ResBos
and QCD aspects of W mass measurement

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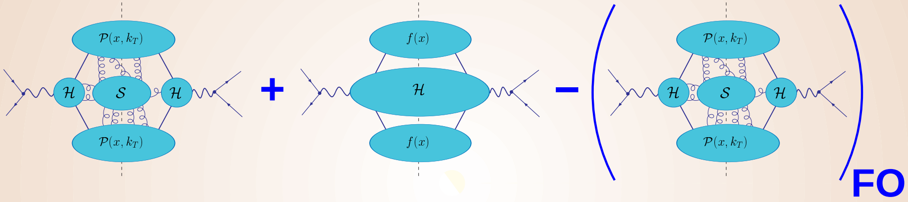
QCD factorization as a function of q_T

(according to Collins, Soper, and Sterman approach)

Small-q_T term | Large-q_T term | Overlap term

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



- k_T-dependent PDFs $\mathcal{P}(x,\vec{k}_T)$
- Sudakov function $\mathcal{S}(x,\vec{k}_T)$

▷ actually, their impact parameter (b) space transforms

- Collinear PDFs $f_a(x,\mu)$
- hard matrix elements $\mathcal{H}$ of order N

- Truncated perturbative expansion

$$\sum_{k=0}^{N} \alpha_s^k \sum_{m=0}^{2k-1} c_{km} \ln^m \left(\frac{q_T^2}{Q^2}\right)$$

Resummed cross section for $AB \to VX$

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

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

$\mathcal{S}$ is the soft (Sudakov) function:

$$\mathcal{S}(b,Q) = \int_{1/b^2}^{Q^2} \frac{d\bar{\mu}^2}{\bar{\mu}^2} \left[\mathcal{A}(\alpha_s(\bar{\mu})) \ln \frac{\bar{\mu}^2}{Q^2} + \mathcal{B}(\alpha_s(\bar{\mu})) \right]$$

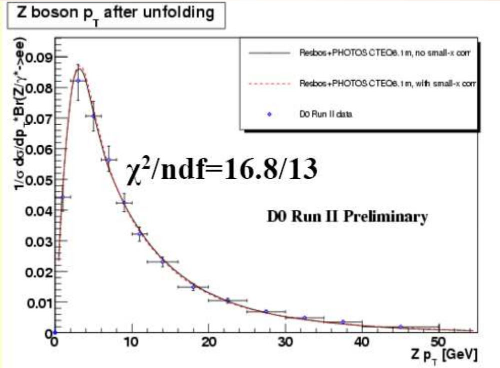
$\overline{\mathcal{P}}_a(x,b)$ are b-dependent PDF's; if $b^2 \ll Q^{-2}$,

$$\overline{\mathcal{P}}_a(x,b) = \sum_c \left[\mathcal{C}_{a/c} \otimes f_c \right] (x, b, \mu_F \sim \frac{1}{b})$$

Y is the difference of the finite-order and overlap (asymptotic) terms

What is in ResBos?

- Resummation module for *W* and *Z* production – slow (**Legacy** — *Ladinsky, Yuan, 1993; Brock, Landry, P. N., Yuan, 2002)*
- Monte-Carlo integration module for *W* and *Z* decay and matching of small-q_T and large-q_T terms – fast (**ResBos** — *Balazs, Yuan, 1997)*

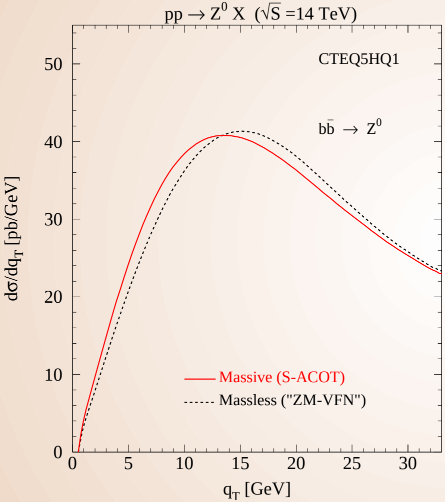


What is in ResBos?

Perturbative QCD contributions

- Finite-order Y term (large q_T):
  - NNLO ($= \mathcal{O}(\alpha_s^2)$) boson-level cross section *(Arnold, Reno, 1989; Arnold, Kauffman, 1991)*
  - parton-lepton spin correlations up to NLO ($= \mathcal{O}(\alpha_s)$)
- Resummed W term (small q_T)
  - NNLL expressions for $\mathcal{S}(b, Q)$ and $\overline{\mathcal{P}}(x, b)$ ($A^{(3)}$, $B^{(2)}$, $C^{(1)}$ coefficients)
  - Two representations for the hard vertex function $\mathcal{H}$ *(Collins, Soper, Sterman; Catani, de Florian, Grazzini)*
    - produce similar predictions for vector boson production
  - $\overline{\mathcal{P}}(x, b)$ for c and b quark scattering in general-mass (ACOT-χ) scheme *(Berge, P. N., Olness, 2006)*

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

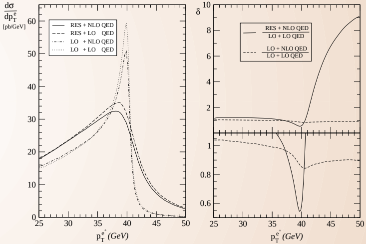


- The shape of "massless" $d\sigma/dQ_T$ varies considerably depending on the assumed continuation to $b > 1/m_b$
- With full m_b dependence, $d\sigma/dQ_T$ is well-defined; low sensitivity to nonperturbative scattering contributions
- 5 MeV effects at the LHC

What is in ResBos?

Electroweak contributions at all Q_T

- W, Z width in effective Born approximation
- ResBos-A: + final-state QED radiation in W and Z production *(Cao, Yuan)*
  - both W term (2004) and Y term (near completion)
- updated $\gamma^* - Z$ interference New!

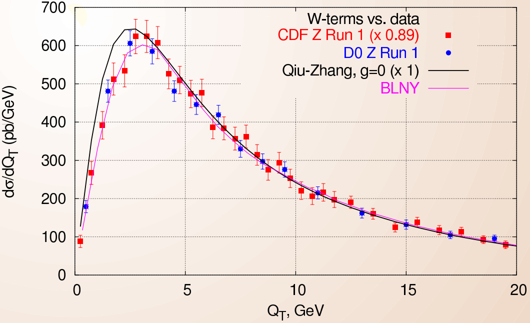


What is in ResBos?

Nonperturbative model at $b \gtrsim 1$ GeV^{-1}:

- revised "b_*" approximation + a power-suppressed term $\propto b^2$ *(Collins, Soper, Sterman, 1985; Konychev, P. N., 2005)*
- replaces BLNY model *(Brock, Landry, P.N., Yuan)* used in Tevatron Run-2 M_W measurements

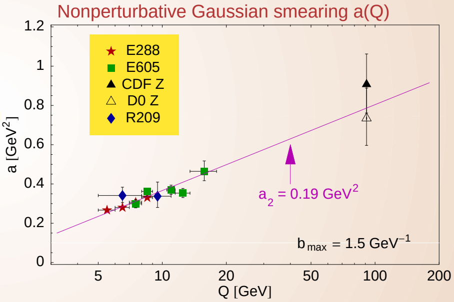
- can approximate a variety of nonperturbative models *(BLNY, Qui, Zhang; Kulesza, Sterman, Vogelsang)*



What is in ResBos?

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, in **quantitative** agreement with SIDIS q_T fit and infrared renormalon estimates *(Tafat)*
- small $\sqrt{s}$ dependence
- no tangible flavor dependence
- supports dominance of soft contributions in $\mathcal{F}_{NP}(b,Q)$
- **applies at** $x \gtrsim 10^{-2}$



What is in ResBos?

PDF reweighting and ROOT ntuple output

If the central PDF cross section σ_0 and PDF uncertainty $\Delta\sigma^2$ are estimated by generating $\overline{N}$ Monte-Carlo integrator events for each error PDF $f^{(i)}(x,\mu)$ ($i = 0{,}2N$), their MC estimates are

$$\overline{\sigma}_0 \sim \sigma_0 + \frac{c}{\overline{N}^{1/2}} \text{ and}$$

$$\overline{\Delta\sigma^2} \sim \Delta\sigma^2 + \frac{c' N}{\overline{N}^{1/2}}$$

- a large factor of $N \sim 22$ in the MC error for $\overline{\Delta\sigma^2}$ due to randomness of event generation for each PDF!
- need N^2 more MC events to evaluate σ^2

What is in ResBos?

PDF reweighting and ROOT ntuple output

- PDF reweighting generates the same sequence of events to compute each of $2N$ cross sections
  - $\overline{\Delta\sigma^2} \approx \Delta\sigma^2 + \mathcal{O}(\overline{N}^{-1})$
- In multi-loop calculations, PDF reweighting saves CPU time drastically by reducing slow computations of hard-scattering matrix elements

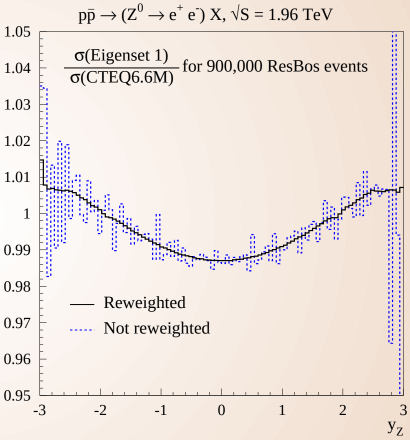
FROOT: a theorist-friendly interface for Monte-Carlo reweighting

- Written in C, can be linked to standalone FORTRAN/C/C++ programs
- Simple – 170 lines of the code
- Writes the output directly into a ROOT ntuple; no need in intermediate PAW ntuples
- Flexible; new columns (branches) with PDF weights or events can be added into an existing ntuple
- Kinematical cuts, selection conditions can be imposed a posteriori in interactive or batch ROOT sessions
- implemented in ResBos

http://www.physics.smu.edu/~nadolsky/projects.html

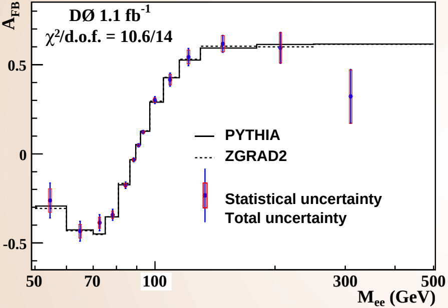
FROOT: a theorist-friendly interface for Monte-Carlo reweighting

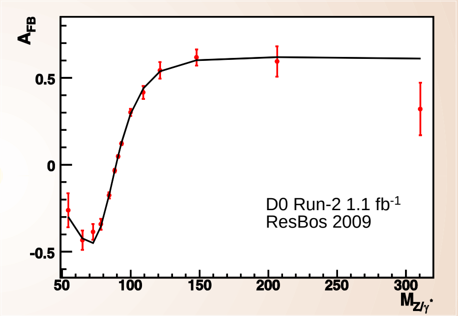
```
// These are the C functions accessible from Fortran.


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"
```



Sanity checks

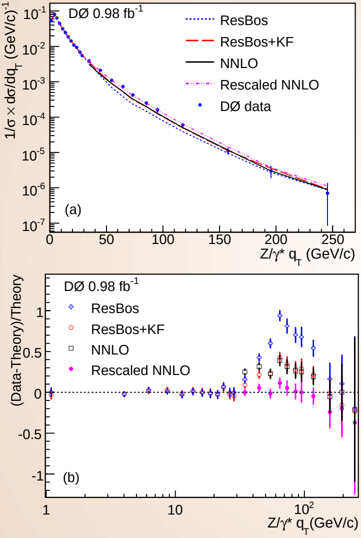
ResBos'2009 predictions for forward-backward asymmetry (C.-P. Yuan)





$\gamma^* - Z$ interference in the latest ResBos correctly reproduces A_{FB} from D0

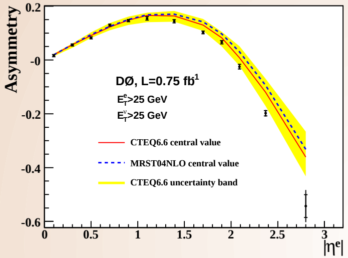
$Z\ q_T$ distribution (D0, 1 fb^{-1})

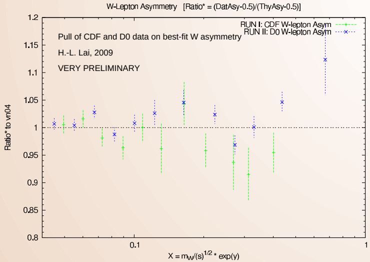


Data shows significant excess above $\mathcal{O}(\alpha_s^2)$ resummed/fixed-order theory at $q_T \approx M_Z$

No analogous data from CDF

W charge asymmetry (D0, 1 fb^{-1})



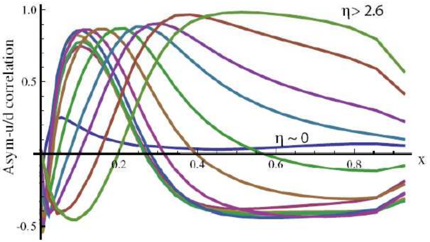


Tensions between D0 W asymmetry with DIS and CDF W asy data in the global fit observed both by CTEQ and MSTW, without clear path to resolution yet

Can CDF reduce the error on their measurement?

Impact of *W* charge asymmetry on PDF's

- Correlation of u(x)/d(x) and A_e for each η_e bin



H. Schellman, talk at BNL, 2009

W asymmetry constrains $d(x, M_W)/u(x, M_W)$ at large x; is *believed* to constrain the PDF uncertainty on M_W

Theoretical uncertainties on M_W: what is essential?

- Measurements of Z differential cross section are (will be) used to constrain or cancel systematic effects in M_W measurement

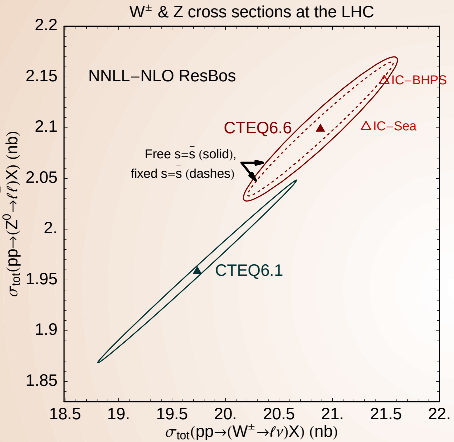
  (see, e.g., Reevaluation of the LHC potential for M_W measurement, N. Besson et al., 2008)

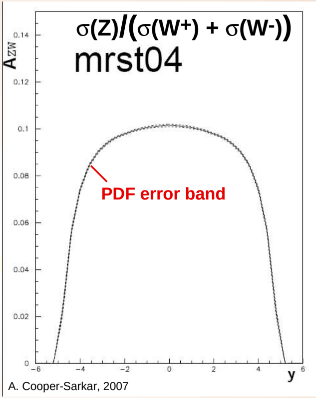
- Common uncertainties of σ_W and σ_Z cancel in M_W measurement $\Rightarrow$ not likely to affect ΔM_W significantly

Theoretical uncertainties on M_W: what is essential?

- Uncertainties that affect σ_W and σ_Z differently may be important
  - EW effects
  - Logarithmic scaling violations;
    $\ln Q$ dependence of $\mathcal{F}_{NP}(b, Q)$ in $d\sigma/dq_T$
  - PDF dependence in subleading (s, c, b) scattering channels
  - Correlations between the PDFs and $\mathcal{F}_{NP}(b, Q)$
  - Strong rapidity dependence of $\mathcal{F}_{NP}(b, Q)$;
    enhanced small-x corrections

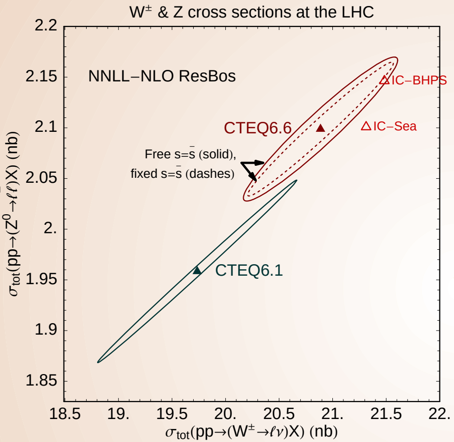
W and *Z* cross sections and their ratio

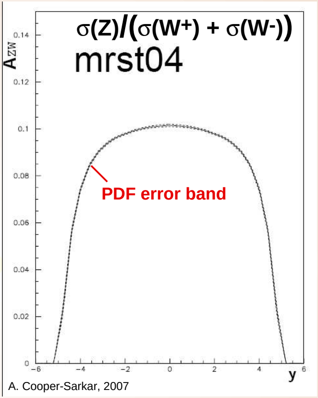




- Radiative contributions have similar structure in $W^{\pm}$ and Z cross sections; cancel well in Xsection ratios
- The PDF uncertainty cancels partially because of differences in s, c, b scattering contributions

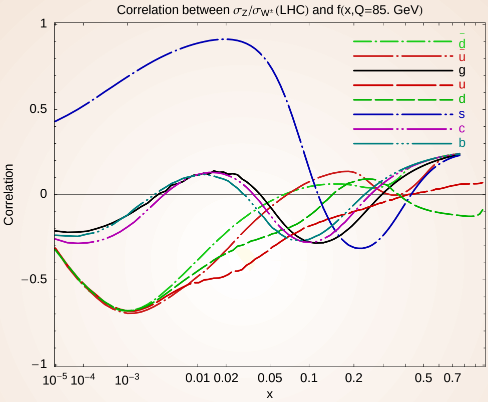
W and Z cross sections and their ratio





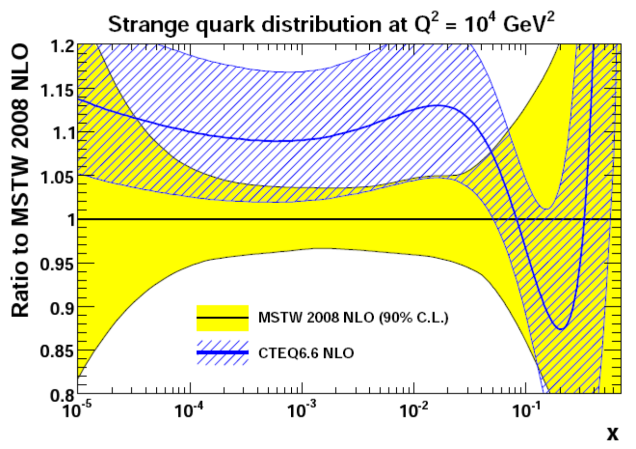
- 27% of $\sigma_{NLO}(W^{\pm})$ from $c\bar{s} \to W^{\pm}$, 20% of $\sigma_{NLO}(Z^0)$ from $s\bar{s} \to Z^0$
- non-negligible effects from free strangeness and intrinsic charm (IC) PDF's

σ_Z/σ_W at the LHC



The remaining PDF uncertainty in σ_Z/σ_W is mostly driven by $s(x)$; increases by a factor of 3 compared to CTEQ6.1 as a result of free strangeness in CTEQ6.6

Strangeness is the least constrained PDF

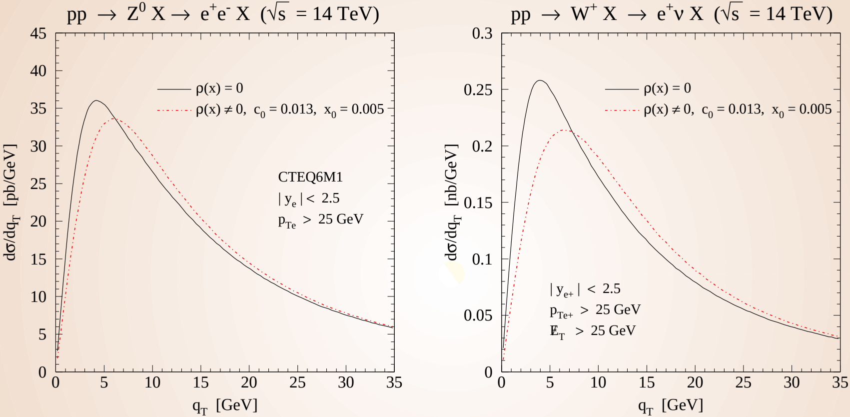


Resummation at $x < 10^{-2}$

(S. Berge, P. N., F. Olness, C.-P. Yuan, Phys. Rev. D72, 033015 (2005))

- W (Z) production at the LHC: typical $x \sim 0.005$ (0.0065); behavior of higher-order resummed terms is far from certain
- Novel effects such as hardening (broadening) of q_T distributions are possible
- magnitude of broadening will be different in W and Z channels!
- Recent D0 search for broadening in $p\bar{p} \to ZX$ at $|y| \geq 1$ was inconclusive

q_T broadening at small x



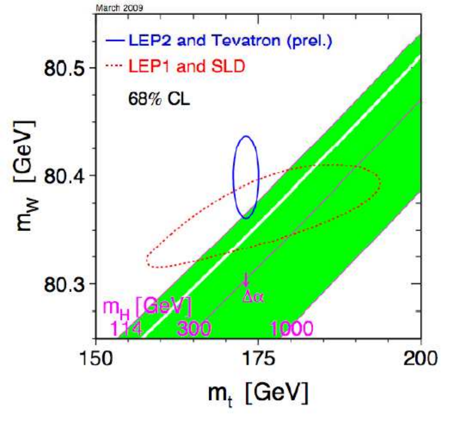
- $d\sigma/dQ_T$ with SIDIS-inspired small-x contributions (red) is wider comparatively to conventional models (black)
- The Q_T broadening increases at large y; has different magnitude in W^+, W^-, and Z production

Combined analysis of PDF's and resummed nonperturbative function

(Lai, P.N., Pumplin, Tung, Yuan, to be presented at DIS'2009)

- The common origin of collinear PDF's $f_a(x,\mu)$ and $\mathcal{F}_{NP}(b,Q)$ from k_T-dependent PDF's indicates importance of their simultaneous analysis
  - The best-fit $\mathcal{F}_{NP}(b,Q)$ is correlated with $f_a(x,\mu) \Rightarrow$ consequences for EW precision measurements
  - P_T data constrains poorly known degrees of freedom in $f_a(x,\mu)$
- The q_T resummation module is interfaced with the CTEQ PDF fitting package to carry out a combined PDF+q_T fit

Concluding remarks



Impact of M_W measurements on EW precision analysis/Higgs mass can't be overemphasized

Leading QCD uncertainties on M_W are mostly associated with our understanding of global aspects of QCD (especially PDF's and nonperturbative resummed function)

Still a lot of work to be done!

Backup slides

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

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- $b \lesssim 0.5$ 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

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 $b \gtrsim b_{max} \sim 1\ \mathrm{GeV}^{-1}$

For example, in the "b_*" model *(CSS, 1985)*:

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

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

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 $b \lesssim 2\ \text{GeV}^{-1}$
- 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: $a_2 = 0.19^{+0.12}_{-0.09}\ \text{GeV}^2$ *(Tafat)*

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

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

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

eps/muF_2bstar_bstar.eps

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

Scan over b_{max}

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eps/a3_vs_bmax.eps

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

E288 and E605

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eps/e605.eps

$d\sigma/dq_T$ for Z bosons with large rapidities (D0, 1 fb $^{-1}$)