# A-dependence of $Z^0$ production at LHC

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Based on work done with Kang, …

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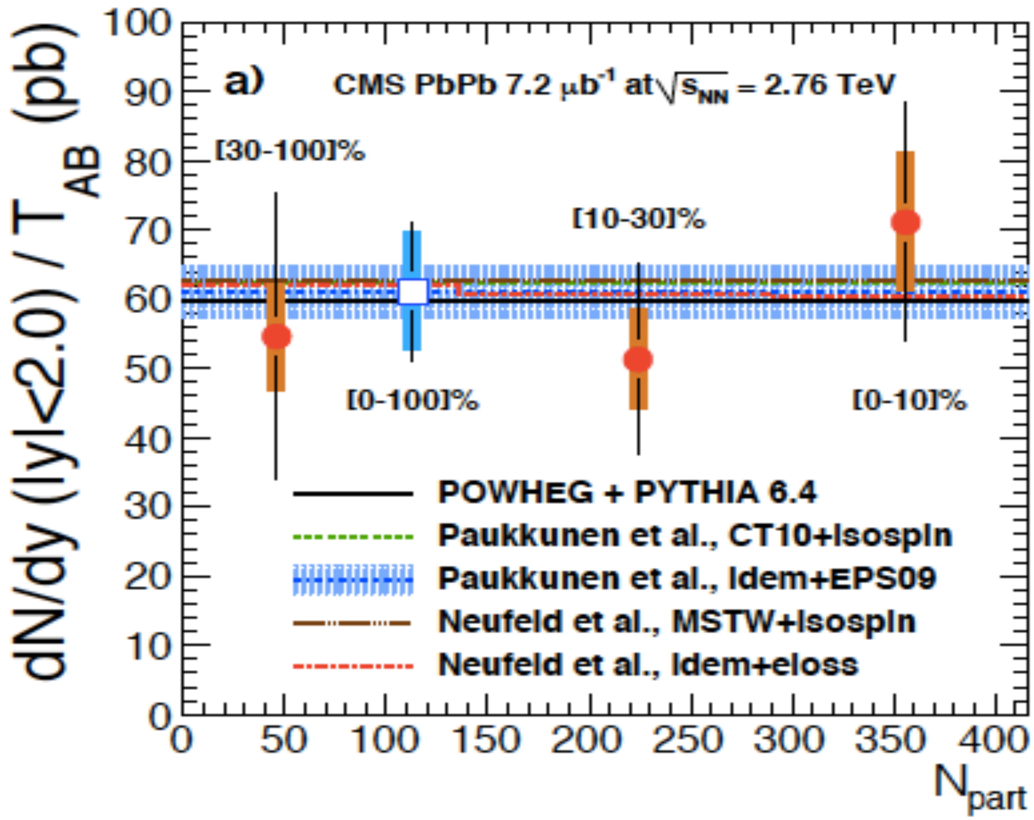
# Outline of my talk

- Why $Z^0$ and its $p_T$ distribution?
- Two-scale cross sections and QCD resummation
- Collins-Soper-Sterman (CSS) formalism
- The b-space and role of nonperturbative large b-region
- pA collision and nuclear A-dependence
- Rapidity dependence and shadowing
- Summary

# What do we know?

## ❑ $Z^0$ in AA-collision:



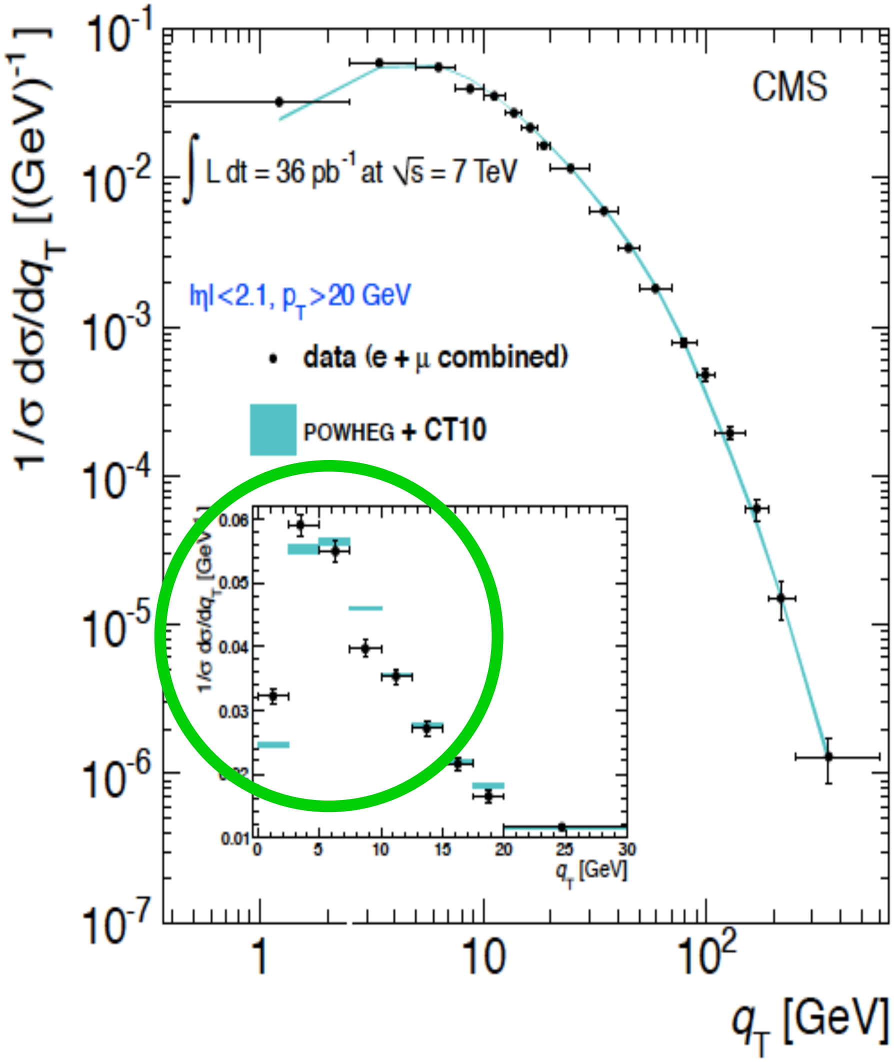

**Very small centrality (or A) dependence**

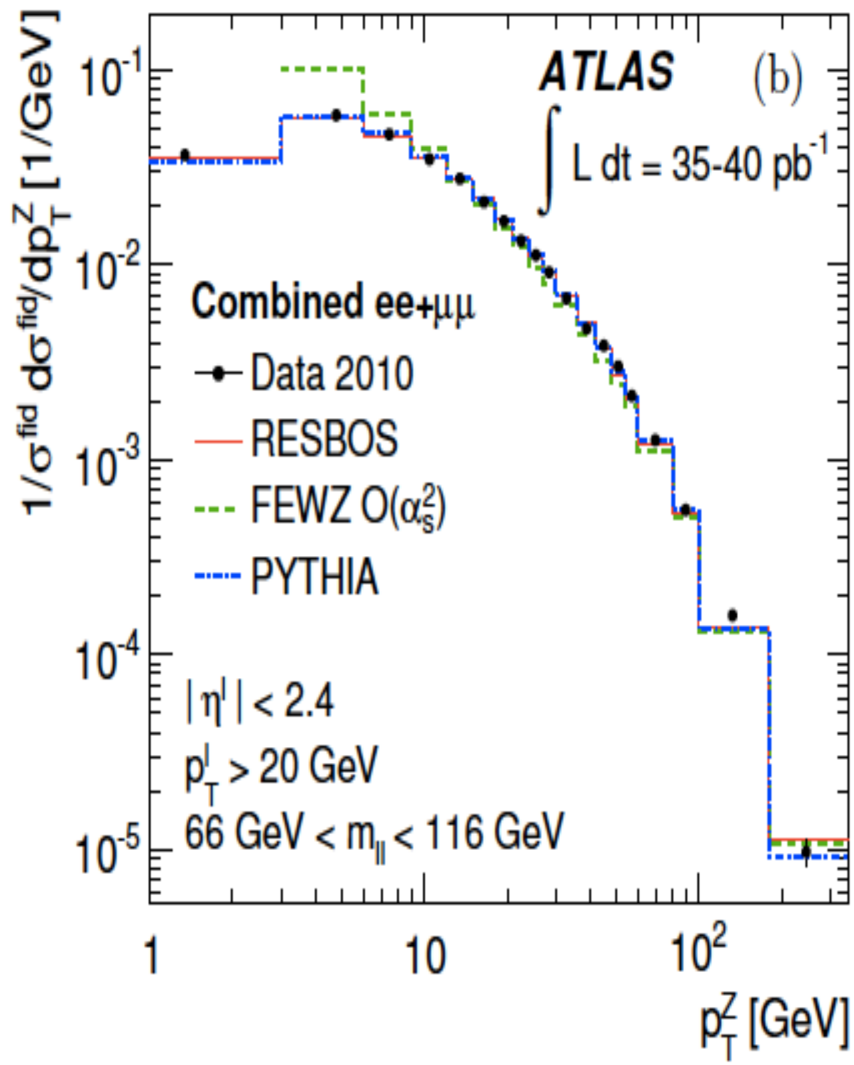
✧ **Final-state: No strong interaction**

✧ **Initial-state: Not too small $x \sim 0.03$ (weak antishadowing in EPS09)**

# Transverse momentum distribution

- ❑ $Z^0$-PT distribution in pp collisions:



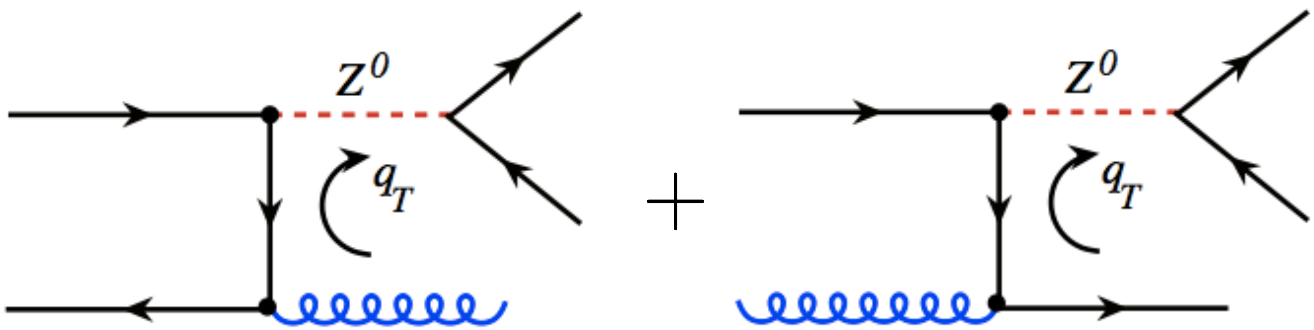




$P_T$ as low as [0,2.5] GeV bin (or about 1.25 GeV)

# Cross section of two very different scales

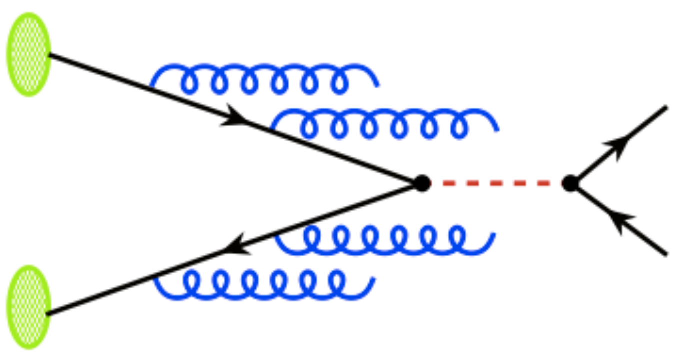
- **Interesting region: $p_T << M_Z \sim 91$ GeV**

- **Fixed order pQCD calculation is not stable!**




$$\propto \frac{1}{q_T^2} \rightarrow \infty$$

- **Large logarithmic contribution from gluon shower:**

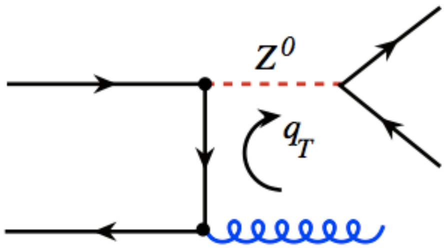


$$\left[\alpha_s \ln^2\left(\frac{M_Z^2}{q_T^2}\right)\right]^n$$

**Resummation is necessary!**

# Early approach to resummation

- **LO Differential $Q_T$-distribution as $Q_T \to 0$ :**




$$\frac{d\sigma}{dy\,dQ_T^2}_{\text{LO}} \approx \left(\frac{d\sigma}{dy}\right)_{\text{Born}} \times 2C_F\left(\frac{\alpha_s}{\pi}\right)\frac{\ln\left(Q^2/Q_T^2\right)}{Q_T^2} \Rightarrow \infty$$

$$\Longrightarrow \int_0^{Q^2} \frac{d\sigma}{dy\,dQ_T^2}_{\text{real+virutal}} dQ_T^2 \approx \left(\frac{d\sigma}{dy}\right)_{\text{Born}} + O(\alpha_s) \qquad \text{with } Q^2 \approx M_W^2$$

- **Integrated $Q_T$-distribution:**

$$\int_0^{Q_T^2} \frac{d\sigma}{dy\,dp_T^2}_{\text{real+virutal}} dp_T^2 \equiv \left[\int_0^{Q^2} - \int_{Q_T^2}^{Q^2}\right] \frac{d\sigma}{dy\,dp_T^2}_{\text{real+virutal}} dp_T^2$$

$$\approx \left(\frac{d\sigma}{dy}\right)_{\text{Born}} \times \left[1 - \int_{Q_T^2}^{Q^2} 2C_F \frac{\alpha_s}{\pi} \frac{\ln\left(Q^2/p_T^2\right)}{p_T^2} dp_T^2\right] = \left(\frac{d\sigma}{dy}\right)_{\text{Born}} \times \left[1 - C_F\frac{\alpha_s}{\pi}\ln^2\left(Q^2/Q_T^2\right)\right]$$

$$\approx \left(\frac{d\sigma}{dy}\right)_{\text{Born}} \times \exp\left[-C_F\frac{\alpha_s}{\pi}\ln^2\left(Q^2/Q_T^2\right)\right]$$

Effect of gluon emission

Assume this exponentiates

# Resummed $Q_T$ distribution

- Differentiate the integrated $Q_T$-distribution:

$$\frac{d\sigma}{dy\,dQ_T^2} \approx \left(\frac{d\sigma}{dy}\right)_{\text{Born}} \times 2C_F\left(\frac{\alpha_s}{\pi}\right)\frac{\ln\left(Q^2/Q_T^2\right)}{Q_T^2} \times \exp\left[-C_F\left(\frac{\alpha_s}{\pi}\right)\ln^2\left(Q^2/Q_T^2\right)\right] \Rightarrow 0$$

as $Q_T \to 0$

- compare to the explicit LO calculation:

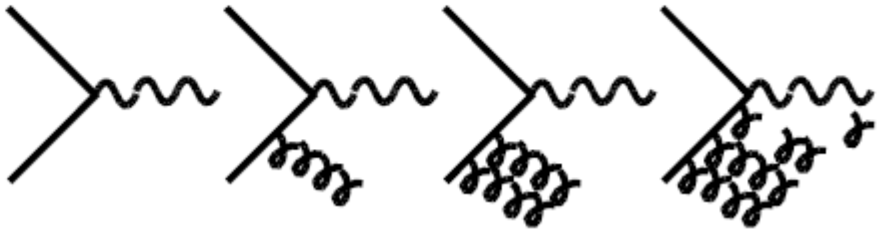
$$\left.\frac{d\sigma}{dy\,dQ_T^2}\right|_{\text{LO}} \approx \left(\frac{d\sigma}{dy}\right)_{\text{Born}} \times 2C_F\left(\frac{\alpha_s}{\pi}\right)\frac{\ln\left(Q^2/Q_T^2\right)}{Q_T^2} \Rightarrow \infty$$

$Q_T$-spectrum (as $Q_T \to 0$) is completely changed!

- We just resummed (exponentiated) an infinite series of soft gluon emissions – double logarithms

$$e^{-\alpha_s L^2} \approx 1 - \alpha_s L^2 + \frac{(\alpha_s L^2)^2}{2!} - \frac{(\alpha_s L^2)^3}{3!} + \ldots$$

$L \propto \ln\left(Q^2/Q_T^2\right)$



Soft gluon emission treated as uncorrelated

# Still a wrong $Q_T$-distribution

❑ **Experimental fact:**

$$\frac{d\sigma}{dy\,dQ_T^2} \Rightarrow \text{finite [neither } \infty \text{ nor } 0!] \text{ as } Q_T \to 0$$

❑ **Double Leading Logarithmic Approximation (DLLA):**

- ✧ **Radiated gluons are both soft and collinear with strong ordering in their transverse momenta**
- ✧ **Ignores the overall vector momentum conservation**
- ✧ **Double logs ~ random work ~ zero probability to be $Q_T = 0$**

**DLLA over suppress small $Q_T$ region**

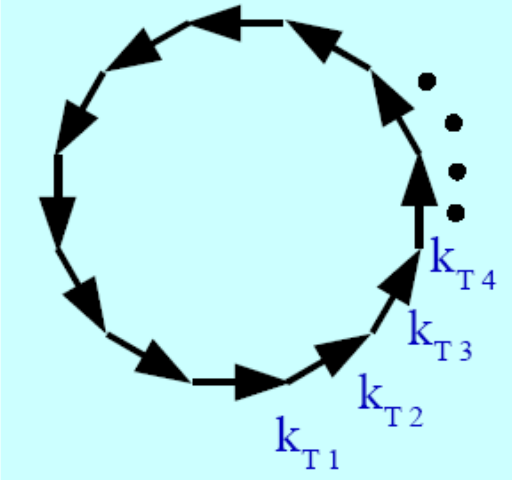
**Resummation of uncorrelated soft gluon emission leads to too strong suppression at $Q_T$=0**

# Importance of momentum conservation

- Vector momentum conservation:

  Particle can receive many finite $k_T$ kicks via soft gluon radiation, but, yet still has $Q_T$=0

  → Need vector sum!



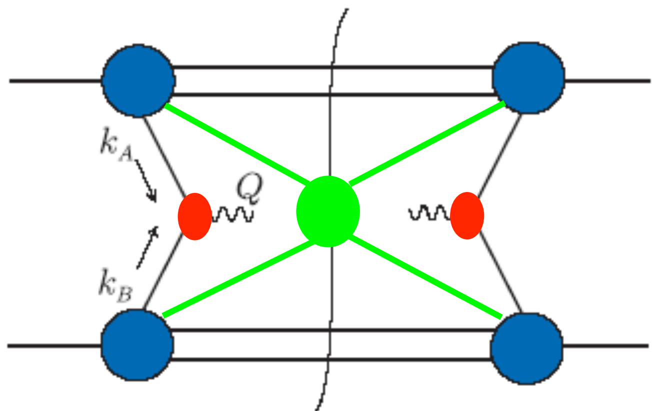

- Subleading logarithms are equally important at $Q_T$=0

- Solution:

  Impose 4-momentum conservation at each step of soft gluon resummation

# CSS b-space resummation formalism

- **Leading order $K_T$-factorized cross section:**




$$\frac{d\sigma_{AB}}{dQ^2 dQ_T^2} = \sum_f \int d\xi_a d\xi_b \int \frac{d^2k_{A_T} d^2k_{B_T} d^2k_{s,T}}{(2\pi)^6}$$
$$\times P_{f/A}(\xi_a, k_{A_T}) P_{\bar{f}/B}(\xi_b, k_{B_T}) H_{f\bar{f}}(Q^2) S(k_{s,T})$$
$$\times \delta^2(\vec{Q}_T - \vec{k}_{A_T} - \vec{k}_{B_T} - \vec{k}_{s,T})$$

$$\delta^2(\vec{Q}_T - \prod_i \vec{k}_{i,T}) = \frac{1}{(2\pi)^2}\int d^2b\, e^{i\vec{b}\cdot\vec{Q}_T} \prod_i e^{-i\vec{b}\cdot\vec{k}_{i,T}}$$

$$\frac{d\sigma_{AB}}{dQ^2 dQ_T^2} \equiv \frac{1}{(2\pi)^2}\int d^2b\, e^{i\vec{b}\cdot\vec{Q}_T} \tilde{W}_{AB}(b,Q) + Y_{AB}(Q_T^2, Q^2)$$

$$= \frac{1}{(2\pi)}\int_0^\infty db\, J_0(bQ_T)\, b\tilde{W}_{AB}(b,Q) + \left[\frac{d\sigma_{AB}^{(\mathrm{Pert})}}{dQ^2 dQ_T^2} - \frac{d\sigma_{AB}^{(\mathrm{Asym})}}{dQ^2 dQ_T^2}\right]$$

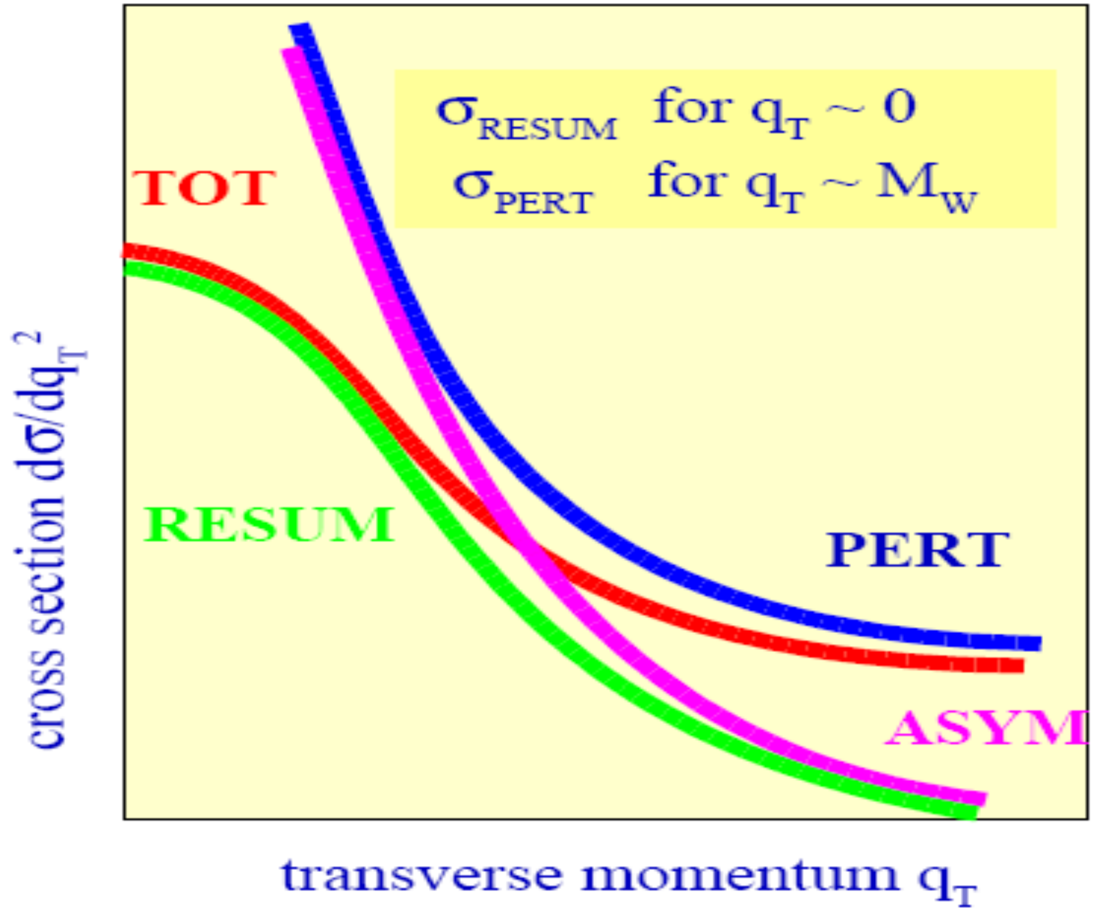
**resummed**

**No large log's**

**The $Q_T$-distribution is determined by the b-space function:** $b\, W_{AB}(b,Q)$

# Role of each term in CSS formalism

$$\sigma_{TOT} = \sigma_{RESUM} + \sigma_{PERT} - \sigma_{ASYM}$$



# b-space resummation

- b-space distribution:

$$W_{AB}(b,Q) = \sum_{ij} W_{ij}(b,Q)\hat{\sigma}_{ij}(Q)$$

- Collins-Soper equation:

$$\frac{\partial}{\partial \ln Q^2}\tilde{W}_{ij}(b,Q) = \left[K(b\mu,\alpha_s) + G(Q/\mu,\alpha_s)\right]\tilde{W}_{ij}(b,Q) \qquad (1)$$

- Evolution kernels satisfy RG equation:

$$\frac{\partial}{\partial \ln \mu^2}K(b\mu,\alpha_s) = -\frac{1}{2}\gamma_K(\alpha_s(\mu)) \qquad (2)$$

$$\frac{\partial}{\partial \ln \mu^2}G(Q/\mu,\alpha_s) = \frac{1}{2}\gamma_K(\alpha_s(\mu)) \qquad (3)$$

- Solution - resummation:

$$W_{ij}(b,Q) = W_{ij}(b,1/b)\,\mathrm{e}^{-S_{ij}(b,Q)}$$

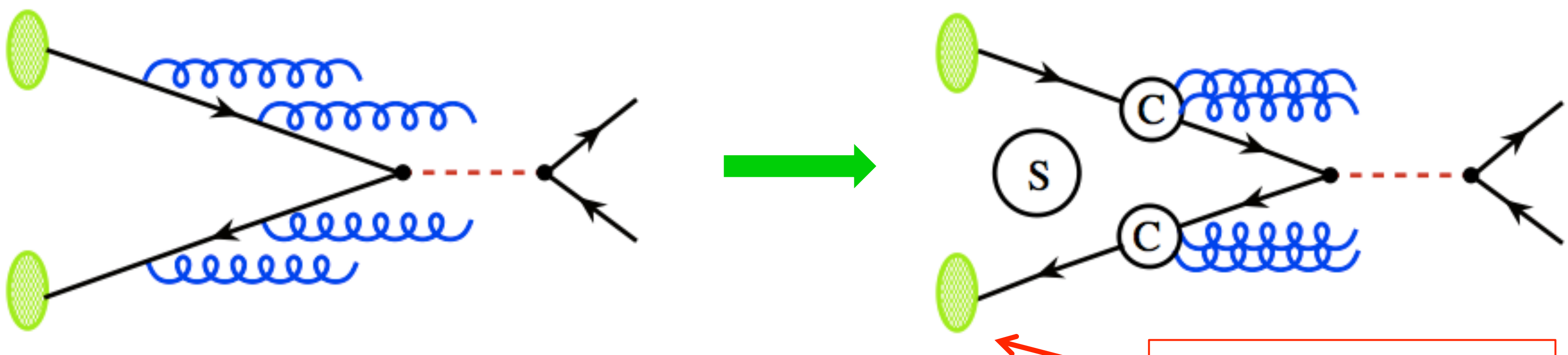
Sudakov form factor
All large logs

Boundary condition – perturbative if b is small!

# Perturbative solution

- ❑ **Boundary condition – collinear factorization:**

$$W_{ij}(b,Q) = \sum_{a,b} \sigma_{ij\to Z}\left[\phi_{a/A}\otimes C_{a\to i}\right]\otimes\left[\phi_{b/B}\otimes C_{b\to j}\right]$$




Collinear PDFs

- ❑ **Perturbative solution:**

$$W_{AB}^{\text{pert}}(b,Q) = \sum_{a,b,i,j} \sigma_{ij\to Z}\left[\phi_{a/A}\otimes C_{a\to i}\right]\otimes\left[\phi_{b/B}\otimes C_{b\to j}\right]\times \mathrm{e}^{-S_{ij}(b,Q)}$$

- ❑ **Extrapolation to large-b?**

  - ✧ **Non-perturbative**
  - ✧ **Predictive power?**

$$\sigma^{\text{Resum}} \propto \int_0^\infty db\, J_0(q_T\, b)\, b\, W(b,Q)$$

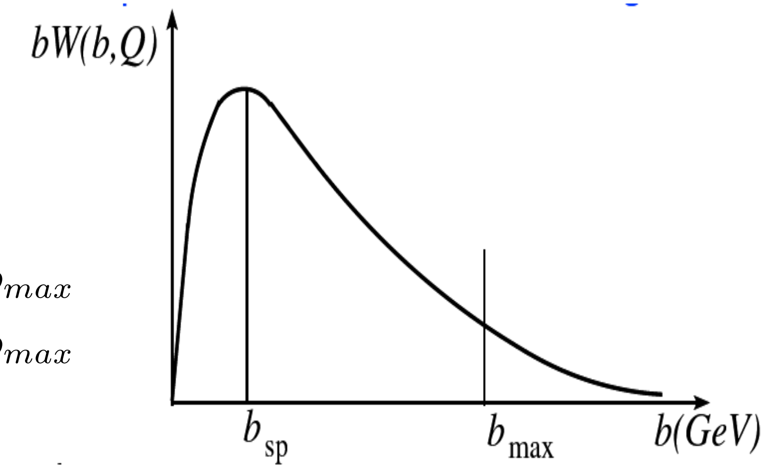
# Phenomenology

Qiu, Zhang, 2001

- Resumed cross section:

$$\frac{d\sigma^{\rm resum}_{AB\to Z}}{dq_T^2} \propto \int_0^\infty db\, J_0(q_T b)\, b\, W(b,Q)$$

$$W(b,Q) = \begin{cases} W^{\rm pert}(b,Q) & b \le b_{max} \\ W^{\rm pert}(b_{max},Q) F^{NP}_{QZ}(b,Q,b_{max}) & b > b_{max} \end{cases}$$




- Resumed cross section:

$$F^{NP}_{QZ}(b,Q;b_{max}) = \exp\left\{ -\ln\left(\frac{Q^2 b_{max}^2}{c^2}\right) \left[ g_1 \left( (b^2)^\alpha - (b_{max}^2)^\alpha \right) + g_2 \left( b^2 - b_{max}^2 \right) \right] - \bar{g}_2 \left( b^2 - b_{max}^2 \right) \right\}$$

Leading twist

Intrinsic power corrections

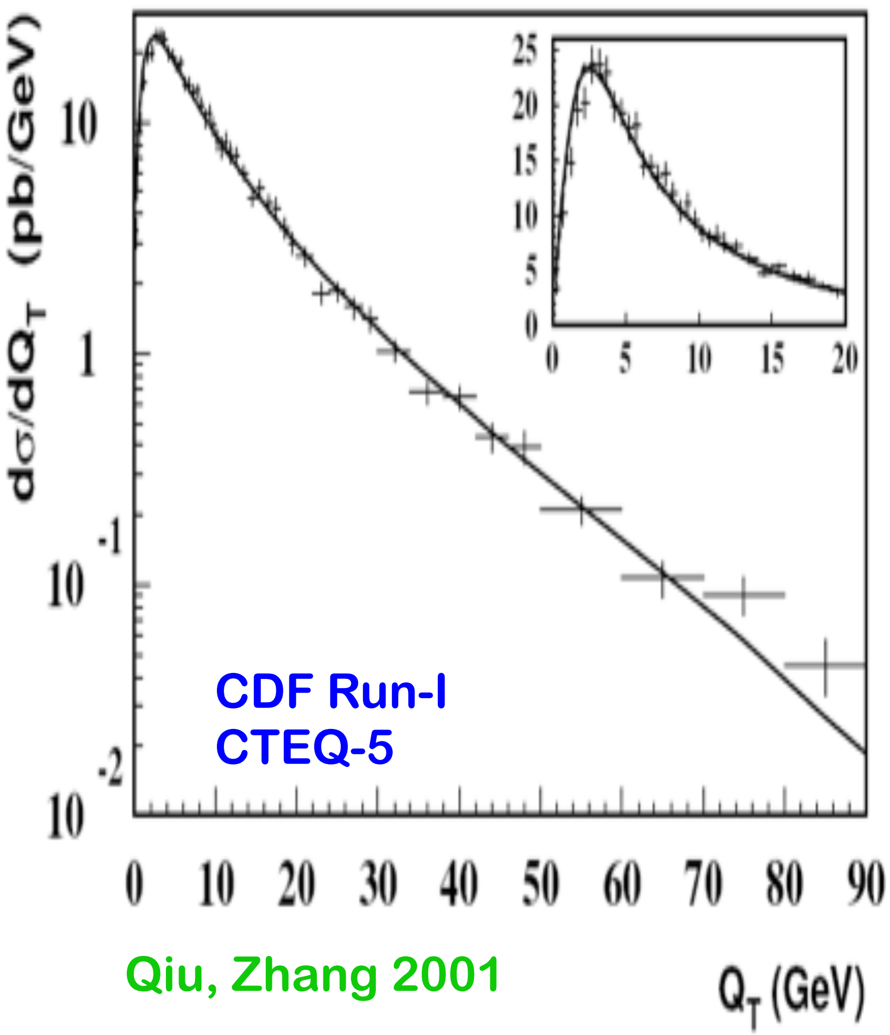
Dynamical power corrections

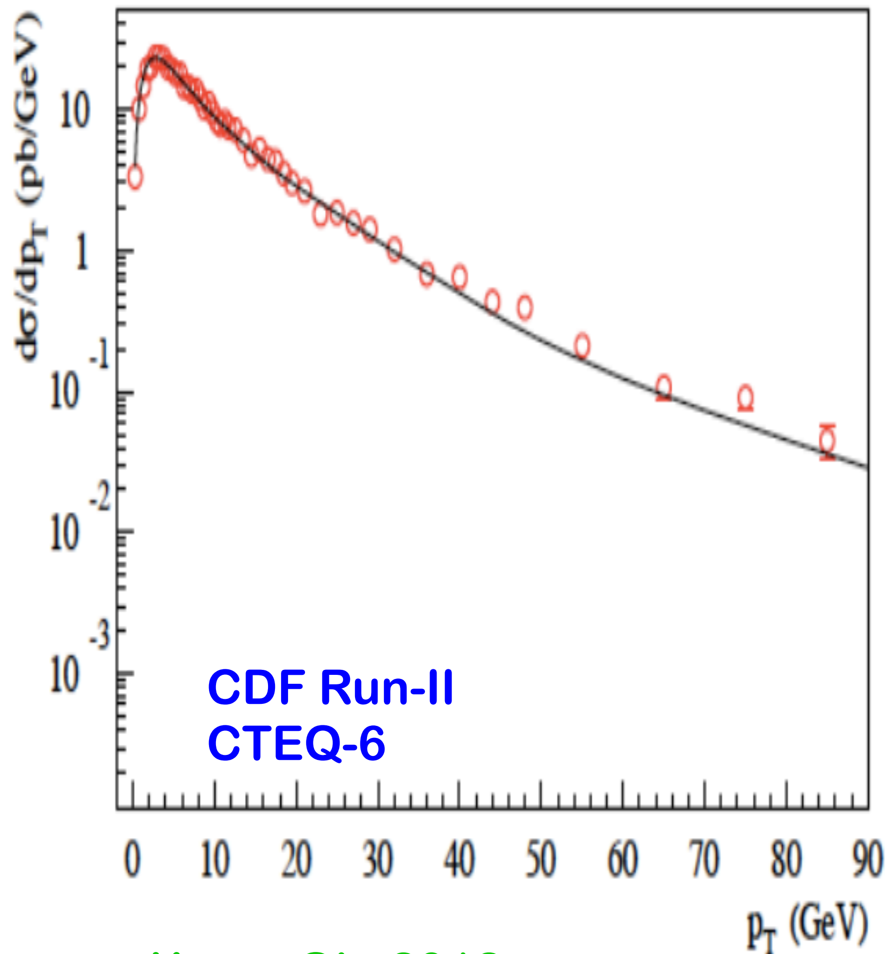
- Predictive power:

✧ Larger Q
✧ Larger S

→ Smaller $b_{sp}$ → Better prediction

# Phenomenology – Tevatron



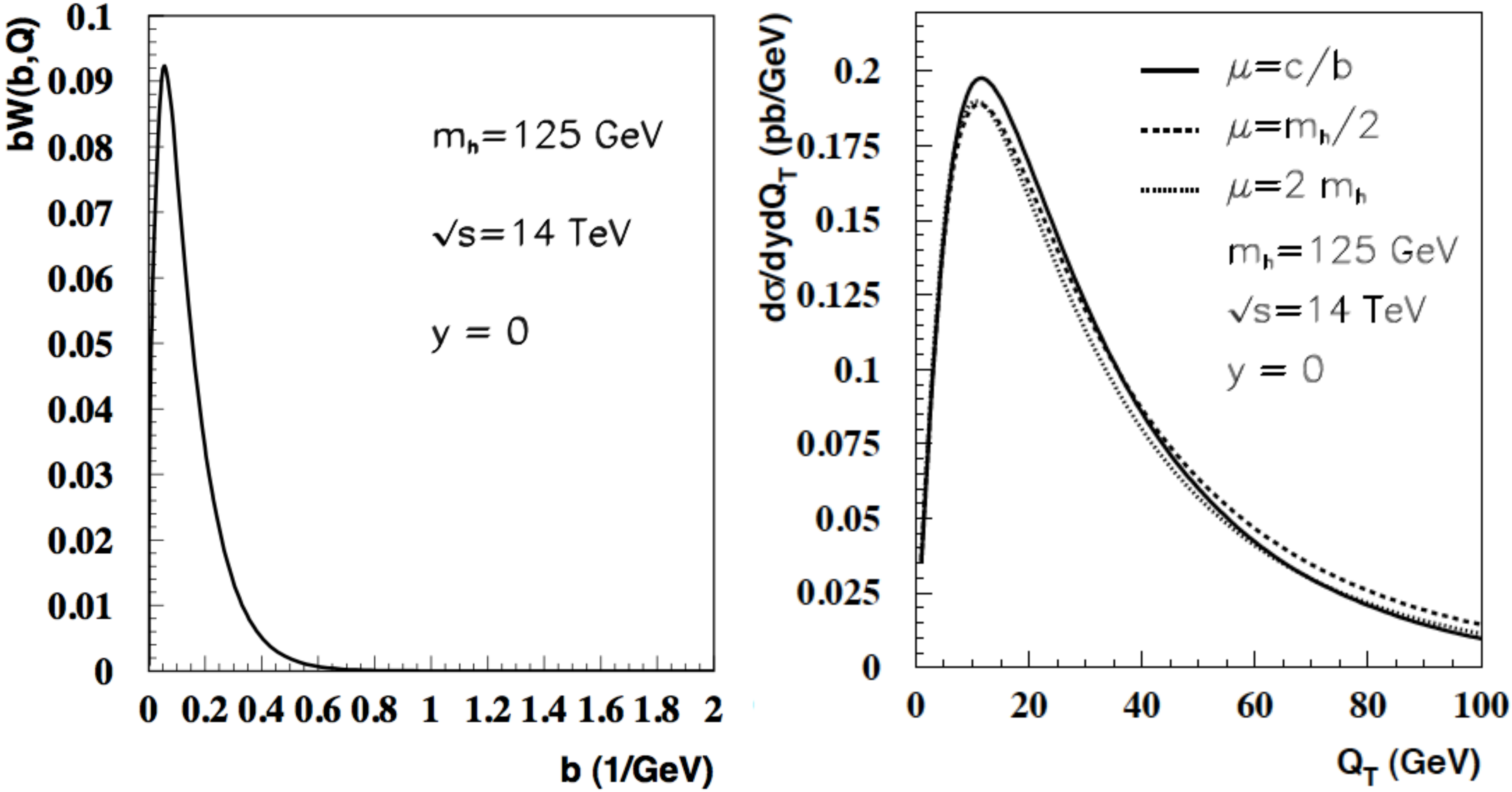

Qiu, Zhang 2001

Kang, Qiu 2012

**No free fitting parameter!**

# Phenomenology – Higgs

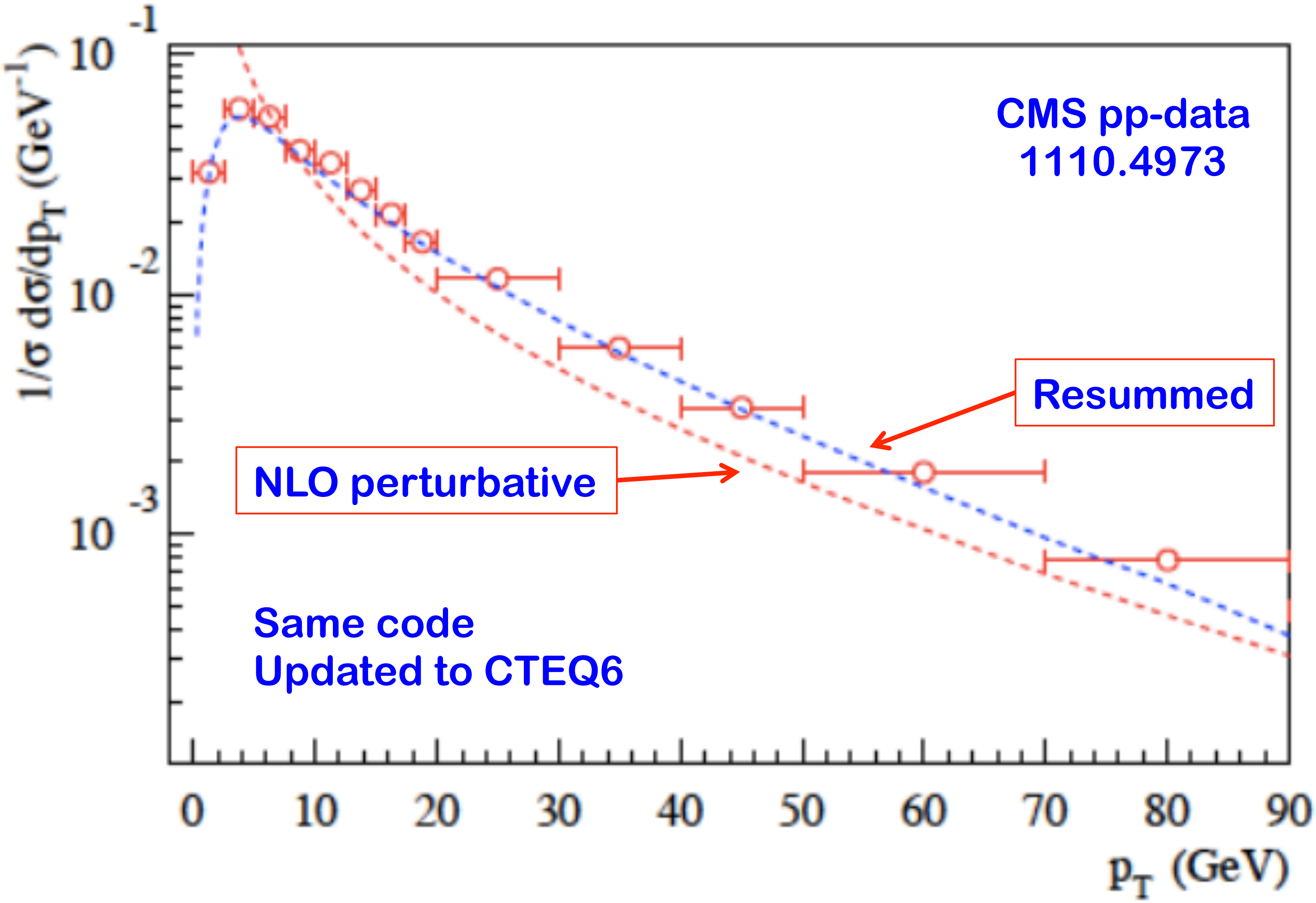
Berger, Qiu, 2003




**Effectively no non-perturbative uncertainty!**

# Phenomenology – $Z^0$ @ LHC

Kang, Qiu, 2012




**Effectively no non-perturbative uncertainty!**

# Nuclear dependence in pA

- **Resummed partonic hard parts are insensitive to A:**

$$W_{AB}^{\text{pert}}(b,Q) = \sum_{a,b,i,j} \sigma_{ij\to Z} \left[\phi_{a/A} \otimes C_{a\to i}\right] \otimes \left[\phi_{b/B} \otimes C_{b\to j}\right] \times \mathrm{e}^{-S_{ij}(b,Q)}$$

Only source of A-dependence is from nPDFs

- **Large-b non-perturbative parts are sensitive to A:**

$$W^{\text{Nonpert}}(b,Q) = W^{\text{pert}}(b_{max},Q)\, F_{QZ}^{NP}(b,Q,b_{max})$$

$$F_{QZ}^{NP}(b,Q;b_{max}) = \exp\left\{ -\ln\left(\frac{Q^2 b_{max}^2}{c^2}\right)\left[g_1\left((b^2)^\alpha - (b_{max}^2)^\alpha\right) + g_2\left(b^2 - b_{max}^2\right)\right] - \bar{g}_2\left(b^2 - b_{max}^2\right)\right\}$$

Leading twist

Dynamical power corrections

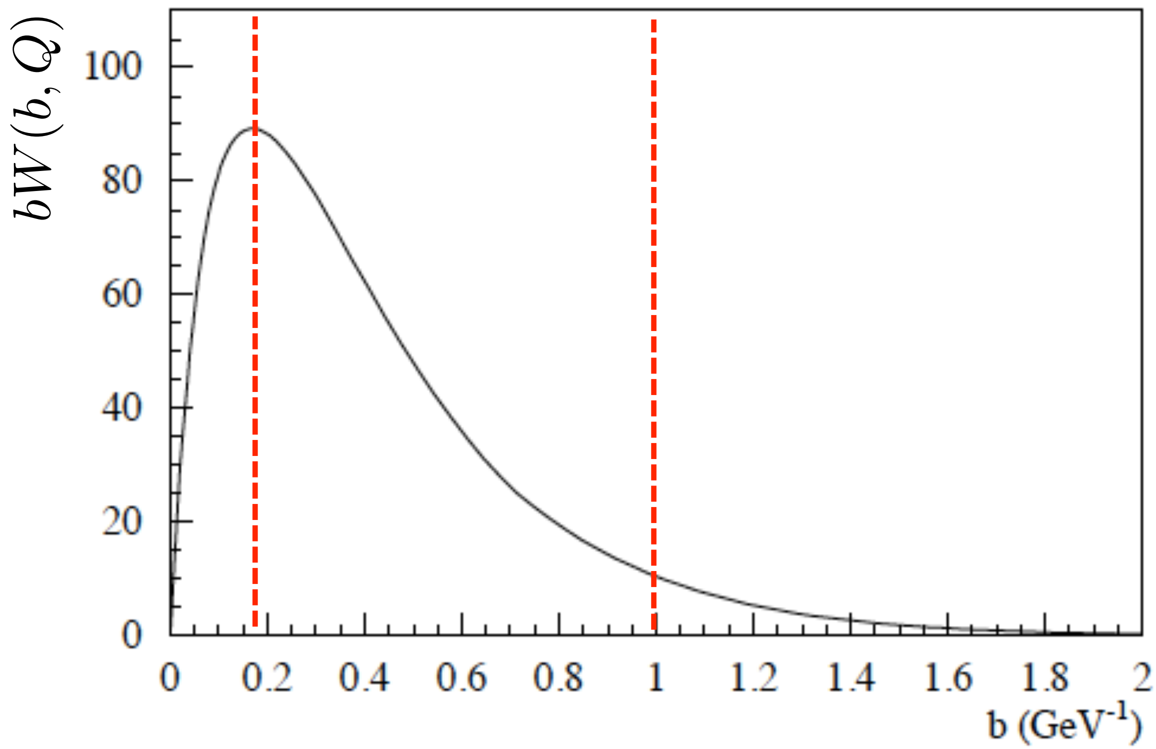
Intrinsic power corrections

- **$g_2$ = Power correction to evolution of K and G:**

$$g_2 \propto Q_s^2 \quad \Longrightarrow \quad g_2 \Rightarrow g_2\, A^{1/3}$$

# Expectations – pA @ LHC

- Strong gluon shower ➡ $\langle p_T^2 \rangle \gg Q_s^2$




Small contribution from large-b

Small A-dependent power corrections

- Dependence on nPDFs:

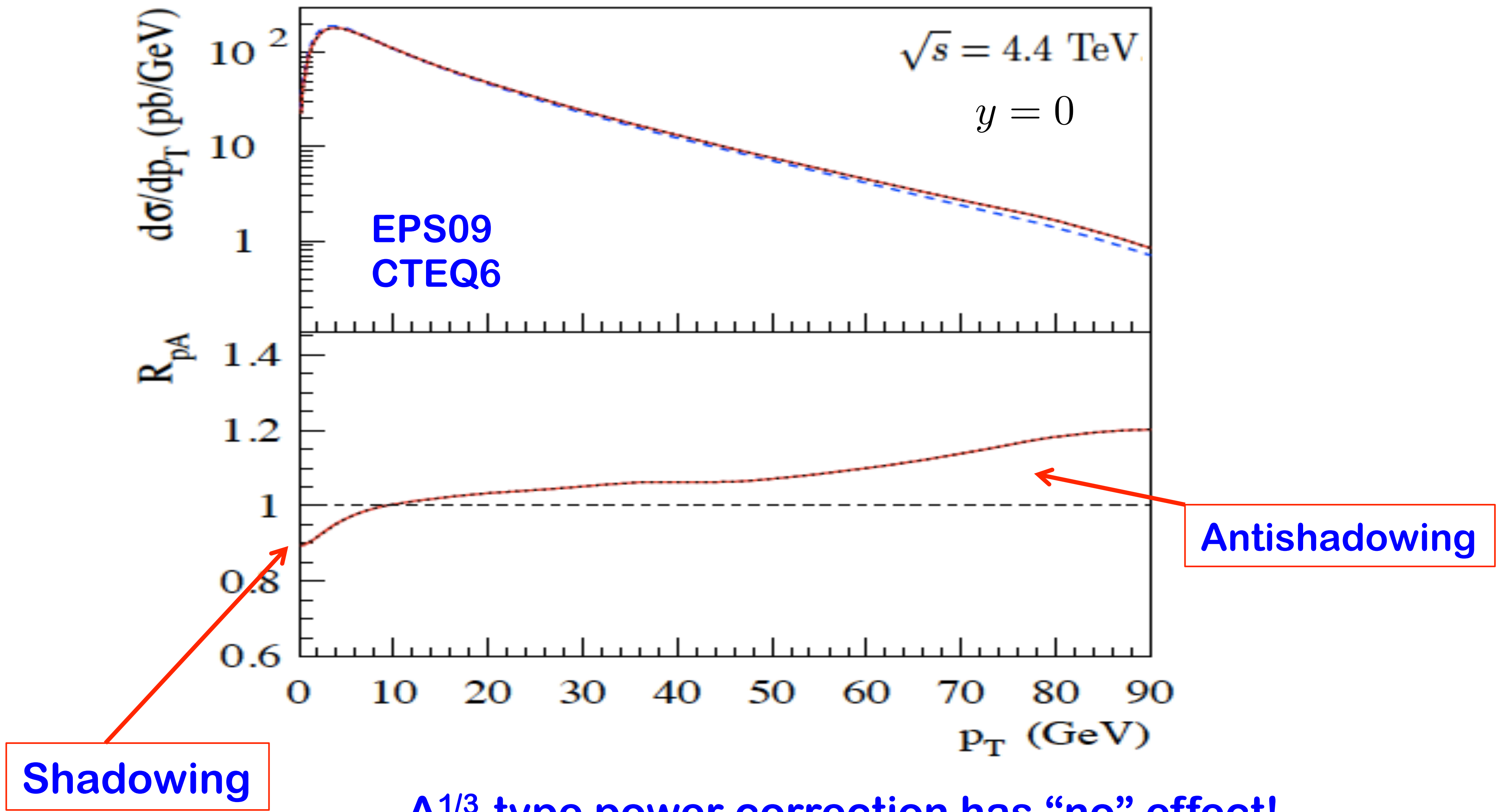
$$\mu = \frac{C_2}{b} \approx \frac{1}{b} > b_{max}^{-1} > 1 - 2 \text{ GeV}$$

Cover nPDFs for a much wider range of Q (or $\mu$)!

Strong shadowing effect for $Z^0$ – production!

# Predictions – pA @ LHC

❑ "Cronin" effect for $Z^0$ production?




$A^{1/3}$-type power correction has "no" effect!

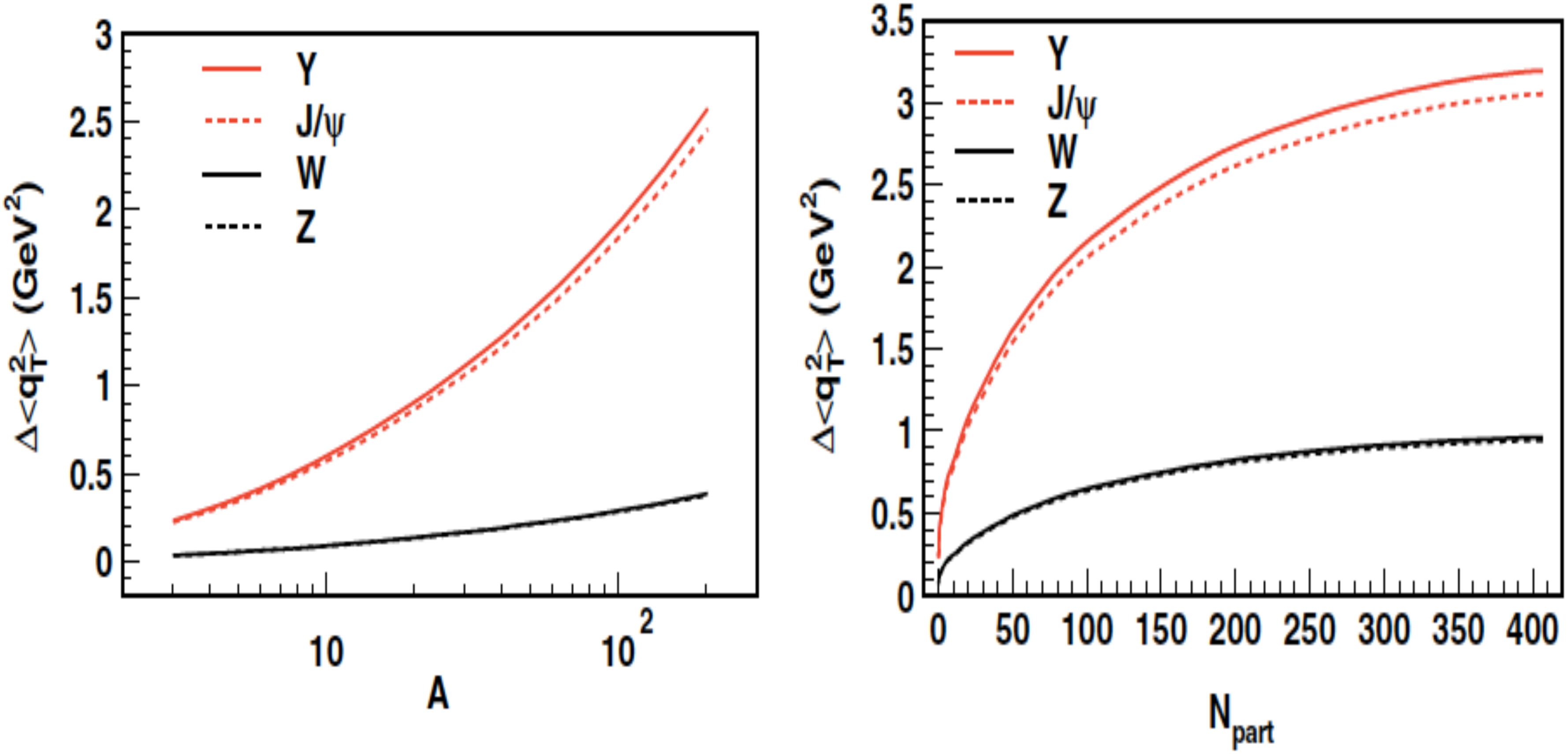
# Transverse momentum broadening for $Z^0$

Kang, Qiu, 2008

- **Broadening:**

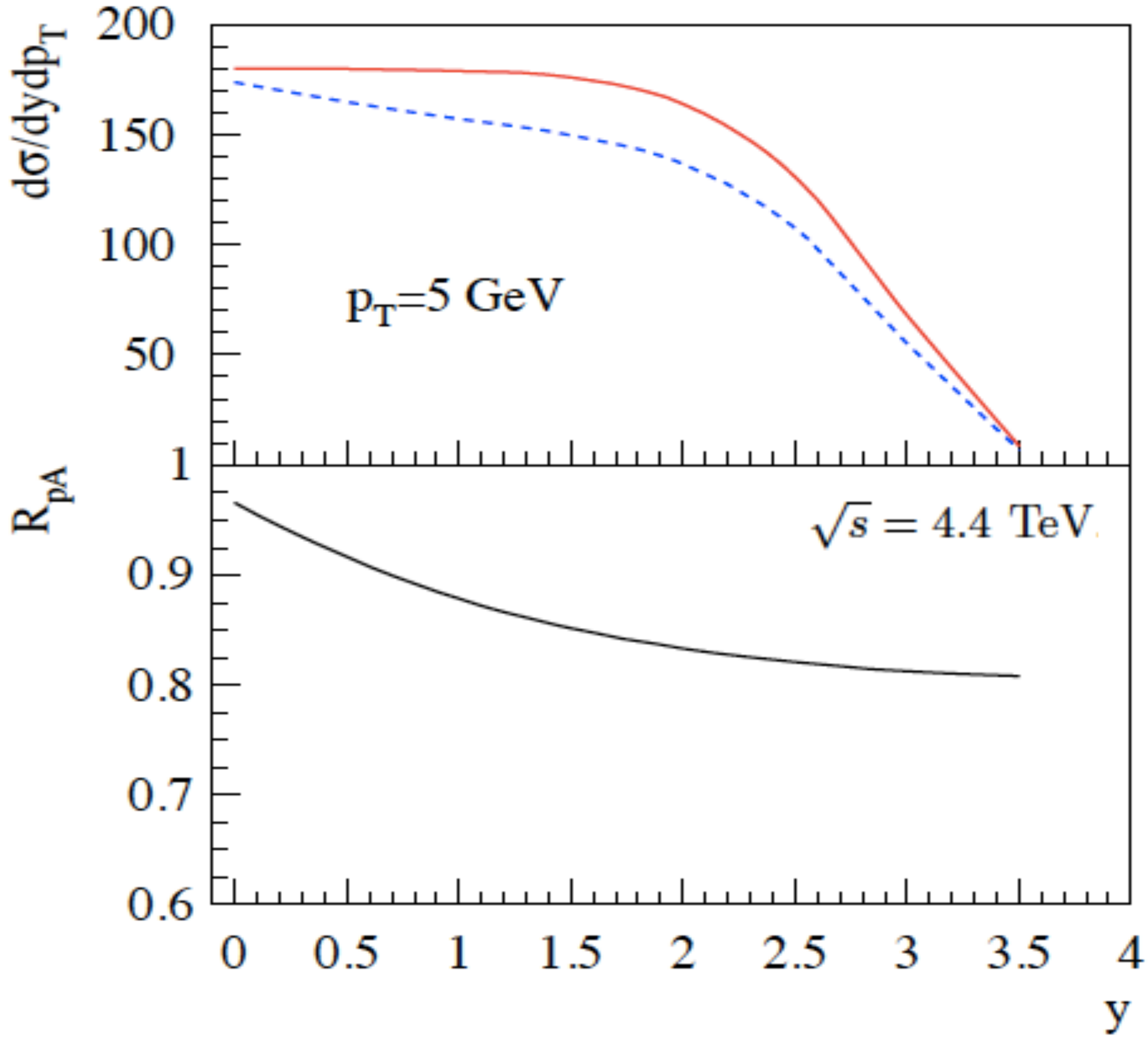
$$\Delta\langle q_T^2\rangle_{pA} = \langle q_T^2\rangle_{pA} - \langle q_T^2\rangle_{pN}$$

- **Much weak broadening:**



# $Z^0$ – Rapidity distribution

- $R_{pA}$ of $Z^0$ is determined by nPDFs:




Suppression in forward y region even for $Z^0$

# Summary

- Rapidity distribution, $d\sigma/dy$ , clean probe of nPDFs at $M_Z$
- Gluon shower dominates the $p_T$ distribution of $Z^0$
- $R_{pA}$ vs $p_T$ could probe both shadowing and antishadowing at a scale << $M_Z$:
- $Z^0$ production in pA is an excellent benchmark:

  Theoretical calculation is insensitive to non-perturbative physics other than nPDFs!

**Thank you!**