Small-x and heavy flavor effects in Z/W/H production at Tevatron and LHC

Small x: S. B., P. Nadolsky, F. Olness, C.-P. Yuan, hep-ph/0410375
Heavy flavor: S. B., P. Nadolsky, F. Olness (paper in preparation)

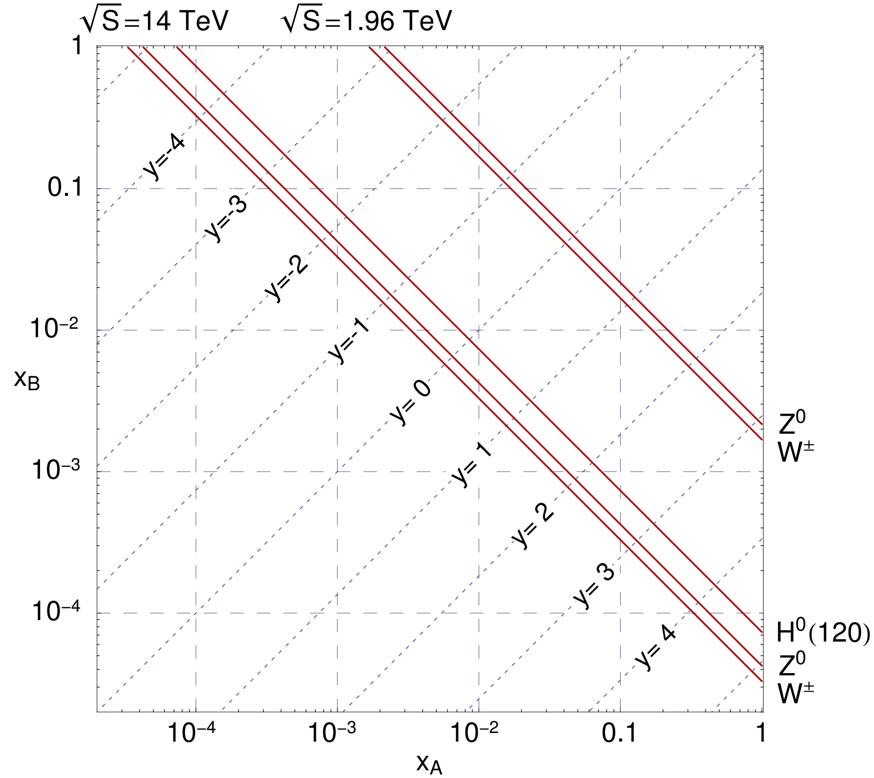
Stefan Berge, SMU, Dallas, TX
TeV4LHC, 29 April '05, CERN

1. Introduction
2. Small-x effects in W/Z/H production
3. Heavy Flavor effects in W/Z/H production
4. Conclusion

Small-x grid files for W and Z^0 boson production at Tevatron Run II can be downloaded from:
http://hep.pa.msu.edu/people/nadolsky/ResBos/grids/tev1960/rap/
www.physics.smu.edu/∼berge/small-x/

1. Introduction

Want to measure boson production $(Z/W^{\pm}/H)$ at Tevatron and LHC:



i) E.g. Measurement of W-boson mass M_W and width Γ_W in $pp/p\bar{p} \rightarrow WX \rightarrow l\nu X$

Important for precision tests of SM

✓ Consistency between different experiments and SM

✓ Together with Top quark mass, constraint on Higgs boson mass

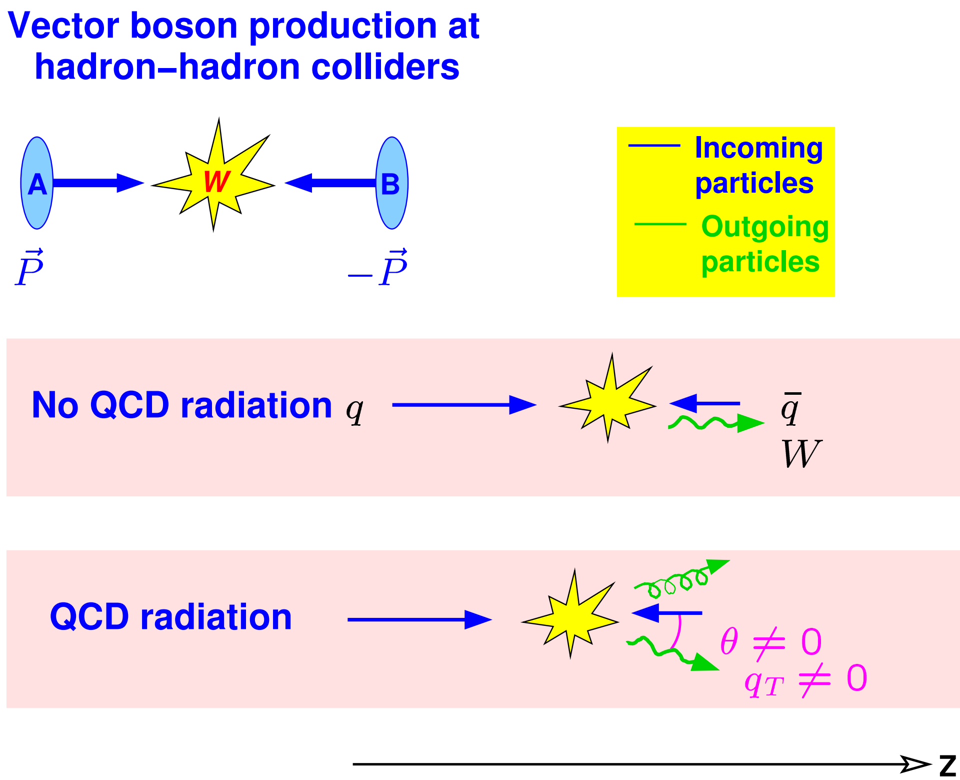
Tevatron Run-2 goal: reduce δM_W to 30 MeV (present error 59 MeV)
LHC goal: $\delta M_W \simeq 15$ MeV

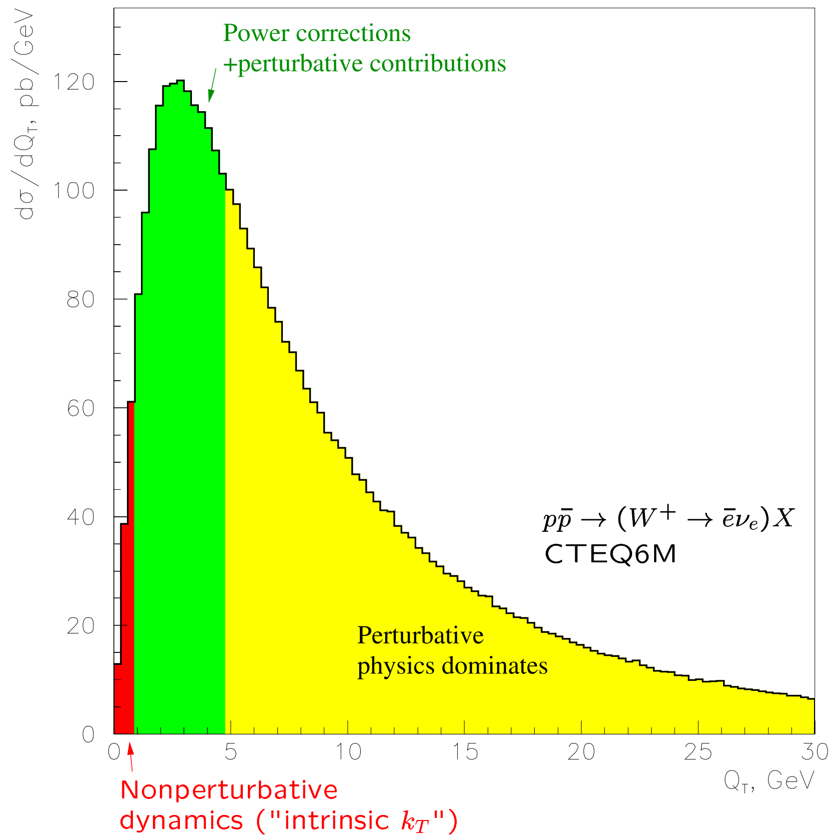
How is such accuracy achieved given that the W-bosons are not observed directly

1. Measure the lepton transverse mass distribution
2. Measure $d\sigma/dq_T^l$-distribution $\longrightarrow$ determine p_T distribution for W-bosons

ii) Need consistent theoretical predictions for small x $(5 \cdot 10^{-4} \leq x \leq 0.01)$

1. Introduction



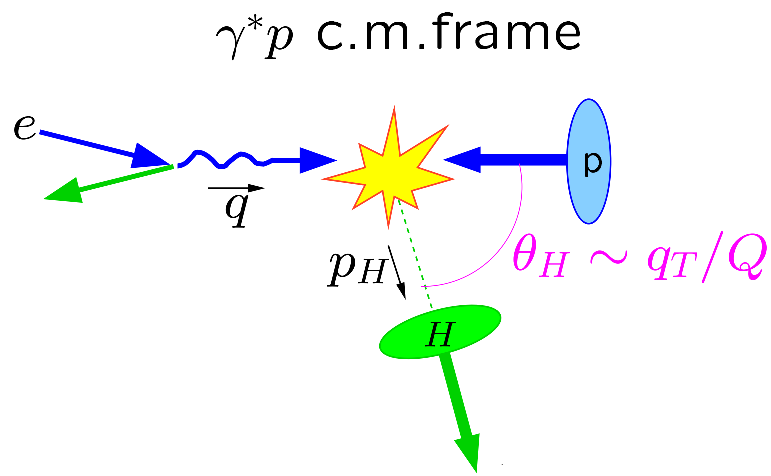


NLO; calculated using ResBos (Balazs, Nadolsky, Yuan)

Resummation needed to describes the whole q_T range

Important to precisely measure W-boson mass

2. Semi-inclusive DIS



<u>2000:</u> Nadolsky, Stump, Yuan, hep-ph/0012261

Analysed semi-inclusive production of hadronic final states. Transverse energy flow using the CSS (Collins, Soper, Sterman, 1985) formalism:

$$\frac{d\Sigma_z}{dx\,dQ^2 dq_T^2} = \int_0^\infty \frac{b\,db}{2\pi}\; J_0(q_T b)\; \widetilde{W}_z(b, Q, x) + Y_z(q_T, Q, x).$$

using the b_* prescription:

$$\widetilde{W}_z(b, Q, x) = \frac{\pi}{S_{eA}} \sum_{j=u,\bar{u},\ldots} \sigma_j^{(0)} \mathcal{C}_z^{out}(b_*)\, \overline{\mathcal{P}}_j^{(S)}(x, b)\, e^{-\mathcal{S}_P(b_*,Q) - \mathcal{S}_{NP}(b,Q,x;b_*)}$$

$S(b, Q)$: soft (Sudakov) factor

$\overline{\mathcal{P}}_j^{(S)}(x, b) = \left[\mathcal{C}_{j/a}^{in(S)} \otimes f_a\right](x, b_*)$: b-dependent parton distribution

2. Semi-inclusive DIS

2000: Nadolsky, Stump, Yuan, hep-ph/0012261

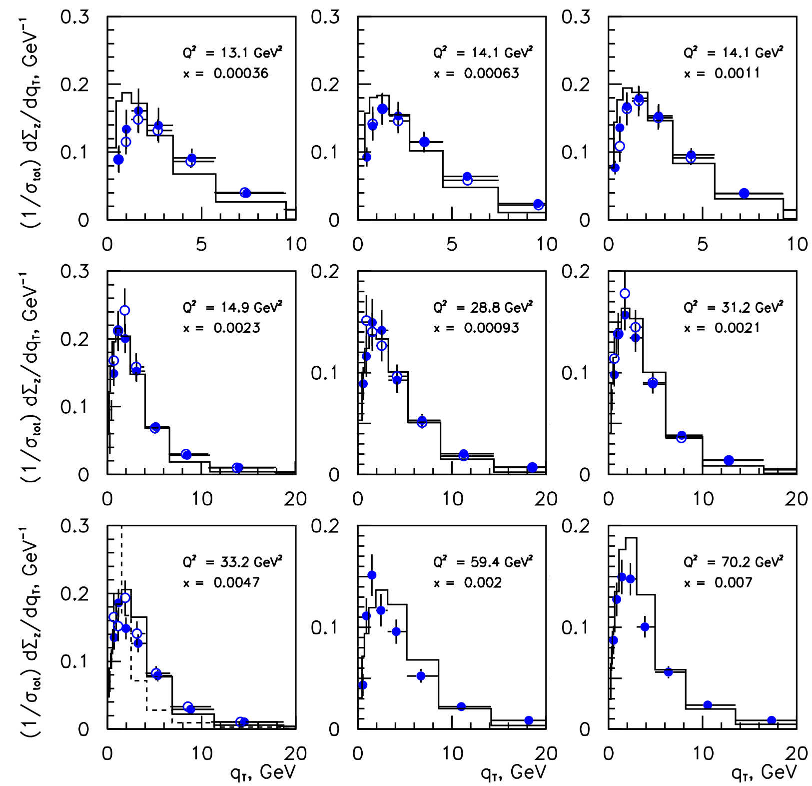
From the fit of the $\mathcal{O}(\alpha_s)$ resummed z-flow to the Hera H1 data:
$\longrightarrow$ small-x behaviour is only consistent with the data if an q_T-broadening factor

$$\sim exp\left\{ - c_0 \frac{b^2}{x^p} \right\}$$

was introduced. Best fit for p = 1 and $c_0 = 0.013$.
Identify:

$$\overline{\mathcal{P}}_j^{(S)}(x,b) = \left[\mathcal{C}_{j/a}^{in(S)} \otimes f_a \right](x, b_*)\; e^{-0.013\,\frac{b^2}{x}}$$

Data from H1 Collaboration



$8 \times 10^{-5} < \langle x \rangle < 7 \times 10^{-3}$

Assumption supported by recent perturbative higher order calculations:
(Maniatis et al. hep-ph/0411300, Daleo et al. hep-ph/0411212, Fontannaz hep-ph/0410021, Aurenche et al. 2004)

2. Boson production at Hadron Collider

Use HERA results as a phenomenological approch for $x \ll 10^{-2}$ to predict boson production at Hadron Colliders:

$$\frac{d\sigma_{AB\to VX}}{dQ^2dydq_T^2} = \int \frac{d^2b}{(2\pi)^2} e^{-i\vec{q}_T\cdot\vec{b}} \sum_{a,b} \frac{\sigma_{ab}^0}{S} \left[\mathcal{C}_{a/c}^{in} \otimes f_c\right](x_A, \frac{b_0}{b_*}) \left[\mathcal{C}_{b/d}^{in} \otimes f_d\right](x_B, \frac{b_0}{b_*})$$

$$\times\, e^{-S_P(b_*,Q) - S_{NP}^{BLNY}(b,Q) - b^2\rho(x_A) - b^2\rho(x_B)} + Y$$

with

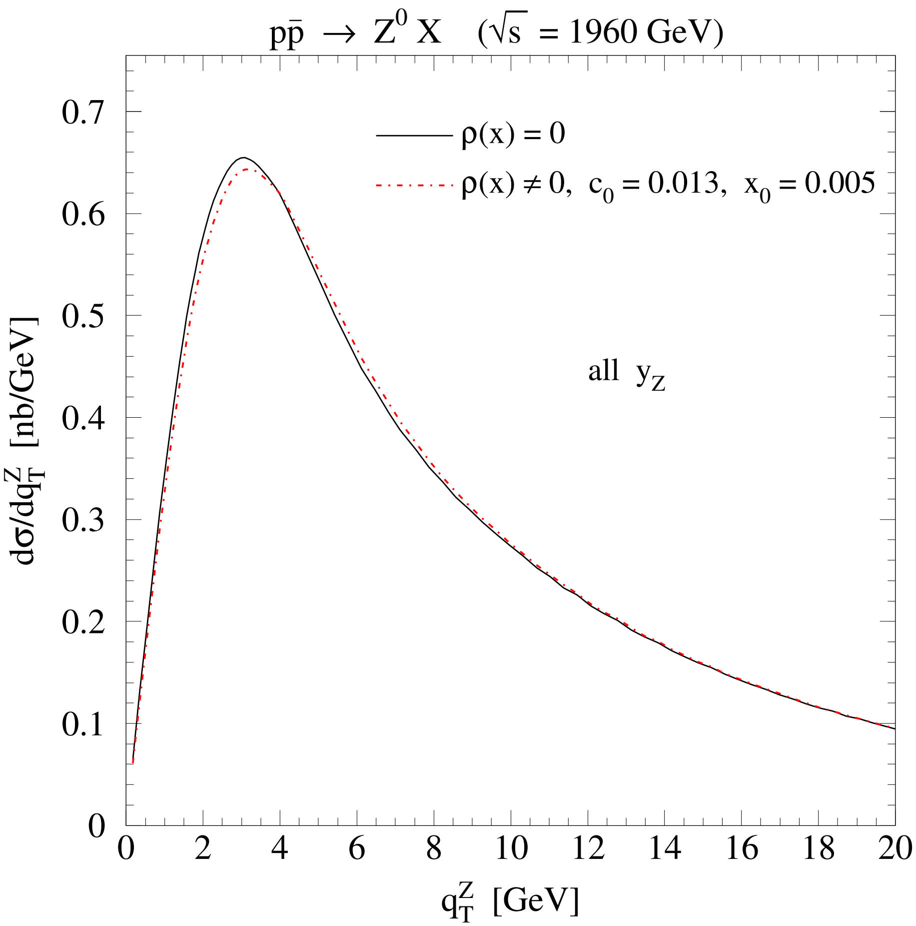
$$\rho(x) = c_0\left(\sqrt{\frac{1}{x^2}+\frac{1}{x_0^2}} - \frac{1}{x_0}\right), \qquad \begin{cases} x \ll x_0 : & \rho(x) \sim c_0/x & \text{fits to SIDIS data} \\ x \gg x_0 : & \rho(x) \to 0 & \text{fits to Run I, BLNY} \end{cases}$$

$$c_0 = 0.013, \quad x_0 = 0.005$$

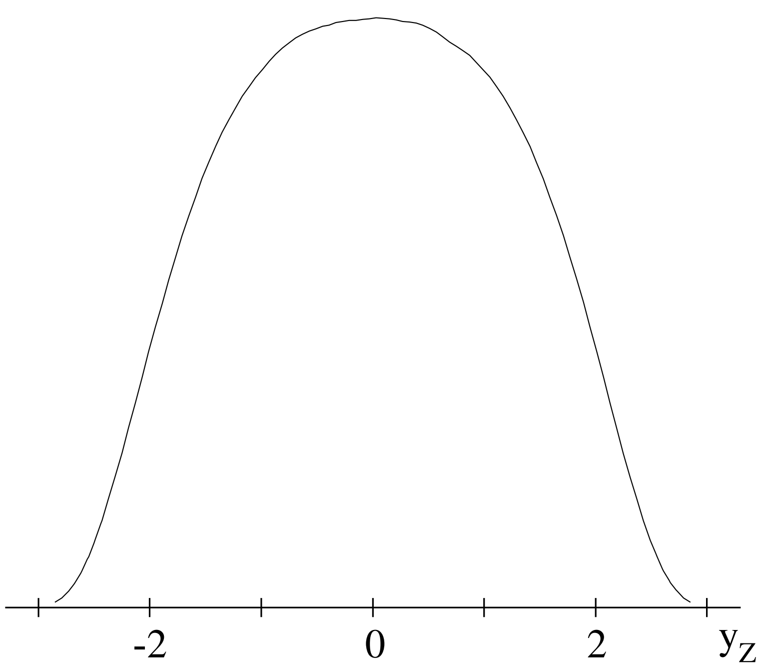
$b_* = b/\sqrt{1+b^2/b_{max}^2}$. Above equation reduces to the conventional CSS cross section at large x and includes sources of additional q_T broadening at small x $(x \lesssim 10^{-2})$.

2. Small x: Numerical Results

Small x broadening in $p\bar{p} \longrightarrow Z^0 X$ at Tevatron Run II



Rapidity distribution of Z^0 bosons



No y_W cut

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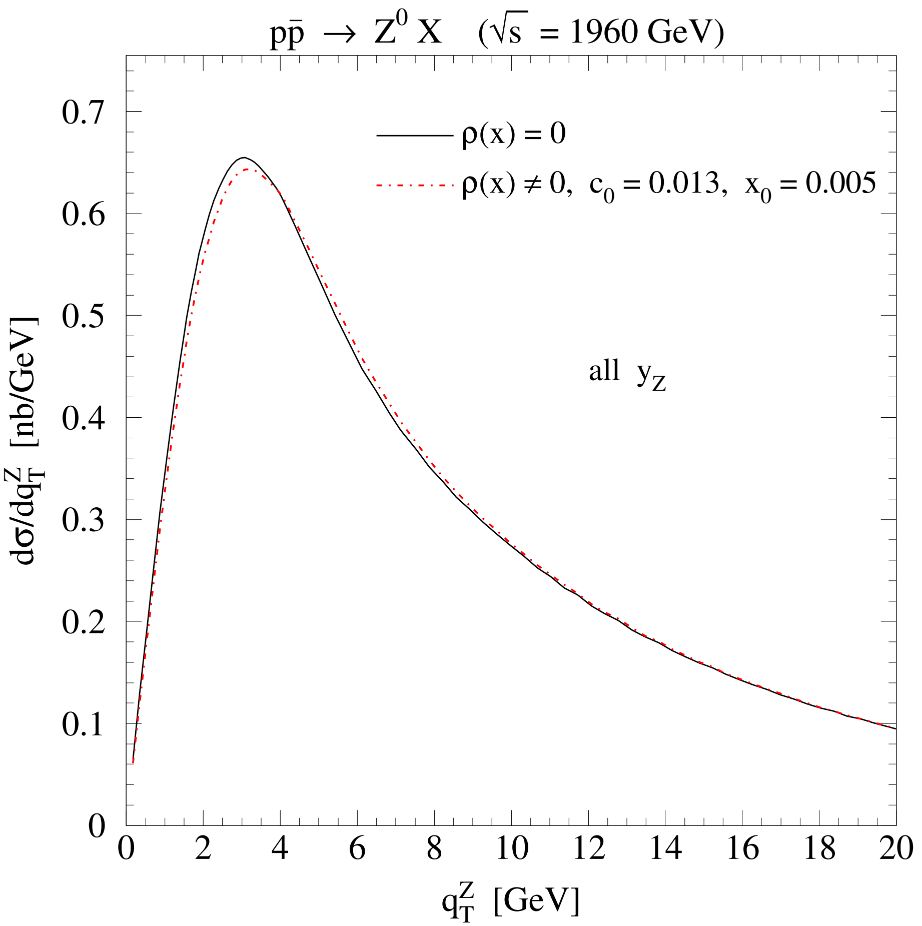

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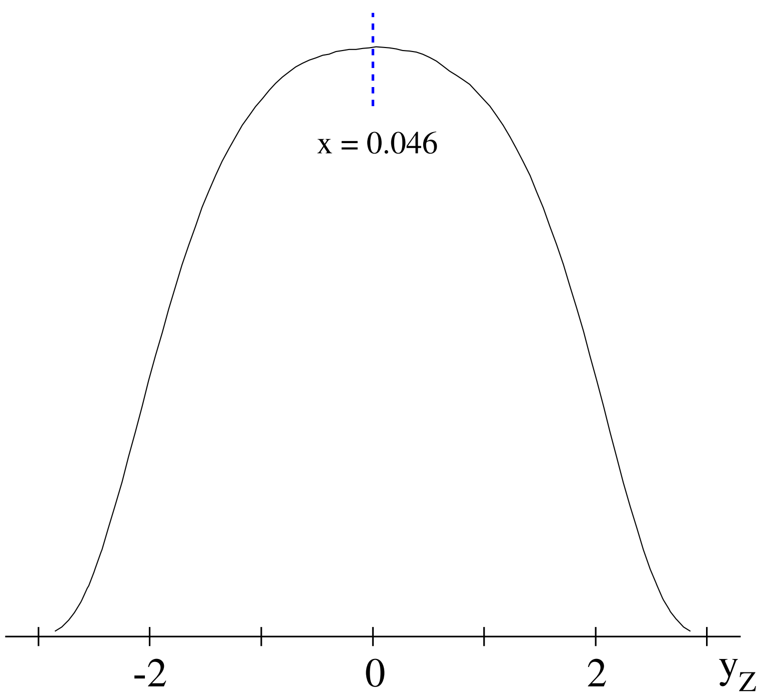

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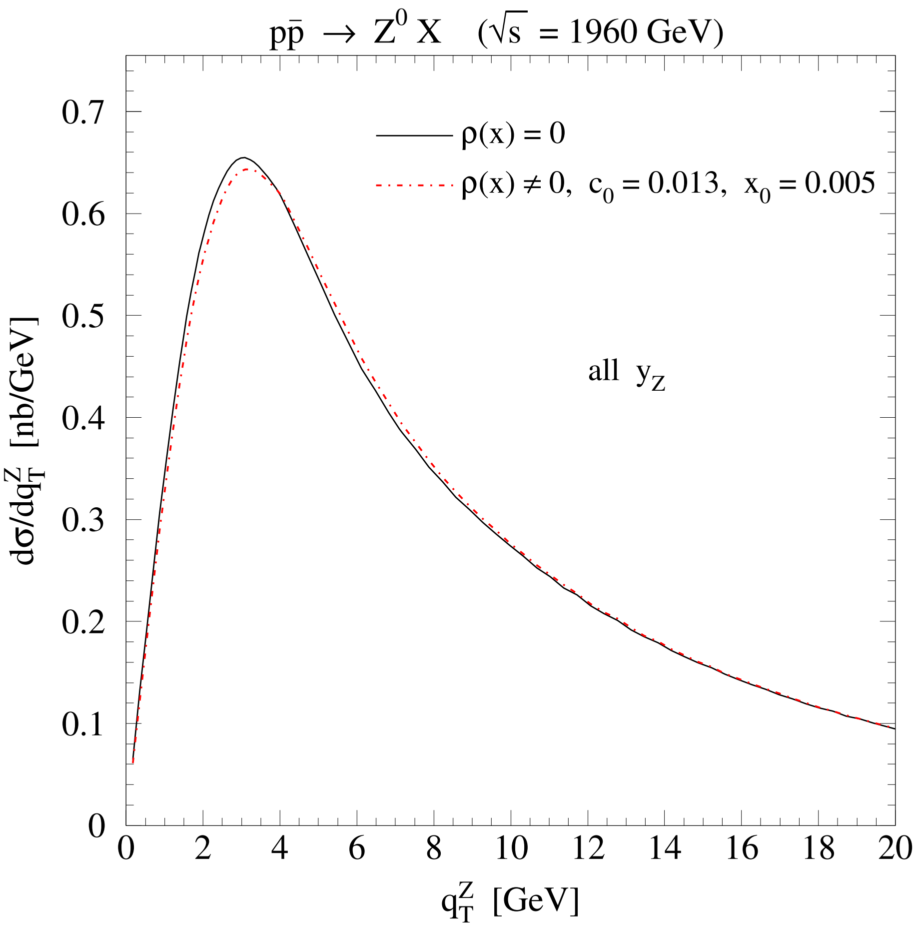

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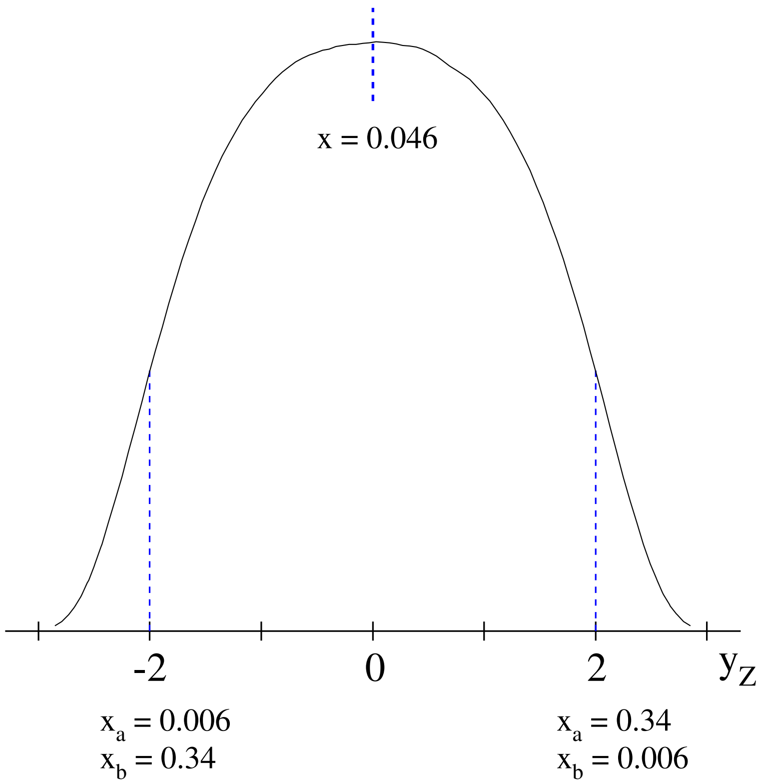

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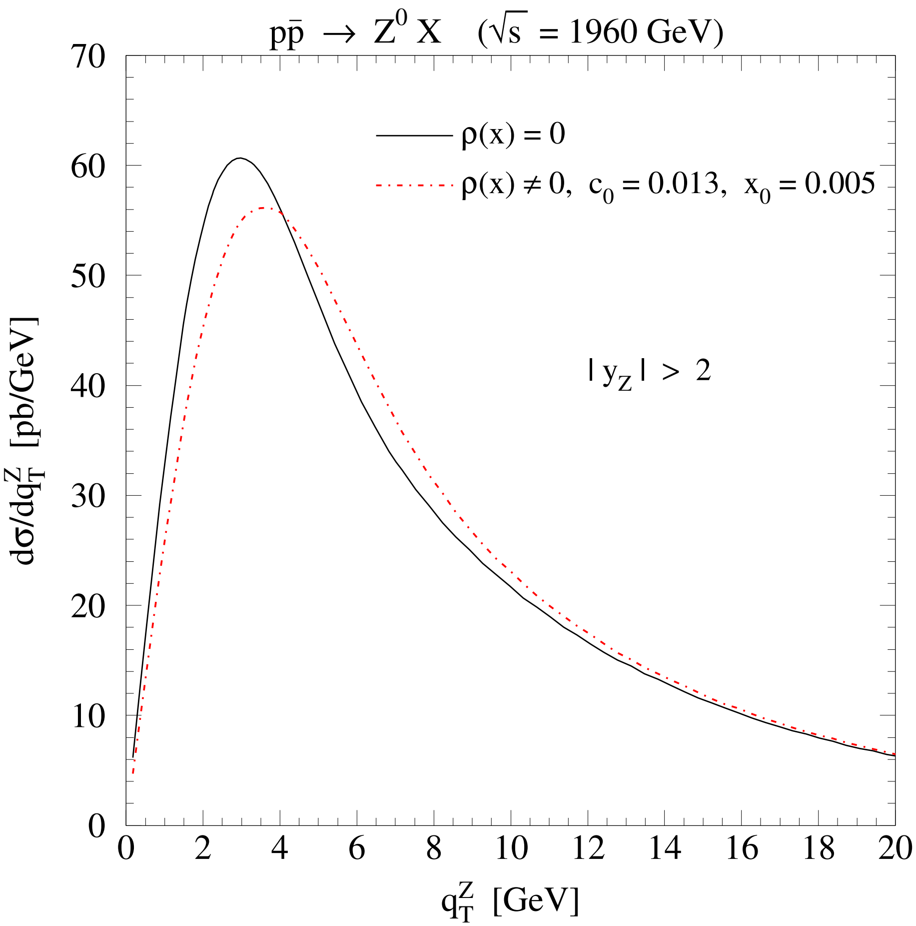
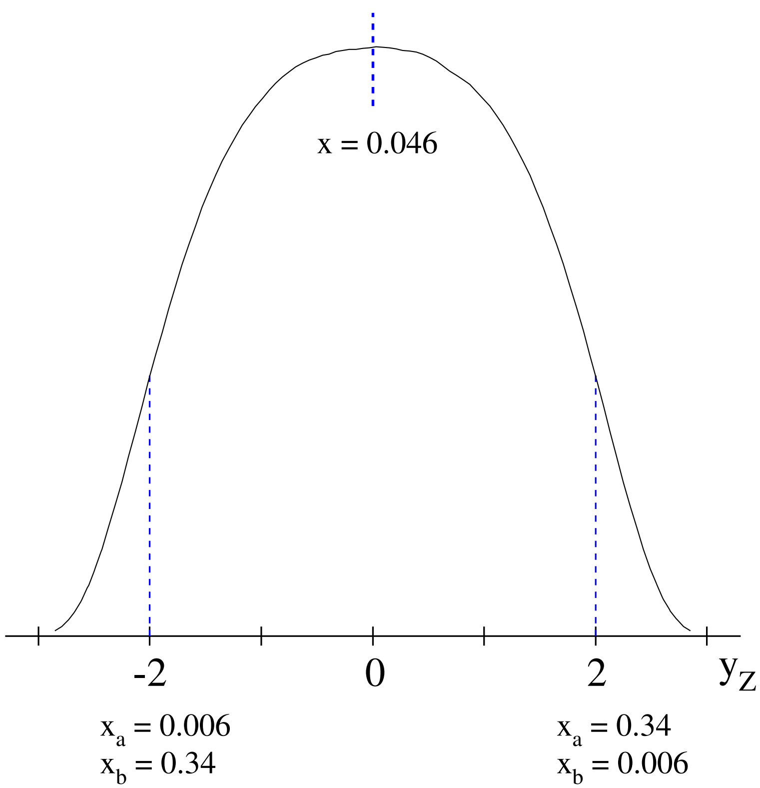


$|y_W| > 2$



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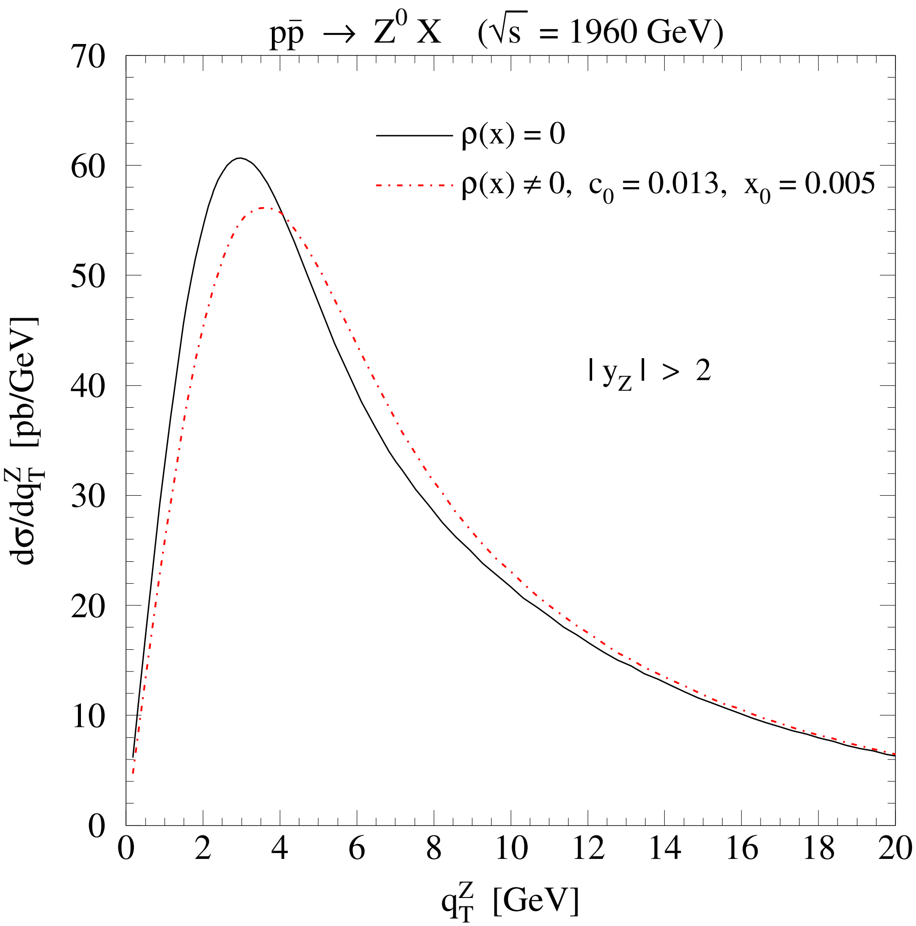
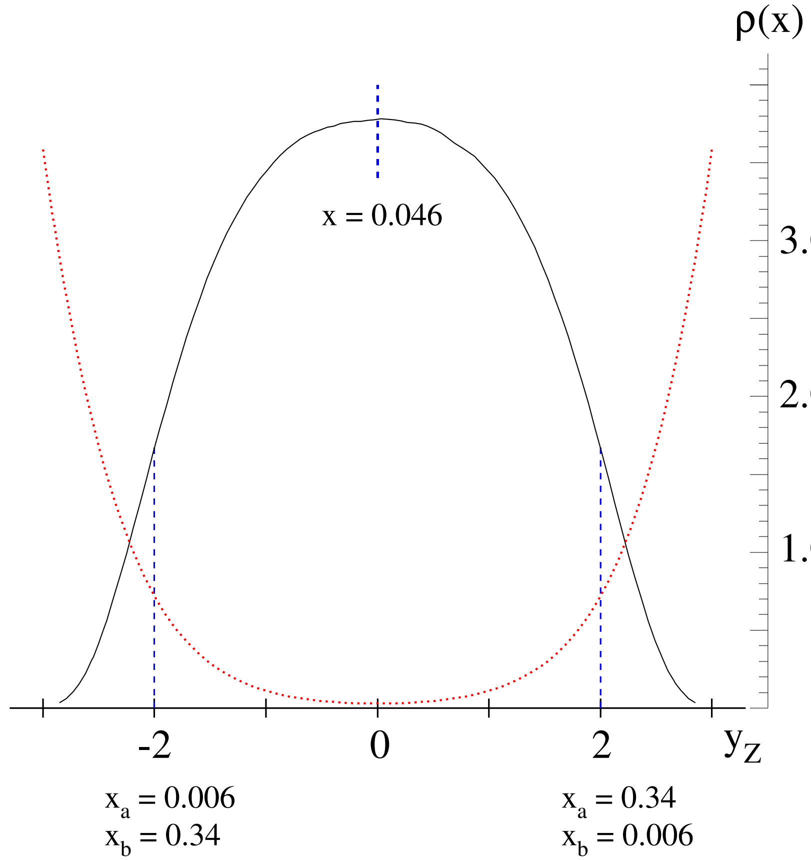
Small x broadening in $p\bar{p} \longrightarrow Z^0 X$ at Tevatron Run II

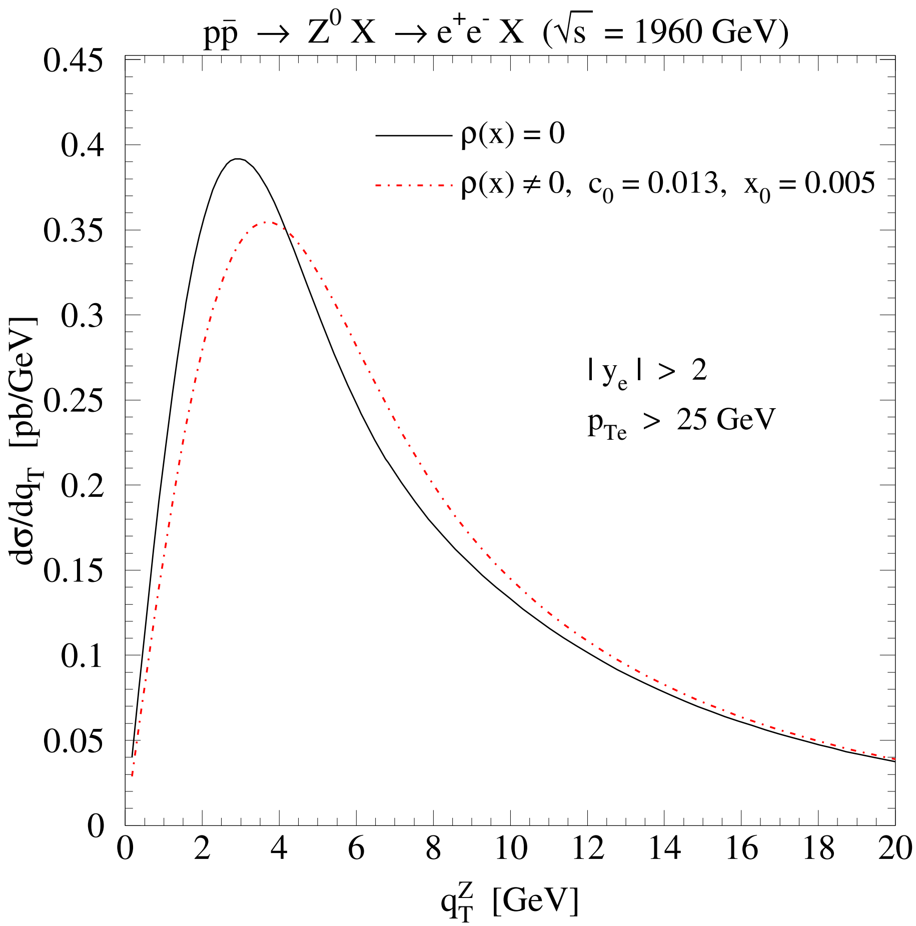




$|y_W| > 2$

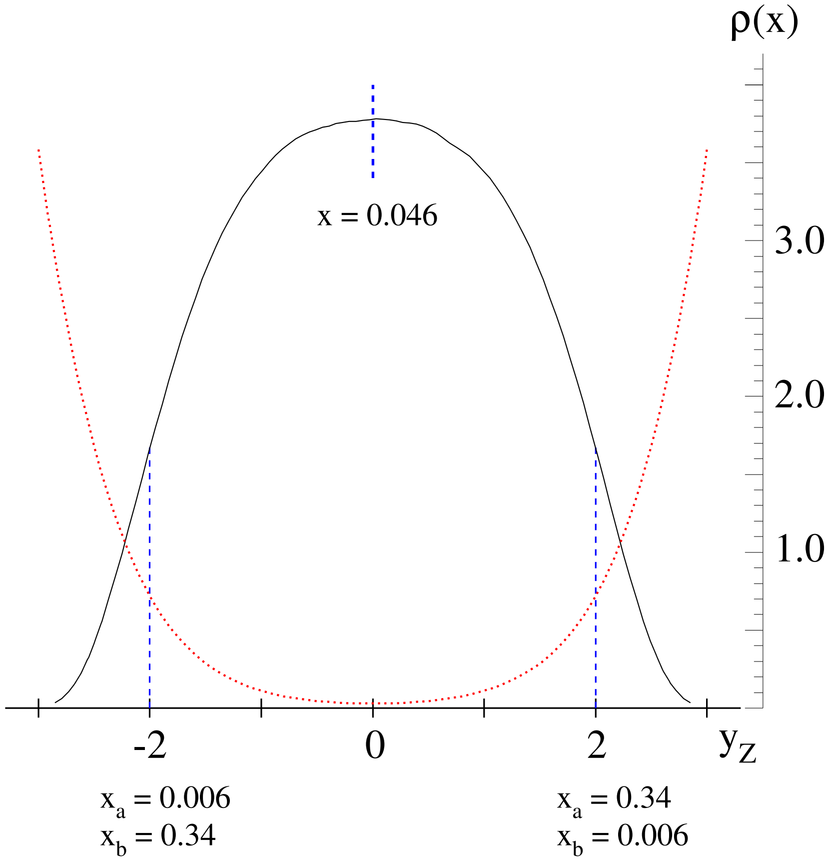
2. Small x: Numerical Results

Small x broadening in $p\bar{p} \longrightarrow Z^0X$ at Tevatron Run II



$|y_e| > 2,\ p_{Te} > 25$ GeV

Rapidity distribution of Z^0 bosons



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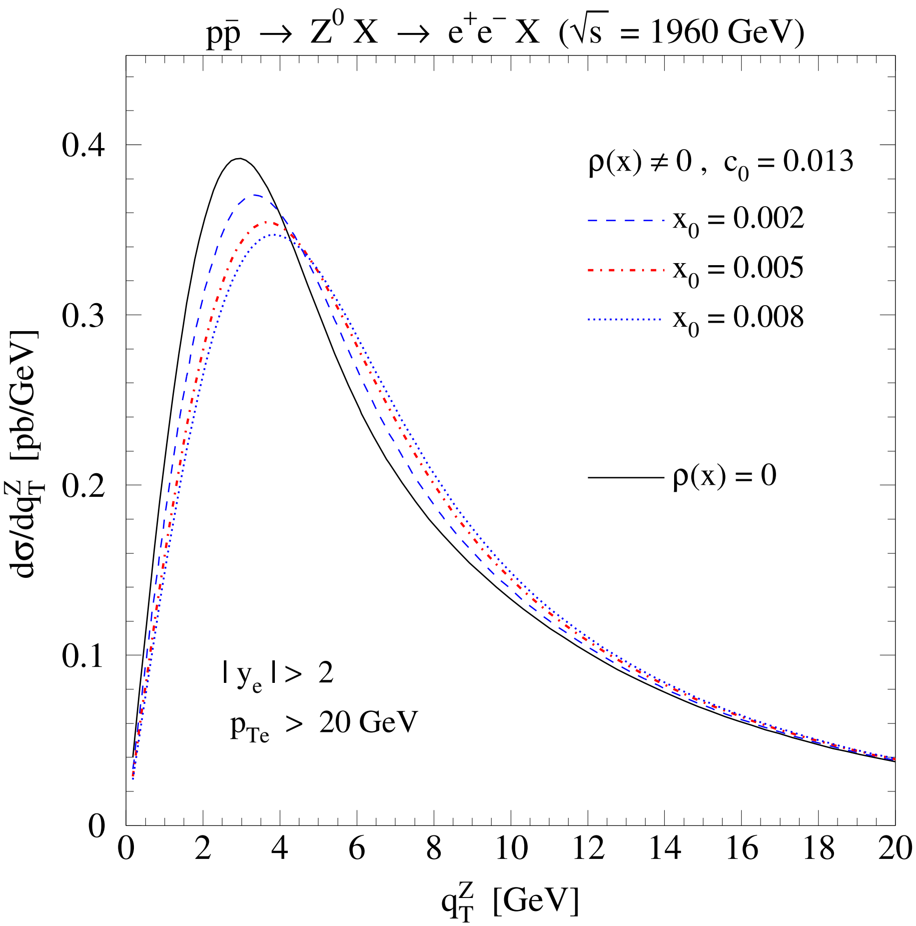

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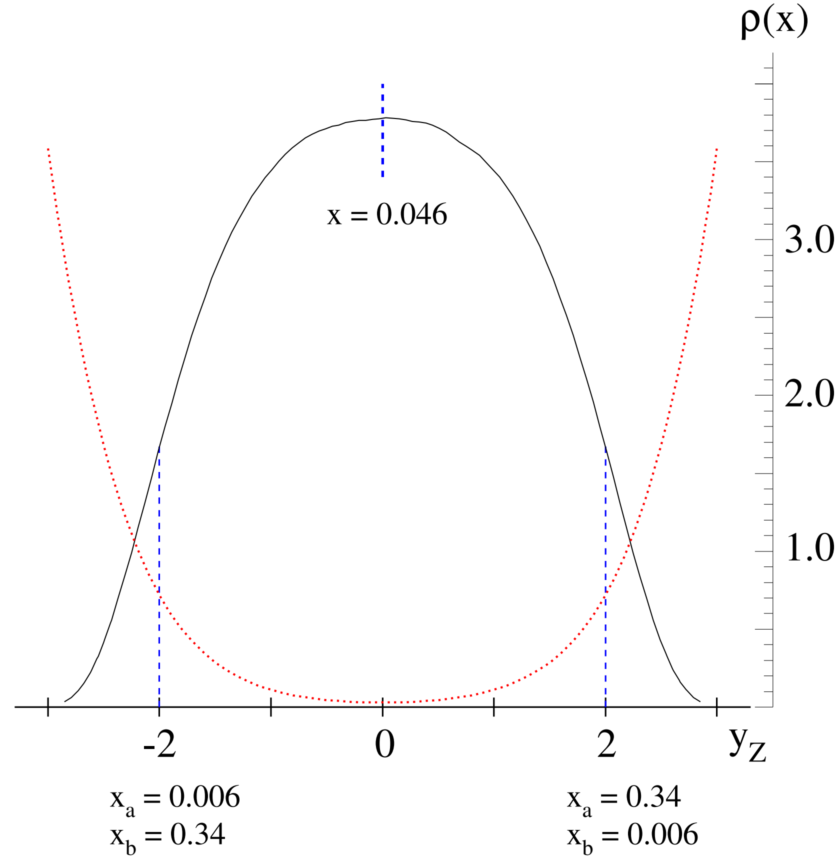
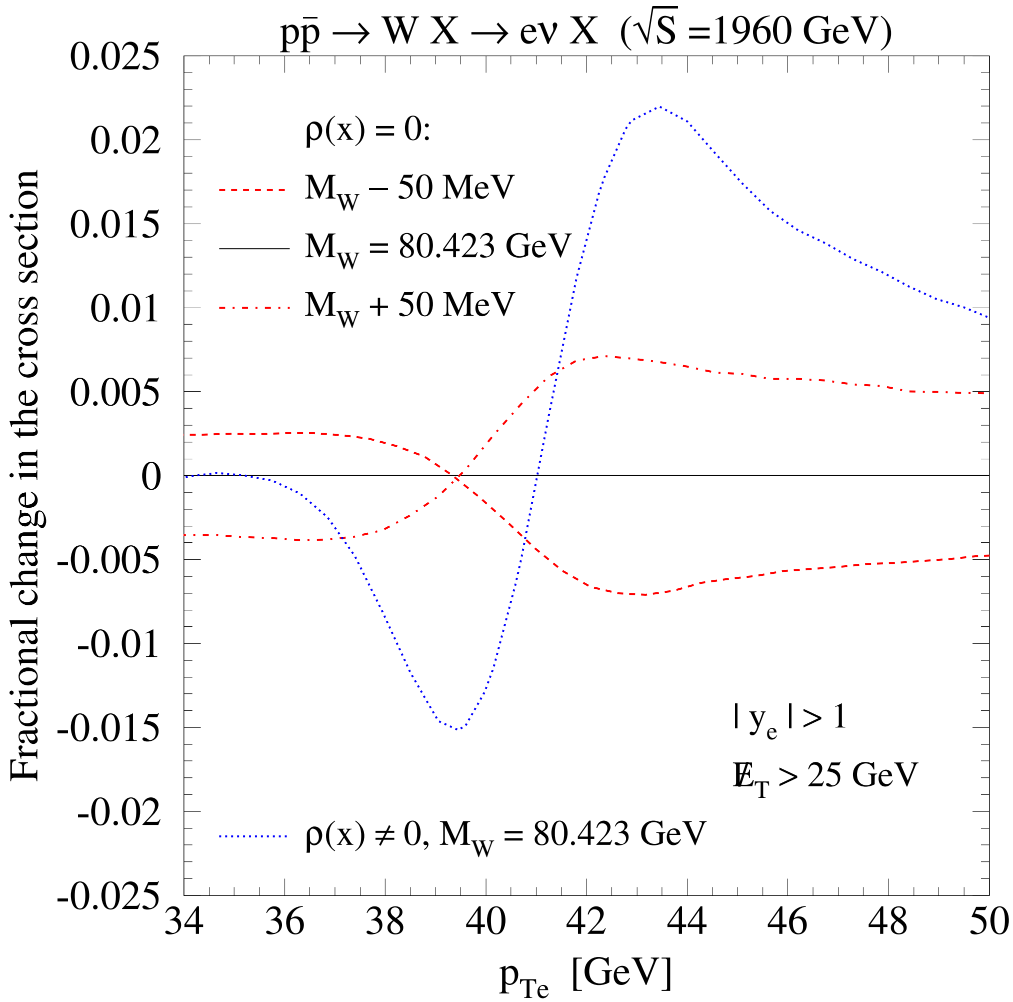
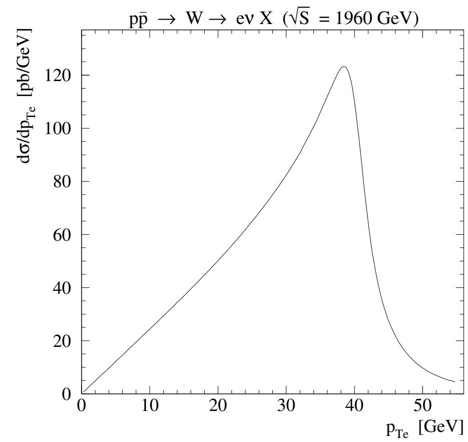


$|y_e| > 2, \; p_{T_e} > 20$ GeV

Small x: $p\bar{p} \to W^+X \to e^+\nu_e X$ at Tevatron



$|y_e| > 1$



Small x broadening (blue line) compared to a shift of the W boson mass of ± 50 MeV (red line).

Plotted is the ratio

$$\frac{d\sigma_X / dq_T^e}{d\sigma_{M_W}^{\rho(x)=0} / dq_T^e}$$

over the lepton transverse momentum q_T^e!

For $|y_e| < 1$, small-x effect is comparable with a 10-20 MeV mass shift.

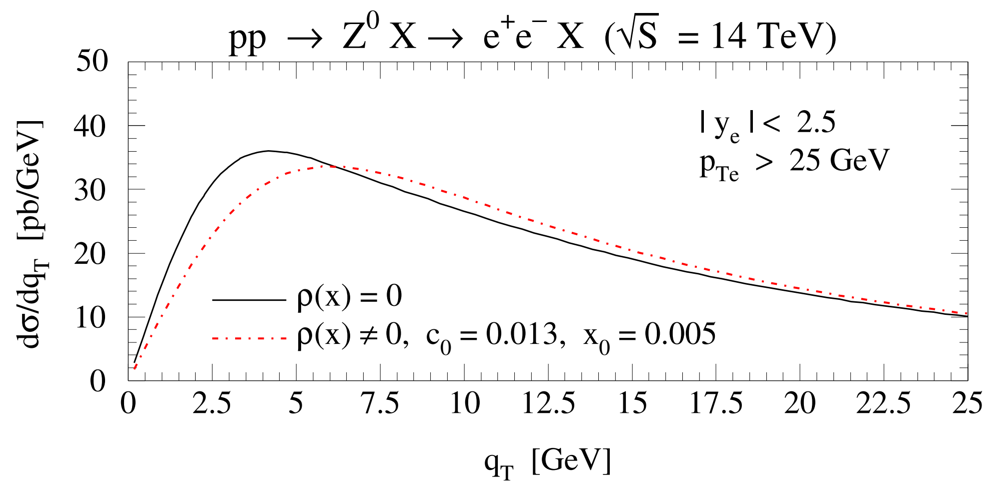
Small x: $pp \to Z/W + X$ at LHC

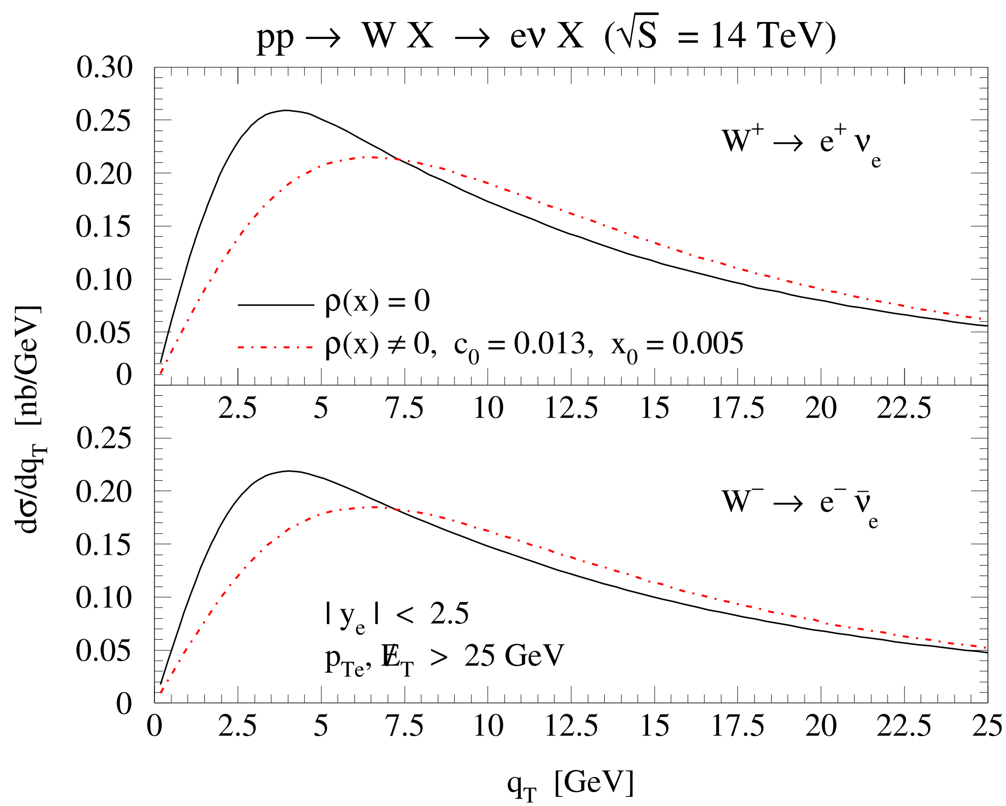
$|y_e| < 2.5$:

- x stays above 10^{-4} (SIDIS data)
- coverage of the inner ATLAS detector

Small x broadening enhanced even in the central region due to $x|_{y\approx 0} \approx 0.006$

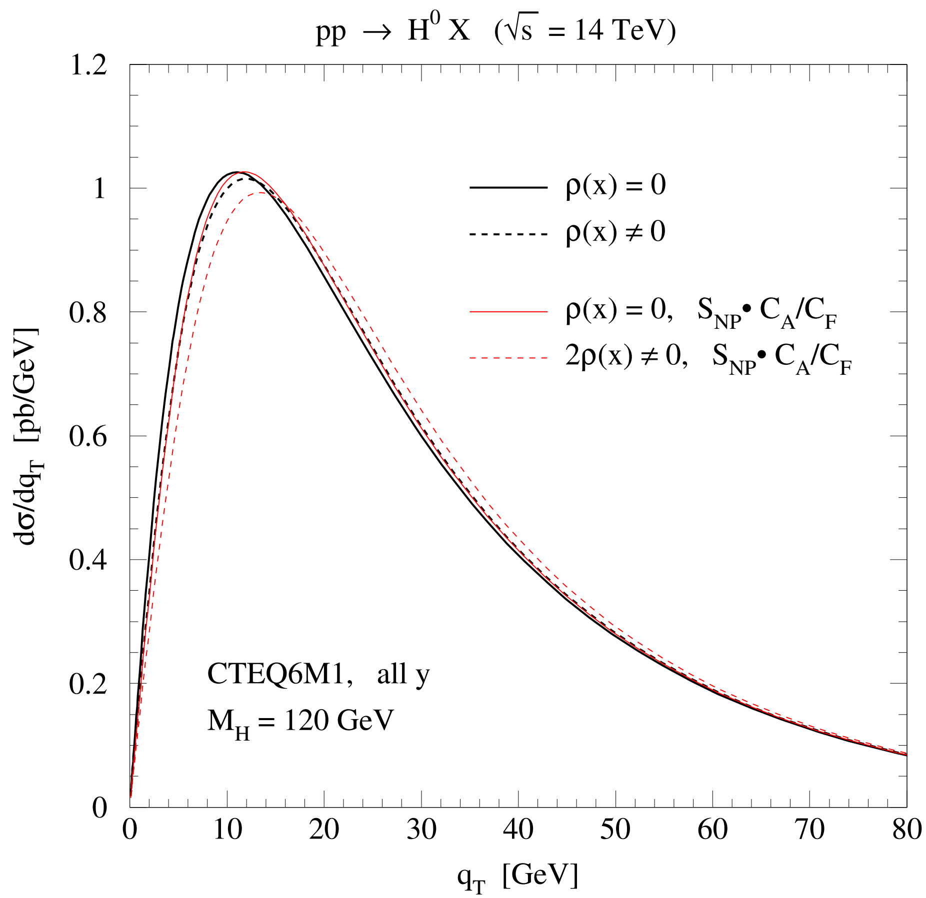
Dependence of $d\sigma/dq_T^W$ on transverse W-boson momentum q_T^W





Small x: $pp \to H^0 + X$ at LHC

Higgs Boson production at LHC: $pp(\to gg) \to H^0 X$



Dependence of $d\sigma/dq_T^{H^0}$ on transverse H-boson momentum $q_T^{H^0}$

No y_H cut $\longrightarrow$ no large small-x broadening

Distribution peaks at $q_T = 10 - 20$ GeV

black line: $\rho(x)$ and S_{NP} are the same as for Z^0 production

red line: S_{NP} multiplied by $\frac{C_A}{C_F} = \frac{9}{4}$ due to larger leading-logarithm coefficient (C_A) in gg channels compared to $q\overline{q}$ channels (C_F)

3. Resummation in heavy flavor production:

- It is well know, how to calculate $d\sigma/dq_T$ for massless quarks (resummation for $\ln(q_T^2/Q^2)$, e.g. CSS)
- Massless approximation neglects terms $\sim M_H^2/q_T^2$, which may be important at small q_T

$$\frac{1}{q_T^2 + M_H^2} = \frac{1}{q_T^2}\left(\frac{1}{1+\frac{M_H^2}{q_T^2}} \right)$$

- Systematic calculation of differential distributions in reactions with heavy quarks $H(H = c, b)$ in the presence of 3 distinct momentum scales (Nadolsky, Kidonakis, Olness, Yuan, 2003)

  e.g. Boson production - relevant momentum scales:
  - Heavy quark mass M_H
  - Virtuality Q of the produced boson ($\Lambda^2_{QCD} \ll M_H^2 \ll Q^2$)
  - Transverse momentum q_T of the produced boson ($0 \leq q_T^2$)
- Relies on the usage of a massive variable flavor number (VFN) factorization scheme

3. Heavy flavor contribution in W and Z bosons production

W^+ production:

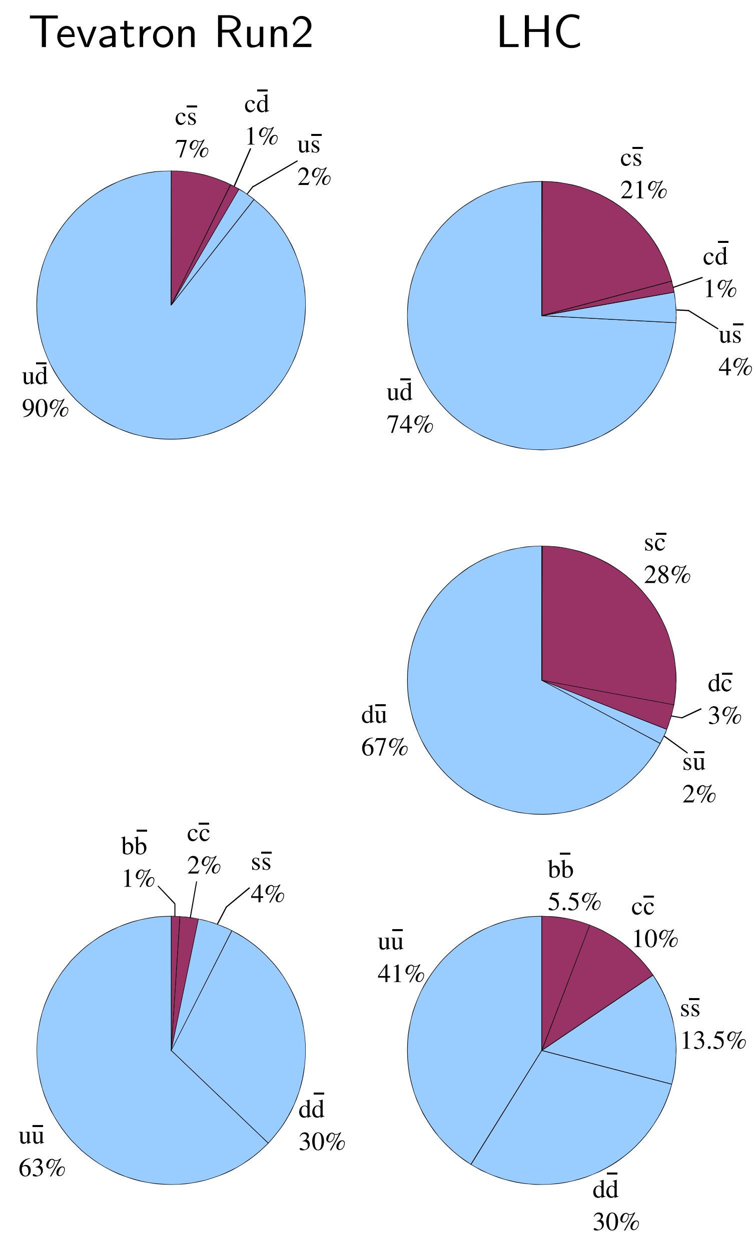
$V_{\rm CKM}^2 \times$ Parton Luminosity $\sim \sigma_{Born}$

W^- production:

$V_{\rm CKM}^2 \times$ Parton Luminosity $\sim \sigma_{Born}$

Z^0 production:

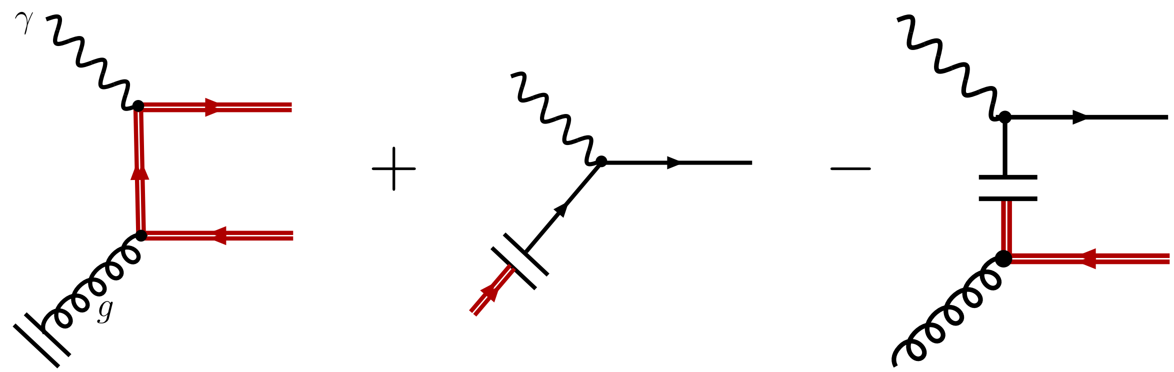
Parton Luminosity $\sim \sigma_{Born}$



Largest heavy quark contribution in charm quark channel in W^- boson production (31%) at LHC.

3. Heavy Quark

Simplified ACOT factorization scheme
(Collins 1998;
Kramer, Olness, Soper, 2000)



- Set $M_H = 0$ in coefficient functions for incoming heavy quarks
- Only graphs with explicit flavor creation retain $M_H \neq 0$
- Significantly simplifies calculations
- M_H is dropped in the Sudakov factor $S(b, Q)$
- Quark initiated processes from the massless calculation: M_H is dropped in the function $C^{in}_{jq}(x, b\mu_F)$, $C^{out}_{bj}(z, b\mu_F)$ with incoming heavy quarks
- Numerical closed to the conventional ACOT scheme
- Included $\mathcal{O}(\alpha_s)$ contribution of $g \to q\bar{q}$ for $M_H \neq 0$ into Legacy (Landry, Brock, Nadolsky, Yuan, 2003)
- Following plots are computed with Resbos (Balazs, Yuan, 1997)

3. Heavy Quark: Z-boson production at LHC

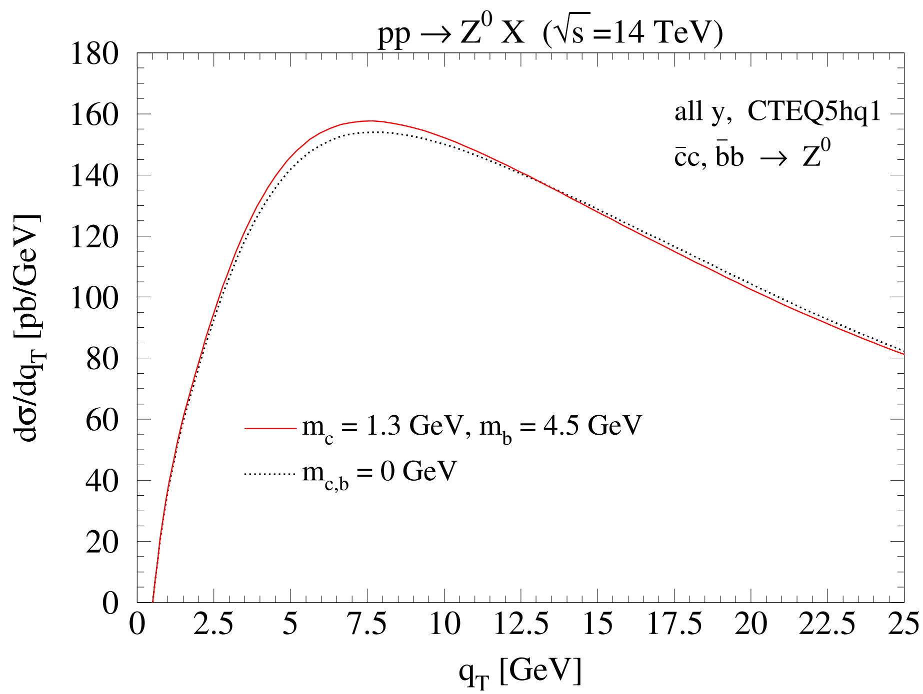
Consider heavy flavor channels ($c\bar{c}, b\bar{b}$) for Z boson production at LHC:

$d\sigma/dq_T$ enhanced by 2.5% in peak region $q_T \sim 7.5$ GeV

$d\sigma/dq_T$ slightly reduced for $q_T > 15$ GeV

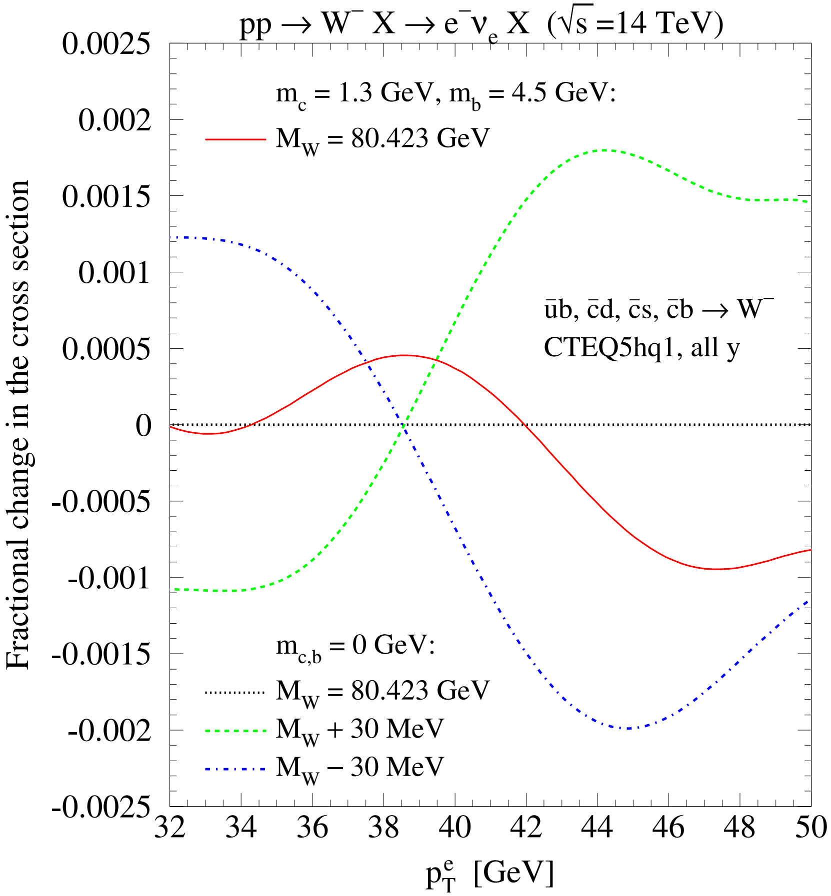
Heavy flavor channels contribute only to 15% to total cross section
$\longrightarrow$ increase of less than 0.3% remains
$\longrightarrow$ curves not distinguishable for cross section including all possible inital quark combinations

Effect for Z^0 production at Tevatron negligible.



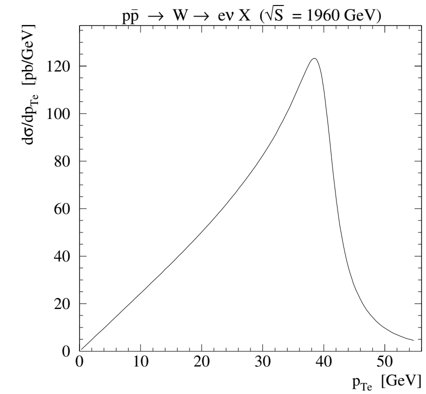
Dependence of $d\sigma/dq_T^Z$ on transverse momentum q_T for the $c\bar{c}, b\bar{b} \longrightarrow Z^0$ channels only

3. Heavy Quark: W^- production at LHC



plotted is $\dfrac{d\sigma_X/dq_T^e}{d\sigma_{M_W}^{massless}/dq_T^e}$

$\bar{u}b, \bar{c}d, \bar{c}s, \bar{c}b \longrightarrow W^-$



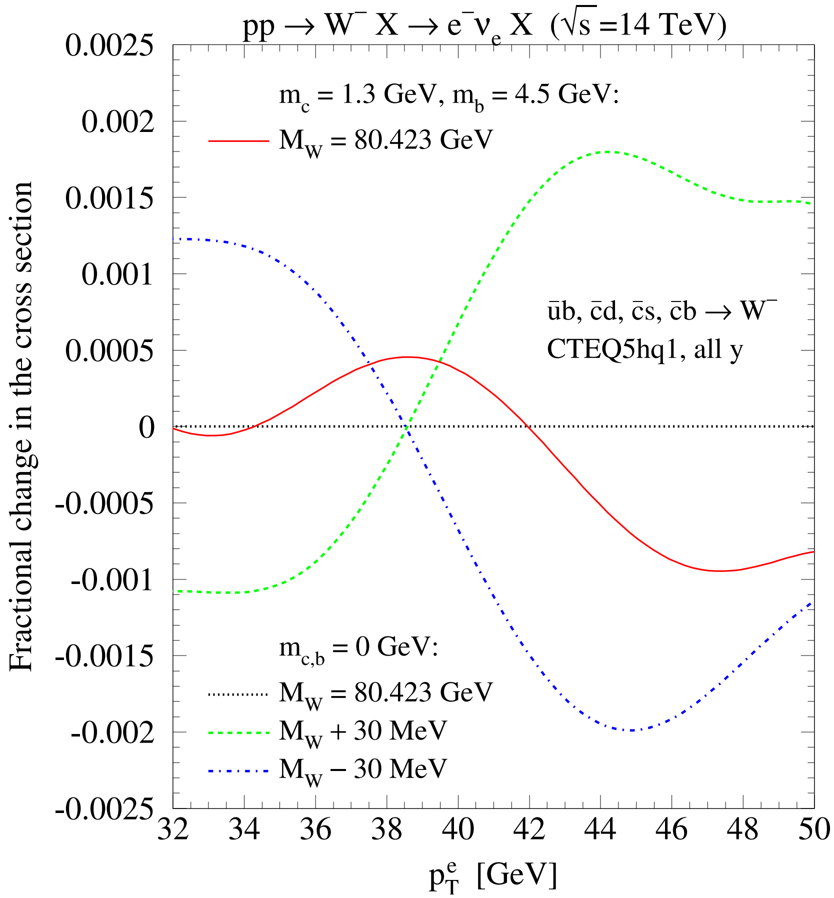
Heavy flavor channels only:

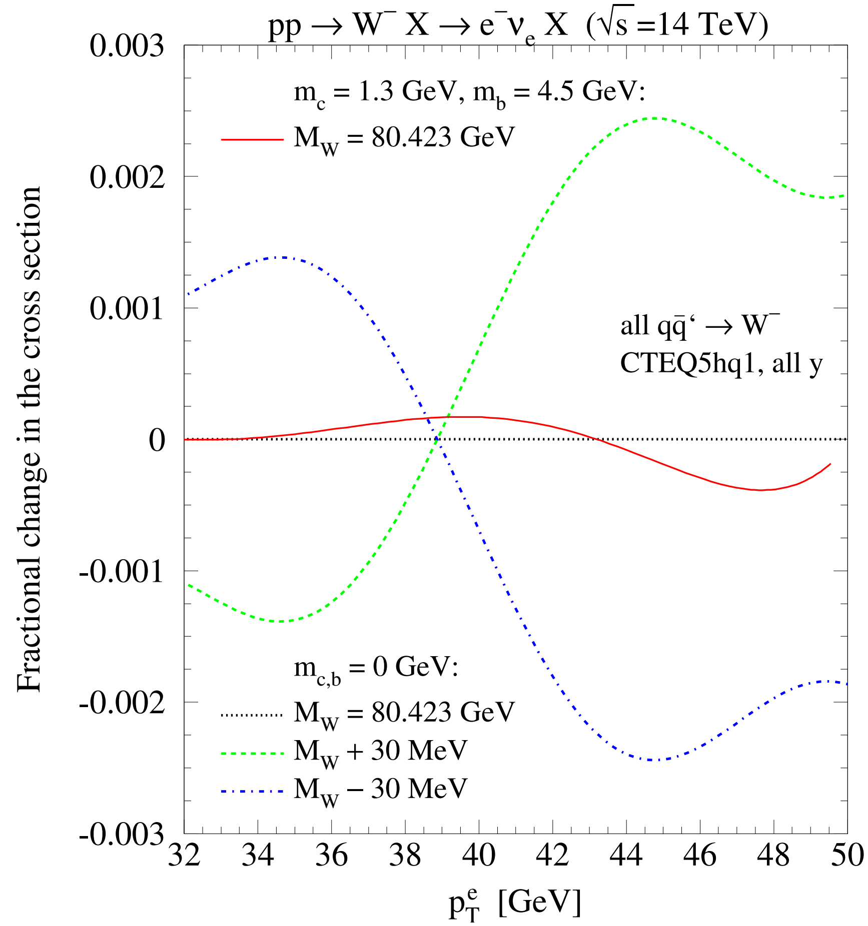
Shifts the Jacobian peak in the negative direction

Size of this effect is comparable to a M_W shift of about -15 MeV

Similar behavior and size for W^+ production at LHC and W production at Tevatron (because dominant channel is always $c\bar{s} \longrightarrow W^+$ or $\bar{c}s \longrightarrow W^-$)

3. Heavy Quark: W^- production at LHC





plotted is $$\frac{d\sigma_X/dq_T^e}{d\sigma_{M_W}^{massless}/dq_T^e}$$

$\bar{u}b, \bar{c}d, \bar{c}s, \bar{c}b \to W^-$

all $q\bar{q}' \to W^-$

$W^-(W^+)$ at LHC: $-5(-1.8)$ MeV

W at Tevatron: -1.2 MeV

3. Heavy Quark: Higgs boson production

Consider Higgs boson production in:

$pp \longrightarrow b\bar{b} \longrightarrow H^0$

$M_h = 120$ GeV

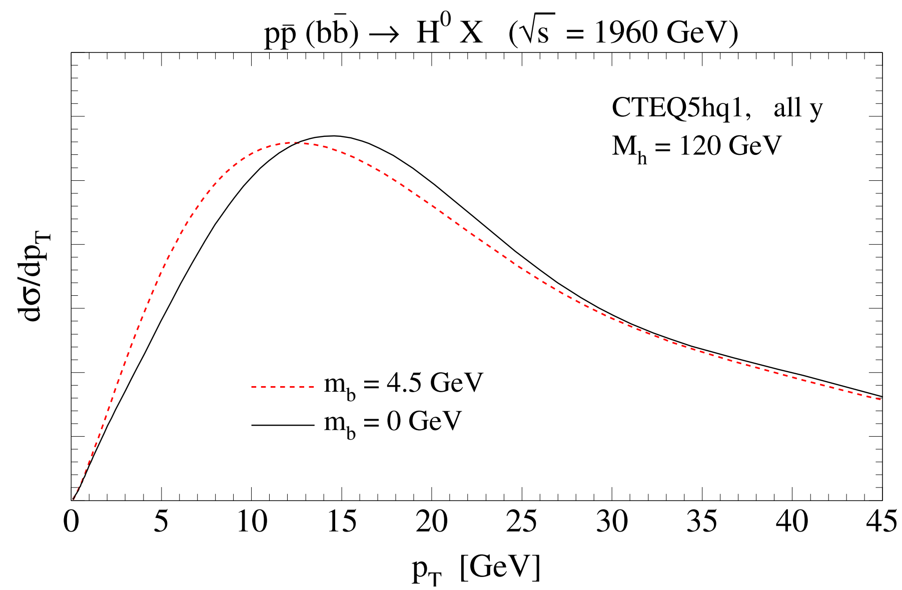
Contributes in SM less than 1% $\longrightarrow$ negligible

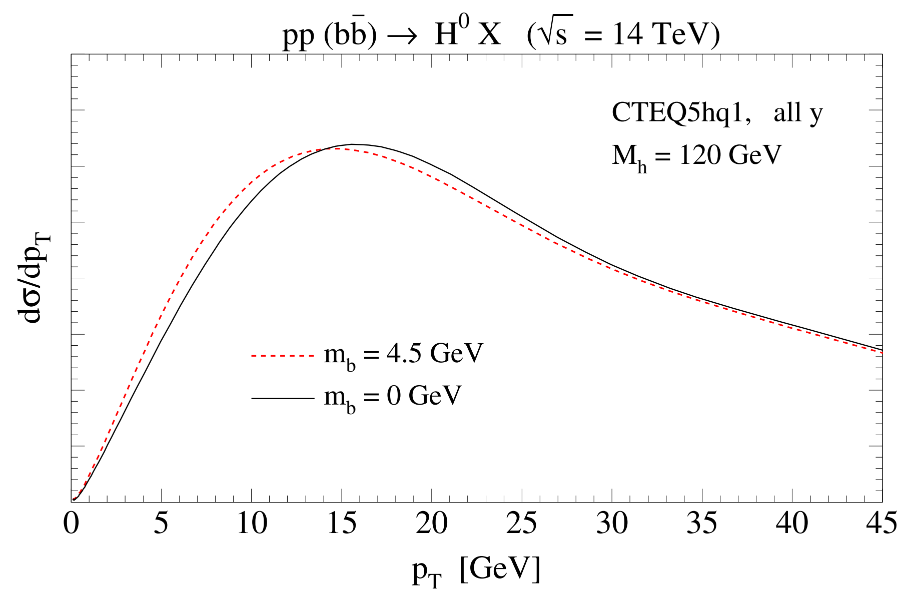
Can be dominant in MSSM for large $\tan\beta$ because $b\bar{b}H$ coupling is enhanced, $t\bar{t}H$ coupling mostly suppressed

Shift in the peak reagion:
At Tevatron: -2.0 GeV
At LHC: -1.2 GeV

(Decreases to -0.6 GeV for $M_h = 600$ GeV)

Other channels with one initial bottom quark may be affected: $gb \longrightarrow Zb$, $gb \longrightarrow H^0 b$, $gb \longrightarrow H^- t$, $u\bar{b} \longrightarrow \bar{d}t$ ...



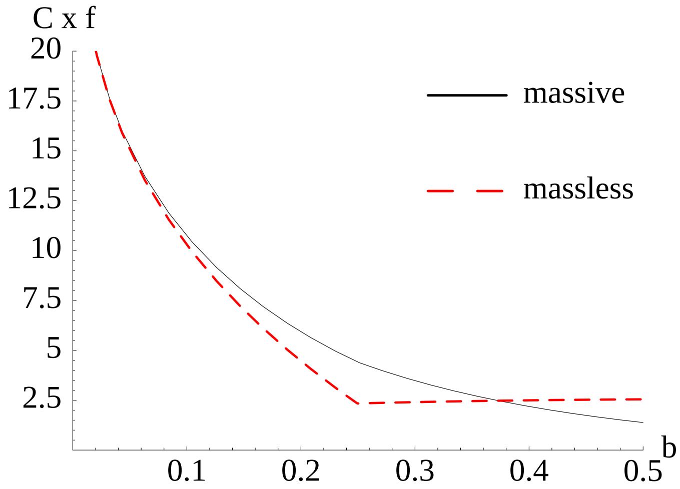


4. Conclusion

- Small x:
  - Based on semi-inclusive DIS data, we hypothesize broadening of q_T distributions at $x \lesssim 10^{-2}$
  - q_T broadening can possibly measured in the forward rapidity range ($|y| \geq 2$) in Z-boson production at Tevatron and will affect the W mass measurement for $|y| \geq 1$
  - q_T broadening will strongly influence predictions for W and Z production at LHC
  - For H^0 transverse momentum distribution, q_T broadening might be less important at the LHC

- Heavy flavor effects on transverse momentum distribution:
  - Heavy flavor effects on Z and W boson production at Tevatron are negligible
  - Heavy flavor effects on W mass measurement at LHC are smaller than the experimental uncertainties
  - Bottom-antibottom initiated processes can be strongly affected (e.g. $b\bar{b} \longrightarrow H$ at LHC: peak shifted by $-1.2\,\text{GeV}$)

3. Heavy Quark



- Included $\mathcal{O}(\alpha_s)$ contribution of $g \longrightarrow q\bar{q}$ for $M_q \neq 0$ into Legacy

- Following plots are computed with Resbos

m

2. Introduction

HERA $\longrightarrow$? Tevatron/LHC

SIDIS

$\overline{\mathcal{P}}_j^{(S)}(x,b)$

Z^0, $W^\pm$ ($\delta M_W = 30/15$ MeV?)

$\overline{\mathcal{P}}_j^{(T)}(x,b)$

$$\overline{\mathcal{P}}_j^{(I)}(x,b) = \left|\mathcal{H}^{(\mathcal{I})}(b_0/b)\right| \widetilde{U}(b_0/b)^{1/2} \widehat{\mathcal{P}}_j(x,b),$$ (Collins, Soper; '82)

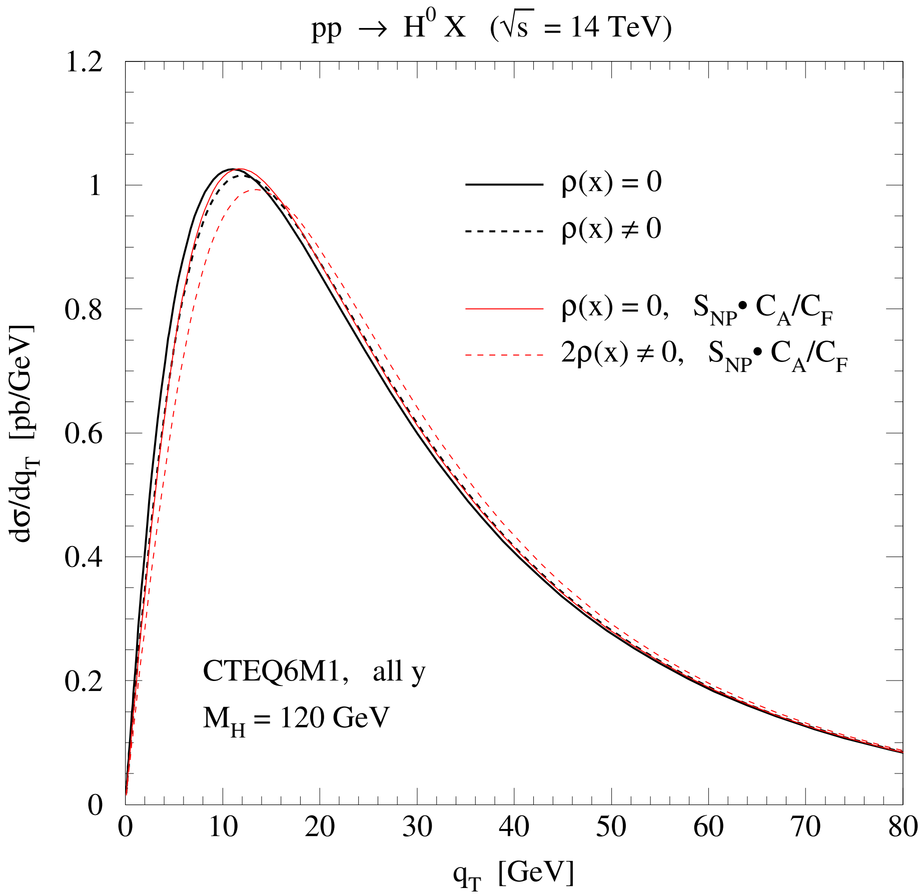
$\mathcal{H}^{(\mathcal{I})}(b_0/b)$ ... virtual corr. to the hard vertex

$\widetilde{U}(b_0/b)^{1/2}$ ... collects soft subgraphs attached to $\mathcal{H}^{(\mathcal{I})}(b_0/b)$

$\widehat{\mathcal{P}}_j(x,b)$ ... is the same in SIDIS and Drell-Yan, (Collins, Metz; hep-ph-0408249)

4. Numerical Results

Higgs Boson production at LHC: $pp(\to gg) \to H^0 X$



Dependence of $d\sigma/dq_T^{H^0}$ on transverse H-boson momentum $q_T^{H^0}$

No y_H cut $\longrightarrow$ no large small x broadening

Distribution peaks at $q_T = 10 - 20$ GeV

black line: $\rho(x)$ and S_{NP} are the same as for Z^0 production

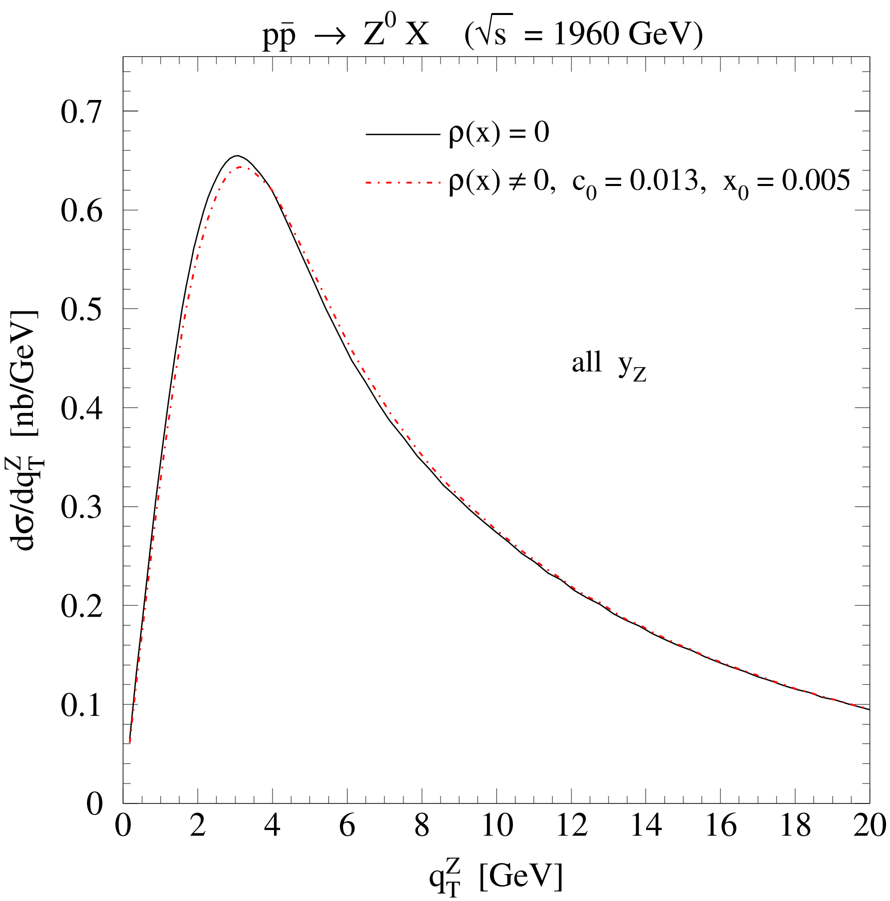
red line: S_{NP} multiplied by $\frac{C_A}{C_F} = \frac{9}{4}$ due to larger leading-logarithm coefficient (C_A) in gg channels compared to $q\overline{q}$ channels (C_F)

$gg \longrightarrow (H \longrightarrow \gamma\gamma)X$:
Signal significance can be increased by selecting events with $q_T^{\gamma\gamma} \gtrsim 30$ GeV (Abdullin et al.)

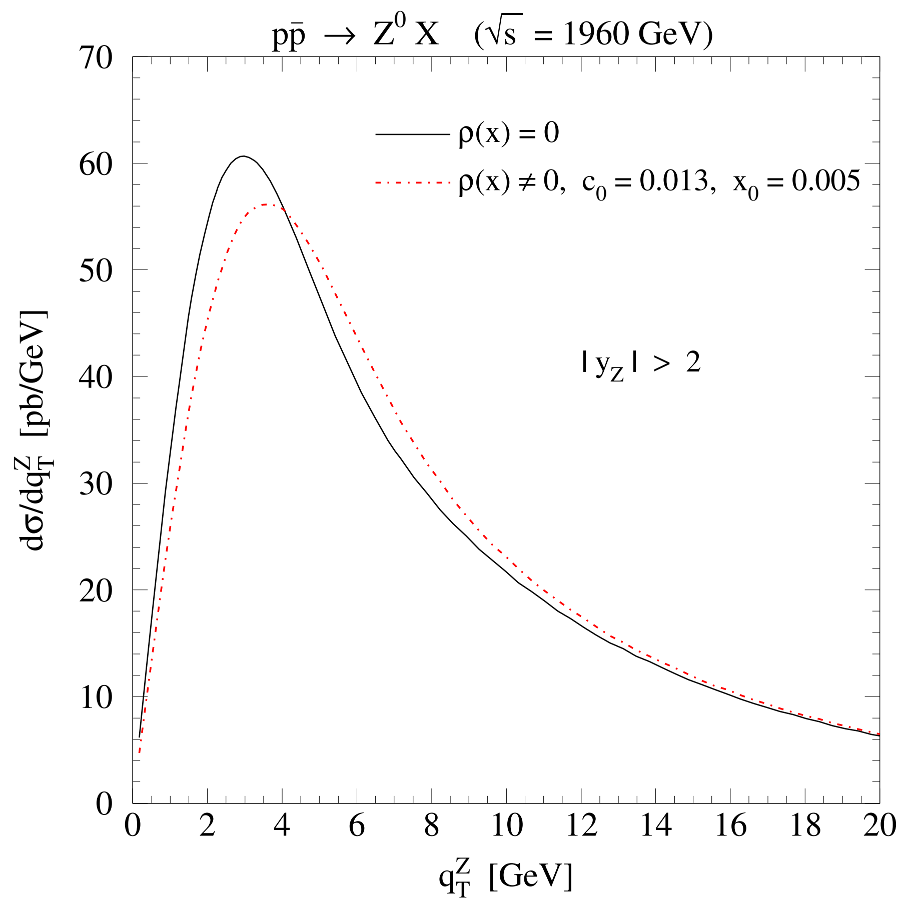
End

Numerical Results

Small-x effects on $p\bar{p} \longrightarrow Z^0 X$ at the Tevatron



No y cut



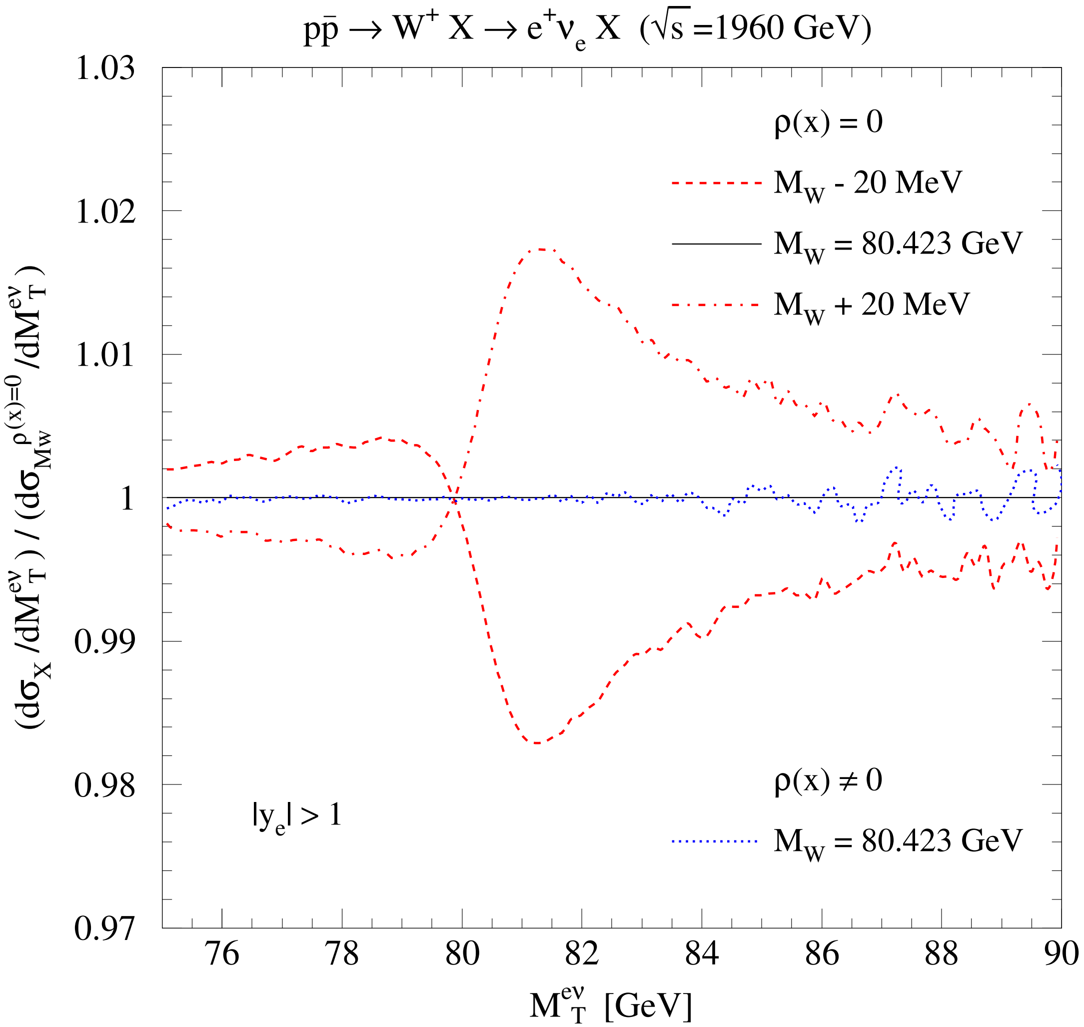
$|y| > 2$

(the dominant contribution comes from $x|_{y \approx 0} \approx 0.05$)

Effect measurable in the Tevatron Run-2

Visible broadening in the forward region
90% of cross section between $2 < |y| < 2.5$

Ratio of W transverse mass distribution

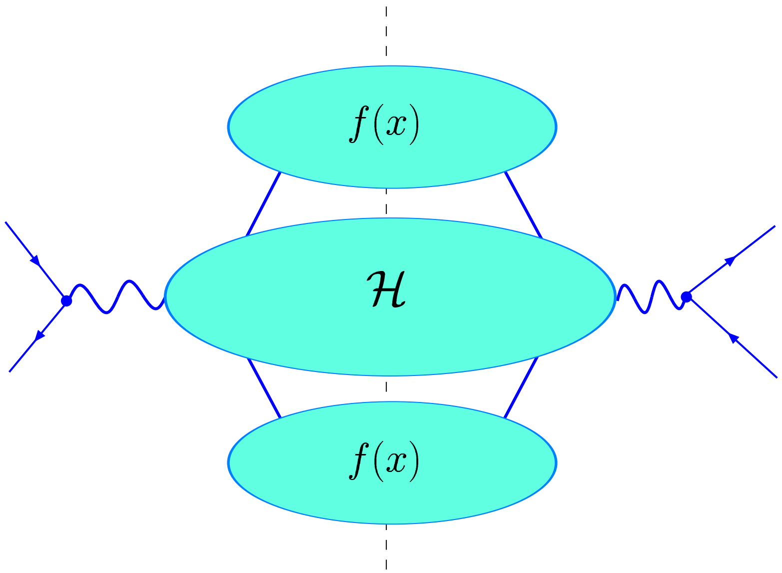


Resummation

QCD factorization in hard and soft regions

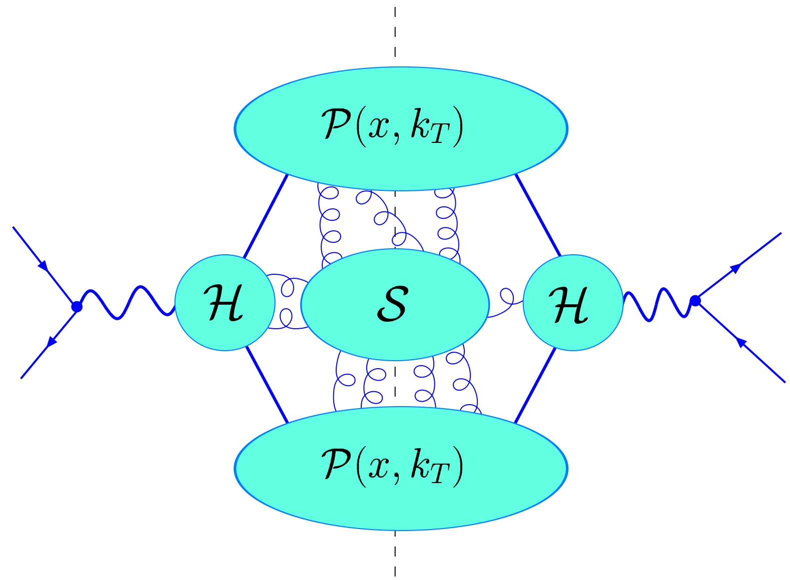
Finite-order (FO) factorization

$\Lambda^2_{QCD} \ll q_T^2 \sim Q^2$



Small-q_T factorization

$\Lambda^2_{QCD} \ll q_T^2 \ll Q^2$



Solution for all q_T: