ECT* workshop on
Parton propagation through strongly interacting matter
Trento, Italy, September 26 – October 7, 2005

Partonic Rescattering Effects in Strongly Interacting Matter

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based work done with X. Guo, Ma Luo, G. Stermen, I. Vitev, X. Zhang, et al.

Outline of the Talk

- ❑ Is there an ideal probe for the strong interacting matter?
- ❑ Partonic multiple scatterings
- ❑ Collinear factorization is an approximation
- ❑ Parton k_T is important
- ❑ Can pQCD calculate the effects of parton k_T?
- ❑ Difference between QED and QCD induced parton shower (energy lose)?
- ❑ Summary and outlook

Is there an ideal probe?

- **Basic requirements:**
  - Cleanly measurable experimentally
  - Reliably calculable theoretically

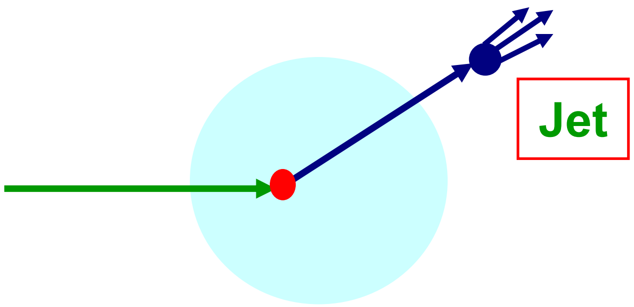
- **Necessary conditions:**
  - Sensitive to the scales and properties of strong interacting matter (SIM) – low momentum scale
  - Large momentum transfer to ensure pQCD calculation

    ⟹ a hard probe sensitive to low momentum physics

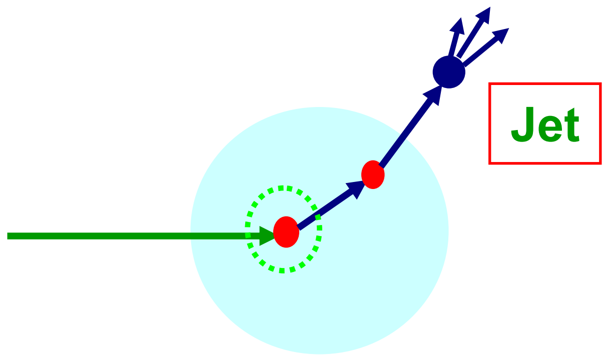
- **Potentially good probes:**
  - Have two observed scales (one hard and one soft)
  - Have one observed hard scale and a steeply falling distribution

Hard Probes

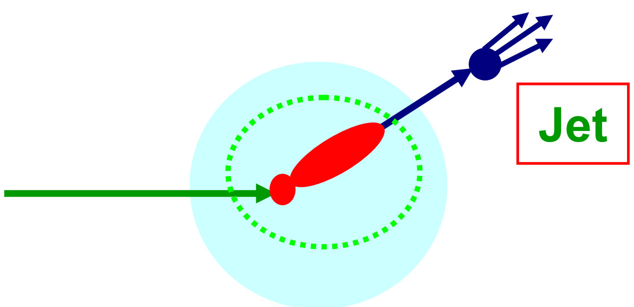
- ❑ Single hard scattering
  - ❖ probes local parton densities
  - ❖ probes short-distance QCD dynamics – pQCD factorization



- ❑ Independent/incoherent multiple scattering
  - ❖ probes parton densities at different impact parameters
  - ❖ changes the distribution, not total rate

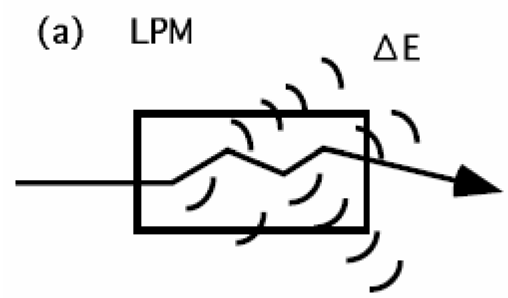


- ❑ Coherent hard multiple scatterings
  - ❖ changes production rate
  - ❖ no additional scale – power suppressed
  - ❖ probe multiparton correlations

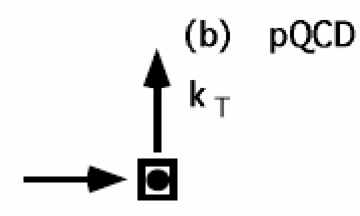


Partonic multiple scatterings

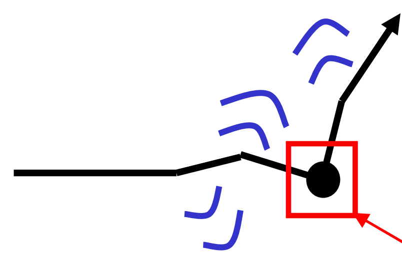
- Coherent many soft rescatterings
  - ➡ LPM effect and energy lose
  - No hard scale is required



- Coherent hard multiple scatterings
  - ➡ power suppressed, pQCD factorization
  - A hard scale is required
  - most relevant for inclusive observables



- A complete analysis of hard probe in a strong interaction matter should involve **both** coherent (energy lose and hard momentum transfer) and incoherent scattering



Coherent hard multiple scattering

- **Predictive power:**
  - factorization approach enables us to quantify the high order corrections
  - express non-perturbative quantities in terms of matrix elements of well-defined operators – universality
- **Relevance:**
  - Hard probe might limit the region of coherence – small target
  - Power corrections – suppressed at large momentum transfer
  - Good for inclusive observables
- **Helper:**
  - Hard probe at small x could cover a large nuclear target and enhance power corrections

Small-x and coherence length

- **Hard probe – process with a large momentum transfer:**

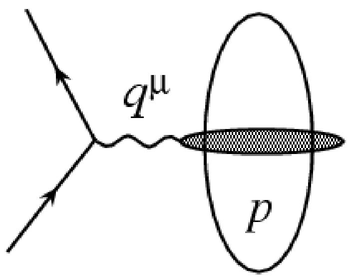
$$q^\mu \quad \text{with} \quad Q \equiv \sqrt{|q^2|} \gg \Lambda_{\text{QCD}}$$

- **Size of a hard probe is very localized and much smaller than a typical hadron at rest:**

$$\frac{1}{Q} \ll 2R \sim \text{fm}$$

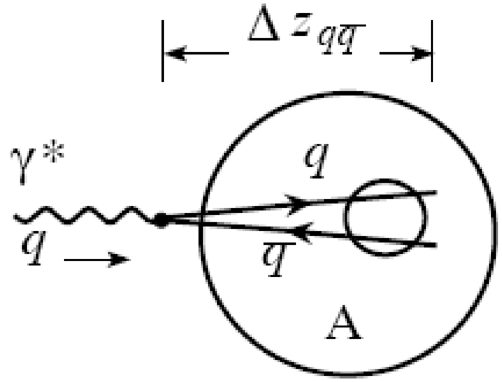
- **But, it might be larger than a Lorentz contracted hadron:**

$$\frac{1}{Q} \sim \frac{1}{xp} \gg 2R\left(\frac{m}{p}\right) \quad \text{or equivalently} \quad x \ll x_c \equiv \frac{1}{2mR} \sim 0.1$$



If an active parton *x* is small enough
the hard probe could cover several nucleons
In a Lorentz contracted large nucleus!

Coherence length in different frames



- Use DIS as an example – in target rest frame:

  virtual photon fluctuates into a q-qbar pair

  – Lifetime of the $q\bar{q}$ state:

  $$\Delta E_{q\bar{q}} \sim \nu - E_{q\bar{q}} \sim \frac{Q^2}{2\nu}\left[1 + \mathcal{O}\left(\frac{m_{q\bar{q}}^2}{Q^2}\right)\right]$$

  $$\Delta z_{q\bar{q}} \sim \frac{1}{\Delta E_{q\bar{q}}} \sim \frac{2\nu}{Q^2} = \frac{1}{m x_B}$$

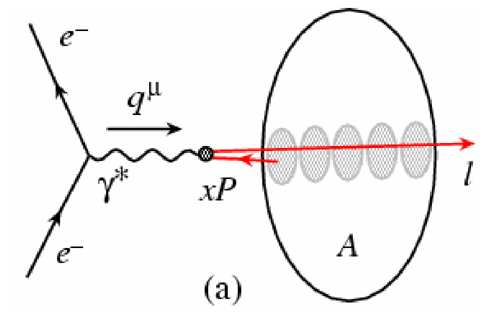
  – $\Delta z_{q\bar{q}} \gg 2$ fm, inter-nuclear distance, if $x_B \ll 0.1$

- If $x_B \ll 0.1$, the probe – q-qbar state of the virtual can interact with who hadron/nucleus coherently.

The conclusion is frame independent

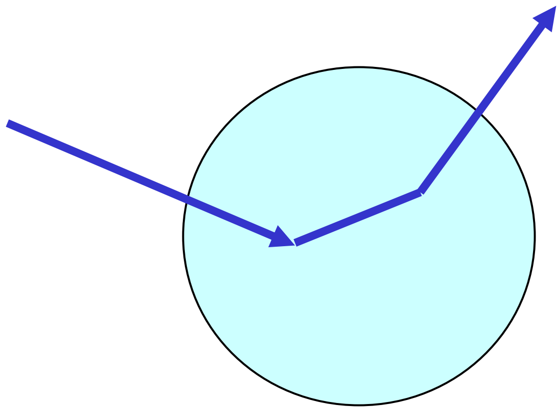
- In Breit frame:

  coherent final-state rescattering



Dynamical power corrections

❑ Coherent multiple scattering leads to dynamical power corrections:



$$\frac{d\sigma^{(D)}}{d\sigma^{(S)}} \sim \alpha_s \frac{1/Q^2}{R^2} \langle F^{+\alpha} F_\alpha^{+} \rangle A^{1/3}$$

$$d\sigma \approx d\sigma^{(S)} + d\sigma^{(D)} + \ldots$$

❑ Characteristic scale for the power corrections: $\langle F^{+\alpha} F_\alpha^{+} \rangle$

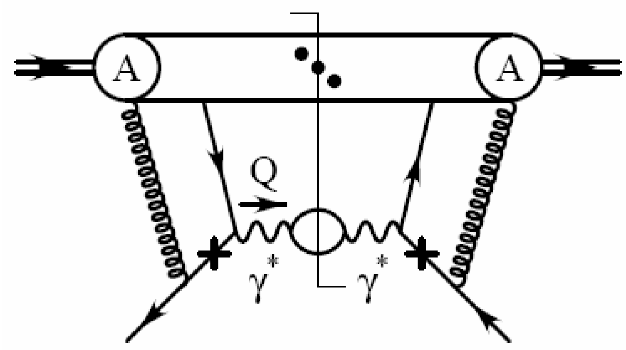
❑ For a hard probe: $\frac{\alpha_s}{Q^2 R^2} \ll 1$

❑ To extract the universal matrix element,
we need new observables more sensitive to $\langle F^{+\alpha} F_\alpha^{+} \rangle$

Total Q_T broadening

- **Direct Q_T from multiple scattering is not perturbative:**

$$\frac{d\sigma}{dQ^2 dQ_T^2} \Big/ \frac{d\sigma}{dQ^2} \propto \frac{\alpha_s}{Q_T^2} T_q(x, A)$$



- **Drell-Yan Q_T average is perturbative:**

$$\langle Q_T^2 \rangle \equiv \int dQ_T^2 \left(Q_T^2\right)\left(\frac{d\sigma}{dQ^2 dQ_T^2}\right) \Big/ \int dQ_T^2 \left(\frac{d\sigma}{dQ^2 dQ_T^2}\right)$$

Single scale Q

- **Drell-Yan Q_T broadening:** $\Delta\langle Q_T^2 \rangle \equiv \langle Q_T^2 \rangle^{hA} - A\langle Q_T^2 \rangle^{hN} \propto \sigma^{(D)}$

- **Four-parton correlation:**

$$T_q(x, A) = \int \frac{dy^-}{2\pi} \mathrm{e}^{ixp^+ y^-} \int dy_1^- dy_2^- \theta\left(y^- - y_1^-\right)\theta\left(-y_2^-\right)$$

$$\times \langle p_A | F_\alpha^+\left(y_2^-\right)\bar{\psi}(0)\frac{\gamma^+}{2}\psi\left(y^-\right)F^{+\alpha}\left(y_1^-\right)| p_A \rangle \approx \frac{9A^{1/3}}{16\pi R^2}\langle F^{+\alpha} F_\alpha^+ \rangle q_A(x)$$

- **Characteristic scale:**

$$\langle F^{+\alpha} F_\alpha^+ \rangle \equiv \frac{1}{p^+}\int dy_1^- \langle N | F^{+\alpha}(0) F_\alpha^+\left(y_1^-\right)| N \rangle \theta\left(y_1^-\right)$$

Guo, PRD 58 (1998)

$\langle F^{+\alpha} F_{\alpha}^{+} \rangle$ from Drell-Yan Q_T broadening

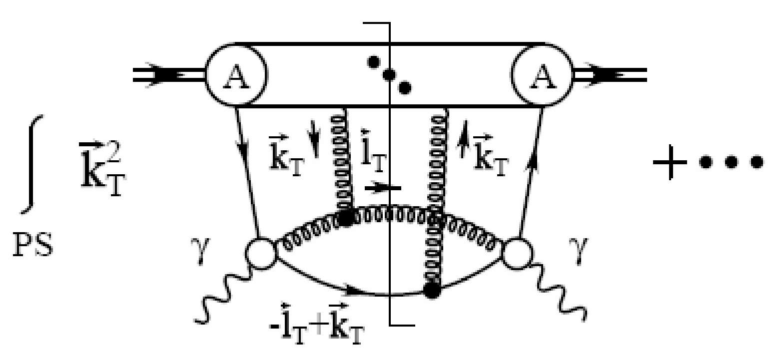
- Drell-Yan Q_T broadening:

$$\Delta\langle Q_T^2\rangle \equiv \langle Q_T^2\rangle^{hA} - A\langle Q_T^2\rangle^{hN} = \left(\frac{3\pi\alpha_s}{4R^2}\right)\langle F^{+\alpha} F_{\alpha}^{+}\rangle A^{1/3}$$

E772 and NA10 data: ⟹ $\langle F^{+\alpha} F_{\alpha}^{+}\rangle \sim 3$ Guo, PRD 58 (1998)

In cold nuclear matter

- Di-jet momentum imbalance in $\gamma + A$ collisions



⟹ $\langle F^{+\alpha} F_{\alpha}^{+}\rangle_{Di-jet} \sim 15-30$

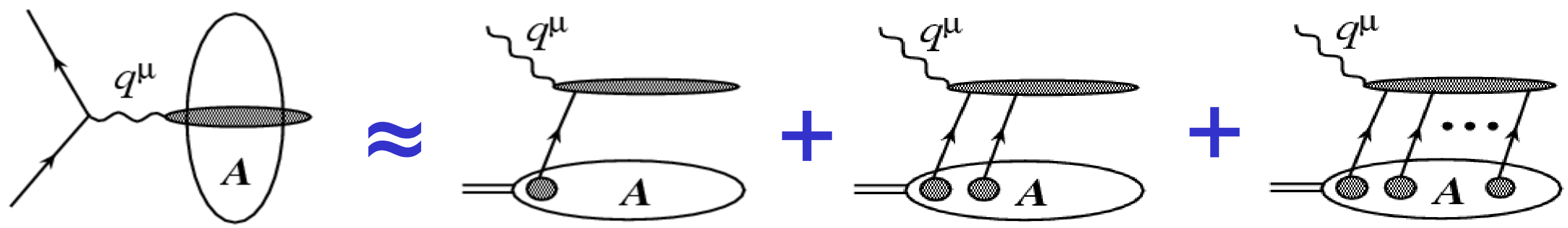
Luo et al, PRD 49 (1994)

Need more independent measurements to test the universality!

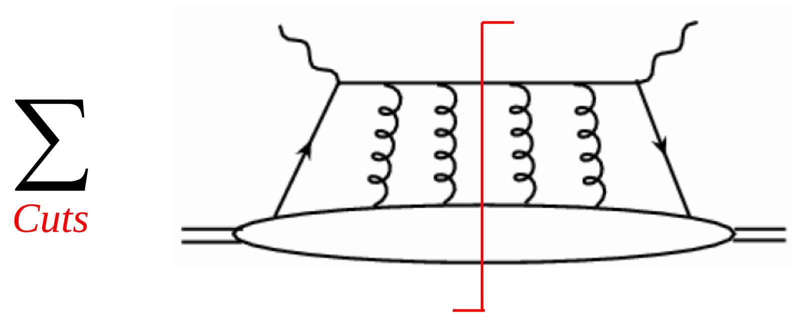
Inclusive deep inelastic scattering

Nuclear shadowing data are available for $x_B < 0.1$

At small x, the hard probe covers several nucleons, coherent multiple scattering could be equally important at relatively low Q



To take care of the coherence, we need to sum over all cuts for a given forward scattering amplitude



Summing over all cuts is also necessary for IR cancellation

Factorization beyond leading power

- **Collinear factorization to DIS cross section:**

Leading twist

$$d\sigma_{DIS}^{\gamma^* h} = d\hat{\sigma}_2^i \otimes [1 + C^{(1,2)}\alpha_s + C^{(2,2)}\alpha_s^2 + \ldots] \otimes T_2^{i/h}(x)$$

$$+ \frac{d\hat{\sigma}_4^i}{Q^2} \otimes [1 + C^{(1,4)}\alpha_s + C^{(2,4)}\alpha_s^2 + \ldots] \otimes T_4^{i/h}(x)$$

$$+ \frac{d\hat{\sigma}_6^i}{Q^4} \otimes [1 + C^{(1,6)}\alpha_s + C^{(2,6)}\alpha_s^2 + \ldots] \otimes T_6^{i/h}(x)$$

$$+ \ldots$$

Power corrections

Factorization breaks in hadronic collisions beyond $1/Q^2$ terms

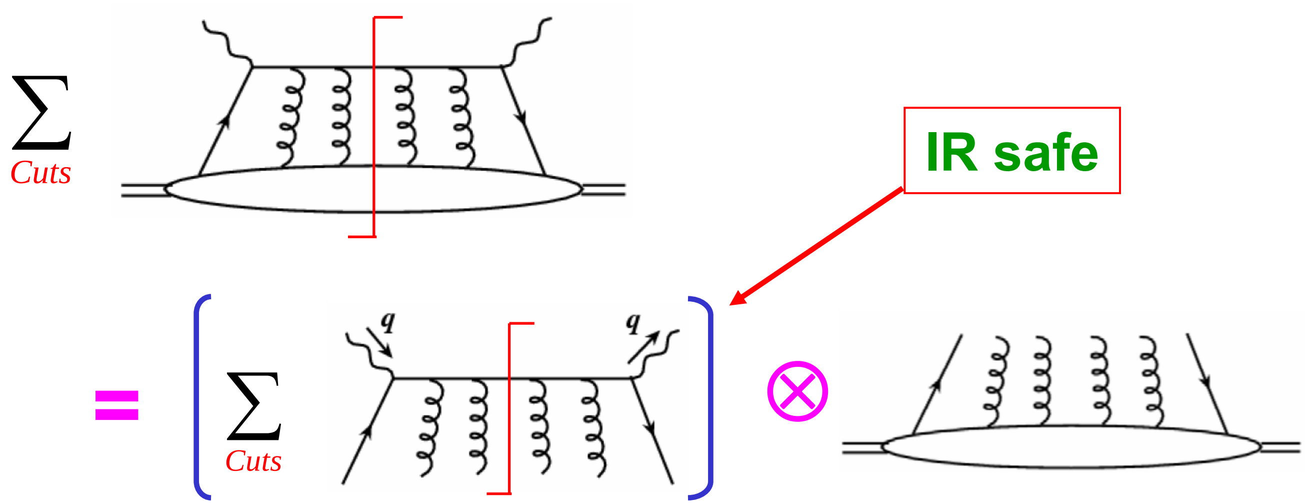
- **Nonperturbative contributions:**

$T_{4,\ldots}^{i/h}(x)$ should include both $\langle k_T^2 \rangle$ and multiple scattering effect $\langle F^{+\alpha} F_\alpha^{\ +} \rangle$

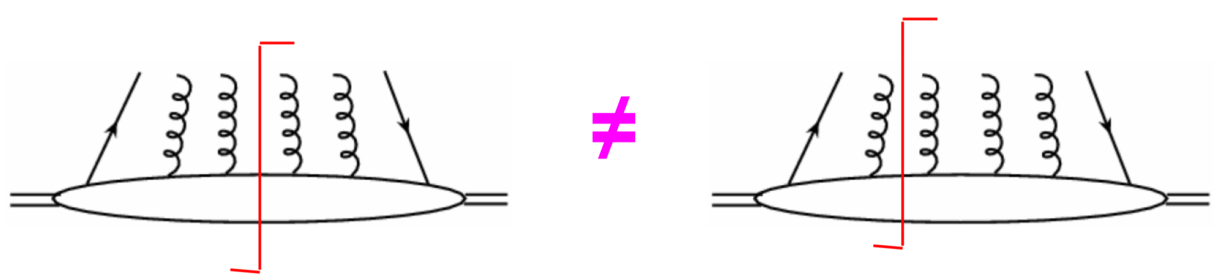
Resummation of leading power corrections: $\sum_N \left(\frac{\alpha_s}{Q^2 R^2} \langle F^{+\alpha} F_\alpha^{\ +} \rangle A^{1/3} \right)^N$

Collinear approximation is important

With collinear approximation:

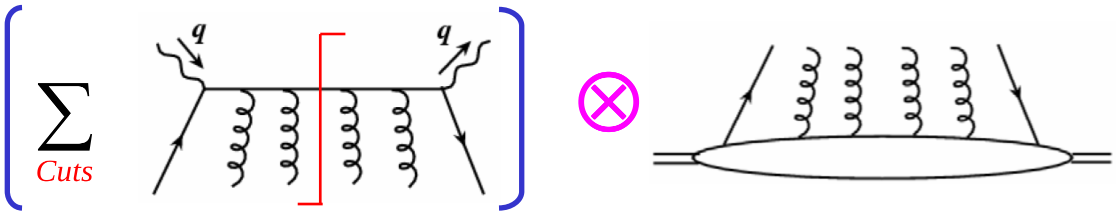


Different cuts for matrix elements of partons with k_T are not equal:



Multiparton correlation functions

- Parton momentum convolution:



$$\propto \int \prod_i dy_i^- \; e^{i x_i p^+ y_i^-} \langle P_A | \prod_i F^{+\perp}(y_i^-) | P_A \rangle$$

All coordinate space integrals are localized if x is large

- Leading pole approximation for dx_i integrals :
  - dx_i integrals are fixed by the poles (no pinched poles)
  - $x_i = 0$ removes the exponentials
  - dy integrals can be extended to the size of nuclear matter

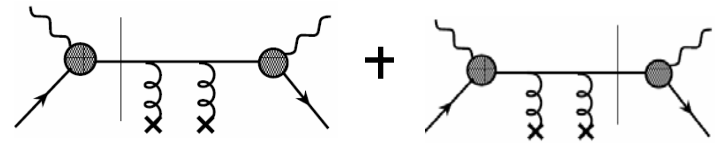
Leading pole leads to highest powers in medium length, a much small number of diagrams to worry about

Resummation of multiple scattering

- **LO contribution to DIS cross section:**

$$\Rightarrow \quad \delta(x - x_B)$$

- **NLO contribution:**

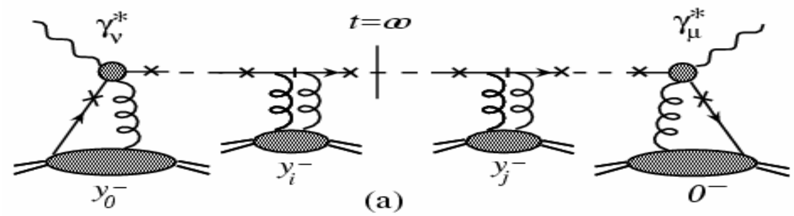


$$\Rightarrow \quad \frac{g^2}{Q^2}\left(\frac{1}{2N_c}\right)\left[2\pi^2\tilde{F}^2(0)\right] x_B \lim_{x_1\to x}\left[\frac{1}{x-x_1}\delta(x_1-x_B)+\frac{1}{x_1-x}\delta(x-x_B)\right]$$

$$2\pi^2\tilde{F}^2(0) = \int \frac{dy_2^-\, dy_1^-}{(2\pi)^2}\left[F^{+\alpha}(y_2^-)F_\alpha^{\ +}(y_1^-)\right]\theta(y_2^-)$$

$$\lim_{x_1\to x}\left[\ldots\right] = x_B\left[-\frac{d}{dx}\delta(x-x_B)\right]$$

- **Nth order contribution:**



$$\Rightarrow \quad \left[\frac{g^2}{Q^2}\left(\frac{1}{2N_c}\right)\left[2\pi^2\tilde{F}^2(0)\right]\right]^N x_B^N \lim_{x_i\to x}\sum_{m=0}^{N}\delta(x_m-x_B)\left[\prod_{i=1}^{m}\left(\frac{1}{x_{i-1}-x_m}\right)\right]\left[\prod_{j=1}^{N-m}\left(\frac{1}{x_{m+j}-x_m}\right)\right]$$

$$x_B^N\left[(-1)^N\frac{1}{N!}\frac{d^N}{dx^N}\delta(x-x_B)\right]$$

Infrared safe!

Contributions to DIS structure functions

Qiu and Vitev, PRL (2004)

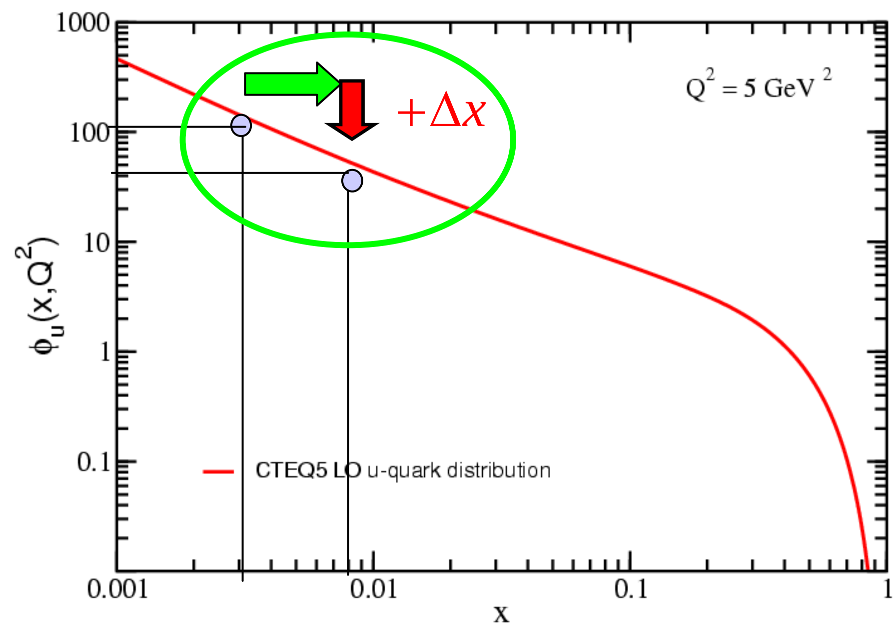
- Transverse structure function:

$$F_T(x_B,Q^2)=\sum_{n=0}^{N}\frac{1}{n!}\left[\frac{\xi^2}{Q^2}\left(A^{1/3}-1\right)\right]^n x_B^n\frac{d^n}{dx_B^n}F_T^{(0)}(x_B,Q^2)$$

$$\approx F_T^{(0)}(x_B(1+\Delta),Q^2)$$

$$\Delta\equiv\frac{\xi^2}{Q^2}\left(A^{1/3}-1\right)$$

$$\xi^2=\frac{3\pi\alpha_s}{8R^2}\langle F^{+\alpha}F_\alpha{}^{+}\rangle$$

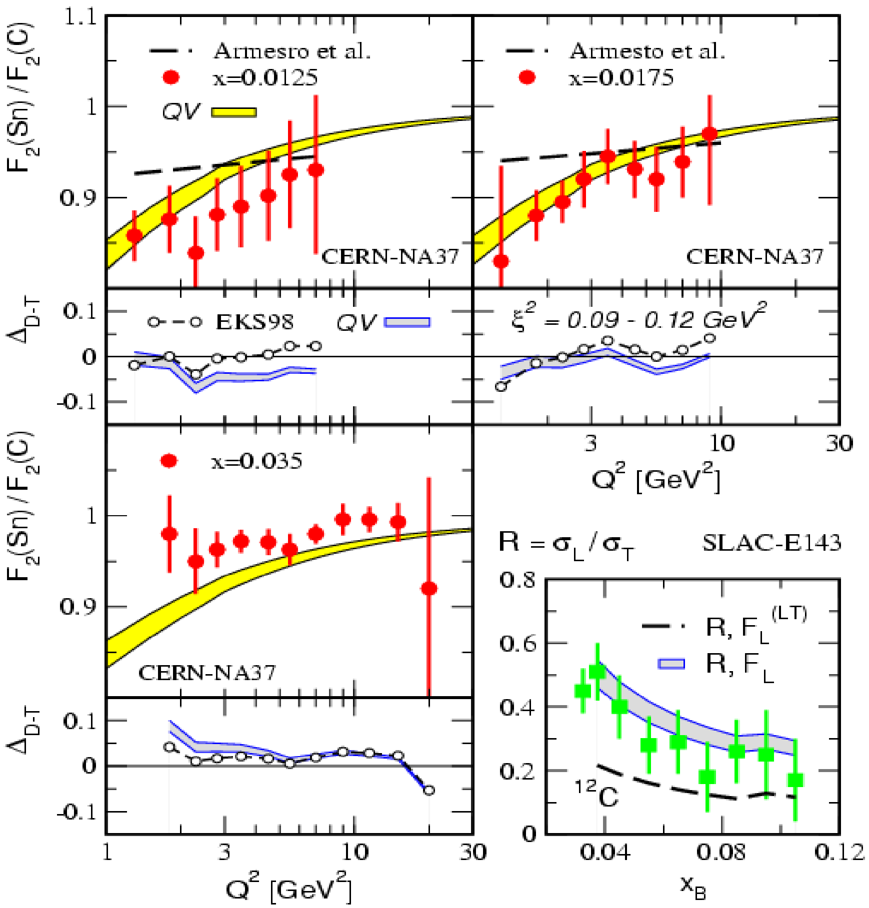


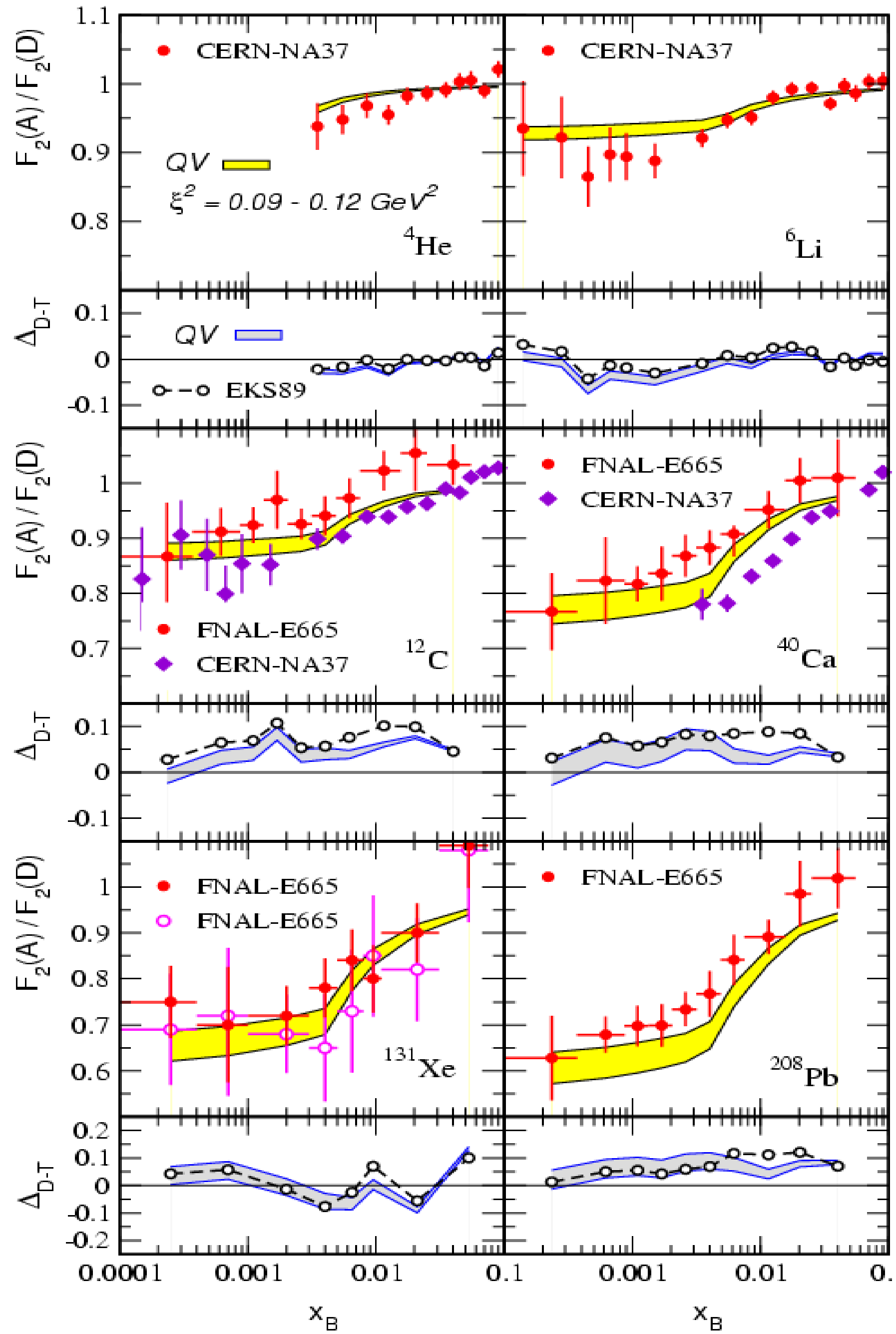
Single parameter for the power correction, and is proportional to the same characteristic scale

- Similar result for longitudinal structure function

Neglect LT shadowing upper limit of ξ^2

$\xi^2 \sim 0.09 - 0.12\ \mathrm{GeV}^2$





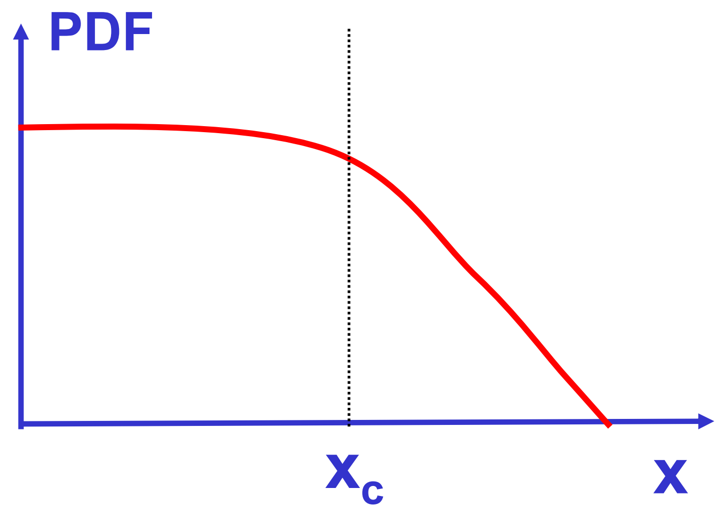
Leading twist shadowing

- Power corrections complement to the leading twist shadowing:
  - Leading twist shadowing changes the x- and Q-dependence of the parton distributions
  - Power corrections to the DIS structure functions (or cross sections) are effectively equivalent to a shift in x
  - Power corrections vanish quickly as hard scale Q increases while the leading twist shadowing goes away much slower

- If leading twist shadowing is so strong that x-dependence of parton distributions saturates

  for $x < x_c$,

  additional power corrections, the shift in x, should have no effect to the cross section!



Upper limit of $\langle F^{+\alpha} F_{\alpha}^{+} \rangle$ from DIS data

- Drell-Yan Q_T-broadening data:

$$\Longrightarrow \quad \langle F^{+\alpha} F_{\alpha}^{+} \rangle_{DY} \sim 3 \quad \Longrightarrow \quad \xi^2 \approx 0.05\ \text{GeV}^{-2}$$

- Upper limit from the shadowing data:

$$\Longrightarrow \quad \xi^2_{Max} \approx 0.09 - 0.12\ \text{GeV}^{-2} \quad \Longrightarrow \quad \langle F^{+\alpha} F_{\alpha}^{+} \rangle_{DIS} < 5-6$$

- Physical meaning of these numbers:

$$\langle F^{+\alpha} F_{\alpha}^{+} \rangle \equiv \frac{1}{p^+} \int dy_1^- \langle N | F^{+\alpha}(0) F_{\alpha}^{+}(y_1^-) | N \rangle \theta(y_1^-) \approx \frac{1}{2} \lim_{x \to 0} xG(x, Q^2)$$

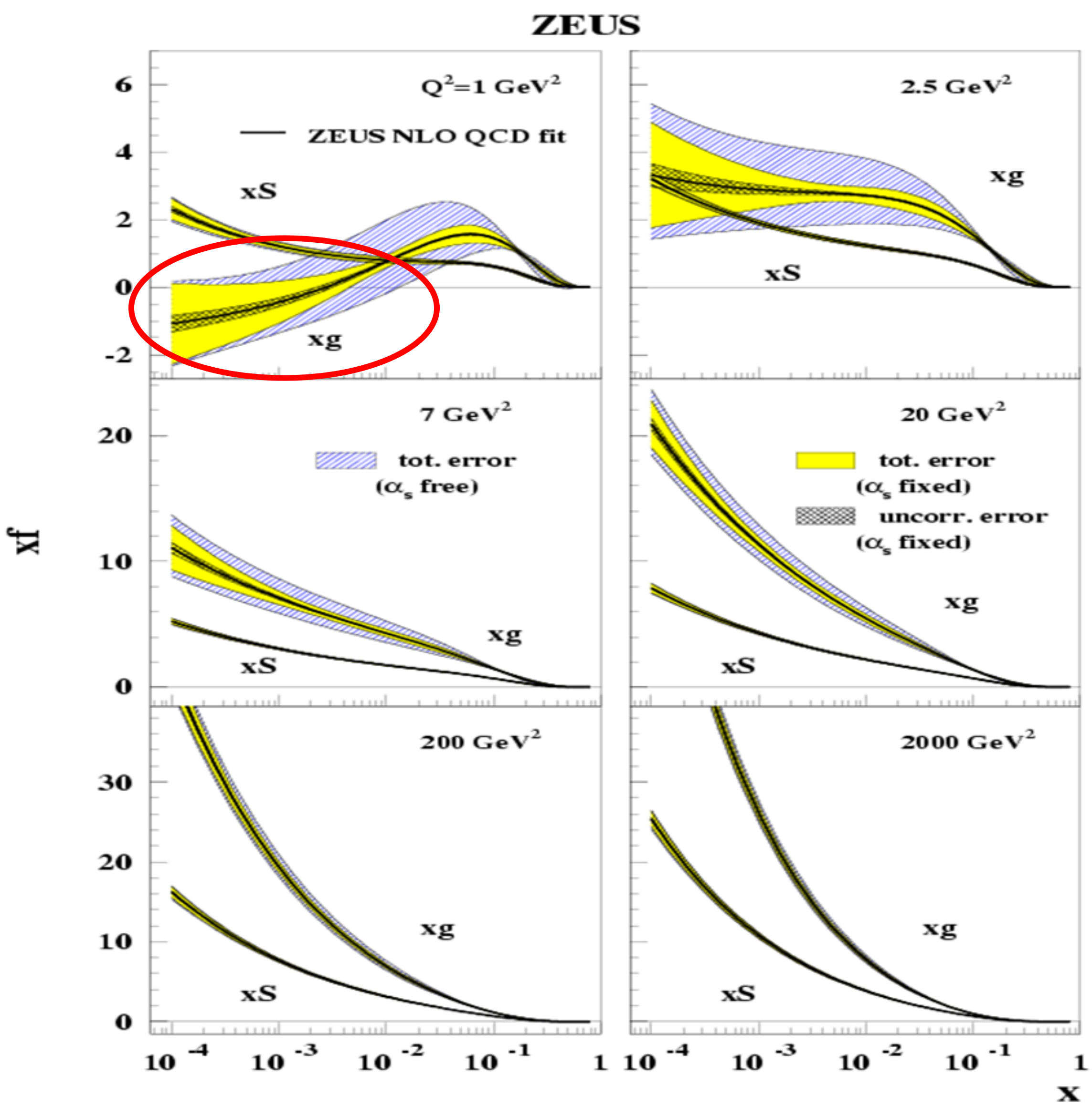
$$\Longrightarrow \quad \langle xG(x \to 0, Q_s^2) \rangle < 10 \ \text{ in cold nuclear matter(?)}$$

Negative gluon distribution at low Q

- ❑ NLO global fitting based on leading twist DGLAP evolution leads to **negative** gluon distribution
- ❑ MRST PDF's have the same features

Does it mean that we have no gluon for $x < 10^{-3}$ at 1 GeV?

No!



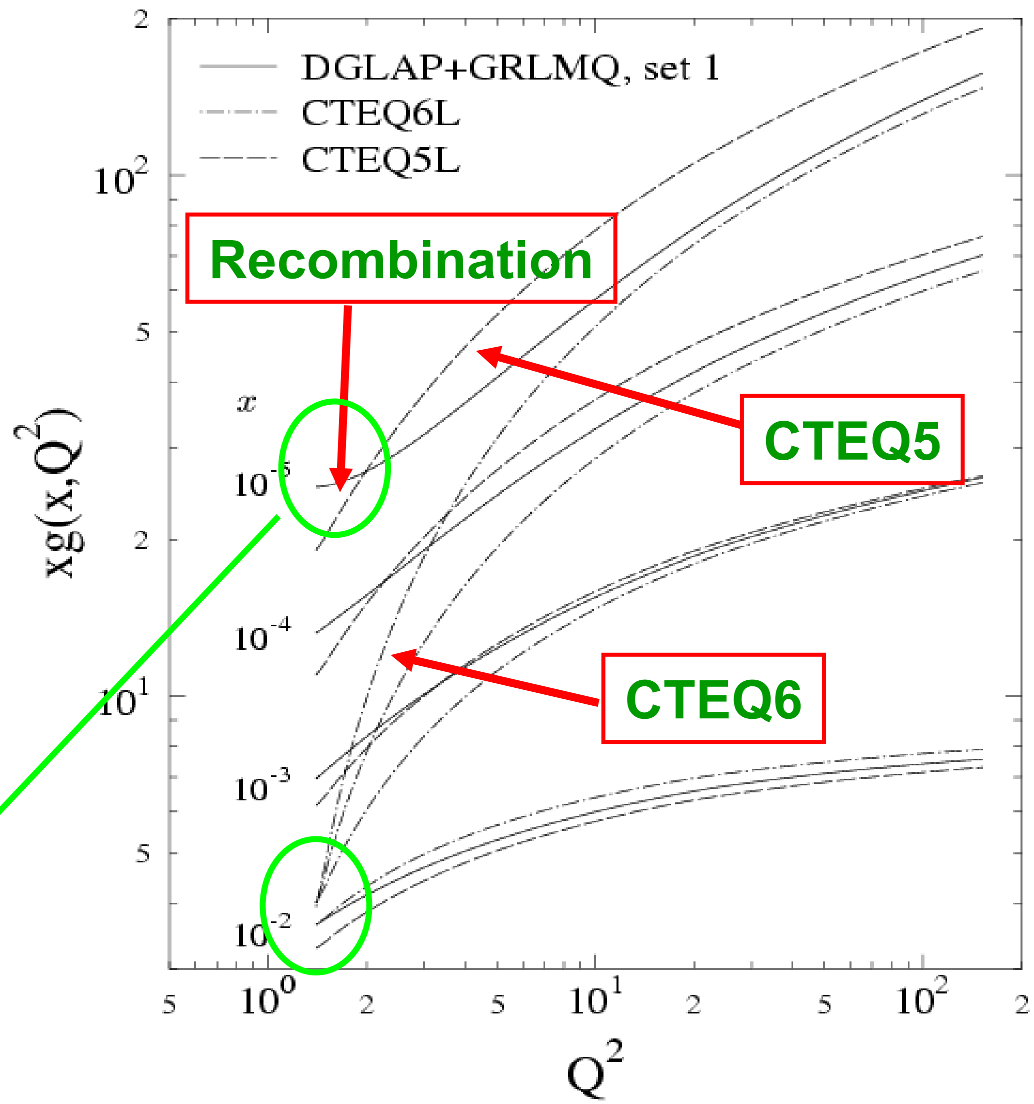
Recombination prevents negative gluon

- In order to fit new HERA data, like MRST PDF's, CTEQ6 gluon has to be much smaller than CTEQ5, even negative at Q = 1 GeV

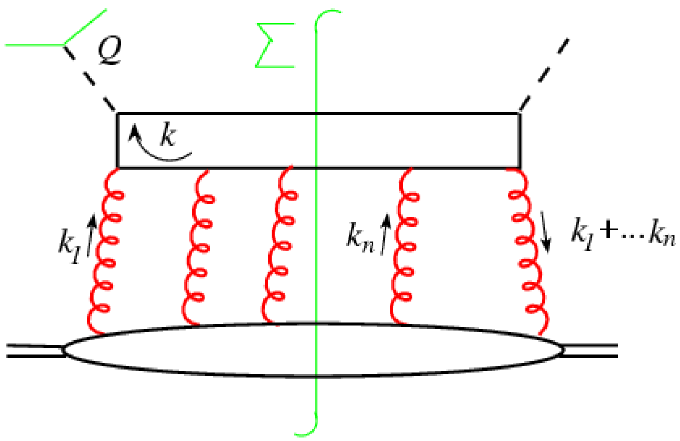
- The power correction to the evolution equation slows down the Q^2-dependence, prevents PDF's to be negative

$$\langle xG(x \to 10^{-5}) \rangle \sim 3$$

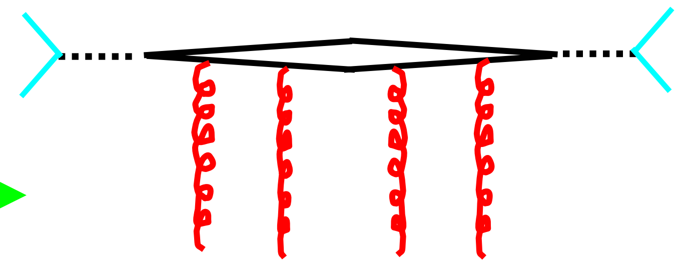
Eskola et al. NPB660 (2003)



LT shadowing vs power corrections



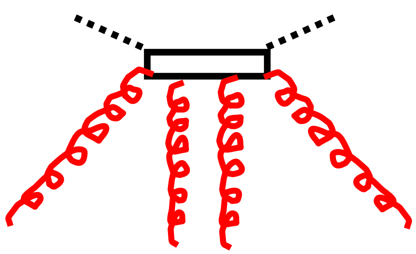
$k^2 \ll Q^2$



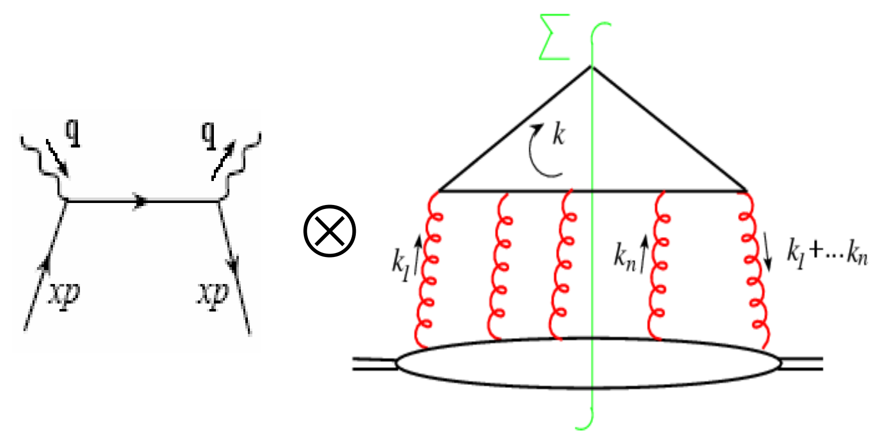
LT shadowing
Diffractive piece

$k^2 \sim Q^2$

Collinear factorization

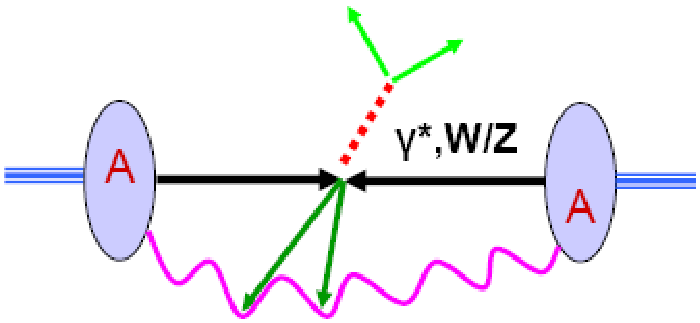


O(α_s) power correction



Factorization is an approximation

- **Drell-Yan cross section is NOT completely factorized!**



$$\frac{d\sigma}{dQ^2} = f^{(2)} \otimes f^{(2)} \otimes \frac{d\hat{\sigma}^{(2)}}{dQ^2}$$

$$+ \frac{1}{Q^2} f^{(2)} \otimes f^{(4)} \otimes \frac{d\hat{\sigma}^{(4)}}{dQ^2}$$

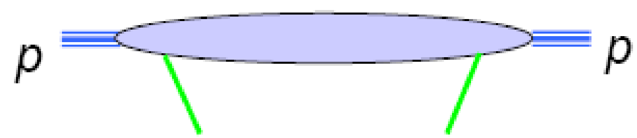
$$+ \frac{1}{Q^4} F\left(\frac{Q^2}{S}\right) + \ldots$$

Not factorized!

- There is **always** soft gluon interaction between two hadrons!
- Gluon field strength is **one power** more Lorentz contracted than ruler

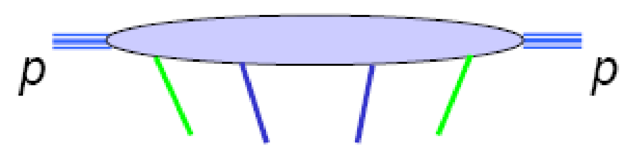
$$f^{(2)} \propto \langle p | \bar{\psi}(0)\gamma^{+}\psi(y^{-}) | p \rangle,$$

$$\langle p | F^{+\alpha}(0) F_{\alpha}^{\ +}(y^{-}) | p \rangle$$



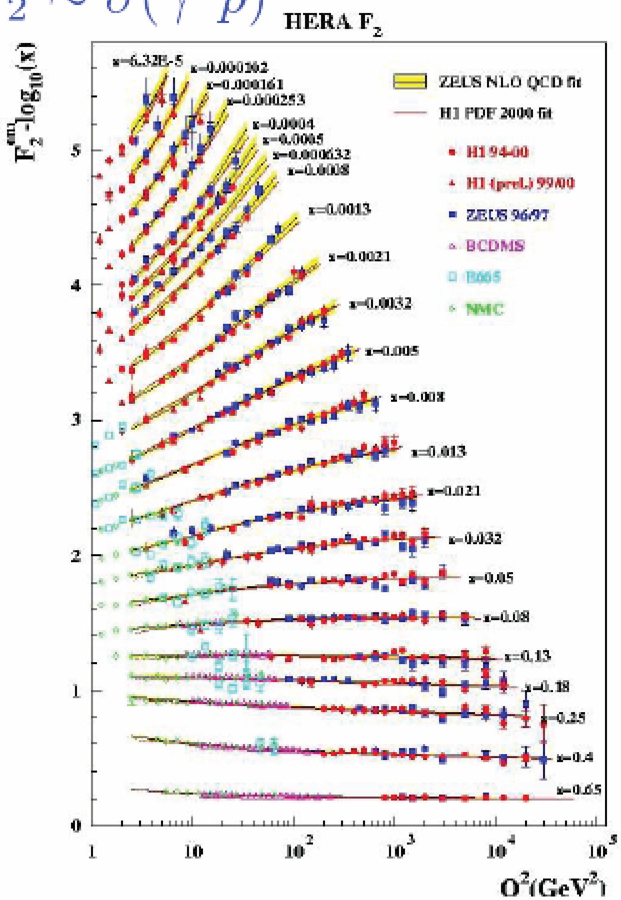
$$f^{(4)} \propto \langle p | \bar{\psi}(0)\gamma^{+} F^{+\alpha}(y_1^{-}) F_{\alpha}^{\ +}(y_2^{-}) \psi(y^{-}) | p \rangle$$

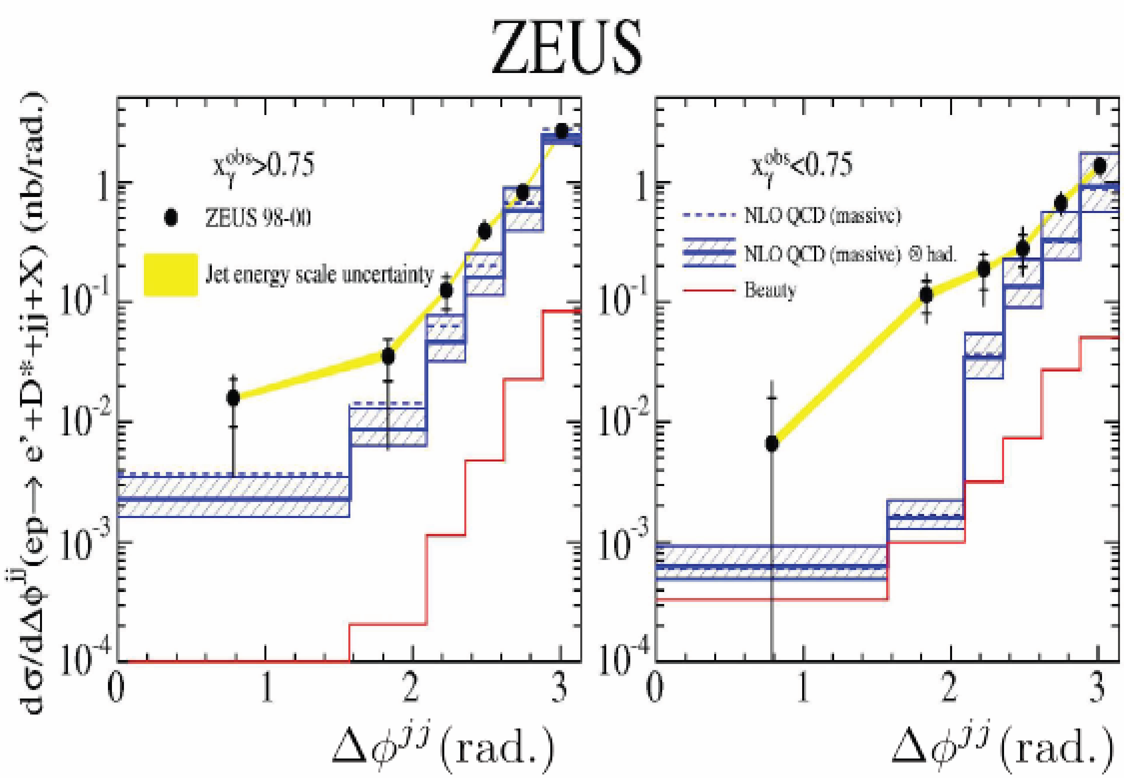
…



Observables sensitive to parton k_T

$F_2 \sim \sigma(\gamma^* p)$





QPM process

total x-section

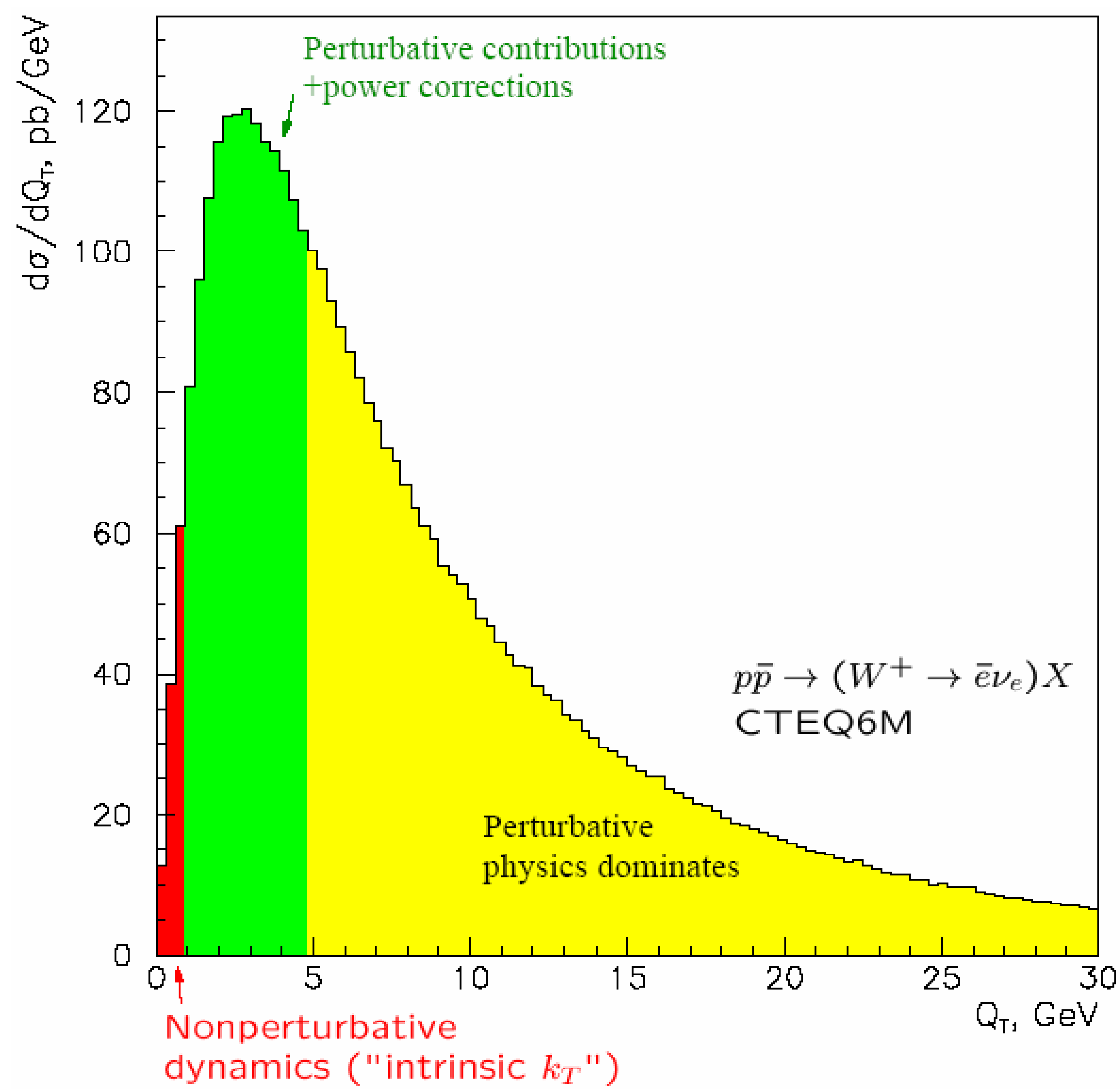
BGF $\mathcal{O}(\alpha_s)$ process $\mathcal{O}(\alpha_s^2)$ process

heavy quarks (charm & bottom)

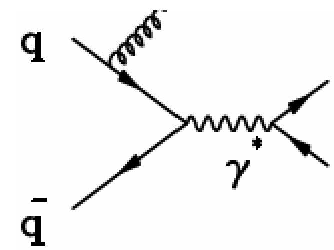
2-jet 3-jet

H. Jung, QCD at cosmic energies, Skopolos, 2005

Parton k_T is important



Drell-Yan type subprocess



Photon can replaced by W, Z, Higgs, etc.

Q_T-distribution is sensitive to parton k_T

QCD resummation

- For processes with <u>two</u> large observed scales,

$$Q_1^2 \gg Q_2^2 \gg \Lambda_{\rm QCD}^2 \qquad e.g.\ p_T\text{-distribution of } Z^0$$

we could choose: $\mu = Q_1$ or Q_2, or somewhere between

→ $\alpha_s\left(Q_1^2\right)$ is small, $\alpha_s\left(Q_1^2\right)\ell n(Q_1^2/Q_2^2)$ is not necessary small

Cannot remove the logarithms by choosing a proper μ

→ **Resummation of the logarithms is needed**

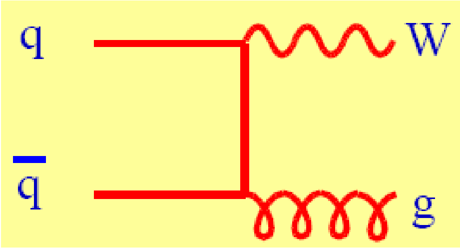
– the virtual photon fragmentation functions

- For a massless theory, we can get <u>two</u> powers of the logarithms at each order in perturbation theory:

$$\alpha_s\left(Q_1^2\right)\ell n^2(Q_1^2/Q_2^2)$$

because of an overlap region of IR and CO divergences

Double log resummation



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

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

- **Resum the double leading logarithms – DDT formula:**

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

as $Q_T \to 0$

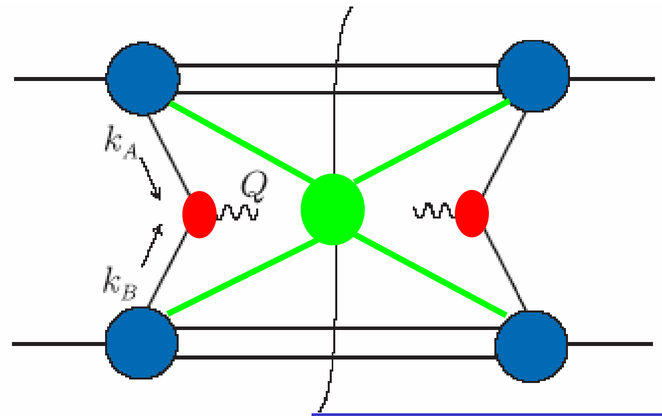
- **Experimental fact:** $\frac{d\sigma}{dy\,dQ_T^2} \Rightarrow$ finite [neither ∞ nor 0!] as $Q_T \to 0$

Double leading logarithm approximation (DLLA) over constrains phase space of radiated gluons (strong ordering in transverse momenta)

Ignore overall transverse momentum conservation

CSS b-space resummation formalism

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



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

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

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

resummed | **No large log's**

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

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

The b-space resummation

- **The b-space distribution:** $\tilde{W}_{AB}(b,Q) \equiv \sum_{i,j} \tilde{W}_{ij}(b,Q)\hat{\sigma}_{ij}(Q)$
- The $\tilde{W}_{ij}(b,Q)$ obeys the evolution equation

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

- Evolution kernels satisfy RG equations

Power corrections

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

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

- CSS Resummation of the large logarithms $\Longleftrightarrow$
  - Integrate $\ln\mu^2$ in Eq.(2) from $\ln\frac{c^2}{b^2}$ to $\ln\mu^2$
  - Integrate $\ln\mu^2$ in Eq.(3) from $\ln Q^2$ to $\ln\mu^2$
  - Integrate $\ln Q^2$ in Eq.(1) from $\ln\frac{c^2}{b^2}$ to $\ln Q^2$
  - $c = 2e^{-\gamma_E} \sim 1$

Leading power in $1/Q^2$

- homogeneous evolution equation
  $\Rightarrow$ solution proportional to boundary condition

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

- if $b \ll 1/\Lambda_{\rm QCD}$, boundary condition $W_{ij}(b,1/b)$
  - depends only on one perturbative scale $\sim 1/b$
  - should be fully perturbative, and
  - have no large logarithms

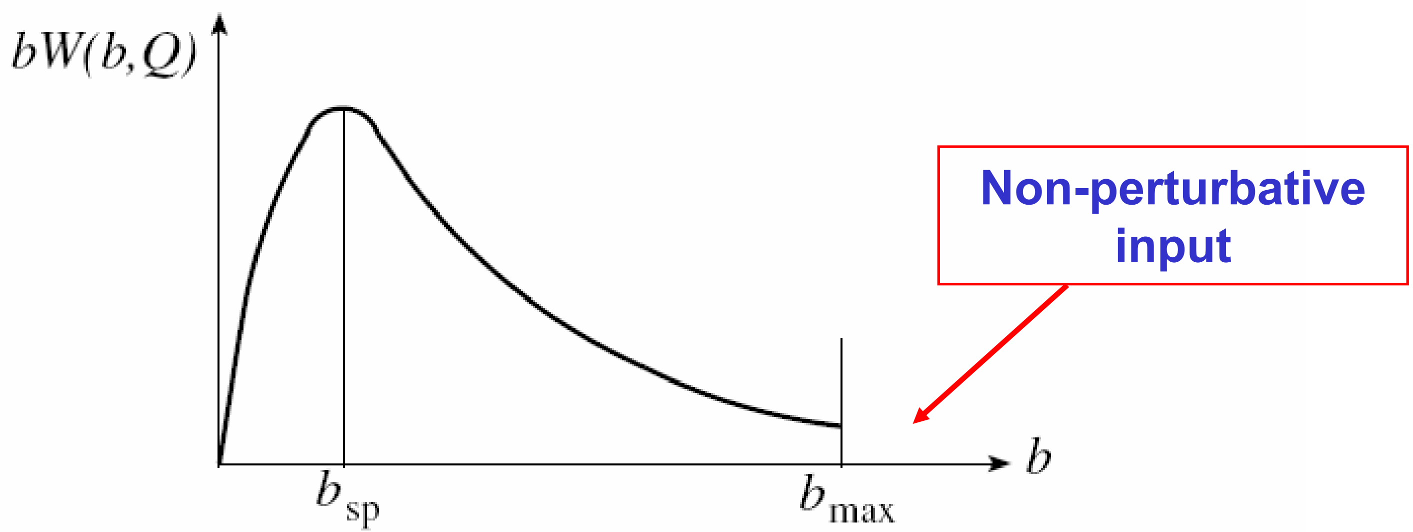
  $\Rightarrow$ perturbative b-distribution

$$W^{\rm pert}(b,Q) = \sum_{a,b,i,j} \sigma^{(LO)}_{ij\to C}\left[\phi_{a/A}\otimes C_{a\to i}\right] \otimes \left[\phi_{b/B}\otimes C_{b\to j}\right] \times \mathrm{e}^{-S(b,Q)}$$

❑ Sudakov form factor:

$$S(b,Q) = \int_{c^2/b^2}^{Q^2} \frac{d\mu^2}{\mu^2}\left[A\left(\alpha_s\left(\mu^2\right)\right)\ell n\left(\frac{Q^2}{\mu^2}\right) + B\left(\alpha_s\left(\mu^2\right)\right)\right]$$

- all large logarithms are summed into $S(b,Q)$, and $S(b,Q)$ is perturbative for b not too large
- functions: $C_{a\to i}$ and $C_{b\to j}$ are perturbative



- Need non-perturbative input at large b:

Predictive power of the formalism

- b-space distribution:

$$\int_0^\infty db\, J_0(q_T b)\, b\, \mathrm{e}^{-S(b,Q)} \left[\phi_{a/A} \otimes C_{a\to j}\right] \otimes \left[\phi_{b/B} \otimes C_{b\to \bar{j}}\right]$$

- pQCD dominates if $\int_0^{b_{max}} db(\ldots) \gg \int_{b_{max}}^\infty db(\ldots)$

- or saddle point $b_{sp} \ll b_{max}$:

  – b-dep of $b e^{-S(b,Q)} \to b_{sp} \propto (\frac{\Lambda_{\rm QCD}}{Q})^\lambda,\ \lambda \sim 0.4$

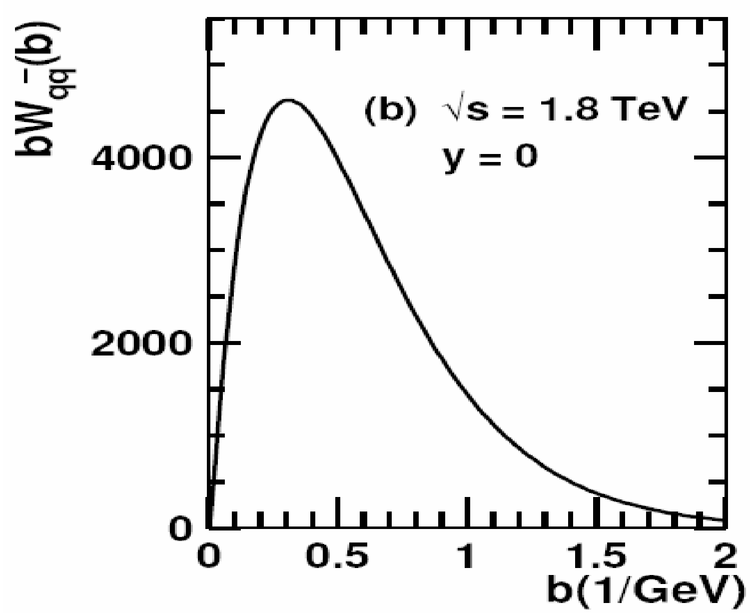
  – b-dep of $\phi_{a/A}(x, \frac{1}{b})$ and $\phi_{b/B}(x', \frac{1}{b})$
  $\Leftrightarrow$ DGLAP evolution

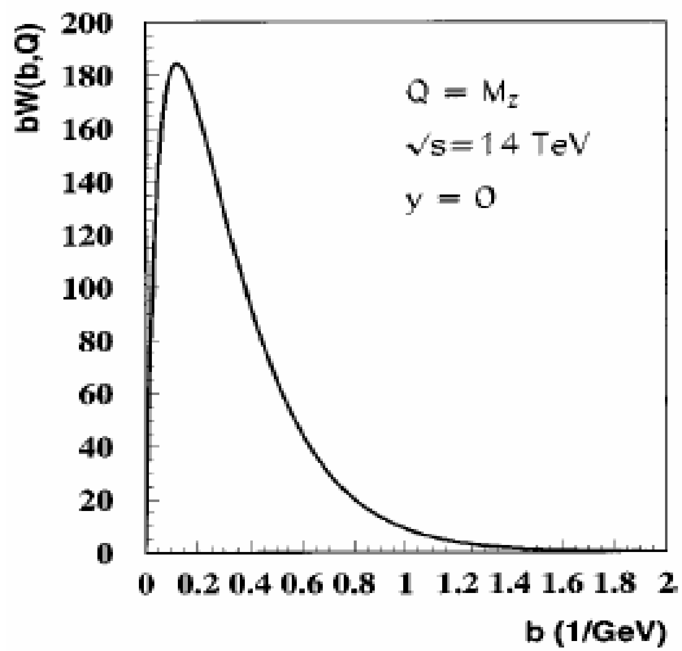
$$\frac{d}{db}\phi(x,\frac{1}{b}) = -\frac{1}{b}\frac{d}{d\ln\frac{1}{b}}\phi(x,\frac{1}{b}) < 0 \quad \text{for } x < x_c \sim 0.1$$

  $\Rightarrow$ larger $\sqrt{S}$, smaller x, and smaller b_{sp}

Location of the saddle point

❑ Z production (collision energy dependence):



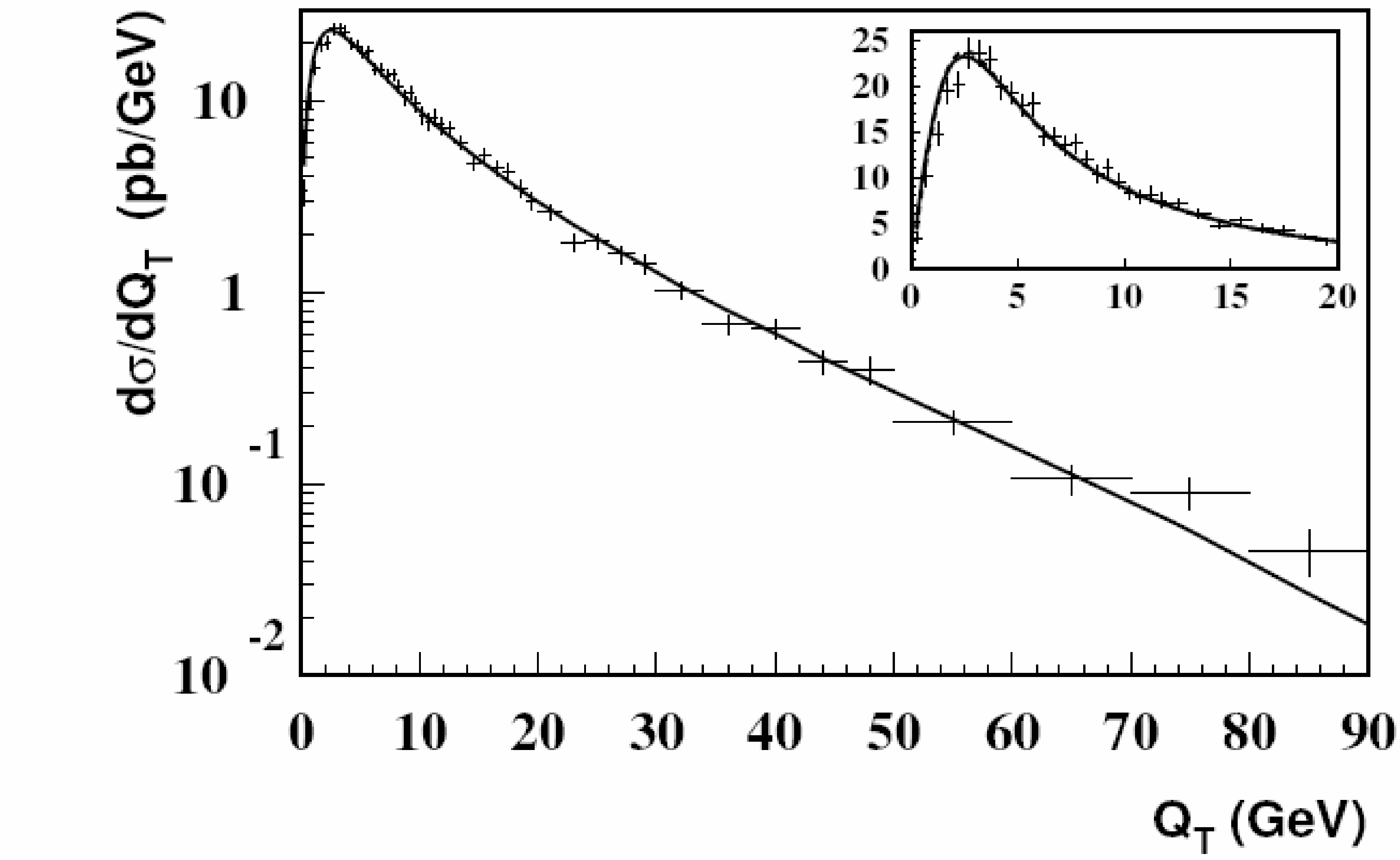


Higher collision energy = larger phase space
= more gluon shower
= larger parton k_T

Shift of the peak is calculated perturbatively!

Qiu, Zhang

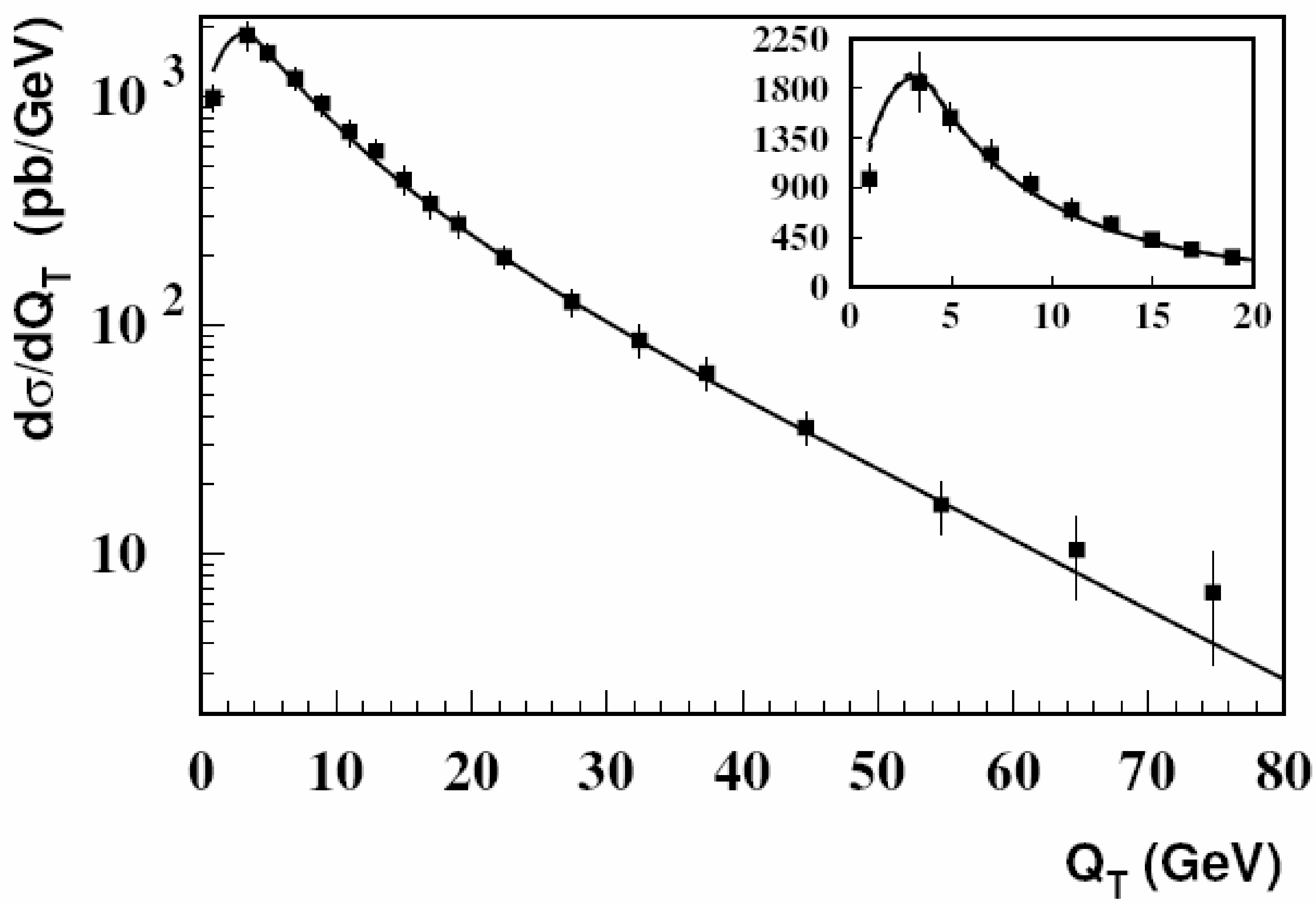
- Fermilab CDF data on Z at $\sqrt{S} = 1.8$ TeV



Large <Q_T> here is generated by gluon shower, but, is perturbatively calculated!

Power correction is very small, excellent prediction! **Qiu, Zhang**

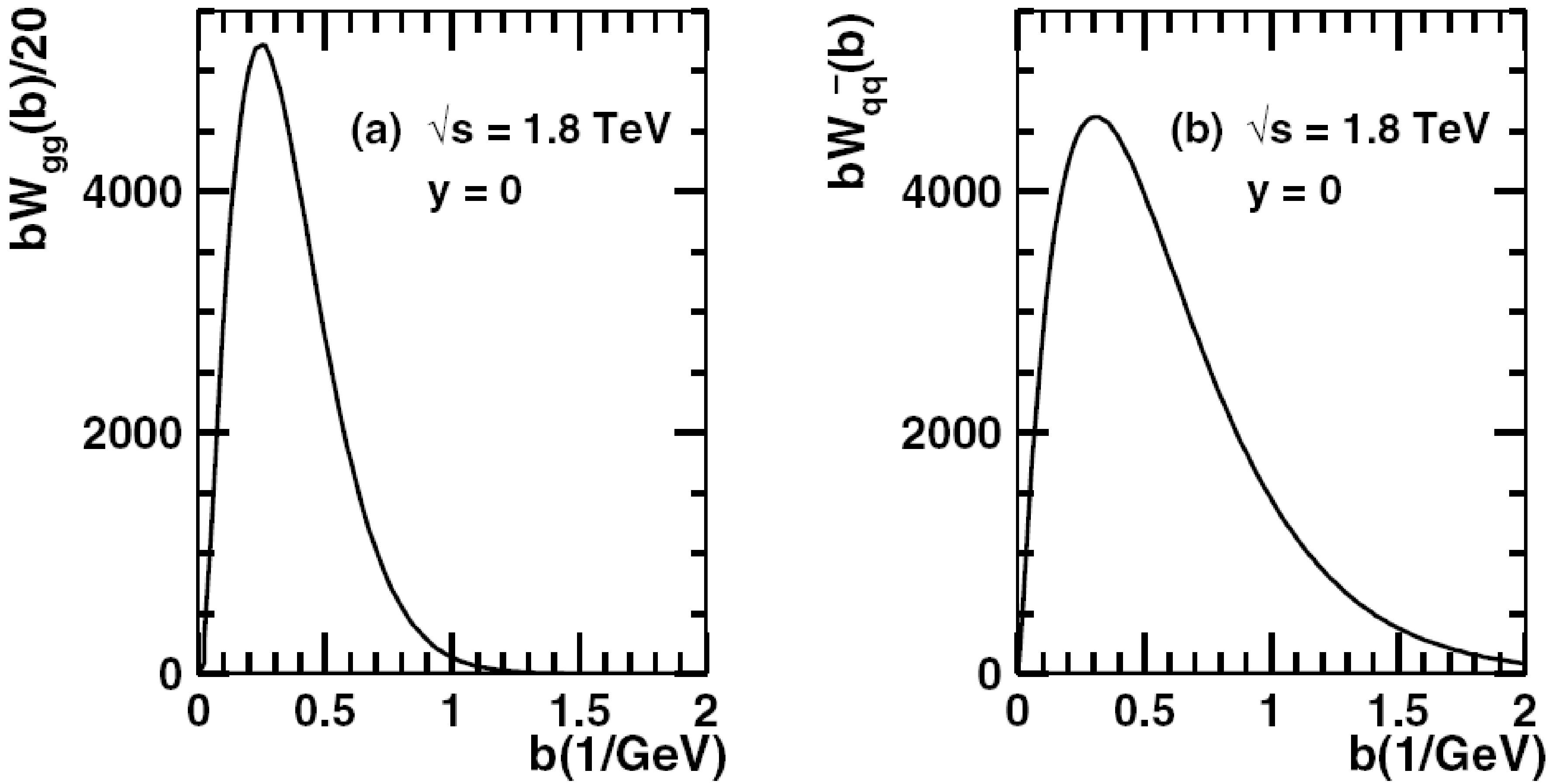
- Fermilab D0 data on W at $\sqrt{S} = 1.8$ TeV



No free fitting parameter!

Qiu, Zhang

Upsilon production

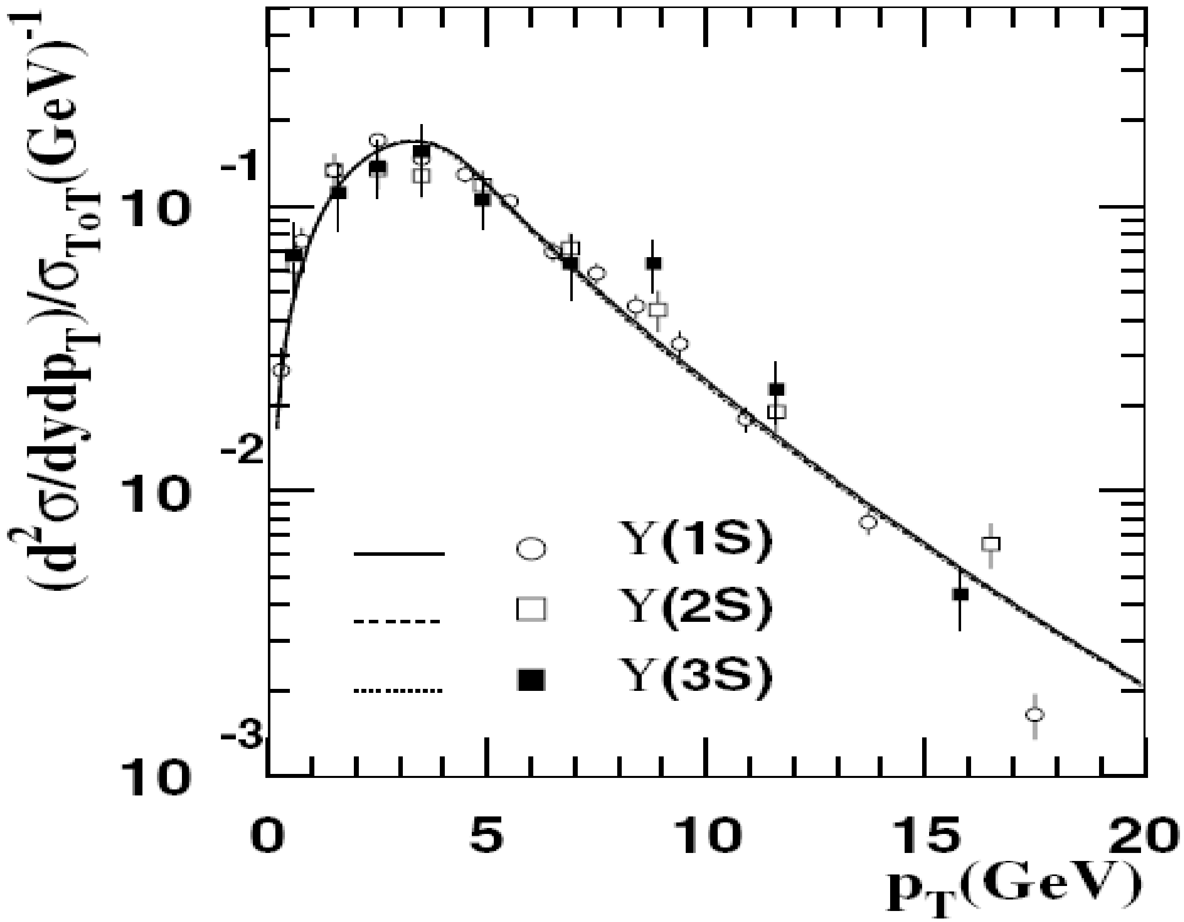


Dominated by gluon-gluon fusion

Narrow b-distribution = reliable perturbative calculation

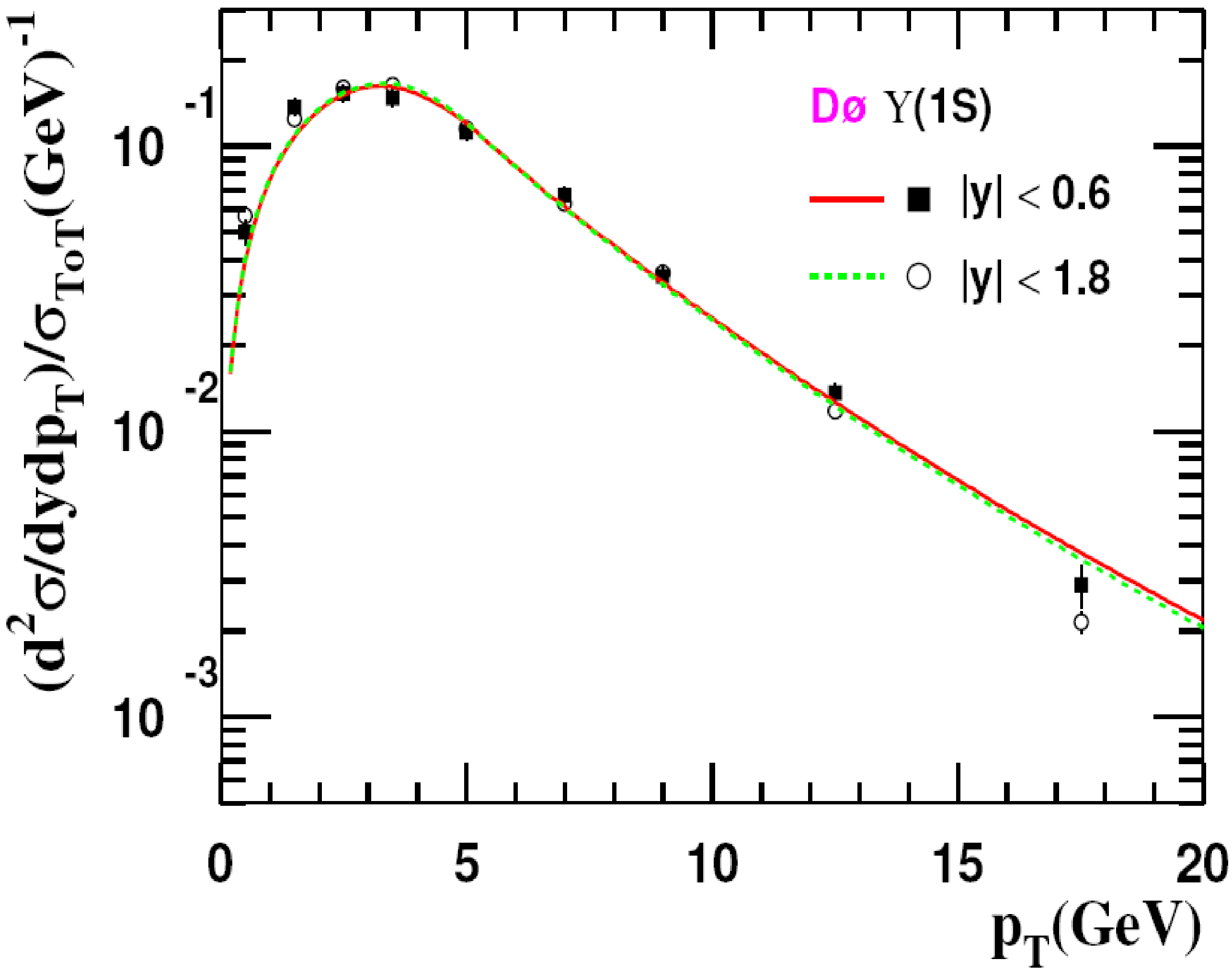
Berger, Qiu, Wang

CDF Run – I Upsilon data



Berger, Qiu, Wang

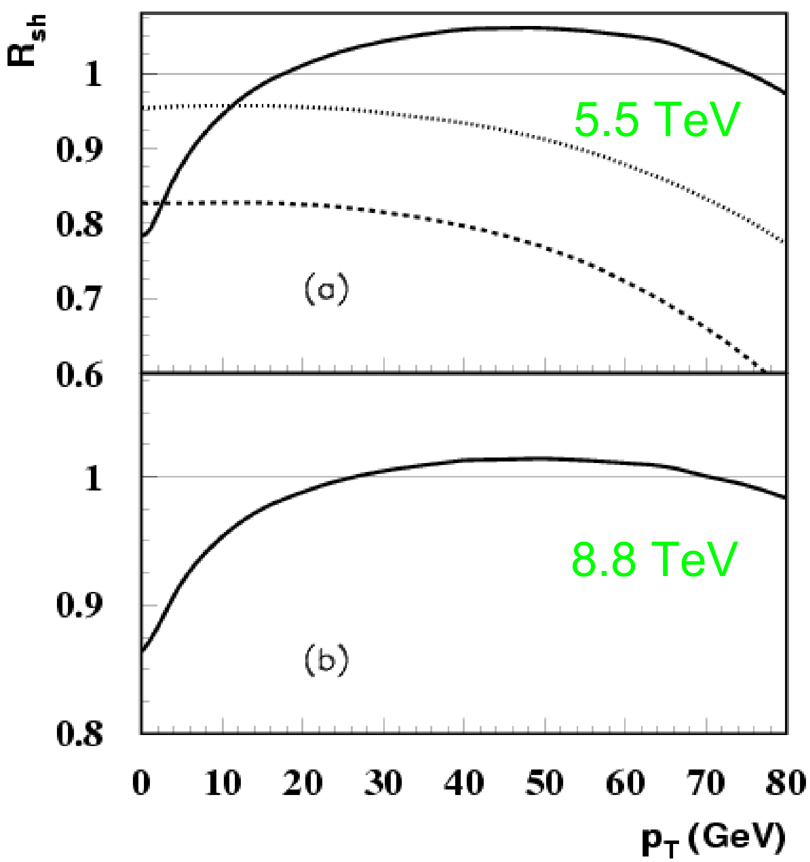
D0 Run – II Upsilon data



Berger, Qiu, Wang

Shadowing alone leads to suppression and enhancement in p_T distributions

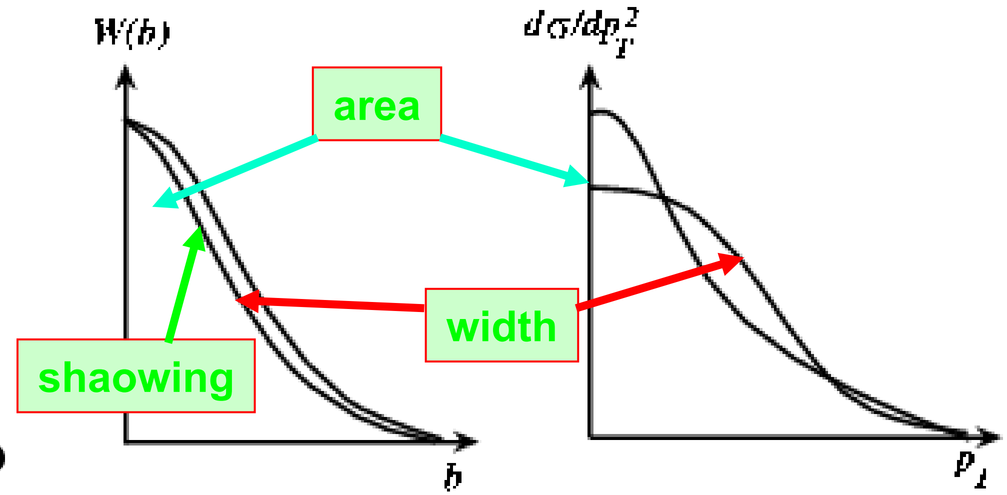
- W/Z production is dominated by low p_T region
- the shape is controlled by the gluon shower



$$R_{sh} = \frac{d\sigma^{(sh)}(p_T, A, B)}{dp_T^2} \Big/ \frac{d\sigma(p_T, A, B)}{dp_T^2}$$

Fixed order pQCD: $x_{parton} < 0.05$, $R_{sh} < 1$

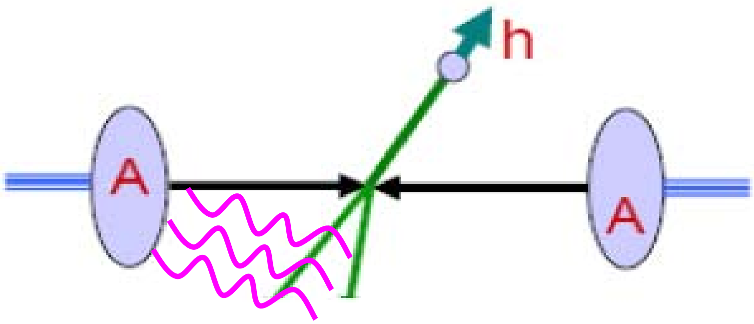
Resummed pQCD: shadowing in *b*-space



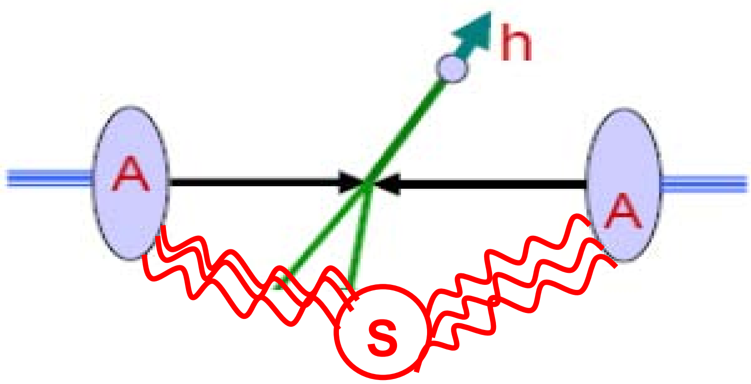
Fai, Qiu, Zhang

QCD vs QED parton shower

- ❑ Photon does not directly interact with another photon:



- ❑ Gluon does directly interact with another gluon:



- ❑ Make a general hadronic k_T factorization difficult – there is none so far

Summary and outlook

- Coherent hard multiple scattering is always there in physical observables
- Leading medium size enhanced nuclear effects due to power corrections can be systematically calculated, and they complement to the leading twist (universal) nuclear effects
- Two-scale observables and one-scale observables with a steep distribution are potentially good probes for medium properties of strongly interacting matter
- Parton k_T is important for less inclusive observables

  No k_T - factorization proved for hadronic observables
- QCD parton shower differs from QED case – b-space resummation might help