# NNLL studies of transverse-momentum-dependent (TMD) factorization for $Z/\gamma^*$ production at hadron colliders

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# Two studies

1. Nonperturbative contribution in TMD factorization.

   (M. Guzzi, P. M. Nadolsky, and B. Wang. 2013. arXiv:1309.1393)

2. Application of TMD factorization in nuclear collisions (in backup slides).

   ( V. Guzey , M. Guzzi, P. M. Nadolsky, M. Strikman and B. Wang. 2012. arXiv:1212.5344)

# Applications of TMD factorization

- Precision tests of TMD factorization for $q_T$ dependent observables.

- Constraints on measurements of W boson mass and other electroweak observables.

- May be used to obtain better constraints on proton and nuclear PDFs.

# Recent advancement in TMD factorization

Theory: many papers

Resummation programs

G. Ladinsky and C.-P. Yuan, 1994, arXiv: 9311341

C. Balazs and C.-P. Yuan, 1997, arXiv: 9704258

F. Landry, R. Brock, P.M. Nadolsky and C.-P. Yuan, 2003, arXiv: 0212159

NNLL/NNLO calculation:

S. Catani et al, 2012, arXiv: 1209.0158

Nonperturbative contribution:

A. Banfi et al, 2009,2011,2012
arXiv: 0909.5327
arXiv: 1102.3594
arXiv: 1110.4009
arXiv: 1205.4760

Experimental: very precise measurements of $\phi_\eta^*$ distribution by D0, ATLAS.

D0 Collaboration, V.M. Abazov et al, 2011, arXiv: 1010.0262
ATLAS Collaboration, G. Aad et al., 2011, arXiv: 1107.2381

# Definition of $\phi_\eta^*$

## When $q_T$ is small $\phi_\eta^* \sim q_T / Q$

$\phi_\eta^*$ is defined as

$$\phi_\eta^* = \tan(\phi_{acop}/2)\sin\theta_\eta^*$$

where

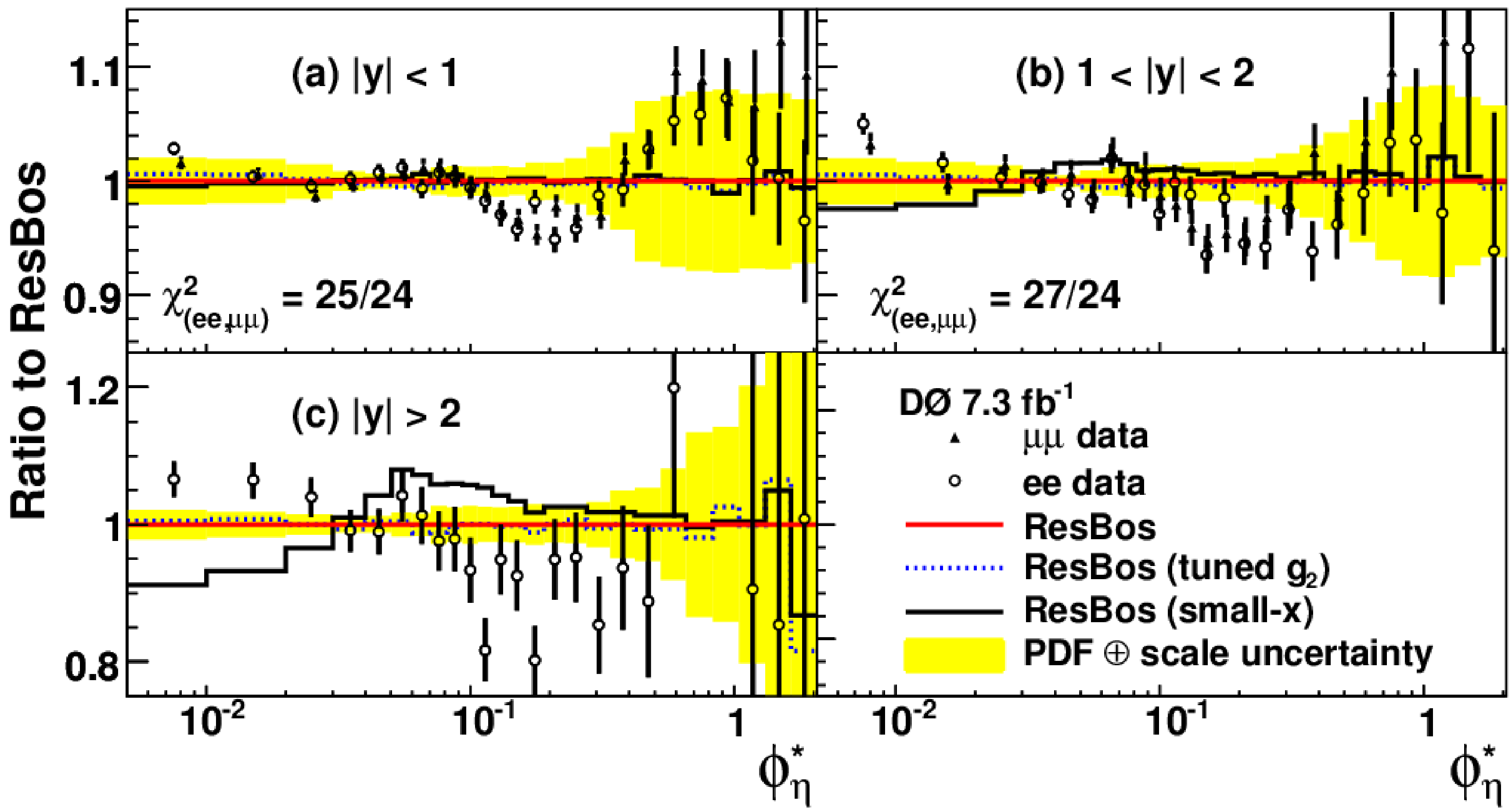
$$\phi_{acop} = \pi - \Delta\varphi$$

And

$$\cos\theta_\eta^* = \tanh\left(\frac{\eta_1 - \eta_2}{2}\right)$$

In the lab frame, $\Delta\varphi$ is the difference in azimuthal angle, $\varphi$ , between the two lepton candidates. $\eta_1$ and $\eta_2$ are the pseudorapidities of the negatively and positively charged lepton, respectively.

# $\phi_\eta^*$ distribution measured at the Tevatron




D0 Collaboration, V.M. Abazov et al, 2011, arXiv: 1010.0262

Error of lower bins in $|y|<1$ inset is $\sim$ 0.5%

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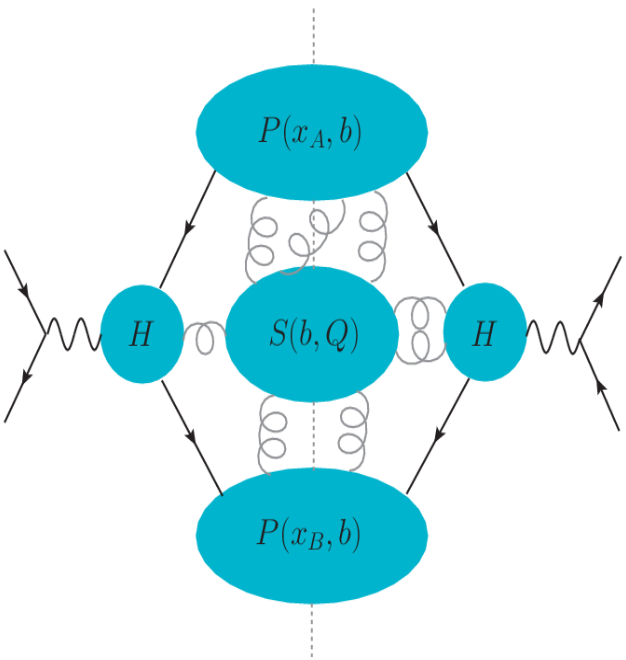
# Small $q_T$ factorization

At small $q_T$ the resummed cross section can be written as




$$\frac{d\sigma_{AB}}{dQ^2 dy dQ_T^2} \approx \int \frac{d^2 b}{(2\pi)^2} e^{i\vec{q}_T \cdot \vec{b}} \widetilde{W}_{AB}(b, Q, y)$$

where $\vec{b}$ is the Fourier conjugate variable of, $\vec{q}_T$. $\widetilde{W}_{AB}$ can be factorized as

$$\widetilde{W}_{AB}(b, Q, y) = \widetilde{W}_{AB}(b, Q, y)$$

$$= \sum_j e^{-S(b,Q)} P_{j/B}(x_b, b) P_{\bar{j}/A}(x_a, b) \left| H_{j,\bar{j}} \right|^2$$

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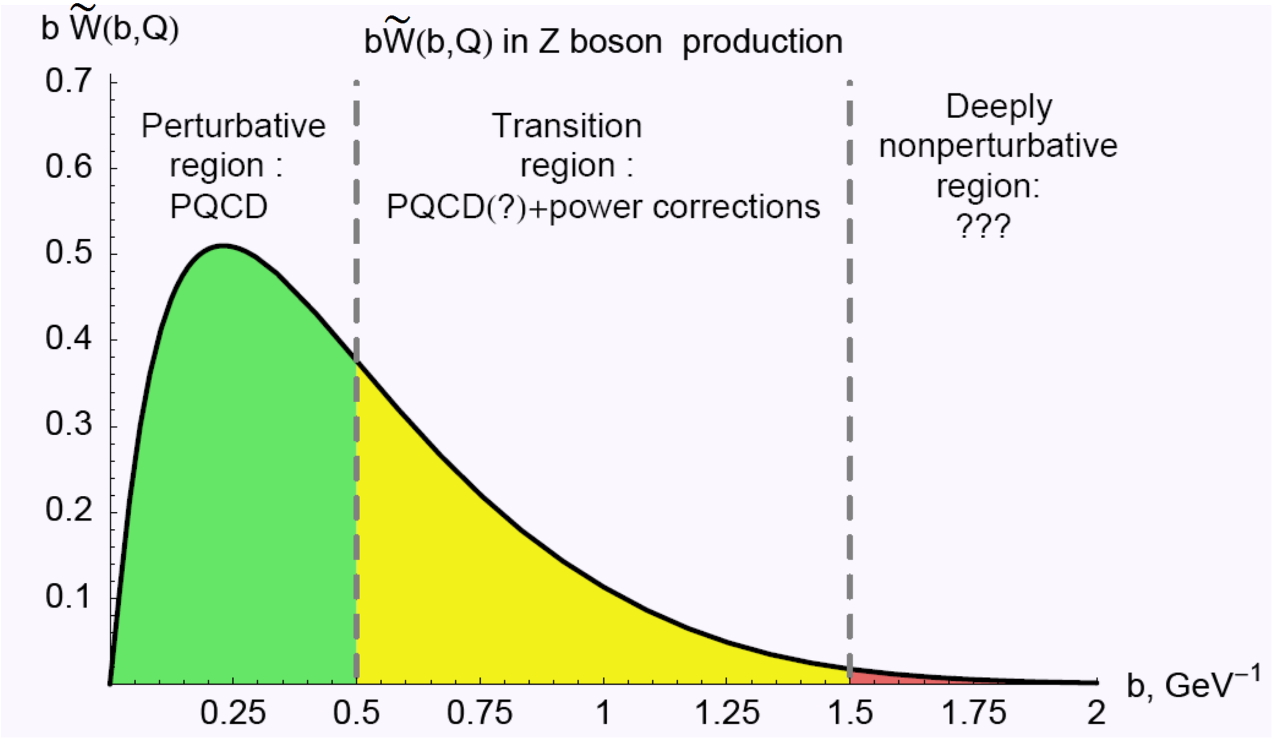
# Three regions of $b\widetilde{W}(b,Q)$

$1/b$ sets the momentum scale of calculation. As $b \gtrsim 0.5\text{GeV}^{-1}$ the nonperturbative effect becomes important.



# Solution for all $b$

Introduce a nonperturbative factor with "$b_*$" prescription

$$\widetilde{W}(b,Q,y)=\widetilde{W}^{pert}(b_*,Q,y)\,\widetilde{W}^{NP}(b,Q,y)$$

$$b_* \equiv \frac{b}{\sqrt{1+\left(b/b_{\max}\right)^2}} \qquad \begin{array}{l} b << b_{\max}, \quad b_* \approx b \\ b >> b_{\max}, \quad b_* \approx b_{\max} \end{array}$$

Where $b_{\max}$ is the parameter to "freeze" $\widetilde{W}^{pert}$ at $b >> b_{\max}$ . It is determined to be around 1.5 $\mathrm{GeV}^{-1}$ in previous studies.

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# Nonperturbative contribution

$\widetilde{W}^{NP}$ can not be computed perturbatively and is parameteriszed as

$$\widetilde{W}^{NP}(b,Q) = \exp\left[-b^2\left(a_1 + a_2 \ln\left(\frac{Q}{2\,Q_0}\right) + a_3 \ln\left(\frac{x_1^{(0)} x_2^{(0)}}{0.01}\right)\right)\right]$$

$$x_{1,2}^{(0)} = (Q/\sqrt{S})e^{\pm y}$$

$$Q_0 = 1.6\,\text{GeV}$$

In the vicinity of $Q$ around $M_Z$ , $\widetilde{W}^{NP}$ reduces to

$$\widetilde{W}^{NP}(b, Q \approx M_Z) = \exp\left[-b^2 a_Z\right]$$

with $$a_Z = a_1 + a_2 \ln\left(\frac{M_Z}{2\,Q_0}\right) + a_3 \ln\left(\frac{M_Z^2}{0.01\ s}\right)$$

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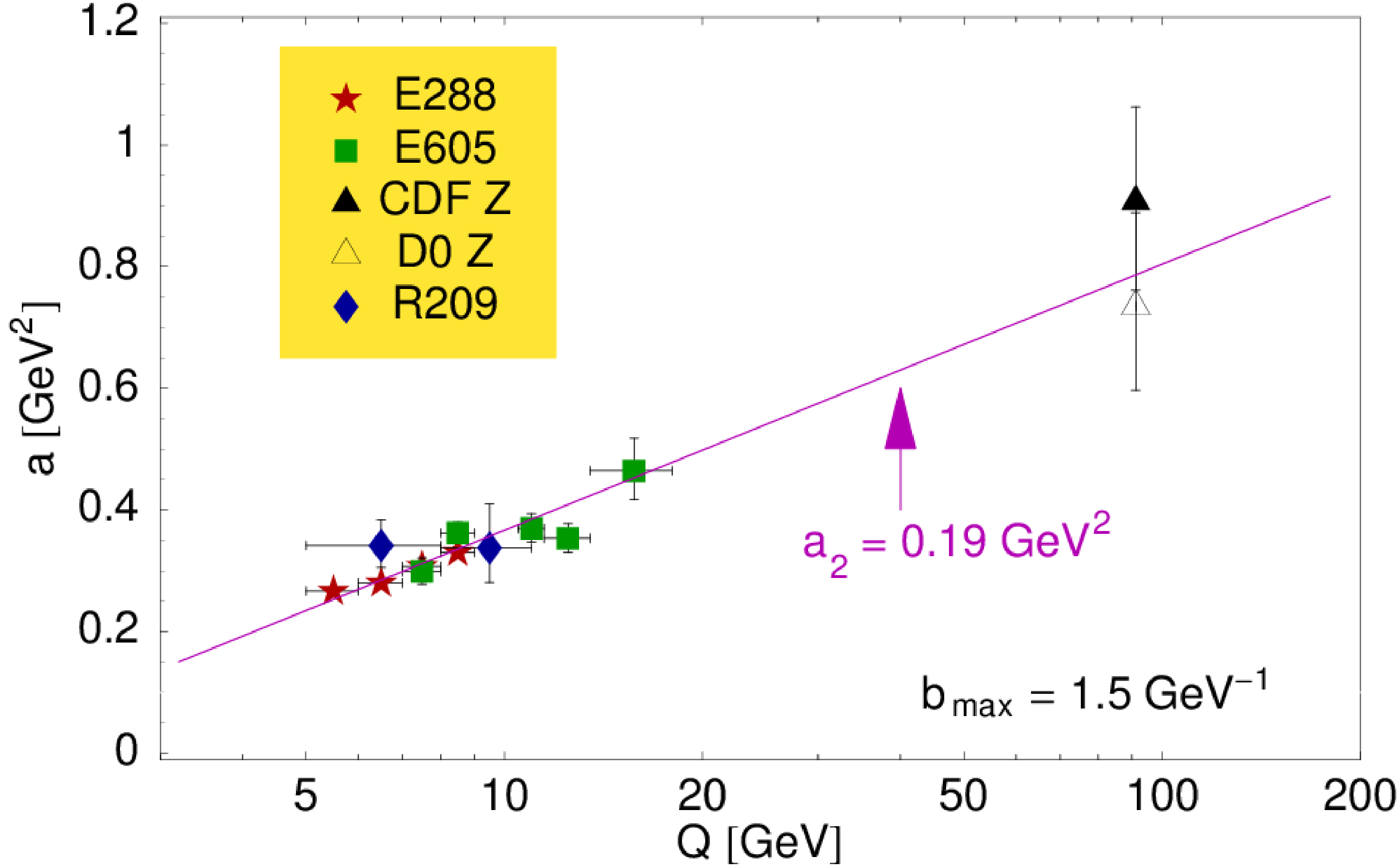
# $a(Q)$ fits to various experiments




A. V. Konychev and P. M. Nadolsky, 2005, arXiv: 0507179

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# Is it necessary to use a non-zero $a_Z$ ?

- The evidence for nonperturbative smearing is inconclusive at the NLL($\alpha_S$) +NLO( $\alpha_{EW}$ ) level because of a large scale dependence. (A. Banfi et al, 2009,2011,2012)

- Small experimental errors of $\phi_\eta^*$ measurements and approximate NNLO QCD ($\alpha_S^2$ ) calculation allow us to make more precise comparisons.

- Theory uncertainties due to perturbative and nonperturbative parameters ($a_Z$ from $\widetilde{W}^{NP}$ and $C_1 = b\mu_b,\ C_2 = \mu_Q / Q,\ C_3 = b\mu_F$ from $\widetilde{W}^{pert}$ ) are determined by fitting to $\phi_\eta^*$ data.

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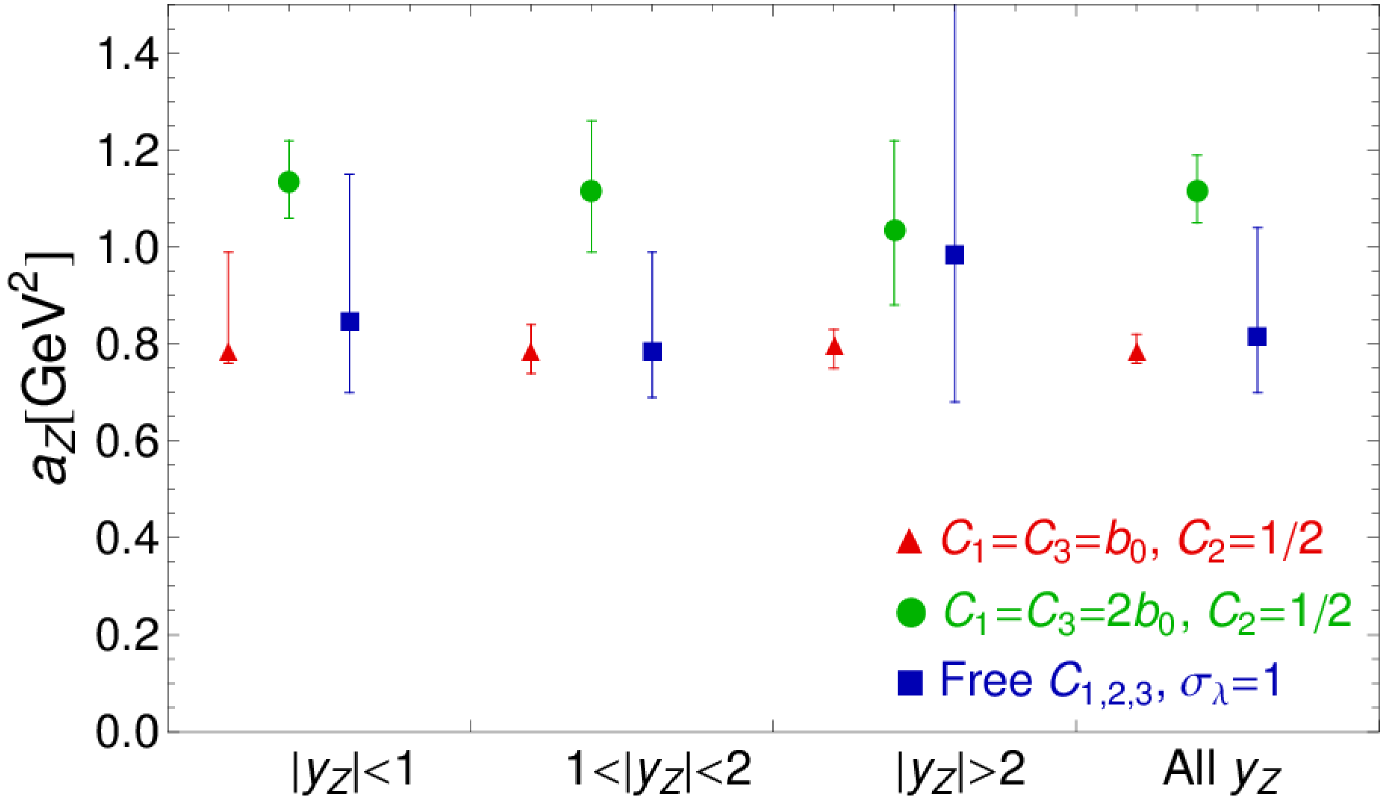
# $a_Z$ fits to $\phi_\eta^*$ data




M. Guzzi, P. M. Nadolsky and B. Wang, 2013, arXiv: 1309.1393

$$a_Z = 0.82\ ^{+0.22}_{-0.11}\ \text{GeV}^2\ \ (\text{free } C_{1,2,3},\ 68\%\,\text{C.L.})$$

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# Conclusion

- TMD factorization is a valuable tool for investigations at low transverse momentum regions.

- We have performed approximate NNLO calculation of pt distribution in $Z/\gamma^*$ production and fit our result to D0 $\phi_\eta^*$ data. The value of nonperturbative parameter is determined to be $a_Z = 0.82\,^{+0.22}_{-0.11}\ \mathrm{GeV}^2,\ 68\%\,C.L.$ with a significant distinction from zero.

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# Backup slides

# Implication for W mass

In terms of $a_Z$ obtained by fitting the D0 data, the nonperturbative parameter for general $Q$ and $\sqrt{S}$ can be written as

$$a(Q,\sqrt{s}) = a_Z(1.96\ \text{TeV}) + a_2 \ln\left(\frac{Q}{M_Z}\right) + a_3 \ln\left(\frac{Q^2}{M_Z^2}\frac{s}{(1.96\ \text{TeV})^2}\right)$$

If we consider W production

$$a_W = a_Z + a_2 \ln\left(\frac{M_W}{M_Z}\right) + a_3 \ln\left(\frac{M_W^2}{M_Z^2}\right)$$

The log terms are small, so it's safe to assume $a_W \approx a_Z$

Therefore our fit of $a_Z$ can be used to reduce uncertainty in W mass measurement.

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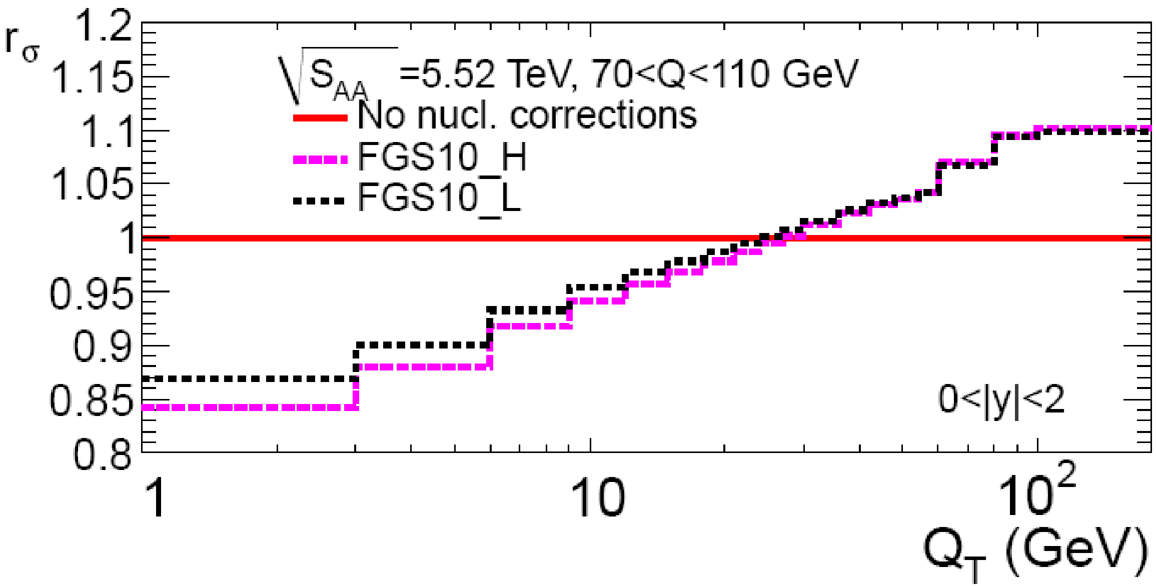
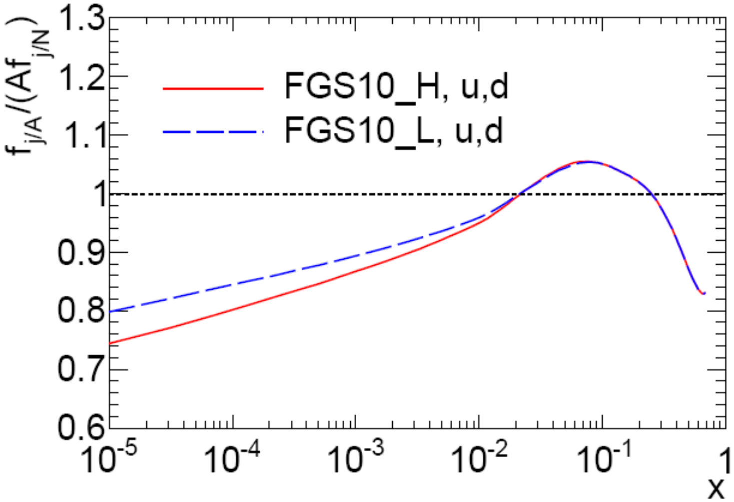
# Application in nuclear collisions




Both figures taken from V. Guzey , M. Guzzi, P. M. Nadolsky, M. Strikman and B. Wang (2012)




Correspondence can be found by reading the ratio of PDFs at the typical momentum fractions

$$\xi_1 \approx \frac{M_T + Q_T}{\sqrt{S}} e^{y}, \text{and } \xi_2 \approx \frac{M_T + Q_T}{\sqrt{S}} e^{-y}$$