CTEQ

Precision Measurements at Hadron Colliders and Global Analysis of PDFs

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Precision Electroweak Physics at Hadron Colliders

Physics of Drell-Yan, *W* and *Z* Bosons

W-boson physics

❶ W-boson production and decay at hadron collider

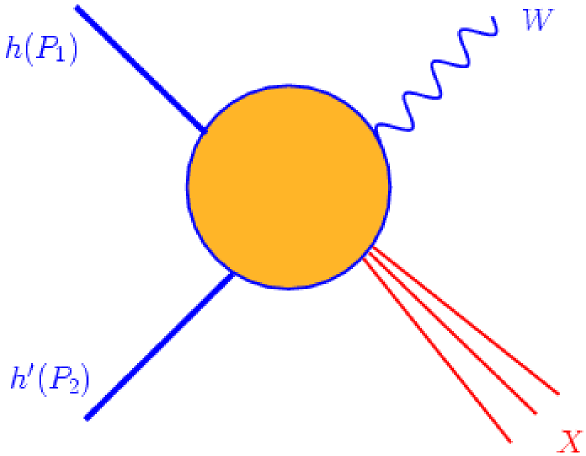
❷ How to measure W-boson mass and width?

❸ High order radiative corrections:

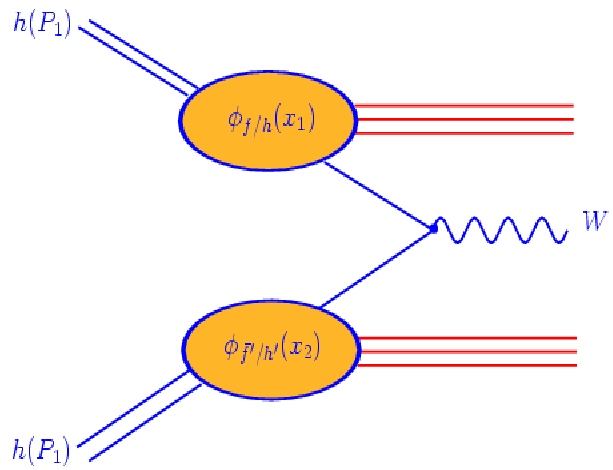
- ☞ QCD (NLO, NNLO, Resummation)
- ☞ EW (QED-like, NLO)

❹ ResBos and ResBos-A

W-boson production at hadron colliders



parton model

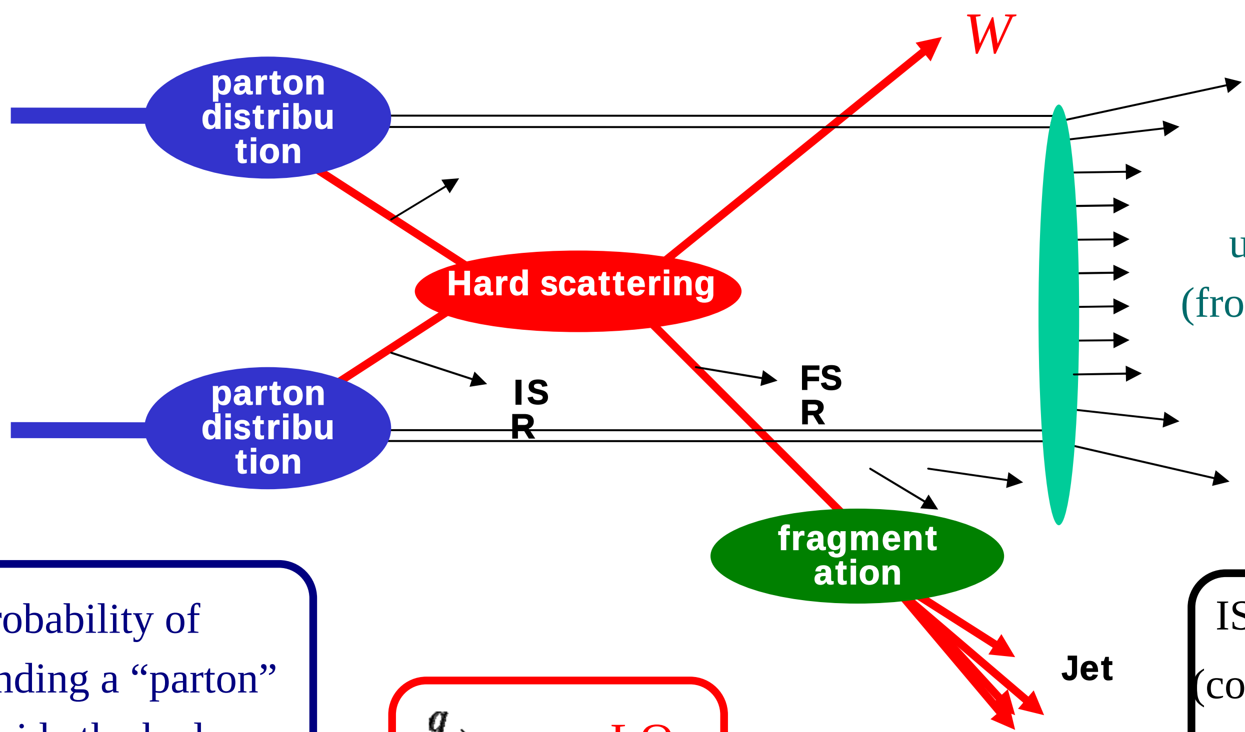


$$\sigma_{hh' \to W+X} = \sum_{f,f'} \int_0^1 dx_1 dx_2 \left\{ \phi_{f/h}(x_1)\, \hat{\sigma}_{ff'}\, \phi_{\bar{f}'/h'}(x_2) + (x_1 \leftrightarrow x_2) \right\}$$

PDFs are known from deep inelastic scattering

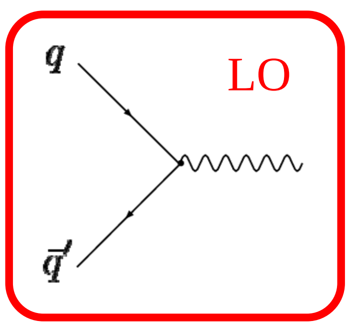
partonic "Born" cross section of $f\bar{f}' \to W^+$

W-boson production at hadron colliders



underlying events
(from proton remnants)

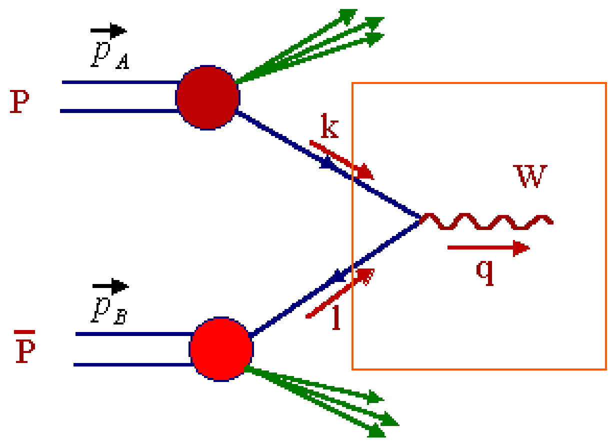
PDFs: probability of
finding a "parton"
inside the hadron



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

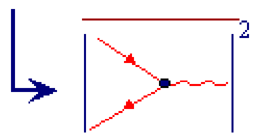
Fixed order pQCD prediction

$\alpha_S^{(0)}$



$$\sigma = \frac{1}{2S}\int \frac{d\xi_A}{\xi_A}\frac{d\xi_B}{\xi_B} f_{i/A}(\xi_A,\mu)\, f_{i/B}(\xi_B,\mu)\cdot d\hat{\sigma}$$

$$d\hat{\sigma} = \overline{|M|^2}\,(2\pi)^4\,\delta^{(4)}(q-k-l)\frac{d^3q}{(2\pi)^3\,2q_0}$$



$$s = (p_A + p_B)^2$$

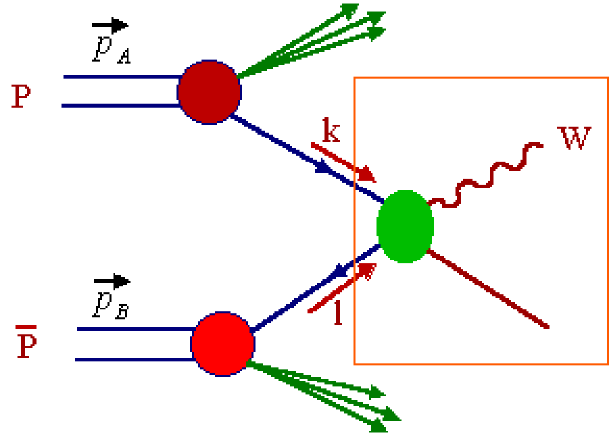
$$k = \xi_A p_A$$

$$l = \xi_B p_B$$

$$\frac{d\sigma}{dq_T^2\,dy\,dQ^2} = \frac{1}{S}\int \frac{d\xi_A}{\xi_A}\frac{d\xi_B}{\xi_B} f_{i/A}(\xi_A,\mu)\, f_{i/B}(\xi_B,\mu) \cdot\left(\frac{\pi^2}{Q^2}\right)\cdot\overline{|M|^2}\cdot\delta\left(1-\frac{x_A}{\xi_A}\right)\cdot\delta\left(1-\frac{x_B}{\xi_B}\right) \cdot\delta\left(q_T^2\right)\cdot\delta\left(Q^2-M_W^2\right)$$

$$Q \equiv \sqrt{Q^2} = \sqrt{q^2},\ \mu = Q = M_W,\ x_A = \frac{Q}{\sqrt{S}}e^{y},\ x_B = \frac{Q}{\sqrt{S}}e^{-y}$$

$\alpha_S^{(1)}$



$$\frac{d\sigma}{dq_T^2\,dy\,dQ^2} = \int \frac{d\xi_A}{\left(\xi_A S + U - Q^2\right)} \left(\frac{\hat{s}\,d\hat{\sigma}}{d\hat{t}}\right) \cdot f_{i/A}\left(\xi_A, \mu\right)$$

$$\cdot f_{j/B}\left(\xi_B = \frac{-Q^2 - \xi_A\left(T - Q^2\right)}{\xi_A S + U - Q^2}, \mu\right) \cdot \delta\left(Q^2 - M_W^2\right)$$

$$+ \int \frac{d\xi_B}{\left(\xi_B S + T - Q^2\right)} \left(\frac{\hat{s}\,d\hat{\sigma}}{d\hat{t}}\right) \cdot f_{j/B}\left(\xi_B, \mu\right)$$

$$\cdot f_{i/A}\left(\xi_A = \frac{-Q^2 - \xi_B\left(U - Q^2\right)}{\xi_B S + T - Q^2}, \mu\right) \cdot \delta\left(Q^2 - M_W^2\right)$$

$$T = Q^2 - \sqrt{q_T^2 + Q^2}\sqrt{S}\; e^{-y},$$

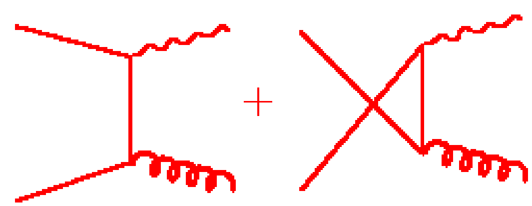
$$U = Q^2 - \sqrt{q_T^2 + Q^2}\sqrt{S}\; e^{y},$$

$$\hat{s} = \xi_A \xi_B S$$

$$\hat{t} = \xi_A\left(T - Q^2\right) + Q^2$$

$$\frac{\hat{s}\,d\hat{\sigma}}{d\hat{t}} = \frac{1}{16\pi^2}\overline{\left|M\right|^2}$$

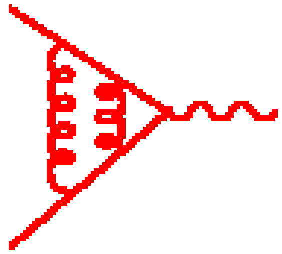
$M =$

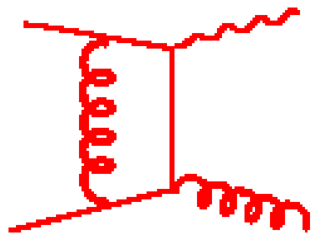


(For simplicity, only consider qq→Wg)

$\alpha_S^{(2)}$

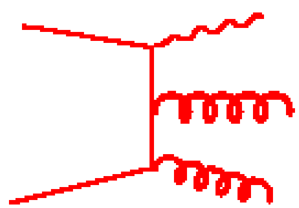
- Virtual Corrections





$+ \cdots$

- Real emission contributions



$+ \cdots$

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,..Horace

  recover NLO (NNLO?) normalization

- Resummed (ResBos)

Important to know strengths/weaknesses of each.

Fixed order Perturbative calculations

- Higher order in $\alpha_S^{(n)}$
  ➡ Less sensitive to Factorization Scale μ

- High q_T and smaller y (i.e. more central)
  ➡ PDF (parton distribution function) better known

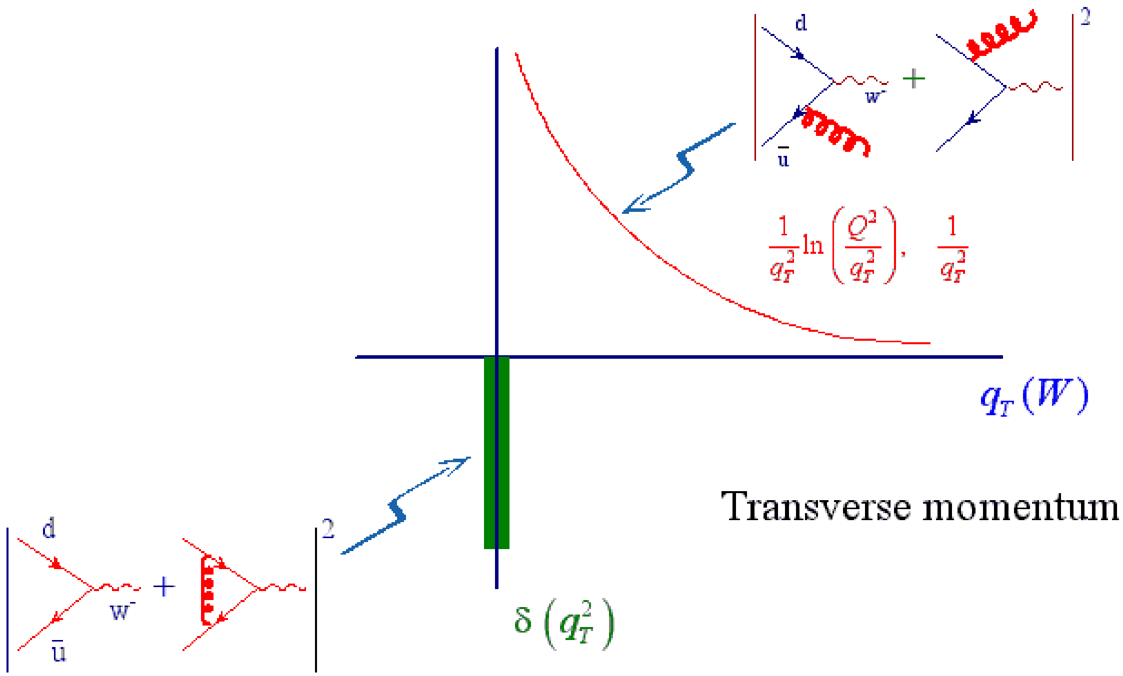
- With larger Luminosity
  ➡ Test QCD in one large scale problem (i.e. $q_T \sim Q$)

- Up to now, most of the Data used in Testing QCD were
  One large scale observables, e.g., Jet-P_T.

- Observables involving Multiple Scales, e.g., q_T of W-Boson with mass M_W, can only be accurately described in QCD after including effects of Resummation.

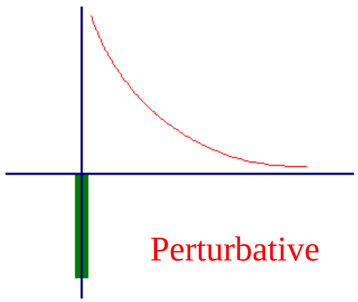
Shortcoming of fixed order calculation

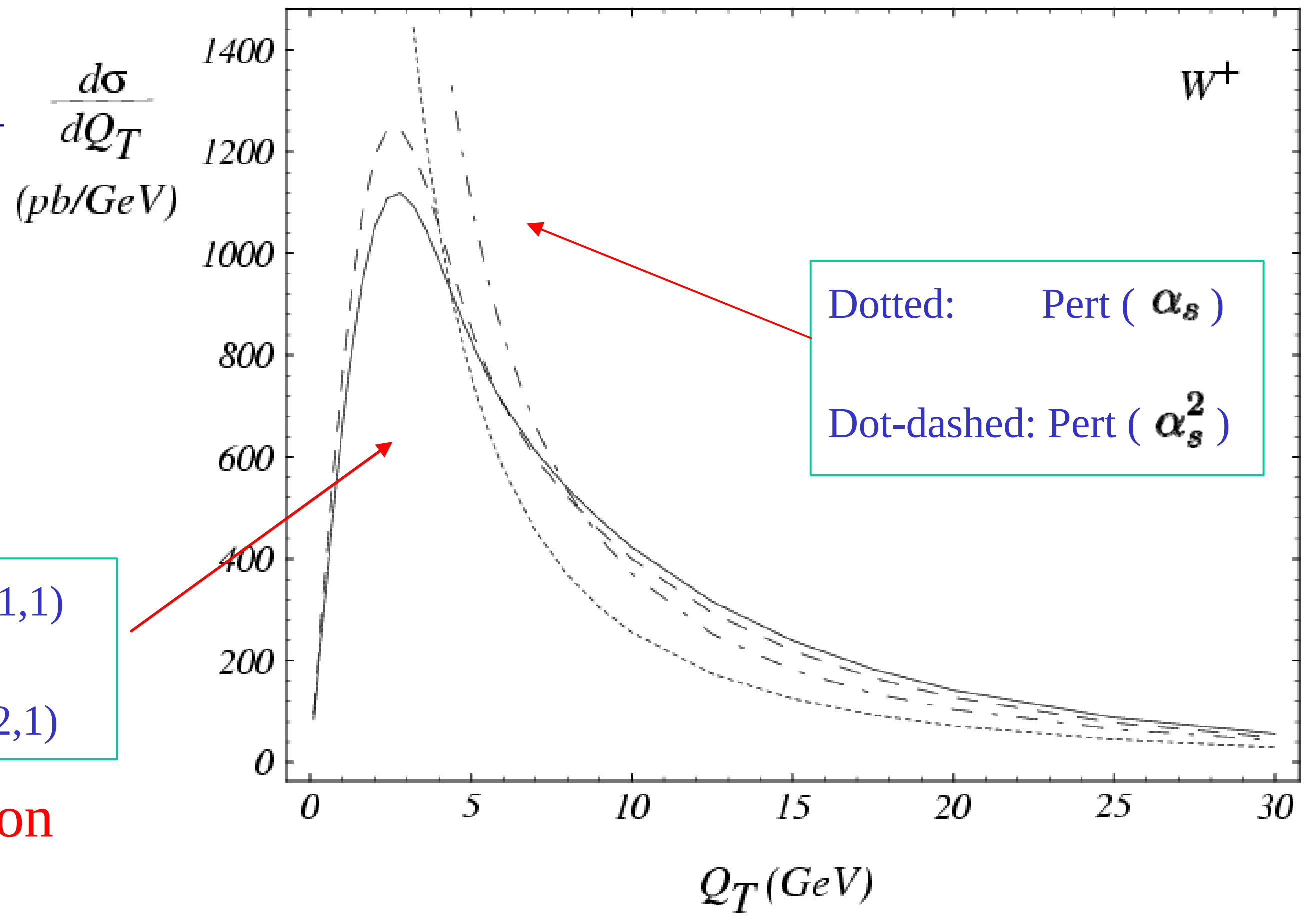
- Cannot describe data with small q_T of W-boson.
- Cannot precisely determine m_W at hadron colliders without knowing the transverse momentum of W-boson. Most events fall in the small q_T region.



(at NLO)

QCD Resummation is needed





Dashed: CSS (1,1,1)

Solid: CSS (2,2,1)

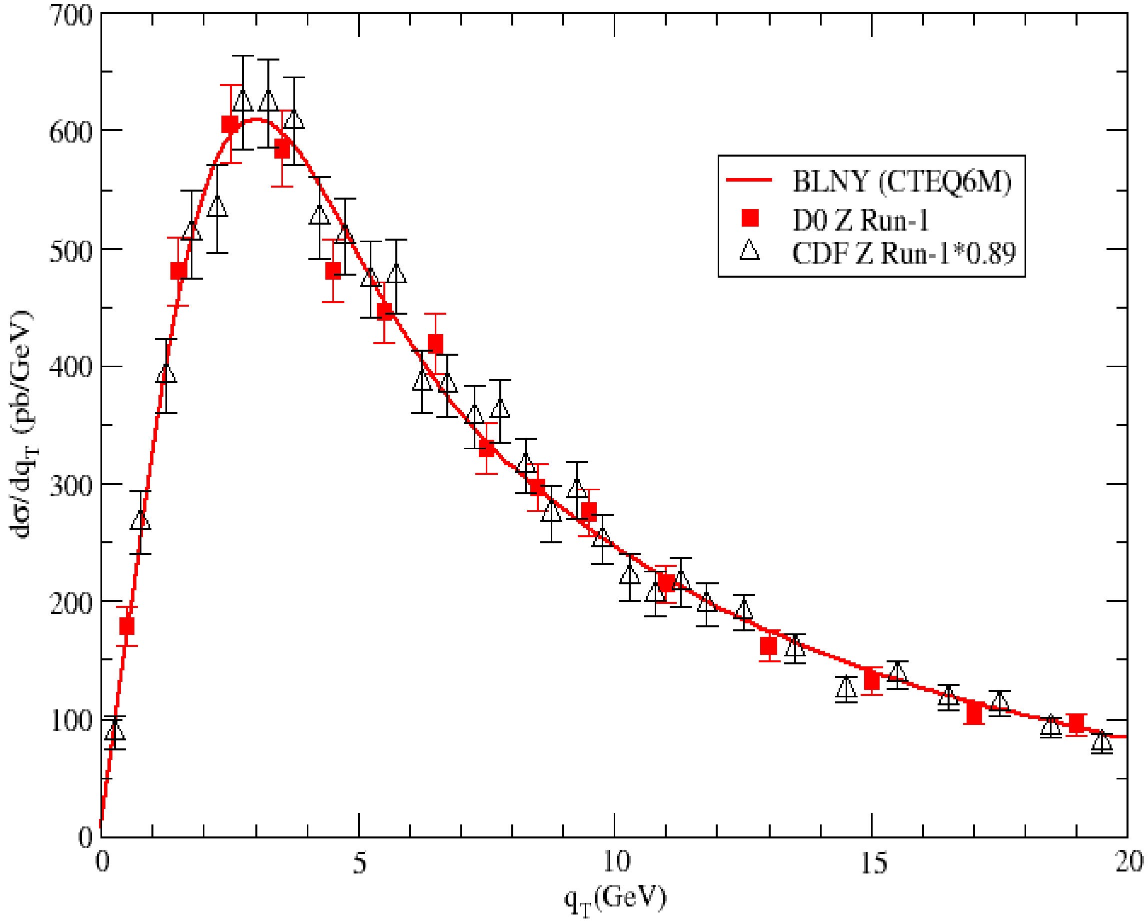
Resummation

Resummation calculations agree with data very well

Predicted by ResBos:

A program that
includes the effect of
multiple soft gluon emission
on the production of
W and Z bosons
in hadron collisions.

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



ResBos

(Resummation for Bosons)

Initial state QCD soft gluon resummation
and
Final state QED corrections

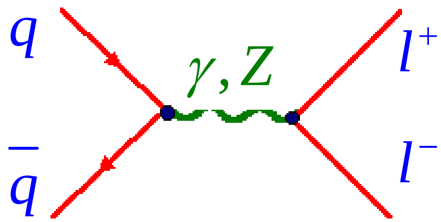
In collaboration with

Csaba Balazs, Alexander Belyaev, Ed Berger,
Qing-Hong Cao, Chuan-Ren Chen, Zhao Li,
Steve Mrenna, Pavel Nadolsky, Jian-Wei Qiu,
Carl Schmidt

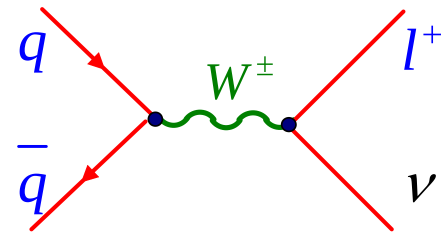
What's it for? An Example

- Transverse momentum of

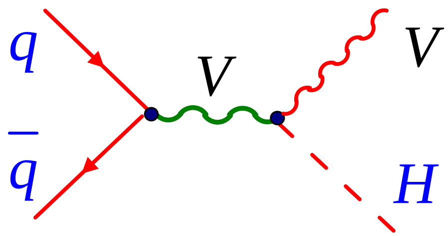
Drell-Yan



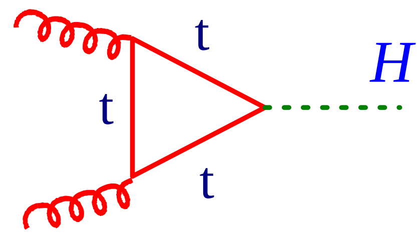
$W^{\pm}$



V H



$g\, g \to H$

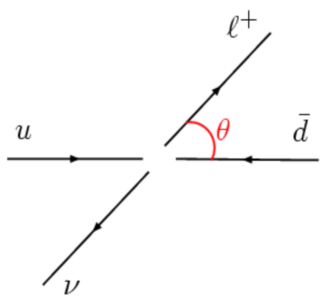


including QCD Resummations.

- Kinematics of Leptons from the decays
  (Spin correlation included)

Transverse momentum of the charged lepton

- In (ud) c.m. system,

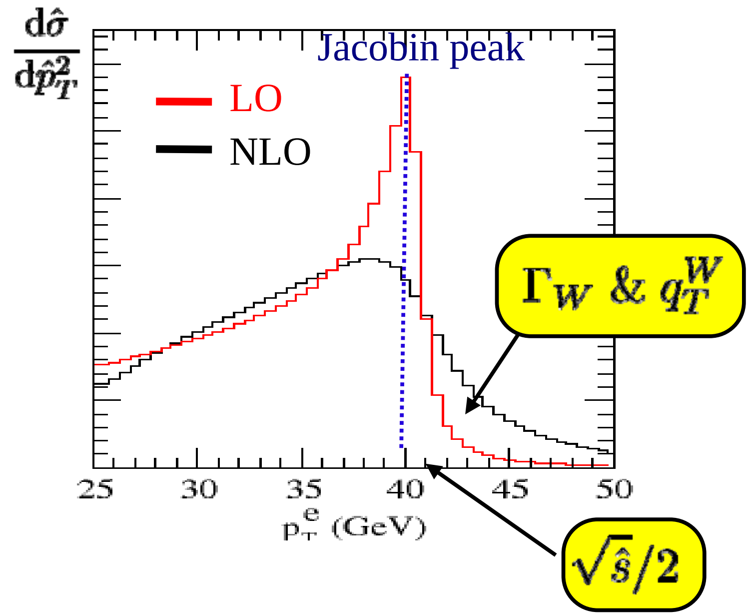


$$\hat{p}_T^2 = \frac{1}{4}\hat{s}\sin^2\theta$$

Jacobin factor

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

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



sensitive region for measuring

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

Γ_W : not a good observable

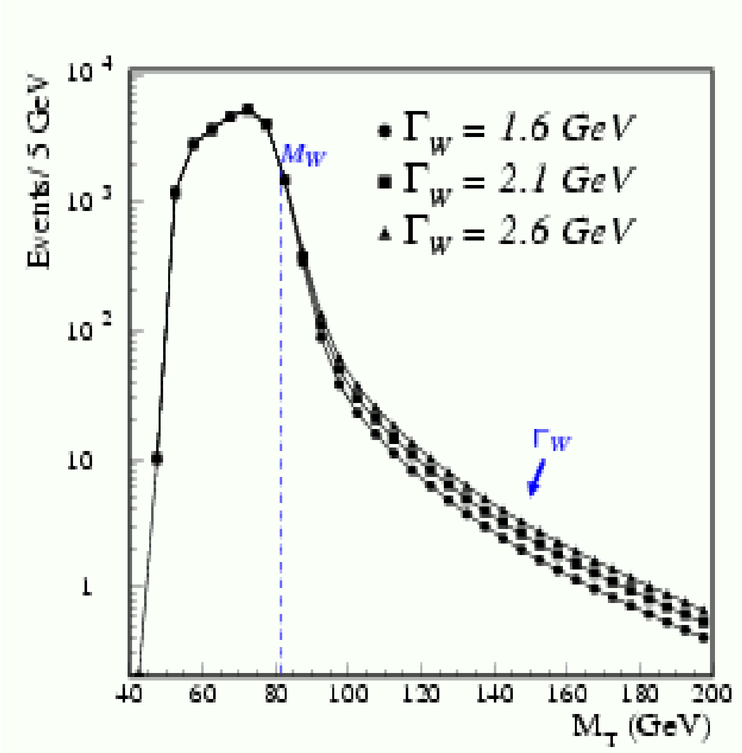
Transverse mass of the W-boson

- 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:

M_W : $M_T \sim 60 - 100$ GeV

Γ_W : $M_T > 100$ GeV

W Charge Asymmetry: A Monitor of Parton Distribution Functions

- 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

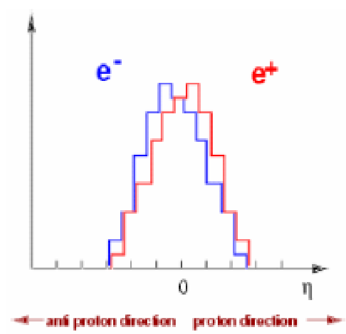
$$A(y_W) = \frac{d\sigma(W^+)/dy_W - d\sigma(W^-)/dy_W}{d\sigma(W^+)/dy_W + d\sigma(W^-)/dy_W}$$

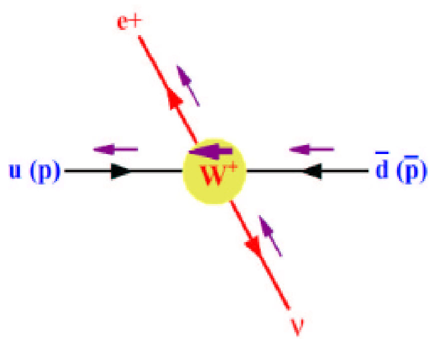
$$A(y_W) \approx \frac{u(x_1)d(x_2) - d(x_1)u(x_2)}{u(x_1)d(x_2) + d(x_1)u(x_2)}$$

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

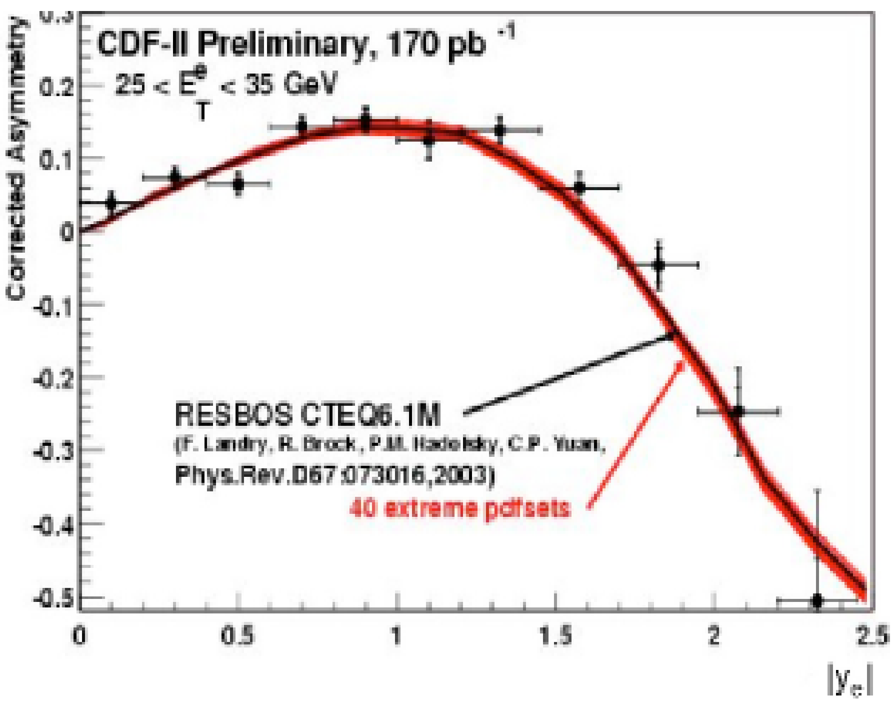
- cannot reconstruct y_W directly
- measure charged lepton only

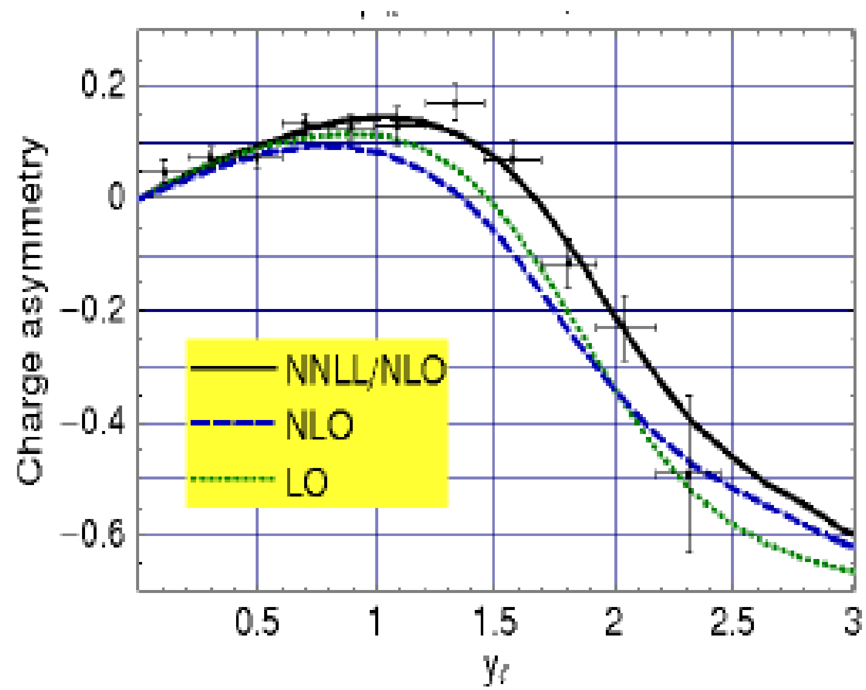
$$A(\eta_l) = \frac{d\sigma(l^+)/d\eta_l - d\sigma(l^-)/d\eta_l}{d\sigma(l^+)/d\eta_l + d\sigma(l^-)/d\eta_l}$$

$A(\eta_l) =$ 

$\otimes$ 

ResBos is also needed for Rapidity distributions





black curve is from ResBos calculation

What's QCD Resummation?

- Perturbative expansion

$$\frac{d\hat{\sigma}}{dq_T^2} \sim \alpha_S \left\{ 1 + \alpha_S + \alpha_S^2 + \cdots \right\}$$

- The singular pieces, as $\frac{1}{q_T^2}$ (1 or log's)

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

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

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

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

$$+ \cdots \quad \}$$

$$L \equiv \ln\left(\frac{Q^2}{q_T^2}\right)$$

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

Resummed results:

Determined by $A^{(1)}$ and $B^{(1)}$

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

Determined by $A^{(2)}$ and $B^{(2)}$

Determined by $A^{(3)}$ and $B^{(3)}$

→ QCD Resummation

In the formalism by Collins-Soper-Sterman, in addition to these perturbative results, the effects from physics beyond the leading twist is also implemented as [non-perturbative functions].

CSS Resummation Formalism

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

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

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

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

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

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

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

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

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

- Example: for $W^{\pm}$

$$\sigma_0 = \left(\frac{4\pi^2\alpha}{3} \sum_{jj'} Q_{jj'}^{(W)} \right), \qquad Q_{jj'}^{(W)} = \frac{1}{4\sin^2\theta_W} \left(kM \right)_{jj'}^2$$

The couplings of gauge bosons to fermions are expressed in the way to include the dominant electroweak radiative corrections. The propagators of gauge bosons also contain energy-dependent width, as done in LEP precision data analysis.

Note:

$$A \equiv \sum_{n=1}^{\infty} \left(\frac{\alpha_S}{\pi} \right)^n \cdot A^{(n)}, \qquad B \equiv \sum_{n=1}^{\infty} \left(\frac{\alpha_S}{\pi} \right)^n \cdot B^{(n)},$$

$$C \equiv \sum_{n=0}^{\infty} \left(\frac{\alpha_S}{\pi} \right)^n \cdot C^{(n)}$$

Make Precision Tests possible

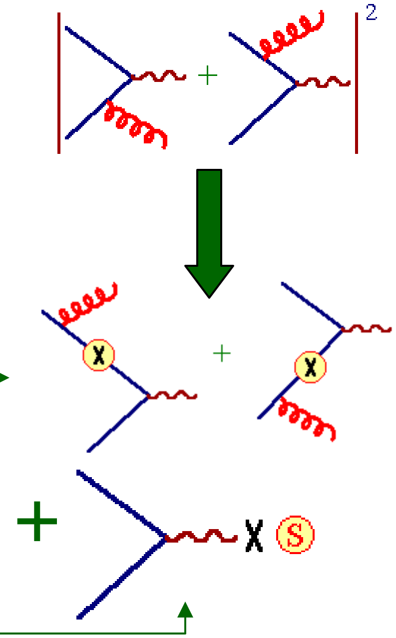
- Weak-mixing angle
- Z boson couplings to up- and down-type quarks.
    - ➢ This could not be done at LEP-I or SLC.
    - ➢ It is correlated to the initial state PDFs.

As $q_T \to 0$

$$
\left.\frac{d\sigma}{dq_T^2\,dy\,dQ^2}\right|_{q_T\to 0}
= \left(\frac{\pi}{s}\sigma_0\right)\cdot\delta\left(Q^2 - M_W^2\right)\cdot\left(\frac{1}{2\pi q_T^2}\right)\left(\frac{\alpha_s(Q)}{\pi}\right)
$$

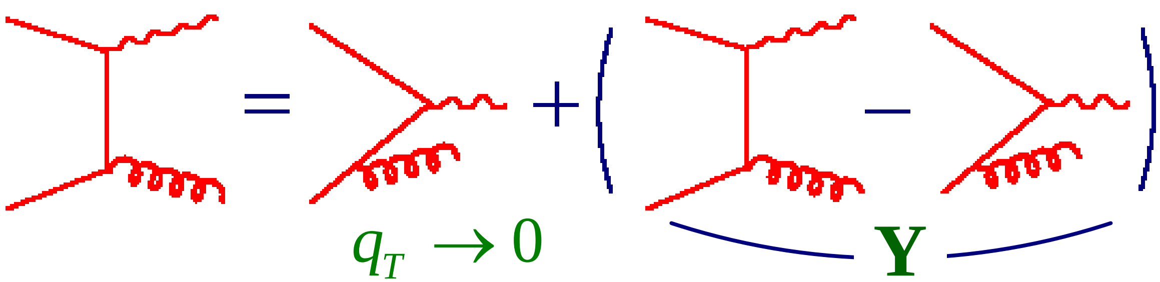
$$
\cdot\left\{ f_{q/A}(x_A,Q)\left[P_{\bar q\leftarrow\bar q}\otimes f_{\bar q}\right]_{x_B,Q} + \left[P_{q\leftarrow q}\otimes f_q\right]_{x_A,Q} f_{\bar q/B}(x_B,Q) + f_{q/A}(x_A,Q)\,f_{\bar q/B}(x_B,Q)\cdot\left[2\left(\frac{4}{3}\right)\ln\left(\frac{Q^2}{q_T^2}\right) + 2(-2)\right]\right\}
$$

Diagramatically,

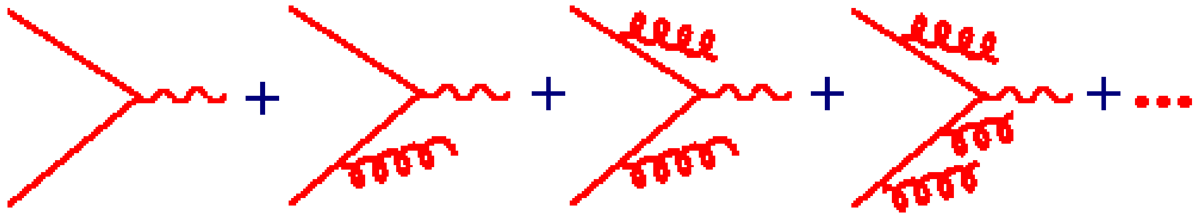


Exponentiate

To preserve transverse momentum conservation, we have to go to the impact parameter space (b-space) to perform resummation.



Diagramatically, Resummation is doing



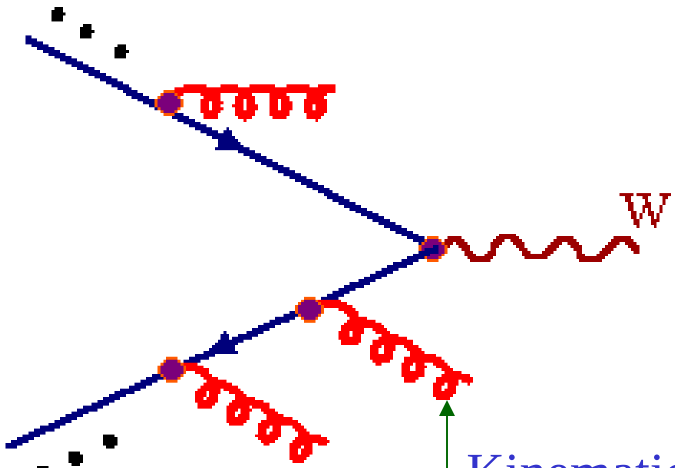
Resum large $\alpha_S^n \ln^m \left(\frac{Q^2}{q_T^2}\right)$ terms

$$\left.\frac{d\sigma}{dq_T^2 dy}\right|_{q_T \to 0} \sim \frac{1}{q_T^2} \sum_{n=1}^{\infty} \sum_{m=0}^{2n-1} \alpha_S^n \ln^m \left(\frac{Q^2}{q_T^2}\right) \cdot C_m^n$$

Monte-Carlo programs ISAJET, PYTHIA, HERWIG contain these physics.

(Note: Arbitrary cut-off scale in these programs to affect the amount of Backward radiation , i.e. Initial state radiation.)

Monte-Carlo Approach



Backward Radiation
(Initial State Radiation)

Kinematics of the radiated gluon, controlled by Sudakov form factor with some arbitrary cut-off. (In contrast to perform integration in impact parameter space, i.e., b space.)

⇨ The shape of q_T (w) is generated. But, the integrated rate remains the same as at Born level (finite virtual correction is not included).

* Recently, there are efforts to include part of higher order effect in the event generator.

Event Generators (PYTHIA, HERWIG)

Note that the integrated rate is the same as the Born level rate ($\alpha_S^{(0)}$) even though the q_T – distribution is different (i.e., not $\delta\left(q_T^2\right)$ any more).

$$\sigma = \int \mathrm{d}q_T^2 \frac{\mathrm{d}\sigma}{\mathrm{d}q_T^2} \sim \int \mathrm{d}^2 b \underbrace{\int e^{i\vec{q}_T\cdot\vec{b}}\, \mathrm{d}^2 q_T}\, \sigma_0 e^{-S(b)}$$

→ $\delta^2(b)$

$$= \int \mathrm{d}^2 b\, \delta^2(b)\cdot\sigma_0\cdot e^{-S(b)}$$

→ 1 at b=0

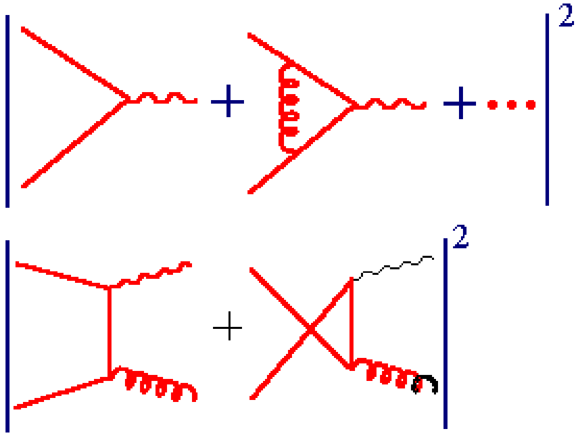
$$= \sigma_0$$

For C-Function = $\delta\left(1-\frac{x_A}{\xi_B}\right)$

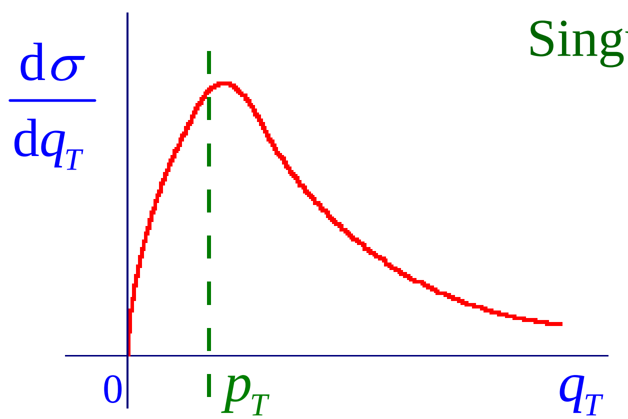
To recover the "K-factor" in the NLO total rate

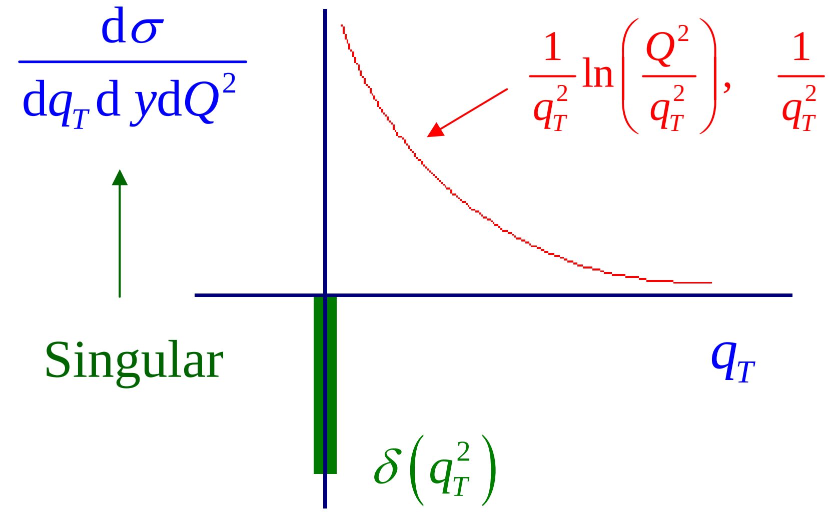
→ To include the C-Functions

$$\frac{d\sigma}{dQ^2 dy} \sim$$



Finite





→ The area under the q_T – curve will reproduce the total rate at the order $\alpha_S^{(1)}$ if Y term is calculated to $\alpha_S^{(1)}$ as well.

Include NNLO in high q_T region

- To improve prediction in high q_T region
- To speed up the calculation, it is implemented through K-factor table which is a function of (Q, q_T, y) of the boson, not just a constant value.

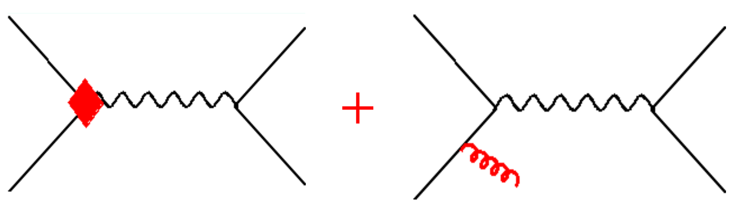
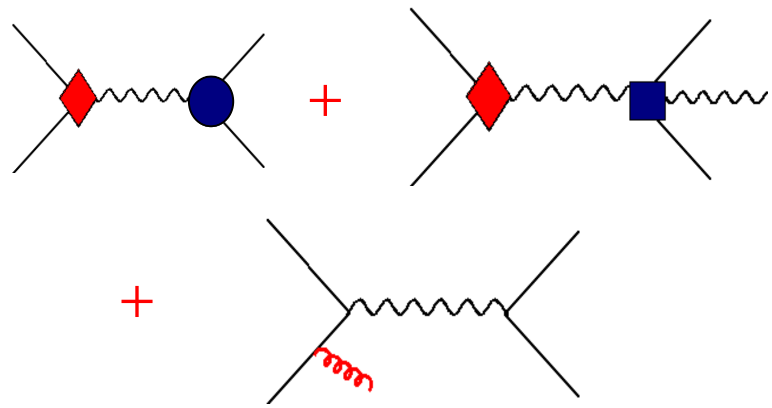
→ ResBos predicts both rate and shape of distributions.

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

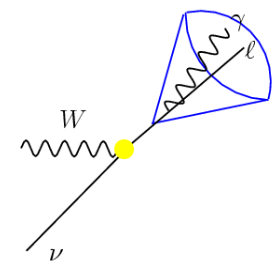
Qing-Hong Cao and CPY

Resum+Born	Resum+NLO
	

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

Need to consider the recombination effect

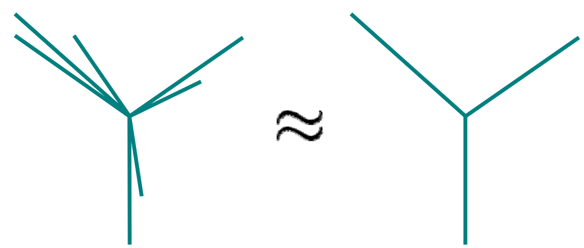
- Experimental: difficult to discriminate between electrons and photons with a small opening angle



- Theoretical: to define infra-safe quantities which are independent of long-distance physics

  Essential feature of a general IRS physical quantity:

  The observable must be such that it is insensitive to whether n or n+1 particles contributed if the n+1 particles has n-particle kinematics.



- Procedure @ Tevatron (for electron)

☞ $p'_e = p_e + p_\gamma$

- $\Delta R(e,\gamma) < 0.2$
- $E_\gamma < 0.15 E_e$ for

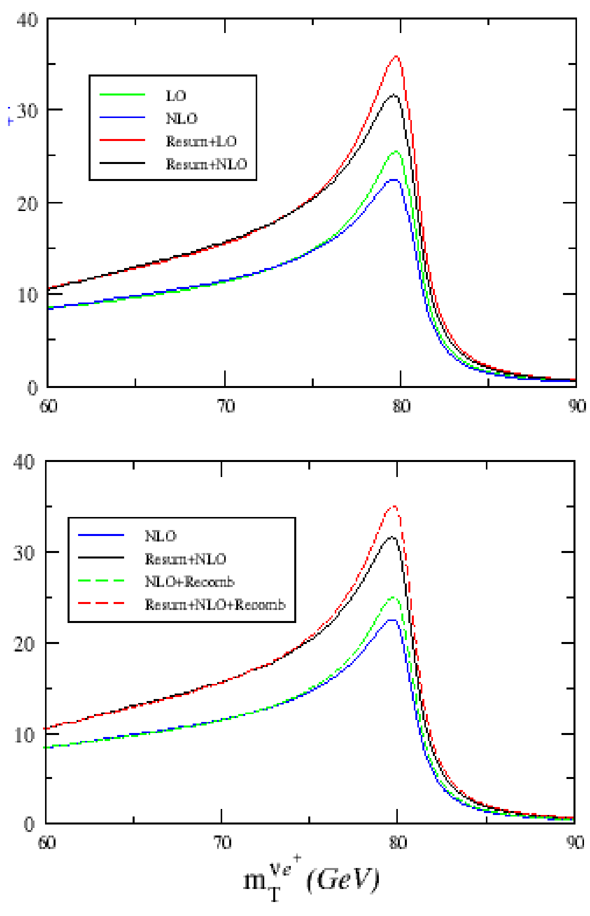
  $0.2 < \Delta R(e,\gamma) < 0.3$

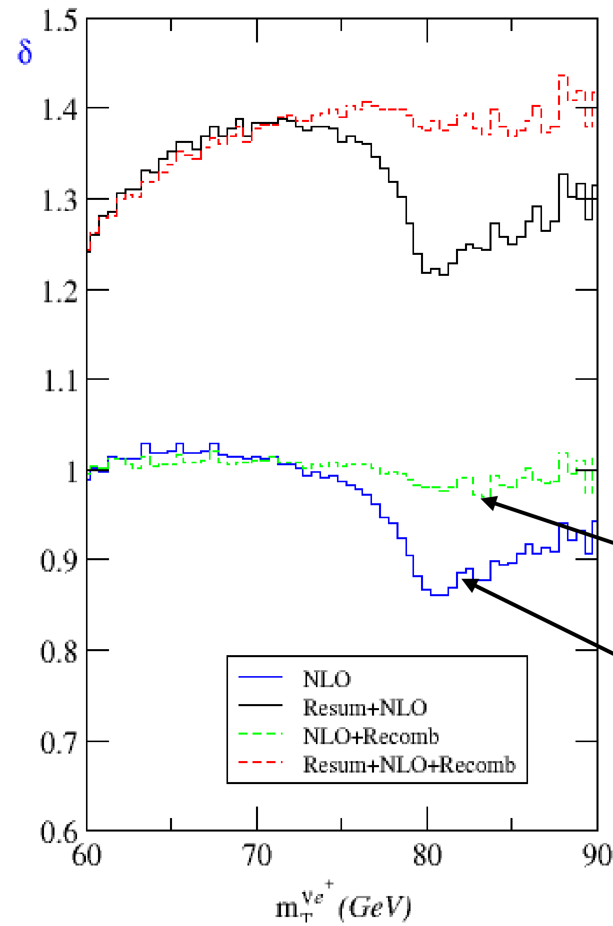
☞ rejection

- $E_\gamma > 0.15\ E_e$ for

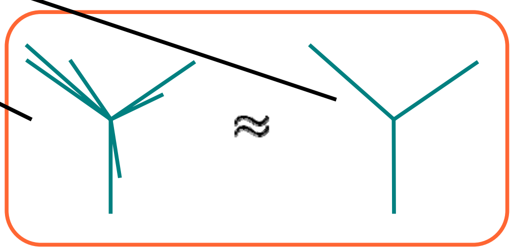
  $0.2 < \Delta R(e,\gamma) < 0.4$

Recombination Effects





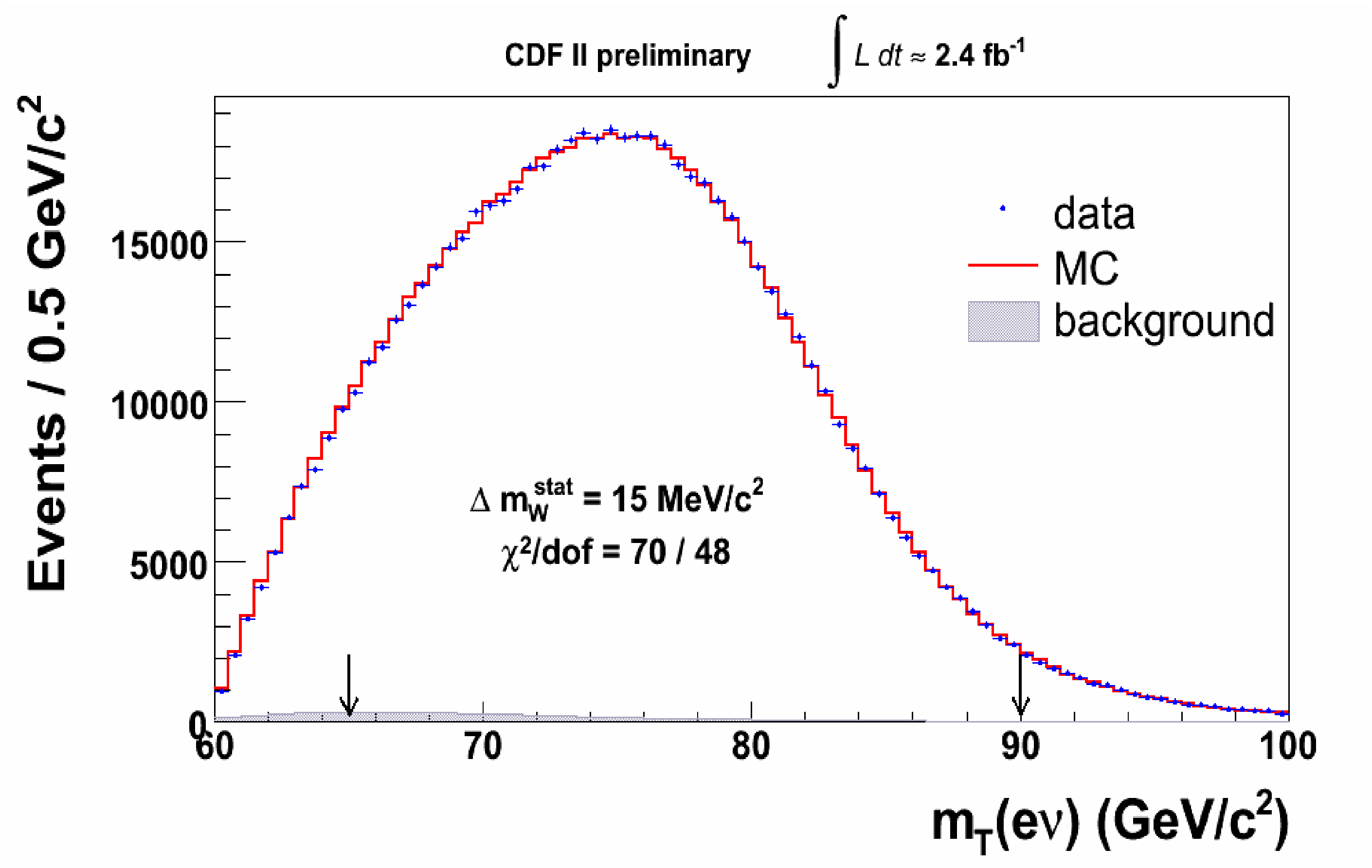
Effects of EW correction decrease significantly after recombination.



infrared-safe

W Mass @ CDF Run-2

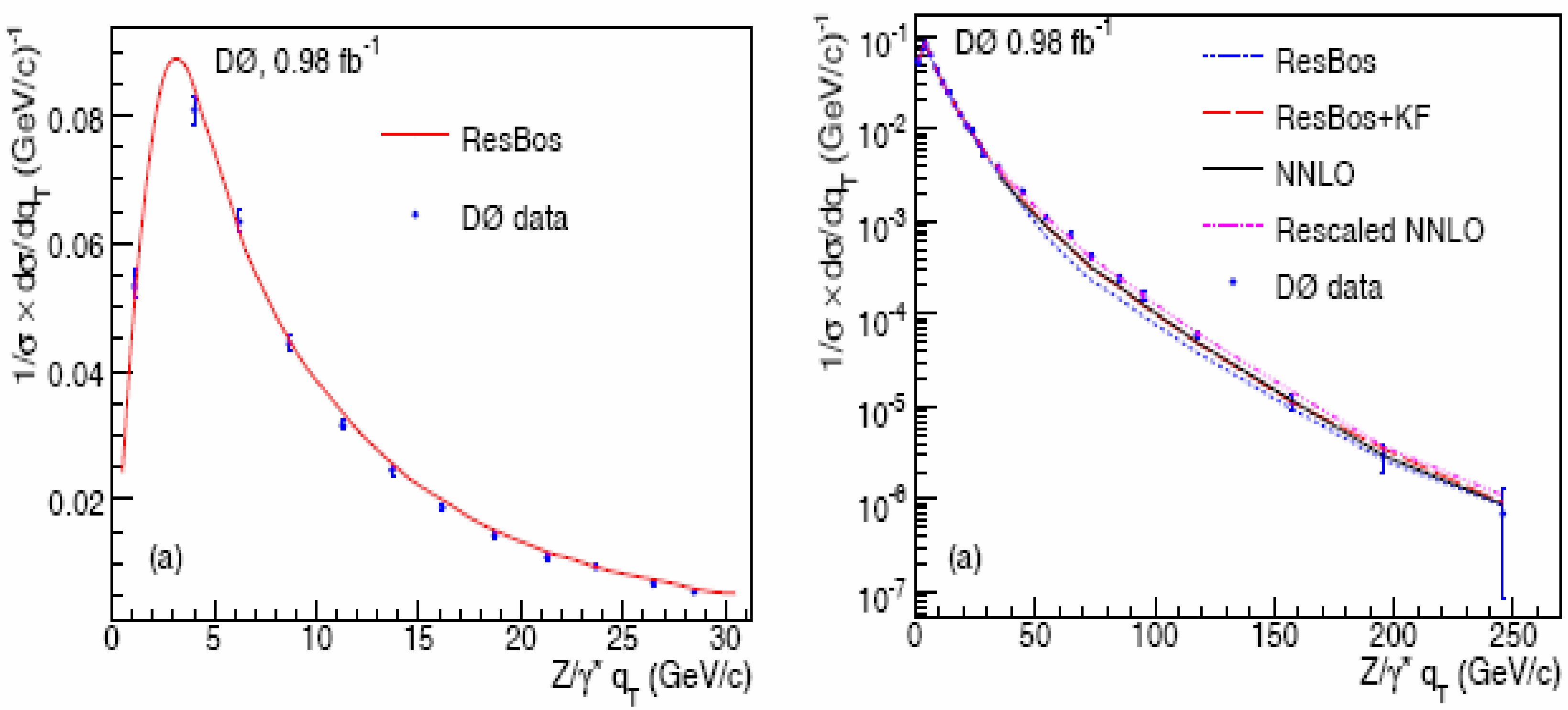
W→eν transverse mass distribution



Statistical error only.

CTEQ

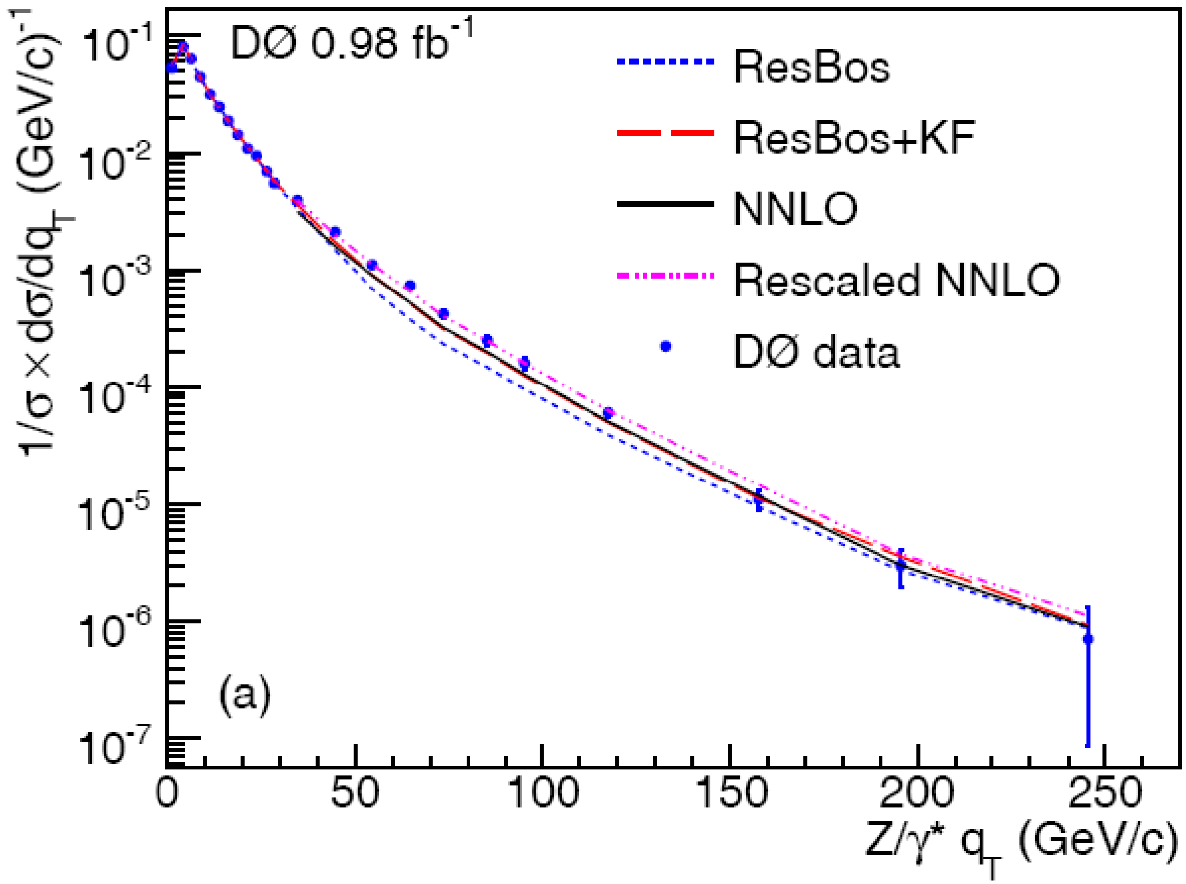
W Boson q_T @ D0 Run-2



low q_T region

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

W Boson q_T @ D0 Run-2



Need to study the difference in the intermediate q_T region.

Where is it?

- **ResBos**: http://hep.pa.msu.edu/resum/
- **Plotter**: http://hep.pa.msu.edu/wwwlegacy

ResBos-A (including final state NLO QED corrections)
http://hep.pa.msu.edu/resum/code/resbosa/
has not been updated.
Why? Because it was not used for Tevatron experiments.

The plan is to include final state QED resummation inside ResBos.

Physical processes included in ResBos

$W^{\pm}$

γ, Z

including gauge invariant set amplitude
for Drell-Yan pairs

H

$\gamma\gamma, ZZ, WW$

New physics: W', Z', H^{+}, A^{0}, H^{0} …

Physics processes inside ResBos

Process	$A^{(i)}$	$B^{(i)}$	$C^{(i)}$	order of Pert. part
$A+B\to W^+\to l^+ +\nu+X$	3	2	1	NNLO
$A+B\to W^-\to l^- +\bar{\nu}+X$	3	2	1	NNLO
$A+B\to Z^0\to l^- +l^+ +X$	3	2	1	NNLO
$A+B\to Z^0/\gamma^*\to l^+ +l^- +X$	3	2	1	NNLO
$A+B\to \gamma^*\to l^+ +l^- +X$	3	2	1	NNLO
$A+B\to gg\to H^0\to \gamma\gamma+X$	3	2	1	NNLO
$A+B\to gg\to H^0\to Z^0Z^0/W^+W^-\to 4l+X$	3	2	1	NNLO
$A+B\to W^{+*}\to W^+ +H^0+X$	3	2	1	NNLO
$A+B\to W^{-*}\to W^- +H^0+X$	3	2	1	NNLO
$A+B\to Z^{0*}\to Z^0+H^0+X$	3	2	1	NNLO
$A+B\to q\bar{q}\to \gamma\gamma+X$	3	2	1	NLO
$A+B\to gg\to \gamma\gamma+X$	3	2	1	NLO
$A+B\to q\bar{q}\to Z^0Z^0+X$	3	2	1	NLO
$A+B\to W^+W^- +X$ (upcoming)	3	2	1	NLO

New Physics (upcoming)

Process	$A^{(i)}$	$B^{(i)}$	$C^{(i)}$	order of Pert. part
$A+B\to W'\to l^- +\bar{\nu}+X$	3	2	1	NNLO
$A+B\to Z'\to l^- +l^+ +X$	3	2	1	NNLO
$A+B\to bb\to A^0/H^0+X$ (THDM)	3	2	1	NNLO
$A+B\to c\bar{s}\to H^+ +X$ (THDM)	3	2	1	NNLO

PYTHIA predicts a different shape (and rate)

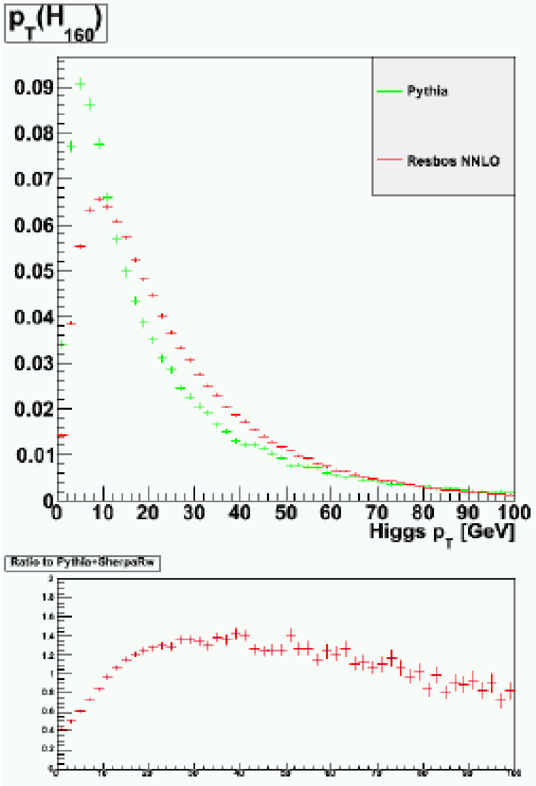
Higgs pT spectrum

All our Higgs MCs are generated with:
Pythia - using LO CTEQ6L1 PDFs

Corrections to the Higgs pT spectrum in gg→H:

In the past: reweight to Sherpa

Plan: reweight to Resbos



Limitations of ResBos

- Any perturbative calculation is performed with some approximation, hence, with limitation.
- To make the best use of a theory calculation, we need to know what it is good for and what the limitations are.

It does not give any information about the hadronic activities of the event.

⇨ It could be used to reweight the distributions generated by (PYTHIA) event generator, by comparing the boson (and it decay products) distributions to ResBos predictions.

This has been done for W-mass analysis by CDF and D0)

Potential of ResBos yet to be explored

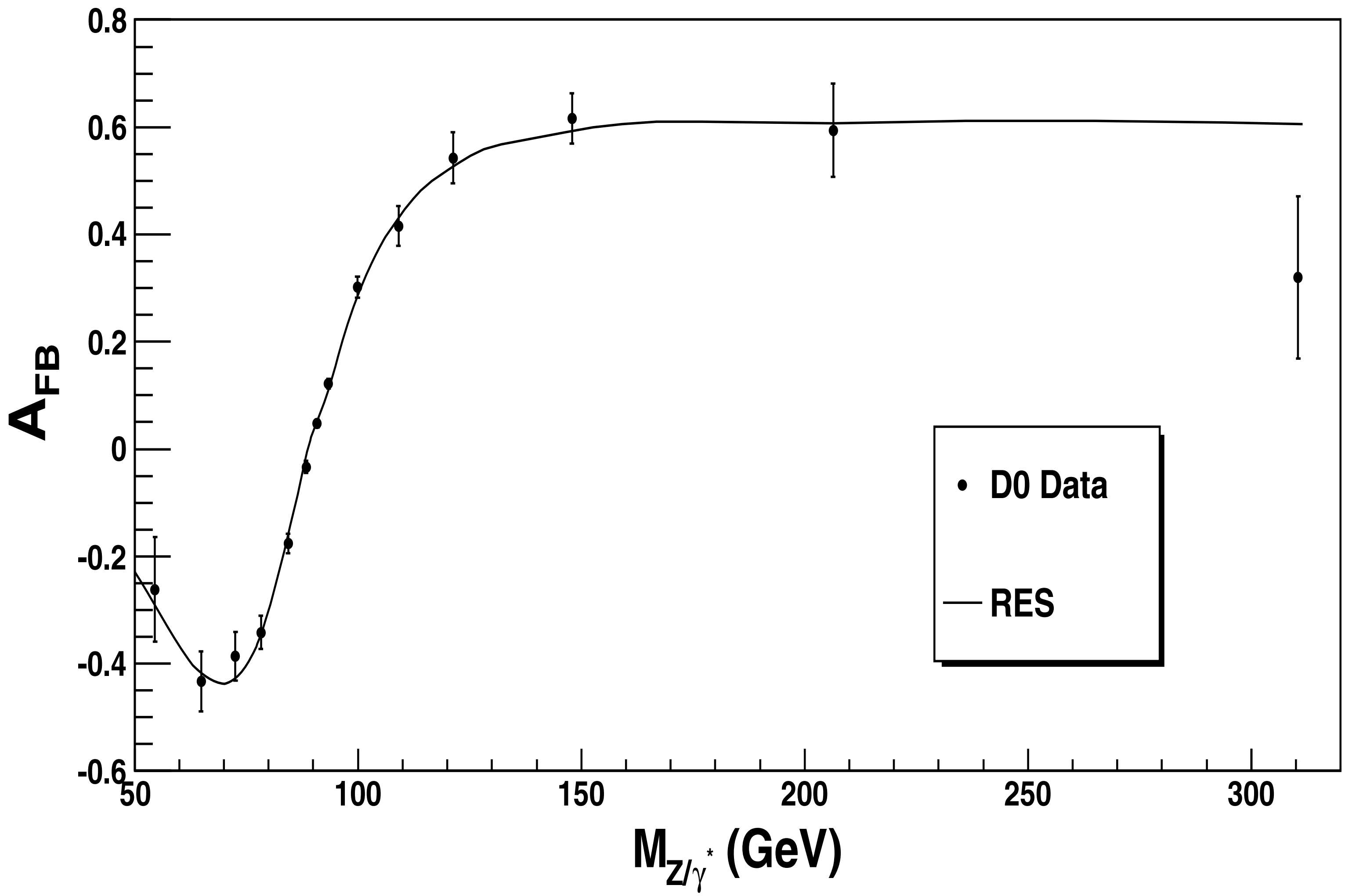
- E.g., in the measurement of forward-backward asymmetry in Drell-Yan pairs.

ResBos can be used for Matrix Element Method by including resummed k_T-dependent parton distribution functions together with higher order matrix element contributions.

For example: The coefficients in front of the complete set of angular functions are given by ResBos

$$\mathcal{L}_0 = 1 + \cos^2\theta,\ \mathcal{A}_0 = \frac{1}{2}(1 - 3\cos^2\theta),\ \mathcal{A}_1 = \sin 2\theta \cos\phi,\ \mathcal{A}_2 = \frac{1}{2}\sin^2\theta\cos 2\phi,$$
$$\mathcal{A}_3 = 2\cos\theta,\ \mathcal{A}_4 = \sin\theta\cos\phi.$$

ResBos vs D0 Run-2 A_{FB} data



Conclusion

- ResBos is a useful tool for studying electroweak gauge bosons and Higgs bosons at the Tevatron and the LHC.
- It includes not only QCD resummation for low q_T region but also higher order effect in high q_T region, with spin correlations included via gauge invariant set of matrix elements.

If you use it, we will keep providing the service to our community. Please send the request to me.

C T E Q

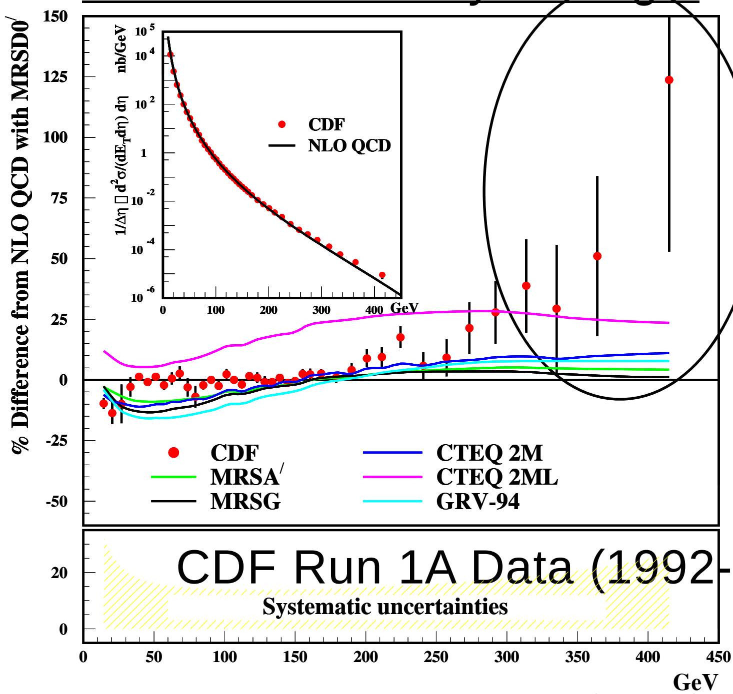
Impact of New
CTEQ Parton Distribution Functions
to LHC Phenomenology:

W/Z, Top and Higgs Physics

C T E Q

New Physics signal found?

Excitement at 10 years ago



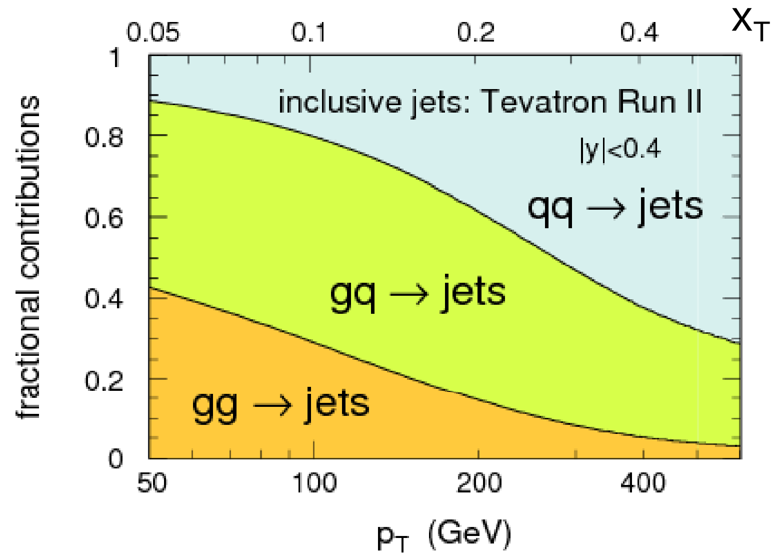
CDF Run 1A Data (1992-93)

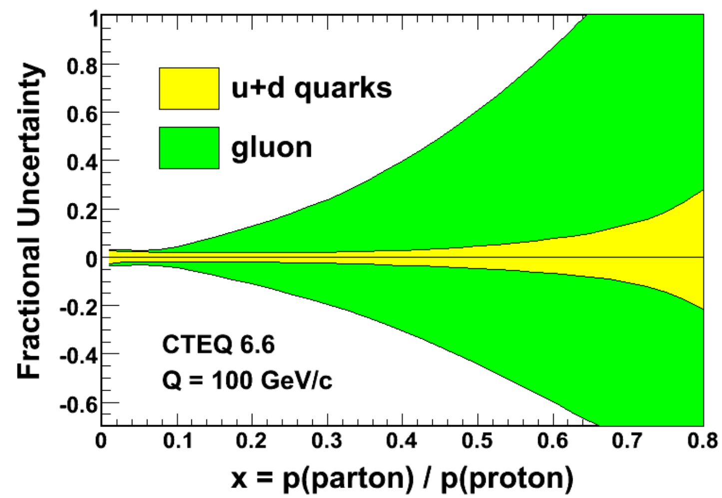
E_T (GeV)

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

High-x gluon not well known

...can be accommodated in the Standard Model

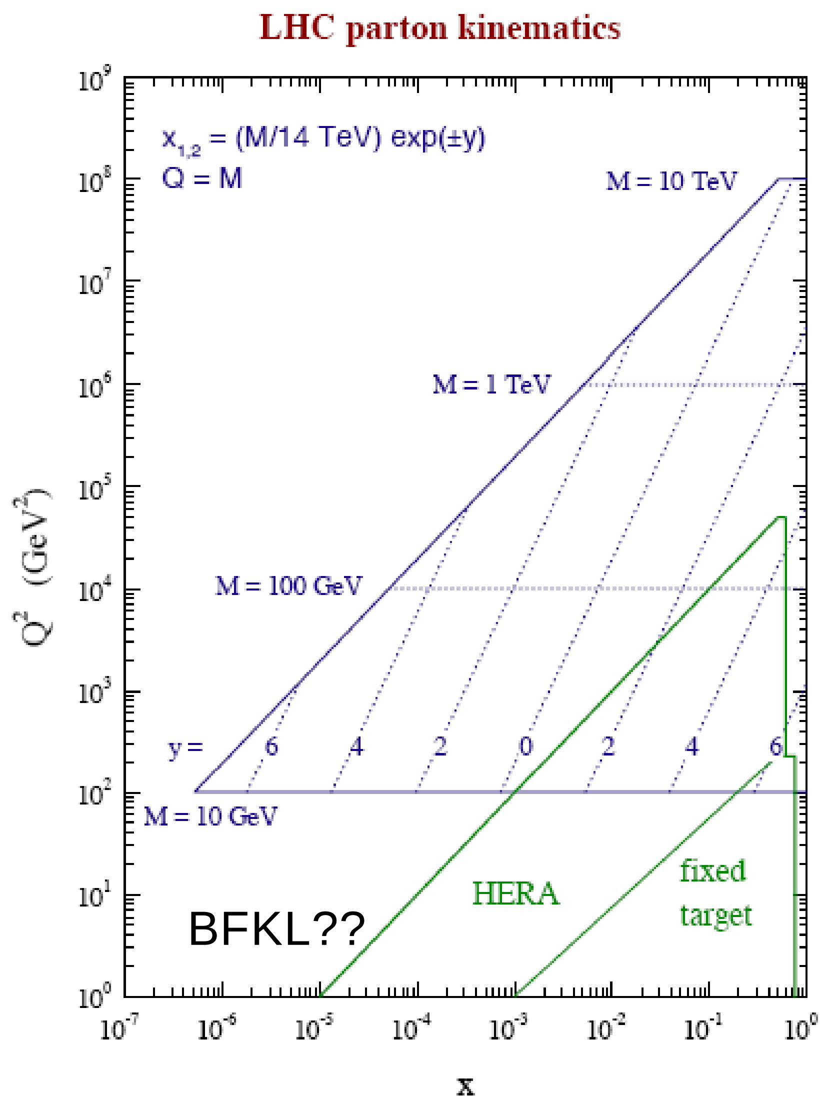




CTEQ

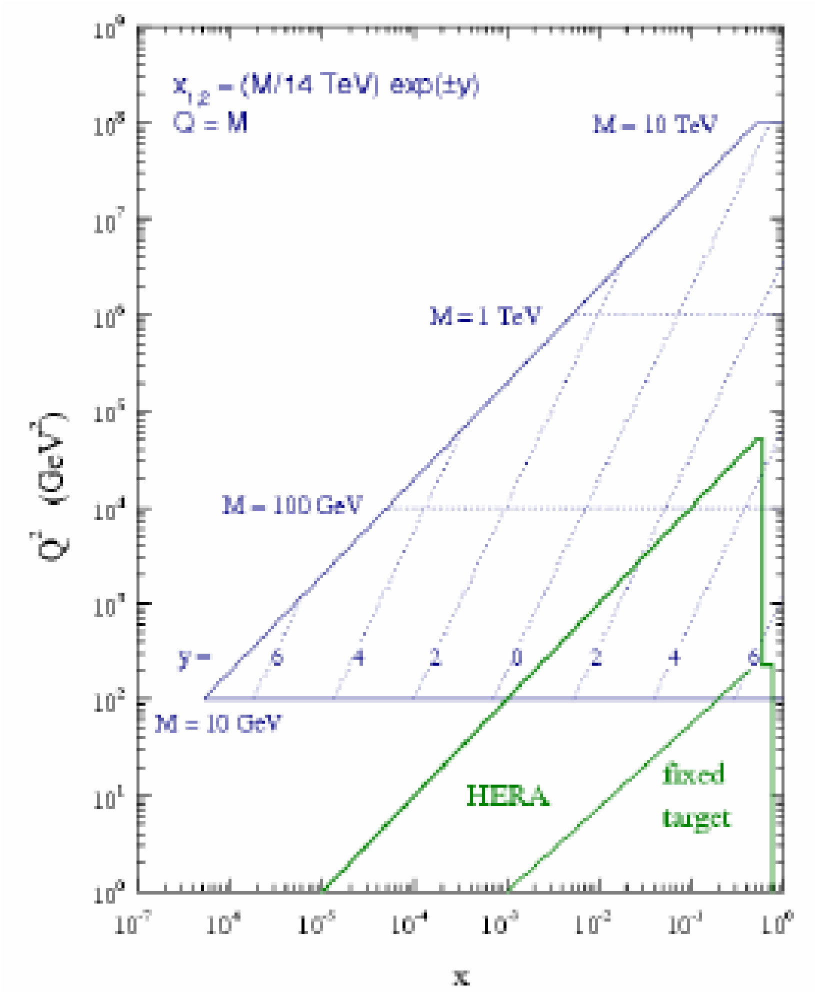
Cross sections at the LHC

- 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"

W Lepton Asymmetry, Parton Distributions, and Implications for Collider Physics

C.-P. Yuan

CTEQ - TEA (Tung et al), Michigan State University

in collaboration with
Hung-Liang Lai, Marco Guzzi, Zhao Li,
Joey Huston, Pavel Nadolsky, Jon Pumplin
BNL @ June 24, 2010

CTEQ-Tung Et Al.: recent activities

- Uncertainty induced by α_s in the CTEQ-TEA PDF analysis

  (arXiv:1004.4624)

- NLO general-purpose PDF fits
  - CTEQ6.6 set (published in 2008) $\longrightarrow$ CT09 $\longrightarrow$ CT10 (to be released)
  - new experimental data, statistical methods, and parametrization forms

- Constraints on new physics
- PDFs for Event Generators *(arXiv:0910.4183)*
- Exploration of statistical aspects (data set diagonalization) and PDF parametrization dependence *(Pumplin, arXiv:0909.0268 and 0909.5176)*

Uncertainty induced by α_s in the PDF analyses

- *Questions addressed:*
  - Two leading theoretical uncertainties in LHC processes are due to α_s and the PDFs; how can one quantify their correlation?
  - Which central $\alpha_s(M_Z)$ and which error on $\alpha_s(M_Z)$ are to be used with the existing PDFs?
  - What are the consequences for key LHC processes ($gg \to H^0$, etc.)?
- recent activities on this issue:
  - **MSTW** *(arXiv:0905.3531)*
  - **NNPDF** *(in 2009 Les Houches Proceedings, arXiv:1004.0962)*
  - **H1+ZEUS** *(arXiv:0911.0884)*

Our findings (arXiv:1004.4624)

Theorem

In the quadratic approximation, the total α_s+PDF uncertainty ΔX, with all correlation, reduces to

$$\Delta X = \sqrt{\Delta X^2_{PDF} + \Delta X^2_{\alpha_s}},$$

where

- ΔX_{PDF} *is the PDF uncertainty with fixed* α_s, *e.g. uncertainty from 44 CTEQ6.6 PDFs with the same* $\alpha_s(M_Z) = 0.118$
- $\Delta X_{\alpha_s} = (X_{high} - X_{low})/2$ *is the* α_s *uncertainty computed with upper/lower* α_s *PDFs, e.g. CTEQ6.6AS PDFs for* $\alpha_s(M_Z) = 0.120$ *and* 0.116

Back-up slides: The main idea illustrated; key cross sections tabulated
The full proof is given in the paper

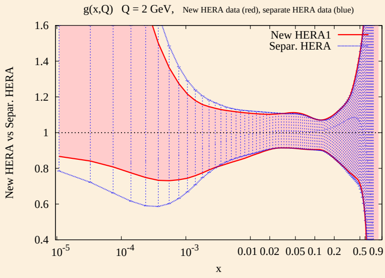
CT10 analysis (in progress)

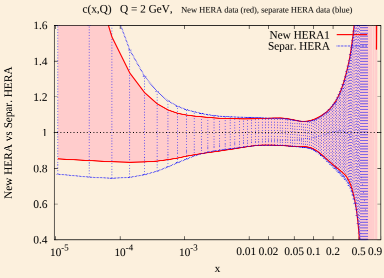
Experimental data

- Combined HERA-1 neutral-current and charged-current DIS data with 114 correlated systematic effects
  - replaces 11 separate HERA-1 sets used in the CTEQ6.6 fit
- CDF Run-2 and D0 Run-2 inclusive jet production
- Tevatron Run-2 Z rapidity distributions from both CDF and D0
- W electron asymmetry from CDF II and D0 II; W muon asymmetry from D0 II (CT10W set)
- Other data sets inherited from CTEQ6.6

CT10 analysis (in progress)

Impact of the new HERA data





Reduction in the uncertainty band at $x < 0.001$

CT10 analysis (in progress)

Developments in statistical techniques

- Experimental normalizations N_i are treated on the same footing as other correlated systematic errors
  - Minimum of χ^2 with respect to N_i is found algebraically
  - normalization shifts are automatically accounted for when producing the eigenvector sets
- Set all data weights of 1, unless otherwise specified
  - do not prefer some experiments over the other experiments
  - Exception: NMC/BCDMS and Run-2 W asymmetry data (see below)

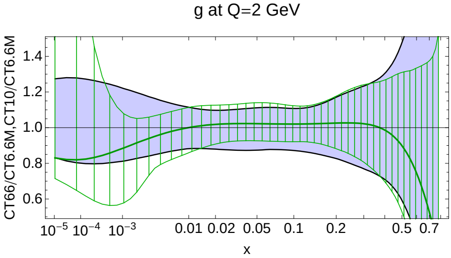
CT10 analysis (in progress)

Revised functional forms at the input scale

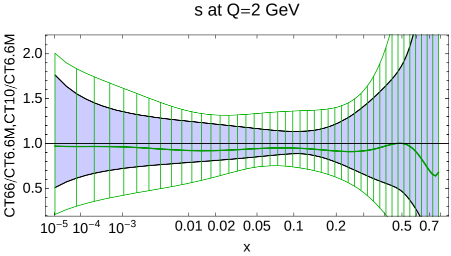
- More data constraints ⇒more flexible (=less biased) parametrizations for $g(x, Q_0)$, $d(x, Q_0)$, and $s(x, Q_0)$
- $R_s = \lim_{x\to 0} (s(x) + \bar{s}(x)) / \left(\bar{u}(x) + \bar{d}(x)\right)$ is not constrained by the data ⇒large uncertainty in $s(x)$ at $x \to 0$
  - allow R_s to vary in the fit, but "softly constrain" it by a penalty on χ^2 to satisfy $0.4 < R_s < 1$
- The resulting CT10 error bands overlap with the MSTW/NNPDF bands
- Alternative parametrizations based on Chebyshev polynomials are also explored *(Pumplin, arXiv:0909.5176)*

More flexible parametrizations

CT10(green) vs. CTEQ6.6(blue) ; PRELIMINARY



$g(x, Q)$: large uncertainty at $x < 10^{-3}$, despite tighter constraints by the combined HERA data



$s(x, Q)$: wider uncertainty, covers both CTEQ6.6 and MSTW'08

Agreement between data sets

- Good overall agreement: $\chi^2/d.o.f. = 1.1$ (out of ~2800 data points)

- Noticable observations on the quality of the fit:

  - **Tevatron single-inclusive jet production:** Run-1 and Run-2 sets are moderately compatible *(arXiv:0904.2424)*

  - **Tevatron Run-2 Z rapidity:** D0 well described; CDF acceptable (higher stat.)

  - **Tevatron Run-2 W lepton asymmetry**
    - is precise; constrains $d(x)/u(x)$ at $x \to 1$
    - apparently disagrees with existing constraints on d/u, mainly provided by the NMC F_2^d/F_2^p and Run-1 W lepton asymmetry data; minor tension against BCDMS F_2^d data

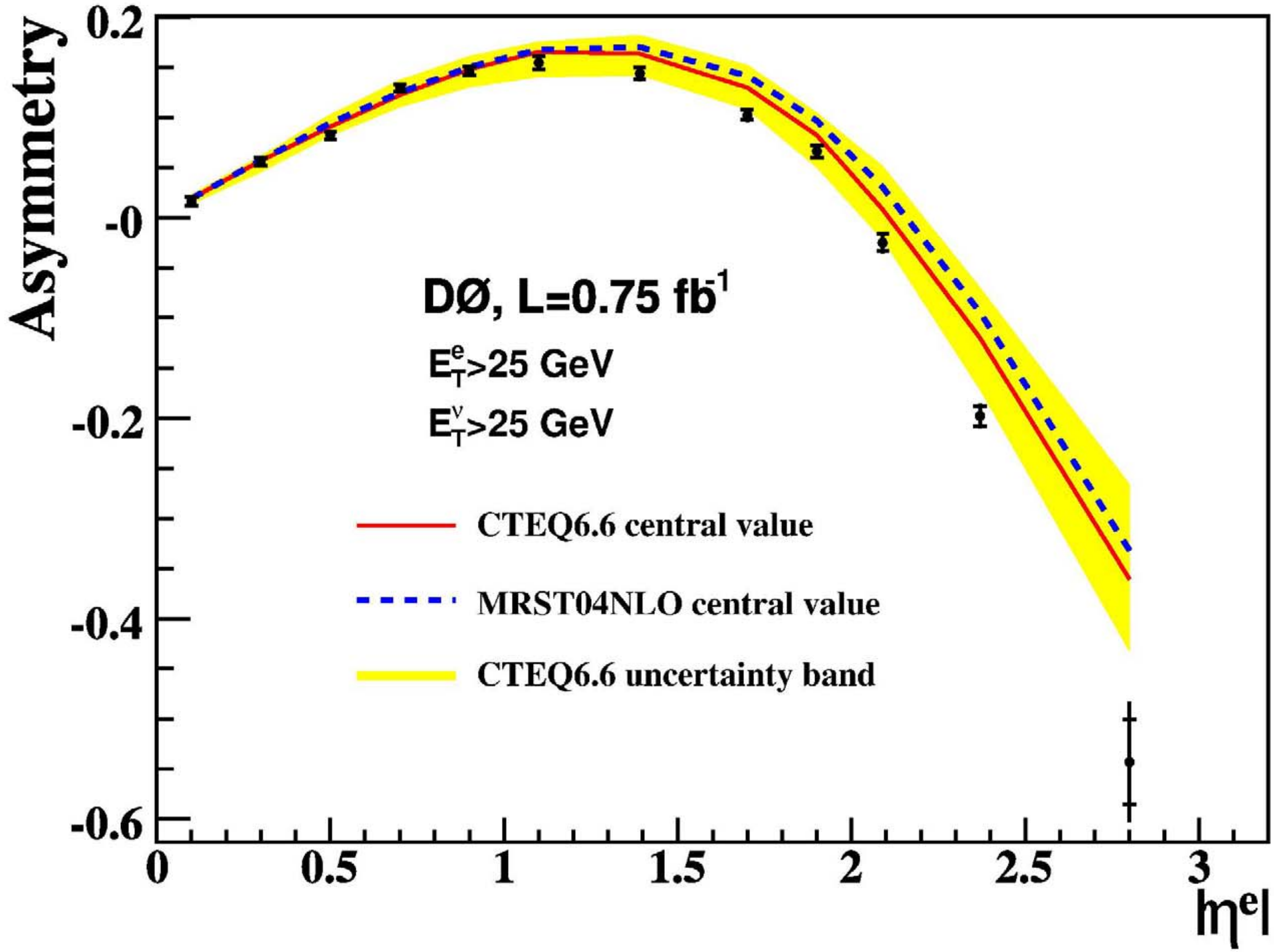
Agreement between data sets

- Reaonable fits to electron (e) asymmetry data are possible without NMC and BCDMS; and vice versa
- No acceptable fit to D0 II e asymmetry and NMC/BCDMS data can be achieved, if they are included on the same footing
- Tension between Run-2 e asymmetry and μ asymmetry
- Good agreement between Run-2 e W asymmetry data and Z y data
- With special emphasis on D0 II e asymmetry data (weight>1), it is possible to obtain a reasonable agreement for W asymmetry ($\chi^2/d.o.f. = 1 - 2$) , with some remaining tension with NMC & BCDMS data, especially at $x > 0.4$

CT10 family

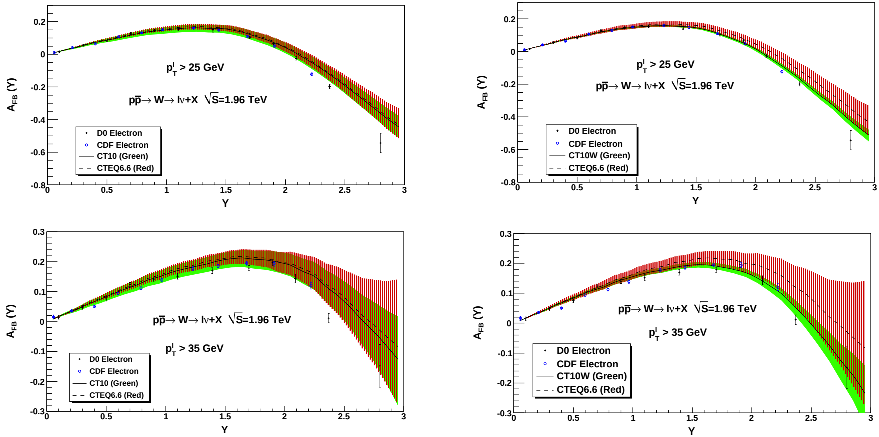
- Two series of PDFs are produced:
  - **CT10:** no D0 Run-2 W asymmetry data are included
  - **CT10W:** include D0 Run-2 W asymmetry, with an extra weight

D0 II electron Asymmetry (0.75 fb^{-1})



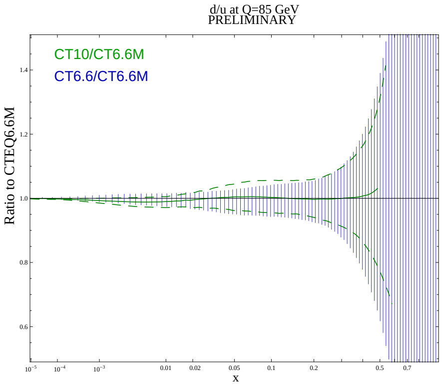
CT10 and CT10W fits with Tevatron Run-2 data

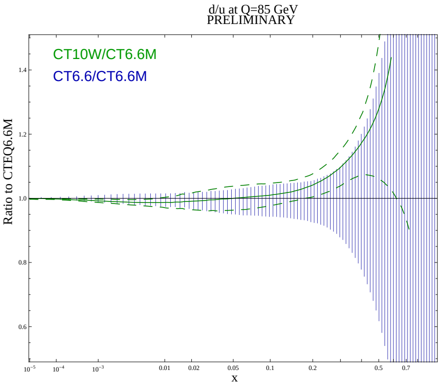
PRELIMINARY



CT10W agrees better with W asy data; has smaller uncertainty than CTEQ6.6 or CT10

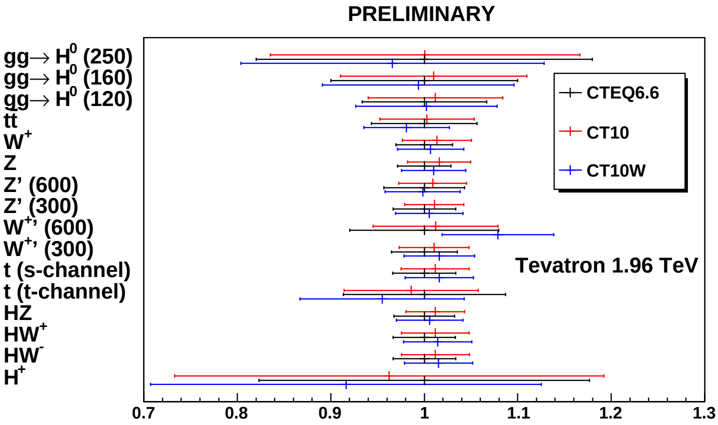
$d(x,Q)/u(x,Q)$ at $Q = 85$ GeV



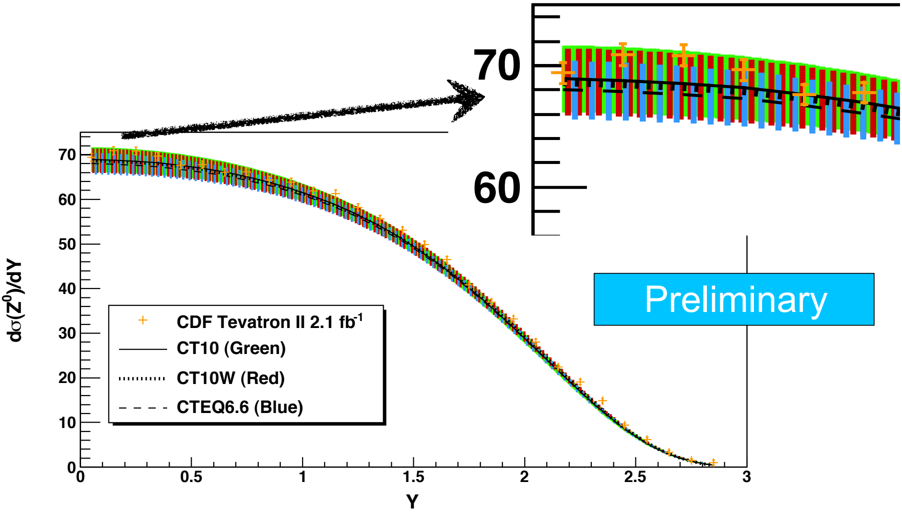


CT10W prefers larger d/u, has smaller uncertainty than CTEQ6.6 or CT10

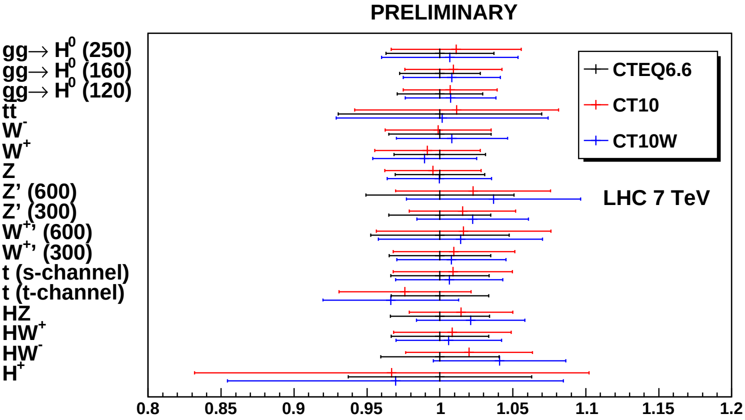
CT10 & CT10W predictions for the Tevatron



CT10 & CT10W predictions for the Tevatron

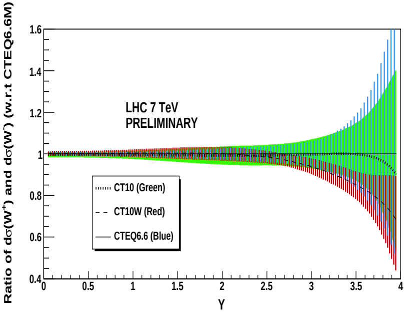


CT10 & CT10W predictions for the LHC



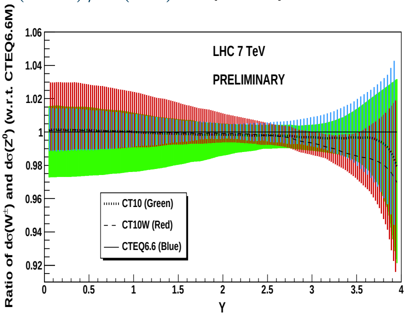
CT10 & CT10W predictions for the LHC

$\sigma(W^+)/\sigma(W^-)$ rapidity dist.



CT10W Uncertainty (red) is clearly smaller than that of CT10 & CTEQ6.6.

$\sigma(W^\pm)/\sigma(Z^0)$ rapidity dist.



CT10 (green) & CT10W (red) uncertainties in central y region are larger than that of CTEQ6.6 (blue), mainly due to larger uncertainty on s distribution.

Summary I

CTEQ6.6AS PDF sets (available in the LHAPDF library):

- from 4 alternative CTEQ6.6 fits for

$$\alpha_s(M_Z) = 0.116, .117, .119, .120$$

- sufficient to compute uncertainty in $\alpha_s(M_Z)$ at ≈68% and 90% C. L., including **the world-average** $\alpha_s(M_Z) = 0.118 \pm 0.002$ as an **input data point**
- **The CTEQ6.6AS** α_s uncertainty should be combined with the CTEQ6.6 PDF uncertainty as

$$\Delta X = \sqrt{\Delta X^2_{CTEQ6.6} + \Delta X^2_{CTEQ6.6AS}}$$

- The total uncertainty ΔX reproduces the full correlation between $\alpha_s(M_Z)$ and PDFs, also applicable to CT10 family and future PDFs.

Summary II

Tevatron Run-2 W asymmetry data...

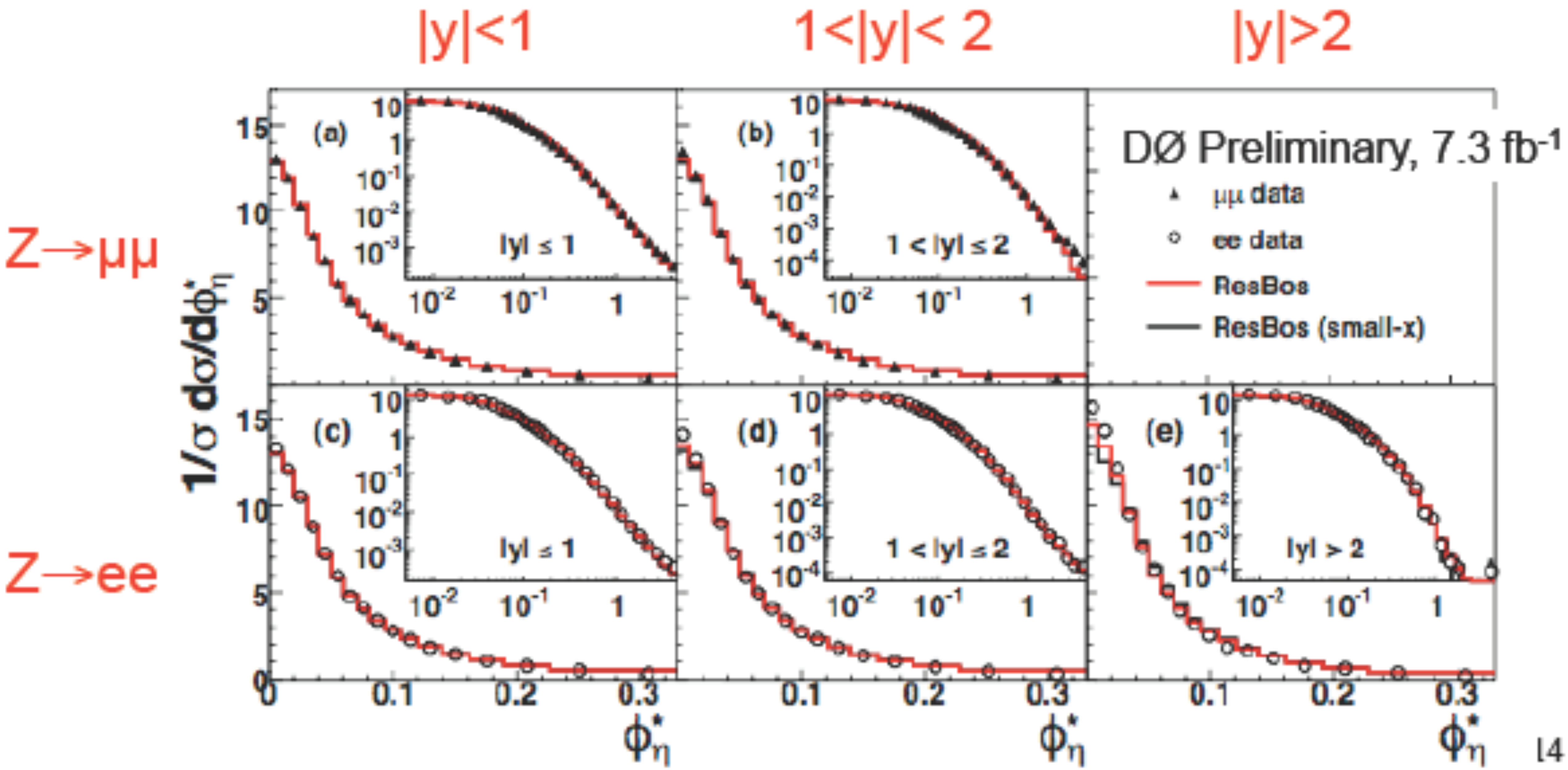
...become increasingly complete and precise (measurements by both CDF and D0; electron and muon channels)

...cannot be explained based on the d/u ratio provided by the previously existing data

- Several cross checks of the theoretical calculation for W asymmetry; no problems were found
- Higher-twist and nuclear corrections in the large-x BCDMS/NMC deuterium data are the usual suspects

  (Virchaux and Milsztajn; Alekhin; Accardi et al.)
- CT10 and CT10W sets of PDFs for practical applications, without and with constraints from the D0 Run-2 W asymmetry

High precision W/Z data @Tevatron

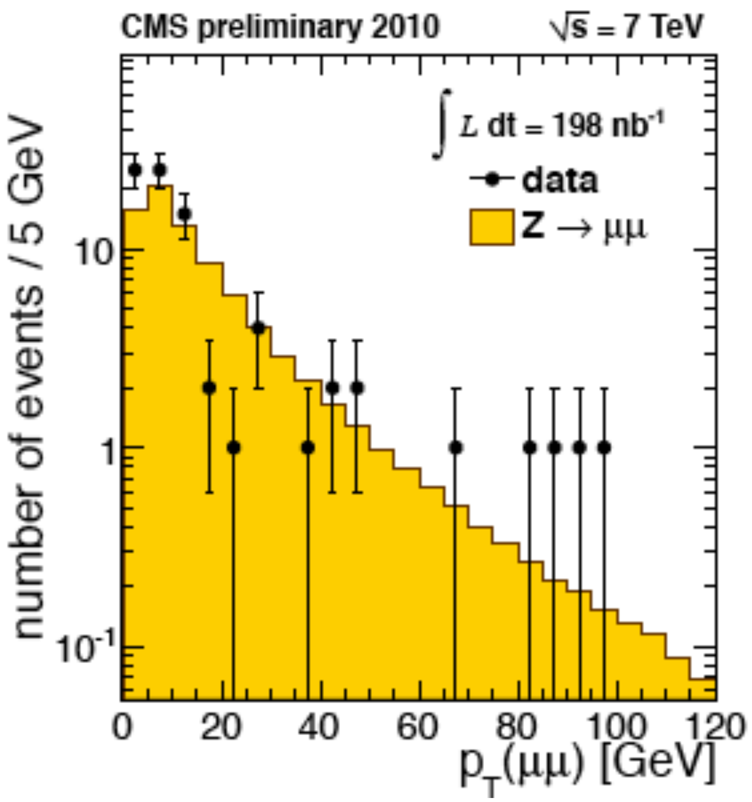


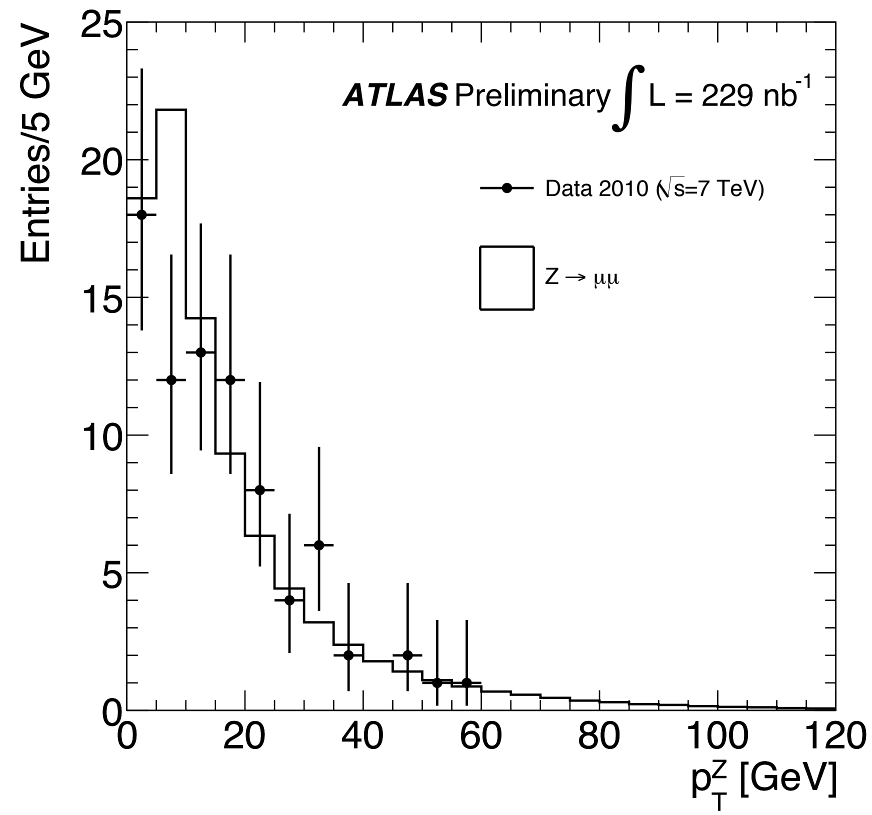
ICHEP 2010 D0 & CDF

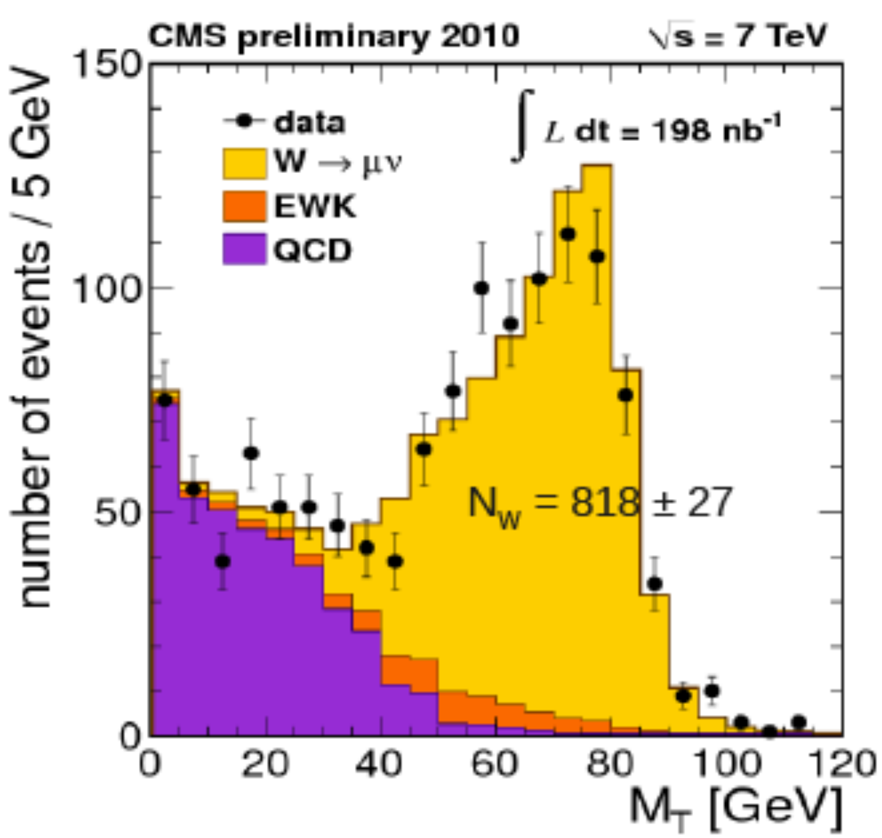
LHC W/Z data

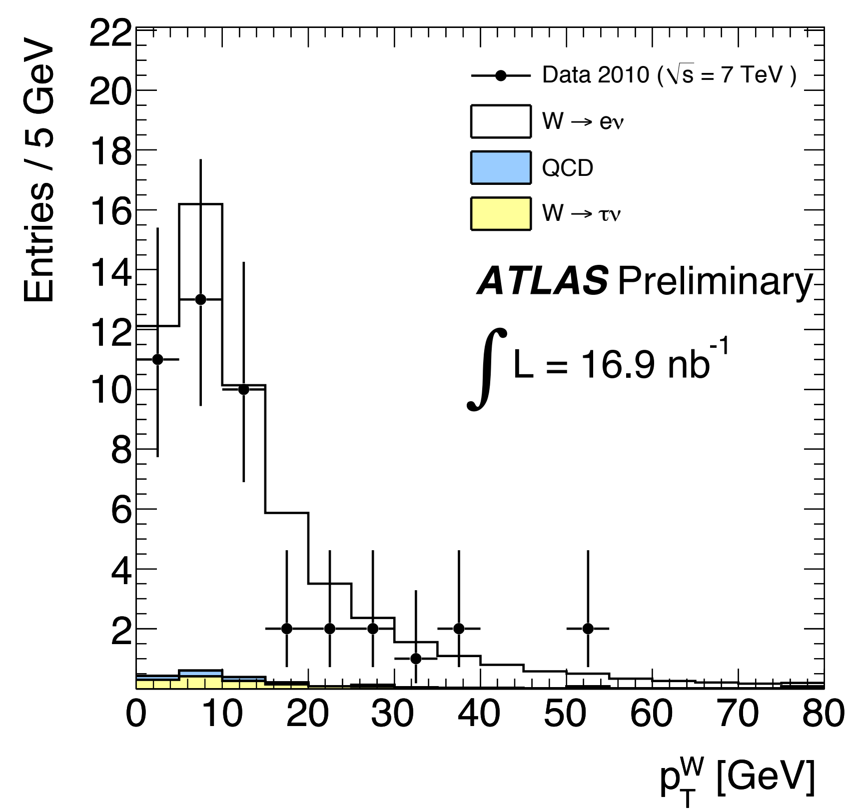
- Need more integrated luminosity (at least of the order of 100 1/pb) to make precision tests using W/Z data.

Measurements of Drell-Yan @ LHC 7 TeV

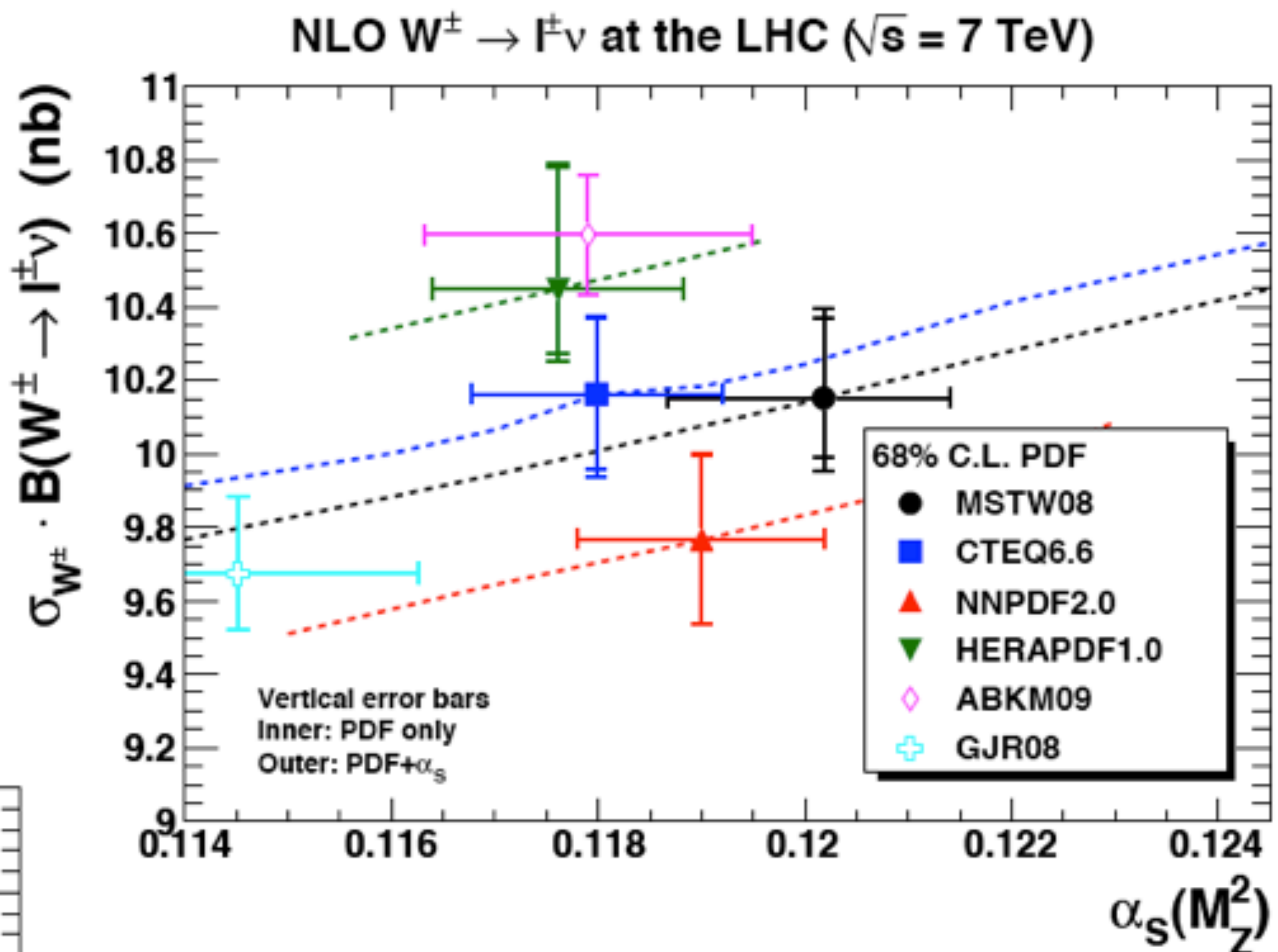


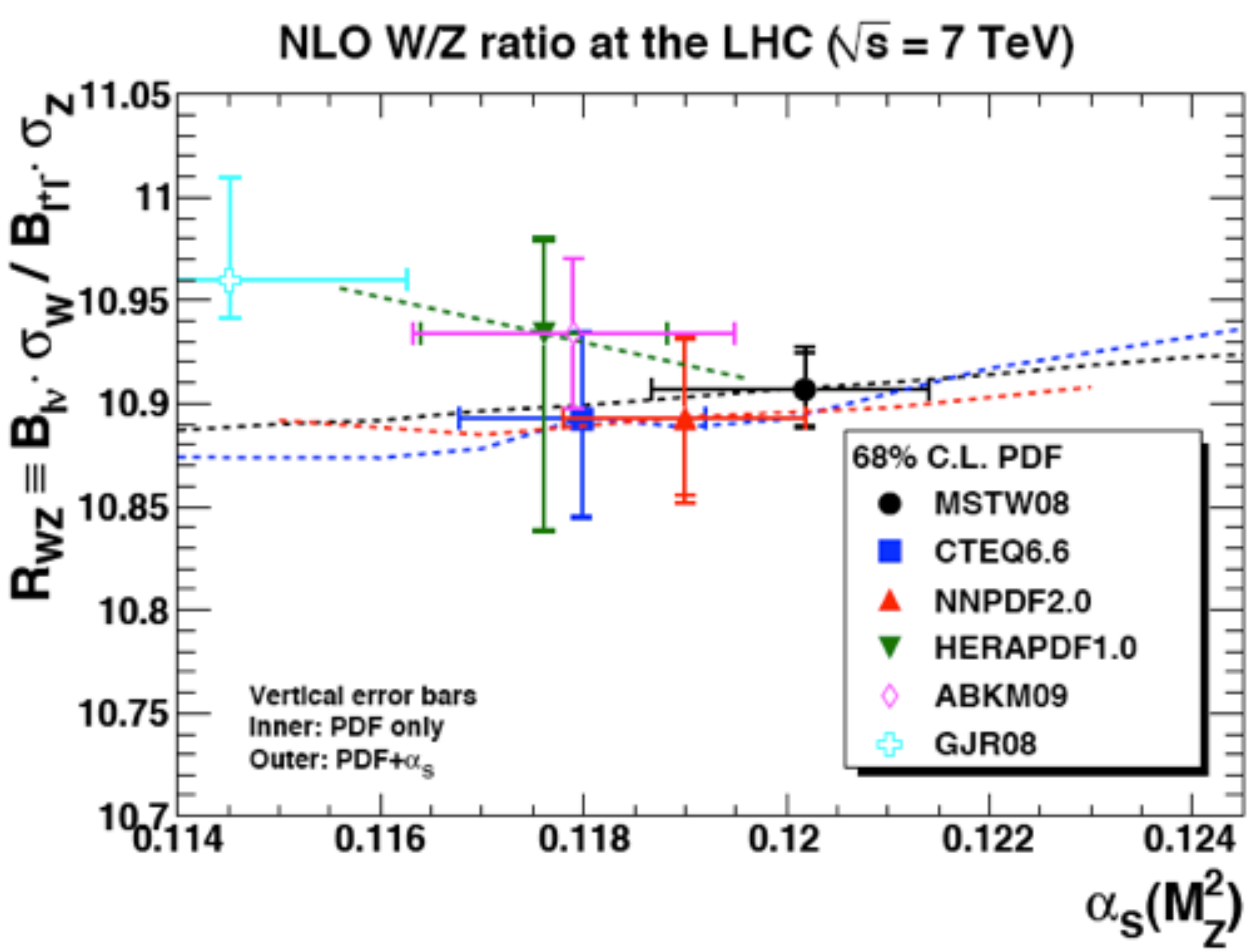






Predictions from different PDF sets





Angular function in Drell-Yan process

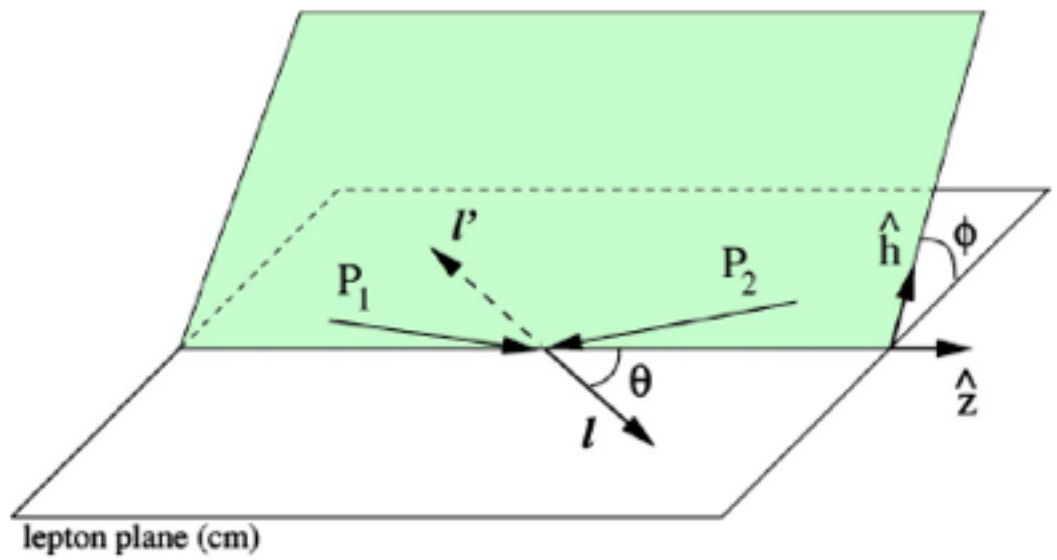
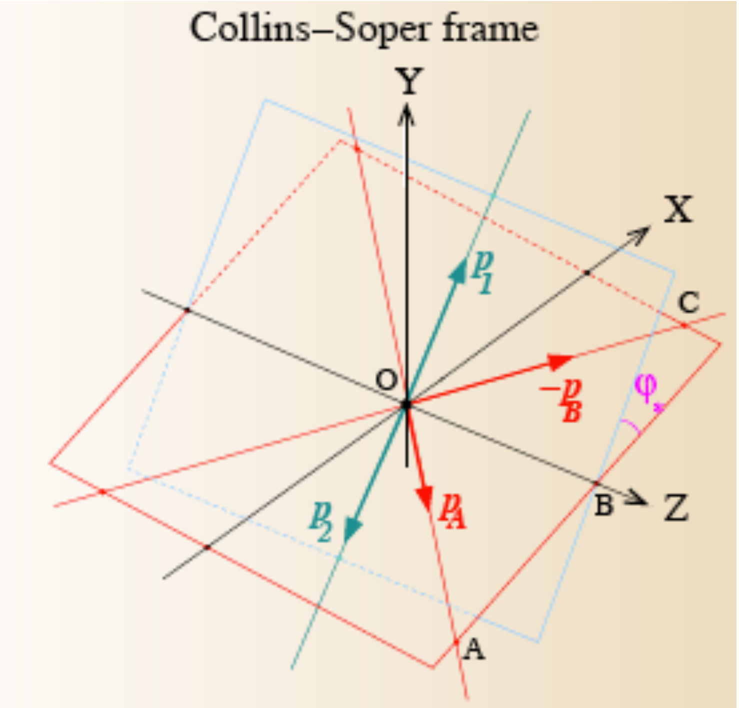


FIG. 1. Kinematics of the Drell-Yan process in the lepton center of mass frame.



Lam-Tung relation

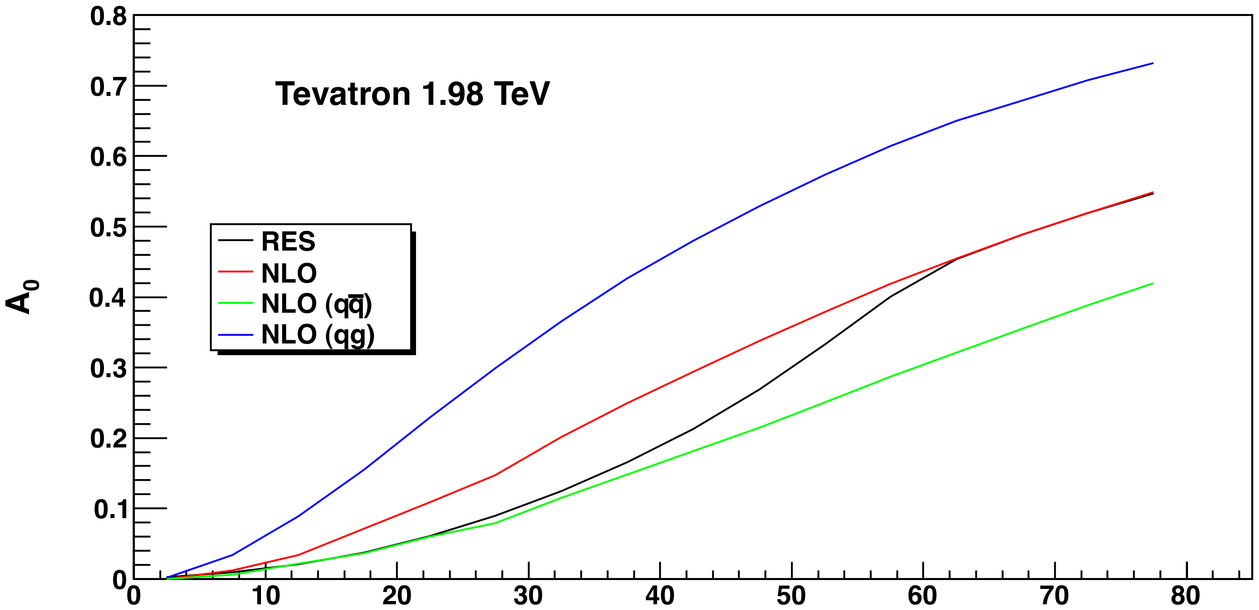
PHYSICAL REVIEW D **16,** 2219 (1977)

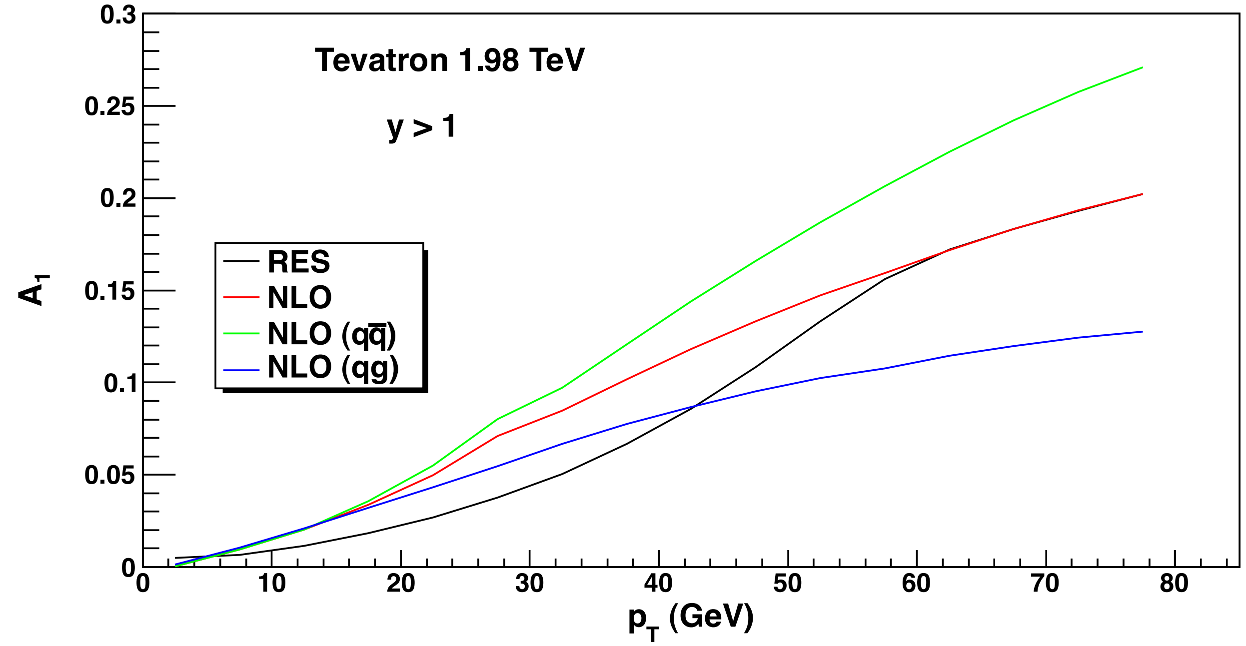
$$\frac{dN}{d\Omega} \propto 1 + \cos^2\theta + (\tfrac{1}{2} - \tfrac{3}{2}\cos^2\theta)A_0 + 2\cos\theta\sin\theta\cos\phi\, A_1 + \tfrac{1}{2}\sin^2\theta\cos 2\phi\, A_2\,,$$

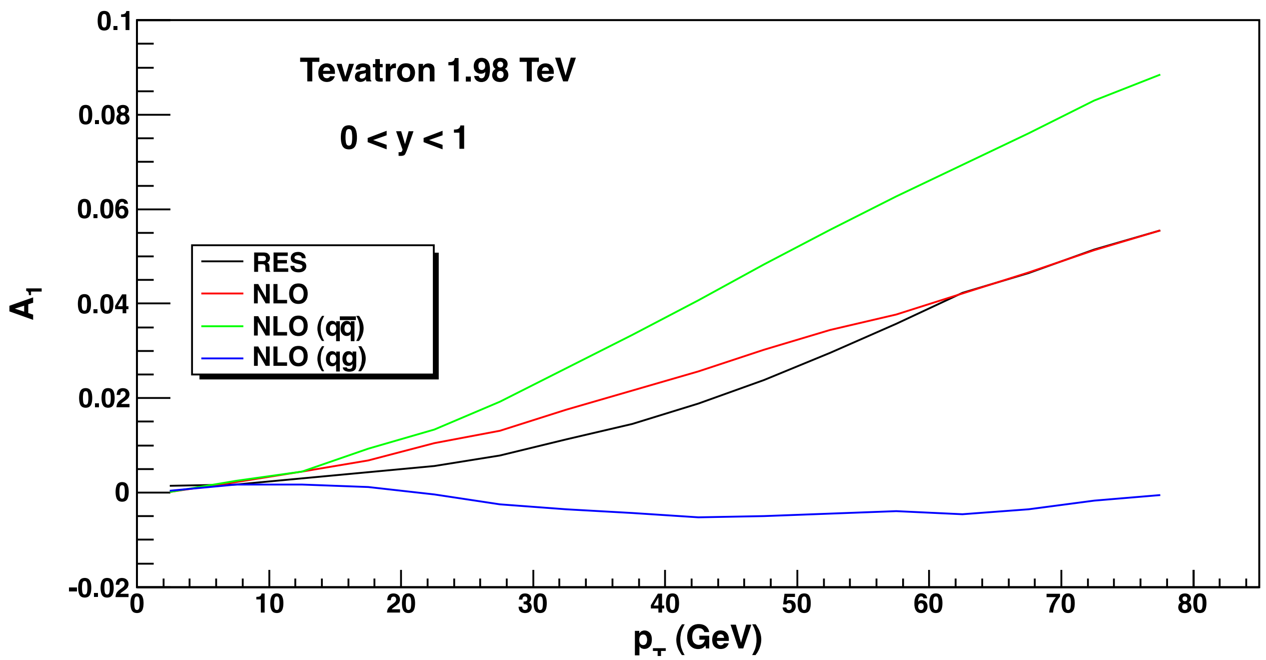
$$A_2 = A_0$$

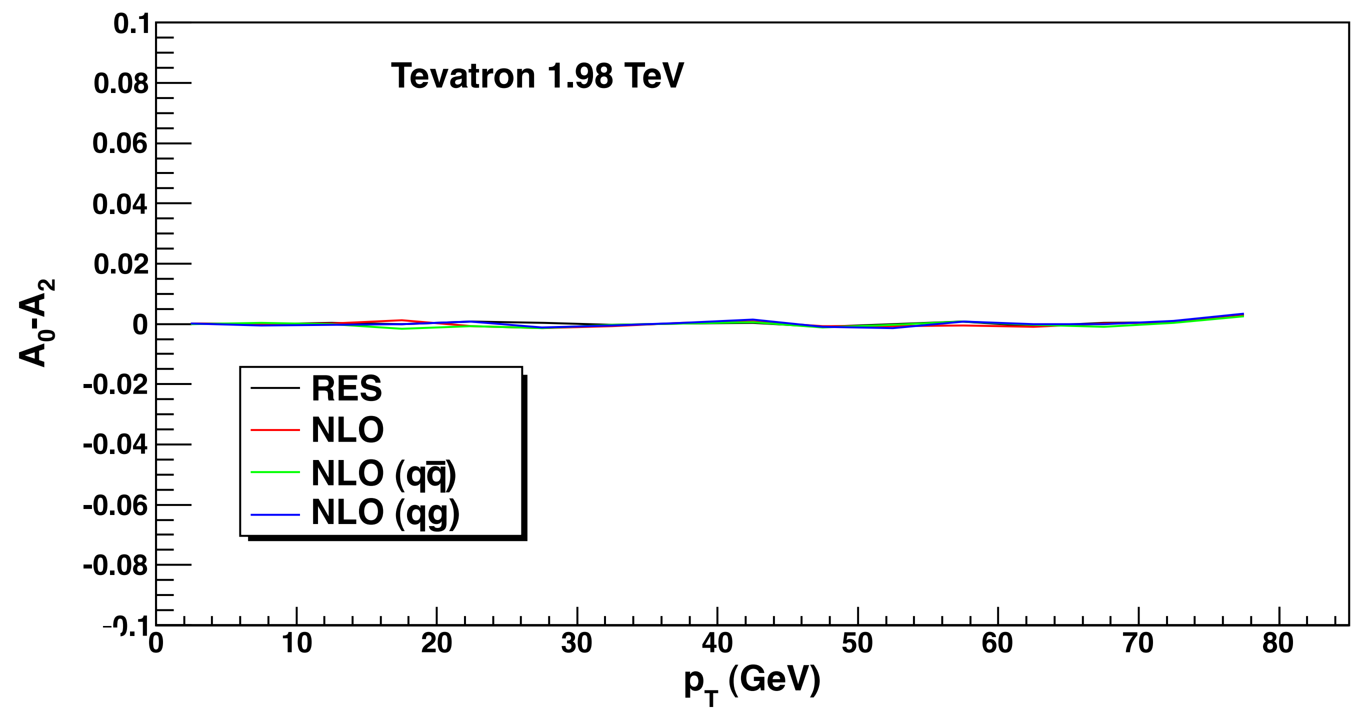
PHYSICAL REVIEW D **73,** 052001 (2006)

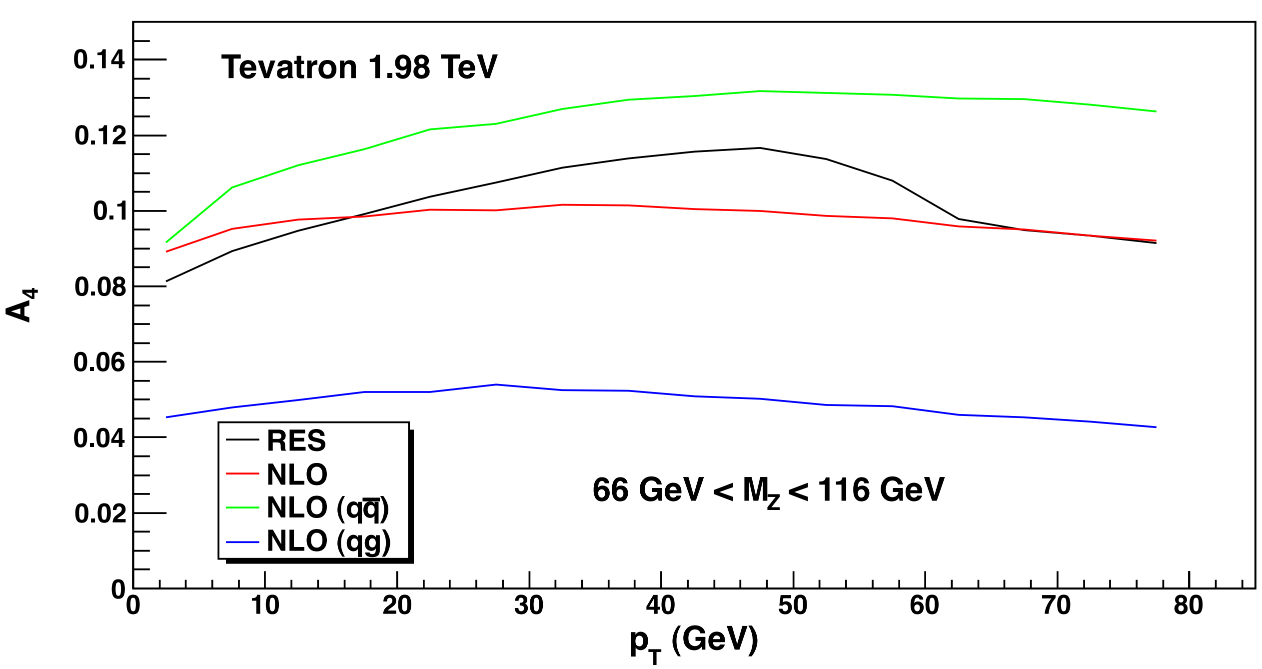
$$\frac{d\sigma}{dq_T^2\,dy\,d\cos\theta\,d\phi} = \frac{3}{16\pi}\frac{d\sigma^u}{dq_T^2\,dy}[(1+\cos^2\theta) + \tfrac{1}{2}A_0(1-3\cos^2\theta) + A_1\sin 2\theta\cos\phi + \tfrac{1}{2}A_2\sin^2\theta\cos 2\phi + A_3\sin\theta\cos\phi + A_4\cos\theta + A_5\sin^2\theta\sin 2\phi + A_6\sin 2\theta\sin\phi + A_7\sin\theta\sin\phi], \quad (1)$$





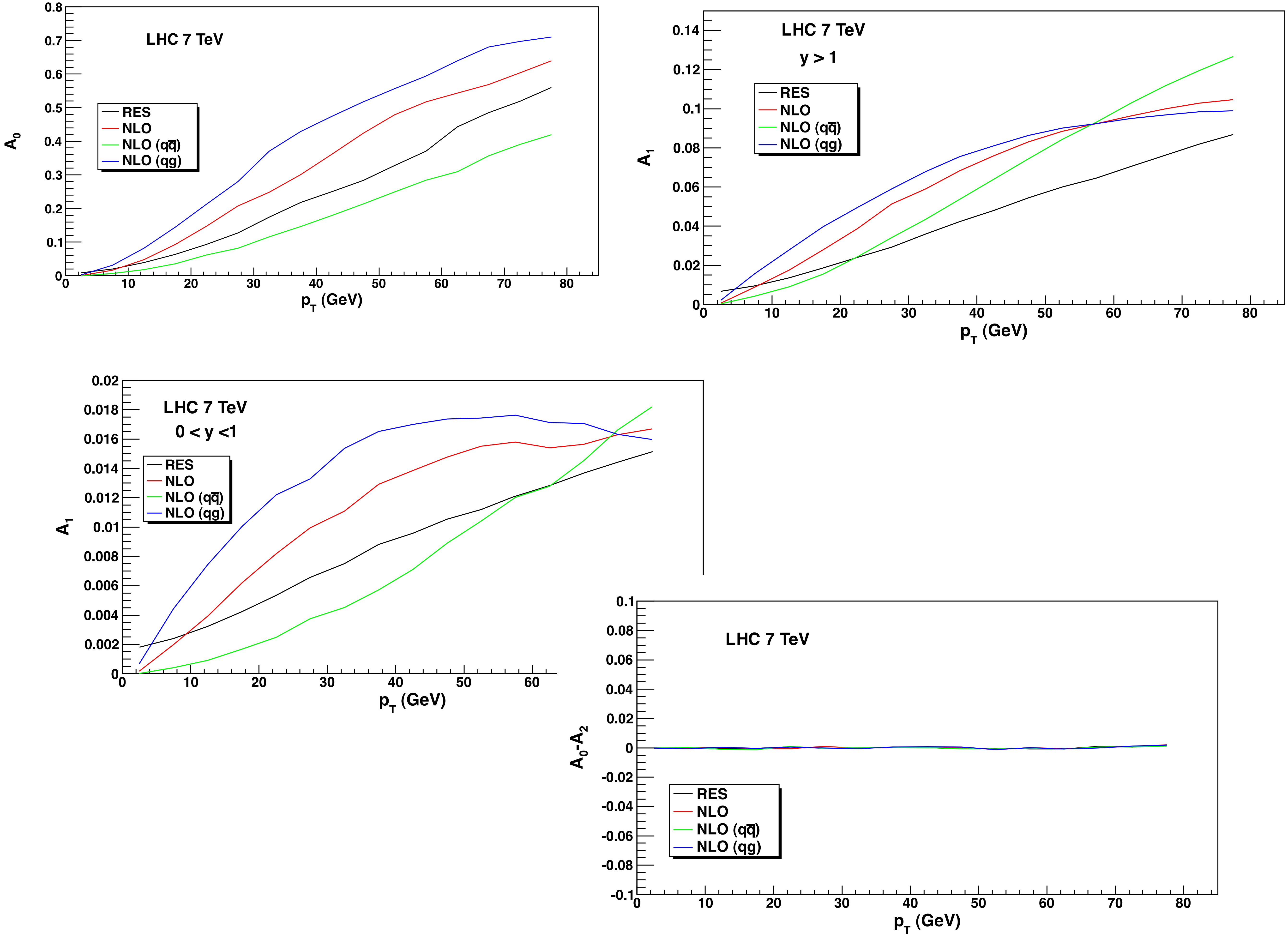






$$A_2 = A_0$$

Lam-Tung relation



LHC 7 TeV
A_0
p_T (GeV)
RES
NLO
NLO ($q\bar{q}$)
NLO (qg)
LHC 7 TeV
y > 1
A_1
p_T (GeV)
RES
NLO
NLO ($q\bar{q}$)
NLO (qg)
LHC 7 TeV
0 < y <1
A_1
p_T (GeV)
RES
NLO
NLO ($q\bar{q}$)
NLO (qg)
LHC 7 TeV
A_0-A_2
p_T (GeV)
RES
NLO
NLO ($q\bar{q}$)
NLO (qg)

Di-jet at Tevatron

- Large scale dependence
- PDF uncertainty

CT10 and CTEQ6.6 differ from MSTW
with larger uncertainty

D0 Di-jet Invariant Mass distributions

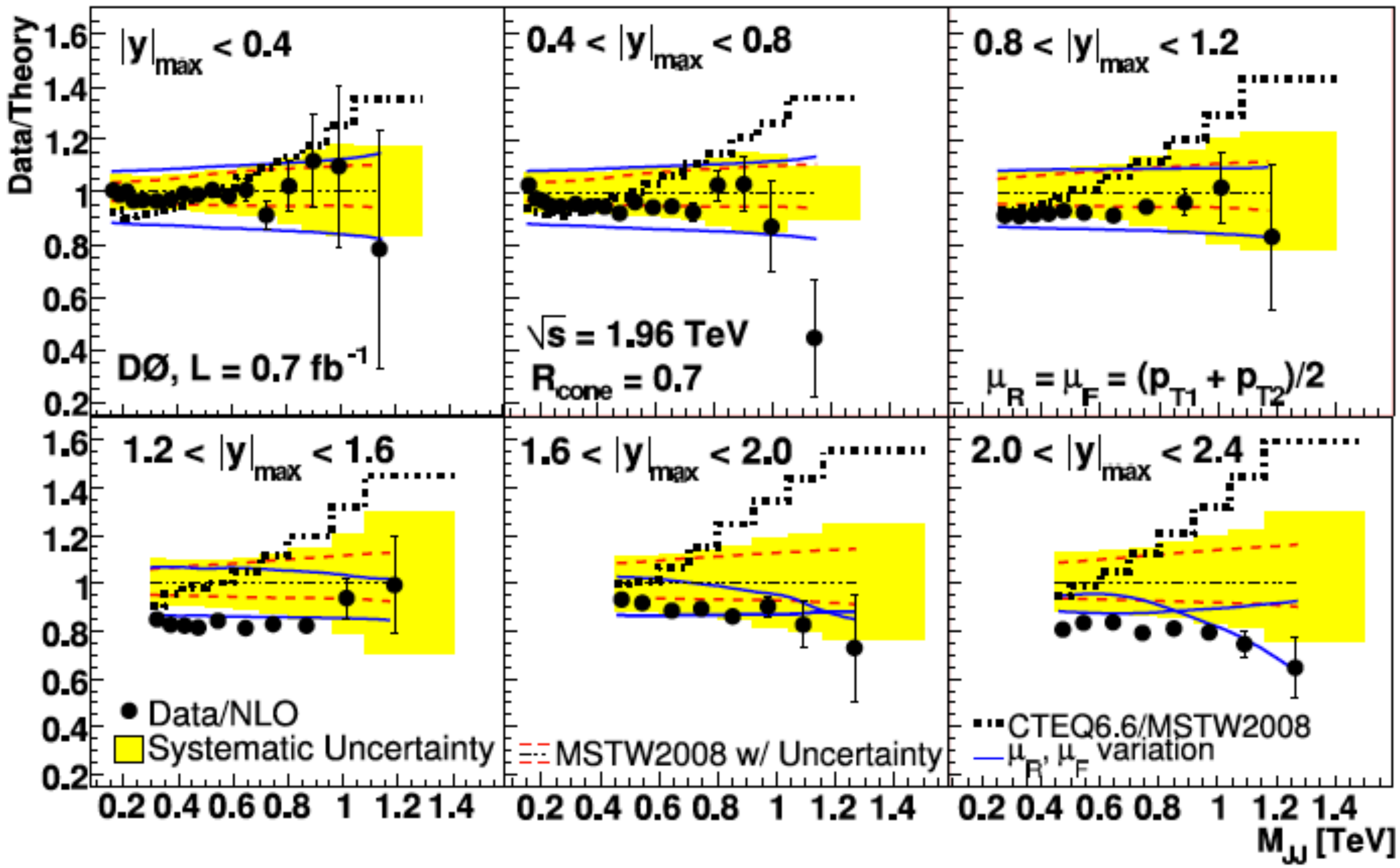
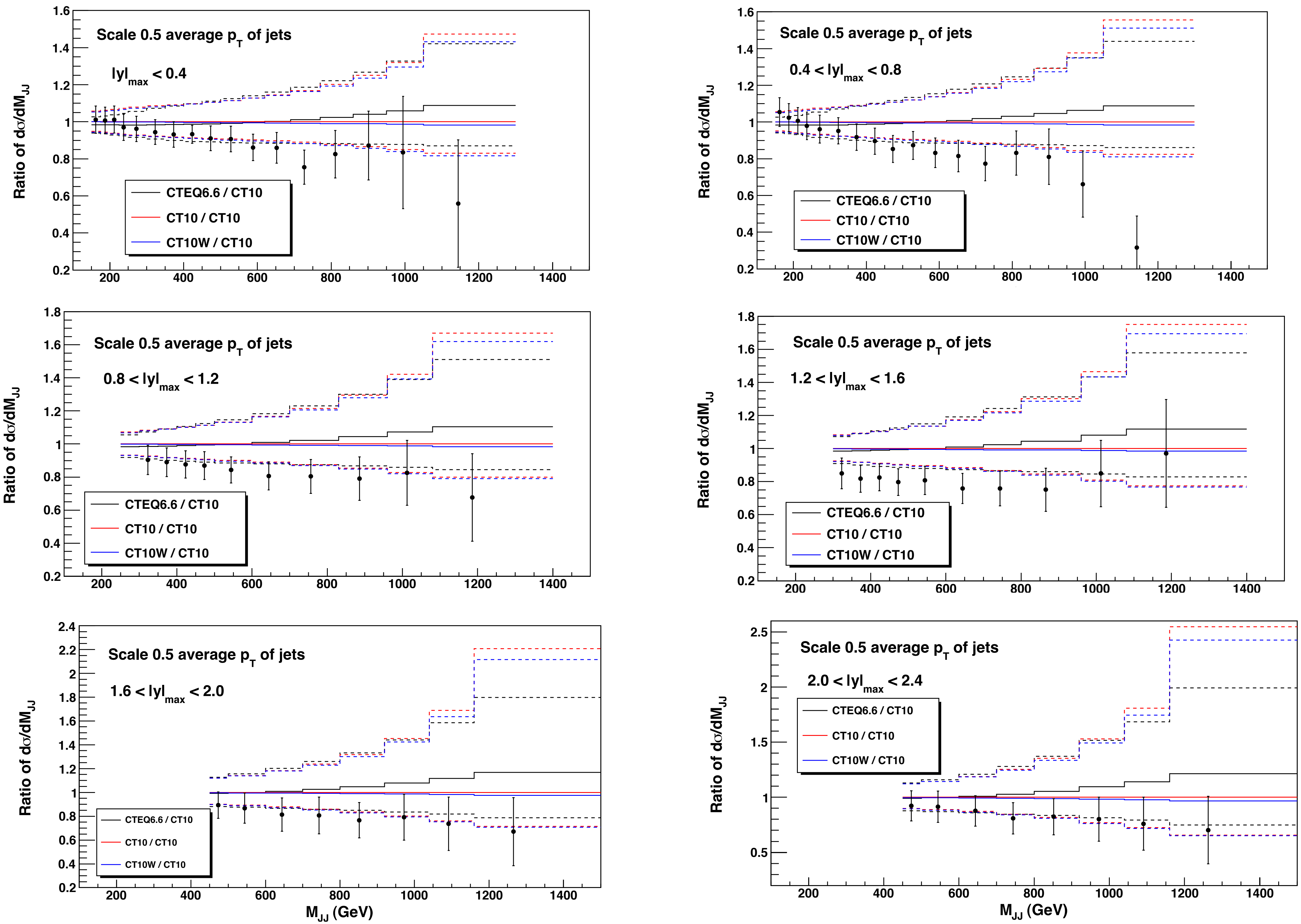


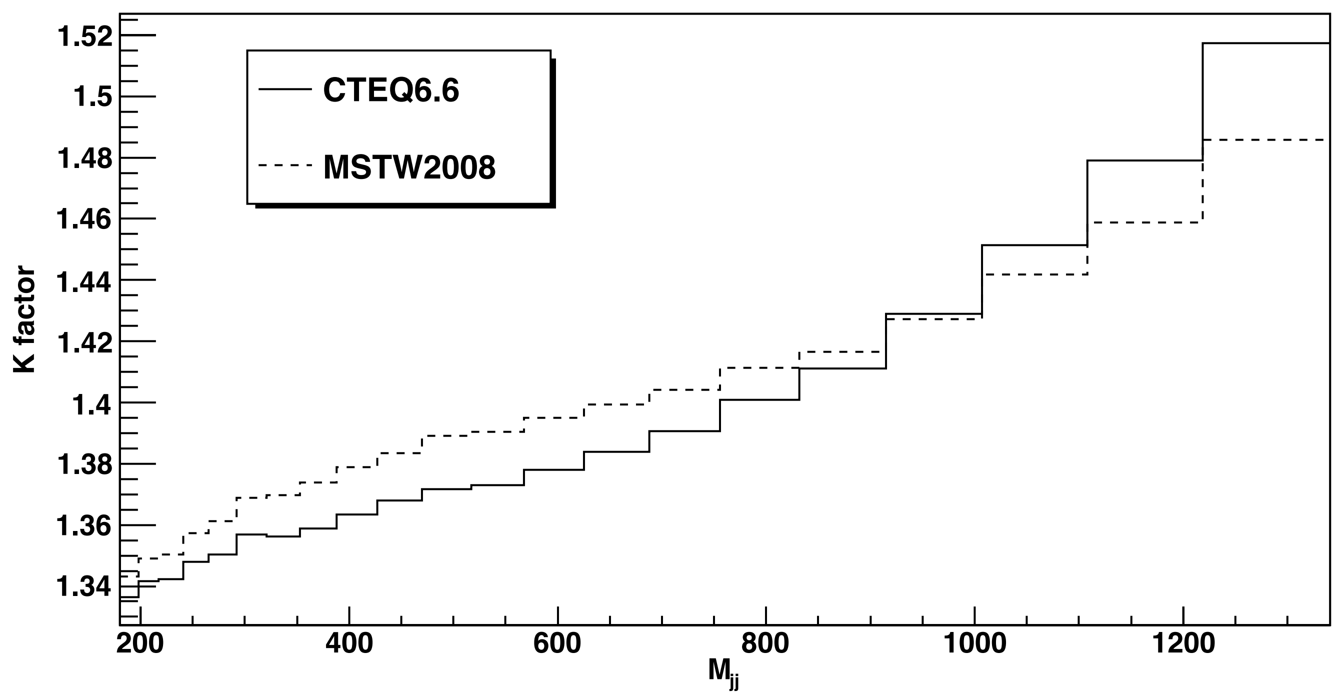
FIG. 2: (color online) Ratio of data over theoretical expectation using MSTW2008NLO PDFs in all six $|y|_{\max}$ bins. The measurement systematic uncertainty is shown as a shaded band. There is an additional fully correlated uncertainty of 6.1% due to the integrated luminosity determination which is not shown in the plots. The legend for all six plots shown is spread out over the three bottom plots with other relevant information in the top three plots.

D0 collaboration, arxiv: 1002.4594



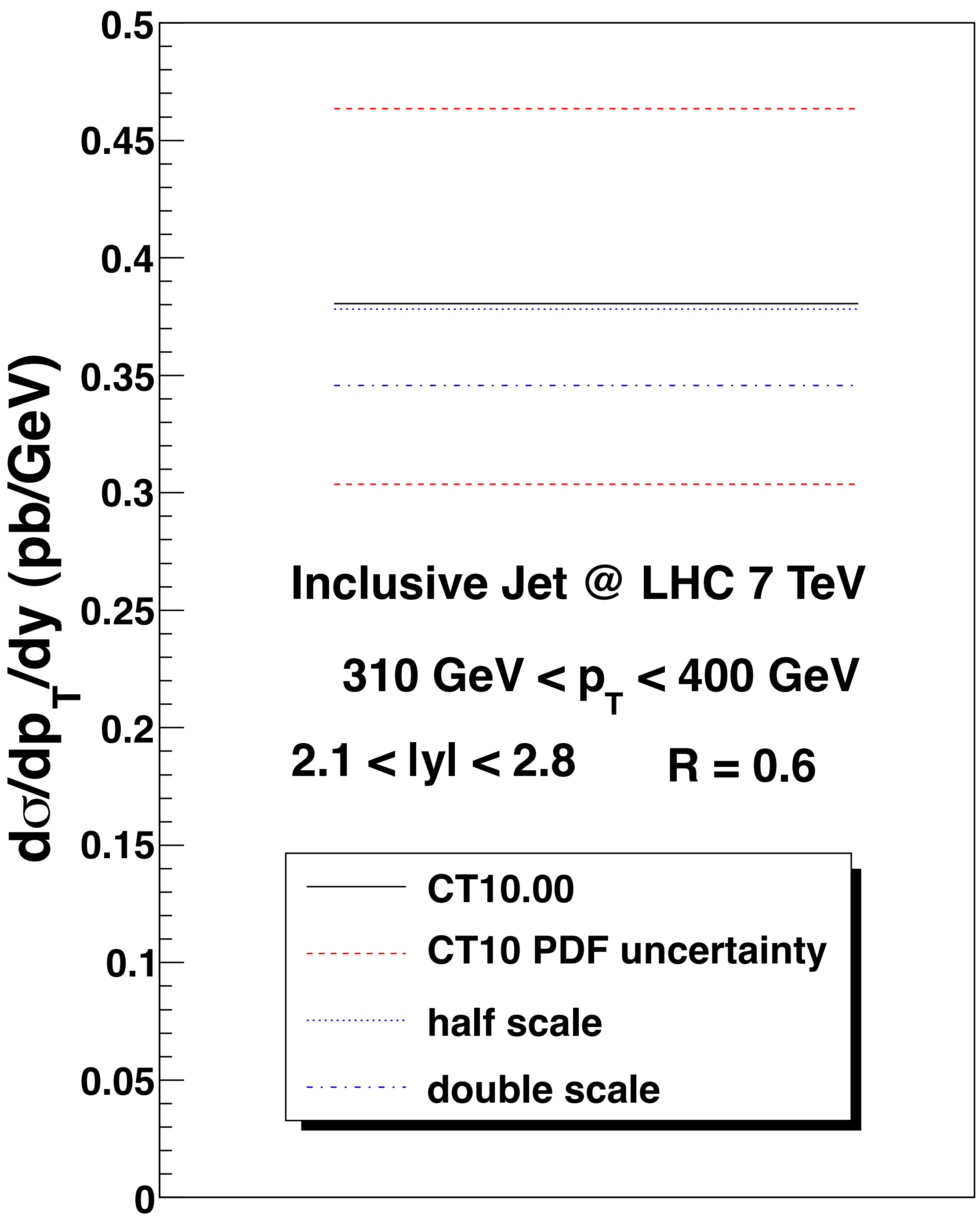
Setting scale as half average pT of jets makes CTEQ6.6 and CT10/W predictions more consistent with data. Also CT10/W improves the predictions with larger PDF uncertainties.

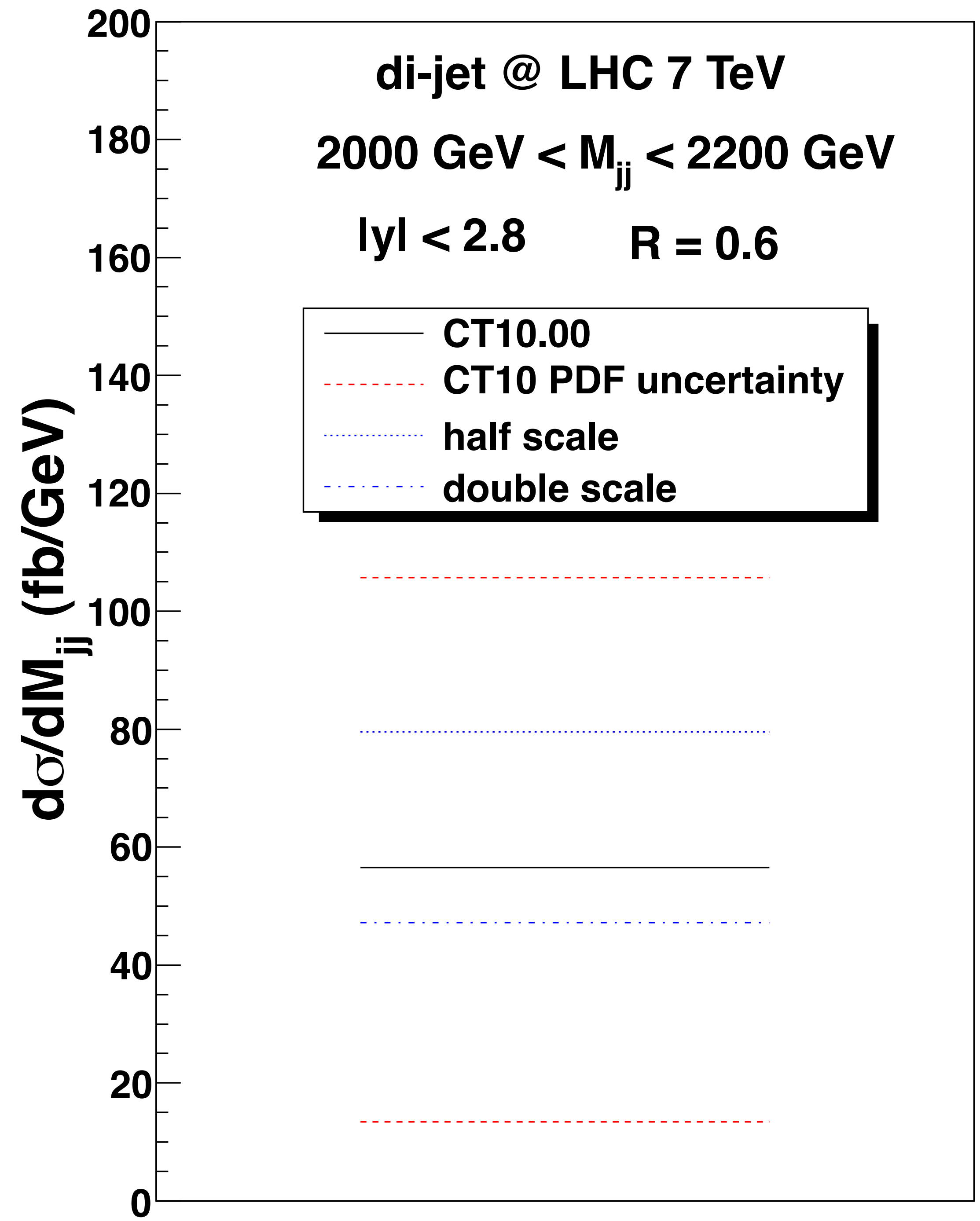
The NLO K factors for di-jet invariant mass distribution



The K factors are almost independent of PDF sets for Tevatron D0 di-jet data.

Theory uncertainties on jets @ LHC 7TeV



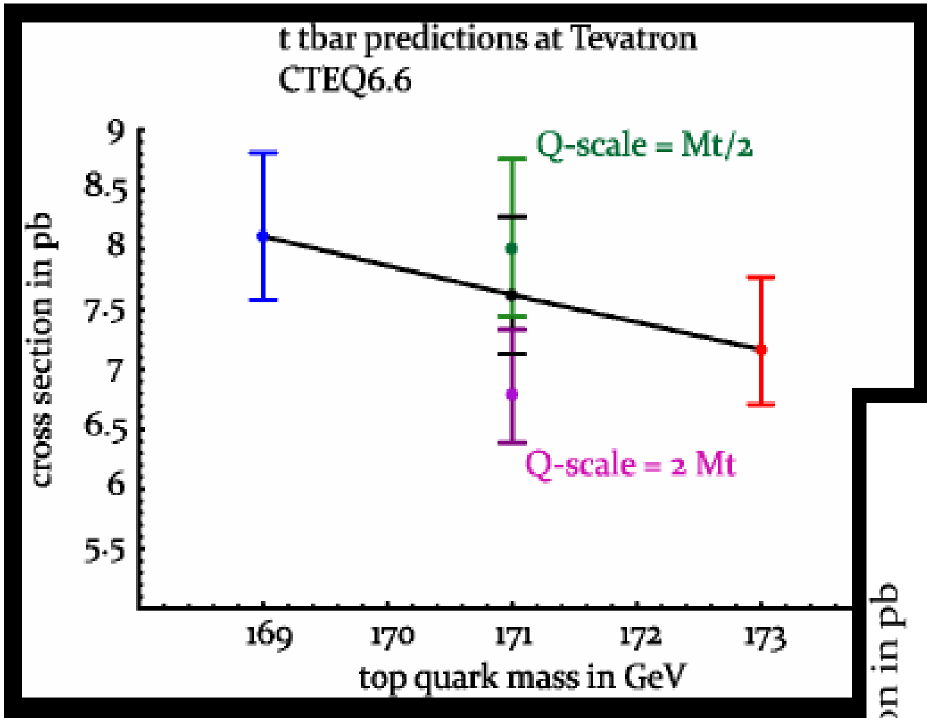


PDF uncertainty dominates.

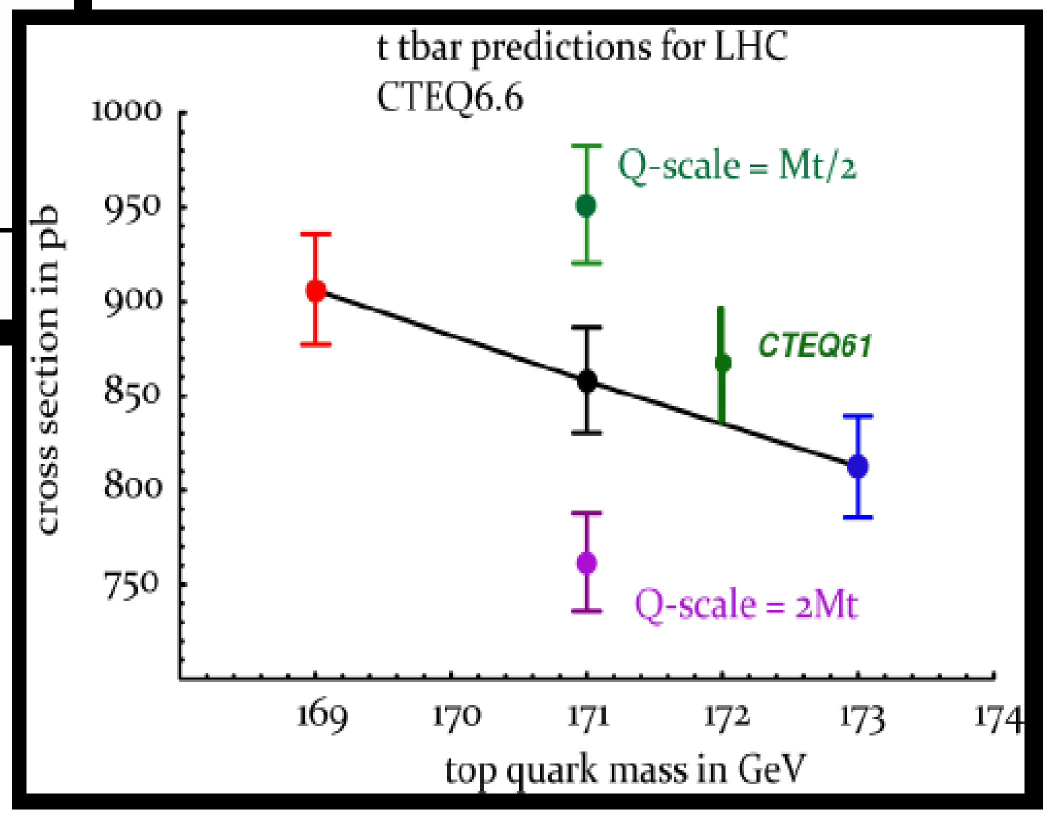
→ Can further constrain PDFs.

C T E Q

Top Quark Pair production rates



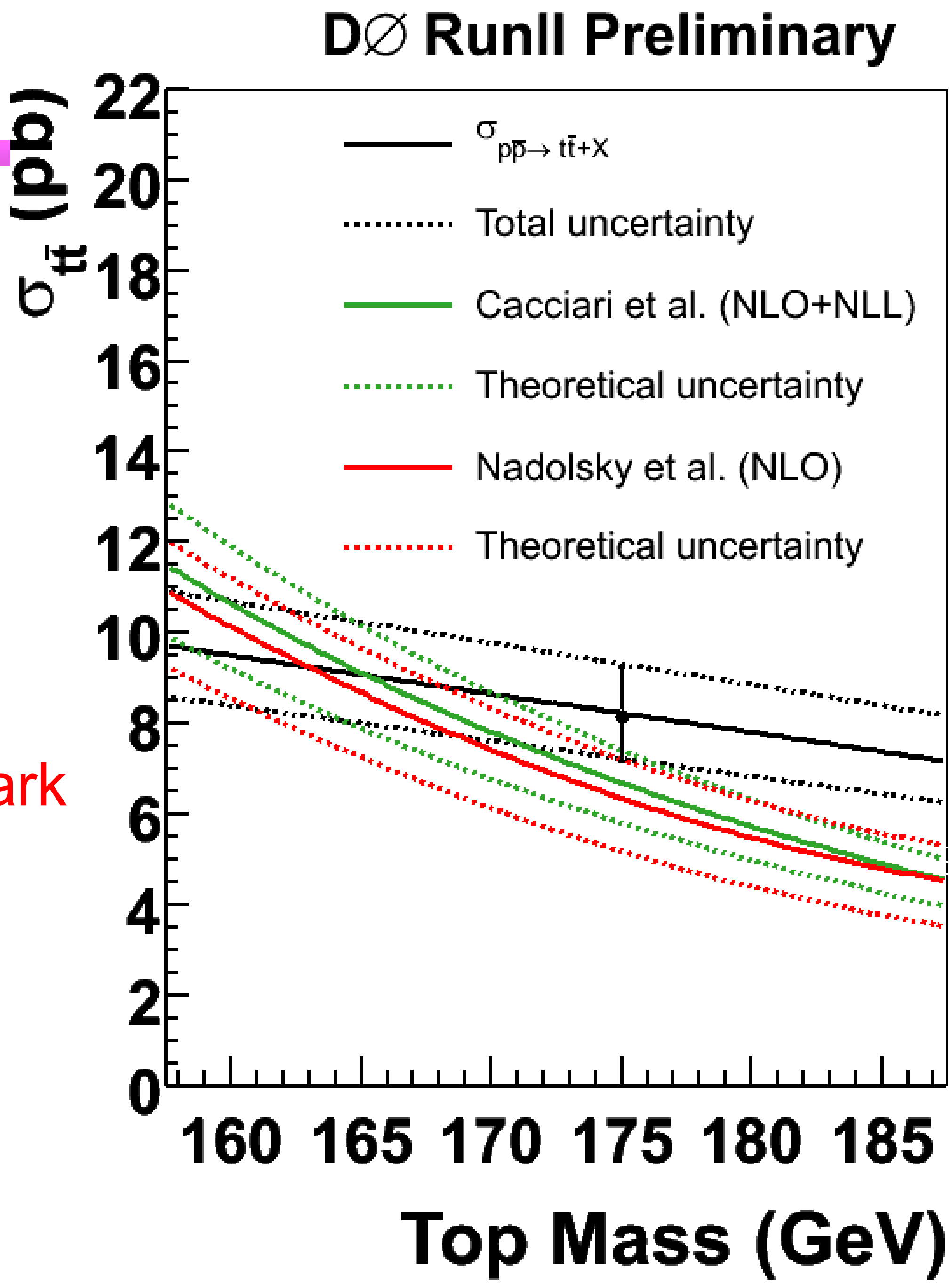
At Tevatron Run-2, uncertainty Incduced by PDFs is sizable.



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



CTEQ

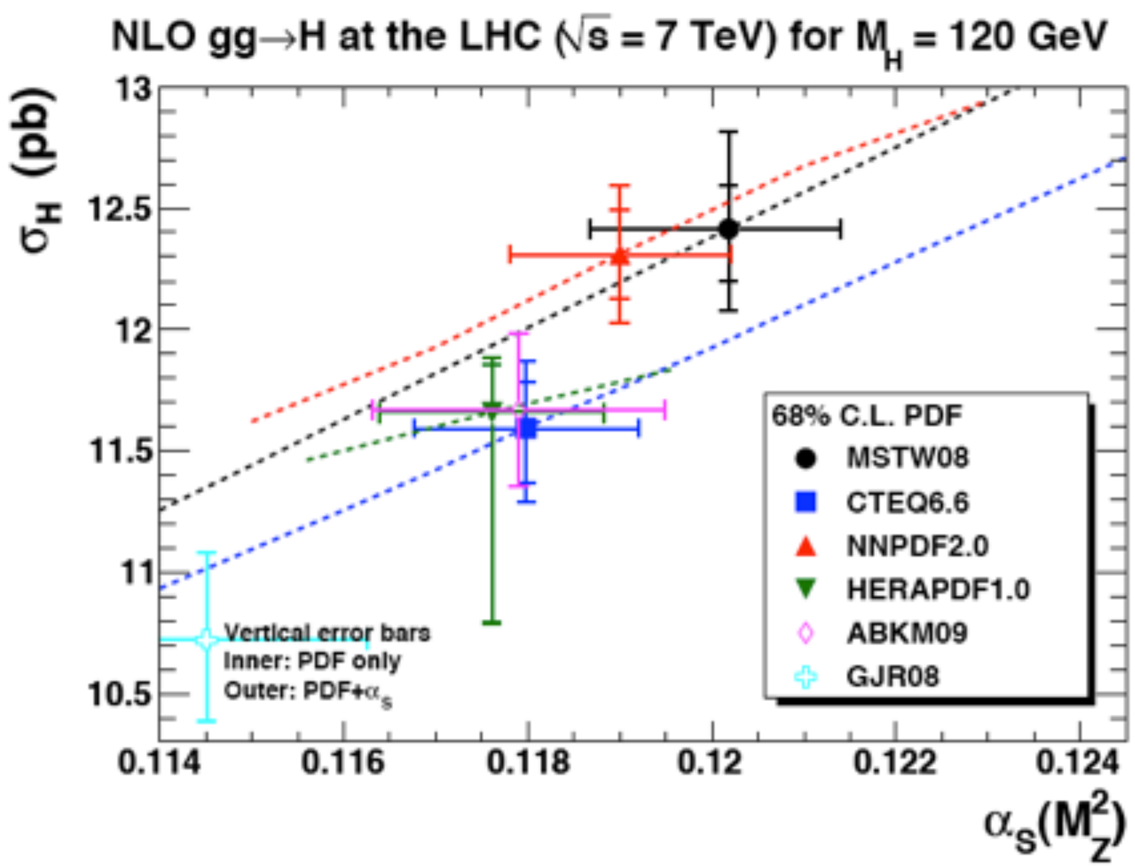
What’s top mass?

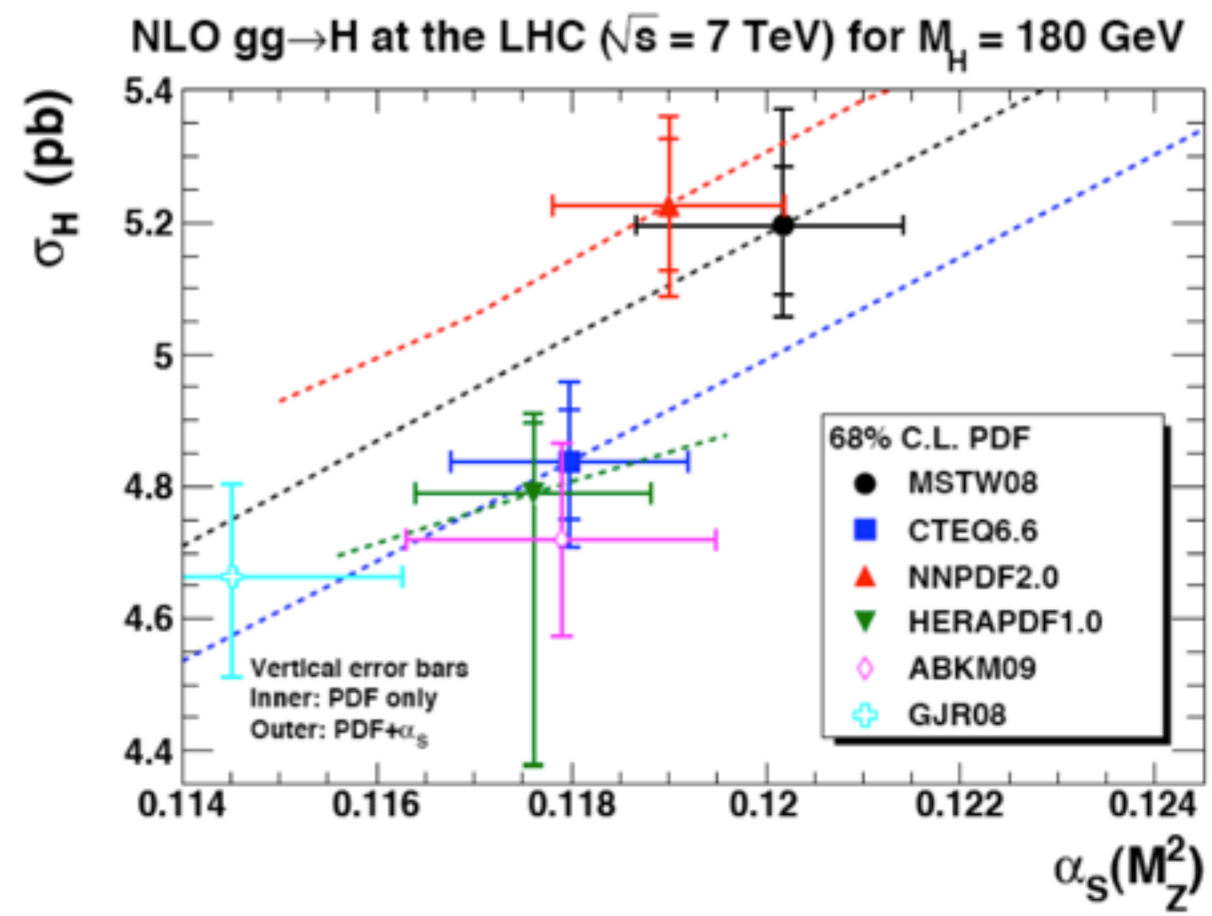
- What’s the top mass in a full event generator, such as PYTHIA?

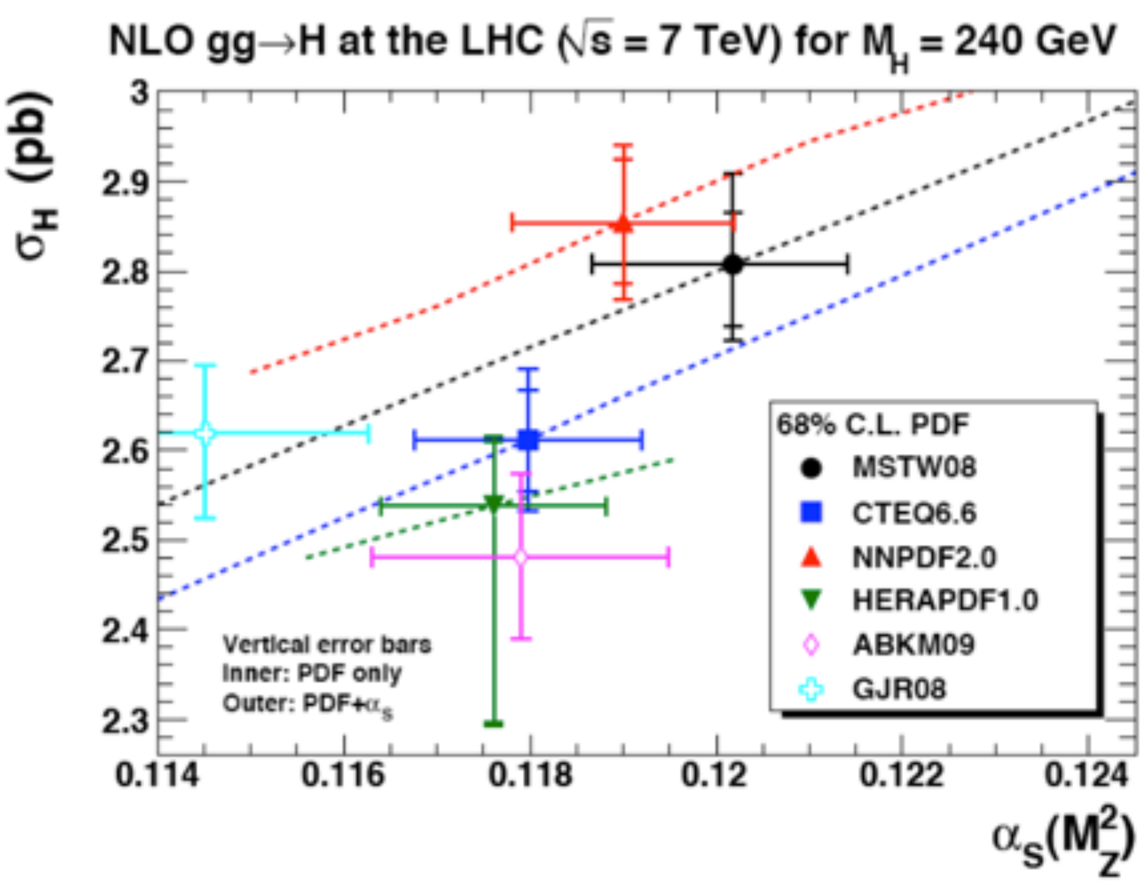
NOBODY KNOWS

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

Higgs predictions with different PDF sets







CT10 prediction is about the same as CTEQ6.6 for Higgs production @LHC 7 TeV

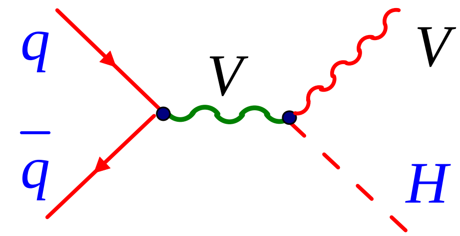
This is an exciting era for High Energy Physics

Thank You!

Backup Slides

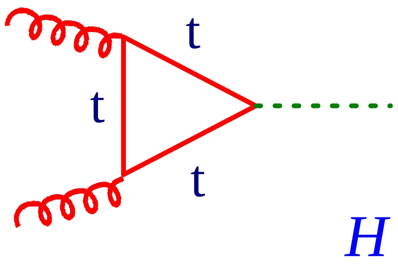
ResBos for Higgs Physics

Quark initiated processes:

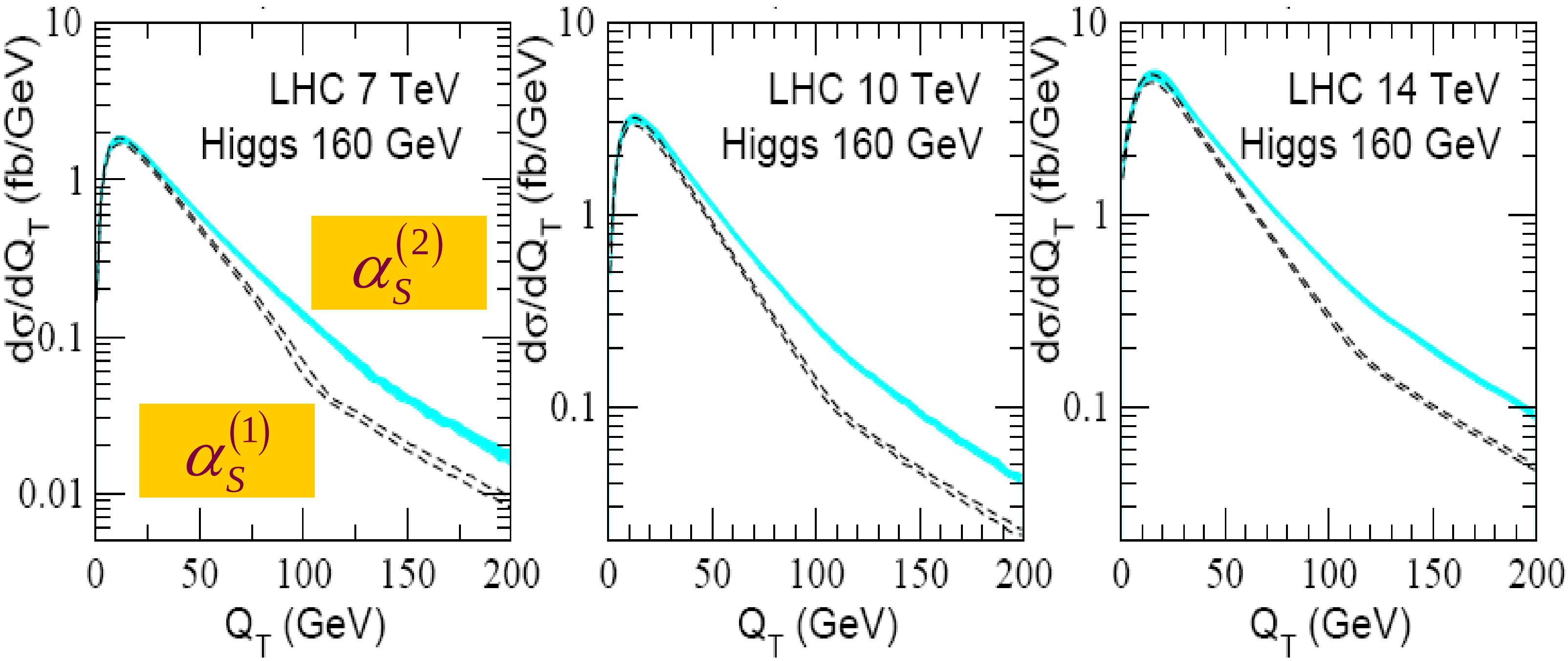


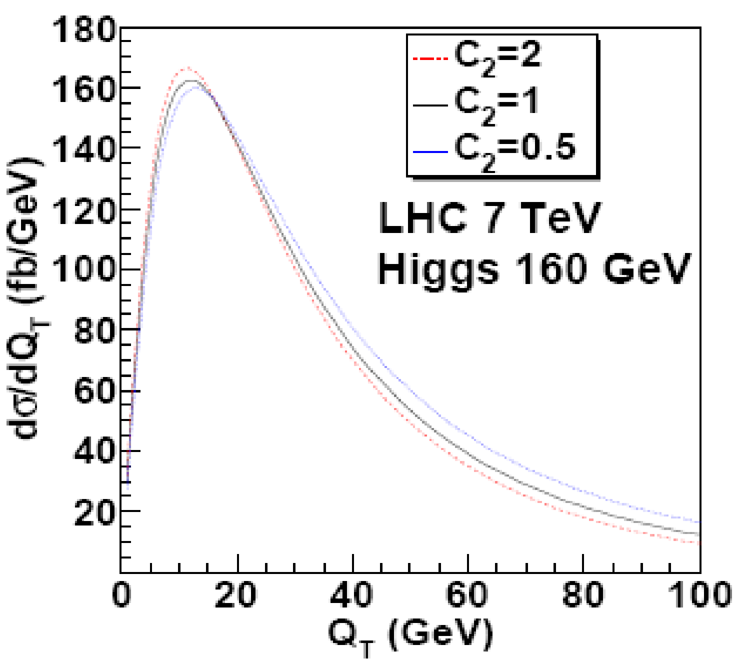
- Rate and shape:
  - at the same order of accuracy as Drell-Yan processes

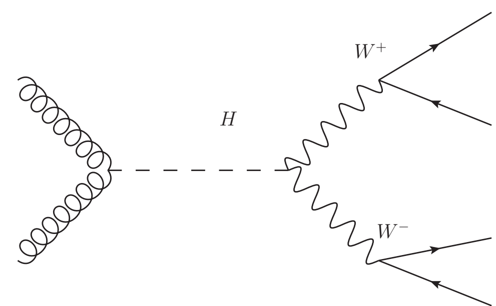
Gluon initiated processes:



- Rate and shape:
  - at the same order of accuracy as Drell-Yan processes
  - consistent with NNLO QCD rate
  - include exact $\alpha_S^{(2)}$ contribution in high P_T







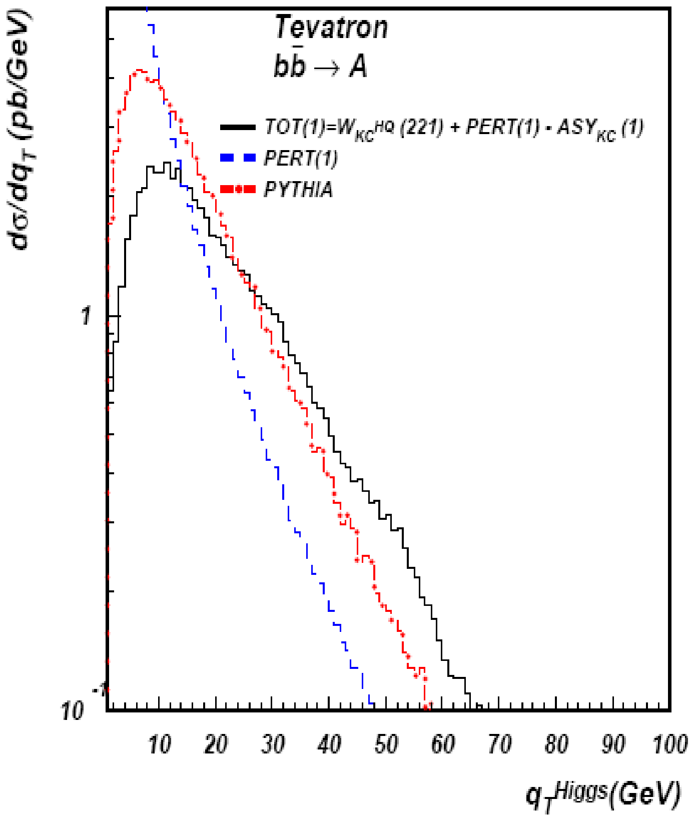
arXiv:0909.2305

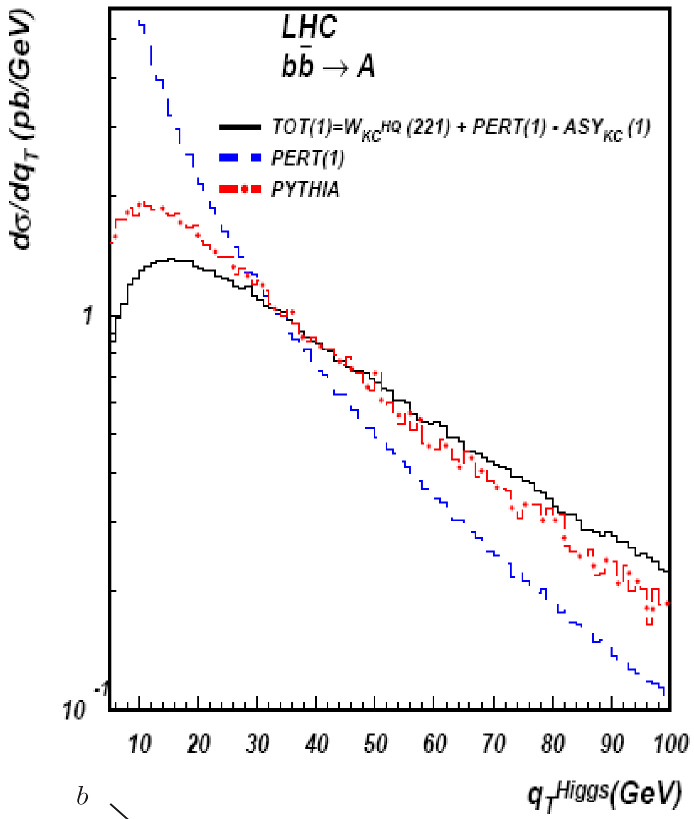
Shape changes from $\alpha_S^{(2)}$
and variation of scales

Predict different shape

ResBos vs PYTHIA vs NLO

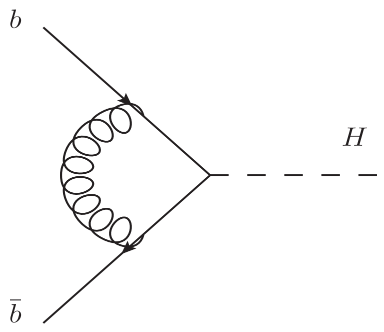
hep-ph/0509100





Consistent treatment of initial state parton mass with CTEQ6.6 PDFs, in GM scheme.

(see Sally Dawson's talk)



MSSM Higgs boson

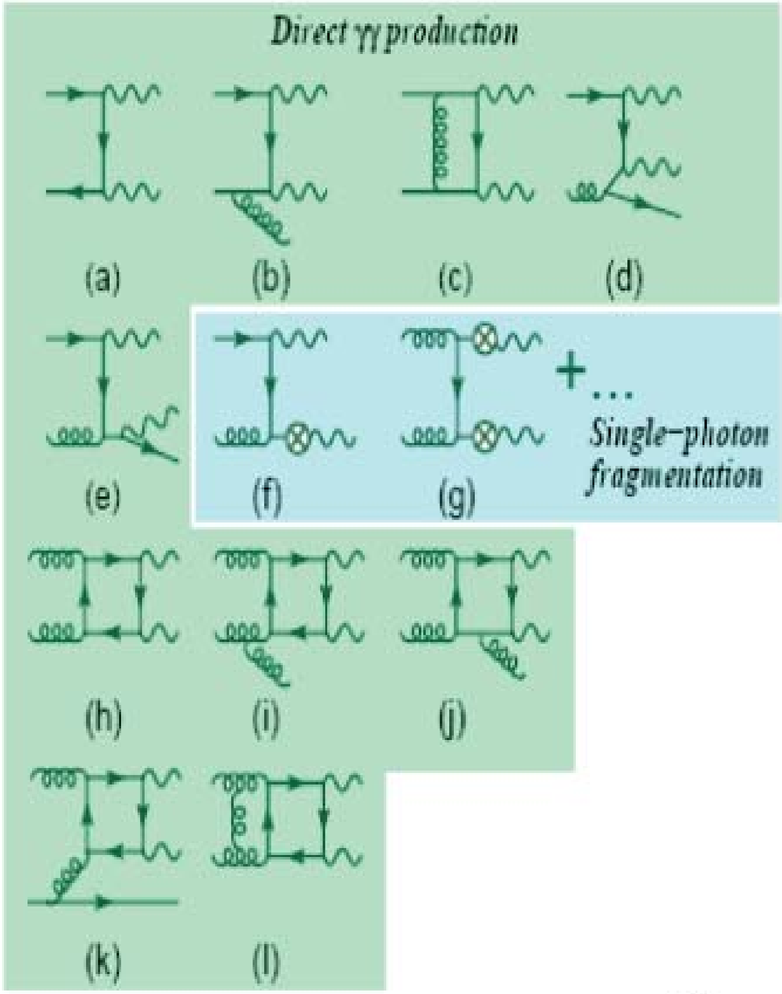
Di-Photon Productions

Theoretical predictions

PYTHIA
- qq→γγ and gg→γγ matrix elements.
- All-orders resummation to LL accuracy via parton shower.
- No fragmentation contributions included.

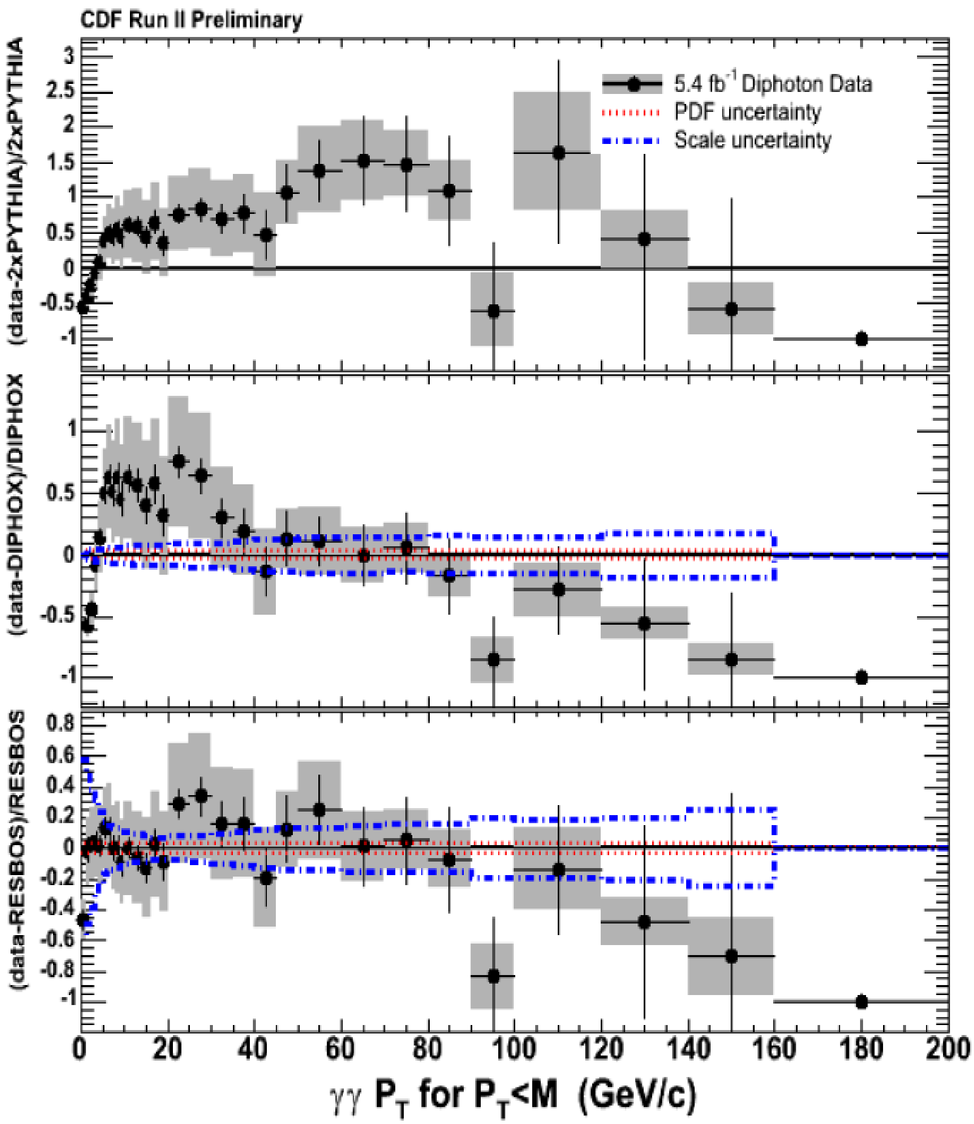
DIPHOX *Eur. Phys. J. C 16, 311 (2000)*
- Fixed-order NLO calculation (except for gg→γγ, which is at LO)
- No resummation:
  → usually avoid divergence by requiring asymmetric $p_{T\gamma 1}-p_{T\gamma 2}>0$.
- Single-photon fragmentation (to NLO) included.

RESBOS *PRD 76, 013009 (2007)*
- All-orders resummation (to NNLL accuracy) matched to NLO.
- Single-photon fragmentation included via parameterization that approximates rate predicted by NLO fragmentation functions.



Compare to CDF Run-2 di-Photon data

Costas Vellidis
Pheno2010

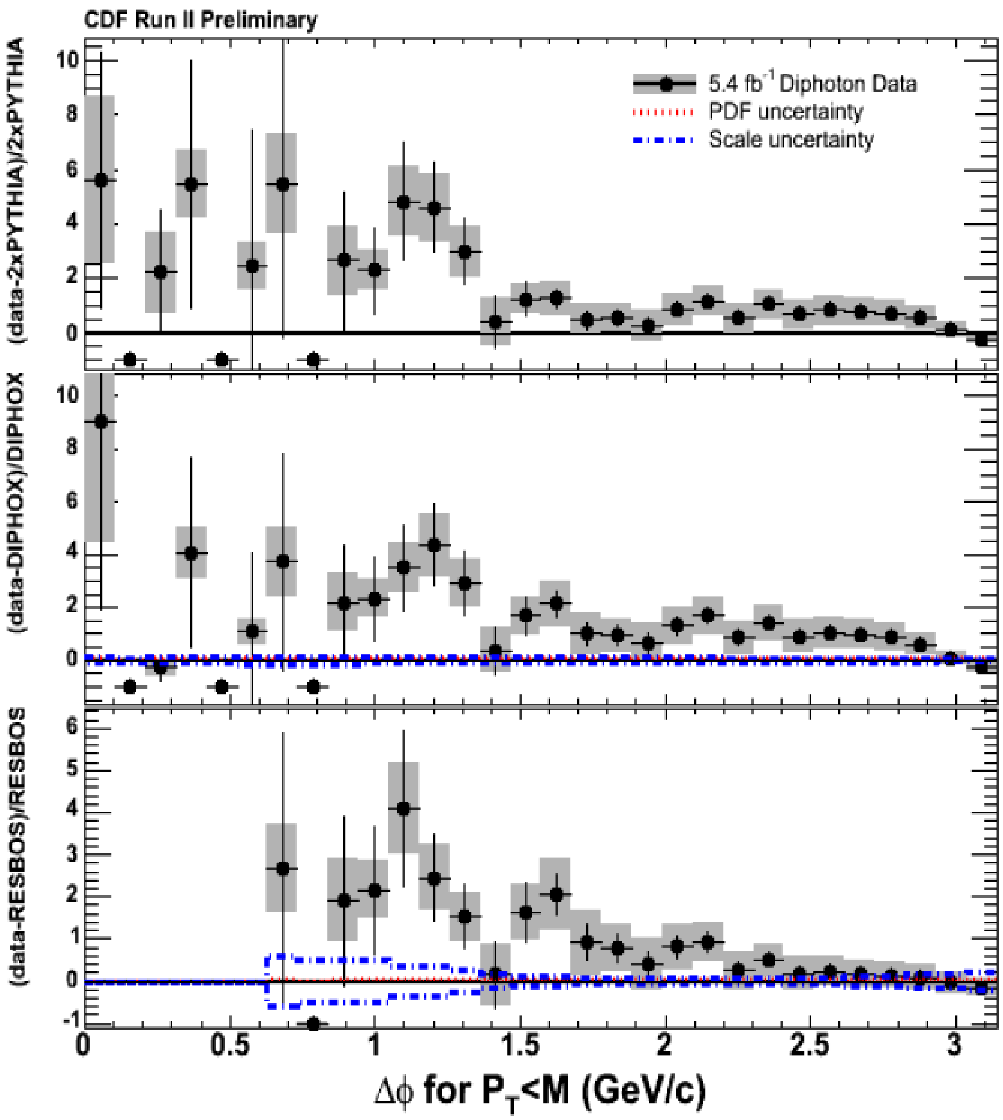


The cut
$P_T < M$
is to suppress
fragmentation
contribution

(Data – theory)/theory vs. the diphoton transverse momentum for Higgs – like kinematics

Compare to CDF Run-2 di-Photon data

Costas Vellidis
Pheno2010

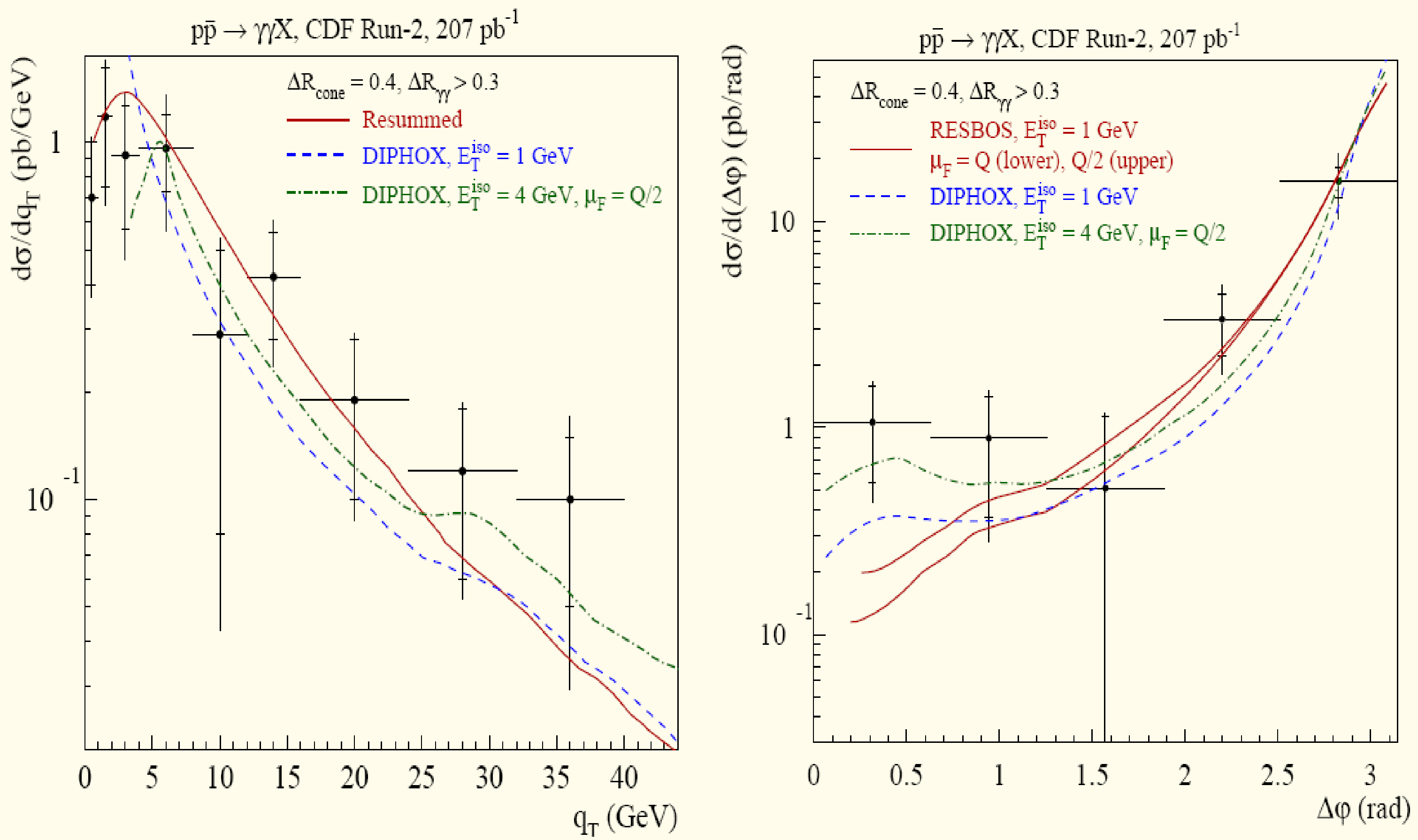


The cut
$P_T < M$
is to suppress
fragmentation
contribution

(Data – theory)/theory vs. the diphoton azimuthal distance for Higgs – like kinematics

Large theoretical uncertainty in fragmentation contribution

arXiv:0704.0001



- Theoretical uncertainties are large in the region $Q \lesssim 25$ GeV, $Q_T \gtrsim 27$ GeV, $\Delta\varphi < \pi/2$, not relevant for the LHC Higgs searches; uncertainties are suppressed by a $Q_T \leq Q$ cut

Backup slides

Details of the CTEQ6.6FAS analysis

- Take the "world-average" $\alpha_s(M_Z) = 0.118 \pm 0.002$ as an **input**:

$$\alpha_s(M_Z)|_{\text{in}} = 0.118 \pm 0.002 \text{ at } 90\% \text{ C.L.}$$

- Find the theory parameter $\alpha_s(M_Z)$ as an **output** of a global fit (CTEQ6.6FAS):

$$\alpha_s(M_Z)|_{\text{out}} = 0.118 \pm 0.0019 \text{ at } 90\% \text{ C.L.}$$

- The combined PDF+α_s uncertainty is estimated as

$$\Delta X = \frac{1}{2}\sqrt{\sum_{i=1}^{22+1}\left(X_i^{(+)} - X_i^{(-)}\right)^2}$$

- **Problem:** each PDF set comes with its own $\alpha_s \Rightarrow$ cumbersome
- **A simple workaround exists!**

A quadrature sum reproduces the α_s-PDF correlation

H.-L. Lai, J. Pumplin

Theorem

In the quadratic approximation, the total α_s+PDF uncertainty $\Delta\sigma$ of the CTEQ6.6FAS set, with all correlation, reduces to

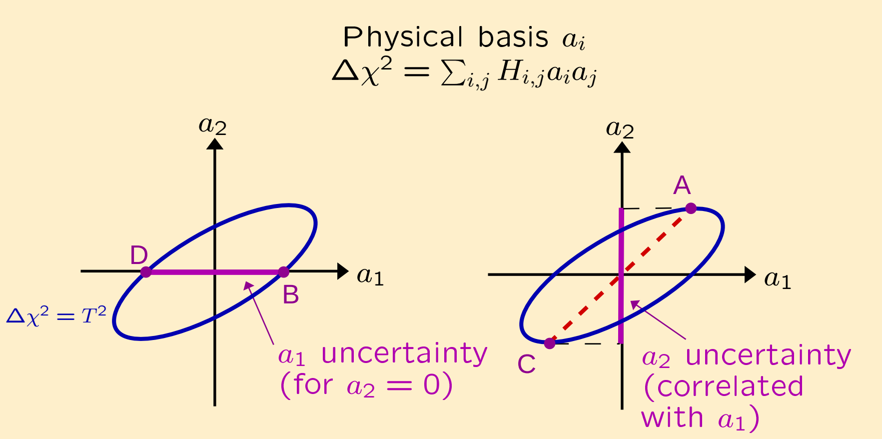
$$\Delta X = \sqrt{\Delta X^2_{CTEQ6.6} + \Delta X^2_{\alpha_s}},$$

where

- $\Delta X_{CTEQ6.6}$ *is the CTEQ6.6 PDF uncertainty from 44 PDFs with the same* $\alpha_s(M_Z) = 0.118$
- $\Delta X_{\alpha_s} = (X_{0.120} - X_{0.116})/2$ *is the* α_s *uncertainty computed with two central CTEQ6.6AS PDFs for* $\alpha_s(M_Z) = 0.116$ *and* 0.120

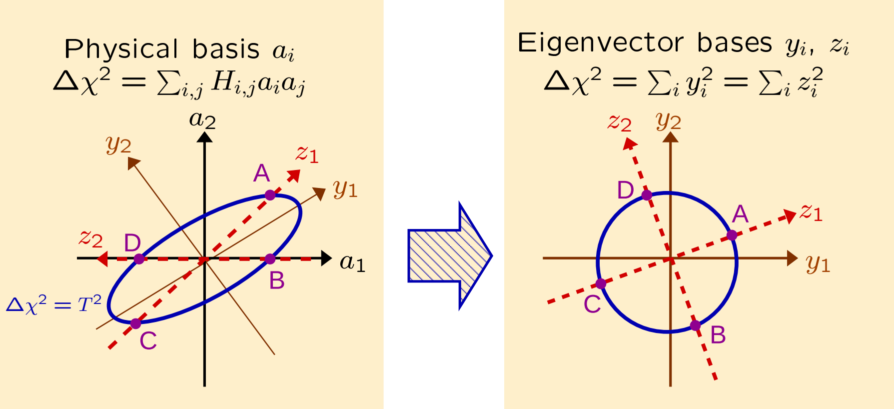
The full proof is given in the paper; the main idea is illustrated for 1 PDF parameter a_1 and α_s parameter a_2

Illustration of the theorem for 2 parameters



$$\Delta X_1^2 = \frac{1}{4}\left(X(B) - X(D)\right)^2 \qquad \Delta X_2^2 = \frac{1}{4}\left(X(A) - X(C)\right)^2$$

Illustration of the theorem for 2 parameters, cont.



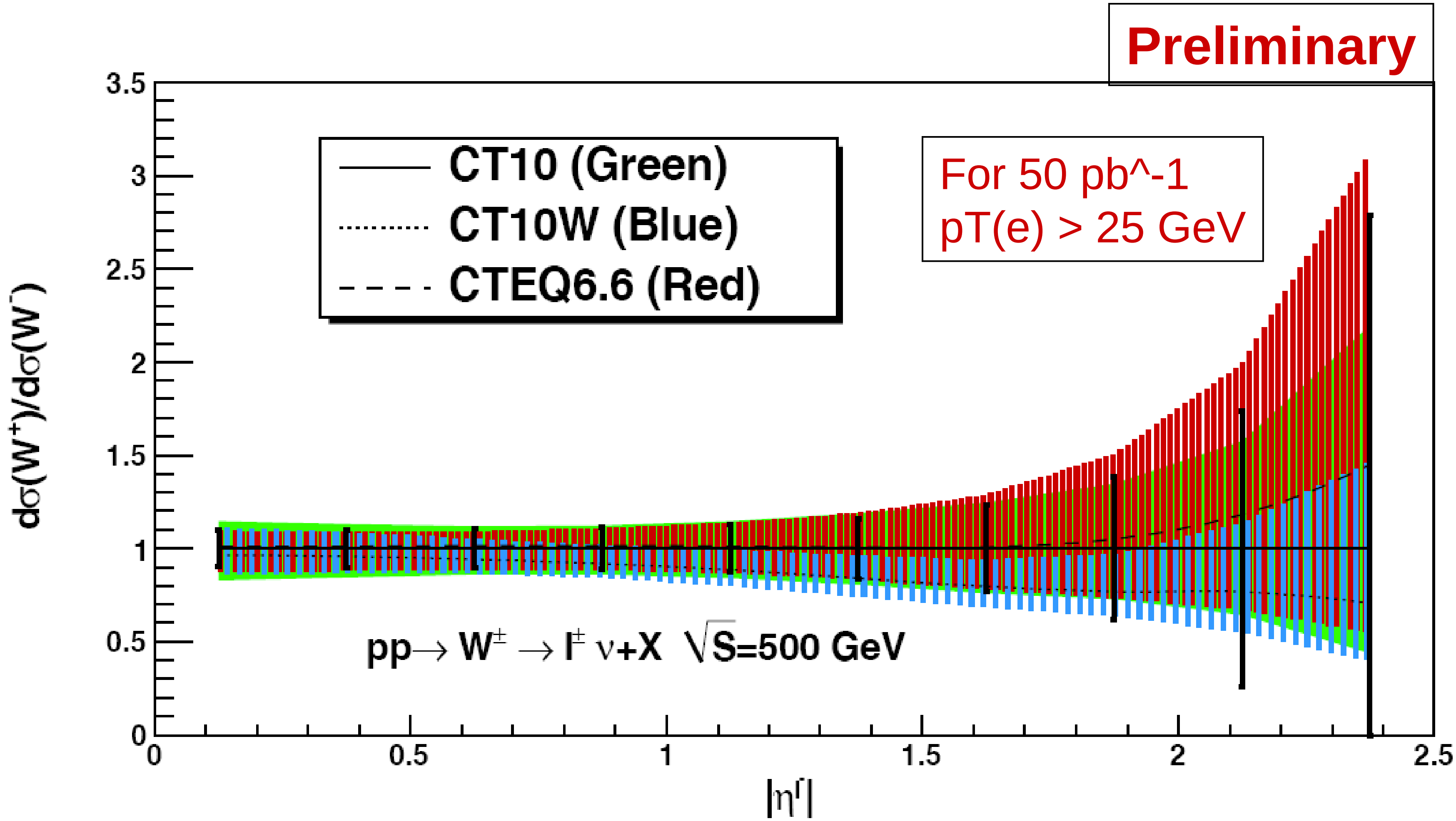
$$\Delta X^2 = \frac{1}{4}\left[\left(X(A) - X(C)\right)^2 + \left(X(B) - X(D)\right)^2\right]$$
$$= \Delta X_1^2 + \Delta X_2^2$$

Full and reduced fits with variable α_s: cross sections

Process	CTEQ6.6+CTEQ6.6AS				CTEQ6.6FAS
$t\bar{t}$ (171 GeV)	σ_0	$\Delta\sigma_{PDF}$	$\Delta\sigma_{\alpha_S}$	$\Delta\sigma$	$\sigma_0 \pm \Delta\sigma$
LHC 7 TeV	157.41	10.97	7.54	13.31	160.10 ± 13.93
LHC 10 TeV	396.50	18.75	16.10	24.71	400.48 ± 25.74
LHC 14 TeV	877.19	28.79	30.78	42.15	881.62 ± 44.27
$gg \to H$ (120 GeV)	σ_0	$\Delta\sigma_{PDF}$	$\Delta\sigma_{\alpha_S}$	$\Delta\sigma$	$\sigma_0 \pm \Delta\sigma$
Tevatron 1.96 TeV	0.63	0.042	0.032	0.053	0.64 ± 0.055
LHC 7 TeV	10.70	0.31	0.32	0.45	10.70 ± 0.48
LHC 10 TeV	20.33	0.66	0.56	0.87	20.28 ± 0.93
LHC 14 TeV	35.75	1.31	0.94	1.61	35.63 ± 1.70
$gg \to H$ (160 GeV)	σ_0	$\Delta\sigma_{PDF}$	$\Delta\sigma_{\alpha_S}$	$\Delta\sigma$	$\sigma_0 \pm \Delta\sigma$
Tevatron 1.96 TeV	0.26	0.026	0.015	0.030	0.26 ± 0.031
LHC 7 TeV	5.86	0.16	0.18	0.24	5.88 ± 0.26
LHC 10 TeV	11.73	0.33	0.33	0.47	11.72 ± 0.50
LHC 14 TeV	21.48	0.68	0.56	0.88	21.43 ± 0.94
$gg \to H$ (250 GeV)	σ_0	$\Delta\sigma_{PDF}$	$\Delta\sigma_{\alpha_S}$	$\Delta\sigma$	$\sigma_0 \pm \Delta\sigma$
Tevatron 1.96 TeV	0.055	0.0099	0.0044	0.011	0.058 ± 0.012
LHC 7 TeV	2.30	0.085	0.081	0.12	2.32 ± 0.12
LHC 10 TeV	5.08	0.14	0.15	0.21	5.10 ± 0.22
LHC 14 TeV	10.03	0.26	0.27	0.37	10.04 ± 0.41

The full (CTEQ6.6FAS) and reduced (CTEQ6.6+CTEQ6.6AS) methods perfectly agree

W Physics at RHIC



$$R = \frac{d\sigma(W^+)/d\eta^e}{d\sigma(W^-)/d\eta^e}$$

for CT10/CTEQ6.6M, etc