Unintegrated gluon densities and saturation in heavy quark production at HERA and LHC

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HERA - LHC, Heavy Quarks WG, DESY, 2 June 2004

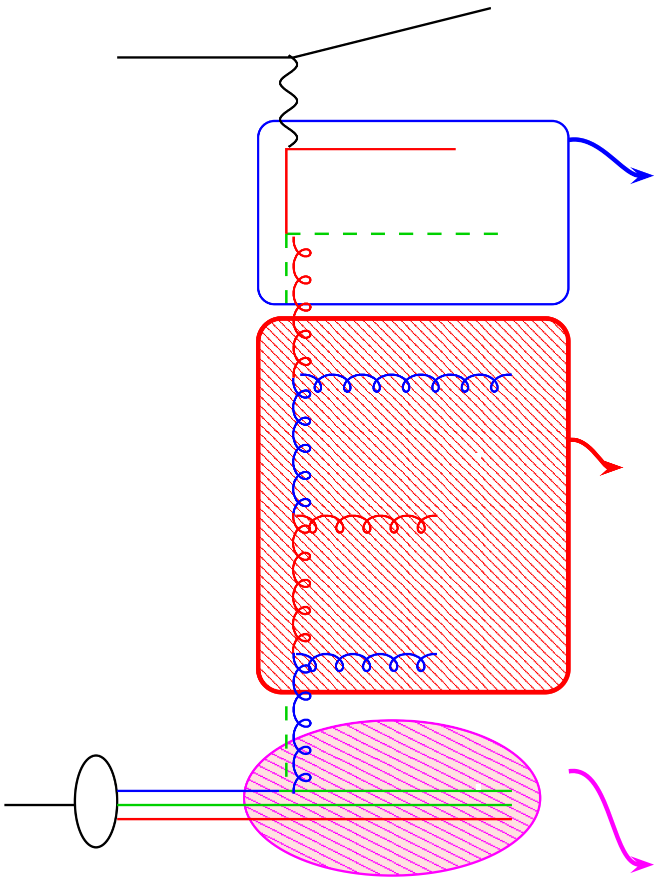
- parton evolution
  - separate initial condition
- saturation
  - soft region
  - perturbative region
- measure saturation
  - soft region: HERA
  - pert. region: LHC
- conclusion

Basic idea - k_t factorisation

CCFM

CCFM (one loop)

- **angular ordering**

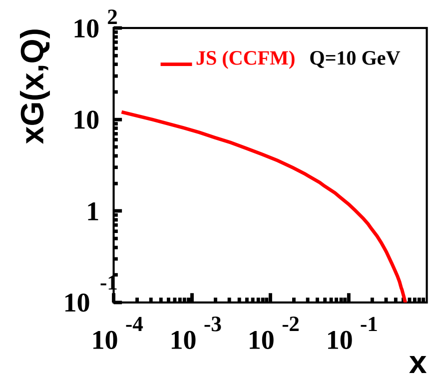


BGF matrix element
off mass shell

evolution of parton cascade
with DGLAP splitting fct.

$$\tilde{P} = \bar{\alpha}_s \left(\frac{1}{1-z} + \frac{1}{z} \right)$$

initial distribution:



$$\sigma(ep \to e' q\bar{q}) = \int \frac{dy}{y} d^2Q \frac{dx_g}{x_g} \int d^2k_t \hat{\sigma}(\hat{s}, k_t, Q) x_g \mathcal{A}(x_g, k_t, \bar{q})$$

with $\int d^2k_t x_g \mathcal{A}(x_g, k_t, \bar{q}) \simeq x_g G(x_g, Q^2)$

Basic idea - k_t factorisation

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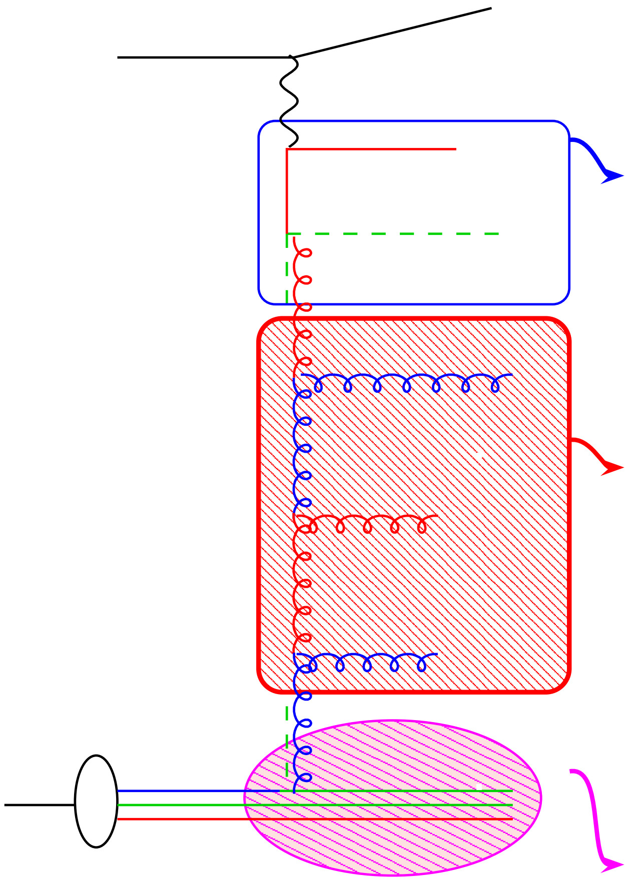


BGF matrix element
off mass shell

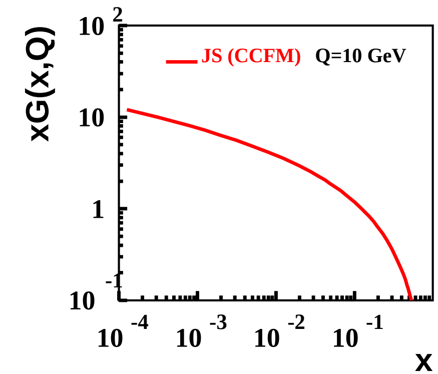
evolution of parton cascade
with CCFM splitting fct.

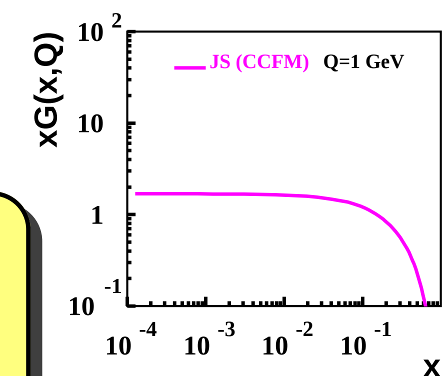
$$\tilde{P} = \bar{\alpha}_s \left(\frac{1}{1-z} + \frac{1}{z} \Delta_n{}^s \right)$$

initial distribution: flat

CCFM (all loops)

- **angular ordering (instead of q_t ordering)**
- **Δ_{ns} (non - Sudakov)**





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with $\int d^2k_t x_g \mathcal{A}(x_g, k_t, \bar{q}) \simeq x_g G(x_g, Q^2)$

Evolution equation – Integral form

integral form: (Ellis, Stirling, Webber: QCD and Collider Physics)

$$\mathcal{A}(x,\bar{q}) = \mathcal{A}(x,q_0)\Delta_s(\bar{q},q_0) + \int \frac{dz}{z} \int \frac{d^2q}{q^2} \cdot \Delta_s(\bar{q},q)\tilde{P}(z,\ldots)\mathcal{A}\left(\frac{x}{z},q\right)$$

differential form (DGLAP)

$$\bar{q}^2 \frac{d}{d\bar{q}^2} \frac{x\mathcal{A}(x,\bar{q})}{\Delta_s(\bar{q},Q_0)} = \int dz\, \frac{\tilde{P}(z,\ldots)}{\Delta_s(\bar{q},Q_0)}\, x'\mathcal{A}(x',\bar{q})$$

CCFM equation: small and large x

$$\mathcal{A}(x,k_t,\bar{q}) = \mathcal{A}_0(x,k_t)\Delta_s(\bar{q},Q_0) + \int \frac{dz}{z} \int \frac{d^2q}{\pi q^2}\Theta(\bar{q}-zq)\cdot\Delta_s(\bar{q},zq)\tilde{P}(z,q,k_t)\mathcal{A}\left(\frac{x}{z},k_t',q\right)$$

CCFM Splitting fct: $\tilde{P}(z,q,k_t) = \frac{\bar{\alpha}_s(q(1-z))}{1-z} + \frac{\bar{\alpha}_s(k_t)}{z}\Delta_{\text{ns}}(z,q,k_t)$

Sudakov $\Delta_s(a,b)$: **probability for no radiation in $[a,b]$**

angular ordering: $\bar{q} > z_n q_n, q_n > z_{n-1}q_{n_1}, ..., q_1 > Q_0$

small x

- **BFKL limit ($z \to 0$)**
- **angular ordering**

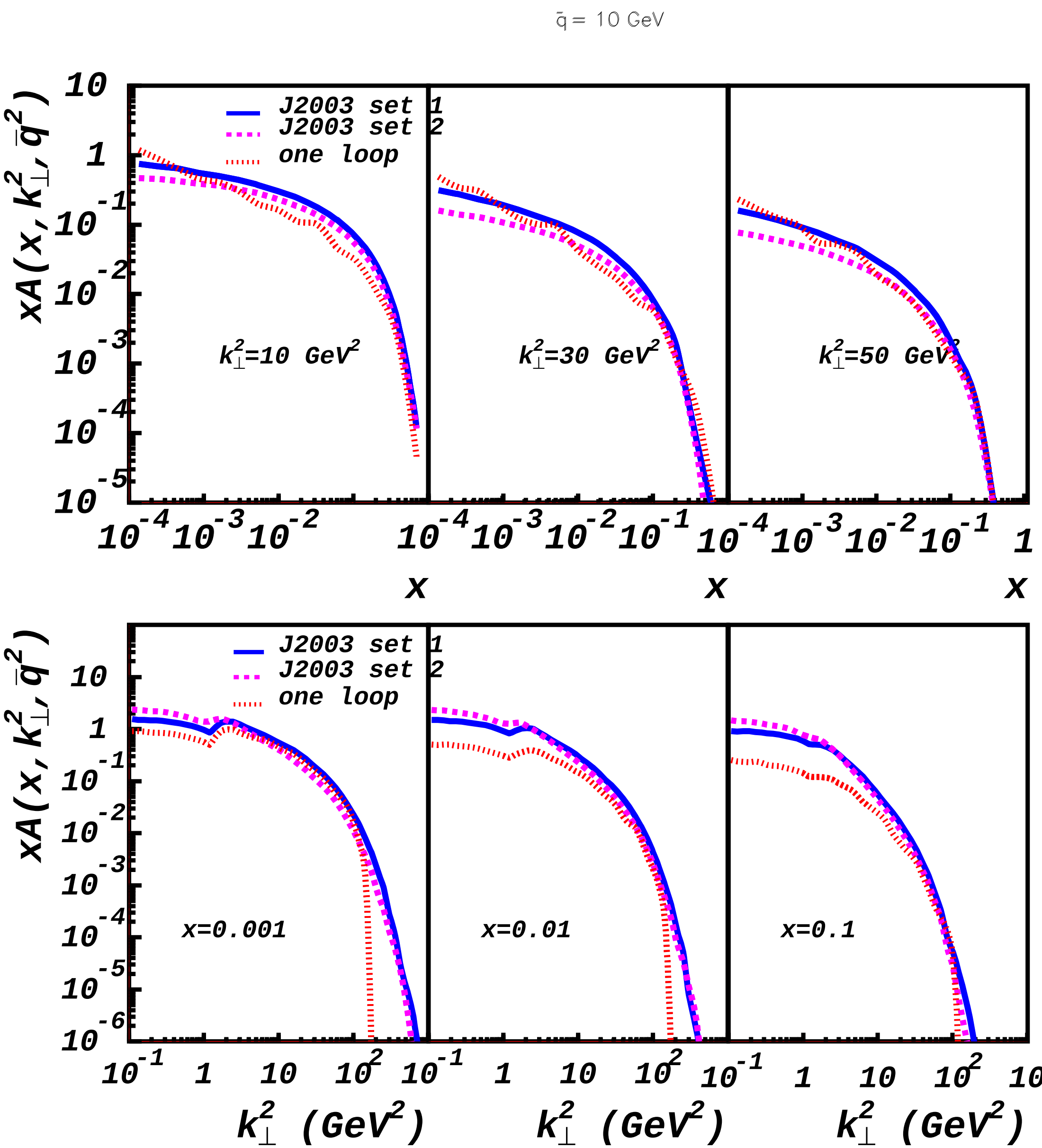
$\to$ **no restriction on q_i**

large x

- **DGLAP limit ($z \gg 0$)**
- **DGLAP splitting fct $\tilde{P}$ with $\Delta_{\text{ns}} = 1$**
- **angular ordering $\to$ q_i ordering**

Un-integrated gluon density

- use H1 + ZEUS F_2 data (from 94 and 96-97)
- fit for $x < 0.01$ $Q^2 > 3.5$ GeV^2
- fit normalization in initial pdf $x\mathcal{A}_0 = N(1-x)^4$
- fit collinear cut Q_0 and starting scale



- **treatment of soft region**
  no k_t ordering
  ☛ diffusion into soft
- **full splitting function**
  (including non-sing. terms)

- **all-loop splitting fct (CCFM)**
  (including non-Sudakov)
- **one-loop splitting fct (DGLAP)**
  steeper rise towards small x

Effect of initial condition — small k_t - region

$$\mathcal{A}(x,k_t,\bar{q}) = \mathcal{A}_0(x,k_t)\Delta_s(\bar{q},Q_0) + \int \frac{dz}{z}\frac{d^2q}{q^2}\Delta_s(\bar{q},zq)\cdot\tilde{P}(z,\ldots)\mathcal{A}\left(\frac{x}{z},k_t',q\right)$$

Effect of initial condition — small k_t - region

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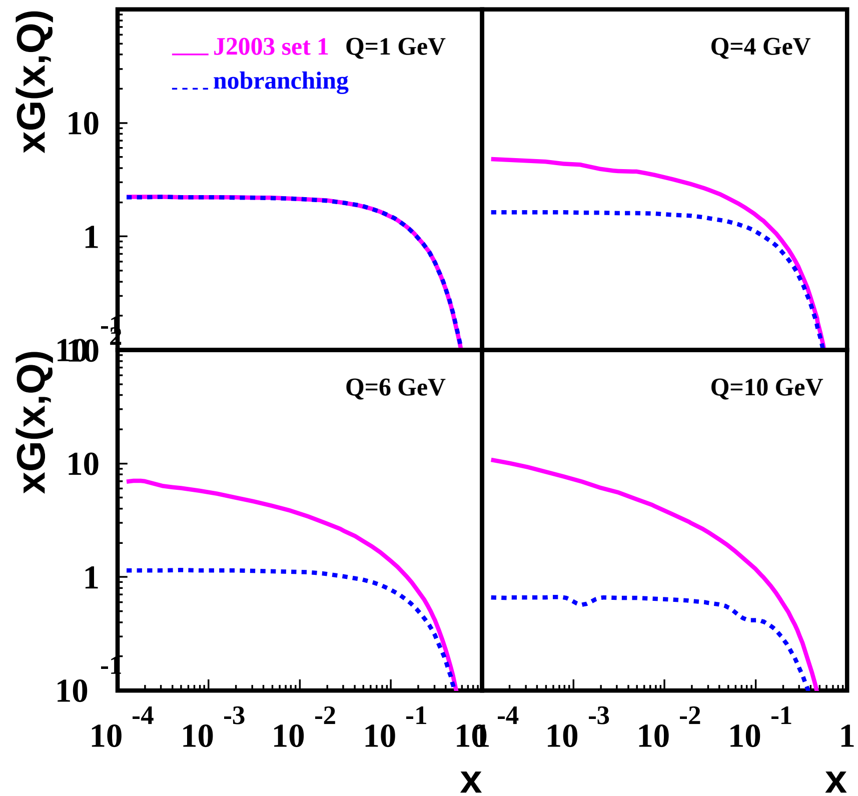
integrated pdf:
effect of evolution and initial condition
not clearly separated ...



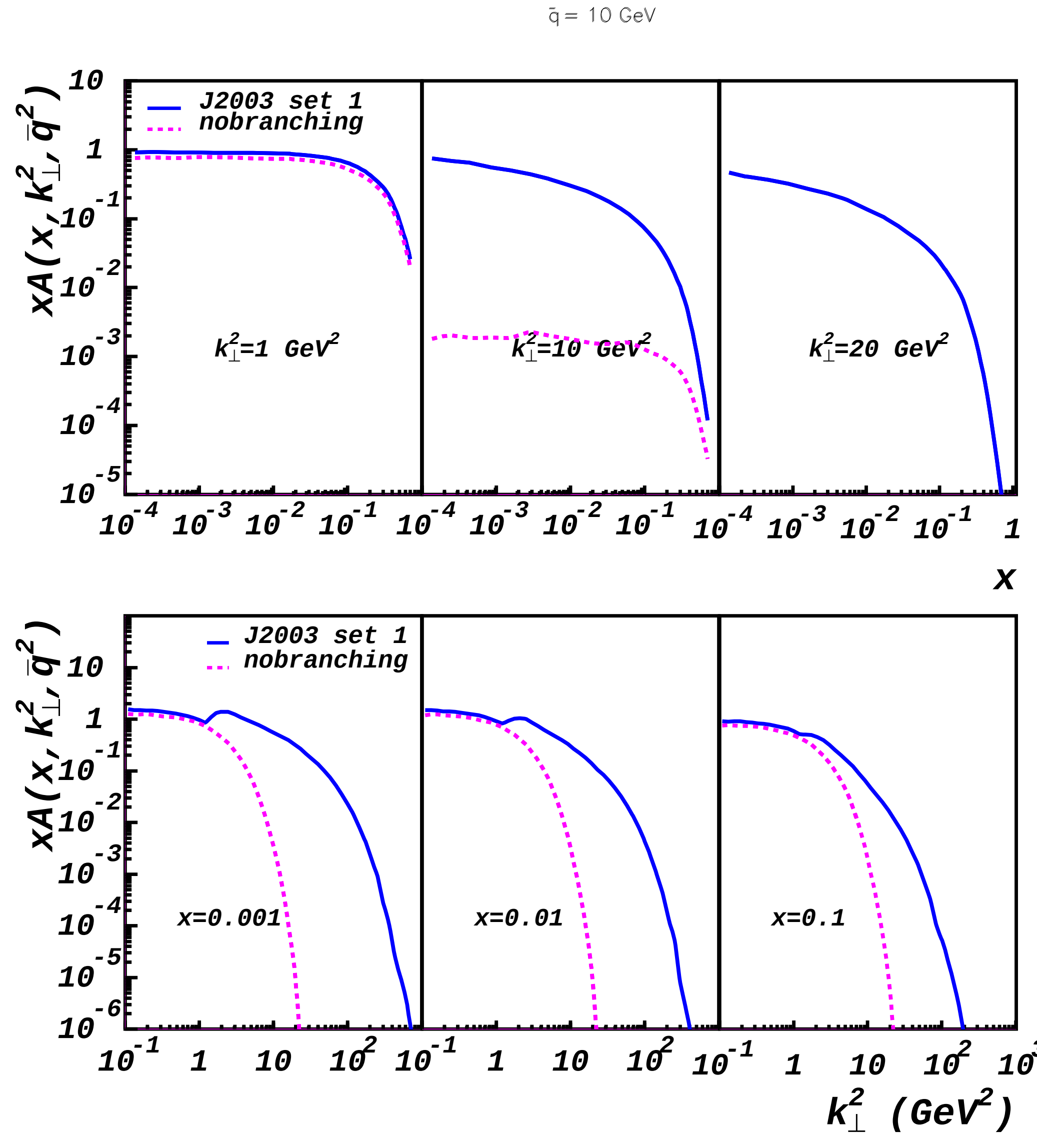
where is:

- **small k_t region ?**
- **saturation region ?**

Effect of initial condition — small k_t - region

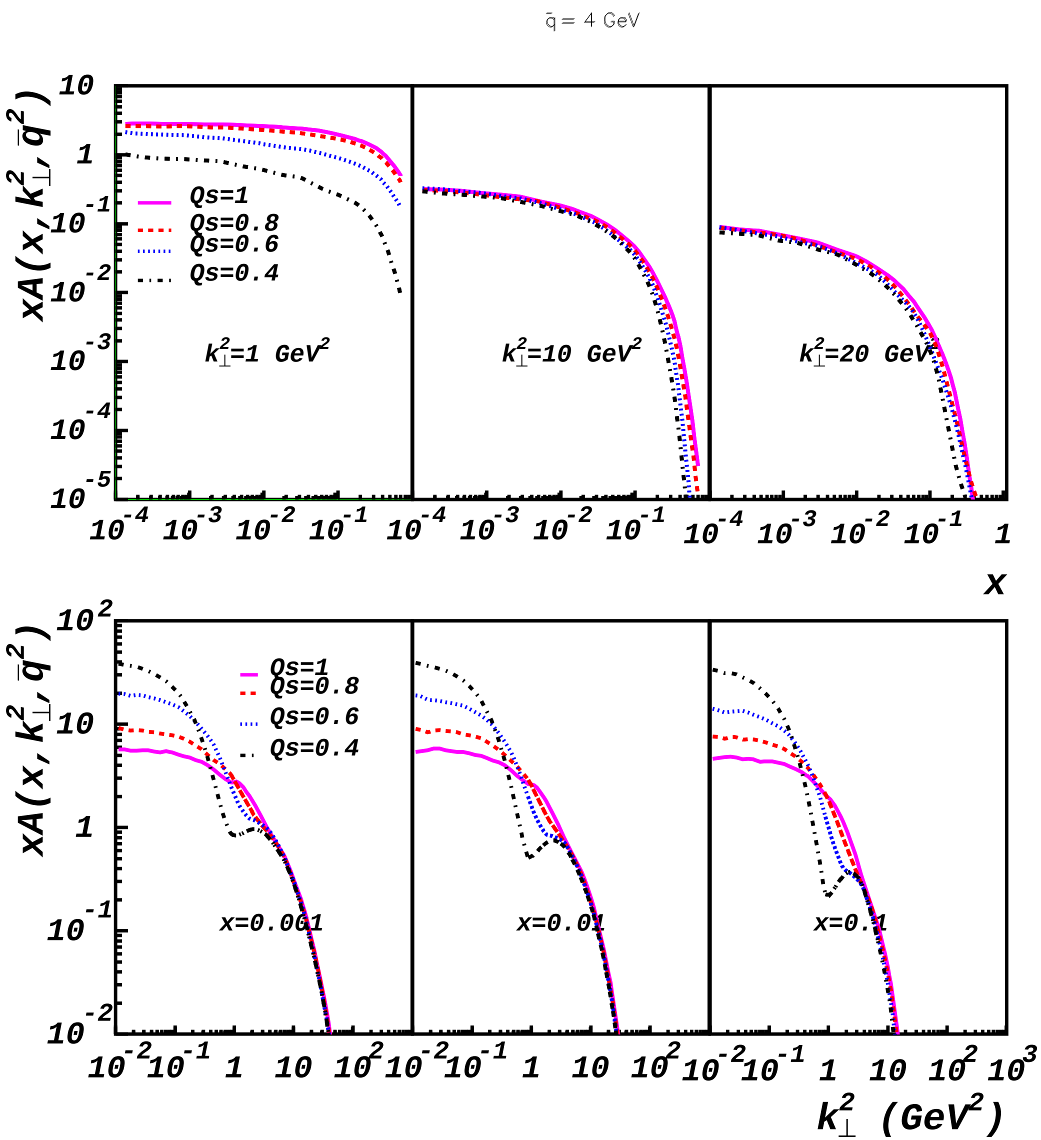
$$\mathcal{A}(x,k_t,\bar{q}) = \mathcal{A}_0(x,k_t)\Delta_s(\bar{q},Q_0) + \int \frac{dz}{z}\frac{d^2q}{q^2}\Delta_s(\bar{q},zq)\cdot\tilde{P}(z,\ldots)\mathcal{A}\left(\frac{x}{z},k_t',q\right)$$

Advantage of uPDF:
initial condition clearly seen
in small k_t region
even at large scales $\bar{q}$

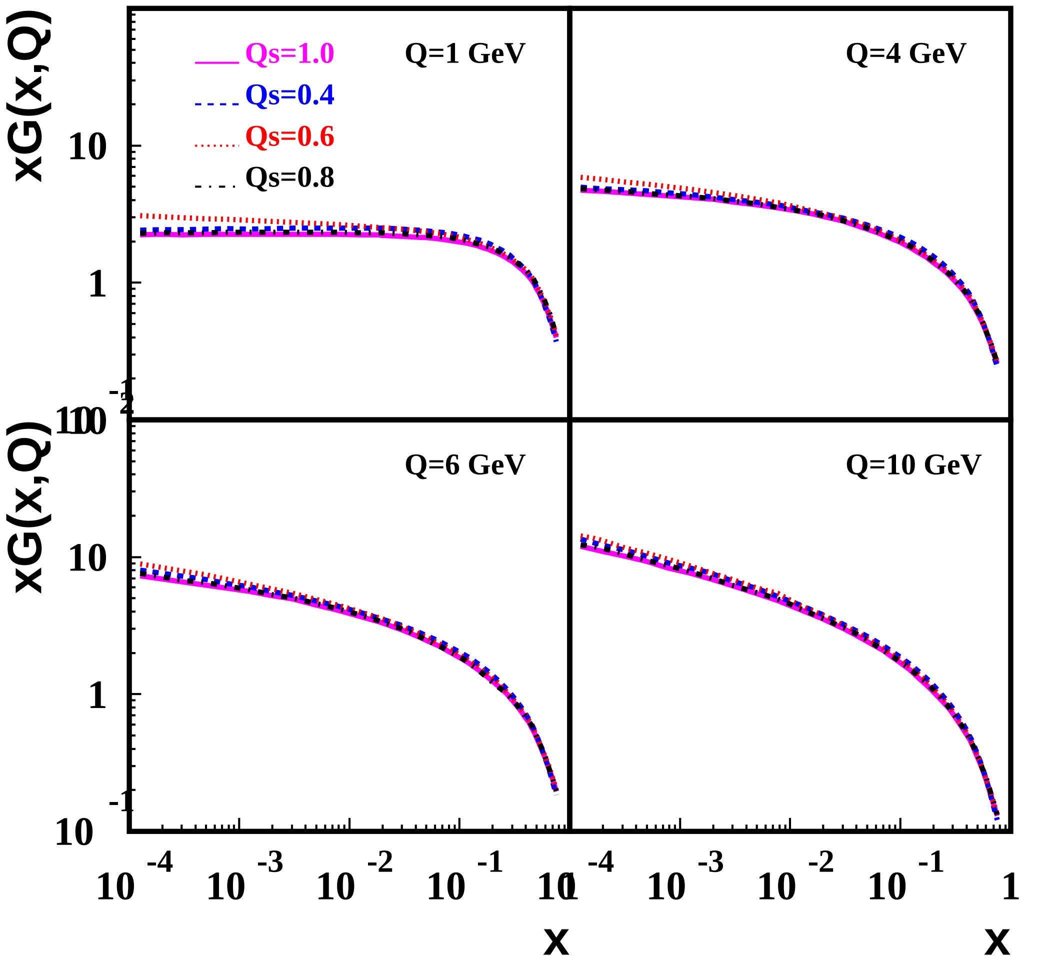


Effect of intrinsic k_t - small k_t - region

- $\mathcal{A}_0(x,k_t) = N x^a (1-x)^b \cdot \exp\left(-k_t^2/{Q_s}^2\right)$
- **different choices for Q_s**
- **matching with evolution**
- **all describe F_2 with similar $\chi^2 \sim 1$**
- **large k_t tail of intrinsic k_t**
- **to be truncated ?**



CCFM unintegrated gluon density - integrated -



CCFM gluon integrated over k_t

$$\int_0^{\bar{q}} dk_t^2 x\mathcal{A}(x, k_t, \bar{q}) = xG(x, \bar{q})$$

- difference in intrinsic k_t **hardly visible**

integrated gluon density:

☛ not sensitive to intrinsic k_t

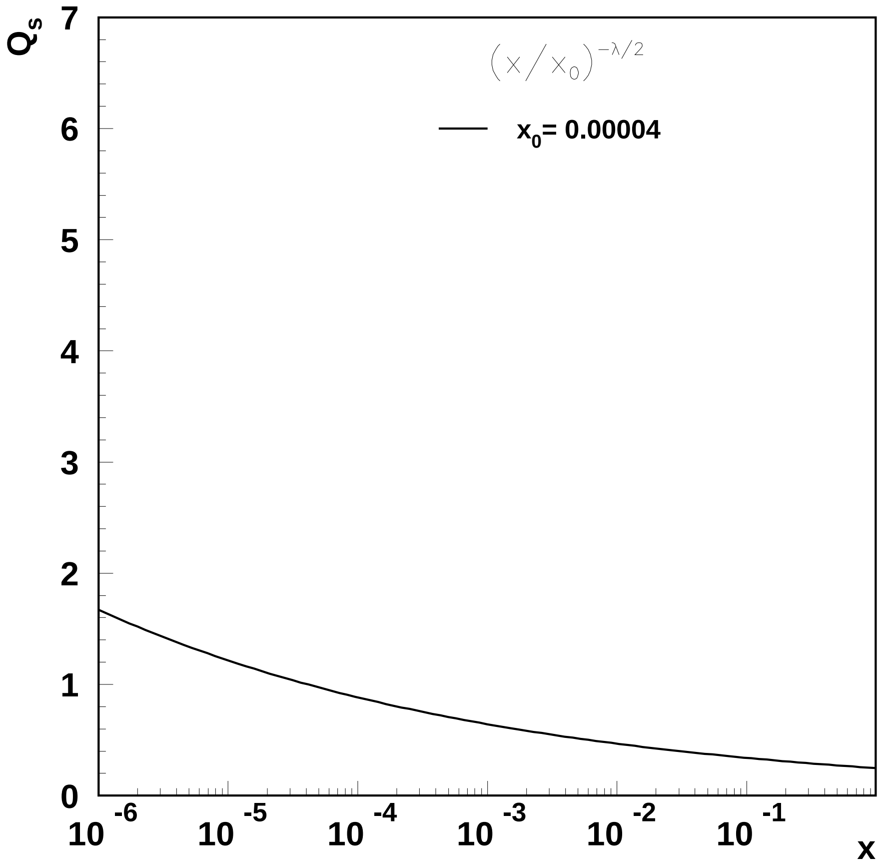
Goto unintegrated pdfs !!!

Saturation: soft (small k_t) region

- saturation scale acc. Golec-Biernat Wüsthoff

  $k_{t\ cut} = \left(\frac{x}{x_0}\right)^{-\frac{\lambda}{2}}$

  $x_0 = 0.00004$ **and** $\lambda = 0.28$
- fix free parameters !!!
- at HERA mainly soft region...



Saturation: soft (small k_t) region

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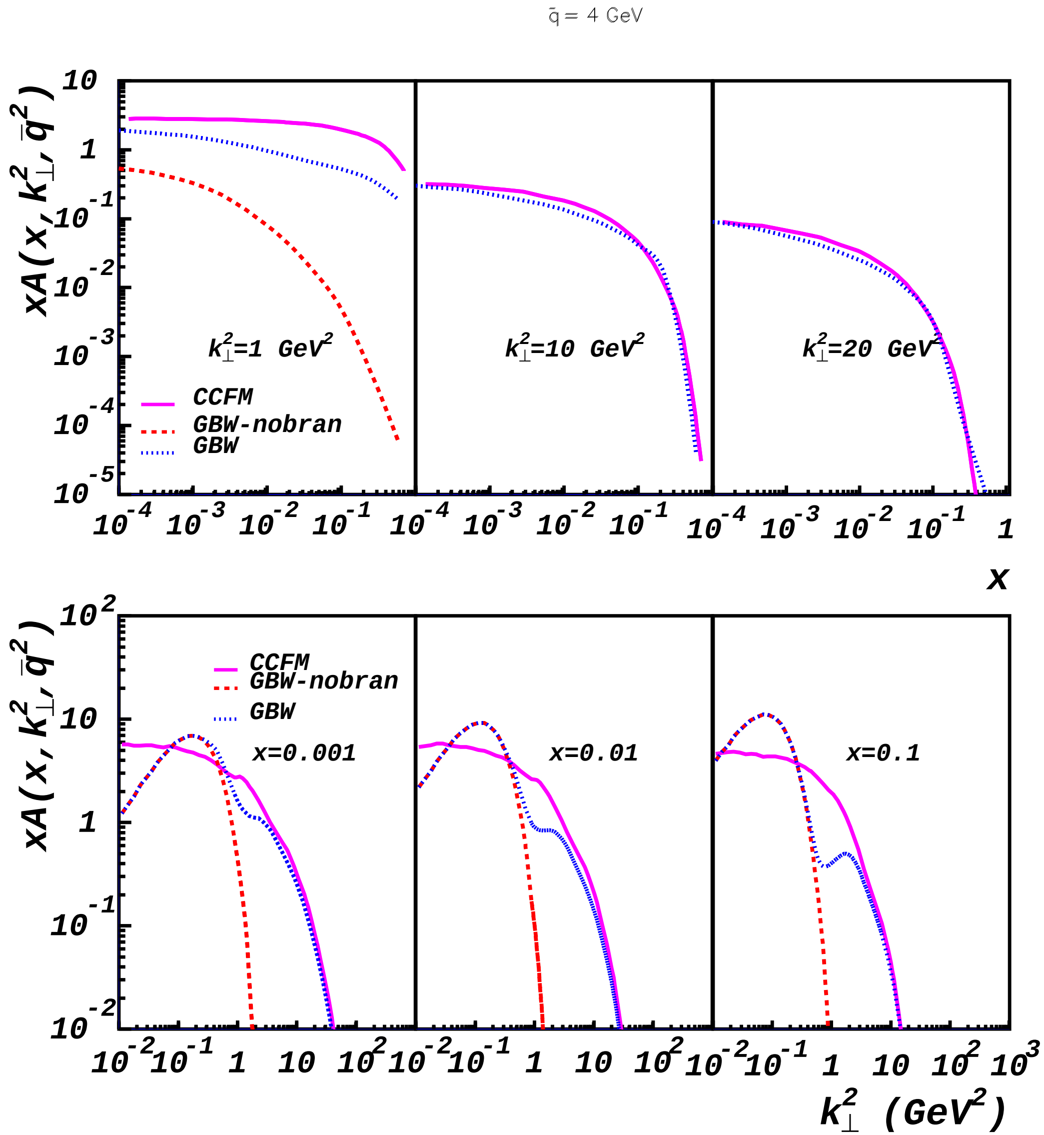
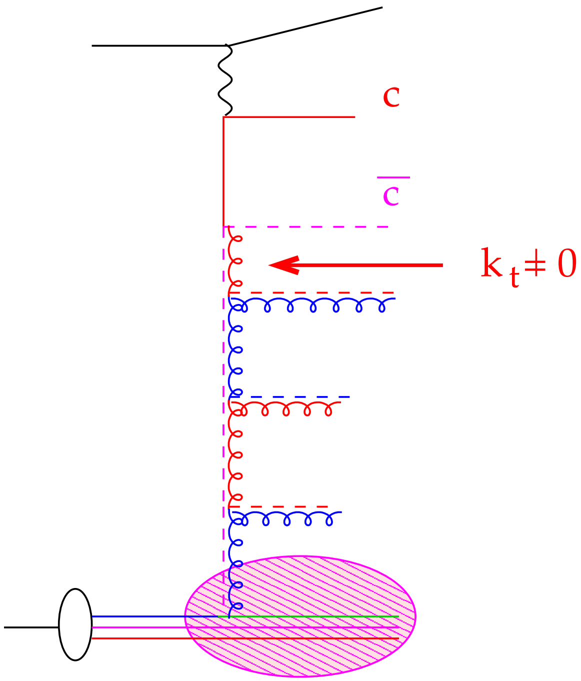
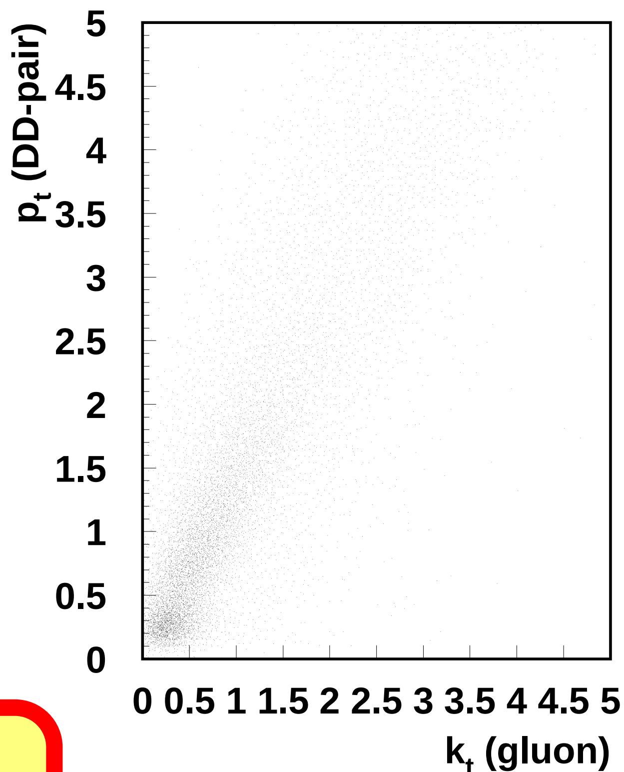
  $$k_{t\ cut} = \left(\frac{x}{x_0}\right)^{-\frac{\lambda}{2}}$$

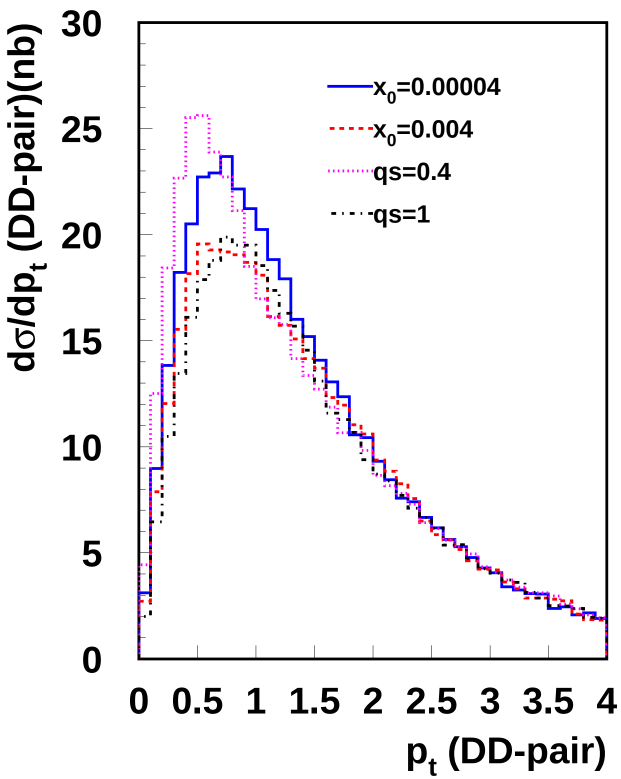
  $x_0 = 0.00004$ **and** $\lambda = 0.28$
- **fix free parameters !!!**
- **at HERA mainly soft region...**
- **saturation in initial condition**
- **in non-perturbative region during evolution with CCFM/BFKL**



Saturation in soft (small k_t) region in $c\bar{c}$ at HERA





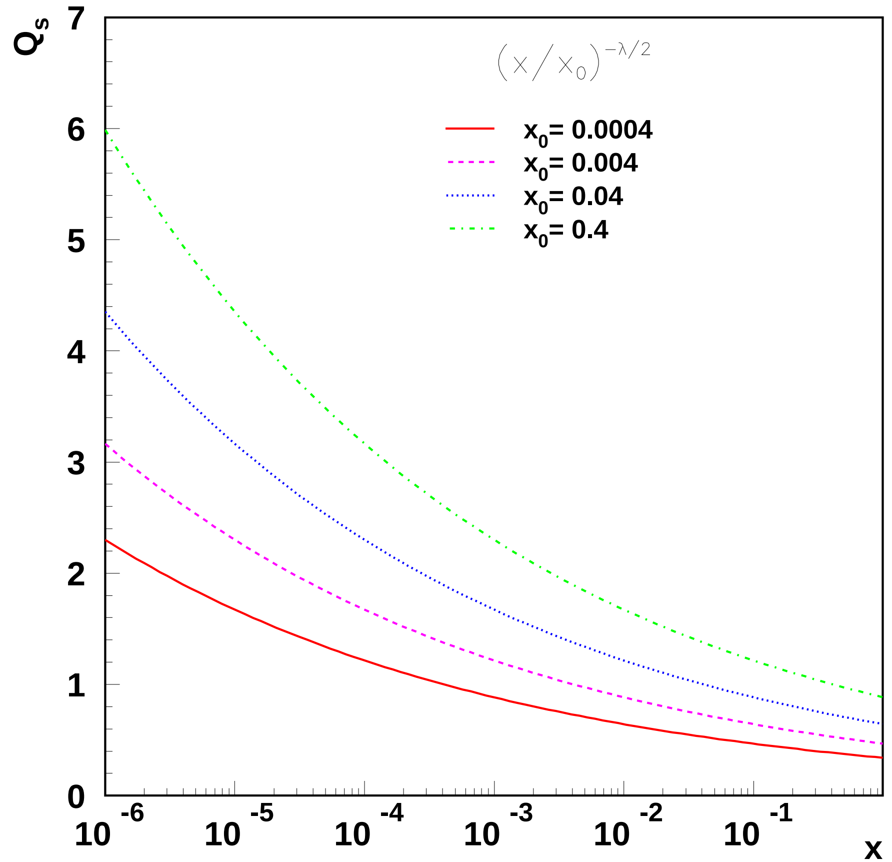


- reconstruct $k_t = p_\perp^c + p_\perp^{\bar{c}} - p_\perp^\gamma$
- in γp CMS: $p_t(D\bar{D})$

☛ sensitive to small k_t
only visible in k_t factorisation

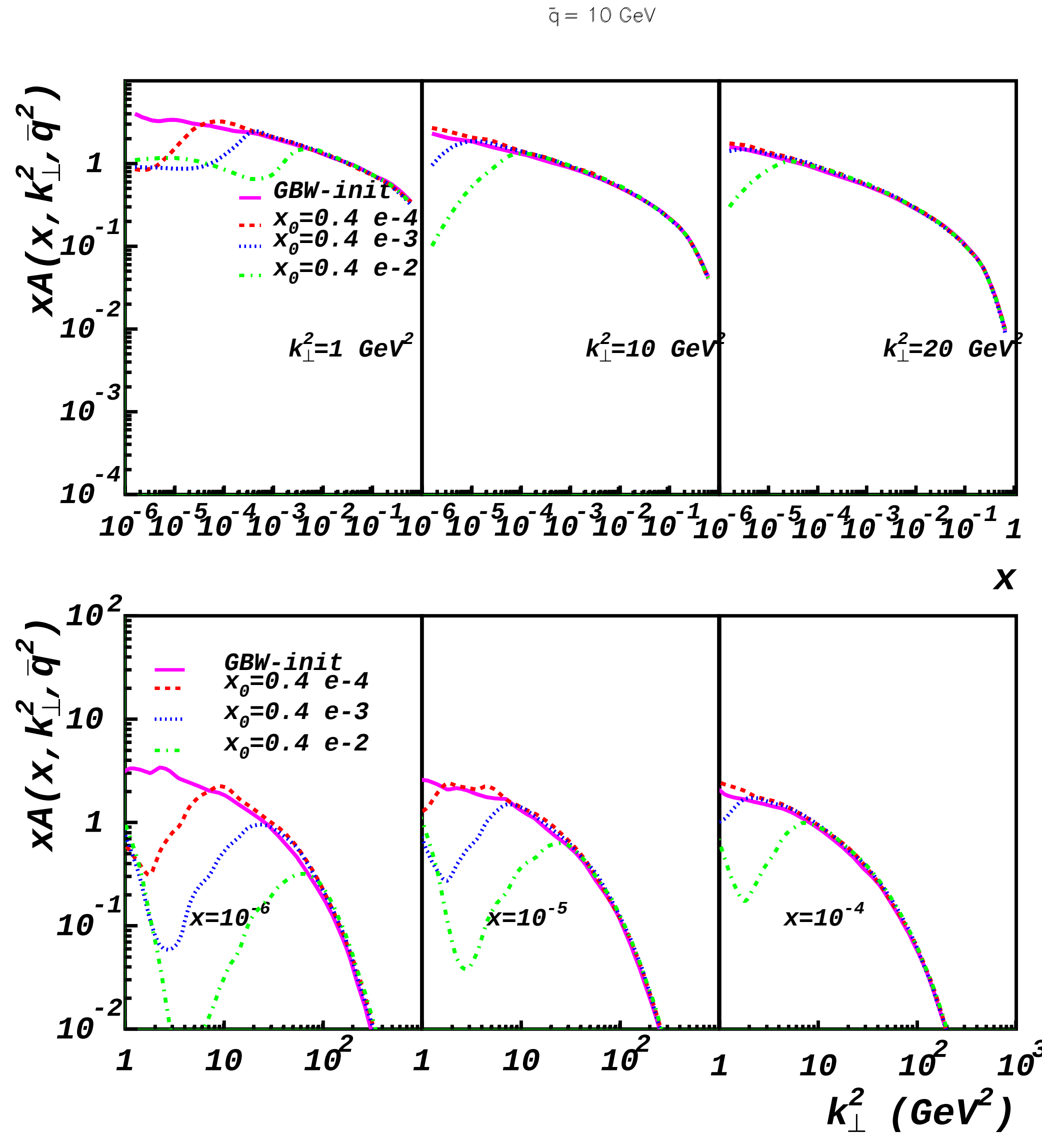
Saturation: perturbative (medium k_t) region

- during evolution with CCFM/BFKL, k_t can become smaller Q_s
  - recombination, non-linear evolution
- which Q_s ?
  - fit parameters from HERA !

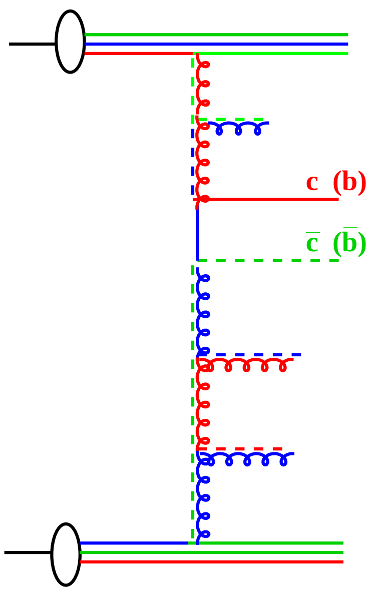


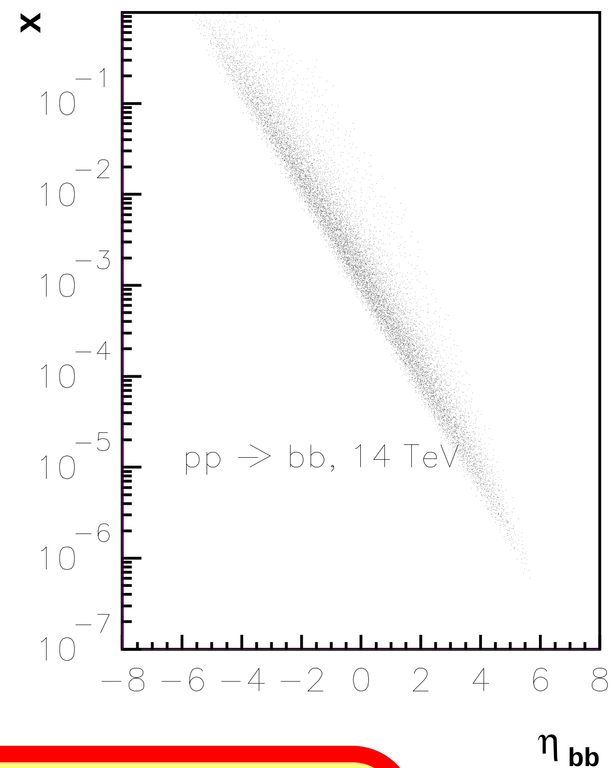
Saturation: perturbative (medium k_t) region

- during evolution with CCFM/BFKL, k_t can become smaller Q_s
  - recombination, non-linear evolution
- which Q_s ?
  - fit parameters from HERA !
- strong dependence on Q_s !
- sizeable effects ...
  visible in u-PDF only...



Perturbative Saturation in $pp \to b\bar{b}$



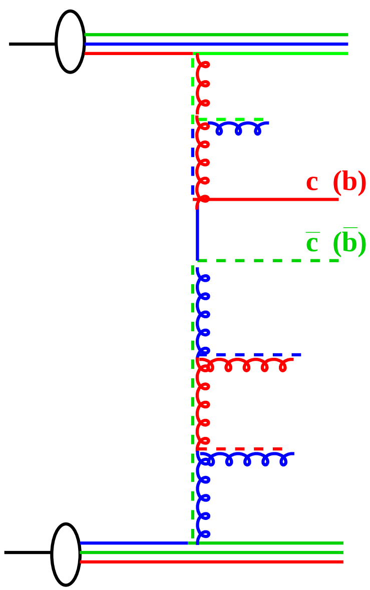


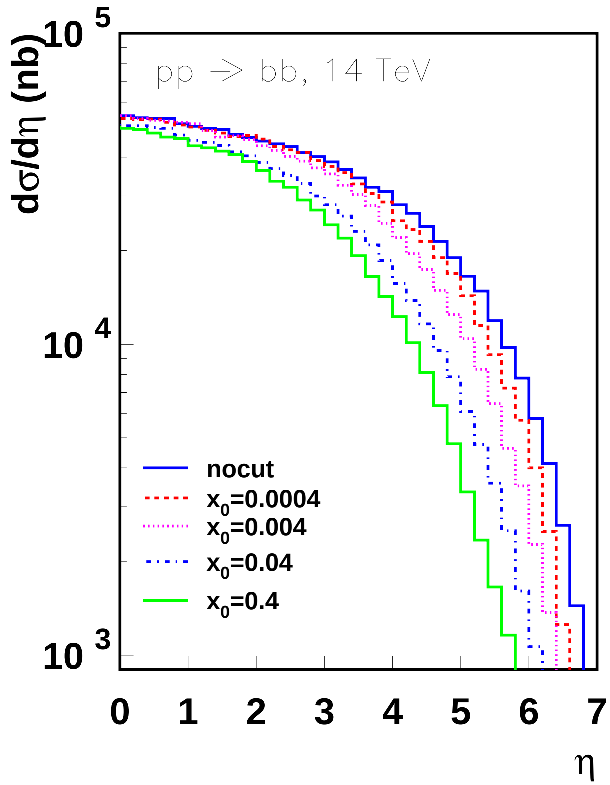
for perturbative saturation, need small $x \sim 10^{-5}$

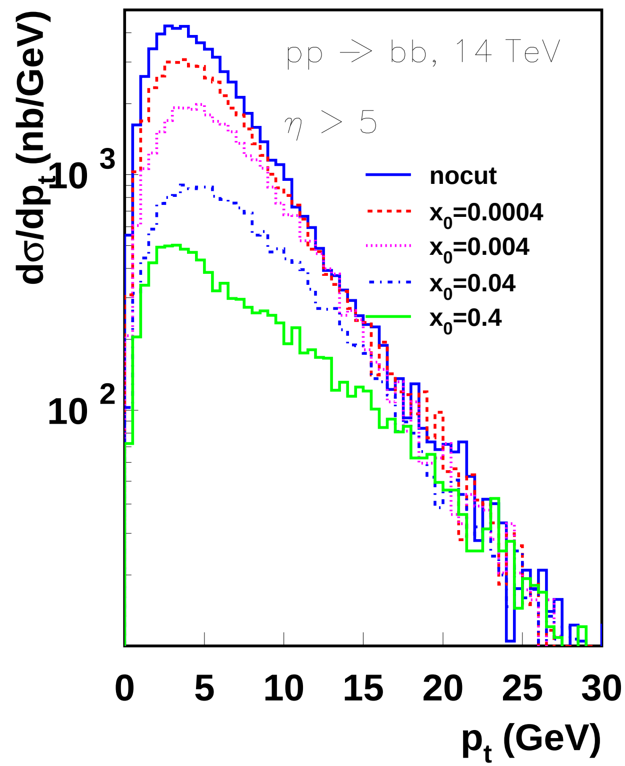
look for bottom production as fct of η

goto forward region

Perturbative Saturation in $pp \to b\bar{b}$







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look for bottom production as fct of η

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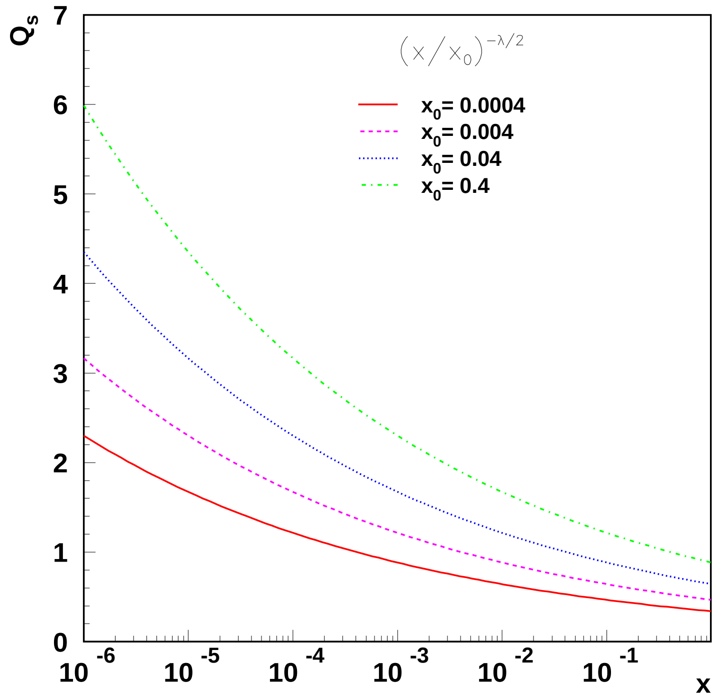
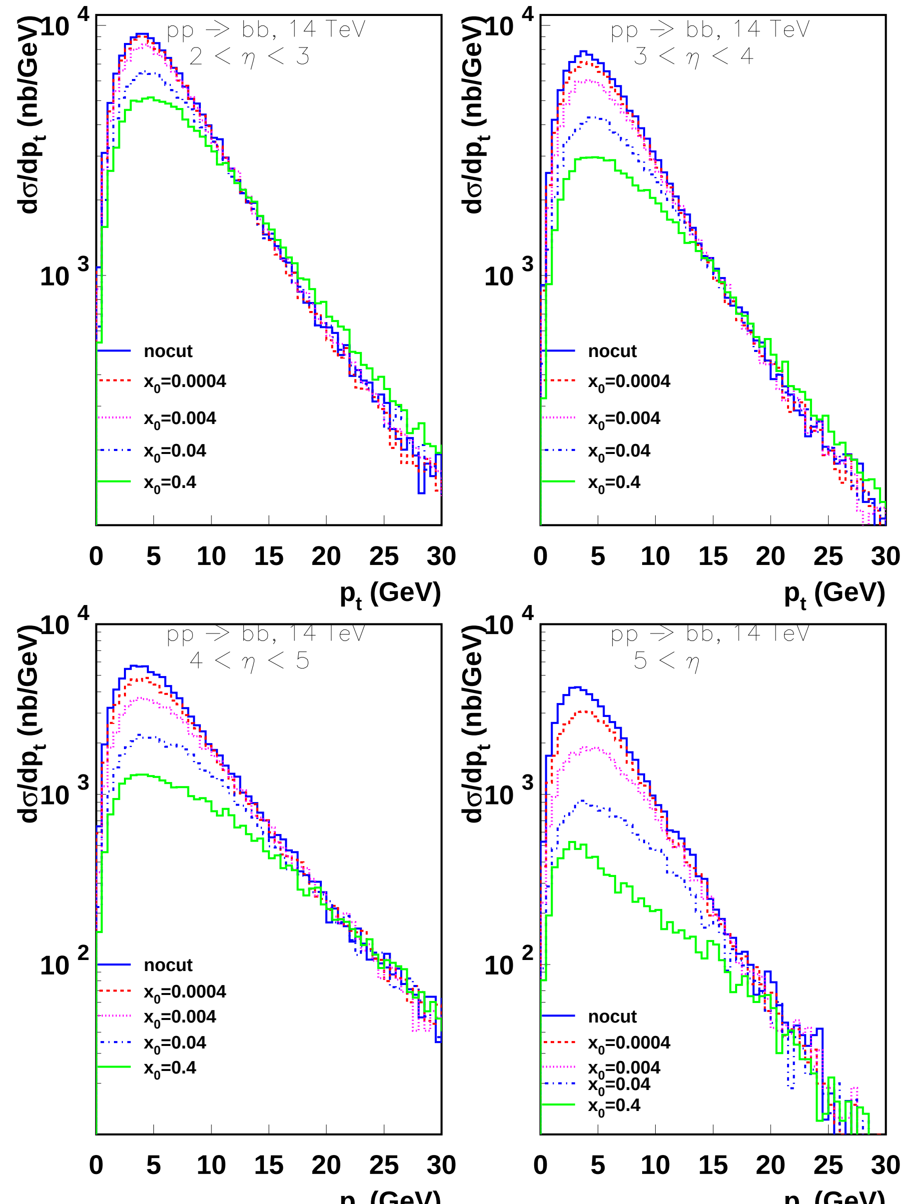
Factors of 5-10 in xsection

Perturbative Saturation in $pp \to b\bar{b}$





saturation effects
even in central η visible

The Beginning, Not the End

- k_t - factorization: the tool for stduy saturation
- study intrinsic k_t distribution
- study soft saturation region at HERA with charm
  - only possible with k_t - factorization
  - coll. factorization NOT applicable
- study perturbative saturation region at LHC
  - visible effects at small x
  - forward region at LHC
  - significant effects in cross section
  - only estimate in k_t - factorization

Be aware of saturation when looking for Higgs ....