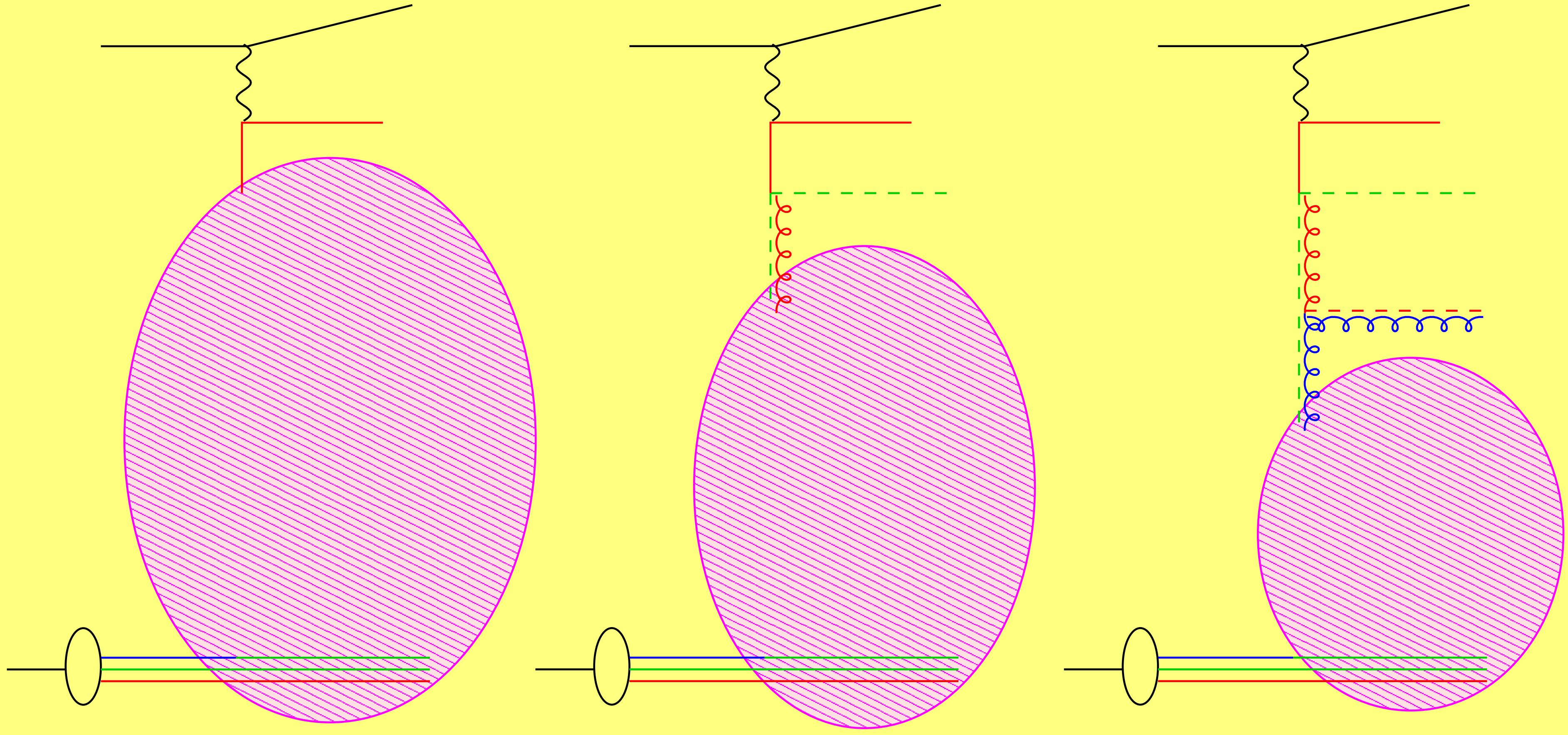
The CASCADE Monte Carlo generator with CCFM parton evolution

H. Jung, DESY

HERA - LHC workshop, MC tools WG, Startup Meeting CERN, March 2004

- the problem at HERA and Tevatron
  - k_t-factorisation - CCFM
- the model for pp
  - applied to heavy quark production
  - applied to minimum bias
  - applied to Higgs at LHC
- conclusion

Where is the problem ? Hadronic Final State !



QPM process	BGF ($\mathcal{O}(\alpha_s)$) process	$\mathcal{O}(\alpha_s^2)$ process
total x-section	**heavy quarks charm & bottom**	
	2 -jet	3 -jets

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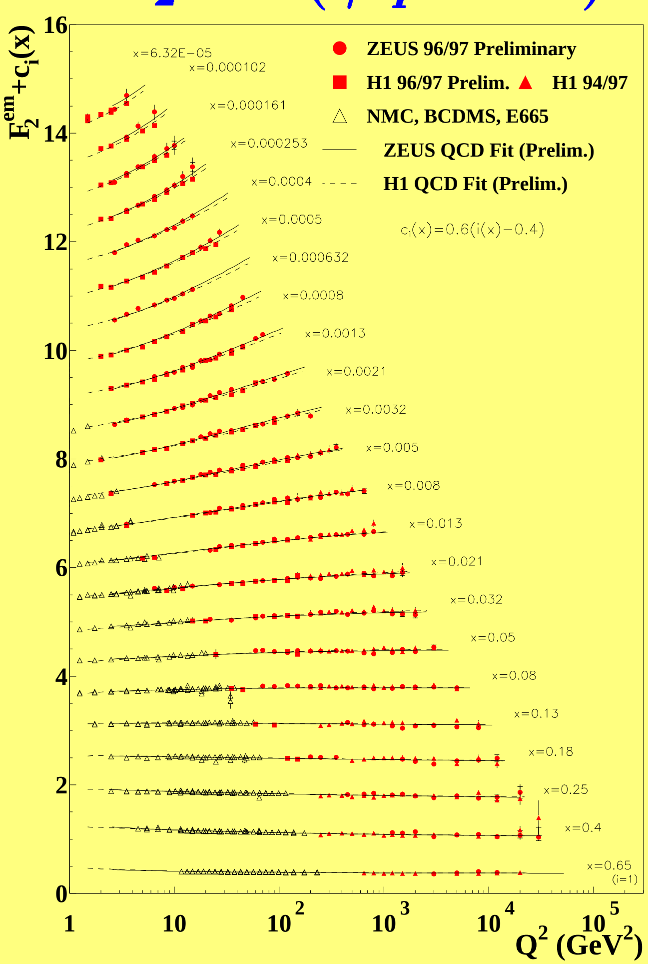
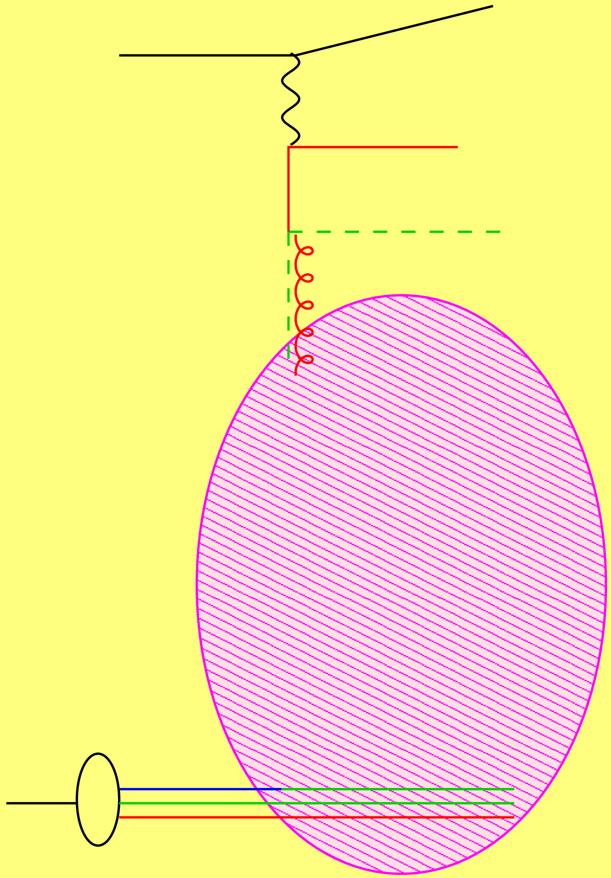
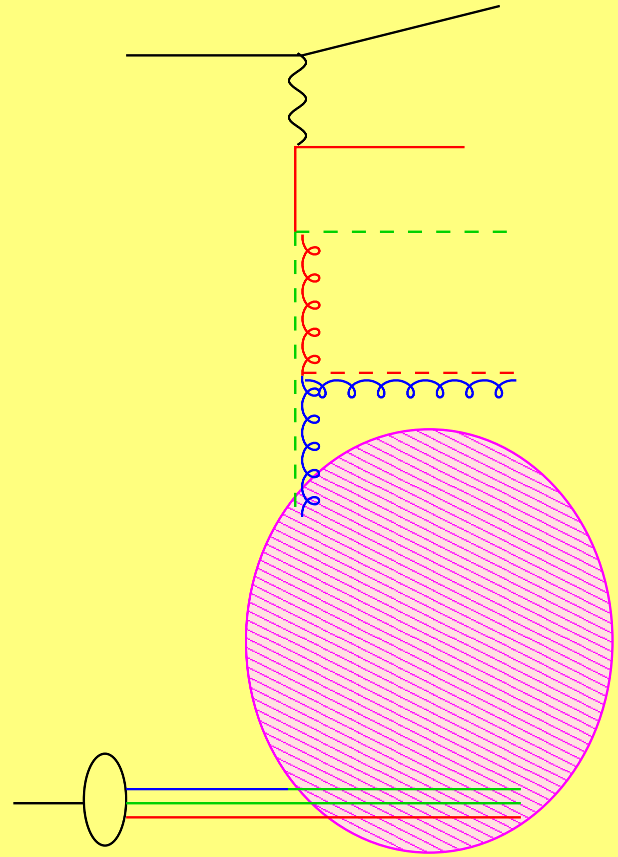
$F_2 \sim \sigma(\gamma^* p \to X)$







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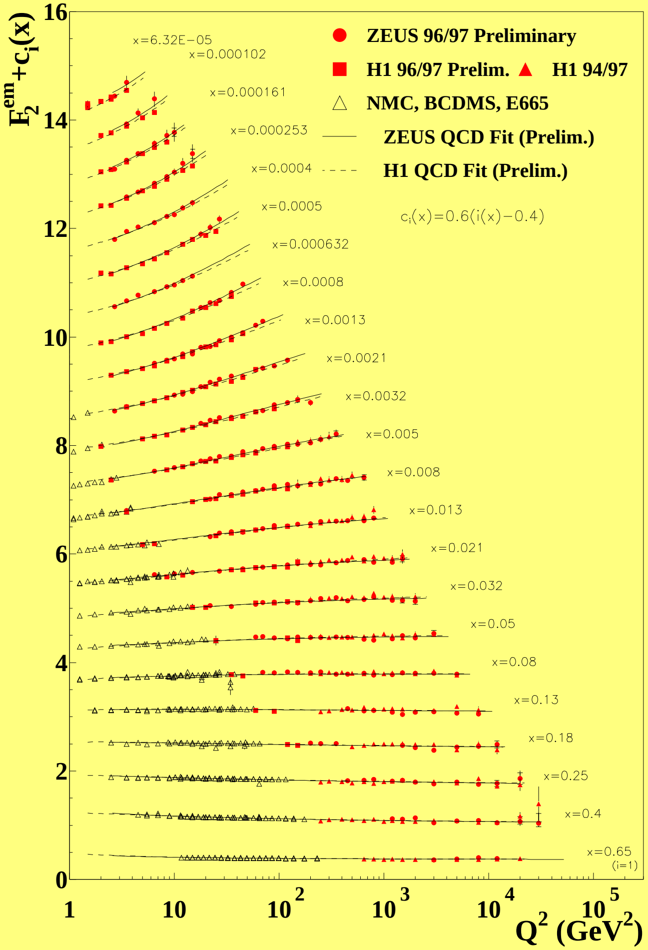
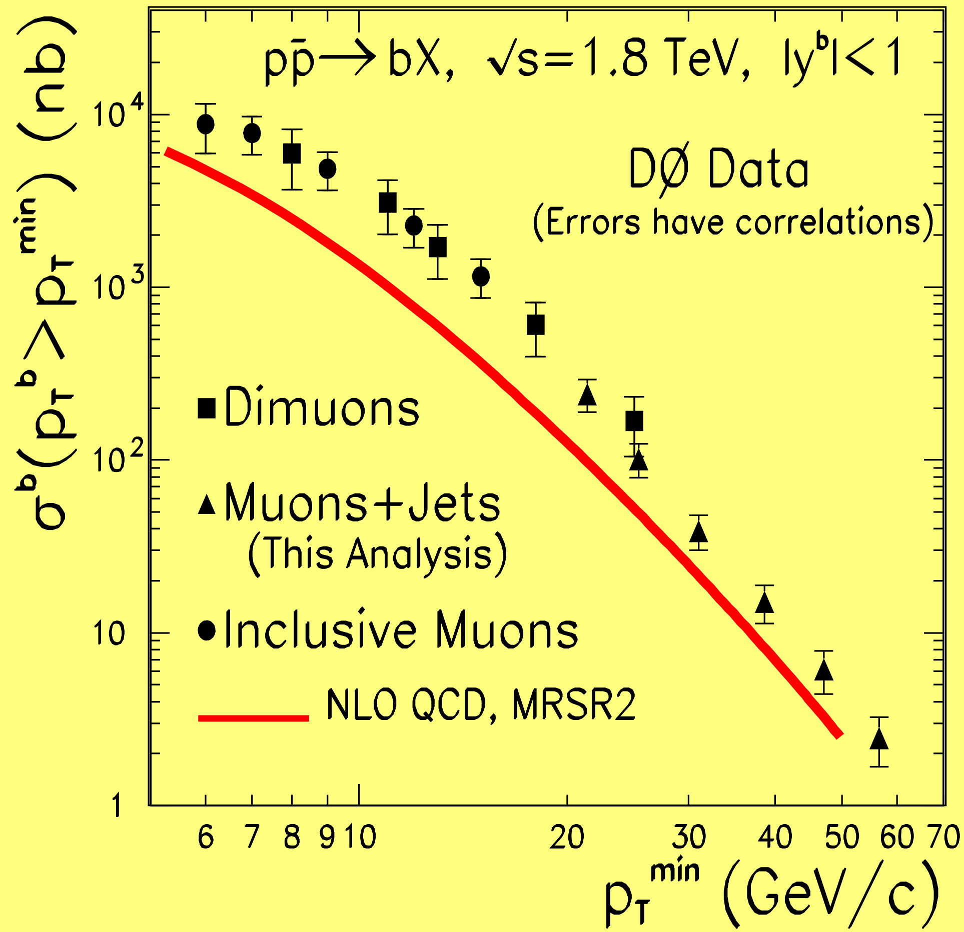


bottom $p\bar{p}$



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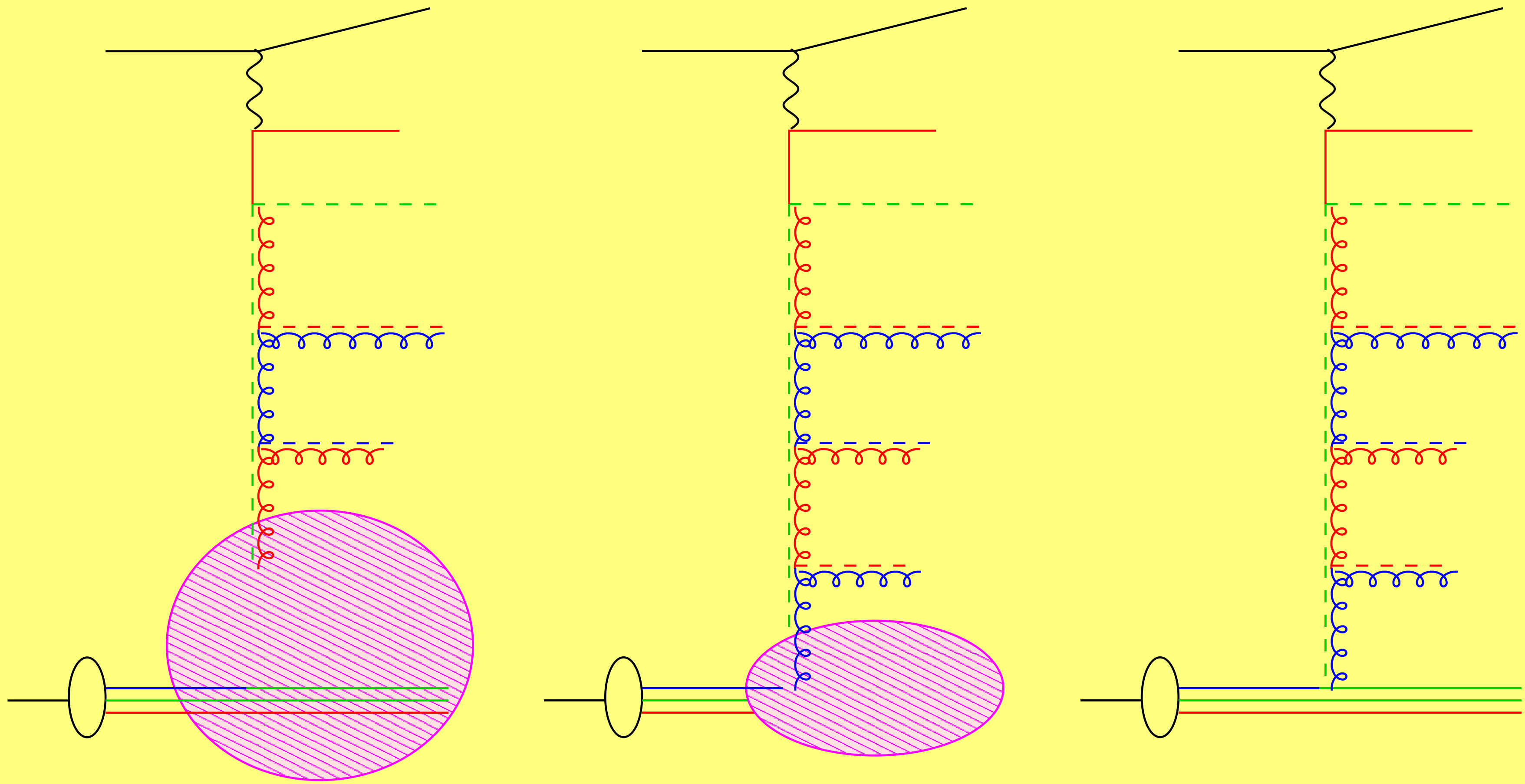

processes of $\mathcal{O} > \alpha_s^3$ have not been calculated explicitely

interesting close to proton region

forward jets !!!

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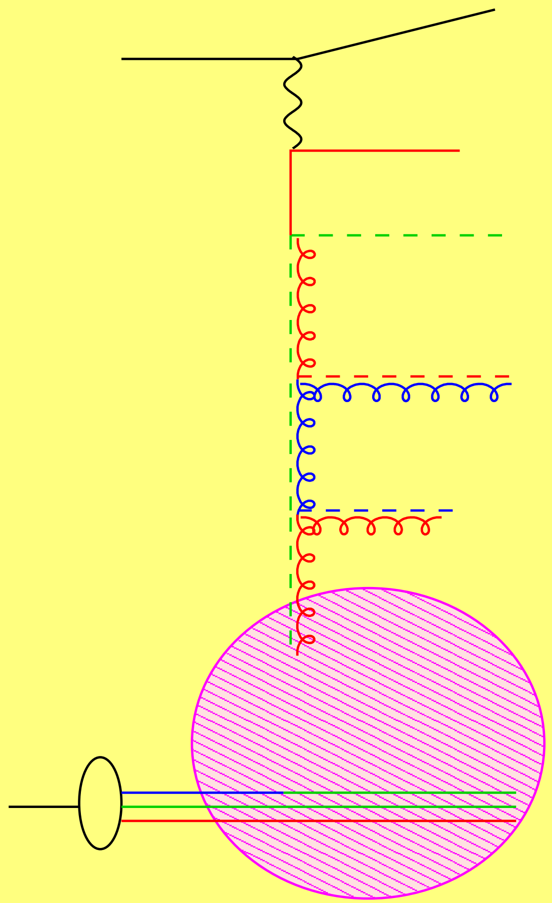

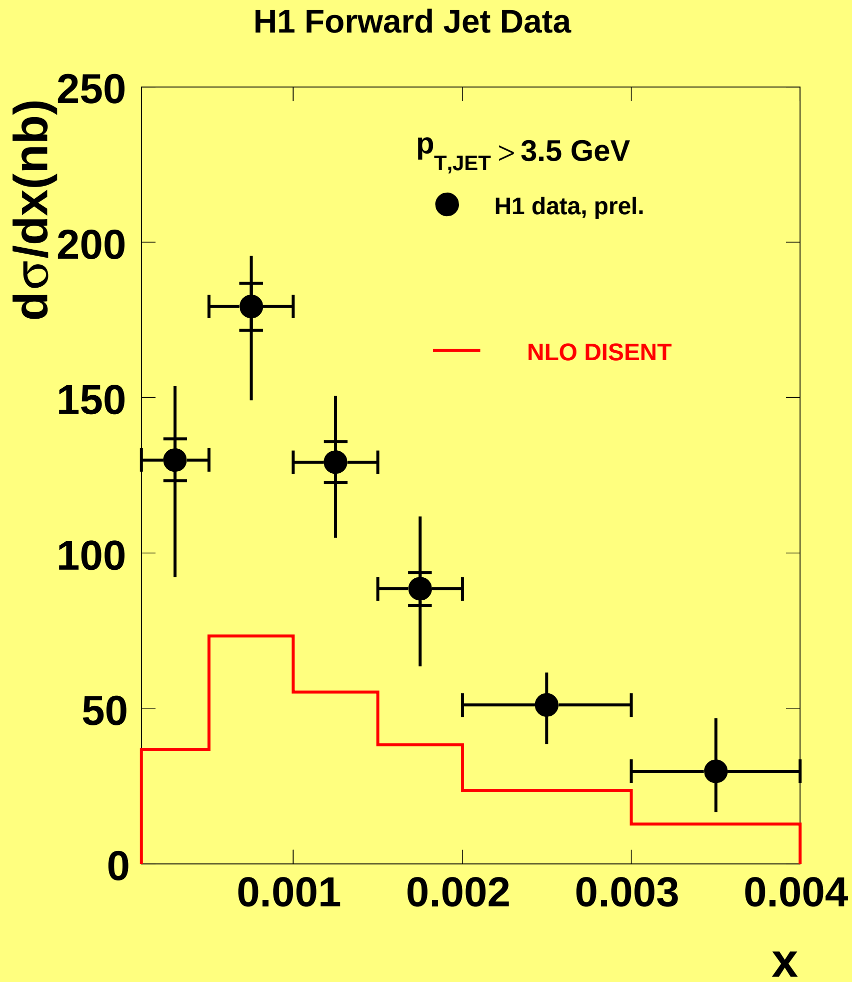

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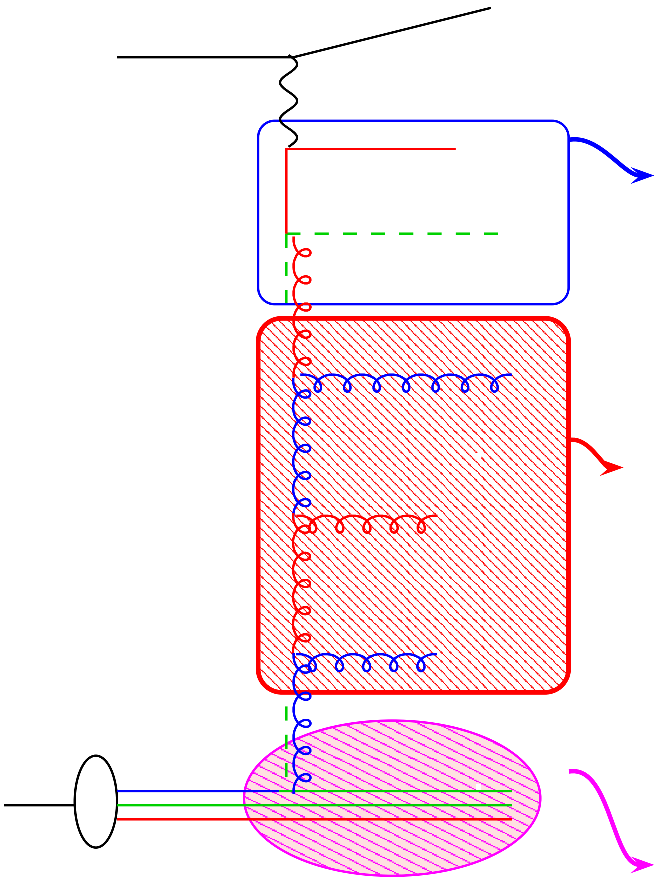
forward jets !!!

Basic idea - k_t factorisation

CCFM

CCFM (one loop)

- **angular ordering**

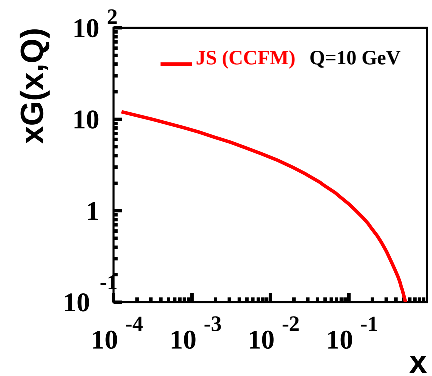


BGF matrix element
off mass shell

evolution of parton cascade
with DGLAP splitting fct.

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

initial distribution:



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

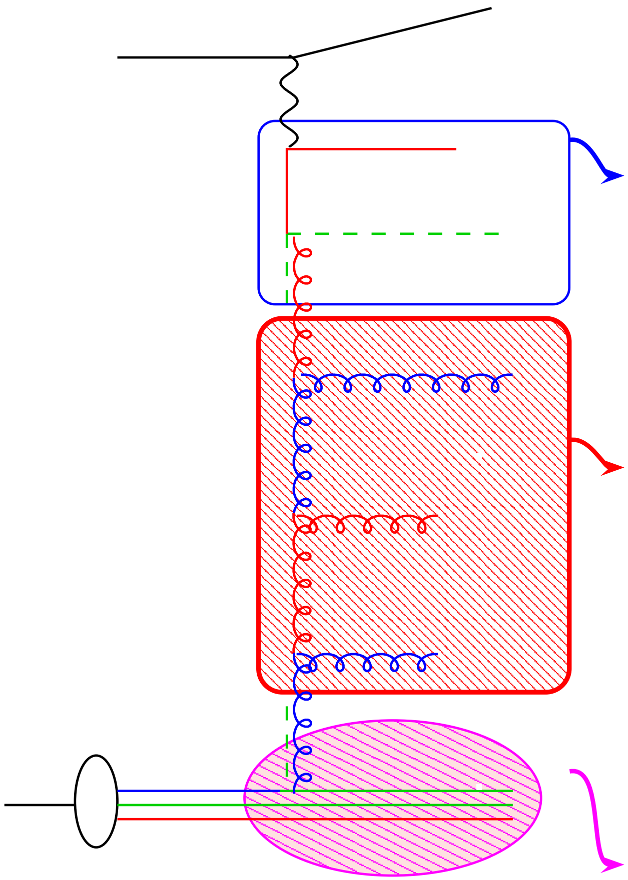
with $\int d^2k_t x_g \mathcal{A}(x_g, k_t, \bar{q}) \simeq x_g G(x_g, Q^2)$

Basic idea - k_t factorisation

CCFM (all loops)

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

CCFM

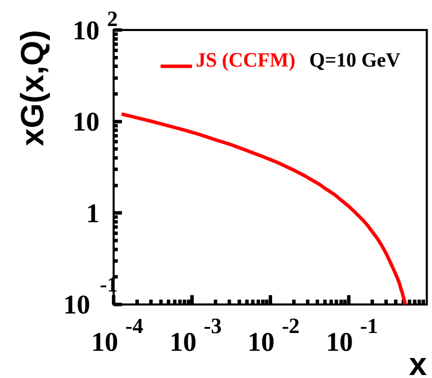


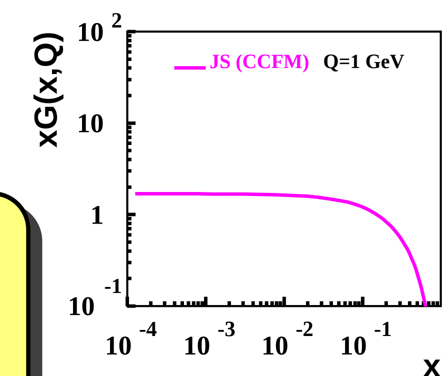
BGF matrix element off mass shell

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





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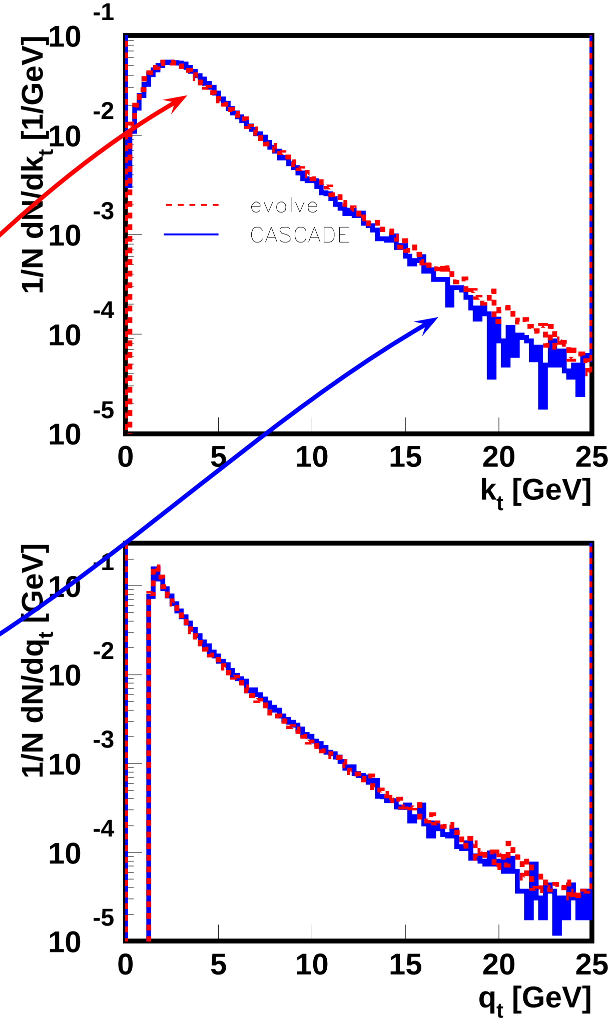
with $\int d^2k_t x_g \mathcal{A}(x_g, k_t, \bar{q}) \simeq x_g G(x_g, Q^2)$

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
- unintegrated parton densities
- CASCADE MC generator



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

The Monte Carlo Generator CASCADE

- Implement CCFM backward evolution into *NEW* MC generator **CASCADE** (http://www-h1.desy.de/$\sim$jung/cascade)
- hard scattering processes included:
  - $\gamma g^* \to q\bar{q}, \gamma^* g^* \to Q\bar{Q}, \gamma g^* \to J/\psi g$
  - $\gamma\gamma \to Q\bar{Q}$
  - $g^* g^* \to q\bar{q}, g^* g^* \to Q\bar{Q}, g^* g^* \to h$
- initial state parton cascade acc. to CCFM with angular ordering
- final state parton showers from quarks
- P-remnant treatment like in PYTHIA (q-di-q, primordial k_t)
- hadronization via JETSET/PYTHIA
- 1st attempts to multiple scatterings

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

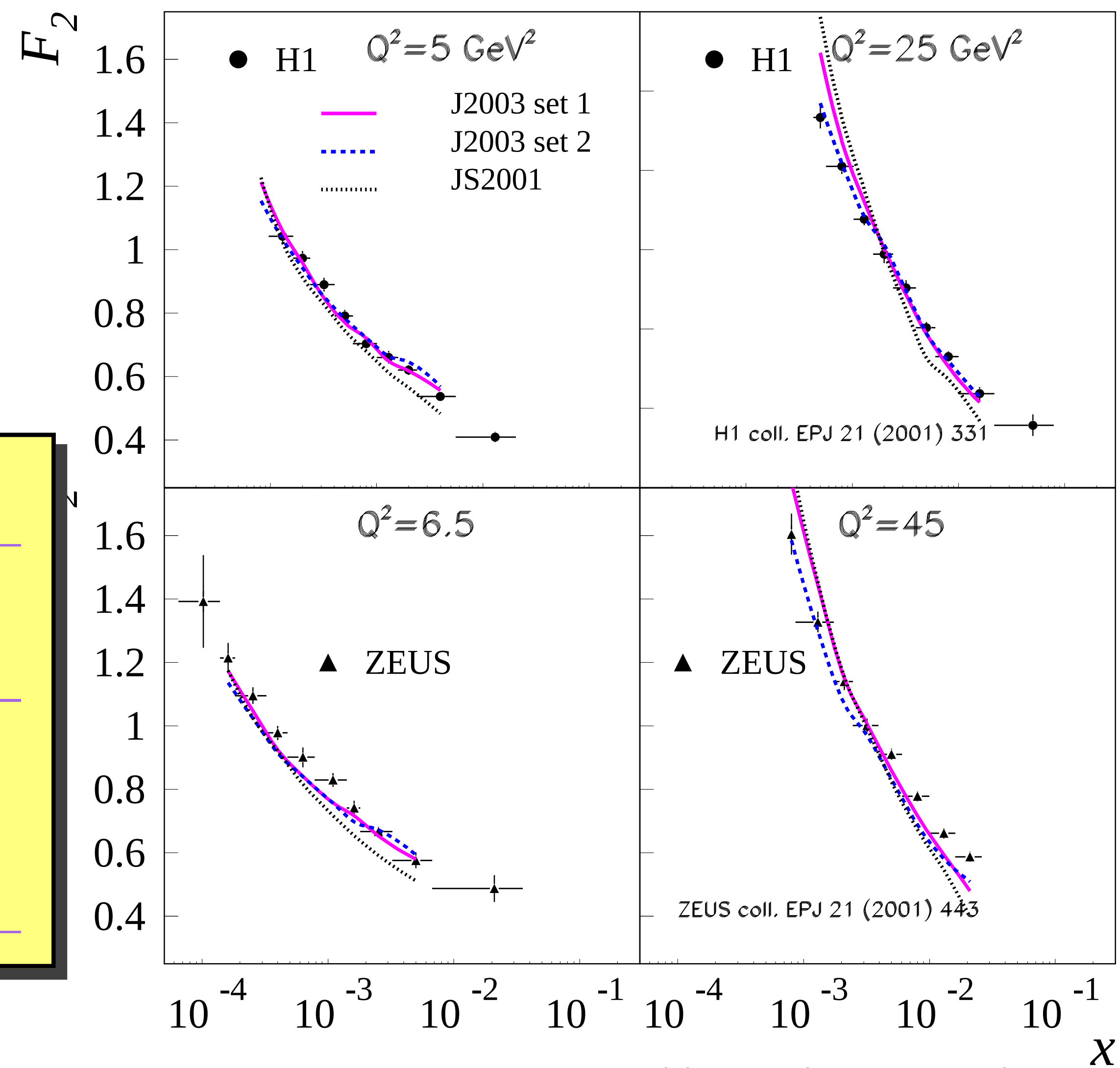
Precision fits to $F_2(x, Q^2)$

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 ?

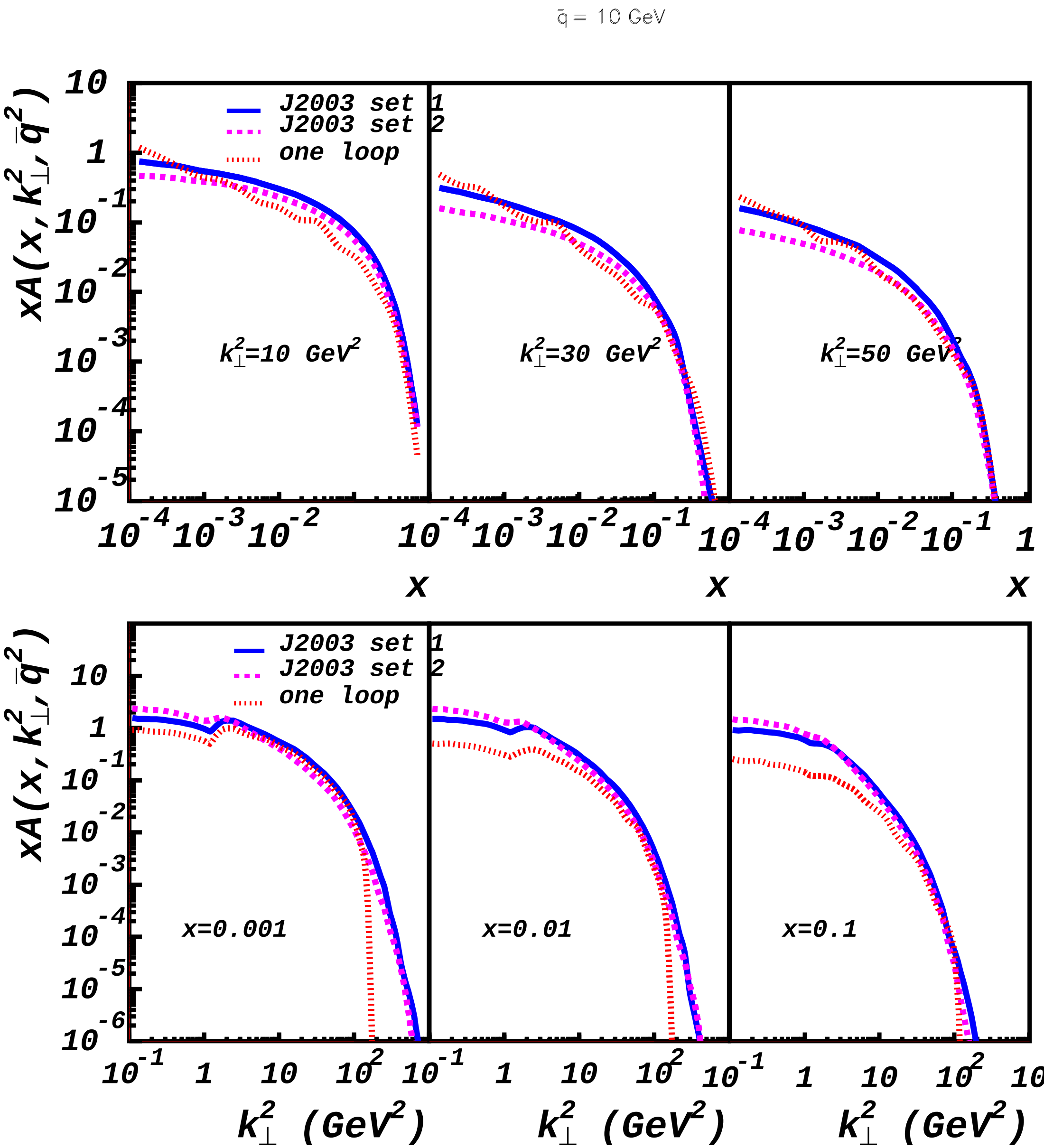
Fits to $F_2(x, Q^2)$

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



Un-integrated gluon density

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



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

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

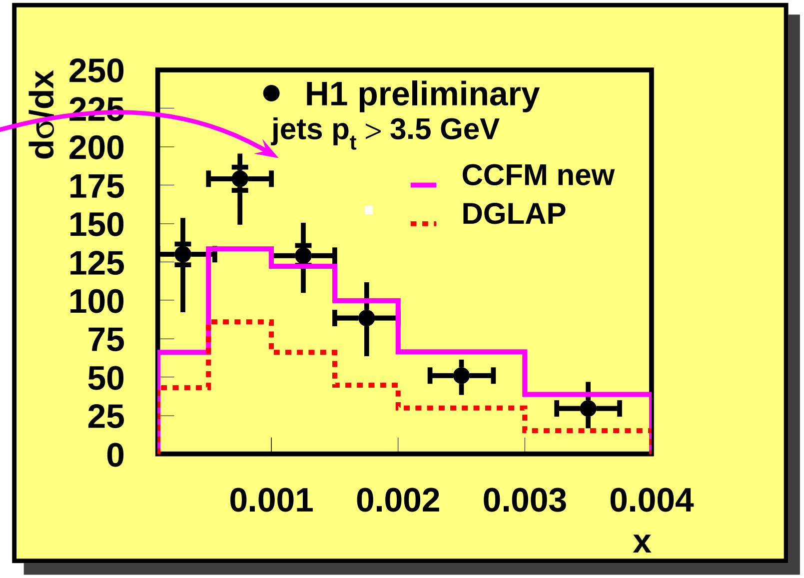
CASCADE with CCFM: the solution ...

Solve CCFM equation
to fit F_2 data from HERA

- obtain CCFM un-integrated gluon

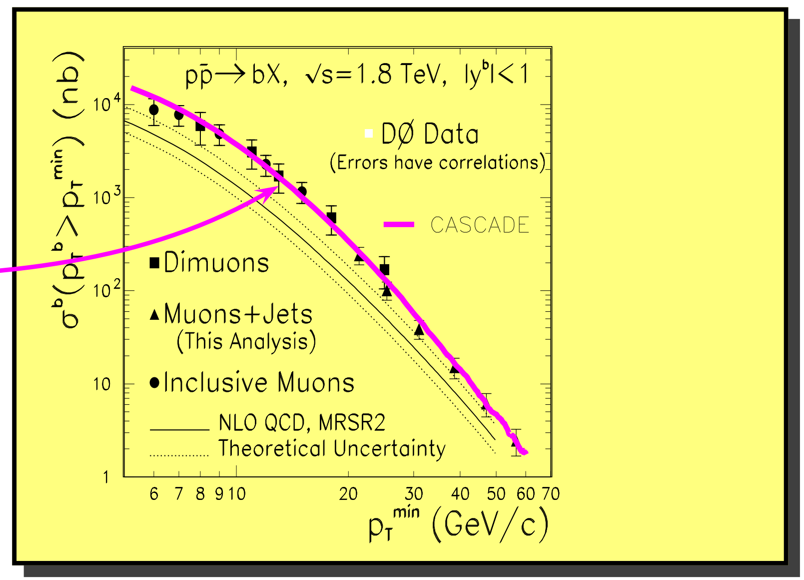
CASCADE MC implements CCFM:

- predict fwd jet x-section at HERA ✔
- predict charm at HERA ✔
- predict bottom at HERA ✔

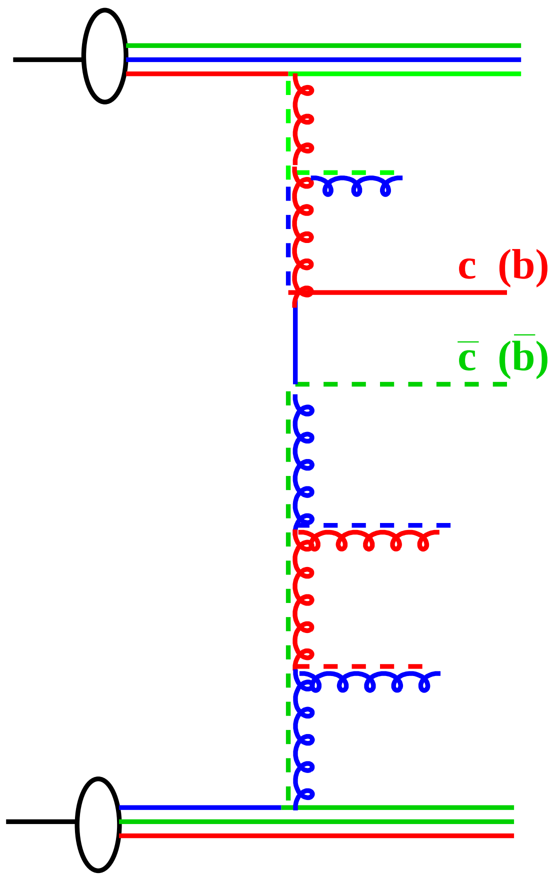


- test universality of un-integrated gluon density from HERA
- predict bottom at Tevatron ✔
- w/o additional free parameters

WOW !!!



The model for heavy quarks in pp



apply model to
charm and bottom production
at Tevatron ✔

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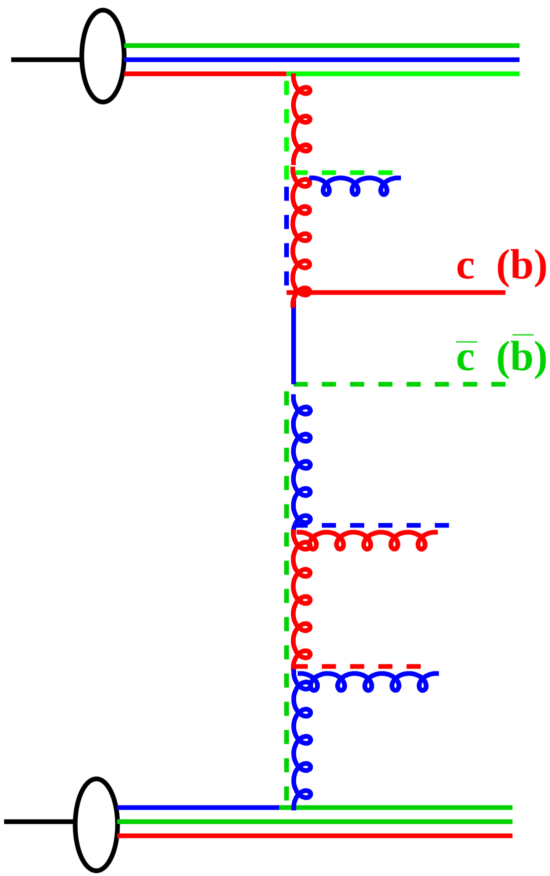

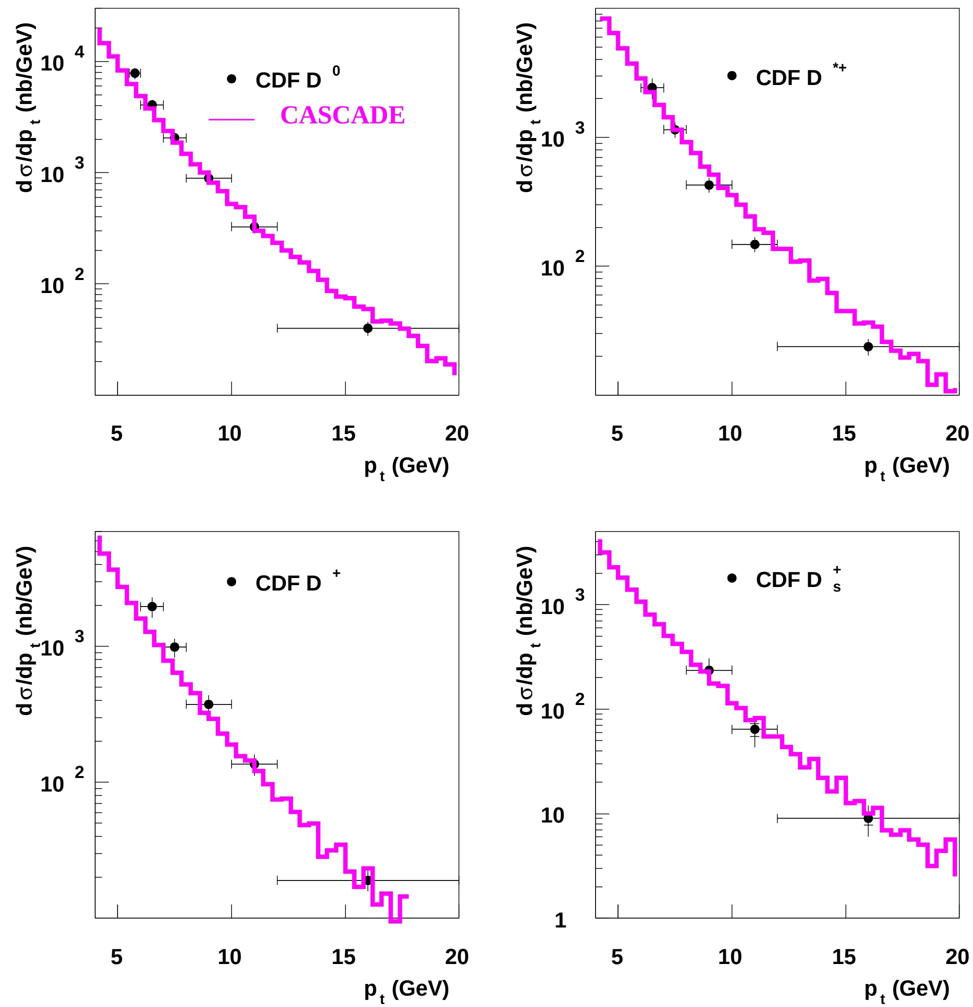

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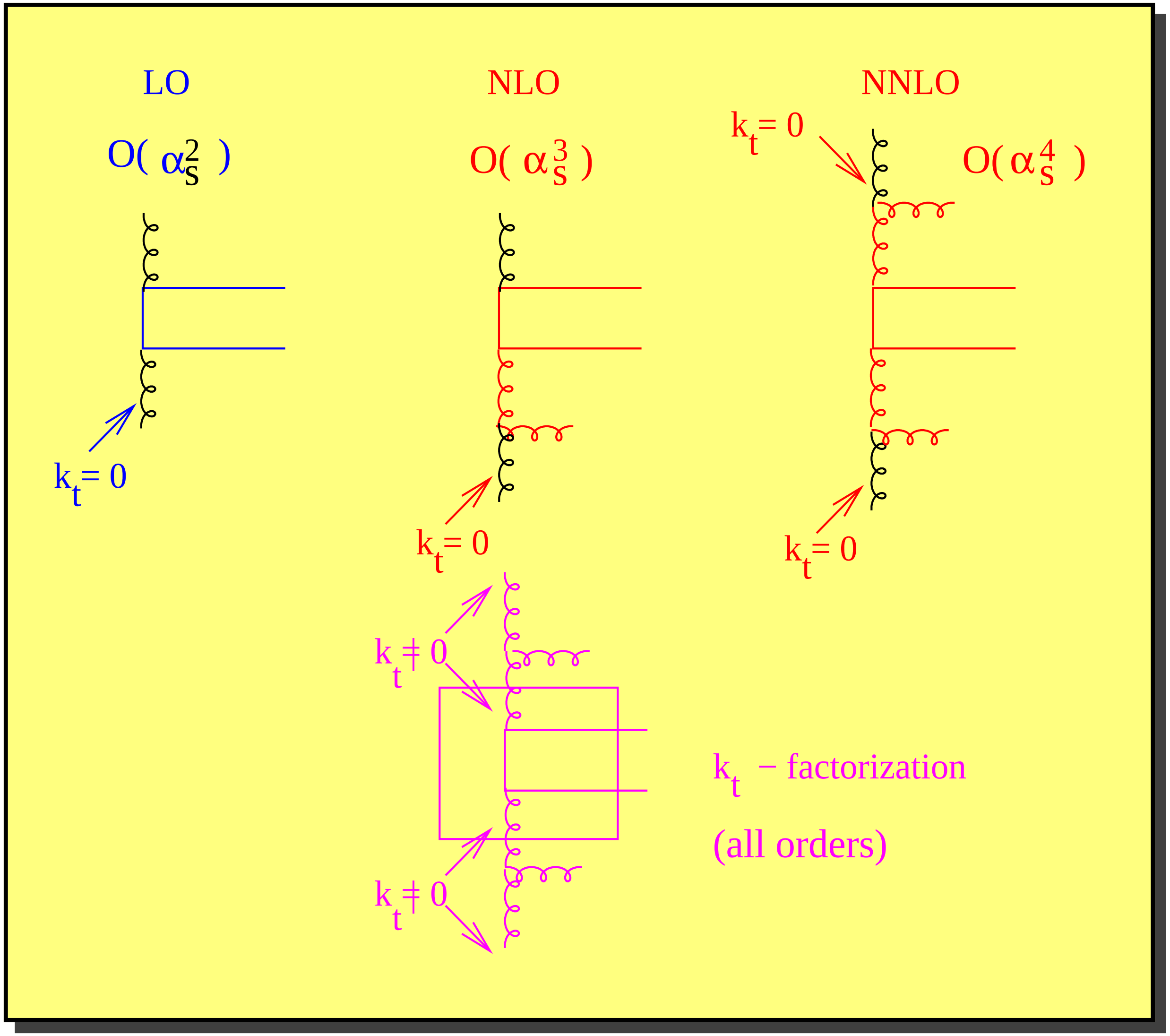
NLO, NNLO and k_t - factorization in pp



k_t factorization

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

k_t factorization has no problem with:

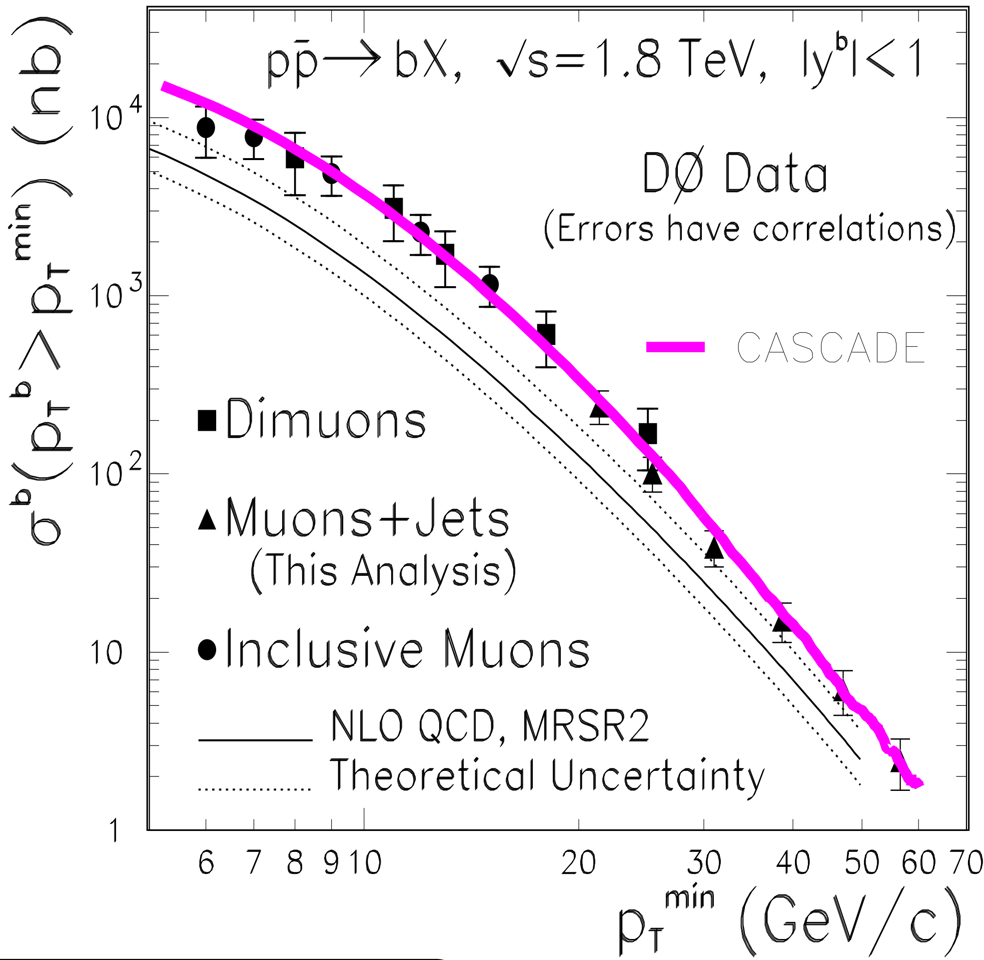
- **negative weights....**
- **matching to PS**
- **matching to hadronsiation**

1st step: $b\bar{b}$ production at Tevatron

Test universality of unintegrated gluon density from HERA

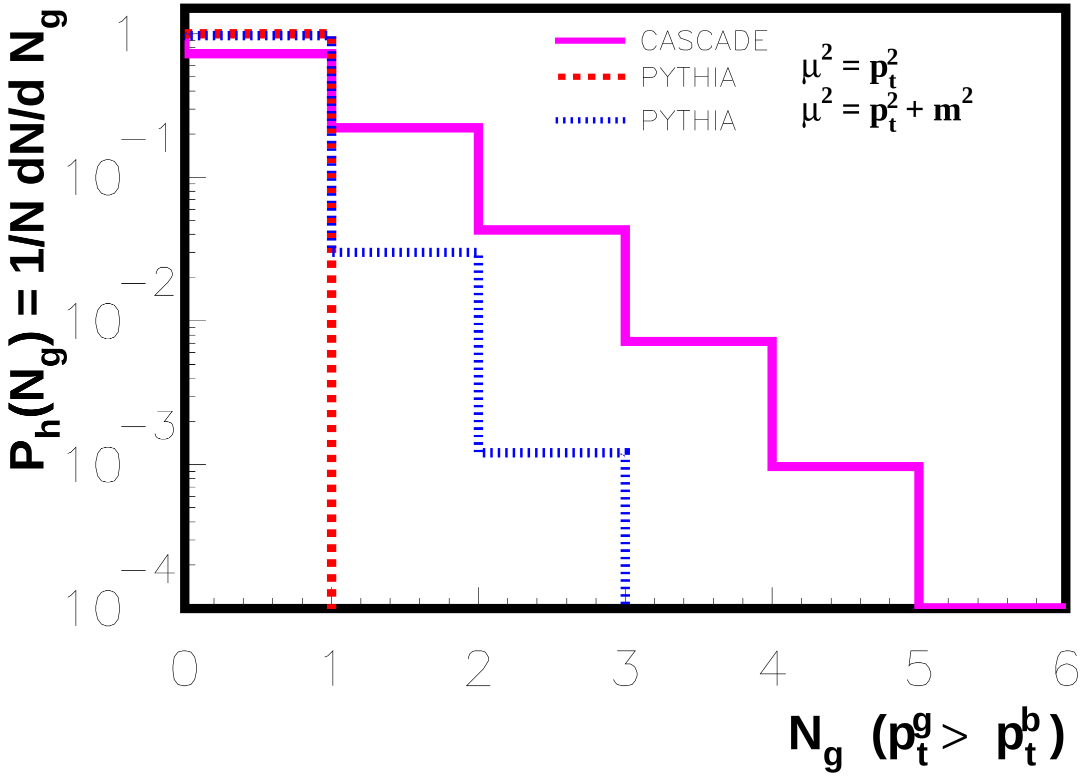
- ➤ use unintegrated gluon as before (from F_2 fit at HERA)
- ➤ use off-shell matrix element for $g^* g^* \to b\bar{b}$ with $m_b = 4.75$ GeV.

NOTE NLO off by factor 2



CASCADE w/o additional free parameters

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 model for min.bias and jets in pp

2nd step:

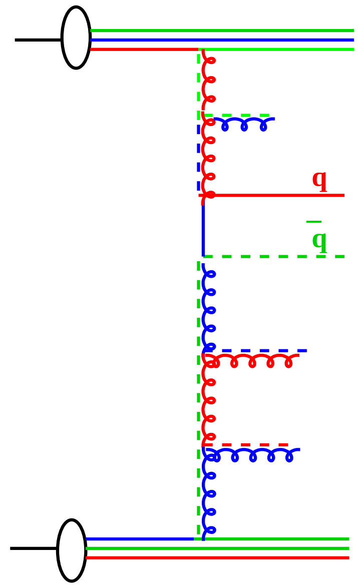
- **apply model to min. bias ???**
- **use light quark masses $m_q = 0.25$ GeV**

☛ as used for fit to F_2

☛ **off-shell ME** ☛ **finite**

☛ **no $\hat{p}_t$ cut needed!!!**

$g^* g^* \to q\bar{q}$ **anywhere in chain ...**



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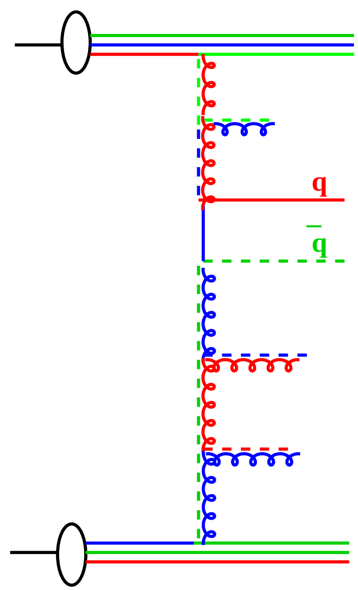
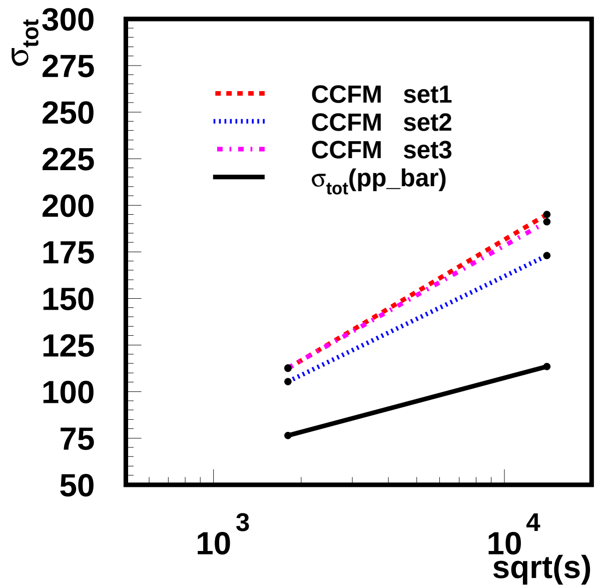


- parton x-sect $\sim \mathcal{O}(\sigma_{tot})$

☛ different sets of unintegrated gluon give similar x-sect.

- no k_t cut, no p_t cut

☛ non-k_t ordered emissions



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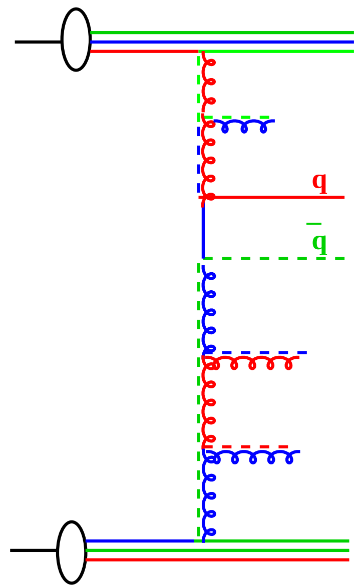


☛ is $g^* g^* \to q\bar{q}$ enough ???

☛ is gluon ladder enough ???

☛ multiple interactions ???

☛ how large is parton x-sect ???

- what about $g^* g^* \to gg$?

(G. Obrant working on that)

☛ partially already in cascade

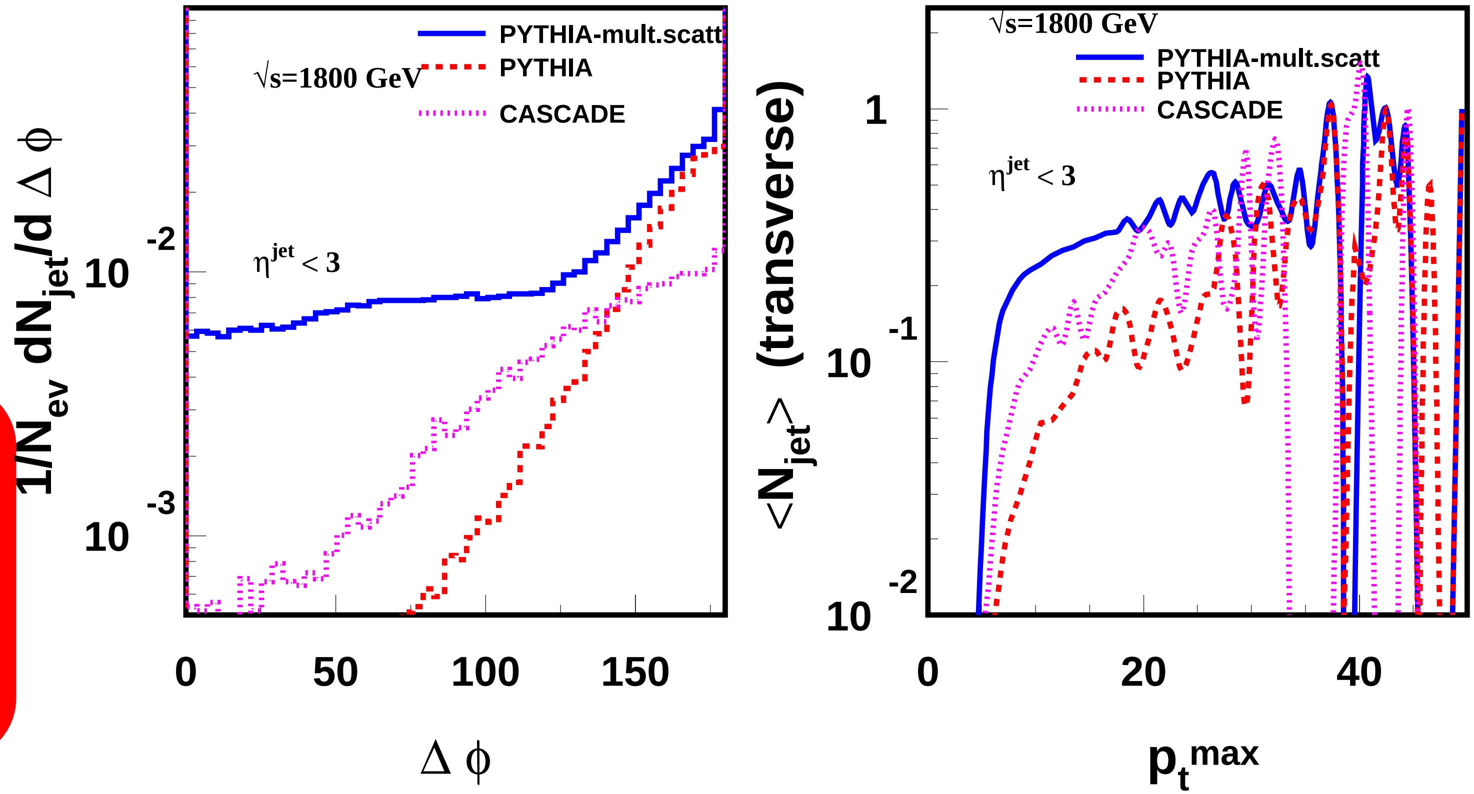
☛ but no timelike shower in cascade

- k_t effects included !!!

Minijets at $\sqrt{s} = 1800$ GeV: ϕ and transverse jets

Minijets
parton level
$p_t > 5$ **GeV**
$|\eta| < 3$

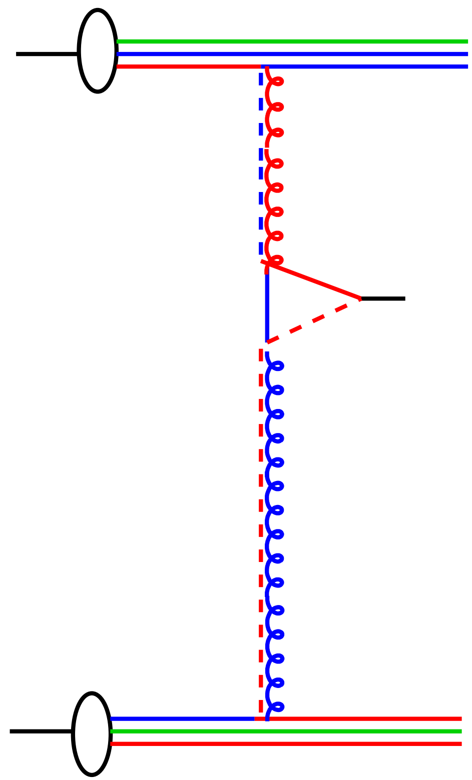
$\Delta\phi =$
$\phi_{\text{leading}} - \phi_{\text{jets}}$
transverse:
$60^o < \Delta\phi < 120^o$



- **finite k_t-effects visible in $\Delta\phi$**
- k_t **factorisation approach predicts difference to DGLAP:**
- **CASCADE predicts ϕ de-correlation without multiple scattering !!!**

Higgs production at LHC

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



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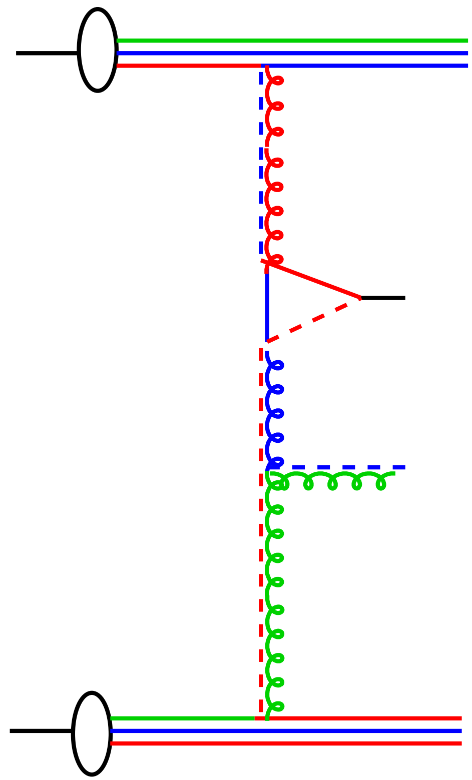
- NLO $\mathcal{O}(\alpha_s^3)$



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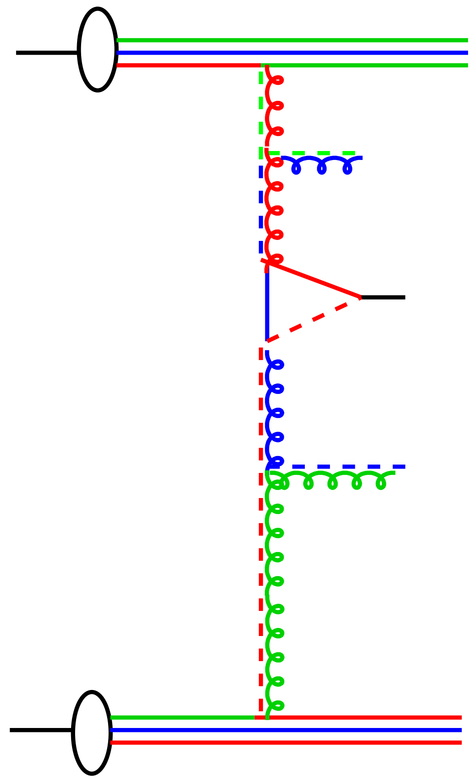

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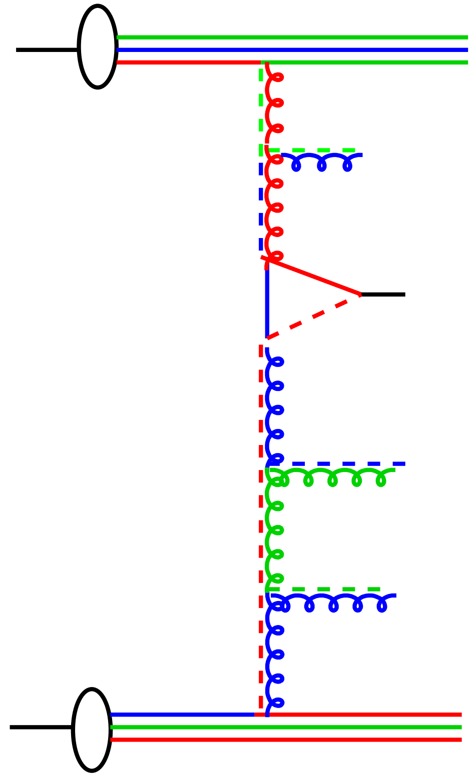
- NNNLO $\mathcal{O}(\alpha_s^5)$ not yet calculated
- available only: NLO + NNLL resummation....
  Bozzi et al (PLB 564 (2003) 65, hep-ph/0302104)



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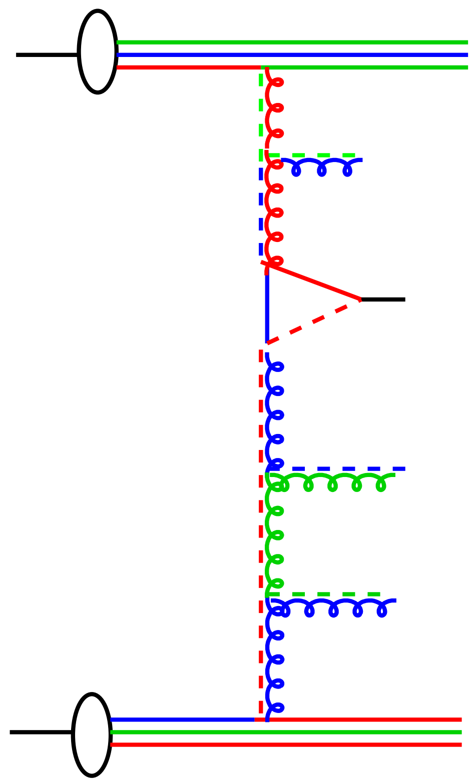
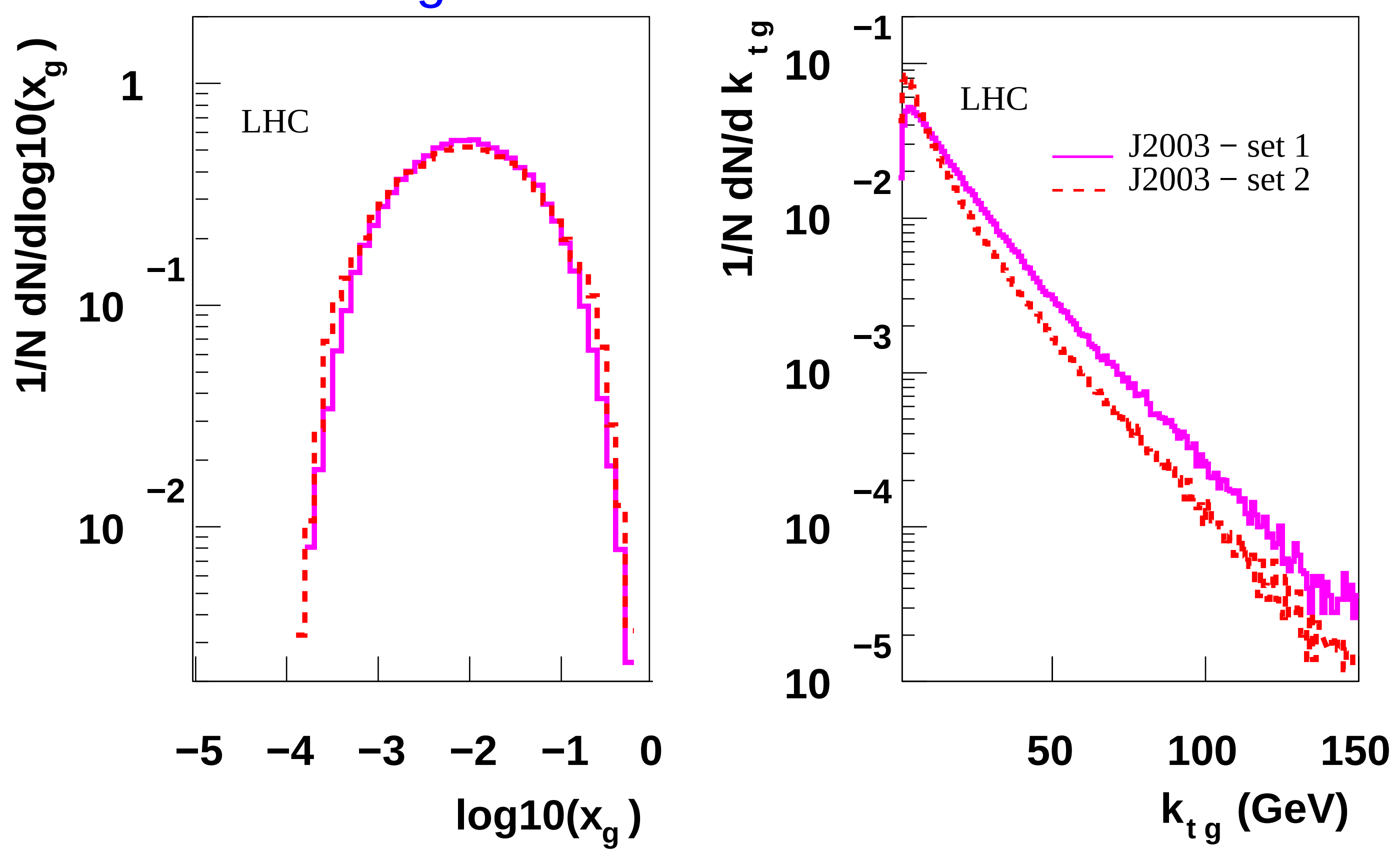
  Bozzi et al (PLB 564 (2003) 65, hep-ph/0302104)
- calculate gg $\to$ Higgs in k_t factorisation
- small x approximation and for for $m_t \to \infty$
  F. Hautmann, PLB 535 (2002) 159
- obtain NNLO correction to gluon-gluon x-section for $x \ll 1$
- estimate higher order corrections ...
- get resummation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



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

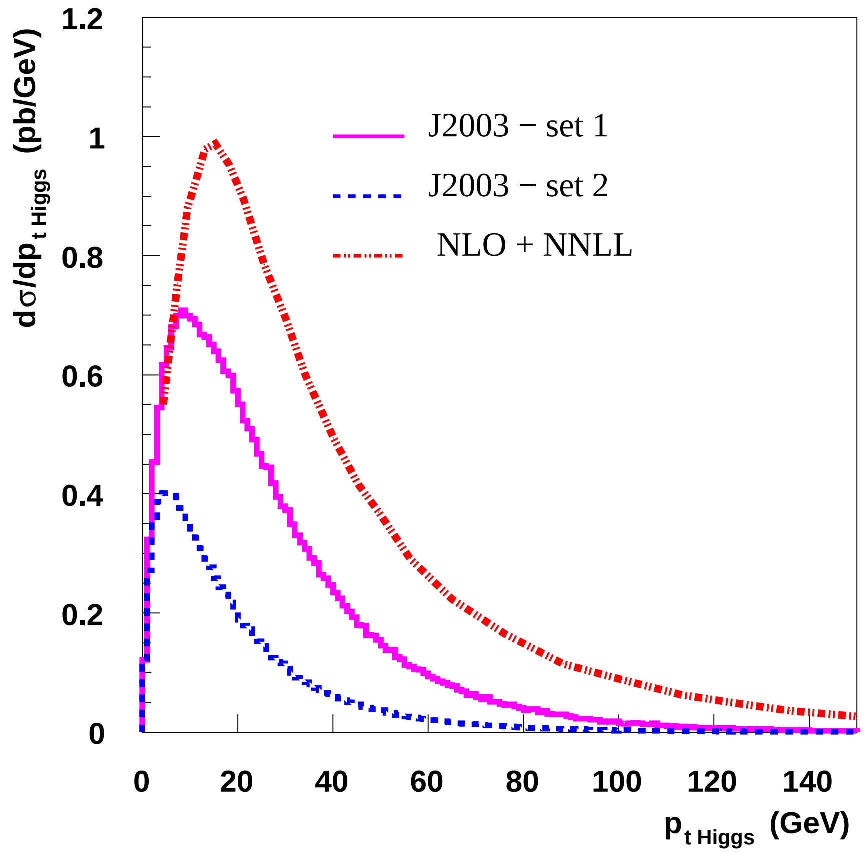
- k_t-factorization: $E_{\text{gluon}} \sim k_t$
- 

- 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

- 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 ...**

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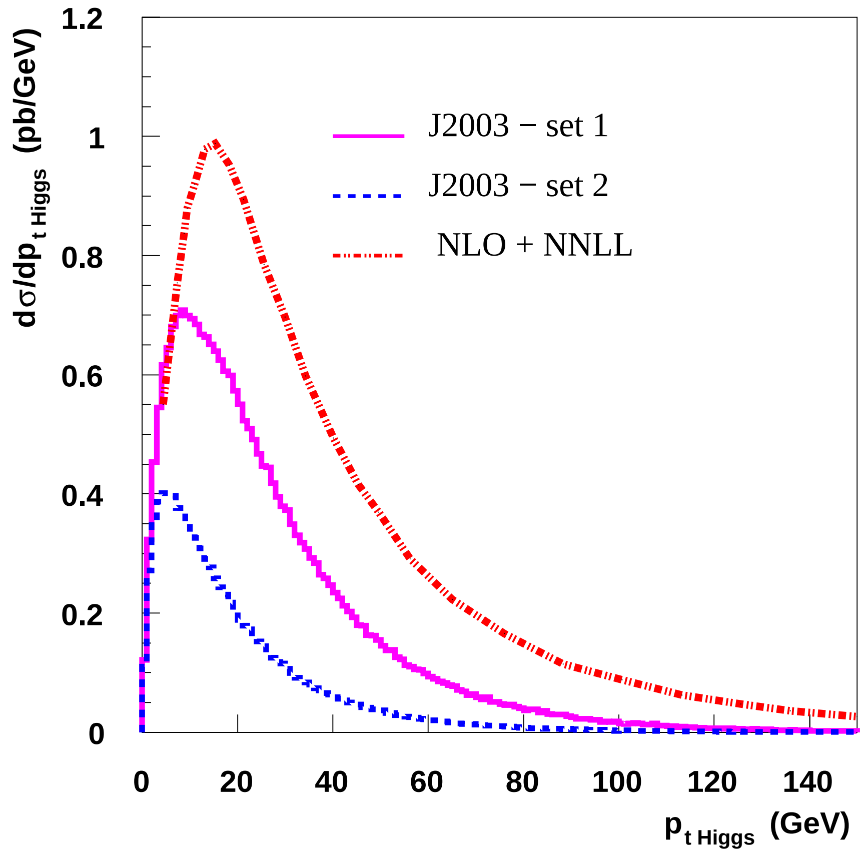
- calculate q_T spectrum with CCFM unintegrated gluon:
  two sets, both determined from HERA
- sensitive to trans. mom. of gluons
- up to now only gluon initiated cascades
- BUT, what about quark initiated cascades?



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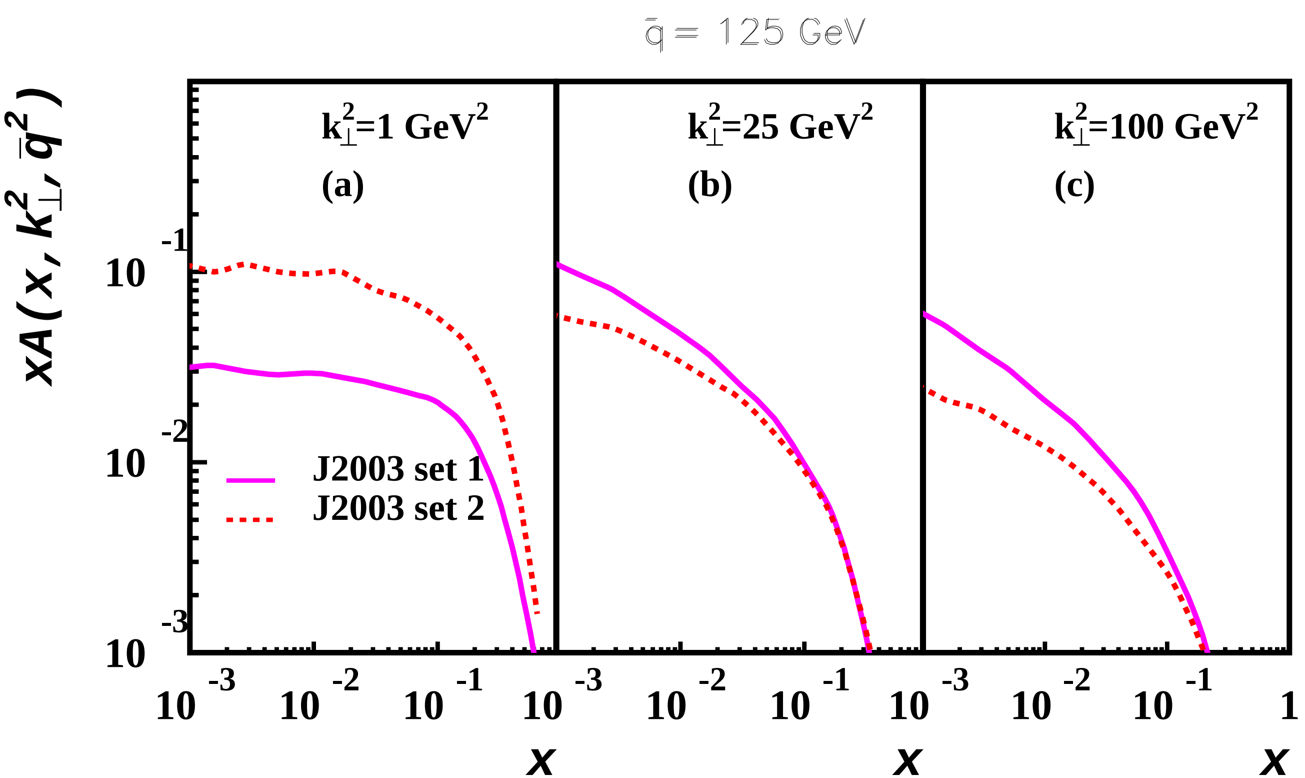
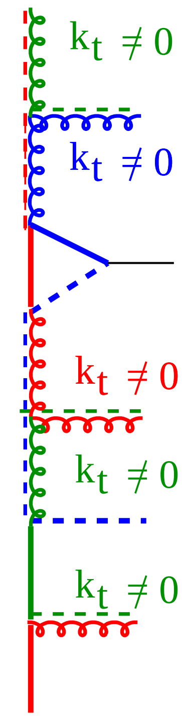
Higgs production at LHC

- 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 ?

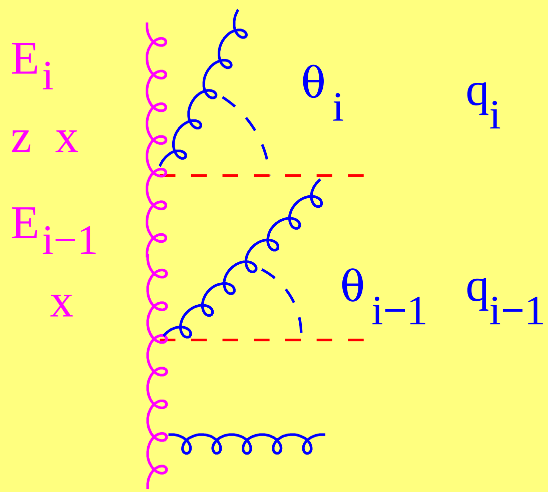
Conclusions

- k_t-factorisation applied to $p\bar{p}$
- no p_t cuts needed
- ☞ off shell ME's and light quark masses from HERA F_2 fits
- only gluon chains included ... already successful
- ☞ what about $g^*g^* \to gg$, worry about quarks ????
- approach works well for heavy quarks at Tevatron
- CCFM and CASCADE describe most data at HERA, whereas DGLAP based models don't...
- Higgs at LHC ... promising, but also x-sects, shapes ???
- attempt to include multiple scatterings ☞ promising

CASCADE (k_t - factorisation with CCFM gluon)
for min bias, heavy quarks ... and Higgs ... !!!

C atani 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

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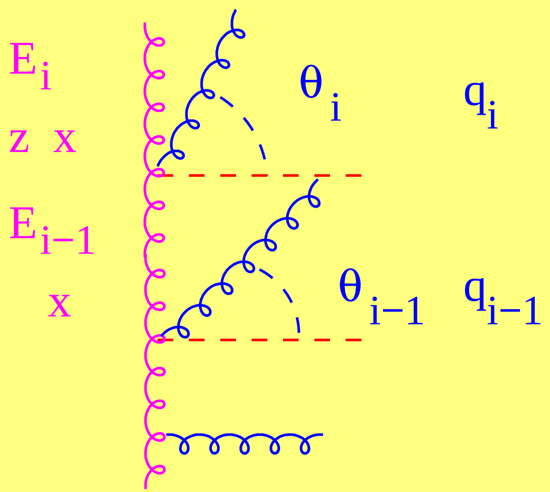

$p_{ti} = |q_i^0| \sin\Theta_i$, $z = \frac{E_i}{E_{i-1}}$

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

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

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

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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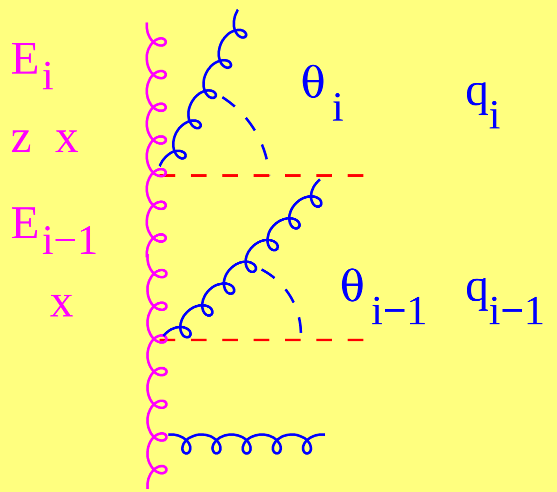

in lab. frame

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

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

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

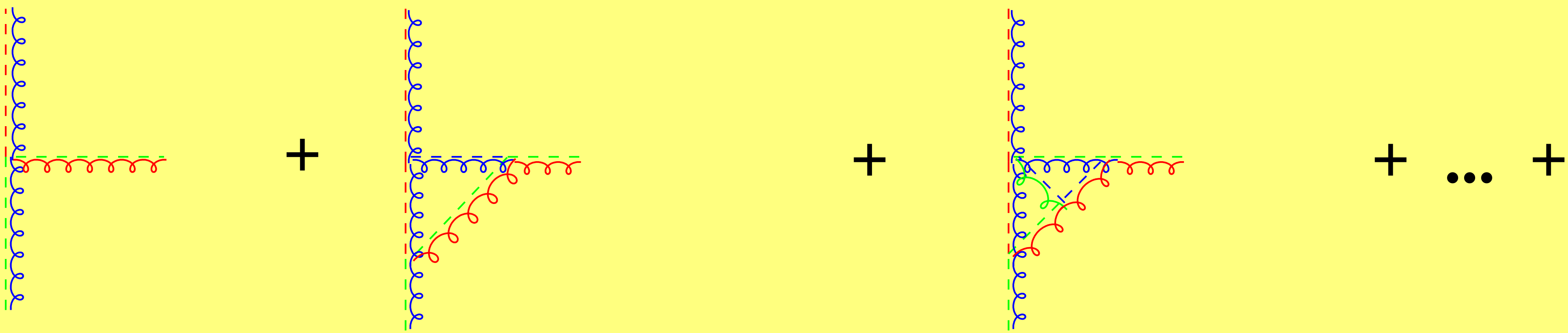
Non-Sudakov and all - loop resummation

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:

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

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



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