Proton – Nucleus Potential at the LHC

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QCD at Cosmic Energies - II
The Highest Energy Cosmic Rays and QCD
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Outline of the Talk

- Introduction and Terminology
- Important role of *d+Au* at RHIC
- *pA* collisions at the LHC
- Benchmark tests (universal *A*-dependence)
- Semihard processes
  (calculable *A*-dependence)
- Summary and Outlook

Introduction and Terminology

- **Cosmic ray energy near GZK region:**

$$S_{\rm GZK} \sim 1000\ S_{\rm LHC}$$

- **typical momentum exchange (y~0):** $\langle x \rangle \sim \dfrac{m_T}{\sqrt{s}/2}$

$$\langle x \rangle_{\rm RHIC}\,(y \sim 0) \sim 10^{-2}$$

$$\langle x \rangle_{\rm LHC}\,(y \sim 0) \sim 10^{-3}$$

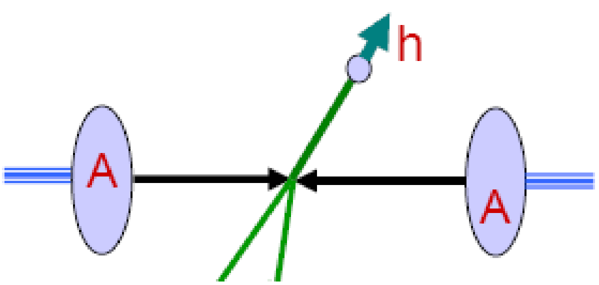
$$\langle x \rangle_{\rm GZK}\,(y \sim 0) \sim 10^{-4} \quad \longrightarrow \quad \langle x_2 \rangle_{\rm GZK}\,(x_1 \sim 0.1) \sim 10^{-8}$$

Unexplored region

- **Is leading power pQCD calculation valid?**

  - Processes
  - $\sqrt{S}$ (or x1,x2)

$$\frac{d\sigma}{dQ^2} = \int dx_1\, dx_2\, f^{(2)}\left(x_1, Q^2\right) f^{(2)}\left(x_2, Q^2\right) \frac{d\hat{\sigma}(x_1,x_2)}{dQ^2} \left[1 + O\left(\frac{1}{Q^\alpha}\right)\right]$$

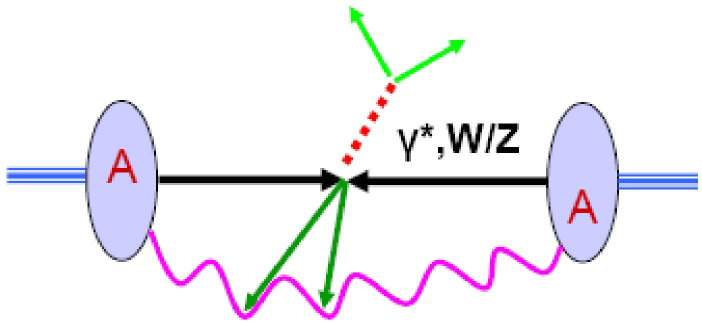


Neglect soft interaction between beams!

→ Universality of PDF's

Factorization is an approximation

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



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

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

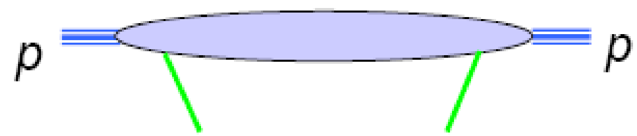
$$+ \frac{1}{Q^2} f^{(2)} \otimes f^{(4)} \otimes \frac{d\hat{\sigma}^{(4)}}{dQ^2}$$

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

Not factorized!

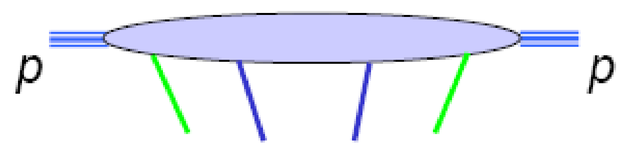
$$f^{(2)} \propto \langle p | \bar{\psi}(0)\gamma^+\psi(y^-) | p \rangle,$$

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



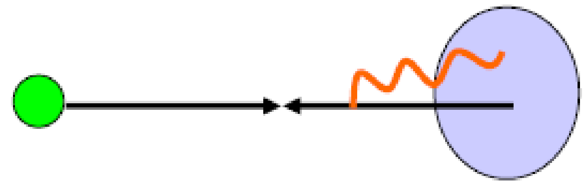
$$f^{(4)} \propto \langle p | \bar{\psi}(0)\gamma^+ F^{+\alpha}(y_1^-) F_\alpha^{\ +}(y_2^-) \psi(y^-) | p \rangle$$

$$\ldots$$



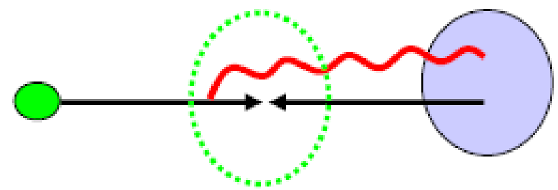
Sources of nuclear dependence

- ❑ Universal nuclear dependence:
  from nuclear wave functions

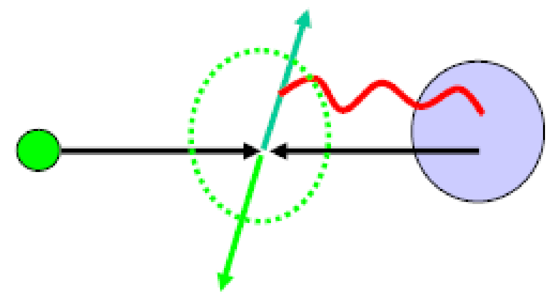


$$f_N^{(2)}(x,Q^2) \rightarrow f_A^{(2)}(x,Q^2) \propto \langle A|\overline{\psi}(0)\gamma^+\psi(y^-)|A\rangle$$

- ❑ Process-dependent nuclear dependence
  (coherent power corrections)
  - **Initial-state:**



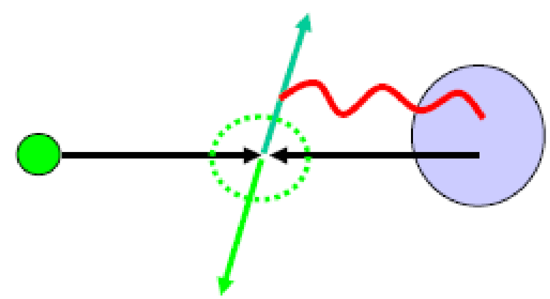
  - **Final-state:**



$$f_N^{(2)}(x,Q^2) \rightarrow f_A^{(4)}(x_1,x_2,x_3,Q^2)$$

- ❖ **Change total cross section**

- ❑ Elastic scattering
  (incoherent multiple scattering)
- ❖ **Does not change total production rate**
- ❖ **Change the spectrum**

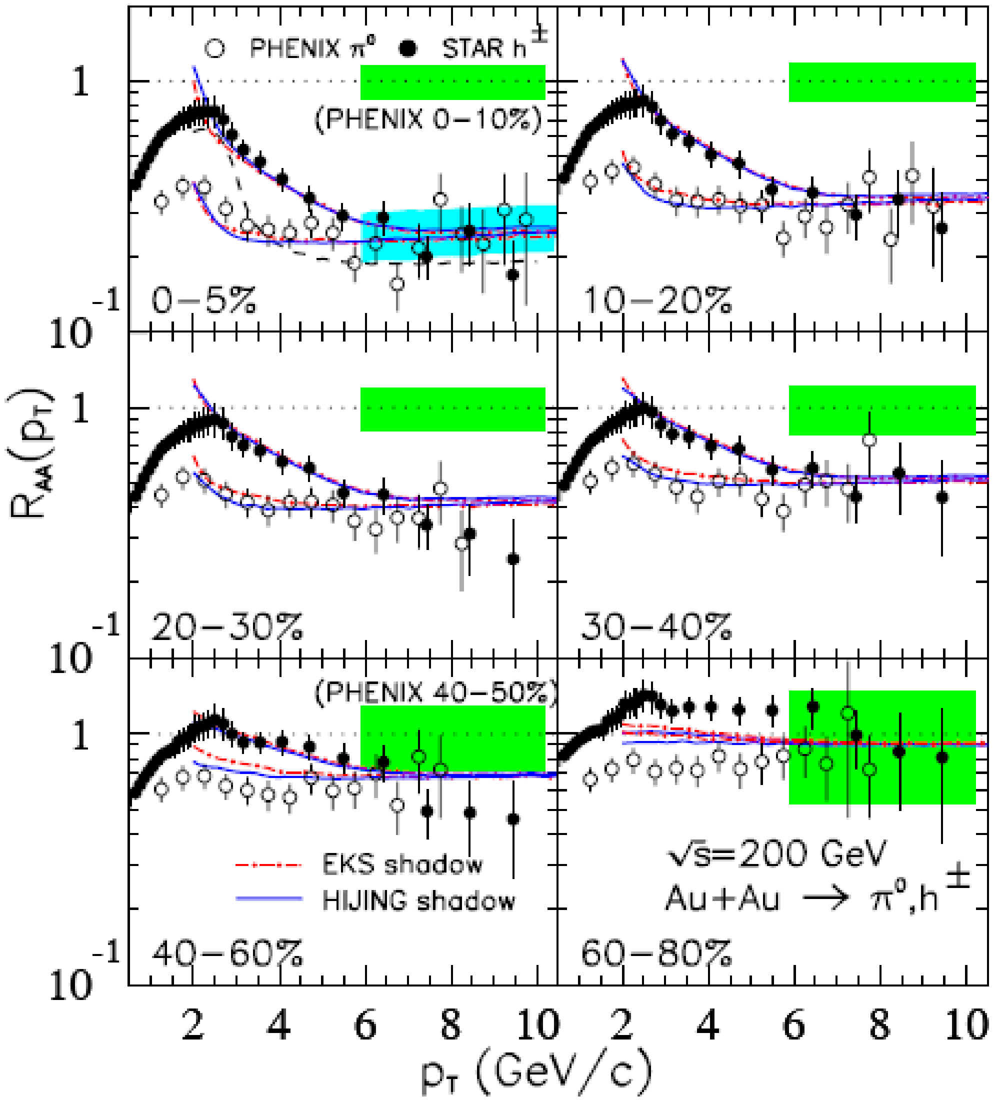


Important role of *dA* at RHIC

- Single inclusive hadron in *AA* collision

$$R^{AB} = \frac{\sigma_{AB}}{\langle N_{\text{binary}} \rangle_{AB} \langle \sigma_{NN} \rangle}$$

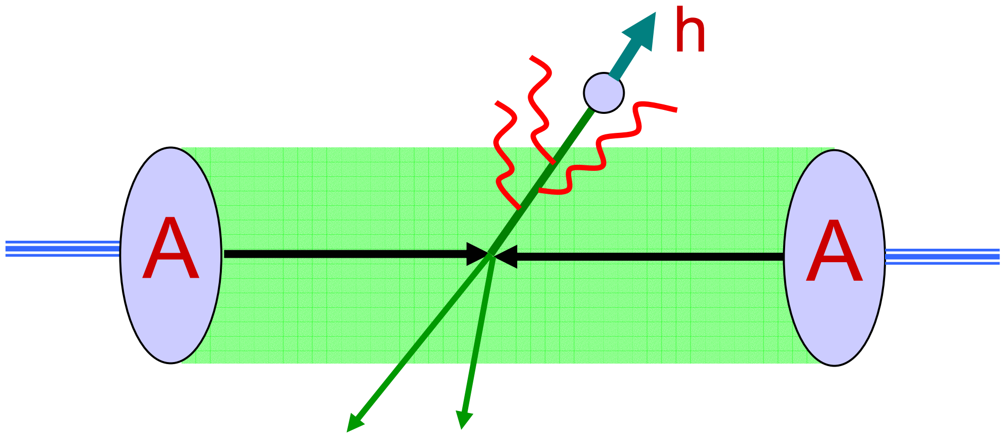
- What cause the suppression or enhancement?
- What should we expect for dA?



Jet quenching

❑ Assumptions:

❖ Soft interactions between the ions does not change the effective PDF's



❖ Multiple scattering with the medium leads to energy loss

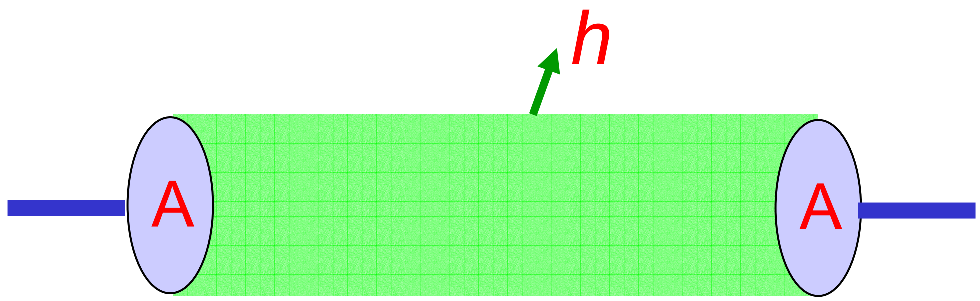
❖ Reduction of leading hadron momentum leads to suppression at high p_T

Suppression is a final-state effect

No suppression expected for dA

Saturation and CGC

- Soft interactions between the ions alter the PDF's



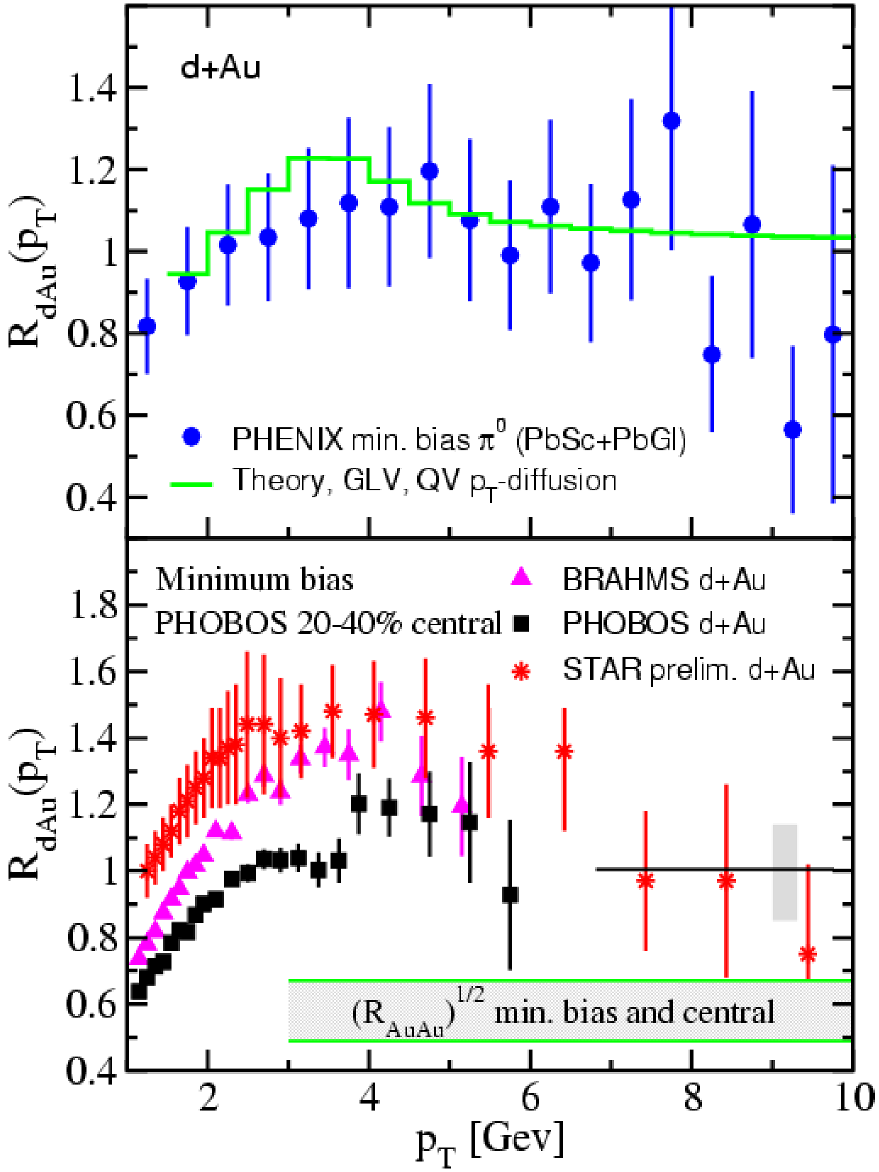
- Convolution of two universal saturated distributions at a saturation scale: $Q_s \sim$ GeV; or
- Solve classical Yang-Mills Equation
  ⟹ gluon density from the *AA* collisions, then convert the gluons to the observed hadron
- Momentum of the GeV hadron *h* is balanced by many soft particles ⟹ no back-to-back hadron correlation

Suppression is a initial-state effect

Large suppression expected for dA

$$R_{dAu} = \sqrt{R_{AuAu}} \ll 1, \quad R_{AuAu} \simeq 0.2 - 0.4$$

Comparison to the d+Au Data



RHIC Data from:

B.Back *et al.* [PHOBOS], Phys.Rev.Lett. 91 (2003)

J.Adams *et al.* [STAR], Phys.Rev.Lett. 91 (2003)

S.Adler *et al.* [PHENIX], Phys.Rev.Lett. 91 (2003)

I.Arsene *et al.* [BRAHMS], Phys.Rev.Lett. 91 (2003)

Theoretical predictions:

I.Vitev and M.Gyulassy, Phys.Rev.Lett. 89 (2002)

I.Vitev, Phys.Lett. B562 (2003)

D.Kharzeev, E.Levin,L.McLerran, Phys.Lett. B 561 (2003)

Current Data from RHIC:
- support Cronin type effect in d+Au
- disfavor the saturation picture in d+Au

Parton *x* is not small enough:
- Increases collision energy – the LHC
- moves to the forward region – lower *x*

pA program at the LHC

- Calibrate the *AA* measurements
  (lesson from RHIC)
- Test QCD dynamics that proton-proton
  cannot provide
  (differences between pA and AA)
- Help extrapolate the hadronic collisions
  to cosmic ray energies
- …

Benchmark Tests

❑ Predictive Power of PQCD - Factorization

Scale of hadron wave function: Λ ~ 1/fm ~ 200 MeV - nonperturbative

Scale of hard partonic collision: Q >> GeV - perturbative

Time dilation:

dynamics at the scale of Λ is effectively frozen
during the partonic hard collision at the scale Q

Parton model:

$$\sigma_{\rm hadron}(Q,\Lambda) \approx \hat{\sigma}_{\rm parton}(Q) \otimes f(\Lambda)$$

QCD Factorization:

$$\sigma_{\rm hadron}(Q,\Lambda) \approx \underbrace{\hat{\sigma}_{\rm parton}(Q/\mu, \alpha_s(\mu))}_{\text{Infrared safe}} \otimes \underbrace{f^{(2)}(\mu,\Lambda)}_{\text{Universal upto power corrections}} + O\left(\frac{1}{Q^{\alpha}}\right)$$

Infrared safe

Universal upto power corrections

❑ Benchmark tests = "no" power corrections = hard probe

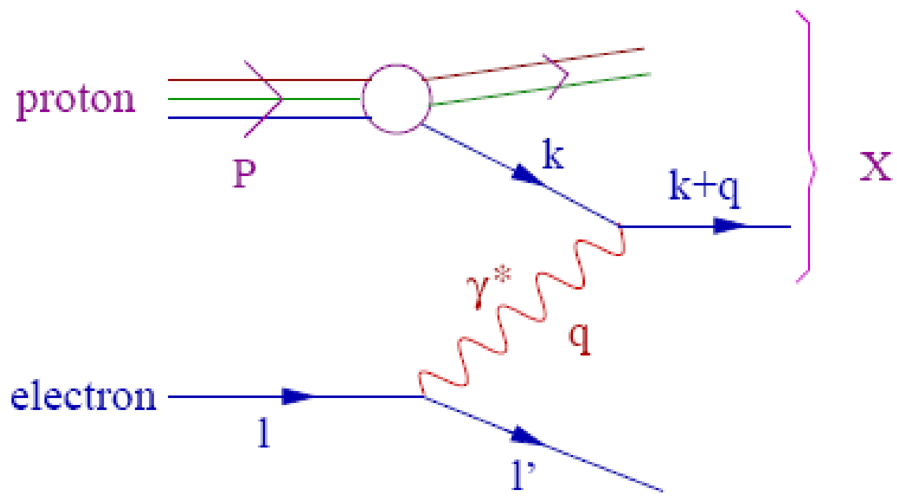
Questions

- Where power corrections come from?
- How can we calculate or estimate the size of power corrections?
- Is power correction more (or less) important at small x?
- Is power correction enhanced or suppressed in nuclear collisions?
- …

An example

Inclusive lepton – hadron deep inelastic scattering

electron (l) + proton (P) $\longrightarrow$ electron (l') + X (P_X)



- Two independent kinematical invariants :
  - $Q^2 \equiv -q^\mu q_\mu \geq 0$
  - $x \simeq Q^2/s$ with $s \equiv (P+q)^2 \gg Q^2$

Iancu's talk

Small-x and coherence length

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

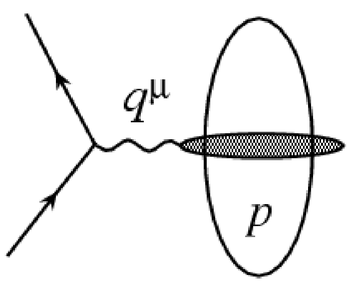
$$q^\mu \quad \text{with} \quad Q \equiv \sqrt{|q^2|} \gg \Lambda_{\text{QCD}}$$

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

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

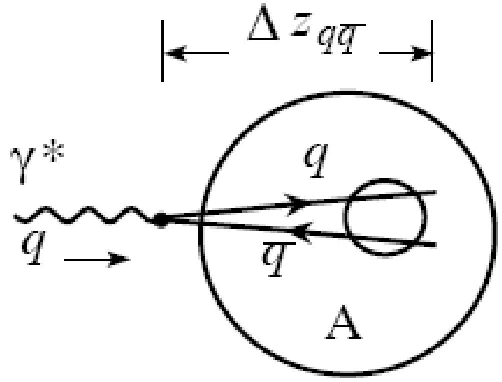
- **But, it might be larger than a Lorentz contracted hadron:**

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



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:

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

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

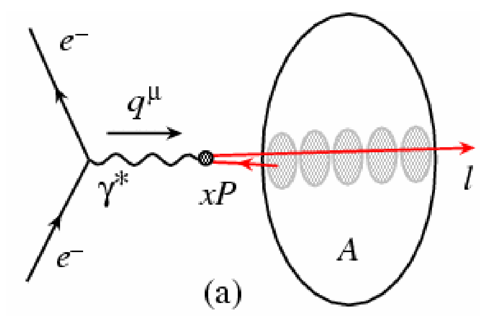
  – $\Delta z_{q\bar{q}} \gg 2$ fm, inter-nuclear distance, if $x_B \ll 0.1$

- **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

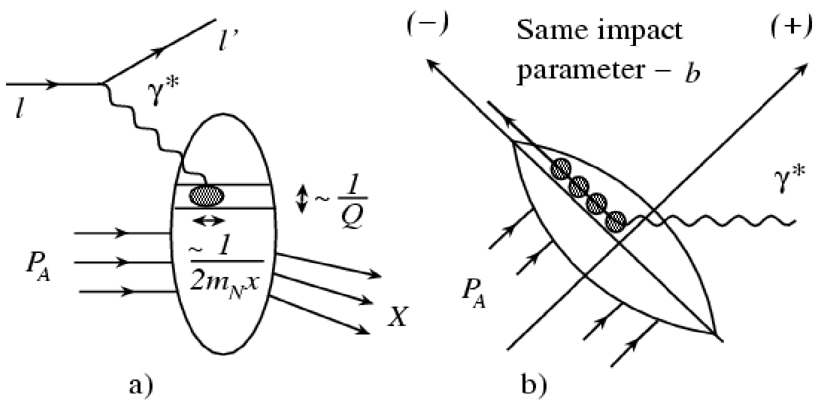
- **In Breit frame:**

  coherent final-state rescattering



Dynamical power corrections

❑ Coherent multiple scattering leads to dynamical power corrections:



2D lightcone dynamics

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

Naïve power counting:

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

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

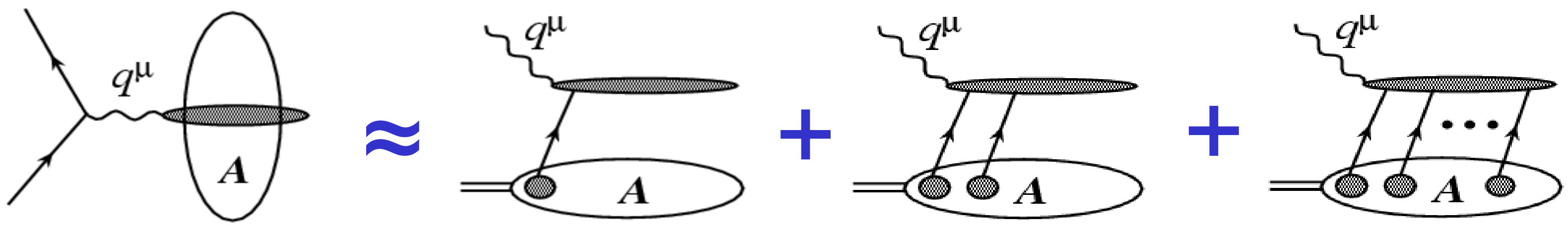
❑ For a hard probe: $\frac{\alpha_s}{Q^2 R^2} \ll 1$

❑ Enhanced by nuclear radius: $A^{1/3} \leq 6$

❑ Enhanced by the slope of small-x distribution: $-\frac{\partial}{\partial x}\varphi(x)$

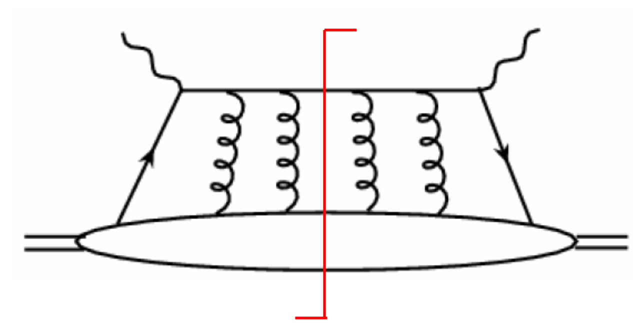
Coherent multiparton interactions

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

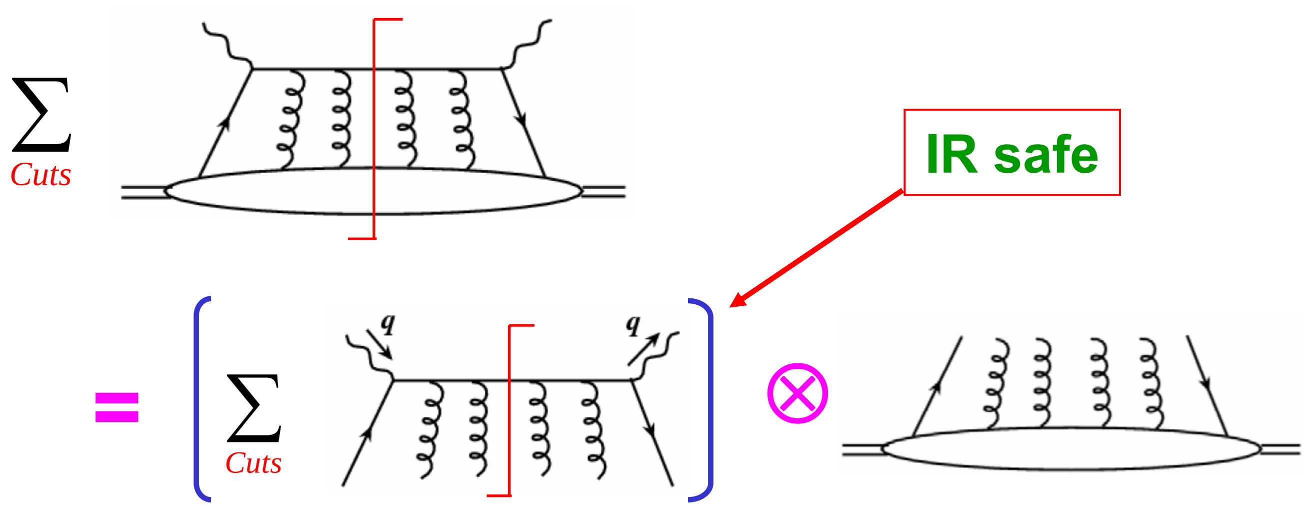
$$\sum_{Cuts}$$



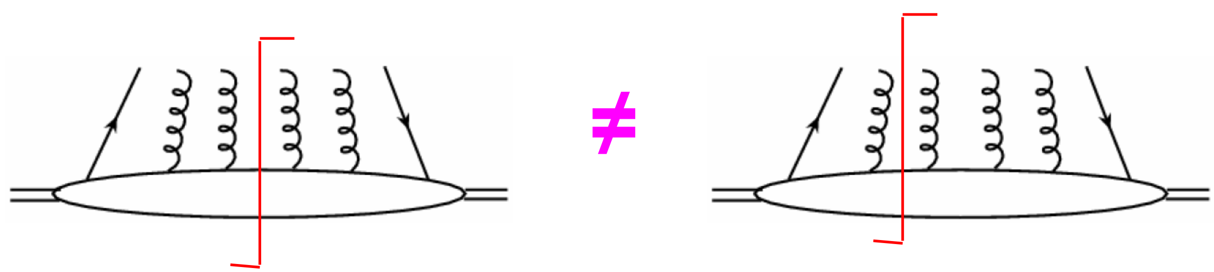
Summing over all cuts is also necessary for IR cancellation

Collinear approximation is important

With collinear approximation:



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



Factorization beyond leading power

- Consequence of OPE:

$$\sigma^h_{phys} = \hat{\sigma}^i_2 \otimes [1 + C^{(1,2)}\alpha_s + C^{(2,2)}\alpha_s^2 + \ldots] \otimes T_2^{i/h}(x)$$
$$+ \frac{\hat{\sigma}^i_4}{Q^2} \otimes [1 + C^{(1,4)}\alpha_s + C^{(2,4)}\alpha_s^2 + \ldots] \otimes T_4^{i/h}(x)$$
$$+ \frac{\hat{\sigma}^i_6}{Q^4} \otimes [1 + C^{(1,6)}\alpha_s + C^{(2,6)}\alpha_s^2 + \ldots] \otimes T_6^{i/h}(x)$$
$$+ \ldots$$

Leading twist

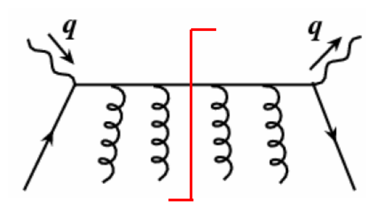
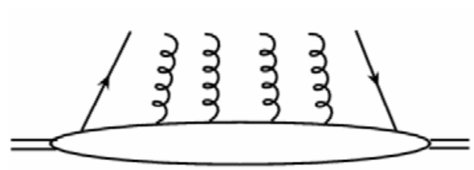
Power corrections

- Predictive power:
  - Coefficient functions are IR safe
  - Distributions/correlations/matrix elements are universal

- Distributions are defined to remove all collinear divergences of the partonic scattering

Multiparton correlation functions

- Parton momentum convolution:

$\left[\sum_{Cuts}$  $\right] \otimes$ 

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

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

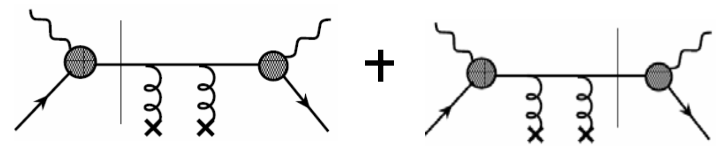
Leading pole leads to highest powers in medium length, a much small number of diagrams to worry about

Multiple soft rescattering at tree-level

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

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

- **NLO contribution:**

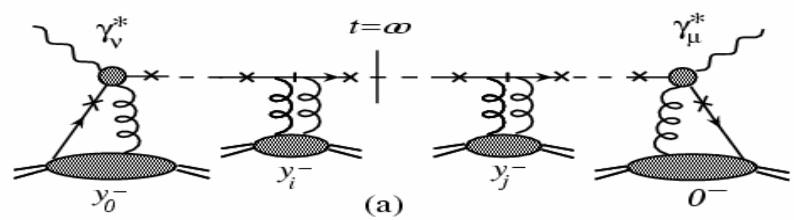


$$\Rightarrow \quad \frac{g^2}{Q^2}\left(\frac{1}{2N_c}\right)\left[2\pi^2 \tilde{F}^2(0)\right] x_B \lim_{x_1\to x}\left[\frac{1}{x-x_1}\delta(x_1-x_B)+\frac{1}{x_1-x}\delta(x-x_B)\right]$$

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

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

- **Nth order contribution:**



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

$$x_B^N \lim_{x_i\to x}\sum_{m=0}^{N}\ldots = x_B^N\left[(-1)^N \frac{1}{N!}\frac{d^N}{dx^N}\delta(x-x_B)\right]$$

Infrared safe!

Model for the correlation functions

- **Matrix elements:**

$$\left\langle P_A \left| \bar{\Psi}(0) \frac{\gamma^+}{2p^+} \Psi(y^-) \left[\prod_{i=1}^{N} \int \tilde{F}^2(0) \right] \right| P_A \right\rangle$$

- **Approximation:**

  Nucleus is made of a group of loosely bound nucleons

$$|P_A\rangle \propto \prod_{i=1}^{A} |p\rangle \quad \text{with} \quad p = \frac{P_A}{A}$$

$$\left\langle P_A \left| \hat{O}_0 \prod_{i=1}^{N} \hat{O}_i \right| P_A \right\rangle \propto A \left\langle p \left| \hat{O}_0 \right| p \right\rangle \prod_{i=1}^{N} \left\langle p \left| \hat{O}_i \right| p \right\rangle$$

- **Reduce the correlation functions to one unknown – a universal matrix element**

$$\left\langle p \left| F^{+\alpha} F_\alpha^{\ +} \right| p \right\rangle$$

Contributions to DIS structure functions

❑ **Transverse structure function:**

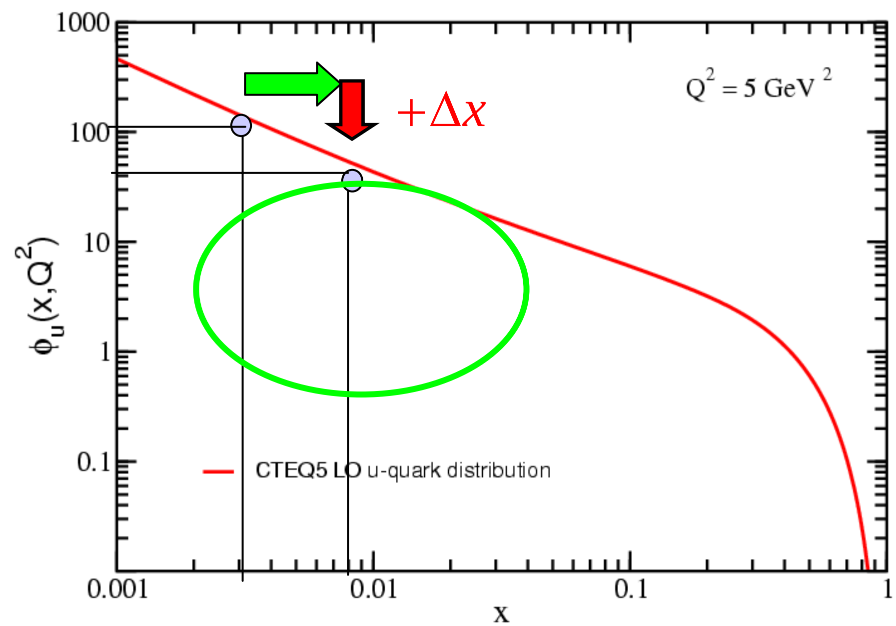
Qiu and Vitev, PRL (2004)

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

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

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

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

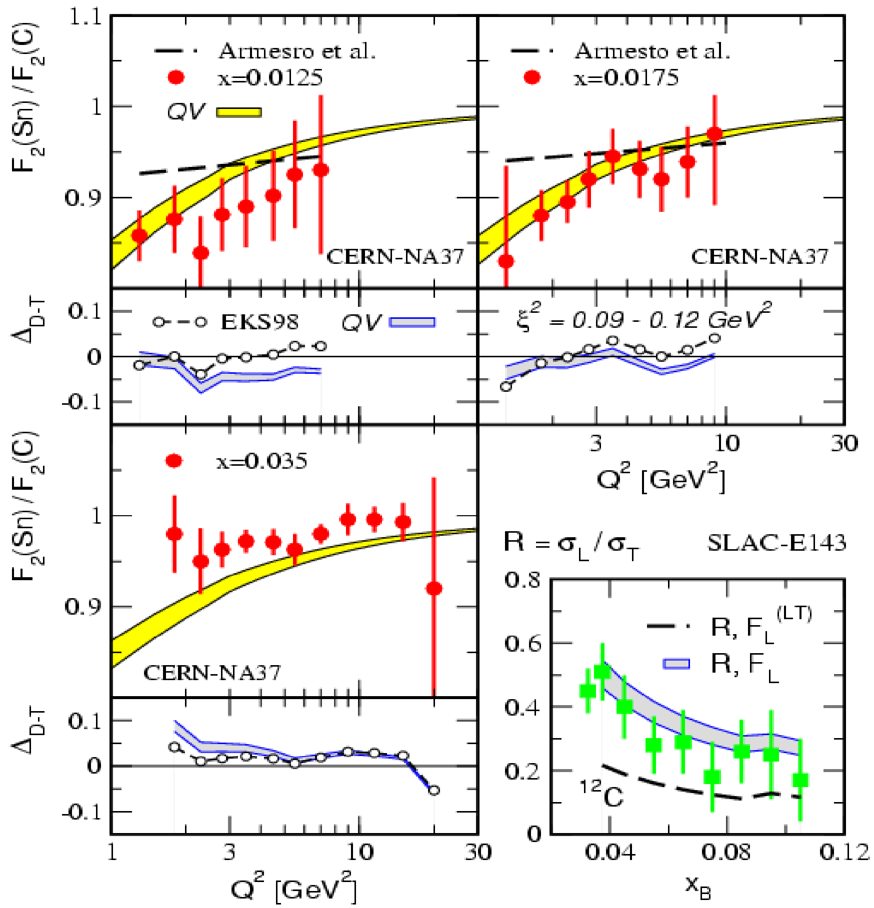


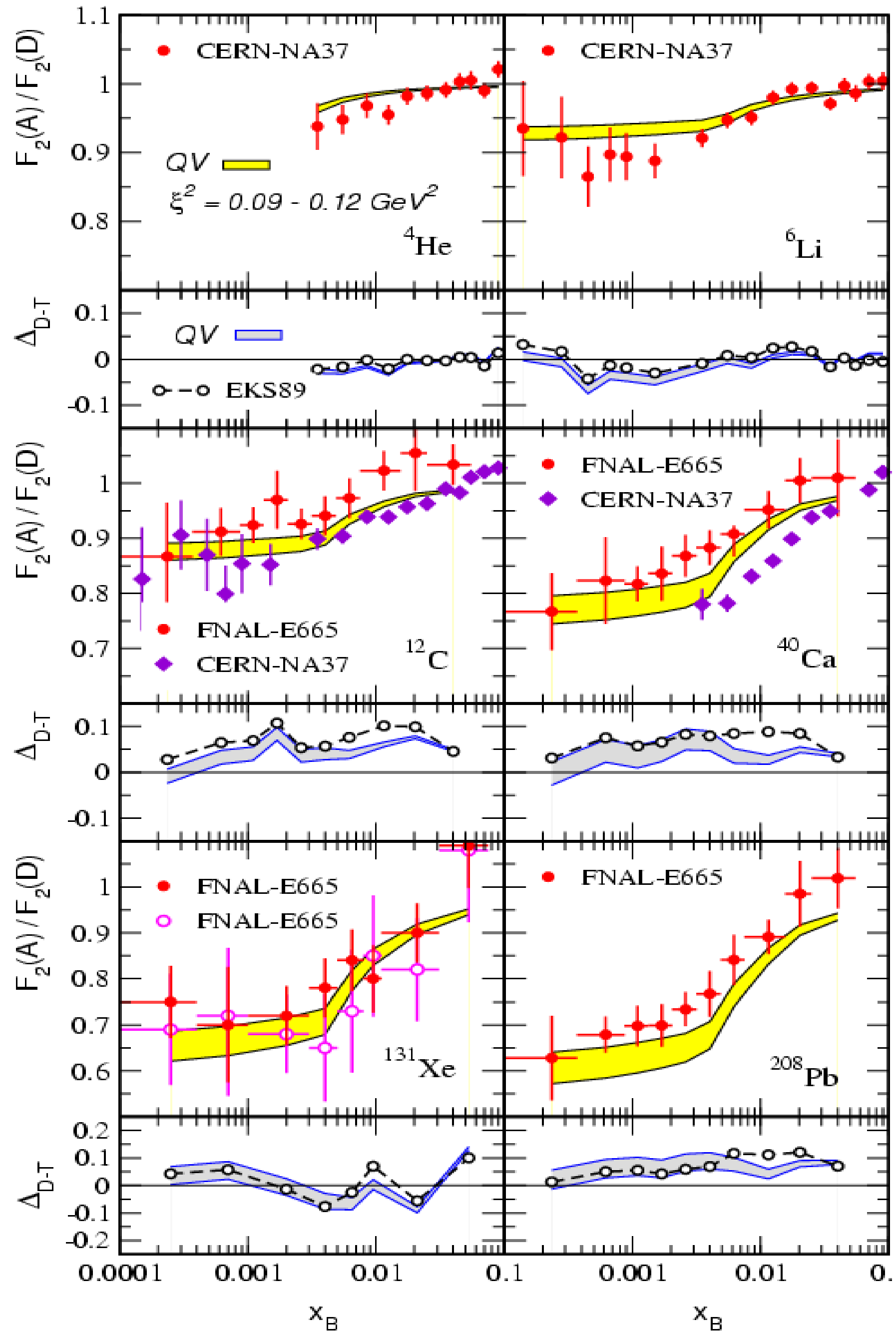
Single parameter for the power correction, and is proportional to the same characteristic scale

❑ **Similar result for longitudinal structure function**

Neglect LT shadowing upper limit of ξ^2

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





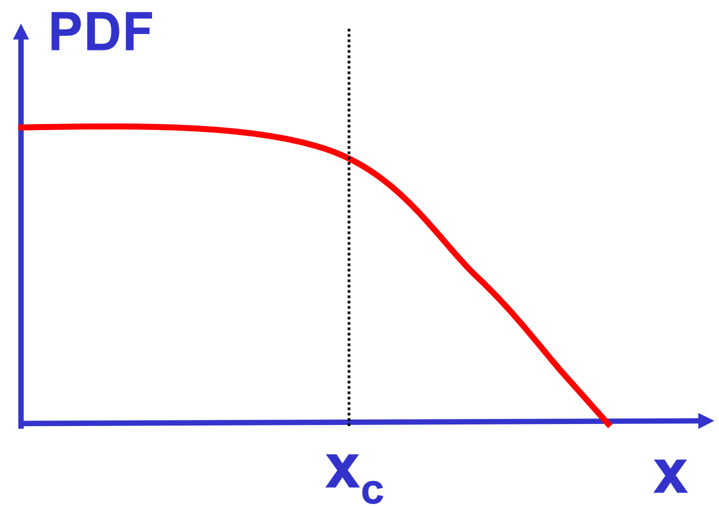
Leading twist shadowing

- 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

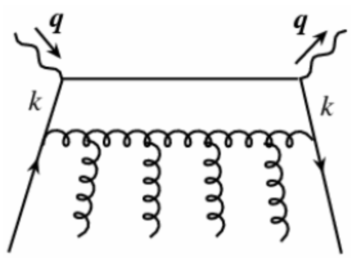
  for $x < x_c$,

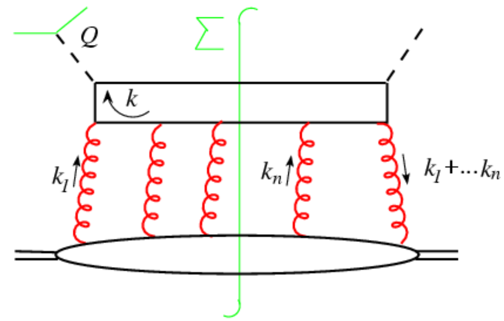
  additional power corrections,
  the shift in x, should have
  no effect to the cross section!



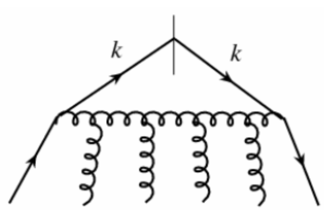
Beyond the tree-level

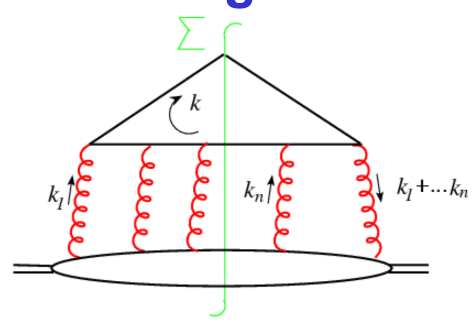
- Correlation functions need to remove all collinear divergences in partonic scattering – factorization
- DGLAP evolved PDFs do not remove the collinear divergences beyond single scattering





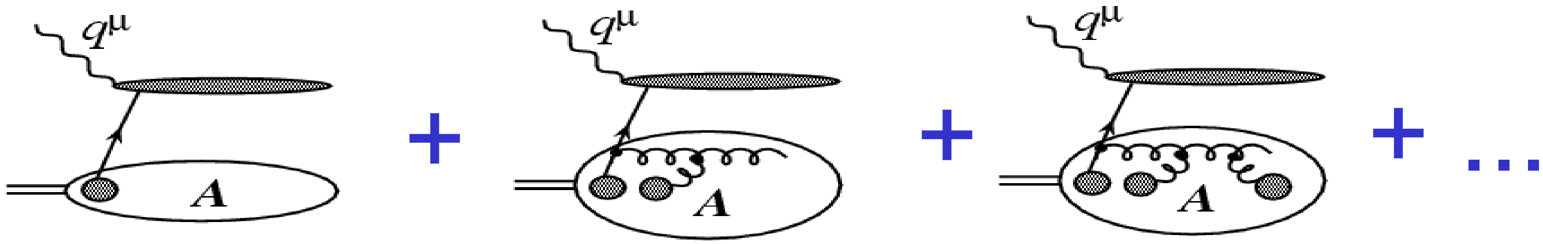
- Redefine PDFs to include all collinear divergences of partonic subprocesses → leading twist shadowing



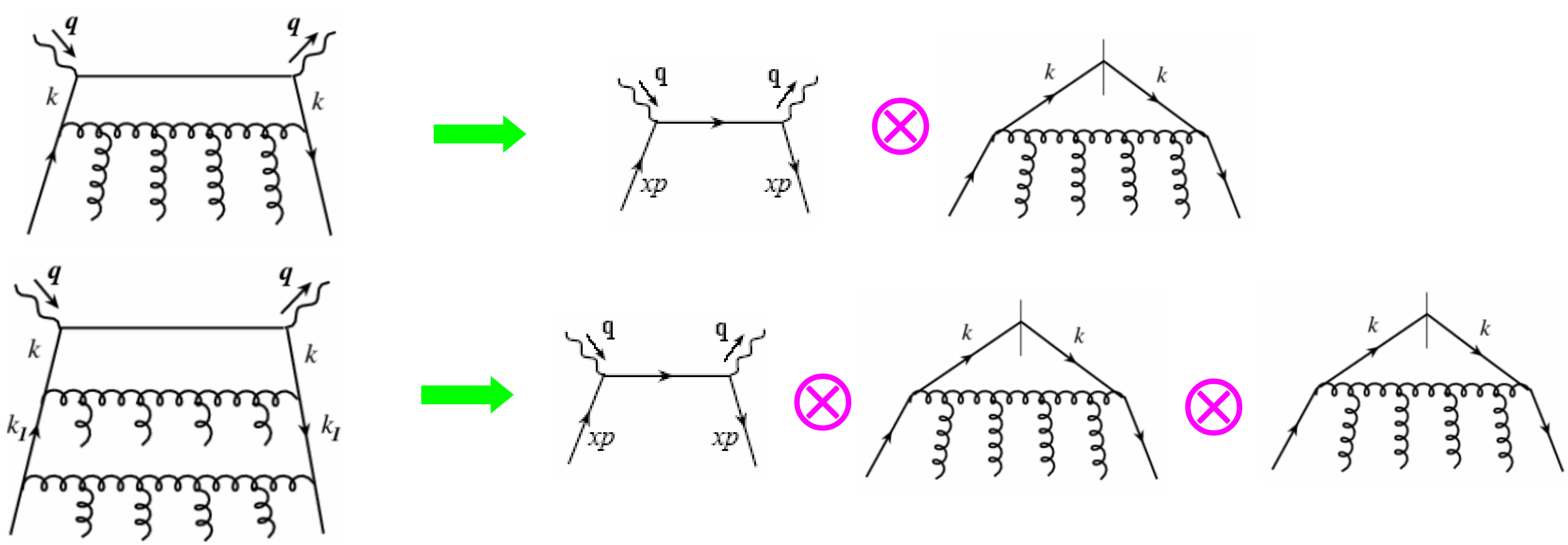


Coherent power corrections to PDFs

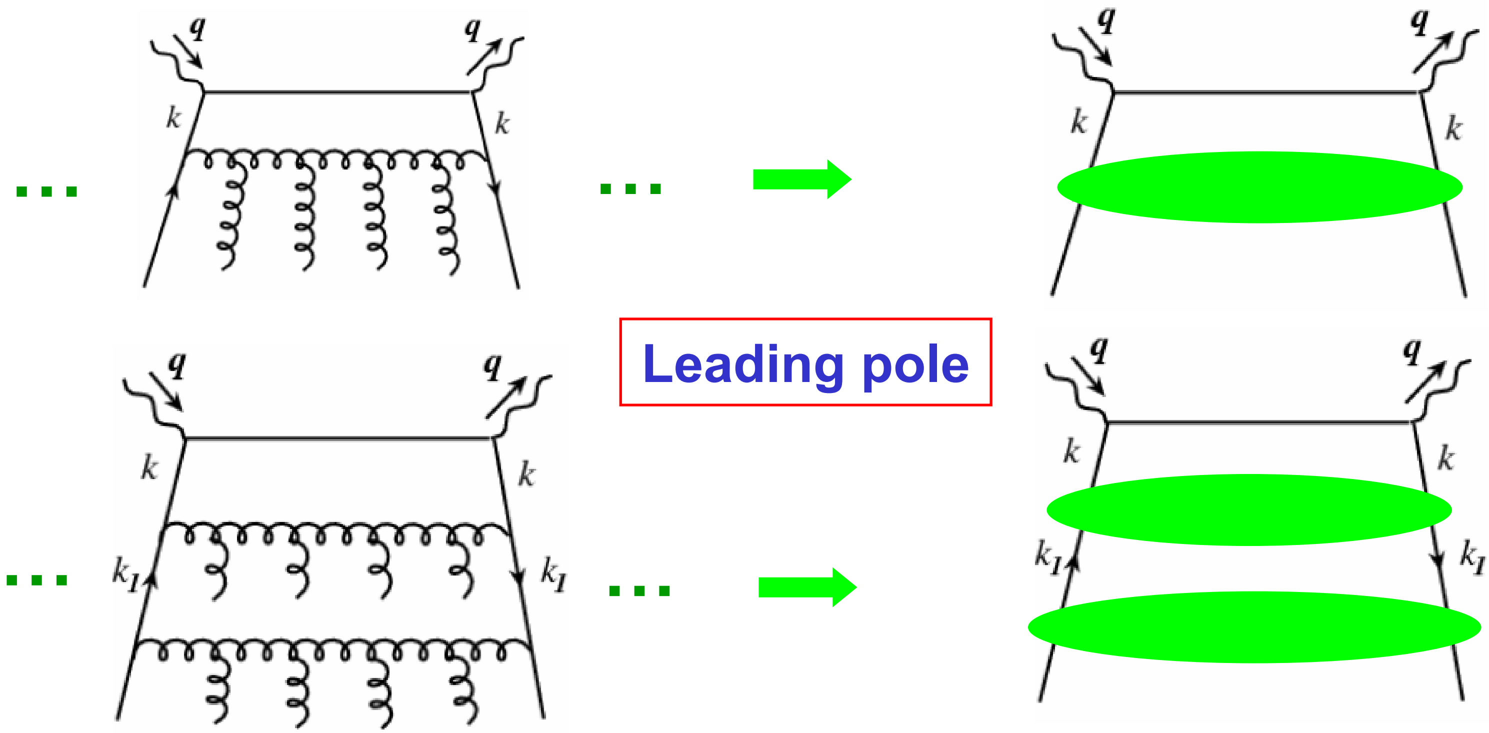
Hard probe sees only one effective parton:



Pinched poles in the ladder diagrams – corrections to evolution



Modified ladder diagrams

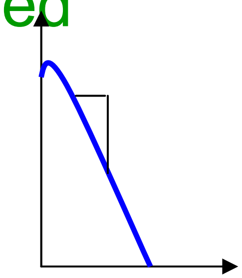


➡ **Modified DGLAP evolution equations**

- ❑ Stay close to collinear factorization – PDF's
- ❑ x is not too small
- ❑ Slow down the evolution in small-x region

A-dependence of benchmark tests

- Coherent multiple scattering is power suppressed
  - But, enhanced by nuclear size
  - Enhanced effect to steep falling distributions

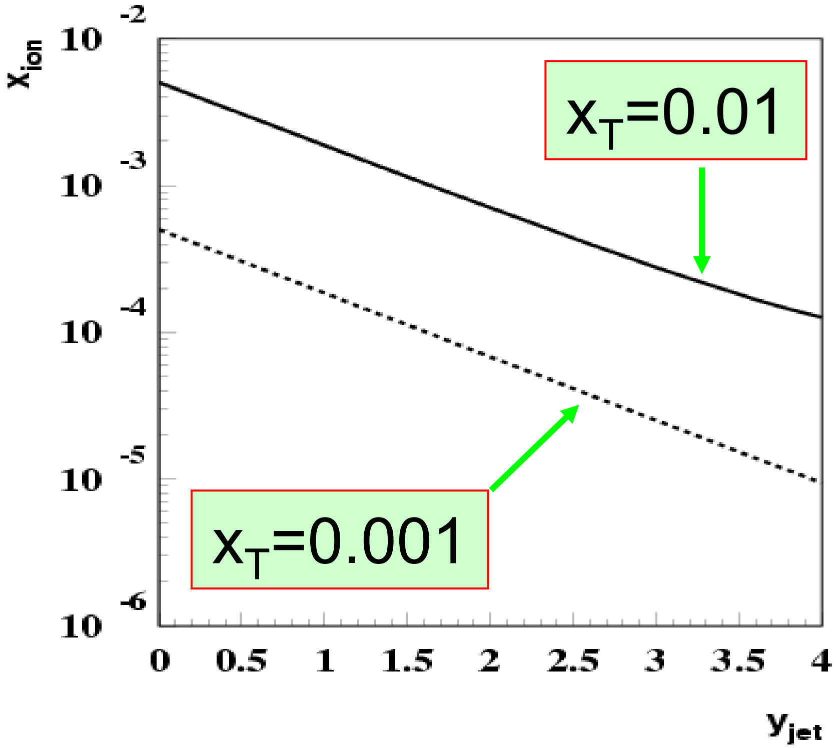


- No power correction = Single hard scattering
- Leading power collinear factorized formula
- A-dependence of benchmark tests should only involve the universal nuclear dependence from PDF's
  - y-dependence of *W, Z*, Higgs, Drell-Yan inclusive cross sections
  - *W, Z*, Higgs, Drell-Yan transverse momentum distributions
  - Low mass Drell-Yan at high p_T, and direct photon (isolation cut?)
  - Inclusive Jets at large E_T
  - Heavy quarkonium transverse momentum distributions at large p_T
  - *etc.*

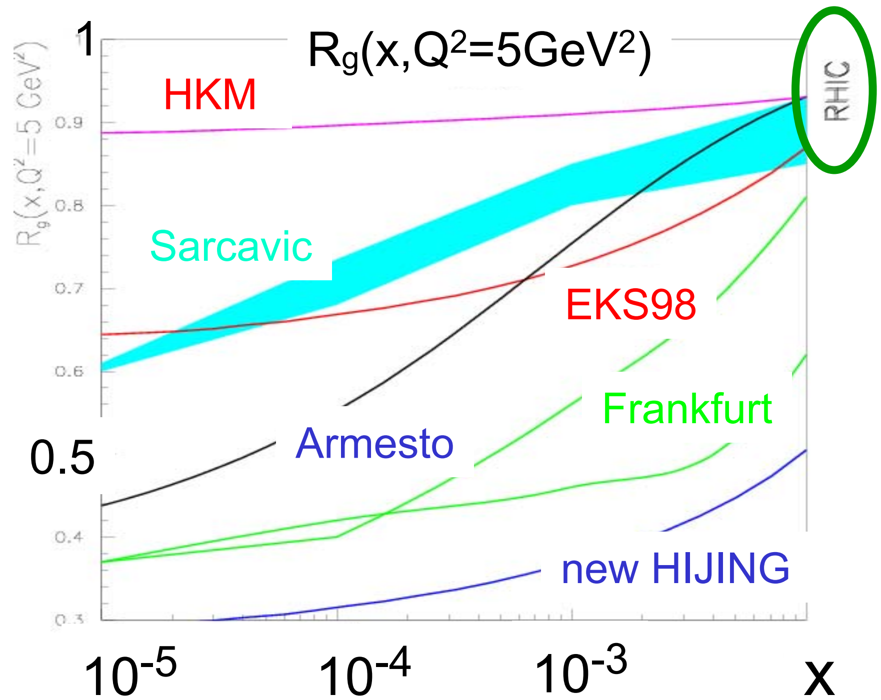
Nuclear Parton Distribution Functions

- Probes small x region

  (for inclusive jet production)



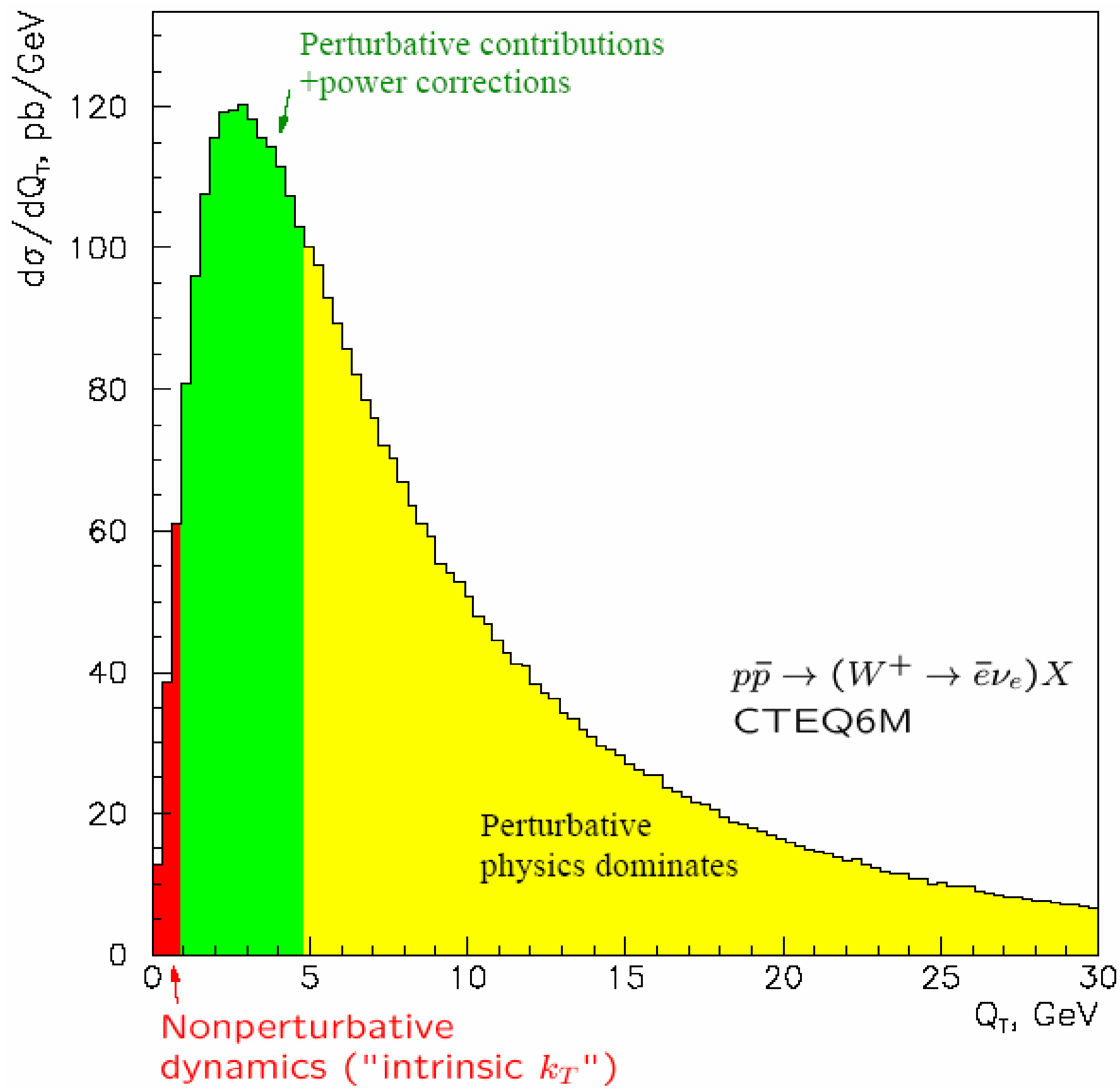
- Poor knowledge on nuclear parton distributions



Hard processes at the LHC can probe parton *x* as small as 10^{-5}!

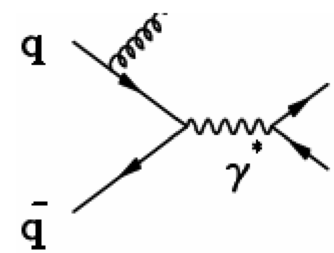
But, nuclear PDF's (in particular, gluon) are poorly constrained!

W/Z, Higgs, Drell-Yan Q_T distribution



Showing the different theoretical regions in momentum space

Drell-Yan type subprocess



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

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

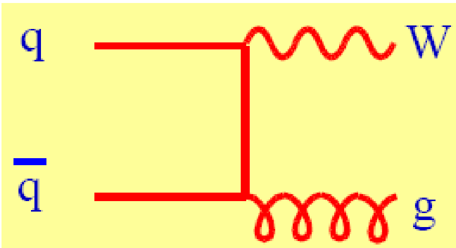
→ **Resummation of the logarithms is needed**
– the virtual photon fragmentation functions

- 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 $Q_T \to 0$:

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

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

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

as $Q_T \to 0$

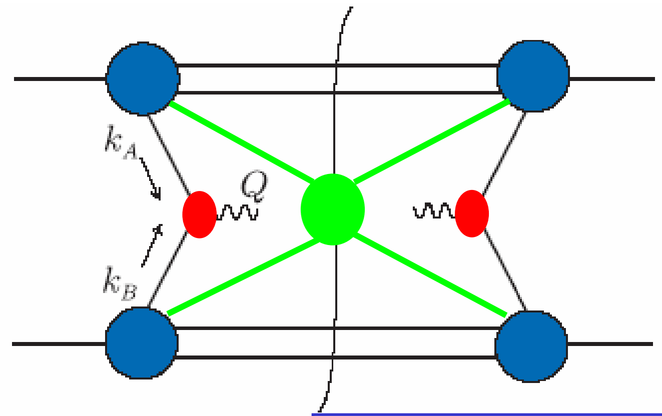
- **Experimental fact:** $\frac{d\sigma}{dy\,dQ_T^2} \Rightarrow$ finite [neither ∞ nor 0!] as $Q_T \to 0$

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:**



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

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

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

No large log's

resummed

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

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

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

- Evolution kernels satisfy RG equations

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

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

- 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 $b \ll 1/\Lambda_{\mathrm{QCD}}$, 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

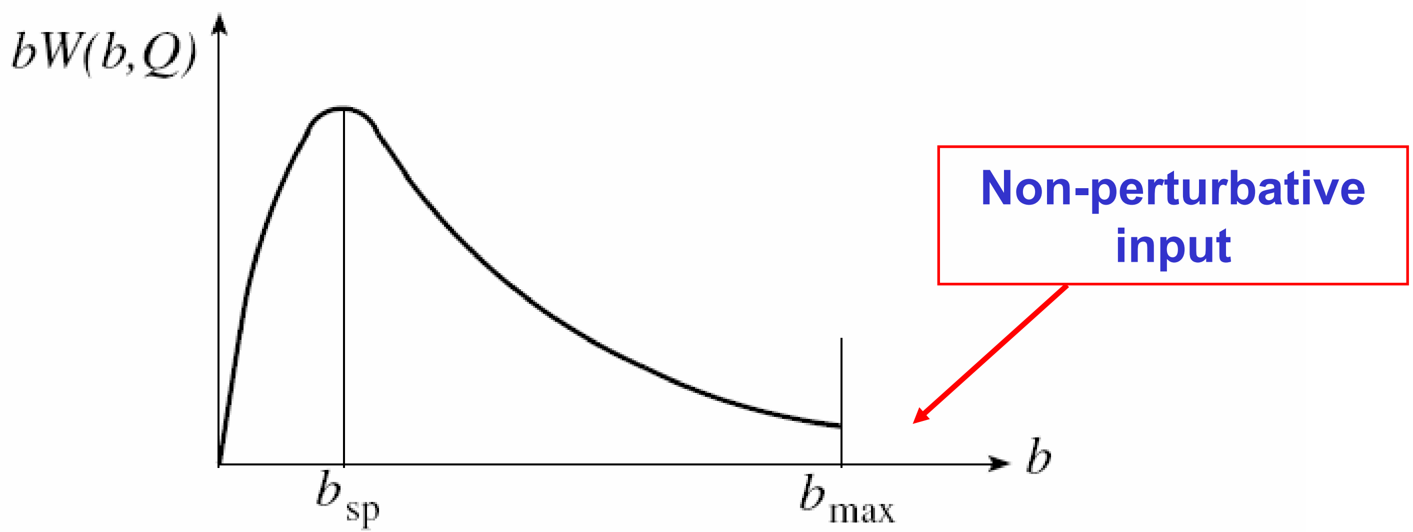
  $\Rightarrow$ perturbative b-distribution

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

❑ 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 $\int_0^{b_{max}} db(\ldots) \gg \int_{b_{max}}^\infty db(\ldots)$

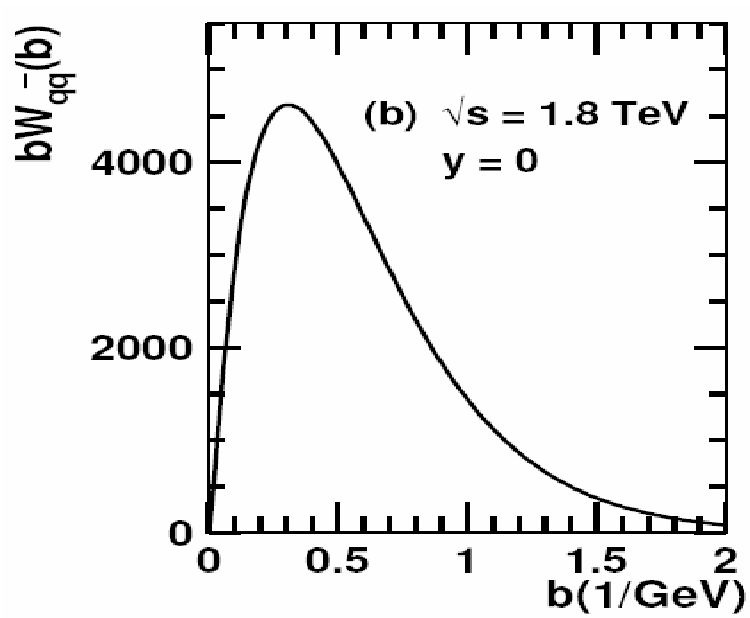
- or saddle point $b_{sp} \ll b_{max}$:
  - b-dep of $be^{-S(b,Q)}$ $\to$ $b_{sp} \propto (\frac{\Lambda_{\rm QCD}}{Q})^\lambda$, $\lambda \sim 0.4$
  - b-dep of $\phi_{a/A}(x, \frac{1}{b})$ and $\phi_{b/B}(x', \frac{1}{b})$
    $\Leftrightarrow$ DGLAP evolution

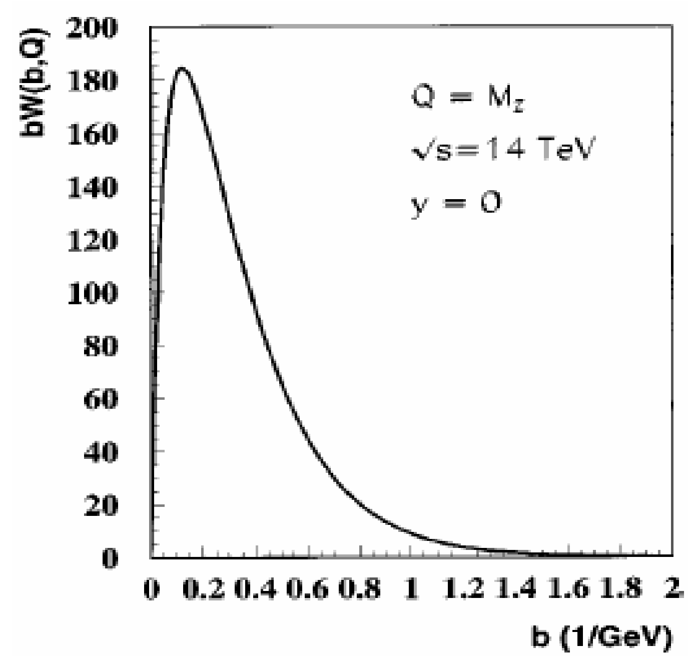
$$\frac{d}{db}\phi(x,\frac{1}{b}) = -\frac{1}{b}\frac{d}{d\ln\frac{1}{b}}\phi(x,\frac{1}{b}) < 0 \quad \text{for } x < x_c \sim 0.1$$

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

Location of the saddle point

❑ Z production (collision energy dependence):



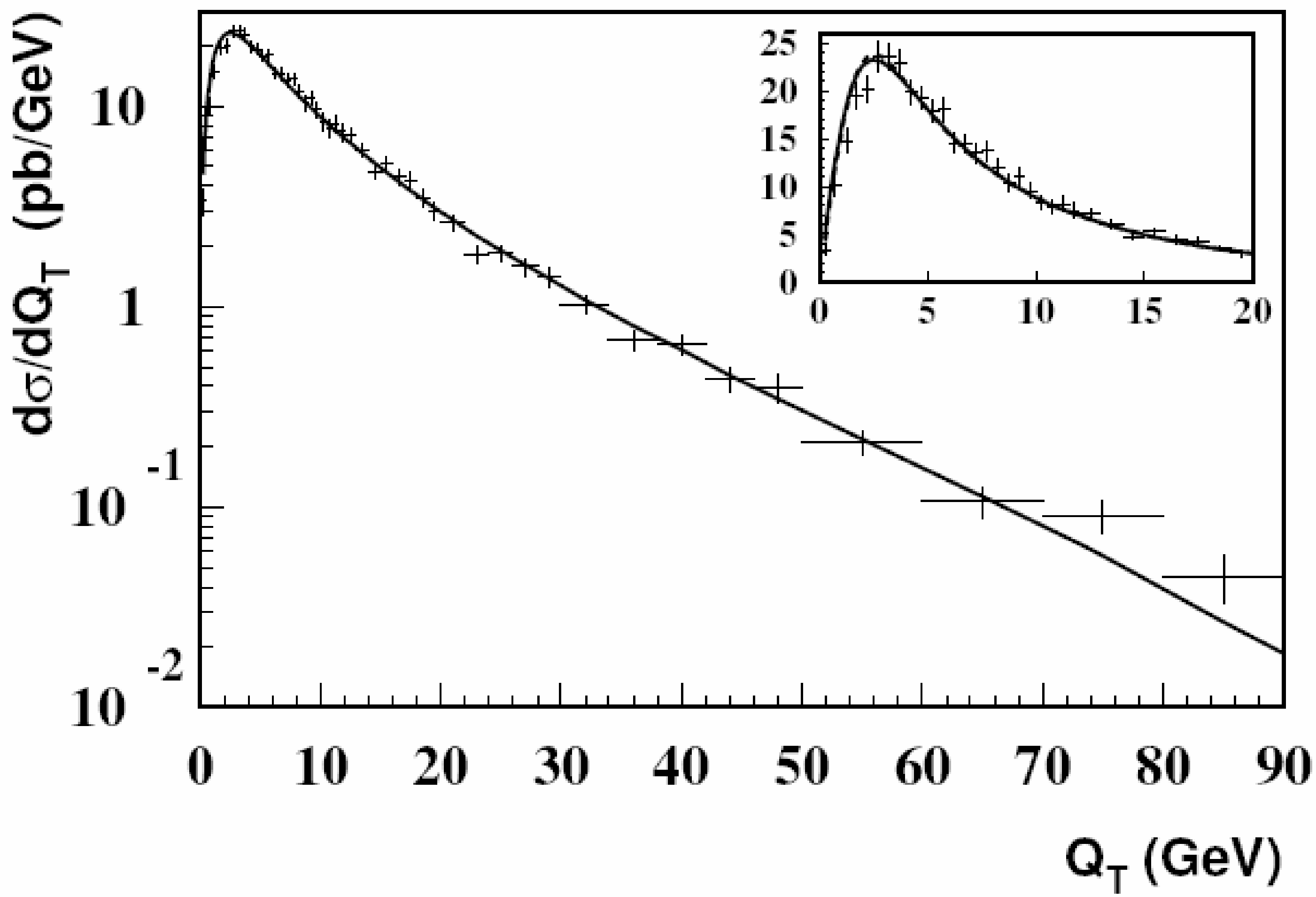


Higher collision energy = larger phase space
= more gluon shower
= larger parton k_T

Shift of the peak is calculated perturbatively!

Qiu, Zhang

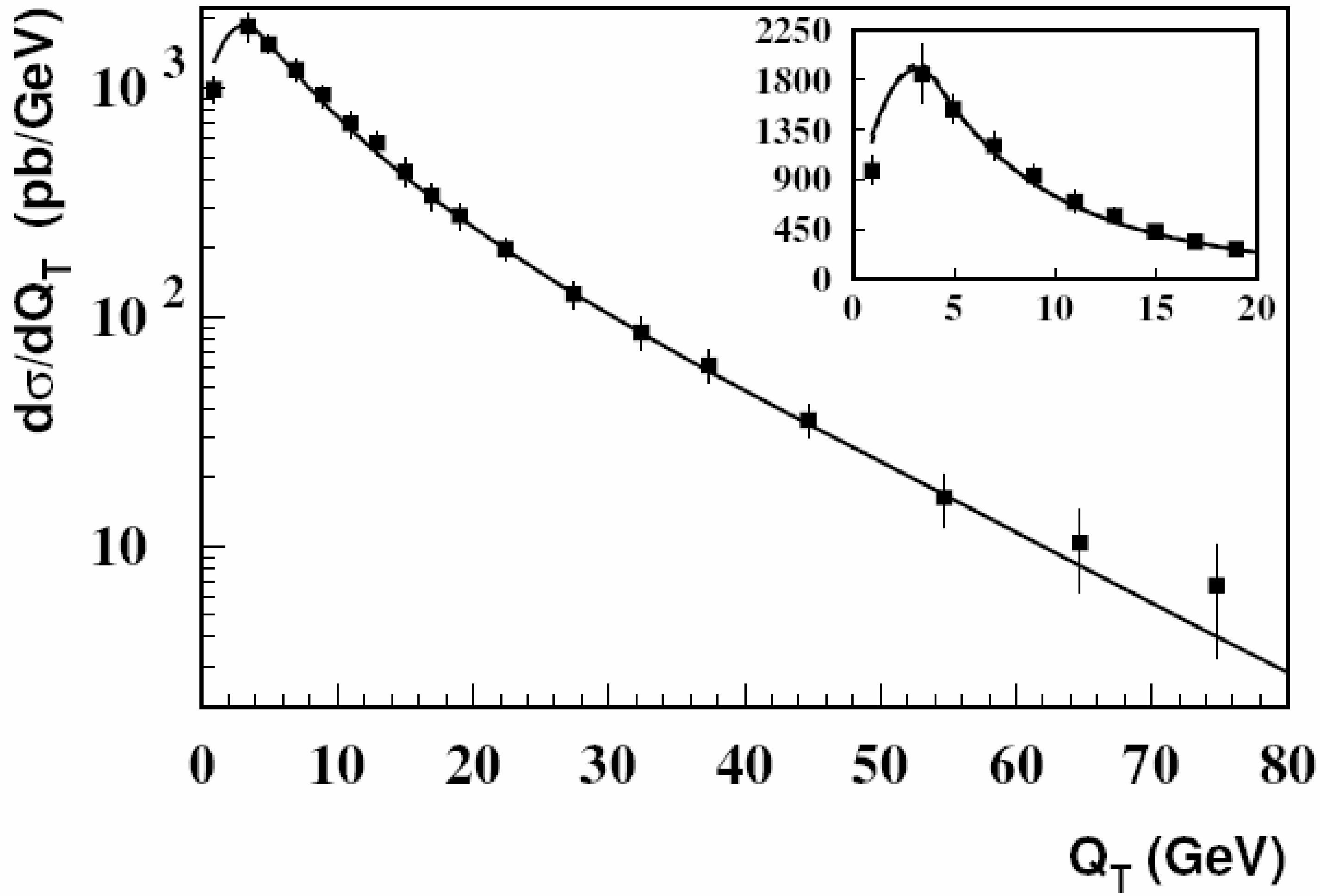
- Fermilab CDF data on Z at $\sqrt{S} = 1.8$ TeV



Power correction is very small, excellent prediction!

Qiu, Zhang

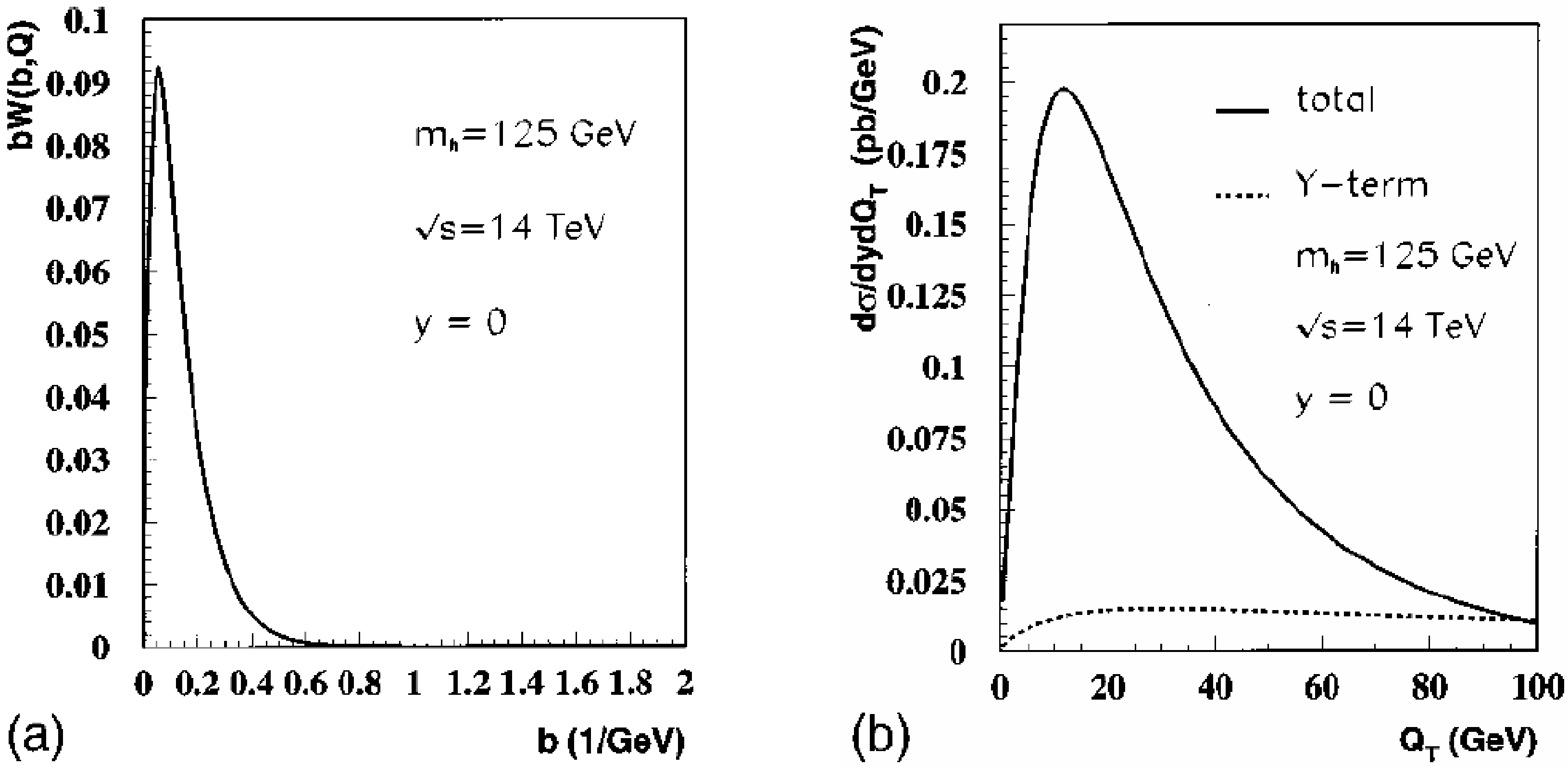
- Fermilab D0 data on W at $\sqrt{S} = 1.8$ TeV



No free fitting parameter!

Qiu, Zhang

Higgs production



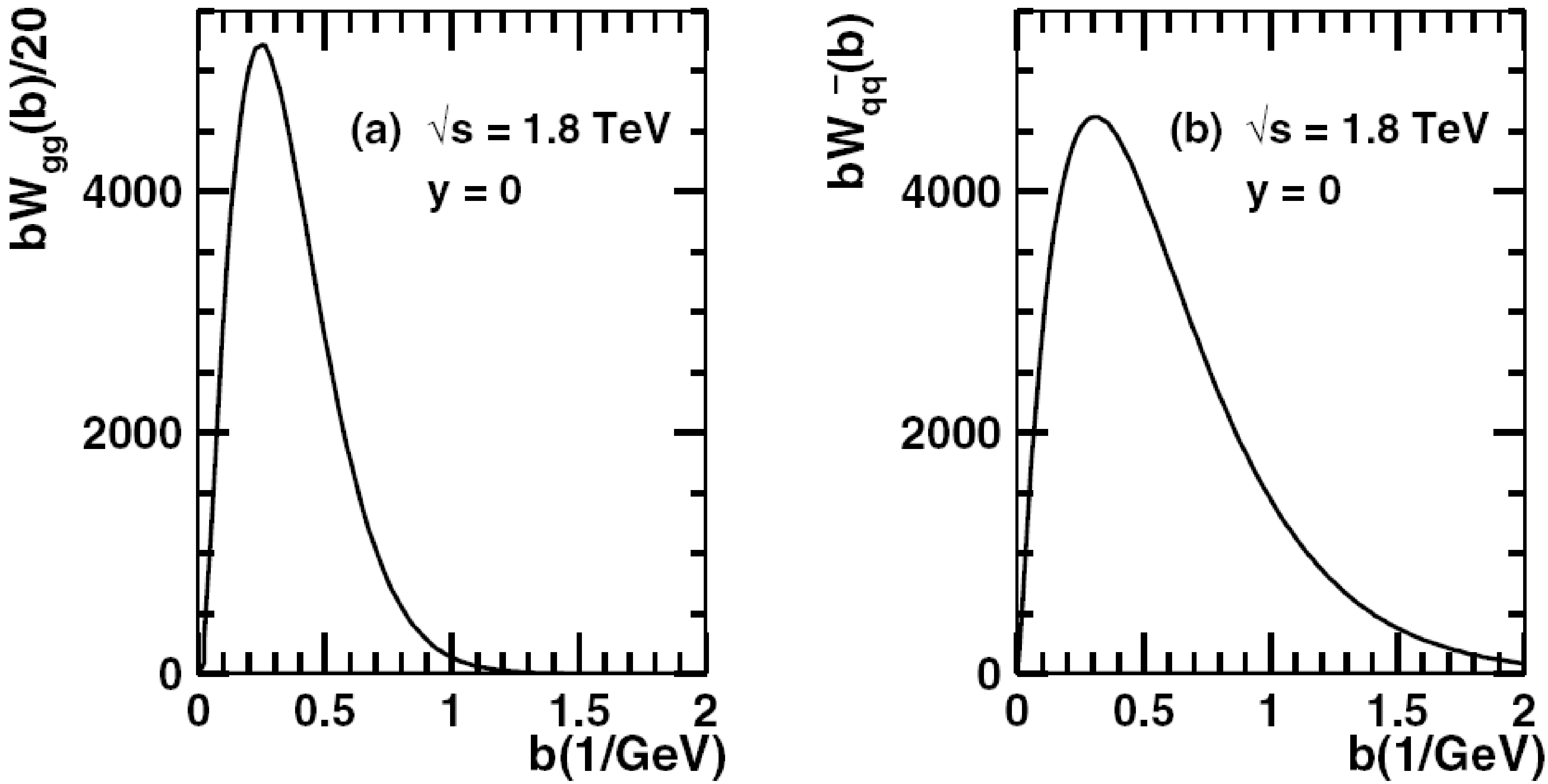
Gluon-gluon domination = narrow b-distribution

= large $\langle Q_T \rangle$

Large $\langle Q_T \rangle$ here is generated by gluon shower, but, is perturbatively calculated!

Berger, Qiu

Upsilon production

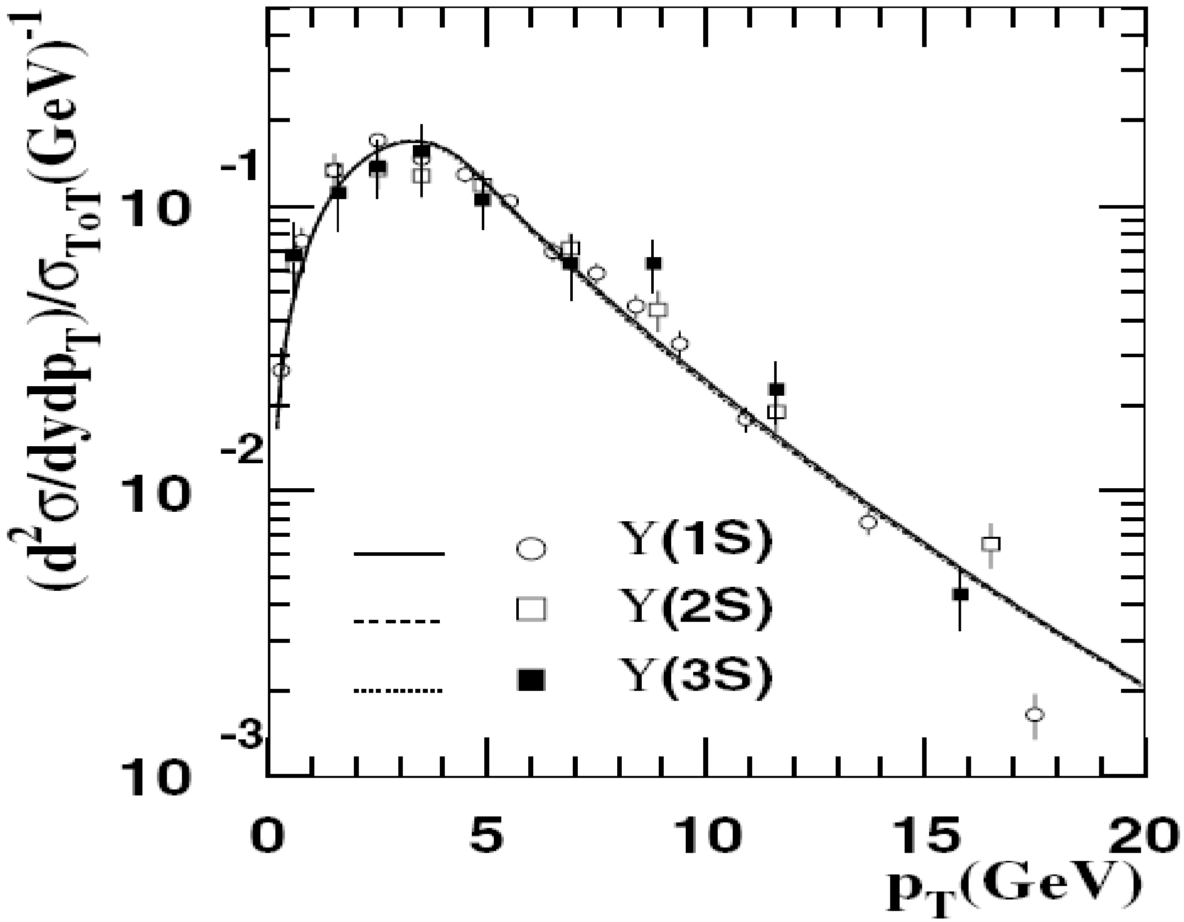


Dominated by gluon-gluon fusion

Narrow b-distribution = reliable perturbative calculation

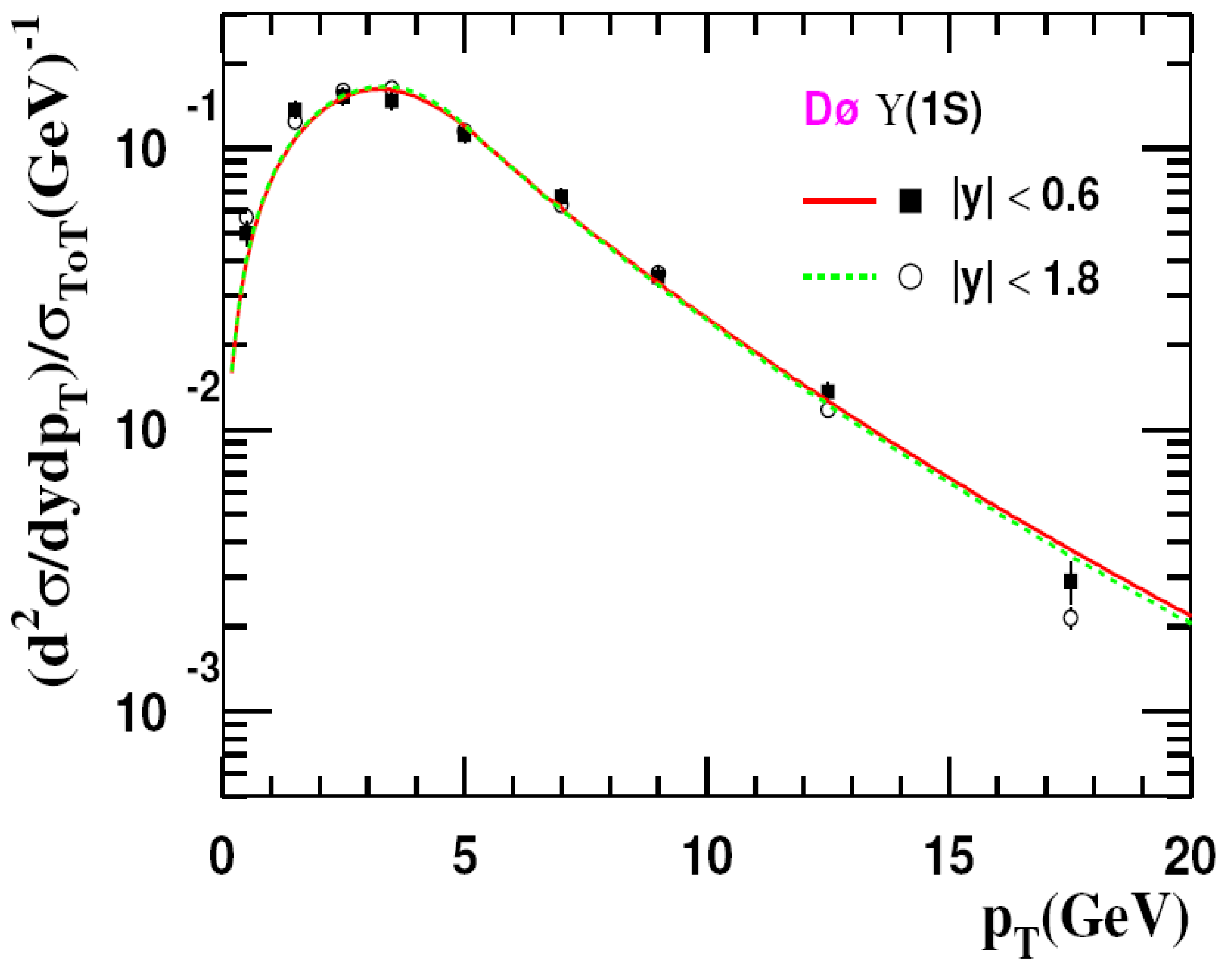
Berger, Qiu, Wang

CDF Run – I Upsilon data



Berger, Qiu, Wang

D0 Run – II Upsilon data



Berger, Qiu, Wang

A good probe of gluon distribution

- Resummed Drell-Yan type process is a good probe of gluon distribution at small-x

Resummed p_T-distribution is determined by b-space distribution

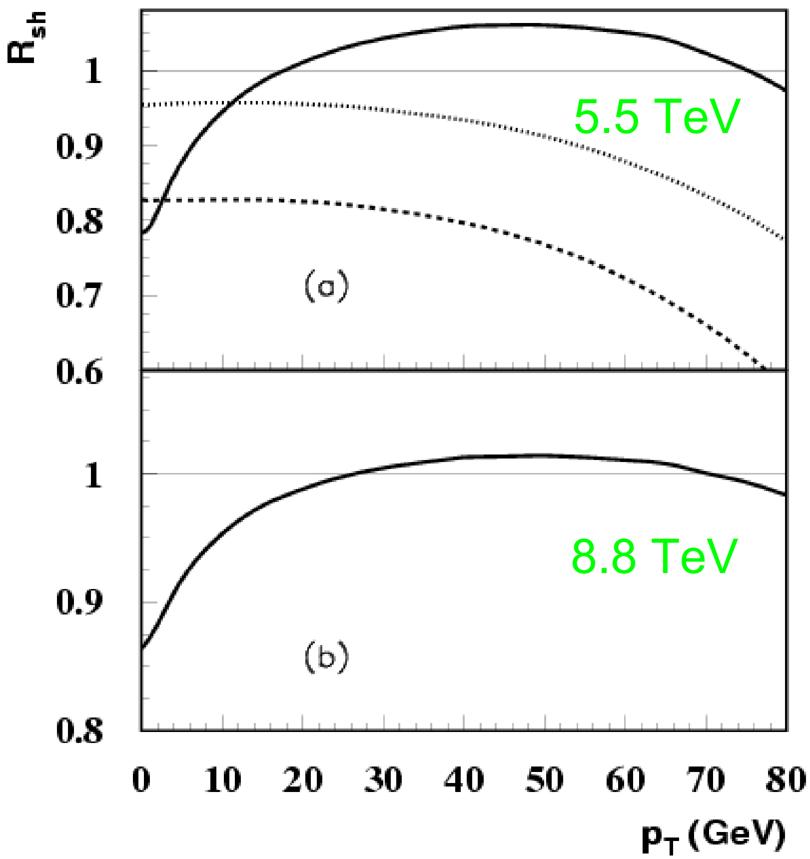
$$x_A = \frac{Q}{\sqrt{S}}\, e^{y}, \quad x_A = \frac{Q}{\sqrt{S}}\, e^{-y}, \quad \text{at } \mu \sim \frac{1}{b_{sp}}$$

- Although infinite soft gluon radiation involved, the broadening of p_T distribution is perturbatively calculable

- Since these particle does not interact much with hadronic matter, this process is a good probe of nuclear gluon distribution in pA collision

Shadowing can lead to enhancement in p_T distributions of W and Z production

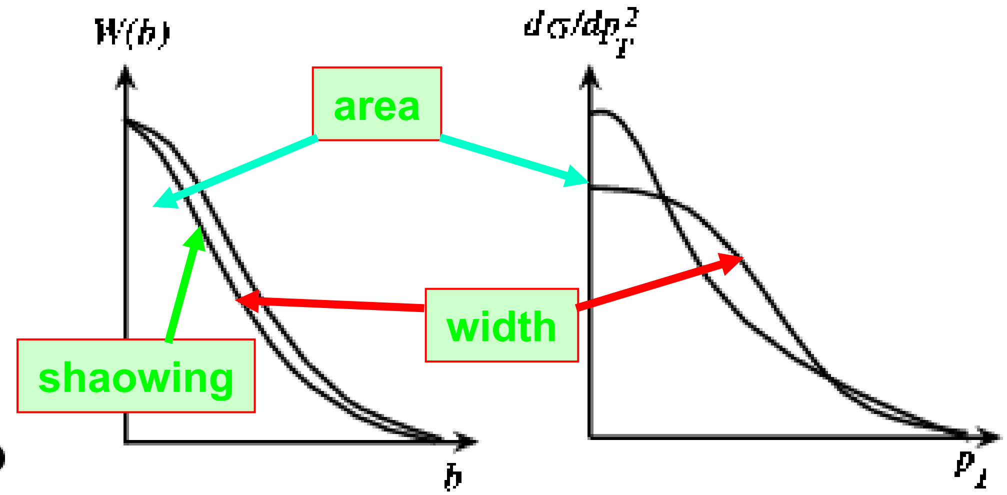
- W/Z production is dominated by low p_T region
- the shape is controlled by the gluon shower



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

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

Resummed pQCD: shadowing in b-space



Fai, Qiu, Zhang

Semihard processes

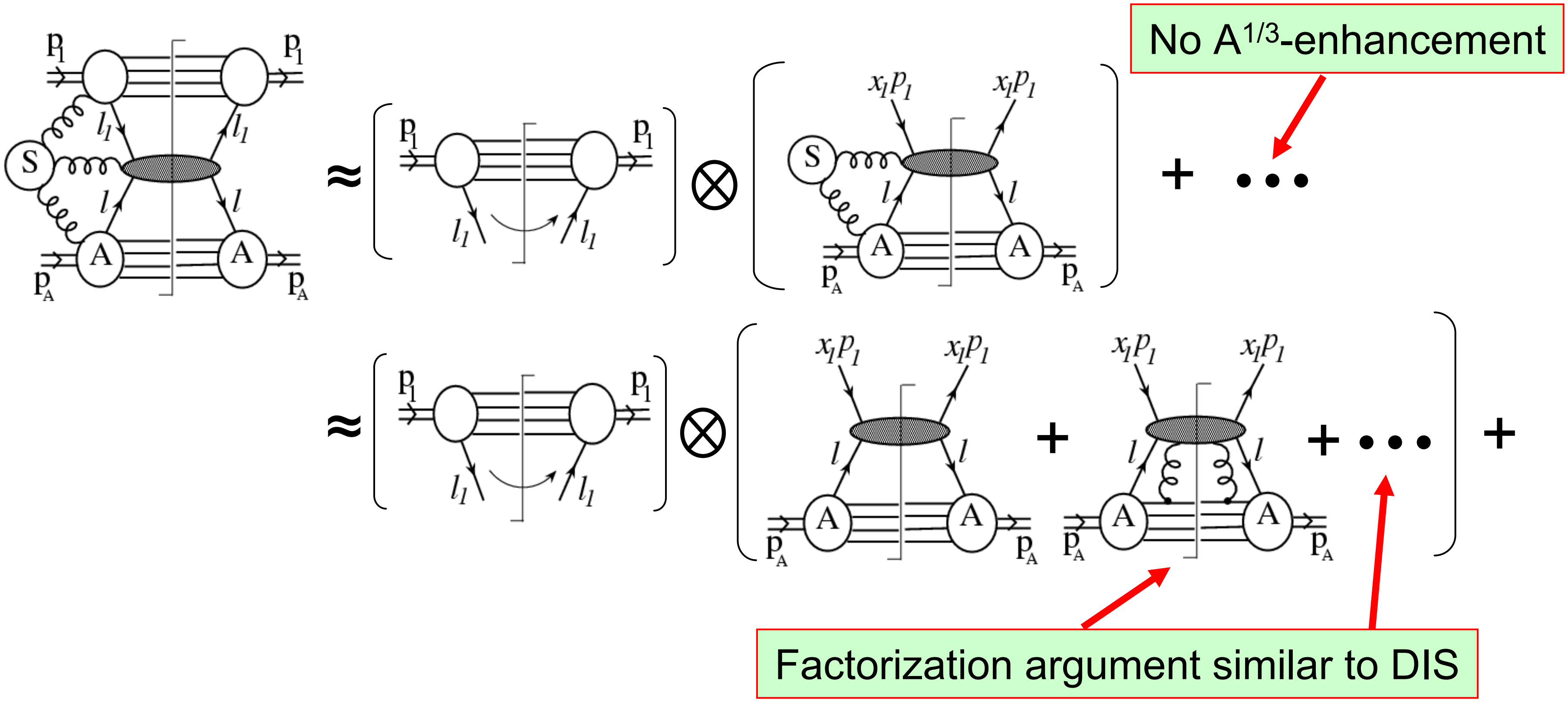
- Momentum exchange in the hard collisions, Q, is much larger than non-perturbative hadronic scale: $1/\text{fm} \sim \Lambda_{QCD}$
- But, the scale, Q, is not large enough that the medium size enhanced power corrections are important

  ⇒ $(A^{1/3}-1)\xi^2/Q^2$ is not too much less than 1

  ξ^2 is a medium sensitive scale $\propto \langle F^{+\alpha} F^{+}{}_{\alpha} \rangle$
- Like the leading power, predictive power of pQCD for the power corrections also relies on the factorization
- Without the factorization, calculations and predictions are model dependent
- Factorization holds for A-enhanced power corrections in pA
- Factorization fails for AA beyond $1/Q^2$

Factorization in p-nucleus collisions

- **A-enhanced power corrections, $A^{1/3}/Q^2$, are factorizable:**



- **But, power corrections to hard parts are process-dependent, and they are different from DIS**

Multiple Scattering

- Single hard scattering of momentum exchange, Q, is localized in space-time of $1/Q$, which is much less than nucleon size ~ fm

  ⟹ the scattering is only sensitive to the local parton densities (or distributions)

- Need multiple scattering to probe the medium properties (or structure)

  - Coherent multiple scattering is suppressed by the powers of the hard momentum scale, $1/Q^n$

    ⟹ Need semihard processes to probe the coherent medium effect

  - Incoherent multiple scattering ⟹ Glauber formalism

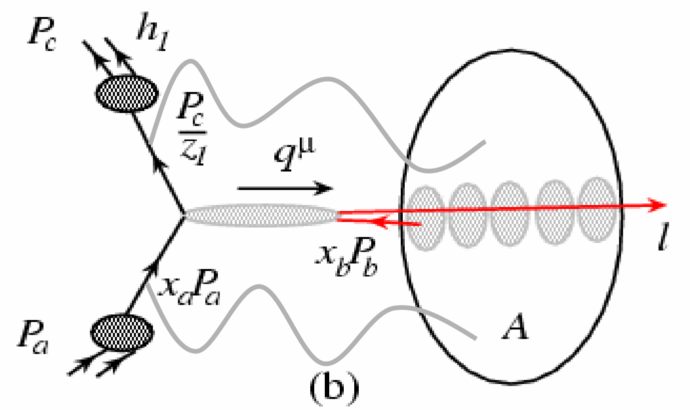
Qiu, Sterman, 2003

Power Corrections in p+A Collisions

- Hadronic factorization fails for power corrections of the order of $1/Q^4$ and beyond

- Medium size enhanced dynamical power corrections in p+A could be factorized

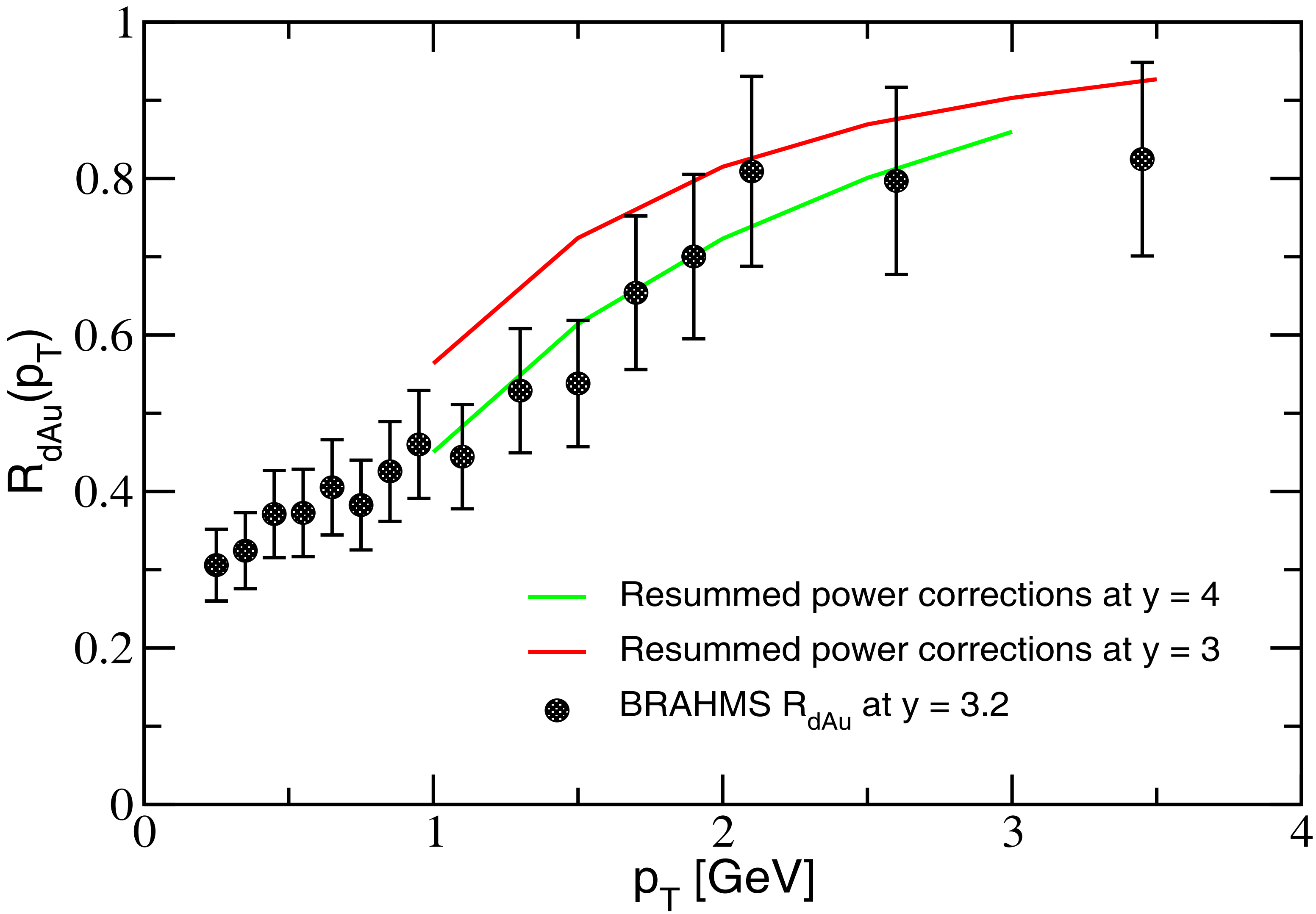
⇨ to make predictions for p+A collisions



- Single hadron inclusive production:

  Once we fix the incoming parton momentum from the beam and outgoing fragmentation parton, we uniquely fix the momentum exchange, q^μ, and the probe size

  ⇔ coherence along the direction of $q^\mu - p^\mu$


1
0.8
0.6
0.4
0.2
0
0
1
2
3
4
$R_{dAu}(p_T)$
p_T [GeV]
Resummed power corrections at y = 4
Resummed power corrections at y = 3
BRAHMS R_{dAu} at y = 3.2

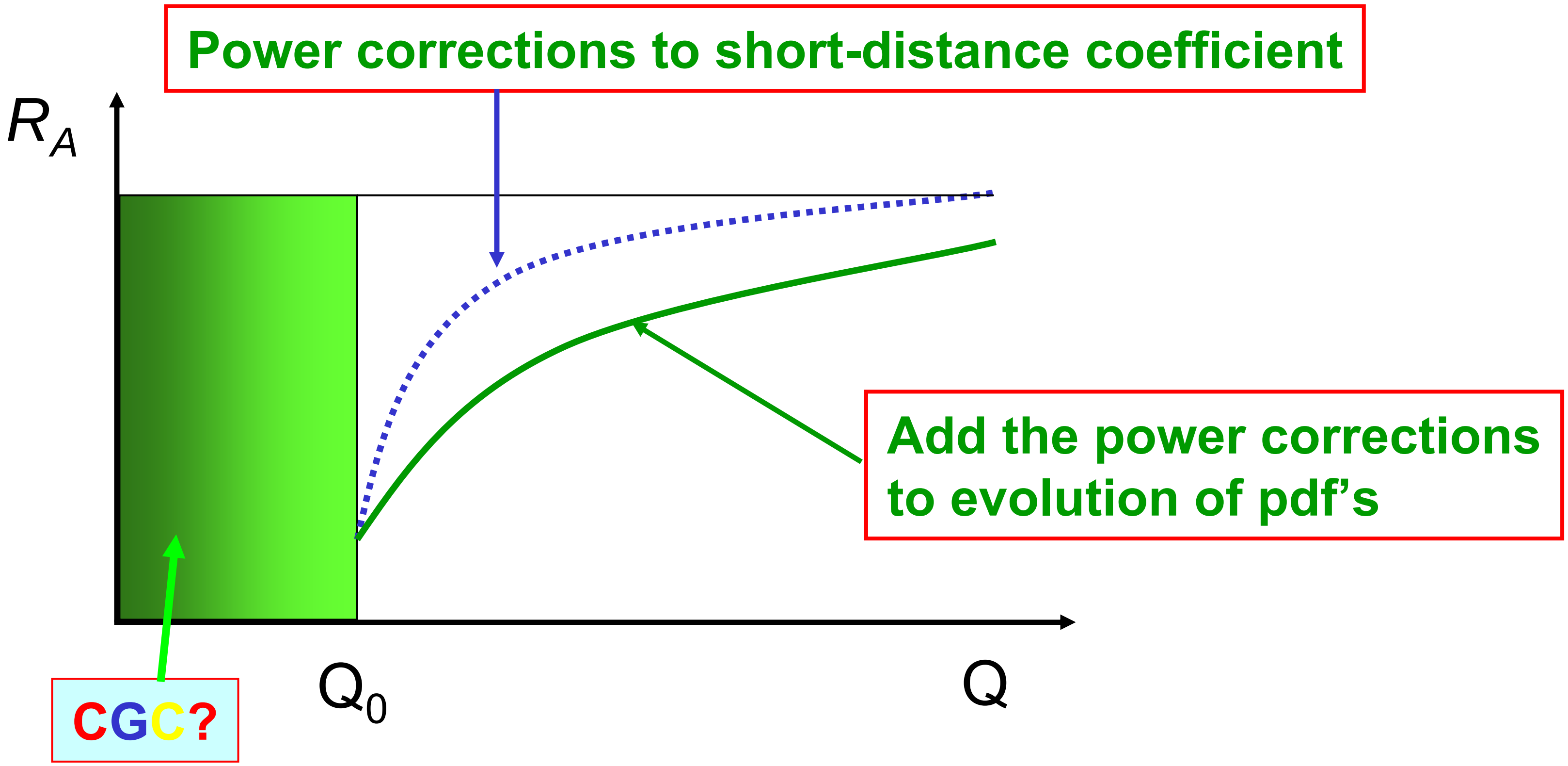
Vitev

Role of coherent power corrections

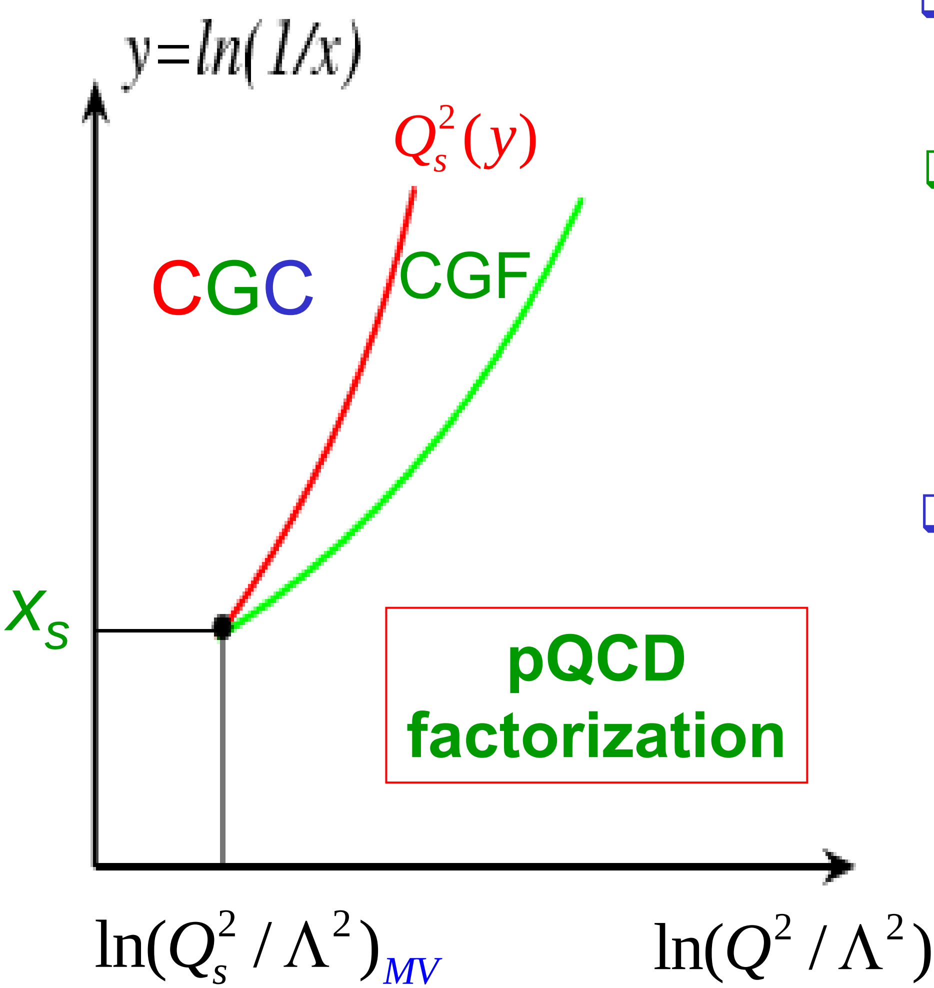
- Ratio of physical observables: R_A

$$R_A \equiv \frac{F_2^A/A}{F_2^D/2}, \qquad \frac{\sigma^{dA}}{\langle N_{coll}\rangle \sigma^{NN}}, \quad \text{etc.}$$

- ❖ power correction to cross section
- ❖ power correction to evolution equation of pdf's



Phase diagram of parton densities



- ❑ Experiments measure **cross sections**, not **PDFs**
- ❑ PDFs are extracted based on
  - ➢ factorization
  - ➢ truncation of perturbative expansion
- ❑ How to probe the boundary between different regions?

- ❑ Look for where pQCD factorization fails
- ❑ Power corrections
  – improve predictive power of factorization approach

Conclusions

- Test the predictive power of pQCD in nuclear collisions by verifying the universality of nPDF's through the hardest probes, only available at the LHC
- Measure the nPDF's over an unprecedented range of x, Q^2
  - find out the true nuclear modification to the PDF's by probing ultra-soft gluons through the y-dependence
  - QCD resummation significantly improve the predictive power, including the low p_T region, which is sensitive to soft gluon shower.
- Study the multiple parton correlations in nuclear medium by probing the semihard subprocesses
  - Heavy quarkonium, low mass Drell-Yan pair, dijet or di-hadron correlations, …
- pA at the LHC can certainly provide a much needed help for extrapolating the hadronic collision to the GZK energy

A new approach to the large b-region

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

- ❖ solution of the CSS evolution equation in small-b region
- ❖ preserve the perturbative small b-region unchanged
- ❖ solution of the modified CSS evolution equation, including leading power corrections, in large b-region

Leading twist

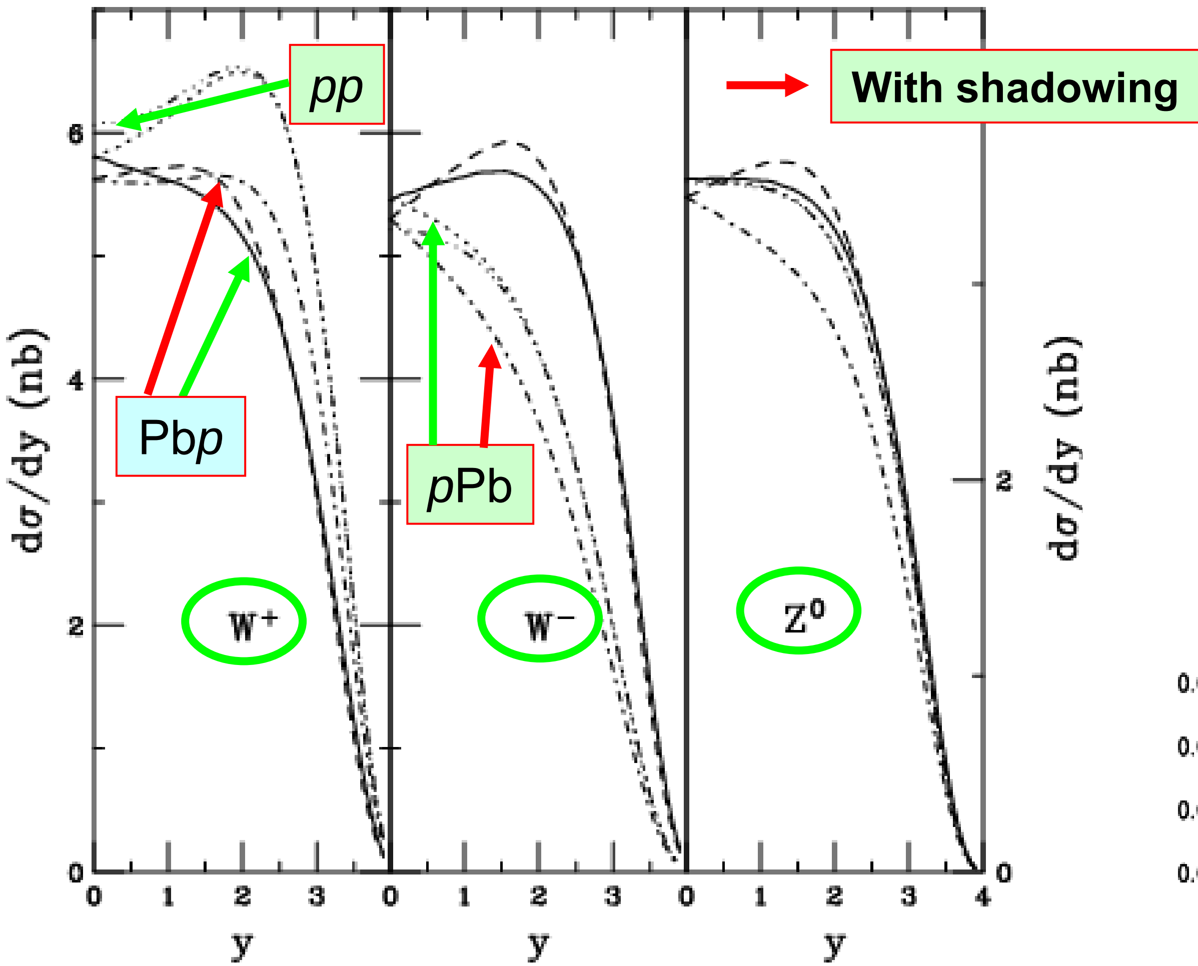
$$F^{NP}_{QZ}(b,Q;b_{max}) = \exp\left\{ -\ln\left(\frac{Q^2 b^2_{max}}{c^2}\right)\left[g_1\left((b^2)^\alpha - (b^2_{max})^\alpha\right) + g_2\left(b^2 - b^2_{max}\right)\right] - \bar{g}_2\left(b^2 - b^2_{max}\right)\right\}$$

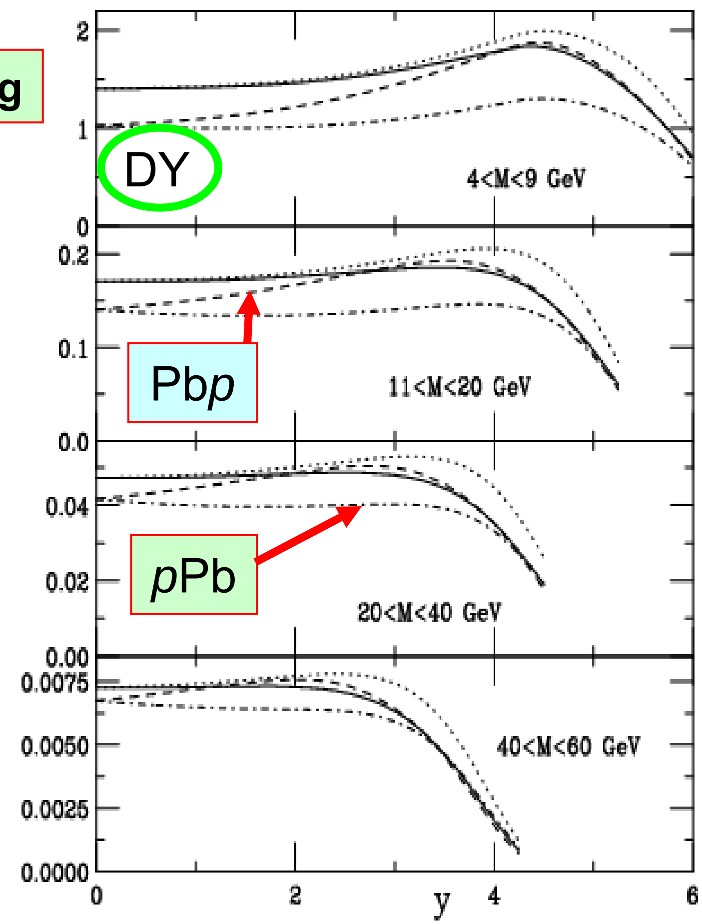
Intrinsic power corrections

Dynamical power corrections

- ❖ g_1 and α are fixed by the continuity of W(b,Q) at b_{max}
- ❖ $\sqrt{S}$ is built in the value of g_1 and α

Rapidity *y*-dependence for W, Z and Drell-Yan cross sections





For $\sqrt{s}$ =5.5 TeV *pp*, *p*Pb, Pb*p* collisions

R. Vogt