Transverse momentum distributions: Tevatron experience and LHC

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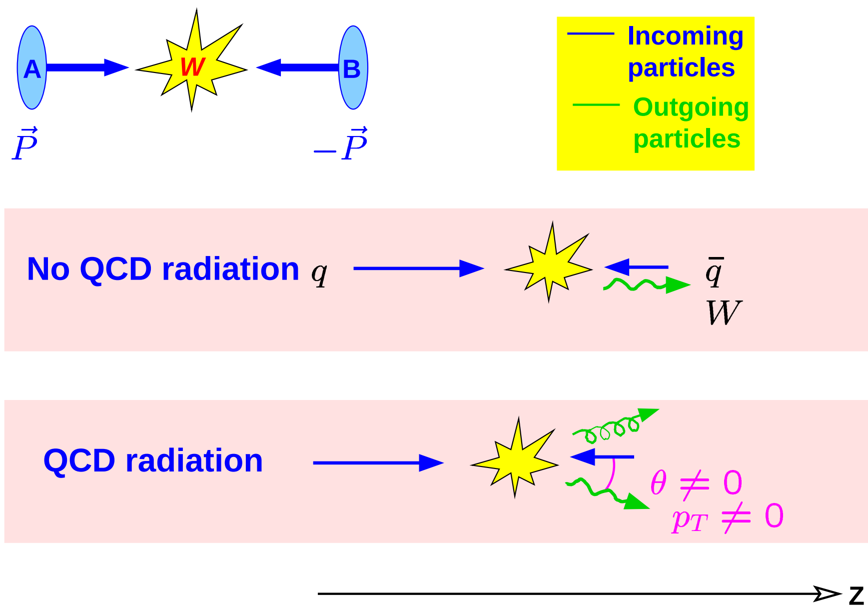
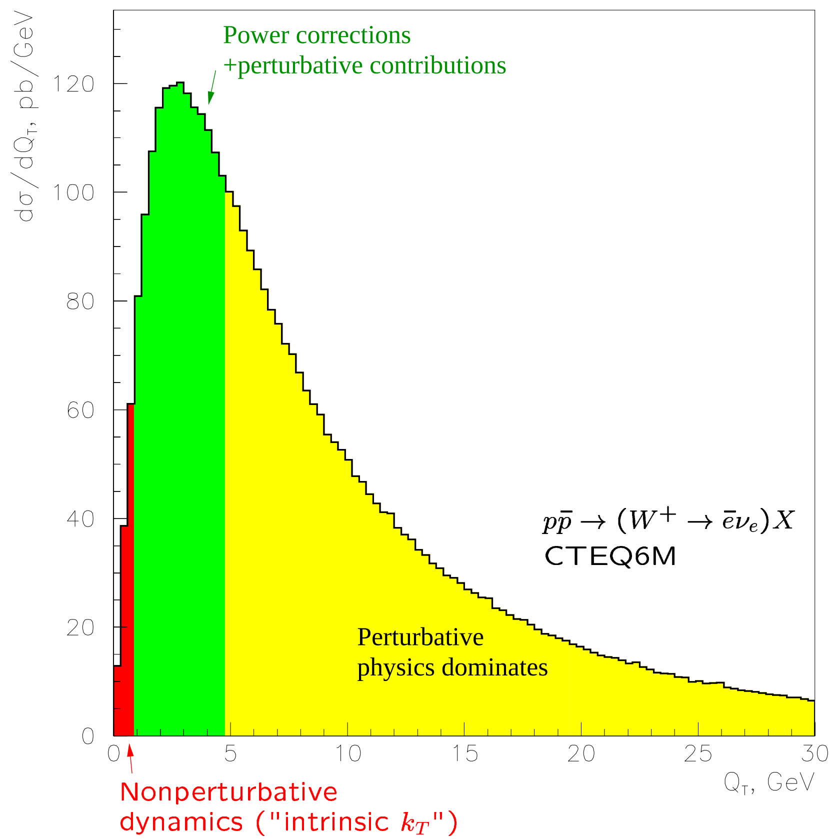
We need to know $d\sigma/dq_T$ well to...

- ✓ measure the W-boson mass ($\delta M_W \sim$ 30 MeV per experiment in the Tevatron Run-2, $\delta M_W \sim$ 15 MeV at the LHC)
  - ♦ Effect of $\delta(d\sigma/dq_T)$: $\delta M_W \lesssim$ a few MeV (tens MeV) in measurement using $d\sigma/dM_T^{e\nu}$ ($d\sigma/dp_T^e$)
- ✓ select SM Higgs boson candidates
  - ♦ A promising channel for $M_H \lesssim$ 140 GeV is $gg \rightarrow H \rightarrow \gamma\gamma$: signal can be enhanced over background by requiring $q_T^{\gamma\gamma} \gtrsim$ 30 GeV
- ✓ select SUSY Higgs boson candidates ($b\bar{b} \rightarrow A_0$,...)
- ✓ learn about QCD: nonperturbative terms in $d\sigma/dq_T$, photon fragmentation in $\gamma\gamma$ production, transition to small-x dynamics,...

q_T resummation for vector boson production at $q_T^2 \ll Q^2$

Resummation: W boson production at the Tevatron





Needed to precisely measure W-boson mass

NLO with elements of NNLO; calculated using ResBos (Balazs, P. N., Yuan)

Resummation describes all q_T range in one unified framework

q_T resummation: available methods

✓ Formalism in impact parameter (b) space *(Collins, Soper, Sterman, 1985)*

- proved by a factorization theorem for k_T-dependent PDF's *(J. Collins, A. Metz, hep-ph/0408249)*
- theory symmetries preserved automatically
- conservation of momentum
- fast and accurate evaluation of Fourier-Bessel transform possible *(ResBos, Balazs, P. N., Yuan)*

✓ Formalism in q_T space *(Altarelli, Ellis, Greco, Martinelli; Ellis, Ross, Veseli)*

✓ analytical evaluation of Fourier-Bessel transform *(Kulesza, Stirling)*

✓ threshold-q_T resummation *(Kulesza, Sterman, Vogelsang)*

Factorization at $q_T \ll Q$

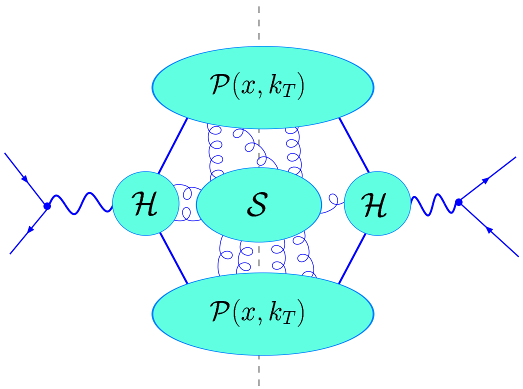
Realized in the space of the impact parameter b (conjugate to q_T)

$$\left.\frac{d\sigma_{AB\to VX}}{dQ^2 dy dq_T^2}\right|_{q_T^2 \ll Q^2} = \sum_{a,b=g,\overset{(-)}{u},\overset{(-)}{d},\dots} \int \frac{d^2 b}{(2\pi)^2} e^{-i\vec{q}_T\cdot\vec{b}} \widetilde{W}_{ab}(b,Q,x_A,x_B)$$

$$\widetilde{W}_{ab}(b,Q,x_A,x_B) = |\mathcal{H}_{ab}|^2 \, e^{-\mathcal{S}(b,Q)} \overline{\mathcal{P}}_a(x_A,b) \overline{\mathcal{P}}_b(x_B,b)$$

$\mathcal{H}_{ab}$ is the hard vertex, $\mathcal{S}$ is the soft (Sudakov) factor, $\overline{\mathcal{P}}_a(x,b)$ is the unintegrated PDF

$$\overline{\mathcal{P}}_a(x,b) = \int d^{n-2}\vec{k}_T e^{-i\vec{k}_T\cdot\vec{b}} \mathcal{P}_a(x,\vec{k}_T)$$



When $b \ll 1\ \mathrm{GeV}^{-1}$, $S(b,Q)$ and $\overline{\mathcal{P}}_a(x,b)$ are calculable in perturbative QCD;
$\overline{\mathcal{P}}_a(x,b)$ factorizes as

$$\overline{\mathcal{P}}_{a/A}(x,b) = \sum_j \int_x^1 \frac{d\xi}{\xi} \mathcal{C}_{ja}(\xi,\mu_F b) f_{j/A}\left(\frac{x}{\xi},\mu_F\right) + \mathcal{O}(b^2) \equiv \left(\mathcal{C}_{ja}\otimes f_{a/A}\right) + \mathcal{O}(b^2)$$

(note the power-suppressed terms)

Resummation in the Tevatron Run-2 ($\delta M_W \sim 30$ MeV per experiment)

Correlated effects of

✓ nonperturbative function $e^{-S_{NP}(b,Q)}$ in $d\sigma/dq_T$

- several available models *(CSS, 1985; Korchemsky, Sterman, 1995; Qiu, Zhang, 2000; Kulezsa, Sterman, Vogelsang, 2002; Guifanti, Smye, 2000; X. Ji, J. Ma, F. Yuan, 2004;...)*
- Effect of $S_{NP}(b,Q)$ on Z^0 production is non-negligible in any non-perturbative model at $q_T < 10$ GeV
- challenge: predict $d\sigma/dq_T$ with accuracy compatible with $\delta M_W \sim 30$ MeV
- b_* prescription: a parametrization describing the low-Q Drell-Yan and Z^0 data *(Brock, Landry, P.N., Yuan, 2002)*

✓ uncertainties in parton distributions

- combined CTEQ analysis of errors in PDF's and $S_{NP}(b,Q)$ *(in progress)*

Correlated effects in the Tevatron Run-2 (continued)

✓ Next-to-leading order electroweak corrections

- QCD resummation + final-state QED radiation *(Q. Cao, C.-P. Yuan, 2004)*
- γZ interference in resummed cross sections (to be implemented)

✓ $\mathcal{O}(\alpha_s^2)$ corrections

- substantial at $q_T \sim Q$ *(Arnold, Reno)*; currently available for on-shell W bosons
- large NNLO K-factor in low-energy Drell-Yan process *(Anastasiou, Dixon, Melnikov, Petriello)*; may affect determination of $S_{NP}(b, Q)$

New factors at the LHC ($\delta M_W \sim$ 15 MeV)

✓ Treatment of heavy-flavor contributions

- Charm contributions in W production at the LHC are sizable ($\sim$ 26% of σ_{tot}) and much larger than in Z production ($\sim$ 8%)
- A different shape of $d\sigma/dp_T^e$ for $c + s \to W^{\pm} + X$ and other heavy-flavor channels shifts δM_W by 3-10 MeV *(Berge, P.N., Olness)*

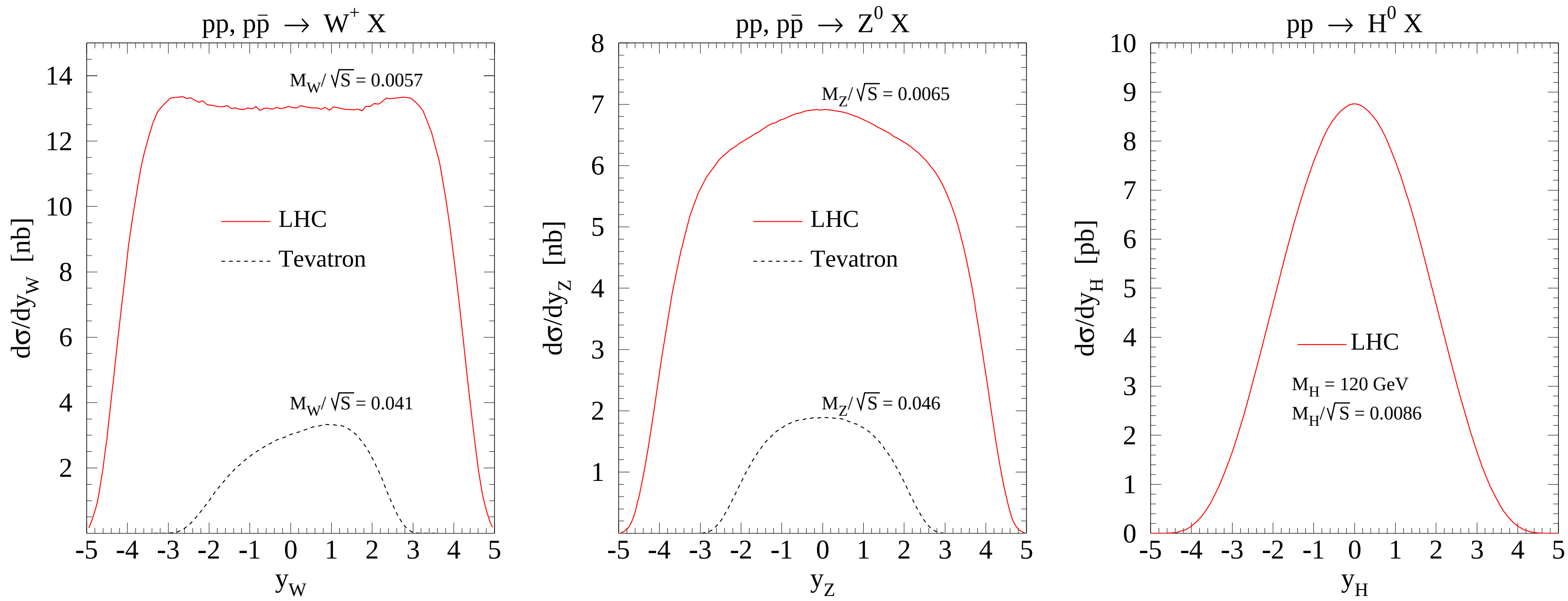
✓ $gg \to H \to \gamma\gamma$: resummation in gluon-initiated channel

- Test resummation and nonperturbative contributions in gg channel in $p\bar{p} \to \gamma\gamma X$ at $Q \sim 30 - 50$ GeV, $p\bar{p} \to \Upsilon X$

✓ Rapidity dependence of $d\sigma/dq_T$

- must be explored in the Tevatron Run-2!

Rapidity distributions for W, Z, and H bosons at the Tevatron and LHC



- ✓ $x|_{y=0} = M_V/\sqrt{S} < 10^{-2}$ ($6 \cdot 10^{-3}$ for W and Z, $> 8 \cdot 10^{-3}$ for H); this region is not probed by Run-1 data!
- ✓ different partonic content ($\sim u\bar{d} + \bar{d}u$ for W^+, $u\bar{u} + d\bar{d}$ for Z^0, gg for H^0) $\Rightarrow$ different shapes of $d\sigma/dy$

Sensitivity to the small-x region varies with the boson type!

Effect of lepton selection cuts

✓ $Z^0 \to e^+e^-$: we can select central-rapidity Z^0 bosons by requiring

$$|y_{e^\pm}| < y_{max}$$

✓ $W \to e\nu$: y_ν cannot be measured

- forward-rapidity W bosons will be present in any event sample

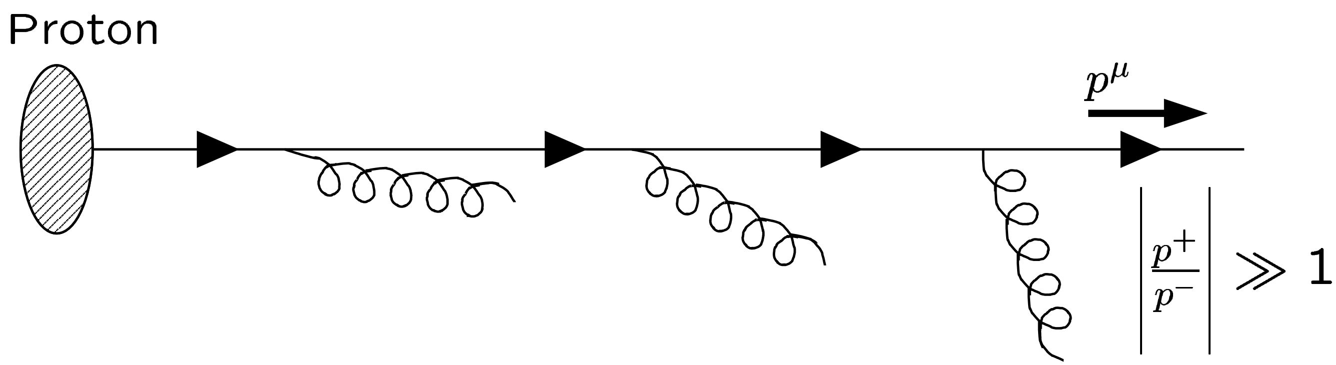
Hypothetical strong dependence of $d\sigma/dq_T$ on y would most strongly affect W boson production!

Resummation for the Tevatron and LHC at small x

(S. Berge, P. N., F. Olness, C.-P. Yuan, hep-ph/0401128; PRD paper near completion)

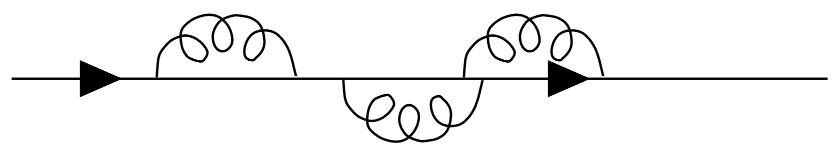
$$x < 10^{-2}$$

Physics behind DGLAP factorization (cartoon)



$$\Lambda^2_{QCD} \ll k^2_{nT} \ll \dots \ll k^2_{2T} \ll k^2_{1T}$$

$+$



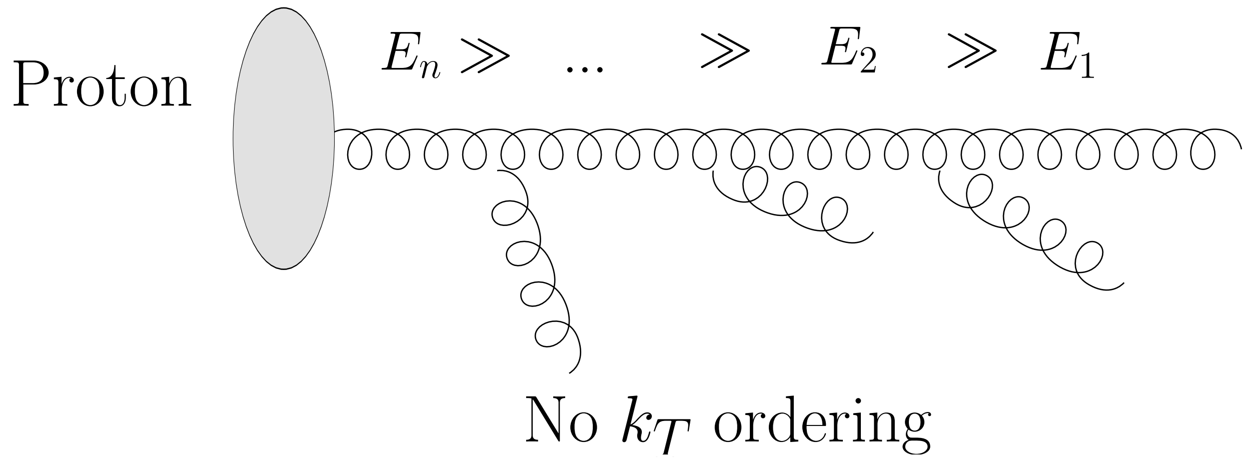
Probed parton is highly boosted throughout all evolution

Soft and collinear radiation

- ✓ dominates parton evolution
- ✓ factorizes from the hard scattering
- ✓ is "collimated" ("k_T-ordered")

Angular distributions are described in a b-space resummation formalism (Collins, Soper, Sterman, 1985)

The ultimate energy loss scenario (BFKL)



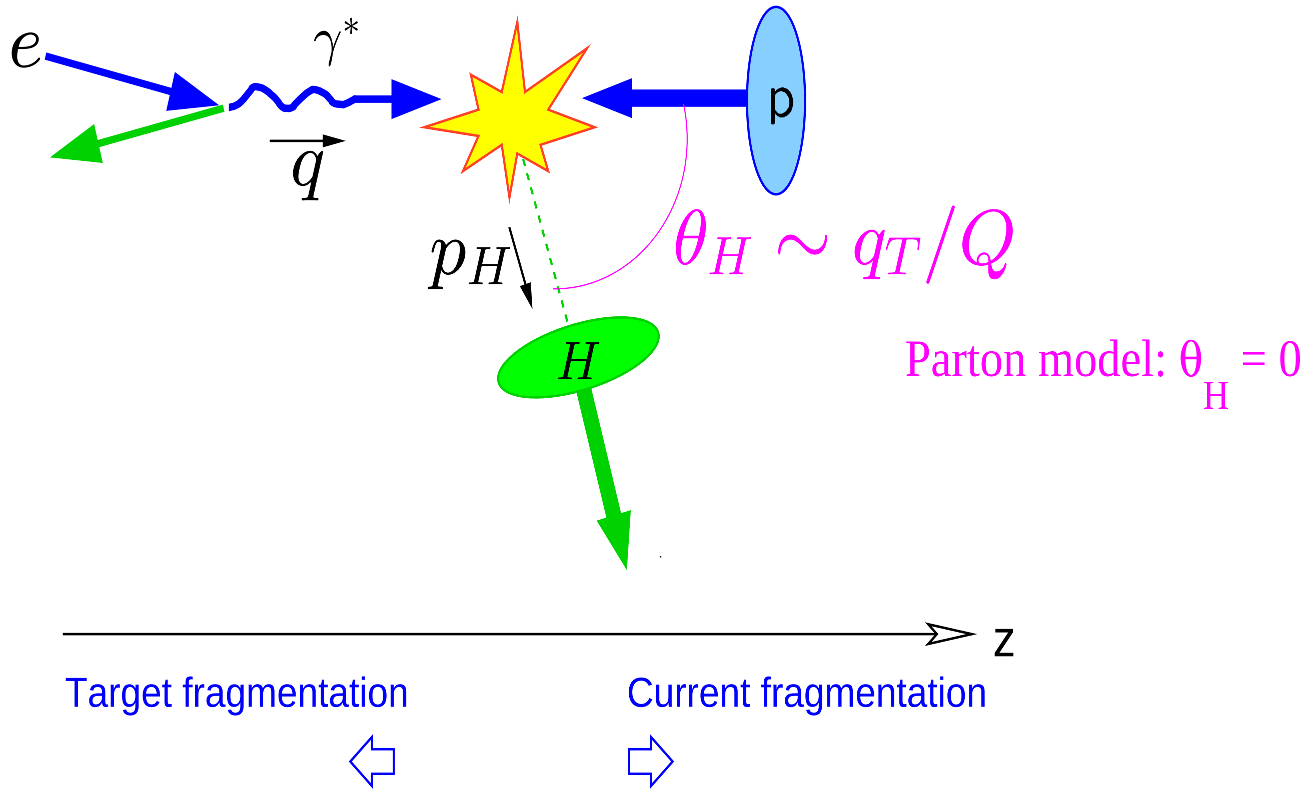
- ✓ The probed parton loses practically all energy through radiation
- ✓ The radiated partons do not have to be k_T-ordered
- ✓ Essential signature: broad angular distributions of the radiated hadrons

As x decreases, k_T-unordered dynamics may turn on faster in q_T distributions than in inclusive cross sections

[Compare $\alpha_S^n(Q)\ \ln^m(1/x)$ and $\alpha_S^n(1/b)\ \ln^m(1/x)$]

Could this dynamics affect q_T distributions at the existing colliders?

Semi-inclusive DIS in $\gamma^* p$ c.m. frame



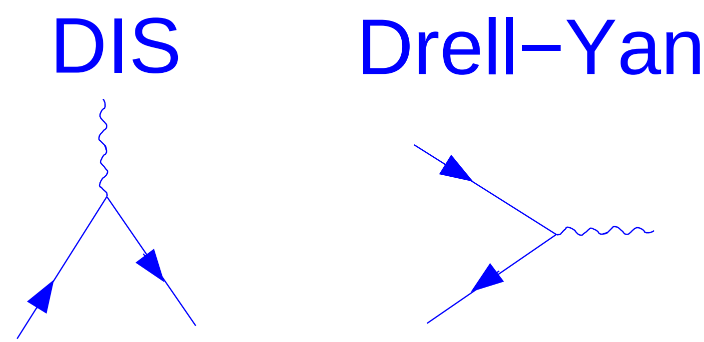
Production of light hadrons: $H = \pi, K, p, ..$
or energy flow

Production of heavy flavors: $H = D, B, ...$

DIS hadroproduction is related to Drell-Yan process through crossing

Due to its Lorentz invariance, CSS formalism should be straightforwardly applicable to DIS hadroproduction

(Collins, 1993; Meng, Olness, Soper, 1996; P. N., D. Stump, C.-P. Yuan, 1998-2000)



q_T resummation is relevant in the current fragmentation region ($\theta_H \sim q_T/Q \to 0$)

Small-q_T cross section is related to a form factor in the impact parameter (b) space

$$\left.\frac{d\sigma}{dx dz dQ^2 dq_T^2}\right|_{q_T\to 0} \propto \int \frac{d^2b}{(2\pi)^2} e^{-i\vec{q}_T\cdot\vec{b}}\overline{\mathcal{D}}(z,b)e^{-S(b,Q)}\overline{\mathcal{P}}(x,b)$$

$S(b,Q)$: soft (Sudakov) factor (same as in DY process)

$\overline{\mathcal{P}}(x,b) \approx (\mathcal{C}\otimes f)(x,b)$: b-dependent parton distribution

$\overline{\mathcal{D}}(z,b) \approx (D\otimes\mathcal{C})(z,b)$: b-dependent fragmentation function

From angular distributions of the hadronic transverse energy flow,

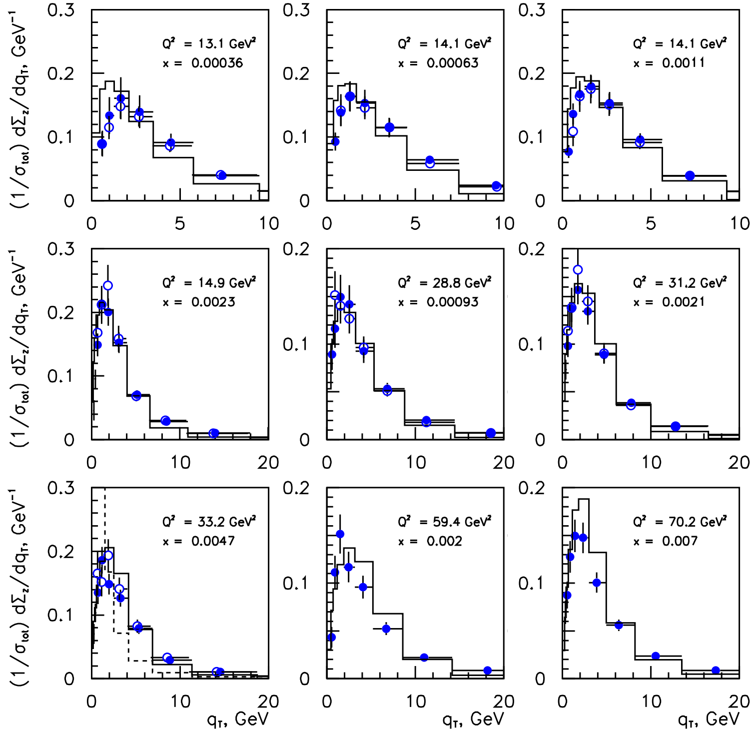
$$\frac{d\langle E_T\rangle}{dx dQ^2 dq_T^2} \propto \int dz\cdot z\cdot\frac{d\sigma}{dx dz dQ^2 dq_T^2}$$

$$\propto \text{const}\cdot\int \frac{d^2b}{(2\pi)^2} e^{-i\vec{q}_T\cdot\vec{b}} e^{-S(b,Q)}\overline{\mathcal{P}}(x,b),$$

one can learn about the x-dependence of $\overline{\mathcal{P}}(x,b)$ and make predictions for the Drell-Yan processes

q_T dependence of E_T flow at small x

Data from *H1 Collaboration*



$13.1 < \langle Q^2 \rangle < 70.2 \quad \mathrm{GeV}^2$,

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

Resummed E_T-flow: CTEQ5M1 PDFs,

$$S_{E_T}^{NP} = b^2 \left\{ 0.013 \frac{(1-x)^3}{x} + 0.19 \ln \left(\frac{Q}{2 \text{ GeV}} \right) \right\}$$

Possible interpretation:
rapid increase of "intrinsic" k_T when x decreases (first signs of k_T-unordered radiation???)
No mechanism for such increase in the $\mathcal{O}(\alpha_s)$ part of the CSS formula

Can be parametrized as

$$\overline{\mathcal{P}}(x,b) = (\mathcal{C} \otimes f)(x, b_*) e^{-\rho(x) b^2},$$
$$\rho(x) \approx \frac{0.013}{x} \text{ at } x \lesssim 10^{-2}$$

A model for resummed form factor in Drell-Yan processes

$$\widetilde{W}(b, Q, x_A, x_B) = \frac{\pi}{S} \sum_{a,b} \sigma_{ab}^{(0)} \left[\mathcal{C}_{a/c} \otimes f_c\right] (x_A, b_*) \left[\mathcal{C}_{b/d} \otimes f_d\right] (x_B, b_*)$$
$$\times \; e^{-\mathcal{S}_P(b_*,Q) - S_{NP}^{BLNY}(b,Q;b_*)} \, e^{-b^2 \rho(x_A) - b^2 \rho(x_B)},$$

where

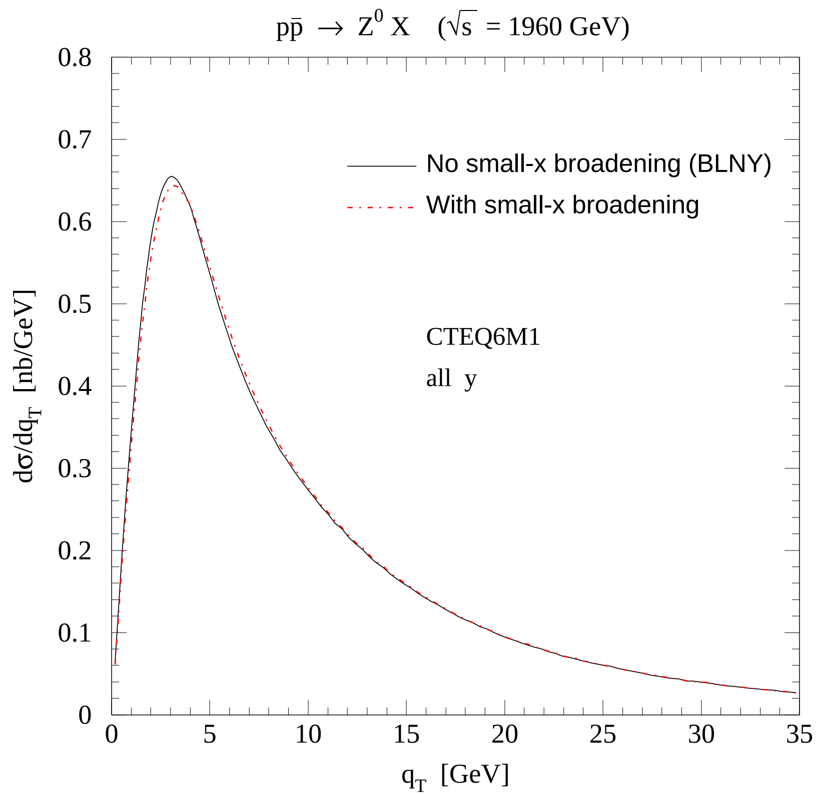
$$\rho(x) = c_0 \left(\sqrt{\frac{1}{x^2} + \frac{1}{x_0^2}} - \frac{1}{x_0} \right)$$

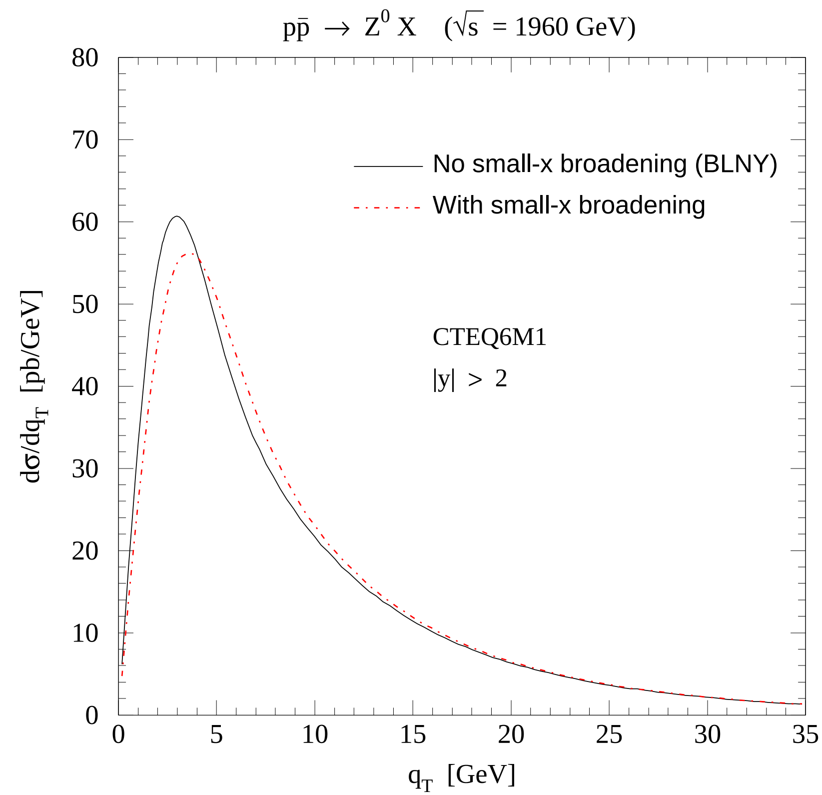
$x \gg x_0$: $\rho(x) = 0 \;\Rightarrow$ BLNY form is reproduced

$x \ll x_0$: $\rho(x) \approx c_0/x$

Based on the observed behavior $\rho(x) \sim 0.013/x$ at $x < 10^{-3} - 10^{-2}$ in SIDIS, we take $c_0 = 0.013$ and $x_0 = 0.005$

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





No cuts: no visible effects

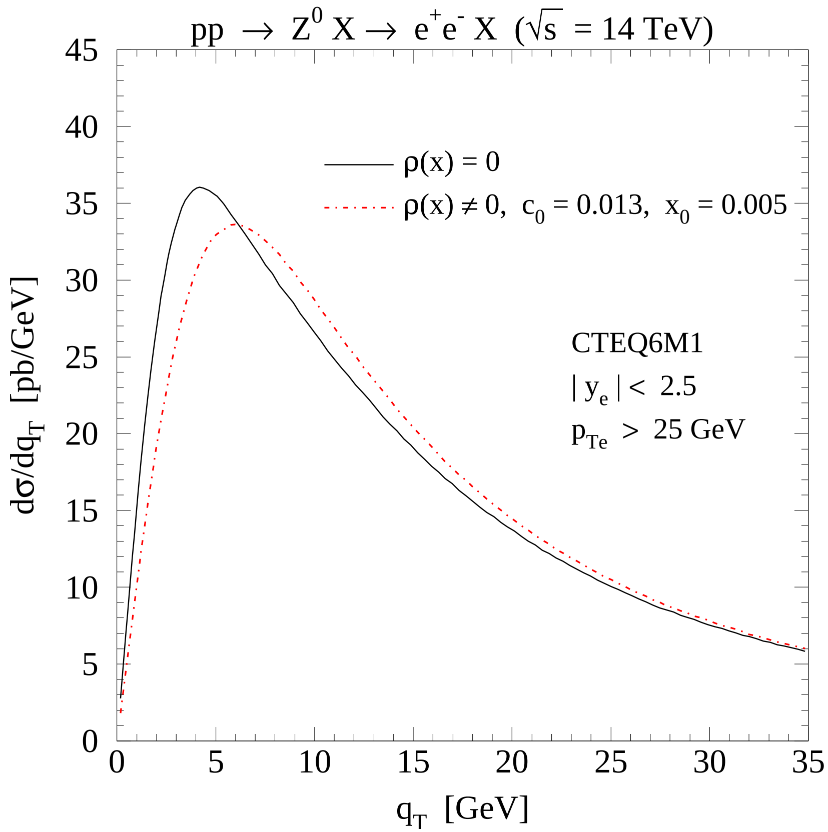
(the dominant contribution comes from $x|_{y\approx 0} \approx 0.05 \gg x_0$)

$|y| > 2$

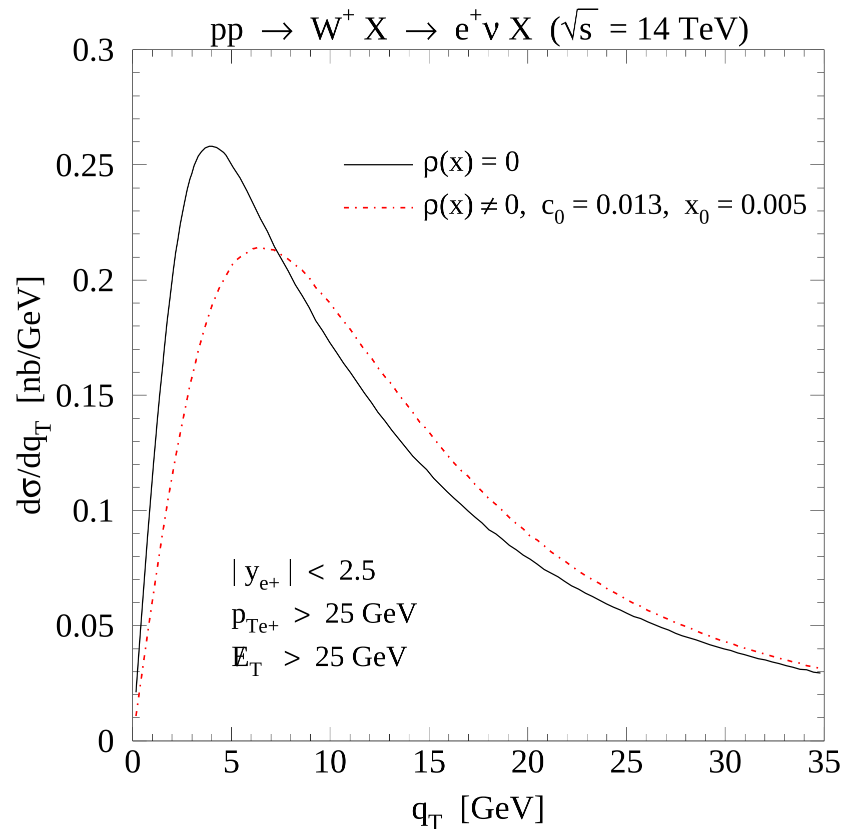
Visible broadening in the forward region

Effect measurable in forward-rapidity events in the Tevatron Run-2

Small-x effects at the LHC: visible even in the central region!



Z^0 production



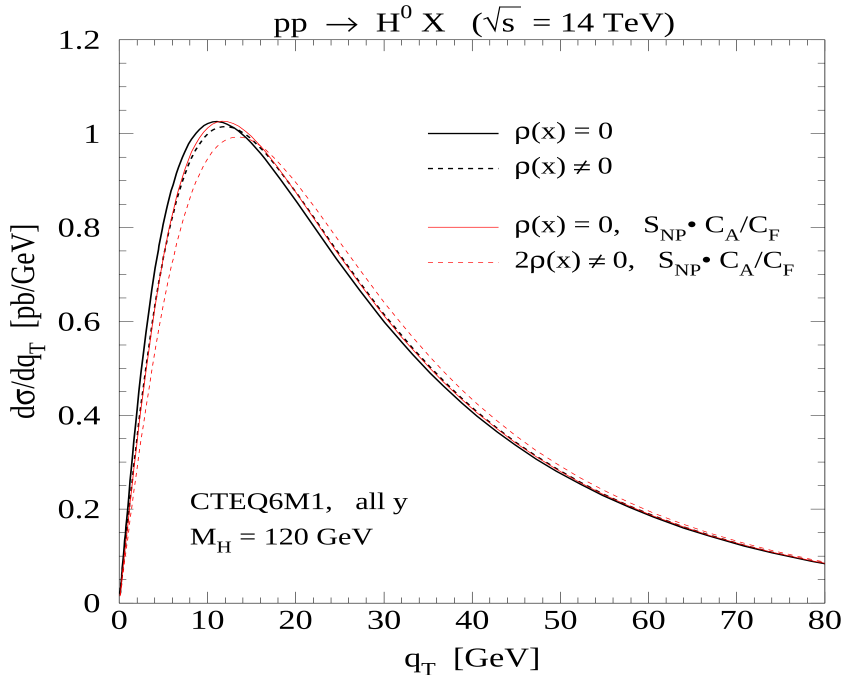
W^+ production

✓ q_T broadening is stronger in W^+ production because

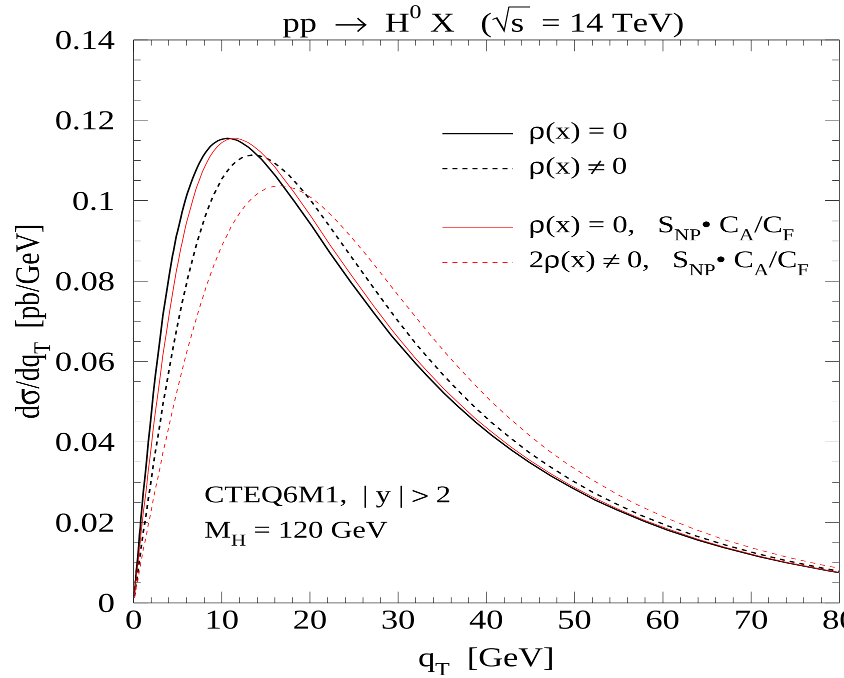
- $M_W < M_Z$
- $d\sigma(W)/dy$ is wider than $d\sigma(Z)/dy$
- y_ν is integrated out

✓ Broadening increases as y grows

SM Higgs boson production



all y



$|y| > 2$

Effects are less pronounced in $gg \to H \to \gamma\gamma$ due to (a) narrower rapidity distribution and (b) harder q_T spectrum

Effects on the background $q\bar{q} \to \gamma\gamma$ may be substantial

If q_T broadening is present, selection cuts on q_T of Higgs boson candidates may have to be revised

Summary

✓ Measurement of M_W with accuracy about 15 MeV at the LHC will be affected by correlated effects on $d\sigma/dq_T$ from

- the nonperturbative function $S_{NP}(b,Q)$
- parton distribution uncertainties
- NLO electroweak and NNLO QCD corrections
- quark flavor dependence

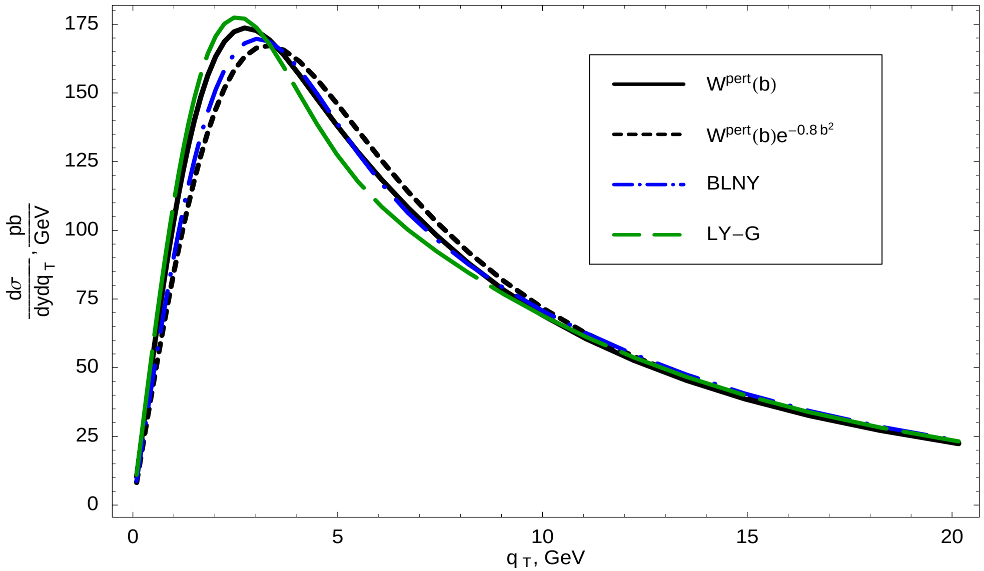
✓ Strong correlations between q_T and momentum fractions x may occur in $d\sigma/dq_T$ in the region $x < 10^{-2}$ (not probed by the Run-1 data)

✓ Semi-inclusive DIS data suggests broadening of q_T distributions at $x \lesssim 10^{-2}$. If observed in forward Z boson production in the Tevatron Run-2, q_T broadening will strongly affect predictions for W and H production at the LHC

Backup slides

Sensitivity of q_T cross sections to nonperturbative contributions

Resummed $d\sigma/dq_T^2$ is expected to include a universal nonperturbative function $S_{NP}(b,Q)$ (analogous to universal PDF's)



Comparison of models for nonpert. terms (b_* and extrapolation)

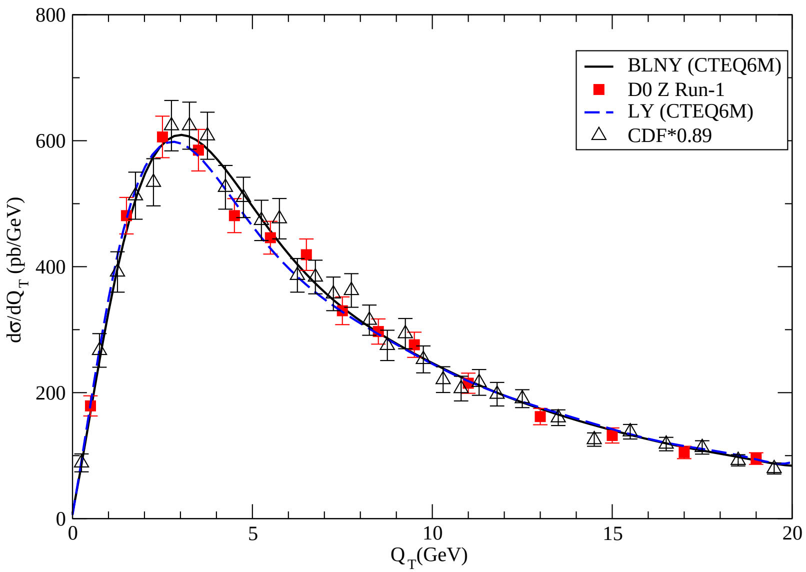
$S_{NP}(b,Q)$ is non-negligible in any non-pert. model at $q_T < 10$ GeV

Variation of non-pert. terms moves the peak of $d\sigma/dq_T$ by 200-500 MeV

- Valid models for $S^{NP}(b,Q)$ must provide accuracy comparable to $\delta M_W \sim 30$ MeV

Models for nonperturbative contributions

- ✓ b_* anzatz *(CSS, 1985)*
  - ♦ simultaneous agreement with all fixed-target Drell-Yan and Z^0 boson data *(Landry, Brock, P. N., Yuan, 2002)*
  - ♦ strong evidence for universality of $S_{NP}(b, Q)$



BLNY result vs. Run-1 Z data

- ✓ freezing $\alpha_s(\mu)$ at $\mu \sim \Lambda_{QCD}$
- ✓ renormalon analysis *(Korchemsky, Sterman, 1995)*
- ✓ extrapolation of leading power terms *(Qiu, Zhang, 2000)*
- ✓ principal value resummation *(Sterman; Kulezsa, Sterman, Vogelsang, 2002)*
- ✓ dispersive equations *(Guifanti, Smye, 2000)*

X.

- ✓ k_T-dependent factorization *(X. Ji, J. Ma, F. Yuan, 2004)*

Ji, J. Ma, F. Yuan, 2004X. Ji, J. Ma, F. Yuan, 2004

In all models, incalculable power correction terms are required for agreement with data ($\sim \exp\{-gb^2\}$, with $g \sim$ 0.8 (2.7) in extrapolation (b_*) model)

Heavy-flavor effects at electroweak scales (in progress)

- ✓ Aside from the flavor dependence of the PDF's $f_a(x,Q)$, mass effects at $Q \sim M_W \gg m_q$ are generally suppressed by $e^{-\mathcal{S}(b,Q)}$
- ✓ W boson production: effects on M_W of the charm mass $m_c \neq 0$ are negligible at the Tevatron, and are of order a few MeV at the LHC
- ✓ Higgs boson production in 2 Higgs-doublet model $b+\bar{b} \rightarrow \text{Higgs} + X$, $b+\bar{b} \rightarrow b + \text{Higgs} + X$: moderate effects at $q_T \lesssim M_b$
- ✓ Application to single-top production at the Tevatron, e.g. $u\bar{b} \rightarrow \bar{d}t$