Un-integrated gluon densities & diffraction
Progress with the CCFM approach

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- Parton dynamics at small x: forward jets in DIS and diffraction
- CCFM un-integrated gluon
  - new fits to new data
  - non leading contributions ...
- non-diffractive forward jets
- CCFM un-integrated gluon applied to diffraction
  - diffractive di-jets
  - diffractive charm
- conclusion

Diffraction and CCFM

Why is

resolved Pomeron model

not enough ???

Diffraction and CCFM

Or

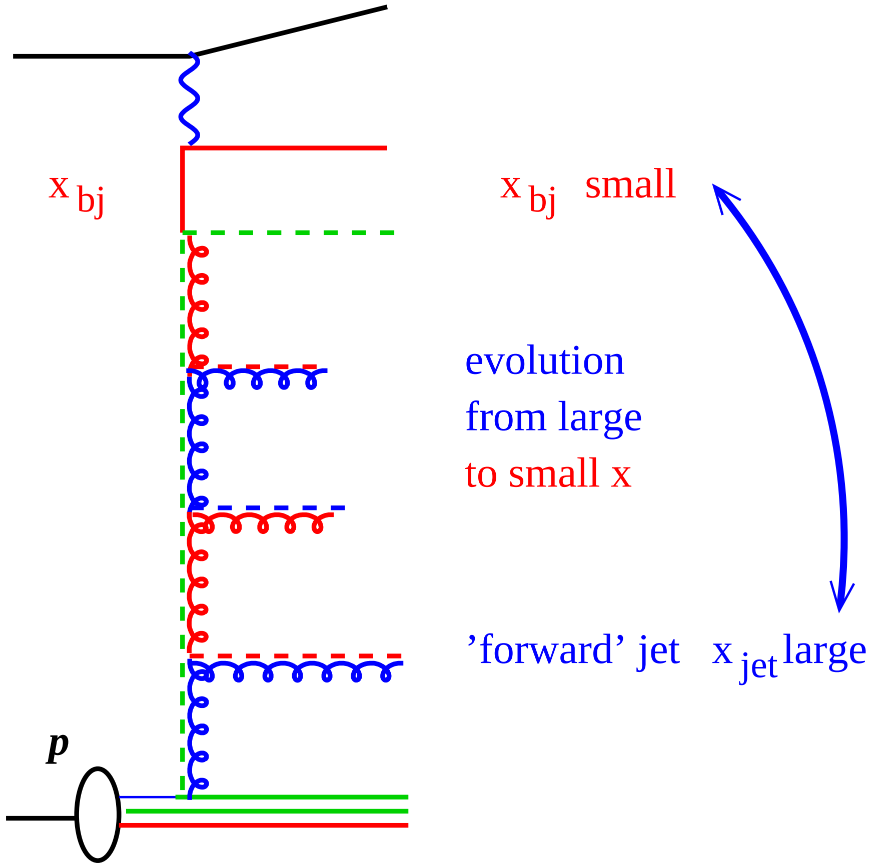
Why is hadronic final state

in DIS

important for diffraction ???

According to L. Lönnblad ...

Parton dynamics at small x: Forward Jets and Diffractive Jets



DIS and forward jet

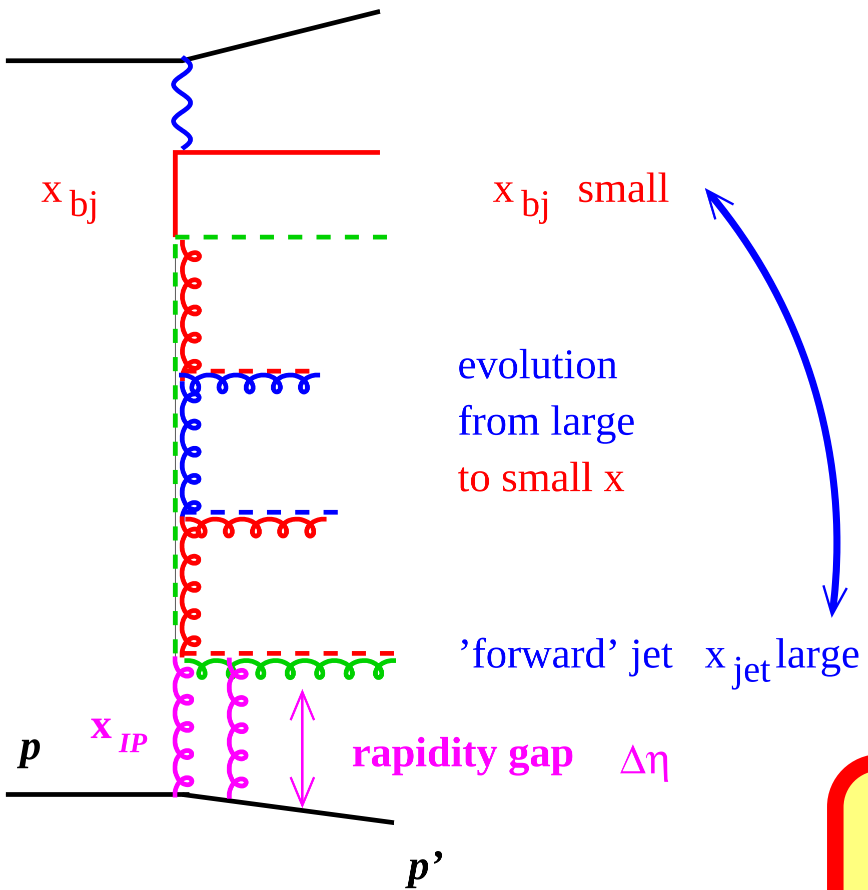
$1.7 < \eta_{jet} < 2.8$

$x_{jet} > 0.035$

$0.5 < \frac{p_{t\ jet}^2}{Q^2} < 2$

$\sigma(\text{fwd jet})/\sigma(\text{DIS}) \sim 1\%$

Parton dynamics at small x: Forward Jets and Diffractive Jets

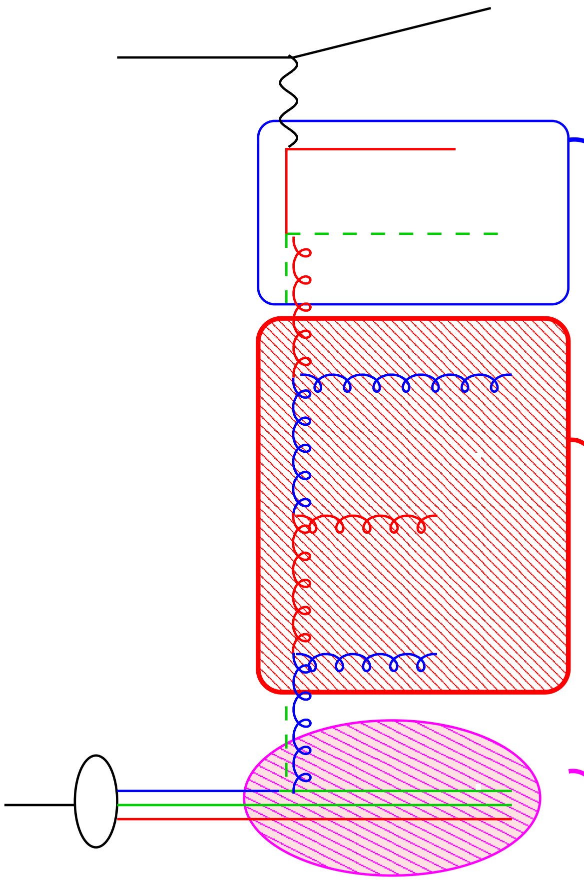


DIS and forward jet
$1.7 < \eta_{jet} < 2.8$
$x_{jet} > 0.035$
$0.5 < \frac{p_{t\ jet}^2}{Q^2} < 2$
$\sigma(\text{fwd jet})/\sigma(\text{DIS}) \sim 1\%$

in diffraction: "forward jet"
close to rapidity gap ...
$\sigma(\text{diff dijet})/\sigma(\text{DIS}) \sim 1\%$

understand radiation close to proton
and radiation close to rapidity gap
more than DGLAP needed
k_t **factorisation with BFKL or CCFM**

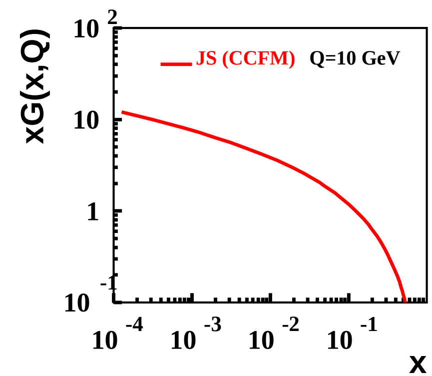
Basic idea - k_t factorisation



BGF matrix element
off mass shell

evolution of parton cascade

initial distribution:

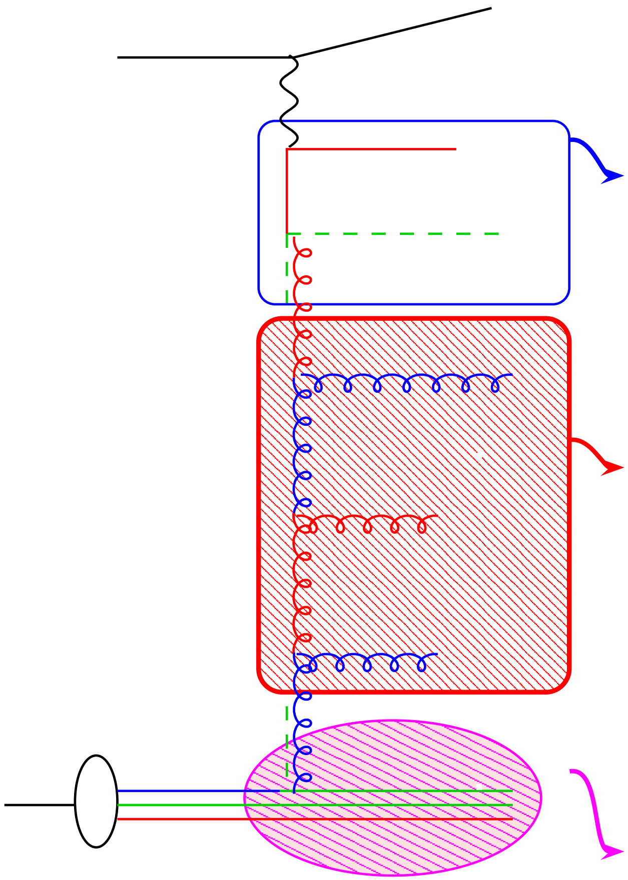


$\boldsymbol{\sigma(ep \to e' q\bar{q})} = \int \frac{dy}{y} d^2Q \frac{dx_g}{x_g} \int d^2 k_t \hat{\sigma}(\hat{s}, k_t, Q) x_g \mathcal{A}(x_g, k_t, \bar{q})$

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

Basic idea - k_t factorisation

CCFM



BGF matrix element
off mass shell

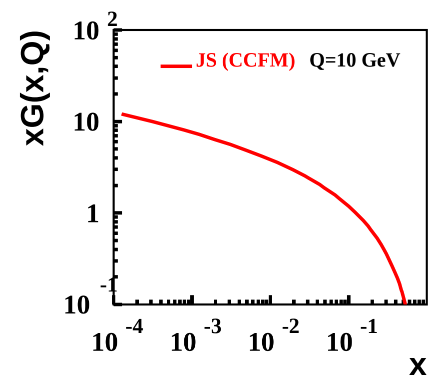
evolution of parton cascade
with CCFM splitting fct.

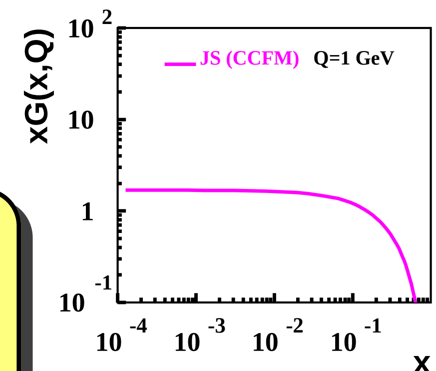
$$\tilde{P} = \bar{\alpha}_s \left(\frac{1}{1-z} + \frac{1}{z} {\Delta_n}^s \right)$$

initial distribution: flat

CCFM !!!

- **angular ordering (instead of q_t ordering)**
- **${\Delta_n}^s$ (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: $\tilde{P}(z,q,k_t) = \frac{\bar{\alpha}_s(q(1-z))}{1-z} + \frac{\bar{\alpha}_s(k_t)}{z}\Delta_{\text{ns}}(z,q,k_t)$

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**

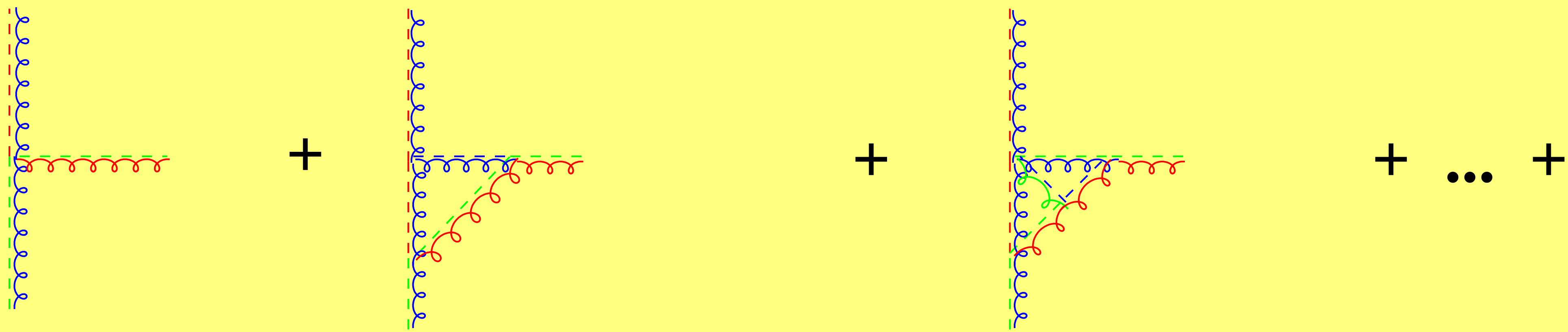
Non-Sudakov and all - loop resummation

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:

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

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



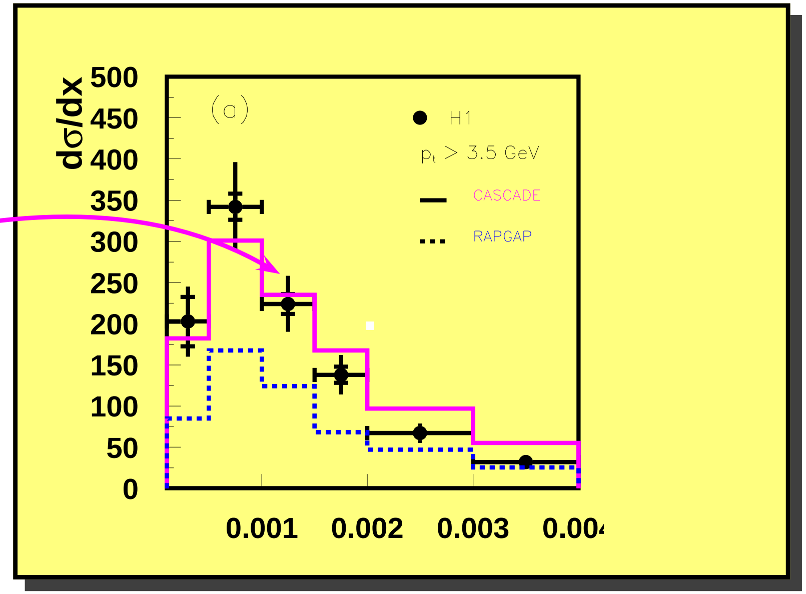
$$\bar{\alpha}_s(k_t)\frac{1}{z}\left[\;1 \quad + \quad \bar{\alpha}_s\log\left(\frac{z}{z_0}\right)\log\left(\frac{k_t^2}{z_0 z q^2}\right) \quad + \quad \frac{1}{2!}\left(\bar{\alpha}_s\log\left(\frac{z}{z_0}\right)\log\left(\frac{k_t^2}{z_0 z q^2}\right)\right)^2 \ldots\right]$$

CASCADE with CCFM: the solution ...

Solve CCFM equation
to fit F_2 data from HERA

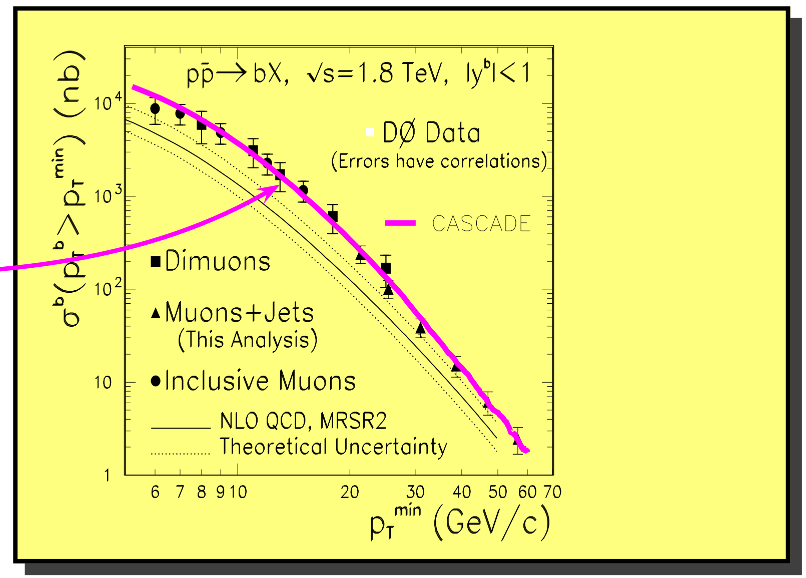
- obtain CCFM un-integrated gluon

  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 !!!



CCFM with non - leading contributions

- **Going beyond leading order CCFM:**
  - **non-leading contributions in splitting function non-singular terms, scale in α_s**

- **NEW**
  - **fit to (94 and 96-97) F_2 data from H1 and ZEUS**
  - **investigation of soft region in cascade, cutoffs, ...**
  - **non-leading contributions (non-sing. terms, scale in α_s)**

- **complicated machinery: MC generation of pdf used in fits**
  ($50 \otimes 2 \cdot 10^6$ calculations of full evolution for pdf, $3 \cdot 10^6$ for x-section)
- **only way for consistent results for hadron level calcs treat kinematics properly (never done for DGLAP !!!)**
- **precision level now reached for k_t - factorization**

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

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

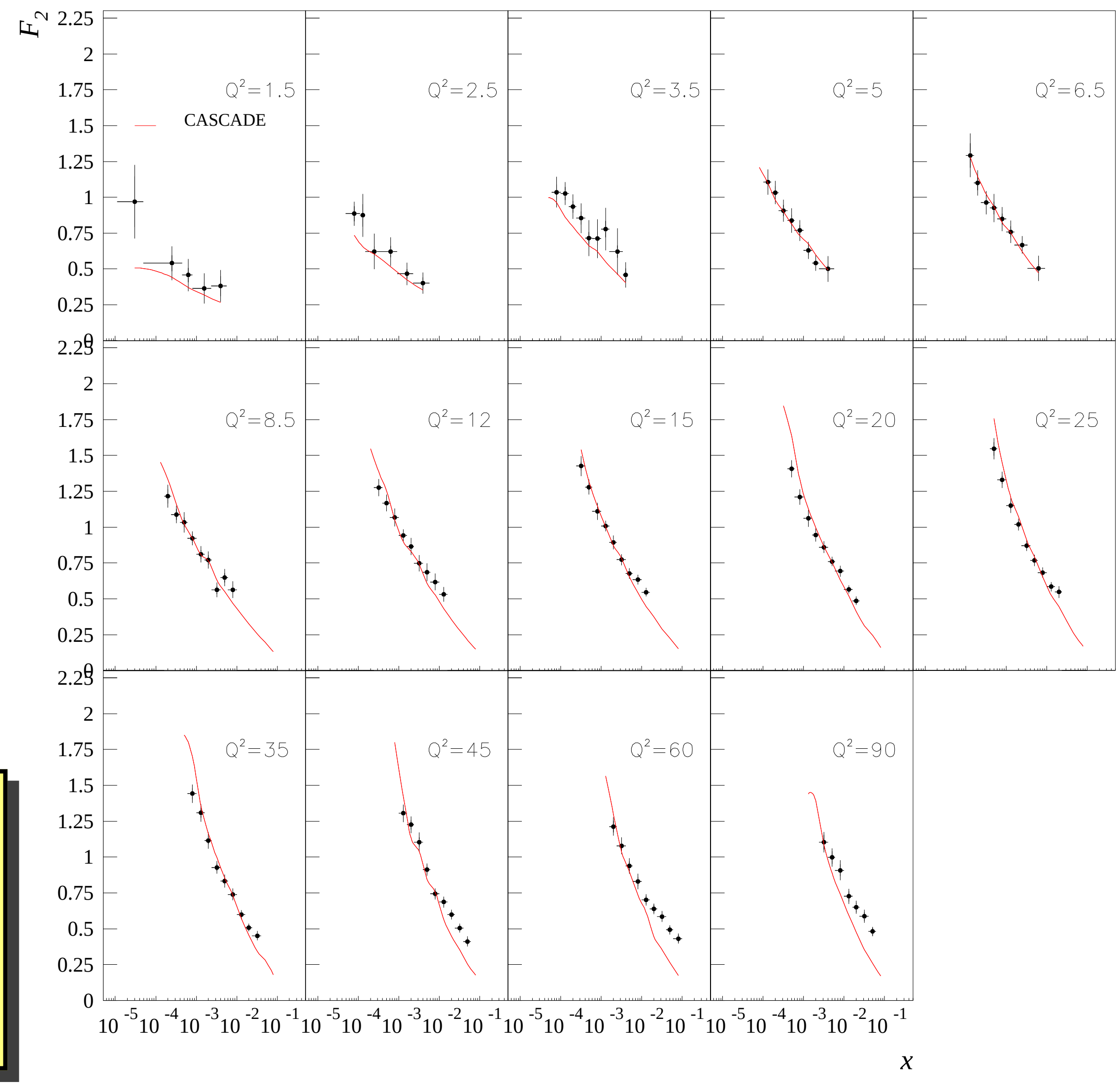
With $\sigma = \int dk_t^2 dx_g \mathcal{A}(x_g, k_t^2, \bar{q}) \sigma(\gamma^* g^* \to q\bar{q})$ fit $F_2(x, Q^2)$

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

Parameters in fit

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

- starting scale & cut-off for resolvable branching $Q_0 = 1.4$ GeV
- freezing of $\alpha_s(k_t)$ for $k_t \to 0$ treatment of soft region ☛ see later
- quark masses: $m_q = 0.250$ GeV, $m_c = 1.5$ GeV
- initial gluon $x\mathcal{A}_0(x, k_{t0}^2)$



un-integrated gluon density

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

obtained from fit to F_2

New fits of 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 Q_0 and normalization in initial pdf $xA_0 = N(1-x)^4$

Treatment of soft region

no k_t ordering ☞ diffusion into soft

- **what about α_s for $k_t < k_t^{cut}$ in splitting fct and non-Sudakov ?**

☞ non - resolvable branching

☞ but keep full kinematics

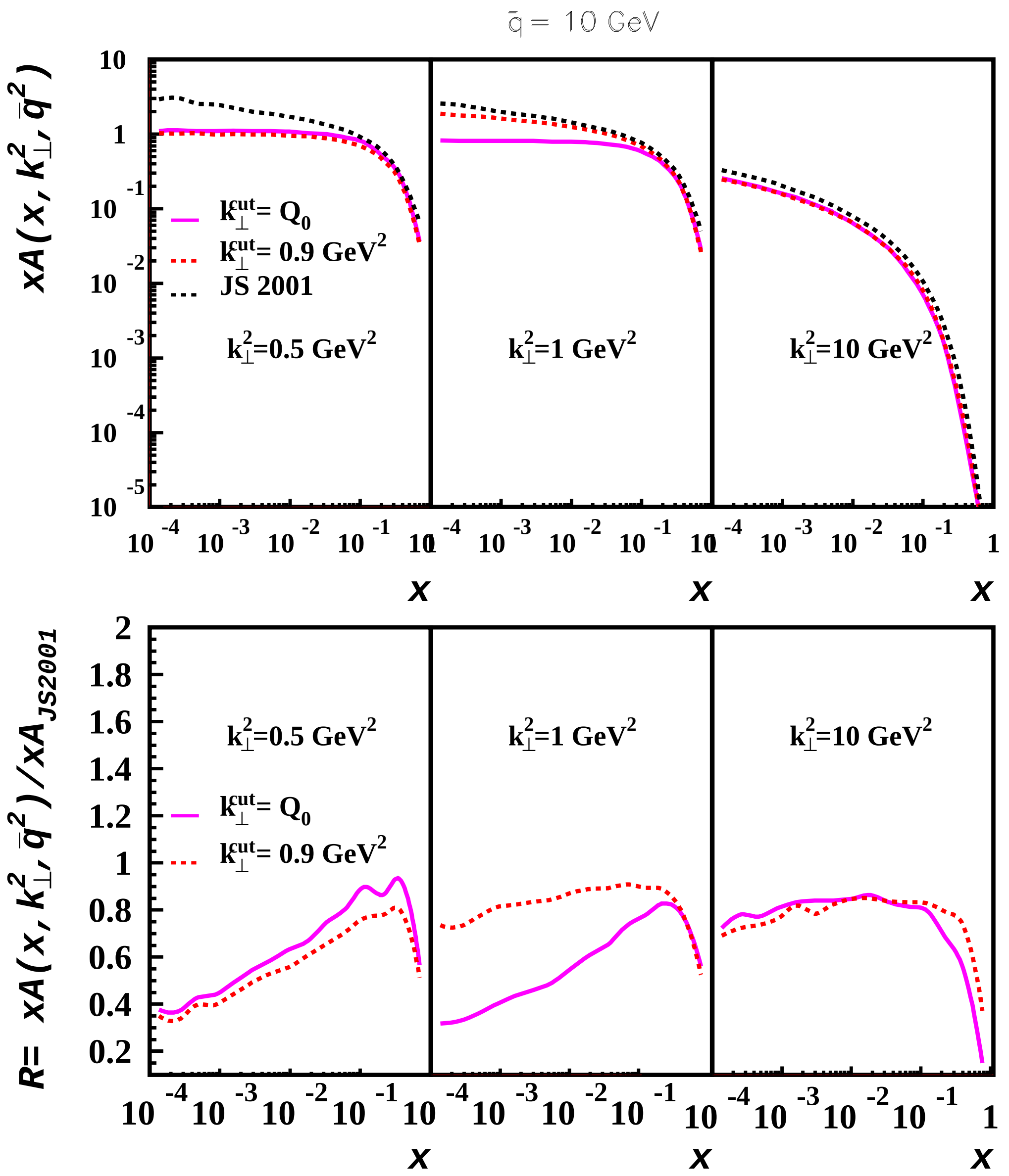
☞ no x-section enhancement

☞ no real emission

☞ but keep full kinematics

What is actual cut - what is soft?

- **JS2001 had soft cut $k_t > 0.25$ GeV**
- **now $k_t > Q_0$**



Improve CCFM Splitting Function: $\bar{\alpha}_s(q_t)$

together with G.P. Salam

Original CCFM Splitting Fct:

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

$$\log\Delta_{ns} = -\bar{\alpha}_s(k_t^2)$$

$$\int_0^1 \frac{dz'}{z'} \int \frac{dq^2}{q^2}\Theta(k_t - q)\Theta(q - z'q_t)$$

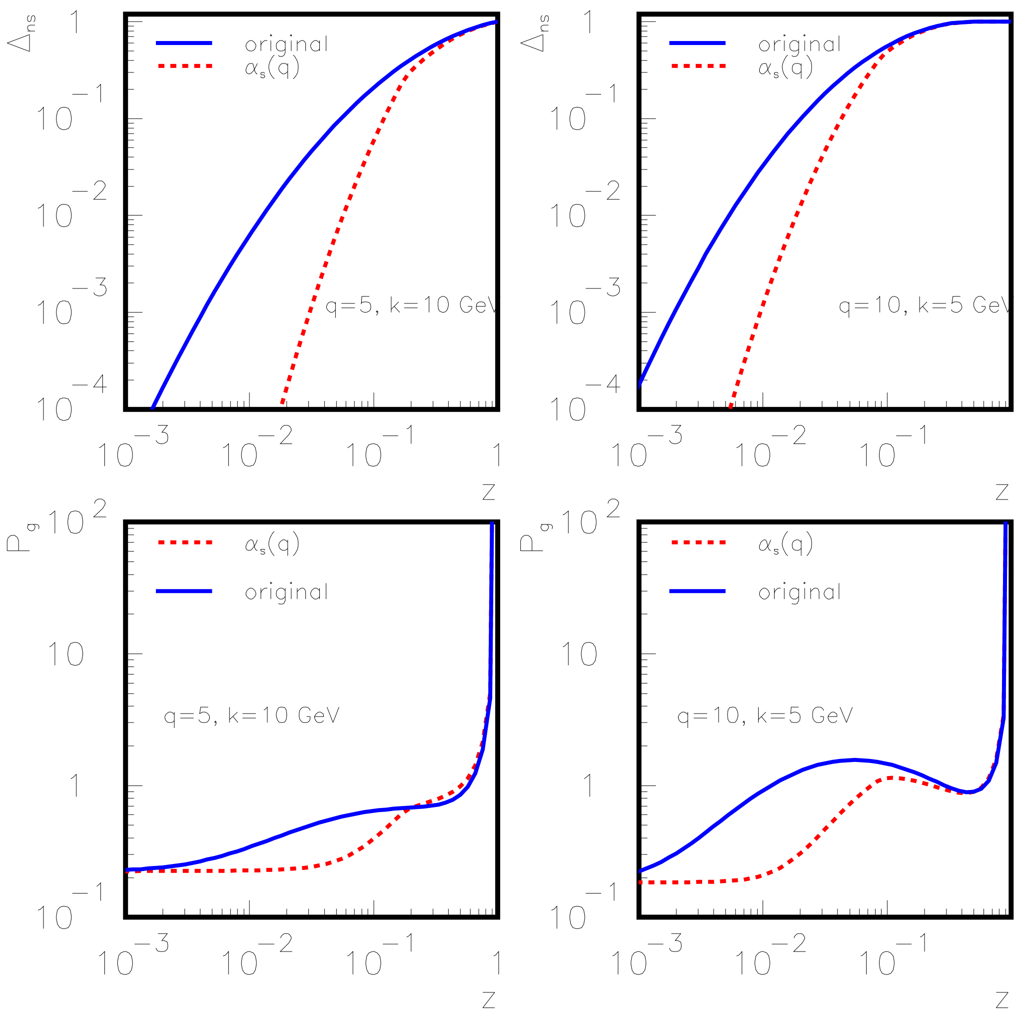
Change scale from k_t to q_t in $\bar{\alpha}_s$:

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

$$\log\Delta_{ns} = -\int_0^1 \frac{dz'}{z'}$$

$$\int \frac{dq^2}{q^2}\bar{\alpha}_s(q)\Theta(k_t - q)\Theta(q - z'q_t)$$

$$\log\Delta_{ns} = \cdots \int_{(z'q_t)^2}^{k_t^2} \frac{dq^2}{q^2} \frac{1}{\log(q/\Lambda_{QCD})}$$



worry: lower limit $z'q_t \ll \Lambda_{QCD}$:

- **keep angular ordering (integral limits),**

☛ **but fix $\bar{\alpha}_s$ below $q^{cut} = 0.9$ GeV**

CCFM including 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**

$$P_{gg} \sim \bar{\alpha}_s \left(\frac{1}{z} \Delta_{ns} - 2 + z(1-z) + \frac{1}{1-z} \right)$$

- **new attempt (idea by G.P. Salam):**

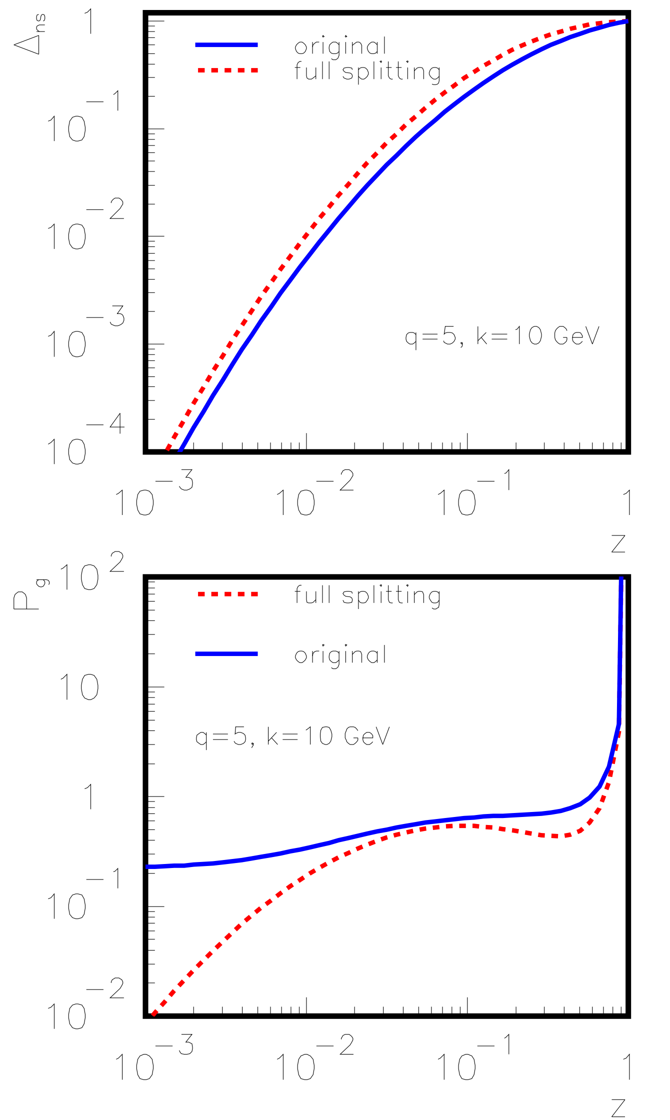
$$P = \bar{\alpha}_s \left(\frac{(1-z)}{z} + \frac{z(1-z)}{2} \right) \Delta_{ns} + \bar{\alpha}_s \left(\frac{z}{1-z} + \frac{z(1-z)}{2} \right)$$

- **need also new Sudakov:**

$$\log \Delta_s = - \int_0^1 \frac{dq'^2}{q'^2} dz' \bar{\alpha}_s \left(\frac{z'}{1-z'} + \frac{z(1-z)}{2} \right)$$

and new non-Sudakov

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

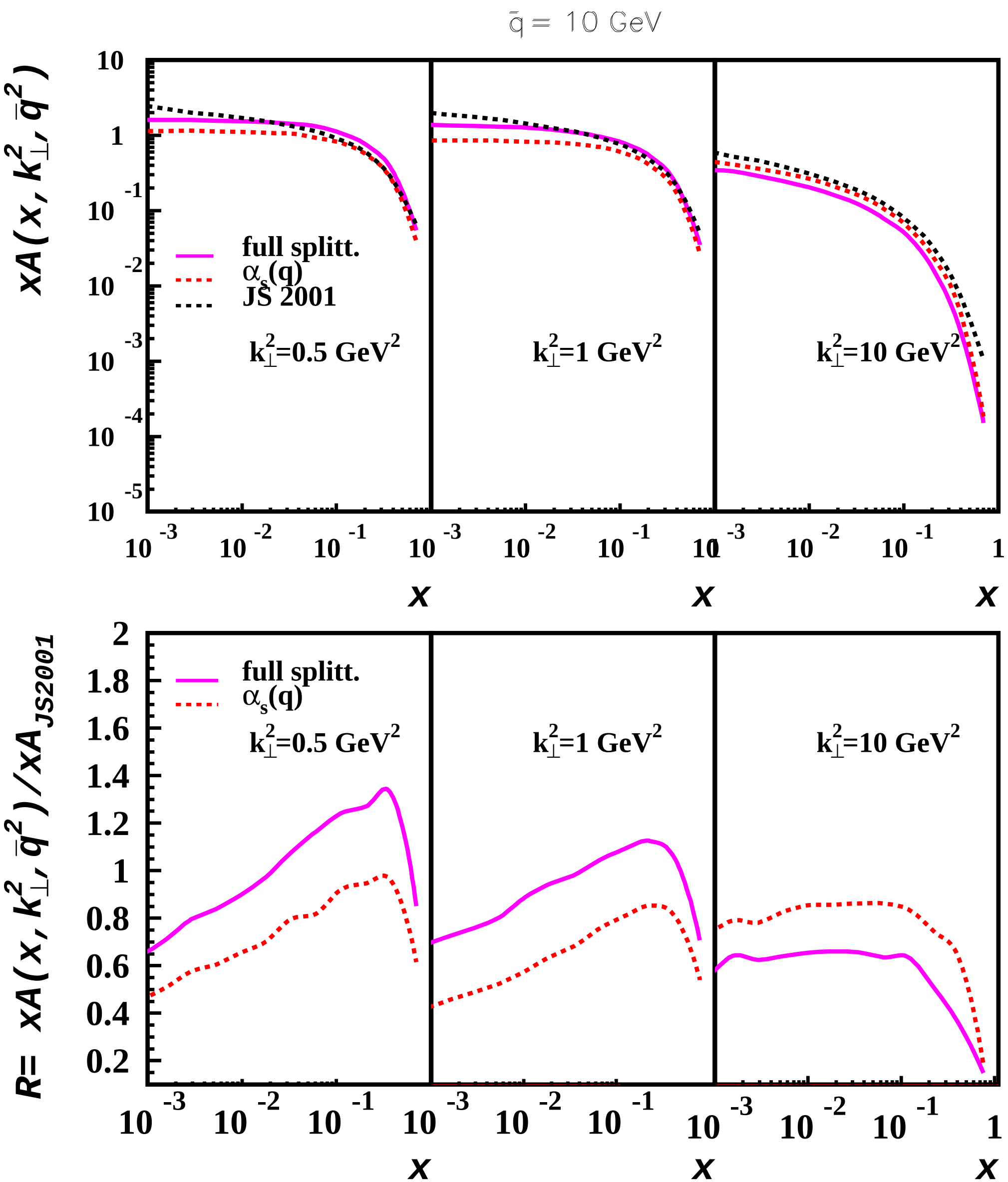


- **soft region in non-Sudakov ???**

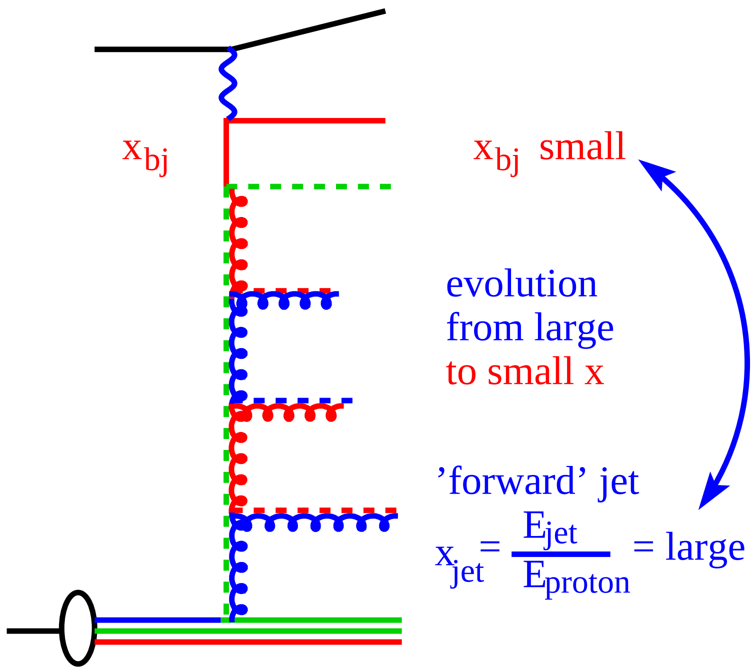
☛ **keep angular ordering**

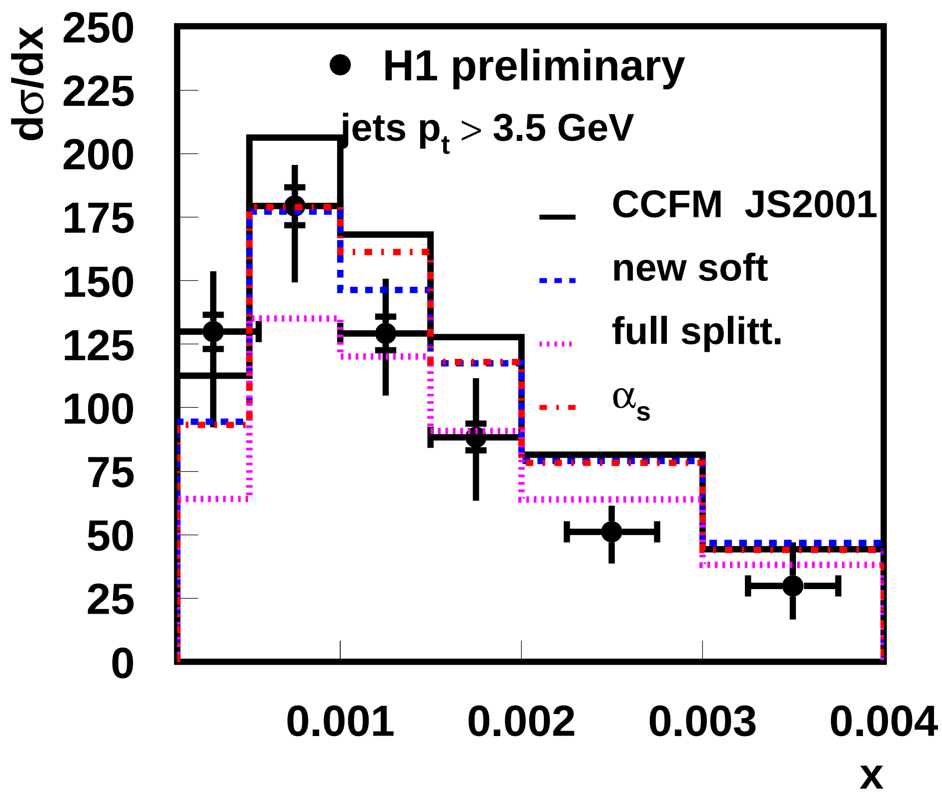
Improve CCFM: $\alpha_s(q_t)$ and full splitting Function

- fit F_2 data
  $x < 0.01$ $Q^2 > 3.5$ GeV^2
  new treatment of soft region
- $\alpha_s(q_t)$
  $\chi^2/N = 1.27$ for $N = 147$
- full splitting
  $\chi^2/N = 1.48$ for $N = 147$
- compare to old set JS2001



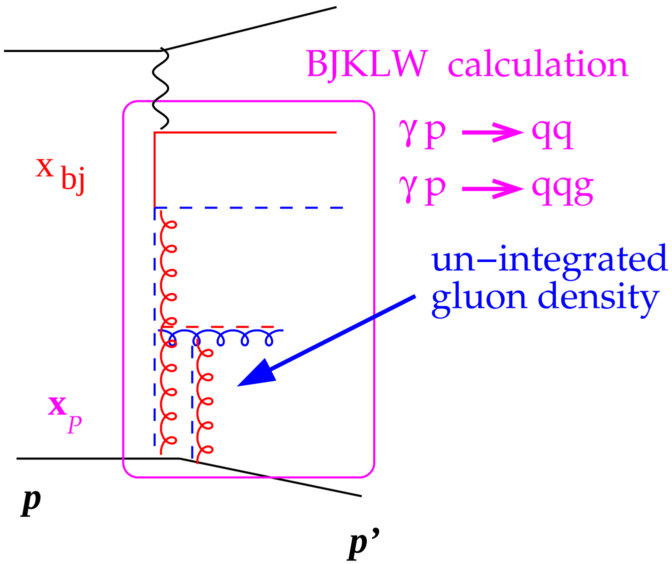
New pdfs and forward jets



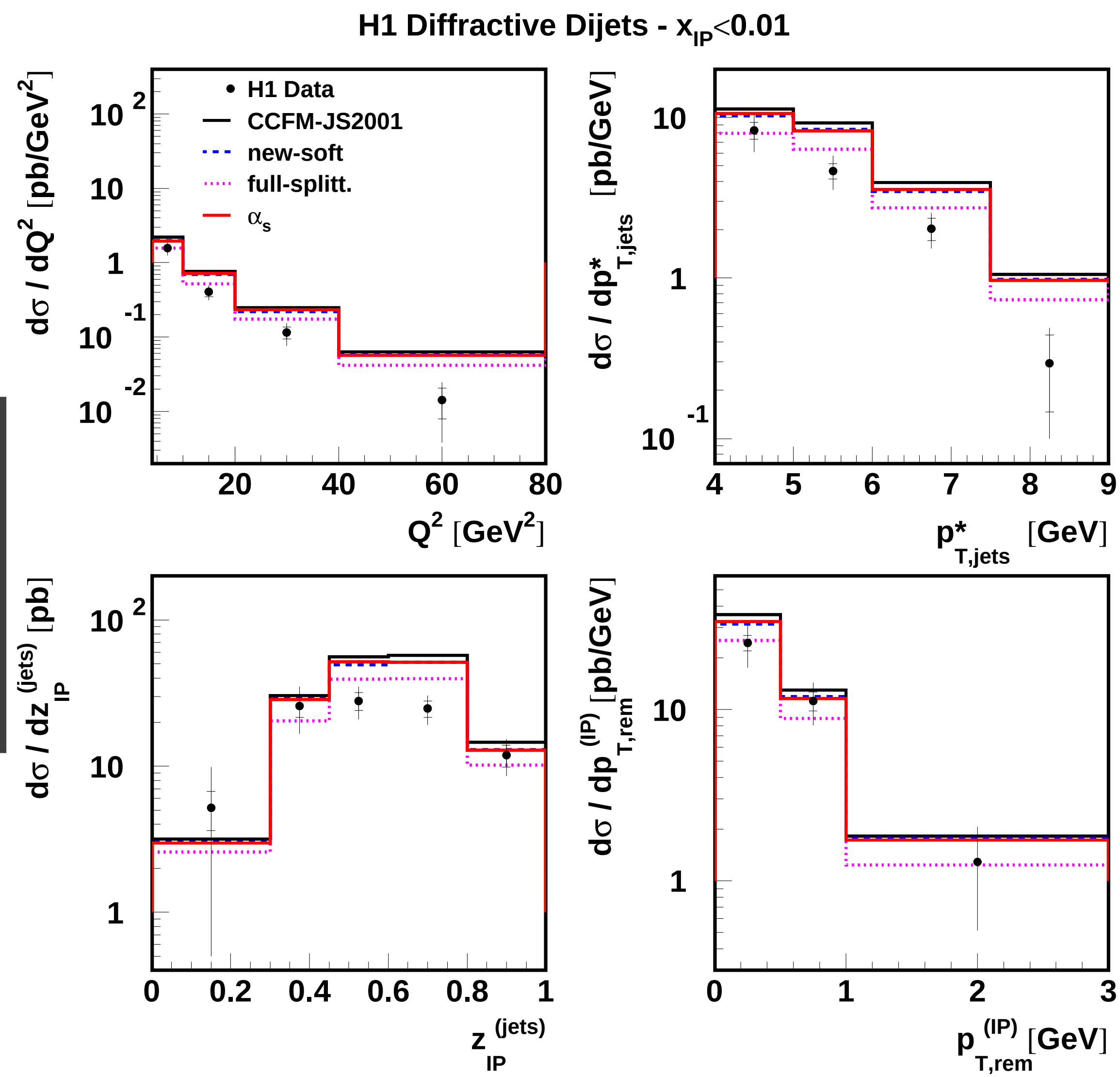


- old set (JS2001) overshoots data
- new fits ☞ smaller x-sect.
- agree better with new data
- even with full splitting fct.
- and with $\alpha_s(q)$

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, $-1.0 < \eta^{lab}_{jet} < 2.2$



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

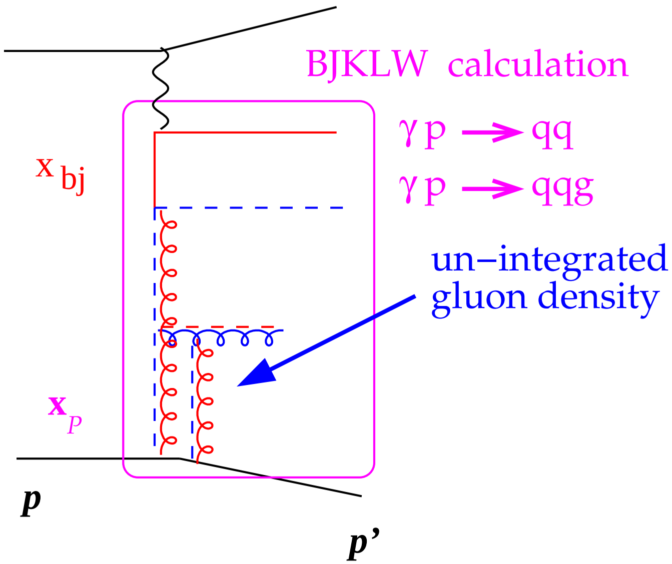
J. Bartels, H. Lotter, M. Wüsthoff, Phys. Lett. **B 379** (1996) 239
N. Nikolaev, B.G. Zakharov, Z. Phys. **C 53** (1992) 331.
E. Gotsman, E. Levin, U. Maor, Nucl.Phys. **B 493** (1997) 354.

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

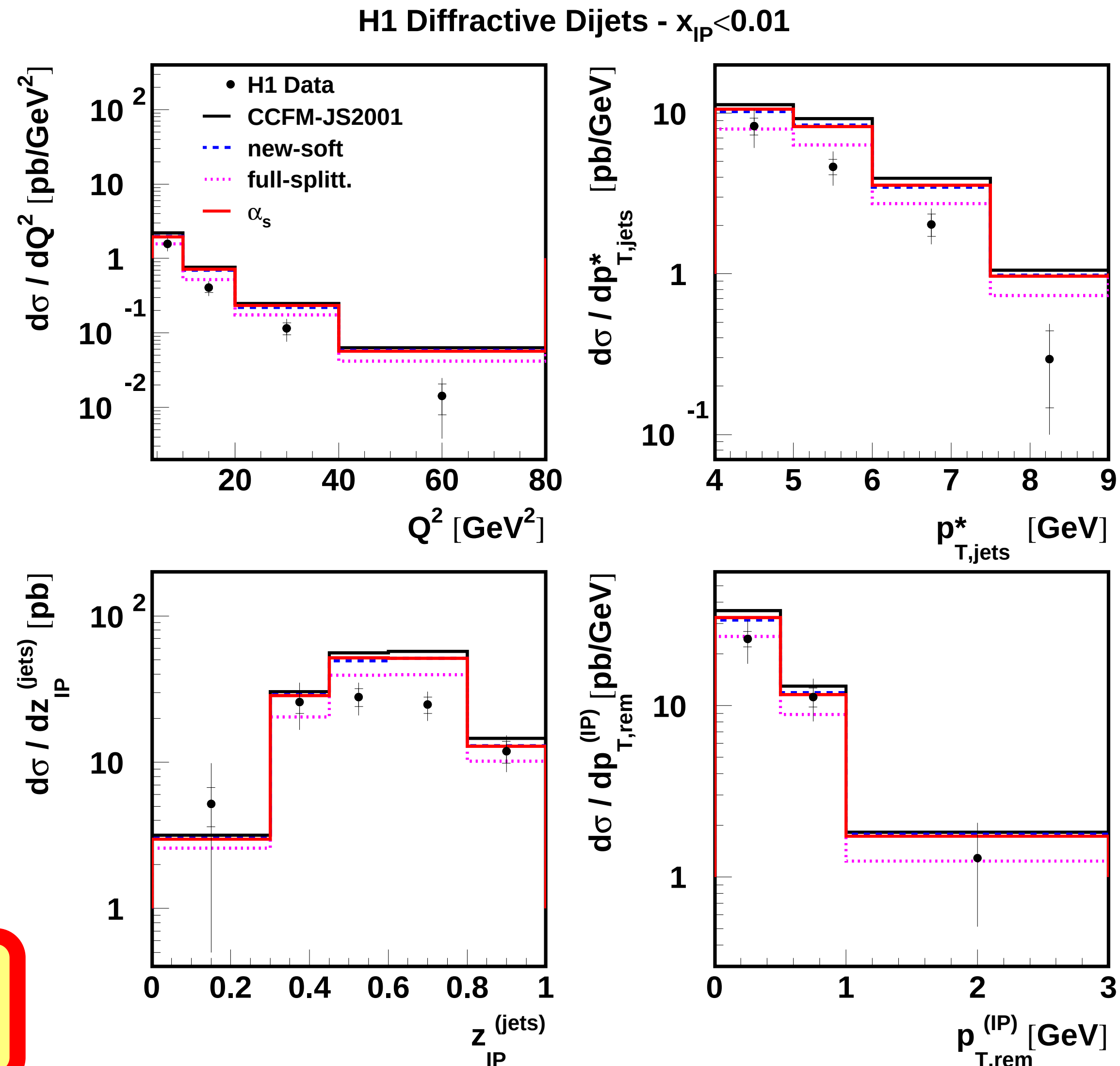
J Bartels H Jung M Wusthoff, Eur. Phys. J. **C11**, 111 (1999)

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, $-1.0 < \eta_{jet}^{lab} < 2.2$

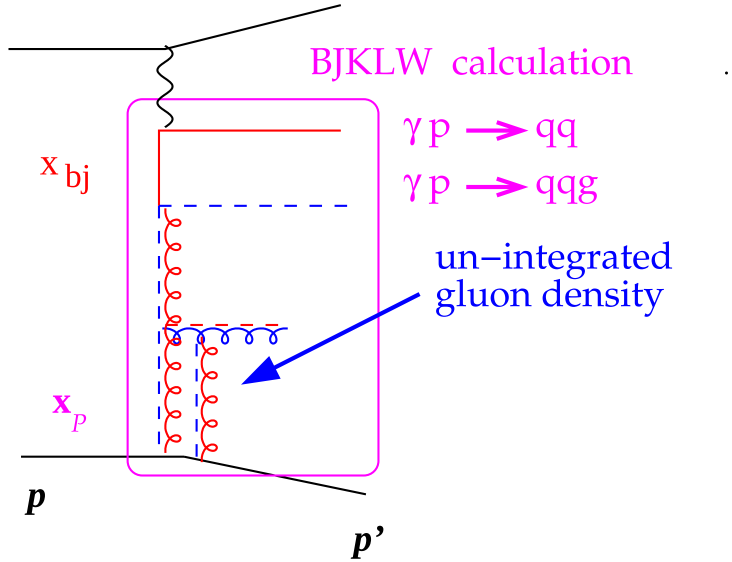


cutoff $p_t > 2.5$ GeV needed

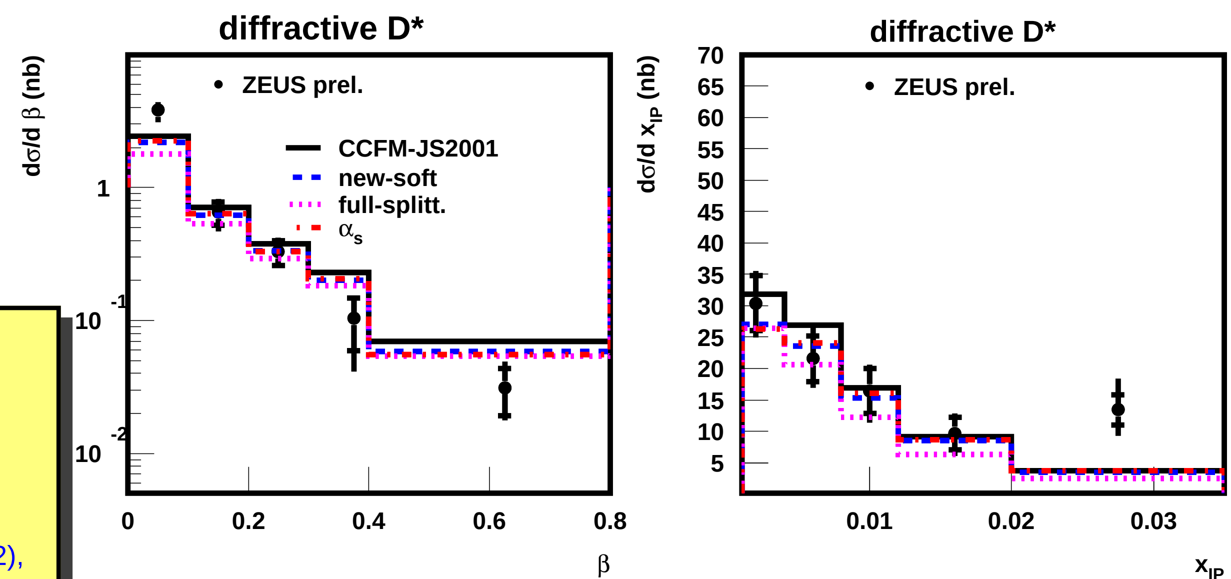
- non-ordered emissions:
- ☞ $p_t^{gluon} > p_t^{q,\bar{q}}$: ~ 30 %
- ☞ not possible in res. pom
- ☞ nor SCI

Gluon from CCFM ✔

Diffractive Charm and CCFM



$0.02 < y < 0.7, 1.5 < Q^2 < 200$ GeV^2
$x_{I\!P} < 0.035, \beta < 0.8$
$1.5 < p_t(D^*) < 10$ GeV, $|\eta(D^*)| < 1.5$



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

H Lotter, Phys. Lett. **B 406** (1997) 171

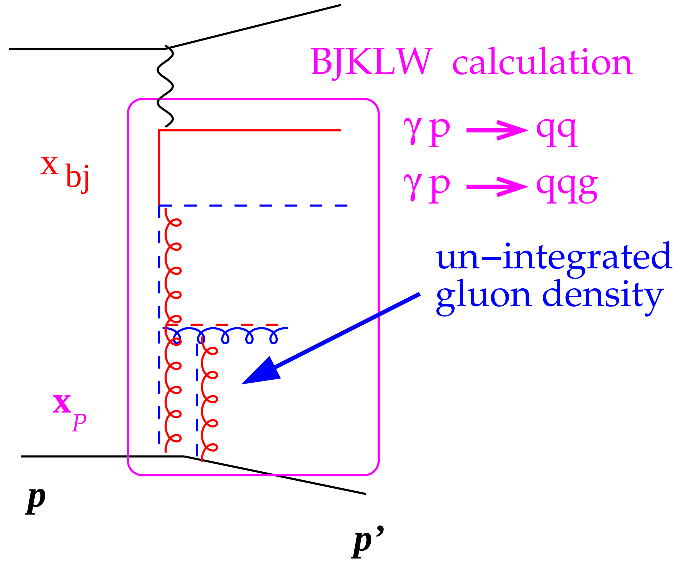
$\gamma p \to Q\bar{Q}g$ (2-gluon exchange)

J Bartels, H Jung, A Kyrieleis, Eur. Phys. J. C **24**, 555 (2002),

apply only to $x_{I\!P} < 0.01$!!!

pert. QCD calculation ...

Diffractive Charm and CCFM



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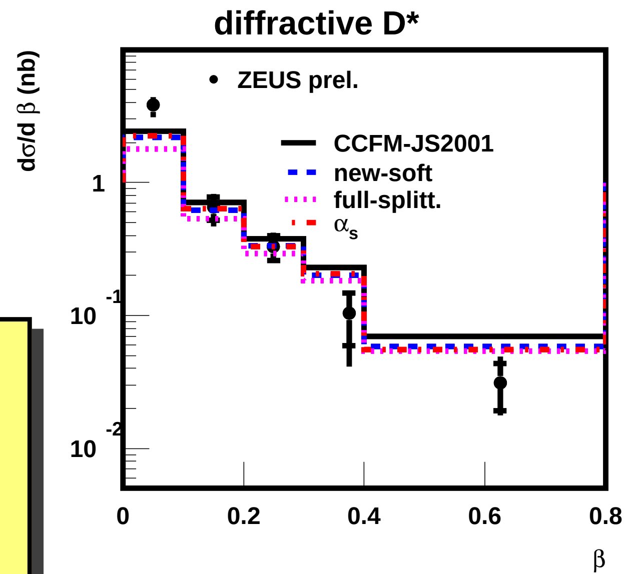

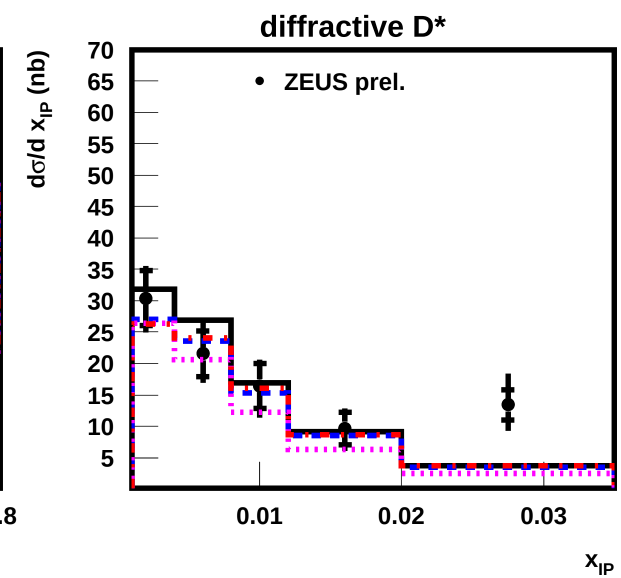

cutoff $p_t^{gluon} > 1.75$ GeV

- non-ordered emissions:
- $p_t^{gluon} > p_t^{q,\bar{q}}$: ~ 20 %
- not possible in res. pom
- nor SCI !!!

Gluon from CCFM ✔

Hard gluon radiation needed for charm & jets ???

Summary and Conclusions

- new CCFM un-integrated pdfs from fits to more F_2 data
- new studies of non-leading effects in CCFM:
  - soft region, scale in α_s and full splitting function
- new pdfs agree better with forward jet data ...
  even including non-leading effects
- un-integrated gluon of proton applied to diffraction
  successful for DIF di-jets and charm

  much better than res. pomeron ...

Forward Jets and
Diffractive Charm & Jets described
with CCFM un-integrated gluon from proton !!!
Diffraction from inclusive scattering consistently