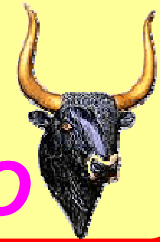
ep interactions at HERA and beyond:
modelling higher orders and the problem of NLO

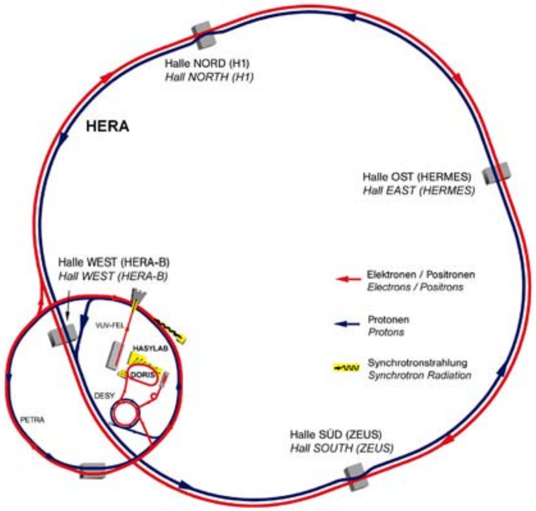


H. Jung (DESY)

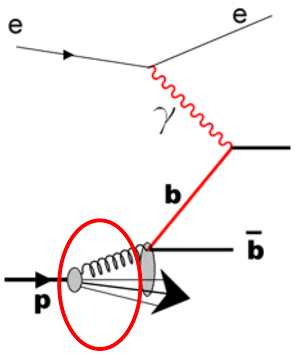
- What is HERA doing in Skopelos ?
- *ep* interactions: where is the problem ?
  - **highest energies:**
    - problem of asymptotia ....
  - **from inclusive to final states:**
    - problem of exclusivity....
    - simulations, even at NLO
  - **need of fully unintegrated pdfs**
- first steps:
  - unintegrated pdfs
  - even for LHC
- conclusions

What is HERA doing in Skopolos ?

electron proton collider HERA
$\sqrt{s}$ = 320 GeV

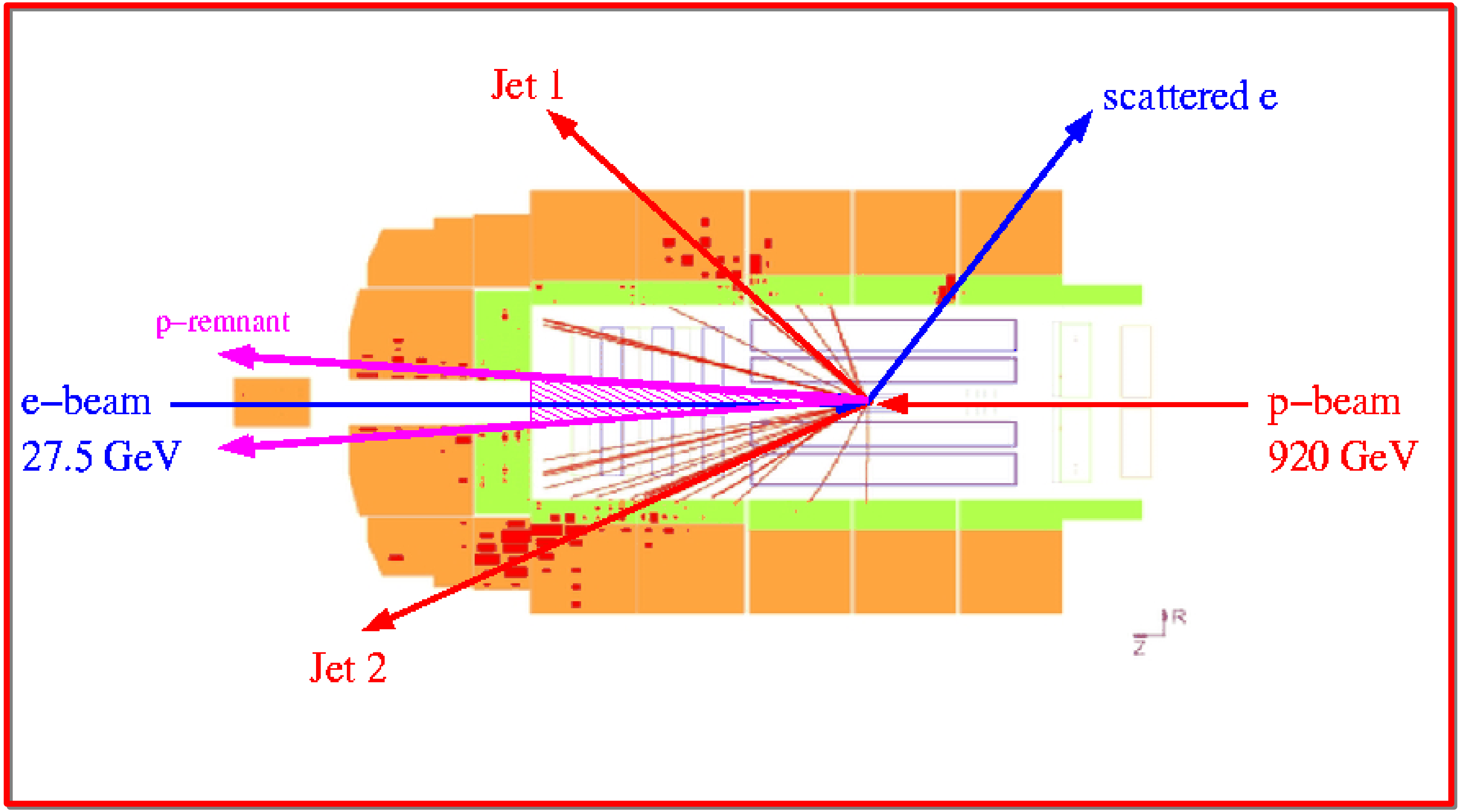


HERA: QCD
structure of the proton



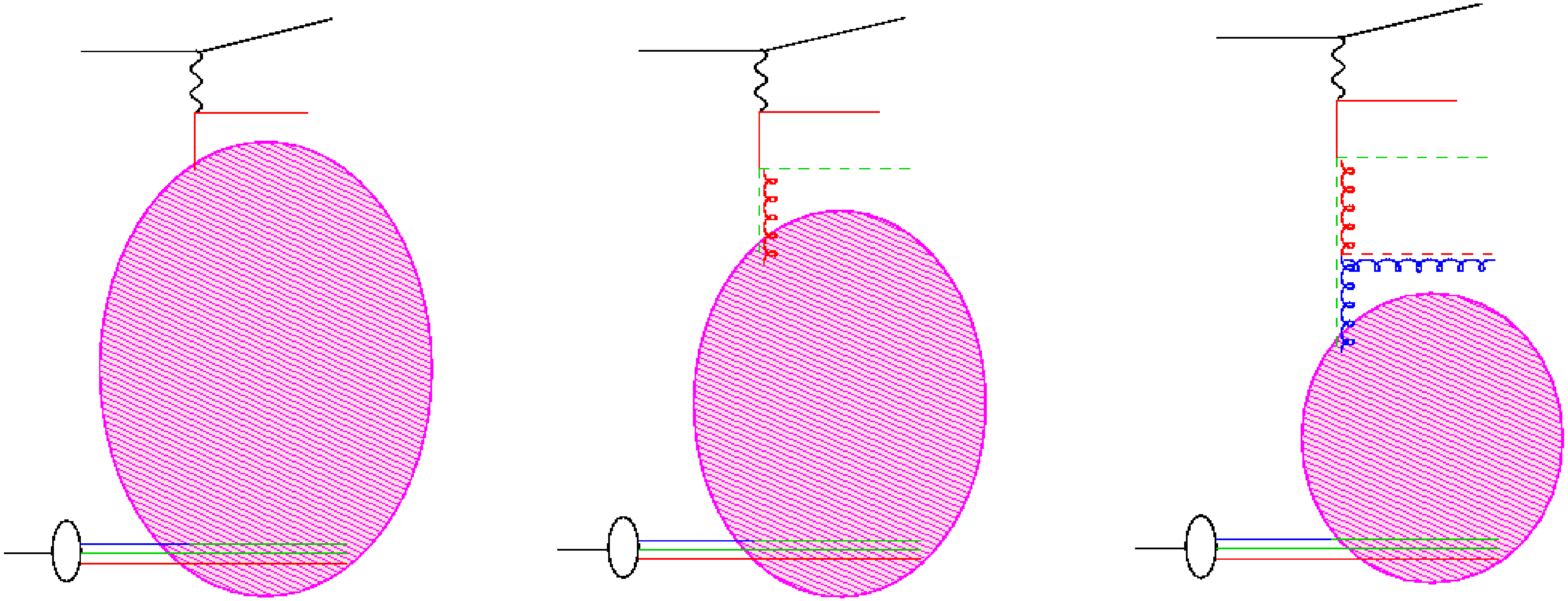
- Electrons: 27.6 GeV
- Protons: 920 GeV
- Physics Program:
  - structure functions, parton density functions
  - jets
  - heavy quarks
  - diffraction in QCD
 - high energy behavior of QCD
 - precision machine for QCD, like LEP was for electroweak...
- planned to run until 2007

A typical ep event at HERA



$\sqrt{s} \sim 318$ GeV $\rightarrow x \sim 7.\ 10^{-5}$ at $Q^2 = 4$ GeV^2

Where is the problem ?

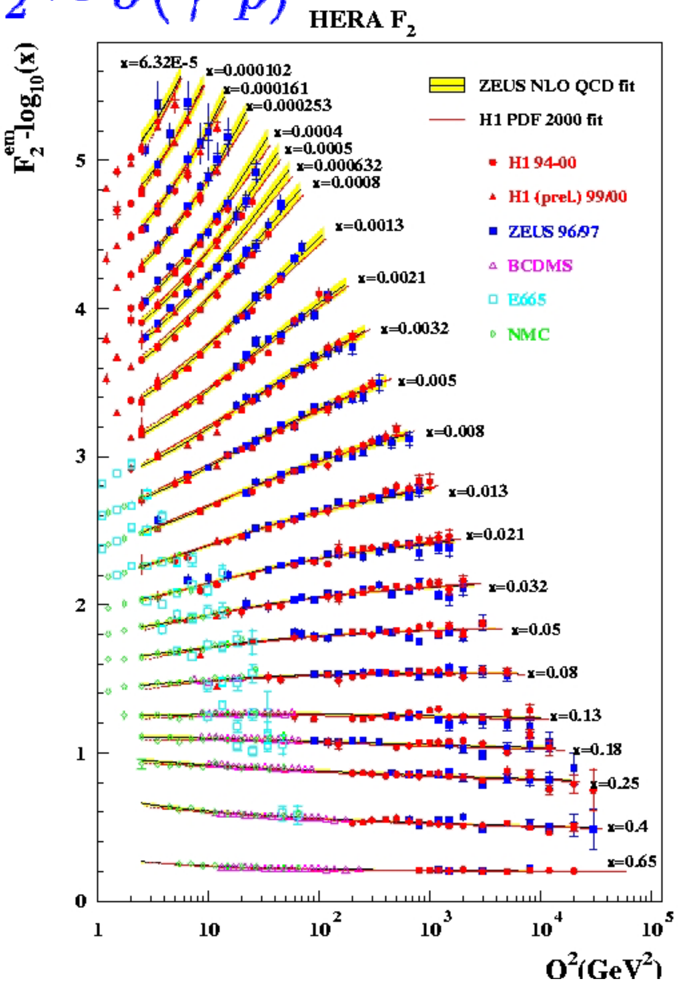


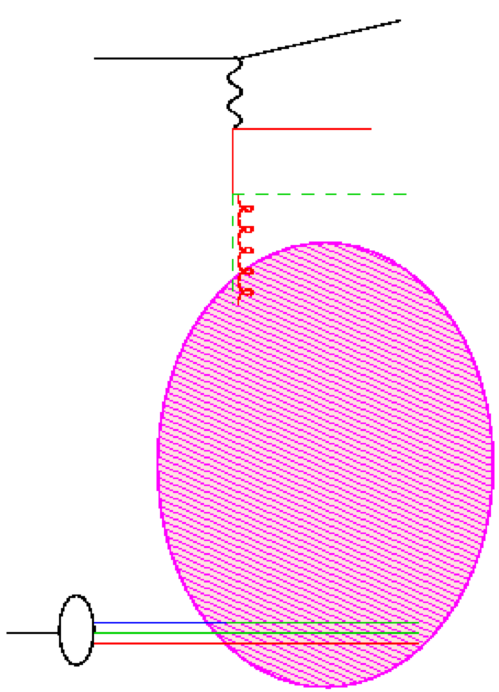
QPM process
total x-section

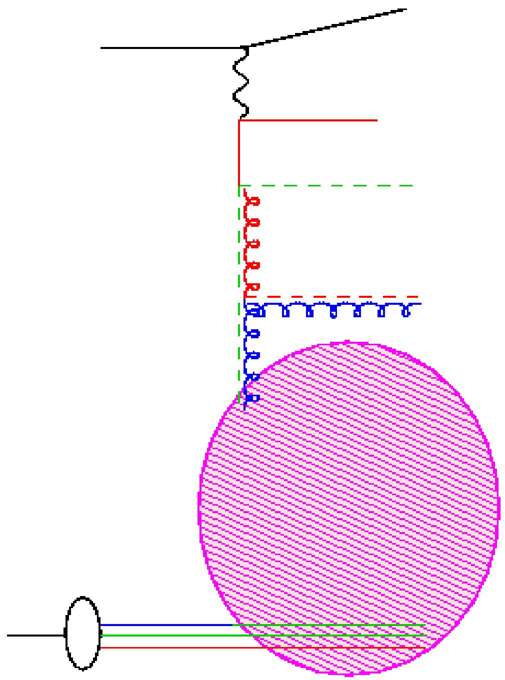
BGF $\mathcal{O}(\alpha_s)$ process
$\mathcal{O}(\alpha_s^2)$ process
heavy quarks (charm & bottom)
2-jet
3-jet

Where is the problem ?

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







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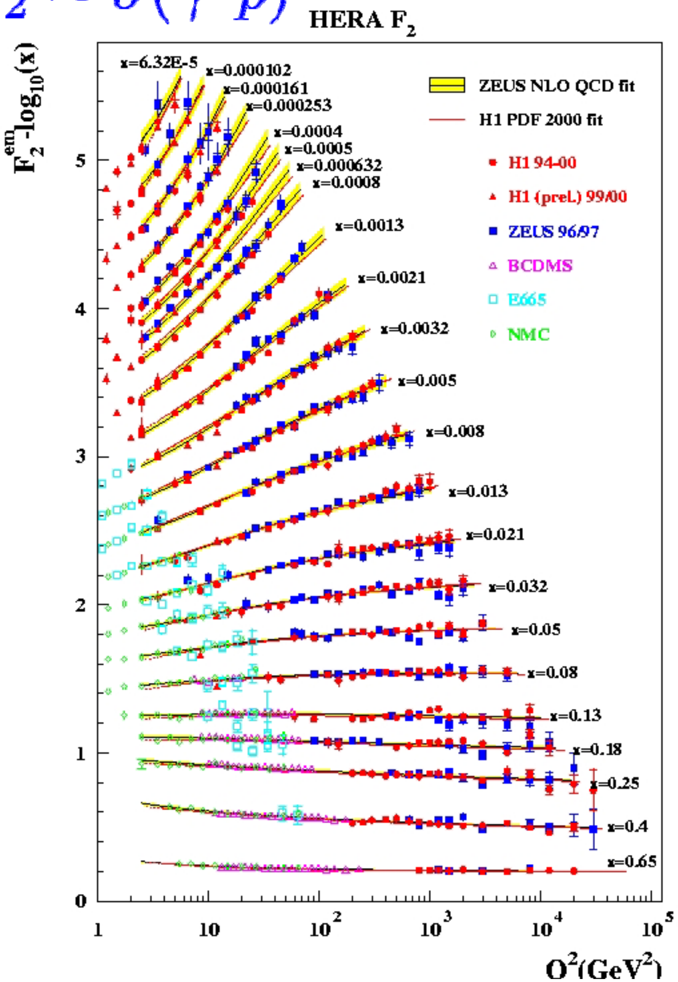
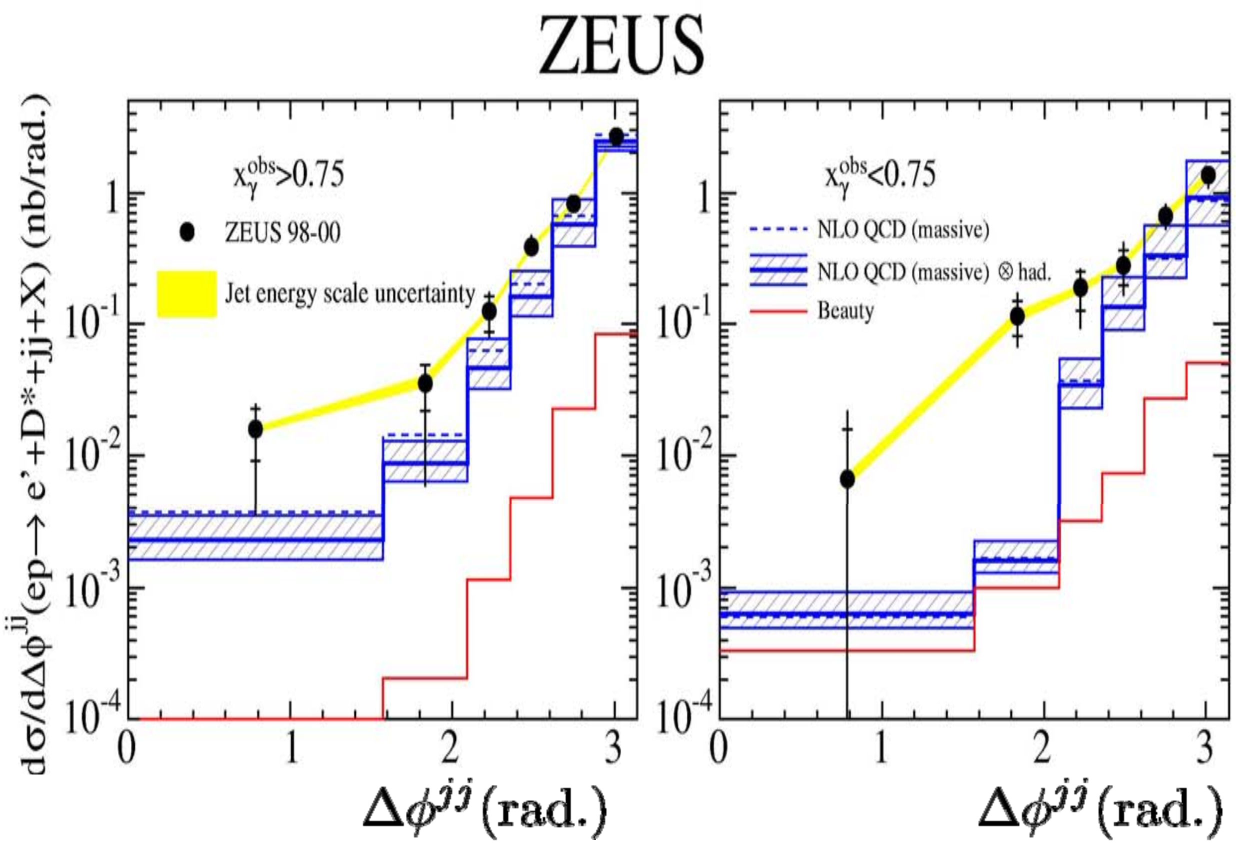
Where is the problem: hadronic final state

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





QPM process

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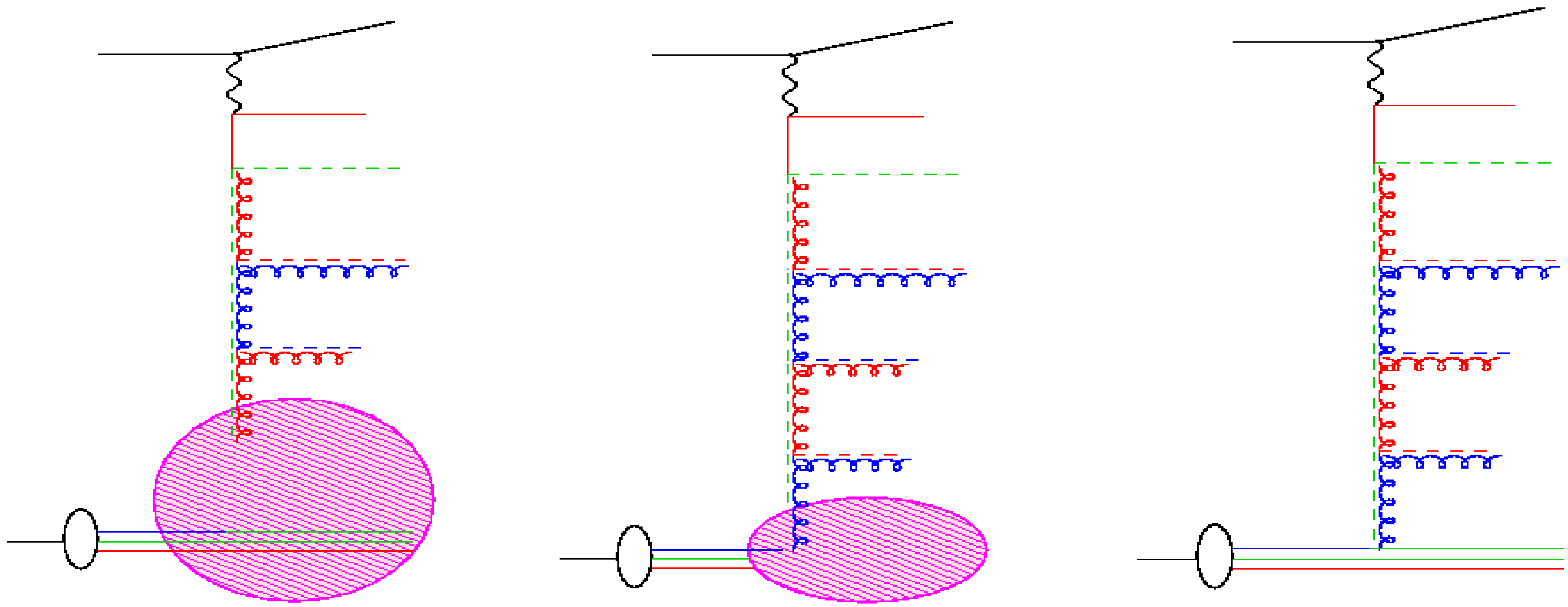
Where is the problem: hadronic final state

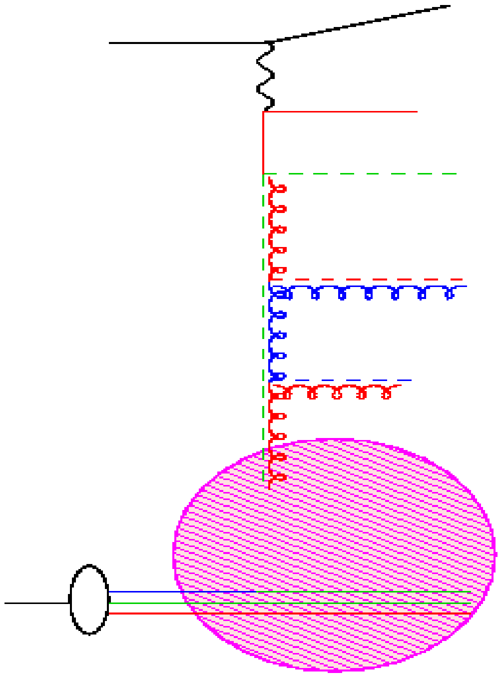


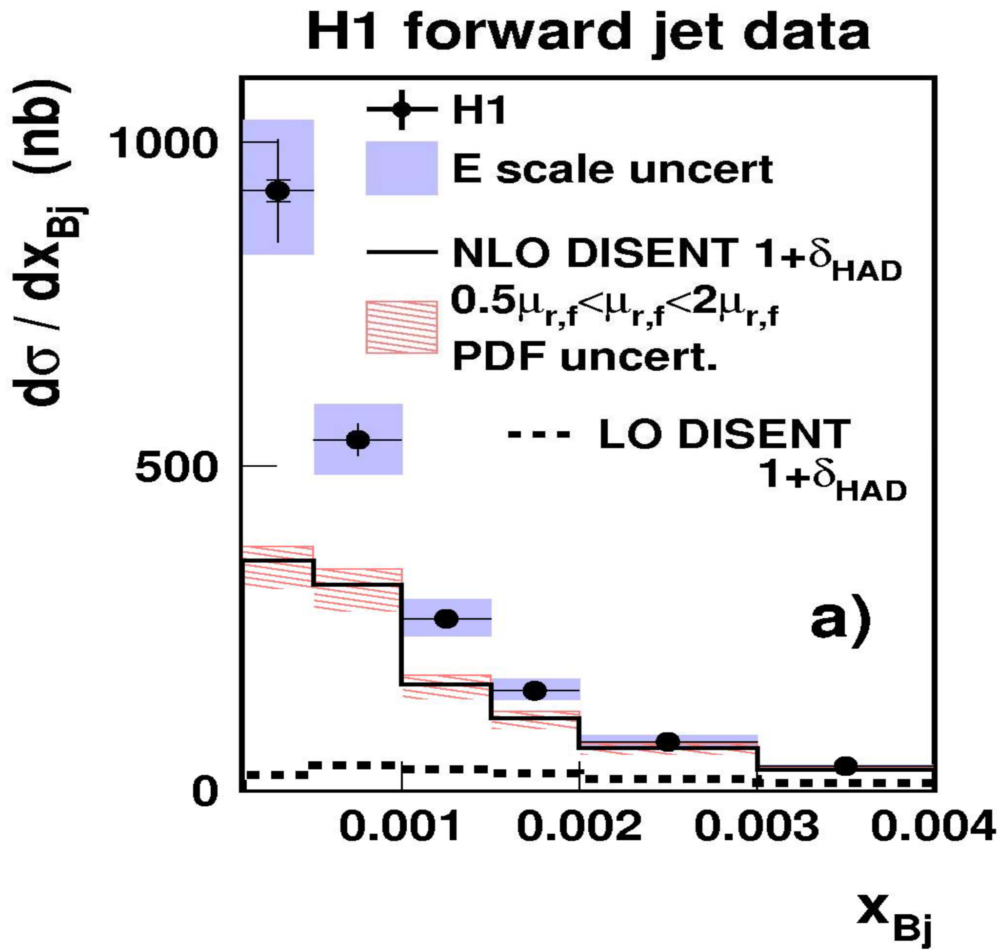
processes of $\mathcal{O} > \alpha_s^3$ have not yet been calculated ...

interesting to go closer to outgoing proton remnant

forward jets !!!

Where is the problem: hadronic final state





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

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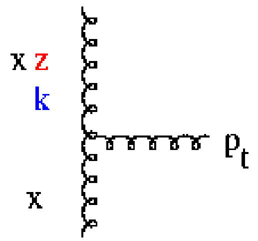
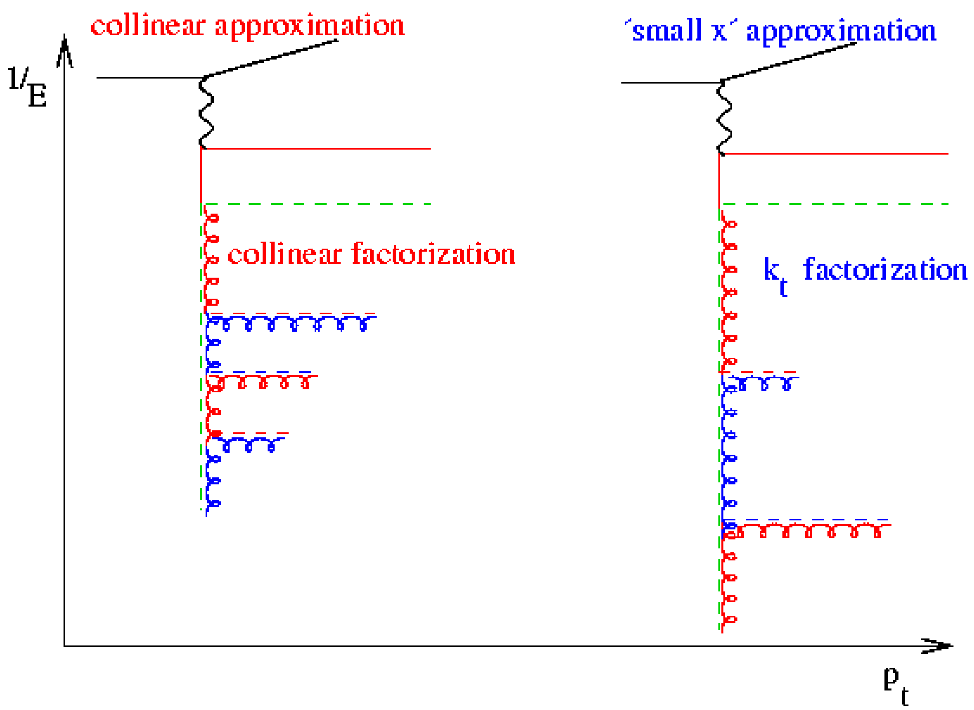
Approximations to higher orders ...

gluon bremsstrahlung

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





DGLAP

- collinear singularities factorized in pdf
- evolution in $Q^2 \sim k^2, \text{ or } k_t^2 \text{ or ?}$

$$\sigma = \sigma_0 \int \frac{dz}{z} C^a\left(\frac{x}{z}\right) f_a(z, Q^2)$$

BFKL

- k_t dependent pdf → unintegrated pdf
- evolution in x

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

The problem of asymptotia

DGLAP is great
at highest $Q^2 \to \infty$

for **inclusive quantities**

BUT has problems

- heavy quarks
- jets
- particle spectra
- small x processes

BFKL is great
at small $x \to 0$
or highest $W \to \infty$
for **inclusive quantities**

BUT has problems

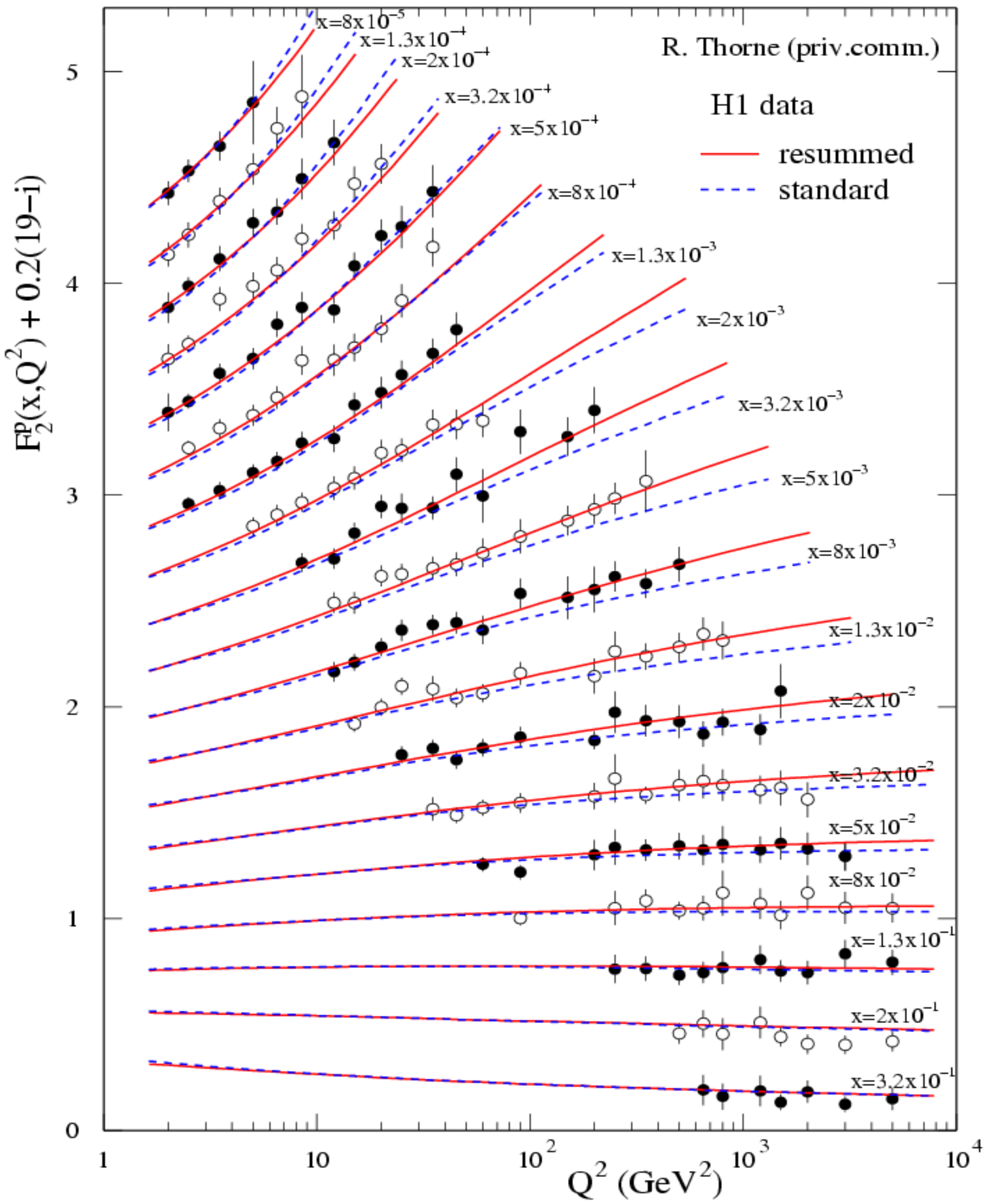
- finite x
- NL corrections
- final states

BUT asymptotia still far away
even for LHC or cosmic energies

From asymptotia to total x-section

- Description of inclusive processes:
  - DGLAP for high Q^2
  - BFKL for small x
- matched DGLAP/BFKL for F_2

  (R. Thorne, Kimber,Martin,Stasto, etc)
  - *resummed gives better fit*
  - *.... not a big effect at HERA !!!*
- *where is asymptotia ?*



From asymptotia to exclusivity

- Description of inclusive processes:
  - DGLAP for high Q^2
  - BFKL for small x
- matched DGLAP/BFKL for F_2
  (R. Thorne, Kimber,Martin,Stasto, etc)
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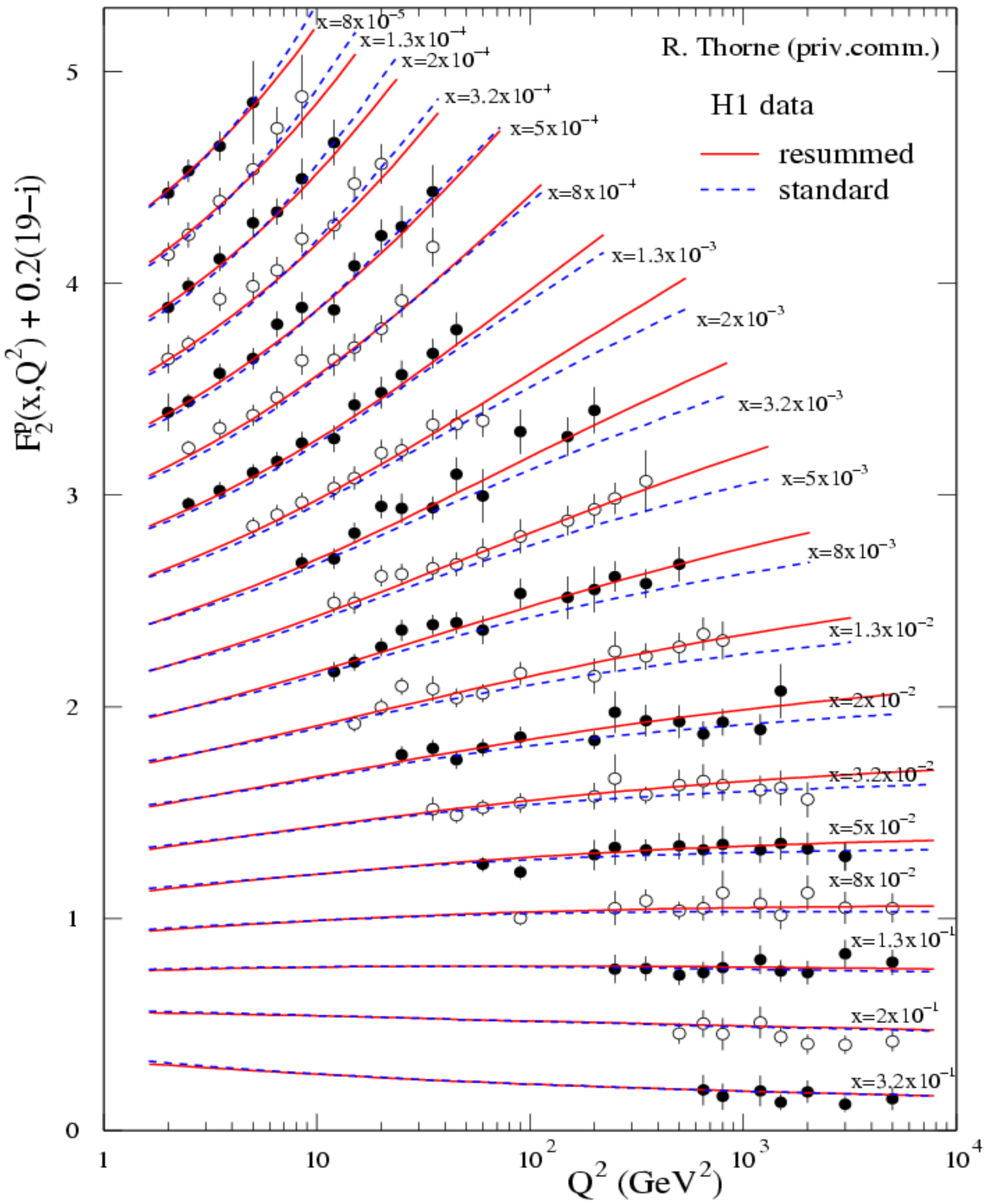
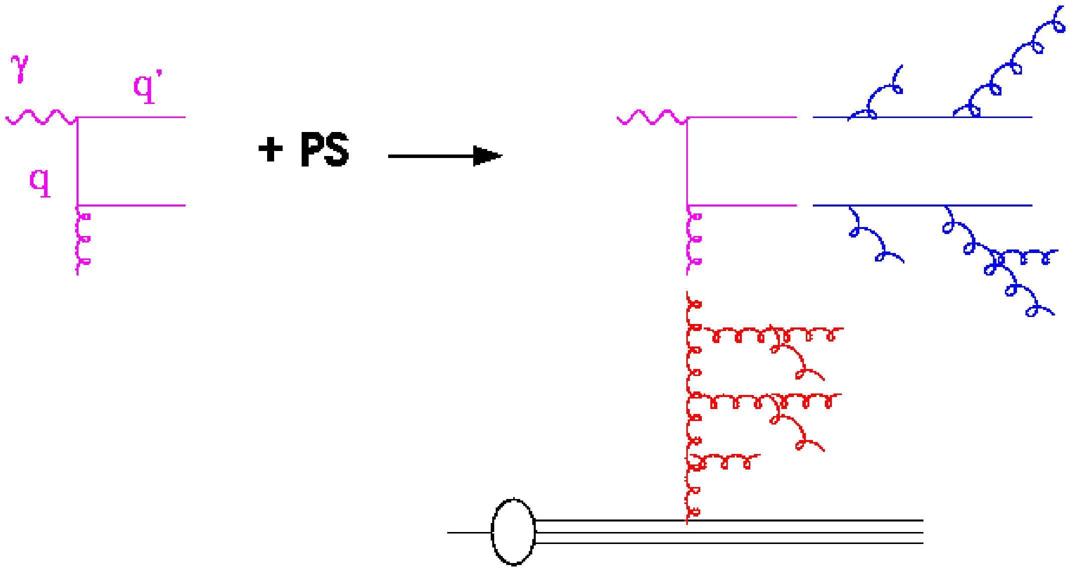


Building up the final states
- Monte Carlo event generators
- fixed order parton level calculations at NLO

DGLAP MC event generators



- *use LO matrix elements*
  - *for light quarks, cutoffs are needed*
- *apply initial and final state parton showers*
  - *matching of cutoff in ME with parton showers*
- *apply hadronization*
- *obtain cross sections fully differential in any observable*
- *BUT:*
  - *only in LO (attempts to include NLO: Collins et al, MC@NLO, etc)*

DGLAP equation

- differential form $$q\frac{\partial}{\partial q}f(x,q) = \int \frac{dz}{z}\frac{\alpha_s}{2\pi}P_+(z)\, f\left(\frac{x}{z},q\right)$$

- modified differential form using *"Sudakov form factor"*

$$\Delta_s(q_0,q) = \exp\left(-\bar{\alpha}_s \int \frac{dz}{z}\int_{q_0}^{q}\frac{dq'}{q'}\tilde{P}(z)\right)$$

$$q\frac{\partial}{\partial q}\frac{f(x,q)}{\Delta_s(q,q_0)} = \int \frac{dz}{z}\frac{\alpha_s}{2\pi}\frac{\tilde{P}(z)}{\Delta_s(q,q_0)}\, f\left(\frac{x}{z},q\right)$$

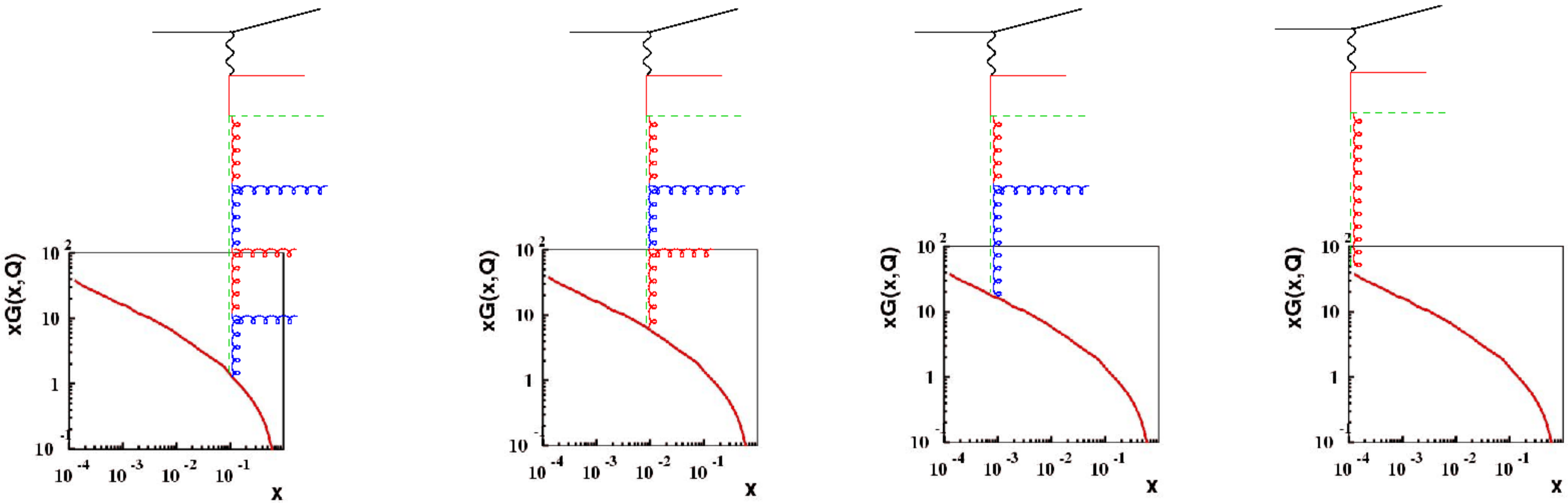
- ***integral form***

$$f(x,q) = f_0(x,q)\Delta_s(q,q_0) + \int \frac{dz}{z}\int \frac{dq'}{q'}\cdot \Delta_s(q',q_0)\tilde{P}(z) f\left(\frac{x}{z},q\right)$$

- ***no-branching probability form q_0 to q***

Initial state parton evolution

- for fixed *x* and Q^2 chains with different branchings contribute
- iterative procedure to calculate parton densities
  - nothing said about parton emissions in DGLAP !!!!!
    - additional assumptions needed for spacelike parton showering

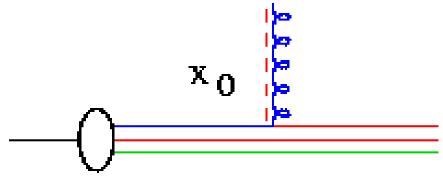


$$f(x,Q) = f_0(x,q_0)\Delta_s(Q,q_0) + \sum_{k=1}^{\infty} f_k(x_k,q_k)$$

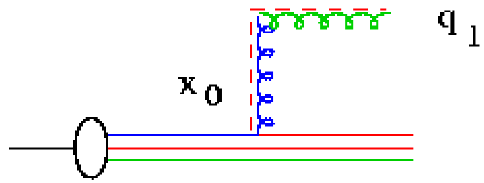
Parton Showers for the initial state

spacelike parton shower evolution

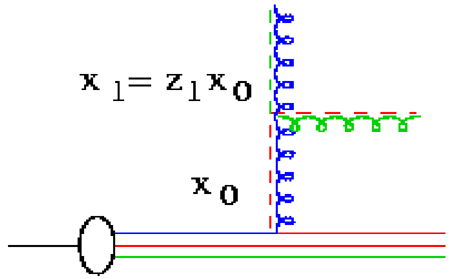
- starting from hadron (fwd evolution)
  or from hard scattering (bwd evolution)



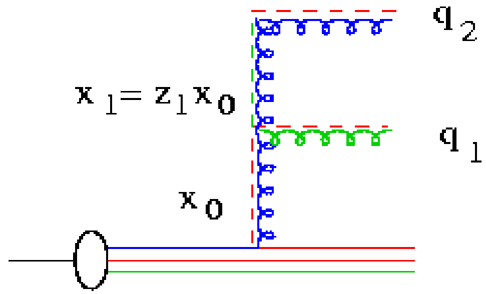
- select q_1 from Sudakov form factor



- select z_1 from splitting function



- select q_2 from Sudakov form factor

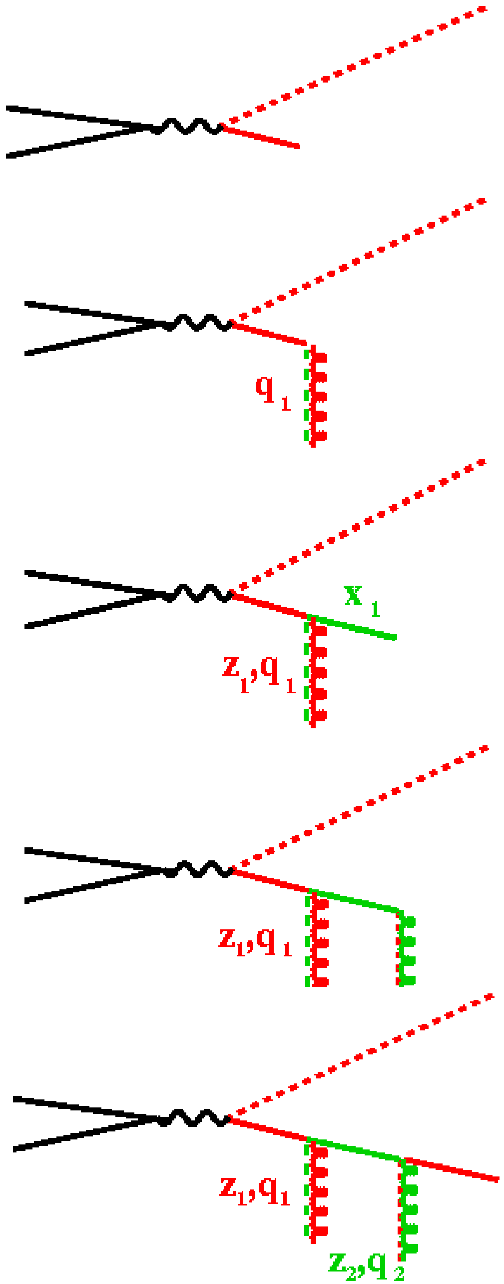


- select z_2 from splitting function
- stop evolution if $q_2<q_0$

Parton Showers for the final state

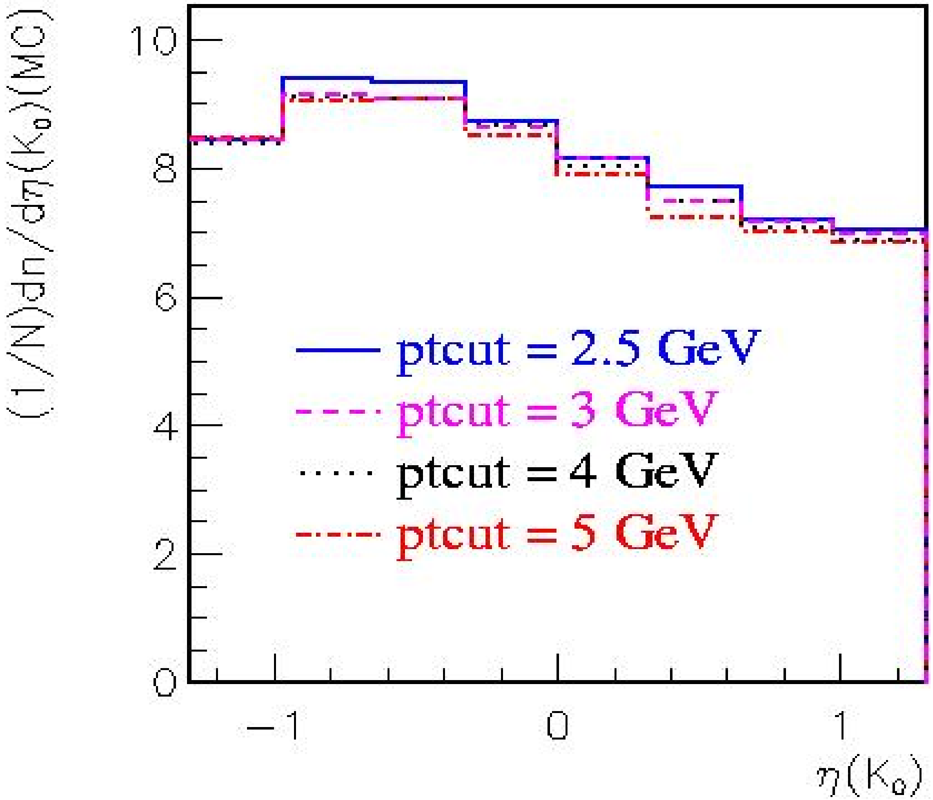
timelike parton shower evolution

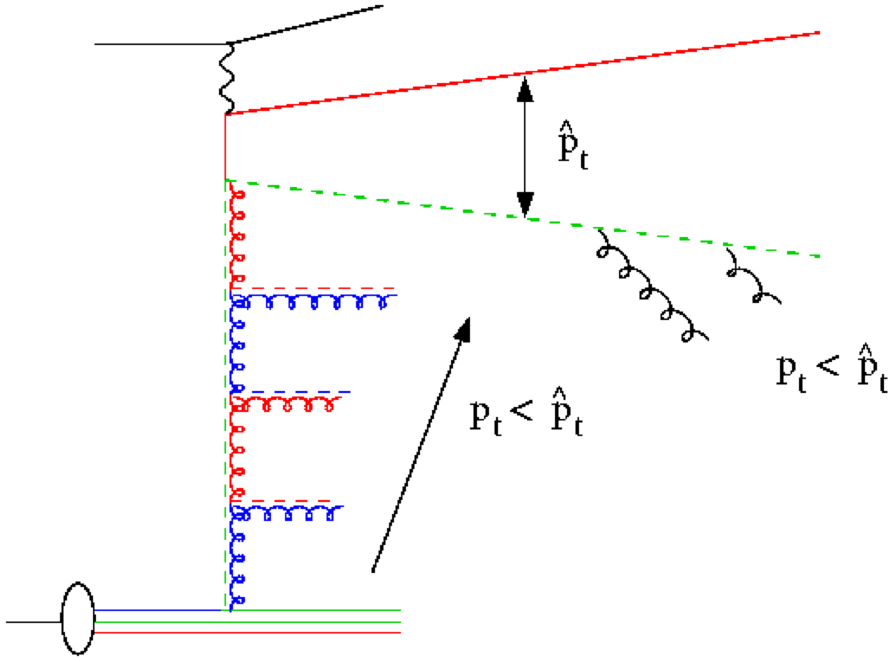
- starting with hard scattering
- select q_1 from Sudakov form factor
- select z_1 from splitting function
- select q_2 from Sudakov form factor
- select z_2 from splitting function
- stop evolution if $q_2<q_0$



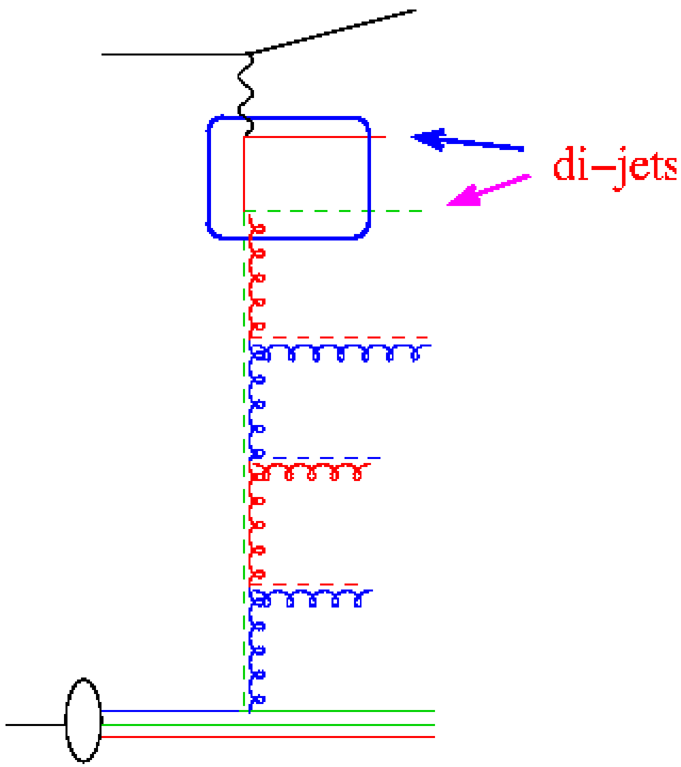
Matching of ME - PS

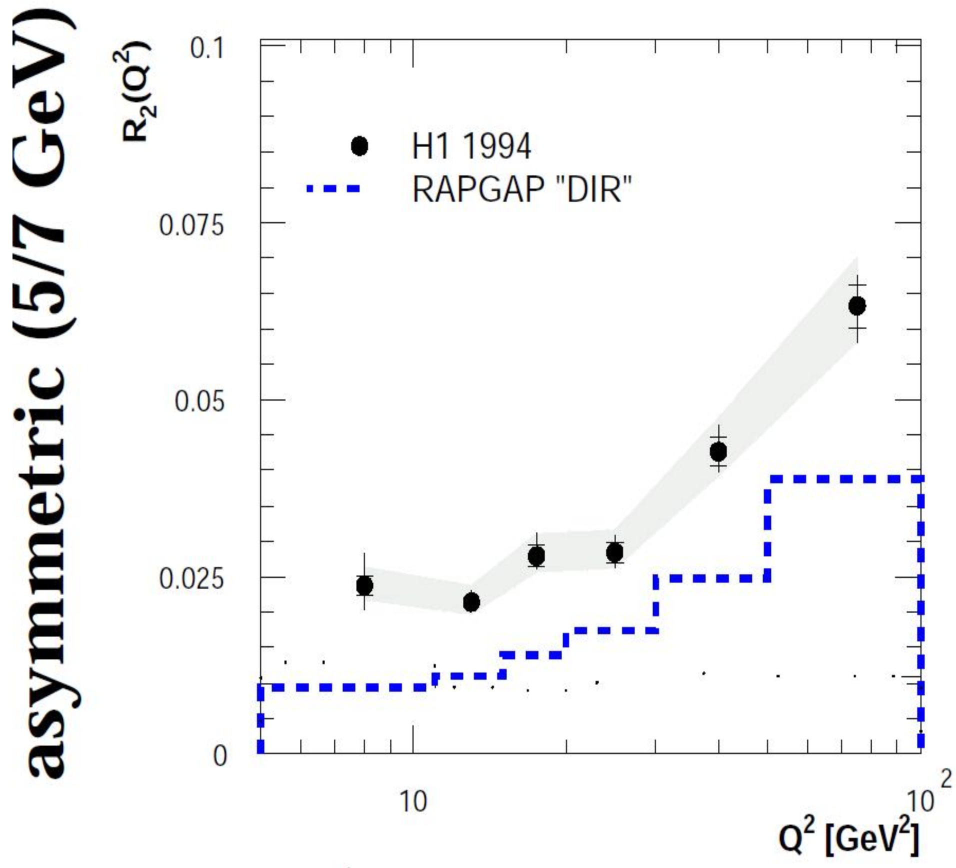
- Approximation to higher orders.....
- using initial and final state radiation according to DGLAP
  - ME sets maximum scale for parton showers
  - check sensitivity on particular choice





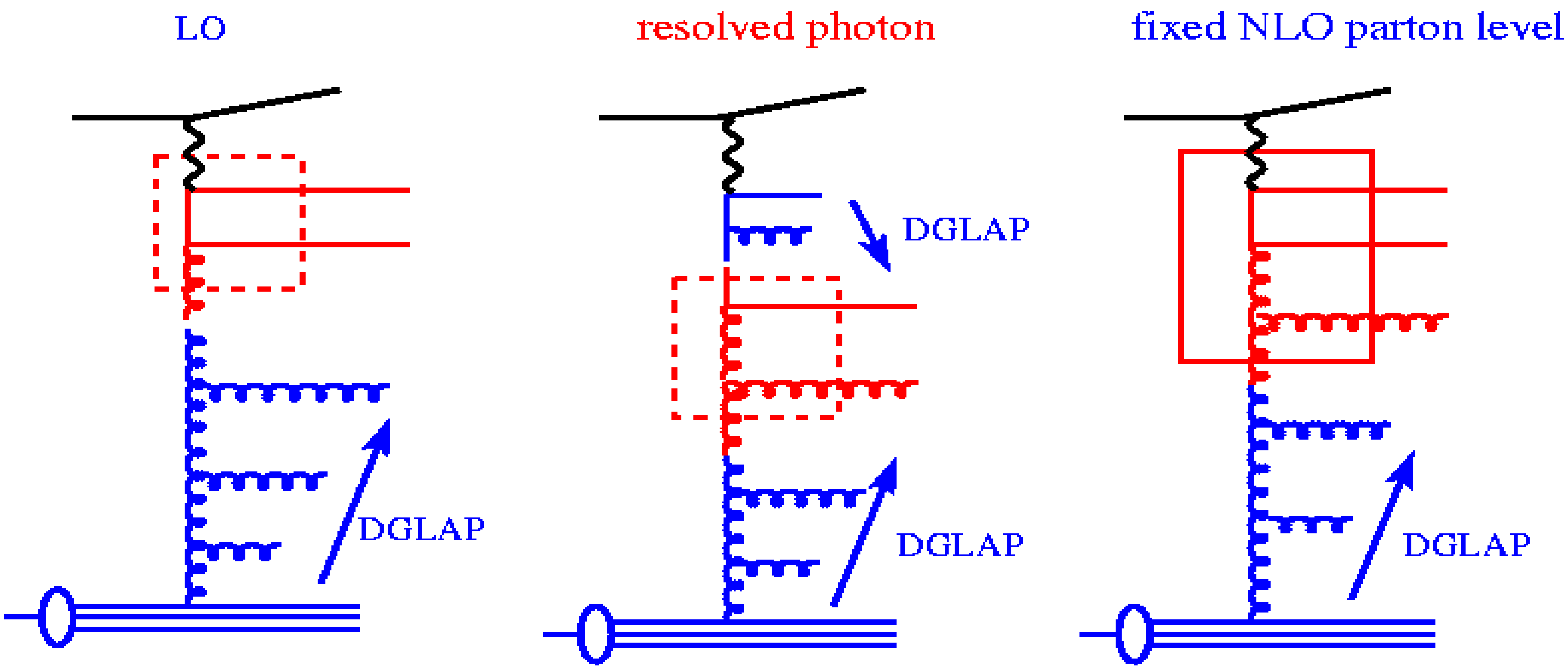
Di-jet rates: LO + PS ?





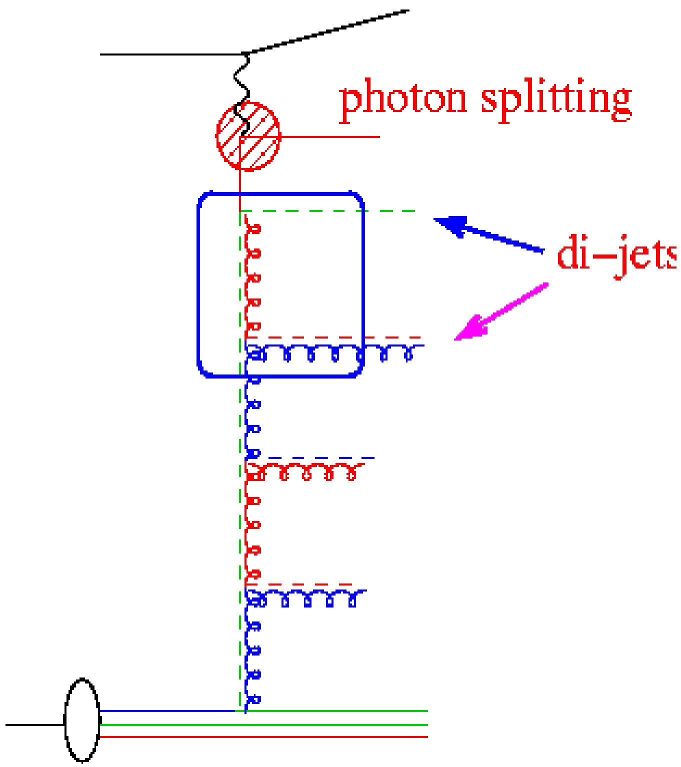
- (2+remnant) jets in DIS for $Q^2 > 5\ GeV^2$, $p_t^{jets} > 5$ GeV
- $\mathcal{O}(\alpha_s)$ processes not enough
  - need higher order contributions

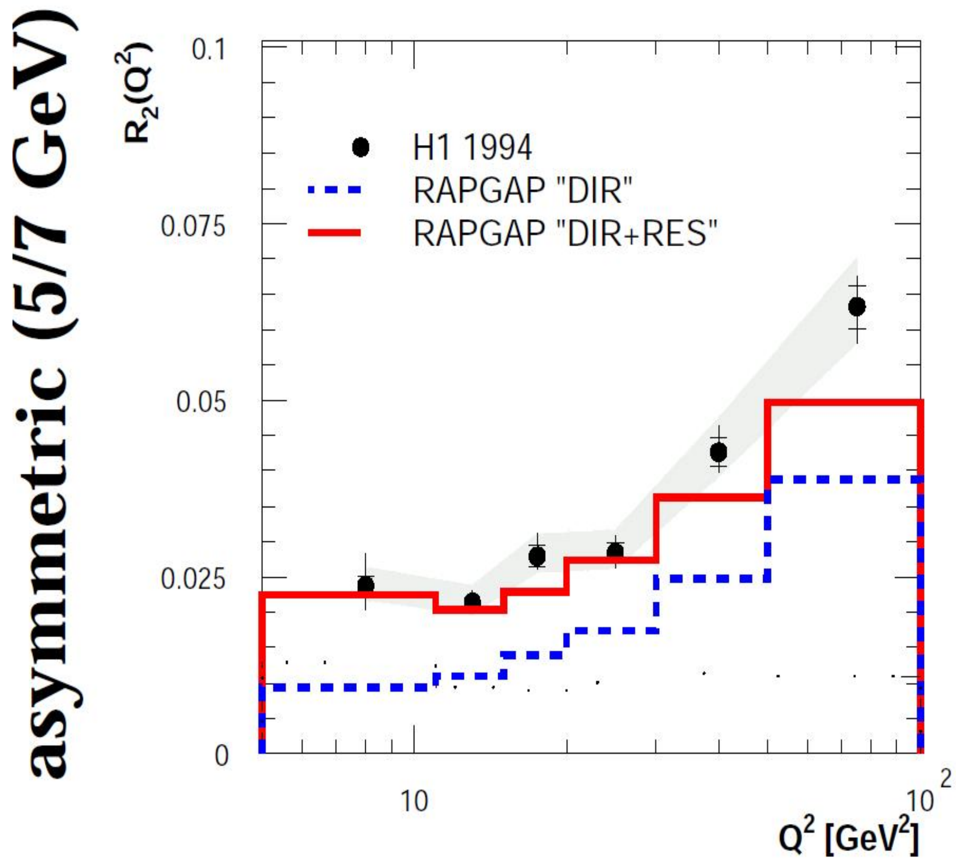
resolved virtual photons and higher orders



- take structure of the photon from QED
  - pointlike splitting for virtual photons
  - approximation to higher order QCD processes
  - BUT: when can photons be resolved: $\mu^2 > Q^2$

Di-jet rates: improving with res. photons

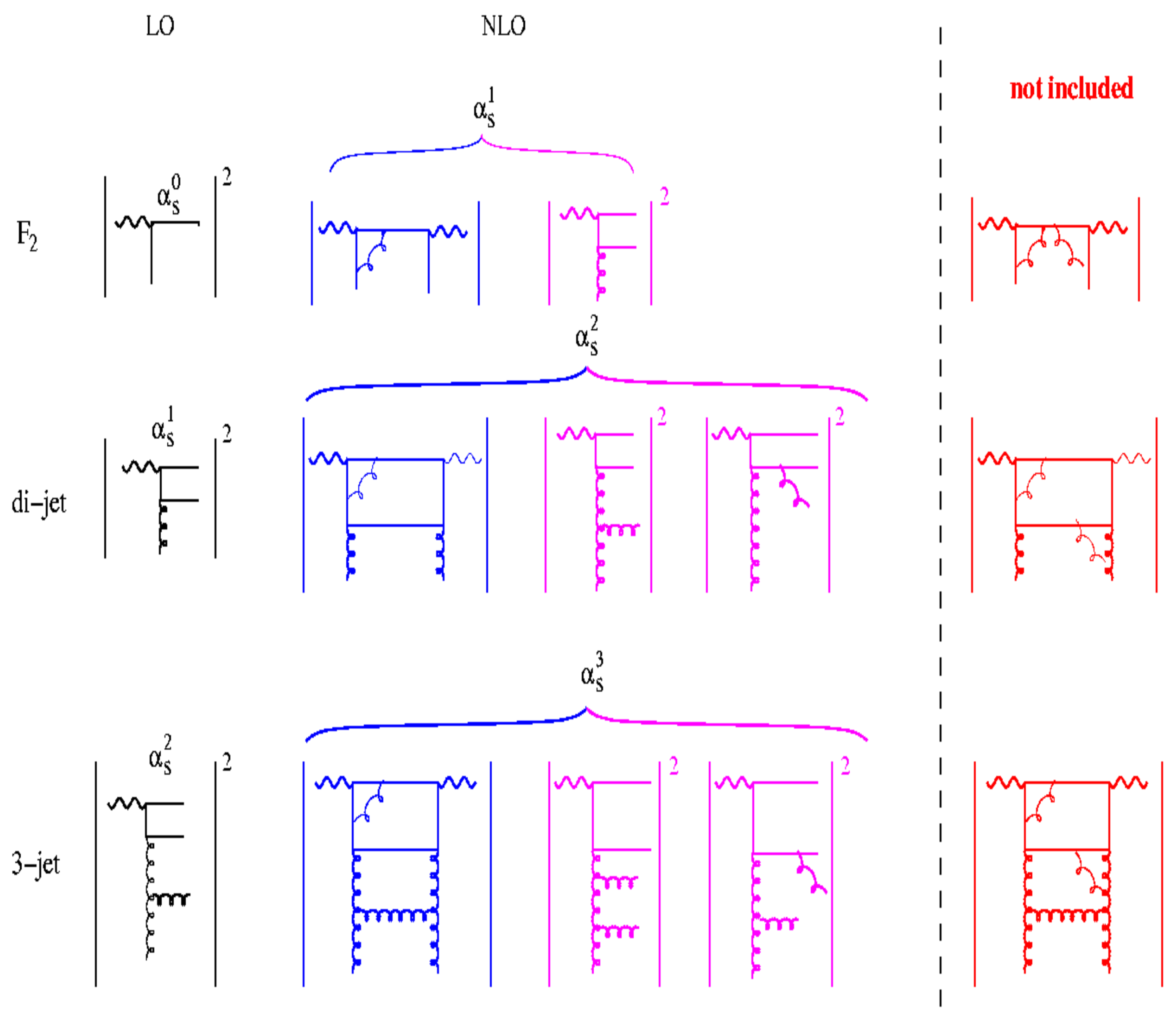




- (2+remnant) jets in DIS for $Q^2 > 5\ GeV^2$, $p_t^{jets} > 5$ GeV
- resolved virtual photon contributions describe data (like NLO...)

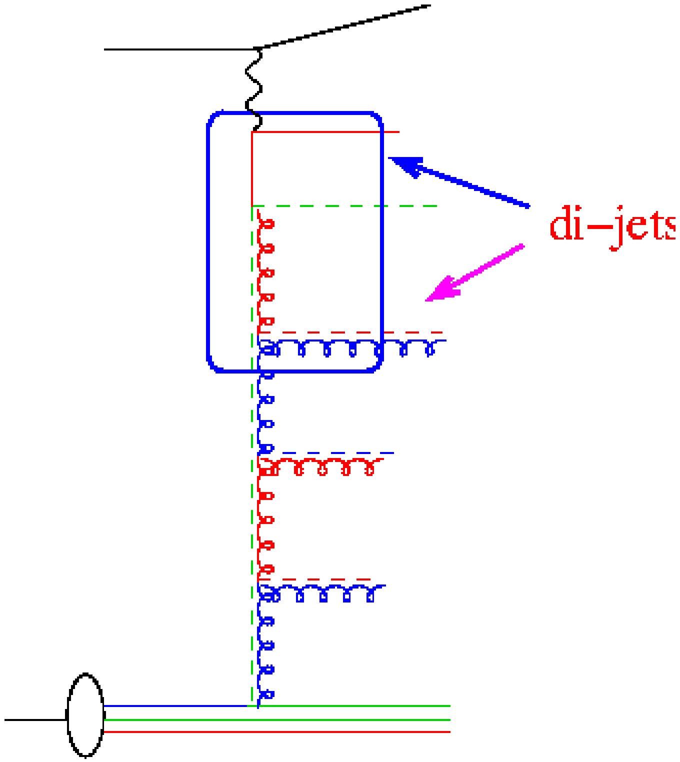
From LO to NLO ...

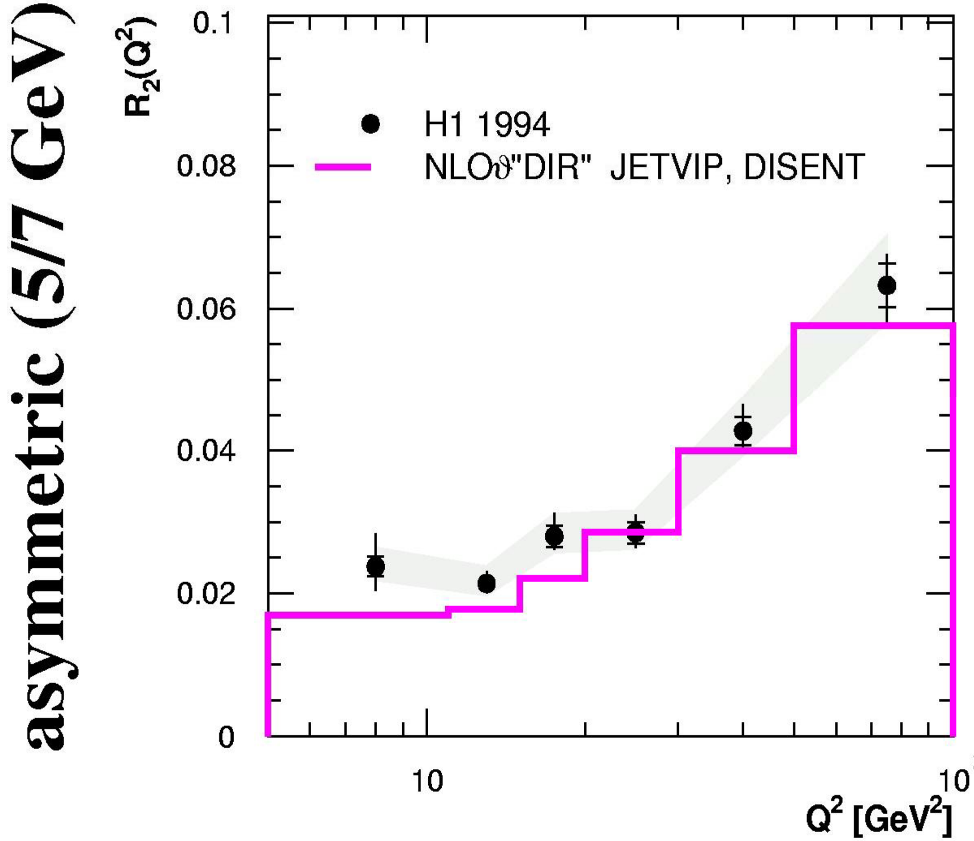
- ***NLO for F_2: $O(\alpha_s)$***
- ***NLO for dijets: $O(\alpha_s{}^2)$***
- ***NLO for 3-jets: $O(\alpha_s{}^3)$***



NOTE: NLO for dijets is **NOT** NNLO for F_2

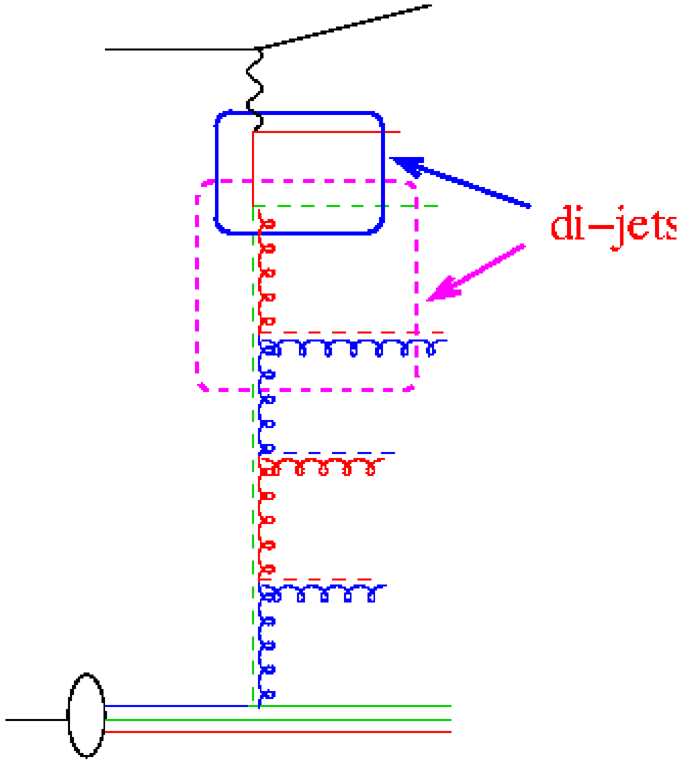
Di-jet rates: NLO calculations

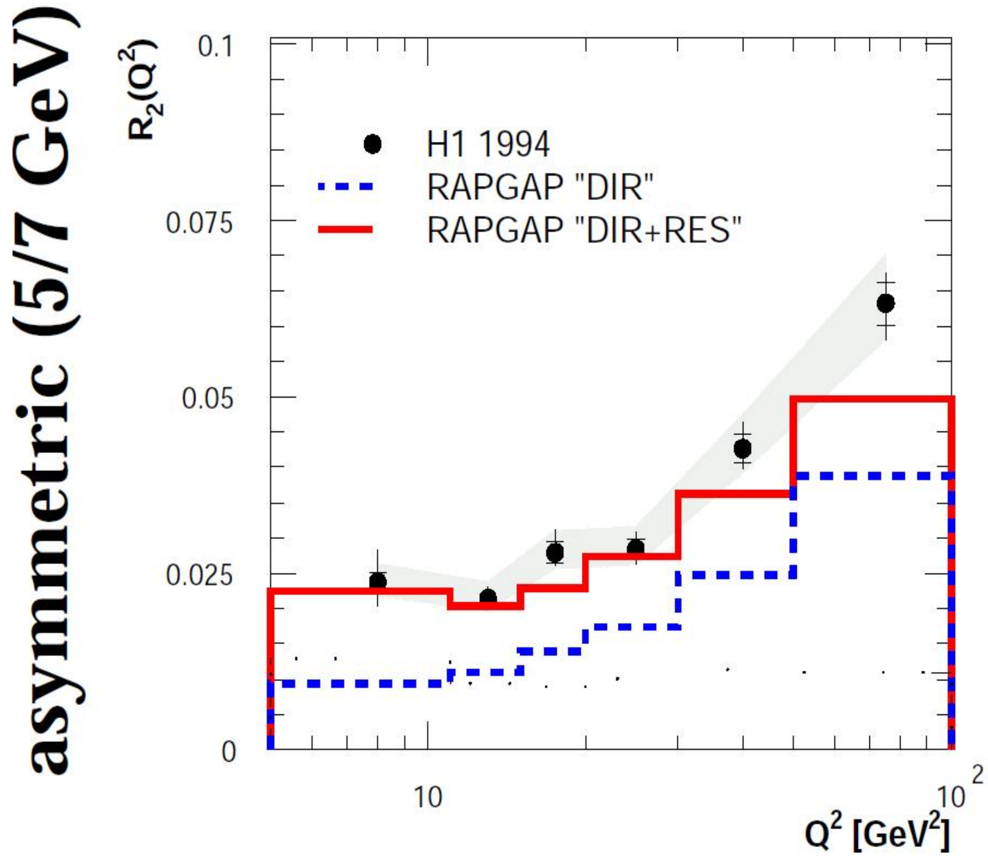




- (2+remnant) jets in DIS for $Q^2 > 5$ GeV^2, $p_t^{jets} > 5$ GeV
- NLO calculations are ok, if $p_{t1} \neq p_{t2}$
- similar to resolved virtual photons ....

Di-jet rates: resolved photons (reminder)





- (2+remnant) jets in DIS for $Q^2 > 5\ GeV^2$, $p_t^{jets} > 5$ GeV
- resolved virtual photon contributions describe data (like NLO...)

Problems in NLO

- asymmetric pt cuts: $p_{t1} \neq p_{t2}$
  needed for cancellation of real
  and virtual emissions....
- loose most of the data...
- unphysical behavior...

Problems in NLO

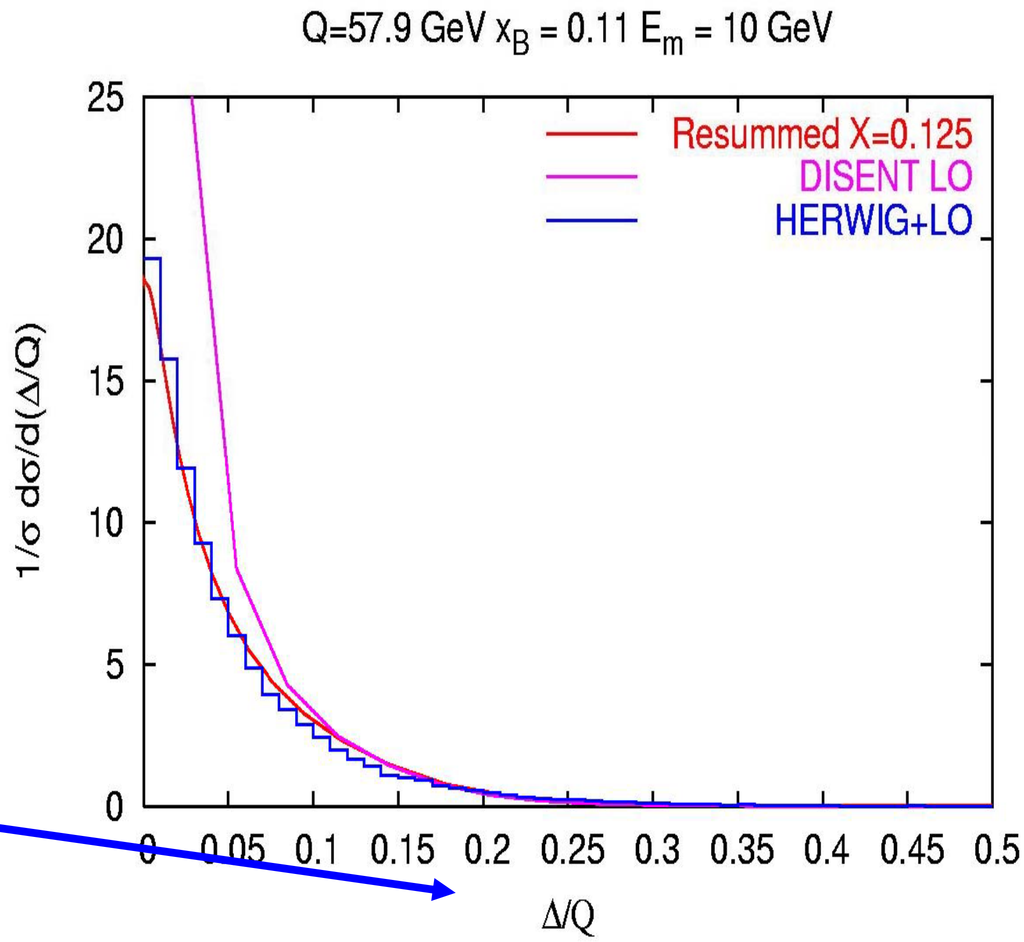
- asymmetric pt cuts: $p_{t1} \neq p_{t2}$
  needed for cancellation of real and virtual emissions....
- loose most of the data...
- unphysical behavior...
- improvements by resummations:

A. Banfi et al hep-ph/0508096

  - soft gluon radiation.... like parton showers... resummed to all orders

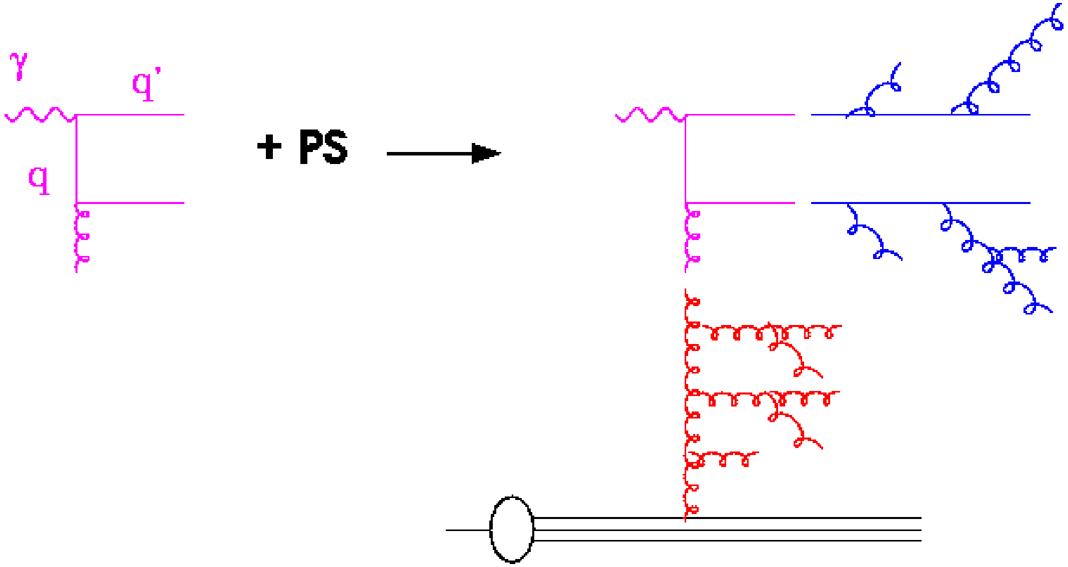
check dijets:

$$\Delta p_t = p_{t1} - p_{t2}$$



  - resummed result at LO agrees with MC using parton showers...

Why all these problems ?



- **Collinear approach:** *incoming/outgoing partons are on mass shell*
  $(\square+q)^2 = q'^2$, $-Q^2 + x\,y\,s = 0 \rightarrow x = Q^2/(ys)$
- **BUT** *final state radiation:*
  $(\square+q)^2 = q'^2$, $-Q^2 + x\,y\,s = m^2 \rightarrow x = (Q^2+m^2)/(ys)$
- **AND** *initial state radiation:*
  $(\square+q)^2 = q'^2$, $-Q^2 + x\,y\,s + q^2 = 0 \rightarrow x = (Q^2-q^2)/(ys)$
- *Collinear approach: $q'^2 = q^2 = 0$, order by order ....*
- *Well known.... since years....*
- *NLO corrections... better treatment of kinematics...*

Attempts to parton shower NLO

- Attempts to include parton showers in NLO: "Initial state parton shower beyond LO", J.C. Collins and X. Zu, JHEP ***0503:059***, 2005, hep-ph/0411332. "Monte-Carlo event generators at NLO", J.C. Collins, Phys.Rev.D***65***, 094016, hep-ph/0110113.
- due to virtualities and k_t's after PS, long. momentum factions x_i *no longer consistent with NLO formulae*
- *complicated subtractions in gluon channel*
- *very complicated in quark channel*
- *needs reformulation for every order*

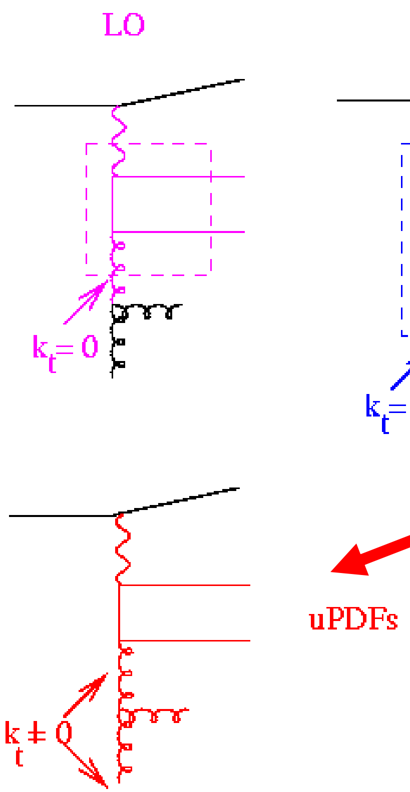
- Need to define new parton densities according to showering scheme
- precisie prescription to transform Msbar to PS scheme (BUT dependent on PS scheme,i.e. Sjostrand scheme or Herwig scheme)

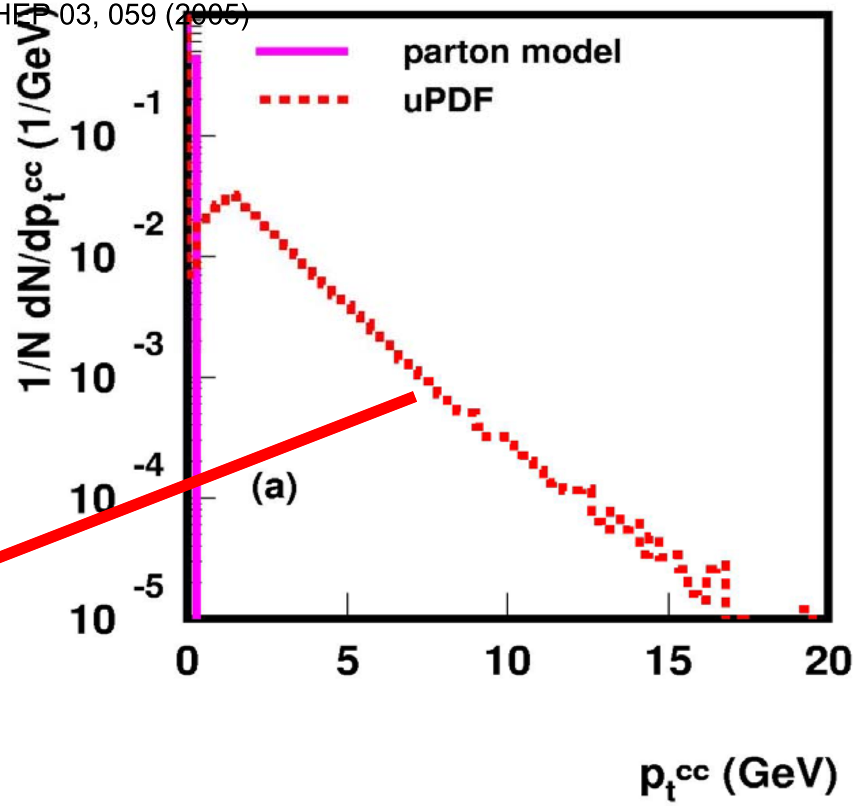
The need for unintegrated PDFs

Watt, Martin, Ryskin, Eur. Phys. J. C3, 73 (2003)
Watt, Martin, Ryskin,Phys. Rev. D70, 014012 (2004)
Collins, Zu, JHEP 03, 059 (2005)

J. Collins, H. Jung

- using integrated pdfs ignores proper kinematics
- large NLO corr comes from wrong kinematics in LO





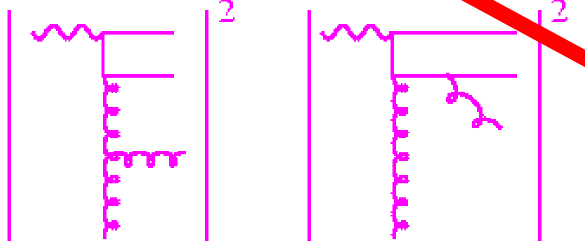
- collinear factorization is wrong if details of final state are investigated
- Need for fully unintegrated PDFs

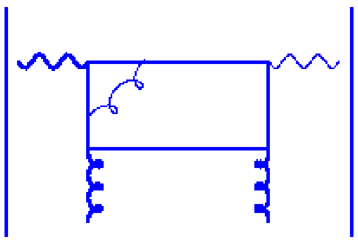
References

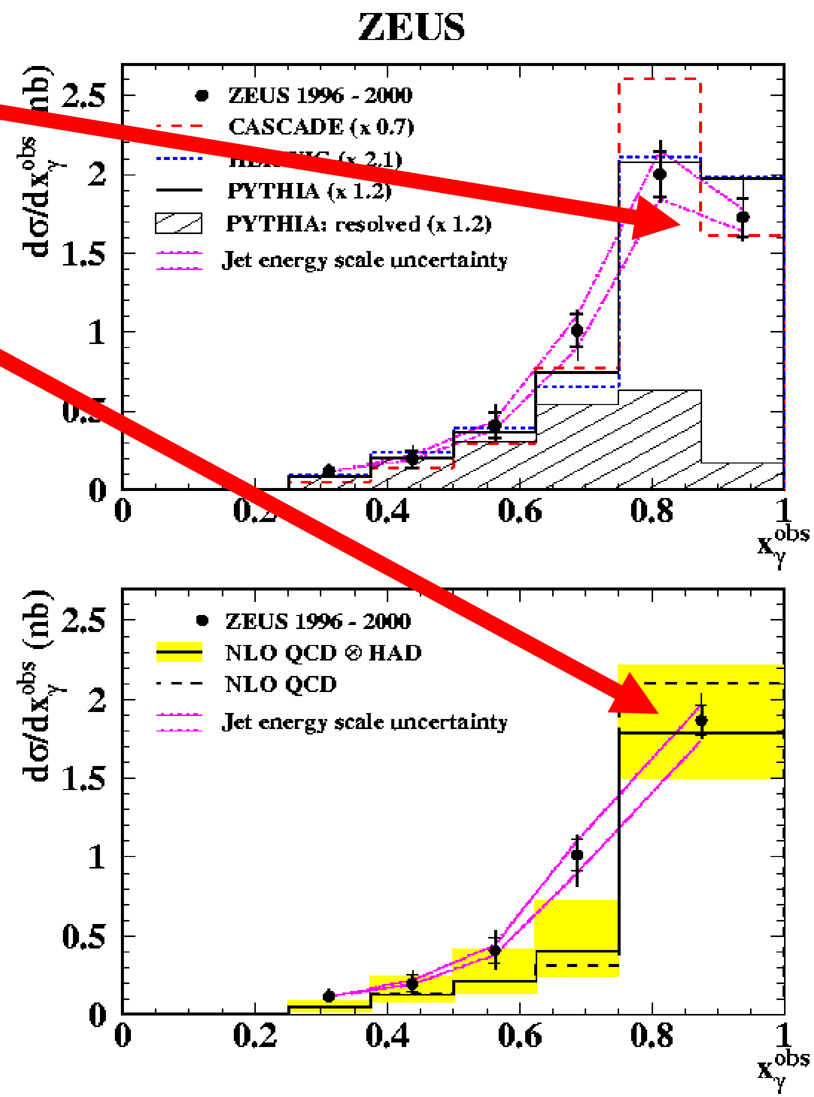
- “Initial state parton shower beyond LO”, J.C. Collins and X. Zu, JHEP ***0503:059***, 2005, hep-ph/0411332.
- “Monte-Carlo event generators at NLO”, J.C. Collins, Phys.Rev.D***65***, 094016, hep-ph/0110113.
- “Universality of soft and collinear factors in hard-scattering factorization”, J.C. Collins and A. Metz, Phys.Rev.Lett.***93***:252001, hep-ph/0408249.
- “Un-integrated parton distributions and inclusive jet production at HERA”, G. Watt, A.D. Martin and M.G. Ryskin, Eur.Phys.J.C***31***:73-89, hep-ph/0306169.
- “Back-to-back jets in QCD”, J.C. Collins and D.E. Soper, Nucl.Phys.B***193***:381,1981, Erratum-ibid.B***213***:545,1983.
- “Sudakov form-factors”, J.C. Collins, Adv.Ser.Direct.High Energy Phys.5:573-614,1989, hep-ph/0312336.

Do HERA data matter ?

- ***Measurements are better than NLO prediction...***
- ***problem lies in simplified kinematics***







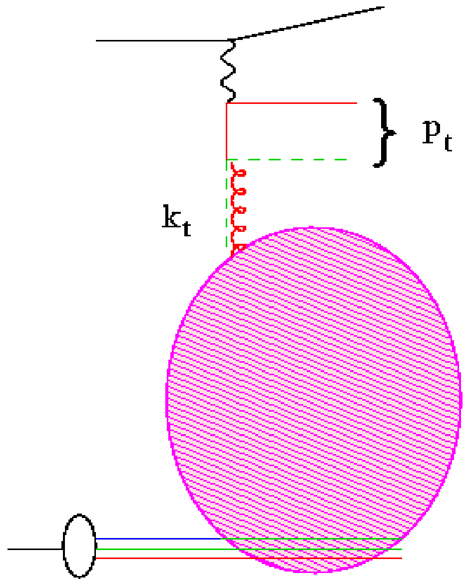
- soft k_t region can be important
- sometimes interesting part is where NLO cannot do ... (i.e factorisation breaking in diffraction....)

Need for uPDFs

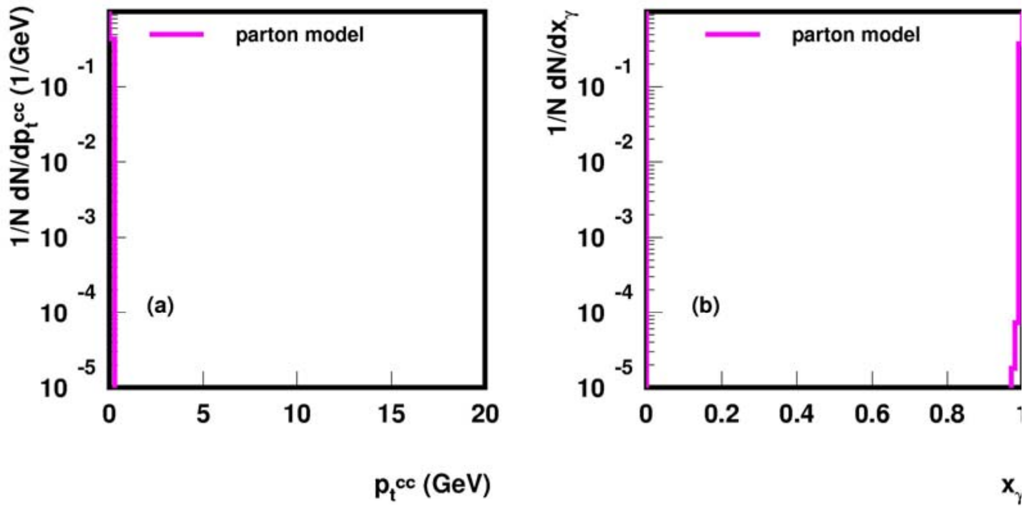
Define:

$p_{T q\bar{q}}$

$$x_\gamma = \frac{\sum_{i=q,\bar{q}} (E_i - p_{z\,i})}{2yE_e} = \frac{p^-_{q\bar{q}}}{q^-}$$



J. Collins, H. Jung



- parton kinematics

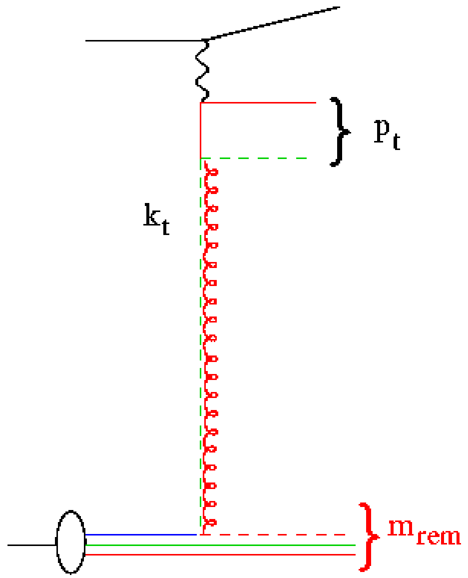
Need for uPDFs

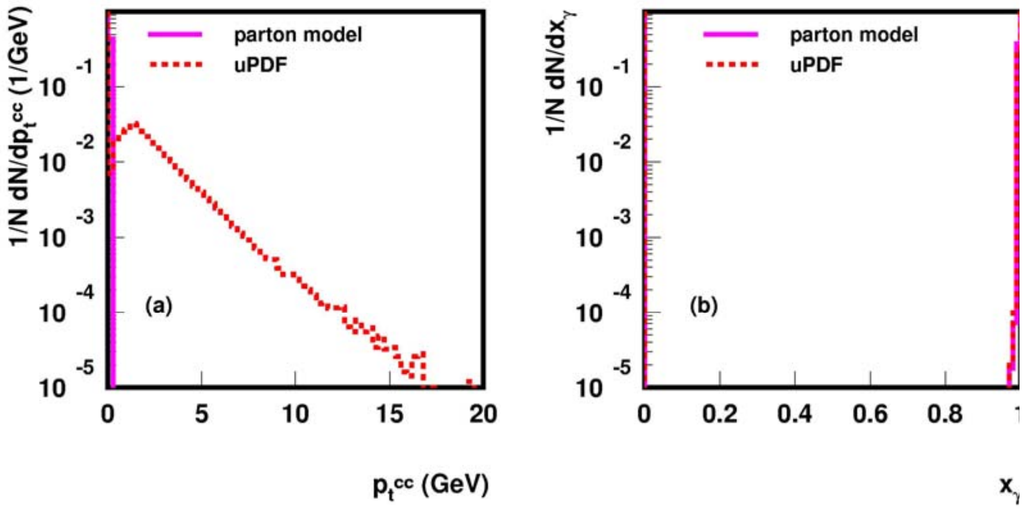
Define:

J. Collins, H. Jung

$p_{T\,q\bar{q}}$

$$x_\gamma = \frac{\sum_{i=q,\bar{q}}(E_i - p_{z\,i})}{2yE_e} = \frac{p^-_{q\bar{q}}}{q^-}$$





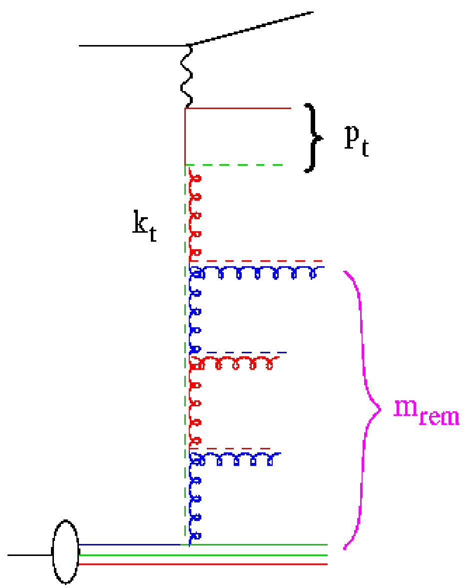
- parton kinematics
- uPDFs

Need for uPDFs

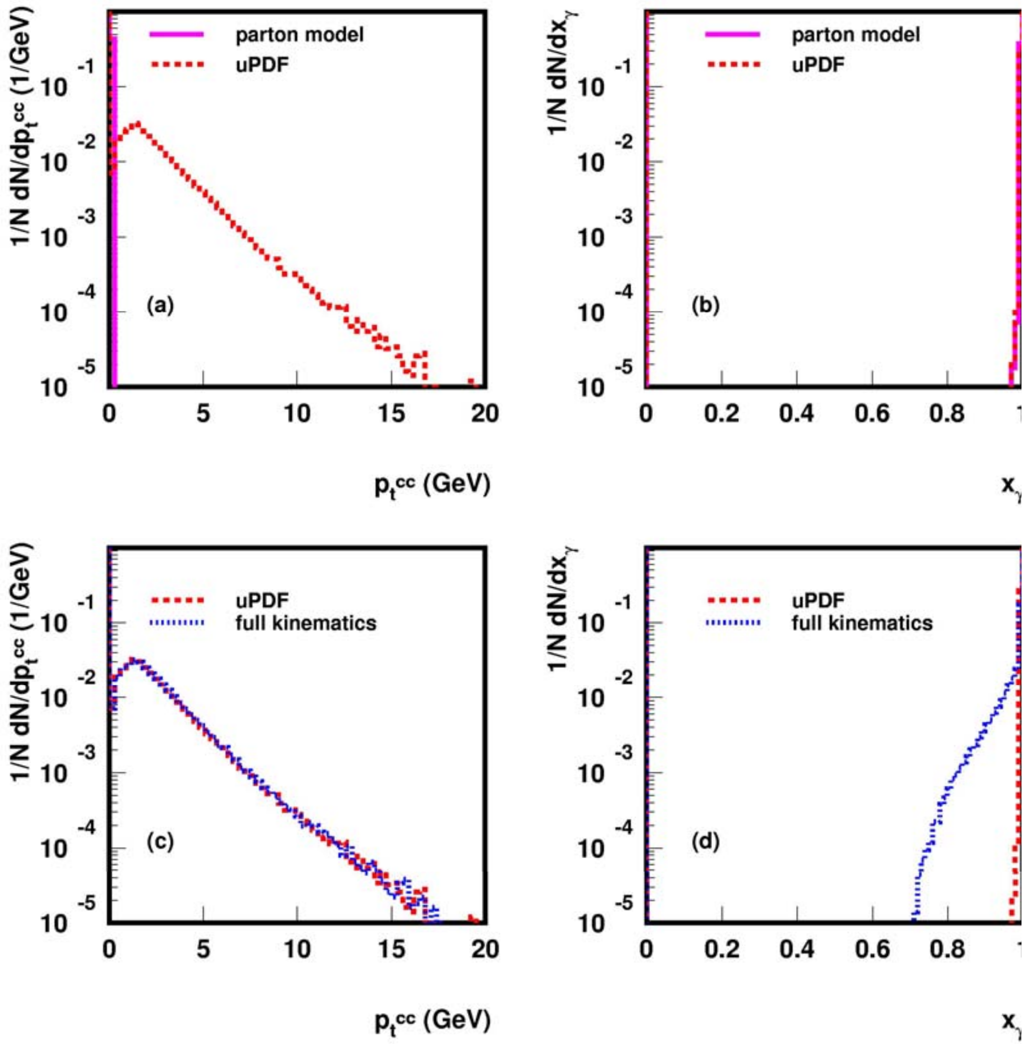
Define:

$p_{T q\bar{q}}$

$$x_\gamma = \frac{\sum_{i=q,\bar{q}}(E_i - p_{z\,i})}{2yE_e} = \frac{p^-_{q\bar{q}}}{q^-}$$



J. Collins, H. Jung

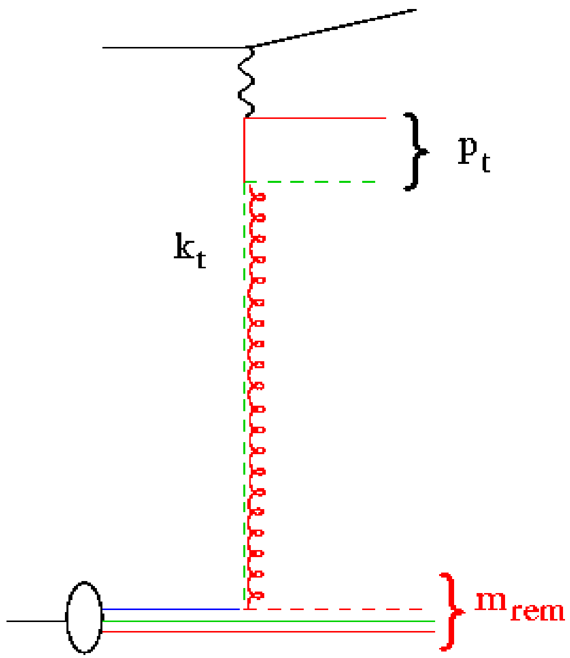


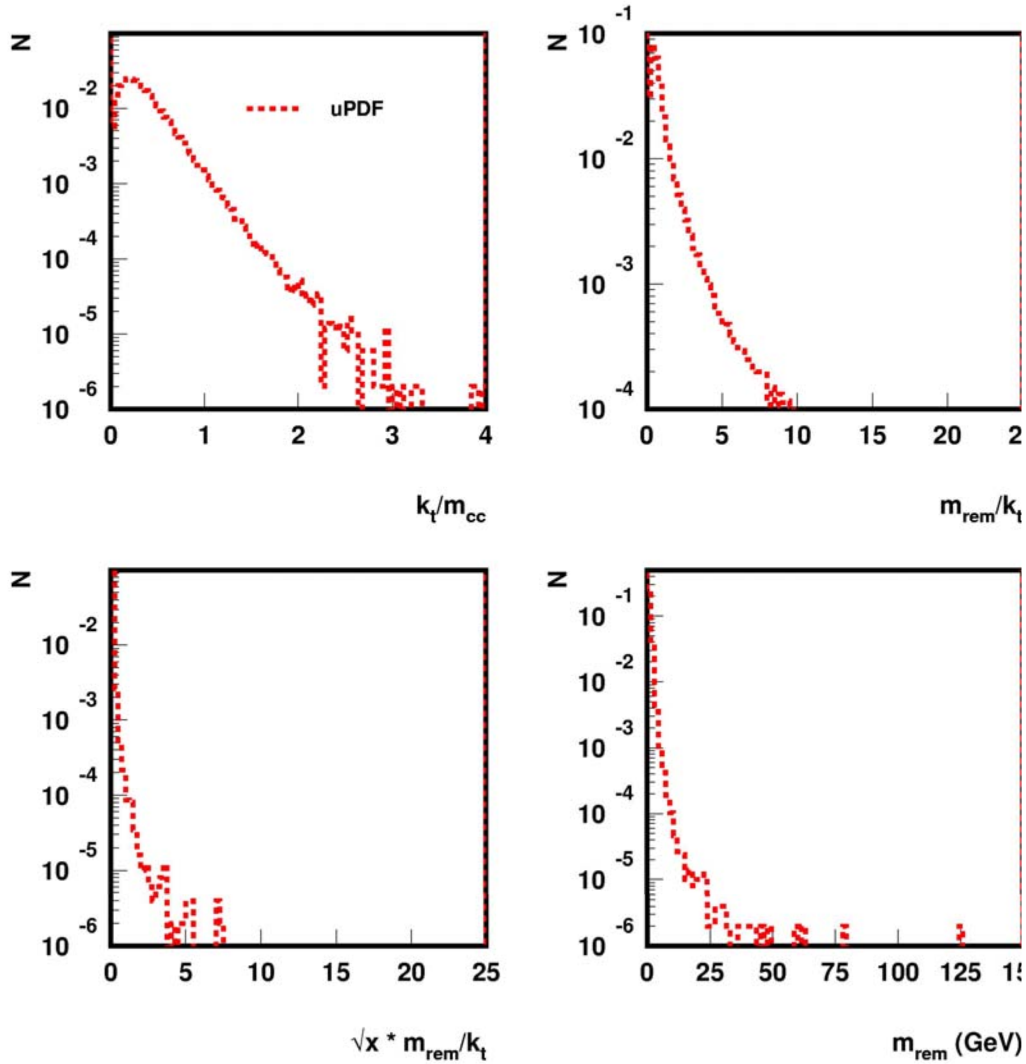
- parton kinematics
- uPDFs
- full kinematics

Need for double uPDFs

J. Collins, H. Jung

$$k^2 = -(k_t^2)/(1-x)$$



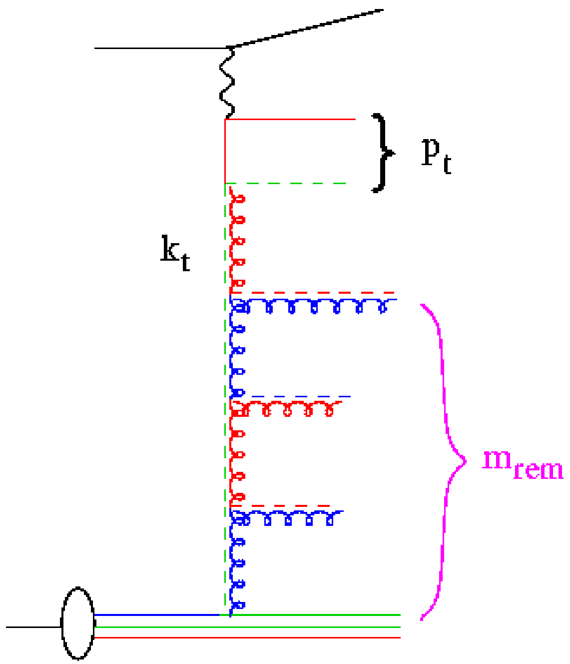


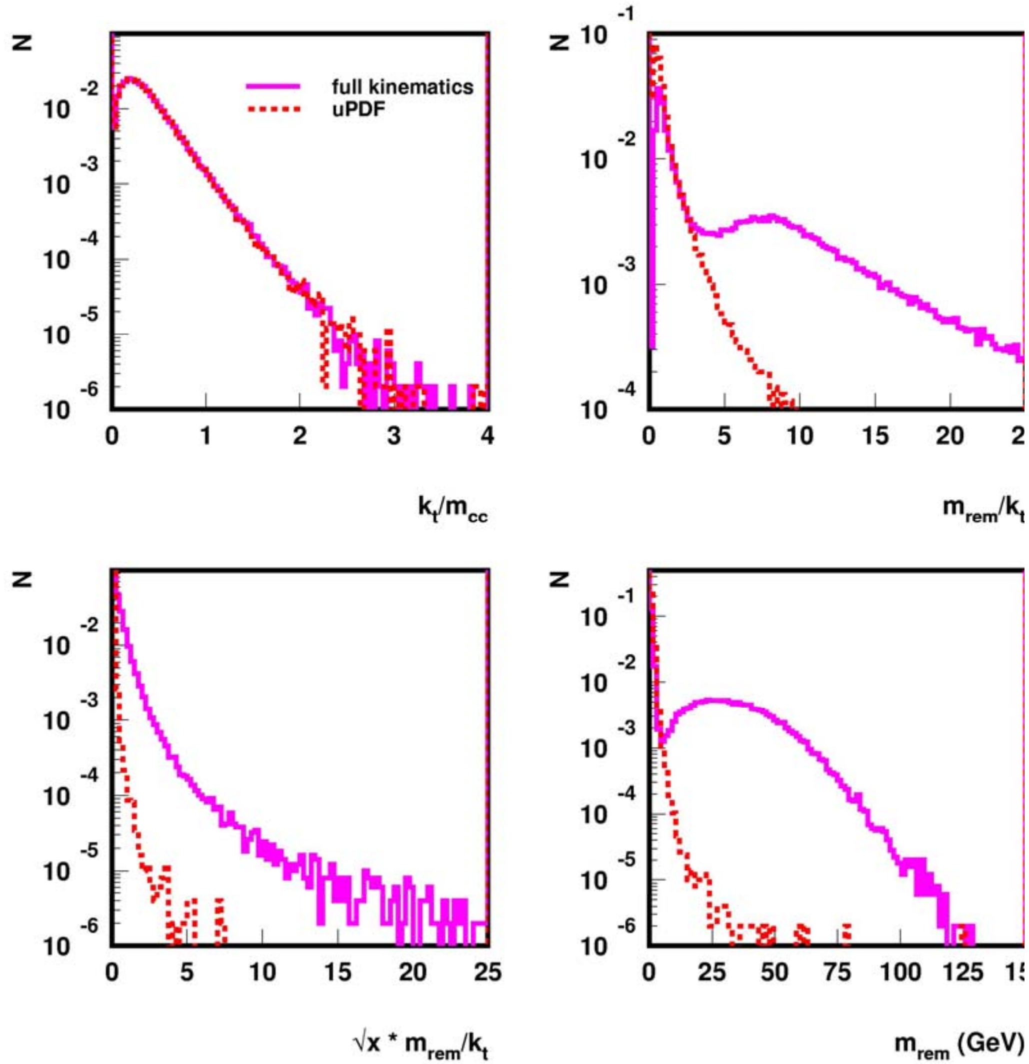
Need for double uPDFs

J. Collins, H. Jung

$$k^2 = -(k_t^2)/(1-x)$$

$$k^2 = -(k_t^2 + x m_{\rm rem}^2)/(1-x)$$





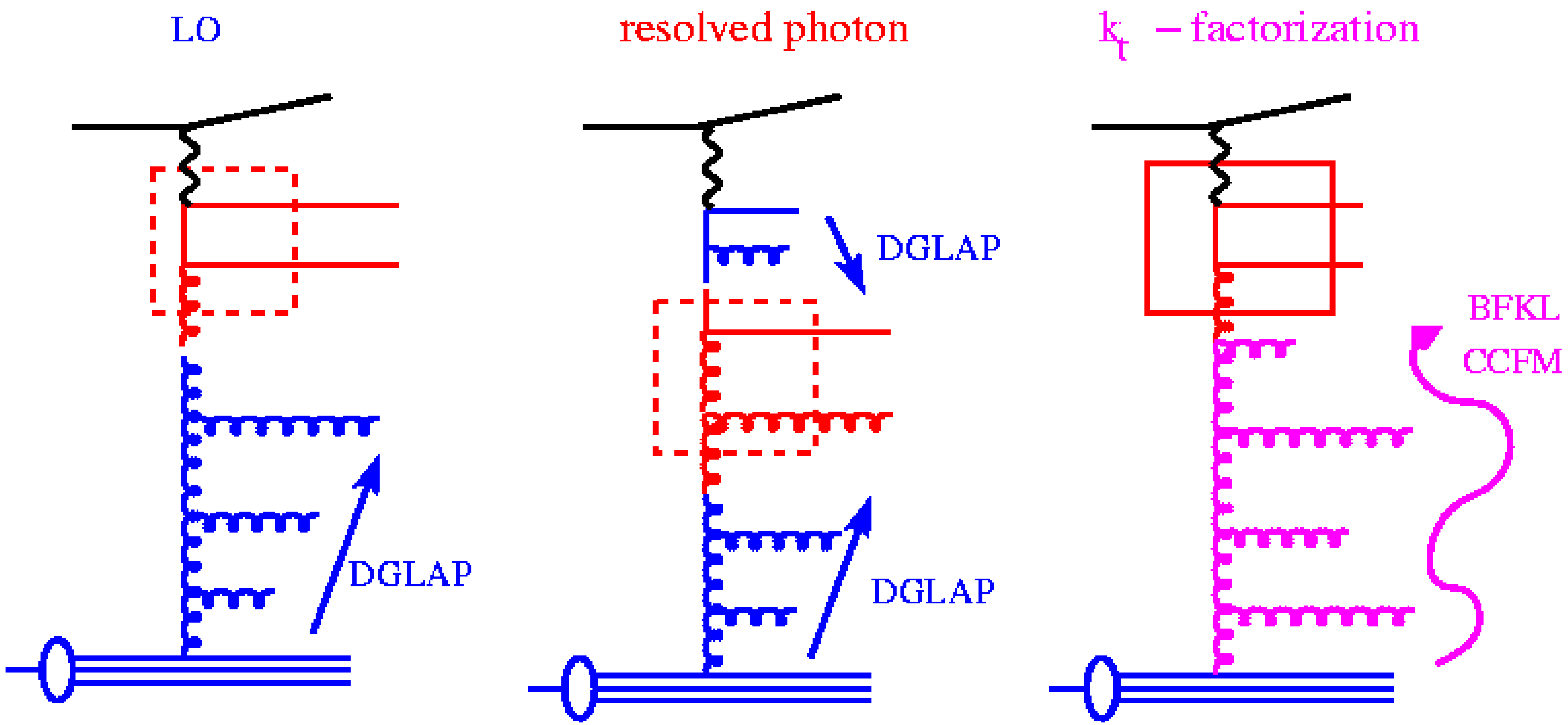
Need for fully uPDFs

- full kinematics can only be described by fully (double) uPDFs
- dependence on k_t^2 and k^2
- *reformulate pQCD methods in terms of fully uPDFs*
- *extension of k_t factorisation*
- *Advantages:*
  - *kinematics correct already at LO*
  - *NLO corrections much smaller (BFKL example: 70 % from kinematics)*
  - *no need for separate methods (resummation or the CCS (Collins Soper Sterman))*
  - *unified treatment of ME calcs and MC generators*

Different steps of approximations

- fully uPDFs
- uPDFs (*k_t factorisation)*
- *integrated PDFs + parton showers*
- *integrated PDFs + fixed order calculations in LO and NLO*

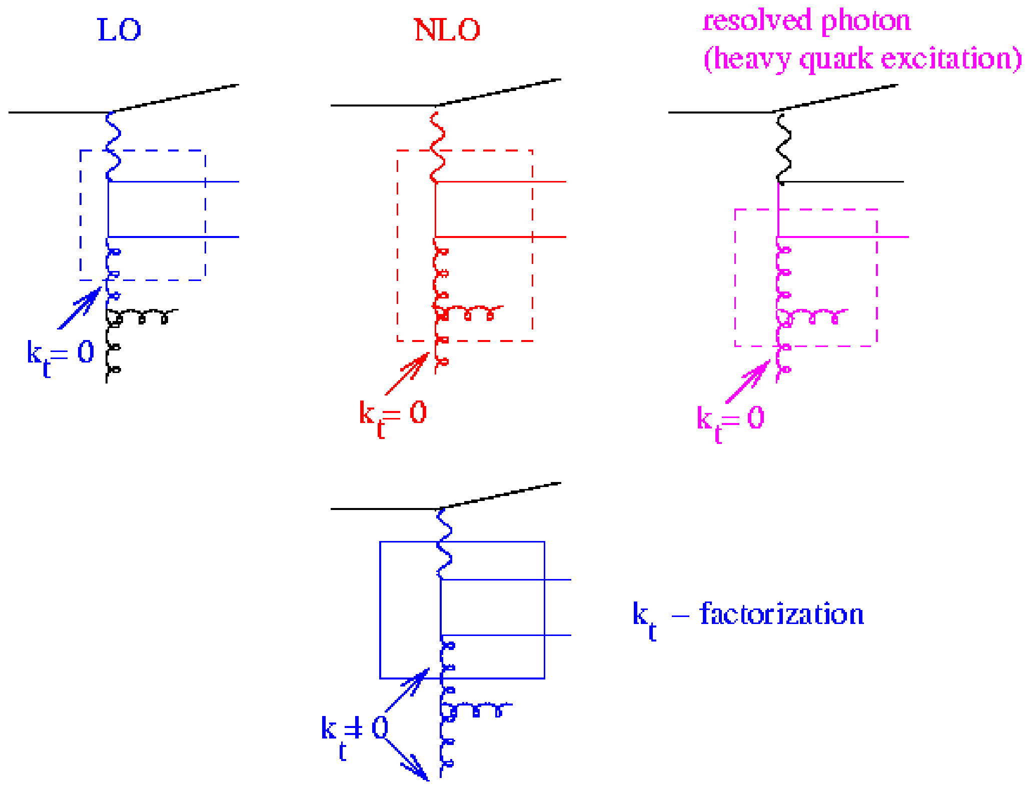
k_t-factorization and CCFM



- kt-factorisation: treat transverse momentum of incoming gluon ...
  - allow $k_t \geq \mu_f$
- **C**iafaloni**C**atani**F**iorani**M**archesini :equations treat explicitly gluon emissions
  - according to color coherence ... angular ordering
  - angular ordering includes DGLAP and BFKL as limits...

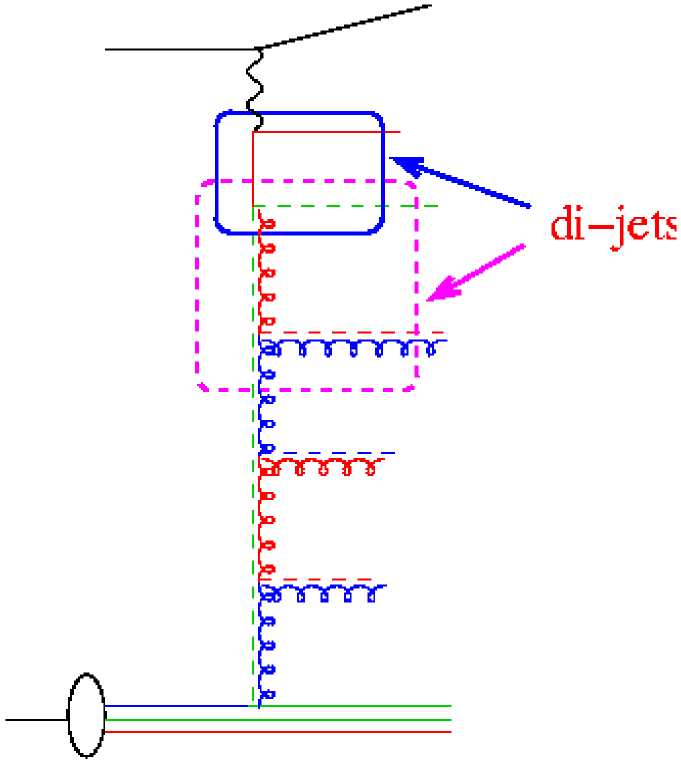
k_t-factorization and collinear NLO

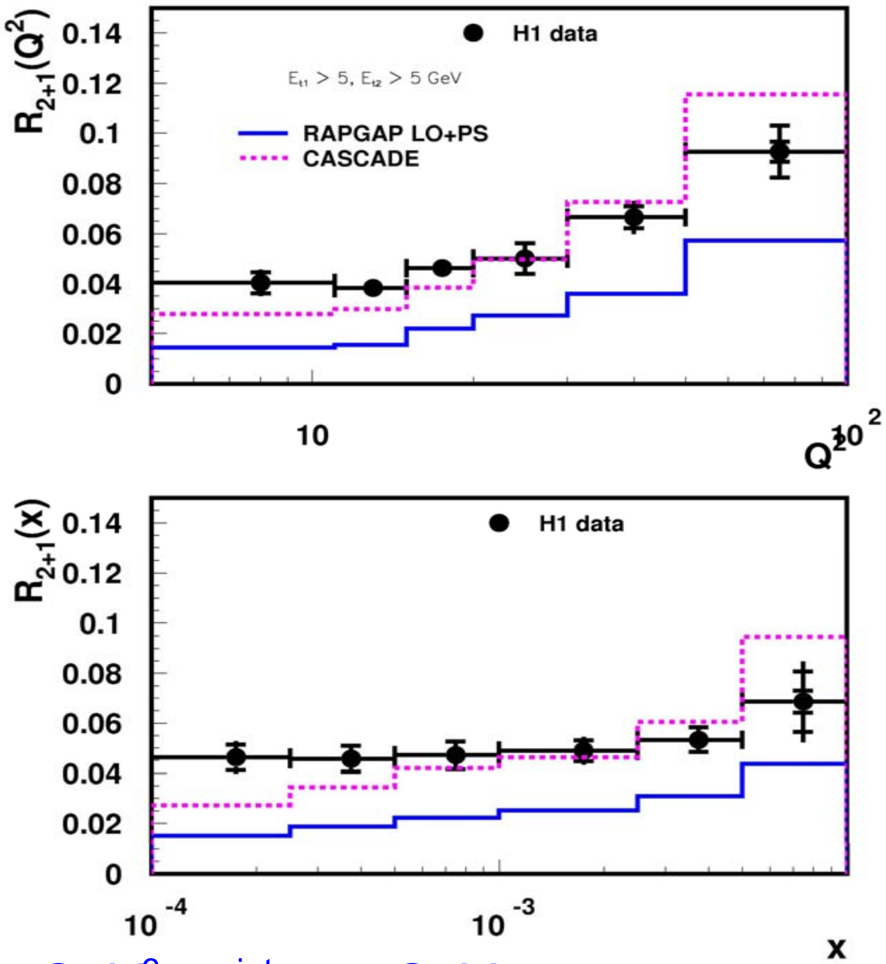
- off-shell matrix elements (kt – factorization) includes most NLO corrections:



- even soft kt region is properly treated (not the case in part.level NLO calc)
- in addition contributions to all orders are included

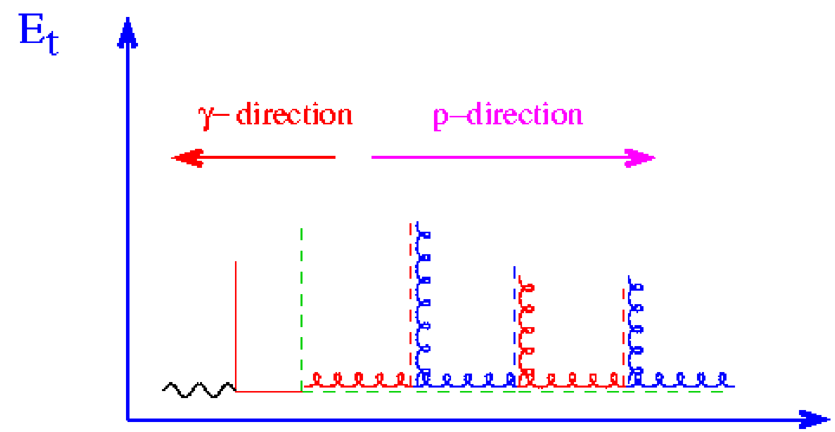
Hadronic final state: Di-jet rates





- (2+remnant) jets in DIS for $Q^2 > 5\ GeV^2$, $p_t^{jets} > 5$ GeV
- $\mathcal{O}(\alpha_s)$ processes not enough
  - needs $\mathcal{O}(\alpha_s^2)$ or resolved virtual photon contributions
  - kt-factorisation with CCFM uPDFs is as good as NLO

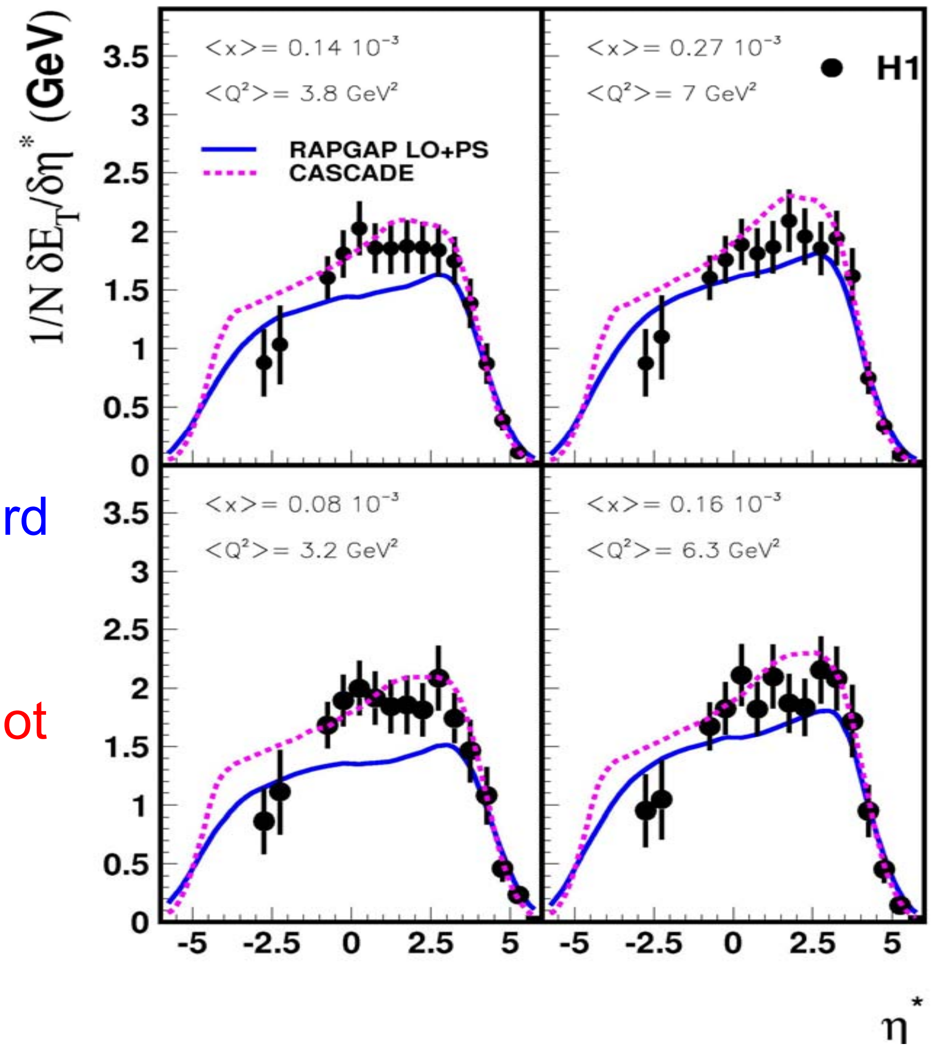
Hadronic final state: Energy flow



- Et flow in DIS at small x and forward angle (p-direction):

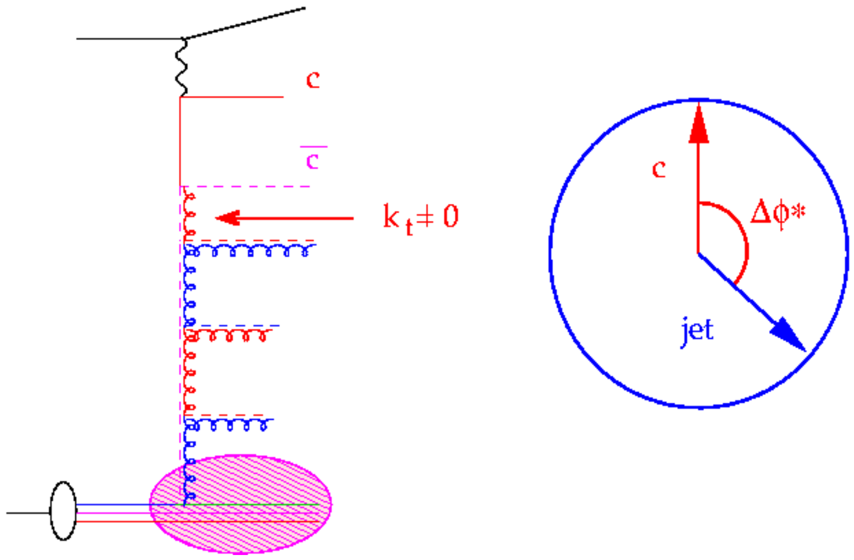
➔ $\mathcal{O}(\alpha_s)$ processes not enough

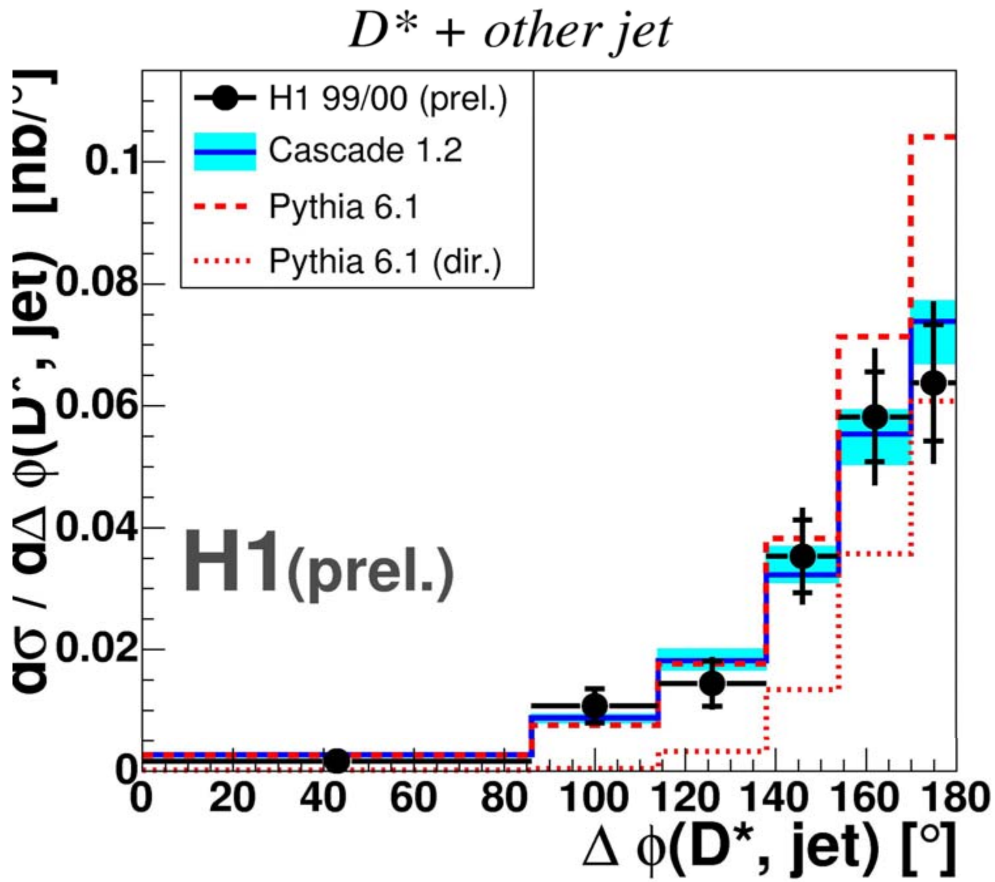
➔ even DGLAP parton showers do not help

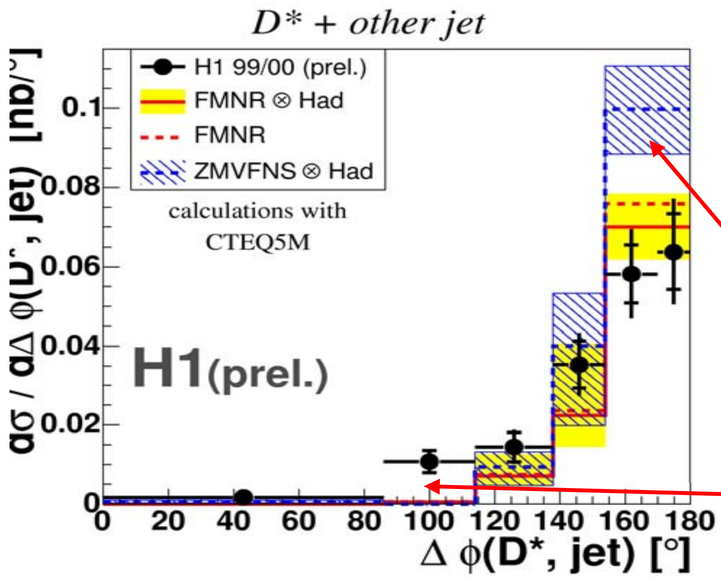


- need higher order contributions...
- k_t factorisation with CCFM very good !!!!!

Charm production

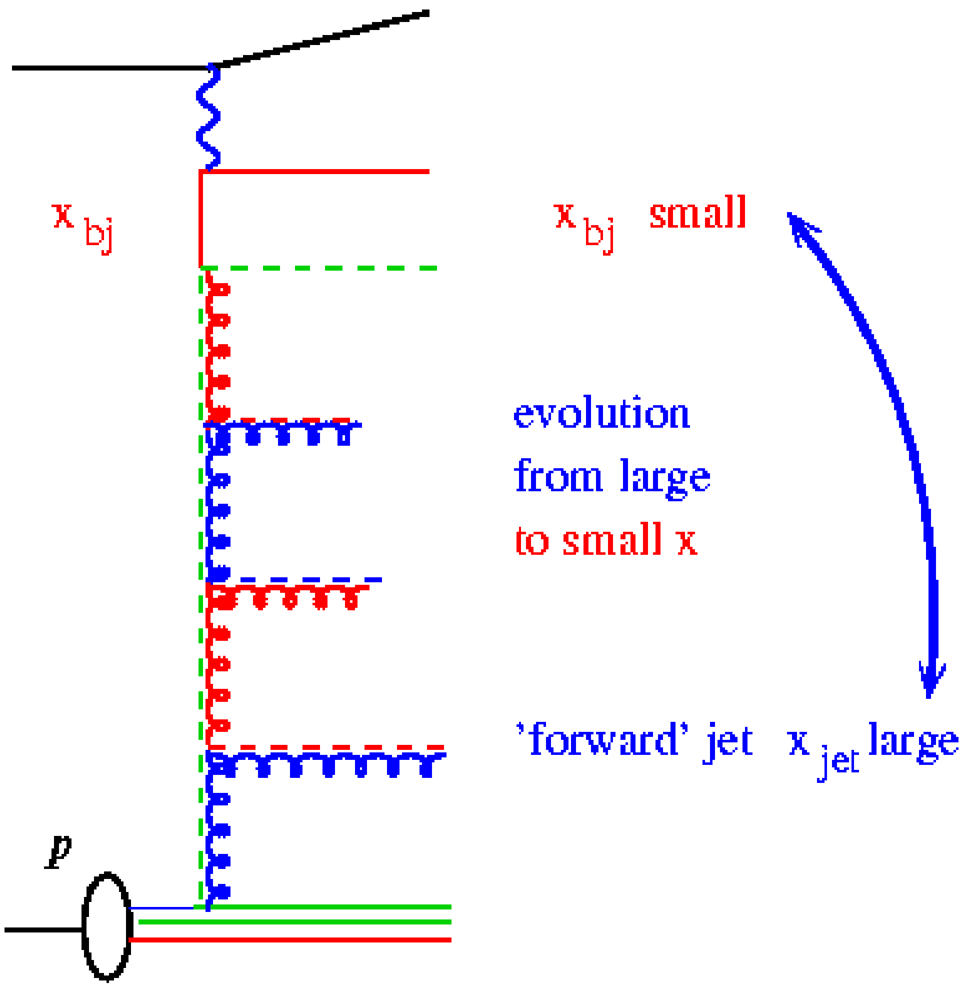






- $\Delta\phi$ x-section better described by CASCADE (uPDF)
- problems at small and large $\Delta\phi$ in NLO calc.

forward jet production and diffraction



- DIS and forward jet:

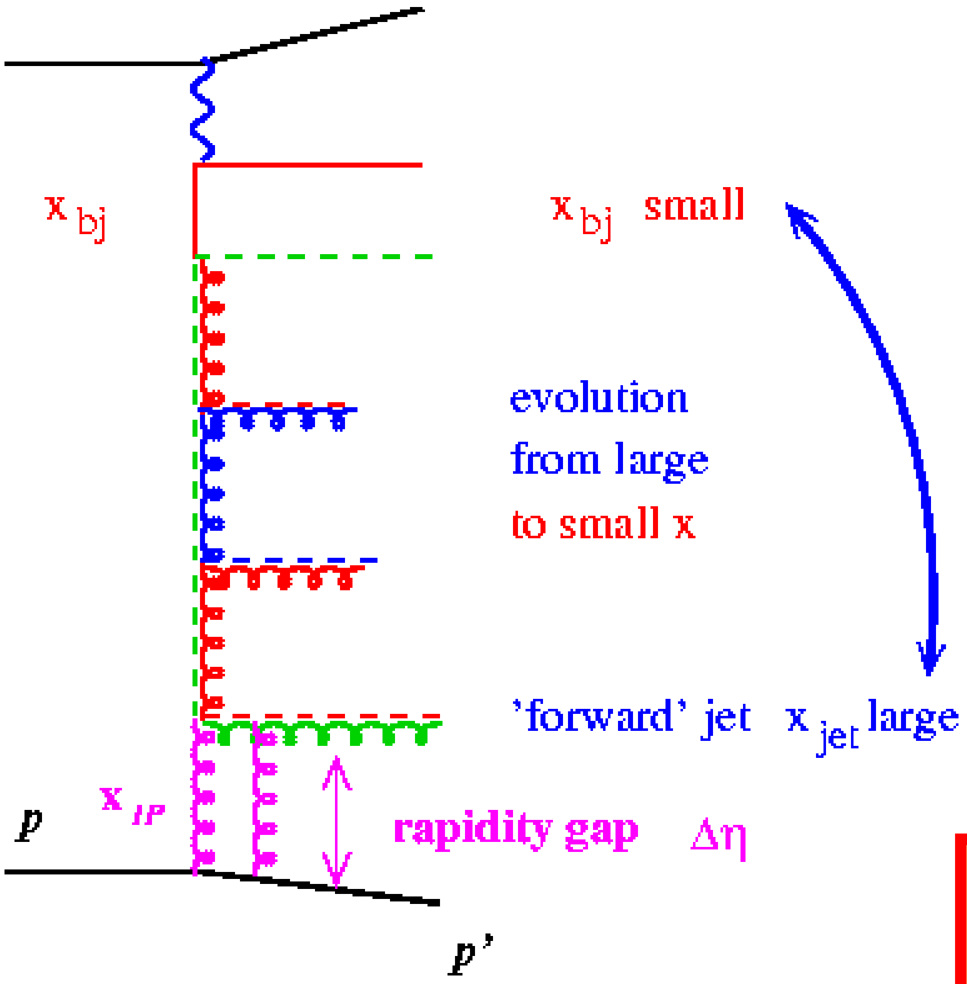
  $1.7 < \eta_{jet} < 2.8$

  $x_{jet} > 0.035$

  $0.5 < \frac{p_{t\ jet}^2}{Q^2} < 5$

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

forward jet production and diffraction

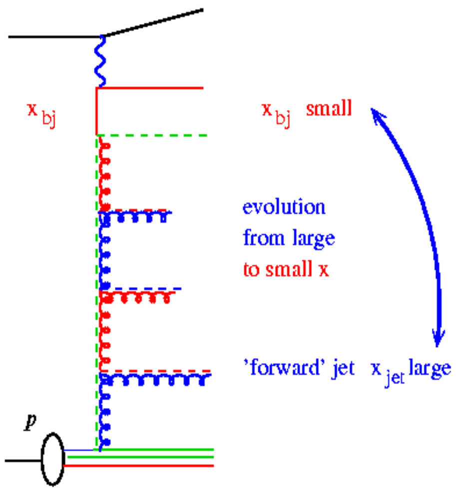


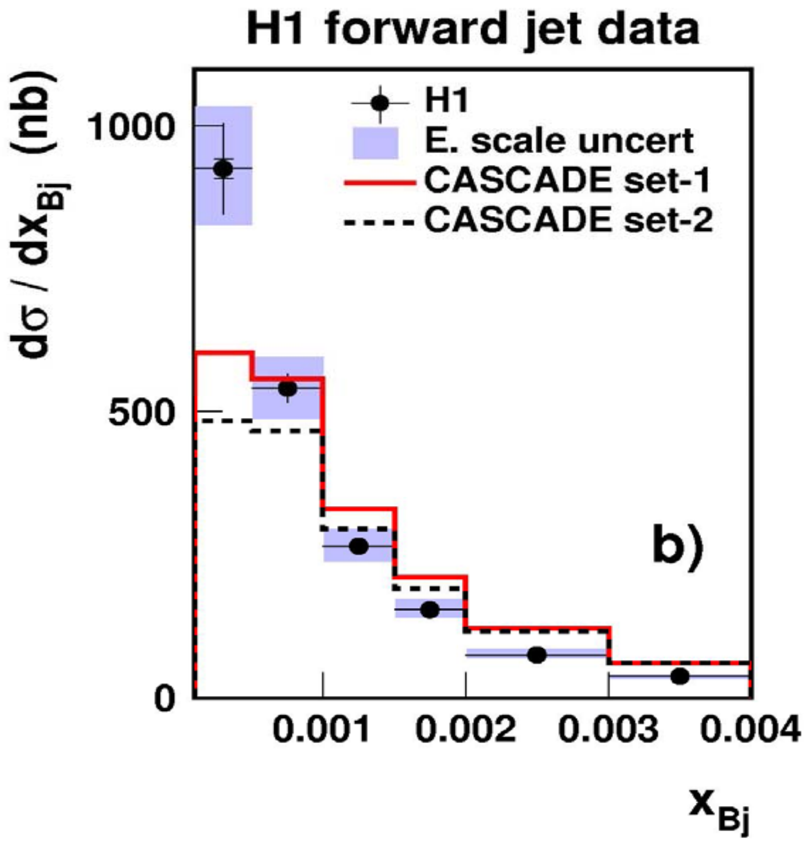
- DIS and forward jet:
  $1.7 < \eta_{jet} < 2.8$
  $x_{jet} > 0.035$
  $0.5 < \frac{p^2_{t\ jet}}{Q^2} < 5$
  $\sigma(\text{fwd jet})/\sigma(\text{DIS}) \sim 1\%$

- 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
- is DGLAP parton radiation enough ? or is BFKL or CCFM needed ?

forward jet production





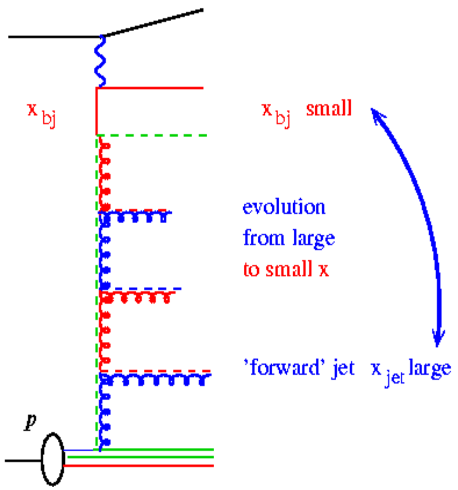
- DIS and forward jet:
  $1.7 < \eta_{jet} < 2.8$

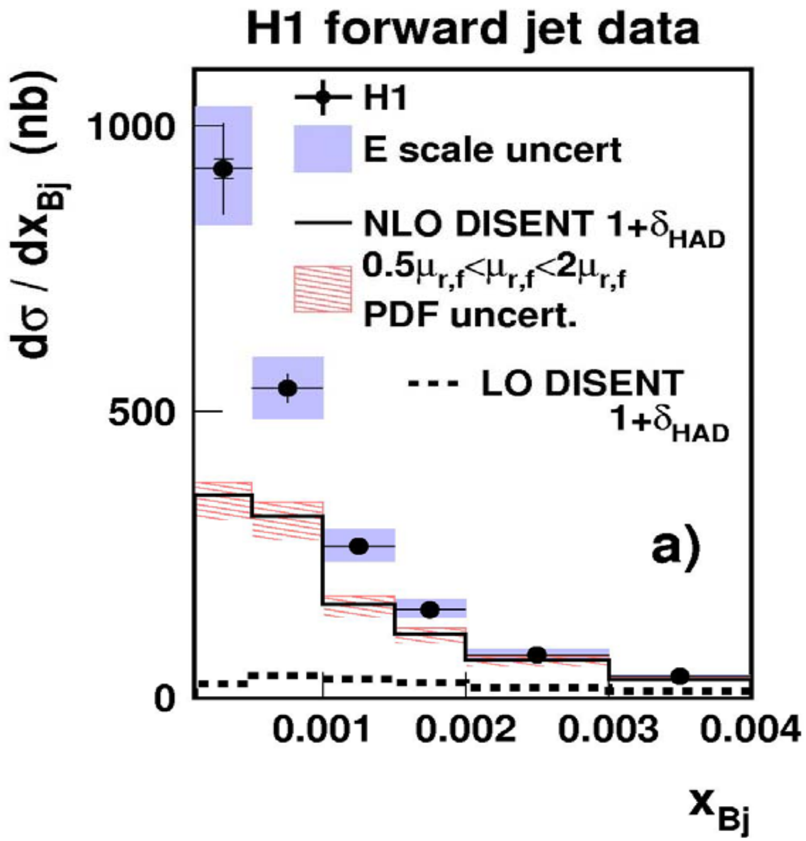
  $x_{jet} > 0.035$

  $0.5 < \frac{p_{t\,jet}^2}{Q^2} < 5$

- **CASCADE (CCFM) evolution closer to data**

forward jet production





- DIS and forward jet:

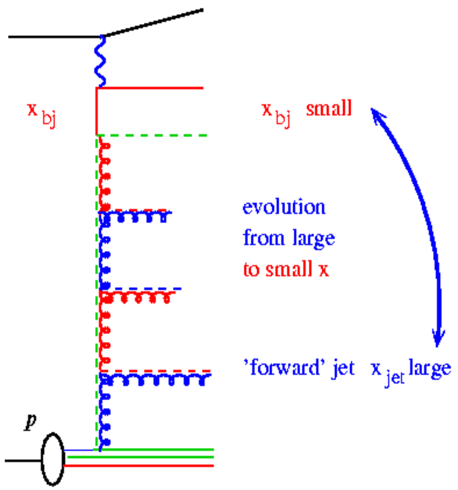
$$1.7 < \eta_{jet} < 2.8$$

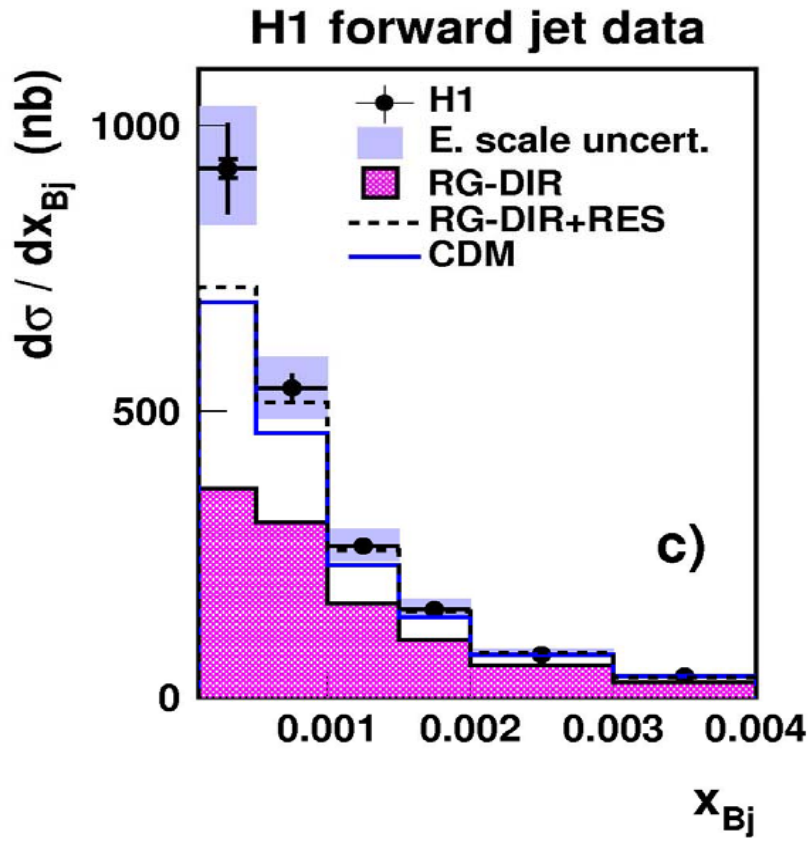
$$x_{jet} > 0.035$$

$$0.5 < \frac{p_{t\ jet}^2}{Q^2} < 5$$

- **"NLO" too low**

forward jet production





- DIS and forward jet:
  $1.7 < \eta_{jet} < 2.8$

  $x_{jet} > 0.035$

  $0.5 < \frac{p_t^2 \; jet}{Q^2} < 5$

resolved virtual photon picture and CDM best !!!

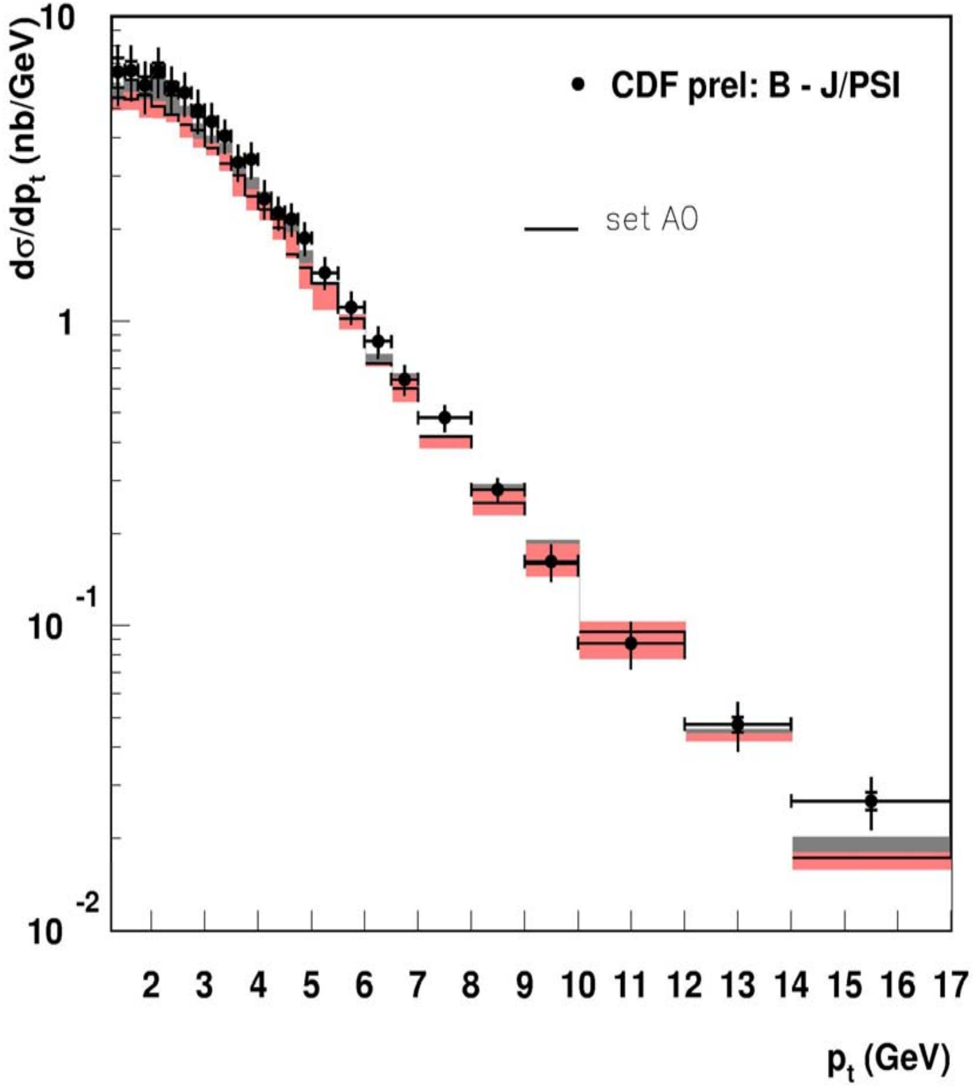
- **details of parton cascade still not well understood ...**

Bottom at TeVatron

- bottom xsection at CDF

	$\sigma(b, \|y\| < 1)$
CASCADE	$24.95\ \mu b$
Cacciari et al (FONLL)	$23.6\ \mu b$
CDF	$24.9 \pm 0.6 \pm 6.2\ \mu b$

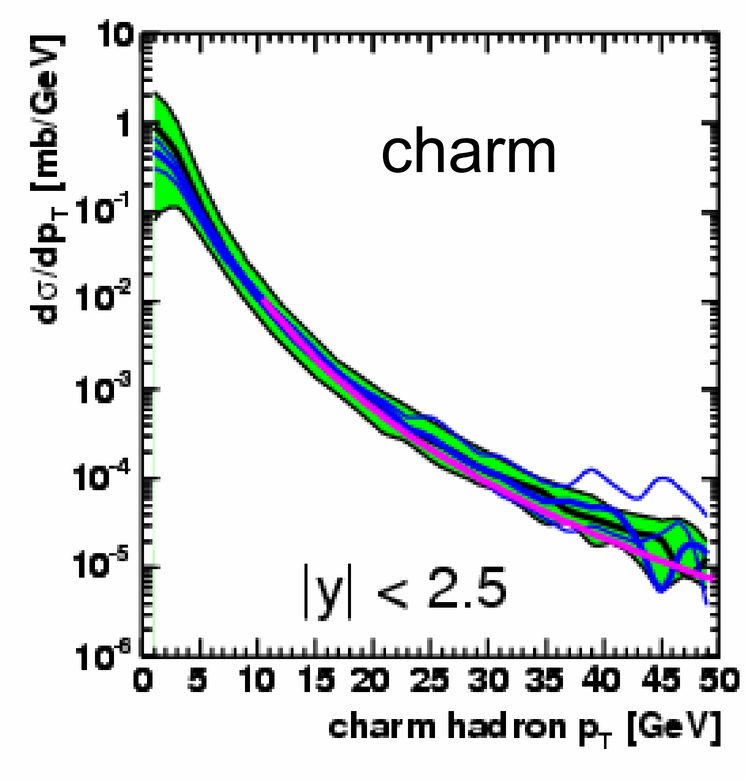
	$\sigma(b, \|y\| < 0.6)$ $BR(B \to J/\psi \to \mu)$
CASCADE	$17.2\ nb$
... with PYTHIA BR	$15.2 nb$
MC@NLO	$17.2\ nb$
Cacciari et al (FONLL)	$19.0^{+8.4}_{-6.0}\ nb$
CDF	$19.9^{+3.8}_{-3.2}\ nb$



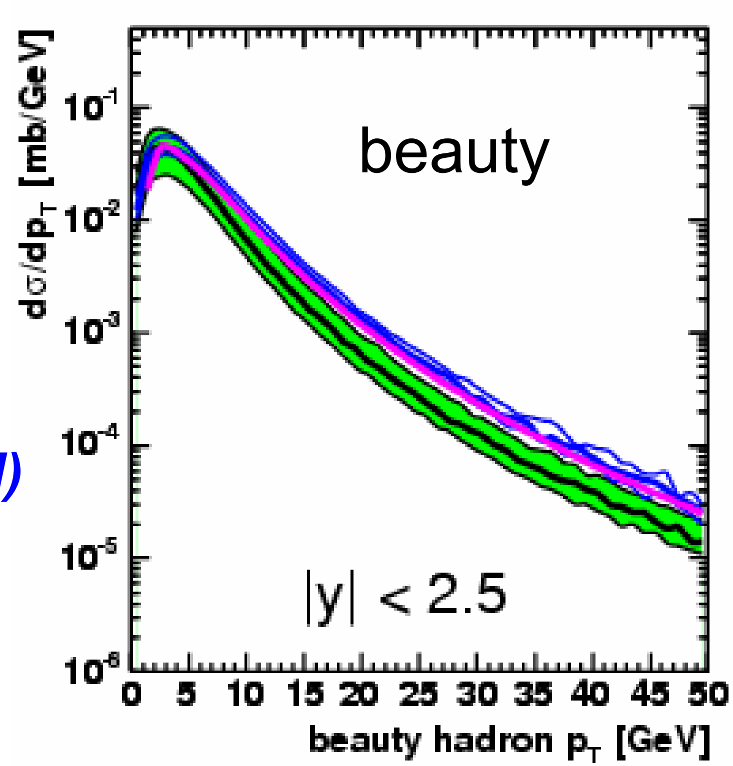
- Remarkable agreement CASCADE and MC@NLO
- Good agreement CASCADE and FONLL

charm and beauty at the LHC

MNR (massive NLO) – FONLL (matched NLL) – CASCADE (uPDF)



MNR band
FONLL central
CASCADE (CCFM)



- CASCADE agrees perfectly well with FONLL
- uPDFs at similar level with NLO+resummed
- uPDFs better than pure NLO

CASCADE: H.Jung and G.P.Salam, Eur.Phys.J. **C19** (2001) 351

M.Cacciari, H.Jung, K.Peters, A.Dainese

Advantage of u-pdfs

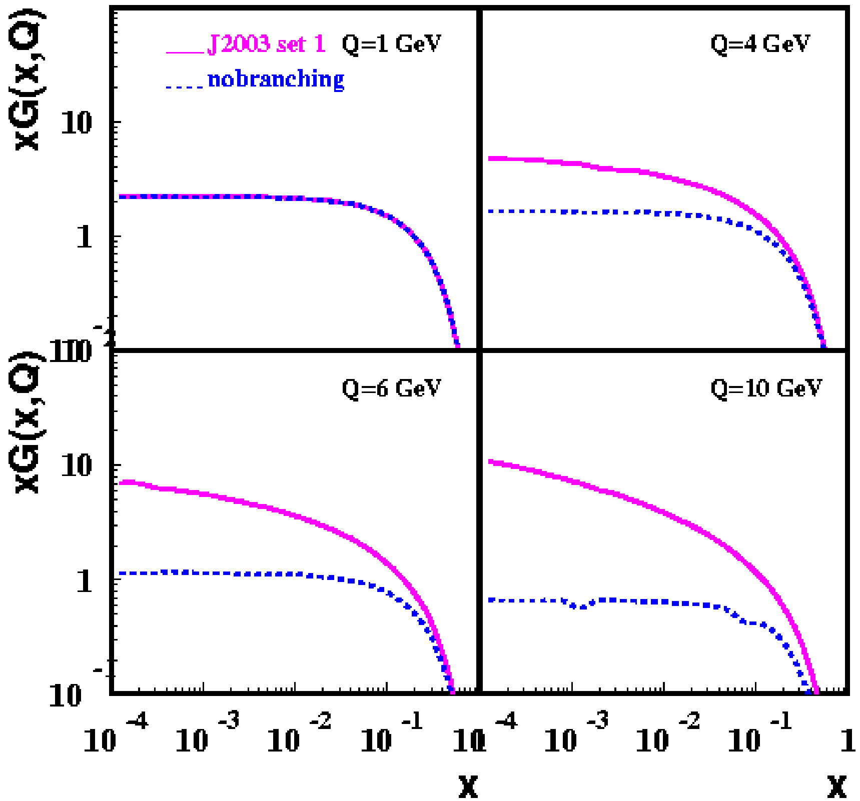
$$\mathcal{A}(x,k_t,\bar{q}) = \mathcal{A}_0(x,k_t)\Delta_s(\bar{q},Q_0) + \int \frac{dz}{z}\frac{d^2q}{q^2}\Delta_s(\bar{q},zq)\cdot\tilde{P}(z,\ldots)\mathcal{A}\left(\frac{x}{z},k_t',q\right)$$

integrated pdf:

- ***effect of evolution and initial condition***
- ***not clearly separated***

where is:

- small k_t region
- saturation region

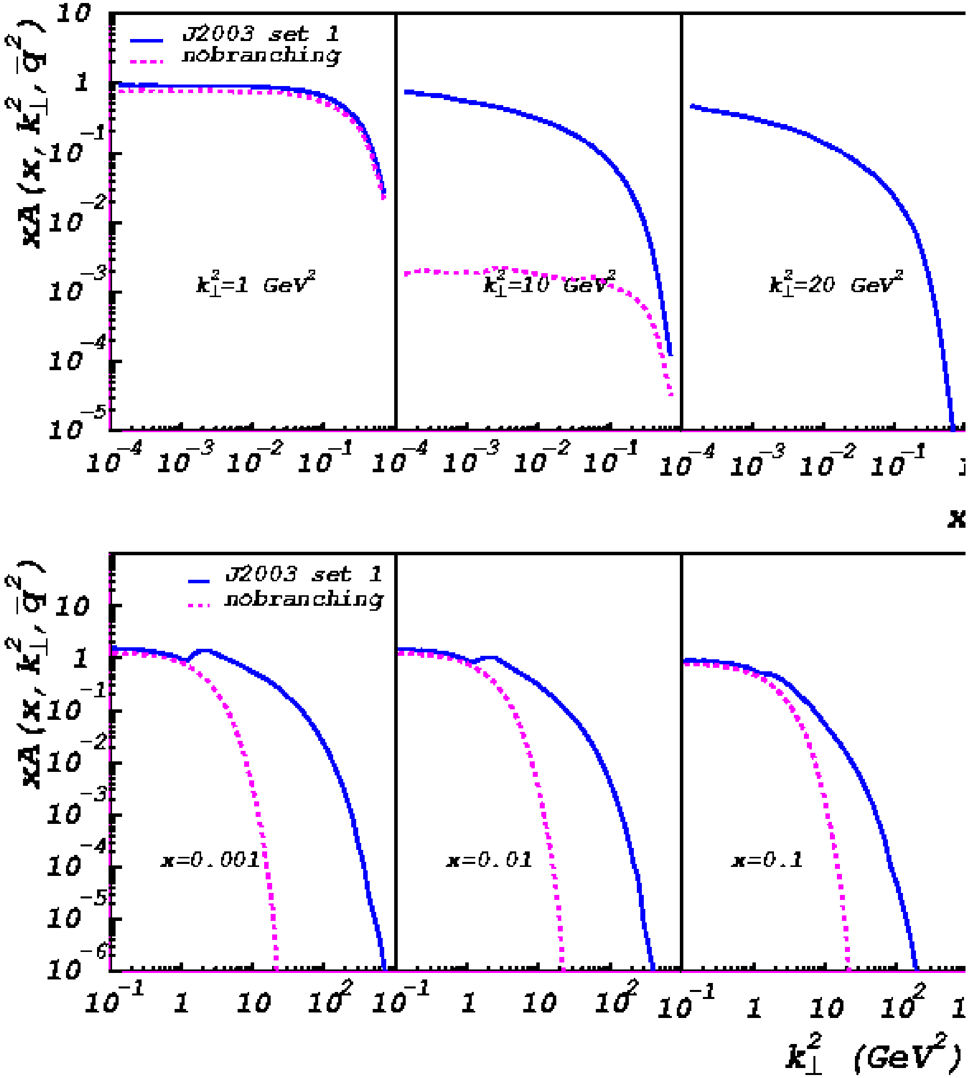


Advantage of uPDFs

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

Advantage of uPDF:

- *initial condition clearly seen in small k_t region*
- *even at large scales q*

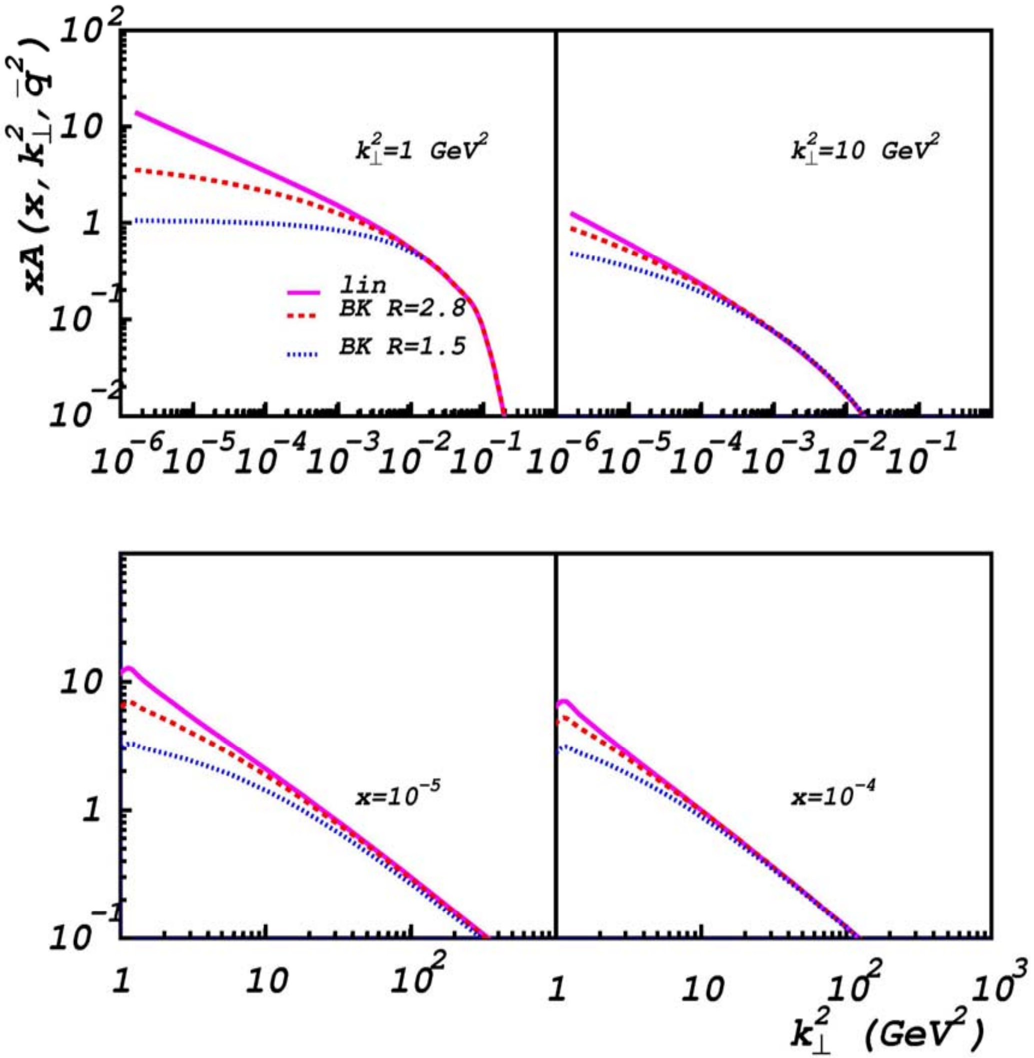


Non-linear effects in uPDFs

Advantage of uPDF:

- *non-linear effects come at* $k_t < Q_s$
- **onset of non-linear effects clearly visible**
- **BUT:**

  in region where non-linear are large, expect breaking of kt-factorisation



Non-linear effects at LHC

Nonlinear evolution equation for unintegrated gluon distribution.

$$f(x,k^2) = \tilde{f}^{(0)}(x,k^2) + K^1 \otimes f - K^2 \otimes f^2$$

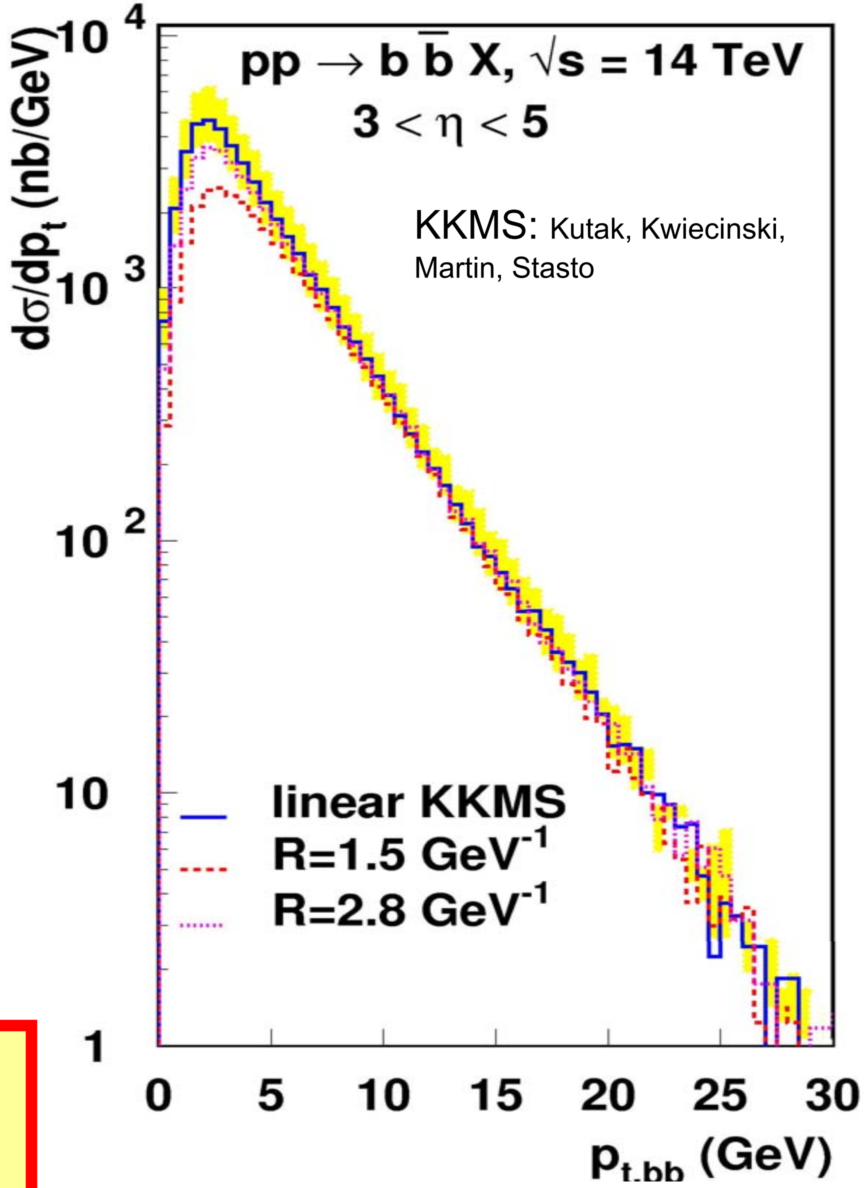
$$\tilde{f}^{(0)}(x,k^2) \longrightarrow \text{input}$$

$$K^1 \otimes f \rightarrow \text{BFKL}$$

$$K^2 \otimes f^2 = \left(1 - k^2 \frac{d}{dk^2}\right)^2 \frac{k^2}{R^2} \times$$

$$\int_x^1 \frac{dz}{z} \left[\int_{k^2}^{\infty} \frac{dk'^2}{k'^4} \alpha_s(k'^2) ln \left(\frac{k'^2}{k^2}\right) f(z,k'^2)\right]^2$$

Bottom suppression due to non-linear effects in BK



- Significant effects...
- up to factor of 2 in hot spot scenario
- factorization still ok ?

Conclusions

- challenge to describe final states in detail
- simple collinear factorisation approach can lead to wrong results even at NLO for special differential observables
  - proper treatment of kinematics very important (as usual)
- need for fully unintegrated PDFs
  - *needed for consistent calculations*
    - *theoretical work progressing*
  - k_t effects important for proper simulation of hadronic final state
  - k_t factorisation with CCFM gives results consistent with NLO + resumm., only much simpler
- detailed understanding of parton cascade is still challenging
  - small x effects - saturation important for proper xsection estimates
- most of effects can be studied and tested at HERA
- important for extrapolation to cosmic energies but also for LHC