CASCADE and small x final states

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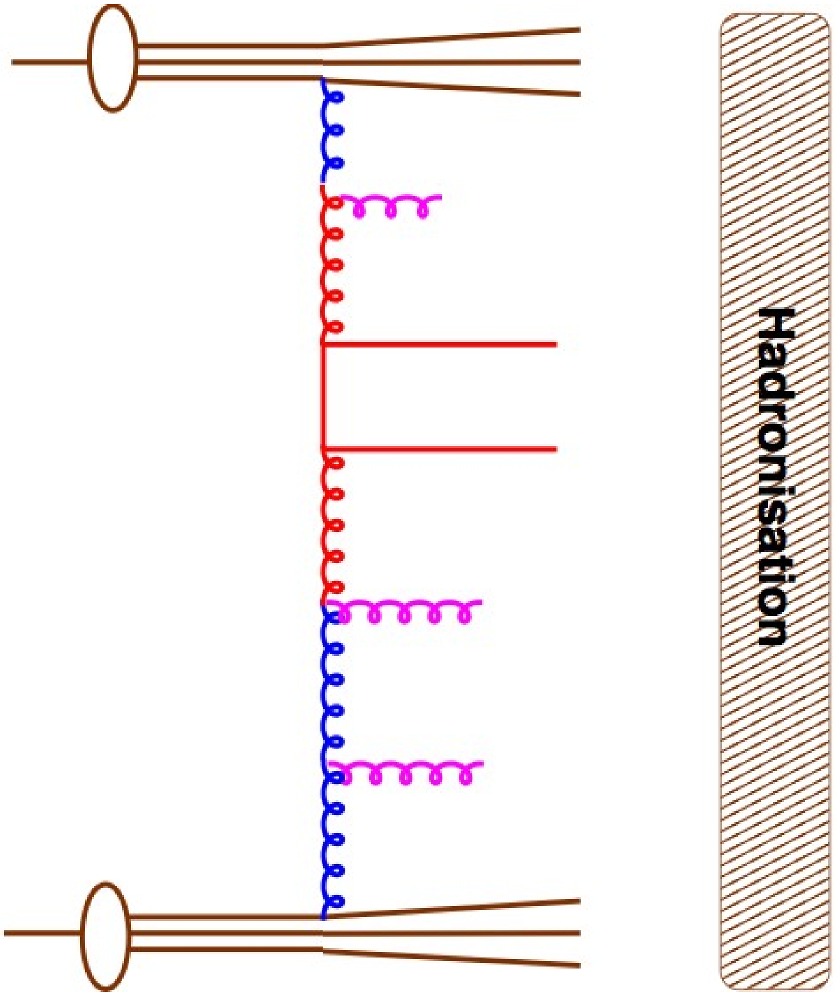
- basics of the CASCADE MC generator
  - matrix elements and uPDFs
- the small x hadronic final state
  - Onium production
  - forward DY
  - forward jets

CASCADE basic elements

- CASCADE elements are:
  - Matrix Elements:
    - ➔ on shell/off shell
  - PDFs
    - ➔ unintegrated PDFs
  - Parton Shower
    - ➔ angular ordering (CCFM)
- Proton remnant, final state PS and hadronization handled by standard hadronization program: **PYTHIA**



$$\sigma(pp \to q\bar{q} + X) = \int \frac{dx_{g1}}{x_{g1}} \frac{dx_{g2}}{x_{g2}} \int d^2 k_{t1} d^2 k_{t2} \hat{\sigma}(\hat{s}, k_t, \bar{q}) \times x_{g1} \mathcal{A}(x_{g1}, k_{t1}, \bar{q}) x_{g2} \mathcal{A}(x_{g2}, k_{t2}, \bar{q})$$

Which uPDFs ? CCFM approach

- Color coherence requires angular ordering instead of p_t ordering ...

$$q_i > z_{i-1} q_{i-1} \quad \text{with} \quad q_i = \frac{p_{ti}}{1 - z_i}$$

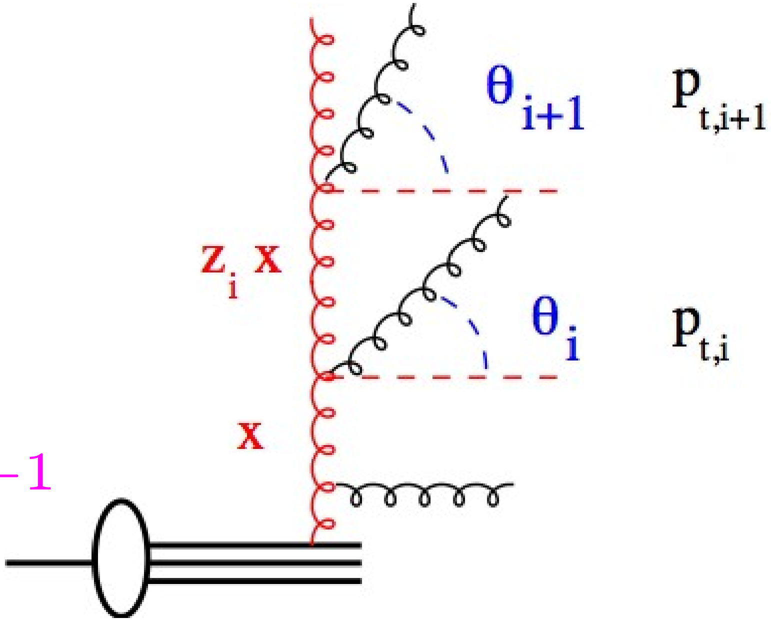
➔ recover DGLAP with q ordering

at medium and large x

➔ at small x, no restriction on q

p_{ti} can perform a random walk

➔ NOTE: HERWIG uses $q_i > q_{i-1}$



➔ CataniCiafaloniFioraniMarchesini evolution forms a bridge between DGLAP and BFKL evolution

➔ important for comparison with collinear NLO calculations ...

uPDF fit to F_2: x-dependence

- $$\chi^2 = \sum_i \left(\frac{(T-D)^2}{\sigma_i^{2\ stat} + \sigma_i^{2\ uncor}} \right)$$
- fit parameters of starting distributic

  $$x\mathcal{A}_0(x,\mu_0) = N x^{-B_g} \cdot (1-x)^4$$
- using F_2 data H1

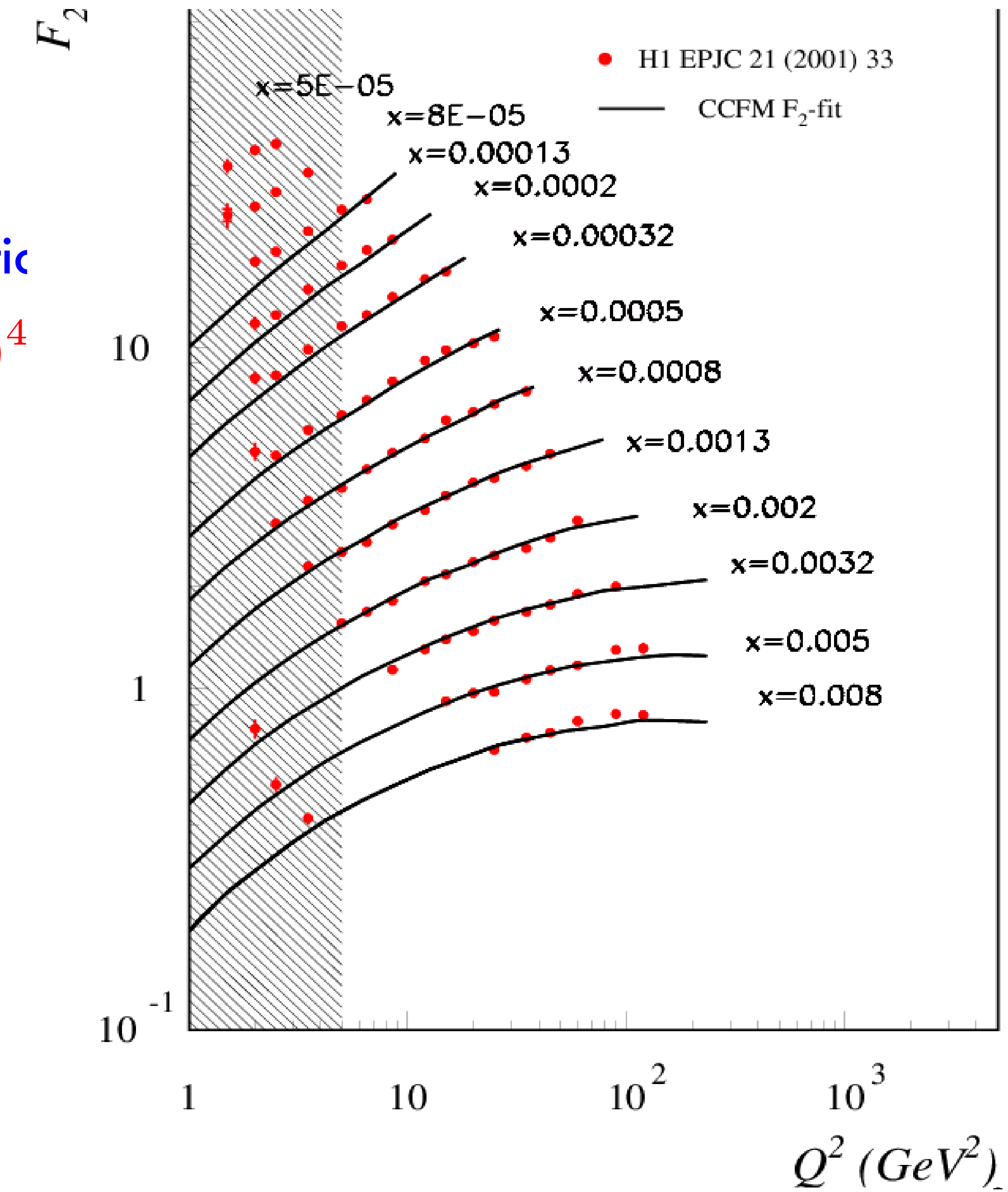
  (H1 Eur. Phys. J. C21 (2001) 33-61, DESY 00-181)

  $$x < 0.05 \quad Q^2 > 5\ \mathrm{GeV}^2$$
- parameters: $\mu_r^2 = p_t^2 + m_{q,Q}^2$

  $$m_q = 250\ \mathrm{MeV}, m_c = 1.5\ \mathrm{GeV}$$
- Fit (only stat+uncorr):

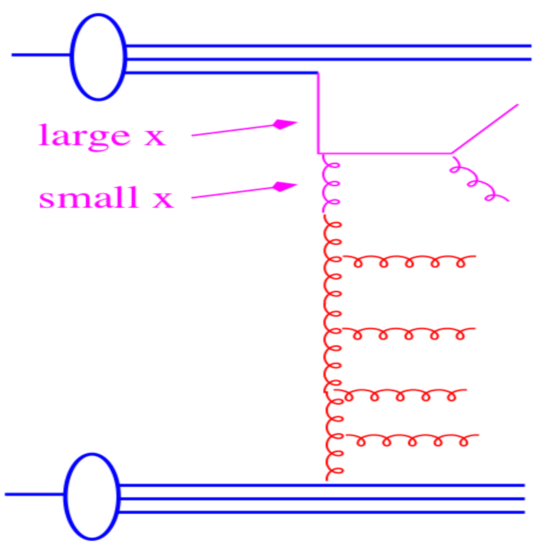
  $$\frac{\chi^2}{\mathrm{ndf}} = \frac{111.8}{61} = 1.83$$

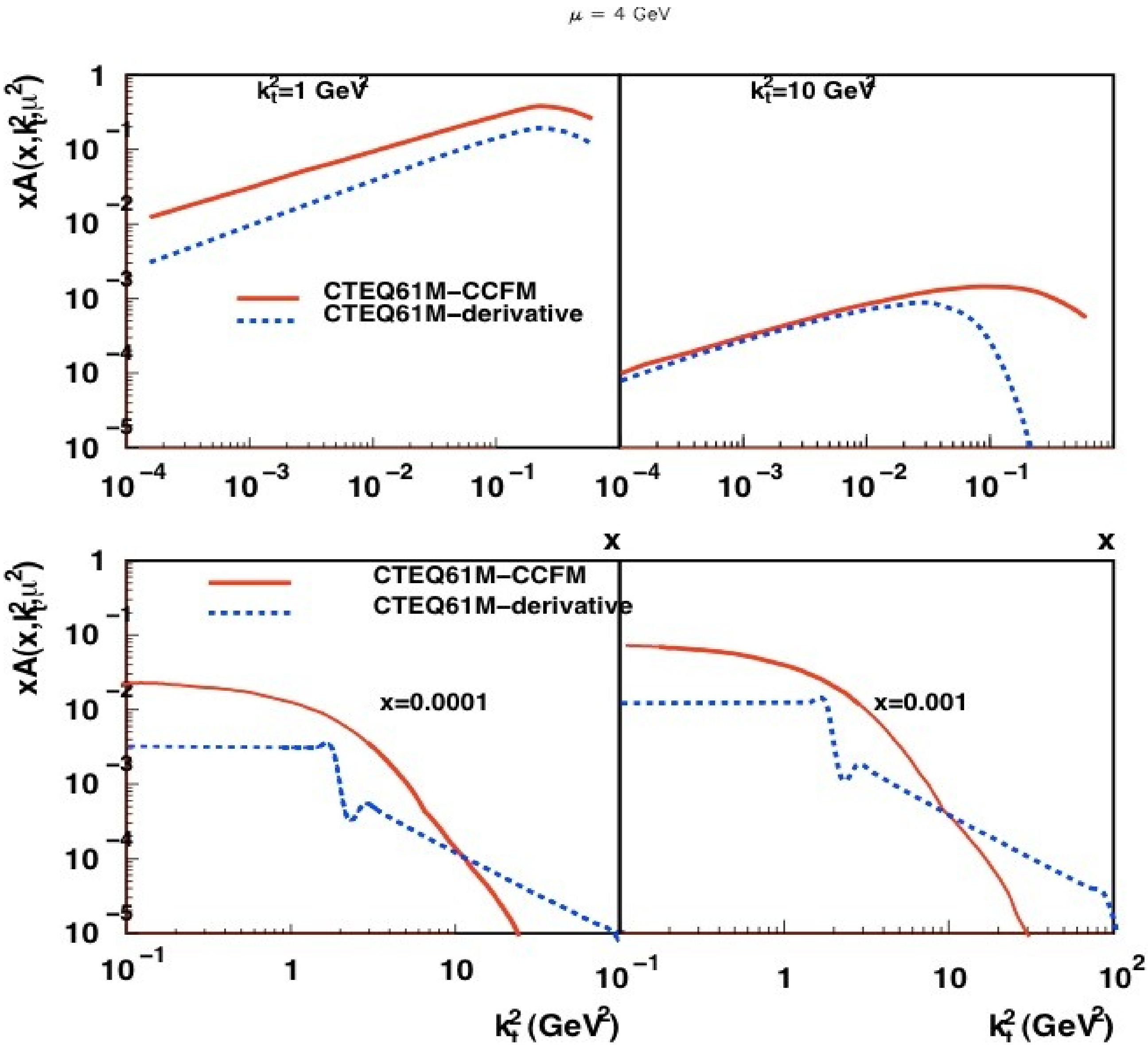
  $$B_g = 0.028 \pm 0.003$$



Including valence quarks

- unintegrated valence quarks:
  - ➔ use CTEQ61 as initial condition
  - ➔ evolve with "CCFM-type" splitting function
  - ➔ needed for:





uPDF fits: prospects

- new unintegrated gluon determination in progress (A. Knutsson)
  - using latest precise HERA (H1 + ZEUS combined) F_2 measurements
  - including full treatment of experimental systematic uncertainties
    - ➔ uPDF uncertainty sets, ala CTEQ
  - using more flexible starting distribution

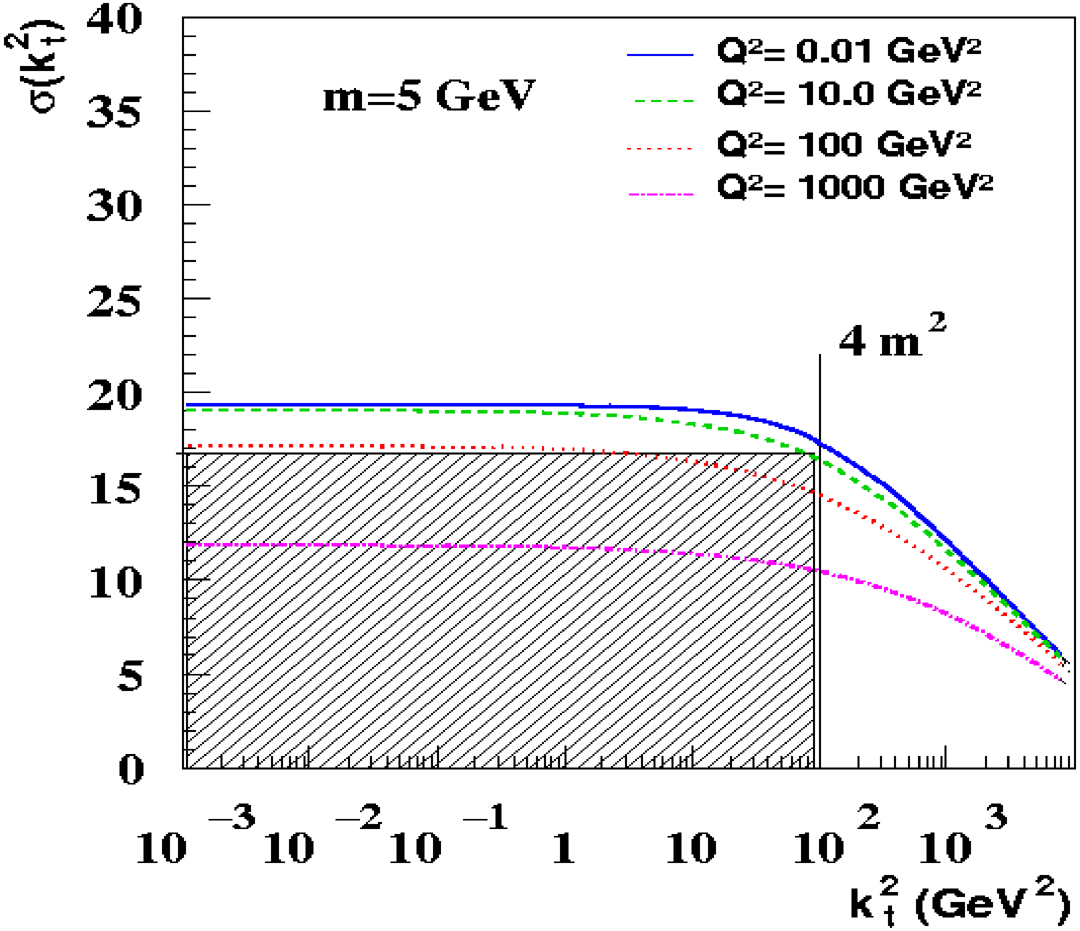
➔ to be ready for DIS (April 2010) !!!!!

Why off-shell matrix elements ?

- Example: $\gamma^* g \to Q\bar{Q}$
  - ME is finite for $k_\perp \to 0$
  - ME has tail to large k_t
- collinear factorization:
  - integration over k_t

$$\int_0^{\mu^2} dk_\perp \hat{\sigma}(k_\perp, ...)$$

up to $\mu^2 \sim 4m^2$



off-shell matrix elements for ep

- ep

$$\begin{aligned} \gamma g^* &\rightarrow q\bar{q} \\ \gamma^* g^* &\rightarrow Q\bar{Q} \\ \gamma g^* &\rightarrow J/\psi g \end{aligned}$$

at HERA tested well !!!

- inclusive cross section
- DIS and γp
  - particle spectra
  - jet production
  - heavy quarks

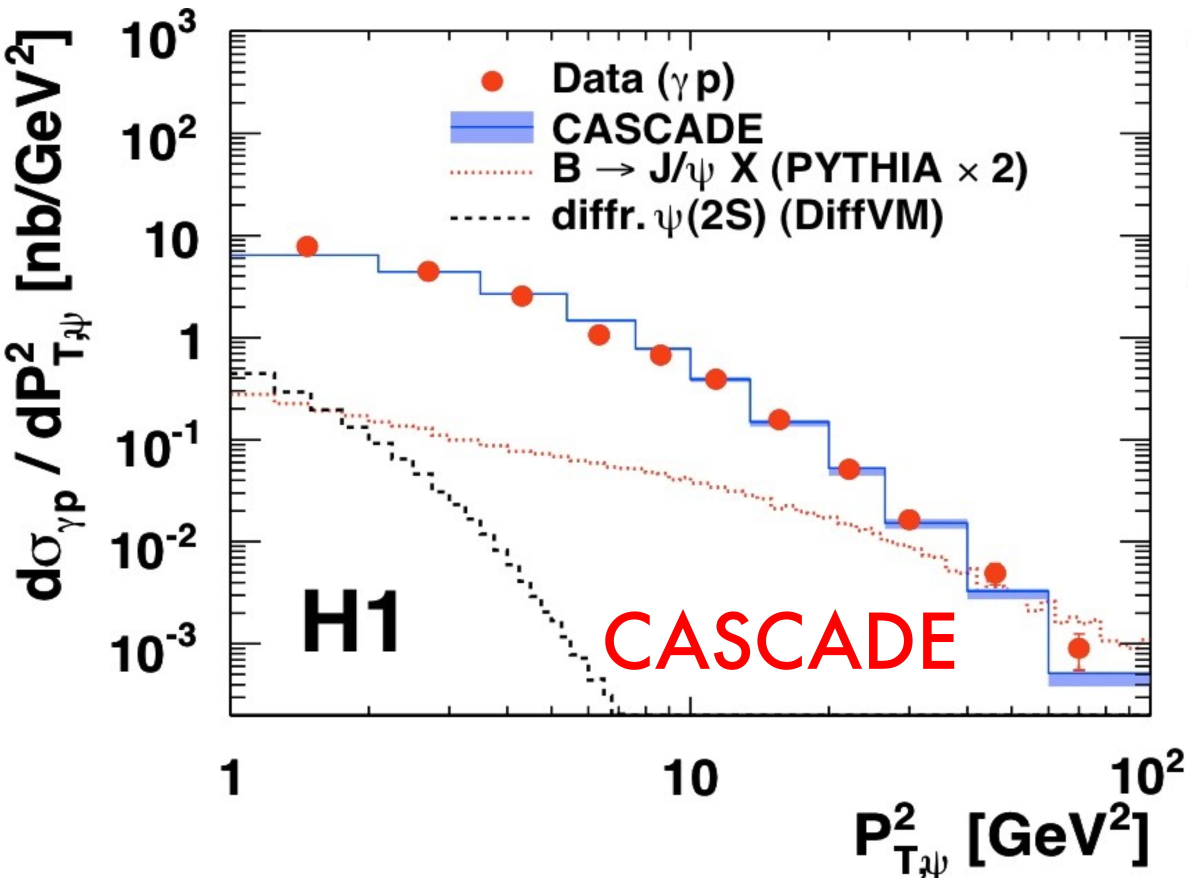
off-shell matrix elements for ep

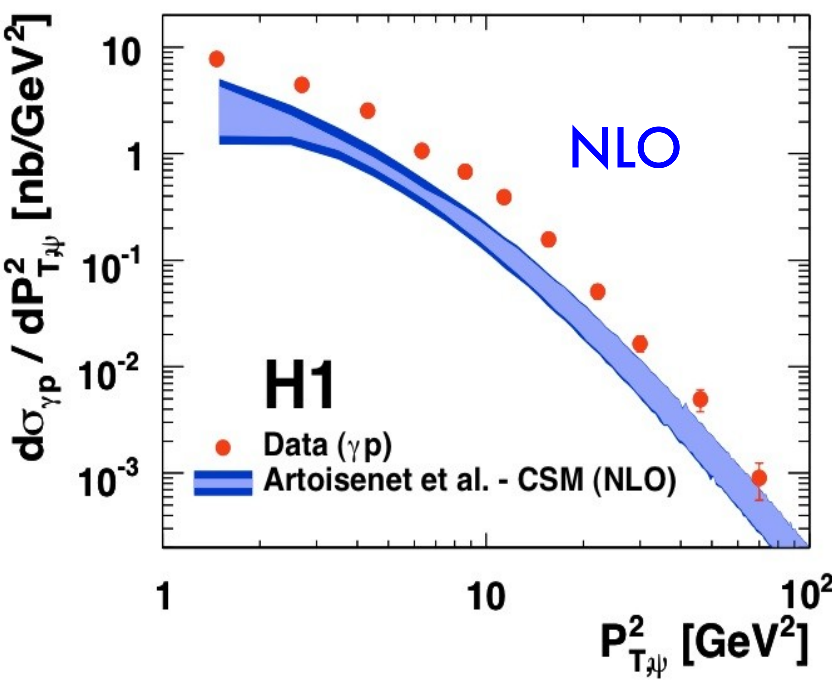
- ep

$$\gamma g^* \rightarrow q\bar{q}$$
$$\gamma^* g^* \rightarrow Q\bar{Q}$$
$$\gamma g^* \rightarrow J/\psi g$$

at HERA tested well !!!

example: J/ψ





off-shell matrix elements for pp

- heavy quarks

$$g^* g^* \rightarrow Q\bar{Q}$$

$$g^* g^* \rightarrow J/\psi g$$

$$g^* g^* \rightarrow \chi_c$$

HQ at TeVatron tested !!!
...overview by M. Kraemer at DIS 2010

NEW

- Gauge boson & Higgs

$$g^* g^* \rightarrow h$$

$$g^* g^* \rightarrow Z + Q\bar{Q}$$

$$g^* g^* \rightarrow W + q_i q_j$$

$$q g^* \rightarrow Zq$$

NEW

- QCD processes – forward jets

$$g^* g^* \rightarrow q\bar{q}$$

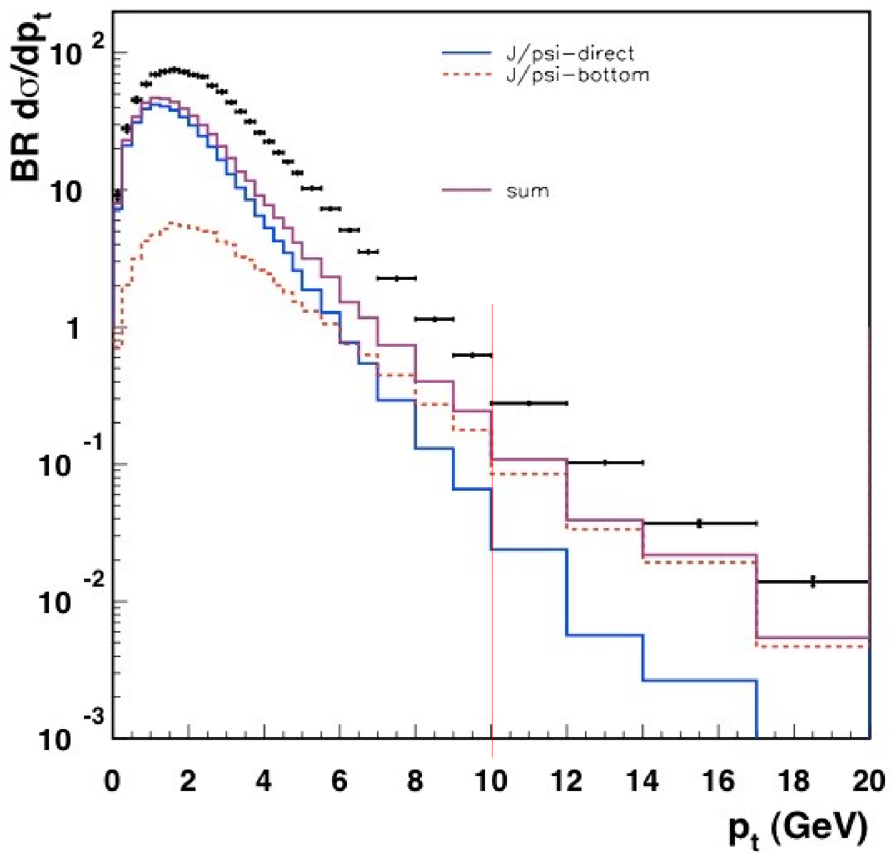
$$q g^* \rightarrow qg$$

$$g g^* \rightarrow gg$$

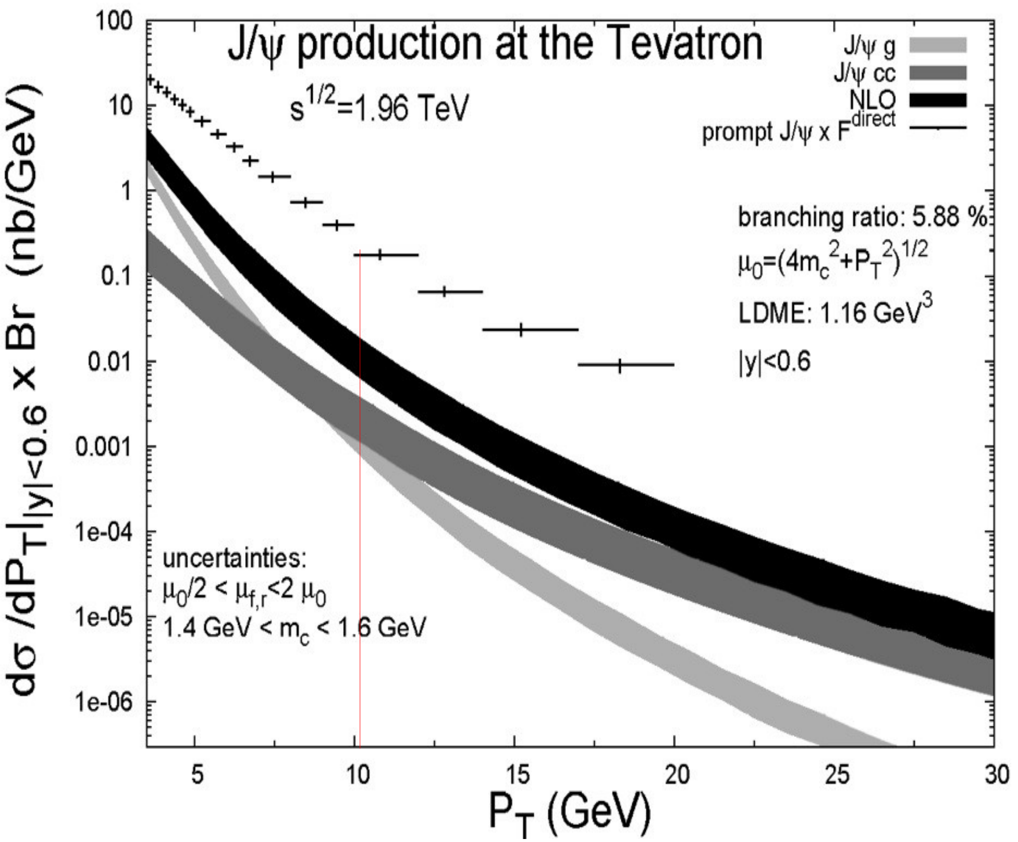
NEW

inelastic J/psi production

- **off-shell matrix element**
  (S. P. Baranov. Highlights from the kT factorization approach on the quarkonium production puzzles. *Phys. Rev.*, D66:114003, 2002.)

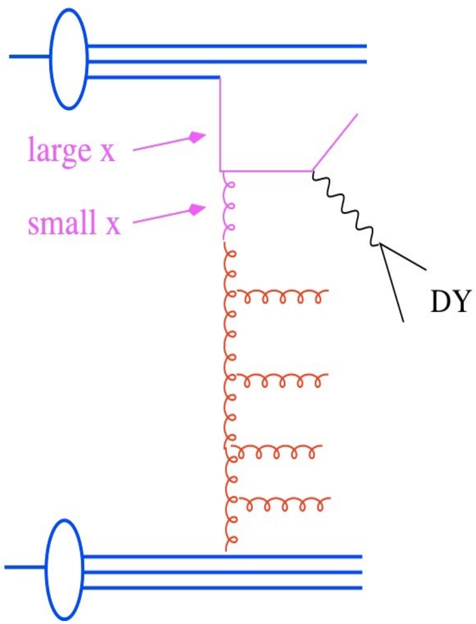


- **NLO calculation**
  (QCD corrections to heavy quarkonium production. P. Artoisenet, AIP Conf.Proc.1038:55-62,2008.)



➔ **even in CSM much closer to data than in collinear NLO**

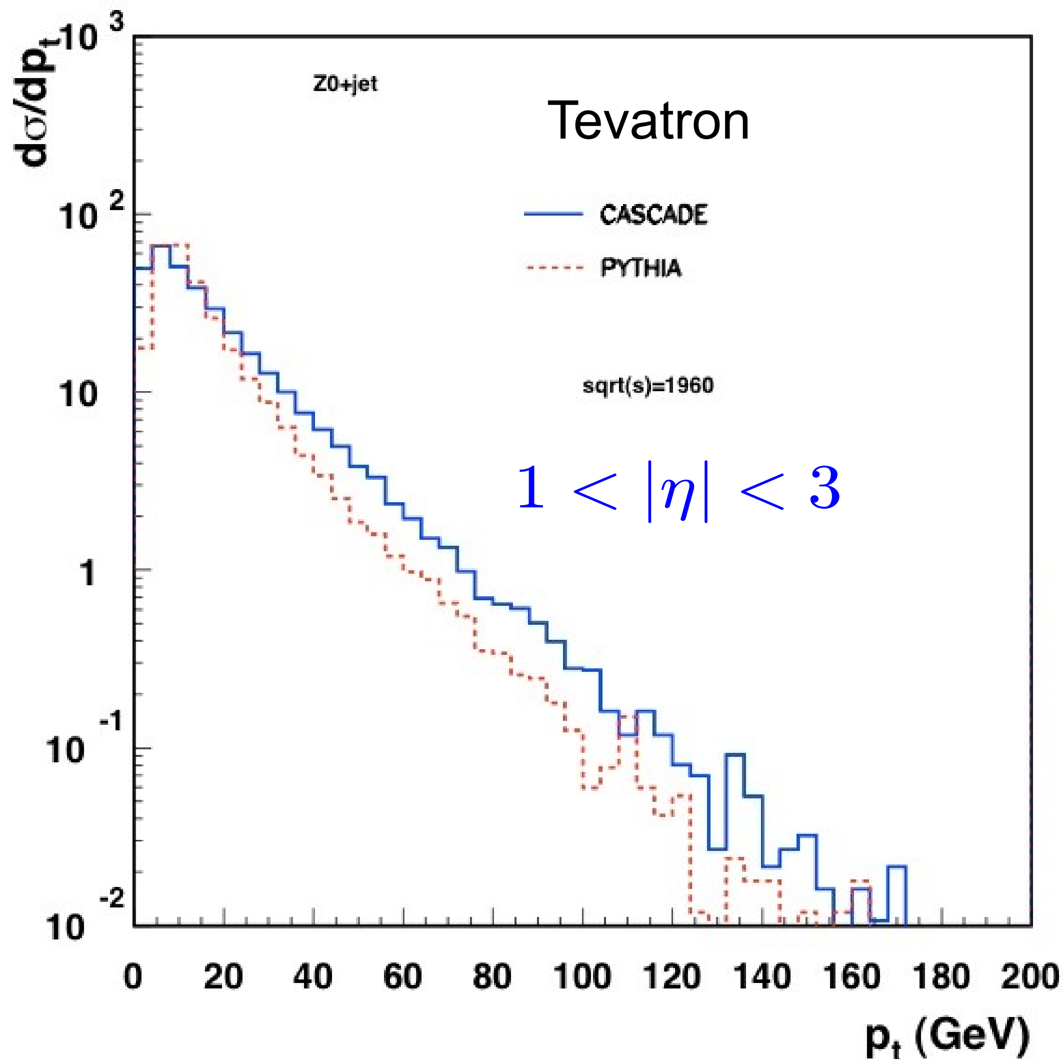
forward DY production



$$qg^* \quad \rightarrow \quad Zq$$

- forward DY production
- (S. Marzani and R. D. Ball. High Energy Resummation of Drell Ya Processes, Nucl Phys B814:246-264, 2009

by F. Hautmann, A. Dafinca



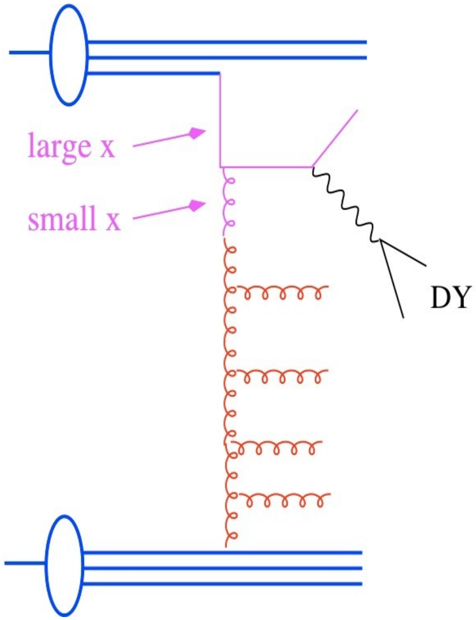
- need un-integrated quark distribution
- look into forward region

$1 < |\eta| < 3$ for TeVatron

$3 < |\eta| < 5$ for LHC

➔ larger high p_t tail compared to PYTHIA

forward DY production



$qg^* \rightarrow Zq$

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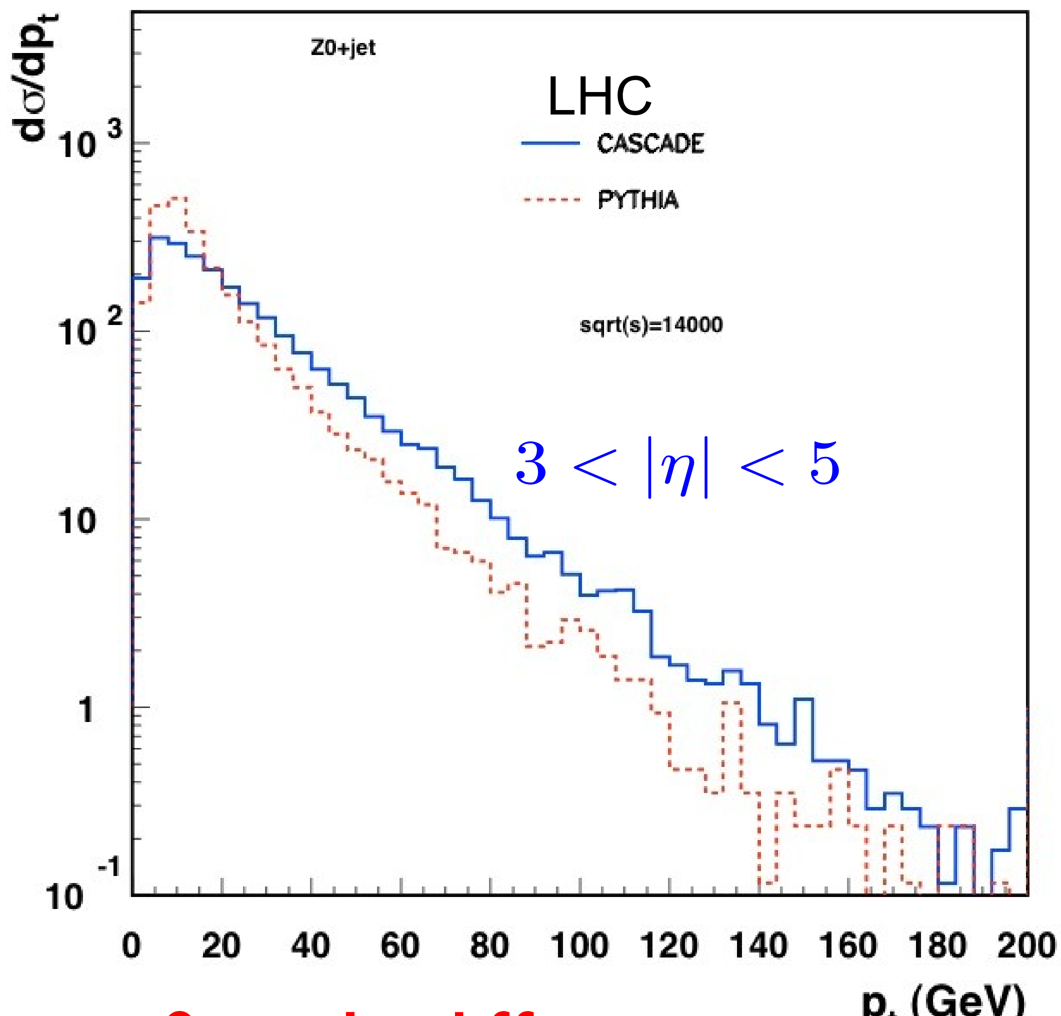


- need un-integrated quark distribution
- look into forward region

$1 < |\eta| < 3$ for TeVatron

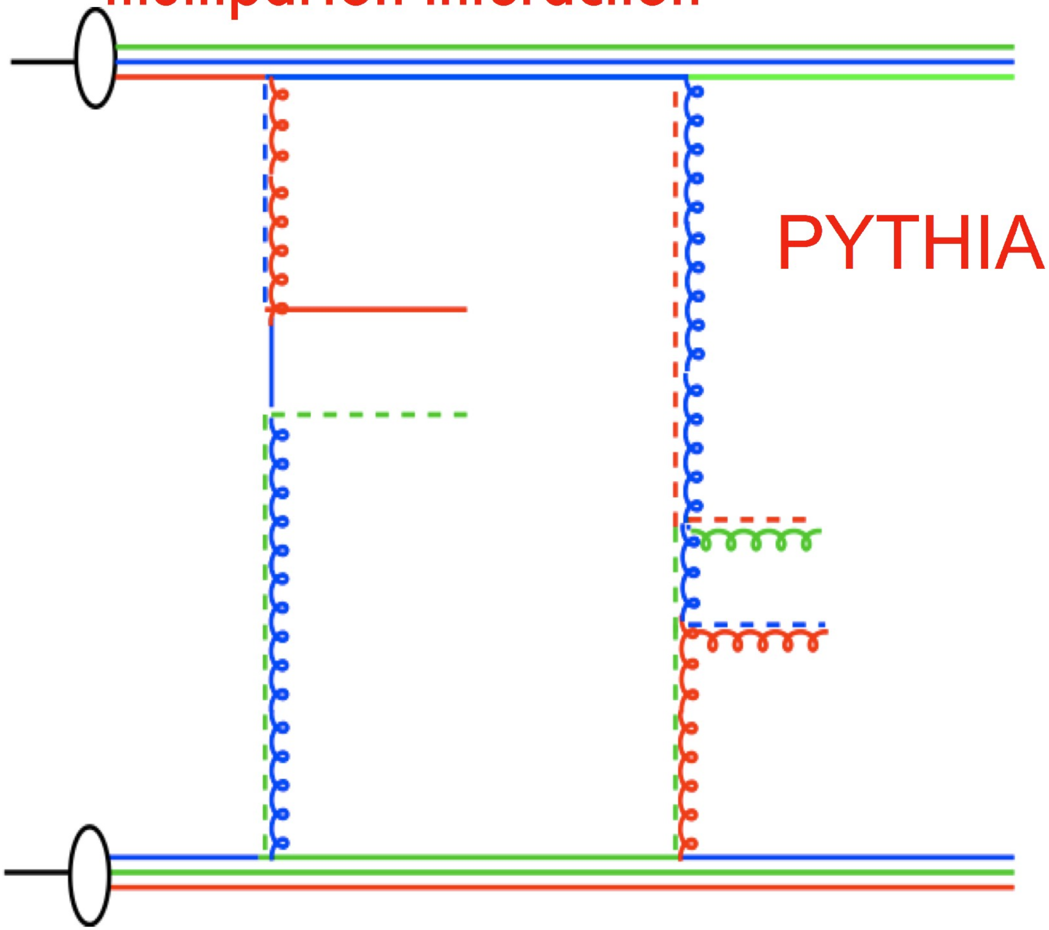
$3 < |\eta| < 5$ for LHC ➔ significantly different spectrum compared to PYTHIA

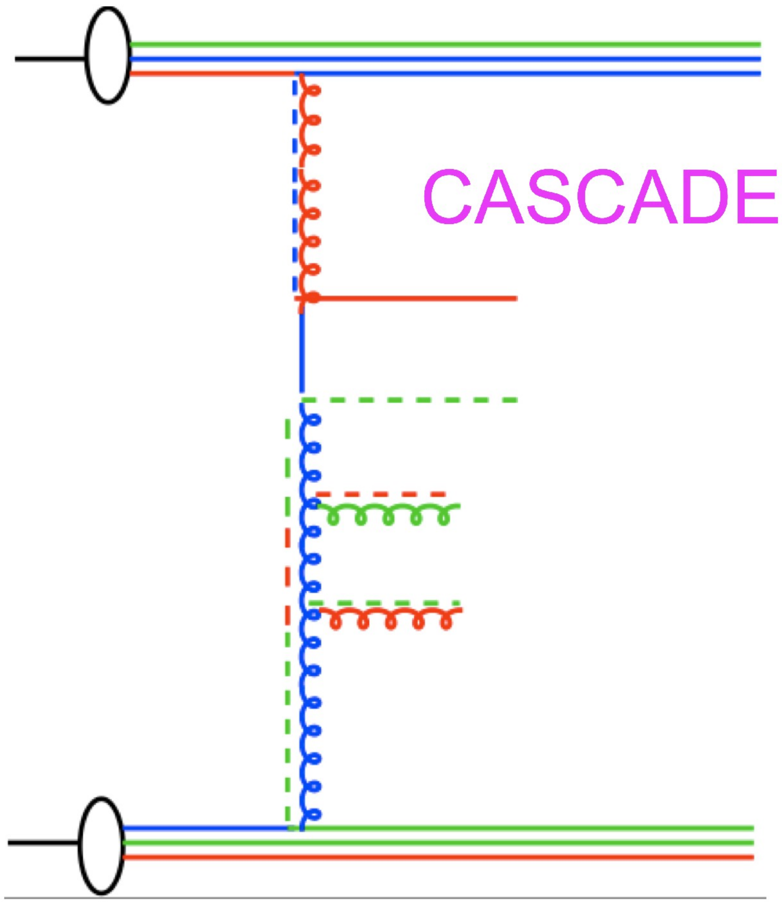
How well do we know parton radiation in forward region ?

- parton radiation in forward region:

multiparton interaction

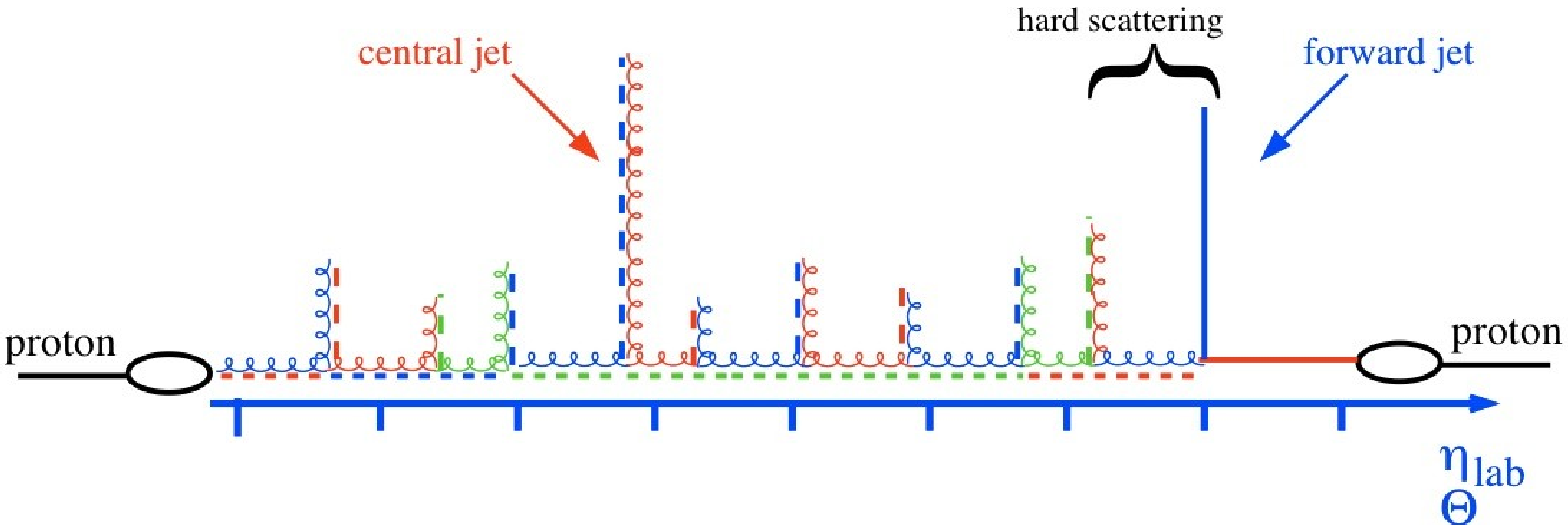
single chain at small x





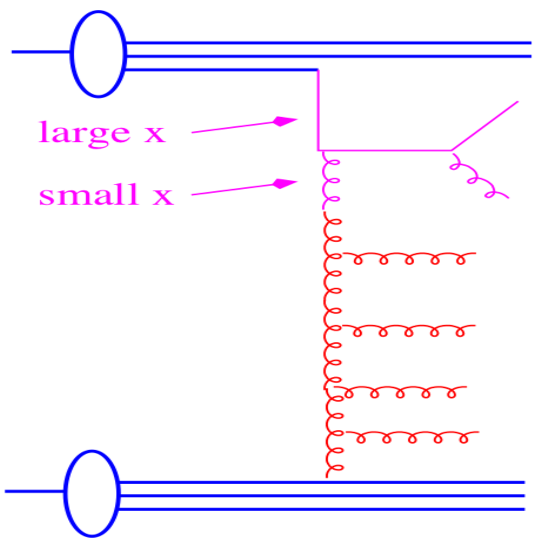
- which of the two is correct or are they both describing the same ... ???

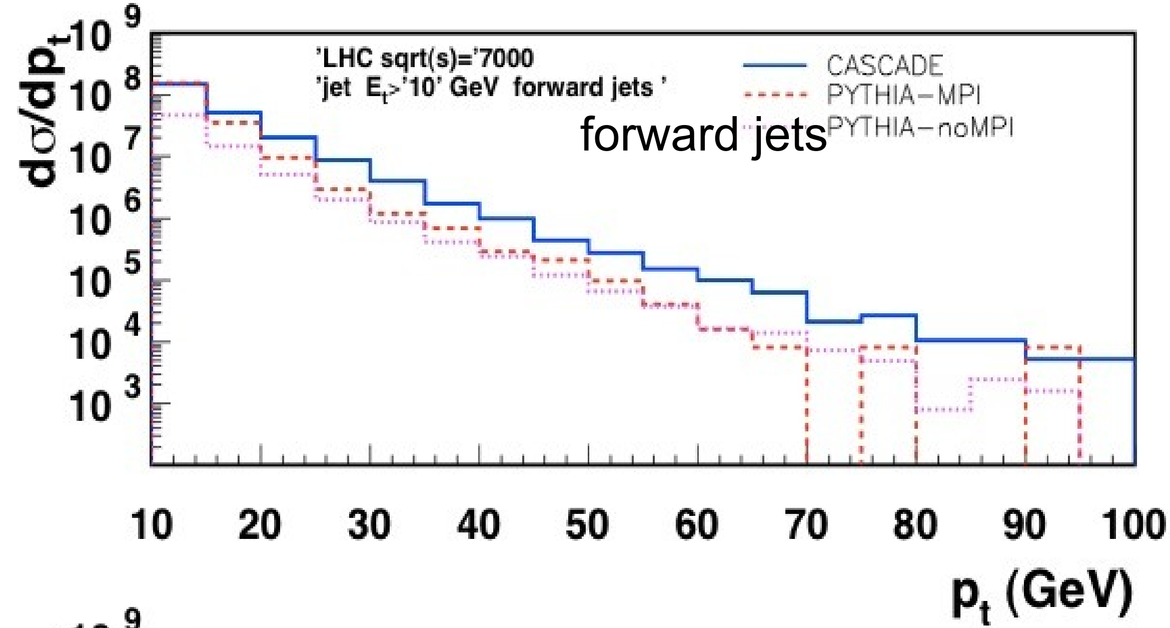
forward jet production

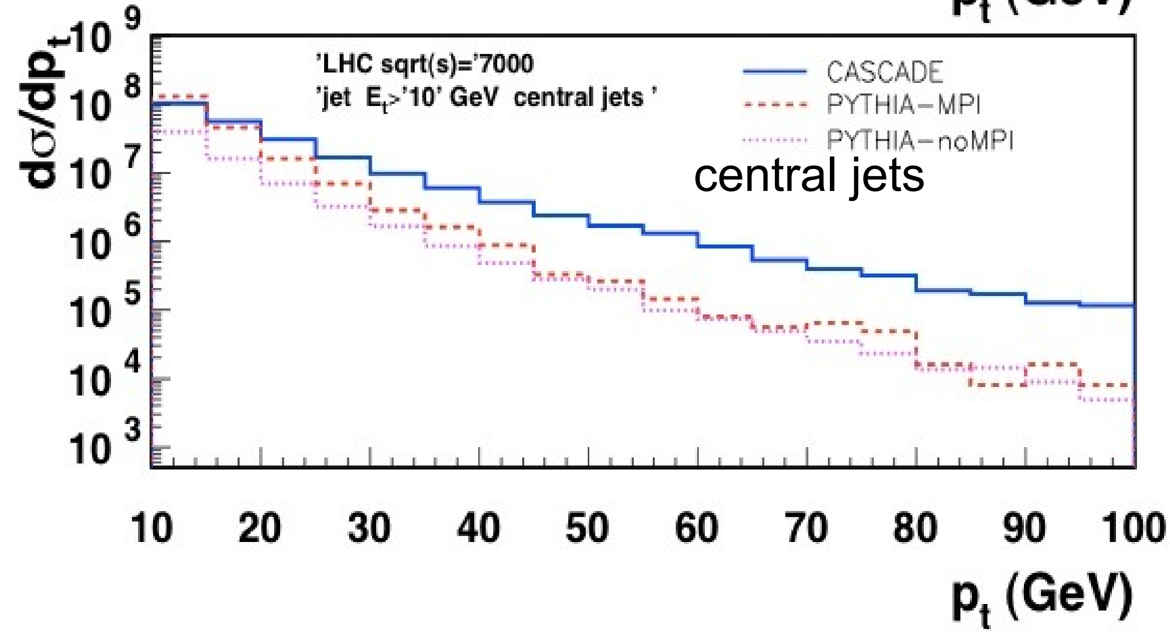


- **forward jet** $E_t > 10\ GeV,\ \ 3 < |\eta| < 5$
- **central jet** $E_t > 10\ GeV,\ \ |\eta| < 2$

Forward – central jets

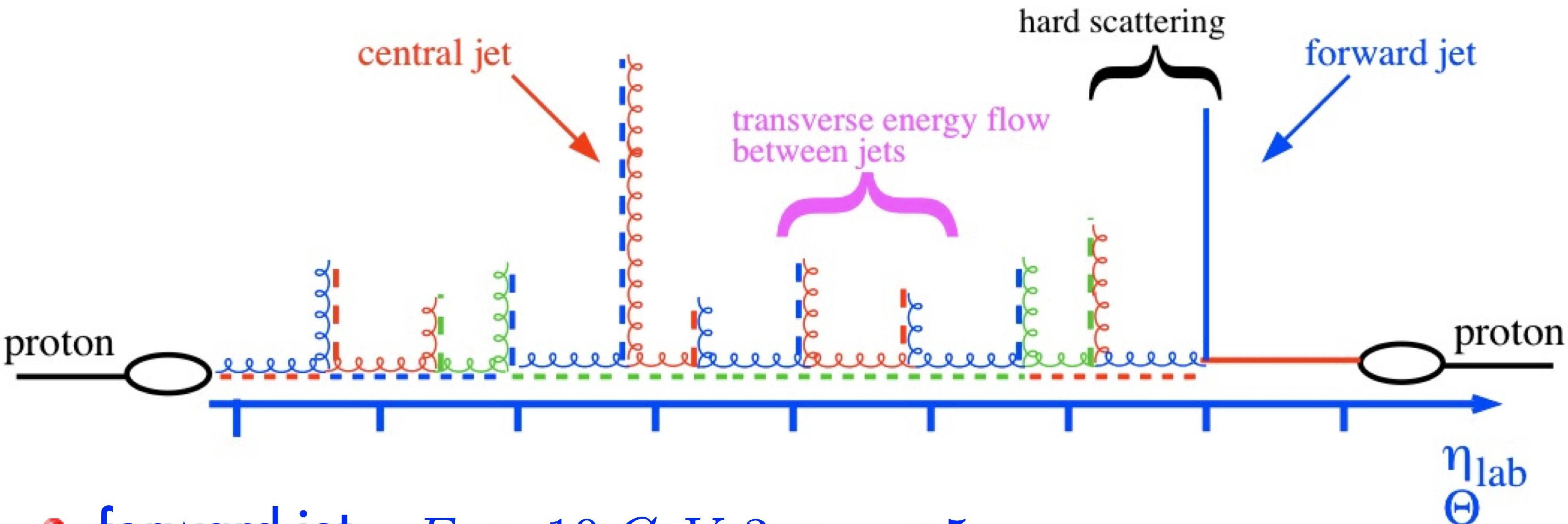






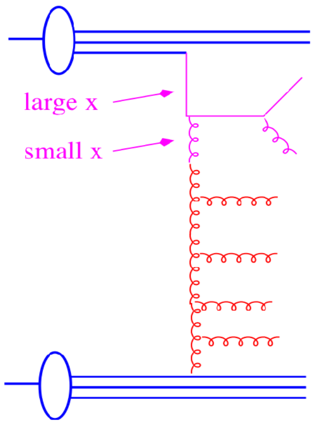
- harder pt spectrum in CASCADE
- small x effects are directly visible
- even larger than in multiparton model

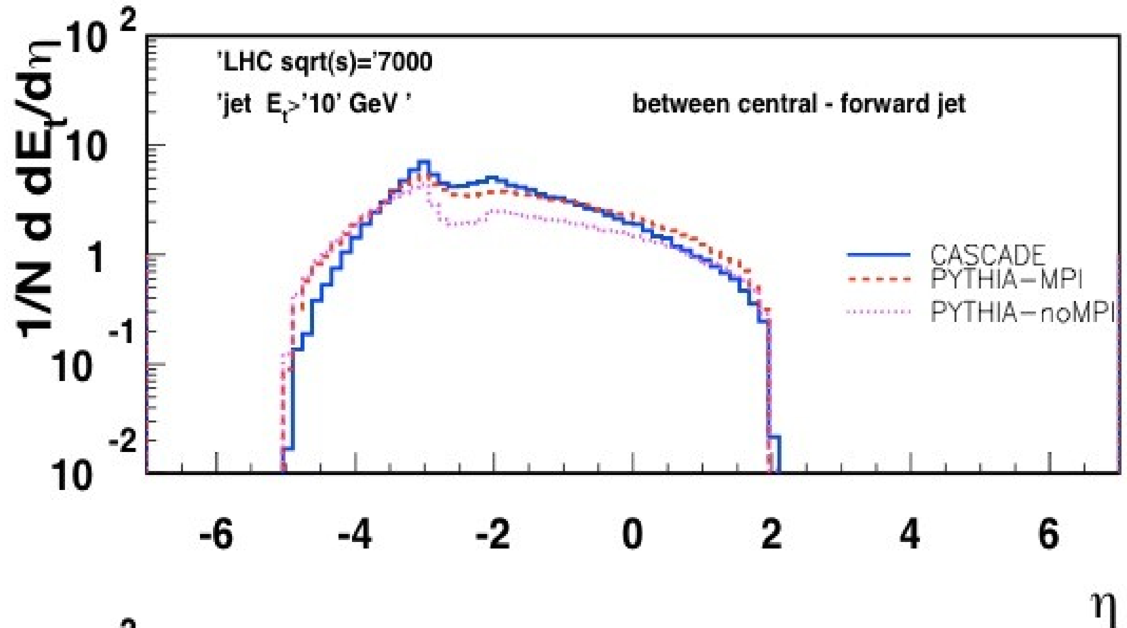
forward jet production – Et flow



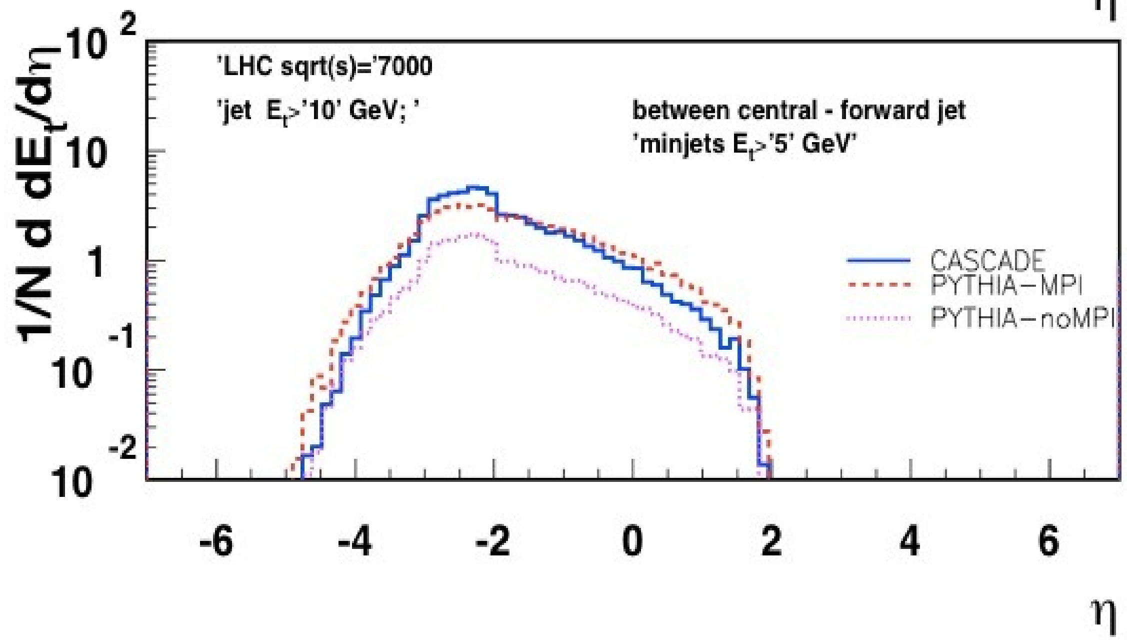
- forward jet $E_t > 10\ GeV, 3 < \eta < 5$
- central jet $E_t > 10\ GeV, -2 < \eta < 0$
  - look at transverse energy flow $\frac{1}{N_{ev}} \frac{d\sum_i E_{t\,i}}{d\eta}$
    - inclusive
    - from minjets with $E_t > 5$ GeV

Forward – central jets

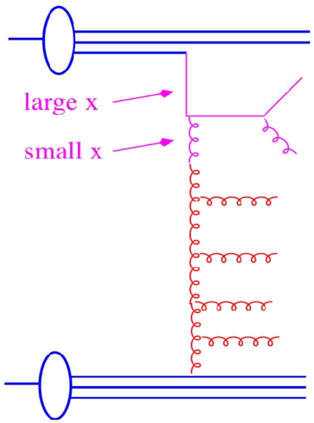


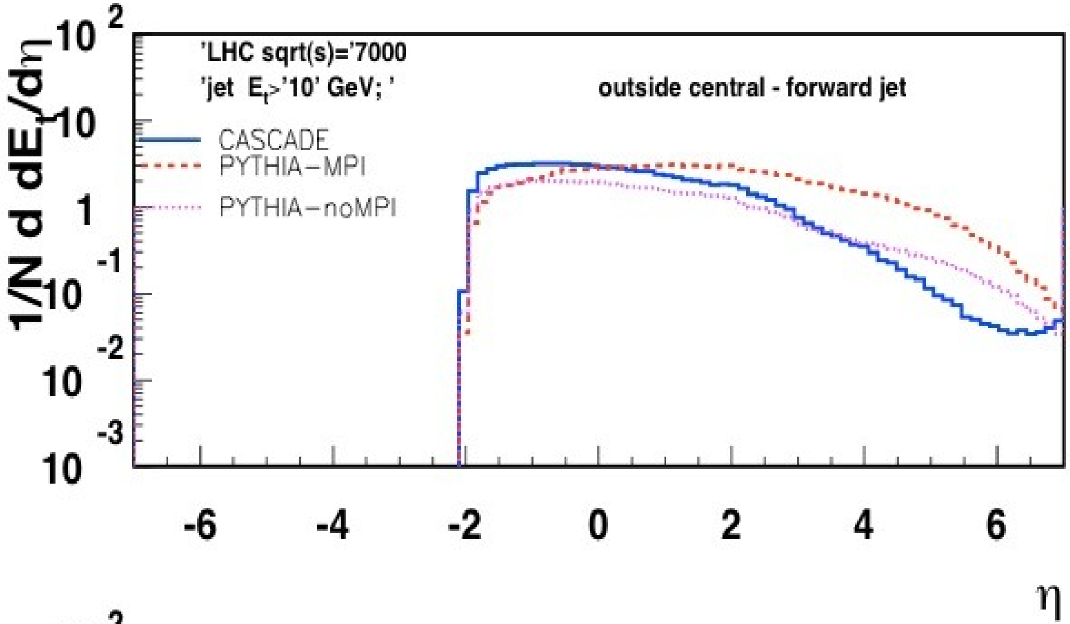


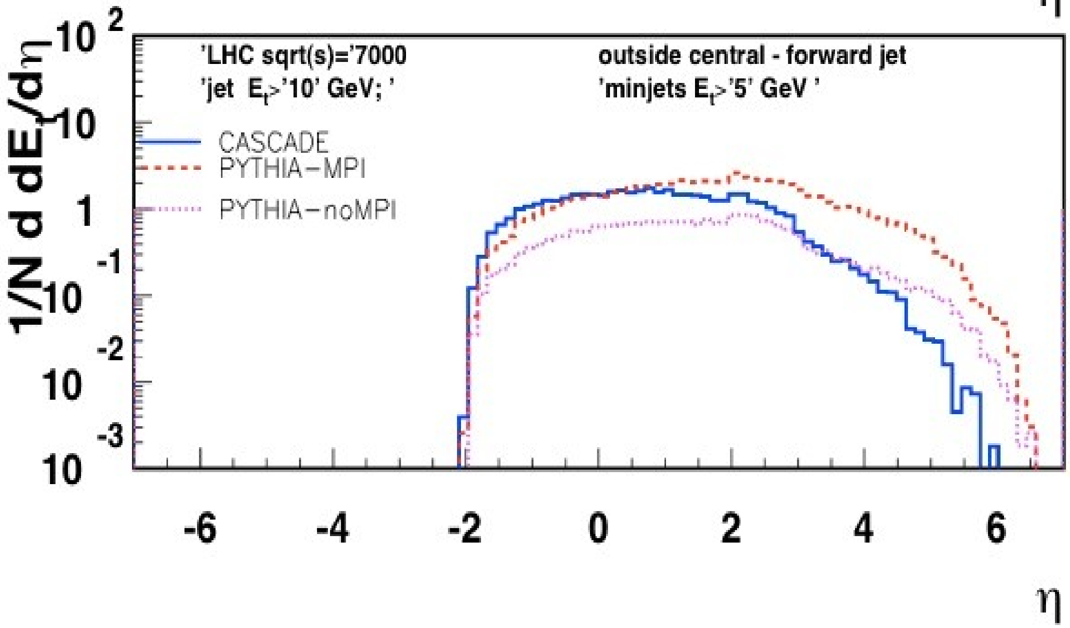
- energy flow between jets is similar to what expected from multiparton model
- significant effect from small x evolution (as CCFM or MPI)



Forward – central jets







- large Et flow outside jets
- differences to multiparton model observed (coming from ordering at large x)

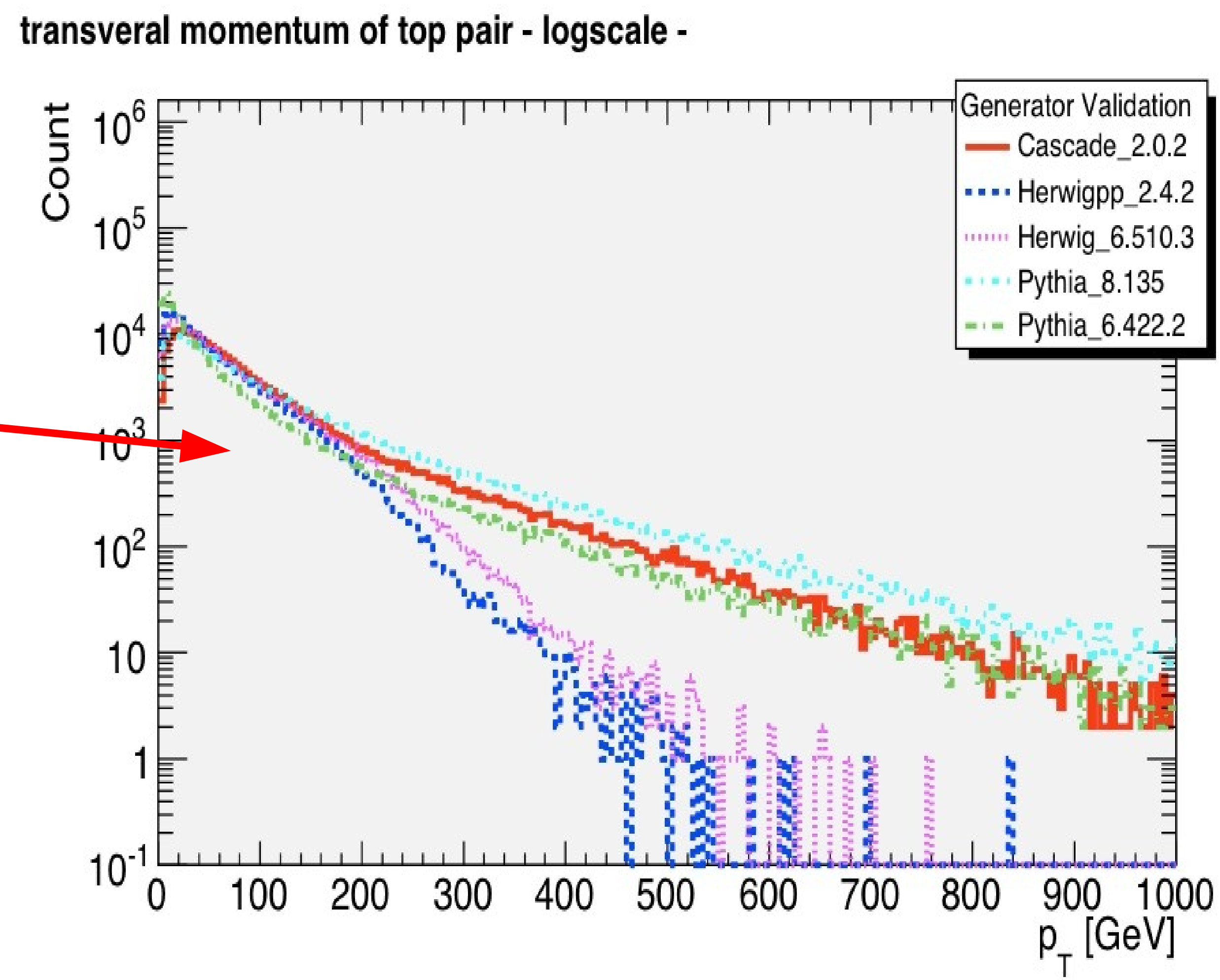
Outlook – future

- more processes to be implemented:
  - include all QCD also for large x and central region
    - need off-shell ME and quark uPDFs
  - more on DY
    - also for central region
  - more of Higgs — VBF
  - more on Onium production
  - speed up initial parton shower (A. Grebenyuk)
  - ....
- **major rewrite of CASCADE:**
  - to be part of ThePEG-"BC" for generators beyond collinear factorization (M. Kraemer)

Outlook – future

- implementation into experiment software
  - ATLAS – already done
  - CMS – soon to come
  - LHCB - ?
- part of GENSER and validation tools
  - web – interface to HepMCAnalyser (A. Knutsson, J. Katzy)

http://lcgapp.cern.ch/project/simu/generator/hepmcanalysis/hepmcanalysis.html



Conclusions

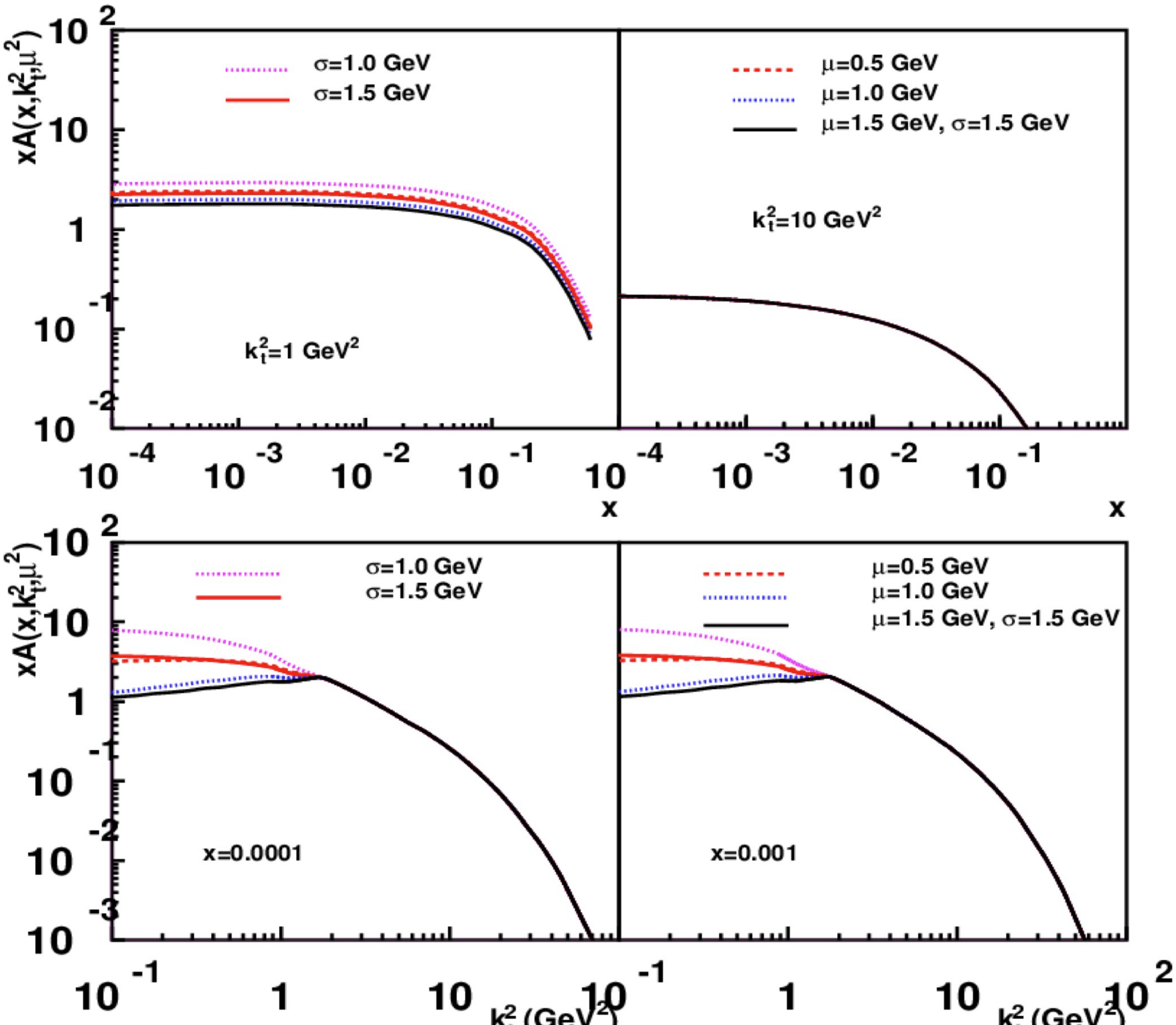
- CASCADE has many advantages compared to other Monte Carlo event generators:
  - ➔ treats kinematics correct from the beginning
  - ➔ agrees well with standard NLO calculations, where applicable !!!
  - ➔ includes naturally transition to small x via angular ordering in CCFM
- CASCADE for pp at high energies
  - ➔ at $x < 10^{-3}$ small x improved parton radiation is needed
  - ➔ gives different spectra than obtained in DGLAP models (w/o MPI)
  - ➔ in some cases similar to multiparton interaction model
- upgrades and improvements are foreseen for the future
  - ➔ at present main focus on small x processes i.e. forward region
  - ➔ future: plan for extension to larger x

Backup slides

uPDFs from di-jets: intrinsic k_t

$$xA(x,\mu_0^2) = Nx^{-B_g} \cdot (1-x)^4 \cdot \exp\left(-(k_{t0}-\mu)^2/\sigma^2\right)$$

μ = 4 GeV



- different intrinsic k_t-distributions only accessible in uPDFs
- sensitive to the mix of small and large k_t

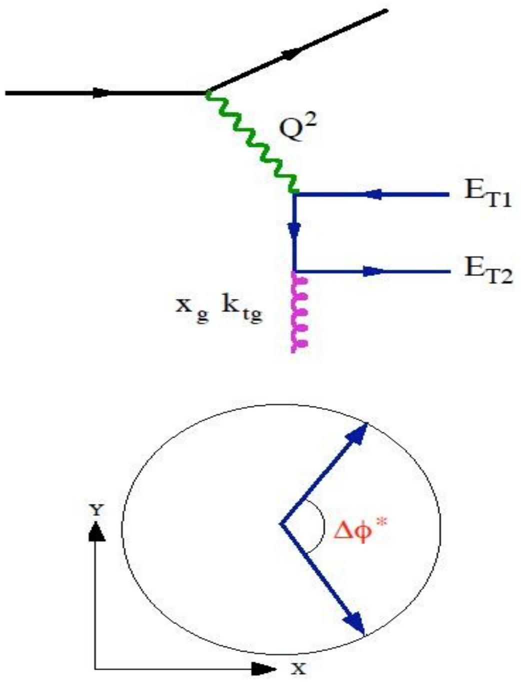
➔ small kt determines total x-section

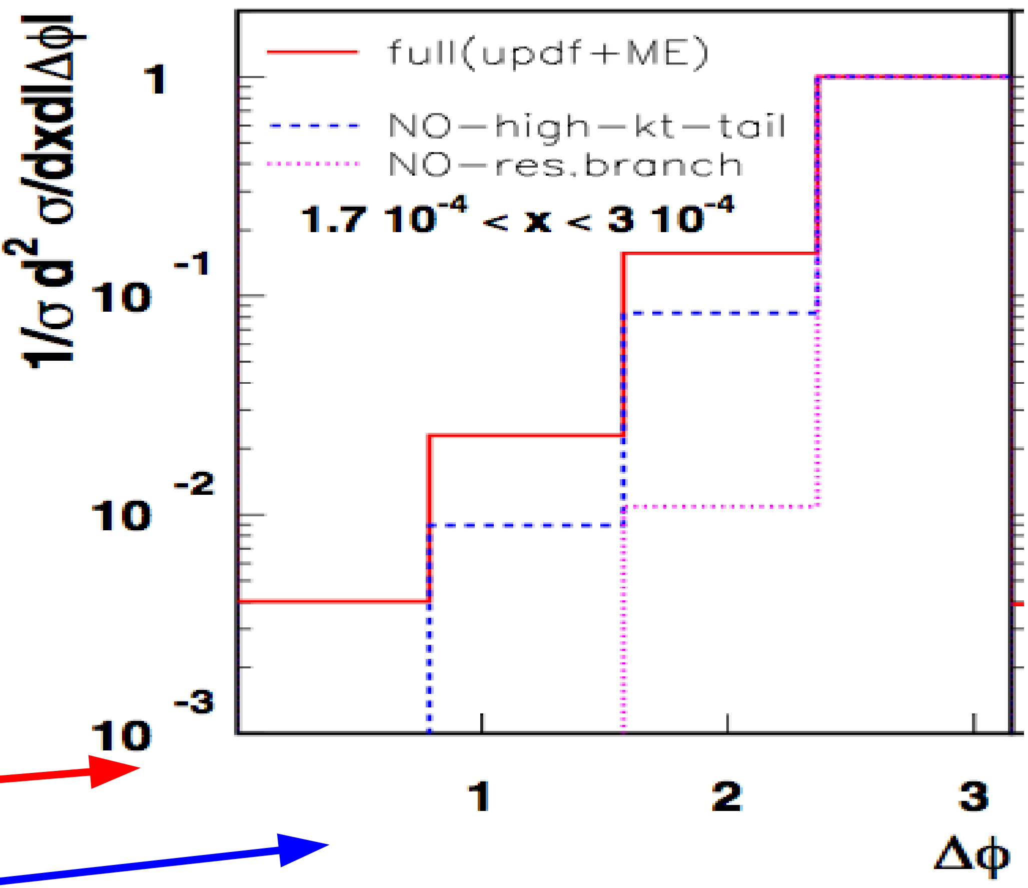
➔ large kt influences perturbative tails ...

Why off-shell matrix elements ?

- check $\Delta\phi$ between jets

F. Hautmann, H.Jung, JHEP 2008 10 113
arXiv 0805.1049

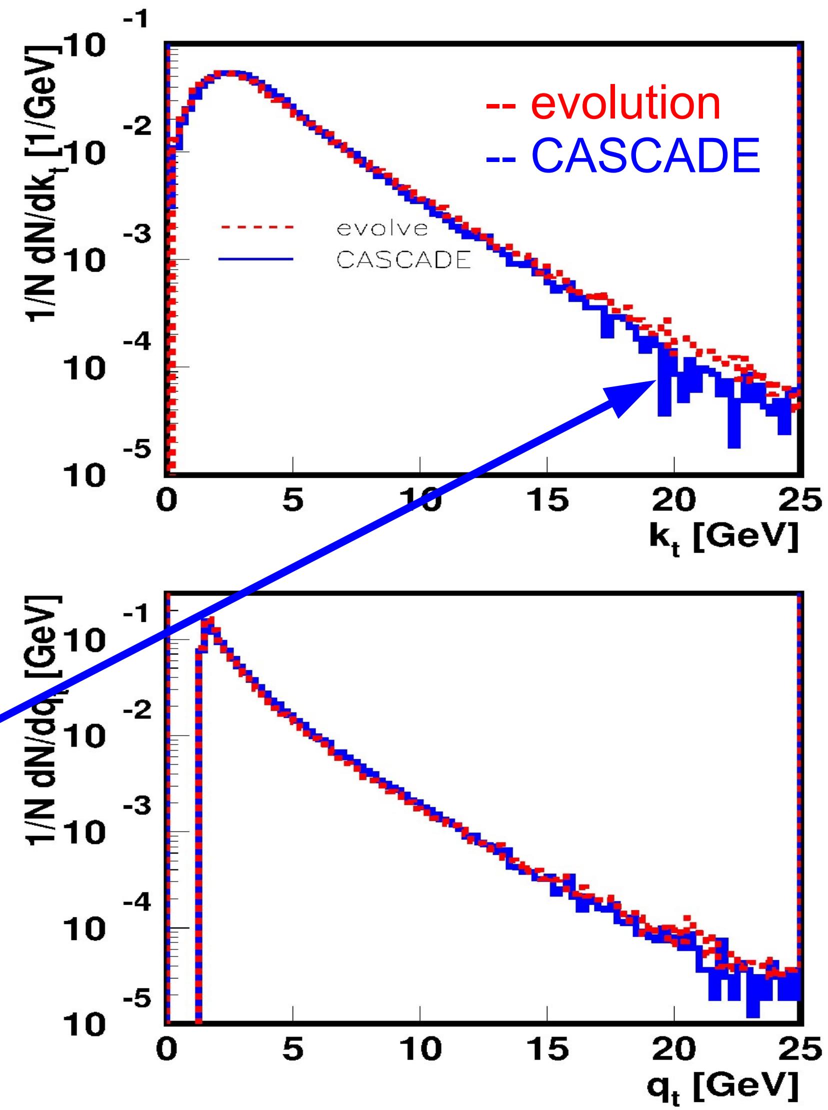




- ➔ full off shell ME
- ➔ on-shell ME $k_\perp < \mu^2$
- ➔ ... significant effect $k_\perp^2 > \mu^2$
- ➔ ... is also included in full NLO calculation

Parton shower and uPDFs

- DGLAP evolution equations:
  - ➔ only inclusive predictions
  - ➔ no information on emitted partons
- CCFM treats explicitly
  - ➔ partons emitted during cascade
  - ➔ color coherence
  - ➔ energy momentum conservation
- best to implement in MC generator
  - ➔ compare evolution and parton shower



BUT need determination of unintegrated parton densities