Semi-Inclusive Processes in Electron-Ion Collisions

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Based on work done with Kang, Vitev, …

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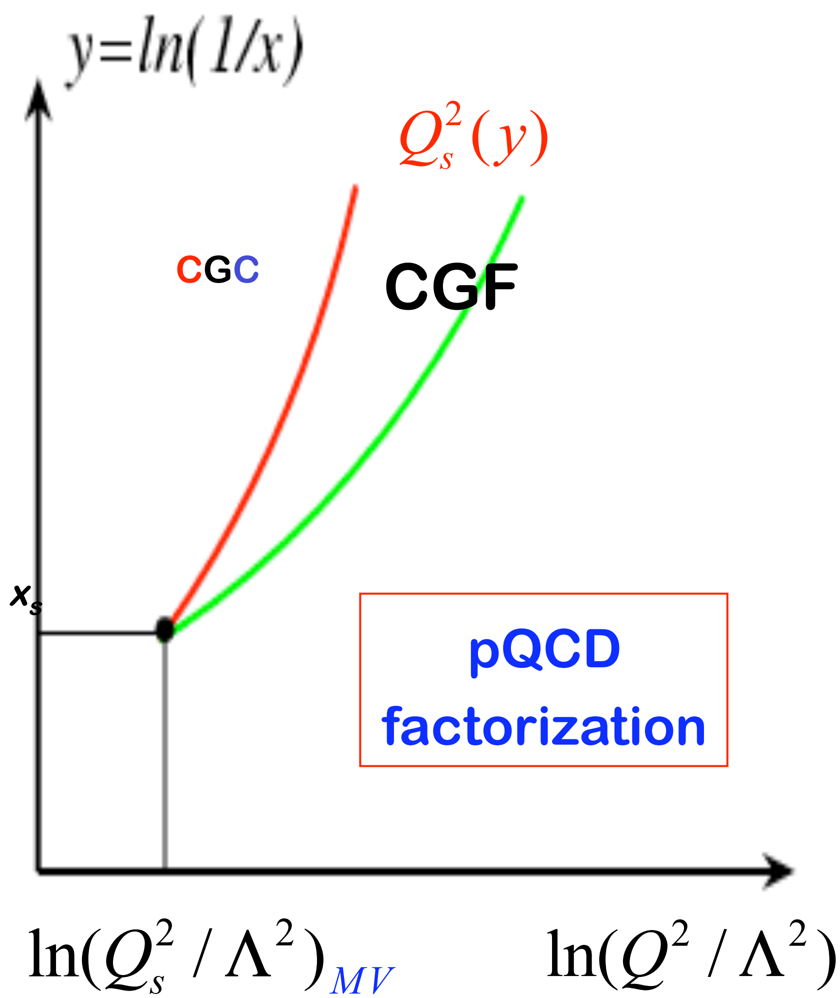
Phase diagram of parton densities



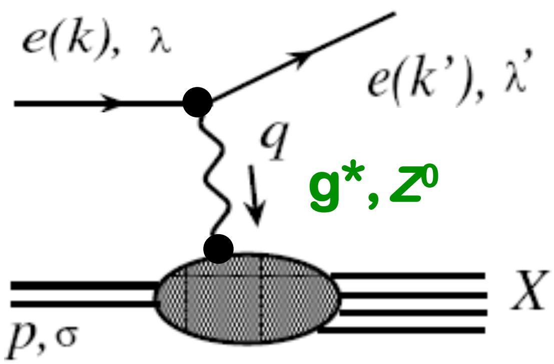
- Experiments measure cross sections, not PDFs
- PDFs are extracted based on
  - factorization
  - truncation of perturbative expansion
- How to probe the boundary between different regions?

Look for where pQCD factorization approach fails

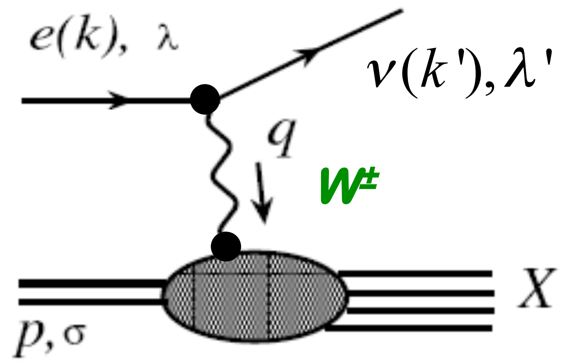
Inclusive DIS in ep and eA Collisions

❑ Inclusive DIS cross section:

Neutral current (NC)



Charged current (CC)



❑ Kinematic variables:

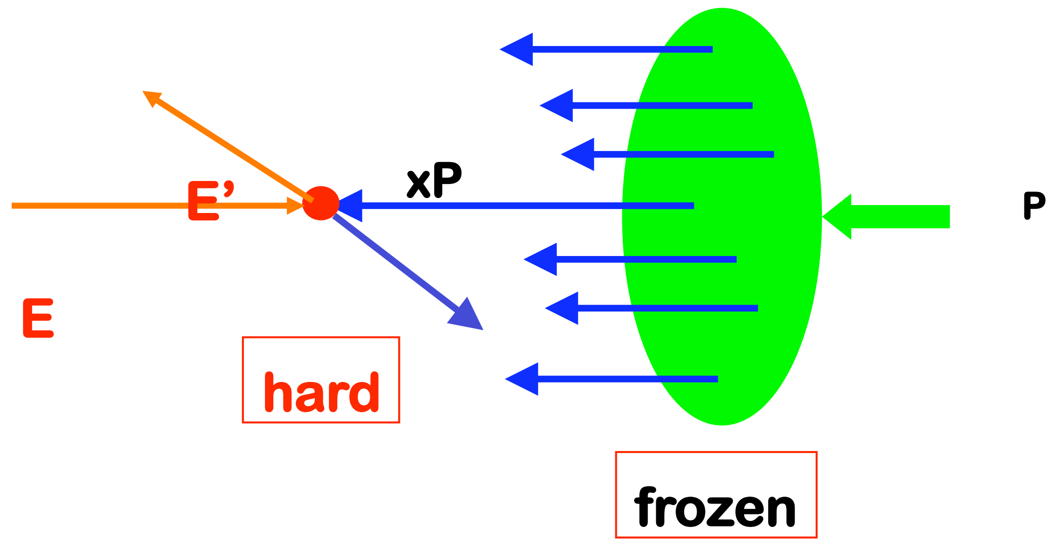
- ✧ **4-momentum transfer:** $Q^2 = -q^2$
- ✧ **Bjorken variable:** $x_B = \dfrac{Q^2}{2p\cdot q}$
- ✧ **Squared CMS energy:** $s = (p+k)^2 = \dfrac{Q^2}{x_B\, y}$
- ✧ **Inelasticity:** $y = \dfrac{p\cdot q}{p\cdot k}$
- ✧ **Final-state hadronic mass:** $W^2 = (p+q)^2 \approx \dfrac{Q^2}{x_B}(1-x_B)$

❑ Structure functions:

$$F_T,\ F_L \text{ or } F_1,\ F_2 \quad (F_3 \text{ for parity violating interaction})$$

Naïve parton model

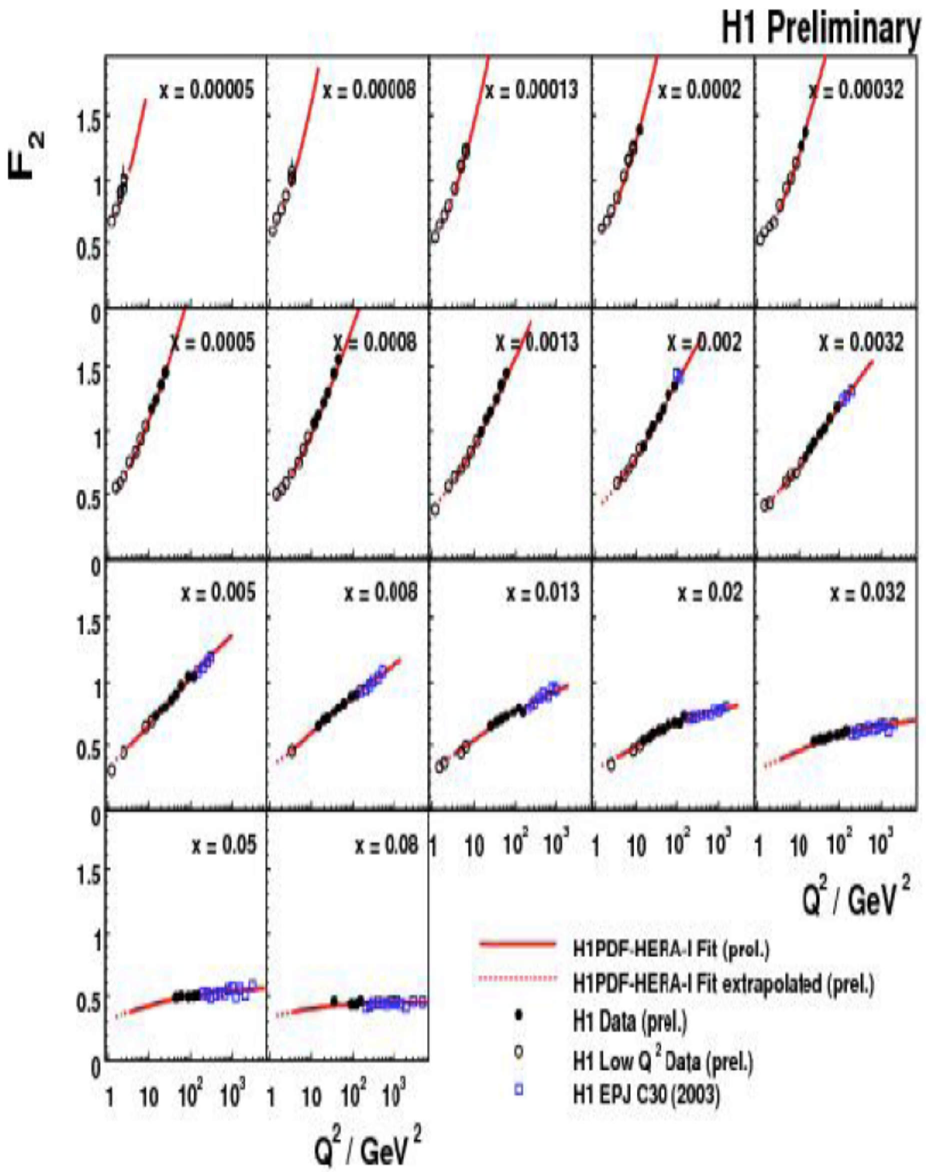
Hard probe – Impulse approximation – Parton model

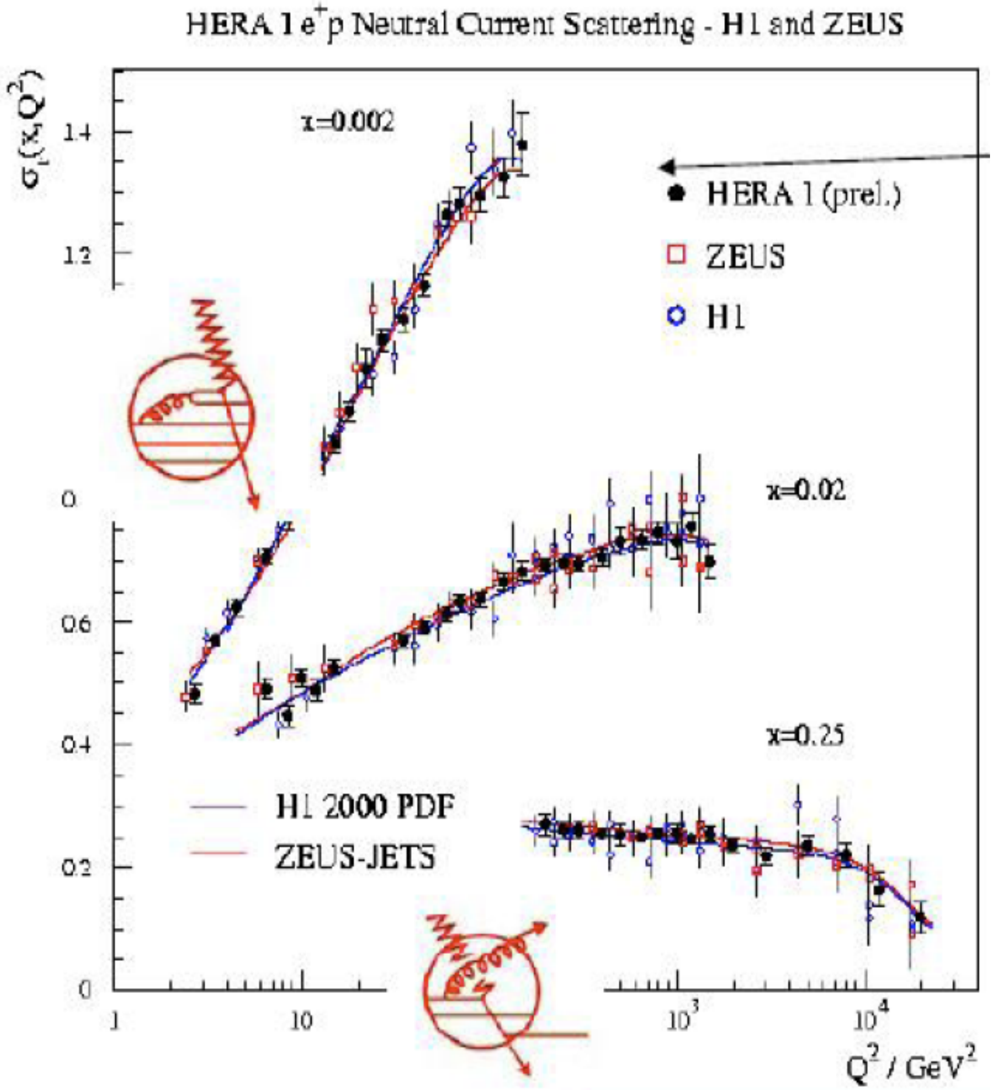


$$\sigma_{lP}(Q) \approx \int dx\, f_{q/P}(x)\, \hat{\sigma}(x,Q)$$

Convolution of two probability functions

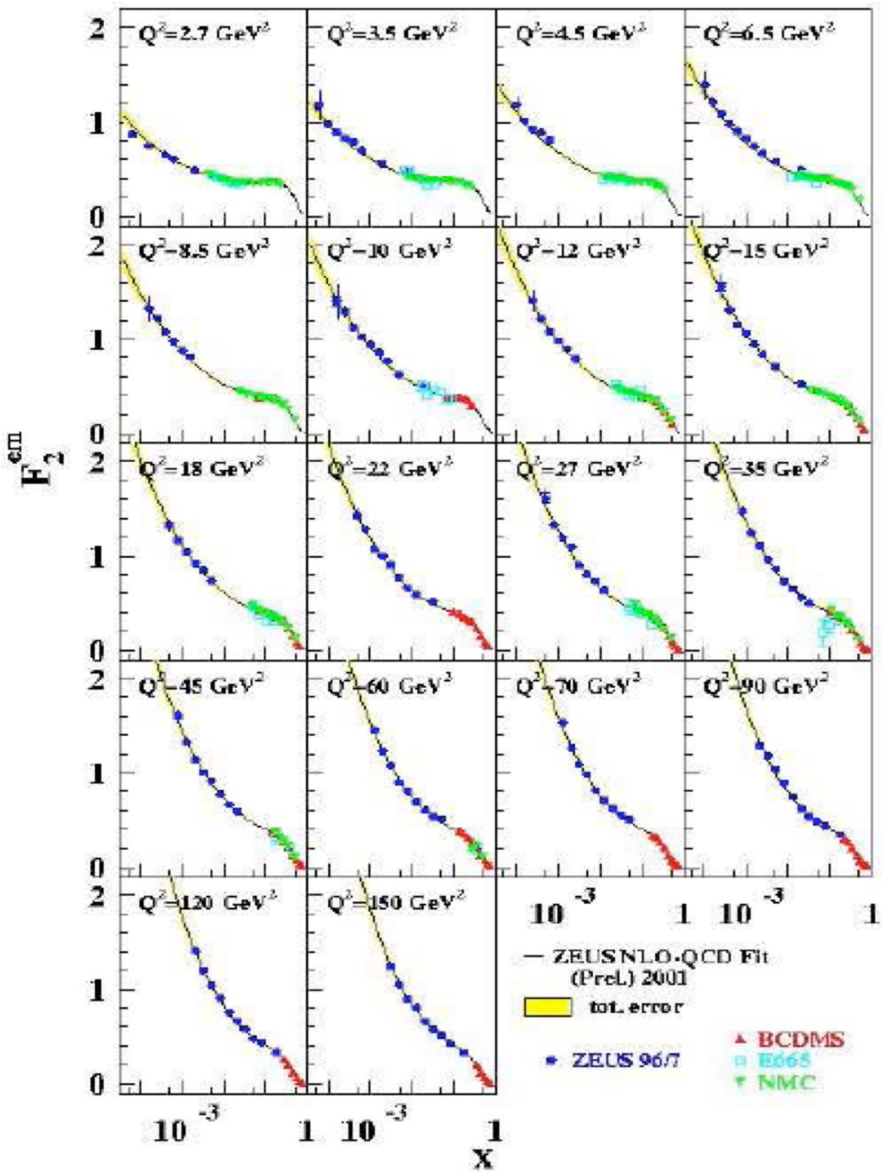
Structure Functions as a Function of Q^2

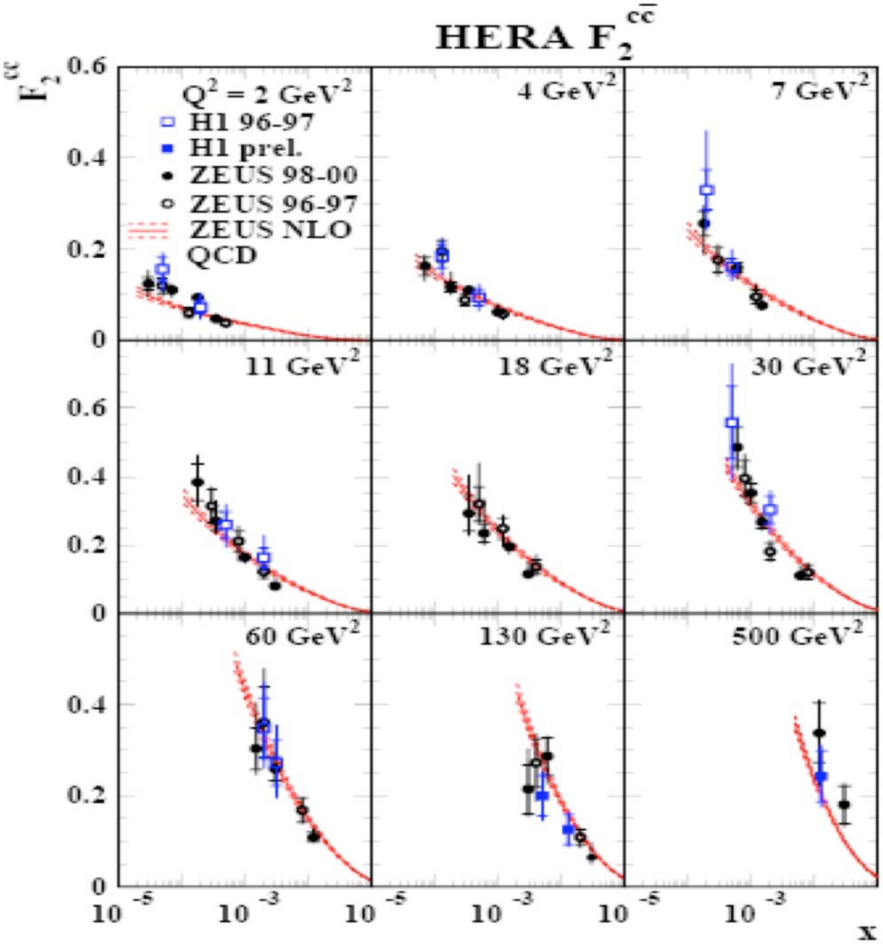




DGLAP works!

Structure Functions as a Function of x_B

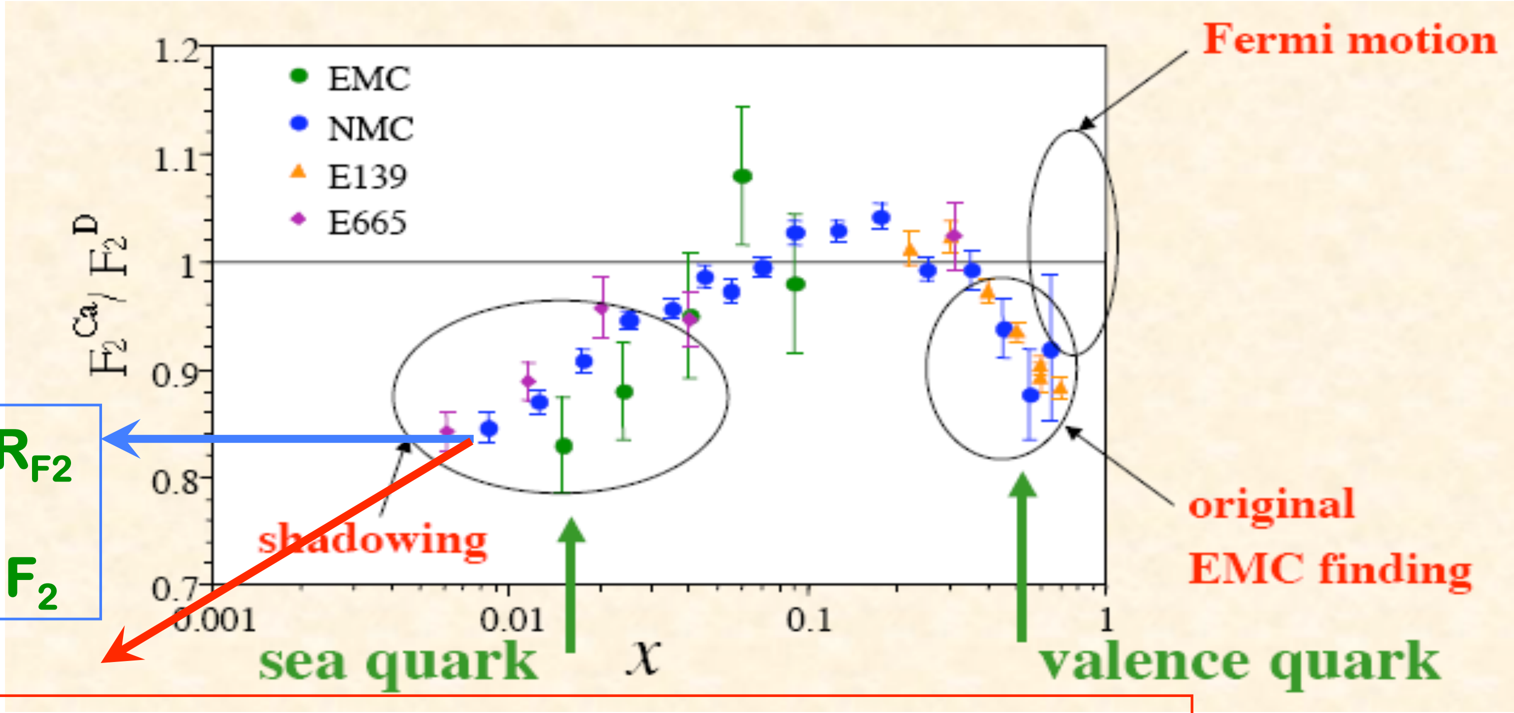




- ✧ At Q~1.5 GeV, F_2 still grows
- ✧ F_2(charm) or gluon also grows

What have we learned from eA collisions?

- EMC effect, Shadowing and Saturation:



Saturation in R_{F2} ≠ Saturation in F_2

Saturation in $F_2(A) = R_{F2}$ decreases until saturation in $F_2(D)$

- EIC – R_{F2} as a function of x_B at a fixed Q^2 for various A

Need x_B as small as 10^{-3} at Q^2=2GeV^2 to probe the saturation

(More in tomorrow's talk)

The Question

Can pQCD calculate the structure functions at small x?

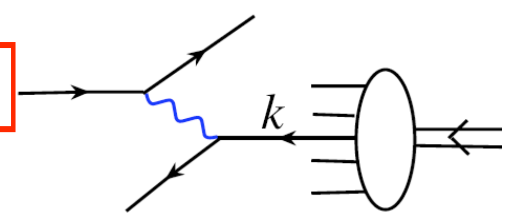
❑ Facts:

- ✧ **PQCD cannot calculate parton dynamics at the hadronic scale**
- ✧ **Inclusive DIS – single hard momentum transfer: Q >> 1/fm**
- ✧ **OPE is expected to work – separation of scales - Factorization**

$$
\begin{aligned}
\sigma^{h}_{phys} = \ & \hat{\sigma}^{i}_{2} \otimes [1 + C^{(1,2)}\alpha_s + C^{(2,2)}\alpha_s^2 + \ldots] \otimes T_2^{i/h}(x) \\
+ \ & \frac{\hat{\sigma}^{i}_{4}}{Q^2} \otimes [1 + C^{(1,4)}\alpha_s + C^{(2,4)}\alpha_s^2 + \ldots] \otimes T_4^{i/h}(x) \\
+ \ & \frac{\hat{\sigma}^{i}_{6}}{Q^4} \otimes [1 + C^{(1,6)}\alpha_s + C^{(2,6)}\alpha_s^2 + \ldots] \otimes T_6^{i/h}(x) \\
+ \ & \ldots
\end{aligned}
$$

Leading twist

Power corrections

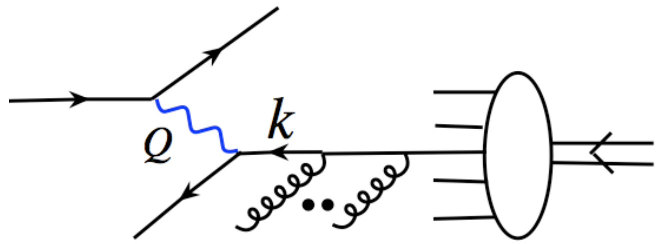


❑ Breakdown:

Collinear factorization fails when parton momentum $k^+ = xp \sim k_T$

Semi-inclusive DIS in ep and eA Collisions

- **Parton's transverse momentum at the hard collision:**



Gluon shower: $k_T^2 \propto \Lambda_{\rm QCD}^2 \ln(Q^2/\Lambda_{\rm QCD}^2) \ln(s/Q^2)$

- **Single hadron production at p_T:**

  ✧ **Hard scale: Q assures a hard collision and pQCD calculation**

  ✧ **Soft Scale: p_T probes parton's transverse momentum at the collision point**

- **Mean transverse momentum square:**

$$\langle q_T^2 \rangle \equiv \int dq_T^2\, q_T^2 \frac{d\sigma_{A\to h}}{dx_B\, dQ^2\, dz\, dq_T^2} \Bigg/ \frac{d\sigma_{A\to h}}{dx_B\, dQ^2\, dz}$$

Kinematics and Cross Section

❑ Collision energies:

$$S_{\gamma^*-A} = (q+p)^2 \approx Q^2 \left[\frac{1-x_B}{x_B}\right] \sim \frac{Q^2}{x_B}$$

$$\hat{s}_{\gamma^*-p} = (q+\xi p)^2 \approx Q^2 \left[\frac{\xi}{x_B} - 1\right] \quad \Rightarrow \xi \approx x_B \left[1 + \frac{\hat{s}_{\gamma^*-p}}{Q^2}\right]$$

- small $x_B \neq$ small parton momentum fraction ξ

  for semi-inclusive process

- small ξ requires small q_T^2

❑ Factorized cross section:

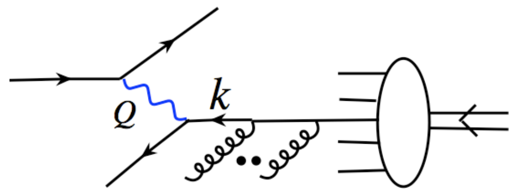
$$\frac{d\sigma_{A\to h}}{dx_B dQ^2 dz dq_T^2} = \sum_{a,c} \int_z^1 \frac{d\eta}{\eta} D_{c\to h}(\eta) \int_{x_B}^1 \frac{d\xi}{\xi} f_{a/A}(\xi) \left[\frac{d\hat{\sigma}_{a\to c}}{d\hat{x} dQ^2 d\hat{z} dq_T^2}\right]$$

with parton level variables:

$$\hat{x} = \frac{Q^2}{2p_a\cdot q} = \frac{x_B}{\xi}, \qquad \hat{z} = \frac{p_c\cdot p_a}{q\cdot p_a} = \frac{z}{\eta}$$

Gluon Shower when q_T is small

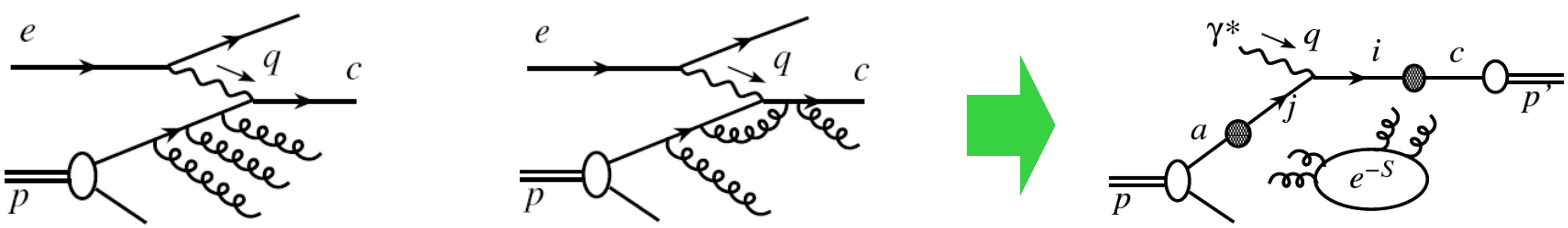
- **When q_T is small, fixed order calculation diverges:**



LO: $\frac{\alpha_s}{q_T^2}\left[a + b\log(Q^2/q_T^2)\right] \rightarrow \infty$ as $q_T^2 \rightarrow 0$

initial-state and final-state soft gluon radiations generate large logarithms: $\frac{1}{q_T^2}\alpha_s^n \log^{2n-1}(Q^2/q_T^2)$

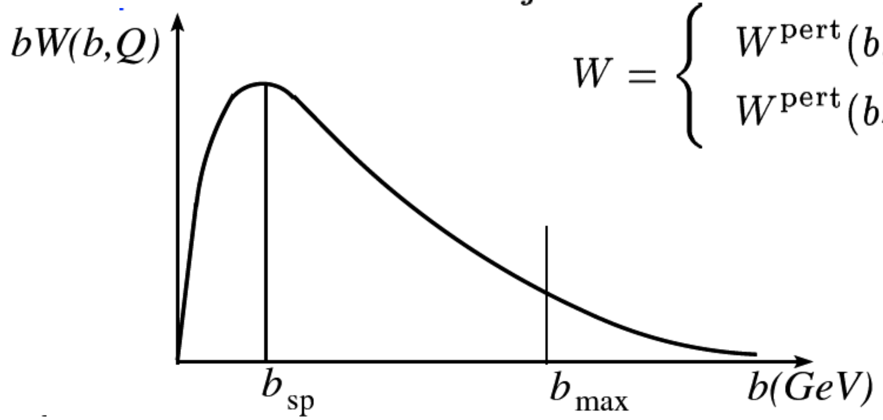
- **QCD resummation:**



Calculation in the b-space

❑ **Resummed x-section:** $$\frac{d\sigma^{(\text{resum})}_{A\to h}}{dx_B\, dQ^2\, dz\, dq_T^2} \propto \int \frac{d^2b}{(2\pi)^2}\, e^{i\vec{q}_T\cdot\vec{b}}\, W(b,x,z,Q)$$

$$W^{\text{pert}}(b,x,z,Q) = \sum_j e_j^2 \left[f_{a/A} \otimes C^{in}_{a\to j}\right]\left[C^{out}_{j\to c} \otimes D_{b\to h}\right] \times e^{-S(b,Q)}$$



$$W = \begin{cases} W^{\text{pert}}(b,x,z,Q) & b \le b_{max} \\ W^{\text{pert}}(b_{max},x,z,Q)\, F^{NP}(b,Q;b_{max}) & b > b_{max} \end{cases}$$

❑ **Features:**

– Sudakov form factor $\to\ b_{sp} \propto (\frac{\Lambda_{\text{QCD}}}{Q})^{\lambda},\ \lambda \sim 0.5$

– evolution of $f_{a/A}$ and $D_{c\to h}$ also moves b_{sp}

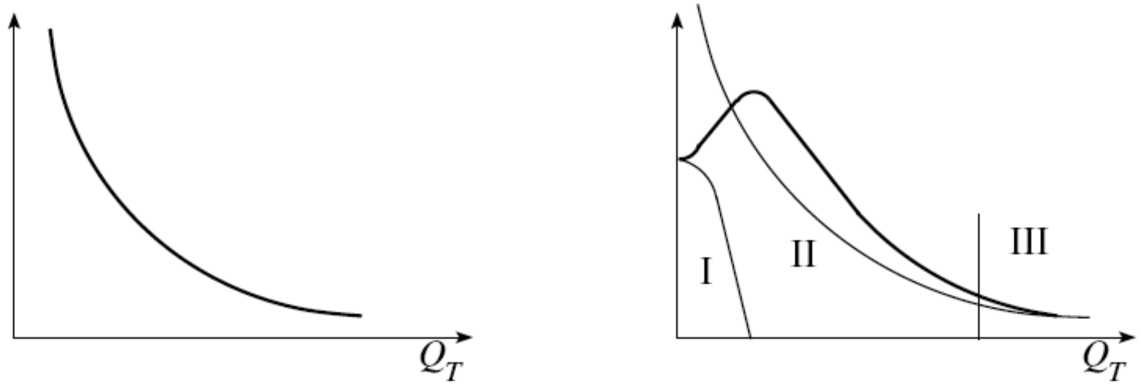
smaller $\xi \Rightarrow \mu\frac{\partial}{\partial\mu} f_{a/A}(\xi) > 0 \Rightarrow$ lower b_{sp}

– parton recombination reduces the evolution

$\Rightarrow$ moves b_{sp} to the right $\Rightarrow$ more Gaussian like

Resummed Q_T Distribution

❑ Remove the divergence:



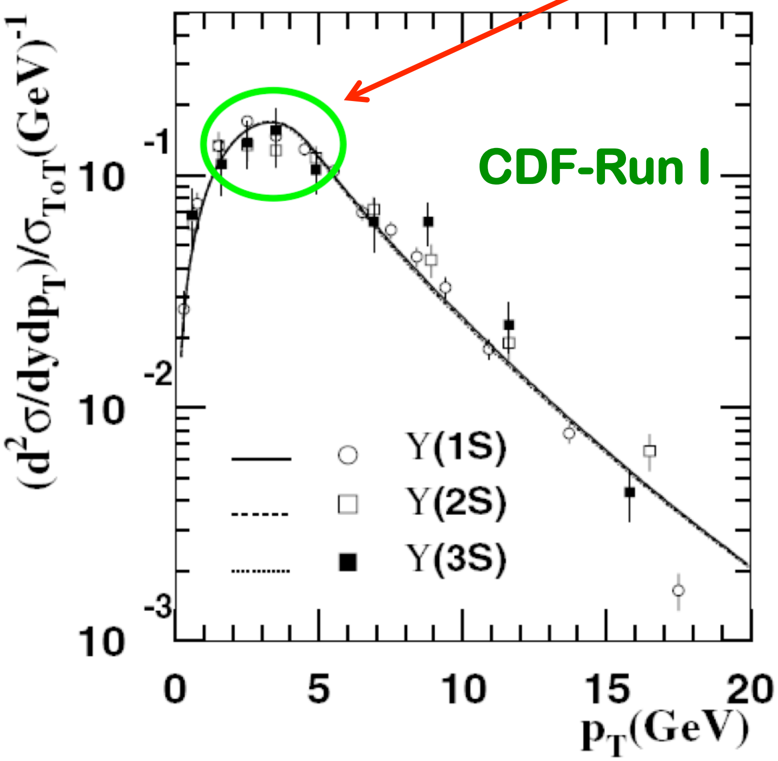
❑ Features:

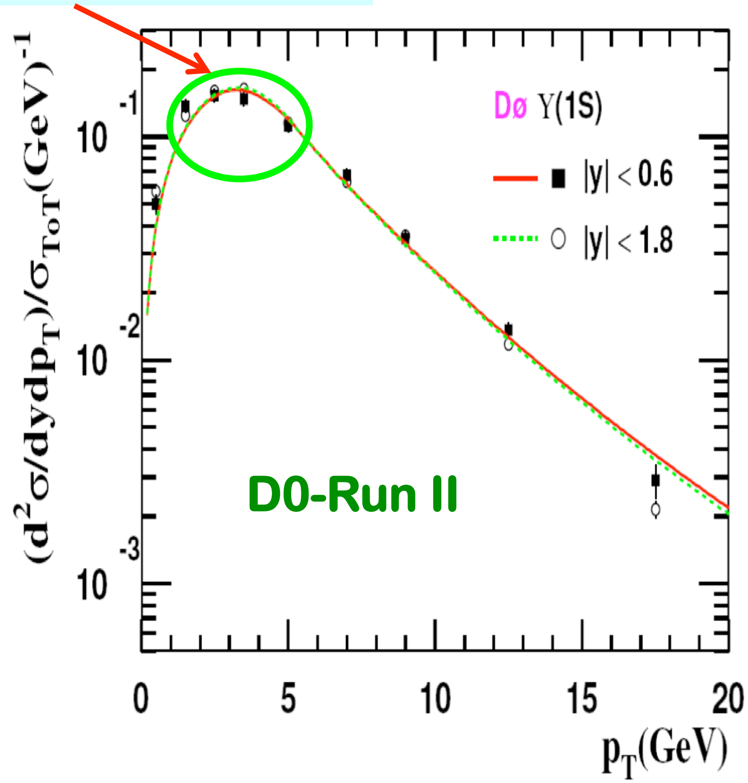
- (I): dominated by intrinsic k_T (Gaussian type)
- (II): pQCD soft-gluon resummation ($q_T \leq Q$)
- (III): pQCD fixed order calculation ($q_T \sim Q$)
- relative size of three regions depend on Q^2 and S
- large Q^2 and large $S \Rightarrow$ smaller region (I)
- smaller $Q^2 \rightarrow$ smaller logs $\rightarrow$ smaller region (II)

Works for heavy boson production

- Upsilon at Tevatron:

Dominated by perturbative small-b contribution in its Fourier conjugate space

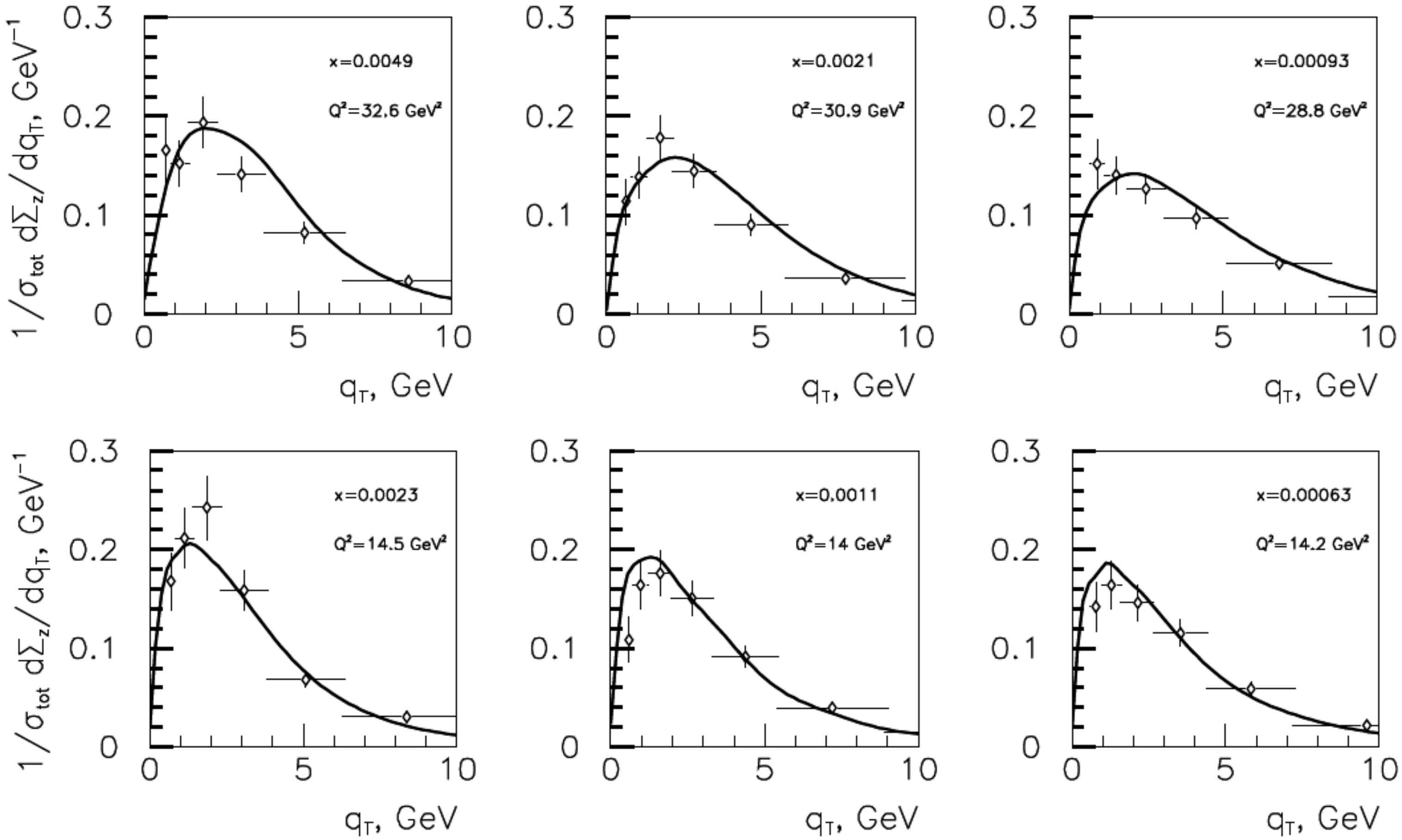




- Works better for W/Z, also work for Drell-Yan, …

Also work for HERA data

$$\sum_h \int dz\, z \frac{d\sigma_{A\to h}}{dx_B\, dQ^2\, dz\, dq_T^2}$$

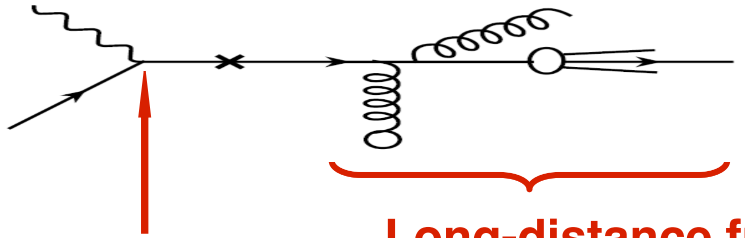


Nadolsky, et al, 1999, 2001

Broadening in Cold Nuclear Matter

Guo & Wang PRL 2000, …
Wang & Wang, PRL 2002, …

- **Induced radiation – energy lose:**



- **Transverse momentum broadening:**

$$\Delta\langle q_T^2\rangle \equiv \langle q_T^2\rangle^{hA} - \langle q_T^2\rangle^{hN} = \left(\frac{4\pi^2\alpha_s}{3}\right)\ \lambda^2\ A^{1/3}$$

Guo, PRD 1998

– increases the effective “intrinsic k_T”

– reduces the phase space for soft-gluon shower

$\Rightarrow$ broadening the q_T distribution

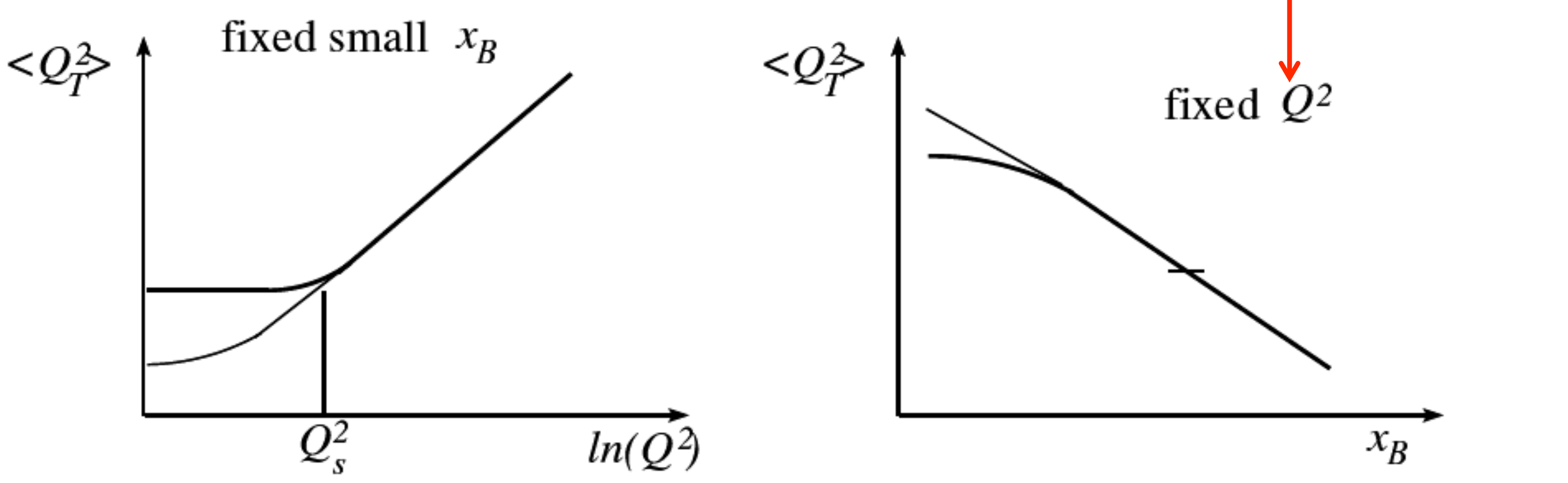
Probe the Saturation

For a fixed A!

- **At small x_B (large S_{γ^*-A}), large phase space for shower Q_T-distribution could be calculable at low Q_T**

- **Saturation stops the evolution:**

$$\Rightarrow \mu\frac{\partial}{\partial\mu} f_{a/A}(\xi) \rightarrow 0 \qquad \Rightarrow \text{increase } b_{sp}$$



Same measurement for a larger A!

Summary

- Semi-inclusive DIS in ep and eA provide clean multiple scale observables
  – probe parton's transverse momentum scale at hard collision

- pQCD resummation technique should be valid for calculating the q_T distribution if x_B is small (**$S_{\gamma^*\text{-}A}$** Large)

  Without saturation, $\langle q_T^2 \rangle$ grows as $\log(1/x_B)$ increases, due to the phase space increases and large evolution rate of PDF at small ξ

  With saturation, PDF stop growing, $\langle q_T^2 \rangle$ deviates from the pQCD resummed prediction

- **A good place to see saturation:**

  Decreases x_B while keeping a moderate Q^2

Backup slides