Unintegrated pdfs in CCFM

H. Jung, DESY

DIS, Strbské Pleso, 2004

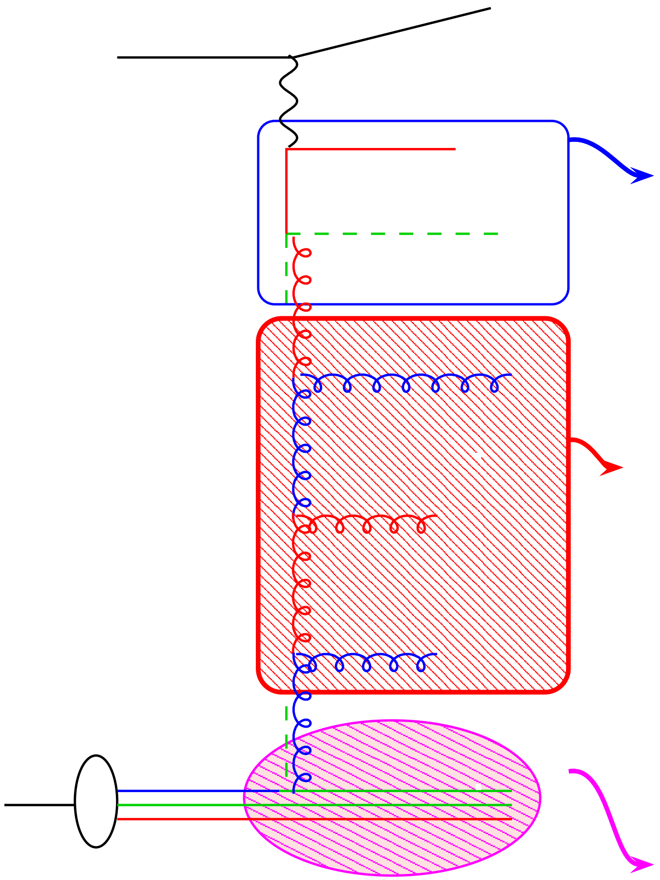
- CCFM equation
  one-loop — all-loops
  collinear- vrs k_t-factorisation
- fits to F_2
  fit initial condition for one-loop — all-loops
  sensitivity to starting scale
  choice of factorsiation scale
  small k_t-behavior
- application to LHC
- conclusion

Basic idea - Collinear factorization

CCFM

CCFM (one loop)

- **angular ordering**



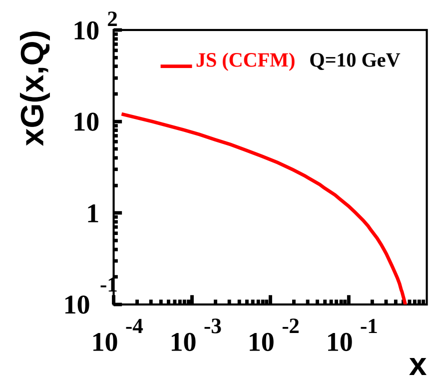
BGF matrix element

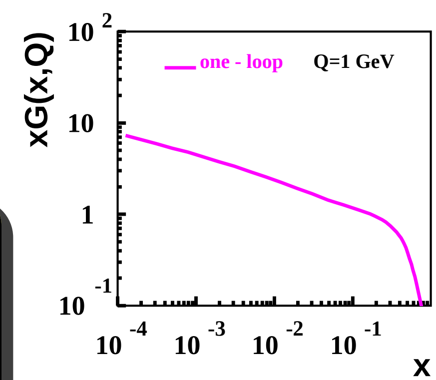
on mass shell

evolution of parton cascade
with DGLAP splitting fct.

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

initial distribution: steep



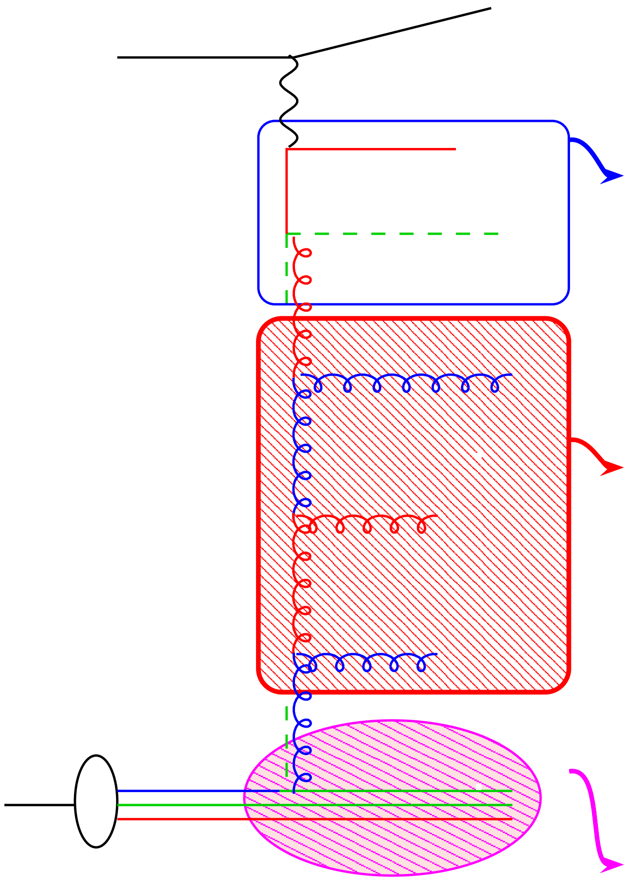


$$\sigma(ep \to e' q\bar{q}) = \int \frac{dy}{y} d^2Q \frac{dx_g}{x_g} \hat{\sigma}(\hat{s}, 0, Q) \int d^2k_t x_g \mathcal{A}(x_g, k_t, \bar{q})$$

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

Basic idea - k_t factorization

CCFM



BGF matrix element
off mass shell

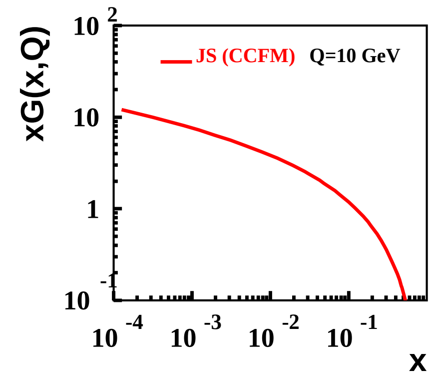
evolution of parton cascade
with CCFM splitting fct.

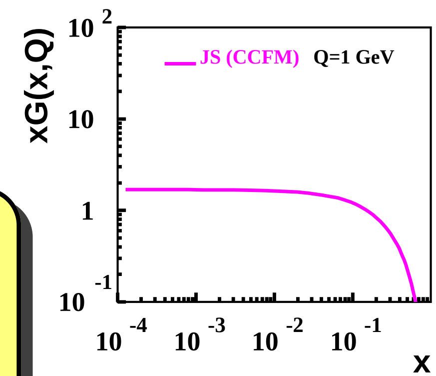
$$\tilde{P} = \bar{\alpha}_s \left(\frac{1}{1-z} + \frac{1}{z} \Delta_{ns} \right)$$

initial distribution: flat

CCFM (all loops)

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





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

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

CCFM equation: one loop — all loops

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

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

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

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

small x (all loops)

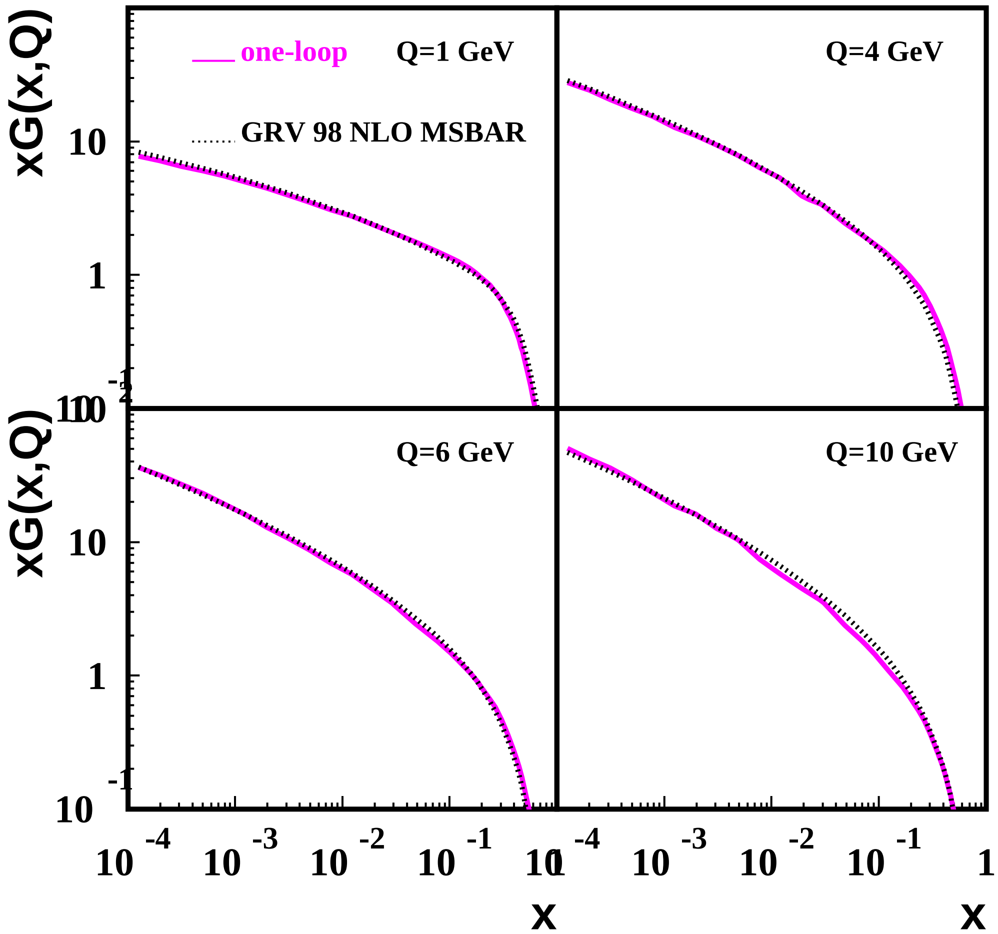
- ☛ **BFKL limit ($z \to 0$)**
- ☛ **angular ordering**

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

large x (one loop)

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

DGLAP unintegrated gluon density - integrated -



one-loop gluon integrated over k_t

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

➤ **compare to evolved DGLAP gluon**

one-loop gluon:

- **at starting scale use GRV**
- **full treatment of kinematics**
- **good agreement with full splitting fct**

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

- **evolution machinery works perfectly**

Non-Sudakov and all - loop resummation

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

Non - Sudakov form factor ➤ all loop resummation:

$$\Delta_{\textbf{ns}} = \exp\left[-\bar{\alpha}_s(k_t^2)\int_0^1 \frac{dz'}{z'}\int\frac{dq^2}{q^2}\Theta(k_t-q)\Theta(q-z'q_t)\right]$$

$$\Delta_{\textbf{ns}} = 1 + \left(-\bar{\alpha}_s(k_t^2)\int\frac{dz'}{z'}\int\frac{dq^2}{q^2}\right)^1 + \frac{1}{2!}\left(-\bar{\alpha}_s(k_t^2)\int\frac{dz'}{z'}\int\frac{dq^2}{q^2}\right)^2 \ldots$$

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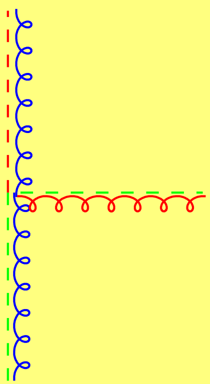

$\bar{\alpha}_\mathrm{s}(k_t)\frac{1}{z}\Big[\ 1$

Non-Sudakov and all - loop resummation

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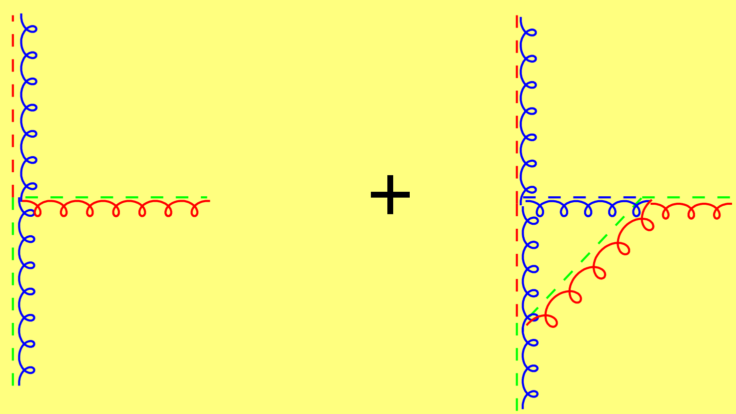

$$\bar{\alpha}_{\mathrm{s}}(k_t)\frac{1}{z}\Big[\ 1 \quad + \quad \bar{\alpha}_{\mathrm{s}}\log\left(\frac{z}{z_0}\right)\log\left(\frac{k_t^2}{z_0 z q^2}\right)$$

Non-Sudakov and all - loop resummation

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

Non - Sudakov form factor ➤ all loop resummation:

$$\Delta_{ns} = \exp\left[-\bar{\alpha}_s(k_t^2)\int_0^1 \frac{dz'}{z'}\int \frac{dq^2}{q^2}\Theta(k_t - q)\Theta(q - z'q_t)\right]$$

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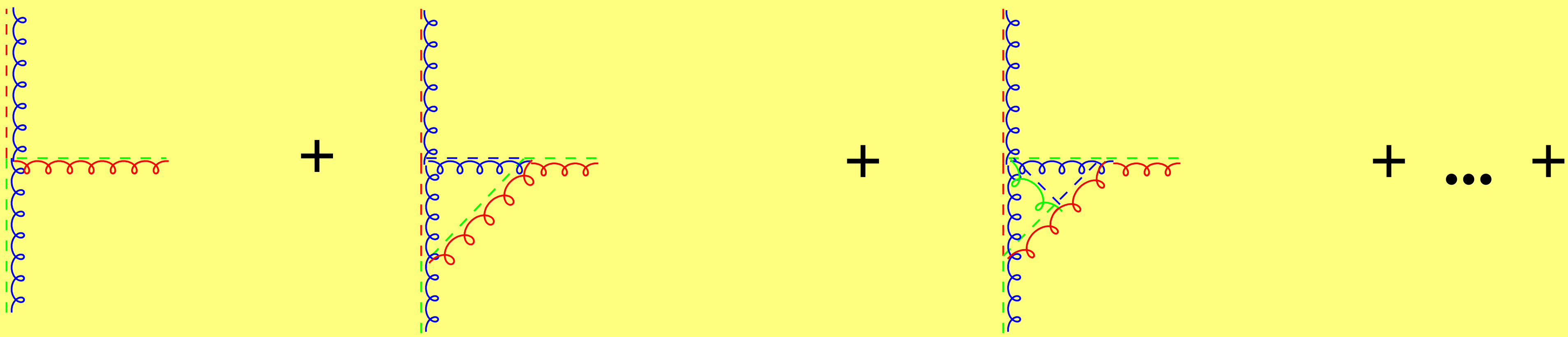


$$\bar{\alpha}_s(k_t)\frac{1}{z}\left[\,1 \quad + \quad \bar{\alpha}_s \log\left(\frac{z}{z_0}\right)\log\left(\frac{k_t^2}{z_0 z q^2}\right) + \frac{1}{2!}\left(\bar{\alpha}_s \log\left(\frac{z}{z_0}\right)\log\left(\frac{k_t^2}{z_0 z q^2}\right)\right)^2 \ldots\right]$$

Structure Function $F_2(x, Q^2)$

together with G.P. Salam, EPJC 19, 351 (2001)

With $\sigma = \int dk_t^2 dx_g \mathcal{A}(x_g, k_t^2, \bar{q}) \sigma(\gamma^* g^* \to q\bar{q})$ fit $F_2(x, Q^2)$

(data from H1 Coll, NPB 470 (1996) 3.)

Parameters in fit

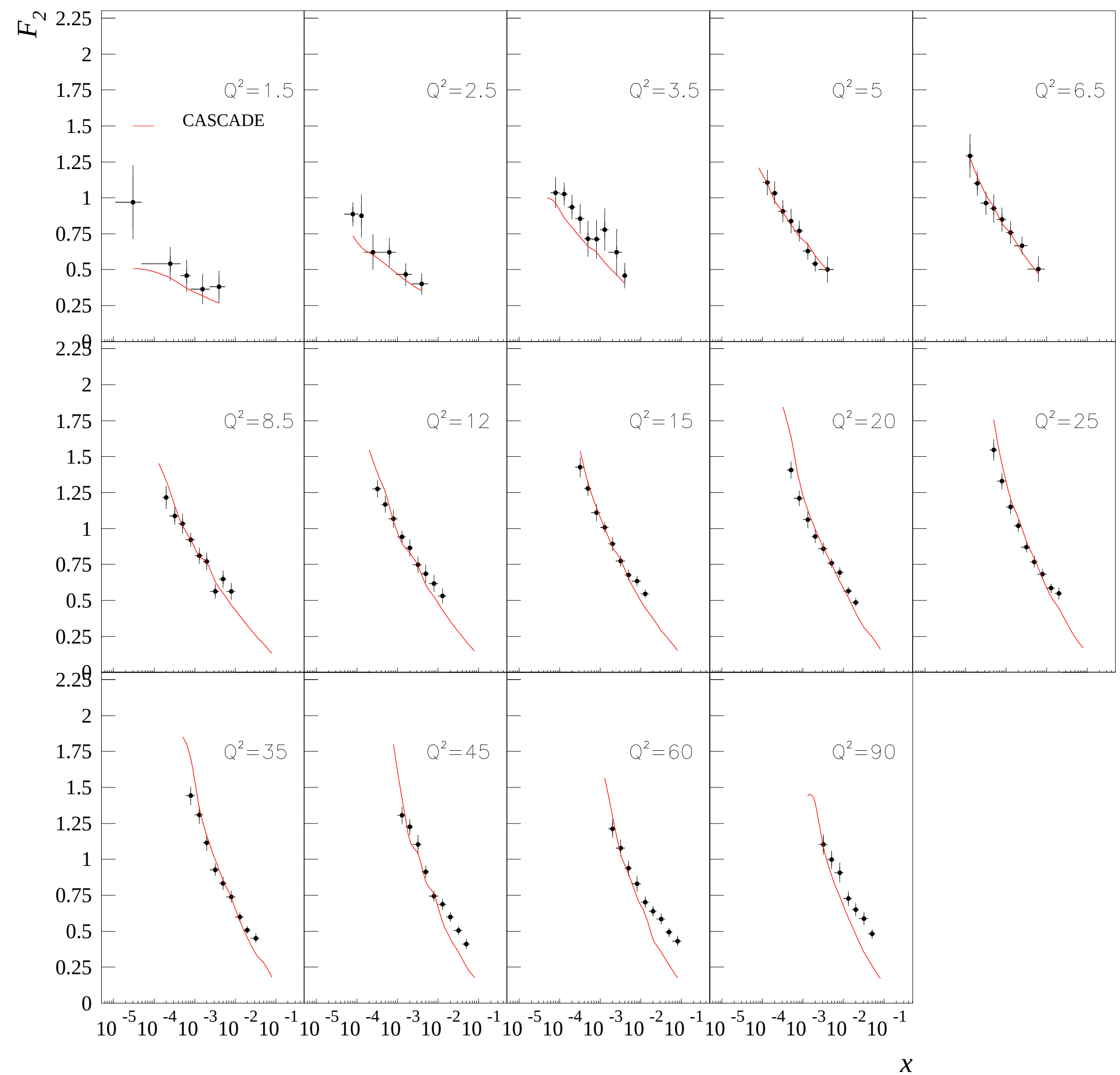
(fitted for $Q^2 > 5$ GeV^2, $x < 10^{-2}$)

- collinear cut-off
  $Q_0 = 1.4$ GeV
- initial gluon $x\mathcal{A}_0(x, k_{t0}^2)$
- freezing of $\alpha_s(k_t)$ for
  $k_t \to 0$
  k_t not constrained ...
- light quark masses:
  $m_q = 0.250$ GeV,
  $m_c = 1.5$ GeV

unintegrated gluon density

$x\mathcal{A}(x, k_t^2, \bar{q})$

obtained from fit to F_2

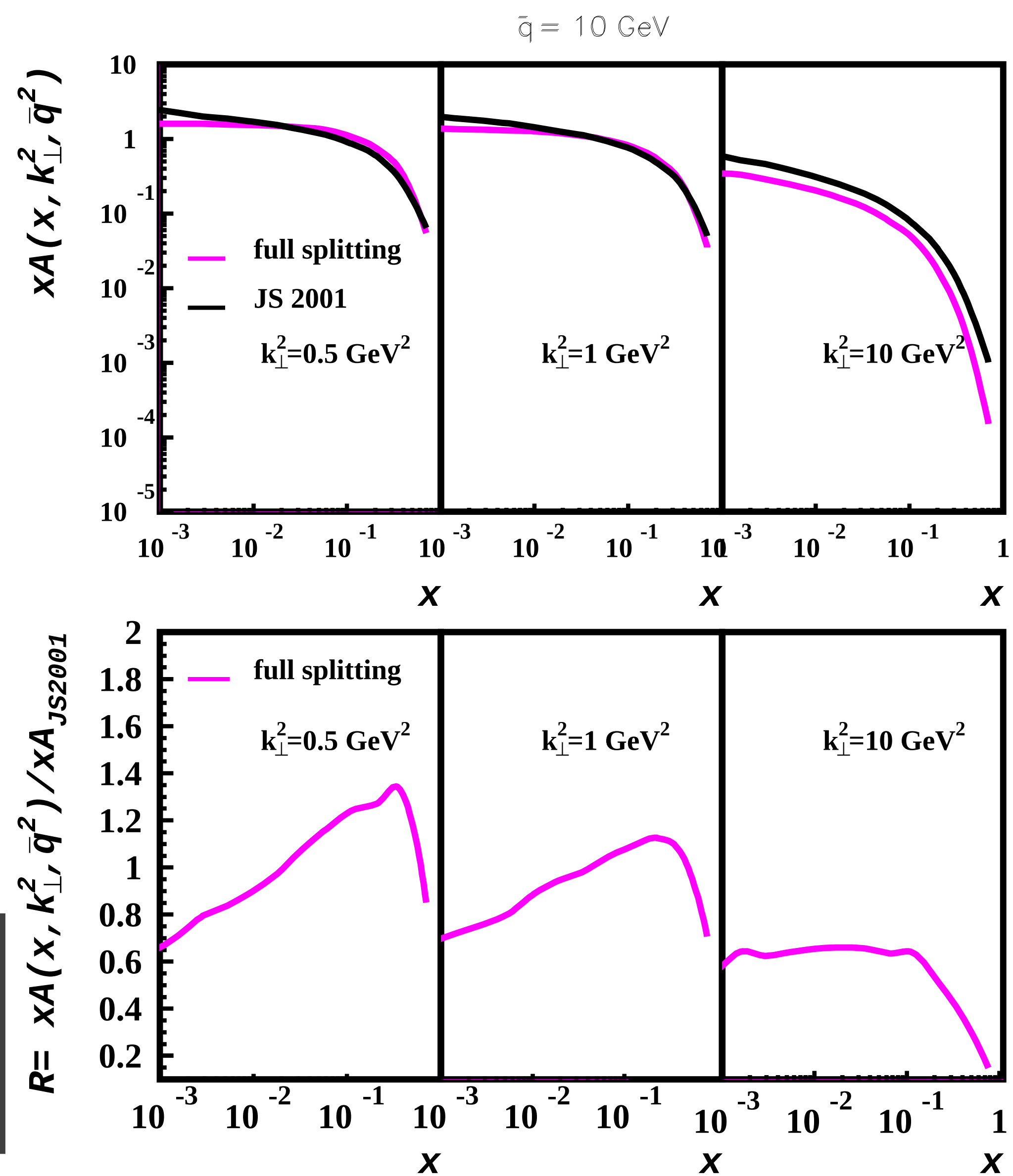


New fit: full splitting function

- improve splitting function
- $P_{gg} \sim \bar{\alpha}_s \left(\frac{1}{z}\Delta_{ns} + \frac{1}{1-z} \right)$

☛ to include non-singular terms
$\frac{1}{z}\Delta_{ns} - 2 + z(1-z) + \frac{1}{1-z}$
???

- new
$P = \bar{\alpha}_s \left(\frac{(1-z)}{z} + \frac{z(1-z)}{2} \right) \Delta_{ns}$
$+\bar{\alpha}_s \left(\frac{z}{1-z} + \frac{z(1-z)}{2} \right)$
- need also new Sudakov
- new non-Sudakov



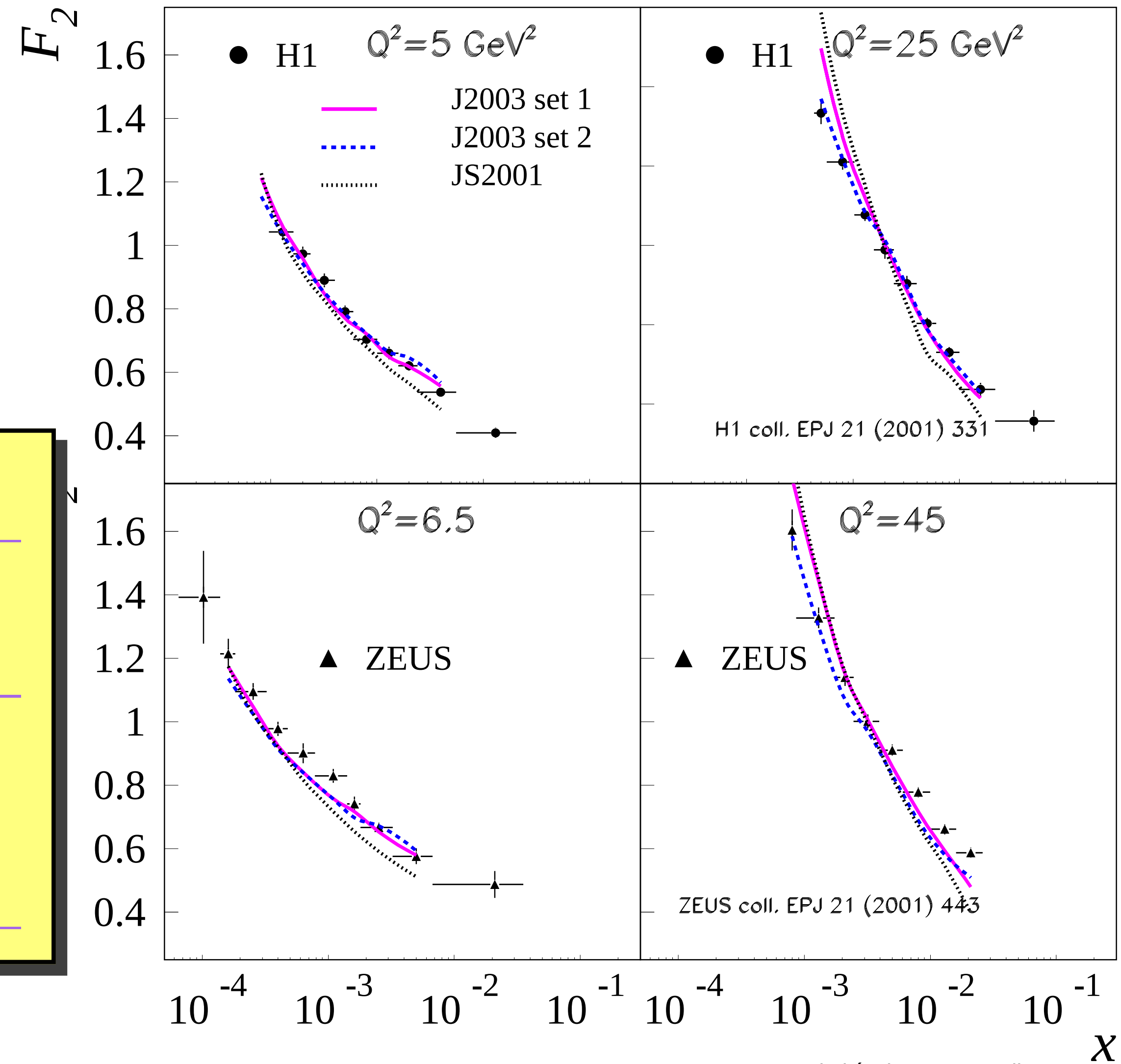
☛ **gluon pdfs are different**

☛ **effect of non-sing. terms visible**

Precision fits to $F_2(x, Q^2)$

With $\sigma = \int dk_t^2 dx_g \mathcal{A}(x_g, k_t^2, \bar{q}) \sigma(\gamma^* g^* \to q\bar{q})$ fit $F_2(x, Q^2)$

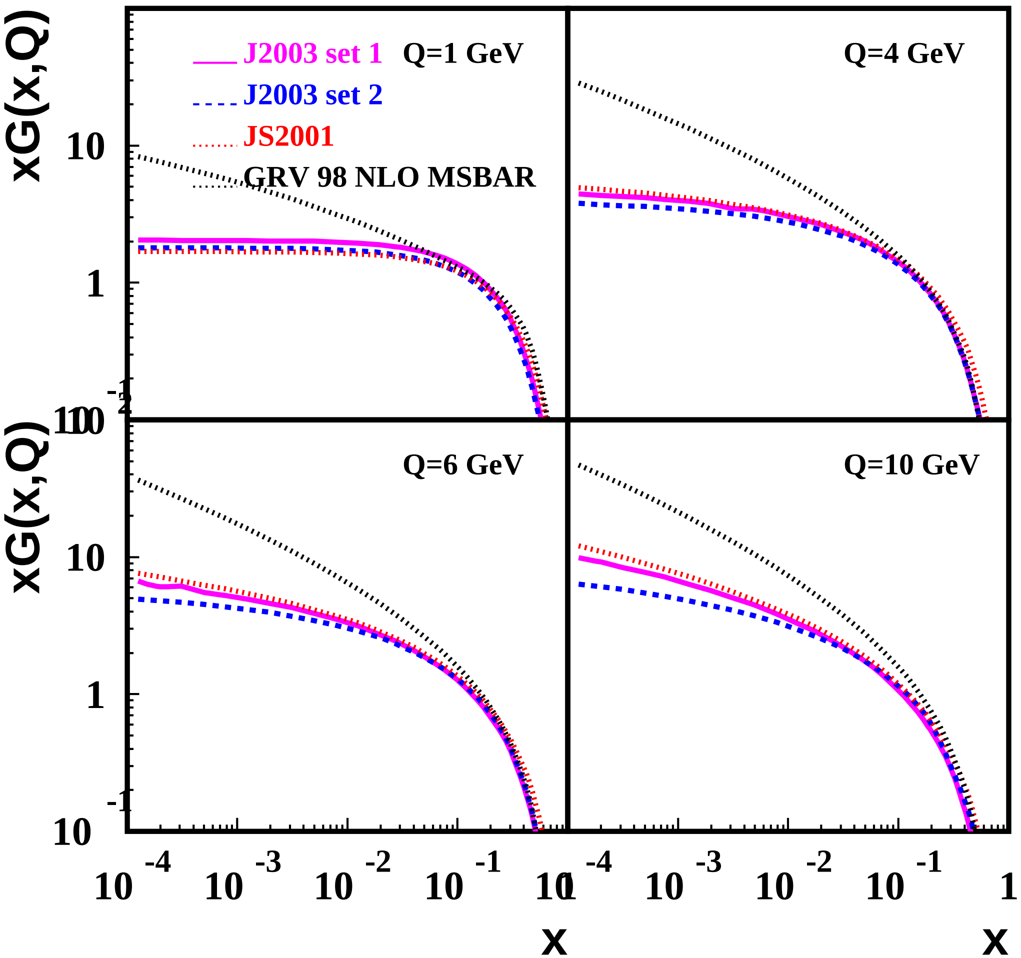
- more precise data:
  H1 NPB 470 (1996) 3., EPJ 21 (2001) 331.
  ZEUS ZPC 72 (1996) 399., EPJ 21 (2001) 443.
- fit $Q^2 > 4.5$ GeV^2, $x < 0.005$
- small k_t - region ?
- full splitting function ?



Fits to $F_2(x, Q^2)$

set	k_t^{cut} (GeV)	χ^2/ndf $ndf = 248$
$k_t^{cut} = Q_0$	**1.33**	**1.29**
full splitting	**1.18**	**1.18**
JS2001	**0.25**	**4.8**

CCFM unintegrated gluon density - integrated -



CCFM gluon integrated over k_t

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

CCFM gluon:

- at starting scale $q = 1$ GeV **flat !!!**
- small x rise generated perturbatively

DGLAP gluon:

- rise at small x at low scales

Remember: gluon density is no observable, only cross sections !!!

One loop fits to $F_2(x, Q^2)$

use one-loop (DGLAP) splitting fct.

replace angular ordering by q ordering

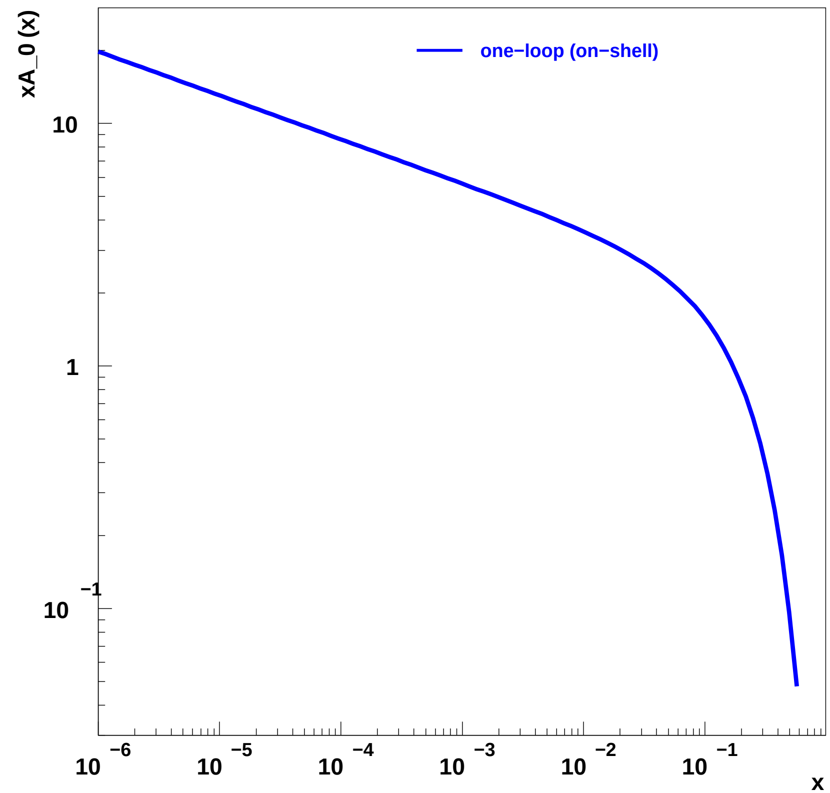
use only gluons

$m_q = 0.250$ **GeV,** $m_c = 1.5$ **GeV**

fit $Q^2 > 4.5$ **GeV**^{2}**,** $x < 0.005$

use standard on-shell BGF ME

initial gluon density



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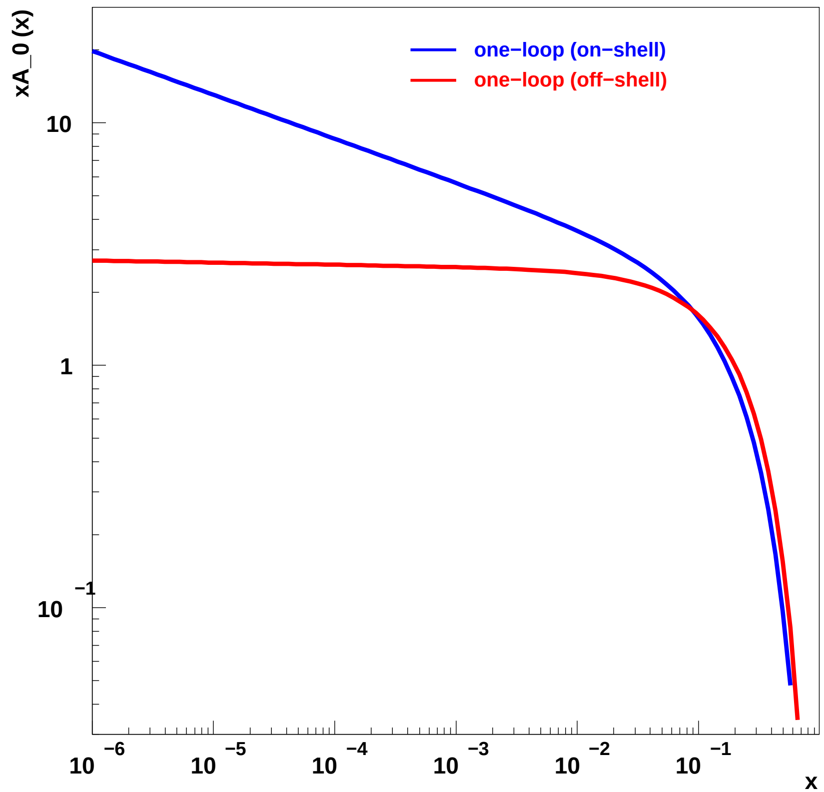
- use off-shell BGF ME

initial gluon density



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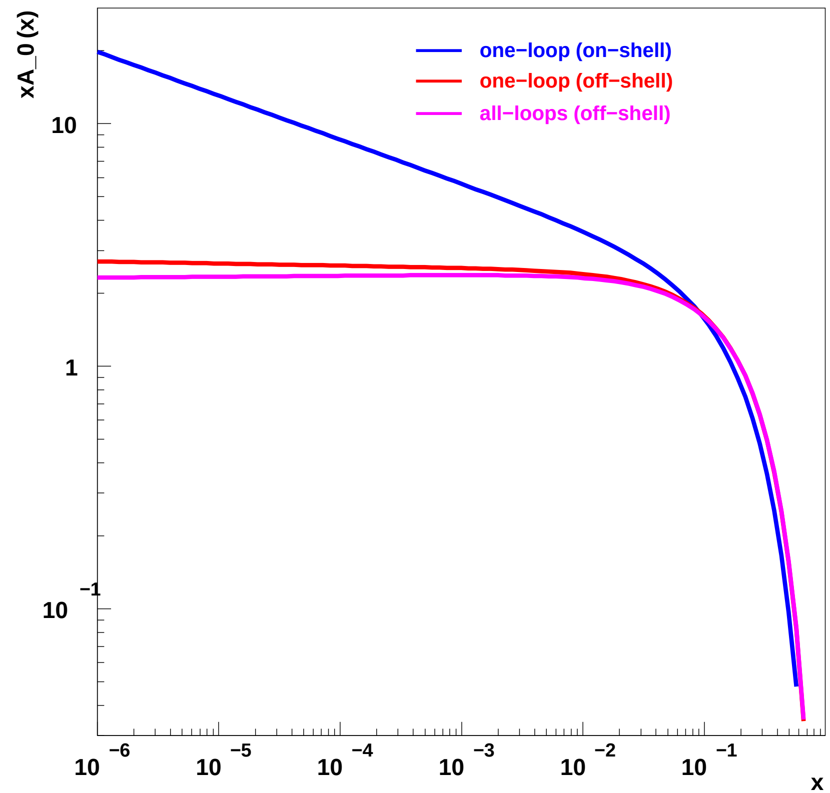
- use off-shell BGF ME
- use off-shell BGF ME and all loops with angular ordering and CCFM splitting fct.

initial gluon density



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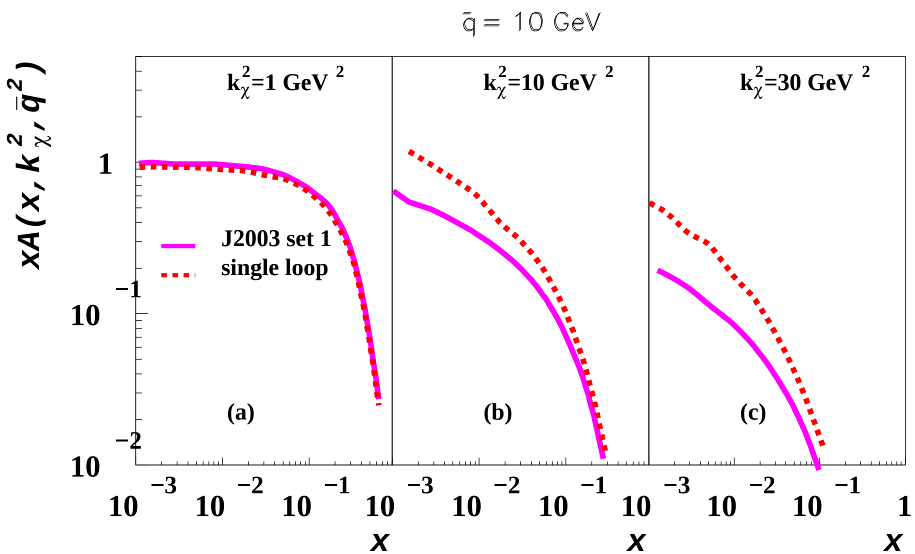
use off-shell BGF ME and all loops

with angular ordering

and CCFM splitting fct.



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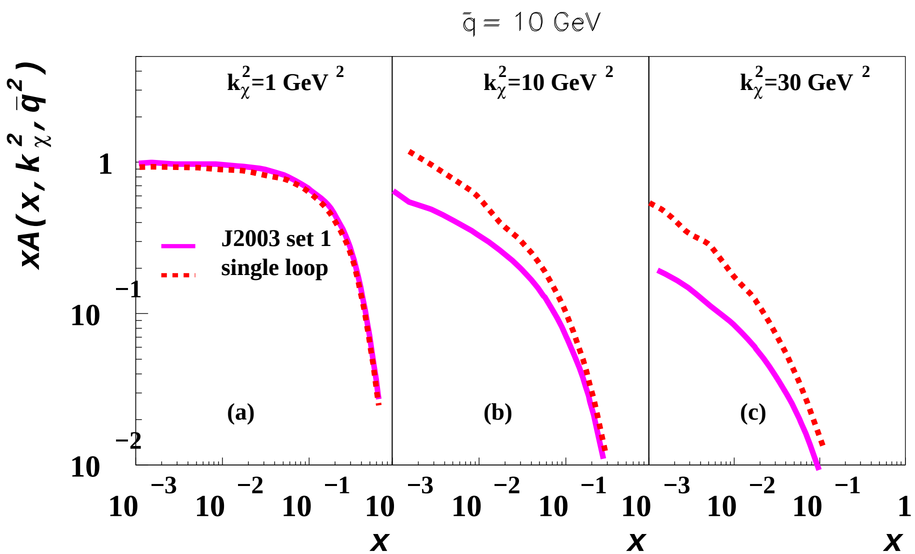


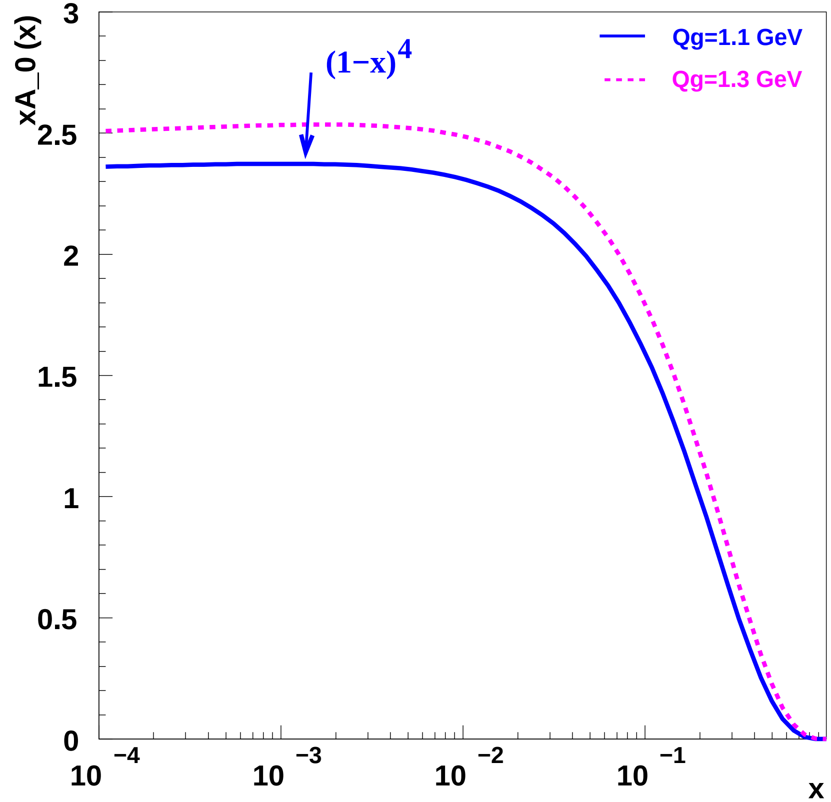
- off-shell ME has large effect
- ☛ simulates NNLO for F_2

All loop fits to $F_2(x, Q^2)$

- all-loop splitting function
- full angular ordering
- use off-shell BGF ME,only gluons
- $m_q = 0.250$ GeV, $m_c = 1.5$ GeV
- fit F_2 for $Q^2 > 4.5$ GeV^2, $x < 0.005$
- similar χ^2 for different intrinsic k_t

  Gaussian: 0.3 - 0.9 GeV
- sensitivity on starting scale

initial gluon density



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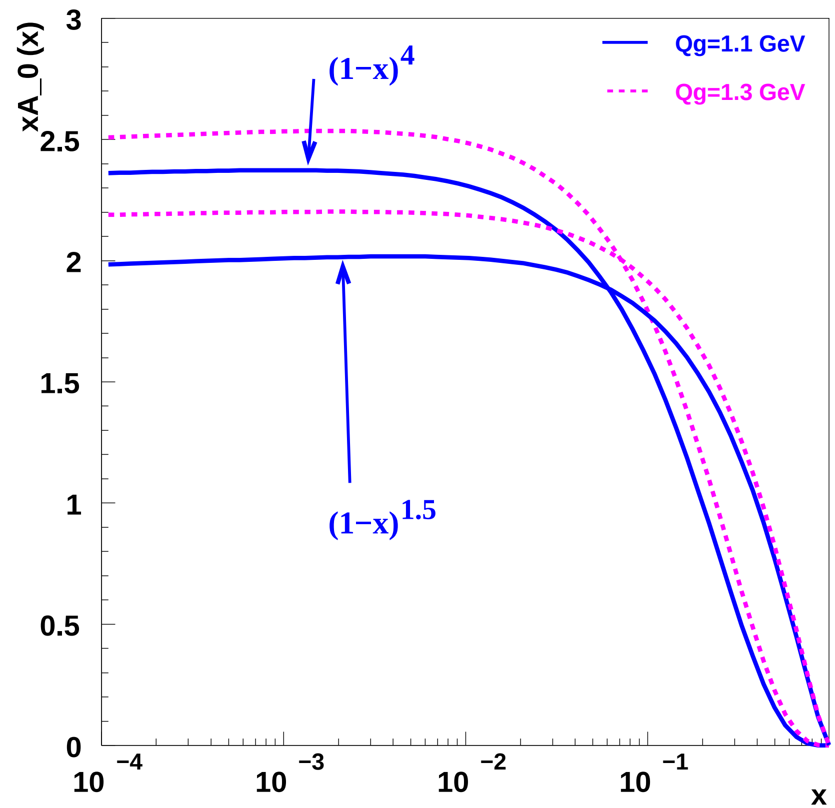
  Gaussian: 0.3 - 0.9 GeV
- sensitivity on starting scale
- find 2 solutions (at least)...
- large x not really constrained
- small x similar

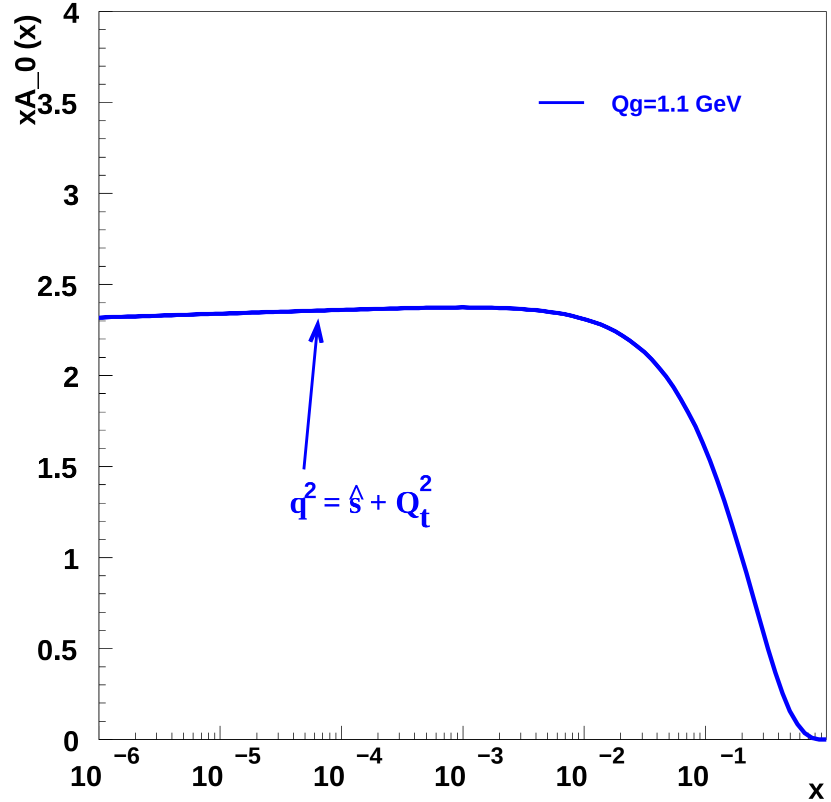
initial gluon density



All loop fits to $F_2(x, Q^2)$ choice of factorization scale ...

- **CCFM: ordering in rapidity of emitted gluons**
- $z_{i-1}q_{i-1} < q_i < \bar{q}$ **with** $q_i = x_{i-1}\sqrt{s\xi_i} = \frac{p_{ti}}{1-z_i}$
- **what is factorization scale $\bar{q}$?**
- $\bar{q}^2 = x_g^{(2)}\Xi s = \hat{s} + Q_t^2$
- **or related to p_t of quarks ?** $\frac{p_{ti}}{1-z_i} \ll \hat{s}$
- **fit F_2 for $Q^2 > 4.5$ GeV^2, $x < 0.005$**

initial gluon density



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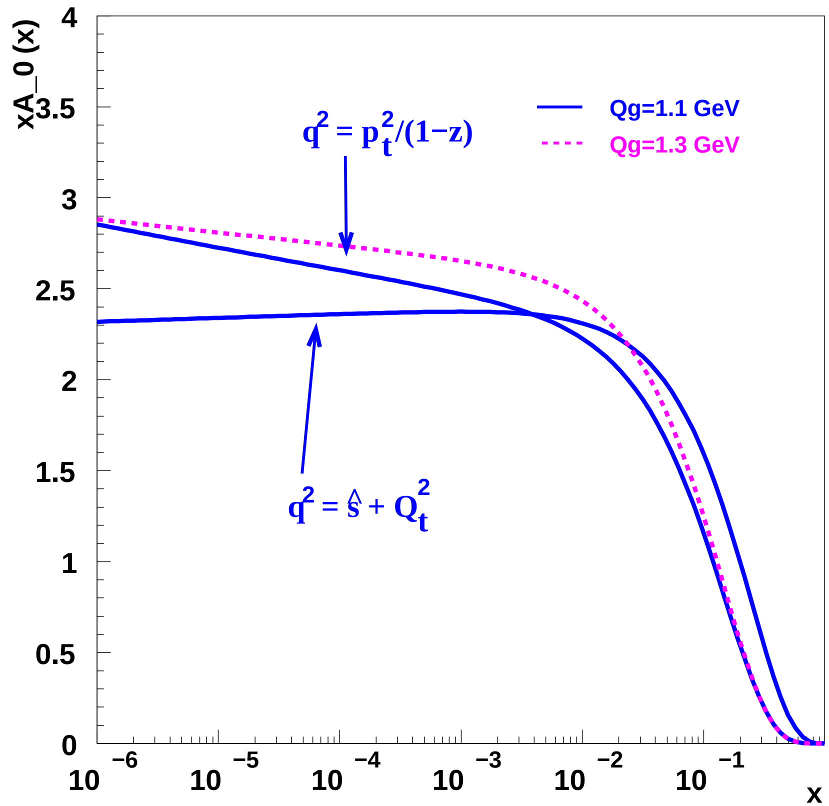
- **fit F_2 for $Q^2 > 4.5$ GeV^2, $x < 0.005$**
- **change of small x behavior...**
- **shorter evolution ladder**

initial gluon density



Effect of initial condition — small k_t - region

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

Effect of initial condition — small k_t - region

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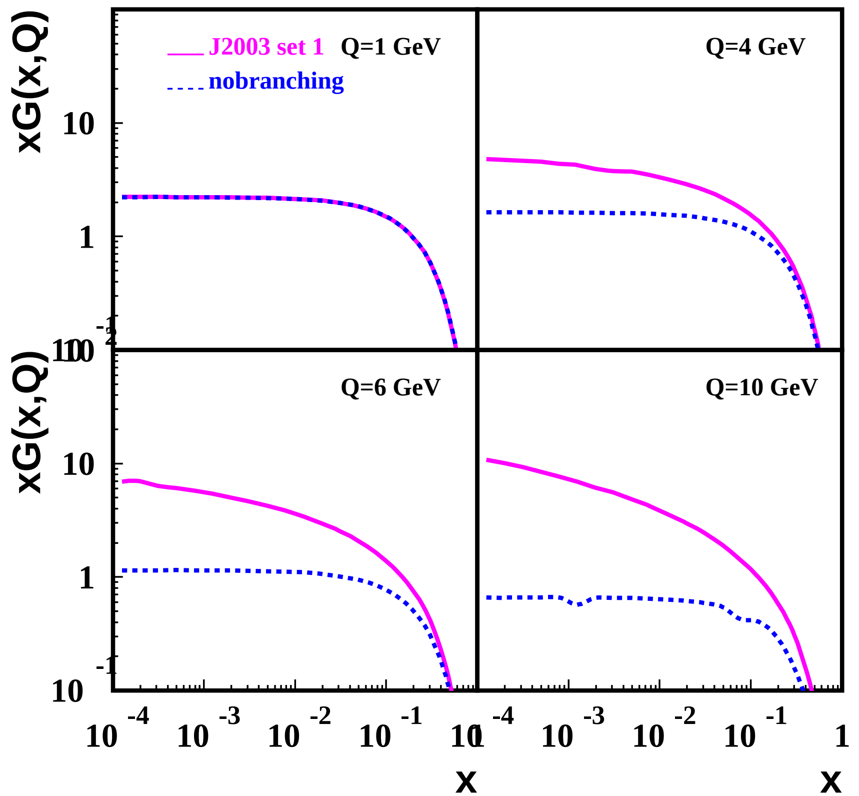
integrated pdf:
effect of evolution and initial condition
not clearly separated ...

where is:

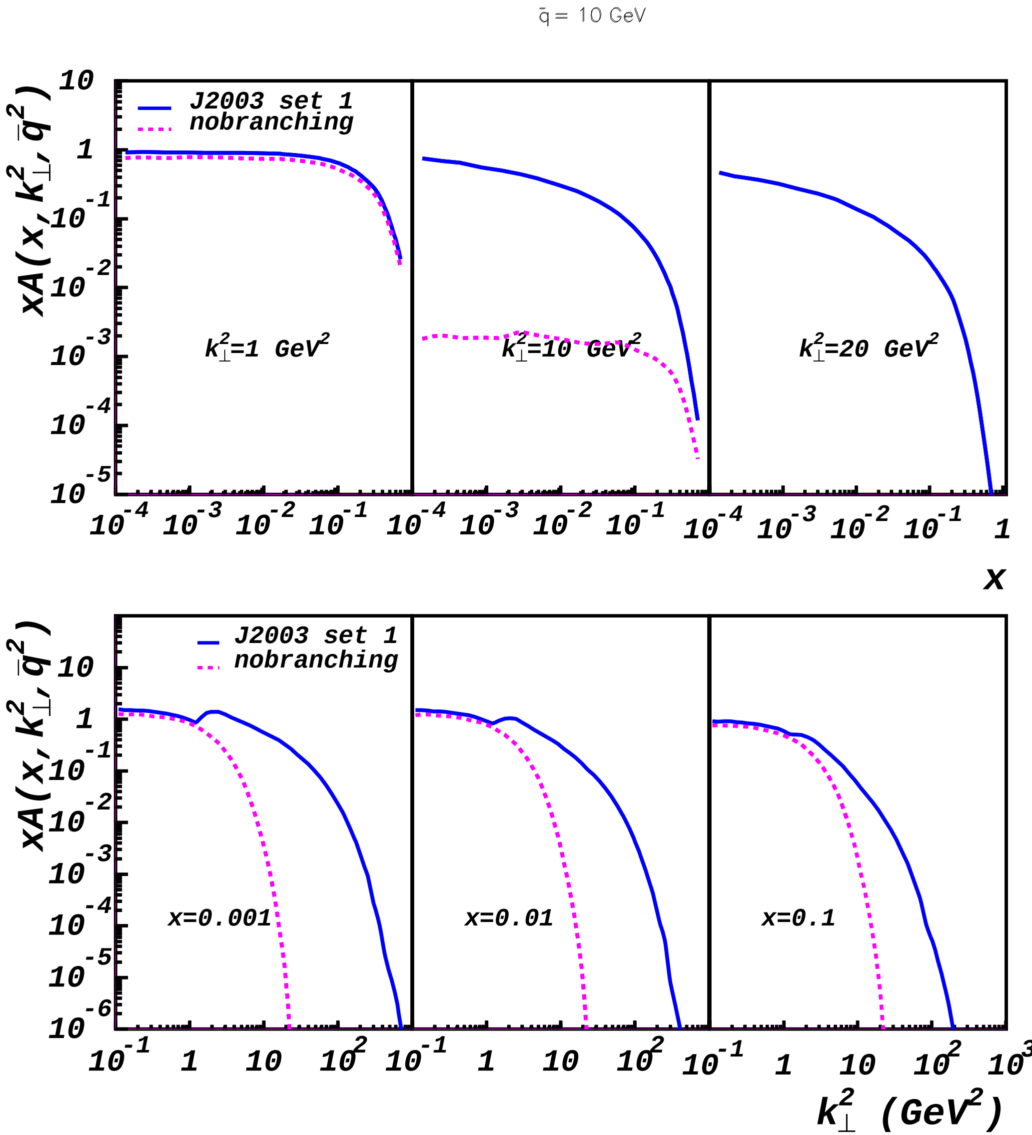
- **small k_t region ?**
- **saturation region ?**



Effect of initial condition — small k_t - region

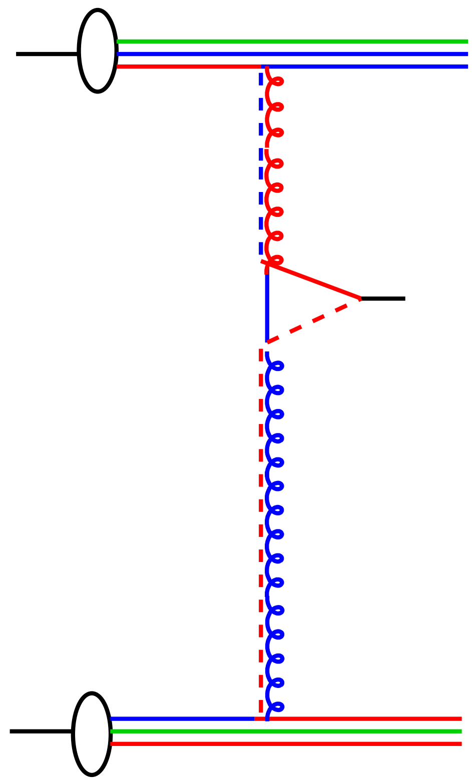
$$\mathcal{A}(x,k_t,\bar{q}) = \mathcal{A}_0(x,k_t)\Delta_s(\bar{q},Q_0)+ \int\frac{dz}{z}\int\frac{d^2q}{\pi q^2}\Theta(\bar{q}-zq)\Delta_s(\bar{q},zq)\cdot \tilde{P}(z,q,k_t)\mathcal{A}\left(\frac{x}{z},k_t',q\right)$$

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



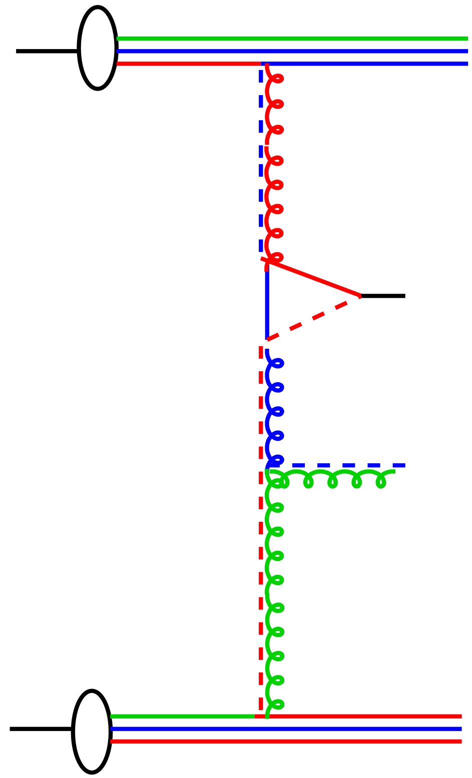
Higgs production at LHC

- search for Higgs ...
- basic process:
  LO $\mathcal{O}(\alpha_s^2)$ gg $\rightarrow$ Higgs



Higgs production at LHC

- search for Higgs ...
- basic process:
  LO $\mathcal{O}(\alpha_s^2)$ gg $\rightarrow$ Higgs
- NLO $\mathcal{O}(\alpha_s^3)$



Higgs production at LHC

- search for Higgs ...
- basic process:
  LO $\mathcal{O}(\alpha_s^2)$ gg $\rightarrow$ Higgs
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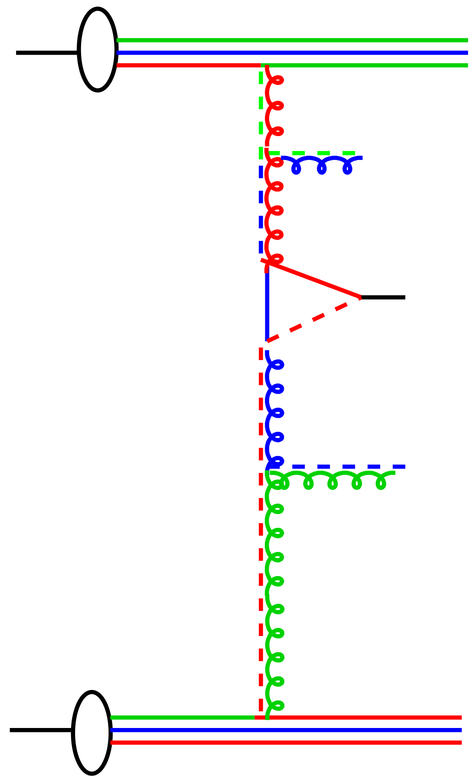
- NNLO $\mathcal{O}(\alpha_s^4)$ not yet calculated



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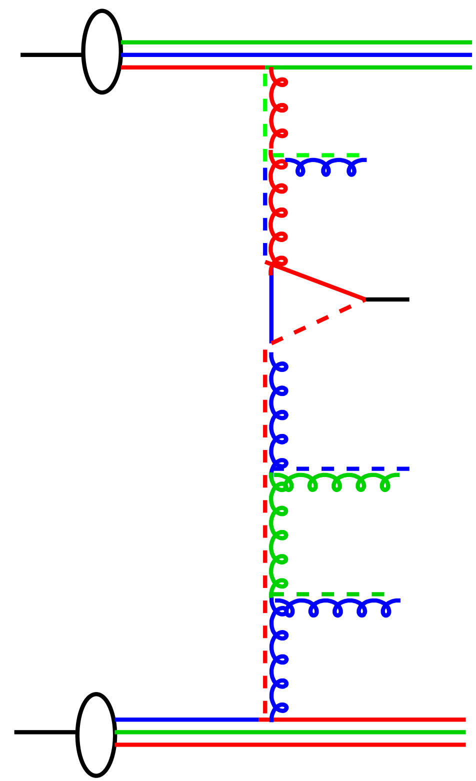
  Bozzi et al (PLB 564 (2003) 65, hep-ph/0302104)



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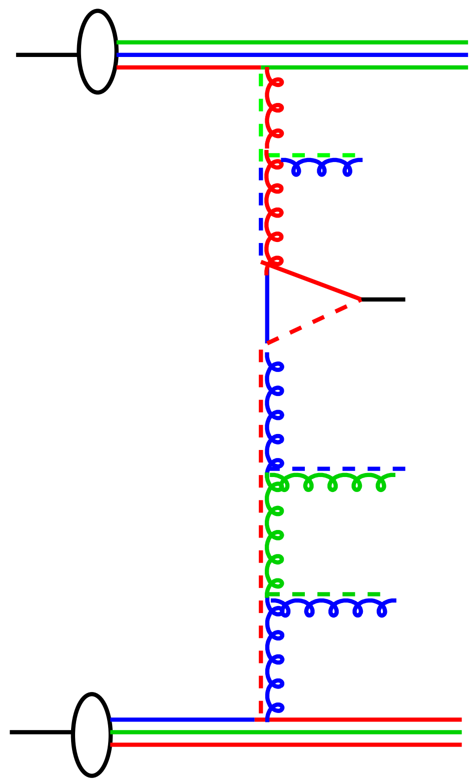
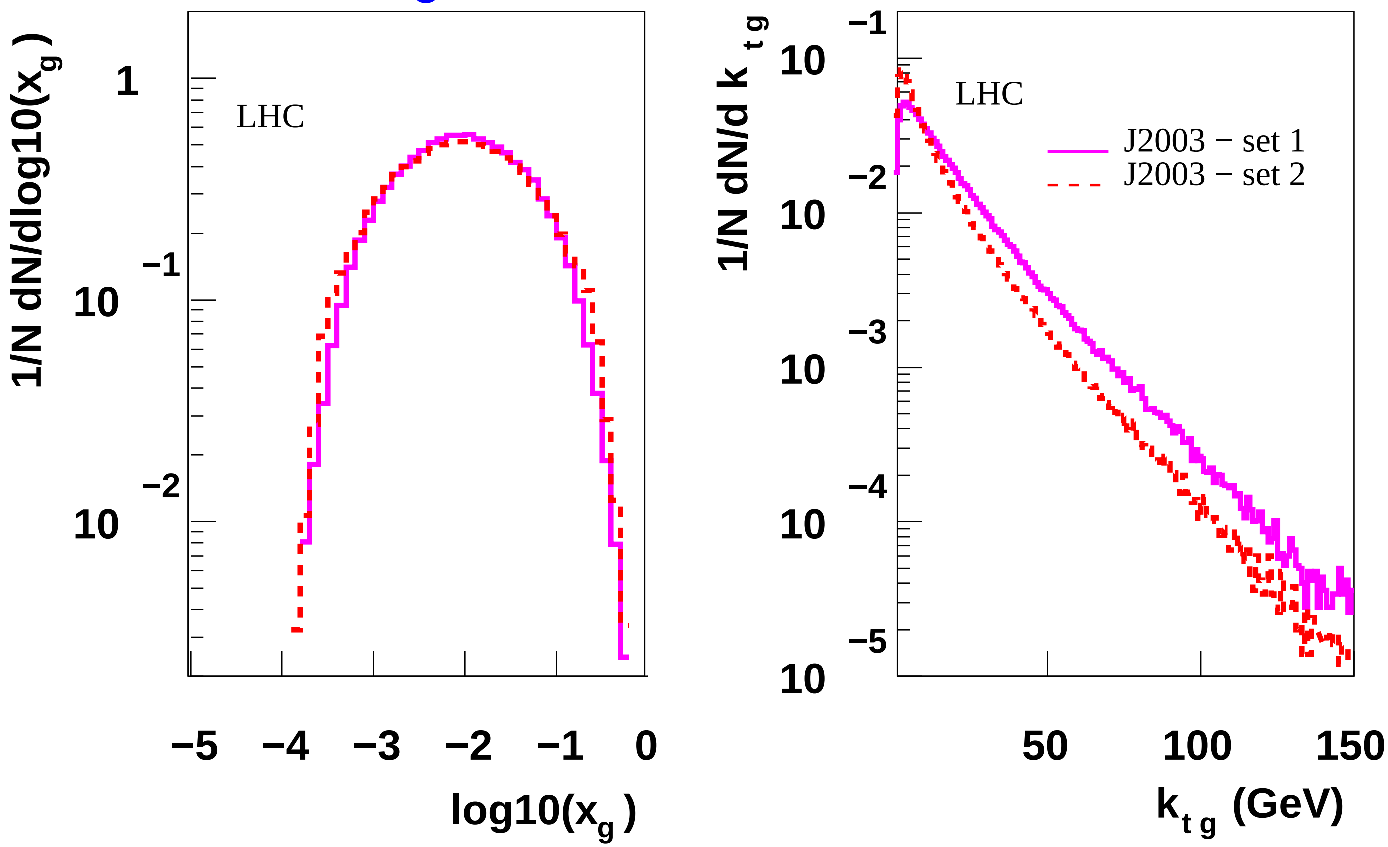
  Bozzi et al (PLB 564 (2003) 65, hep-ph/0302104)
- calculate gg $\to$ Higgs in k_t factorisation
- small x approximation and for for $m_t \to \infty$
  F. Hautmann, PLB 535 (2002) 159
- obtain NNLO correction to gluon-gluon x-section for $x \ll 1$
- estimate higher order corrections ...
- get resummation to all orders



Higgs production at LHC - a typical k_t-factorization process ?????

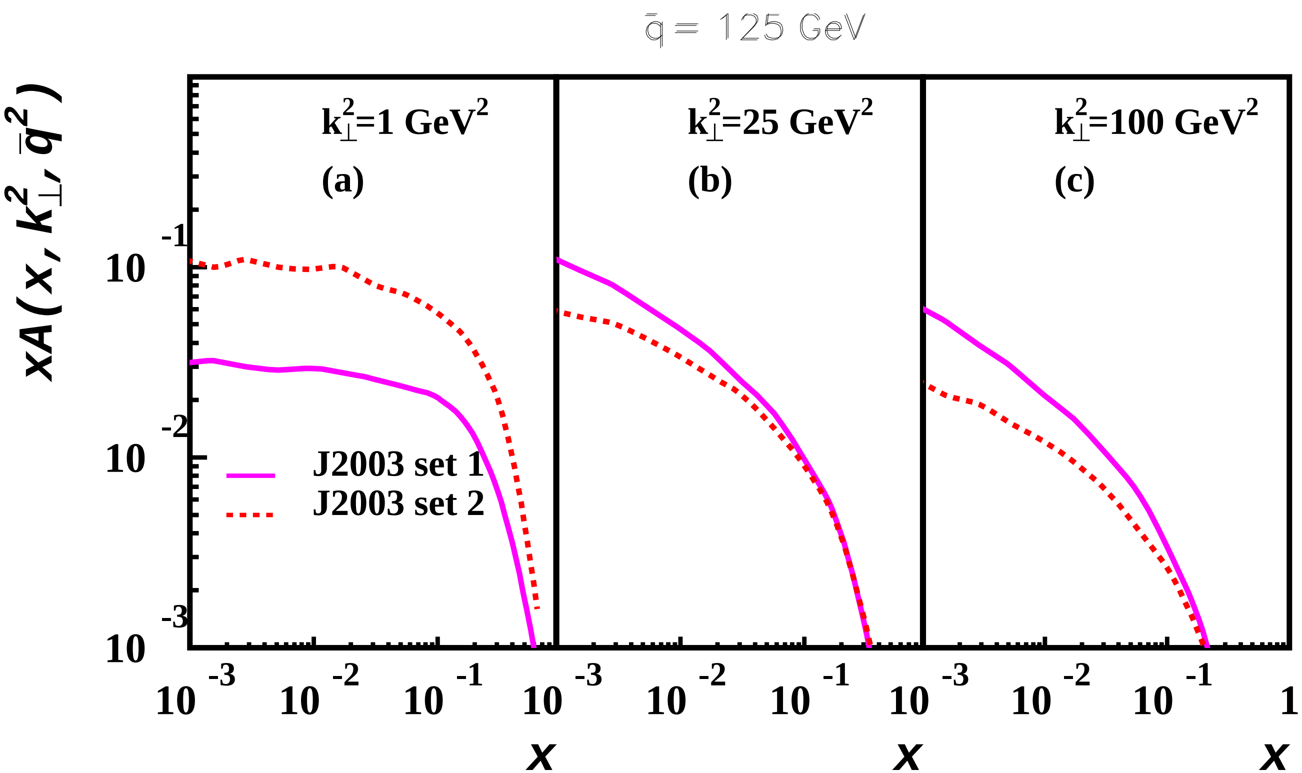
- k_t-factorization: $E_{\text{gluon}} \sim k_t$
- 

- two sets of unintegrated gluon distr.
- both work at HERA
- different k_t's

- $E_{\text{gluon}} \sim 10^{-2} \cdots 10^{-3} \cdot 7000$ GeV compared to mean $k_t \sim \mathcal{O}(15 \text{ GeV})$
- k_t cannot be neglected .... as usually done in DGLAP...

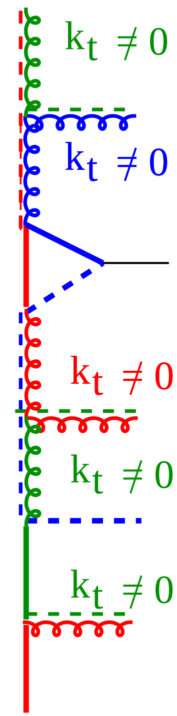
Higgs production at LHC

- gluon density at $\bar{q} = m_{\text{higgs}}$
- on gluon chains included



- gluon densities different at large scales ....
- include also quark chains ???

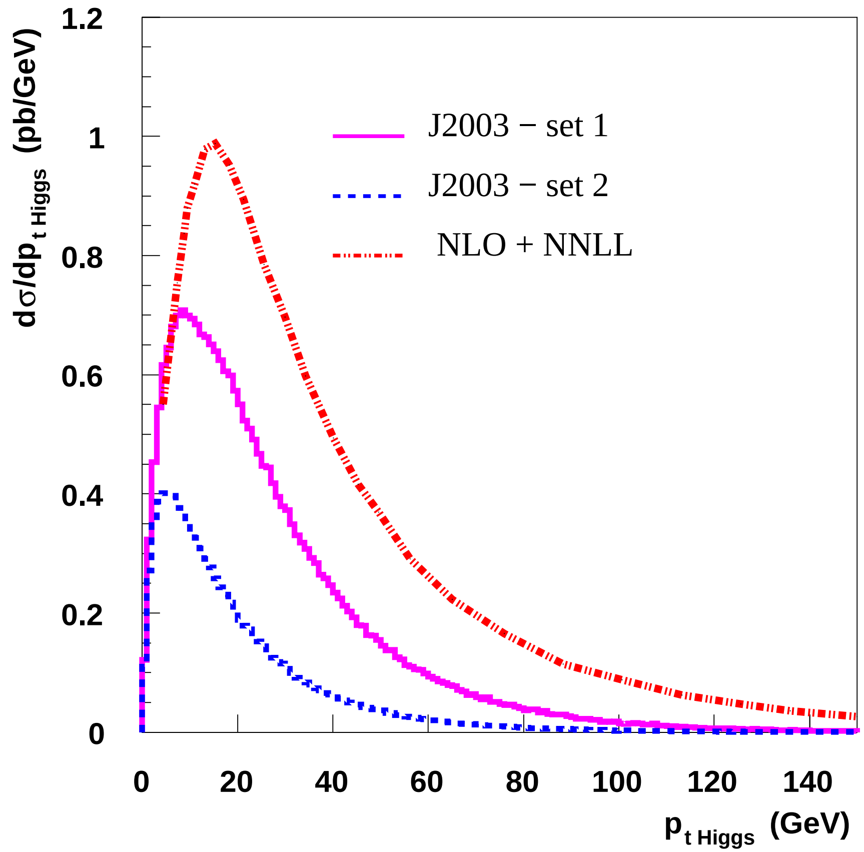
- what about ?



- unintegrated quarks ?

Higgs production at LHC

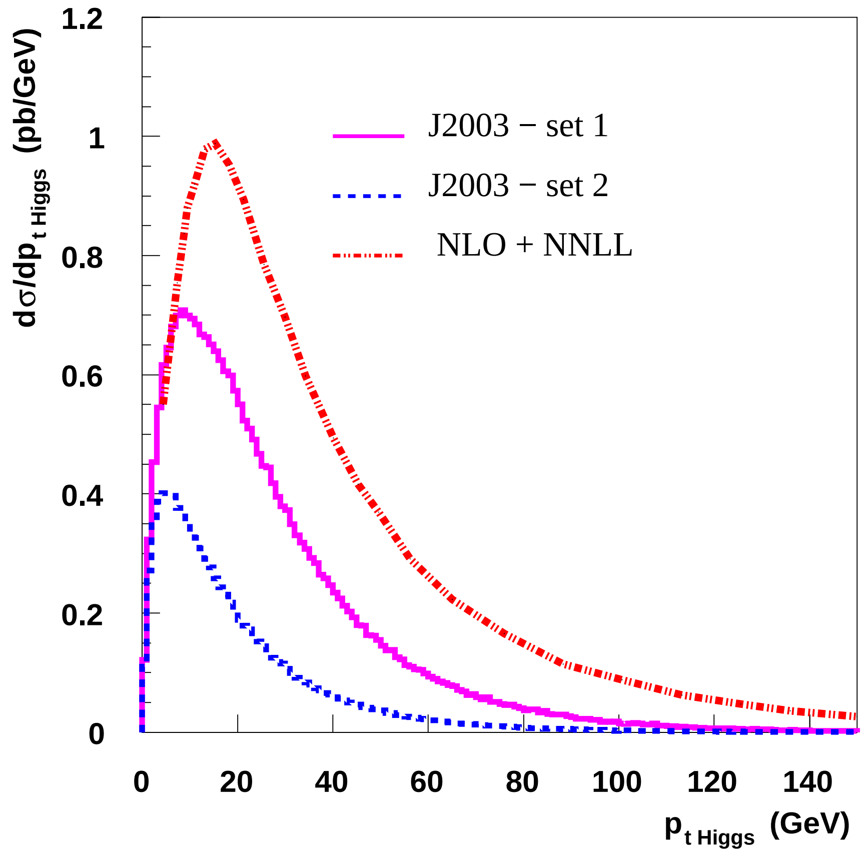
- use new matrix element (off-shell)
  F. Hautmann, PLB 535 (2002) 159
- calculate q_T spectrum with CCFM unintegrated gluon:
  two sets, both determined from HERA
- sensitive to trans. mom. of gluons



- **new approach to calculate Higgs prod. at LHC**
- **important for x-section estimate**
- **different result than NLO ...**
- **better constrain unintegrated gluon ...**

Higgs production at LHC

- use new matrix element (off-shell)
  F. Hautmann, PLB 535 (2002) 159
- calculate q_T spectrum with CCFM unintegrated gluon:
  two sets, both determined from HERA
- sensitive to trans. mom. of gluons
- up to now only gluon initiated cascades
- BUT, what about quark initiated cascades?



- **new approach to calculate Higgs prod. at LHC**
- **important for x-section estimate**
- **different result than NLO ...**
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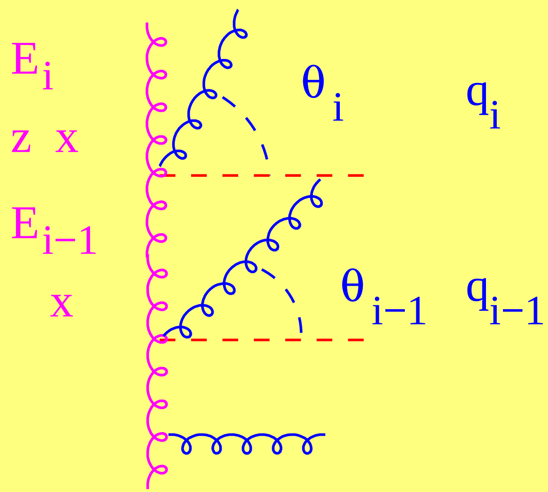
Conclusions

- different limits of CCFM equation
  - ☛ one-loop – all loops
- treatment of matrix element important (on-shell–off-shell)
  - ☛ different small x behavior of staring distribution
- choice of factorization scale ☛ small x behavior
- uPDF important for study of small k_t effects...
  - ☛ starting distribution visible
  - ☛ search for saturation
- use uPDF for detailed study
- perform global fits (including quarks)
- k_t - factorization:
  - ☛ applications also for LHC: Higgs

$\mathbf{C}_{\text{atani}}\mathbf{C}_{\text{iafaloni}}\ \mathbf{F}_{\text{iorani}}\ \mathbf{M}_{\text{archesini}}$ (1988 - 1990)

- including color coherence effects in multi-gluon emissions
- angular ordering of emission angles:



- ordering in q (DGLAP) implies also angular ordering
- unification of DGLAP and BFKL

☛ **WOW**

for small z no restriction in q: ☛ random walk in q

Catani **C**iafaloni **F**iorani **M**archesini (1988 - 1990)

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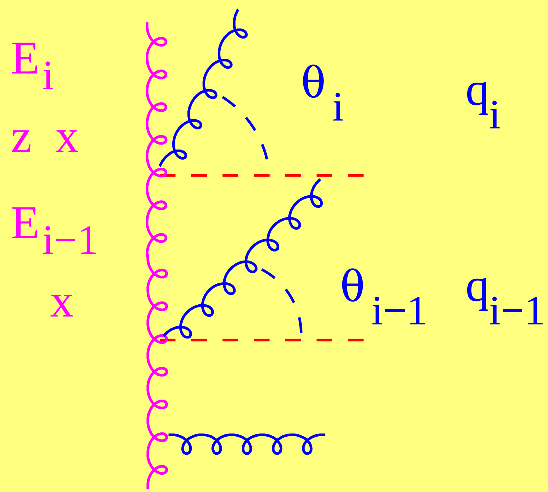

$$p_{ti} = |q_i^0| \sin \Theta_i, \; z = \frac{E_i}{E_{i-1}}$$

$$E_{i-1} = E_i + q_i^0 = zE_{i-1} + q_i^0, ☛ \; q_i^0 = (1-z)E_{i-1}$$

$$p_{ti} = q_i^0 \sin \Theta_i \simeq (1-z)E_{i-1}\Theta_i$$

$$\frac{p_{ti}}{1-z} \simeq E_{i-1}\Theta_i$$

with: $q_i = \frac{p_{ti}}{1-z_i}$ ☛ $\Theta_i = \frac{q_i}{E_{i-1}}$ **and** $\Theta_{i+1} = \frac{q_{i+1}}{E_i}$

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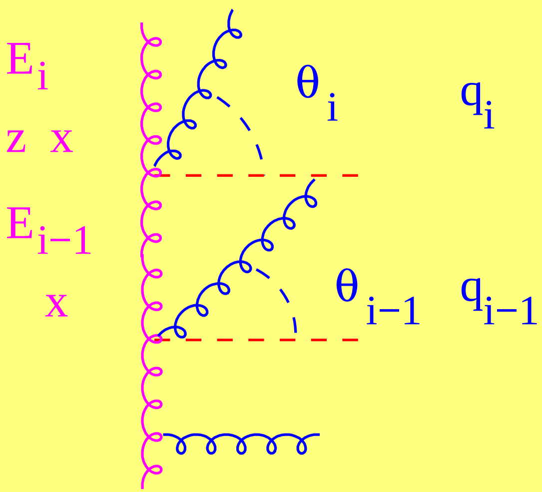

in lab. frame

$$\Theta_{i+1} > \Theta_i$$

$$q_{i+1} > z_i q_i$$

with $q = \frac{p_t}{1-z}$

- ordering in q (DGLAP) implies also angular ordering
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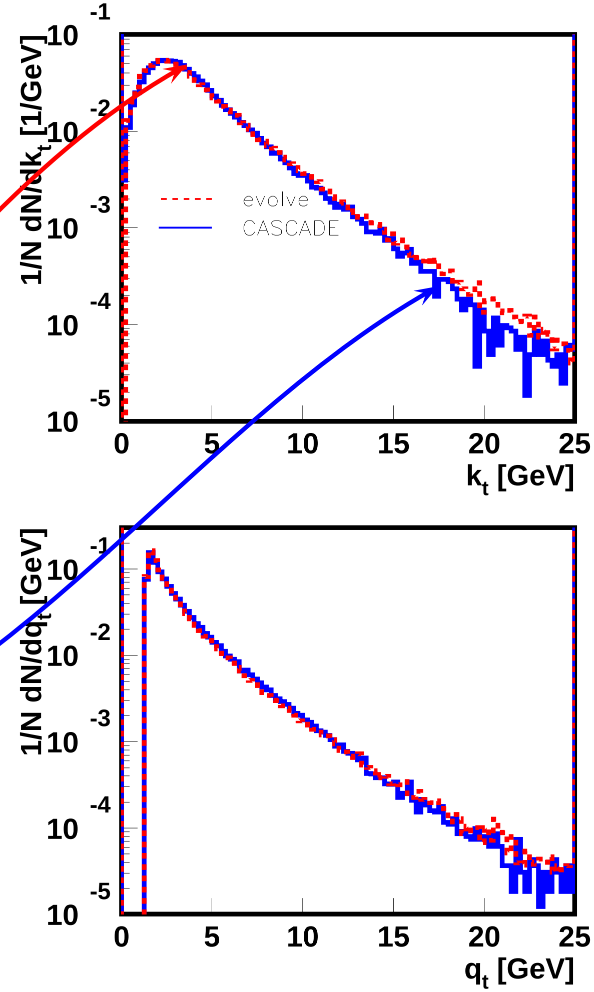
WOW

for small z no restriction in q: random walk in q

Advantage of CCFM: parton emissions

- DGLAP or BFKL
  - only inclusive predictions
  - no info on emitted partons !!!
- CCFM treats explicitely:
  partons emitted during cascade
  color coherence
  energy momentum conservation
- best to implement in MC generator
  - compare evolution and MC
- CASCADE MC generator



evolution - MC parton shower comparison
never shown for DGLAP type MC's!!!

The Monte Carlo Generator CASCADE

- **CCFM backward evolution implemented in MC generator**
  CASCADE (http://www.quark.lu.se/ hannes/cascade)
- **initial state CCFM cascade with strict angular ordering**
- **off-shell hard scattering processes:**
- $\gamma g^* \to q\bar{q}$, $\gamma^* g^* \to Q\bar{Q}$, $\gamma g^* \to J/\psi g$, $\gamma\gamma \to Q\bar{Q}$
- $g^* g^* \to q\bar{q}$, $g^* g^* \to Q\bar{Q}$, $g^* g^* \to h$
- **P-remnant treatment like in PYTHIA (q-di-q, primordial k_t)**
- **final state parton showers added to quarks**
  hadronization via JETSET/PYTHIA

CASCADE is MC implementation of CCFM
for $ep, ee, \gamma\gamma$ and also for $p\bar{p}$

New fit: small k_t - region

- use H1 + ZEUS F_2 data (from 94 and 96-97)
- fit for $x < 0.005$ $Q^2 > 4.5$ GeV^2
- fit Q_0 and normalization in initial pdf $x\mathcal{A}_0 = N(1-x)^4$

Treatment of soft region

no k_t ordering ☚ diffusion into soft

• what about α_s for $k_t < k_t^{cut}$ in

☚ saturation of x-section for $k_t < k_t^{cut}$

What is soft?

• JS2001 $k_t^{cut} > 0.25$ GeV

• now $k_t^{cut} > Q_0$

similar to saturation scale $Q_s \sim 1$ GeV