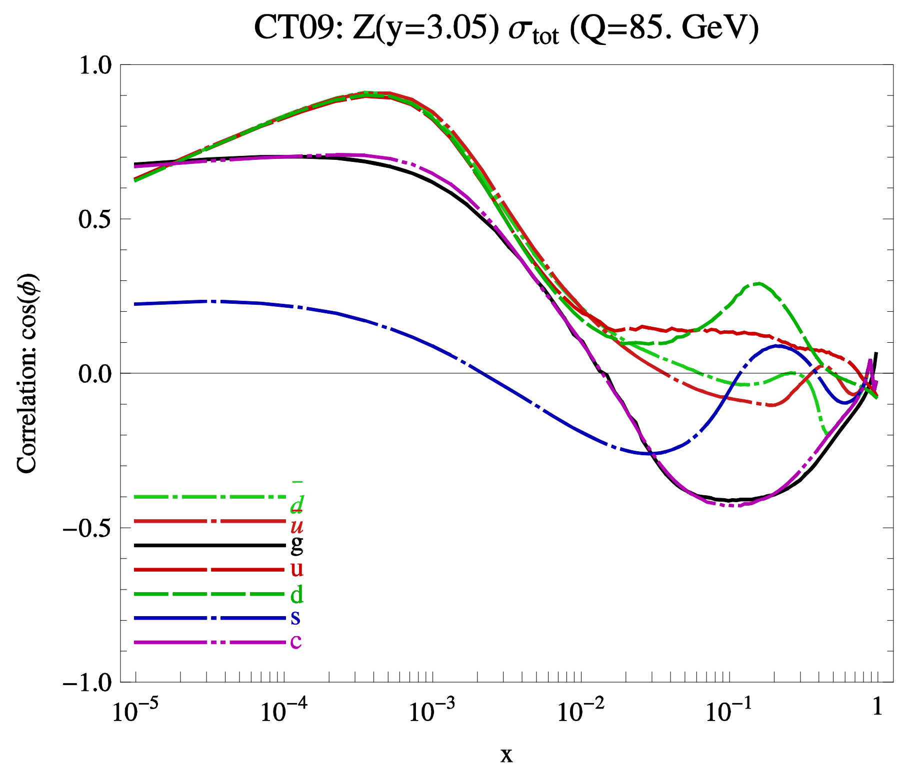


W+ vs Z

C T E Q

Correlations (CT09 PDFs) @ LHC_10





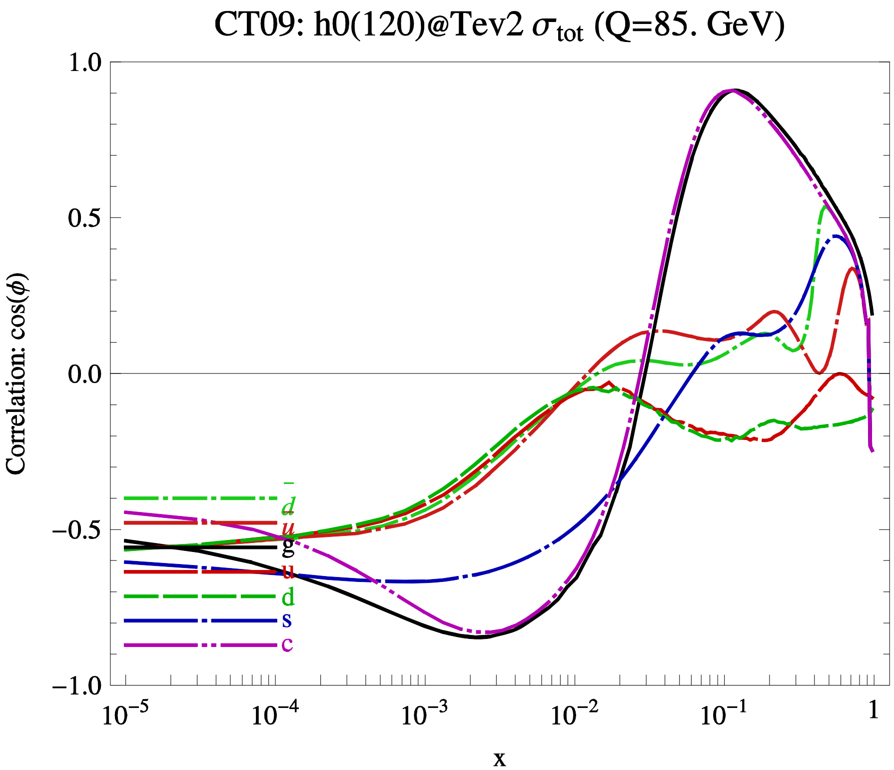
Correlation of Z Rapidity distribution at LHC_10 TeV to CT09 PDFs

Sensitive to different parton flavors at different rapidity.

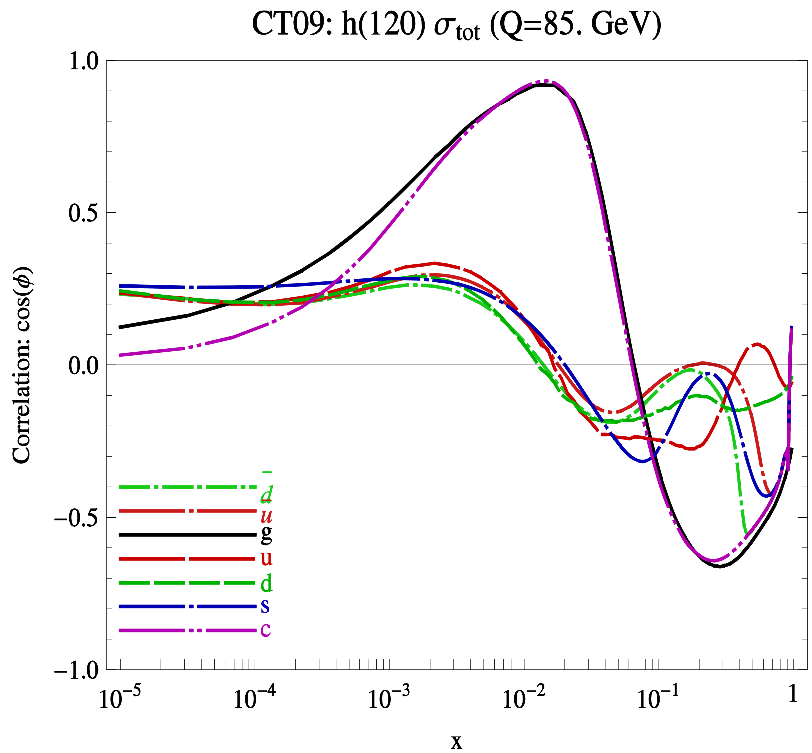
C T E Q

Correlations (CT09 PDFs) for Higgs (120 GeV)

At Tevatron



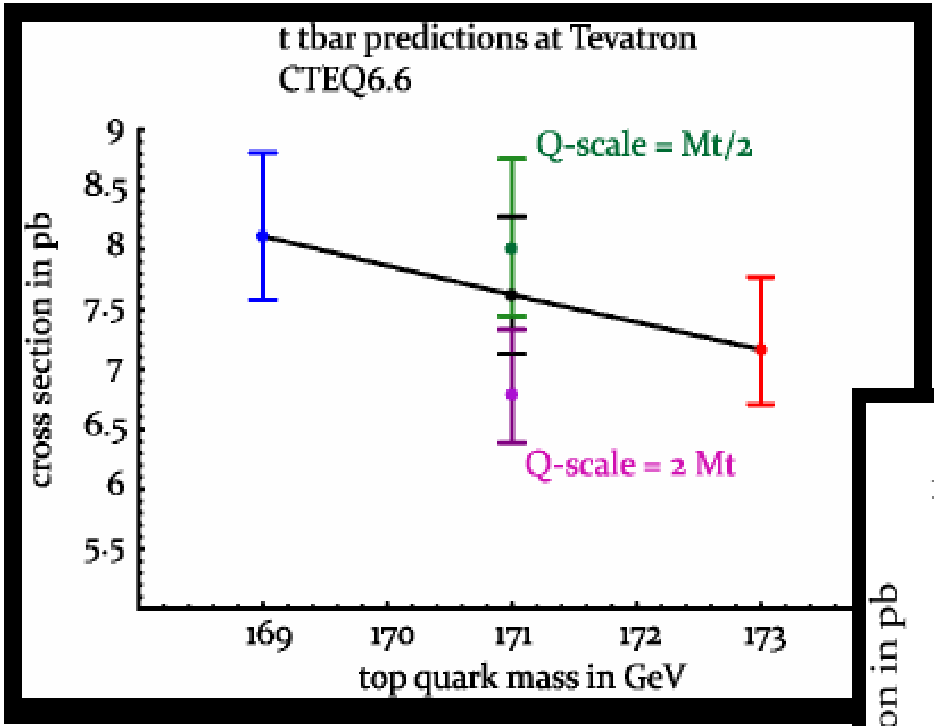
At LHC 10 TeV



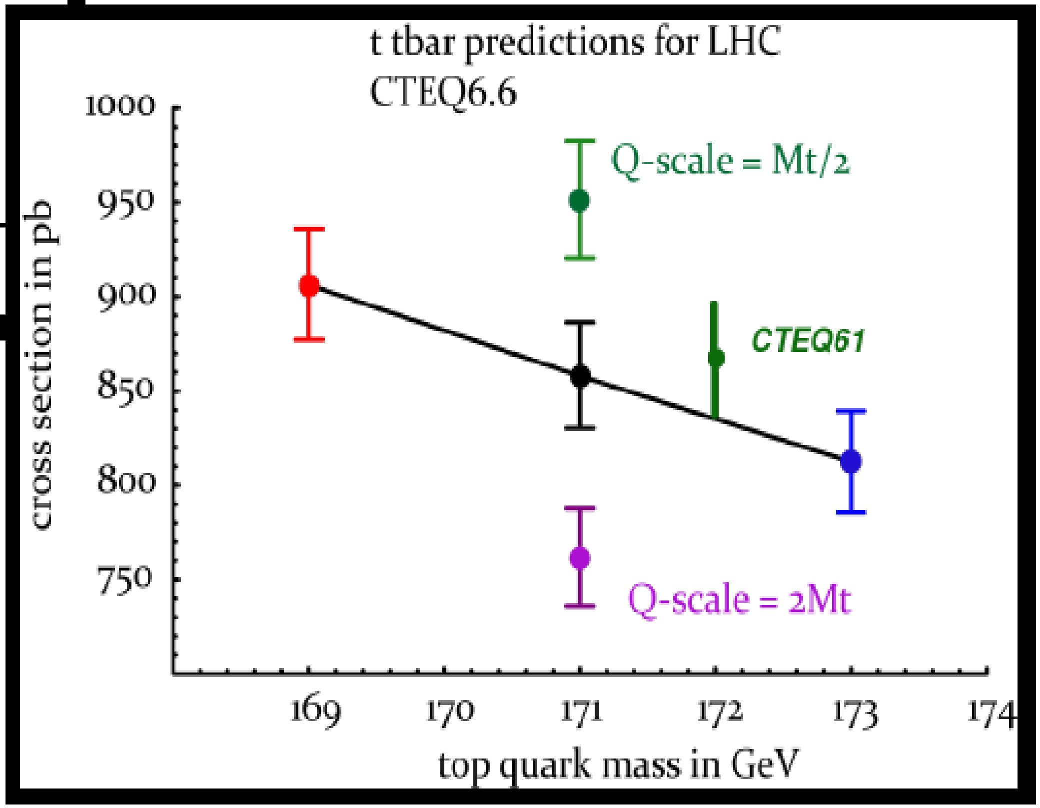
Different sensitivity to partons at various x values
lead to different PDF induced uncertainty in cross sections.

C T E Q

Top Quark Pair production rates



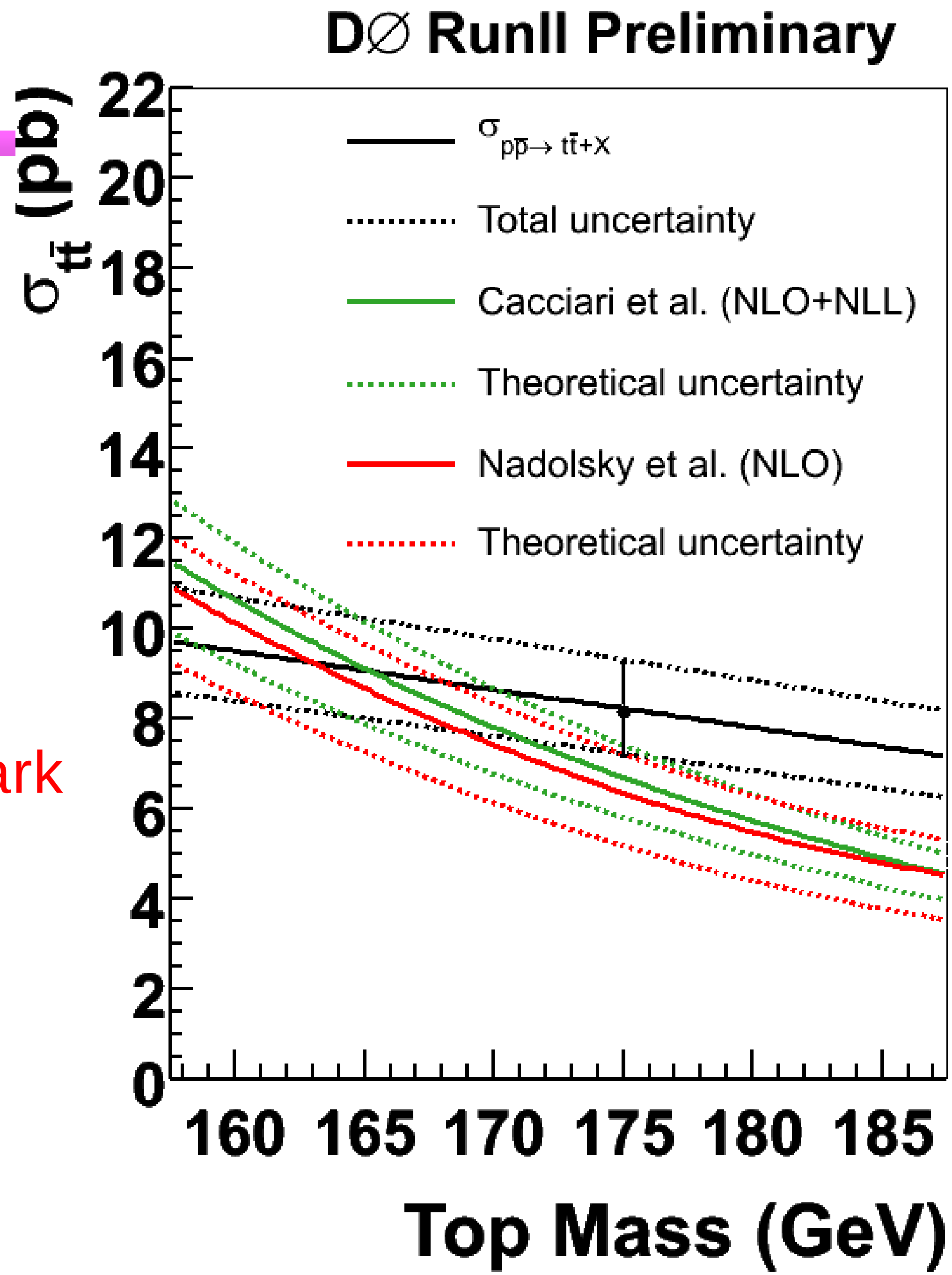
At Tevatron Run-2, uncertainty Incduced by PDFs is sizable.



Uncertainty induced by factorization (and renormalization) scale dependence is large at the LHC. Hence, NNLO calculation Is needed.

C T E Q

Use top quark pair production rate to determine the mass of top quark



Need NNLO result

(A. Mitov, et al.)

CTEQ

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

CTEQ

Resumption: effects of different pdf and higher order @ high p_T

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

Q.-H. Cao, C.-R. Chen, C.R. Schmidt and CPY, in progress.

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

$$k_{pert} = [pert(\alpha_s^3) + pert(\alpha_s^4)] / pert(\alpha_s^3)$$

$$k_Y = [Y(\alpha_s^3) + Y(\alpha_s^4)] / Y(\alpha_s^3)$$

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

M_H=160 GeV

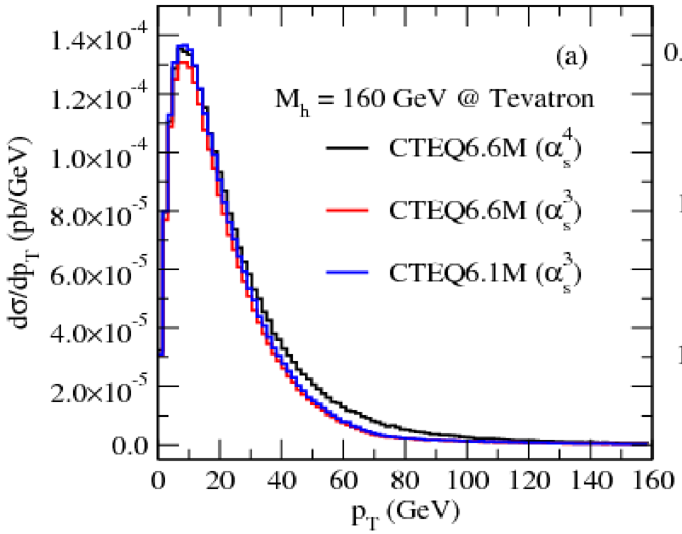
	cteq 6.1M (α_s^3)	cteq 6.6M (α_s^3)	cteq 6.6M (α_s^4)
@Tevatron	2.37 fb	2.26 fb	2.60 fb
@LHC	174 fb	172 fb	205 fb

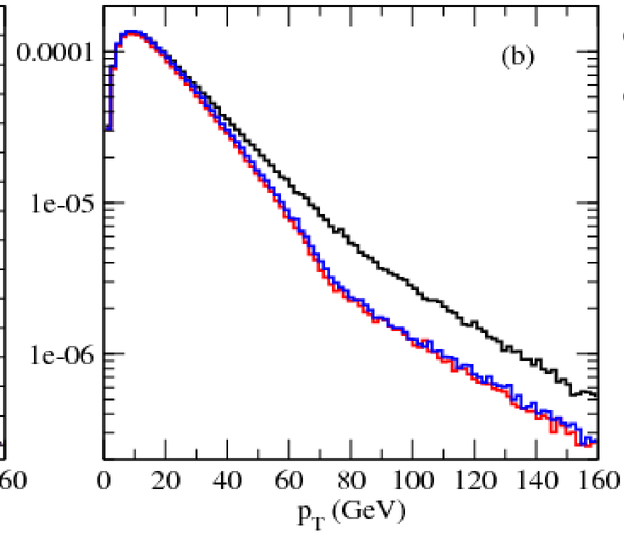
C T E Q

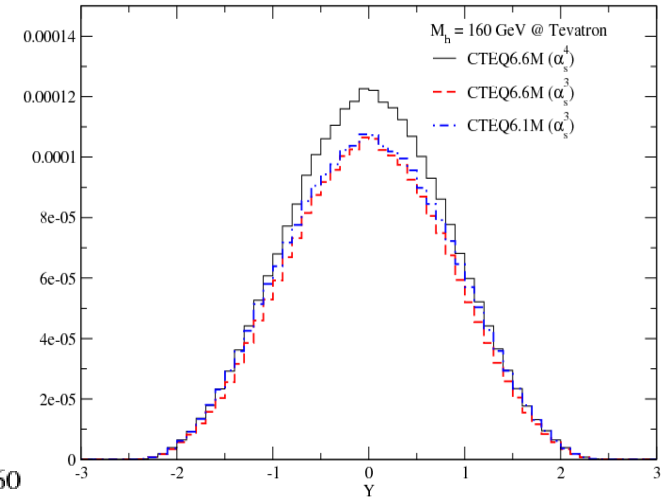
Transverse momentum and rapidity of H

$$gg \to H \to WW \to \ell^+\ell^-\nu\nu$$

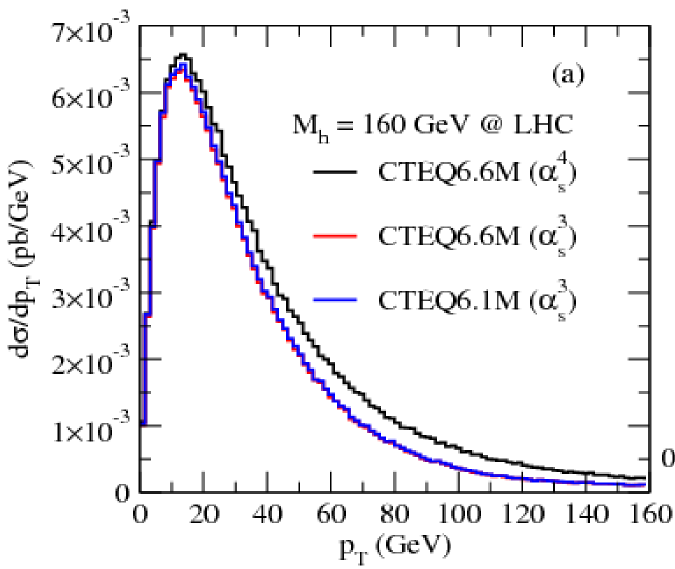
Tevatron

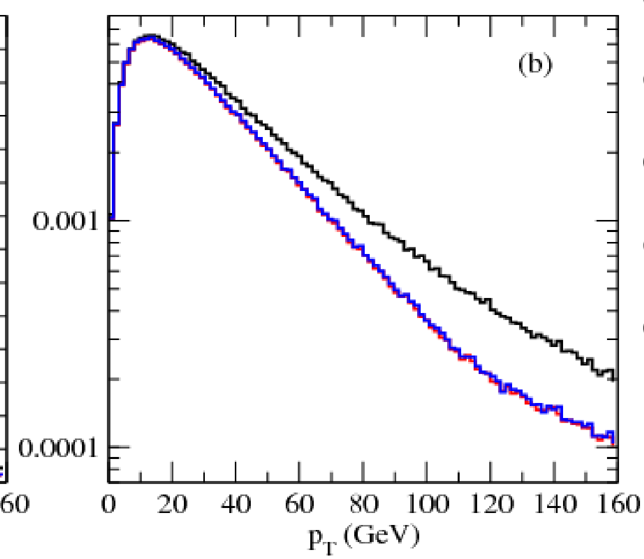


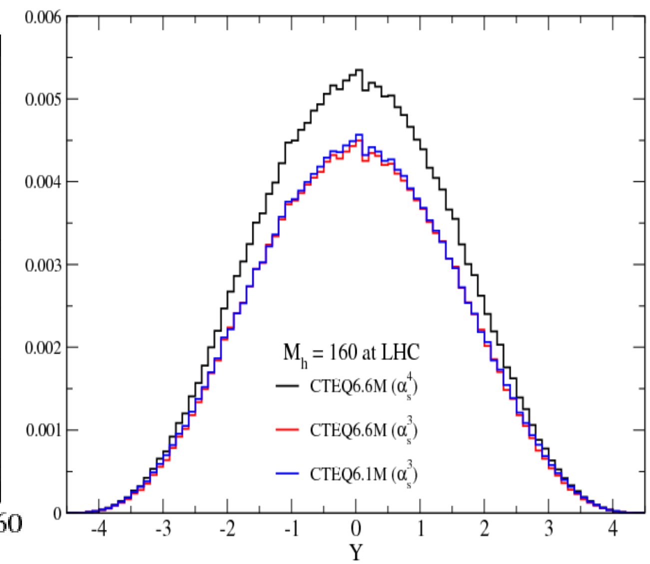




LHC



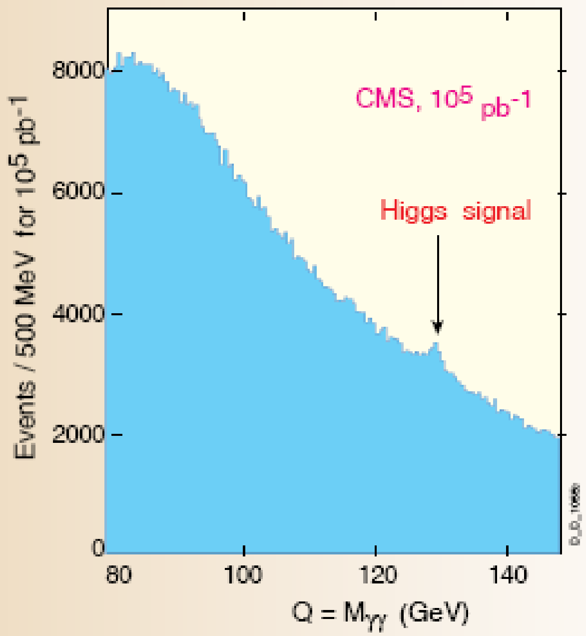




C T E Q

Higgs search Background: Direct di-photon production

The search for Higgs resonance relies on good understanding of the large QCD background



Signal and background in $H \to \gamma\gamma$

- 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 α_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

CTEQ

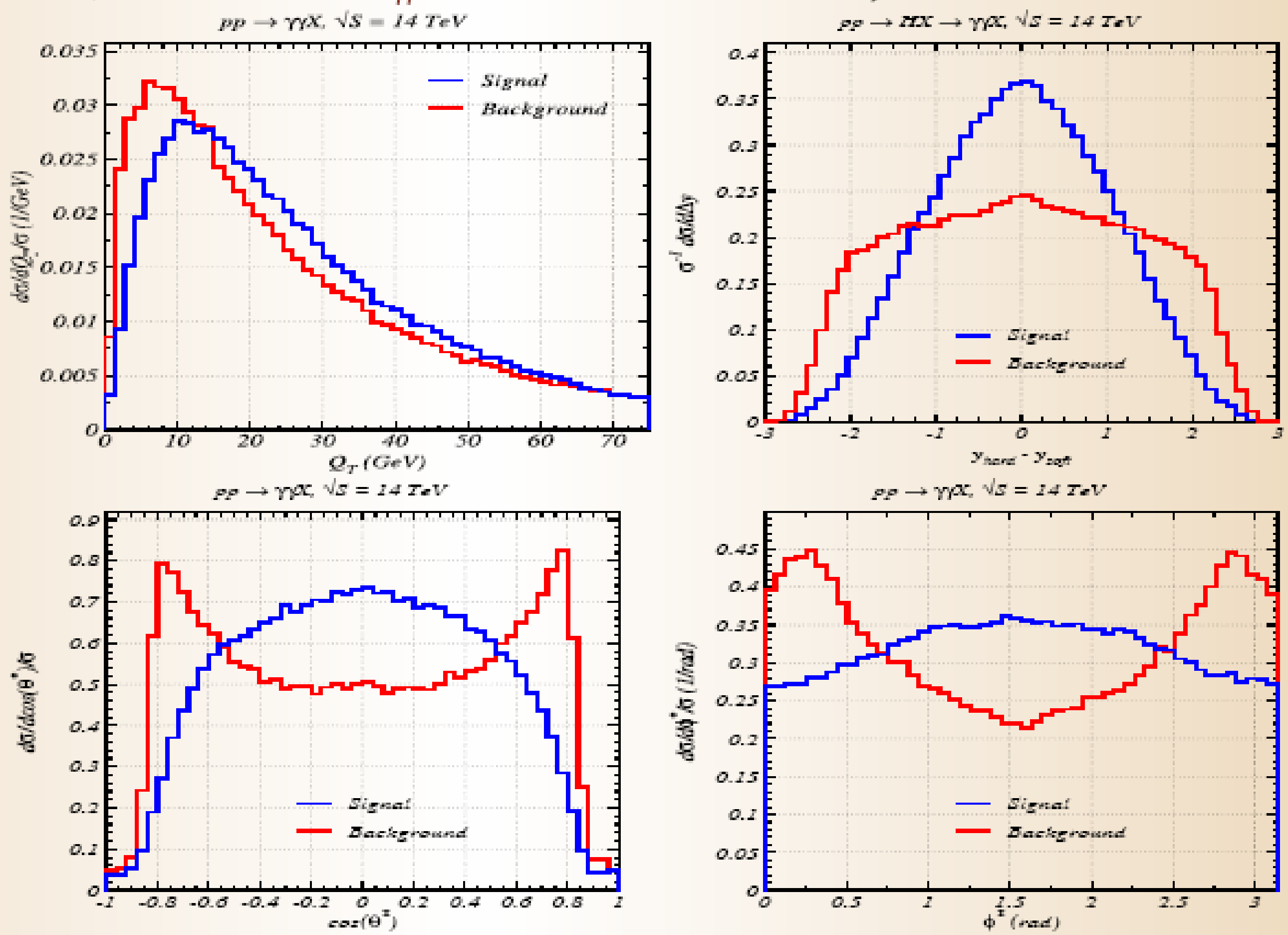
pQCD Resummation Calculation

NNLL/NLO 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 θ_*, φ_* in the $\gamma\gamma$ rest frame

no singularities, in contrast to the fixed-order rate



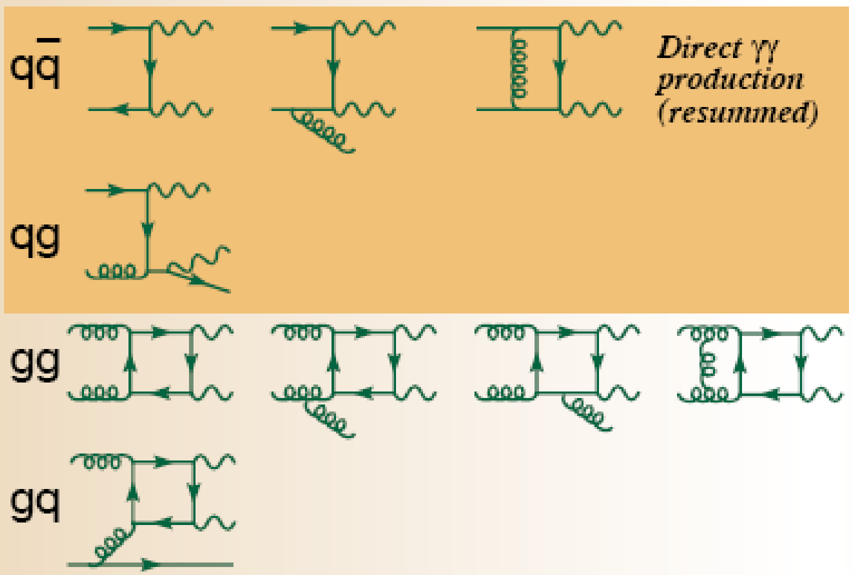
CTEQ

Di-Phootn Production

Direct diphotons

The dominant production mode; evaluated up to NLO in α_S

Balazs, Berger, Nadolsky, Yuan, 2006



$q\bar{q} + qg$ channel

- NLO matrix elements:
  Aurenche 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

CTEQ

Effect of initial state heavy parton

$\mathcal{O}(\alpha_S)$ resummed cross section

Hep-ph/0603049

Simplified ACOT scheme was used

$\therefore M_H \neq 0$ only in the gluon-initiated channels

$S^{pert}(b,Q)$ and functions $C^{in}_{jq}(x, b\mu_F)$,$C^{out}_{bj}(z, b\mu_F)$ do not depend on the mass

Only $C^{in}_{jg}(x, b, M, \mu_F)$ 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.

Effect of initial state heavy parton

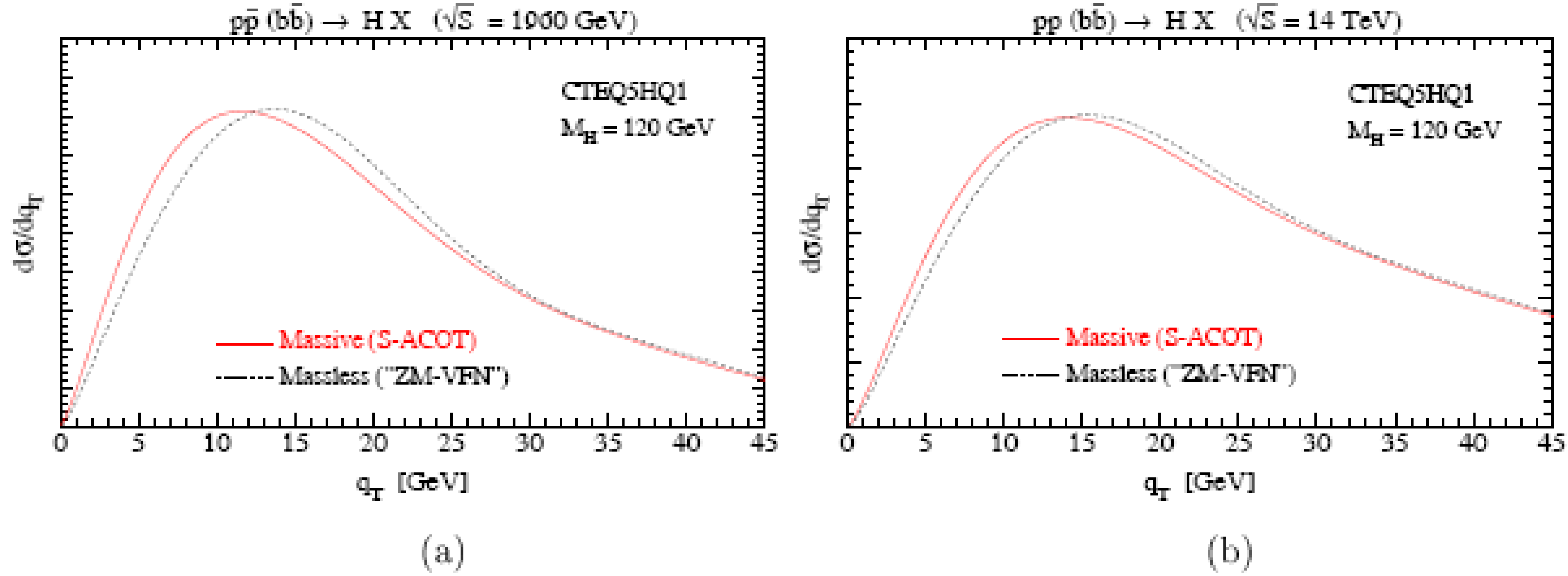


Figure 2: Transverse momentum distribution of on-shell Higgs bosons in the $b\bar{b} \rightarrow \mathcal{H}$ channel at (a) the Tevatron and (b) LHC. The solid (red) lines show the q_T distribution in the massive (S-ACOT) scheme. The dashed (black) lines show the distribution in the massless ("ZM-VFN") 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.

C T E Q

Conclusion

- Precision measurements demand higher order calculations

  ⇒ NLO, NNLO, Resummation

- PDFs need to be refined using the early LHC (W, Z and top) data

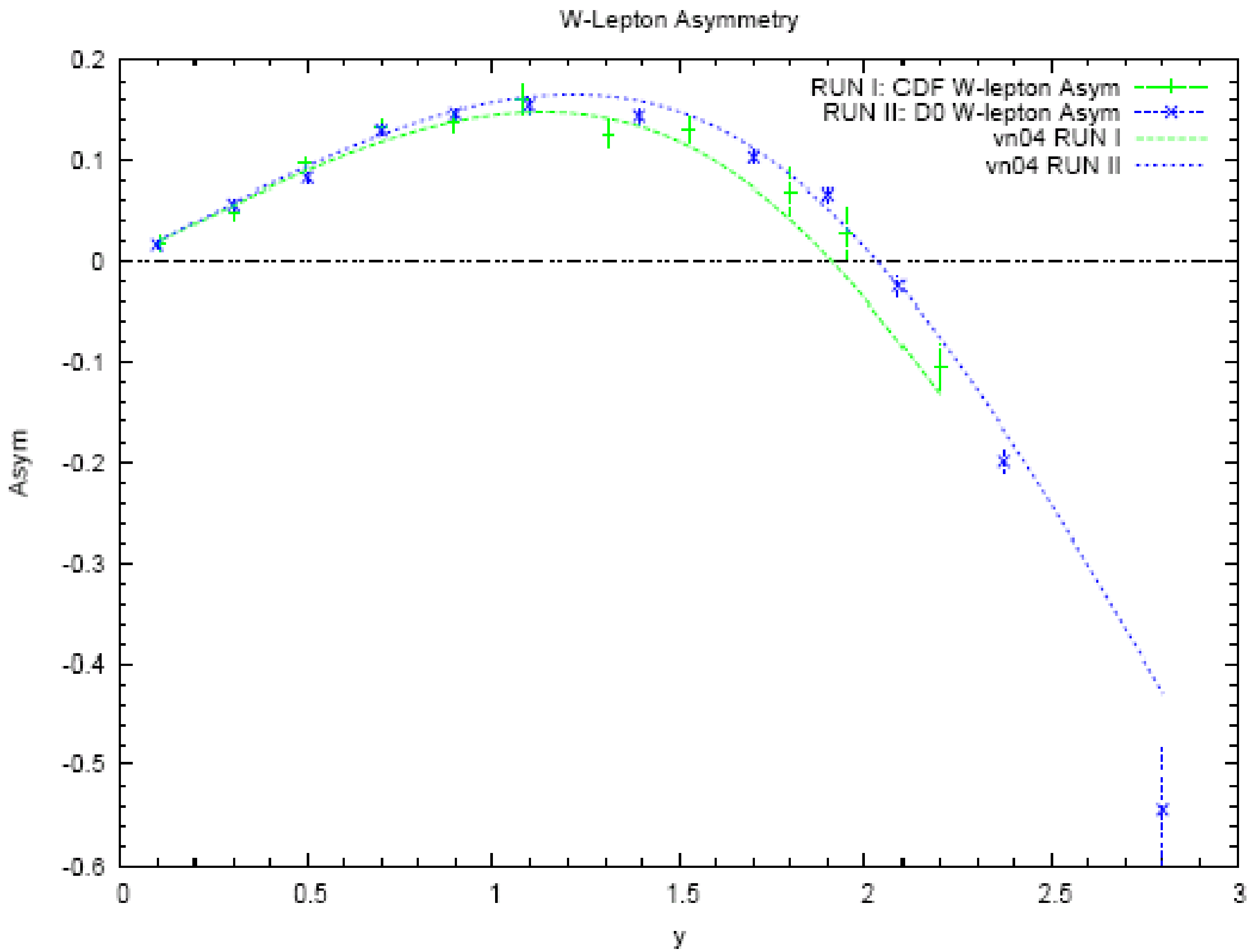
  ⇒ to reliably predict New Physics signal.

CTEQ

Backup Slides

C T E Q

Run-2 W Lepton Asymmetry Data



Run-2 W Lepton Asymmetry Data