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Precision Measurements at Hadron Colliders

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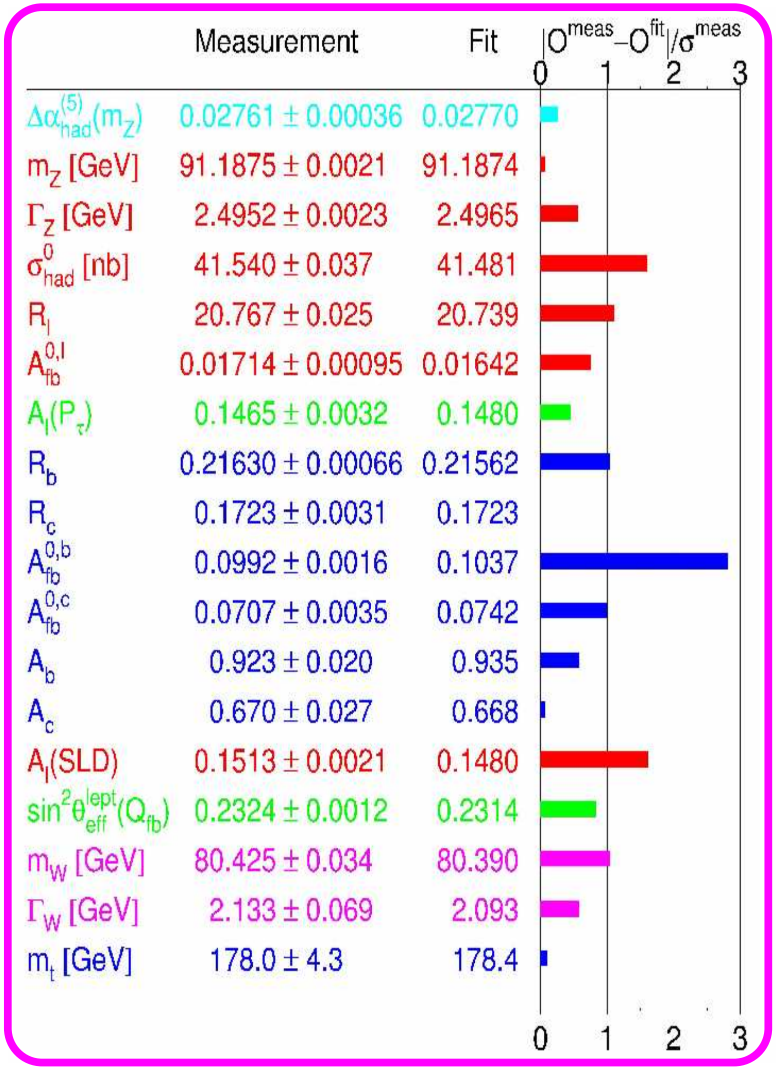
Era of Precision Measurements @ e^-e^+

By comparing measurements and theoretical prediction of electroweak precision observables

- the electroweak sector of Standard Model (SM) is probed at the quantum-loop level
- the consistency of SM is checked by comparing direct measurements with indirect determinations of input parameters, e.g. m_t and M_W.
- the parameters of models beyond the SM can be constrained.

Global SM fit to all electroweak data:
from LEPEWWG (Winter 2004)



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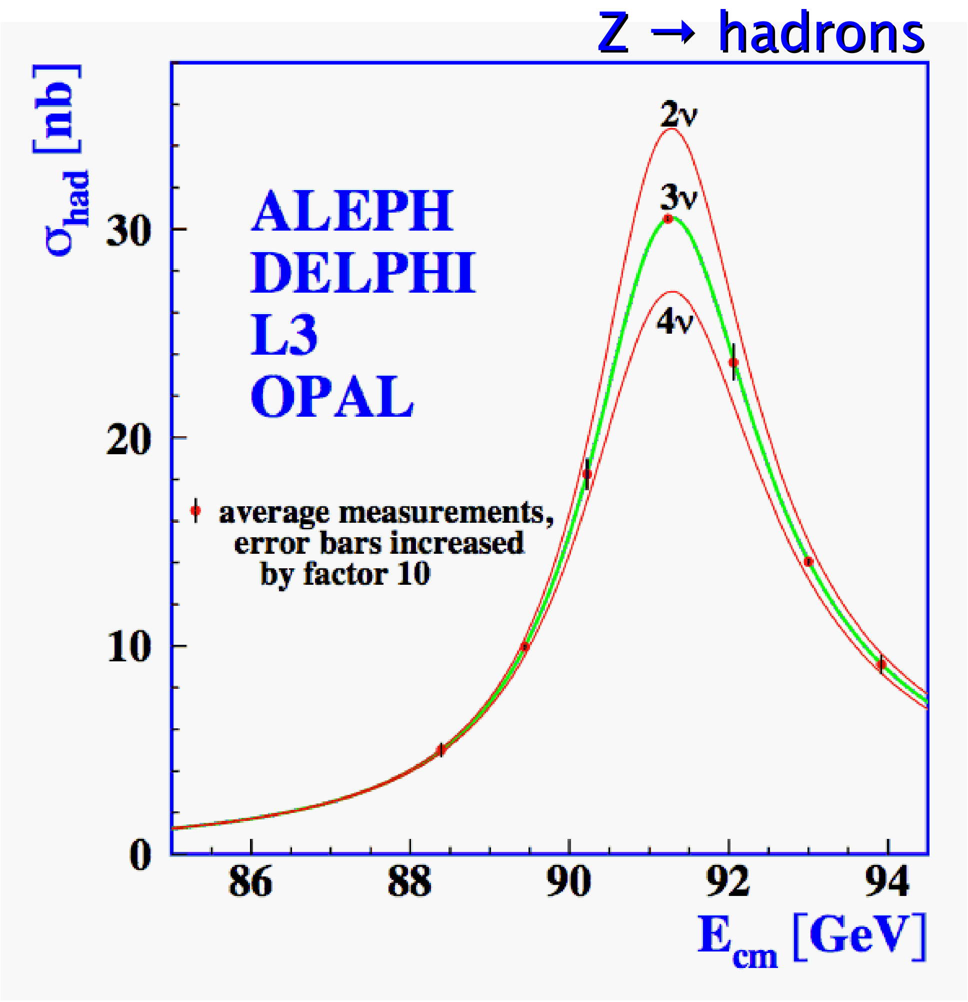
Precision Data

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

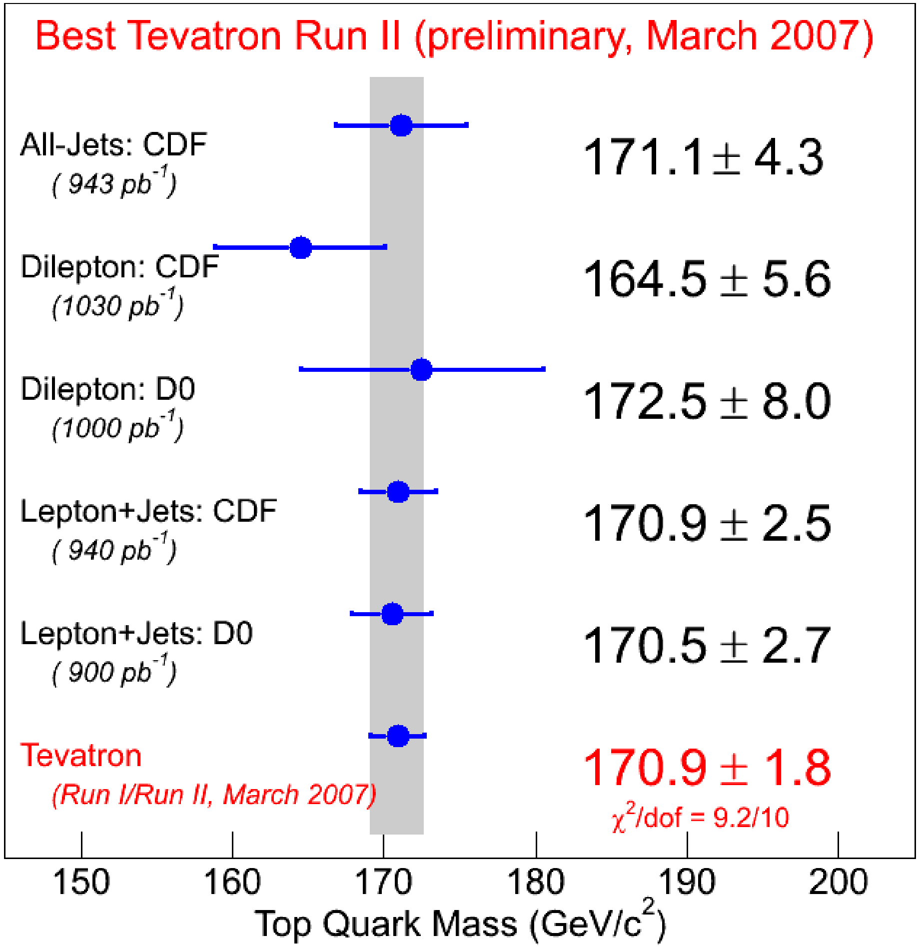
Phase II: Precision Measurements

Z boson



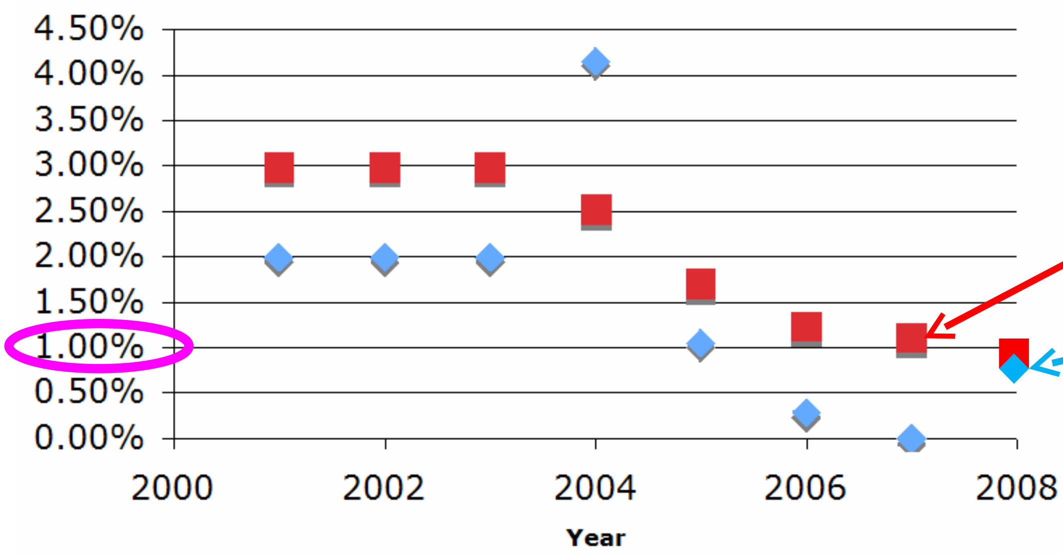
LEP experiments, CERN

top quark



Tevatron experiments, Fermilab

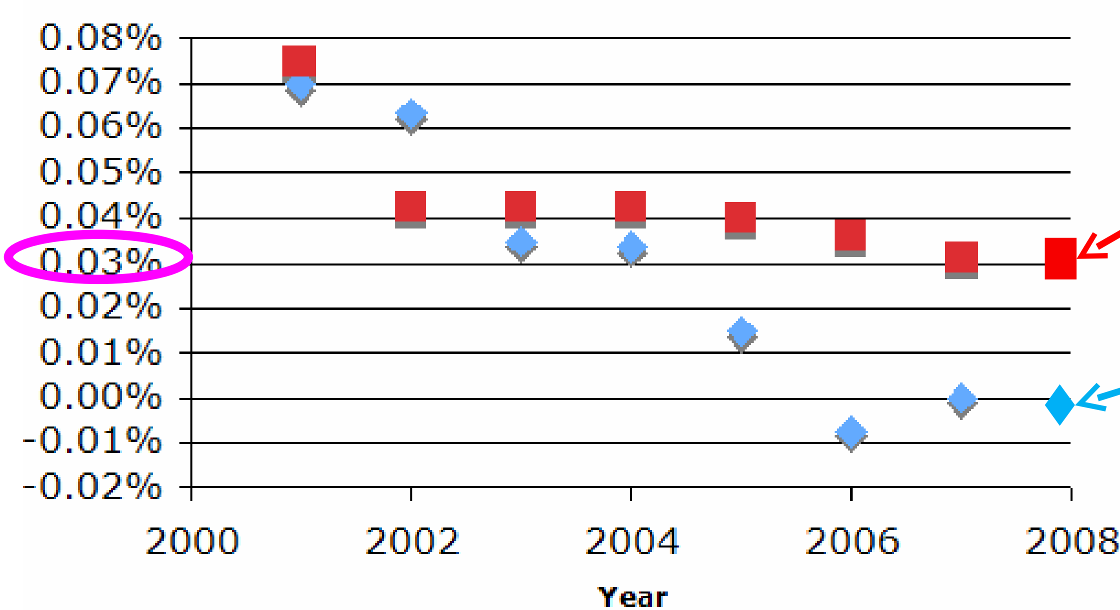
M_t and M_W Uncertainties Steadily Decreasing



$\Delta\ M_t/M_t$

$M_t/170.9 - 1$

$\Delta\ M_{top} = 1.2$ GeV



$\Delta\ M_W/M_W$

$M_W/80.398 - 1$

$\Delta\ M_W = 0.025$ GeV

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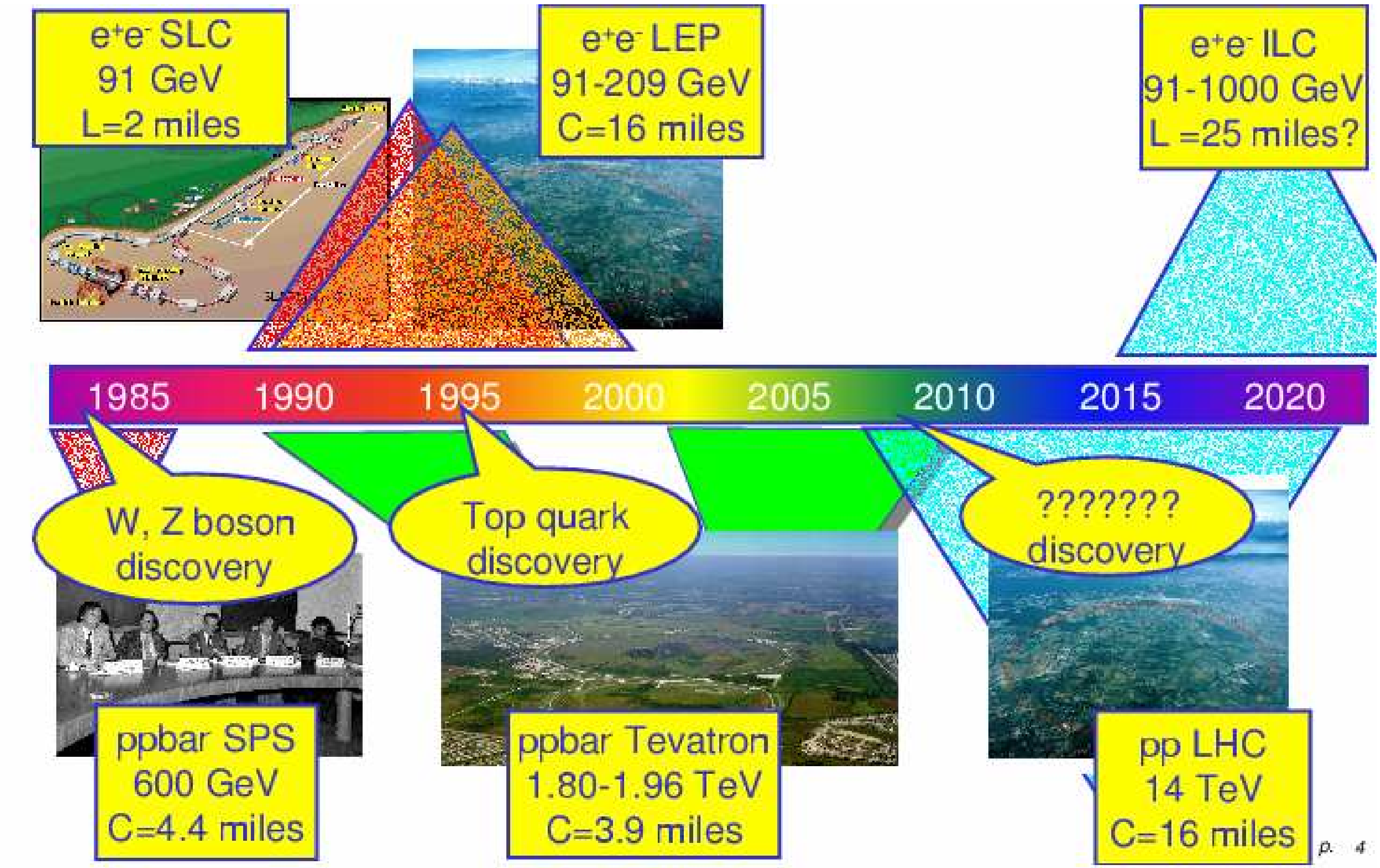
Era of Precision Measurements @ Hadron colliders



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

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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

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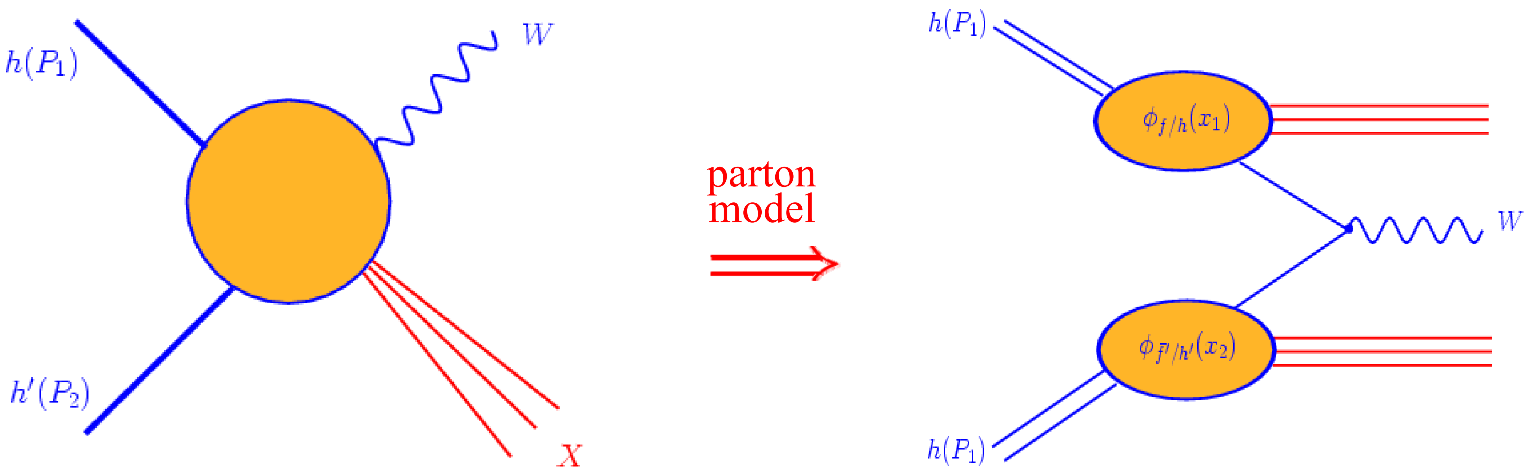
W-boson production at hadron colliders



$$\sigma_{hh' \to W^+ X} = \sum_{f,f'} \int_0^1 dx_1 dx_2 \left\{ \phi_{f/h}(x_1)\, \hat{\sigma}_{f\,f'}\, \phi_{\bar{f}'/h'}(x_2) + (x_1 \leftrightarrow x_2) \right\}$$

PDFs are known from deep inelastic scattering

partonic "Born" cross section of $f\bar{f}' \to W^+$

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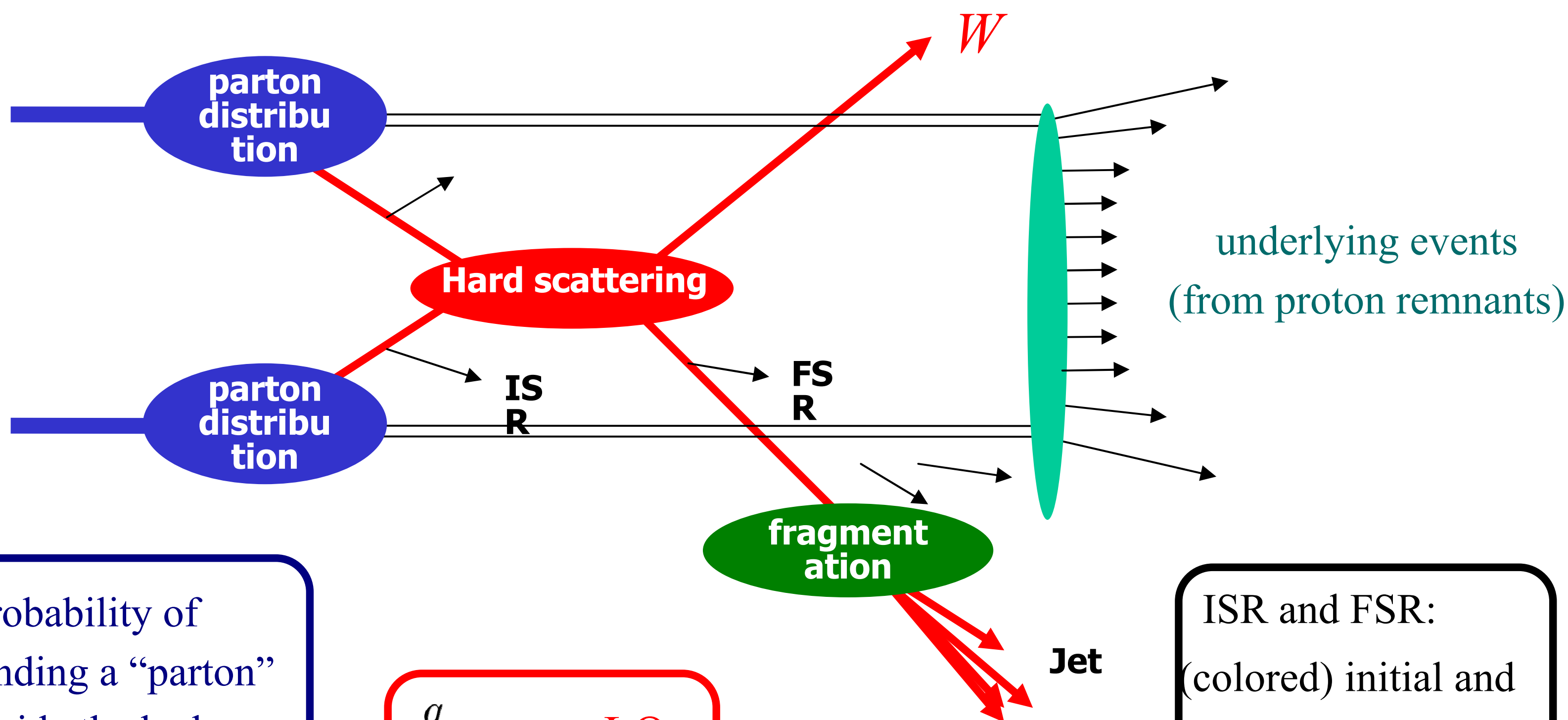
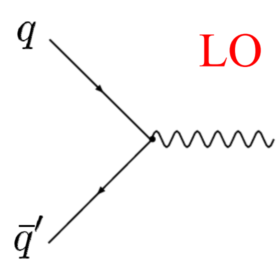


PDFs: probability of
finding a “parton”
inside the hadron



ISR and FSR:
(colored) initial and
final states
can radiate gluons

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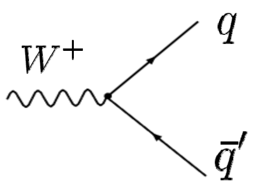
W-boson Decay

- Hadronic mode

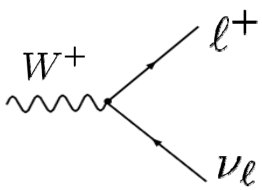


$$Br \sim \frac{6}{9}$$

$$\begin{pmatrix} u & u & u & c & c & c \\ \bar{d} & \bar{d} & \bar{d} & \bar{s} & \bar{s} & \bar{s} \end{pmatrix}$$

hard to detect,
due to huge QCD backgrounds

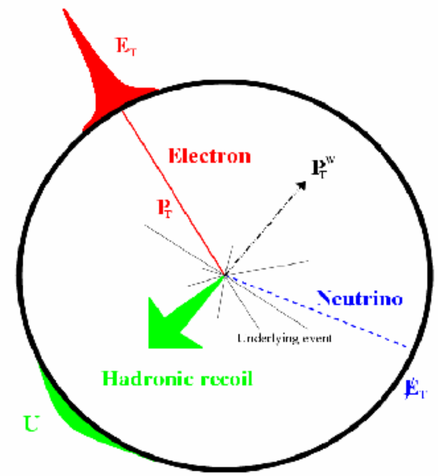
- Leptonic mode



$$Br \sim \frac{3}{9}$$

$$\begin{pmatrix} e^+ & \mu^+ & \tau^+ \\ \nu_e & \nu_\mu & \nu_\tau \end{pmatrix}$$

easy to identify,
but lack of p_z^ν



unknown p_z^ν ⇨ cannot reconstruct invariant mass of W boson

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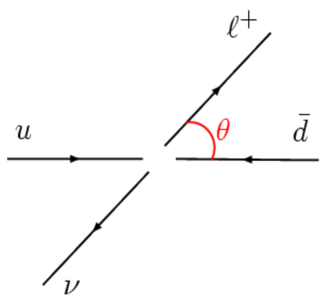
Transverse momentum of the charged lepton p_T^e

- In (ud) c.m. system,

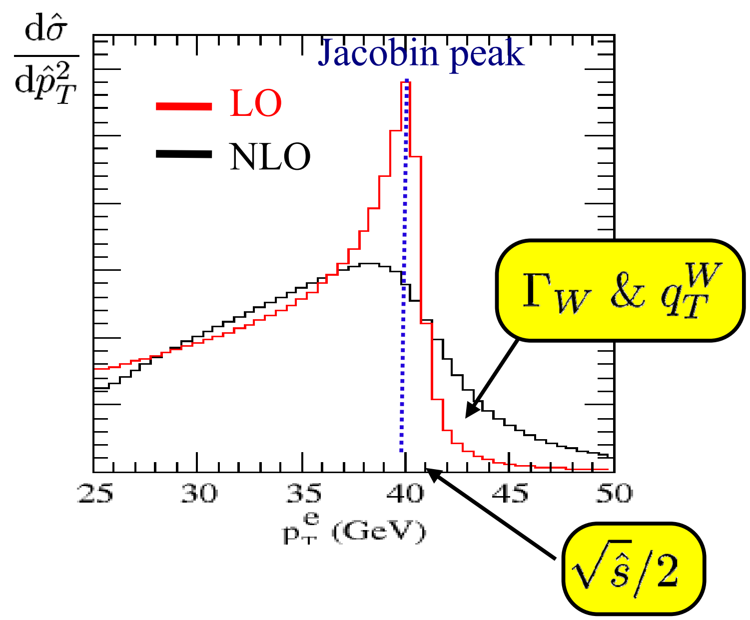


$$\hat{p}_T^2 = \frac{1}{4}\hat{s}\sin^2\theta$$

Jacobin factor

$$\frac{\mathrm{d}\cos\theta}{\mathrm{d}\hat{p}_T^2} = -\frac{2}{\hat{s}}\frac{1}{\sqrt{1-\frac{4\hat{p}_T^2}{\hat{s}}}}$$

$$\Longrightarrow \quad \frac{\mathrm{d}\hat{\sigma}}{\mathrm{d}\hat{p}_T^2} \sim \frac{\mathrm{d}\hat{\sigma}}{\mathrm{d}\cos\theta} \times \frac{1}{\sqrt{1-4\hat{p}_T^2/\hat{s}}}$$



sensitive region for measuring

M_W : $p_T^e \sim 30 - 45$ GeV

Γ_W : not a good observable

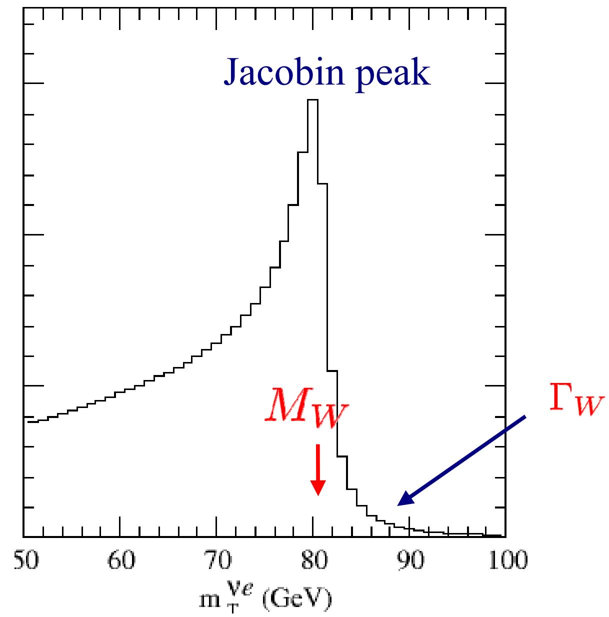
Transverse mass of the W-boson M_T^W

- Definition:

$$m_T^2(\ell,\nu) = 2\, p_T^\ell\, p_T^\nu (1-\cos\phi_{\ell\nu})$$

from overall p_T imbalance

$$\Longrightarrow \quad \frac{d\hat\sigma}{dm_T^2} \sim \frac{1}{\sqrt{1-m_T^2/\hat s}}$$



- ☞ unaffected by longitudinal boosts of $\ell\nu$ system
- ☞ not sensitive to q_T^W
- ☞ tail knows about Γ_W (direct measurement)

:

sensitive region for measuring
M_W : $M_T \sim 60-100\text{GeV}$
Γ_W $M_T > 100$ GeV

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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

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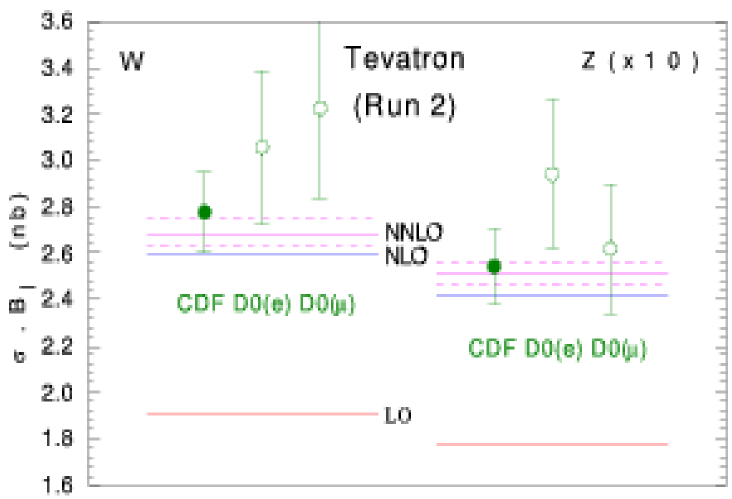
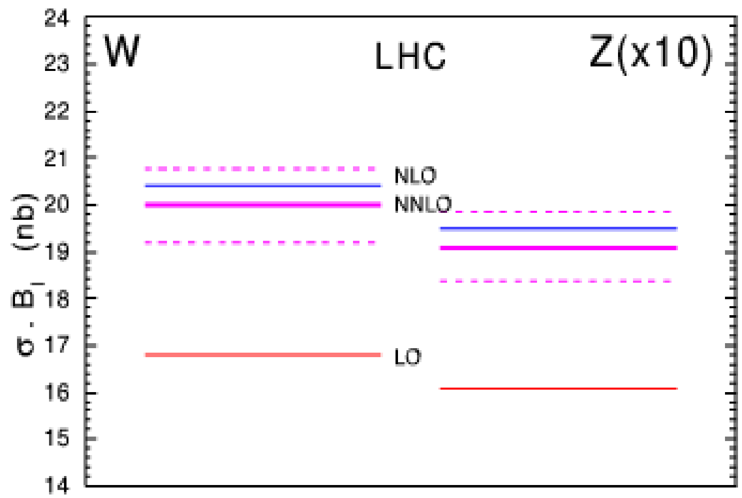
NNLO QCD corrections to the cross section

- NNLO hard cross section





☞ NNLO *K*-factor : 1.04 at Tevatron
0.98 at LHC

MRST'03

☞ scale dependence of order 1%

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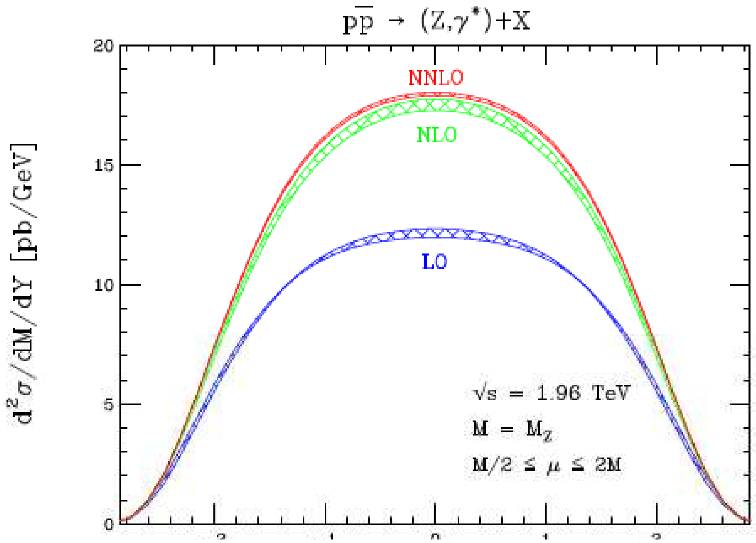
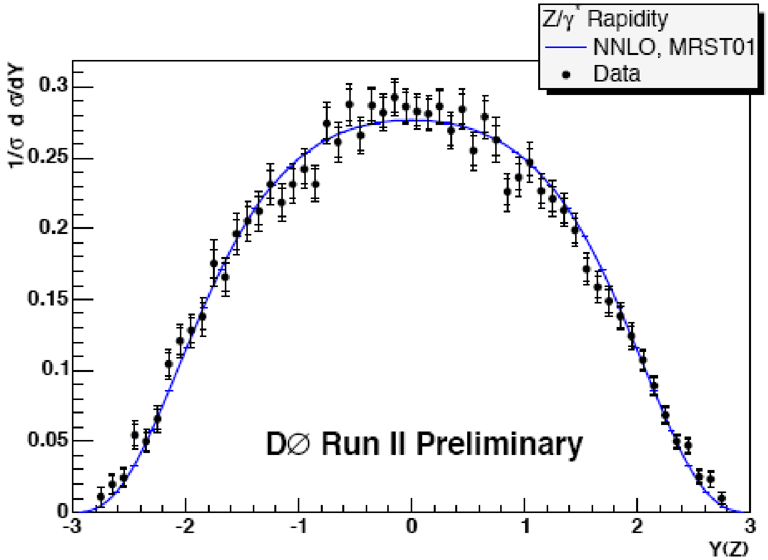
Rapidity distributions

- Little shape difference from NLO to NNLO
  - K-factor should be sufficient
- Z rapidity distributions could/will be used as input for pdf fits





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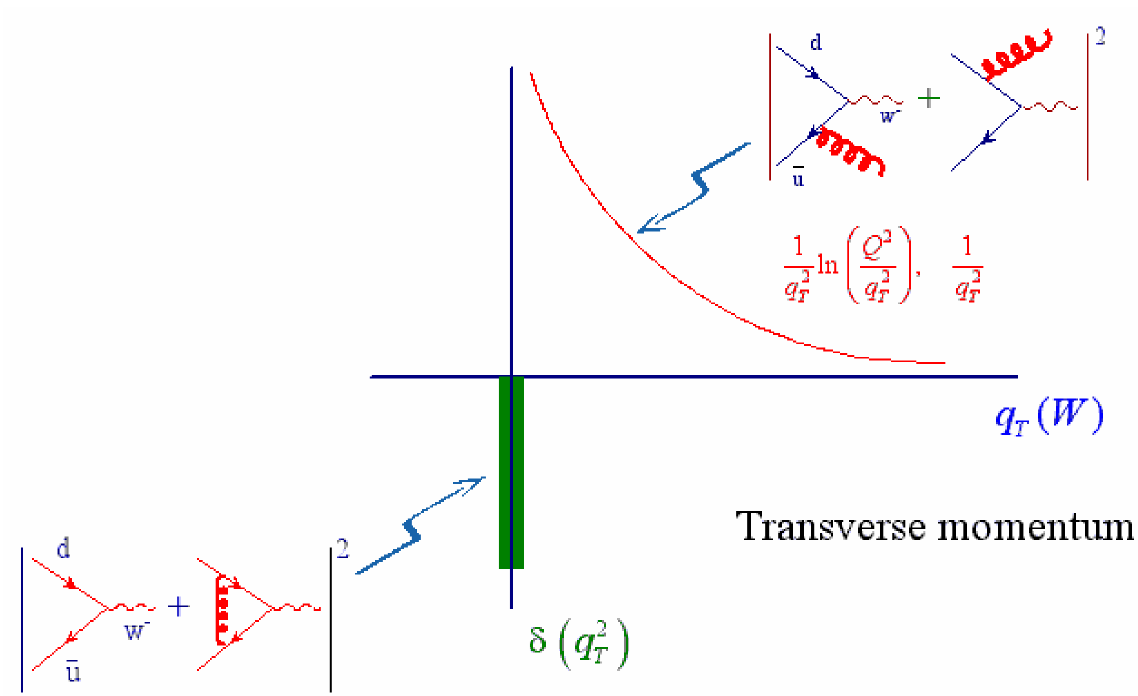
Shortcoming in fixed order pQCD calculations

- 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)

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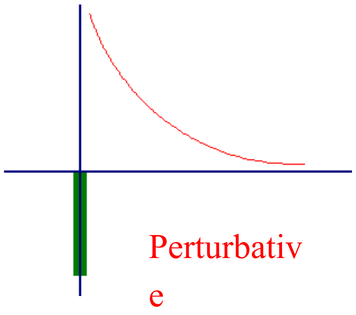
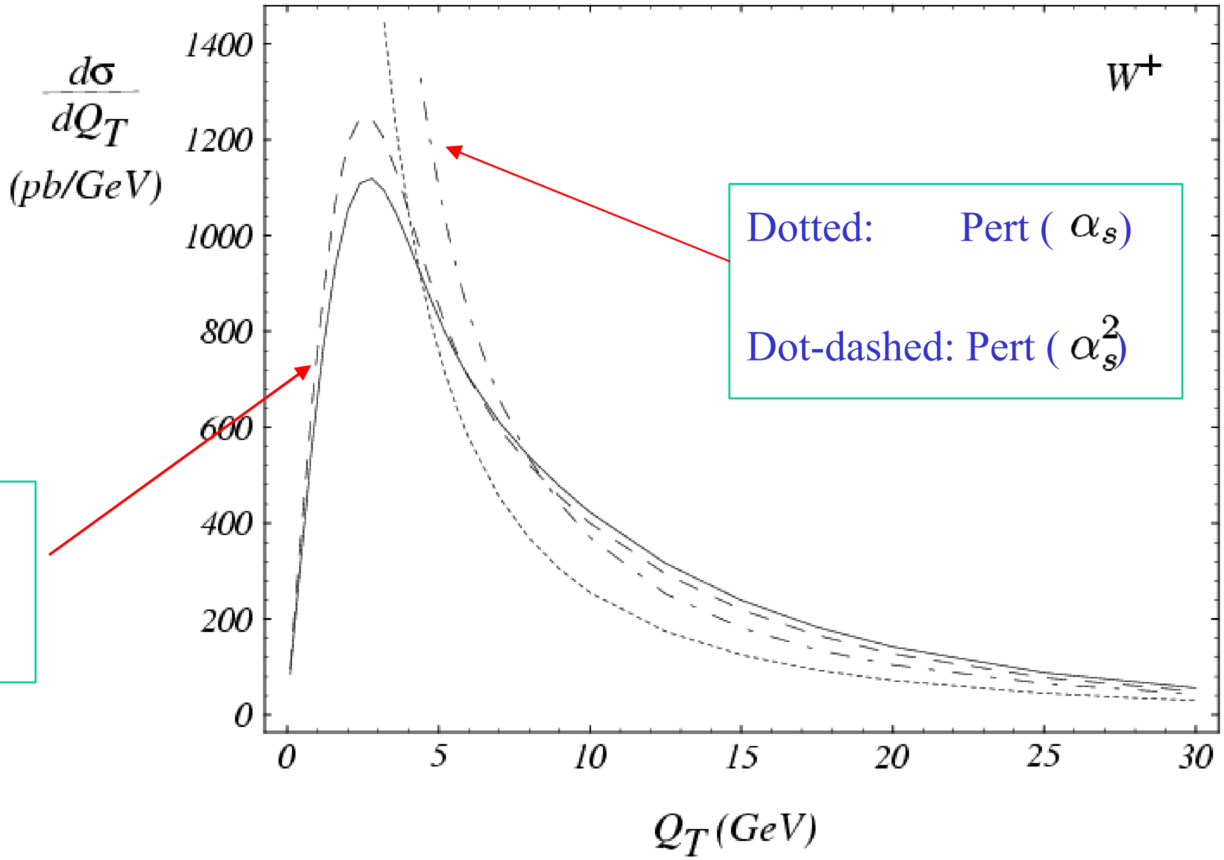
To describe data ⟹ Resummation is needed



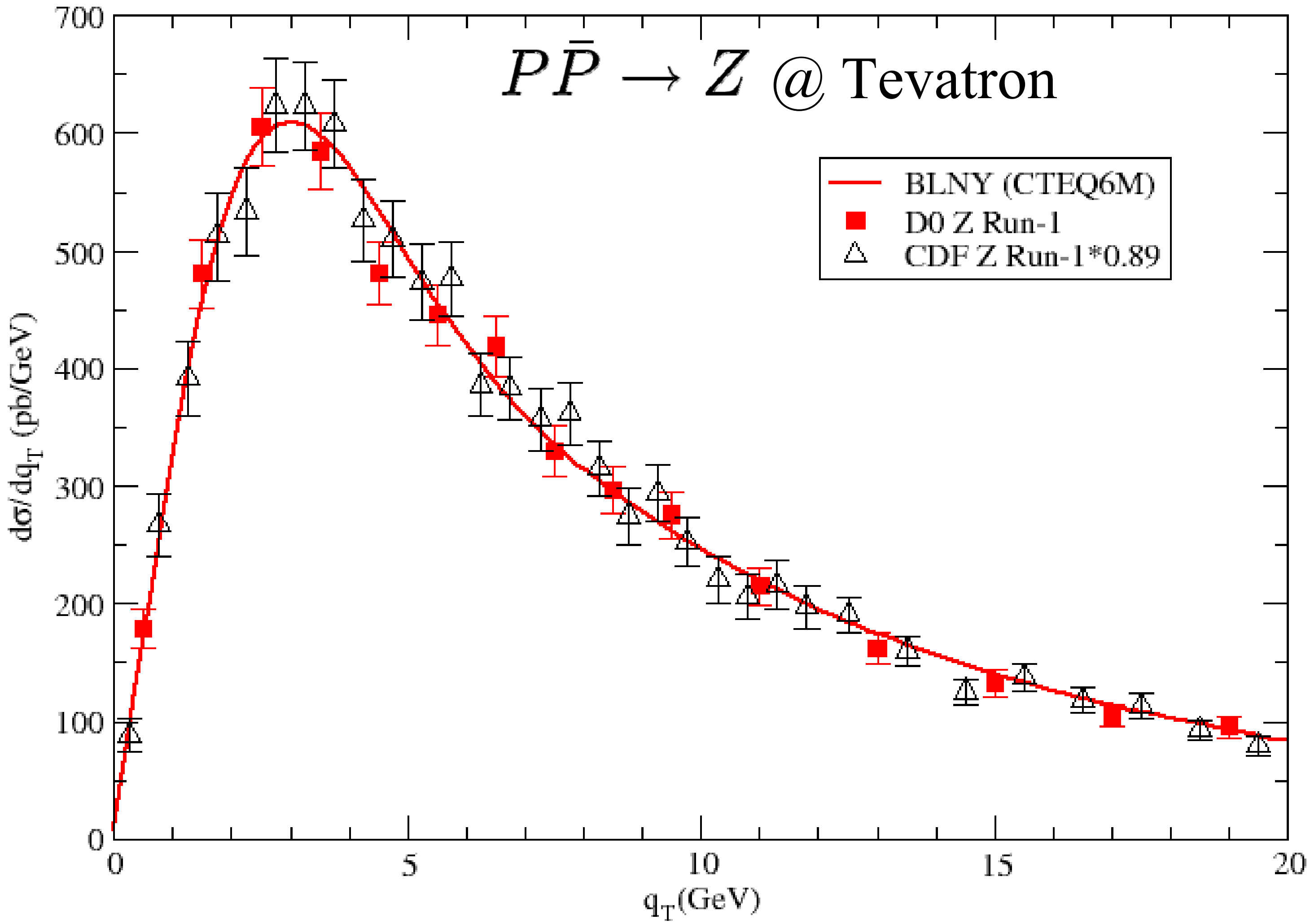


Dashed: CSS (1,1,1)

Solid: CSS (2,2,1)

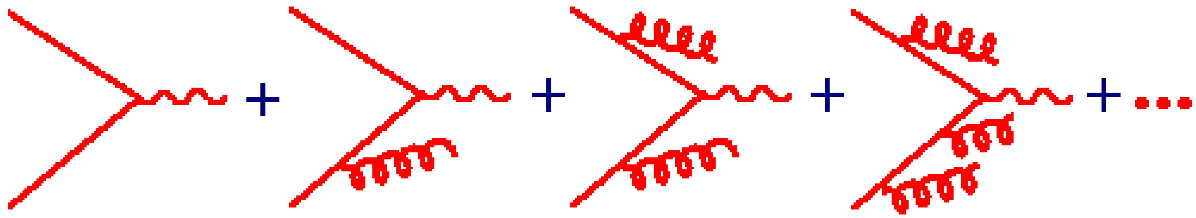
Resummation

Resummation effects agree with data very well



What is QCD resummation ?

- All order quantum corrections



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

$$\sim \frac{1}{q_T^2}\Big\{ \alpha_S\left(\underline{L+1}\right) + \alpha_S^2\left(\underline{L^3+L^2}+\underline{L+1}\right) + \alpha_S^3\left(\underline{L^5+L^4}+\underline{L^3+L^2}+\underline{L+1}\right) + \cdots \Big\}$$

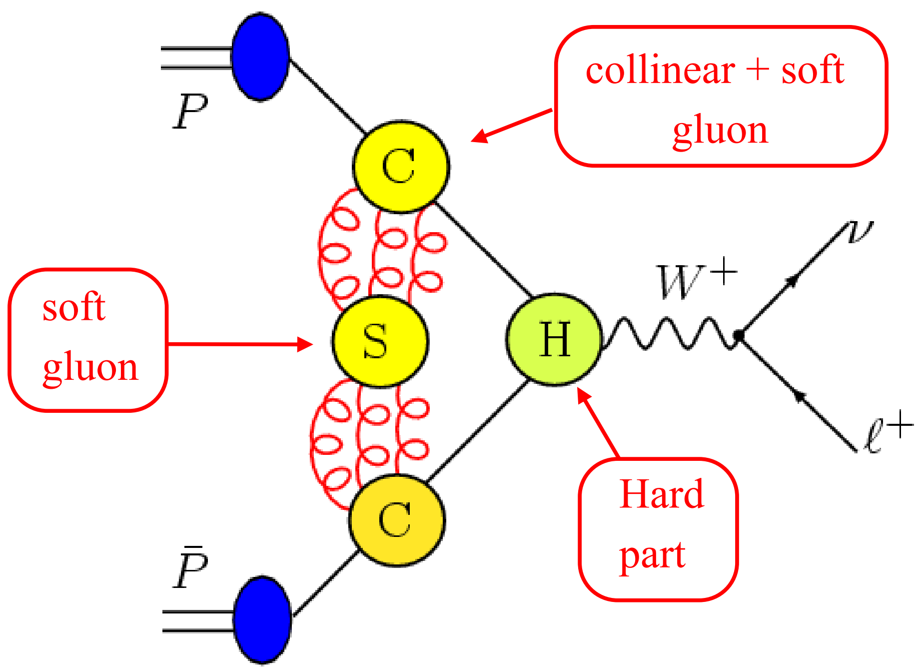
Resummation is to reorganize the results in terms of the large Log's.

What is QCD resummation ?

- reorganization of logs

$$
\begin{aligned}
\frac{d\sigma}{dq_T^2} \sim \frac{1}{q_T^2}\Big\{ & \big[\alpha_S(L+1) + \alpha_S^2(L^3+L^2) + \alpha_S^3(L^5+L^4) + \cdots\big] \\
& + \big[\qquad + \alpha_S^2(L+1) + \alpha_S^3(L^3+L^2) + \cdots\big] \\
& + \big[\qquad\qquad + \alpha_S^3(L+1) + \cdots\big] \\
& + \cdots \Big\}
\end{aligned}
$$

Renormalization Group Technique



CSS resummation formalism

Collins-Soper-Sterman

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

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

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

$$\sum_j \int_{x_A}^{1} \frac{d\xi_A}{\xi_A} C_{qj}\left(\frac{x_A}{\xi_A}, b, \mu\right) \cdot f_{j/A}\left(\xi_A, \mu\right)$$

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

$$\sum_k \int_{x_B}^{1} \frac{d\xi_B}{\xi_B} C_{\bar{q}k}\left(\frac{x_A}{\xi_A}, b, \mu\right) \cdot f_{k/B}\left(\xi_B, \mu\right)$$

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

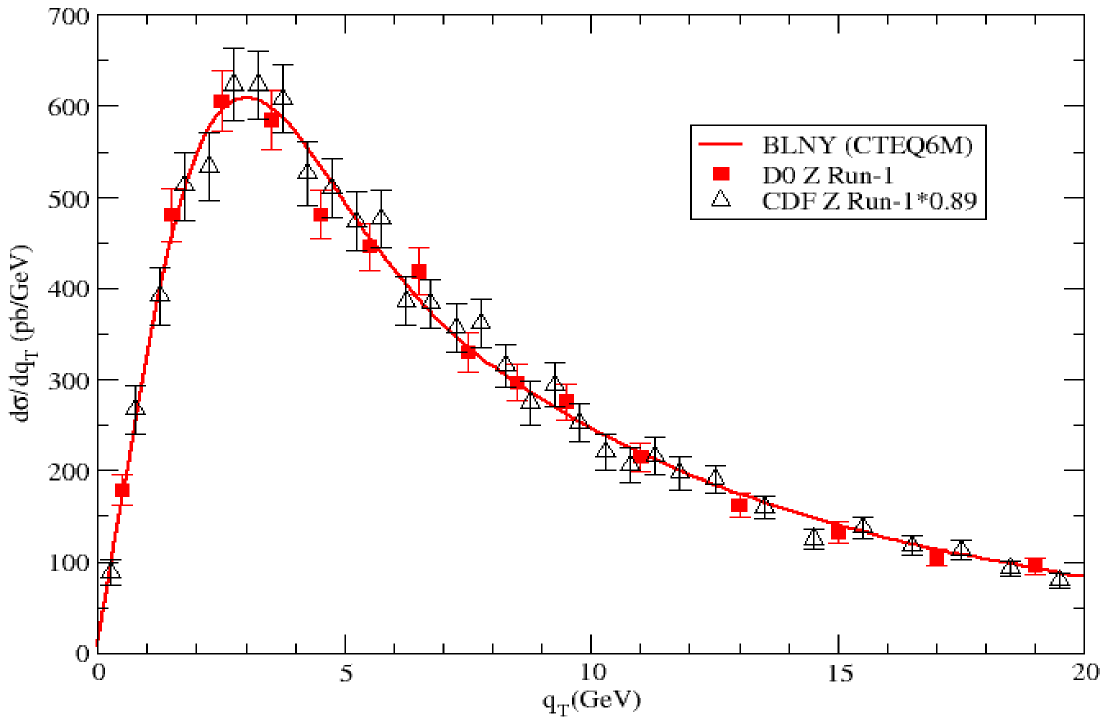
[Non-perturbative functions] are functions of (b, Q, x_A, x_B) which include QCD effects beyond Leading Twist.

Resummation effects agree with data very well

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

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.



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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

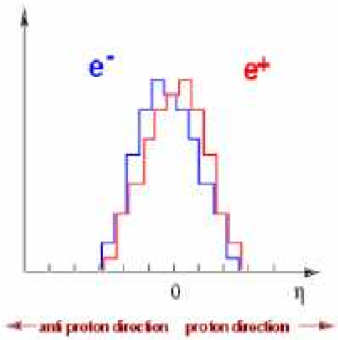
$$A(y_W) = \frac{d\sigma(W^+)/dy_W - d\sigma(W^-)/dy_W}{d\sigma(W^+)/dy_W + d\sigma(W^-)/dy_W}$$

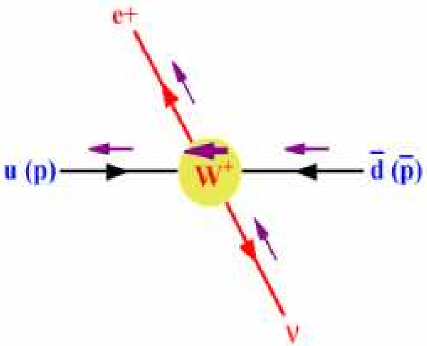
$$A(y_W) \approx \frac{u(x_1)d(x_2) - d(x_1)u(x_2)}{u(x_1)d(x_2) + d(x_1)u(x_2)}$$

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

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

$A(\eta_l) =$ 

$\otimes$ 

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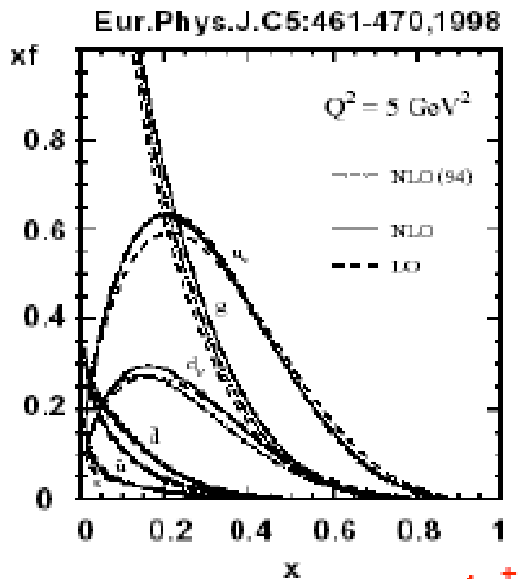
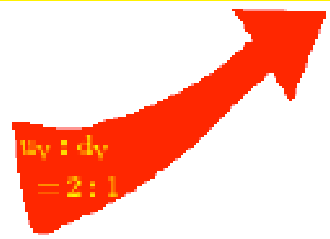
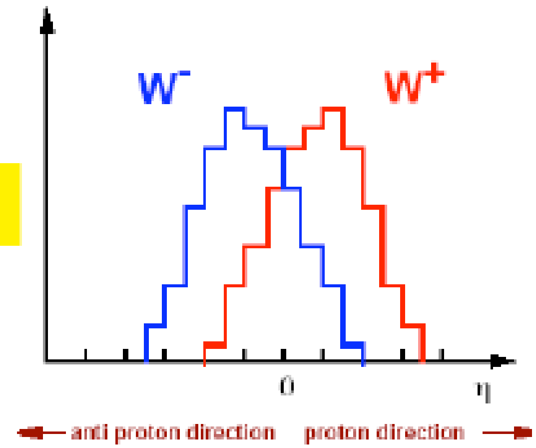
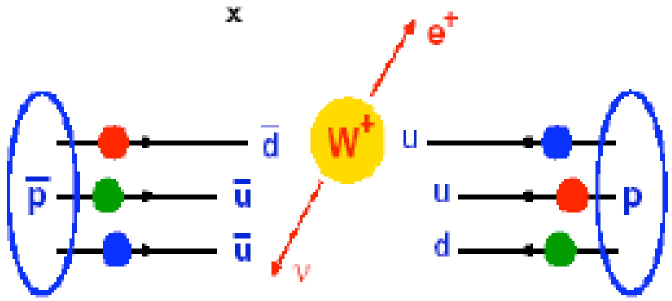
Rapidity Distribution



u higher momentum







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

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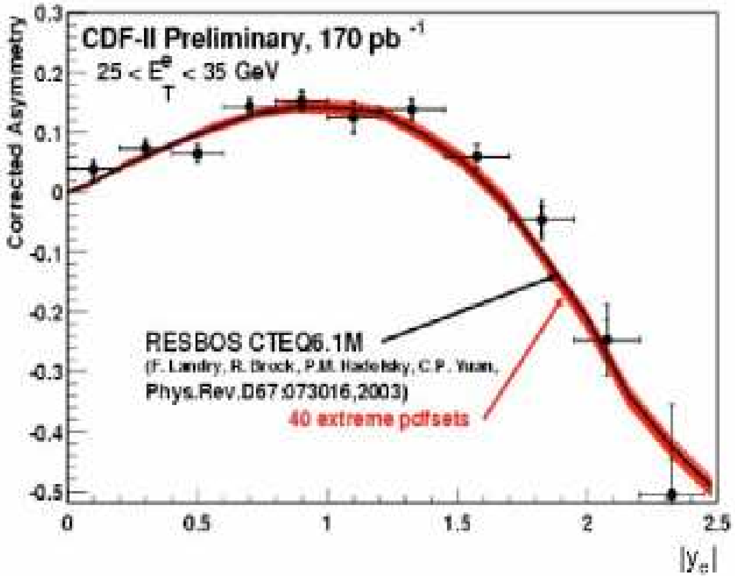
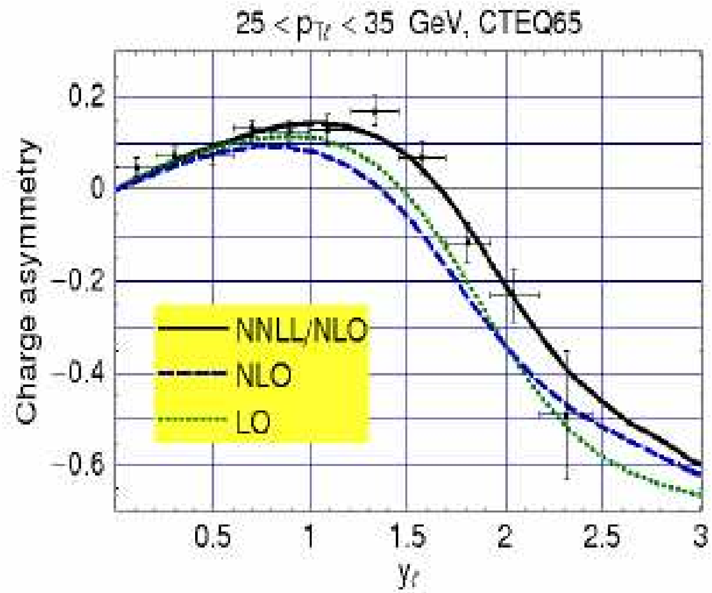
ResBos needed for Rapidity

Charged lepton asymmetry (from W decay)





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

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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.

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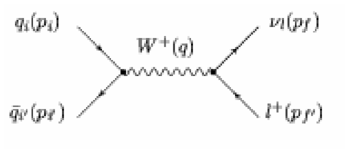
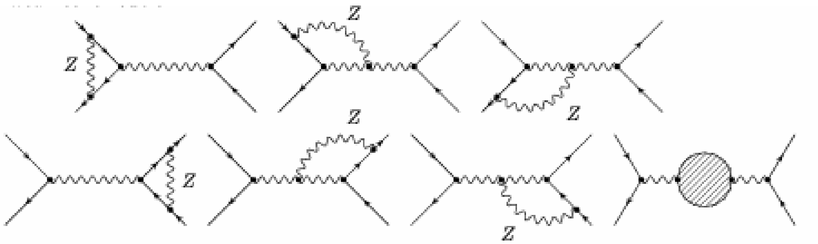
NLO EW corrections to W boson production

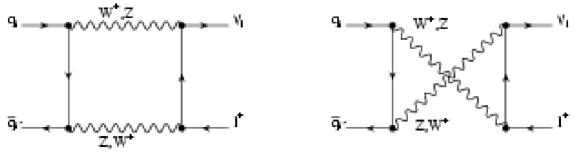
- Born



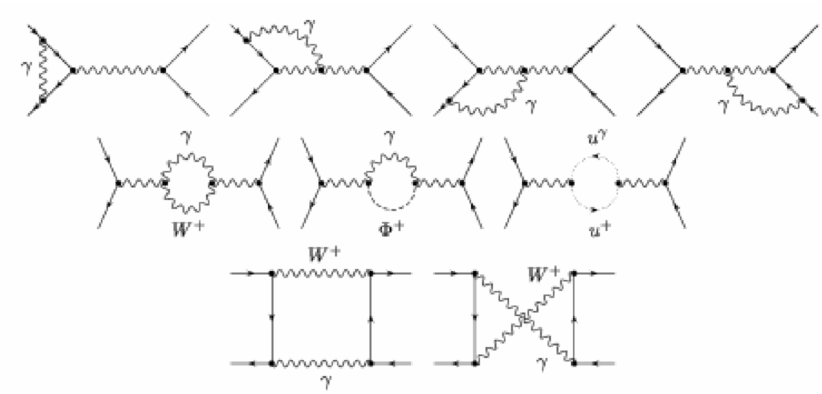
- pure weak contribution



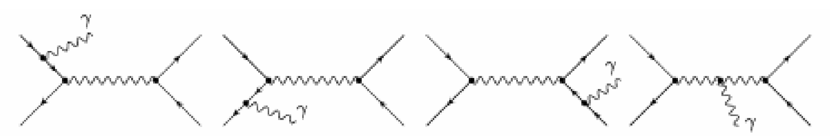
- W-Z box contribution



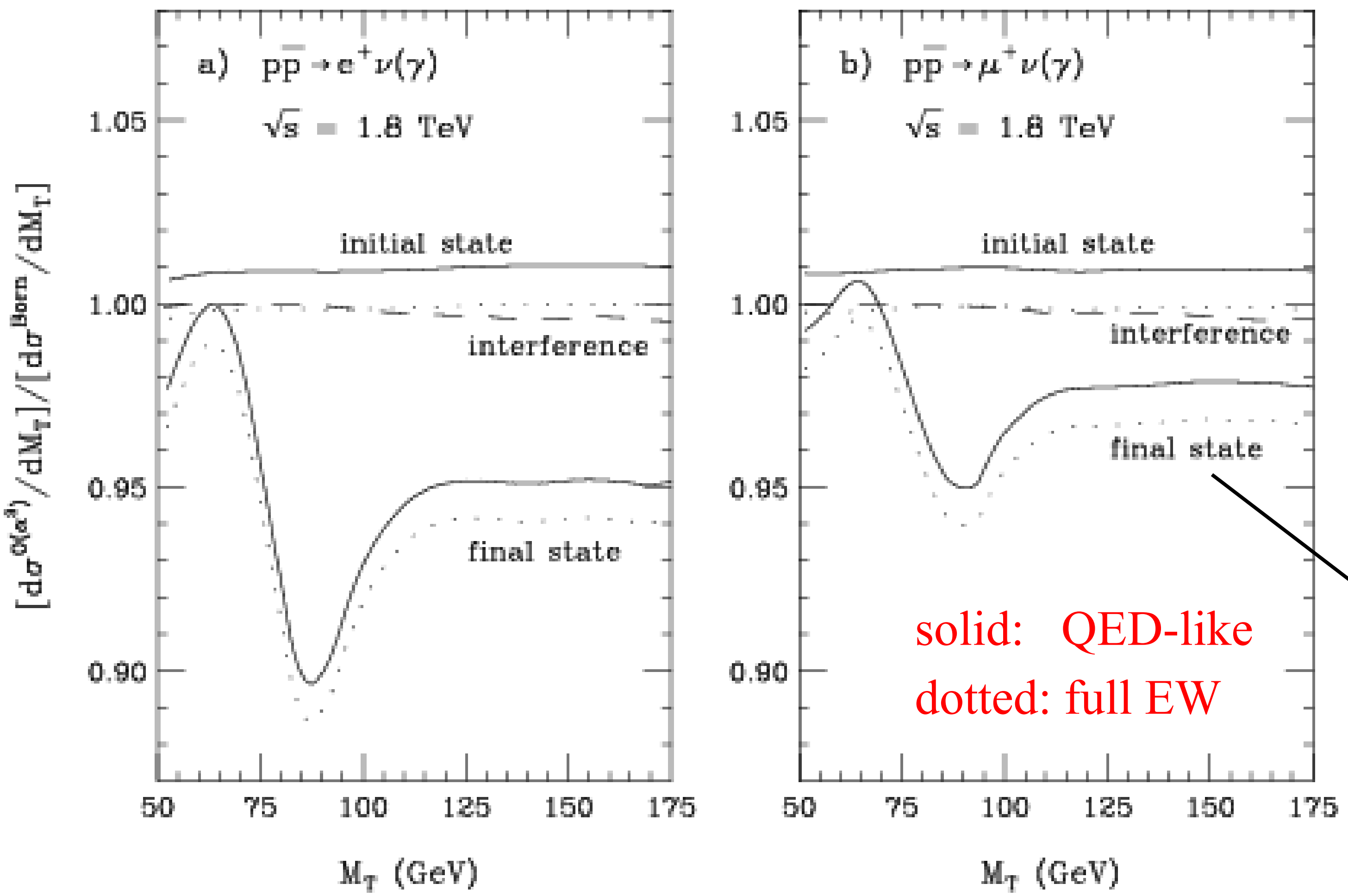
- virtual photon contribution



- real photon contribution



EW corrections (QED-like)



Solid: QED-like
Dotted: Full NLO EW corrections

Large shift in W mass $O(100\text{ MeV})$

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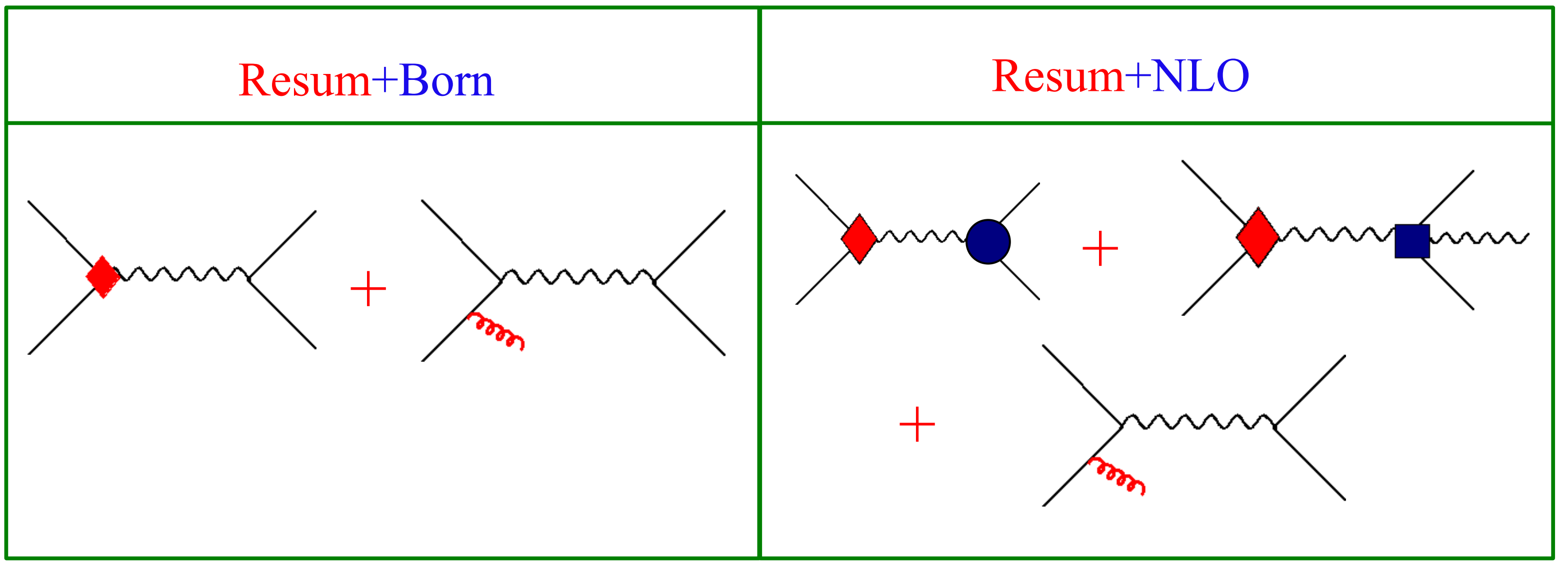
Precision measurements require accurate theoretical predictions

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

hep-ph/0401026

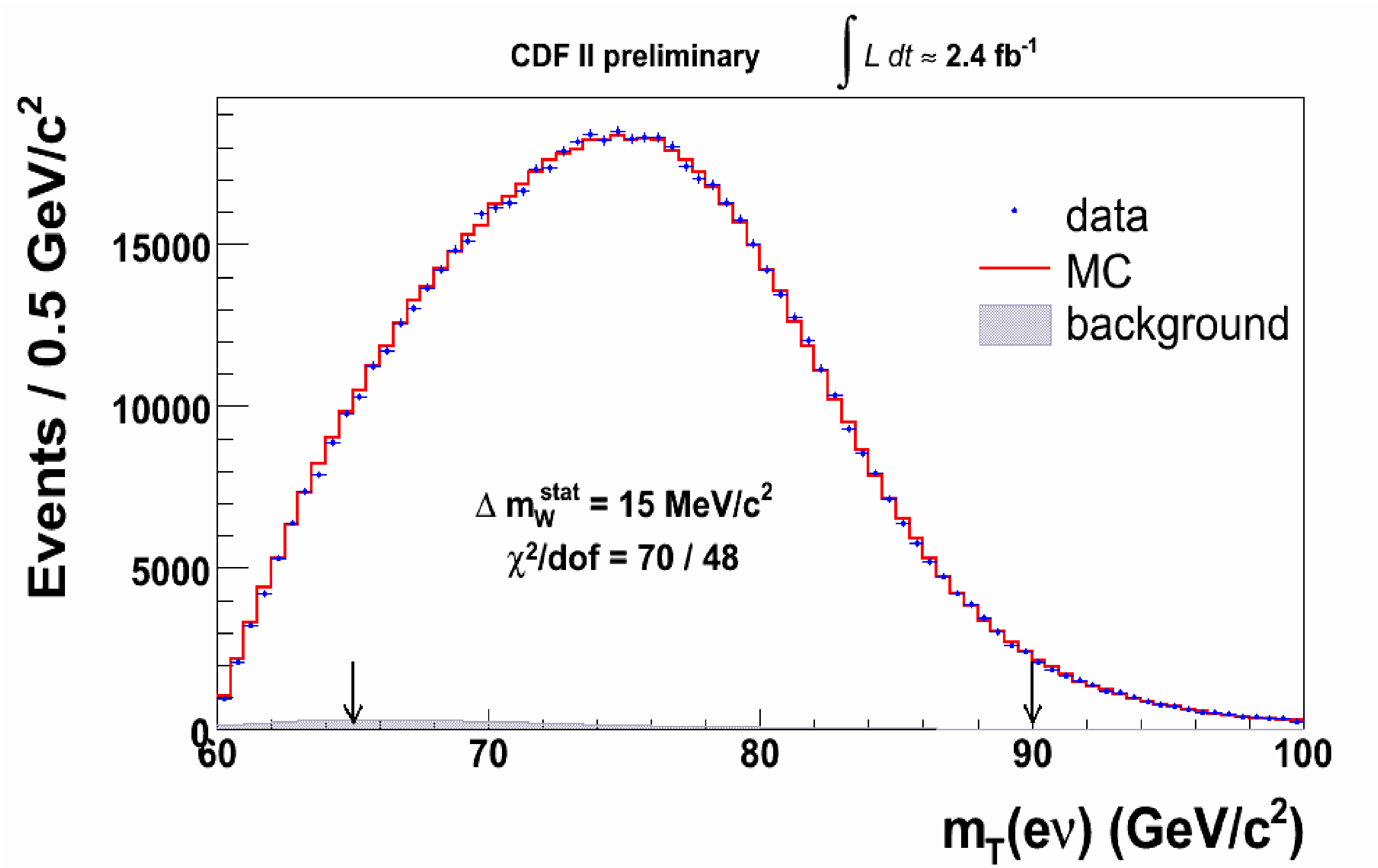
Qing-Hong Cao and CPY



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

W Mass @ CDF Run-2

W→eν transverse mass distribution



Statistical error only.

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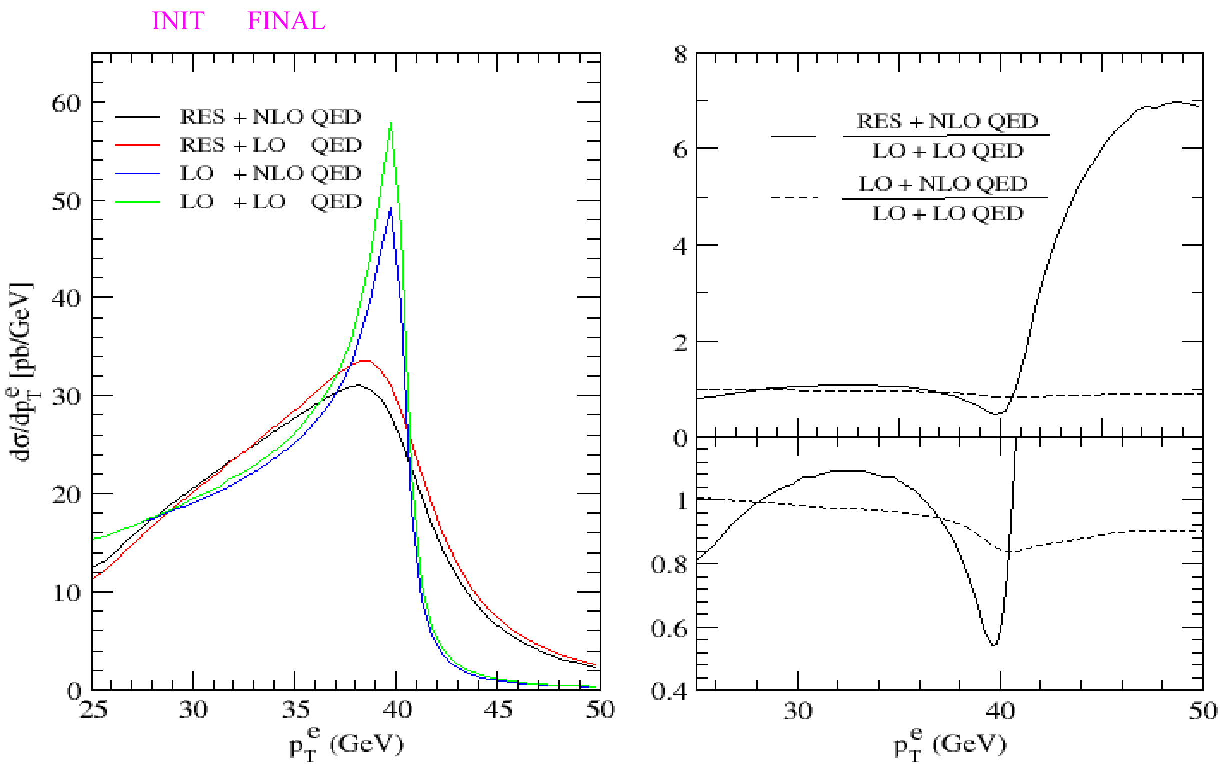
Transverse momentum distribution of charged lepton

p_T^e is sensitive to q_T^W



Cuts:

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

$\not{E}_T > 25$ GeV

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

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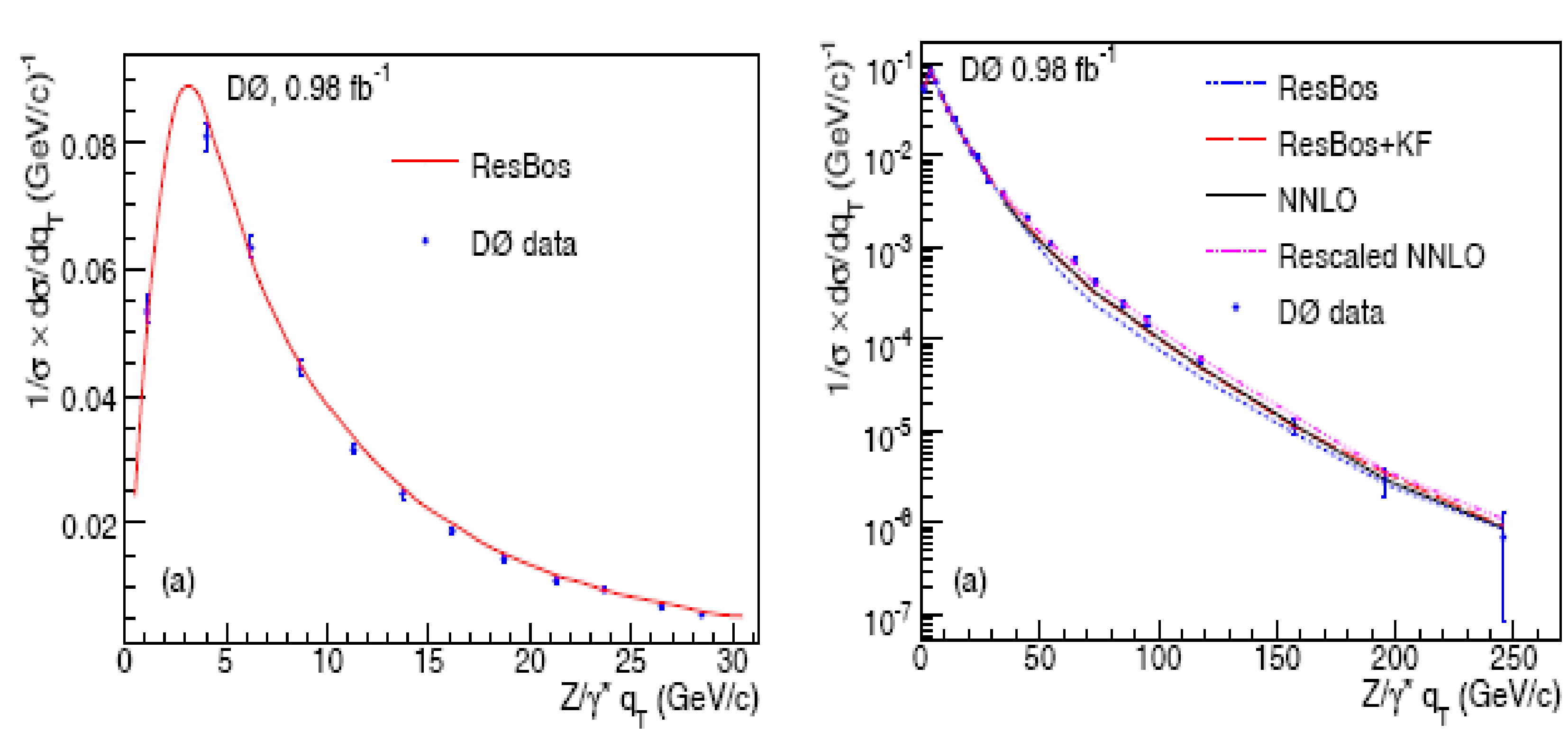
W Boson q_T @ D0 Run-2



low q_T region

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

C T E Q

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

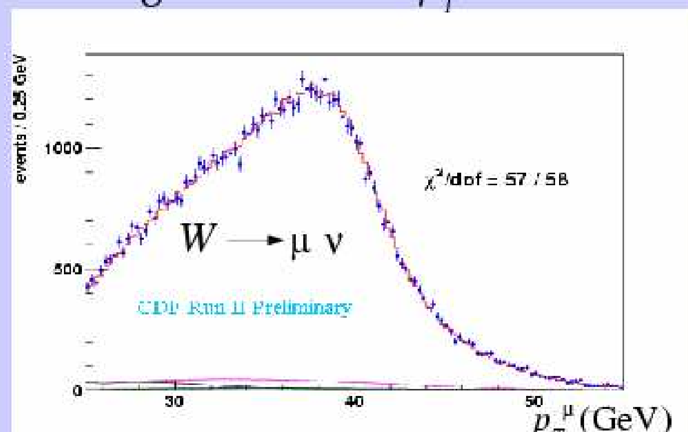
C T E Q

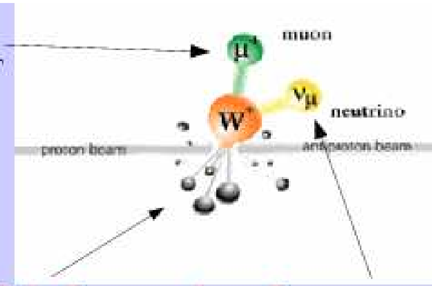
Precision measurement of Z-boson

☞ help to calibrate detector

Mass information comes primarily from lepton p_T

- Run 2 goal: calibrate p_T to ~0.01%

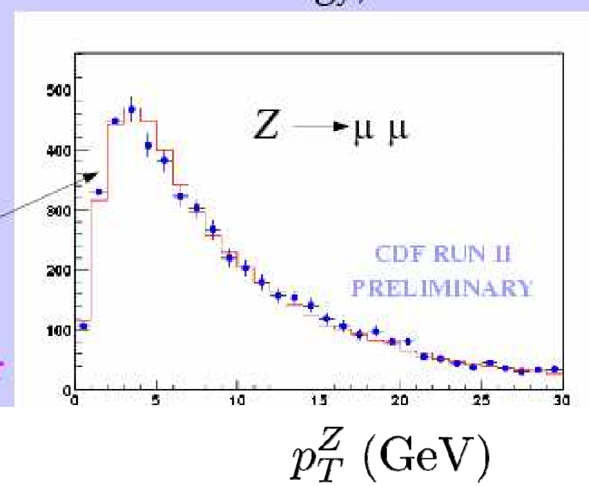




Additional information from ν p_T

(inferred through measurement of hadronic recoil energy)

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

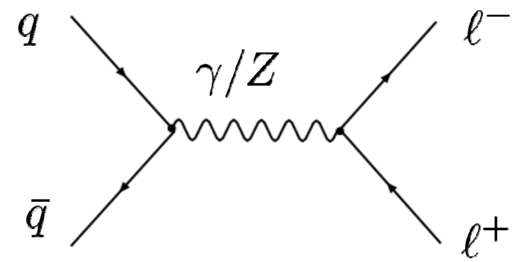


Combine lepton and neutrino p_T to form transverse mass (m_T) for best statistical power

CTEQ

Including photon and Z boson interference effect

- Photon and Z interference effect has been implemented, therefore ResBos-A can be use to low energy Drell-Yan process.



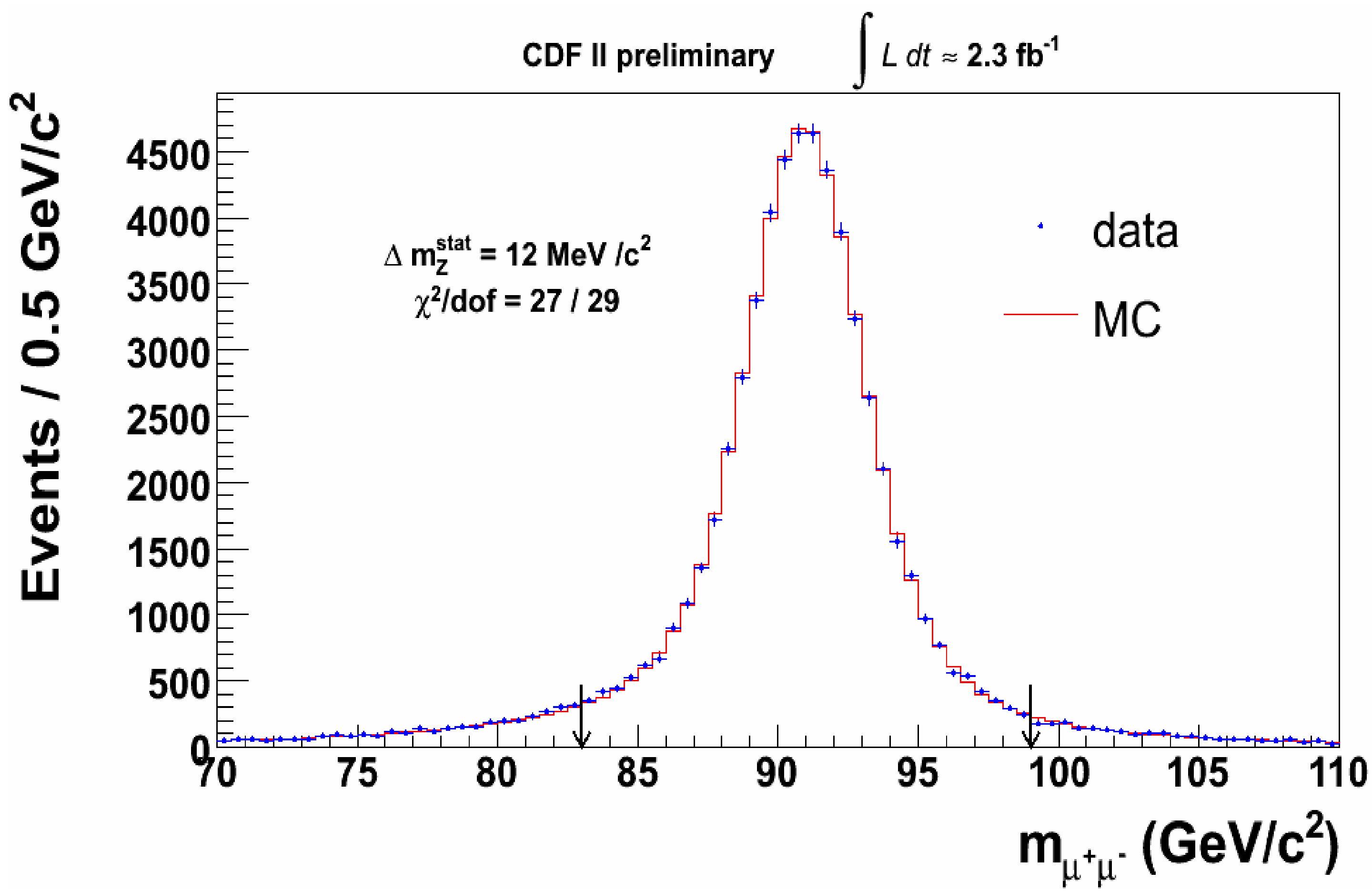
- Effective Born Approximation is adopted in order to include the dominant higher order EW corrections around the Z-pole.

$$\alpha \rightarrow \alpha(\hat{s}) \quad , \qquad v_f \rightarrow v_f^{\text{eff}} = \frac{1}{2s_w}\frac{M_Z}{M_W}(I_3^f - 2Q_f \sin^2\theta_{\text{eff}}^f)$$

- Effect from pQCD soft gluon resummation is included, at the same level of accuracy as that for W boson production and decay.

Z Mass @ CDF Run-2

Z→μ+μ- invariant mass distribution



Statistical error only.

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/

CTEQ

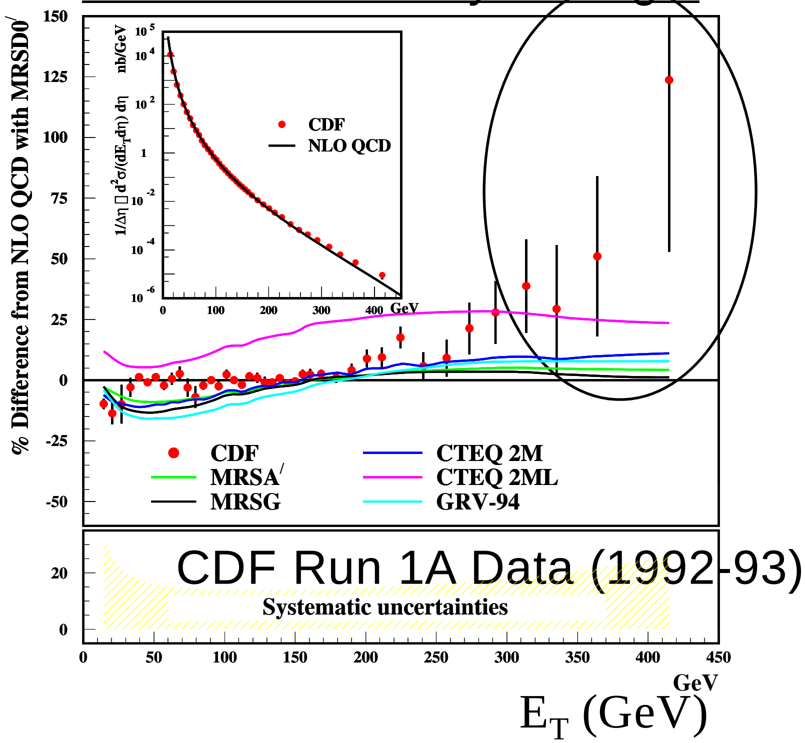
Impact of New
CTEQ Parton Distribution Functions
to LHC Phenomenology:

W/Z, Top and Higgs Physics

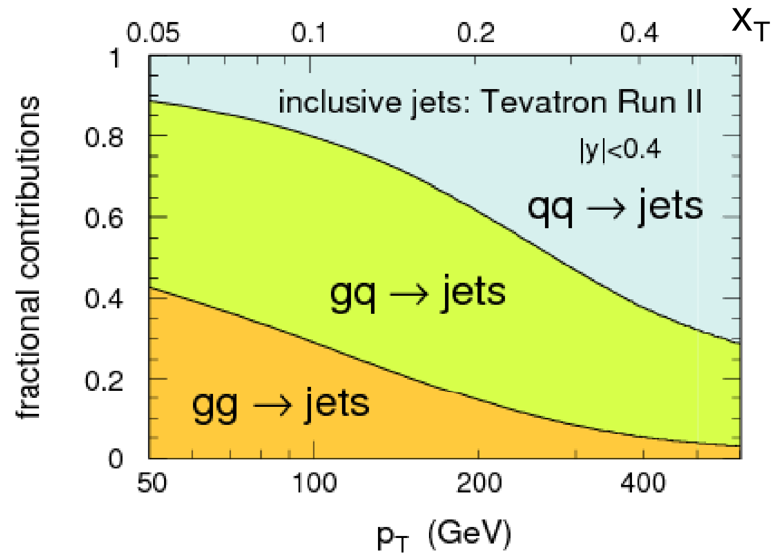
C T E Q

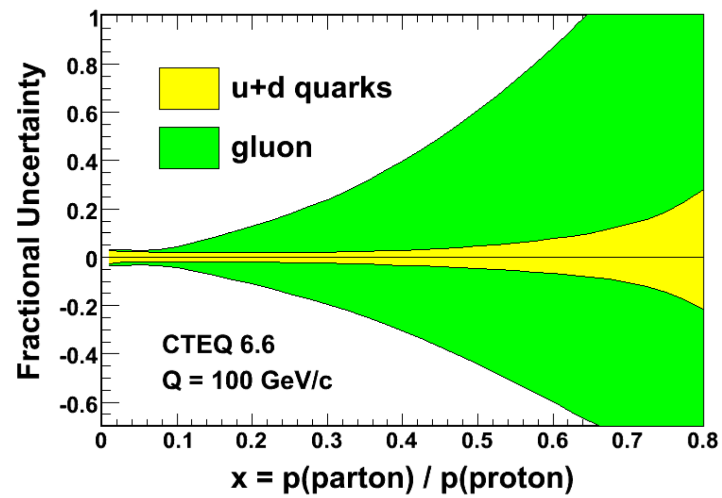
New Physics signal found?

Excitement at 10 years ago



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





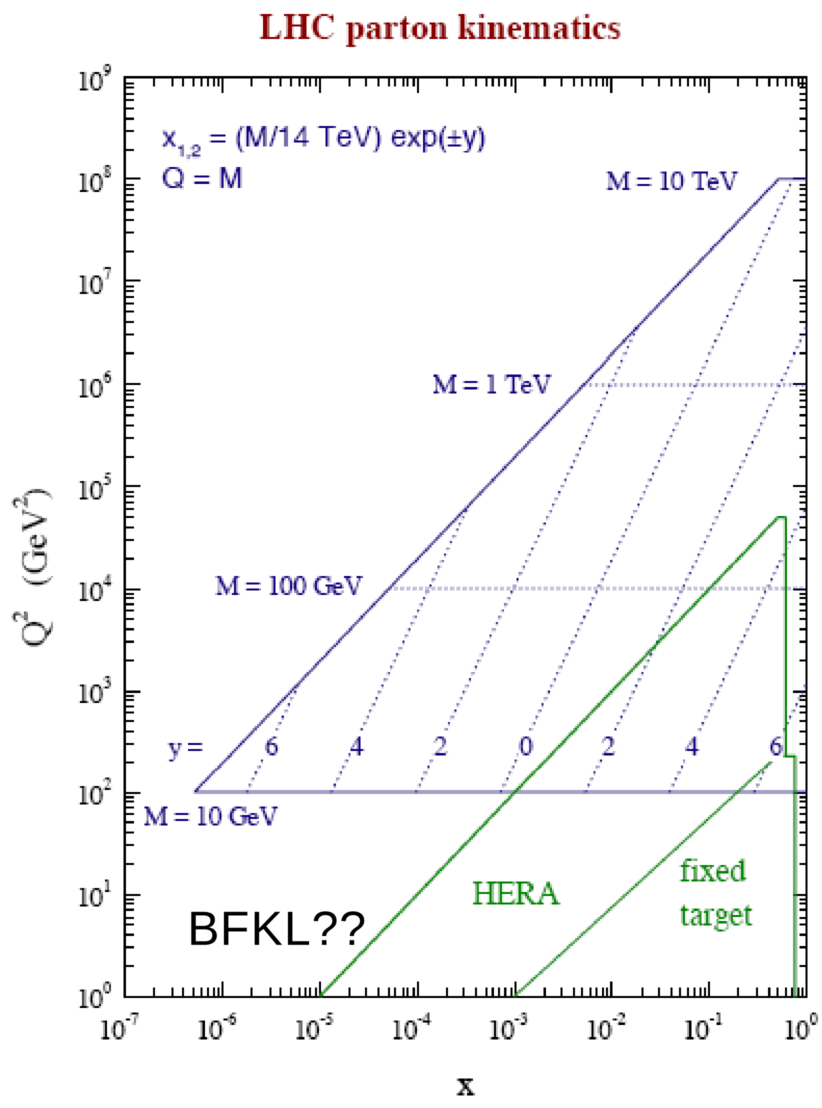
High-x gluon not well known

…can be accommodated in the Standard Model

C T E Q

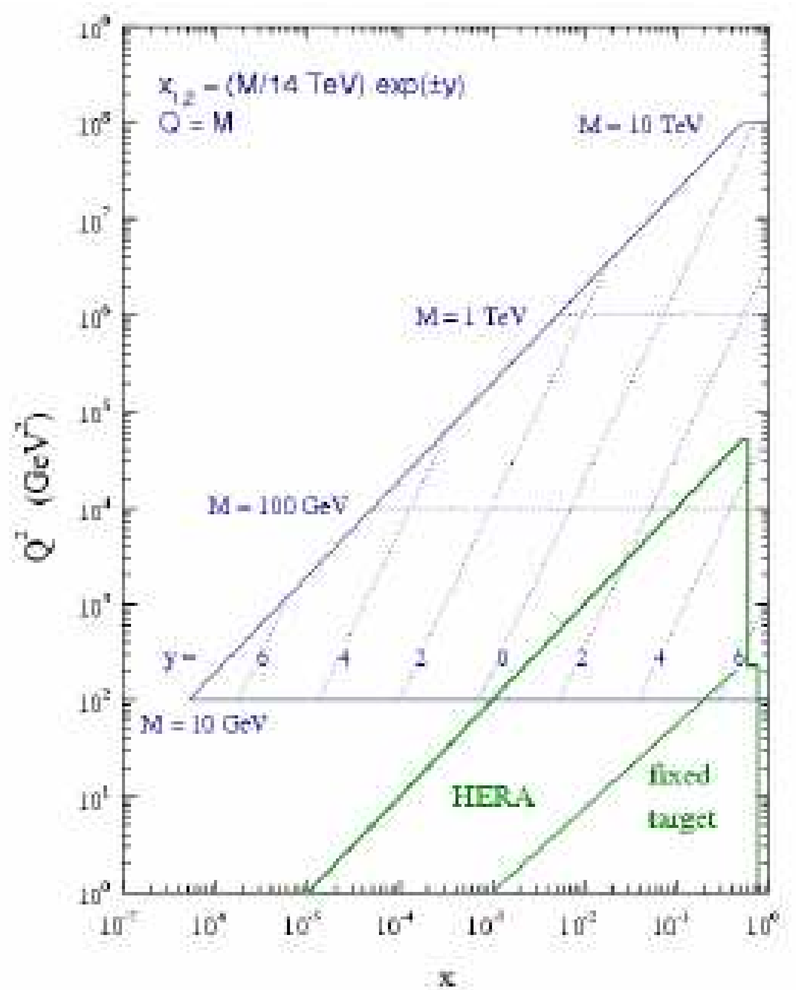
Cross sections at the LHC

- Experience at the Tevatron is very useful, but scattering at the LHC is not necessarily just “rescaled” scattering at the Tevatron
- Small typical momentum fractions x in many key searches
  - dominance of gluon and sea quark scattering
  - large phase space for gluon emission
  - intensive QCD backgrounds
  - or to summarize,…lots of Standard Model to wade through to find the BSM pony



C T E Q

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"

Impact of new CTEQ PDF sets to SM processes: *W*, *Z*, top, Higgs

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

In collaboration with

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

Global analysis at Michigan State/Taiwan/Washington

- a part of the Coordinated Theoretical Experimental study of QCD (CTEQ) in U.S.A.
- development of general-purpose PDF's

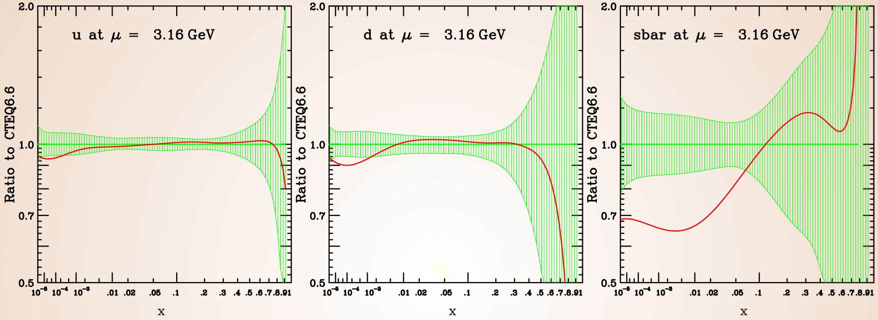
  (Wu-Ki Tung and collaborators)
- new CTEQ6.6M standard set and 44 extreme eigenvector sets *(arXiv:0802.0007)*
  - improved treatment of s, c, b PDF's
  - correlation analysis of collider observables
  - available in the LHAPDF-5.4 library and at www.cteq.org

“Standard candle” processes: W, Z, $t\bar{t}$ production

- Cross sections for $pp \to W^{\pm}X$, $pp \to Z^{0}X$ at the LHC can be measured with accuracy $\delta\sigma/\sigma \sim 1\%$ (tens of millions of events even at low luminosity)
- These measurements will be employed to monitor the LHC luminosity in real time and tightly constrain PDF’s *(Dittmar, Pauss, Zurcher; Khoze, Martin, Orava, Ryskin; Giele, Keller’;...)*

We will see that $t\bar{t}$ production may also potentially become a calibration process at the LHC because of its strong anticorrelation with Z production

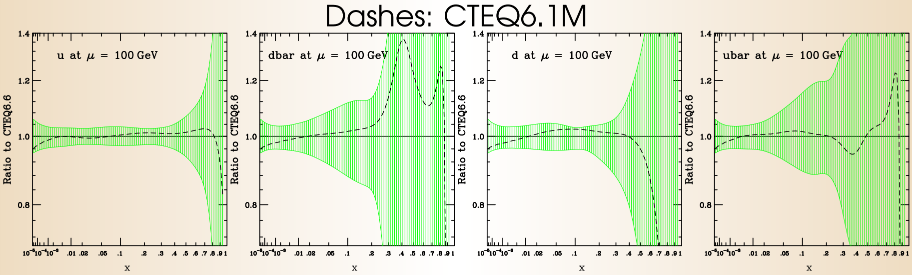
CTEQ6.6 PDF's



dashes: CTEQ6.1M (zero-mass scheme)

- CTEQ6.6 u, d are above CTEQ6.1 at $x \lesssim 10^{-2}$
  - The result of suppressed charm contribution to $F_2(x, Q)$ at HERA in the GM-VFN scheme
- very different strange PDF's

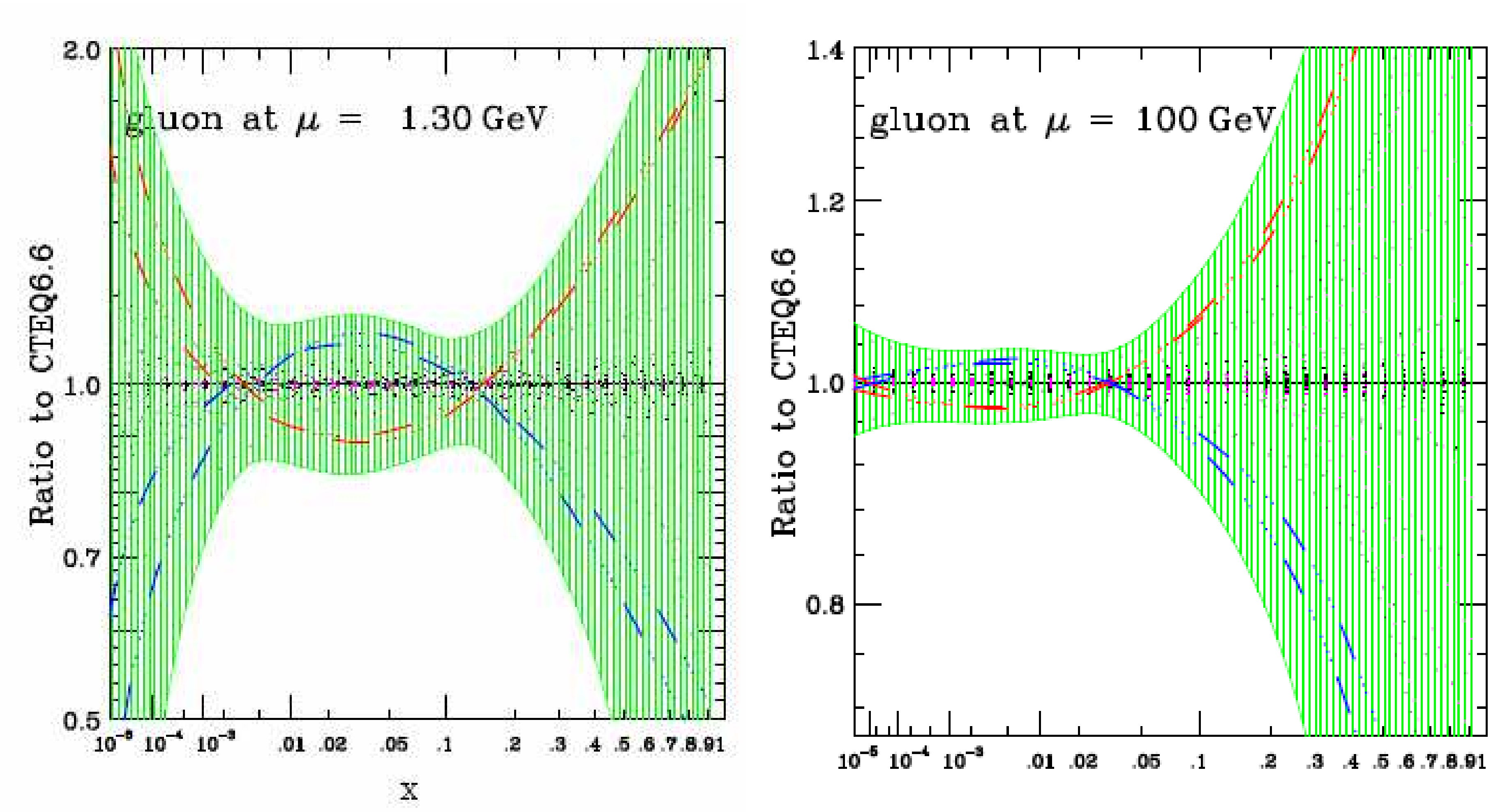
Impact of charm contributions to DIS at HERA



- W,Z production at the LHC: $x \sim 10^{-3} - 10^{-2}$
- Suppression of charm contribution to $F_2(x, Q^2)$ in the GM-VFN scheme results in larger $\overset{(-)}{u}(x)$, $\overset{(-)}{d}(x)$ at small $x \Rightarrow$ larger $\sigma_{W,Z}^{LHC}$

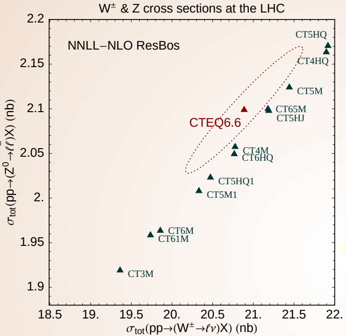
$$\delta\bar{q}_{light}(x)/\bar{q}_{light}(x) = 3\% \quad \Rightarrow \quad \delta\mathcal{L}_{q_i\bar{q}_j}/\mathcal{L}_{q_i\bar{q}_j} = 2(\delta\bar{q}_{light}/\bar{q}_{light}) = 6\%$$

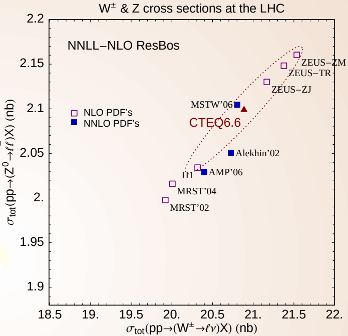
CTEQ6.6 Gluon PDF Uncertainty



At large x, the extremes are given by eigenvector sets 23,24 and 31,32.

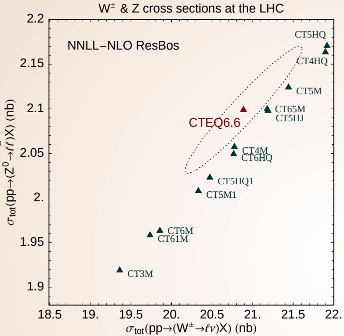
W and Z cross sections at the LHC

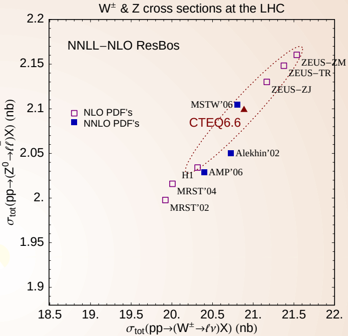




- Such changes in $\sigma_{Z,W}$ exceed NNLO corrections or anticipated experimental error of $\sim 1\%$
- Two latest MSTW predictions are compatible with the CTEQ6.6 result

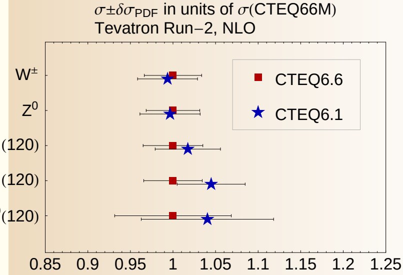
W and Z cross sections at the LHC

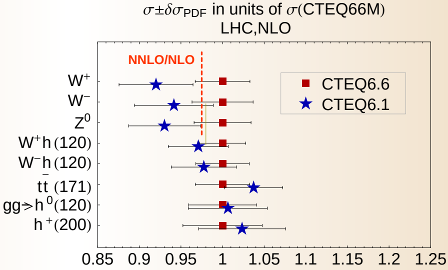




- At the LHC, $\sigma_{W,Z}$(CTEQ6.6M)$\approx 1.06\sigma_{W,Z}$(CTEQ6.1M)
  - reflects a 6% increase in light quark luminosities $\mathcal{L}_{q_i\bar{q}_j}(x_1, x_2, Q) = q_i(x_1, Q)\bar{q}_j(x_2, Q)$ at relevant x and Q

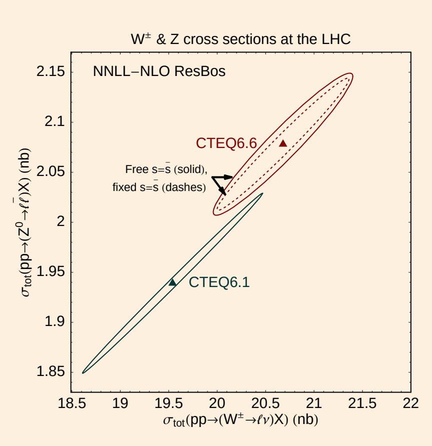
Tevatron and LHC cross sections

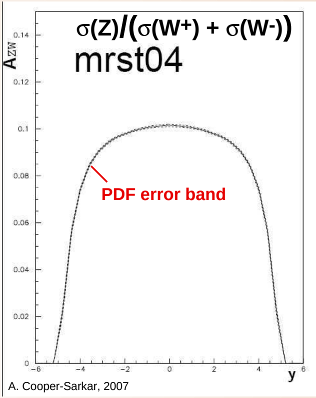




- NLO calculations using ResBos, WTTOT, MCFM
- CTEQ6.5 and CTEQ6.6 cross sections are qualitatively same
- At LHC, $\sigma_{W,Z}$(CTEQ6.6M)$\approx 1.06\sigma_{W,Z}$(CTEQ6.1M)
  - reflects a 6% increase in light quark luminosities $\mathcal{L}_{q_i\bar{q}_j}(x_1, x_2, Q) = q_i(x_1, Q)\bar{q}_j(x_2, Q)$ at relevant x and Q
- finer differences with CTEQ6.5 in precision predictions for W, Z production, strange-quark scattering

Correlations and ratio 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

Correlations between physical observables through PDF degrees of freedom

Misleadingly simple questions

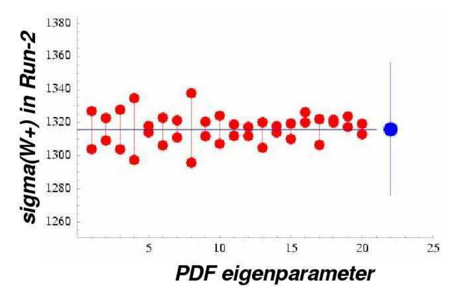
1. Why are PDF induced variations in σ_W and σ_Z strongly correlated?
2. Since both W and Z are mostly produced in light-quark scattering, is their PDF uncertainty mostly coming from light-quark PDF's?
3. How can we test this?

Answers can be found by systematically studying correlations in the PDF parameter space

An inefficient application of the Hessian method

☺Compute σ_W for 44 extreme PDF eigensets

☺Find eigenparameter(s) producing largest variation(s), such as #4 or 8



☺Check that the same eigenparameters produce largest variations in σ_Z

☹It is not obvious how to relate abstract eigenparameters to physical PDF's $u(x)$, $d(x)$, etc.

Correlation analysis for collider observables

(J. Pumplin et al., PRD 65, 014013 (2002); P.N. and Z. Sullivan, hep-ph/0110378)

A technique based on the Hessian method

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

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

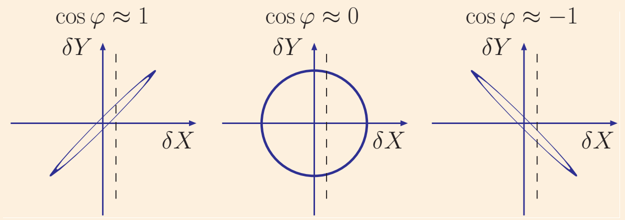
$$\cos\varphi = \frac{1}{4\Delta X\,\Delta Y}\sum_{i=1}^{N}\left(X_i^{(+)} - X_i^{(-)}\right)\left(Y_i^{(+)} - Y_i^{(-)}\right)$$

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

Correlation angle φ

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

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



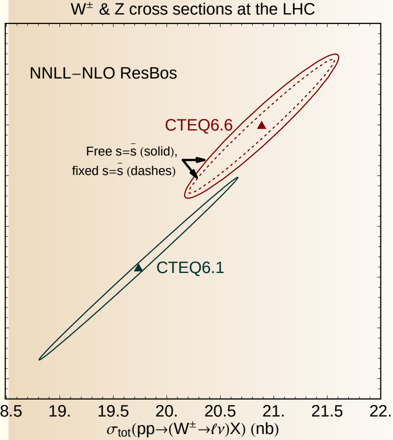
X_0, Y_0: best-fit values

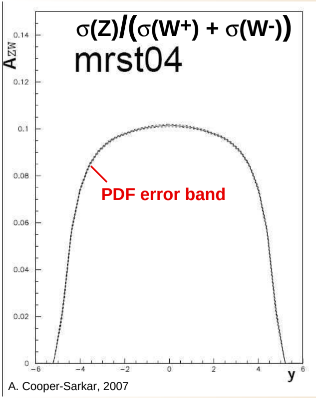
$\Delta X, \Delta Y$: PDF errors

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

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

Correlations and ratios of *W* and *Z* cross sections



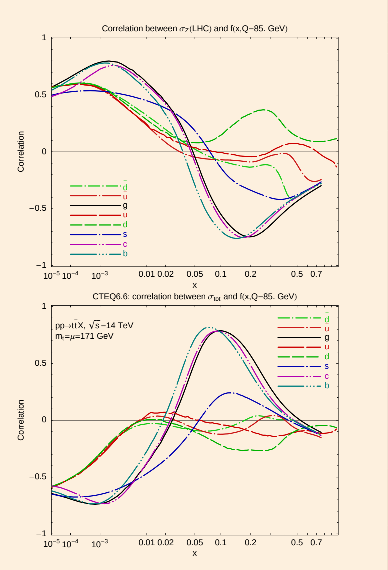


Somewhat surprisingly, the remaining PDF uncertainty is mostly due to $s(x)$

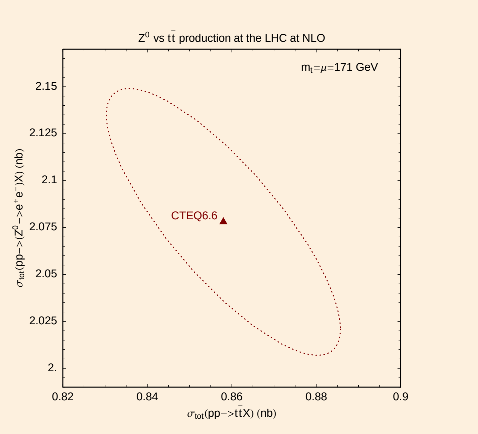
Correlations of Z and $t\bar{t}$ cross sections with PDF's

LHC Z, W cross sections are strongly correlated with $g(x)$, $c(x)$, $b(x)$ at $x \sim 0.005$

$\therefore$ they are strongly anticorrelated with processes sensitive to $g(x)$ at $x \sim 0.1$ ($t\bar{t}$, $gg \to H$ for $M_H > 300$ GeV) as a consequence of momentum sum rule

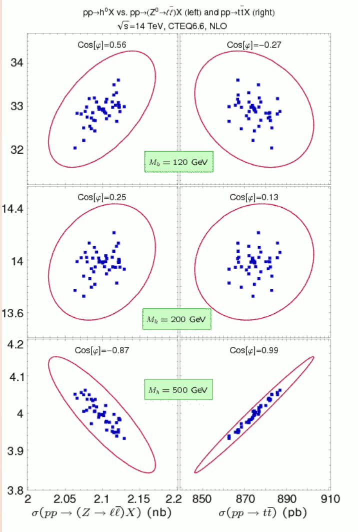


$t\bar{t}$ vs Z cross sections at the LHC



Measurements of $\sigma_{t\bar{t}}$ and σ_Z probe the same (gluon) PDF degrees of freedom at different x values

Correlations between $\sigma(gg \to H^0)$, σ_Z, $\sigma_{t\bar{t}}$



As M_H increases:

- $\cos\varphi(\sigma_H, \sigma_Z)$ decreases
- $\cos\varphi(\sigma_H, \sigma_{t\bar{t}})$ increases

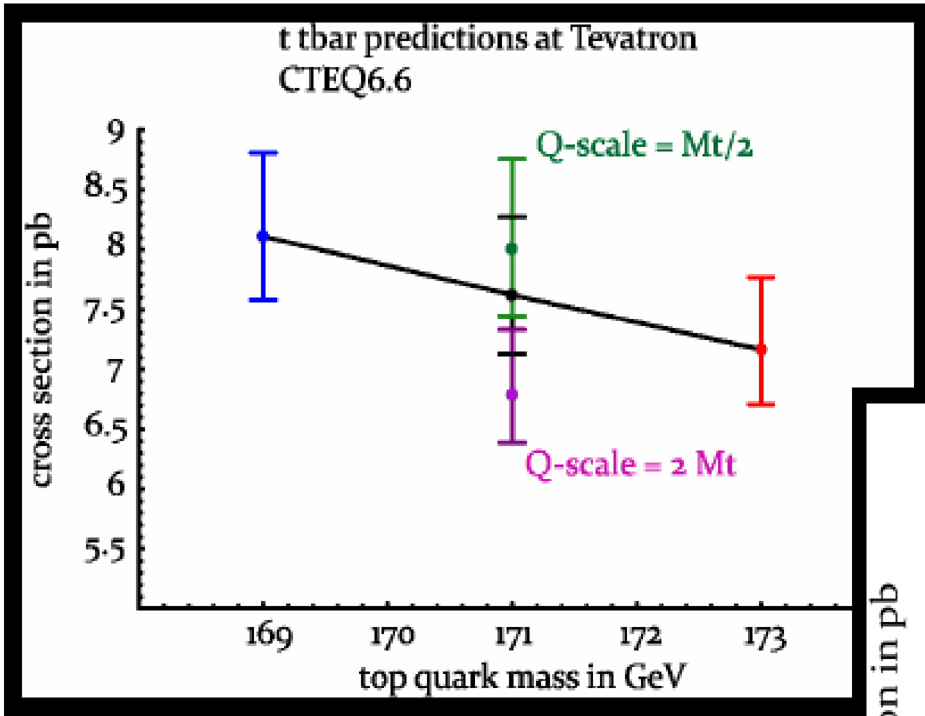
$t\bar{t}$ production as a standard candle process

- Measurements of $\sigma_{t\bar{t}}$ with accuracy $\sim 5\%$ may be within reach
- would provide additional constraints on the large-x gluon PDF
- will be useful for monitoring of $\mathcal{L}_{LHC}$ luminosity in the first years and normalization of LHC event rates

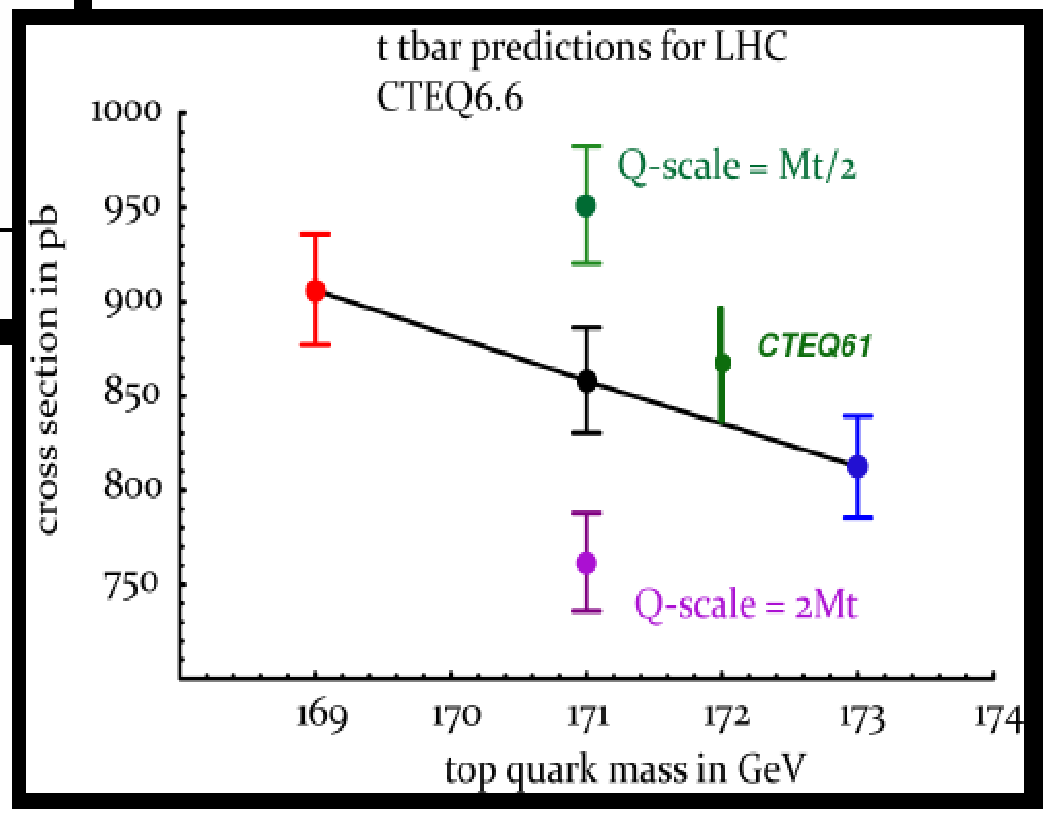
See also the talk by M. Csakon; Moch, Uwer, arXiv:0804.1476; Cacciari et al., arXiv:0804.2800; Kidonakis, Vogt, arXiv:0805.3844

C T E Q

Top Quark Pair production rates

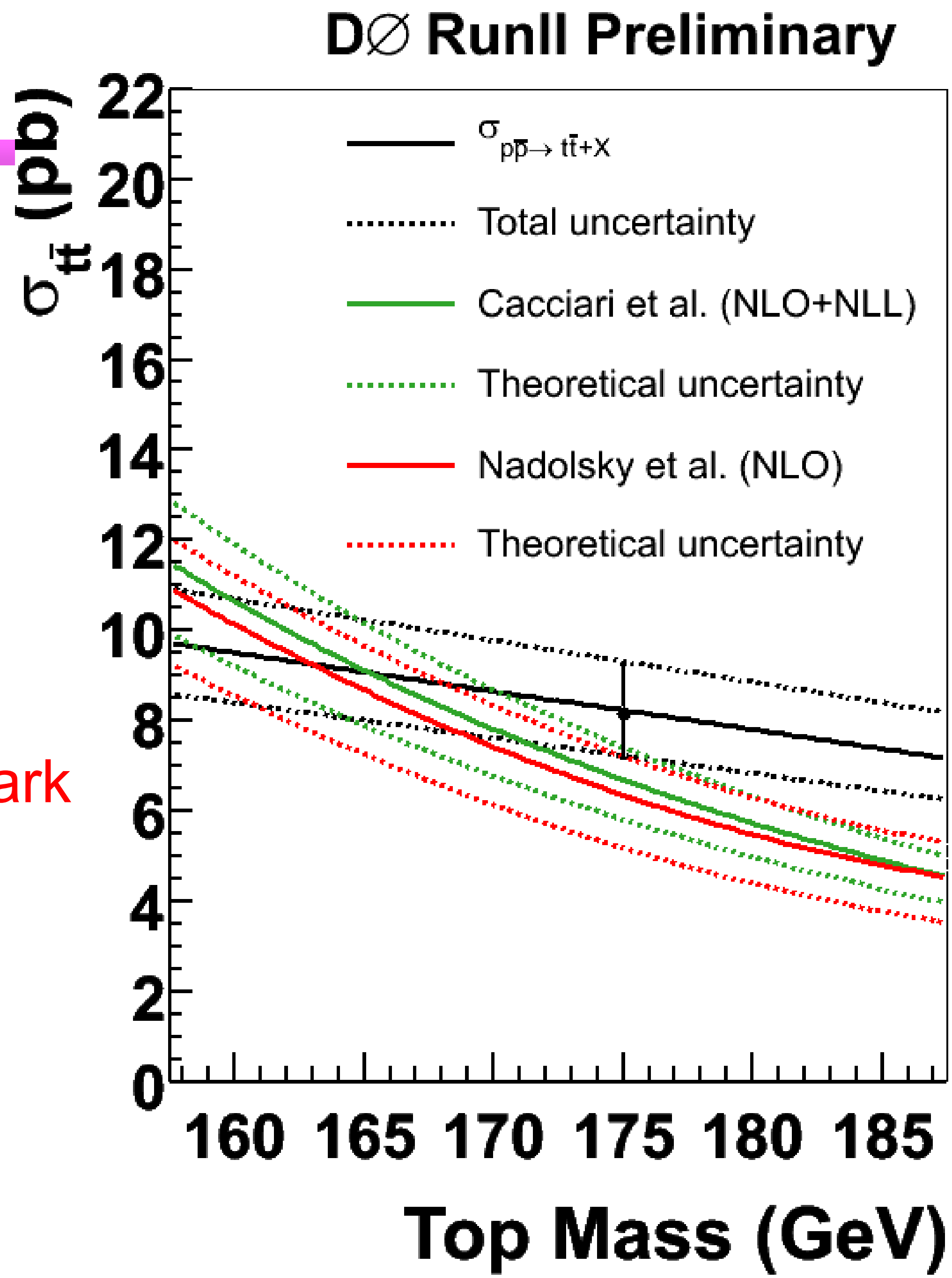


At Tevatron Run-2, uncertainty Incduced by PDFs is sizable.



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

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



What’s top mass?

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

NOBODY KNOWS

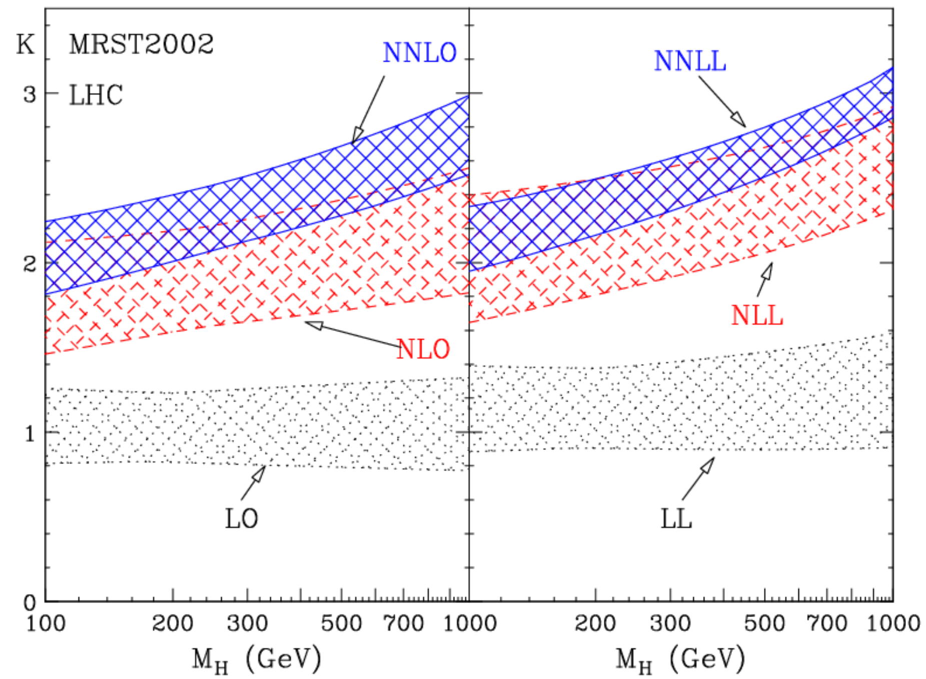
Parton showers generate some higher order corrections in the event shape, but with approximations.

Conclusions

- CTEQ6.6 study confirms most findings of the CTEQ6.5 analyses; predicts some differences in cross sections for heavy-flavor scattering, LHC EW precision physics
- Free parameters in CTEQ6.6 strange PDFs probe a new direction in the PDF parameter space, affect predictions for strange-quark scattering, σ_Z/σ_W at the LHC
- Analysis of correlations in PDF parameter space is a powerful technique to understand relations between physics observables through shared PDF degrees of freedom
- At the LHC, CTEQ6.6 $t\bar{t}$ cross section is anticorrelated with Z cross section via the gluon PDF; can potentially be used as an additional observable to monitor the LHC luminosity

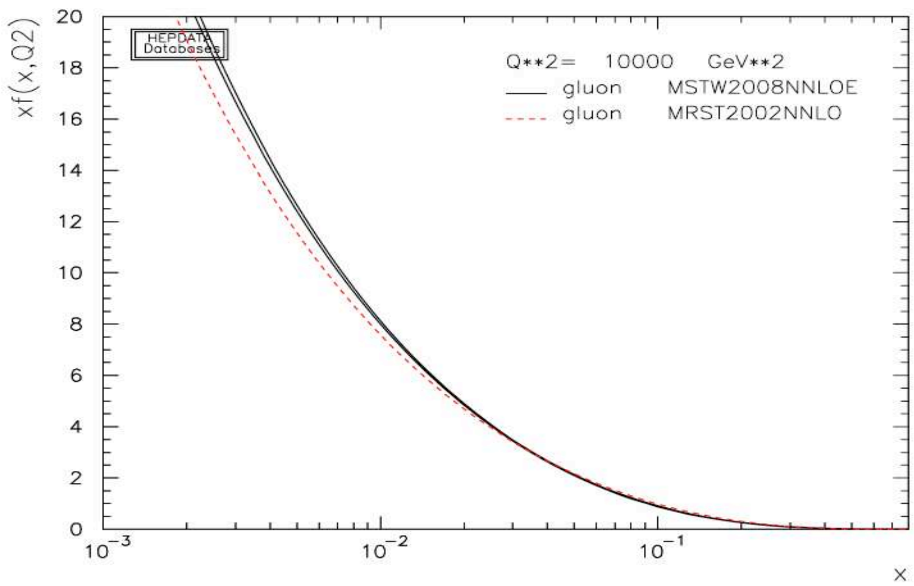
NNLO Higgs

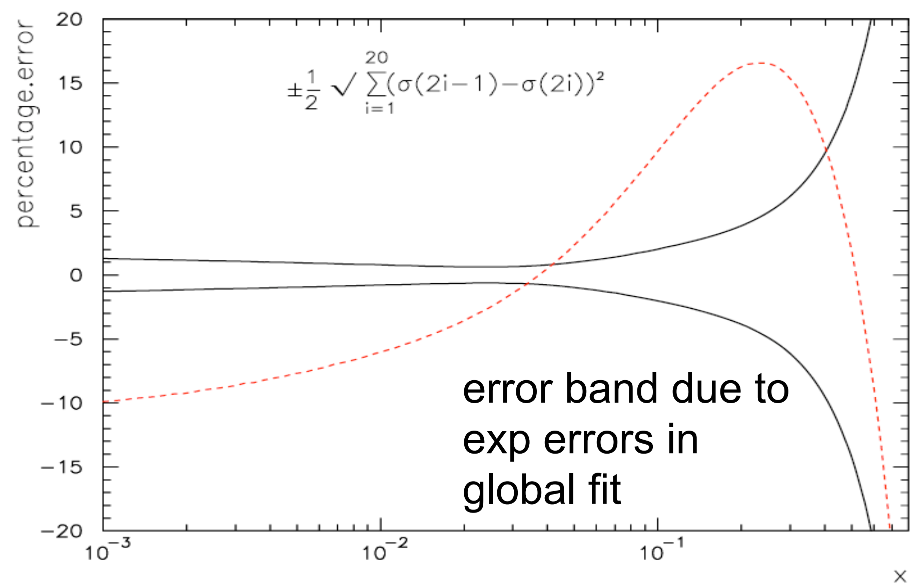
- Substantial contributions to Higgs cross section from LO to NLO and from NLO to NNLO
- For this reason, Higgs cross sections most often calculated to NNLO (with NNLO pdf's)



gg->H with MSTW08

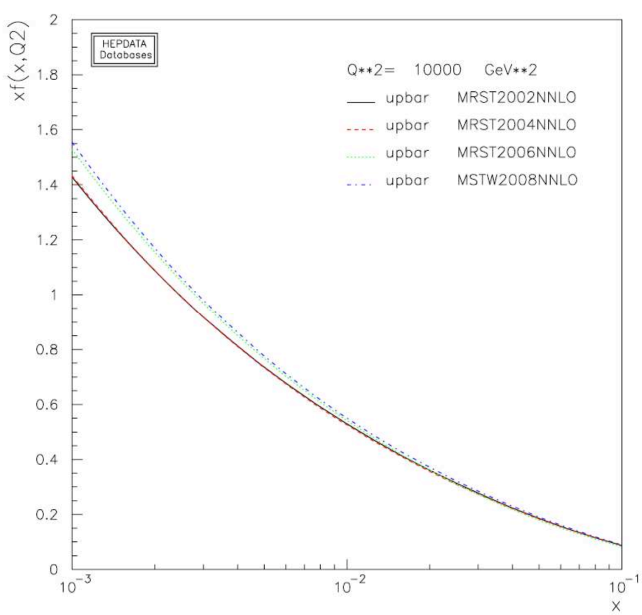
- Higgs cross section at NNLO is 30% (115 GeV) to 9% (300 GeV) larger at the LHC now than in 2003
- Tevatron cross section is +9% (115 GeV) to -9% (200 GeV)
- About half or more of the effect is from the changes in the gluon distribution in MRST->MSTW
  - for low x <0.05, MSTW2008 gluon > MRST2002 gluon
  - for moderate x, 0.05<x<0.5, MRST2002 gluon > MSTW2008 gluon
- (Most of) rest of change is from increase in α_s at NNLO
  - 0.1154->0.1171
  - note that α_s is included in the global fit; CTEQ fixes it at world average
- EW corrections also cause some change



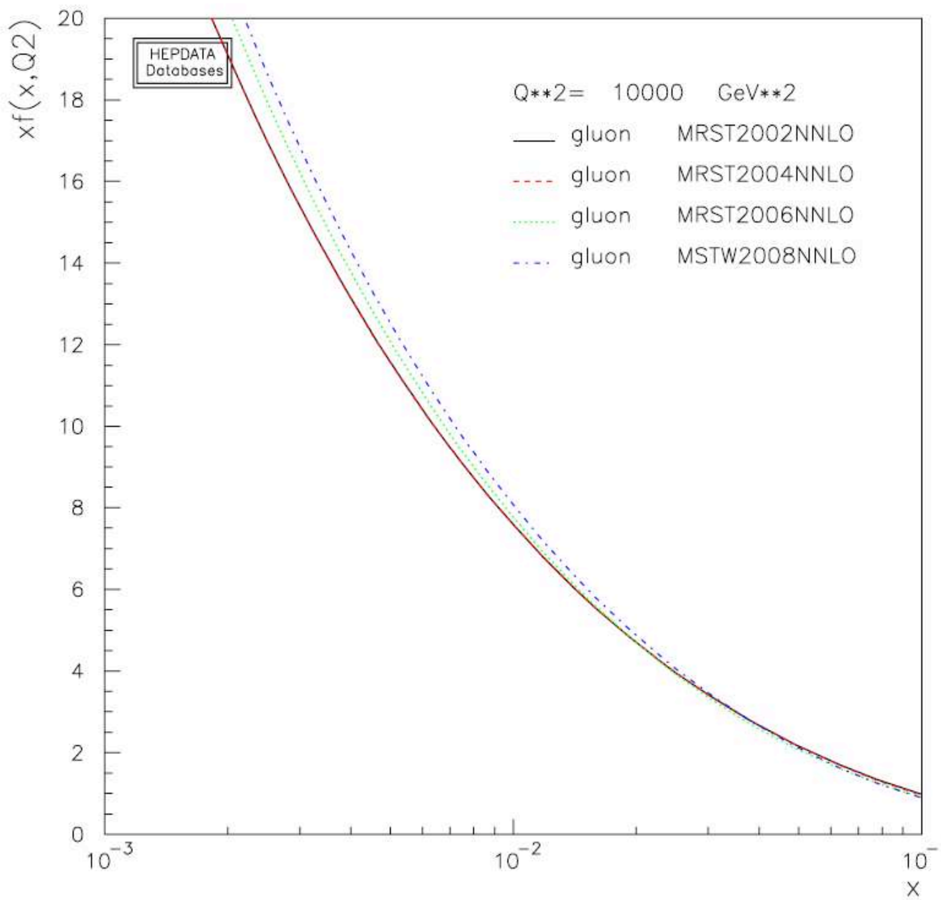


Change in gluon

- About half of the change happened in 2006 and half in 2008
- Due (at least partially) to changes in the heavy quark scheme
  - more light quarks needed at small x
  - flavor threshold effects more complicated in MSTW approach than in CTEQ due to counting of orders (see arXiv:0809.0714)

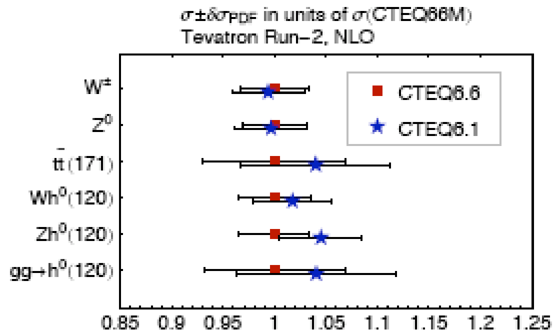


- Change may have worked for Barack Obama but it upsets experimentalists

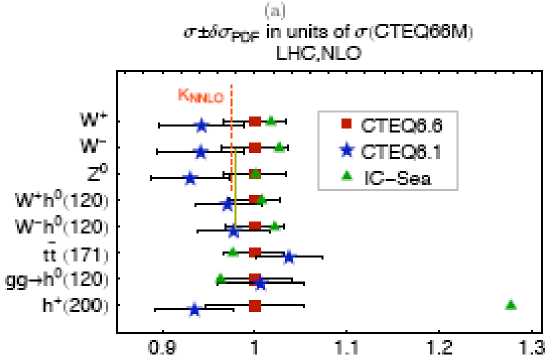


CTEQ

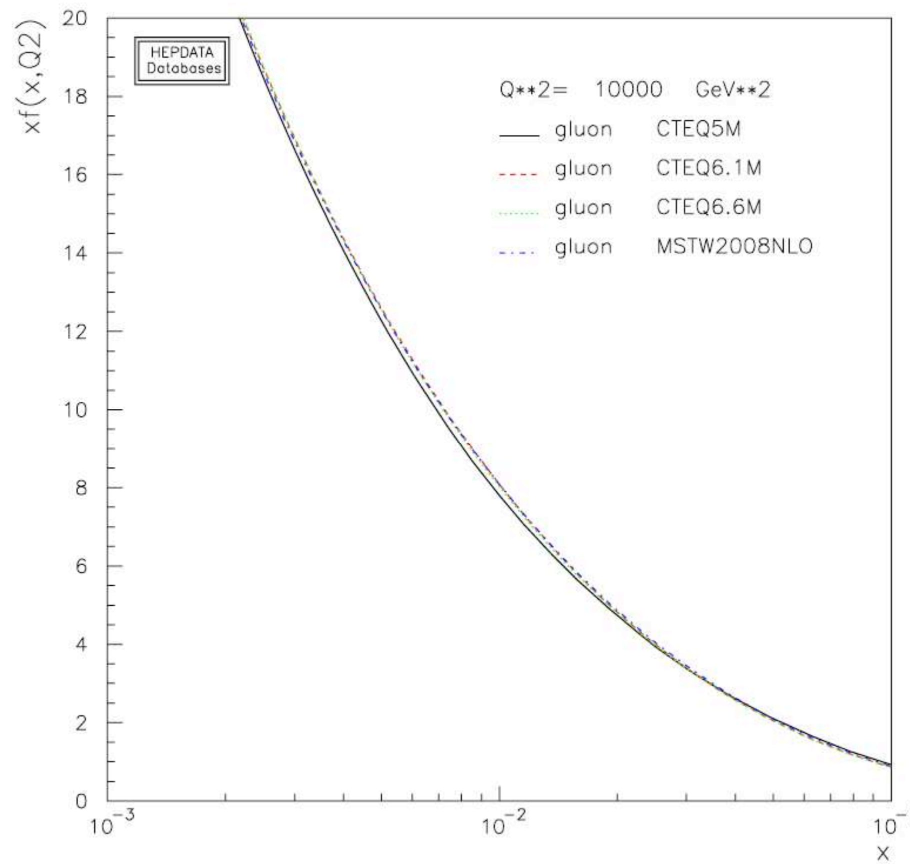
- There's been some change in the CTEQ gluon distribution as well due to the switch to the heavy quark mass scheme, but not as much
- And since we use the world average of α_s (and that hasn't changed much), the Higgs cross section predictions have been somewhat more stable



(a)

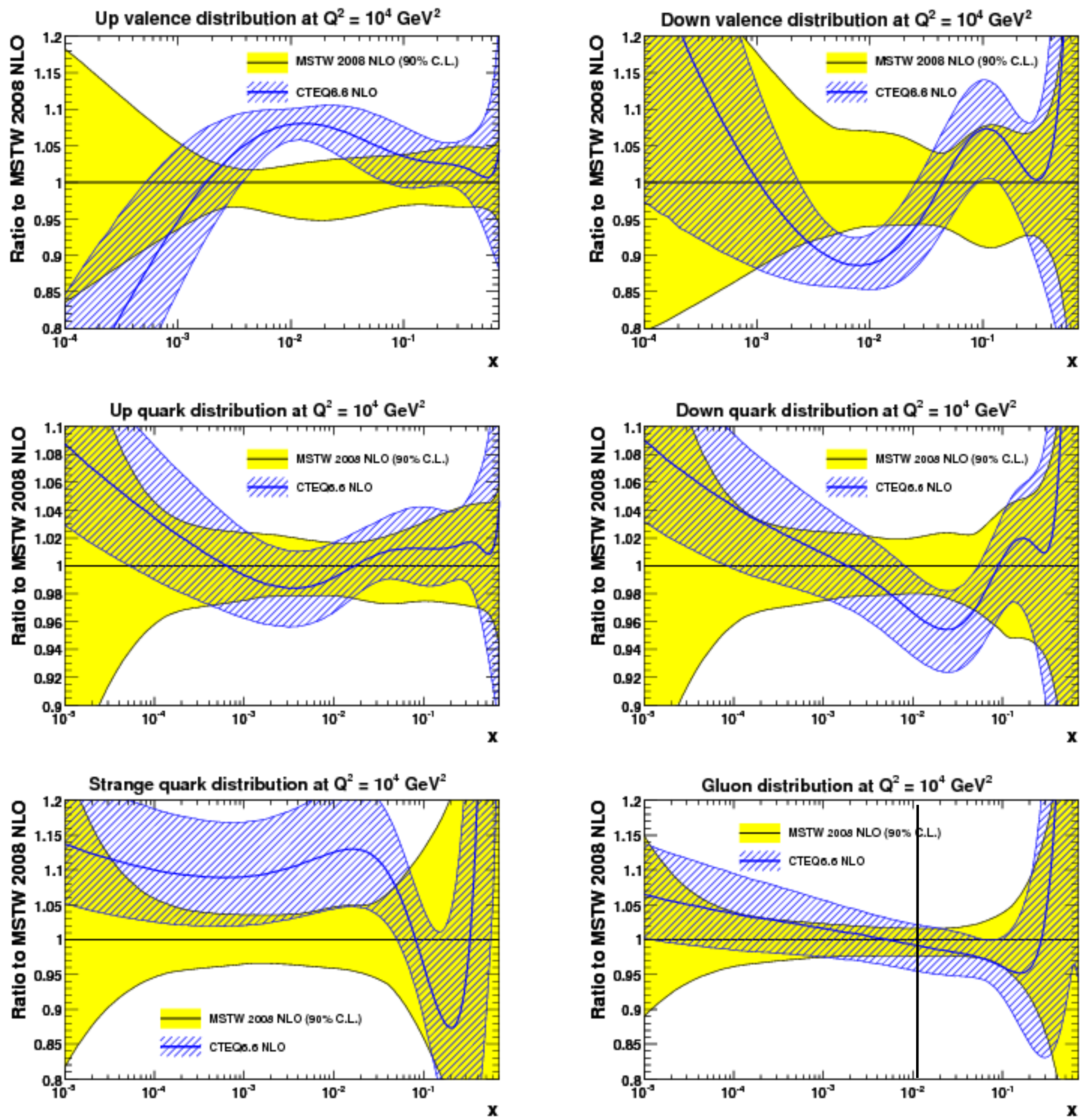


(b)



C T E Q

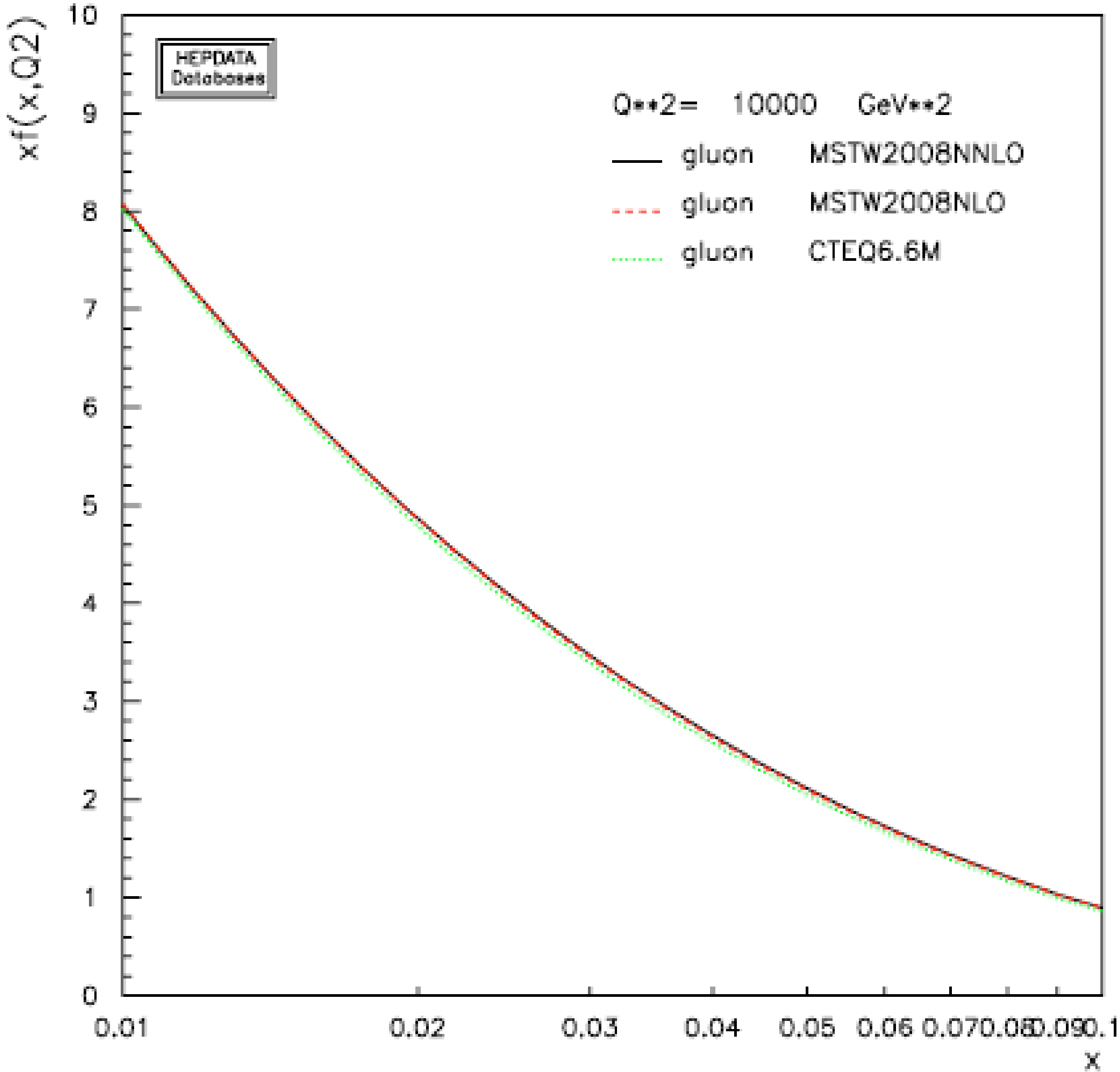
Comparisons at NLO



CTEQ and MSTW fairly close in x range for Higgs production at LHC

C T E Q

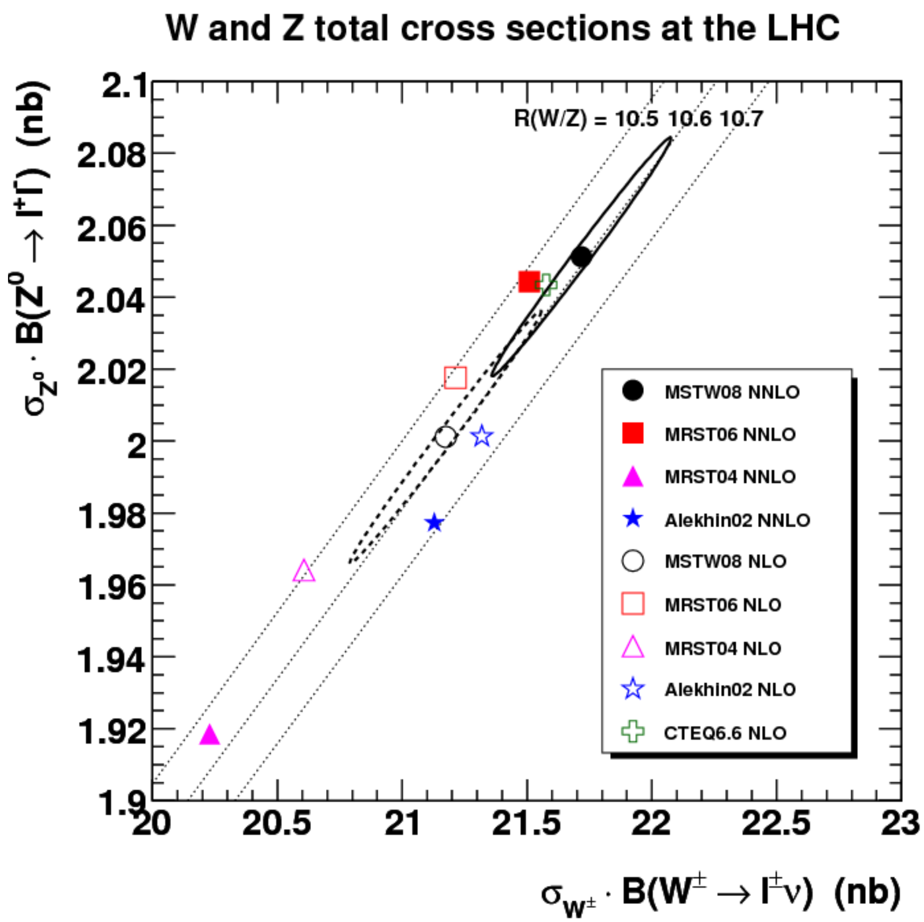
Compare gluons



C T E Q

W and Z cross sections

- CTEQ6.6 and MSTW2008NLO predictions for W and Z cross sections agree amazingly well
- Compare to situation with MRST2004 and CTEQ6.6



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

CTEQ

Backup Slides

W Boson Mass Uncertainties (MeV)

source	M_T	Electron p_T
W statistics	19	23
electron response	29	29
electron linearity	7	6
electron resolution	2	2
recoil response	17	14
recoil resolution	12	2
Background	2	2
Efficiencies	5	6
PDF	15	24
W boson p_T	2	5
QED	8	10
W boson width	<5	<5
Total	45	48

Detector response measured using $Z^0 \rightarrow e^+e^-$ events

Electron charge Asymmetry from W decays

Z/γ * boson p_T distribution

Z/γ * A_{FB} distribution

Important for a measurement with 25 MeV uncertainty (4 fb^{-1})

C T E Q

CTEQ PDF parametrization

- PDF's ($f_a(x,Q)$) are parametrized with a flexible form motivated by physics considerations (Regge behavior, spectator counting, for example) at fixed small Q_o (1.3 GeV for CTEQ) and then evolved for $Q>Q_o$ by DGLAP
  - assume for most of the general analyses that the c and b distributions are zero at scales below their masses and are generated by QCD evolution above
- Parametrization of parton distributions at Q_o used to obtain the CTEQ5 and CTEQ6 parton distributions contained 5 shape parameters (apart from normalization) for each flavor
  - global analysis data sets not sufficiently constraining to determine all of the parameters, so a number are frozen at some particular (motivated) values
  - 20 free parameters for CTEQ6.1/6.5 and 22 for CTEQ6.6 (see next slide)
- For CTEQ6.5/6.6, adopt a simpler form with 4 shape parameters for the valence quarks $u_v(x)$, $d_v(x)$ and the gluon $g(x)$

$$f(x) = a_o x^{a_1}(1-x)^{a_2} e^{a_3 x + a_4 x^2}$$

  - a reasonable generalization of the conventional minimal form

$$f(x) = a_o x^{a_1}(1-x)^{a_2}$$

  - which combines Regge behavior at x->0 and spectator counting at x->1
- Both forms above are positive definite and have simplified logarithmic derivatives

C T E Q

CTEQ PDF Parametrization

- Is this form flexible enough?
- Remember the lesson of Tevatron Run-1 jets, where low x and high x PDFs can easily be (artificially) tied together through the parametrization.
- We find that significantly better fits cannot be achieved by introducing additional parameters or changing the functional form
  - NB: prior to CTEQ6.6, the analysis generally assumed

$$s(x) = \bar{s}(x) \propto \bar{d}(x) + \bar{u}(x)$$

  - that ansatz has been dropped in CTEQ6.6