CASCADE/CCFM predictions and heavy quark data

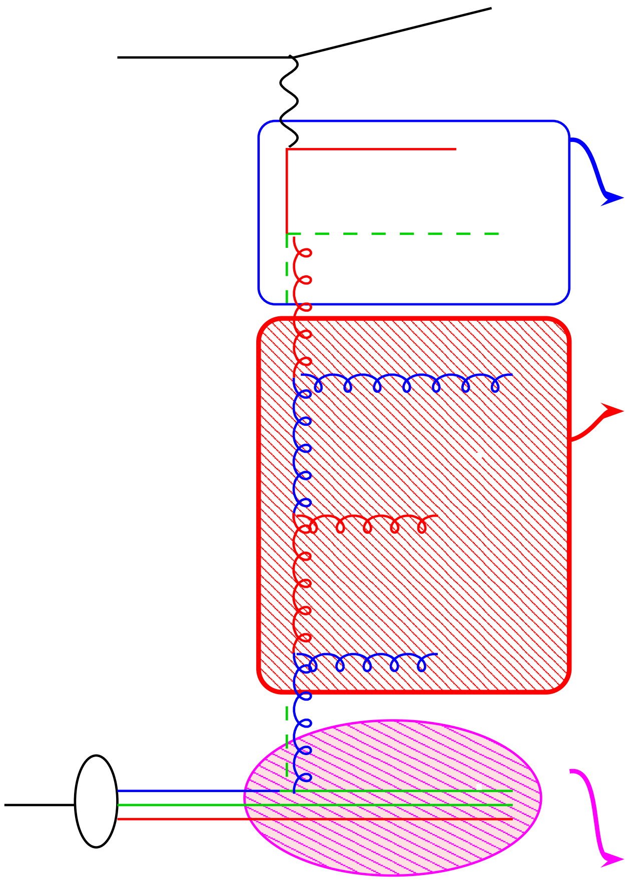
H. Jung, University of Lund

Heavy Quark Physics at the upraded HERA Collider, Weizmann Institute, 19-22 Oct 2003

- basics, factorisation and all that ...
- CCFM equation, solution, new hadron level MC CASCADE
  one-loop (DGLAP) - all loops (CCFM)
- new fits to F_2 - new unintegrated gluon densities
- predict heavy quark production
  at HERA, Tevatron and at LEP ($\gamma\gamma \to b\bar{b}$) ???
- some ideas to measure unintegrated partons
- conclusion

Basic idea - Collinear factorization

DGLAP

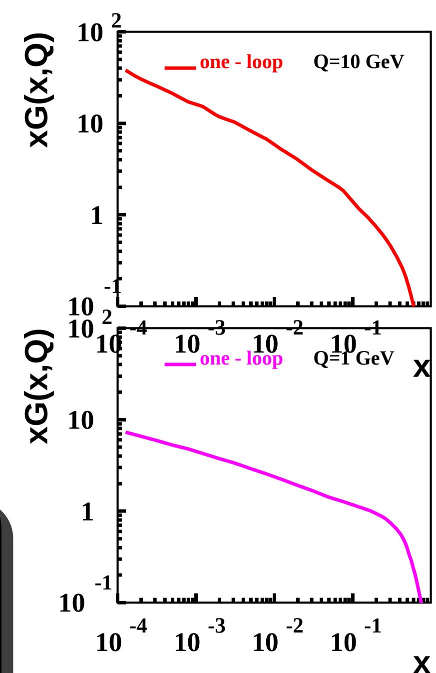


BGF matrix element
on mass shell

evolution of parton cascade
q - ordered
with DGLAP splitting fct.

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

initial distribution: steep



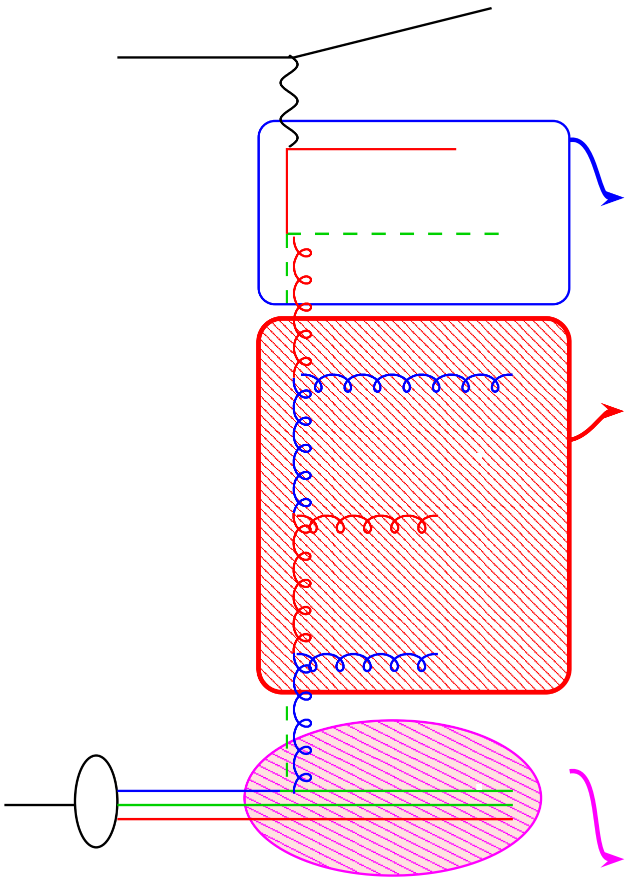
$$\sigma(ep \to e' q\bar{q}) = \int \frac{dy}{y} d^2Q \frac{dx_g}{x_g} \hat{\sigma}(\hat{s}, 0, Q) \int d^2k_t x_g \mathcal{A}(x_g, k_t, \bar{q})$$

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

Basic idea - Collinear factorization

J.C. Collins, X. Zu JHEP 06 (2002) 018
on shell matrix element
is only assumption without proof
and is unphysical !!!
and not necessary for proof of factorization !!!

DGLAP



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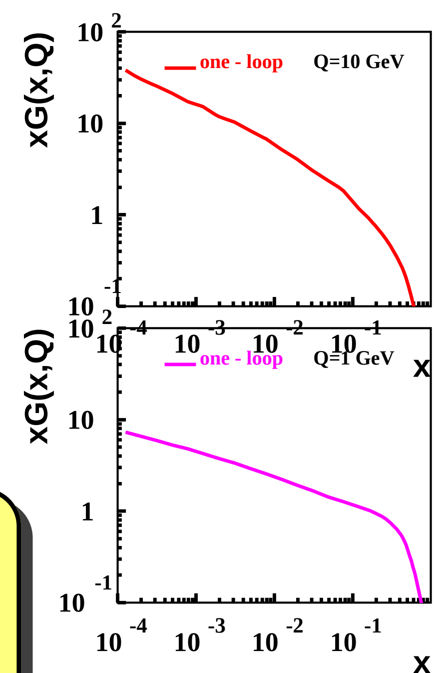
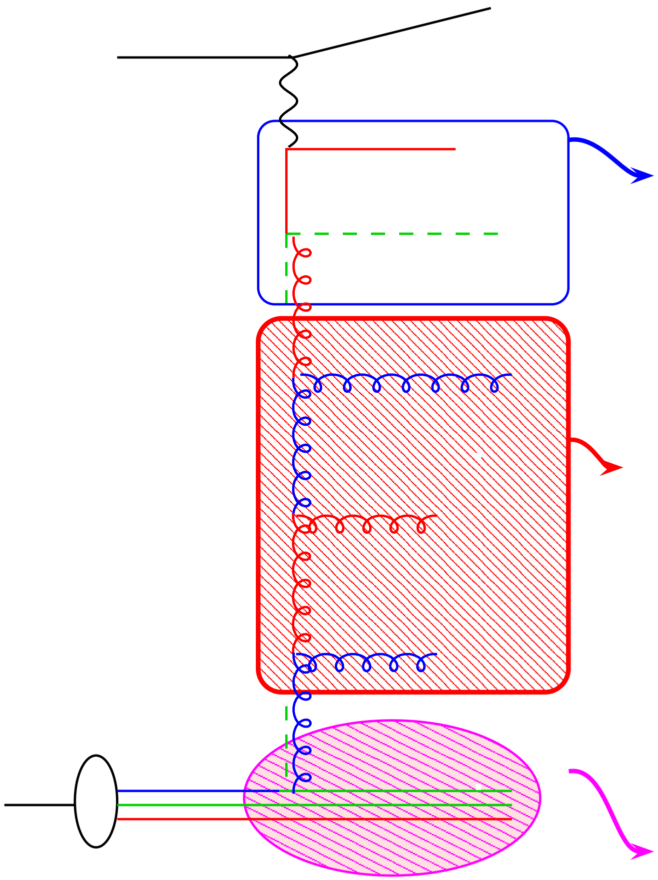


$$\sigma(ep \to e' q\bar{q}) = \int \int d^2 k_t \frac{dy}{y} d^2 Q \frac{dx_g}{x_g} \hat{\sigma}(\hat{s}, k_t, Q) x_g \mathcal{A}(x_g, k_t, \bar{q})$$

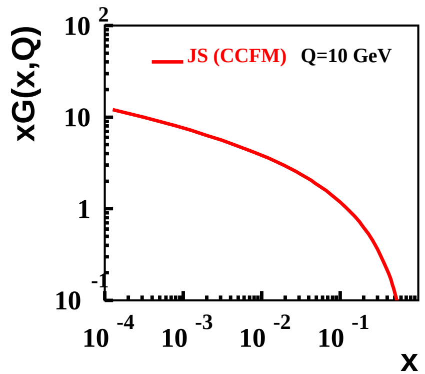
with $\int d^2 k_t x_g \mathcal{A}(x_g, k_t, \bar{q}) \stackrel{?}{=} x_g G(x_g, Q^2)$

Basic idea - k_t factorization



BGF matrix element

evolution of parton cascade



initial distribution:

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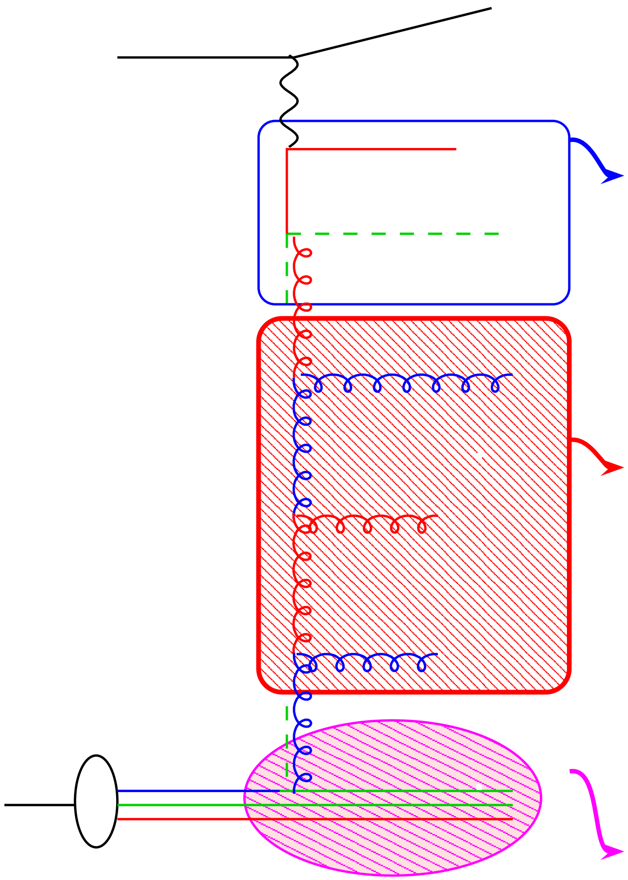
with $\int d^2k_t x_g \mathcal{A}(x_g, k_t, \bar{q}) \simeq x_g G(x_g, Q^2)$

Basic idea - k_t factorization

CCFM



BGF matrix element
off mass shell

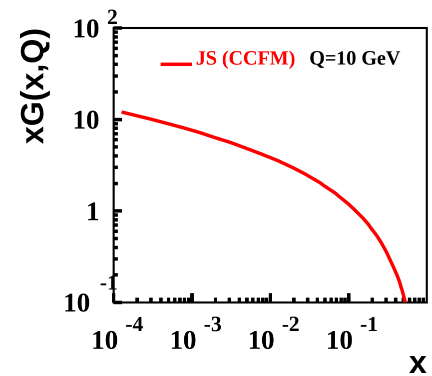
evolution of parton cascade
with CCFM splitting fct.

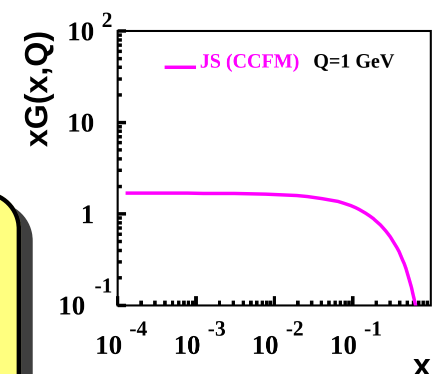
$$\tilde{P} = \bar{\alpha}_s \left(\frac{1}{1-z} + \frac{1}{z} \Delta_{ns} + \cdots \right)$$

initial distribution: flat ?

CCFM !!!

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





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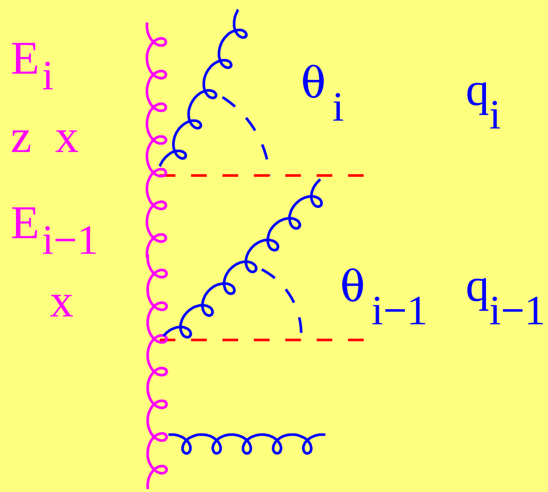
Catani **C**iafaloni **F**iorani **M**archesini (1988 - 1990)

- 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

CCFM: Catani Ciafaloni Fiorani Marchesini (1988 - 1990)

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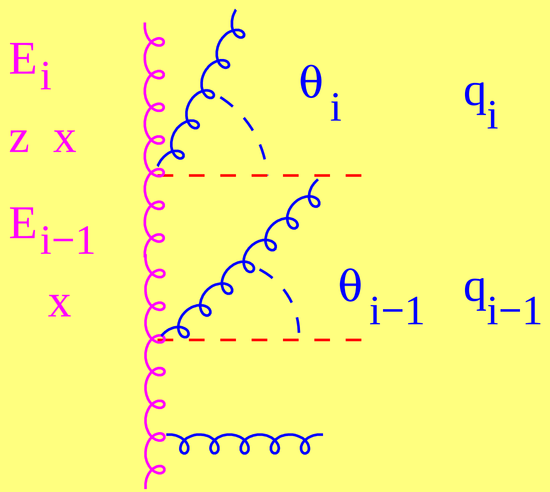

$$p_{ti} = |q_i^0| \sin\Theta_i, \quad z = \frac{E_i}{E_{i-1}}$$

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

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

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

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

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

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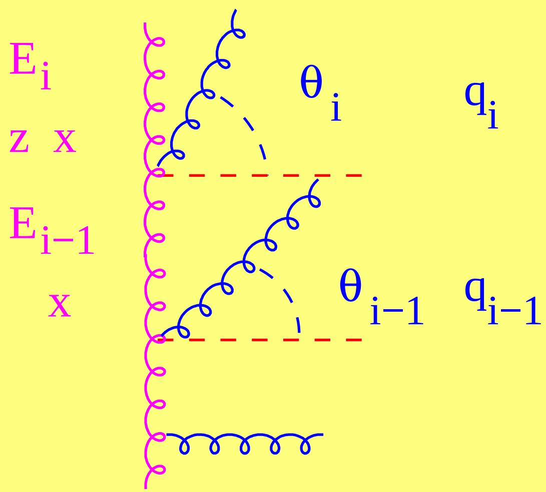


in lab. frame

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

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

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

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

WOW

for small z no restriction in q: random walk in 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: $\tilde{P}(z,q,k_t) = \frac{\bar{\alpha}_s(q(1-z))}{1-z} + \frac{\bar{\alpha}_s(k_t)}{z}\Delta_{\textbf{ns}}(z,q,k_t)$

Sudakov $\Delta_s(a,b)$: **probablility 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**

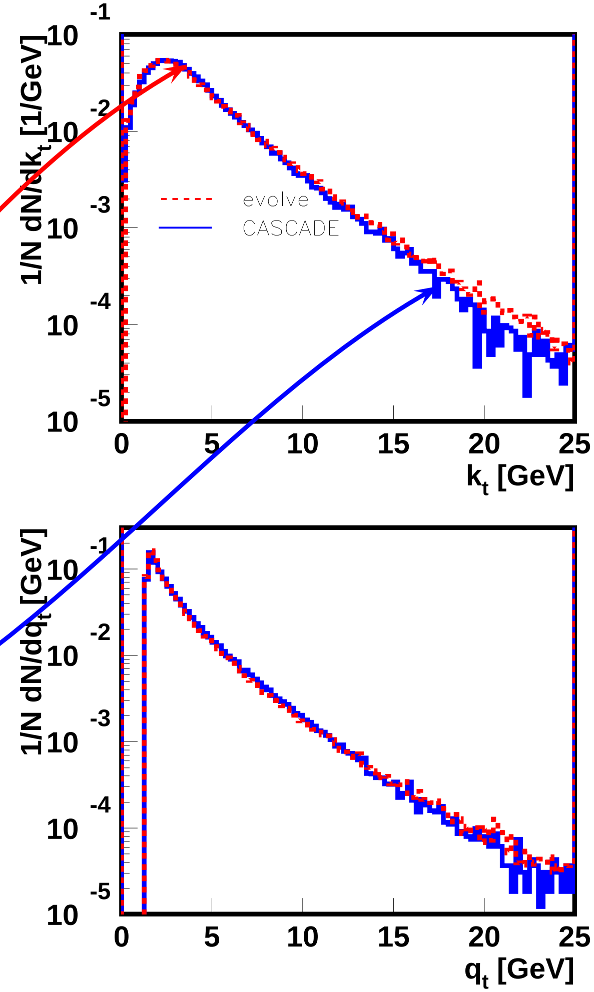
$\to$ **no restriction on q_i**

large x

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

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



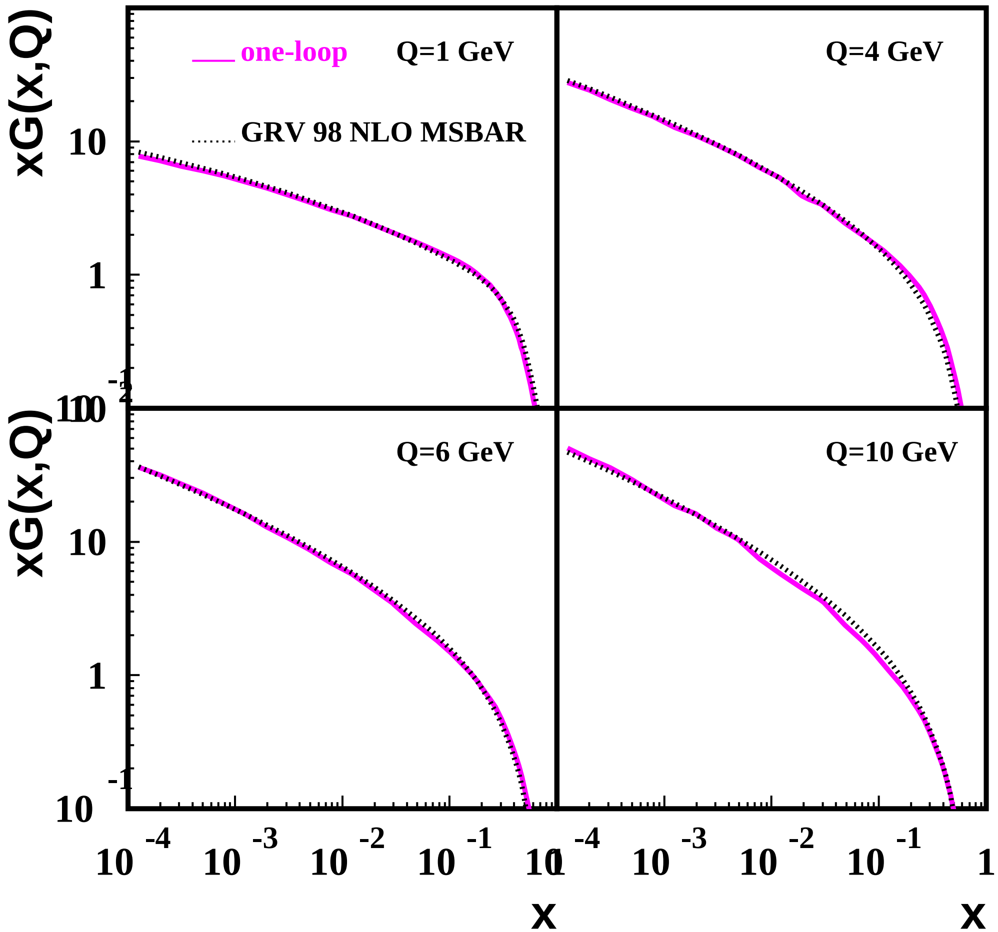
evolution - MC parton shower comparison
never shown for DGLAP type MC's!!!

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** $p\bar{p}$

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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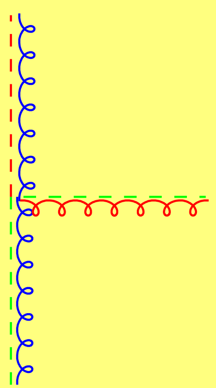

$\bar{\alpha}_{\rm s}(k_t)\frac{1}{z}\Big[\ 1$

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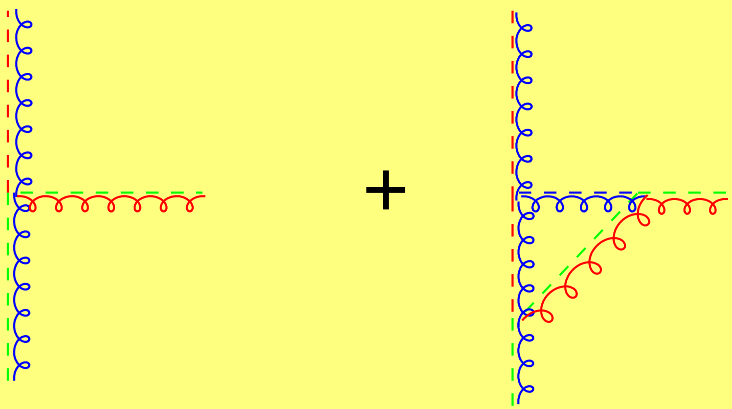

$$\bar{\alpha}_{\mathrm{s}}(k_t)\frac{1}{z} \Big[\; 1 \quad + \quad \bar{\alpha}_{\mathrm{s}} \log\left(\frac{z}{z_0}\right) \log\left(\frac{k_t^2}{z_0 z q^2}\right)$$

Non-Sudakov and all - loop resummation

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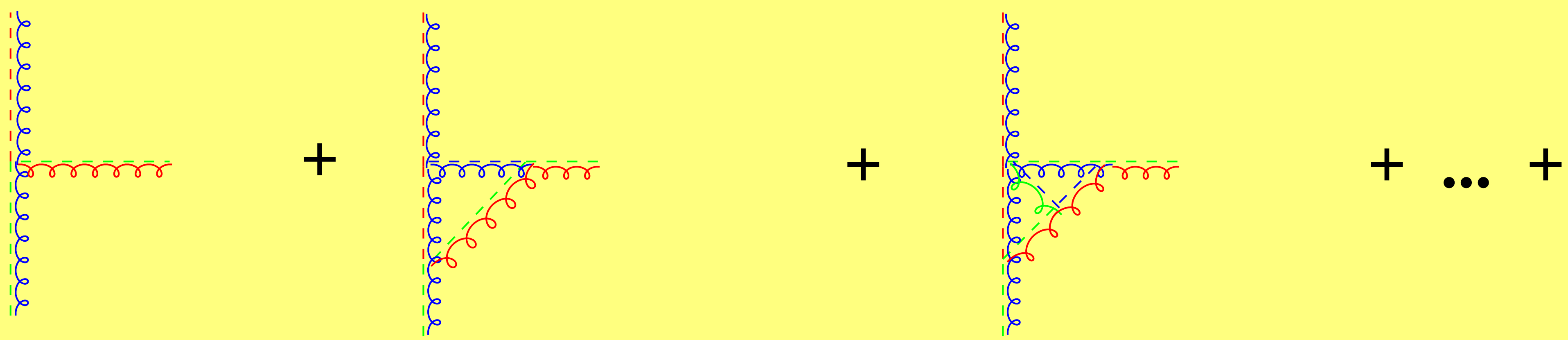


$$\bar{\alpha}_{\rm s}(k_t)\frac{1}{z}\left[\,1 \quad + \quad \bar{\alpha}_{\rm s}\log\left(\frac{z}{z_0}\right)\log\left(\frac{k_t^2}{z_0 z q^2}\right) + \frac{1}{2!}\left(\bar{\alpha}_{\rm s}\log\left(\frac{z}{z_0}\right)\log\left(\frac{k_t^2}{z_0 z q^2}\right)\right)^2 \ldots\right]$$

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

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

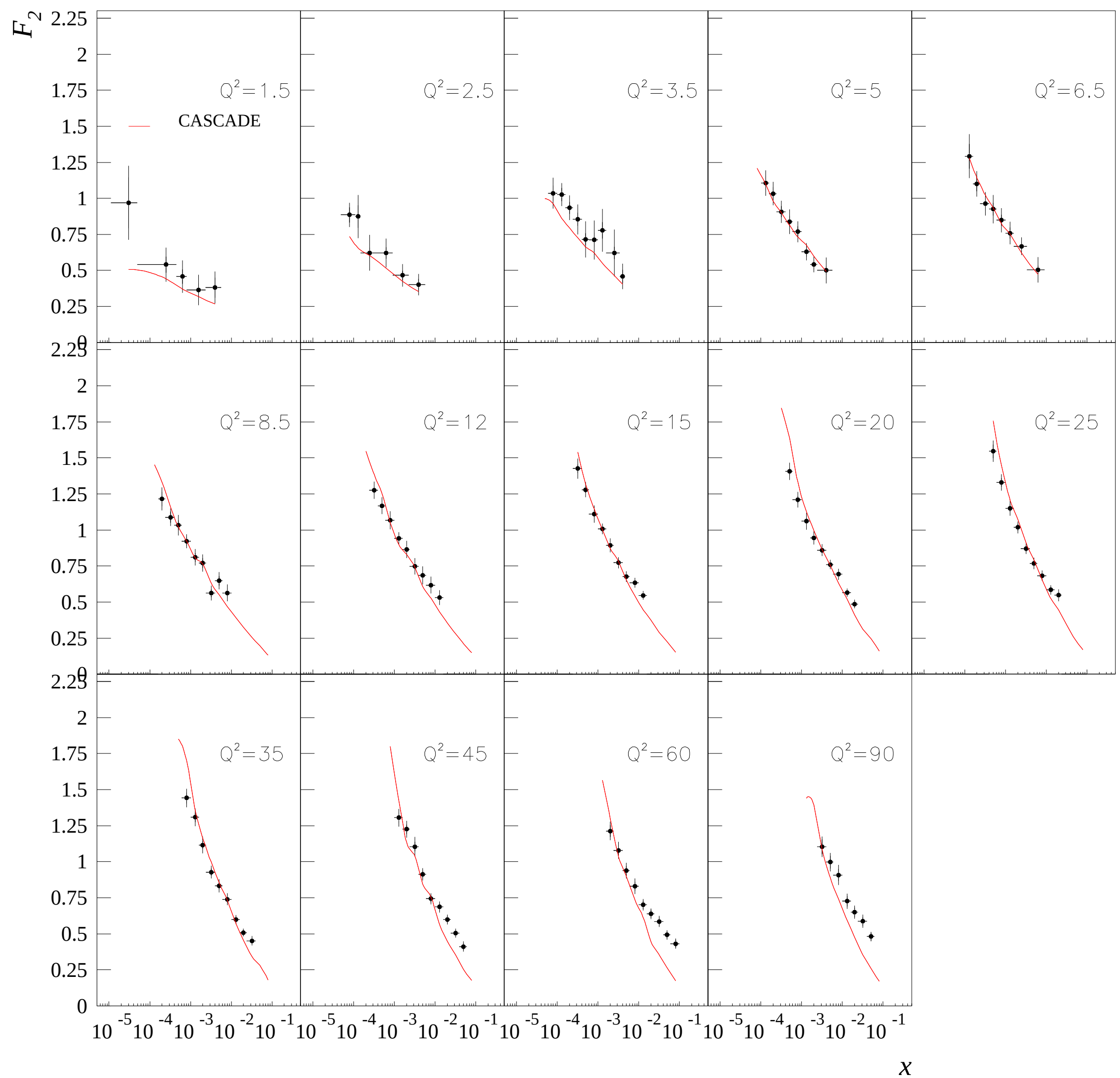
With $\sigma = \int dk_t^2 dx_g \mathcal{A}(x_g, k_t^2, \bar{q}) \sigma(\gamma^* g^* \to q\bar{q})$ fit $F_2(x, Q^2)$

(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: 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

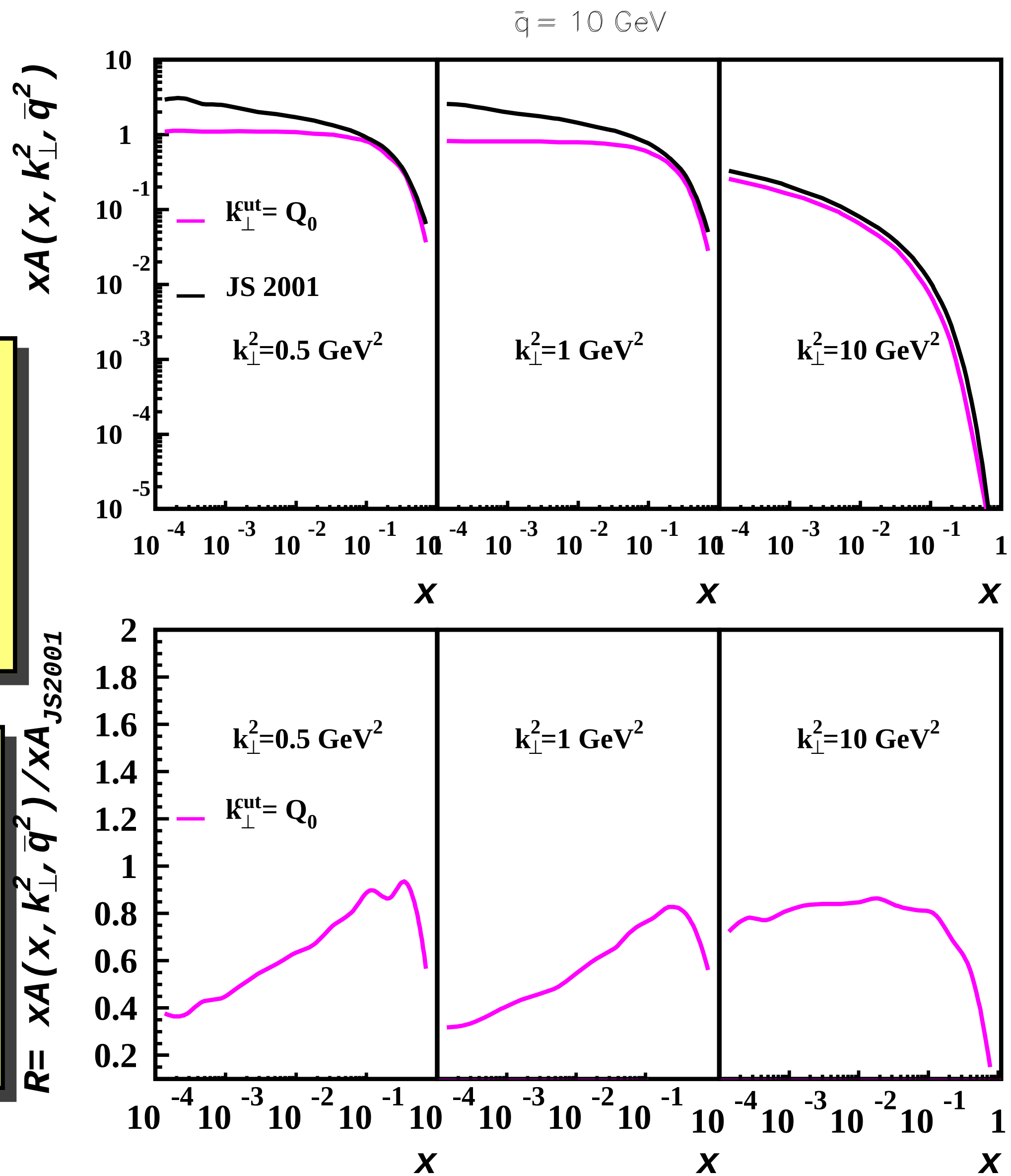
☚ saturation of x-section for $k_t < k_t^{cut}$

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

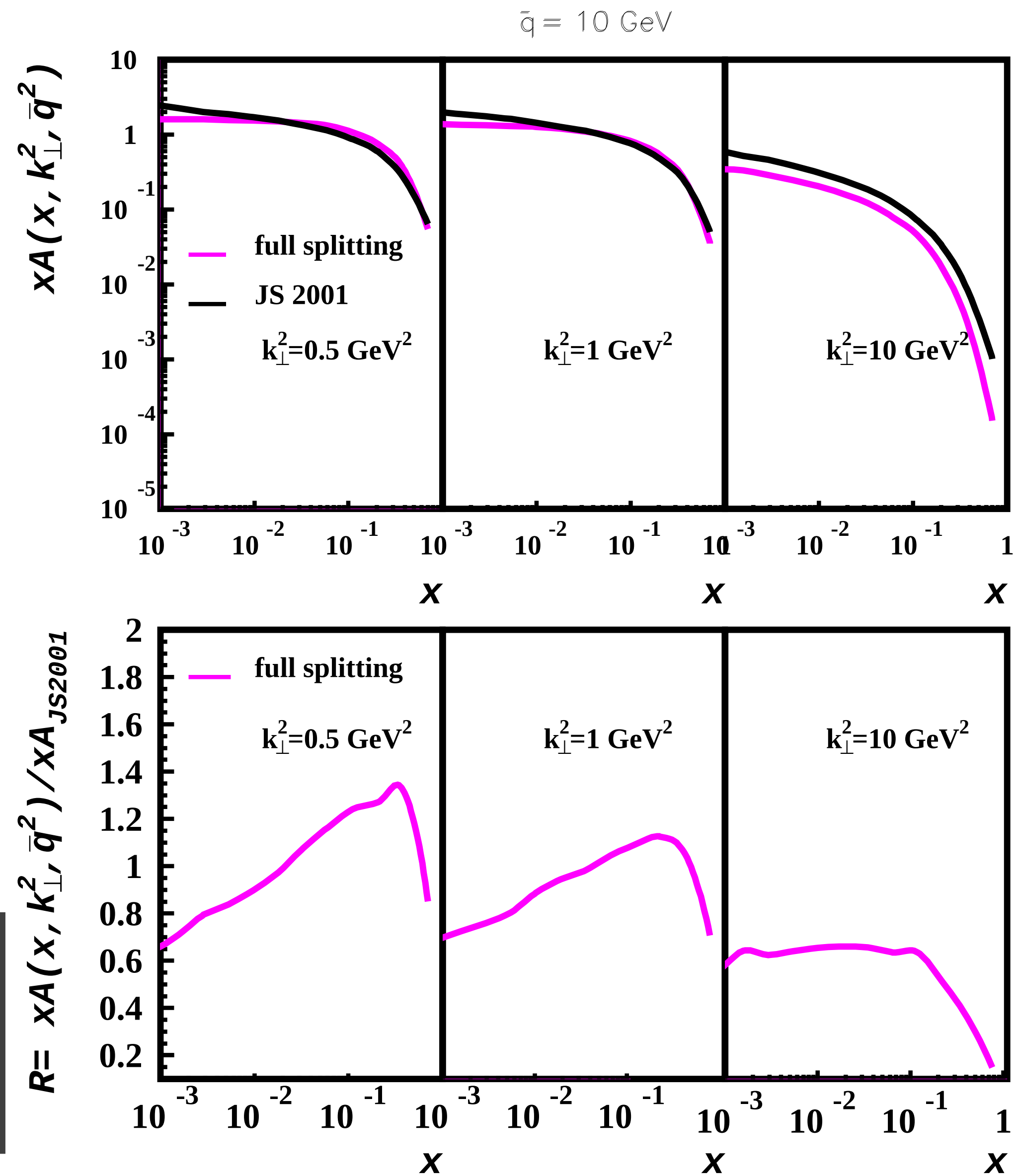


New fit: full splitting function

- 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



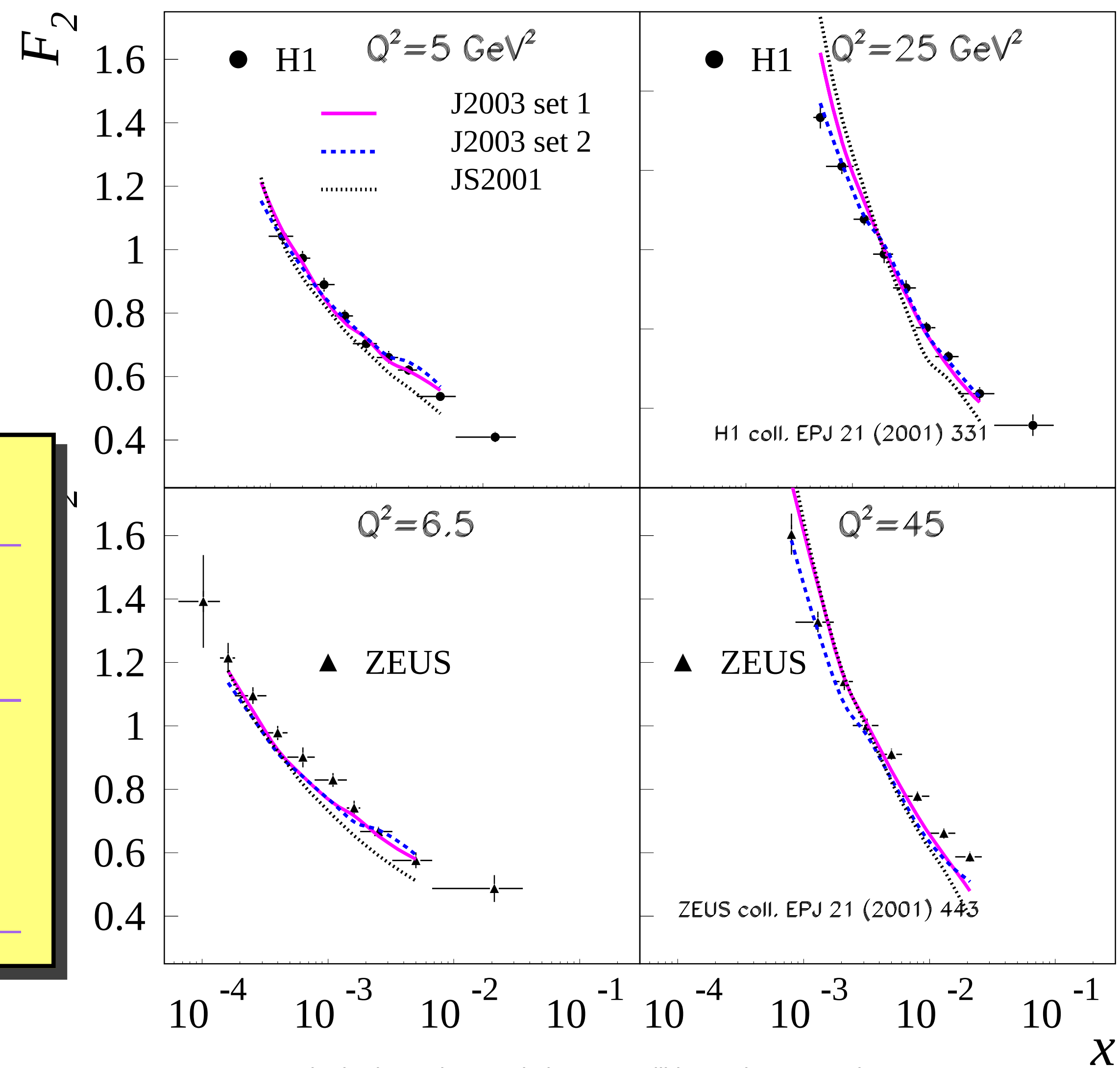
☛ **gluon pdfs are different**

☛ **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 $F_2(x,Q^2)$

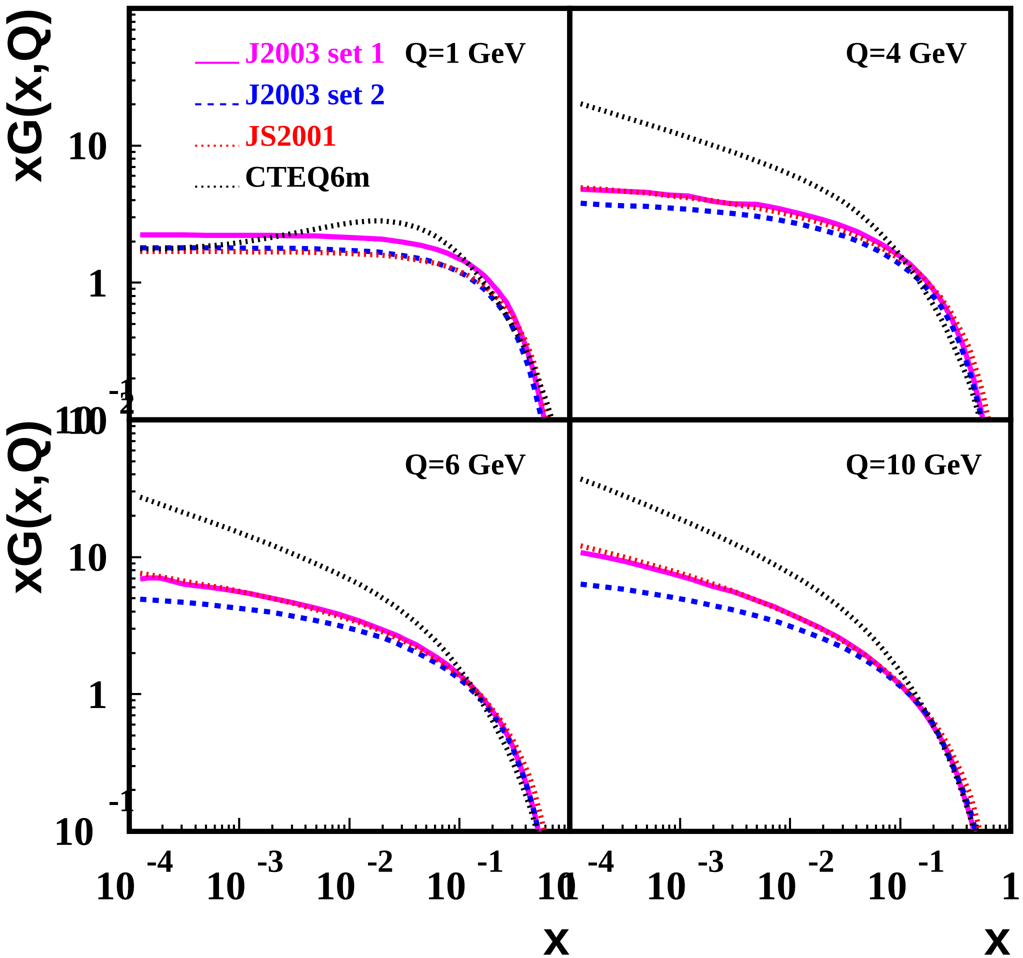
- more precise data:
  H1 NPB 470 (1996) 3., EPJ 21 (2001) 331.
  ZEUS ZPC 72 (1996) 399., EPJ 21 (2001) 443.
- fit $Q^2 > 4.5$ GeV^2, $x < 0.005$
- small k_t - region ?
- full splitting function ?



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:

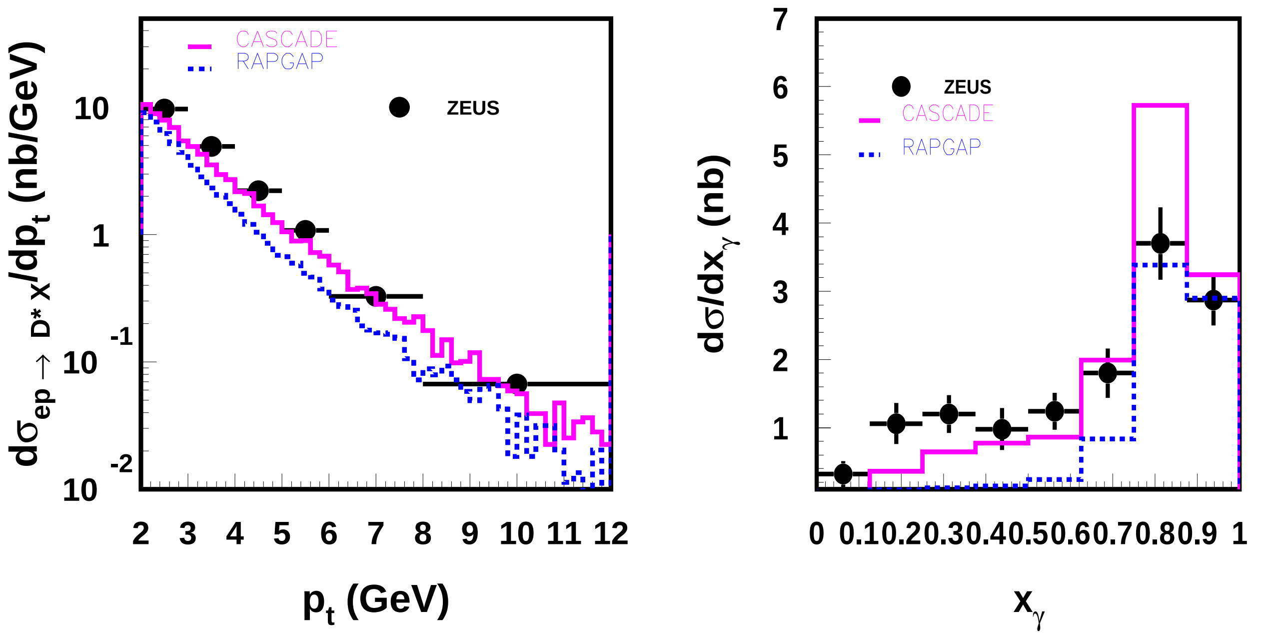
- steep rise at small x

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

Charm in γp

D^* **photo - production** (ZEUS Coll. *EPJC* 6 (1999) 67)

➤ p_t **and** η **spectra well described in normalization and shape**



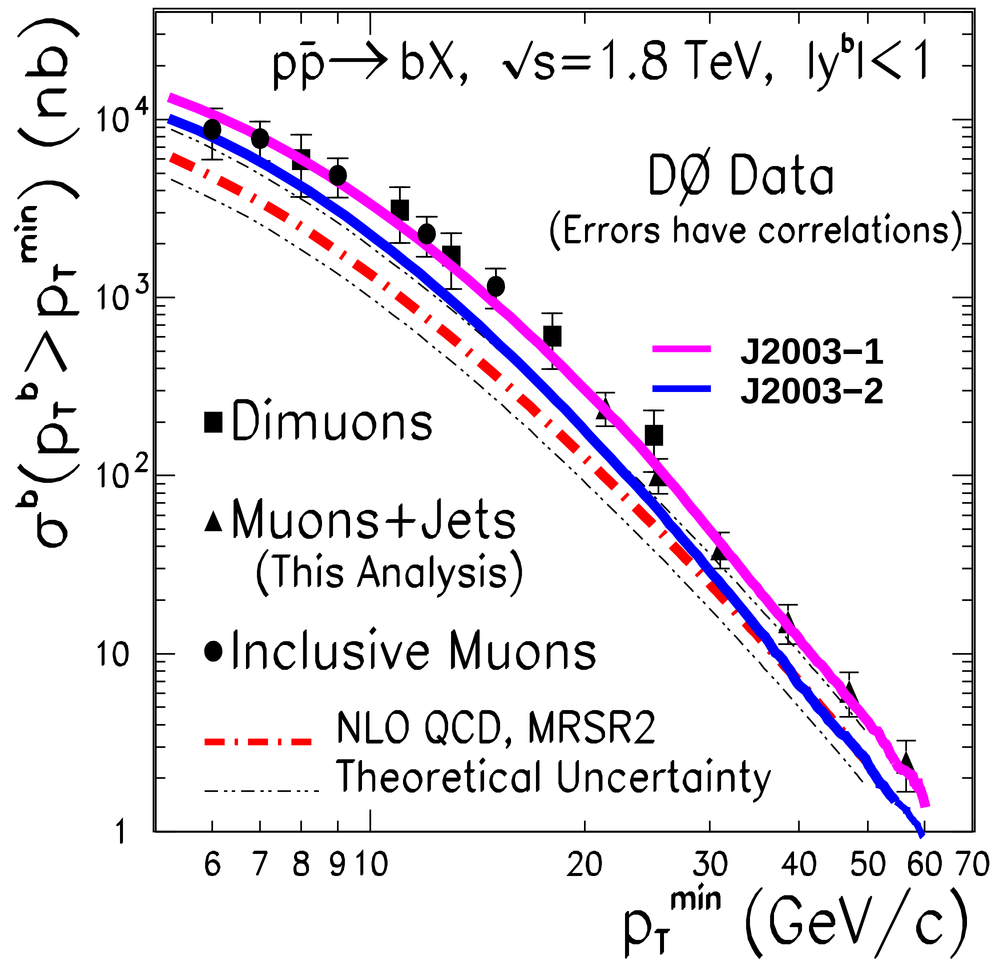
- k_t **factorization includes already anomalous** γ **component**
- **no additional free parameters**
- **only** $m_c = 1.5$ **GeV and fragmentation function**

Solution to the problem: $b\bar{b}$ production at Tevatron

Test universality of unintegrated gluon density from HERA

- use unintegrated gluon from F_2 fit at HERA
- use off-shell matrix element for $g^*g^* \to b\bar{b}$ with $m_b = 4.75$ GeV.
- set with singular terms ok
- even with full splitting fct ok

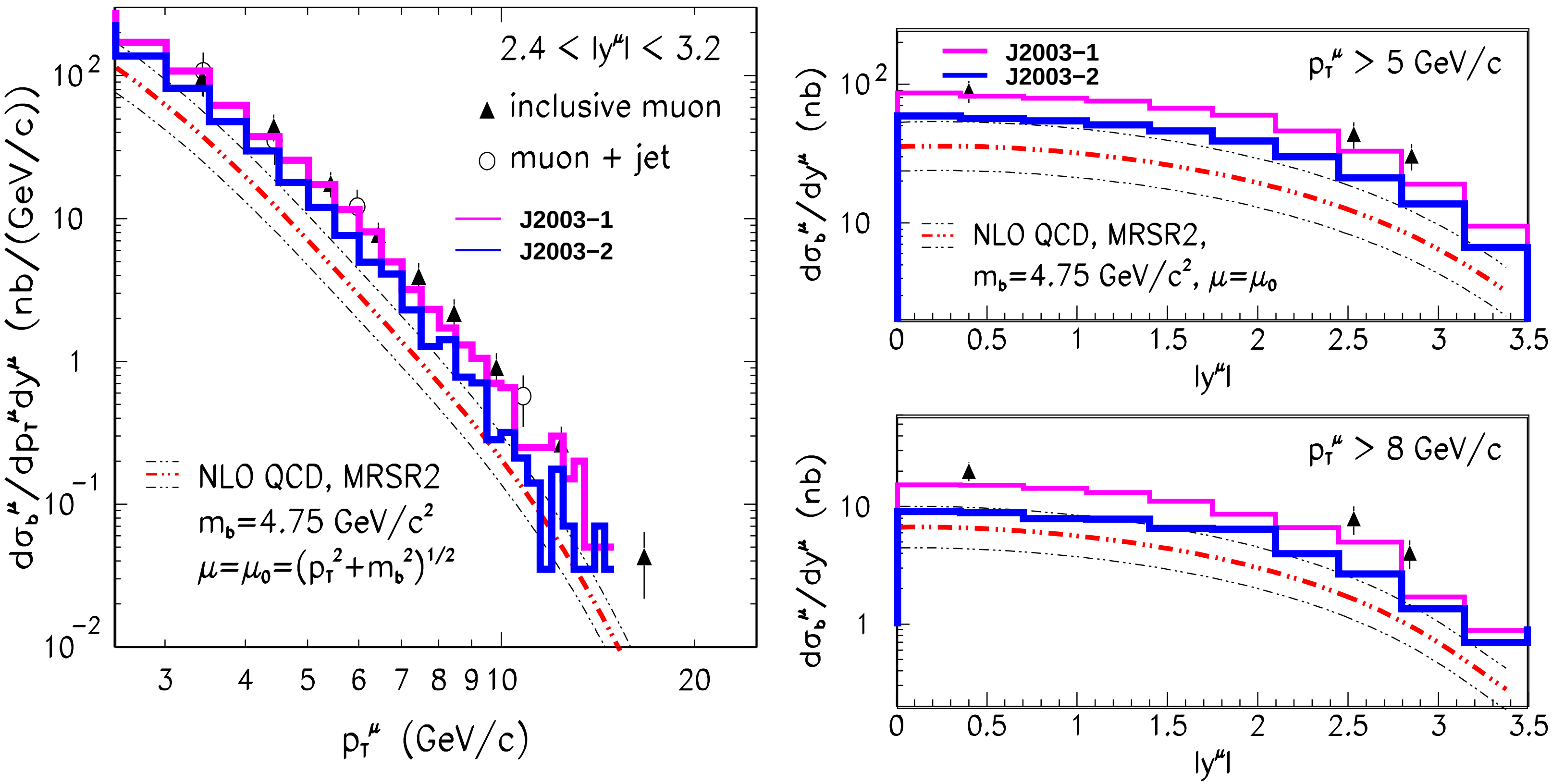
NOTE NLO off by factor 2



CASCADE w/o additional free parameters

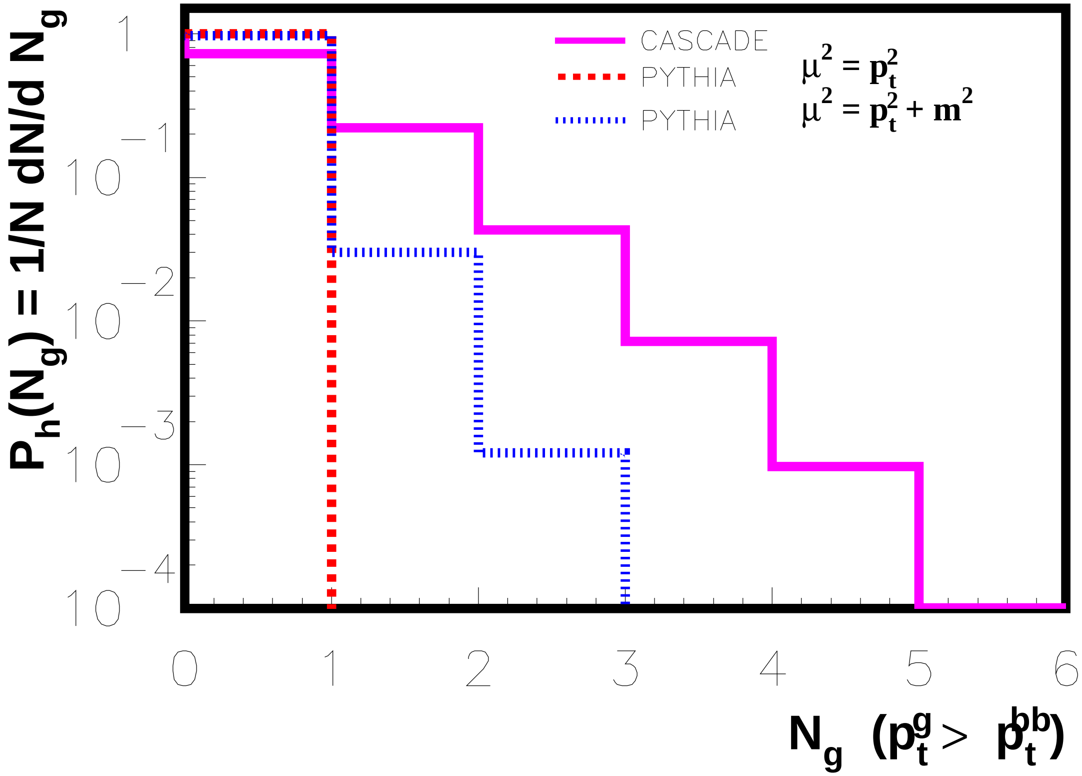
Solution to the problem: $b\bar{b}$ production at Tevatron

data from: D0 Collaboration B. Abbott et al., *Phy.Rev.Lett* 84 (2000) 5478



- CASCADE describes μ spectrum over huge range well
- NLO fails by factor $\sim$ 2 (central) and $\sim$ 4 (forward)

Why does k_t-factorization help for $b\bar{b}$ production at Tevatron



estimate higher order corrections

Nr of gluons with $p_t > p_t^{b\bar{b}}$

LO: $\mathcal{O}(\alpha_s^2) \to N_g = 0$

NLO: $\mathcal{O}(\alpha_s^3) \to N_g = 1$

NNLO: $\mathcal{O}(\alpha_s^4) \to N_g = 2$

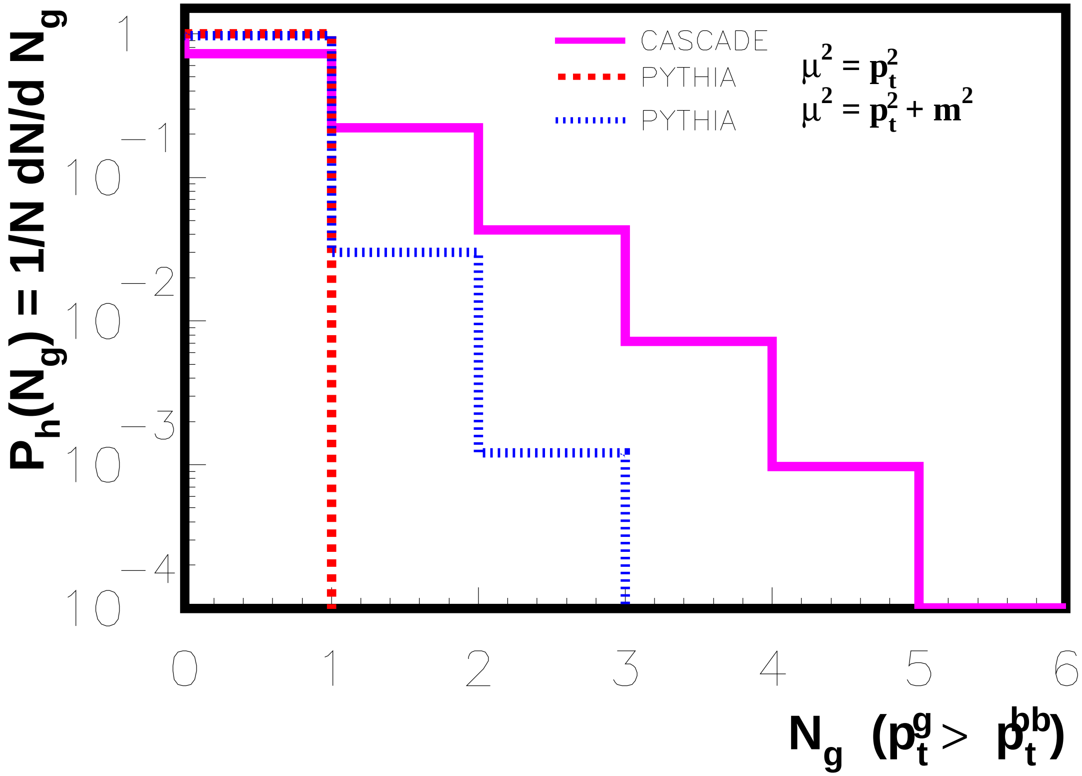
.....

.....

CASCADE $\to \mathcal{O}(\alpha_s^6)$

CASCADE with k_t factorization for estimation of higher order corrections

Why does k_t-factorization help for $b\bar{b}$ production at Tevatron



- recent calc using MC@NLO (Webber, Frixione et al.)
- parton shower in add to NLO increases Xsect (priv.comm.)
- now at 20 % level agreement with D0 data ...
- after years
  .... same result as CASCADE

.....

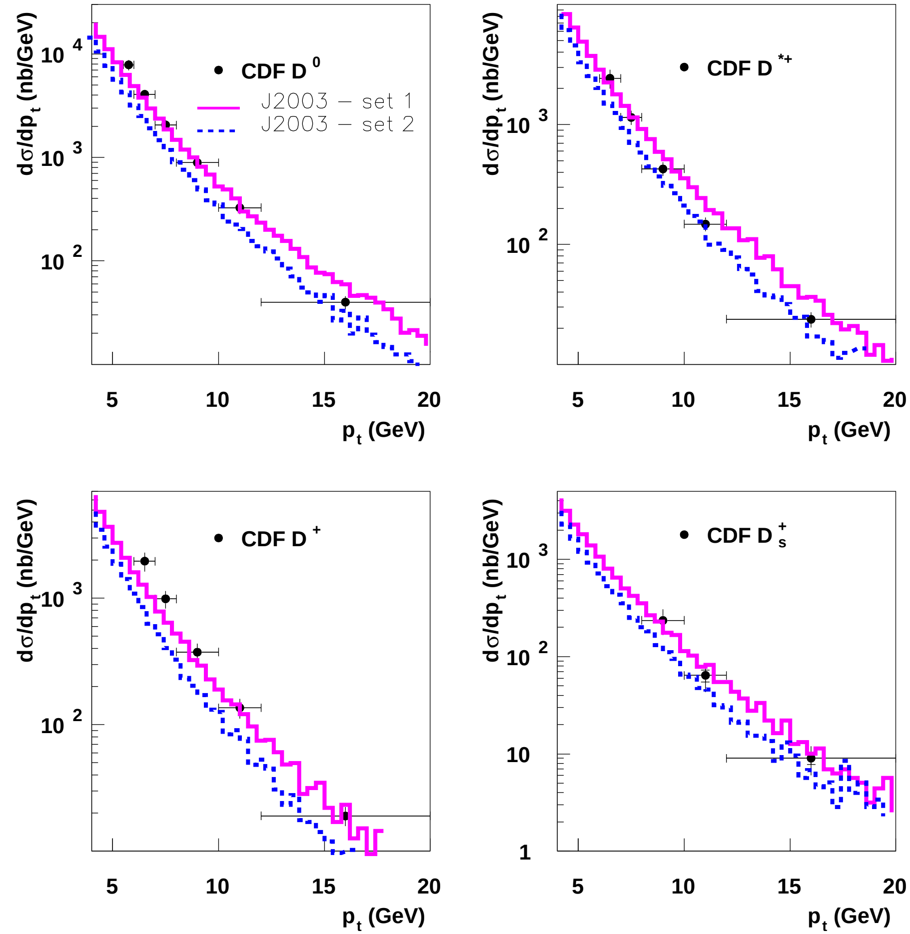
CASCADE $\rightarrow \mathcal{O}(\alpha_s^6)$

CASCADE with k_t factorization for estimation of higher order corrections

Solution to the problem: charm production at Tevatron

data from: CDF Collaboration D. Acosta et al., hep-ex/0307080

- measure charmed mesons in $|y| < 1$
- NLO by 100 - 50 % below data
- same model as for $b\bar{b}$
- similar problems as in $b\bar{b}$



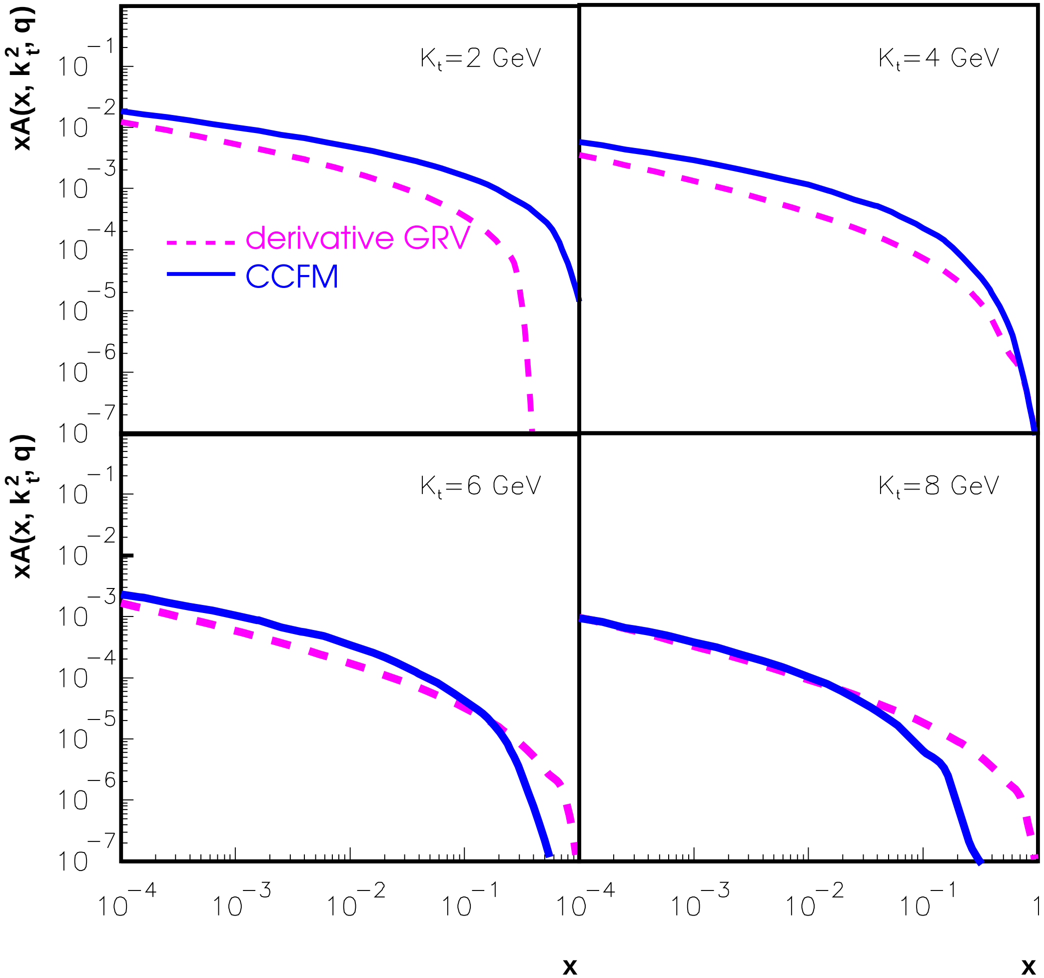
- set with singular terms ok
- set with full splitting fct smaller but still larger than NLO

Success for CASCADE with k_t factorization !!!

Un-integrated Gluon Density of Photon

together with M. Hansson

- test machinery with one-loop (DGLAP)
- use gluon in photon from GRV as input
  use normalization at input scale
- apply CCFM evolution (sing. terms only)
  with parameters obtained from proton ($Q_0 = 1.4$ GeV)

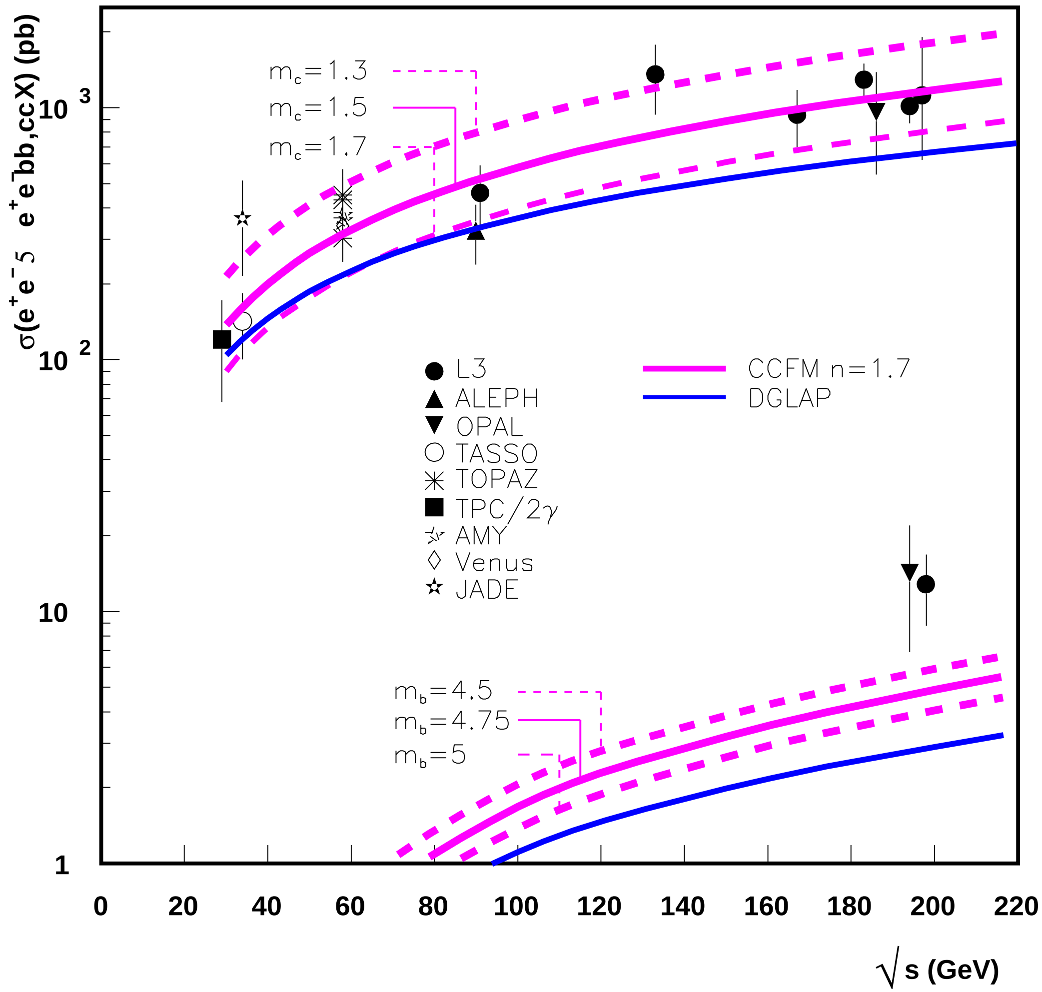


First un-integrated gluon density of real photon with full CCFM evolution

$\gamma\gamma \to b\bar{b}$

together with M. Hansson

- use matrix elements in k_t -factorization
  - $\gamma\gamma \to b\bar{b}$
  - $\gamma g \to b\bar{b}$
  - $gg \to b\bar{b}$
  - universality...



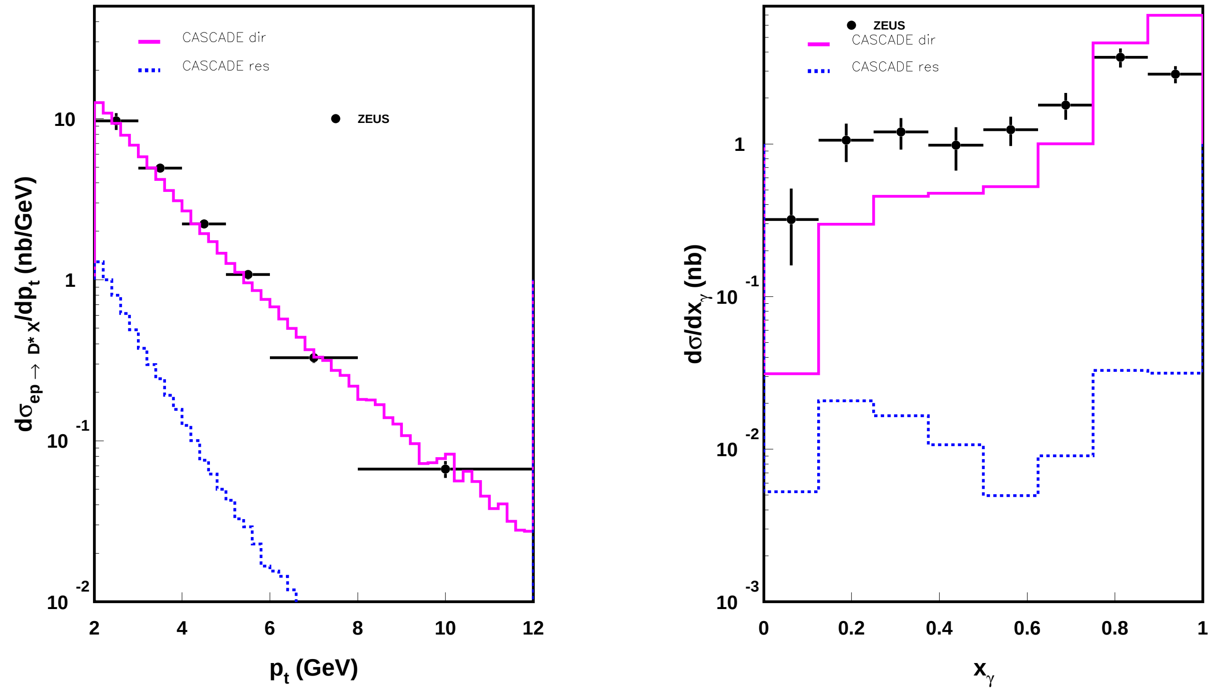
- **compare k_t -factorization & CCFM with NLO:**
- **using norm. from pdf**
  - **CCFM similar to NLO**
- **determine norm. for gluon from charm ($n = 1.7$ for res.γ)**
  - **CCFM larger than NLO**

BUT still low for $\gamma\gamma \to b\bar{b}$

Charm in γp including resolved γ

D^* photo - production (ZEUS Coll. *EPJC* 6 (1999) 67)

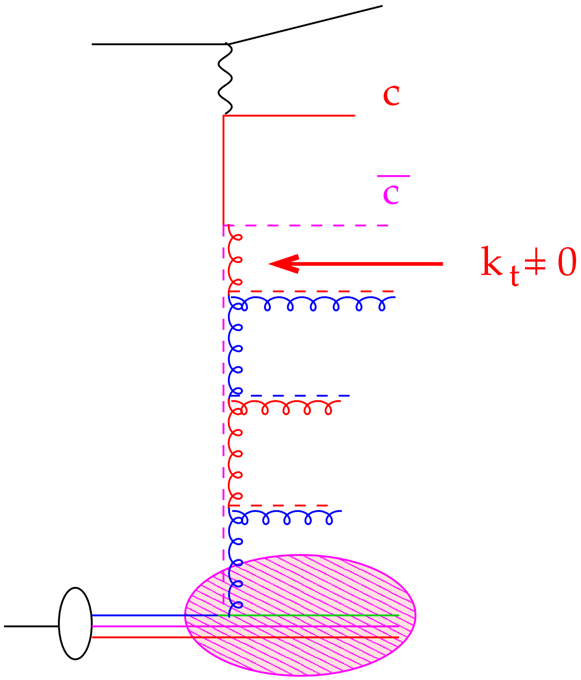
- use unintegrated gluon of γ
- use $gg \to Q\bar{Q}$

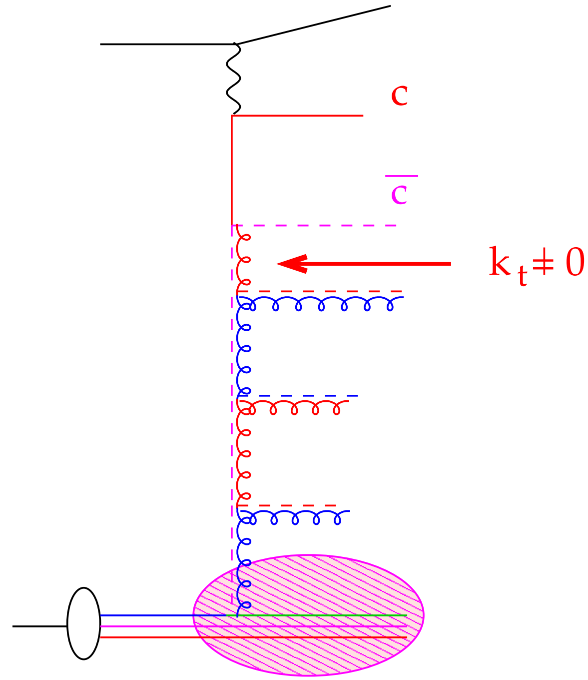


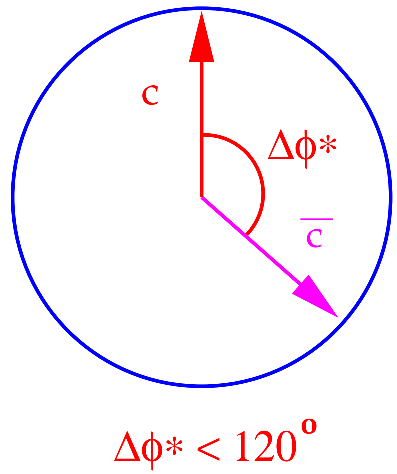
- in direct mode k_t factorization includes already anomalous γ component
- only small contribution from $gg \to Q\bar{Q}$

Unintegrated gluon density with heavy quarks

- identify both charm quarks
- reconstruct x_g
- reconstruct $\bar{q} = x_g \sqrt{s \Xi}$ with $\Xi = \exp(-2\eta^{c\bar{c}})$ in ep cms





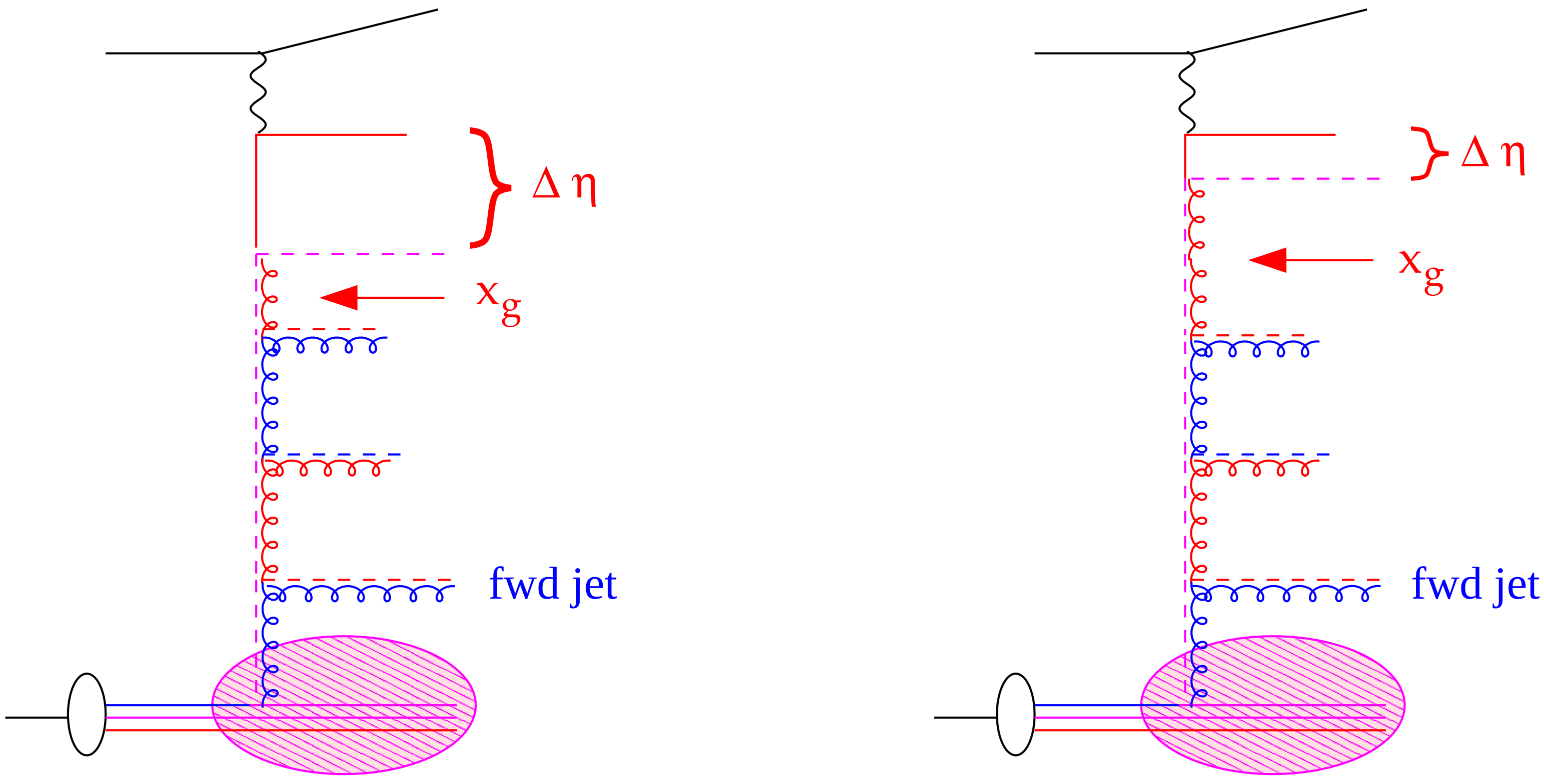


- **reconstruct** $k_t = p_\perp^c + p_\perp^{\bar{c}} - p_\perp^\gamma$

- **reconstruct** $S(x, Q^2, \Delta\Phi) = \frac{\int_0^{120^o} d\sigma d\Phi}{\int_0^{180^o} d\sigma d\Phi}$

Forward jets and charm

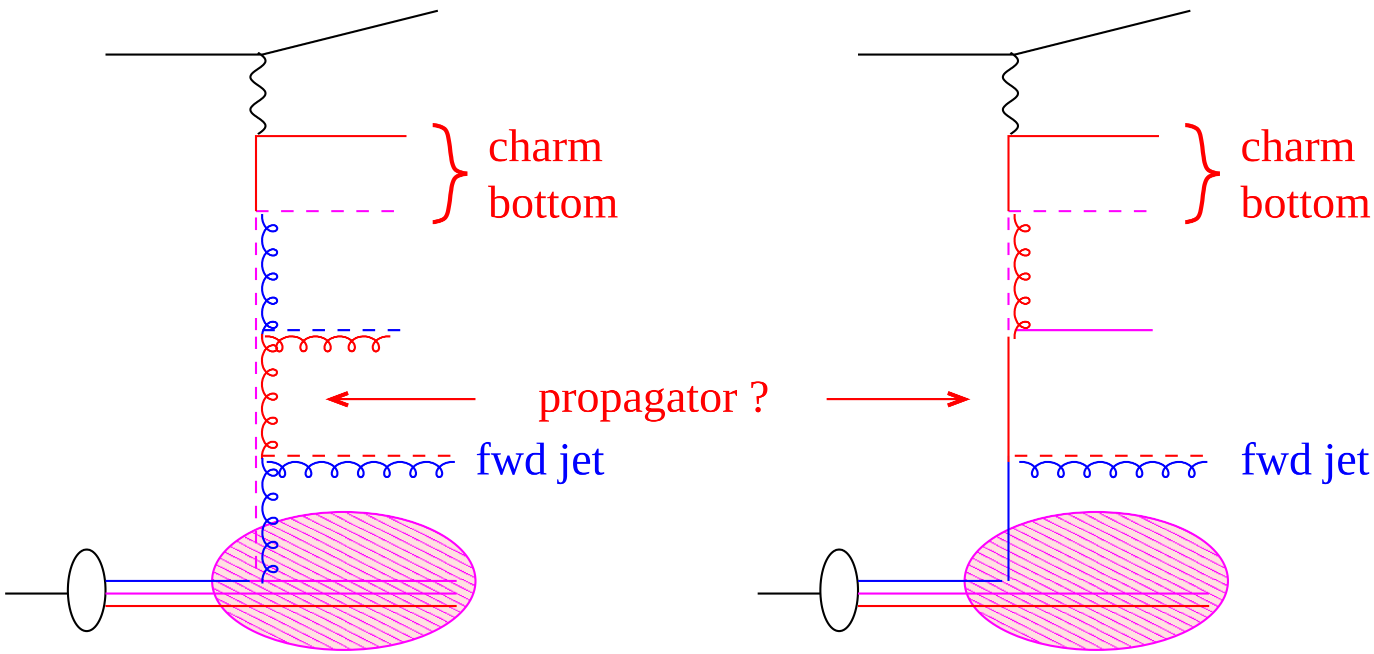
- identify both charm quarks, measure $\Delta\eta^{c\bar{c}}$, small $\Delta\eta^{c\bar{c}}$ ☞ small x_g
- measure $\Delta\eta^{c\bar{c},jet} = \eta^{c\bar{c}} - \eta_{fwd\,jet}$, small $\Delta\eta^{c\bar{c}}$, large $\Delta\eta^{c\bar{c},jet}$



investigate small x effects with heavy quarks...

Differentiate unintegrated density quarks and gluons

- **identify one or both charm quarks reconst. 4 jets (incl. c-jets)**
- **measure $\cos\theta^*$ ... test propagator in initial state cascade !!!**



- **measure contribution of quark initiated charm production**
- **measure unintegrated quark density**

The Beginning, Not the End

- k_t - factorization very successful
  - unintegrated gluon density from CCFM
  - precision fits to F_2, including full splitting fct
  - describes measurements at HERA
  - even where collinear NLO fails
  - works also for charm and bottom in $p\bar{p}$
  - attempts also for bottom in $\gamma\gamma$
  - resummation to all orders helps ....
- investigate details of initial state radiation with heavy quarks
  - chance for very small x_g
  - new effects beyond DGLAP
  - unintegrated pdfs for quarks and gluons

The Beginning, Not the End

k_t - factorization and unintegrated pdfs

promising tool for calculation of higher orders

and correct event simulation at

HERA, Tevatron and **LHC**

Knowledge of unintegrated pdfs

important for Higgs production at

LHC

$b\bar{b}$ production in DIS at HERA: H1 and ZEUS

H1(prel.)

$2 < Q^2 < 100$ **GeV**^{2}, $0.1 < y < 0.8$,

$p_t^\mu > 2$ **GeV,** $35^o < \theta^\mu < 130^o$

visible x-section $ep \to e' b\bar{b}X \to \mu X$:

$\sigma = 39 \pm 8(stat.) \pm 10(syst.)$ pb

NLO: $\sigma = 11 \pm 2$ **pb**

CASCADE $\sigma(ep \to e' b\bar{b}X) = 15$ pb

R_{MC}(**H1**) $= \frac{\sigma_{measured}}{\sigma_{MC}} = 2.6$

ZEUS(prel.) **ICHEP 2002**

$Q^2 > 2$ **GeV**^{2}, $0.05 < y < 0.7$,

$E_{T,jet}^{Breit} > 6$ **GeV,** $-2 < \eta_{jet}^{lab} < 2.5$

$p^\mu > 2$ **GeV,** $30^o < \theta^\mu < 160^o$

x-section $ep \to e' b\bar{b}X \to e' jet \mu X$:

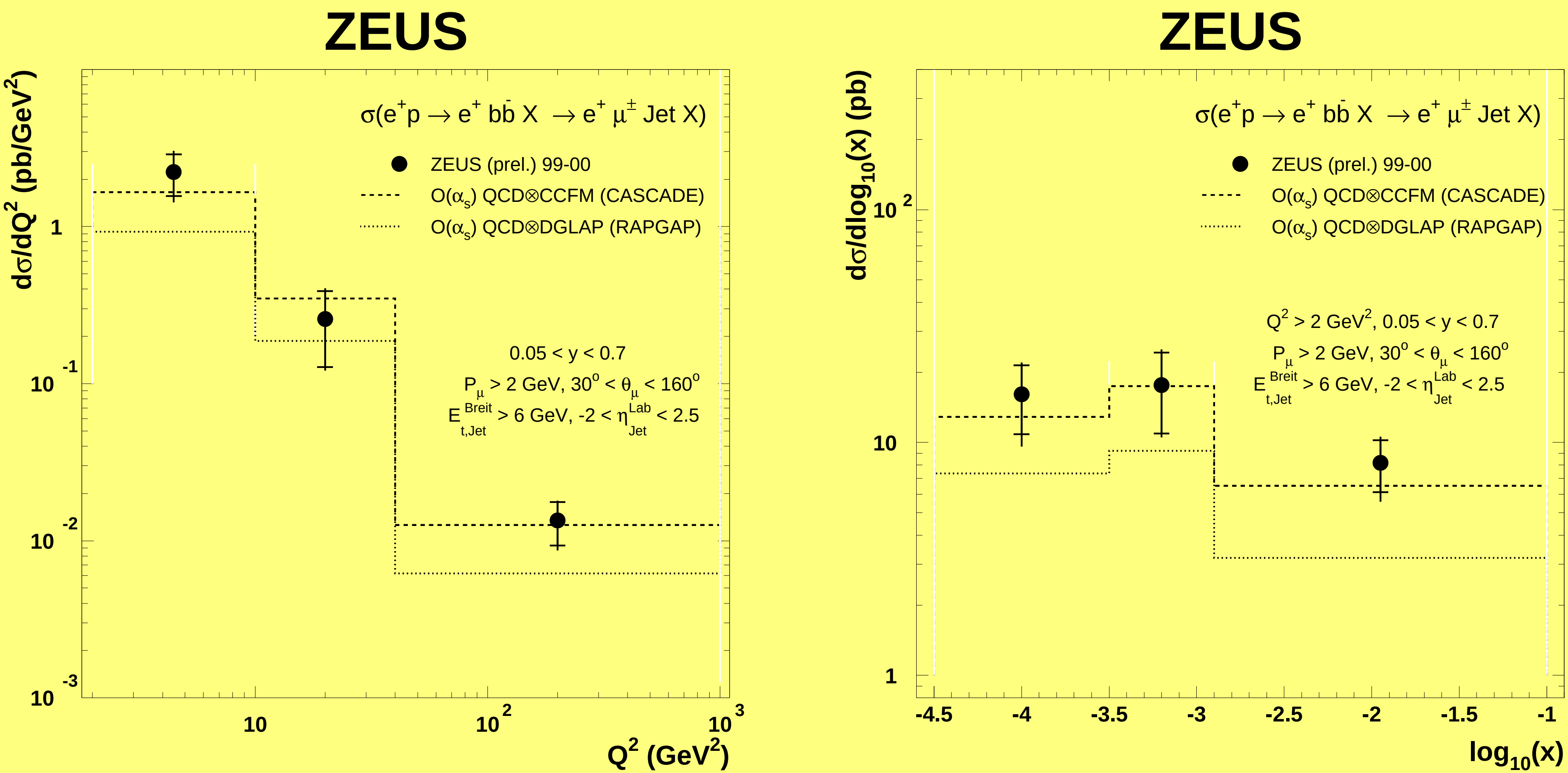
$\sigma = 38.7 \pm 7.7(stat.)^{6.1}_{5.0}(syst.)$ pb

NLO: $\sigma = 28.1 \pm 2$ **pb**

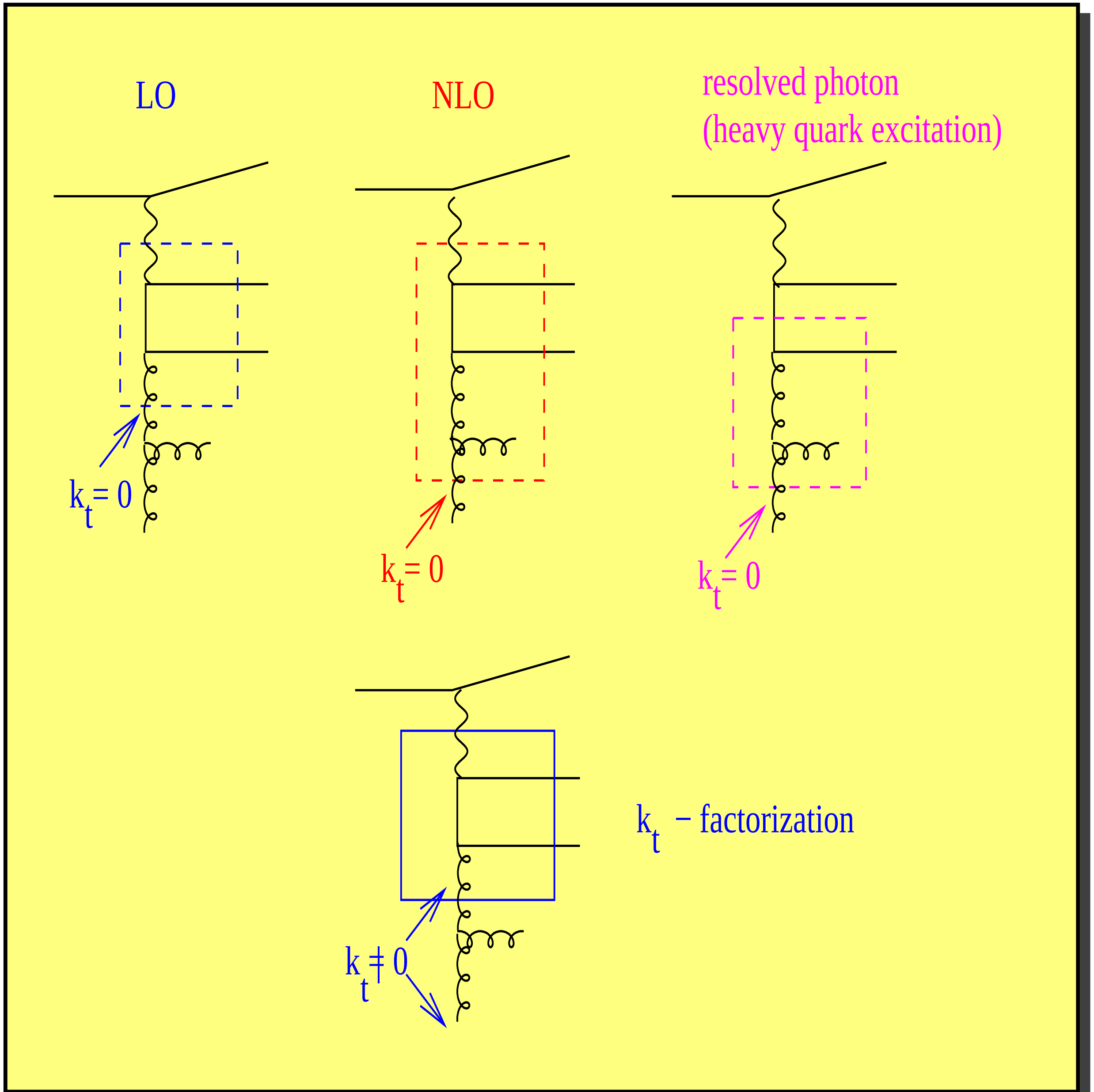
CASCADE $\sigma(ep \to e' b\bar{b}X) = 35$ pb

R_{MC}(**ZEUS**) $= \frac{\sigma_{measured}}{\sigma_{MC}} = 1.1$

$b\bar{b}$ production in DIS at HERA: ZEUS



Resolved - γ, NLO and k_t - factorization



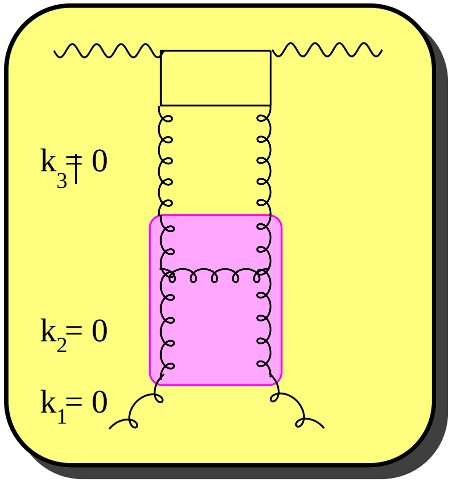
k_t factorization

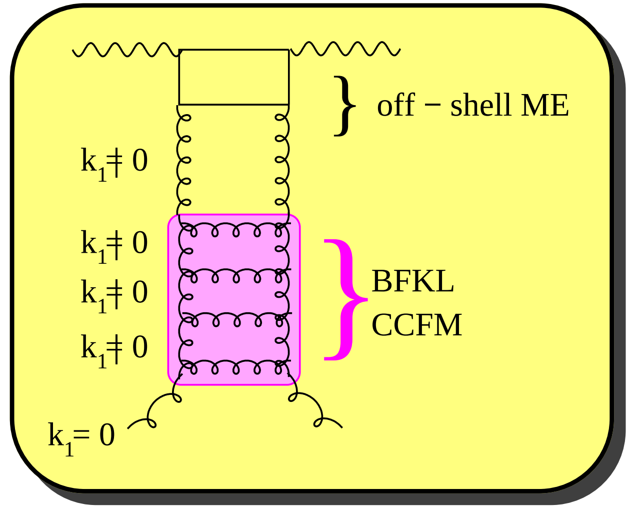
- **NLO corrections**
- **anomalous γ**
- **even in NLO**
- **includes NNLO**
- **includes NNNLO**
- **includes NNNNLO**

k_t factorization has no problem with:

- **negative weights....**
- **matching to PS**
- **matching to hadronsiation**

k_t - and collinear factorization





off - shell matrix element

➤ **1-loop correction to Born approximation**

➤ **high energy limit of NLO !!!**

$$\sigma = \int \frac{dz}{z} d^2 k_t \hat{\sigma}\left(\frac{x}{z}, k_t\right) \mathcal{F}(z, k_t)$$

$$\mathcal{F}(z, k_t) = \int \frac{dz}{z} \tilde{\mathcal{F}}(x/z, k_t; Q_0) \bar{f}_0(z, Q_0)$$

factorize k_t dependence in $\mathcal{F}$ and insert in σ

➤ **improved coefficient and splitting functions to all order**