Recent results from CCFM Evolution

dedicated to the memory of Jan Kwiecinski

H. Jung, University of Lund

ISMD03, Cracow, 8. Sept 2003

- where is the problem ?
  - hadronic final states - jets, heavy quarks - even at Tevatron
  - approximations
- doing it better !
  - CCFM equation, solution
  - implementation into new hadron level MC CASCADE and LDC
- solve problems, also for heavy quarks and even for Tevatron
- conclusion

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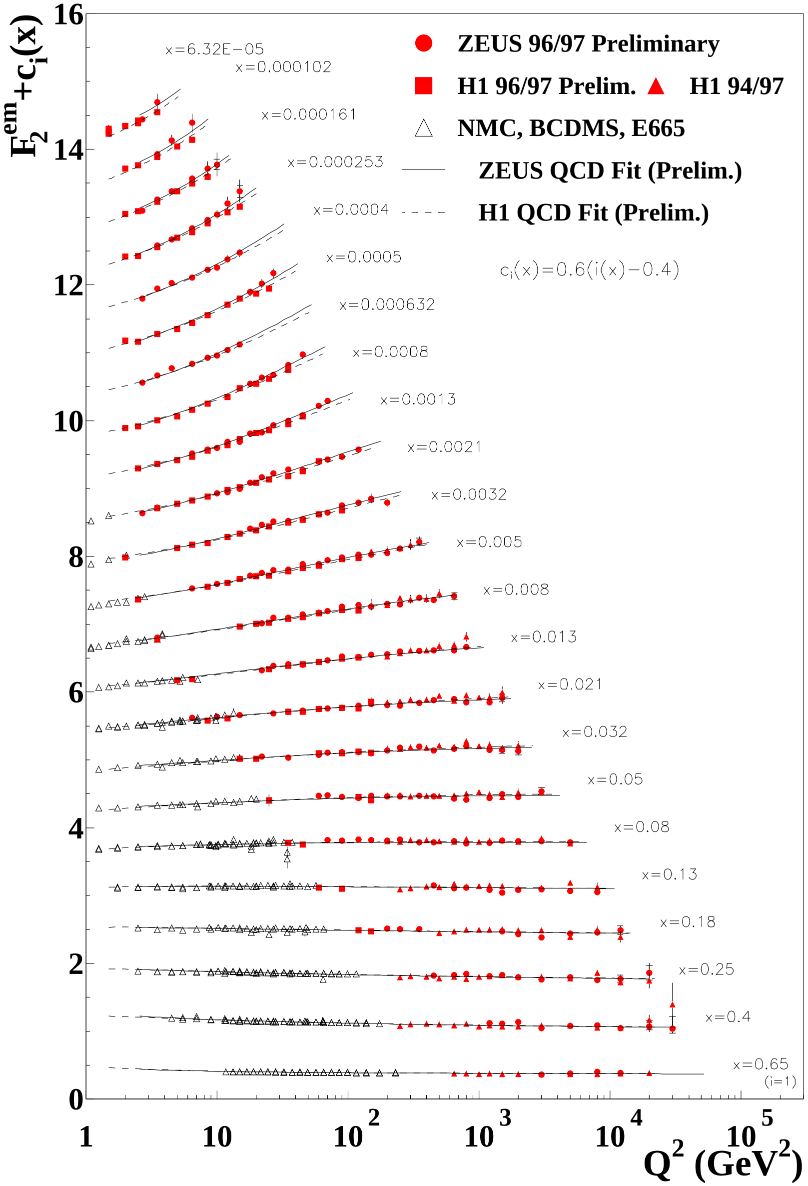
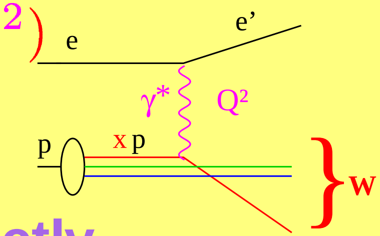
  approximations
- doing it better !
  CCFM equation, solution
  implementation into new hadron level MC CASCADE and LDC
- solve problems, also for heavy quarks and even for Tevatron
- conclusion
- many topics Jan had suggested and investigated:
  CCFM, unintegrated pdf, forward jets, ϕ decorrelation etc ...

The structure function $F_2(x, Q^2)$: DGLAP



$$F_2(x, Q^2) = \sum_i e_i^2 x q_i(x, Q^2)$$

$$x = \frac{Q^2}{W^2 + Q^2}$$



Scaling violations perfectly described with DGLAP:

$0.63 \cdot 10^{-5} < x < 0.65$

$1 < Q^2 < 25000$ **GeV²**

- **adjust input pdf to fit F_2 data**

BUT different sets: MRS, GRV etc

- **use extracted pdf to predict x - sections**
- **even at $p\bar{p}$**

BUT for reliable predictions at HERA II, HERA III, Tevatron, LHC etc

☛ **better understand pdf's**

Where is the problem ?
Bottom at HERA and Tevatron

HERA

ZEUS (ZEUS Coll. *EPJC* (2001))

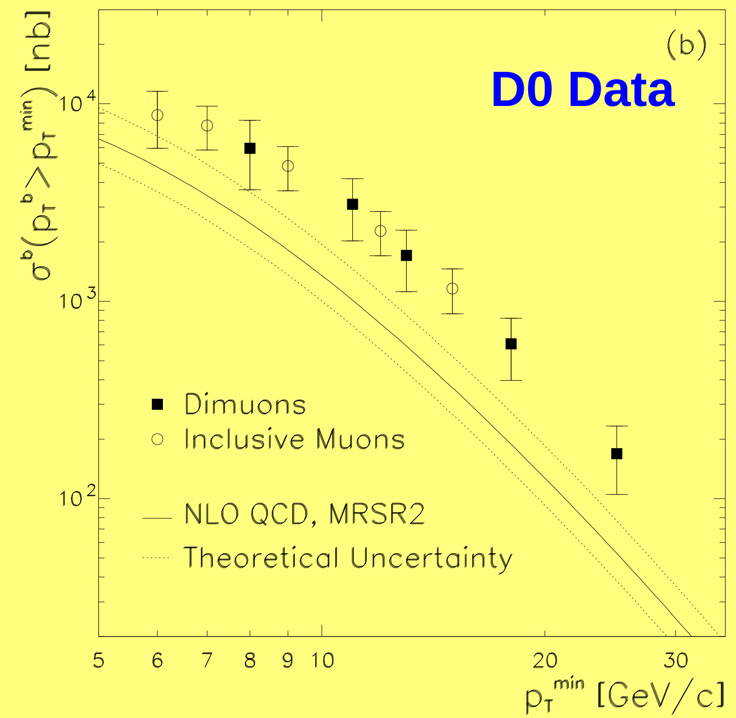
$Q^2 < 1$ **GeV**^{2}, $0.2 < y < 0.8$,

$p_t^b > 5$ **GeV**, $|\eta^b| < 2$

$\sigma = 1.6 \pm 0.4$**(stat.)**$^{+0.3}_{-0.5}$**(syst.)**$^{+0.2}_{-0.4}$**(ext.) nb**

NLO: $\sigma = 0.64^{+0.15}_{-0.1}$ **nb**

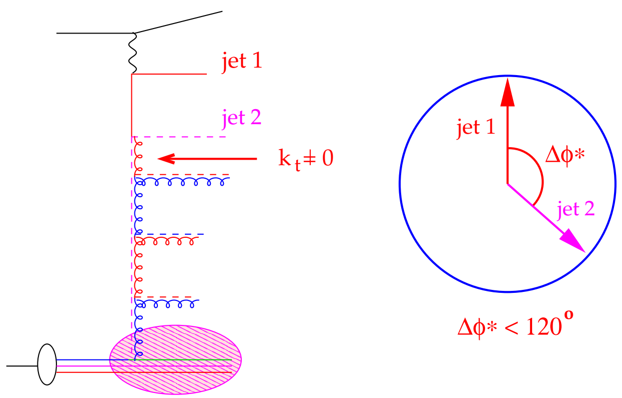
safe extrapolation from visible to total x-section ???



$b\bar{b}$ in photoproduction and hadroproduction:

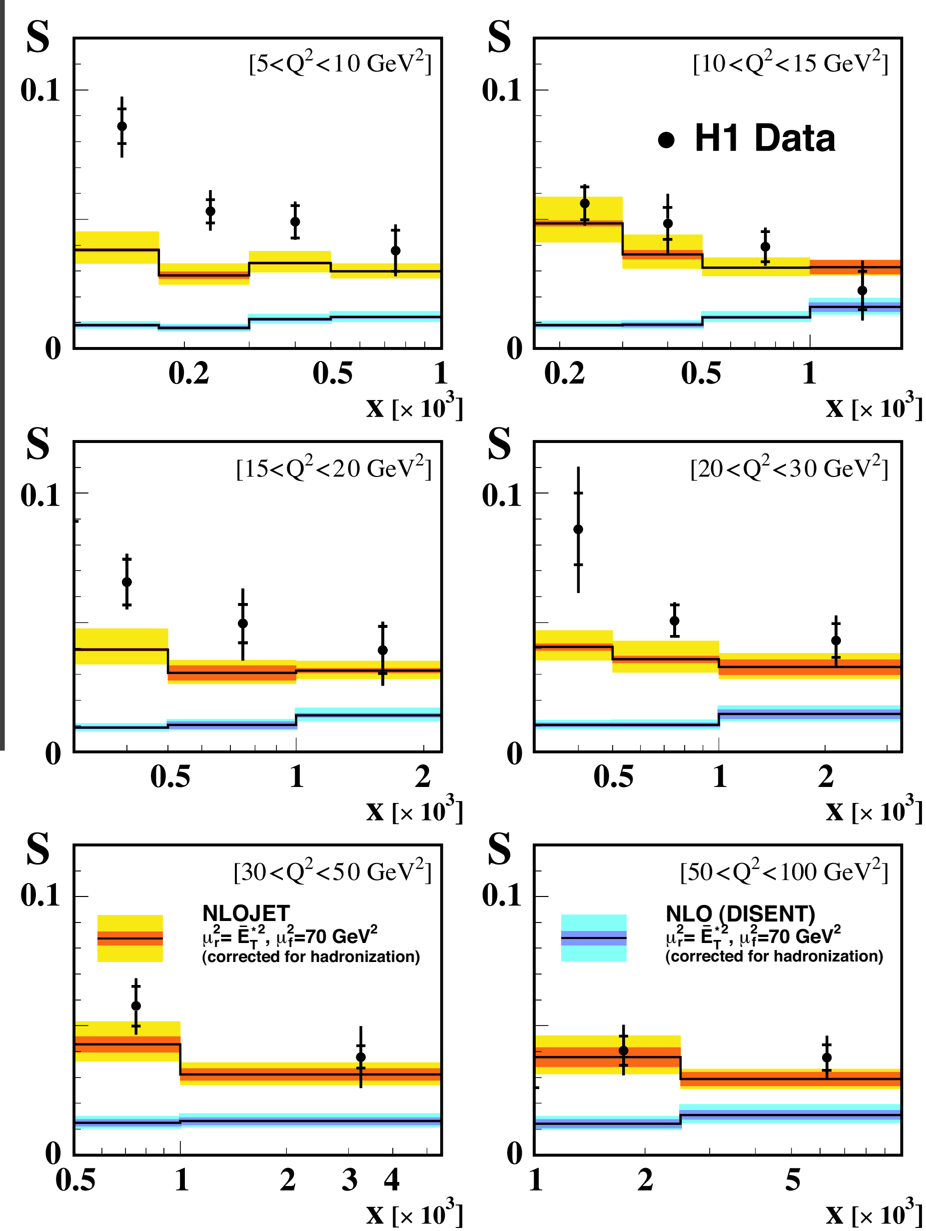
- ☛ **standard DGLAP with NLO calculation**
- ☛ $\sim$ **factor 2 - 4 too small !**

Where is the problem: Di - jets in DIS



- ϕ - decorrelation (J. Kwiecinski et al)
- Measurement of $\frac{d\sigma}{d\Delta\Phi}$ exp. difficult
- Measure (A. Szczurek):

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

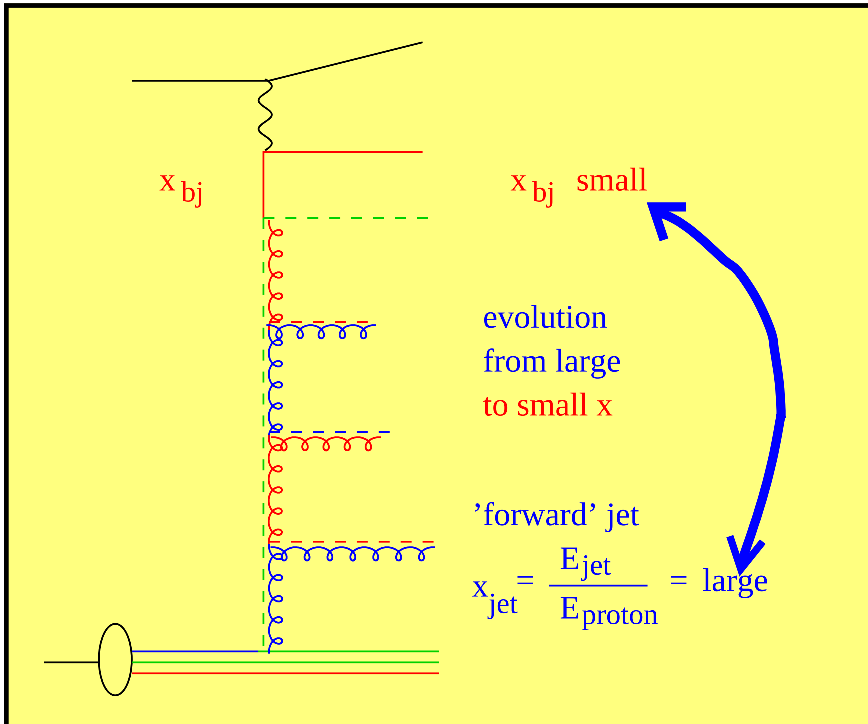


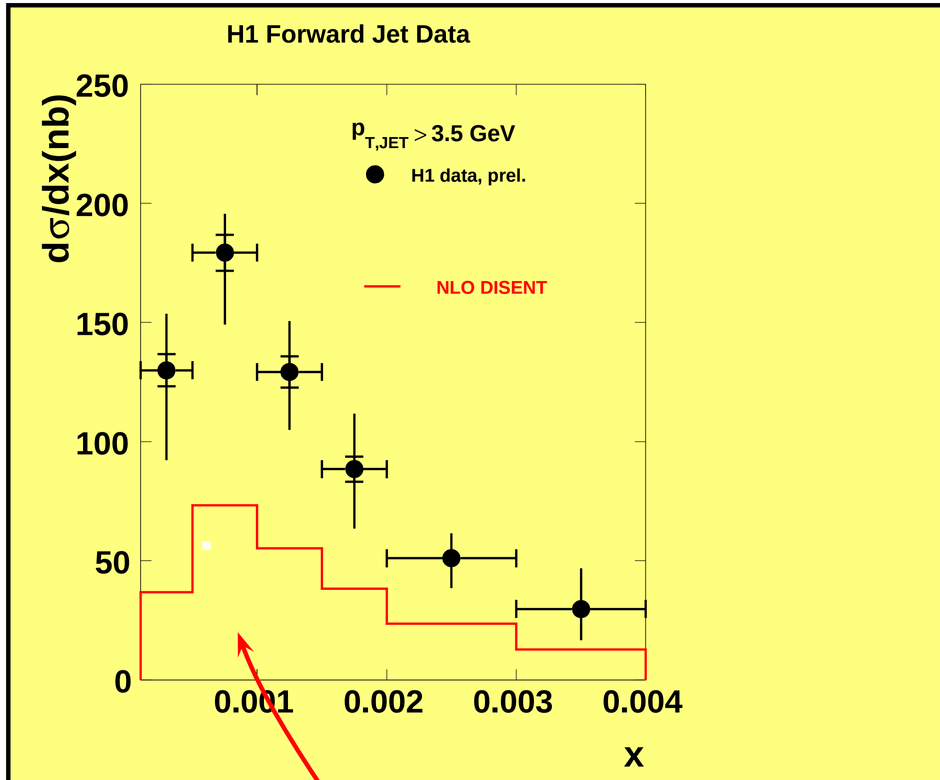
Data much higher than:

- **NLO-$\mathcal{O}(\alpha_s)$**
- **NLO-$\mathcal{O}(\alpha_s^2)$**

new dynamics ???

Where is the problem? Forward Jets





Mueller - Navelet jets in DIS: **Jet in p - direction with**

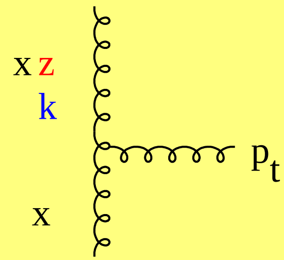
$p_t^2 \sim Q^2$, x_{jet} **large, BUT small** x_{bj}

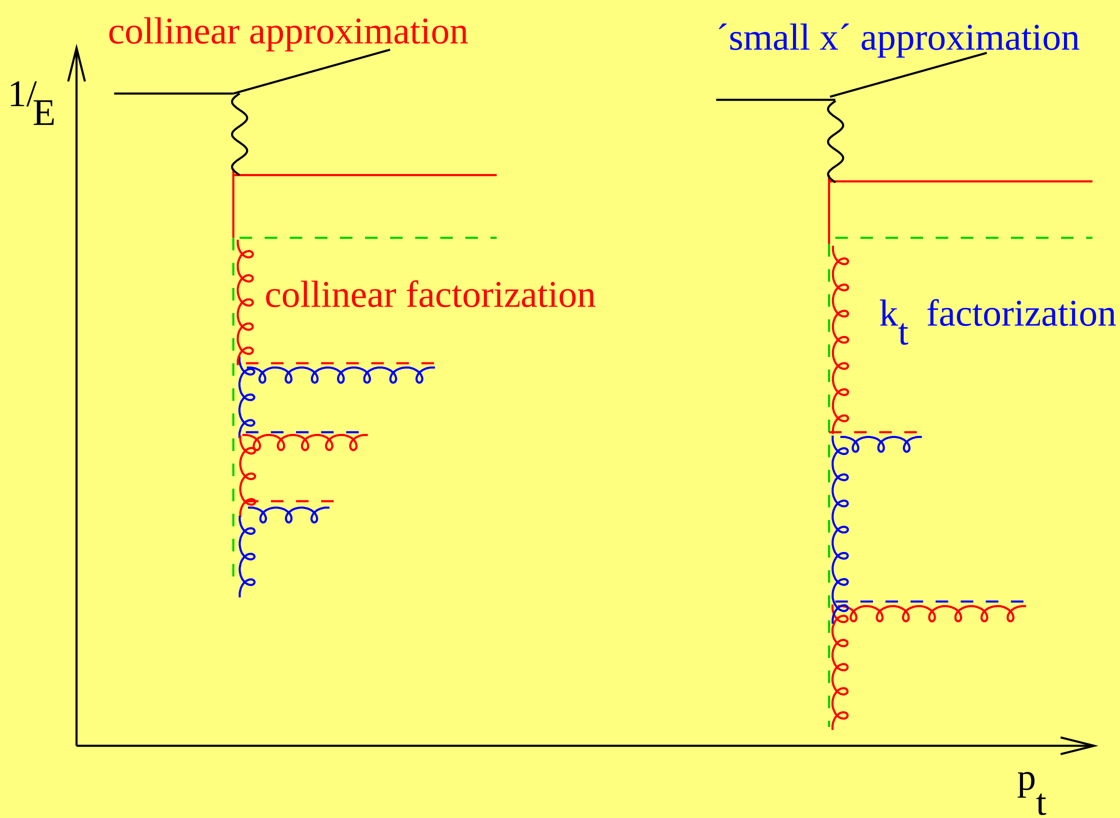
- **suppress DGLAP evolution allow evolution in x**
- **standard DGLAP $\sim$ factor 2 too small!**

Approximation in QCD cascade: Factorization

Gluon Bremsstrahlung:

$$\sim \frac{1}{k^2}\left(\frac{1}{z} + \cdots\right)$$





DGLAP:

- **collinear singularities factorized in pdf**
- **evolution in $Q^2 \sim k^2$, k_t^2 or p_t^2**
- $\sigma = \sigma_0 \int \frac{dz}{z} C^a(\frac{x}{z}) f_a(z, Q^2)$

BFKL:

- **k_t dependent pdf $\rightarrow$ unintegrated pdf**
- **evolution in x**
- $\sigma = \int \frac{dz}{z} d^2 k_t \hat{\sigma}(\frac{x}{z}, k_t) \mathcal{F}(z, k_t)$

The problem of Asymptotia...

DGLAP is great

at large $Q^2 \to \infty$

But has problems:

- **Small x processes:**
  - **heavy quarks**
  - **particle spectra**
  - **jets**

BFKL is great

at small $x \to 0$

But has problems:

- **at finite x:**
  - **NLO corrections**
  - **predictive power**
  - **how to simulate?**

But asymptotia still far away

even for LHC and ...

Attempts to survive in reality

- hack DGLAP and BFKL

  prediction ?
- introduce new concepts: resolved (virtual) photons

  ↪ evolve with DGLAP from proton and photon side

  ↪ similar to $p\bar{p}$

  ↪ works nicely ($\rightarrow$ RAPGAP MC generator)

  BUT theoretical questions: which scale etc ???
- CCFM - new investigation of color coherence

Attempts to survive in reality

hacker: person paid to do hard and uninteresting work ...

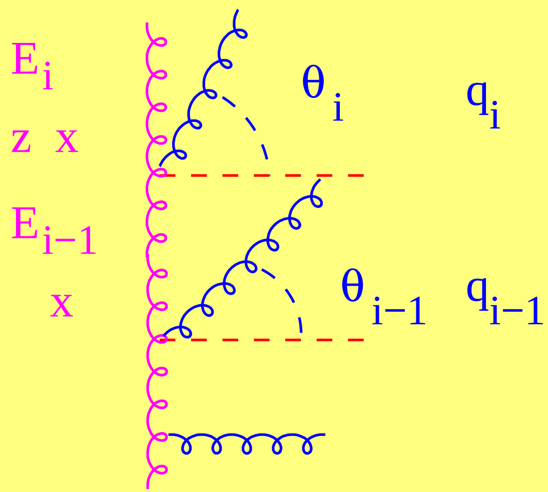
Oxford Advanced Dictionary

- hack DGLAP and BFKL prediction ?
- introduce new concepts: resolved (virtual) photons
  - ↪ evolve with DGLAP from proton and photon side
  - ↪ similar to $p\bar{p}$
  - ↪ works nicely ($\rightarrow$ RAPGAP MC generator)

  BUT theoretical questions: which scale etc ???
- **CCFM - new investigation of color coherence**

$\mathbf{C}_{atani}\,\mathbf{C}_{iafaloni}\,\mathbf{F}_{iorani}\,\mathbf{M}_{archesini}$ (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

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

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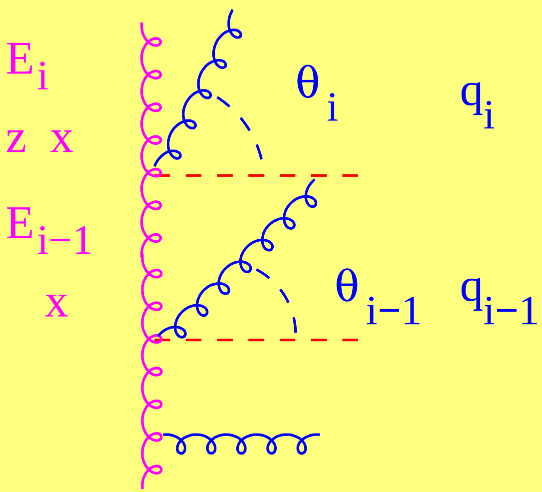

$$p_{ti} = |q_i^0| \sin\Theta_i, \; z = \frac{E_i}{E_{i-1}}$$

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

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

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

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

- ordering in q (DGLAP) implies also angular ordering
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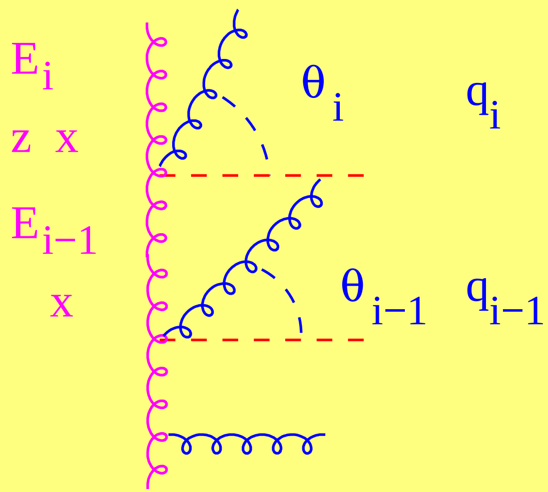


in lab. frame

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

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

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

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

WOW

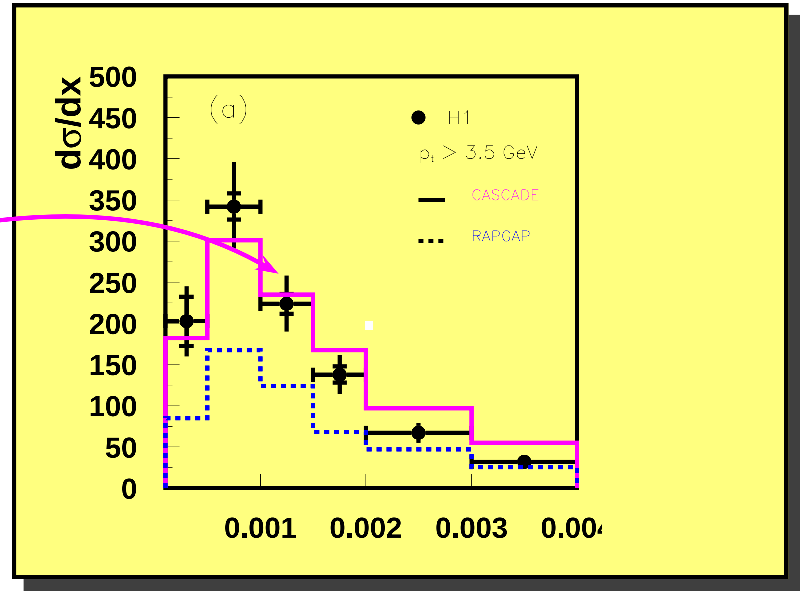
for small z no restriction in q: random walk in q

CCFM solves the problems

Solve CCFM equation
to fit F_2 data from HERA

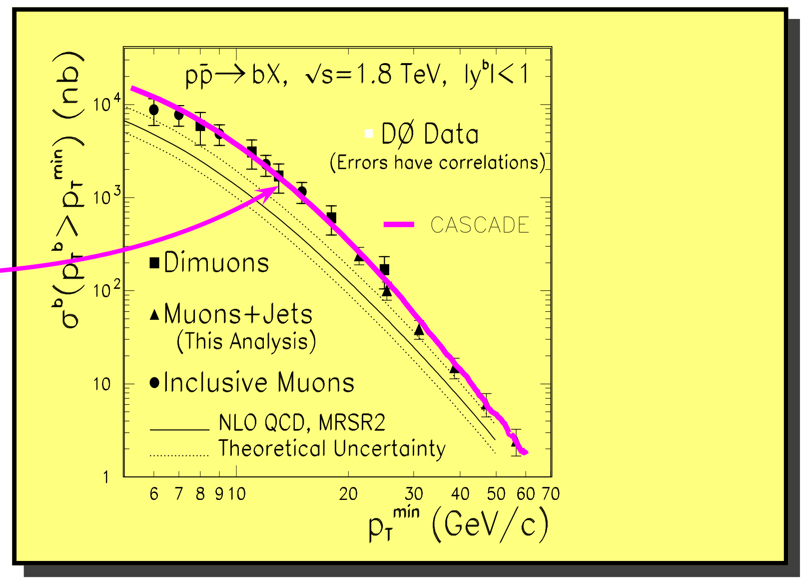
- obtain CCFM un-integrated gluon

  CASCADE MC implements CCFM:
- predict fwd jet x-section at HERA ✔
- predict charm at HERA ✔
- predict bottom at HERA ✔

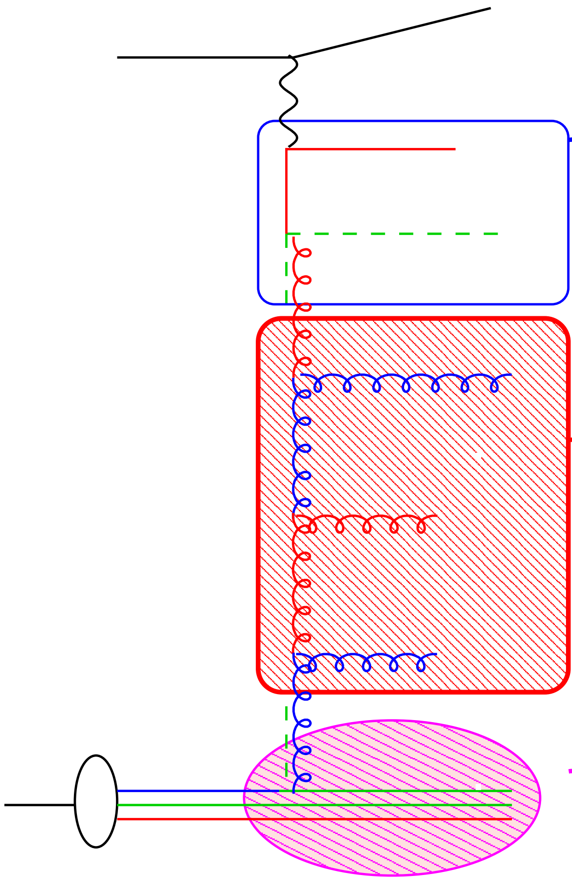


- test universality of un-integrated gluon density from HERA
- predict bottom at Tevatron ✔
- w/o additional free parameters

WOW !!!

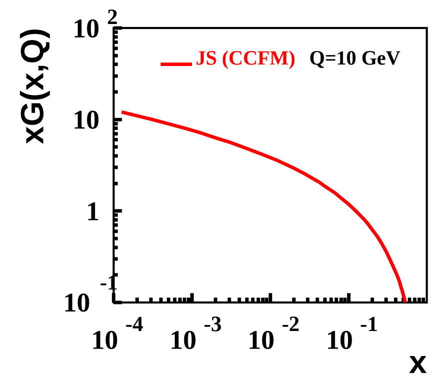


Basic idea - k_t factorisation



BGF matrix element

evolution of parton cascade



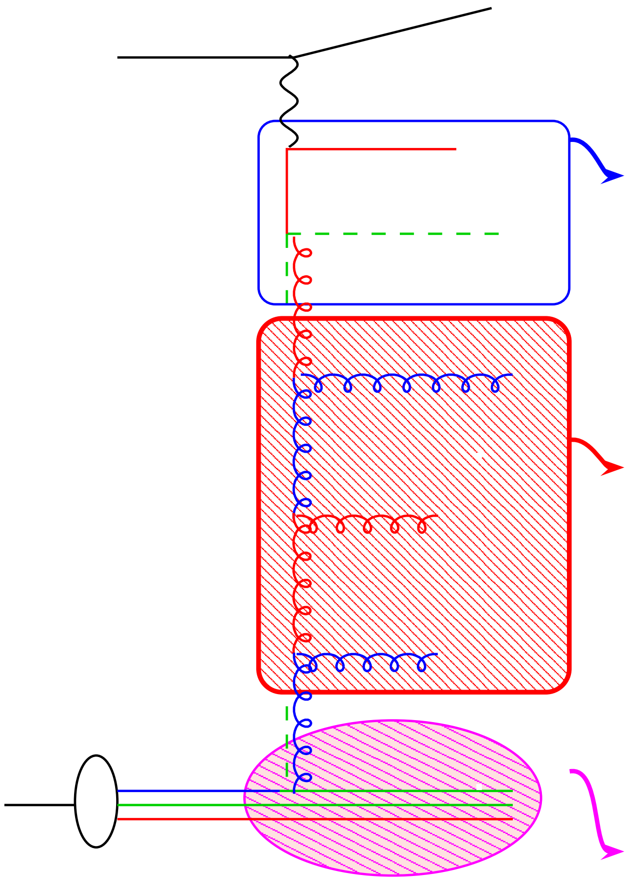
initial distribution:

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

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

CCFM



BGF matrix element
off mass shell

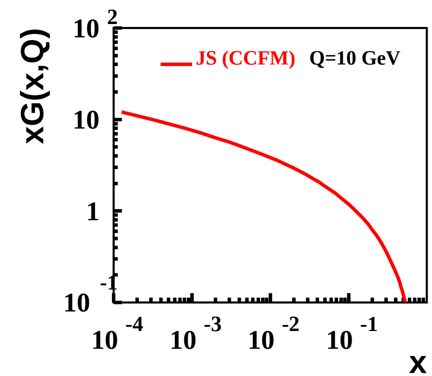
evolution of parton cascade
with CCFM splitting fct.

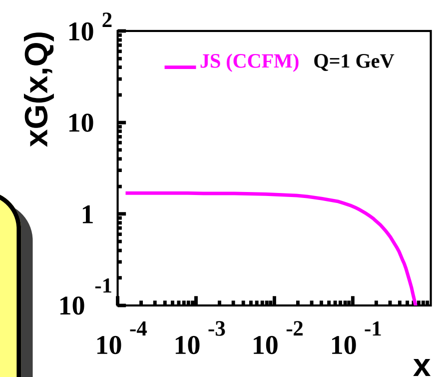
$$\tilde{P} = \bar{\alpha}_s \left(\frac{1}{1-z} + \frac{1}{z}\Delta_{ns} + \ldots \right)$$

initial distribution: flat ?

CCFM !!!

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

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**

Non-Sudakov and all - loop resummation

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

Non - Sudakov form factor ➤ all loop resummation:

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

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

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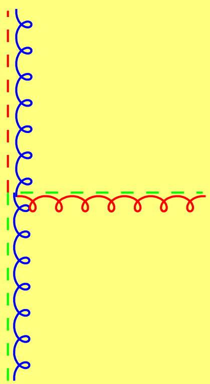

$\bar{\alpha}_{\mathrm{s}}(k_t) \frac{1}{z} \Big[\; 1$

Non-Sudakov and all - loop resummation

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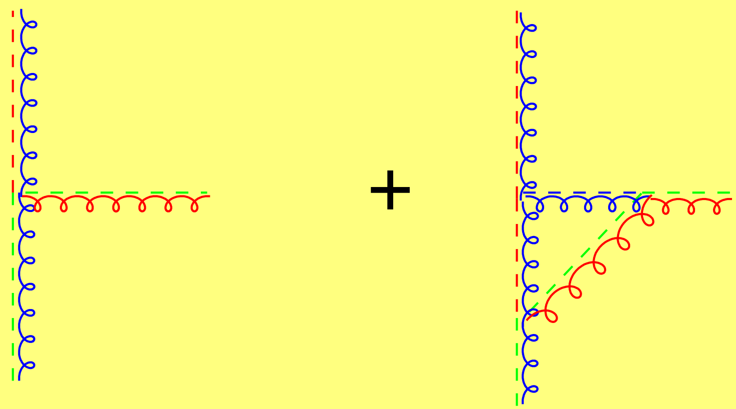

$$\bar{\alpha}_s(k_t)\frac{1}{z}\left[\; 1 \quad + \quad \bar{\alpha}_s \log\left(\frac{z}{z_0}\right)\log\left(\frac{k_t^2}{z_0 z q^2}\right)\right.$$

Non-Sudakov and all - loop resummation

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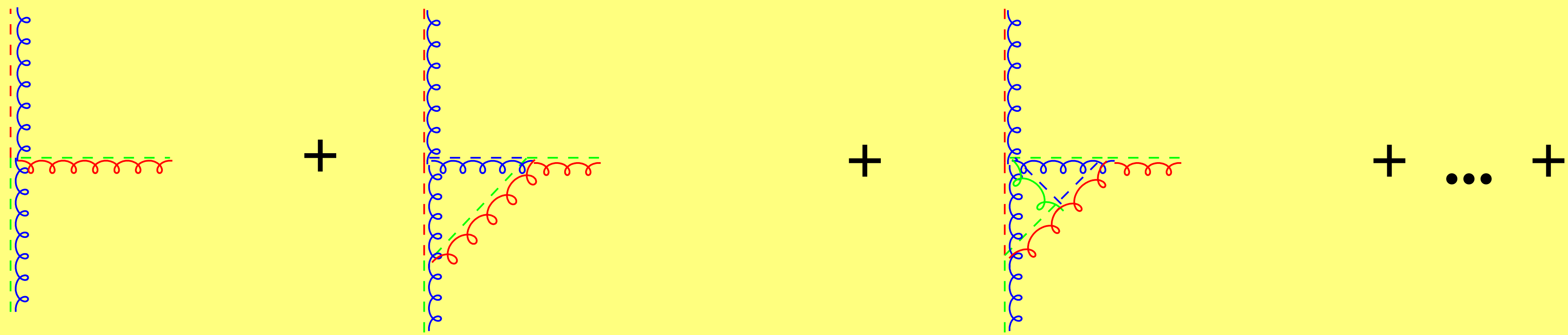
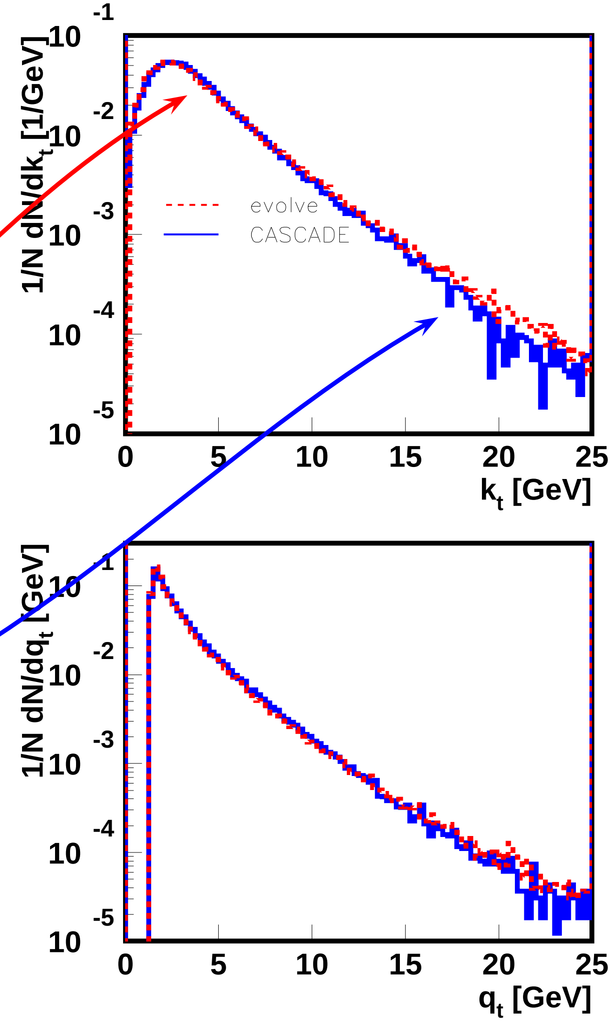


$$\bar{\alpha}_s(k_t)\frac{1}{z} \left[1 \quad + \quad \bar{\alpha}_s \log\left(\frac{z}{z_0}\right) \log\left(\frac{k_t^2}{z_0 z q^2}\right) + \frac{1}{2!} \left(\bar{\alpha}_s \log\left(\frac{z}{z_0}\right) \log\left(\frac{k_t^2}{z_0 z q^2}\right) \right)^2 \ldots \right]$$

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
- LDC MC generator



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

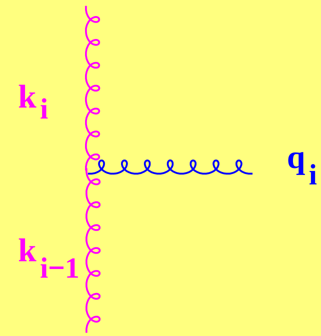
The Monte Carlo Generator CASCADE

- **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 $p\bar{p}$

The Monte Carlo Generator LDCMC

- **L**inked **D**ipole **C**hain is reformulation of CCFM
- redefinition of initial and final emissions
- $q_{\perp i} > \min(k_{\perp i}, k_{\perp i-1})$
  - to cancel non-Sudakov Δ_{ns}
  - forward - backward symmetry
    evolve from proton side or from photon side
  - essentially one scale unintegrated pdf



- MC generator **LDCMC** (http://www.thep.lu.se/ leif/ariadne/)
- also final state cascade included
- optionally full splitting functions and quark ladders
- hadronization via JETSET/PYTHIA

LDCMC is MC implementation of LDC

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

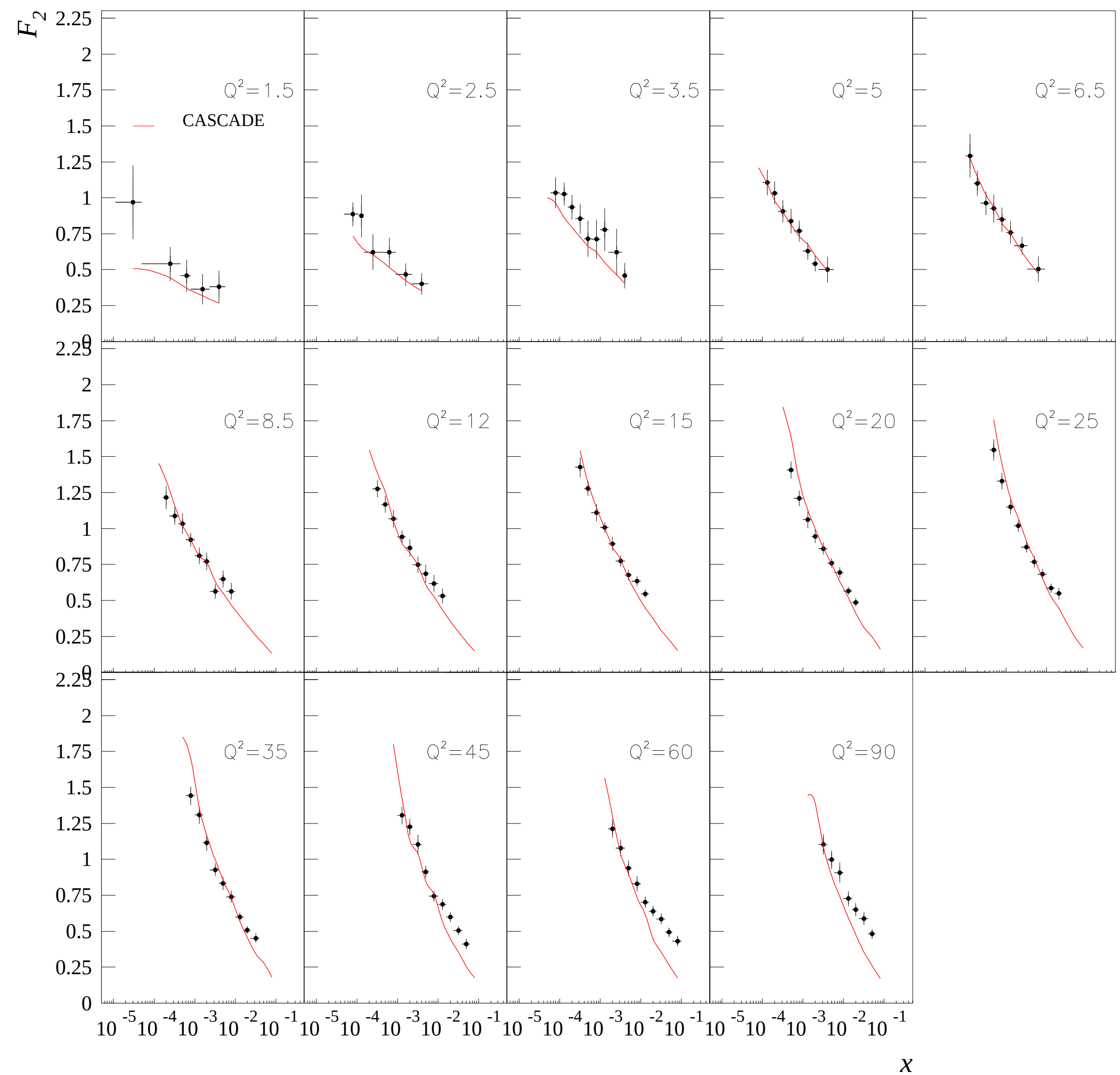
(fitted for $Q^2 > 5$ GeV^2, $x < 10^{-2}$)

- 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

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

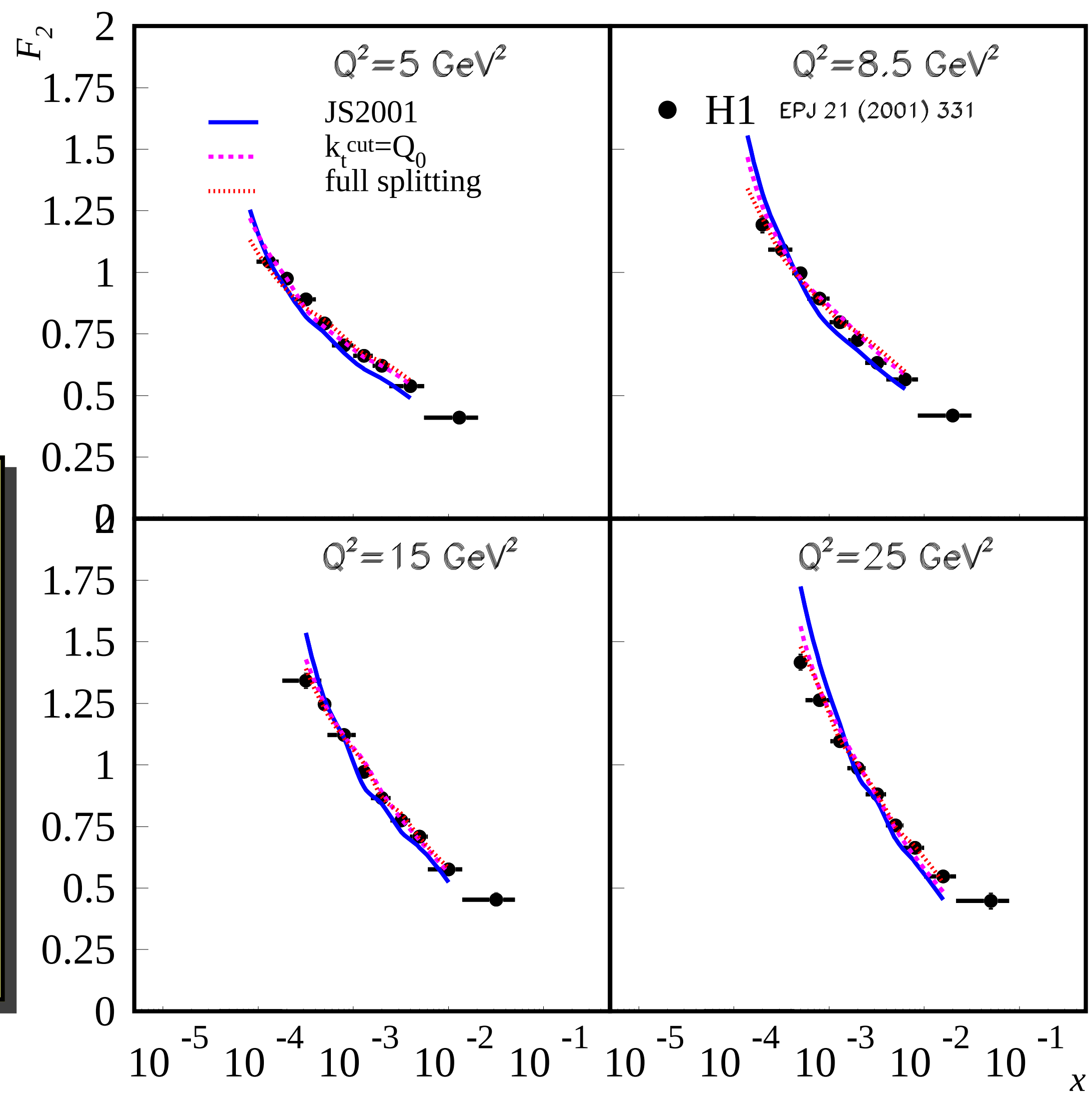
obtained from fit to F_2



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 $F_2(x, Q^2)$

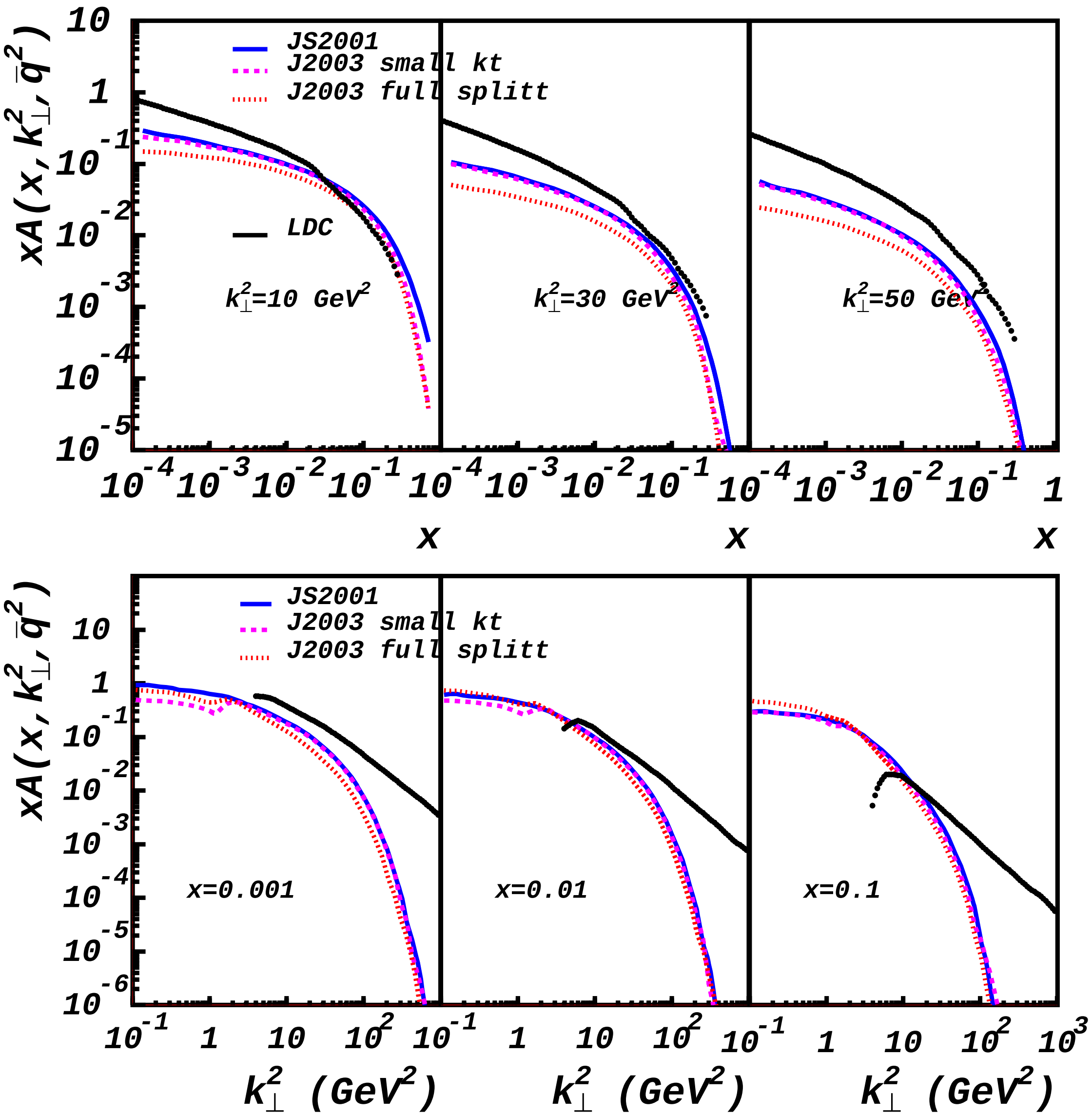
- more precise data:
  H1 NPB 470 (1996) 3., EPJ 21 (2001) 331.
  ZEUS ZPC 72 (1996) 399., EPJ 21 (2001) 443.
- fit $Q^2 > 4.5$ GeV^2, $x < 0.005$
- small k_t - region ?
- full splitting function ?



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

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

Unintegrated gluon density



JS (CCFM) gluon

H. Jung, G.P. Salam, EPJC 19, 351 (2001)

constrained from F_2 fit only for $x_g < 0.03$

for HERA F_2 $x < 0.01$, $Q^2 > 5$

LDC gluonic

G. Gustafson, L. Lönnblad, G. Miu, JHEP09 (2002) 005

only gluons

including full splitting fct

for HERA F_2 $x < 0.013$, $Q^2 > 3.5$

J2003 sets

for HERA F_2 $x < 0.005$, $Q^2 > 4.5$

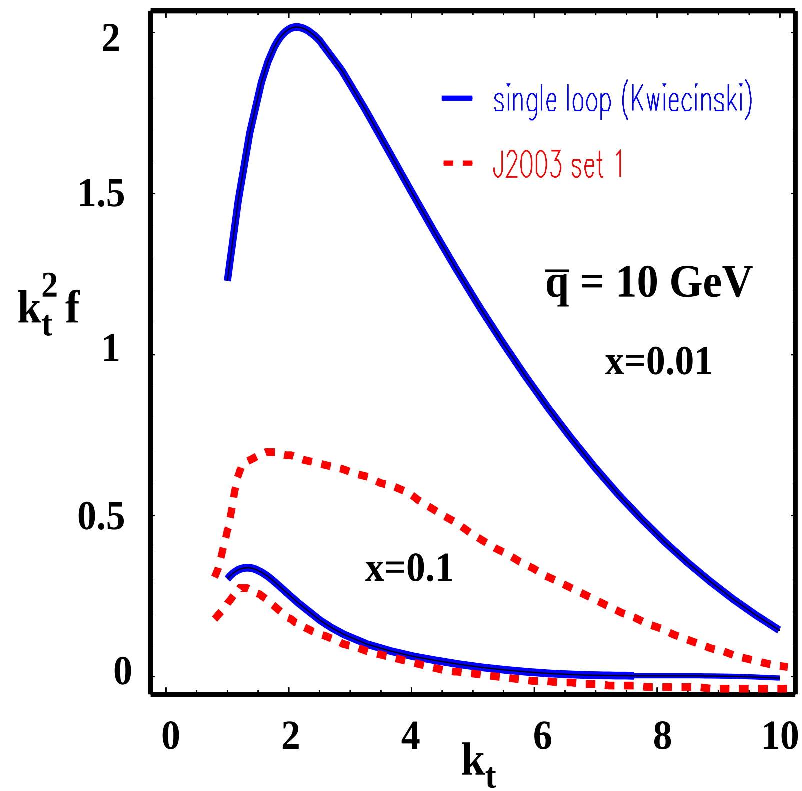
at $\bar{q} = 10$ GeV:

- **small k_t region**
- **full splitting**

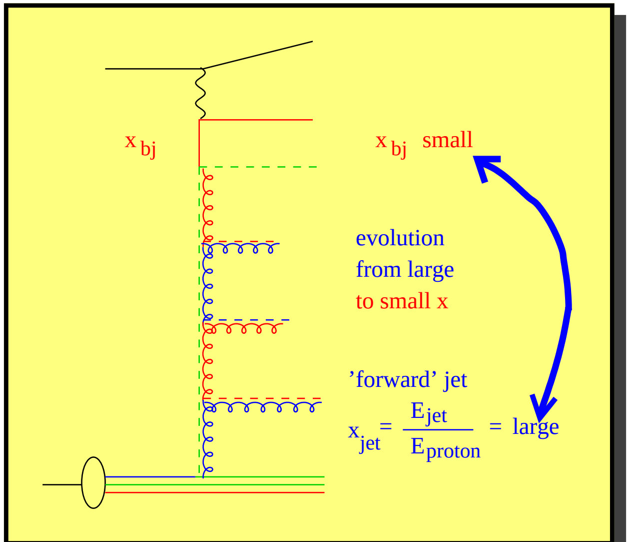
CCFM unintegrated gluon density in transverse coordiante representation

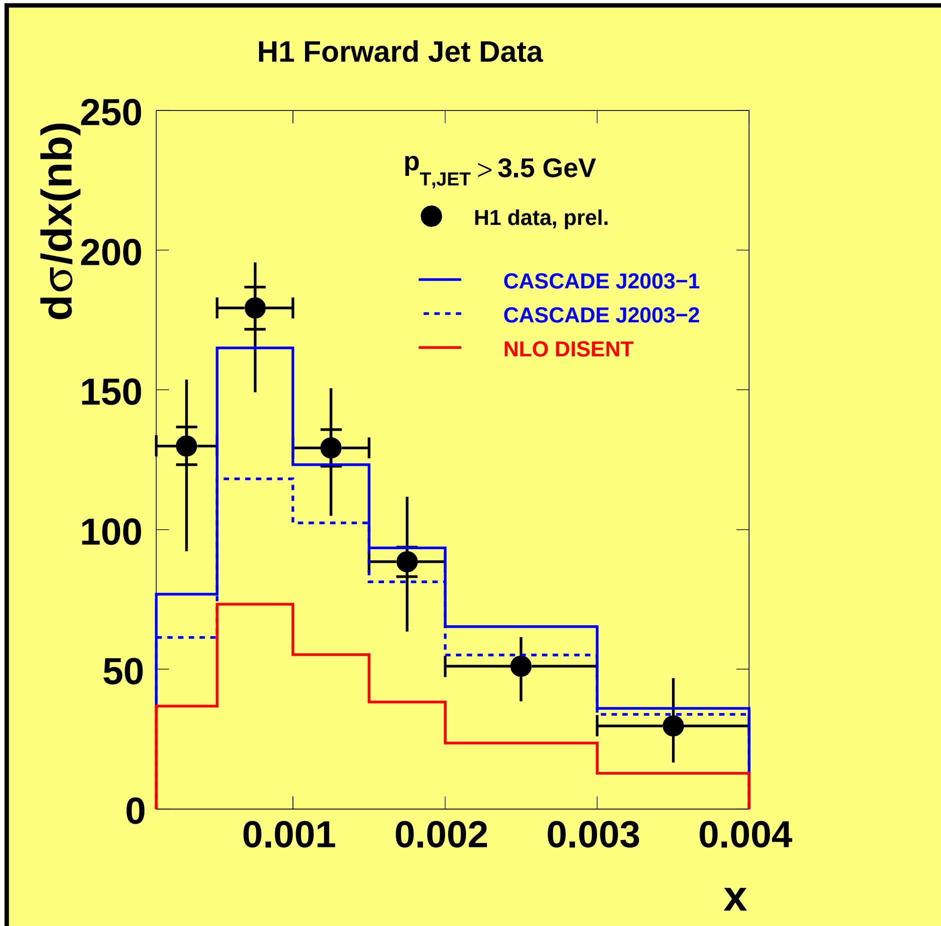
Jan Kwiecinski

- $x\mathcal{A}(x, k_t, \bar{q}) = \int dbbJ_0(k_t b) x\bar{A}(x, b, \bar{q})$
  - use one loop approximation
  - without non-sudakov
  - understand interplay of k_t and $\bar{q}$
- $x\bar{A}(x, 0, \bar{q}) = 0.5xg(x, Q^2)$
- with starting distribution $xg_0(x) = 3(1 - x)^5$
  - solve exactly
- compare to MC solution of CCFM
- connection to dipole models....



Solution to the problem: Forward Jets

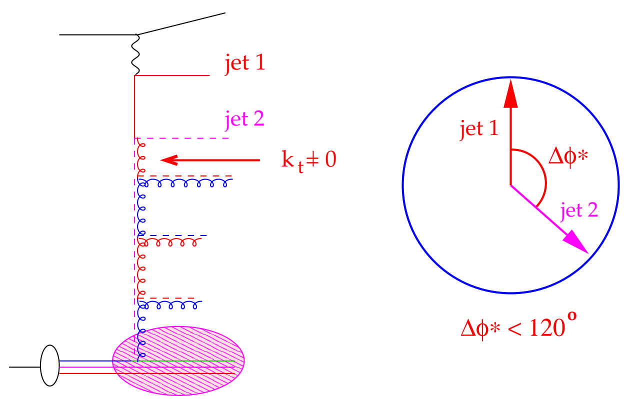




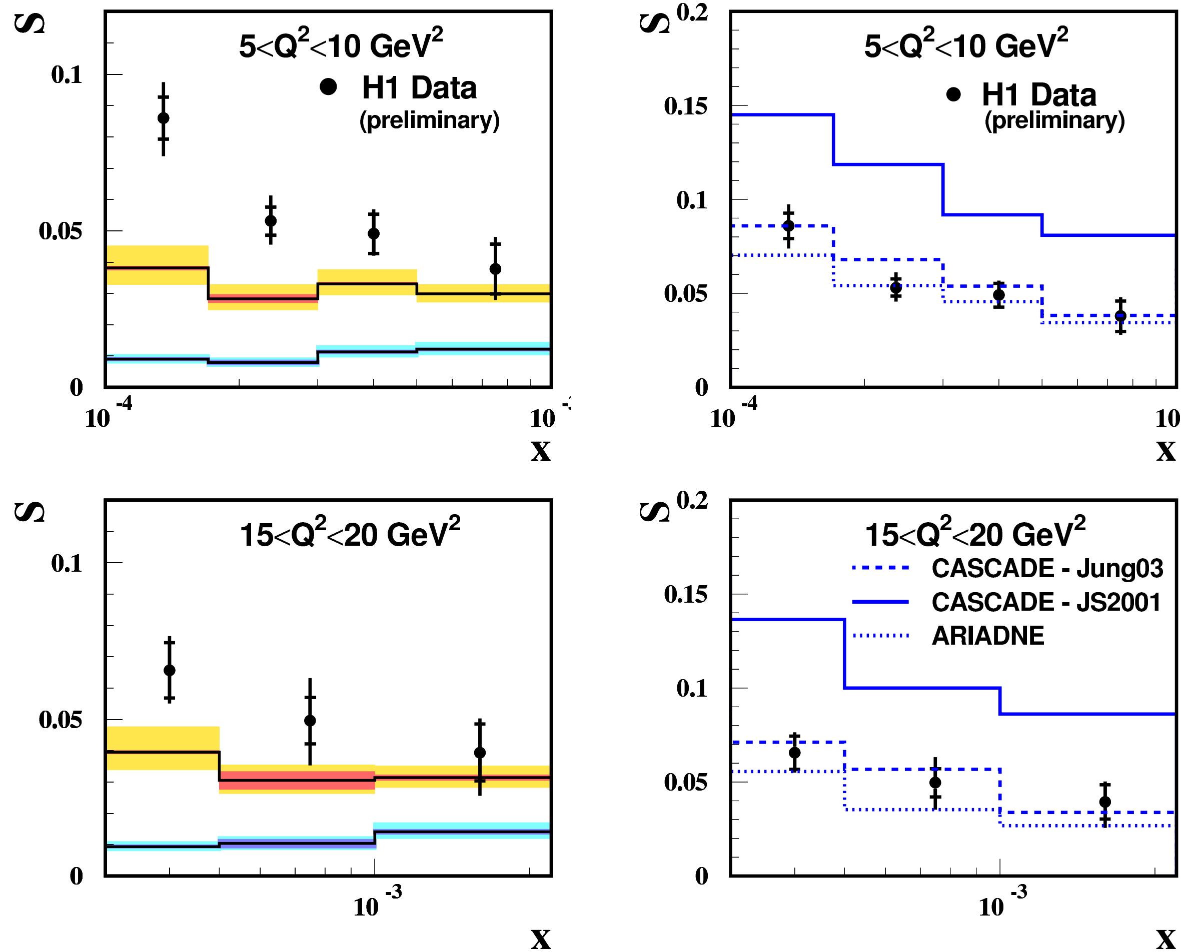
require jets with $p_t > 3.5$ GeV and $0.5 < E_t^2/Q^2 < 2$

- **CASCADE (and LDCMC) well in shape and normalization !!!**
- **NLO off as expected from DGLAP type evolution**

Where is the problem: Di - jets in DIS



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



- NLO-$\mathcal{O}(\alpha_s)$ and NLO-$\mathcal{O}(\alpha_s^2)$ too small at small x
- CCFM unintegrated gluon needed for rise at small x !!!

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

H1 (H1 Coll. *PLB* 467 (1999) 156)

$Q^2 < 1$ **GeV²**, $0.1 < y < 0.8$,

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

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

$\sigma_{vis} = 176 \pm 16$**(stat.)**$^{+26}_{-17}$**(syst.) pb**

NLO: $\sigma = 54 \pm 9$ **pb**

CASCADE $\sigma(ep \to e' b\bar{b}X \to \mu X) = $ **65** pb

R_{MC}(**H1**) $= \frac{\sigma_{data}}{\sigma_{MC}} = 2.7 \pm 0.25^{+0.4}_{-0.26}$

ZEUS (ZEUS Coll. *EPJC* (2001))

$Q^2 < 1$ **GeV²**, $0.2 < y < 0.8$,

$p_t^b > 5$ **GeV**, $|\eta^b| < 2$

$\sigma = 1.6 \pm 0.4$**(stat.)**$^{+0.3}_{-0.5}$**(syst.)**$^{+0.2}_{-0.4}$**(ext.) nb**

NLO: $\sigma = 0.64^{+0.15}_{-0.1}$ **nb**

CASCADE $\sigma(ep \to e' b\bar{b}X) = $ **0.88** $\pm$ **0.08** nb

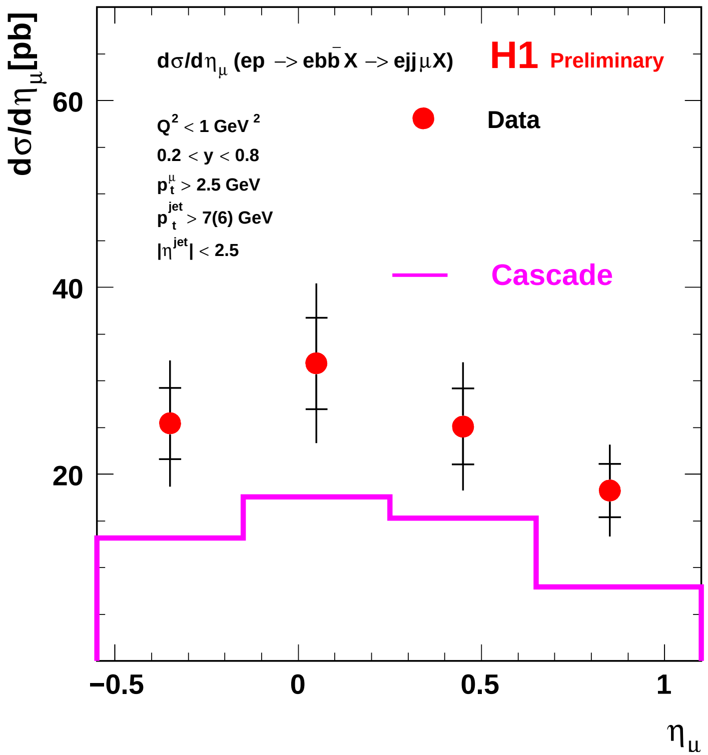
R_{MC}(**ZEUS**) $= \frac{\sigma_{data}}{\sigma_{MC}} = 1.9 \pm 0.45^{+0.34}_{-0.57}$

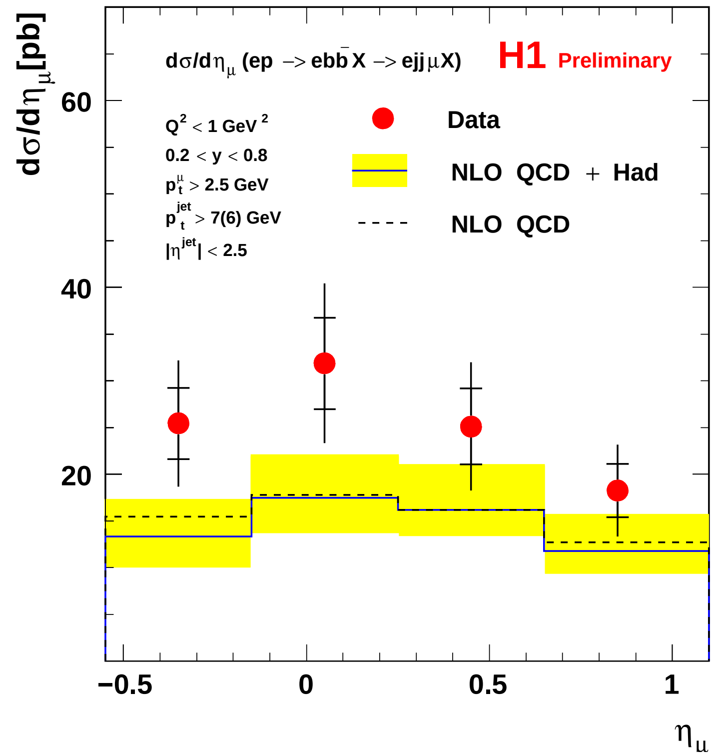
Measurements rely on large extrapolation
from visible to total x-section

really safe ????

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

- large extrapolation from visible to total x-section
- look at visible x-section





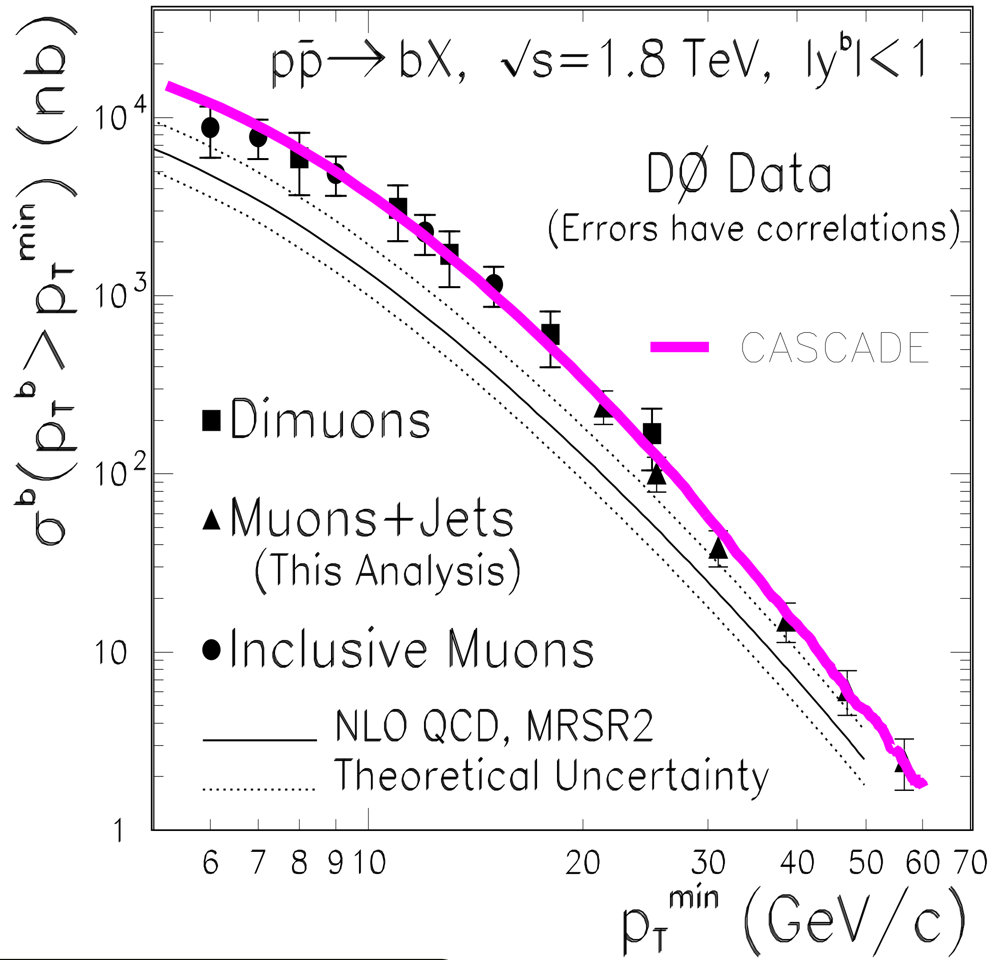
CASCADE $\sim$ ok for visible μ's (similar to NLO)

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

Test universality of unintegrated gluon density from HERA

- use unintegrated gluon as before (from F_2 fit at HERA)
- use off-shell matrix element for $g^*g^* \to b\bar{b}$ with $m_b = 4.75$ GeV.

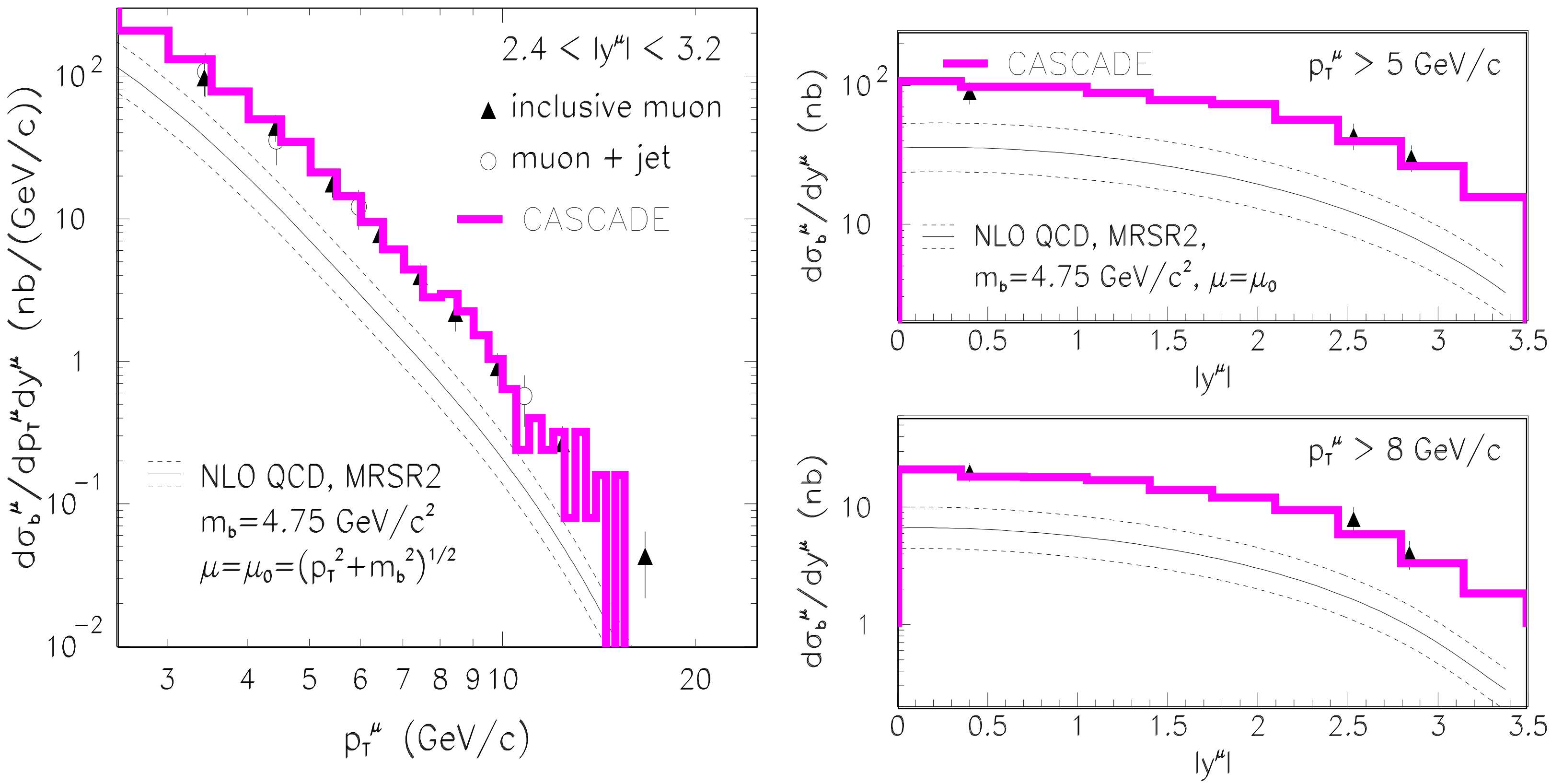
NOTE NLO off by factor 2



CASCADE w/o additional free parameters

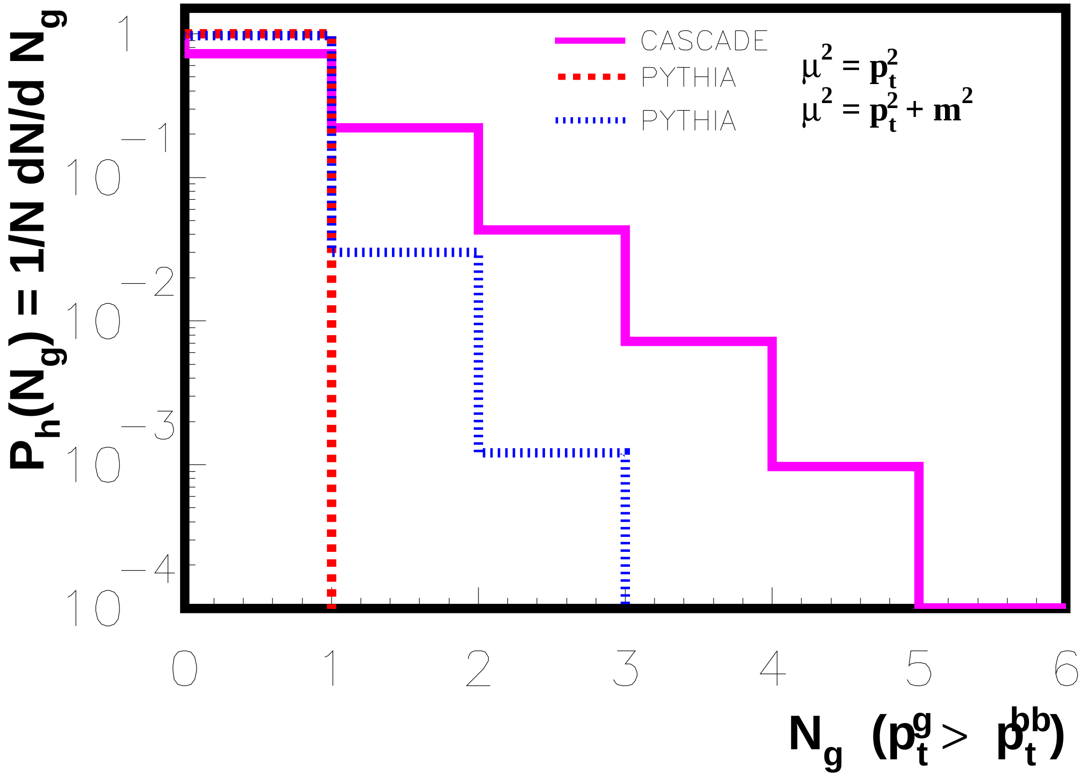
Solution to the problem: $b\bar{b}$ production at Tevatron

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

The Beginning, Not the End

- k_t - factorization very successful
  - unintegrated gluon density from CCFM / LDC
  - precision fits to F_2, including full splitting fct
  - describes measurements at HERA
  - even where collinear NLO fails
  - works also for diffraction
  - works also for bottom in $p\bar{p}$
  - attempts also for bottom in $\gamma\gamma$
  - also for Higgs at LHC ???
- k_t - factorization useful for estimate of higher order corrections
- increasing theoretical interest in k_t - factorization:
  - Lund small x workshops and Small x collaboration

The Beginning, Not the End

Even if there is still a bit to go for a

Theory **O**f **E**verything

we are facing the beginning of an

interesting, bright and challenging future

in small x physics

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

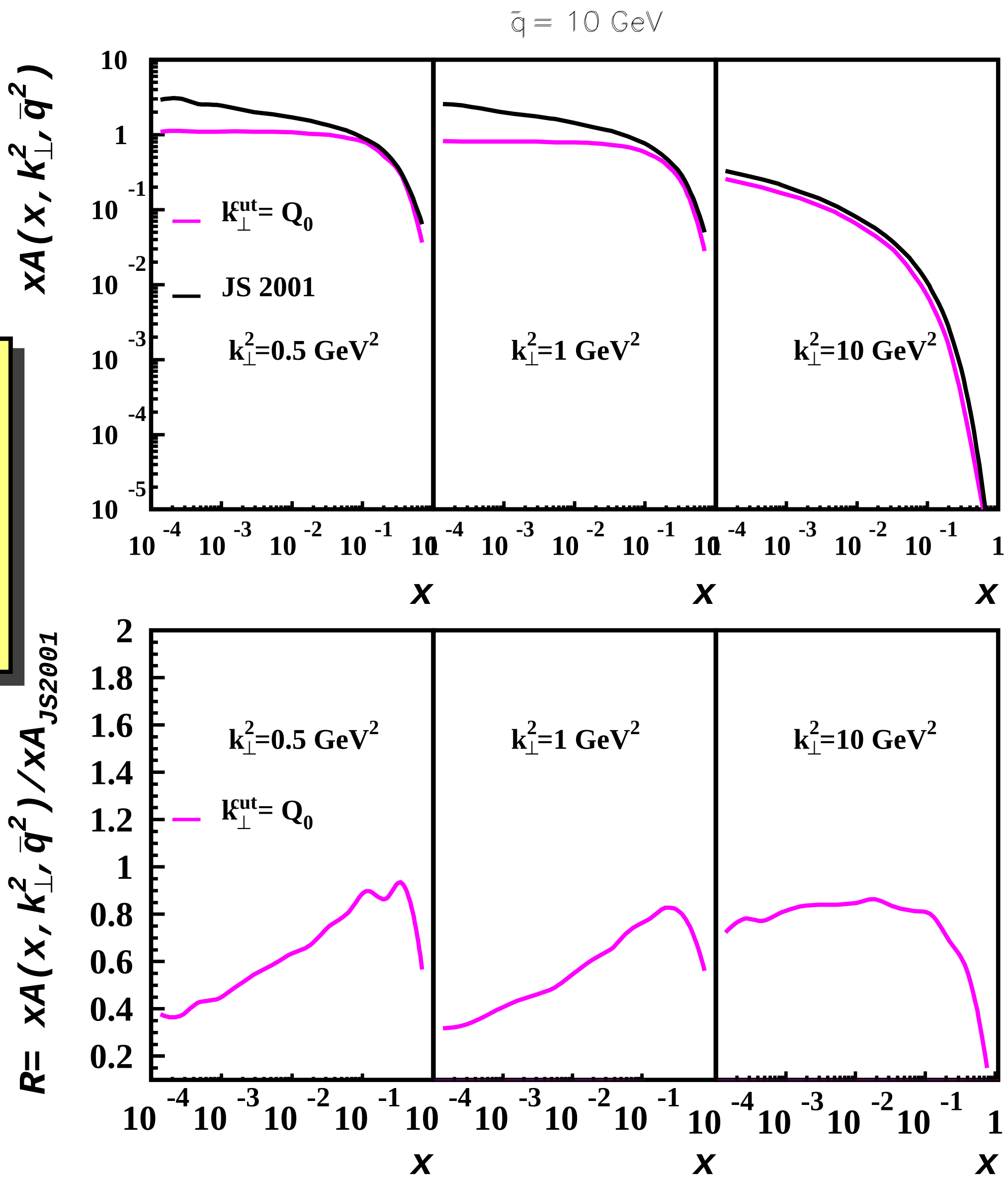
• what about α_s for $k_t < k_t^{cut}$ in

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

What is actual cut - what is soft?

• JS2001 had soft cut $k_t > 0.25$ GeV

• now $k_t > Q_0$

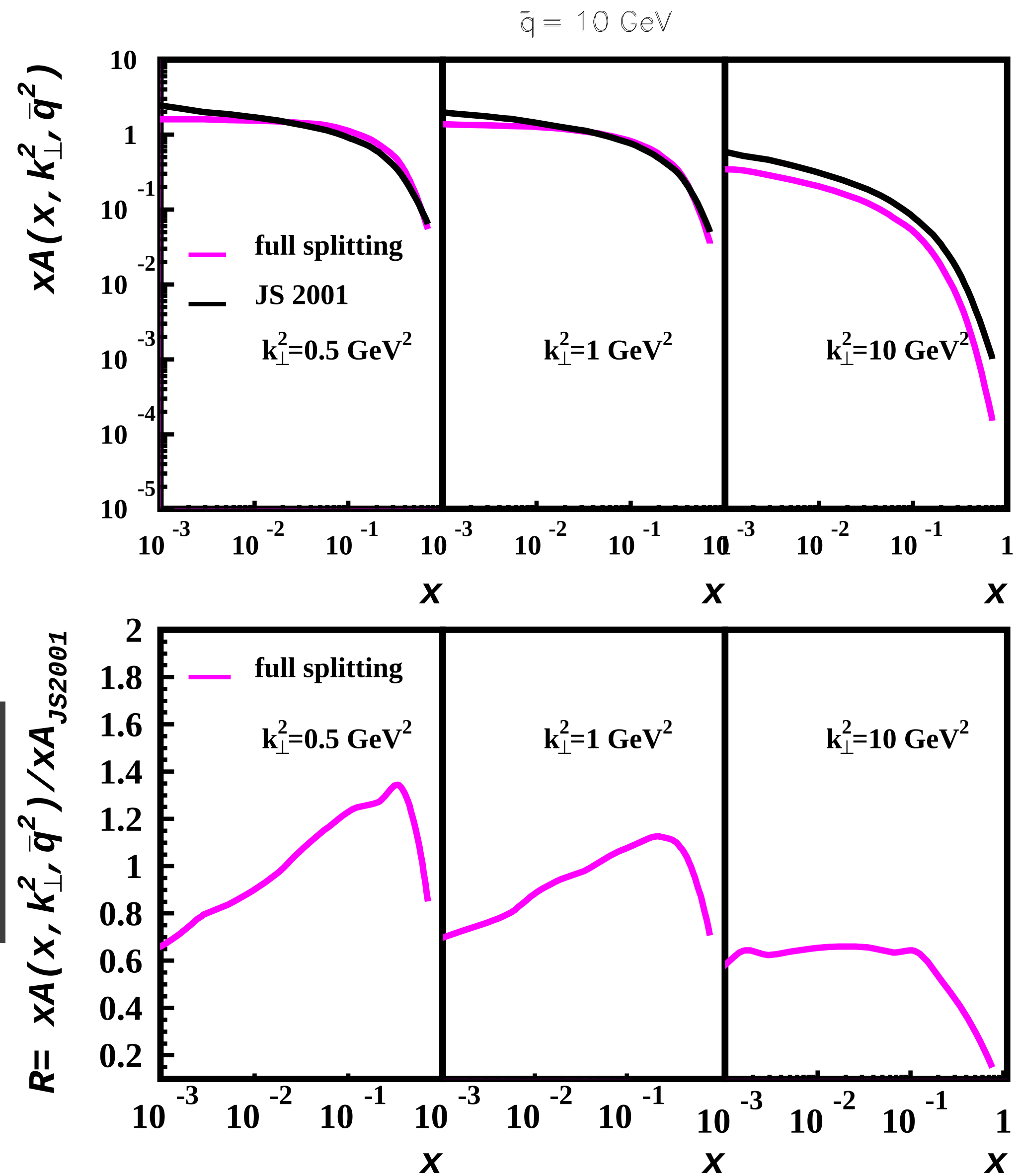


New fit: full splitting function

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

☛ to include non-singular terms

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

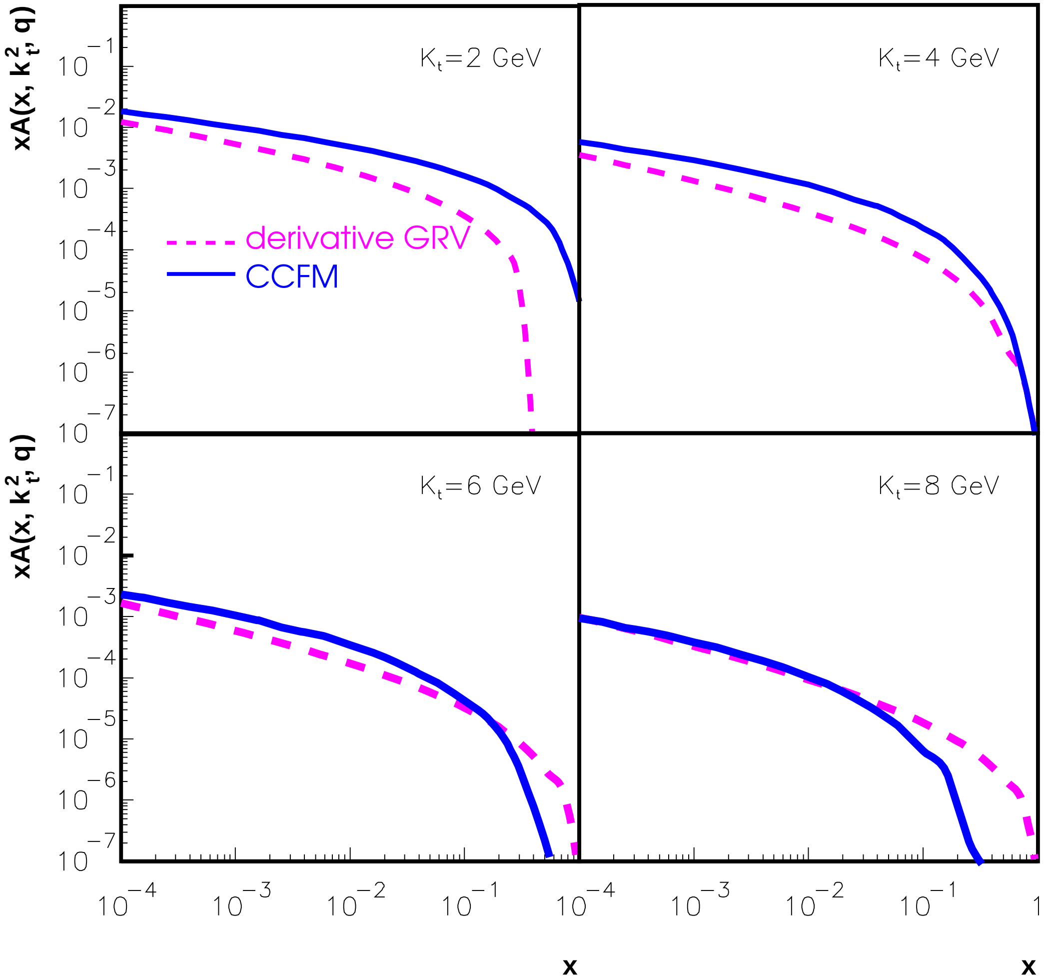


> ☛ **gluon pdfs are different**
>
> ☛ **effect of non-sing. terms visible**

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)

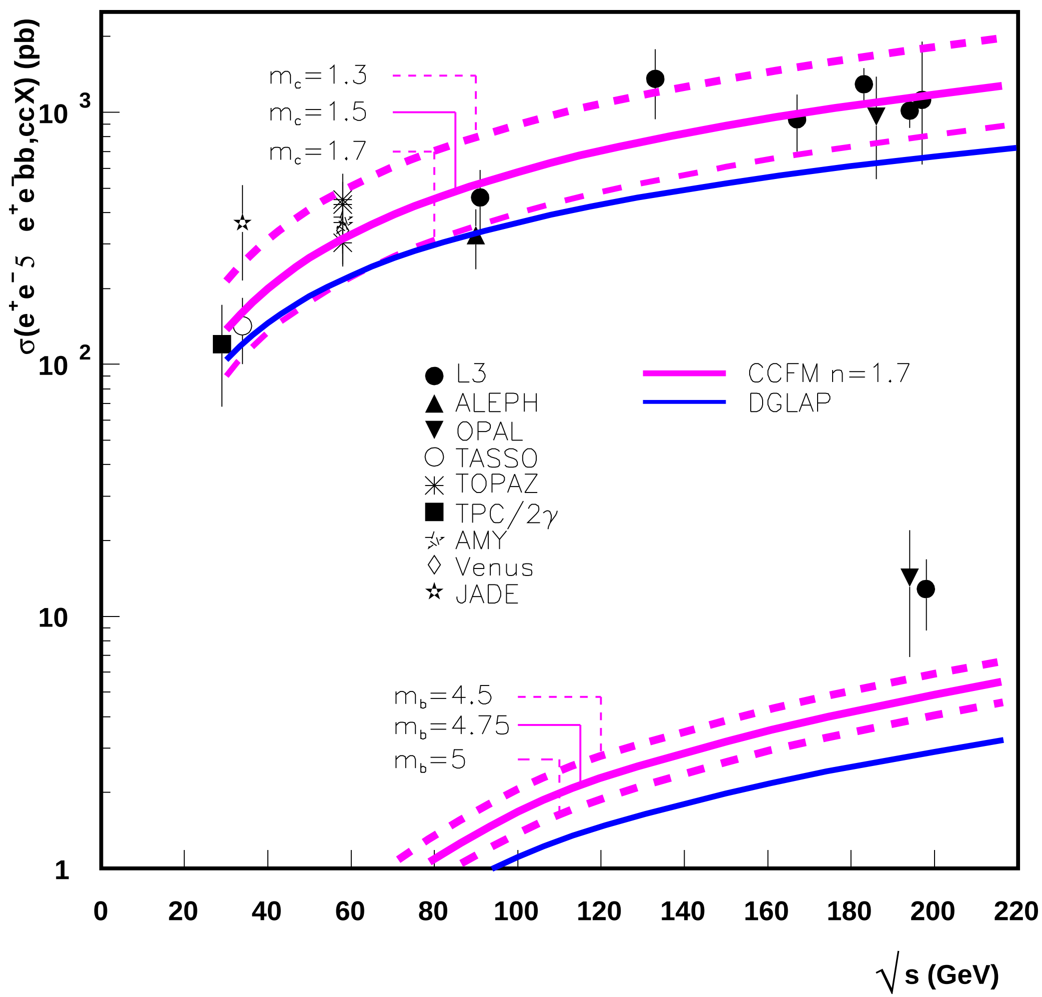


First un-integrated gluon density of real photon with full CCFM evolution

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

together with M. Hansson

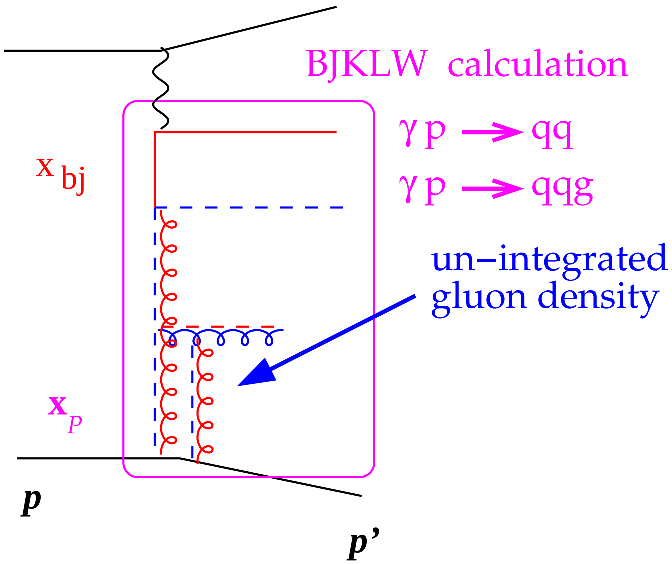
- use matrix elements in k_t - factorization
  - $\gamma\gamma \to b\bar{b}$
  - $\gamma g \to b\bar{b}$
  - $gg \to b\bar{b}$
  - universality...



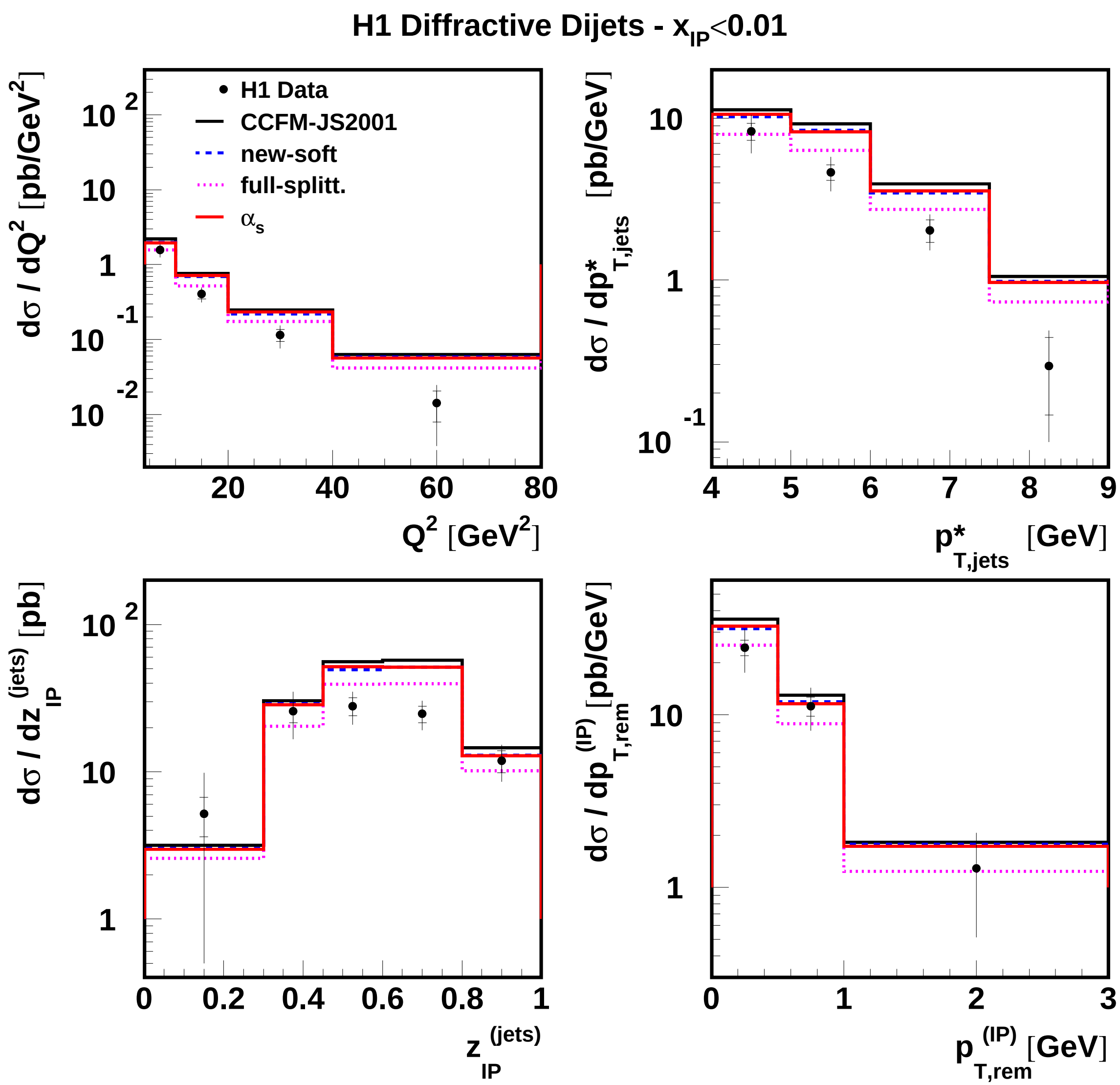
- **compare k_t -factorization & CCFM with NLO:**
- **using norm. from pdf**
  - **CCFM similar to NLO**
- **determine norm. for gluon from charm ($n = 1.7$ for res.γ)**
  - **CCFM larger than NLO**

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

Diffractive Di - Jets and CCFM



$4 < Q^2 < 80$ GeV^2, $0.1 < y < 0.7$ $x_{I\!P} < 0.05$, $M_Y < 1.6$ GeV, $p_{T\,jet} > 4$ GeV, $-1.0 < \eta_{jet}^{lab} < 2.2$



$\gamma p \to q\bar{q}$ (2-gluon exchange)

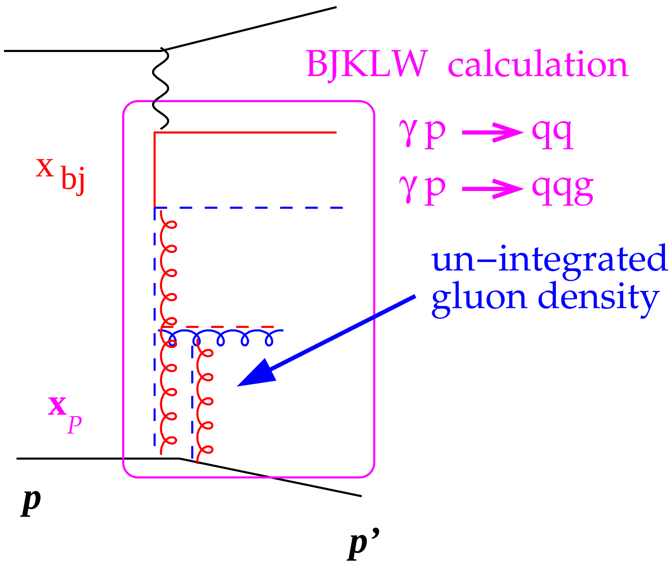
J. Bartels, H. Lotter, M. Wüsthoff, Phys. Lett. **B 379** (1996) 239
N. Nikolaev, B.G. Zakharov, Z. Phys. **C 53** (1992) 331.
E. Gotsman, E. Levin, U. Maor, Nucl.Phys. **B 493** (1997) 354.

$\gamma p \to q\bar{q}g$ (2-gluon exchange)

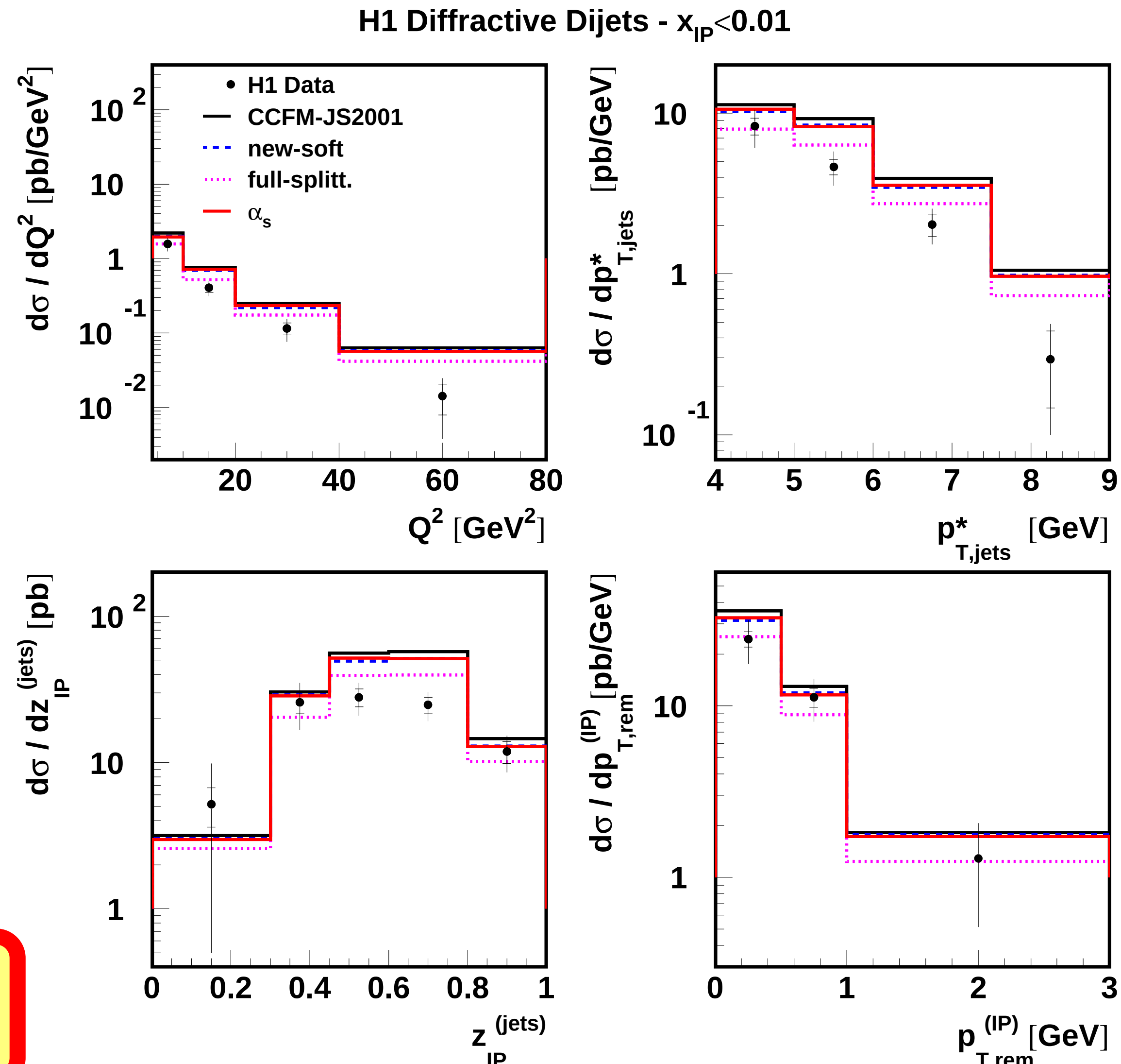
J Bartels H Jung M Wusthoff, Eur. Phys. J. **C11**, 111 (1999)

apply only to $x_{I\!P} < 0.01$!!!
pert. QCD calculation ...

Diffractive Di - Jets and CCFM



$4 < Q^2 < 80$ GeV^2, $0.1 < y < 0.7$ $x_{I\!P} < 0.05$, $M_Y < 1.6$ GeV, $p_{T,jet} > 4$ GeV, $-1.0 < \eta_{jet}^{lab} < 2.2$

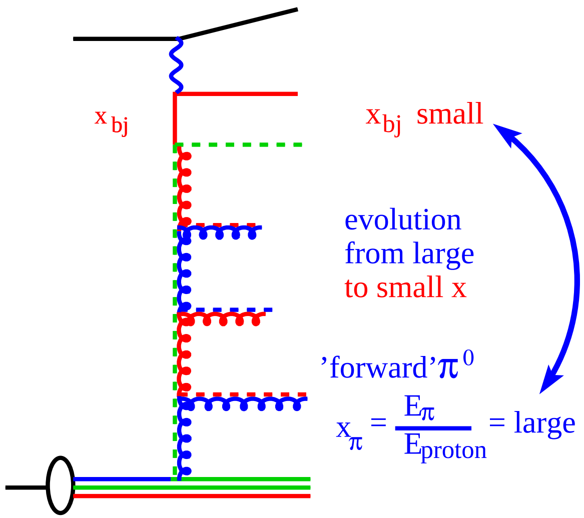


cutoff $p_t > 2.5$ GeV needed

- non-ordered emissions:
- $p_t^{gluon} > p_t^{q,\bar{q}}$: ~ 30 %
- not possible in res. pom
- nor SCI

Gluon from CCFM ✔

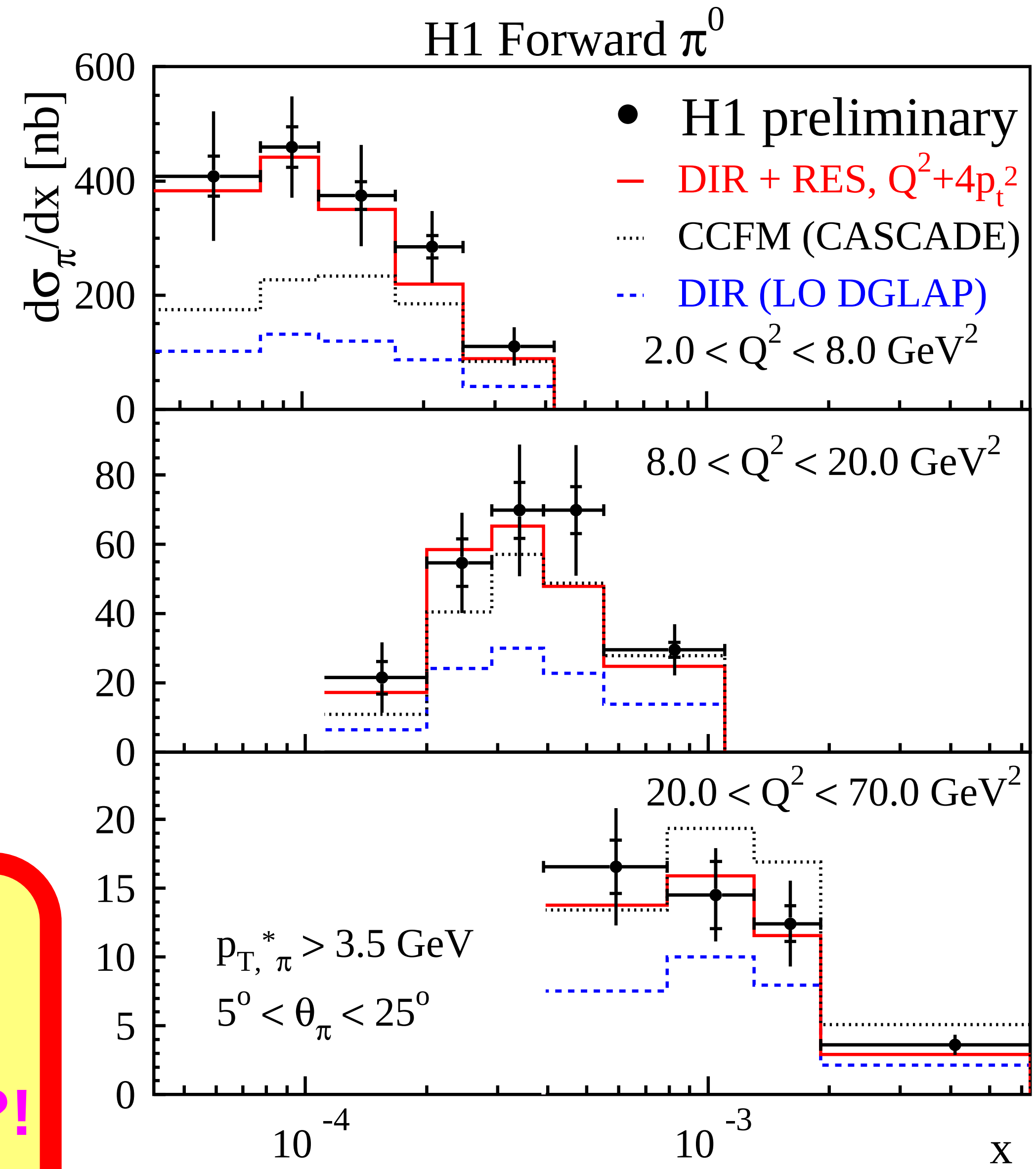
Forward π^0: H1



DIS : forward π^0 (instead of jet)

$5^o < \theta_\pi < 25.0^o$

$x_\pi > 0.01$



DGLAP too small, need:

- **resolved virtual photons ?!?**
- **CCFM too small at small x !?!**
- **WHY ?!?**

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

H1(prel.)

$2 < Q^2 < 100$ **GeV²**, $0.1 < y < 0.8$,

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

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

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

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

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

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

ZEUS(prel.) ICHEP 2002

$Q^2 > 2$ **GeV²**, $0.05 < y < 0.7$,

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

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

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

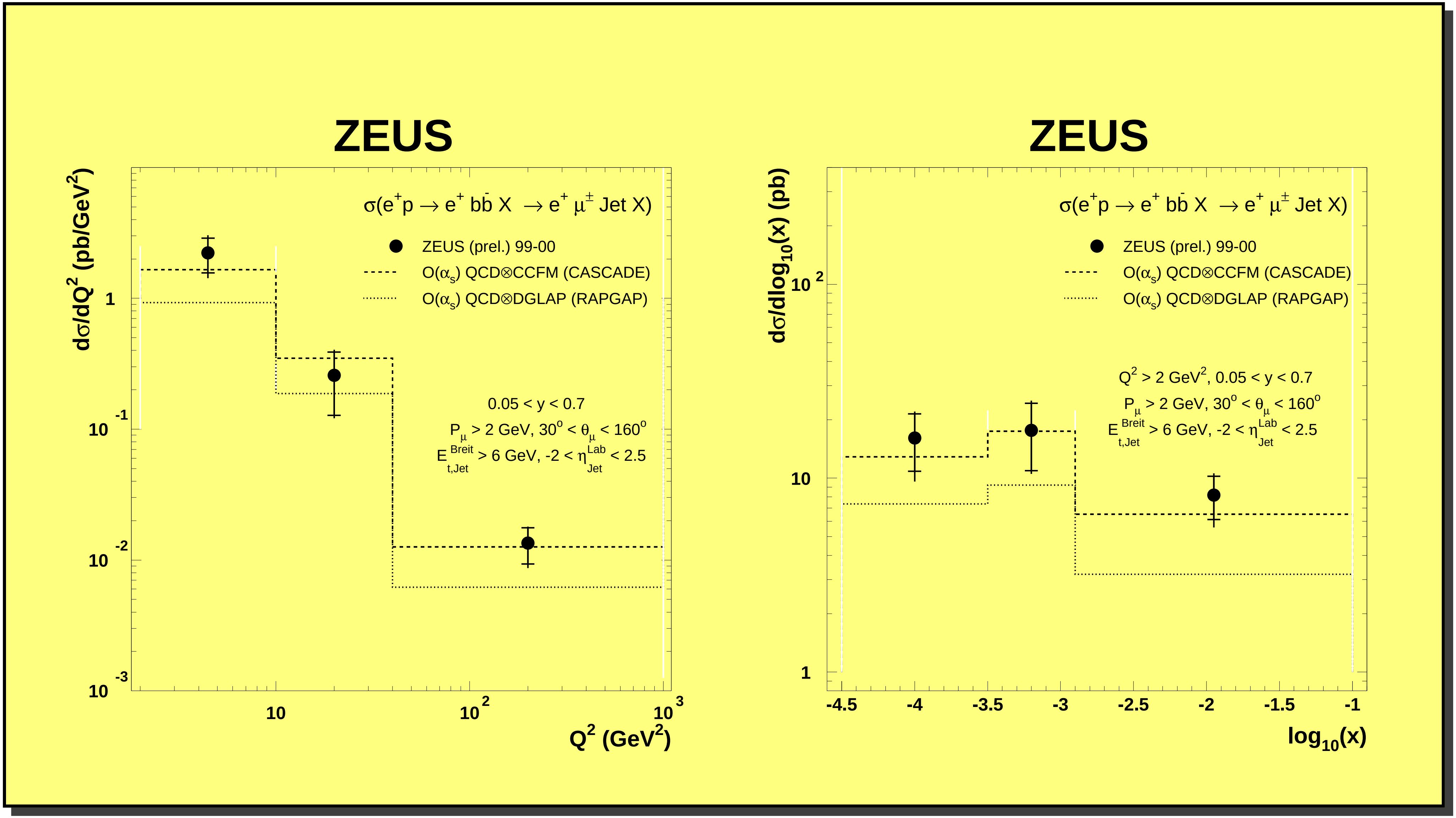
$\sigma = 38.7 \pm 7.7(stat.)^{6.1}_{5.0}(s^{yst.})$ pb

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

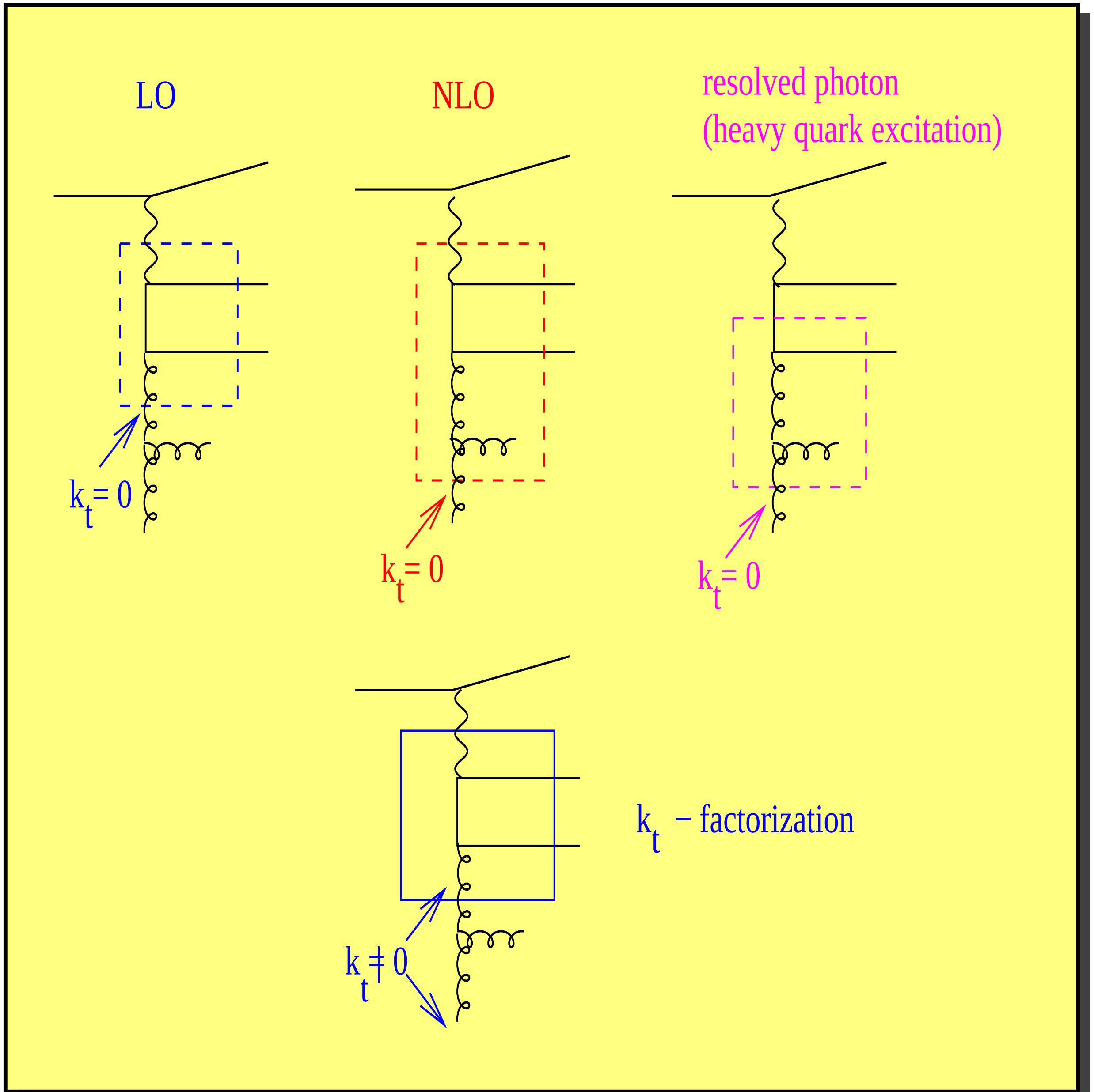
CASCADE $\sigma(ep \rightarrow e' b\bar{b}X) = 35$ pb

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



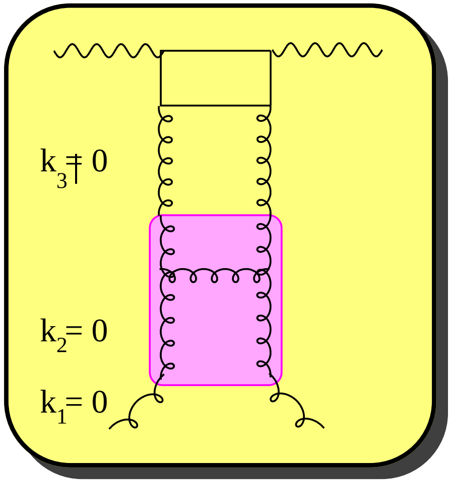
k_t **factorization**

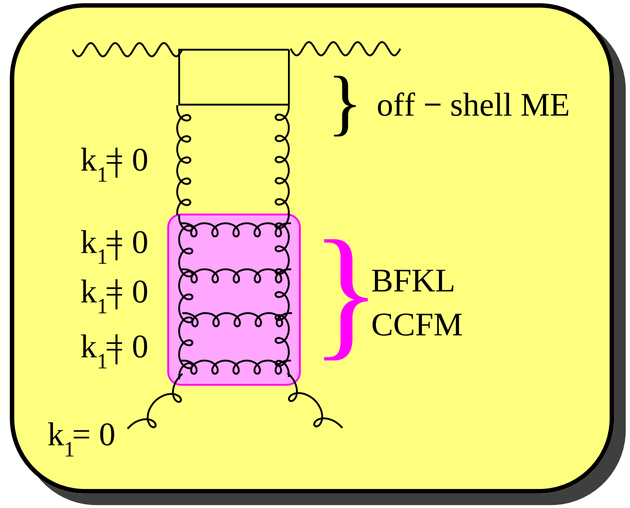
- **NLO corrections**
- **anomalous γ**
- **even in NLO**
- **includes NNLO**
- **includes NNNLO**
- **includes NNNNLO**

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**