ResBos & nonperturbative contributions to Q_T resummation

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Estimation of PDF uncertainties in ResBos

The number of events per iteration should be of order 1000 to reach the fastest convergence of VEGAS

Estimation of PDF uncertainties in ResBos

If $X_i^{(\pm)}$ and $\Delta X^2 = \sum_{i=1}^{N} \left(X_i^{(+)} - X_i^{(-)} \right)^2 / 4$ are computed in $2N = 44$ independent Monte-Carlo runs with $\bar{N}$ events each, their resulting estimates are given by

$$\overline{X}_i^{(\pm)} = X_i^{(\pm)} + \overline{\delta}_i^{(\pm)} \sim X_i^{(\pm)} + \frac{c}{\overline{N}^{1/2}} \text{ and}$$

$$\overline{\Delta X}^2 = \frac{1}{4} \sum_{i=1}^{N} \left(\overline{X}_i^{(+)} - \overline{X}_i^{(-)} \right)^2 \sim \Delta X^2 + \frac{c' N}{\overline{N}^{1/2}}$$

$\overline{\delta}_i^{(\pm)}$ is a **random** MC error dependent on the input PDF, arising, e.g., from importance sampling

As a result of the PDF dependence of $\overline{\delta}_i^{(\pm)}$, the error $\overline{\Delta X}^2 - \Delta X^2$ is increased by a factor $N \sim 22$

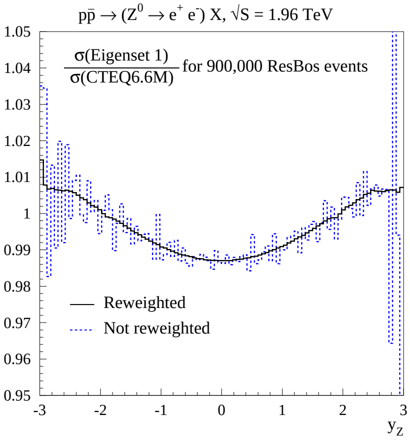
Solution: PDF reweighting

FROOT: a simple interface for Monte-Carlo PDF reweighting

```
// These are the C functions accessible from Fortran.


extern "C" {
  //Initialization of the ROOT file
  void initrootnt_(const char *title, const char *access, int ltitle, int laccess);
  void reinitrootnt_(const char *access, int laccess);
  void addntbranch_(float *element, const char *chtag, int ltag);
  void fillntbranch_(const char *chtag, int ltag);
  int getnumbranches_();
  void rootntoutp_();
  void printnt_();
  void teststr_(const char *str, int lstr);

}//extern "C"
```



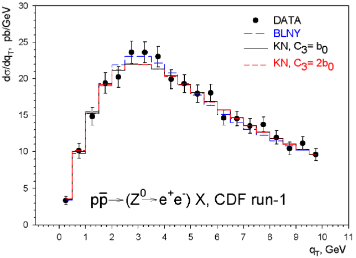
Measurement of M_W and resummation

QCD uncertainties on M_W arise from

- the model for W boson's recoil in the transverse plane
- parton distributions

$d\sigma/dQ_T$ for W & Z bosons is predicted by the resummation formalism, which evaluates $\sum_{n,m} \alpha_s^n \ln^m(Q_T^2/Q^2)$ at $Q_T \to 0$ to all orders of α_s

(Collins, Soper, Sterman, 1985)



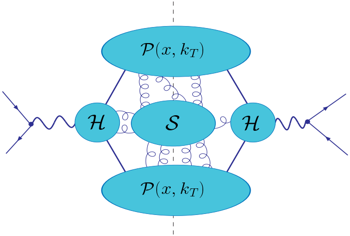
uncertainty in nonperturbative resummed parameters $g_2,\ g_3$ translates into δM_W of a few MeV

Let's discuss QCD theory behind these estimates

QCD factorization at $Q_T \to 0$

Small-Q_T factorization

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

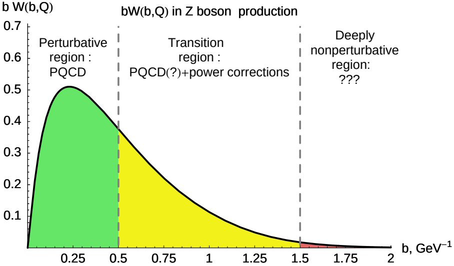


- Realized in space of the impact parameter b (conjugate to Q_T)
- At NNLL accuracy, we include perturbative coefficients up to orders $\mathcal{A}^{(3)}$ *(from Moch, Vermaseren, Vogt, 2004)*; $\mathcal{B}^{(2)}$; and $\mathcal{C}^{(1)}$

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

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

Three regions in $b\widetilde{W}(b,Q)$ in EW boson production



- $b \lesssim 0.5$ GeV^{-1} ($\mu_b \sim 1/b > 2$ GeV):

  dominant region, described in PQCD at NNLL/NLO;

- $0.5 \lesssim b \lesssim 1.5 - 2$ GeV^{-1} ($0.5 - 0.7 \lesssim \mu_b \lesssim 2$ GeV):

higher-order terms in α_s and b^p affect $d\sigma/dQ_T$ at $Q_T \lesssim 10$ GeV; have a large effect on M_W

- $b \gtrsim 1.5 - 2$ GeV^{-1}: largely unknown; negligible effect on the analyzed data

Nonperturbative resummed contributions

were extensively studied; see, for example,

- *Davies, Webber, Stirling, 1984*
- *Ladinsky, Yuan, 1993*
- *Korchemsky, Sterman, 1995*
- *Ellis, Ross, Veseli, 1997*
- *Brock, Landry, Ladinsky, Yuan, 2001*
- *Kulesza, Stirling, 2001*
- *Tafat, 2001*
- *Qiu, Zhang, 2001*
- *Kulesza, Sterman, Vogelsang, 2002*
- *Brock, Landry, P.N., Yuan, 2002*

- ***Konychev, P.N., PL B633, 710 (2006)*** : an improved nonperturbative parametrization, reconciles several studies, better agrees with the Drell-Yan p_T data

Gaussian smearing in Z boson production

The large-b behavior of $\widetilde{W}(b,Q)$ is often approximated as

$$\widetilde{W}(b,Q,x_A,x_B)\Big|_{all\ b} \approx \widetilde{W}'_{LP}(b,Q,x_A,x_B)e^{-a(Q,x_A,x_B)b^2},$$

where $\widetilde{W}'_{LP}(b,Q,x_A,x_B)$ is a continuation of the perturbative (leading-power) contribution to $b \gtrsim b_{max} \sim 1$ GeV^{-1}

For example, in the "b$_*$" model *(CSS, 1985)*:

$$\widetilde{W}'_{LP}(b) \equiv \widetilde{W}_{pert}(b_*) \rightarrow \begin{cases} \widetilde{W}_{pert}(b), & b \ll b_{max} \\ \widetilde{W}_{pert}(b_{max}), & b \gg b_{max} \end{cases}$$

$$b_* \equiv \frac{b}{\sqrt{1+b^2/b_{max}^2}}$$

Gaussian smearing in Z boson production II

The large-b behavior of $\widetilde{W}(b,Q)$ is often approximated as

$$\widetilde{W}(b,Q,x_A,x_B)\Big|_{all\ b} \approx \widetilde{W}'_{LP}(b,Q,x_A,x_B)e^{-a(Q,x_A,x_B)b^2}$$

$a(Q,x_A,x_B)$ is the nonperturbative "Gaussian smearing";

- dominates NP terms at $b \lesssim 2$ GeV^{-1}
- is universal in Drell-Yan-like processes and SIDIS;
- can be found from a fit to p_T data (currently 3 low-Q Drell-Yan pair and 2 Run-1 Z production data sets)
- RG invariance + factorization properties of $\widetilde{W}(b,Q)$:

$$a(Q,x_A,x_B) \approx a_1 + a_2 \ln\frac{Q}{Q_0} + a_3\left[\phi(x_A)+\phi(x_B)\right]$$

Renormalon analysis+lattice QCD: $a_2 = 0.19^{+0.12}_{-0.09}$ GeV^2 *(Tafat)*

Gaussian smearing in global p_T fits

$a_{1,2,3}$ found from the fit are correlated with the assumed form of $\widetilde{W}'_{LP}(b, Q, x_A, x_B)$ (value of b_{max})

Landry, Brock, P. N., Yuan, 2002
($b_{max} = 0.5$ GeV^{-1}):

$a(Q) =$

$$\underbrace{0.21}_{a_1} + \underbrace{0.68}_{a_2} \ln \frac{Q}{3.2} - \underbrace{0.13}_{a_3} \ln(100 x_A x_B)$$

- a_3 is comparable to a_1, a_2
- For $\sqrt{s} = 1.96$ TeV, $a(M_Z) \approx 2.7$ GeV^2 (surprisingly large)

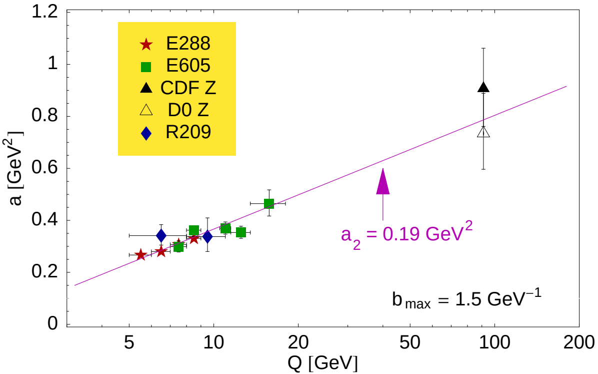
Konychev, P. N., 2006
($b_{max} = 1.5$ GeV^{-1}):

$a(Q) =$

$$0.20 + 0.19 \ln \frac{Q}{3.2} - 0.03 \ln(100 x_A x_B)$$

- $a_2 \sim 0.19$ GeV^2 agrees well with Tafat's calculation
- $a_3 \ll a_1, a_2$; in Z production, $a(M_Z) \approx 0.9$ GeV^2
- reduced $\chi^2/d.o.f. = 110/95$ in the fit

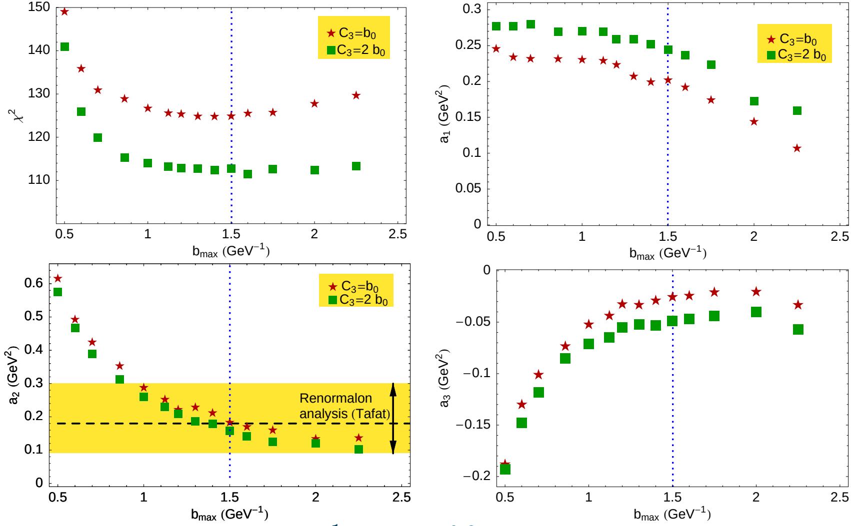
Independent scans of $a(Q)$ in 5 experiments



$$\mathcal{F}_{NP}(b,Q) \approx a(Q) b^{2-\beta}$$

- All experiments prefer $\beta \approx 0$
- $a(Q) \approx a_1 + a_2 \ln(Q/3.2)$
- $a_2 \sim 0.18$ GeV^2 agrees well with the IR renormalon + lattice QCD estimate, $(a_2)_{IR} = 0.19^{+0.12}_{-0.09}$ GeV^2

Scan over b_{max}



Best fit: $b_{max} \approx 1.5$ GeV^{-1}, $\beta = 0^{+0.3}_{-0.4}$ (set to 0), $a_1 \approx 0.23$, $a_2 \approx 0.18$, $a_3 \approx -0.05$

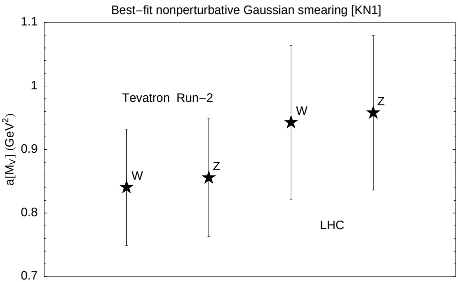
The p_T fit based on the revised b_* model

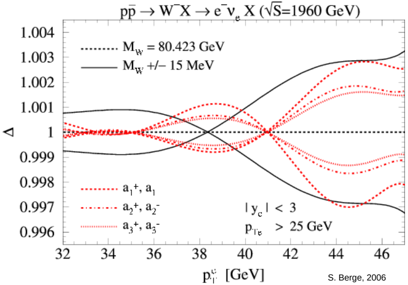
- leads to a consistent picture of the power-suppressed term
- suggests
  - Gaussian
    $\mathcal{F}_{NP}(b,Q) = b^2\,[0.20 + 0.19\,\ln(Q/3.2) - 0.026\,\ln(100 x_A x_B)]$
  - linear $\ln Q$ dependence (consistent with SIDIS)
  - small $\sqrt{s}$ dependence
  - no tangible flavor dependence
- supports dominance of soft contributions in $\mathcal{F}_{NP}(b,Q)$
- **applies to light-flavor (u, d, s) scattering at $x \gtrsim 10^{-2}$**

Uncertainties in the nonperturbative function

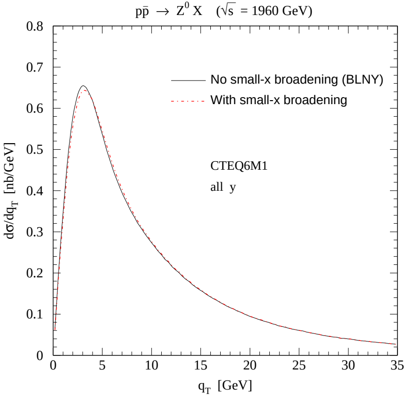
$\mathcal{F}_{NP}(b, Q)$

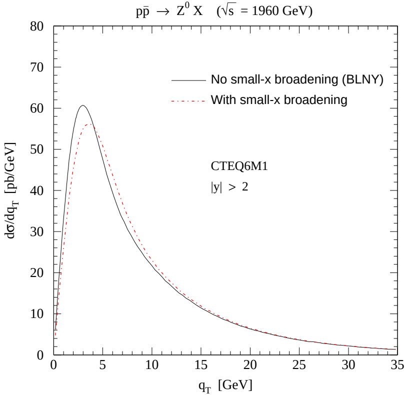
- Lagrange multiplier method
  - Constraints on $a(M_Z)$, $a(M_W)$ from the global fit better than from the Z data alone
- Hessian method
  - RESBOS grids for 6 extreme eigenvectors in $\{a_1, a_2, a_3\}$ space
- Other important uncertainties exist!





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





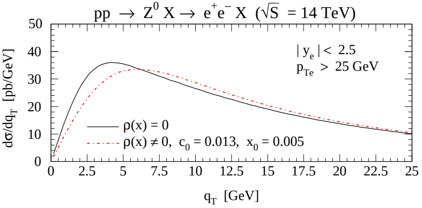
No cuts: no visible effects (the dominant contribution comes from $x|_{y\approx 0} \approx 0.05$)

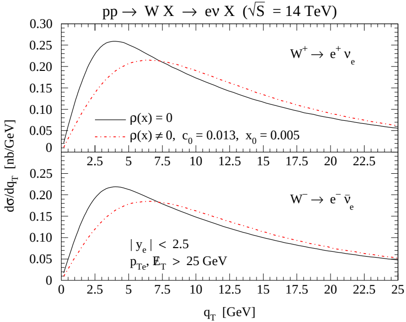
$|y| > 2$

Visible broadening in the forward region

Effect measurable in the Tevatron Run-2; may change M_W by 5-20 MeV

Resummation for $x < 10^{-2}$ at the LHC





- $d\sigma/dQ_T$ with SIDIS-inspired small-x contributions (red) is wider comparatively to conventional models (black)
- The Q_T broadening increases at large y; has different magnitude in W^+, W^-, and Z production

Summary

- KN'2006 parametrizations of the nonperturbative resummed function
  - agree with estimates in the IR renormalon analysis
  - different Q and $\sqrt{s}$ dependence compared to BLNY'2002
  - ResBos grids to evaluate uncertainty in $a(Q)$ in the Hessian method are available at the MSU resummation portal *(http://hep.pa.msu.edu/resum/)*
- Broadening of $d\sigma/dQ_T$ at $x < 10^{-2}$ is observed in SIDIS, can affect W, Z, and H observables at the Tevatron and LHC
- an ongoing PDF+Q_T global analysis will constrain important correlations that may exist between the PDF's and $\mathcal{F}_{NP}(b, Q)$

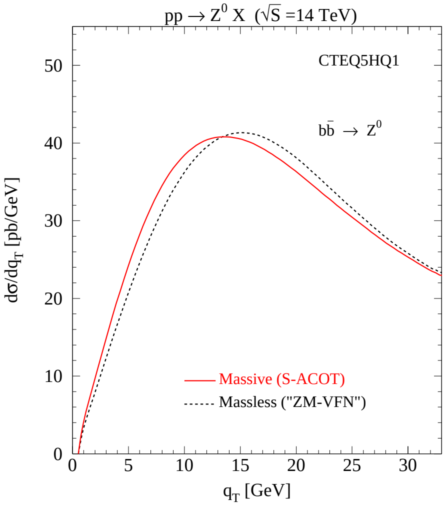
Backup slides

Q_T resummation in heavy-quark scattering

P.N., Kidonakis, Olness, Yuan, 2002; Berge, P.N., Olness, PRD 73, 013022 (2005)

- Fractions of events involving c and b scattering at the Tevatron (LHC)
  - $c\bar{s} \to W$: 8% (30%)
  - $c\bar{c} + b\bar{b} \to Z$: 5% (20%)
- Tangible dependence on heavy-quark masses when $Q_T \approx m_{c,b} \ll Q$
- Resummation is ill-defined if m_c, m_b are set to zero; properly describes $m_{c,b}$ dependence when formulated in a general-mass factorization scheme (S-ACOT scheme)

m_b dependence in $b\bar{b} \to Z^0$



- The shape of "massless" $d\sigma/dQ_T$ varies considerably depending on the assumed continuation to $b > 1/m_b$
- With full m_b dependence, $d\sigma/dQ_T$ is well-defined; low sensitivity to nonperturbative scattering contributions

b_* prescription with a revised μ_F scale

1. Take the original b_* prescription

$$\widetilde{W}(b,Q) = \widetilde{W}_{LP}(b_*,Q)e^{-\mathcal{F}_{NP}(b,Q;b_{max})}$$

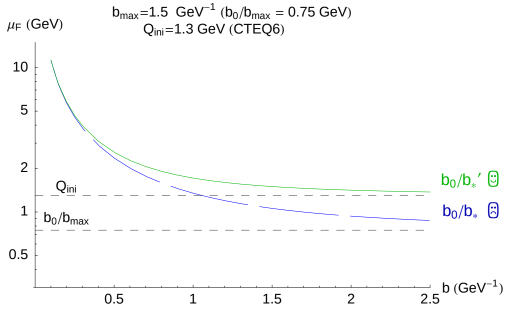
2. Choose $\mu_F = b_0/b'_*$ in $\left[\mathcal{C}_{j/a} \otimes f_{a/A}\right](x, b_*, \mu_F)$, with

$$b'_* \equiv b_*(b, b'_{max}),$$

and

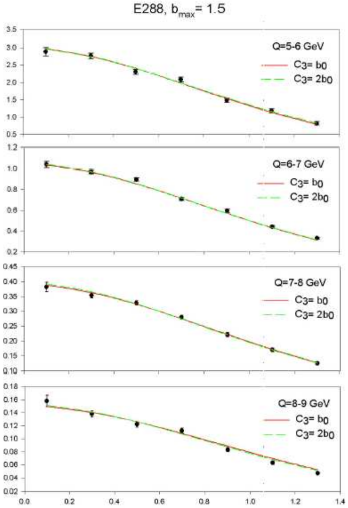
$$b'_{max} = \min\left(b_{max}, 1/Q_{ini}\right)$$

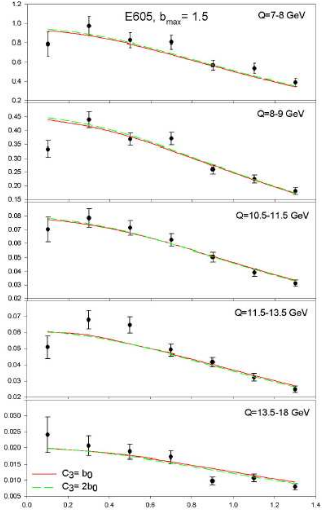
$$\mu_F = \begin{cases} \sim 1/b & \text{for} \quad b \ll Q_{ini} \\ Q_{ini} & \text{for} \quad b \gtrsim Q_{ini} \end{cases}$$



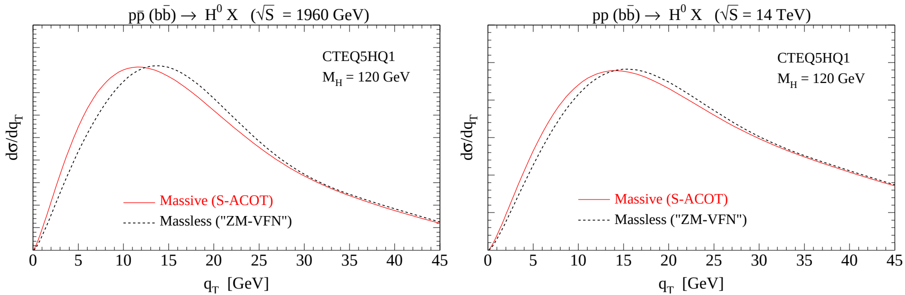
b_{max} can be safely increased at least up to $2-3$ GeV^{-1},
but the scale μ_F in $f_{a/A}(x,\mu_F)$ never exceeds Q_{ini}

E288 and E605





$b\bar{b} \to H$: variations in $d\sigma/dQ_T$ due to m_b effects



- Tevatron, $M_H = 120$ GeV, $\mu = M_H$: the "ZM-VFN" peak is shifted by 2 GeV ($\approx 17\%$) w.r.t. to the S-ACOT peak
- Slightly smaller m_b dependence at the LHC