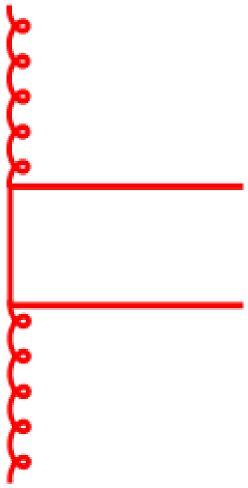
# The CASCADE MC event generator

M. Deak (DESY), F. Hautmann (Oxford),
H. Jung (DESY & Antwerp), K. Kutak (DESY)

- basic ideas of the CASCADE MC generator
  - matrix elements and uPDFs
- determination of uPDFs
- building up the hadronic final state
  - from hard scattering towards incoming hadron

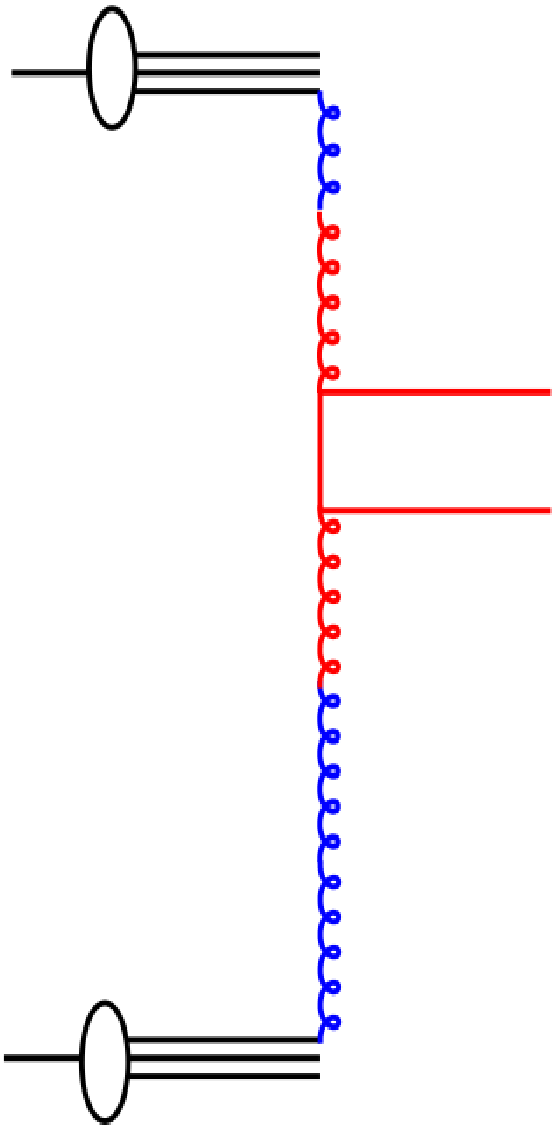
# Basic elements of a MC generator

- start with the matrix element
  for the hard process



# Basic elements of a MC generator

- start with the matrix element for the hard process
- pdfs are also needed



# Basic elements of a MC generator

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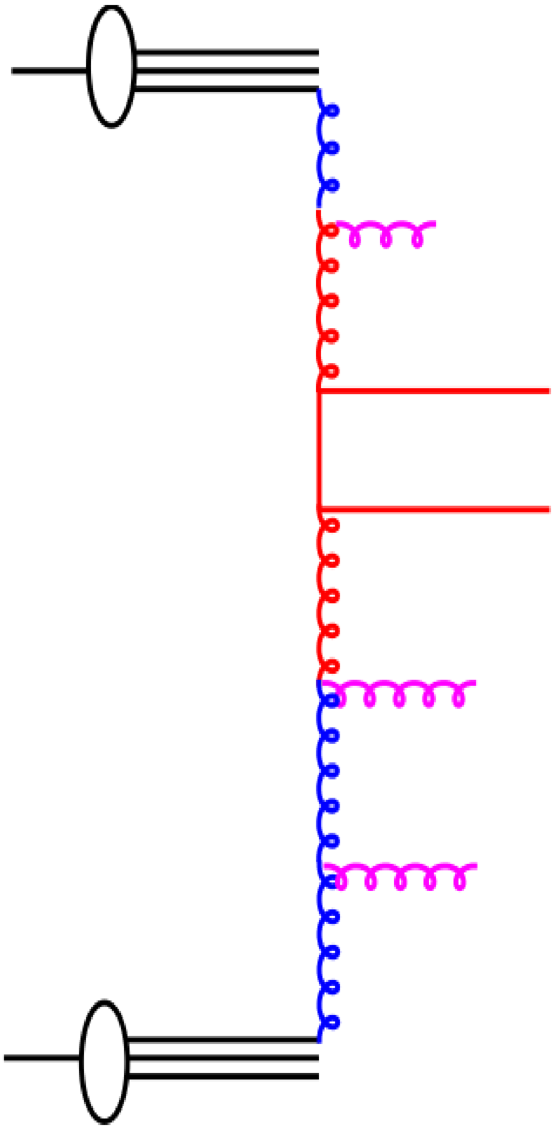
- unfold parton evolution: parton showers



# Basic elements of a MC generator

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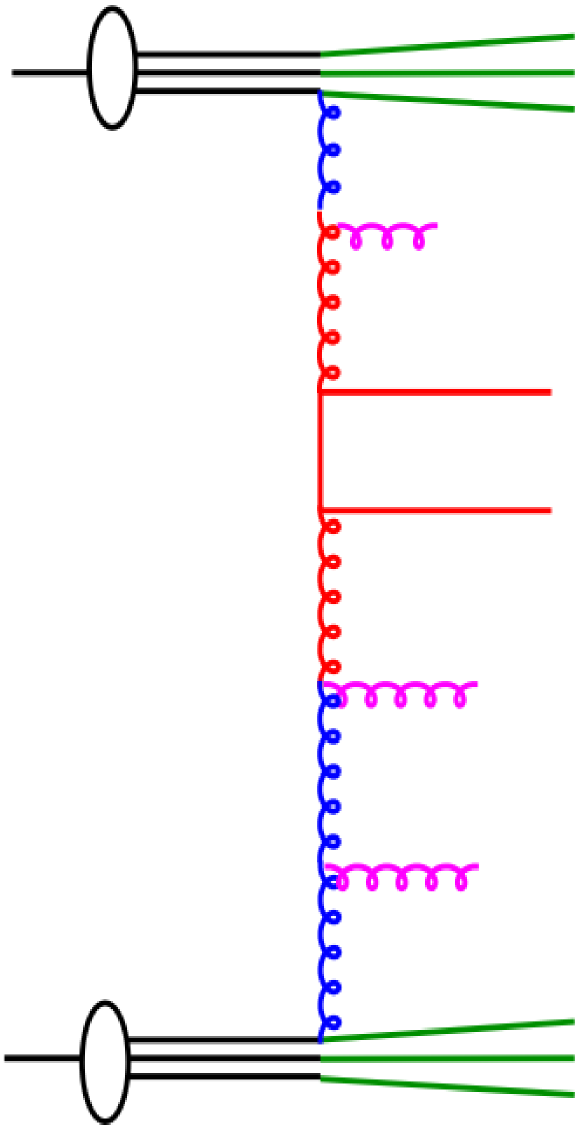
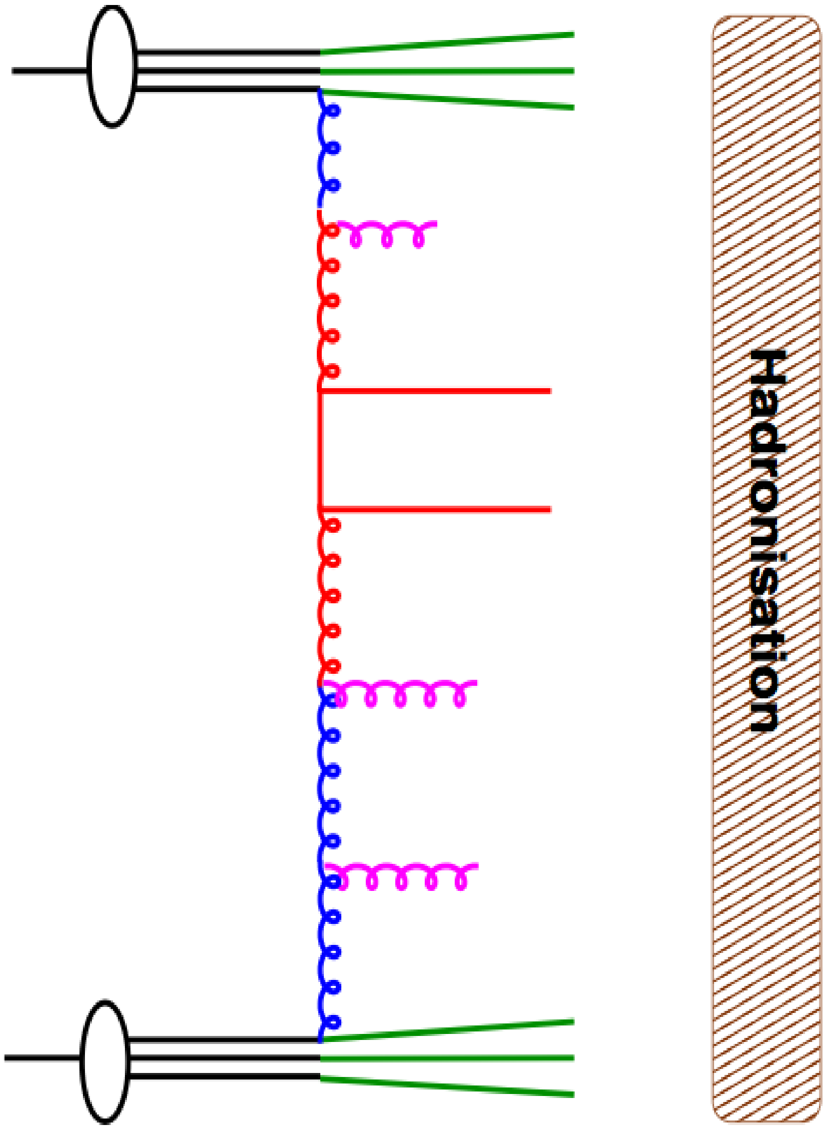
- add proton remnants



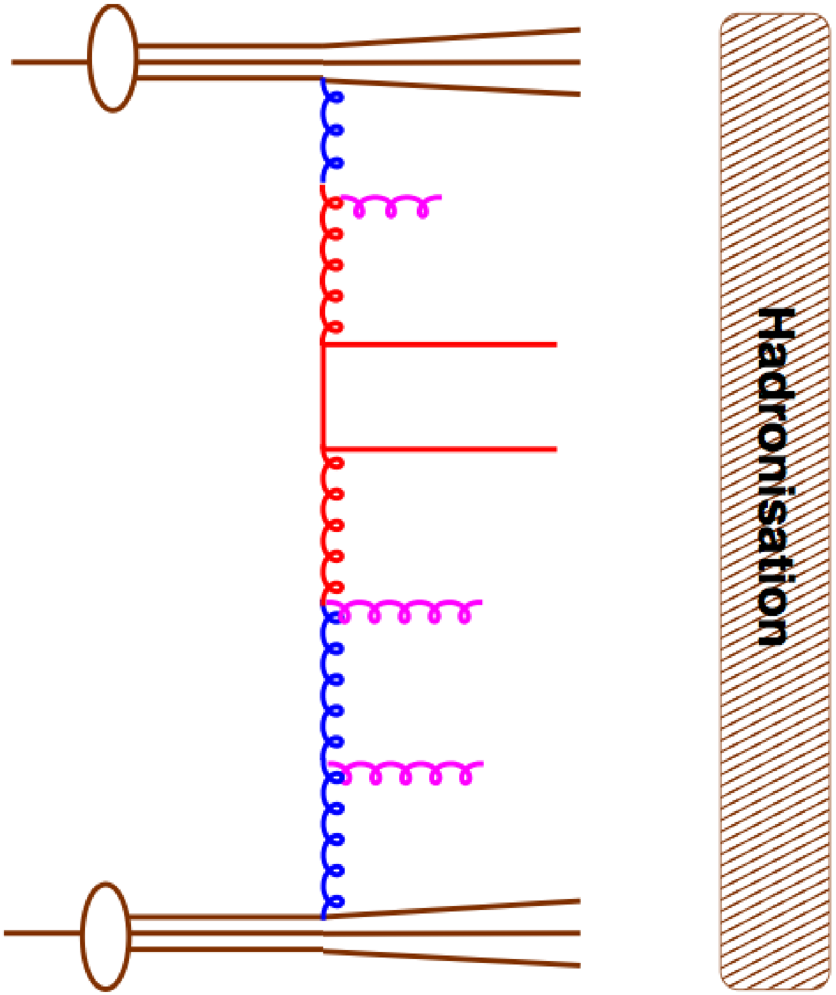
# Basic elements of a MC generator

- start with the matrix element for the hard process
- pdfs are also needed
- unfold parton evolution: parton showers
- add proton remnants
- apply color connections and hadronize it ...



# CASCADE basic idea

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



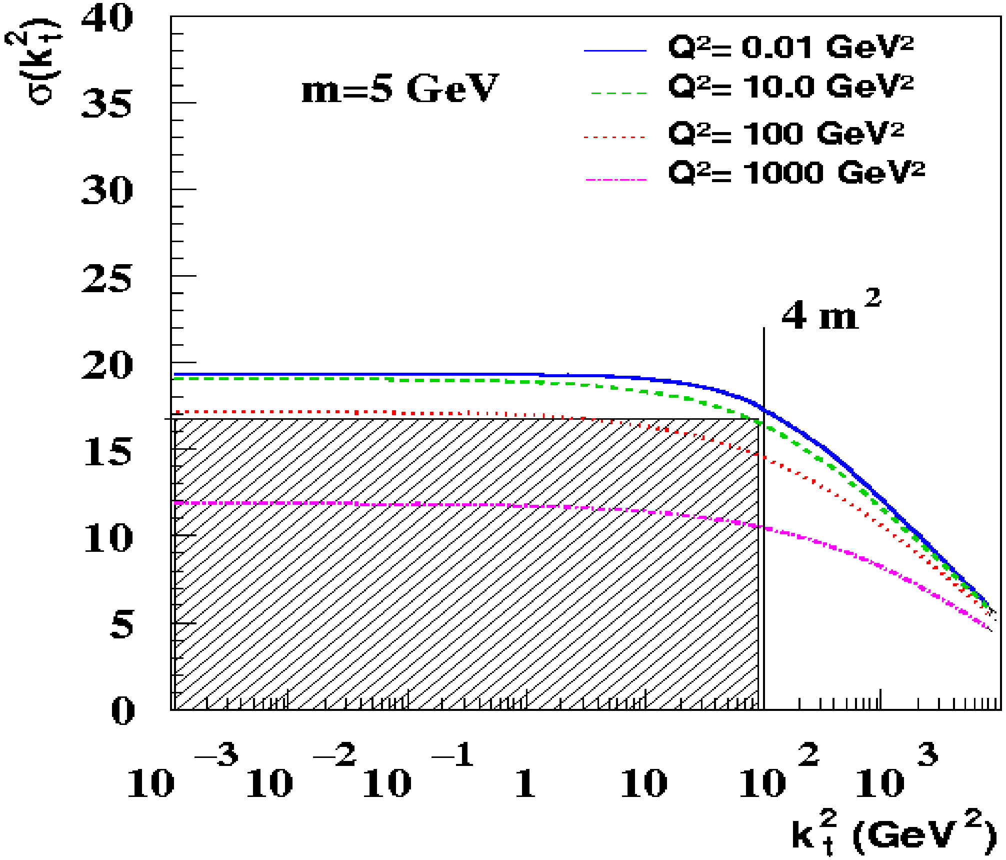

$$\sigma(pp \to q\bar{q} + X) = \int \frac{dx_{g1}}{x_{g1}} \frac{dx_{g2}}{x_{g2}} \int d^2k_{t1} d^2k_{t2} \hat{\sigma}(\hat{s}, k_t, \bar{q}) \times x_{g1}\mathcal{A}(x_{g1}, k_{t1}, \bar{q}) x_{g2}\mathcal{A}(x_{g2}, k_{t2}, \bar{q})$$

# 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 $k_t$

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

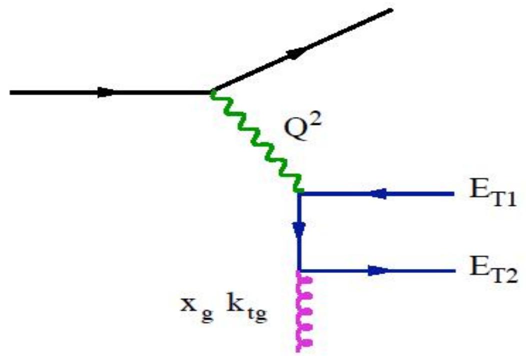
up to $\mu^2 \sim 4m^2$

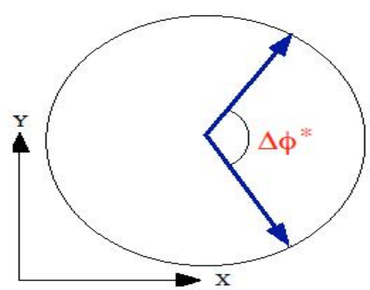


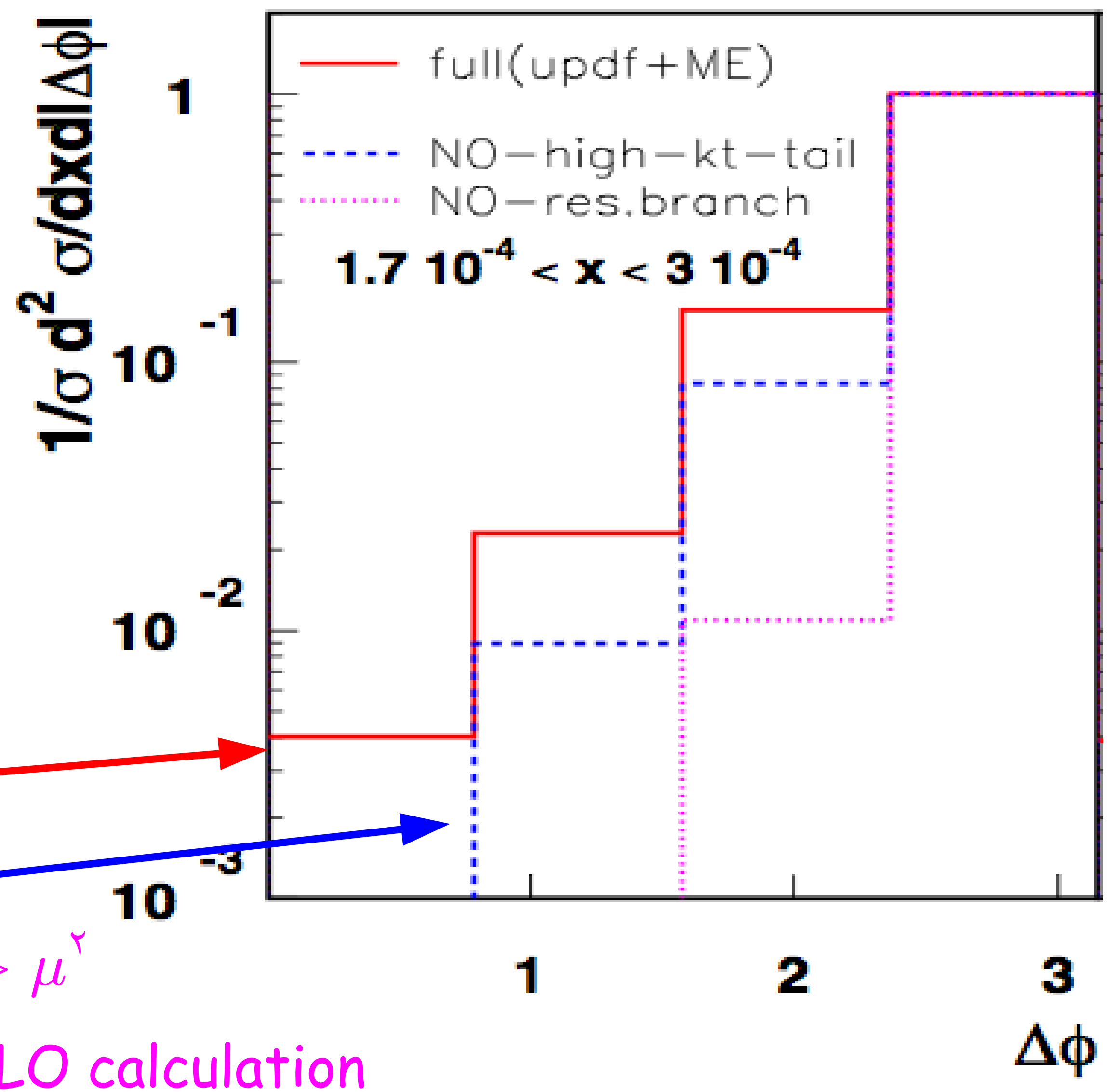
# Why off-shell matrix elements ?

- check $\Delta\phi$ between jets

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



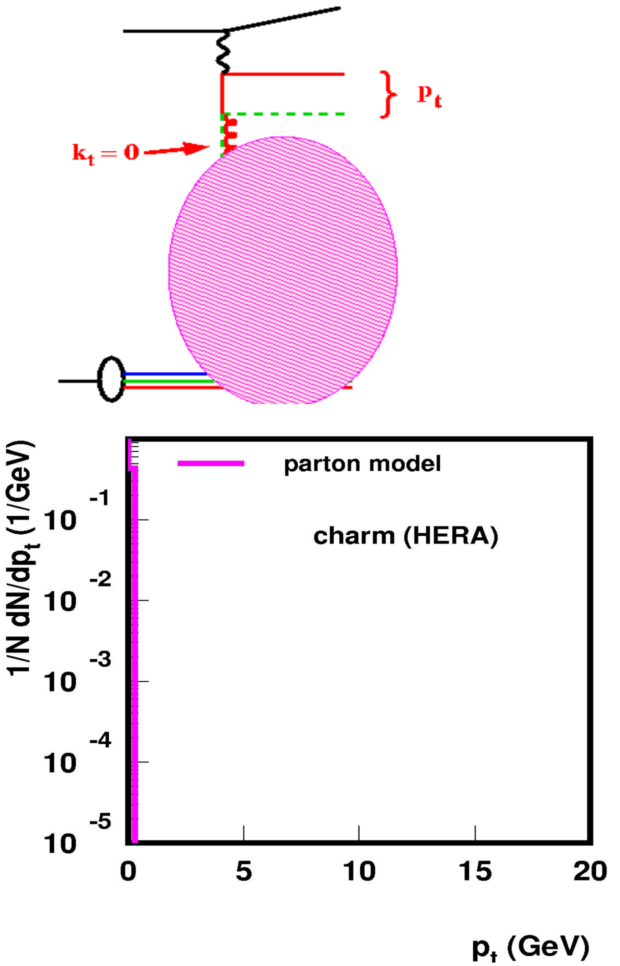




- ➔ full off shell ME
- ➔ on-shell ME $k_\perp^2 < \mu^2$
- ➔ ... significant effect $k_\perp^2 > \mu^2$
- ➔ ... is also included in full NLO calculation

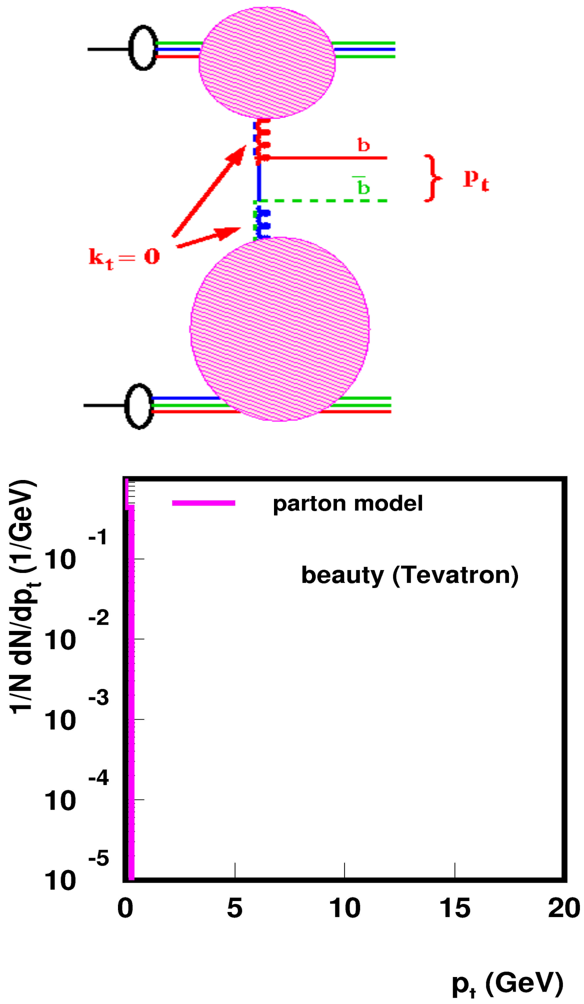
# Why uPDFs ?

J. Collins, H. Jung hep-ph/0508280

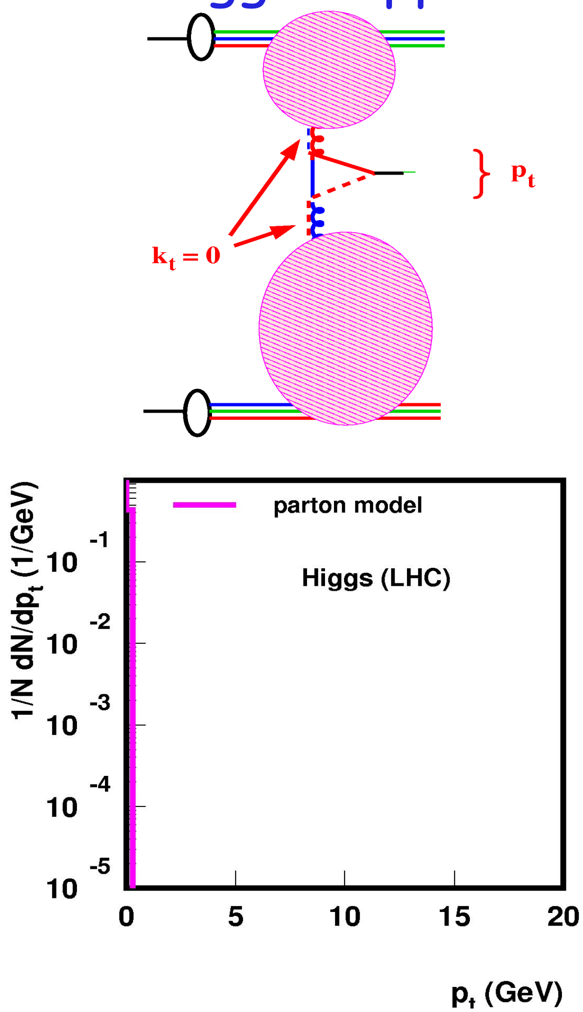
## heavy quarks at HERA




## heavy quarks in pp



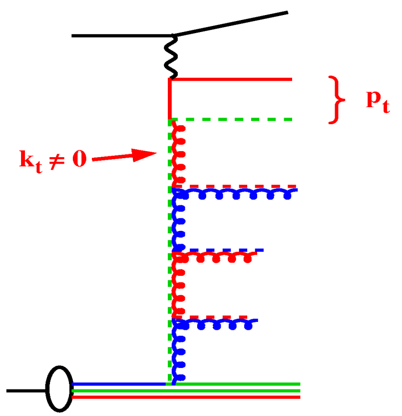

## Higgs in pp

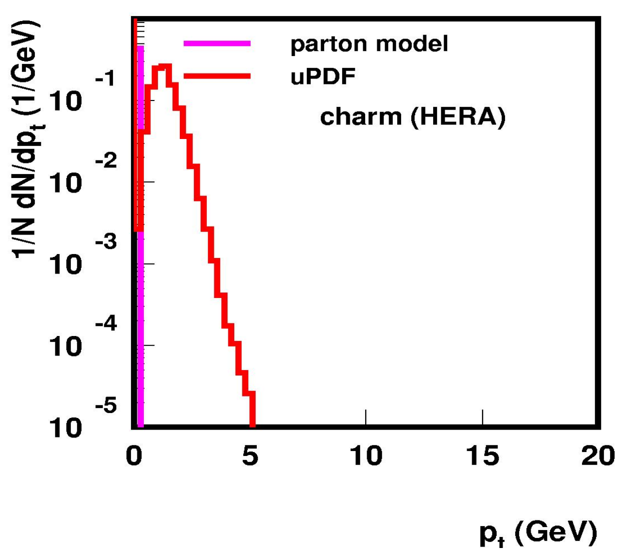


# … because of kinematics from evolution

J. Collins, H. Jung hep-ph/0508280

## heavy quarks at HERA

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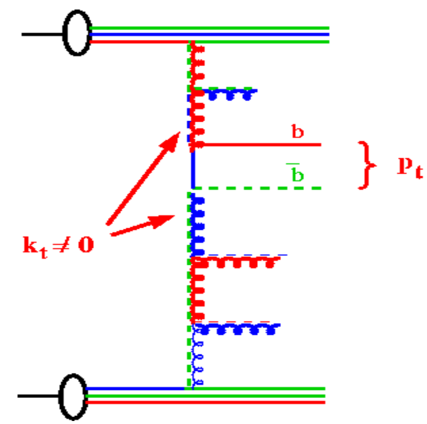


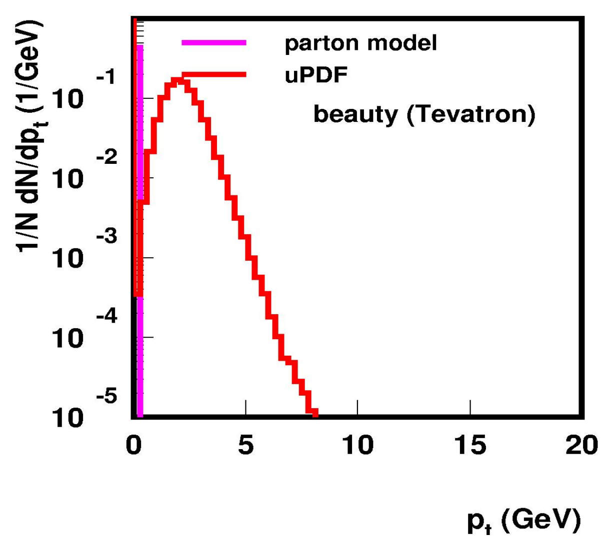


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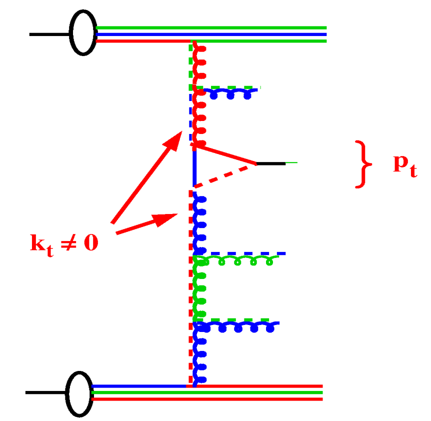
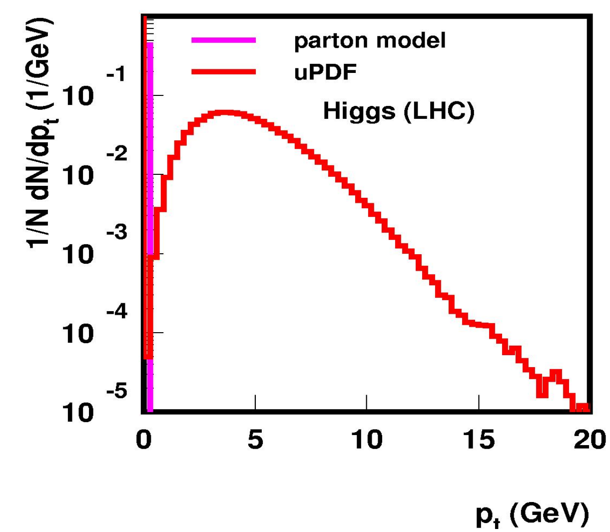



- ➔ doing kinematics correctly already at LO reduces NLO corrections …
- ➔ finite transverse momenta are important for x-section calculations

# Which uPDFs ?

- take derivative of integrated PDF:

$$f(x,k_\perp^2) = \frac{dg(x,k_\perp^2)}{dk_\perp^2} = \left[\frac{\alpha_s}{2\pi}\int_x^{1-\Delta} P(z) g\left(\frac{x}{z},k_\perp^2\right) dz\right]$$

- KMR approach:

$$f(x,k_\perp^2,\mu^2) = \exp\left(-\int_{k_\perp^2}^{\mu^2} \frac{\alpha_s}{2\pi} d\log k_\perp^2 \sum_i \int_0^1 P(z')dz'\right) \times \frac{dg(x,\mu^2}{d\mu^2}$$

using integrated PDF, only last emission generates transverse momentum via sudakov form factor. ...

- appropriate form DGLAP with strong ordering....
- this is what is done in all standard parton shower MCs

# Which uPDFs ? CCFM approach

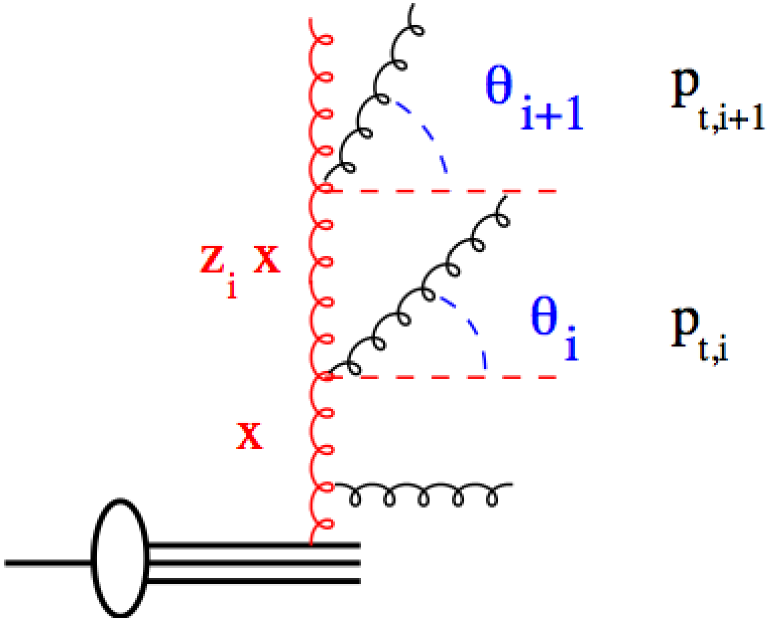
- Color coherence requires angular ordering instead of $p_t$ ordering ...

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

→ recover DGLAP with $q$ ordering at medium and large $x$

→ HERWIG uses: $q_i > q_{i-1}$

→ at small x, no restriction on $q$
$p_{ti}$ can perform a random walk

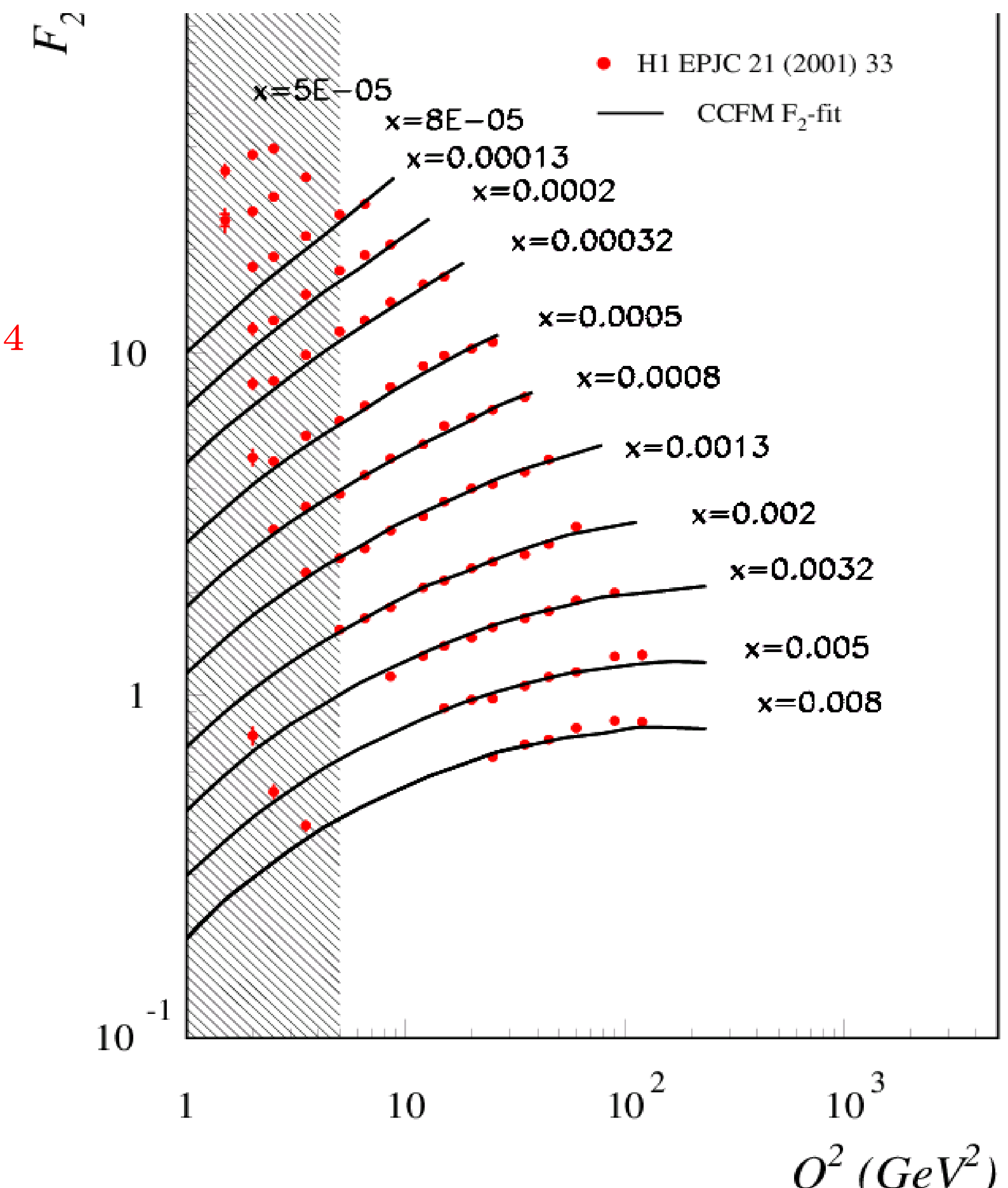



→ CataniCiafaloniFioraniMarchesini evolution forms a bridge between DGLAP and BFKL evolution

→ important for comparison with collinear NLO calculations ...

# uPDF fit to $F_2$: x-dependence

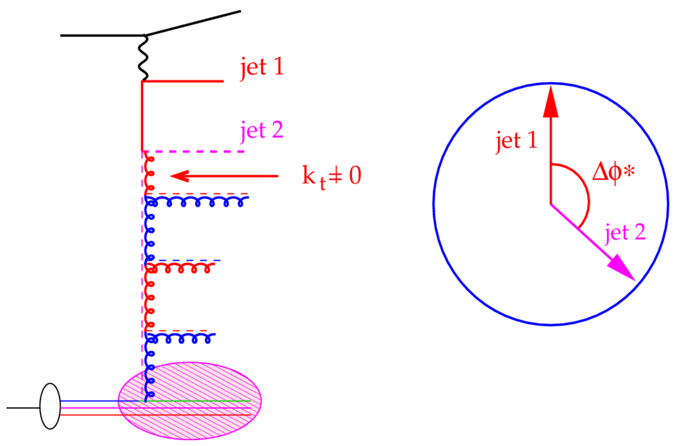
- $$\chi^2 = \sum_i \left( \frac{(T-D)^2}{\sigma_i^{2\ stat} + \sigma_i^{2\ uncor}} \right)$$
- fit parameters of starting distribution
  $$x\mathcal{A}_0(x,\mu_0) = N x^{-B_g} \cdot (1-x)^4$$
- using $F_2$ data H1
  (H1 Eur. Phys. J. C21 (2001) 33-61, DESY 00-181)
  $$x < 0.05 \quad Q^2 > 5\ \mathrm{GeV}^2$$
- 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):
  $$\frac{\chi^2}{\mathrm{ndf}} = \frac{111.8}{61} = 1.83$$
  $$B_g = 0.028 \pm 0.003$$
  → similar to DGLAP fits (~1.5)

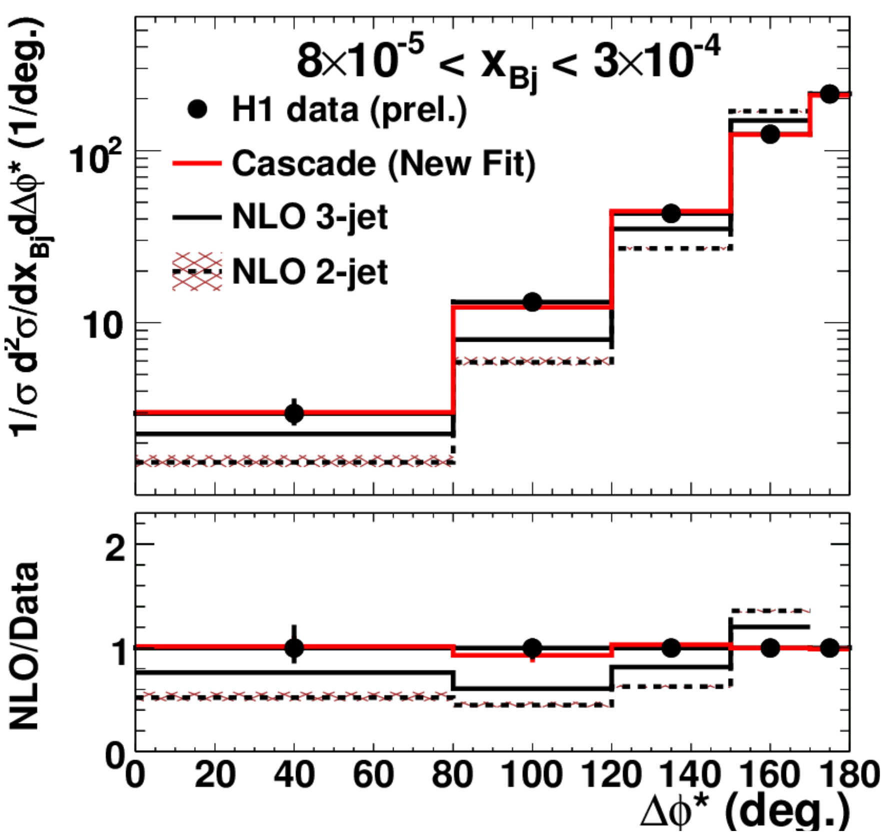


# uPDFs from di-jets: $k_t$-dependence

- $k_t$ dependence with $\frac{1}{\sigma}\frac{d^2\sigma}{d\Delta\phi^*\, dx}$ , with $x\mathcal{A}(x,\mu_0^2) = Nx^{-B_g}\cdot(1-x)^4\cdot\exp\left(-(k_{t0}-\mu)^2/\sigma^2\right)$

M. Hansson (Lund)




- H1 prel data (jets closest to photon)

$$5 < Q^2 < 100 \text{ GeV}^2$$
$$-1 < \eta < 2.5$$
$$E_T > 5 \text{ GeV}$$

- intrinsic gauss:

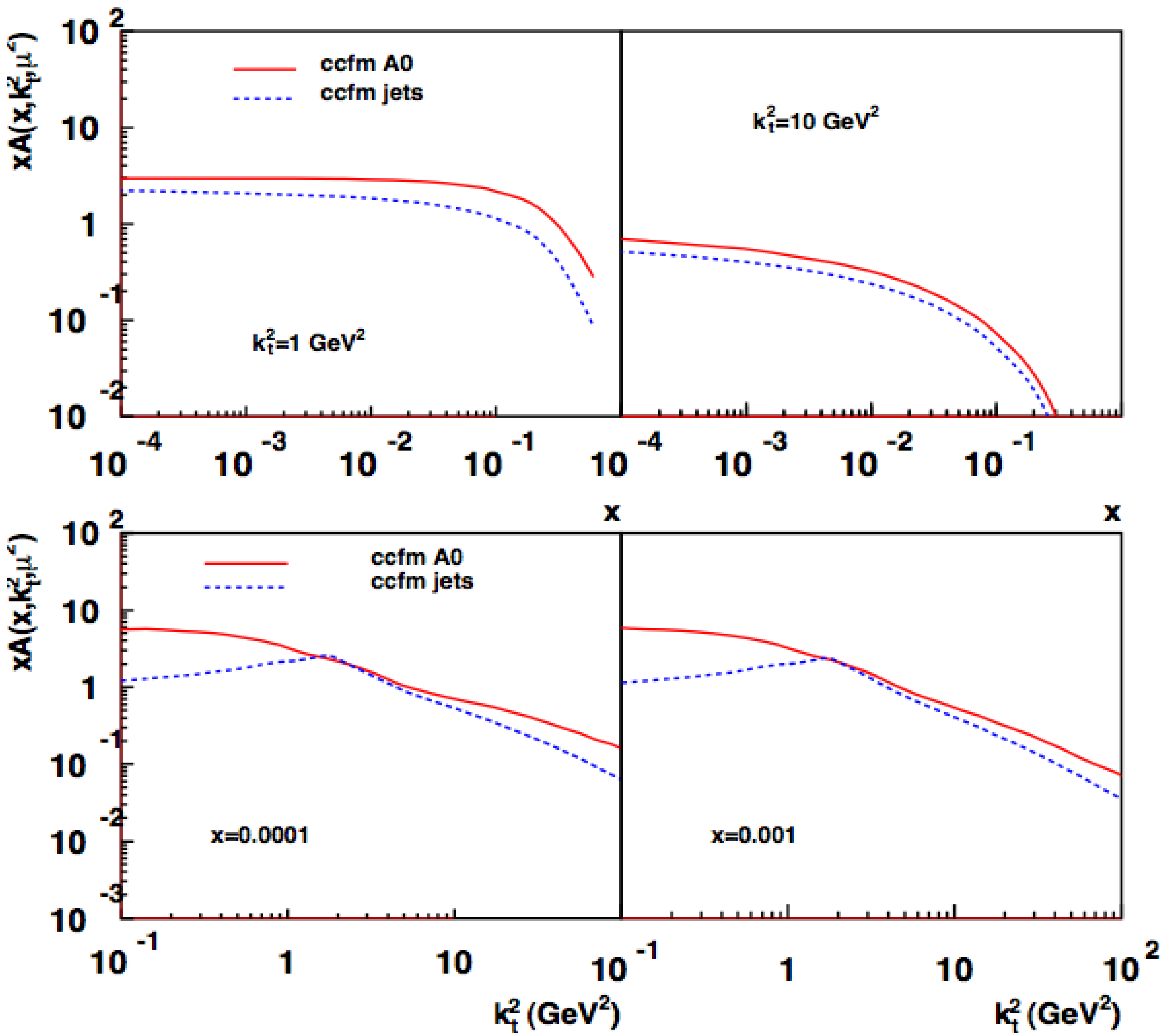
$$\sigma \sim 1.5$$
$$\mu \sim 1.5$$

➔ suggestive a more physics motivated ansatz for the starting distribution

# uPDFs from di-jets: intrinsic $k_t$

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

$\mu = 2\ k_t$




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

➔ small $k_t$ determines total x-section

➔ large $k_t$ influences perturbative tails ...

# Using saturation ansatz

- suppression of uPDF at small kt
  suggests saturation ?!?!?!?

➔ use GBW ansatz for starting distribution:

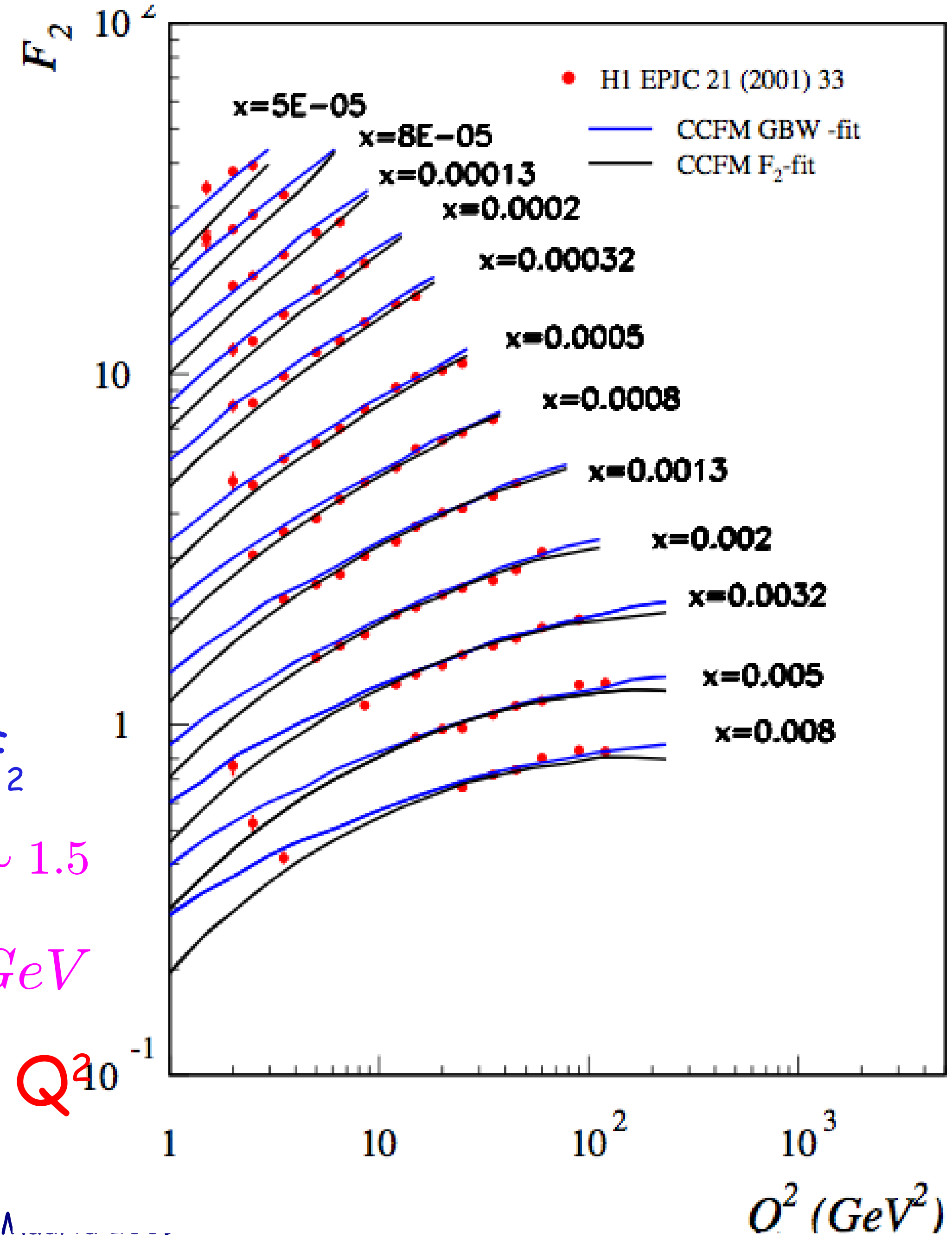
$$x\mathcal{G}(x,k_\perp) \sim R_0^2 k_\perp^2 \exp\left(-R_0^2 k_\perp^2\right)$$

with

$$R_0^2 = \left(\frac{x}{x_0}\right)^\lambda$$

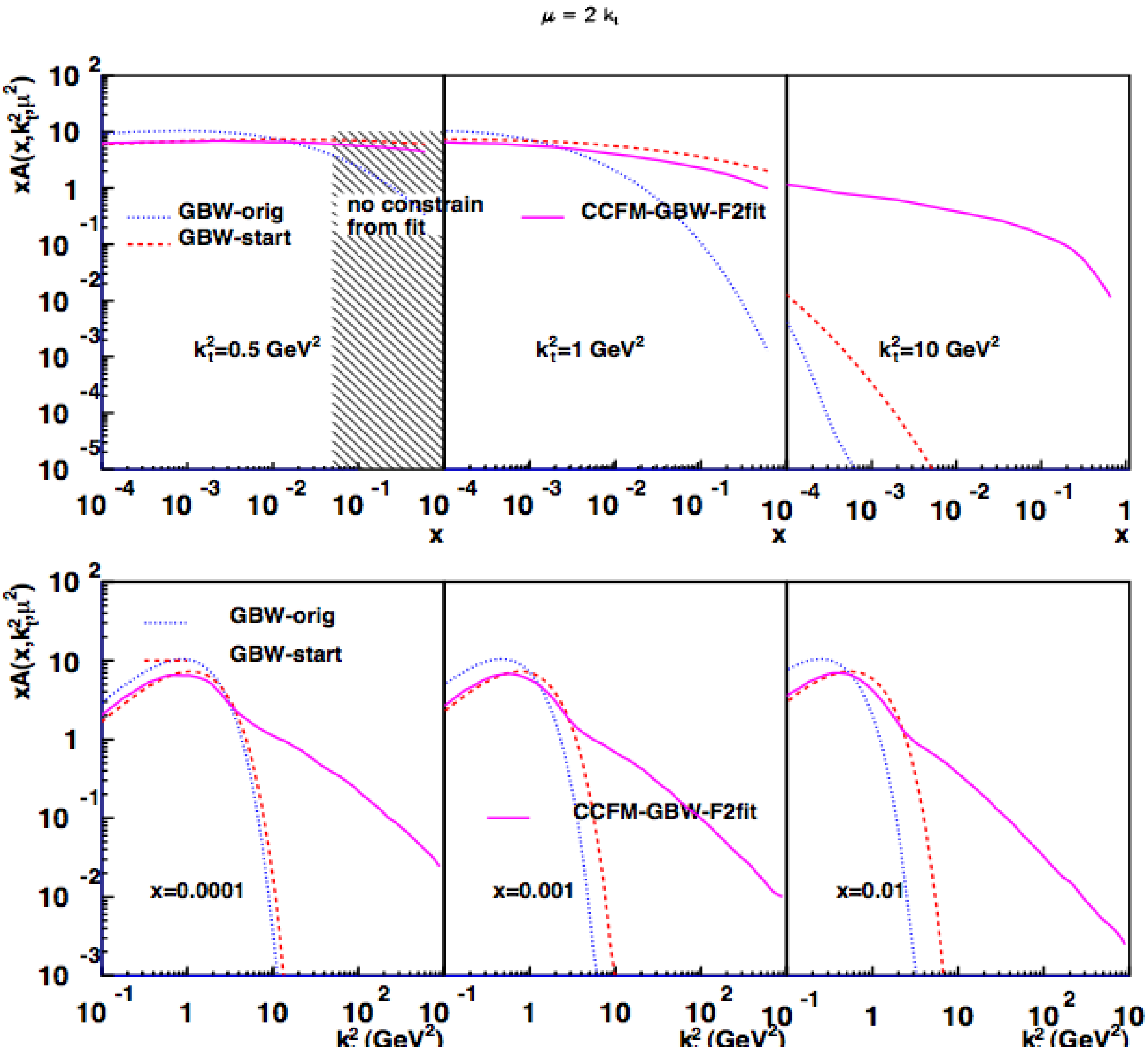
- determine $x_0, \lambda$ from a fit to $F_2$
  $Q^2 > 0.2$ $GeV^2$ (397 points) $\frac{\chi^2}{ndf} \sim 1.5$
  - CCFM evolution for $Q_0 > 1.1 GeV$

➔ describe data down to small $Q^2$



# CCFM evolution with GBW ansatz

- CCFM evolution generates high kt tail
- large x distribution is not constrained by $F_2$ fit (used here)

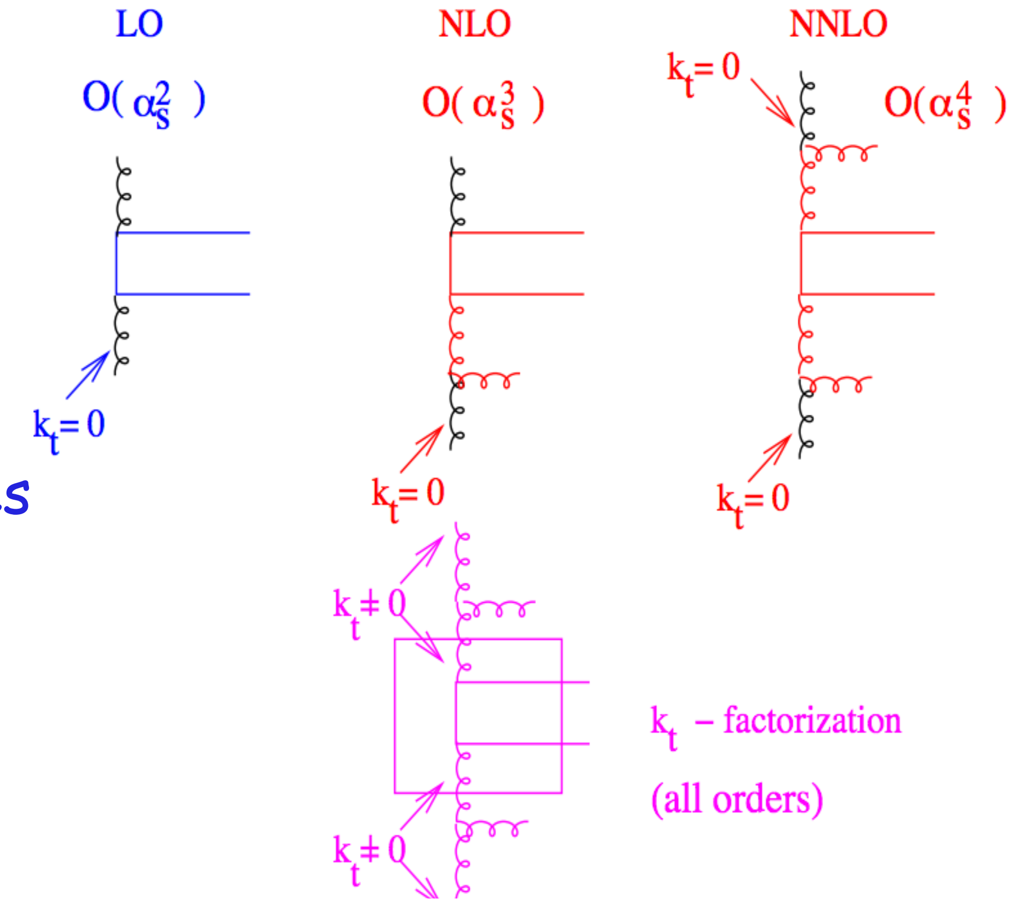


# The hadronic final state

- hard process & hard additional radiation
  - ➔ NLO calculations and/or from parton showers with CCFM

# CASCADE and coll. NLO calculations

- fit of uPDF to inclusive structure functions /x-sections used to determine normalization
  - ➔ includes "all-orders" !!!!
- off-shell matrix element simulates part of real NLO corrections




**uPDFs are important....**

# CASCADE and NLO: ep

- compare CASCADE with NLO dijet calc DISENT

$$Q^2 > 10 \text{ GeV}$$

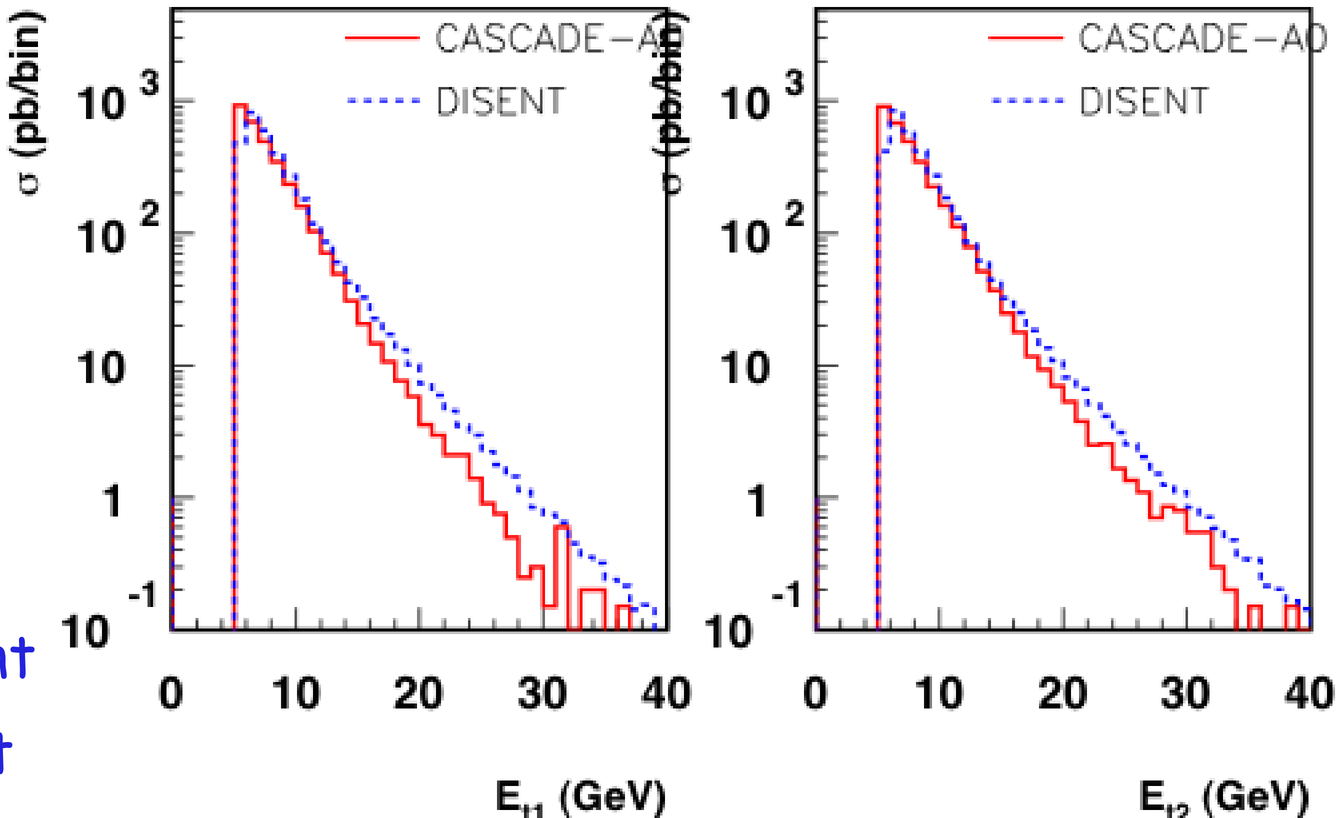
$$0.1 < y < 0.6$$

$$E_t > 5 \text{ GeV}$$

➔ reasonable agreement

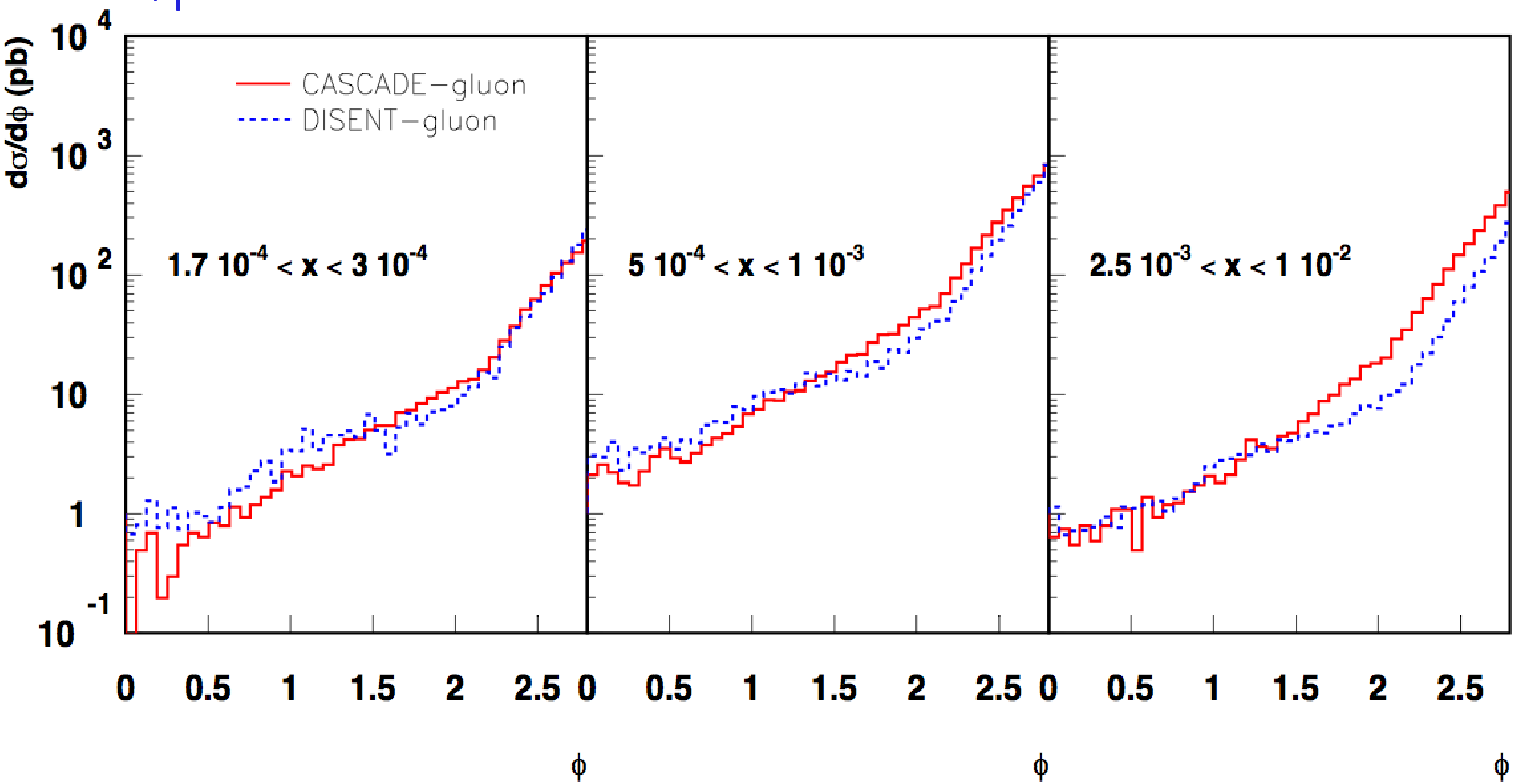
➔ high pt tail different

  ➔ in single inclusive jets



# Comparison with NLO

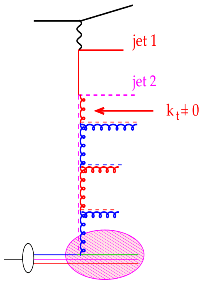
- allow only for 1 additional parton from parton shower
- compare with NLO DISENT calculation

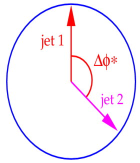



- where gluon emission is dominant, good agreement with NLO

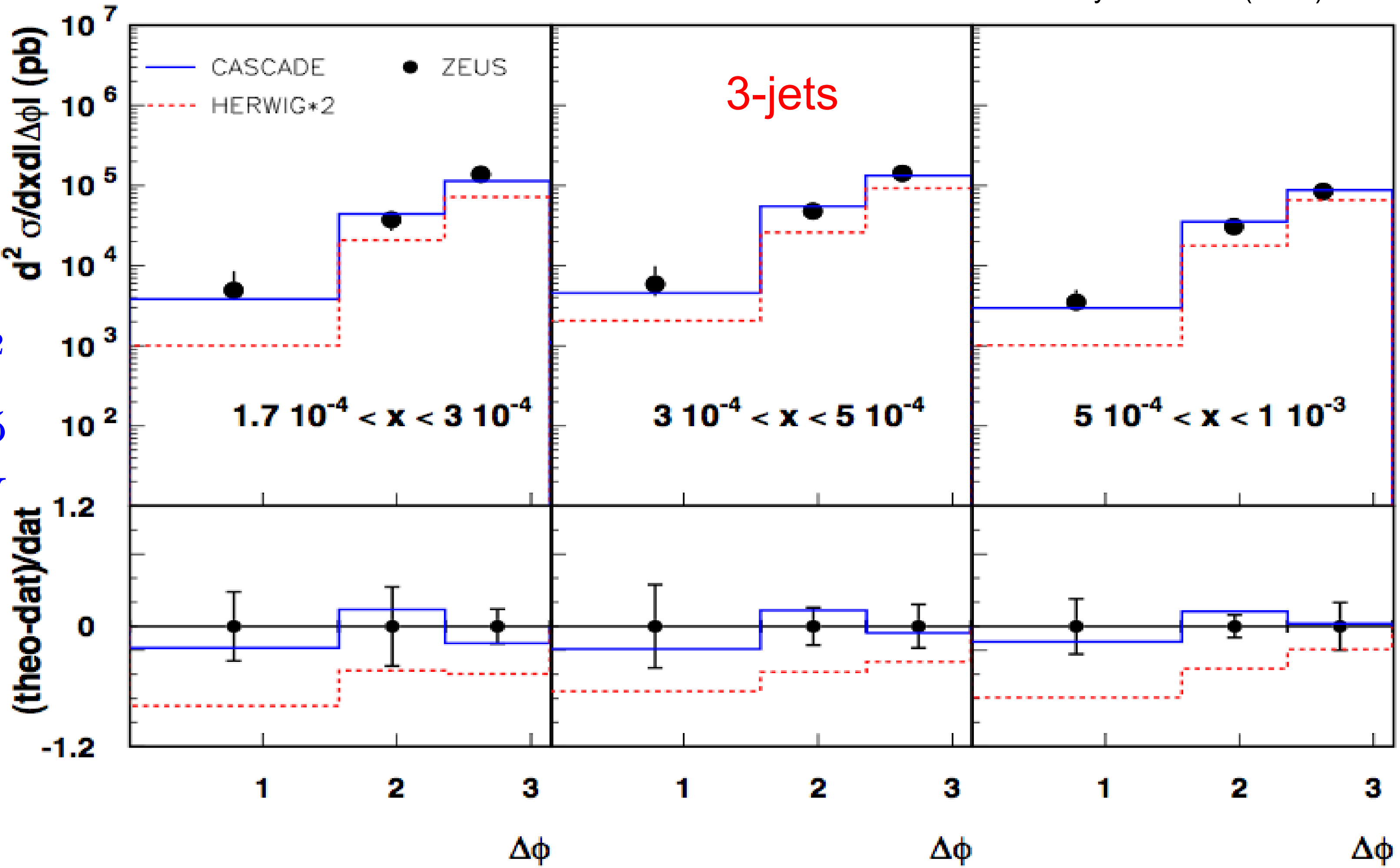
# 3-jets in DIS

S. Chekanov (ZEUS)
Nuclear Physics B 786 (2007) 152-180




$$Q^2 > 10 \text{ GeV}^2$$
$$-1 < \eta < 2.5$$
$$E_T > 7(5) \text{ GeV}$$




- well described by CASCADE using uPDFs

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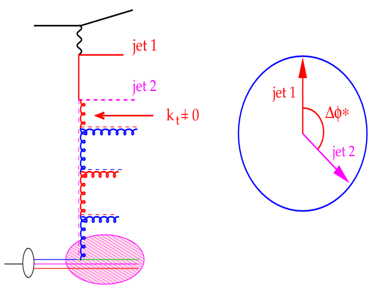


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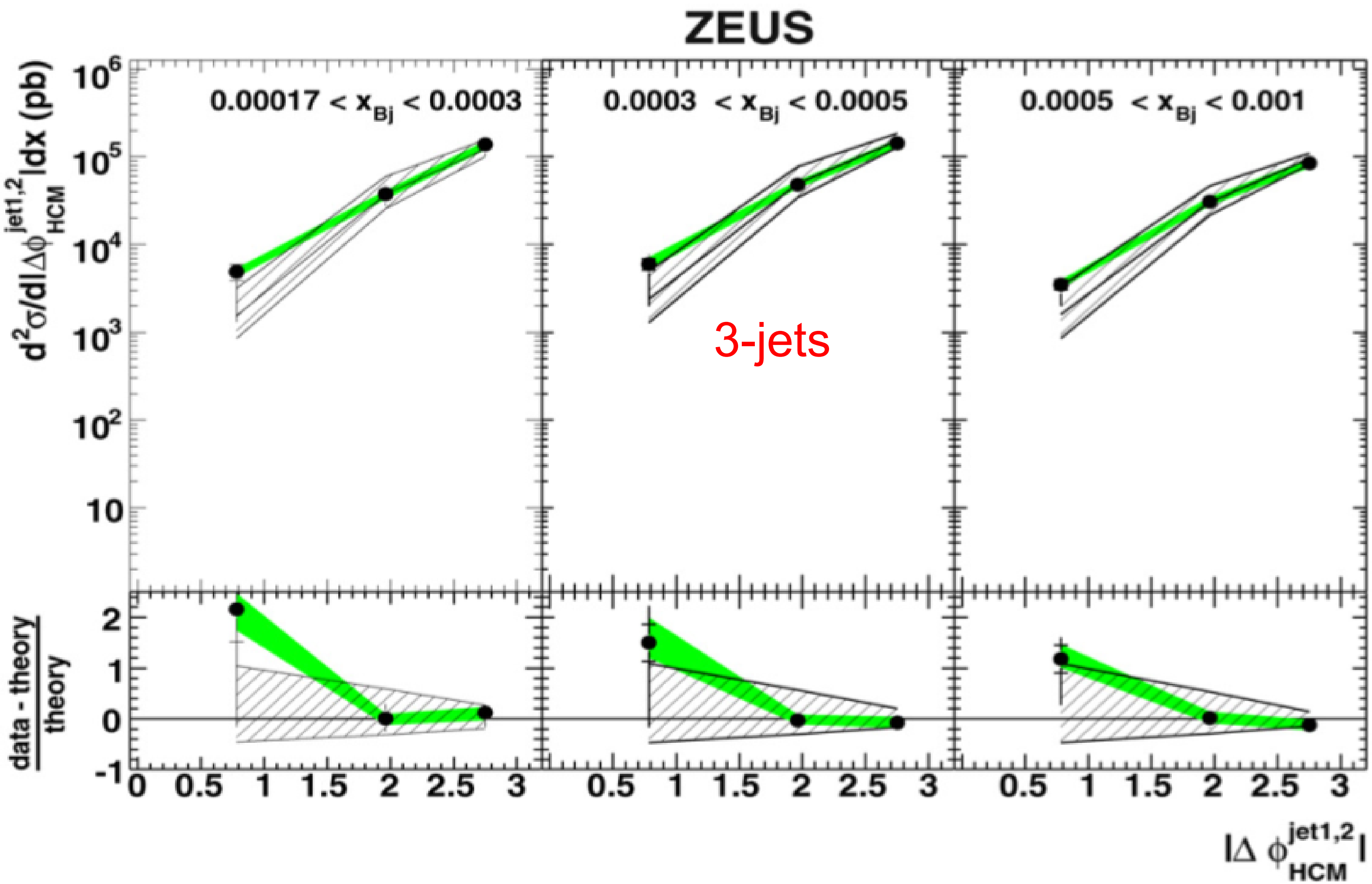
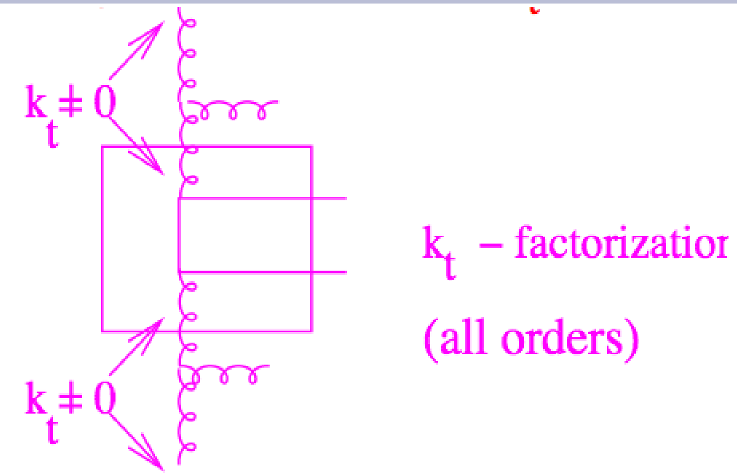



- well described by CASCADE using uPDFs
- ... much better than NLO-3-jet !!!!

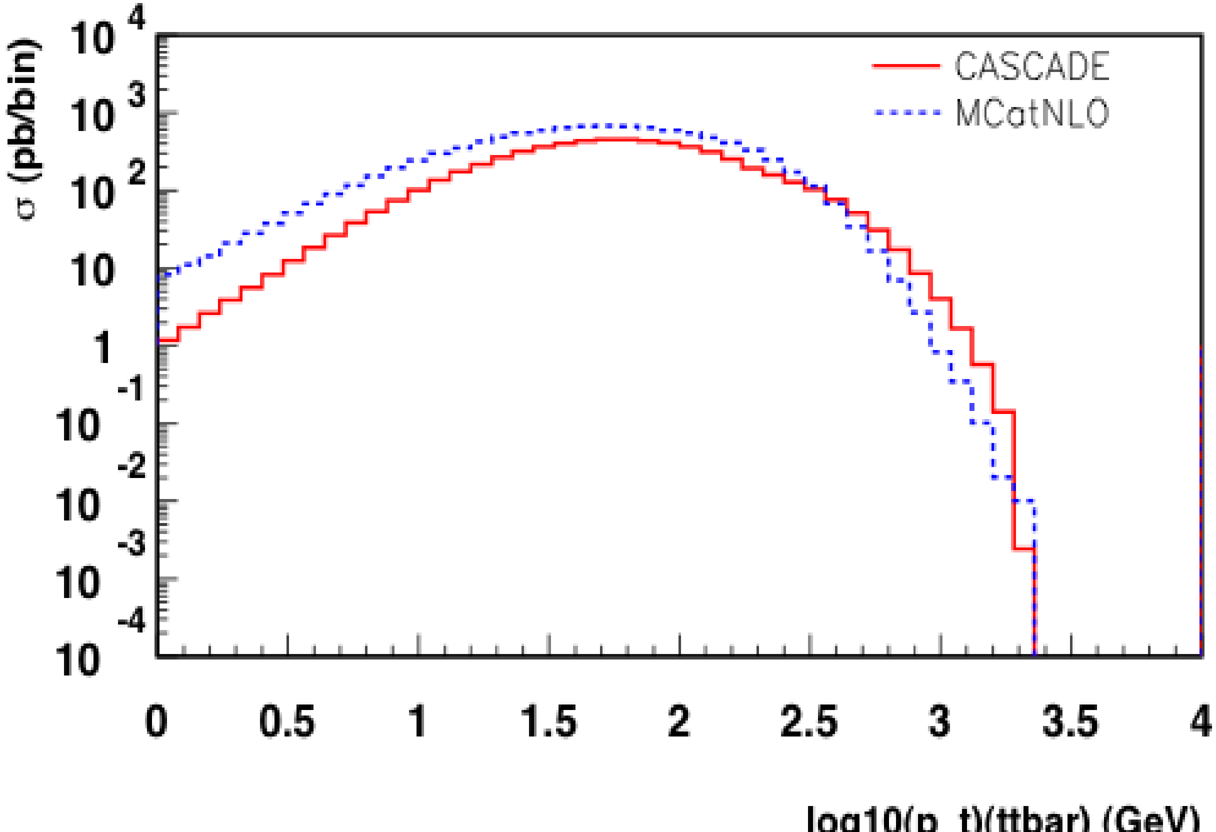
# CASCADE and NLO: pp

- compare CASCADE with MC@NLO for ttbar production at LHC




➔ sudakov suppression at small pt(ttbar-pair)

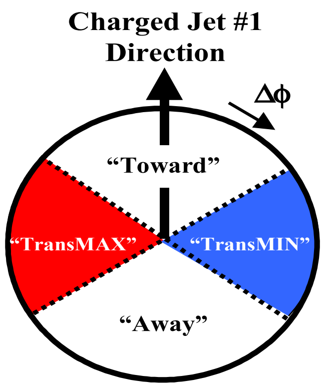
➔ even larger pt tail, coming from 2 off-shell gluons



# The hadronic final state

- hard process & hard additional radiation
  - ➔ NLO calculations and/or from parton showers with CCFM
- hard process & semi-hard radiation
  - ➔ hard multiparton interactions and/or parton showers

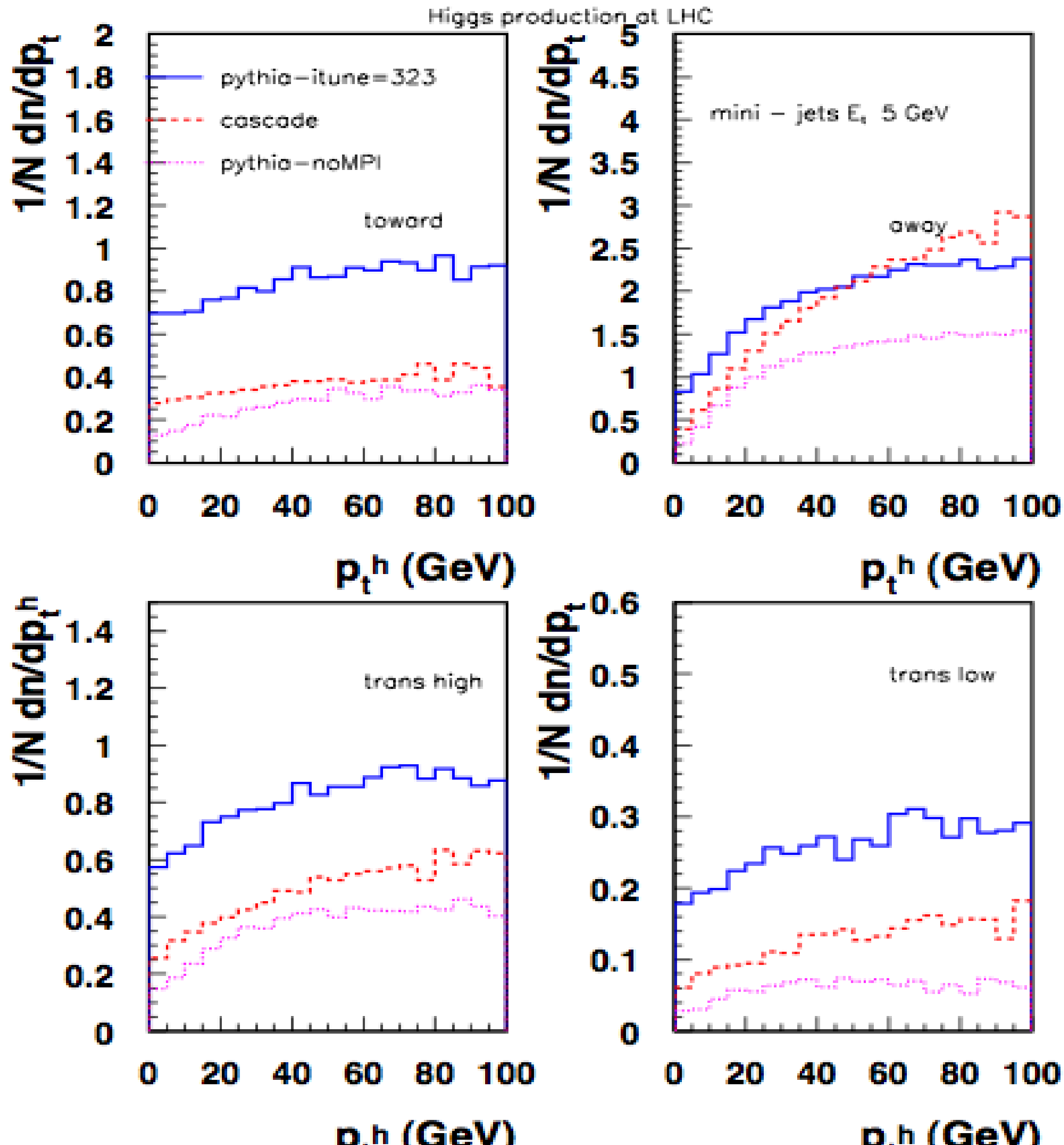
# The underlying event in pp → h X




Mini-jets $E_t$ > 5 GeV

- study underlying event in gluon process
- check $\langle N_{minijet} \rangle$ vrs $p_t^h$

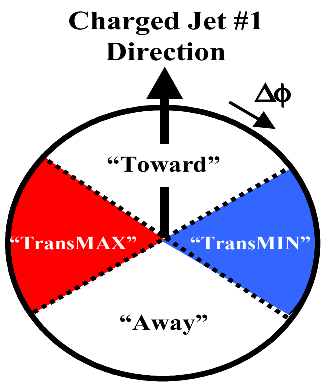
➔ CCFM parton shower produces higher multiplicity w/o Multiparton interactions

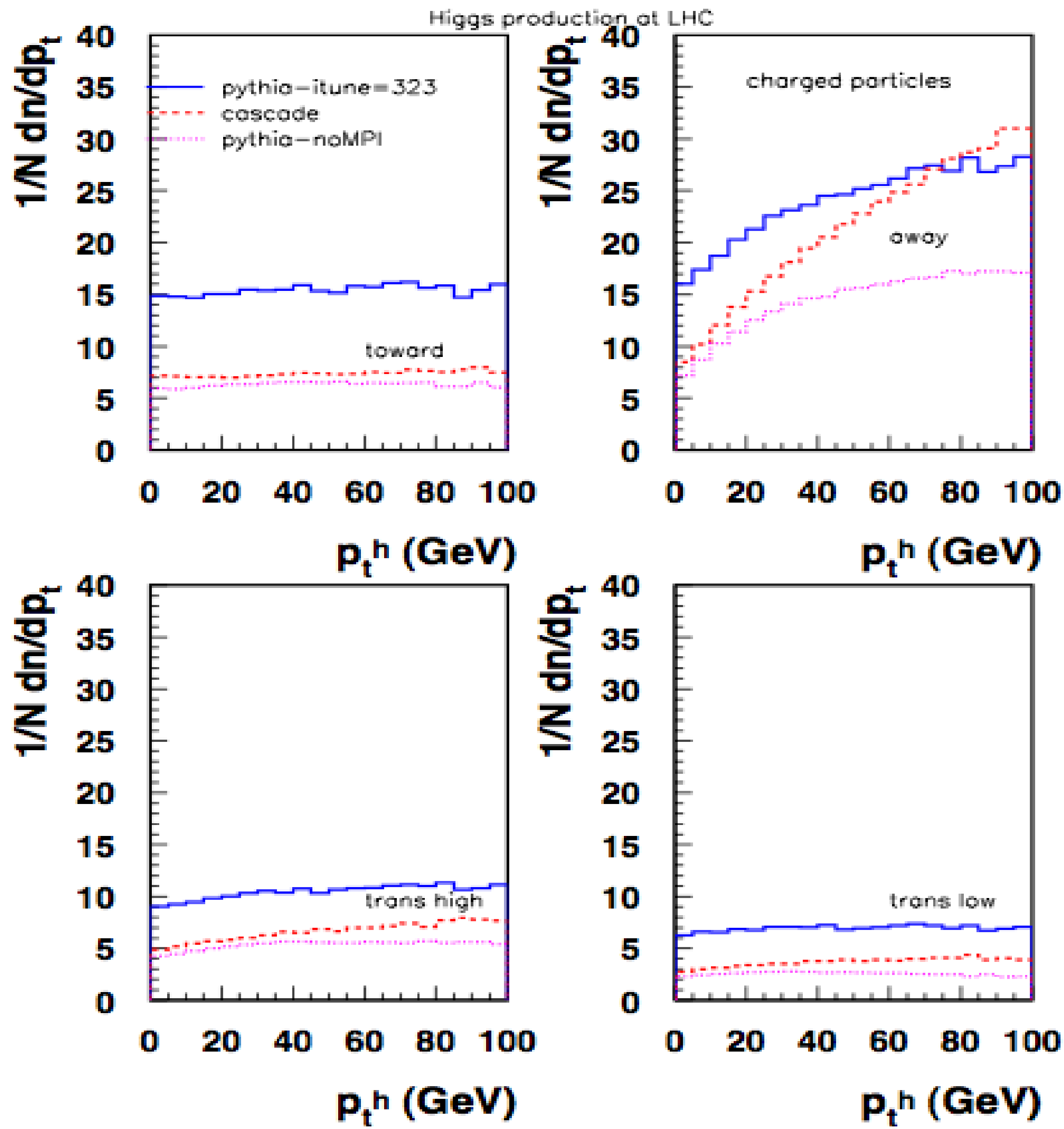


# The hadronic final state

- hard process & hard additional radiation
  - ➔ NLO calculations and/or from parton showers with CCFM
- hard process & semi-hard radiation
  - ➔ hard multiparton interactions and/or parton showers
- hard process & soft radiation
  - ➔ soft underlying events and multiparton interactions
  - ➔ see talk by Ll. Marti on HERA results

# The underlying event in pp → h X




charged particles

- study underlying event in gluon process, similar to UE study at Tevatron
- check $\langle N_{chrg} \rangle$ vrs $p_t^h$

➔ CCFM parton shower produces higher multiplicity

# The hadronic final state

- hard process & hard additional radiation
  - ➔ NLO calculations and/or from parton showers with CCFM
- hard process & semi-hard radiation
  - ➔ hard multiparton interactions and/or parton showers
- hard process & soft radiation
  - ➔ soft underlying events and multiparton interactions
  - ➔ see talk by Ll. Marti on HERA results
- soft process & soft radiation
  - ➔ min bias

# CASCADE for LHC

- Extension of CASCADE towards a **multipurpose event generator** applying $k_t$-factorization
- Inclusion of new processes ... matrix element calculations needed ...

- New processes with $W/Z/\gamma$ (by M. Deak, F. Schwennsen, S. Baranov, A. Lipatov, N. Zotov)

$$pp \rightarrow W^{\pm} + jets + X$$
$$pp \rightarrow Z^{0} + jets + X$$
NEW
$$pp \rightarrow \gamma + jets + X$$

- more on jets:
  see talk by M.Deak
  $qg^* \rightarrow qg$
  NEW

# 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
  - ➔ possibility to include saturation in evolution
- CASCADE for pp at high energies
  - ➔ at $x \ll 10^{-3}$ small x improved parton radiaton is needed
  - ➔ gives higher minijet multiplicity than obtained in DGLAP models

**CASCADE simulates small x QCD parton radiation beyond collinear approach**

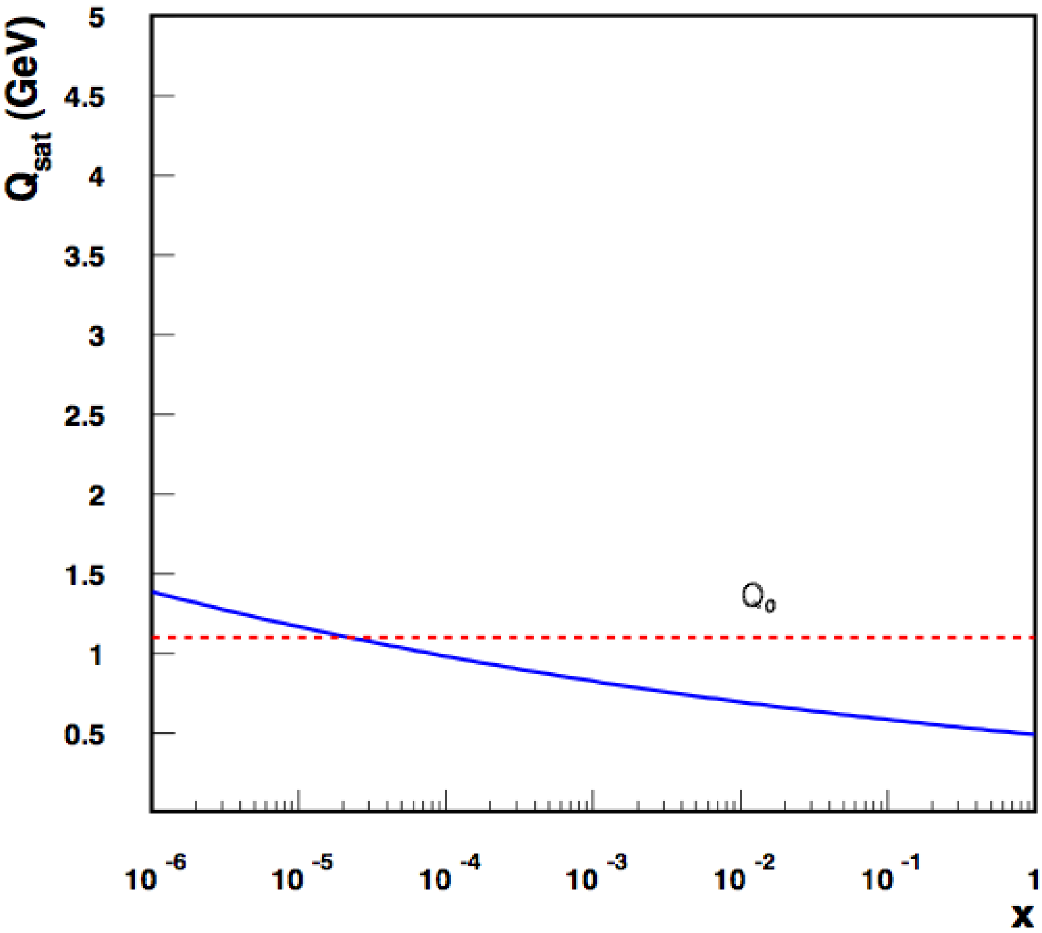
# Backup Slides

# Saturation scale

- saturation during evolution

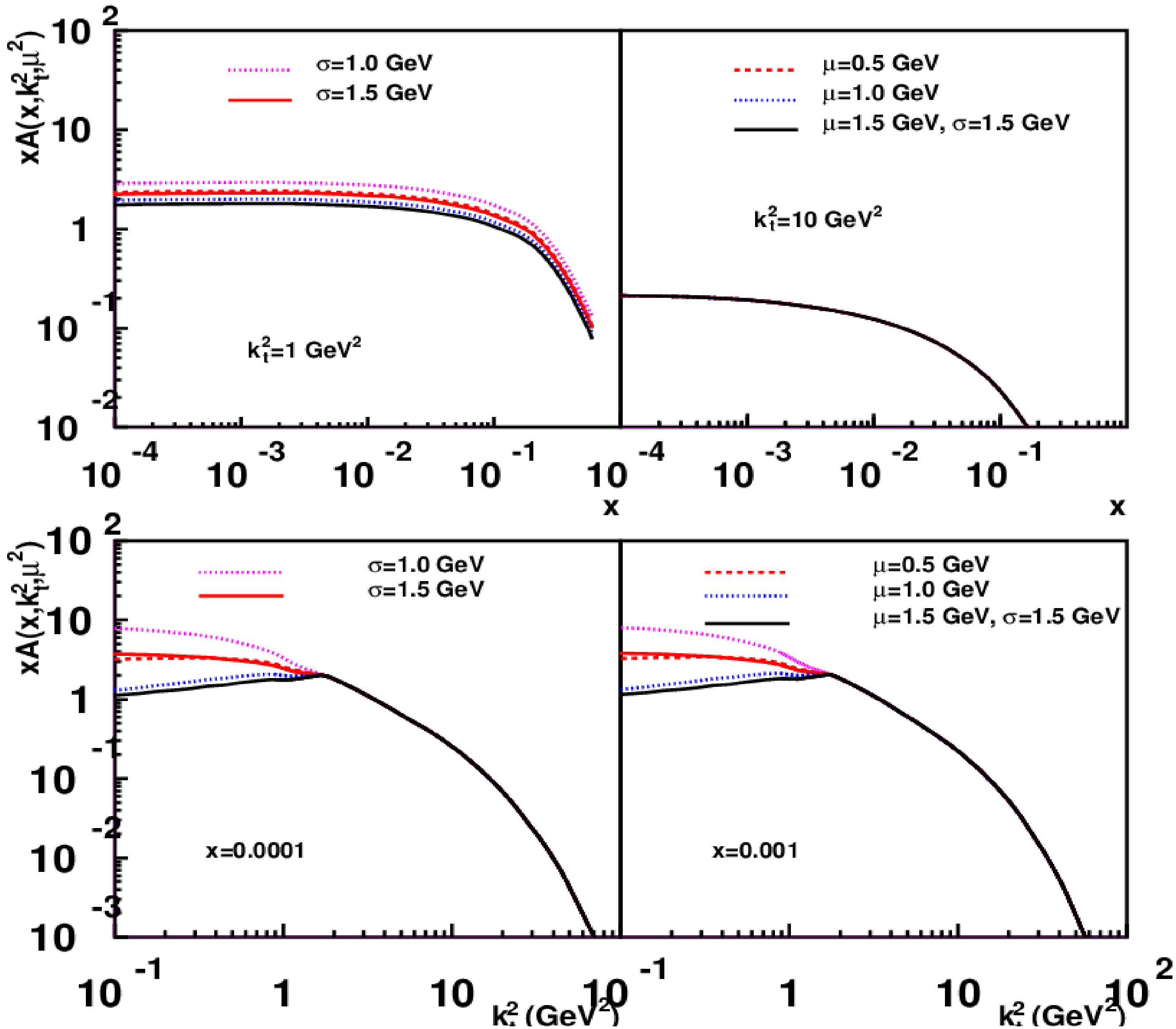
$$Q_{sat} = \max\left(Q_0, \left(\frac{x}{x_0}\right)^{-\lambda/2}\right)$$

- following ansatz from Mueller et al, Avsar et al, Kutak et al:
  - ➔ for $k_t$ below $Q_{sat}$ use absorptive boundary
  - ➔ evolution continues with no-branching from starting distribution
- no – saturation during evolution..



# uPDFs from di-jets: intrinsic $k_t$

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



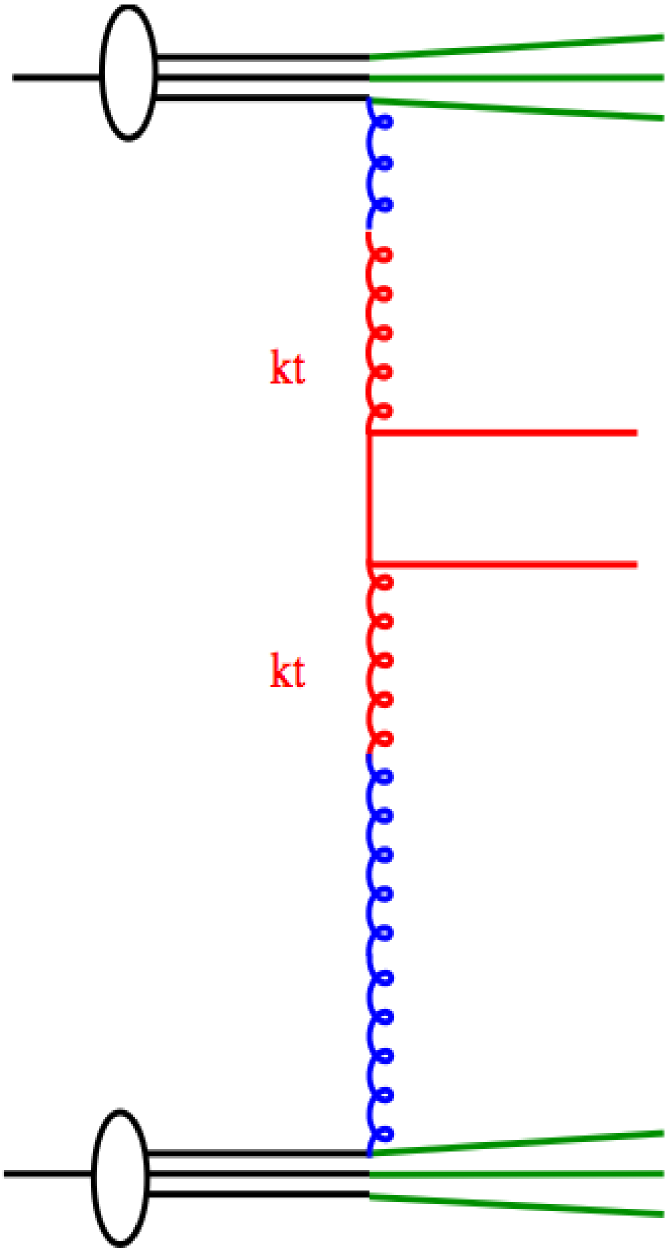

- different intrinsic $k_t$-distributions only accessible in uPDFs
- sensitive to the mix of small and large $k_t$

➔ small kt determines total x-section

➔ large kt influences perturbative tails ...

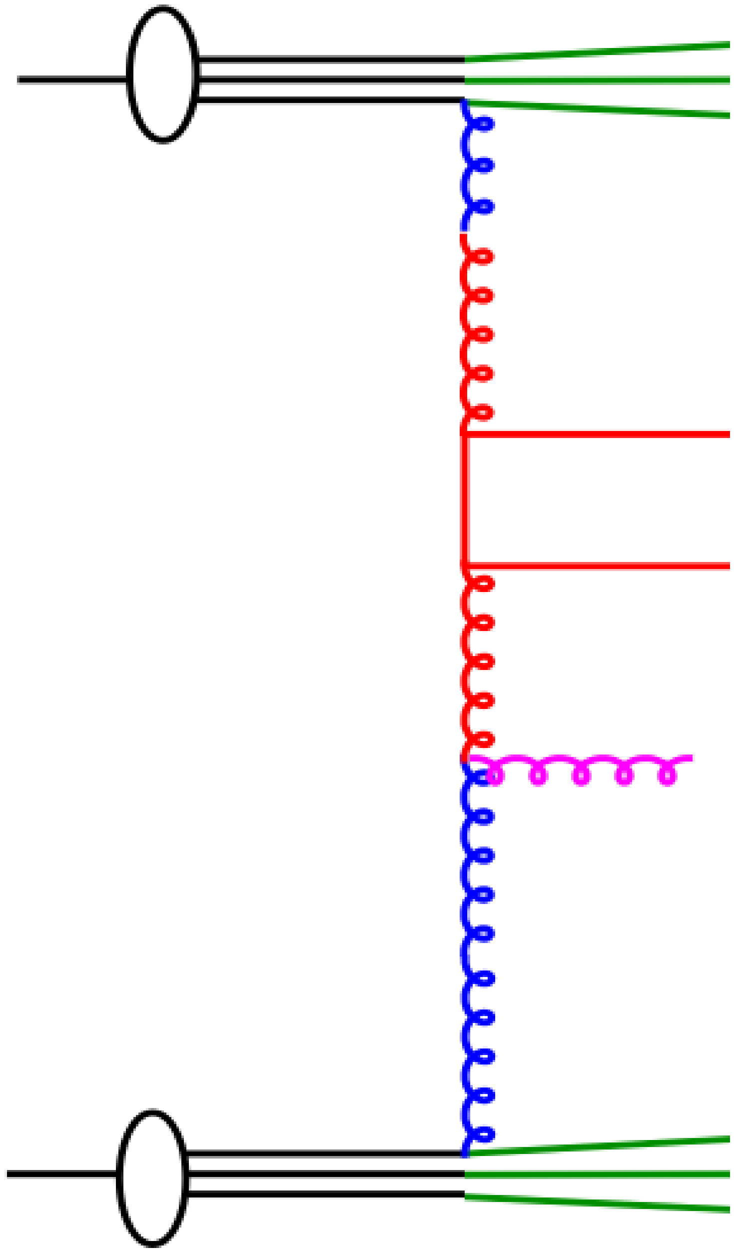
# Constructing the hadronic final state

- use backward evolution, starting from hard scattering.
- kinematics of hard scattering fixed from using uPDF.



# Constructing the hadronic final state

- use backward evolution, starting from hard scattering.
- kinematics of hard scattering fixed from using uPDF.
- real parton emission generated, from Sudakov form factor, splitting function and uPDF



# Constructing the hadronic final state

- use backward evolution, starting from hard scattering.
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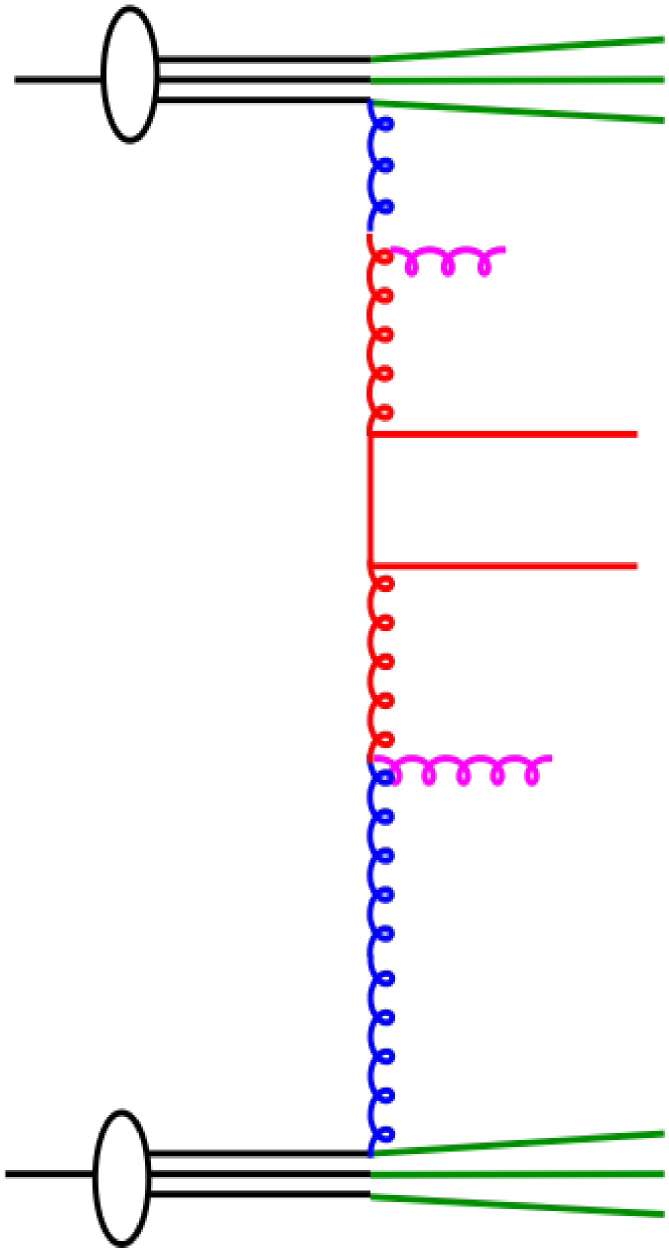
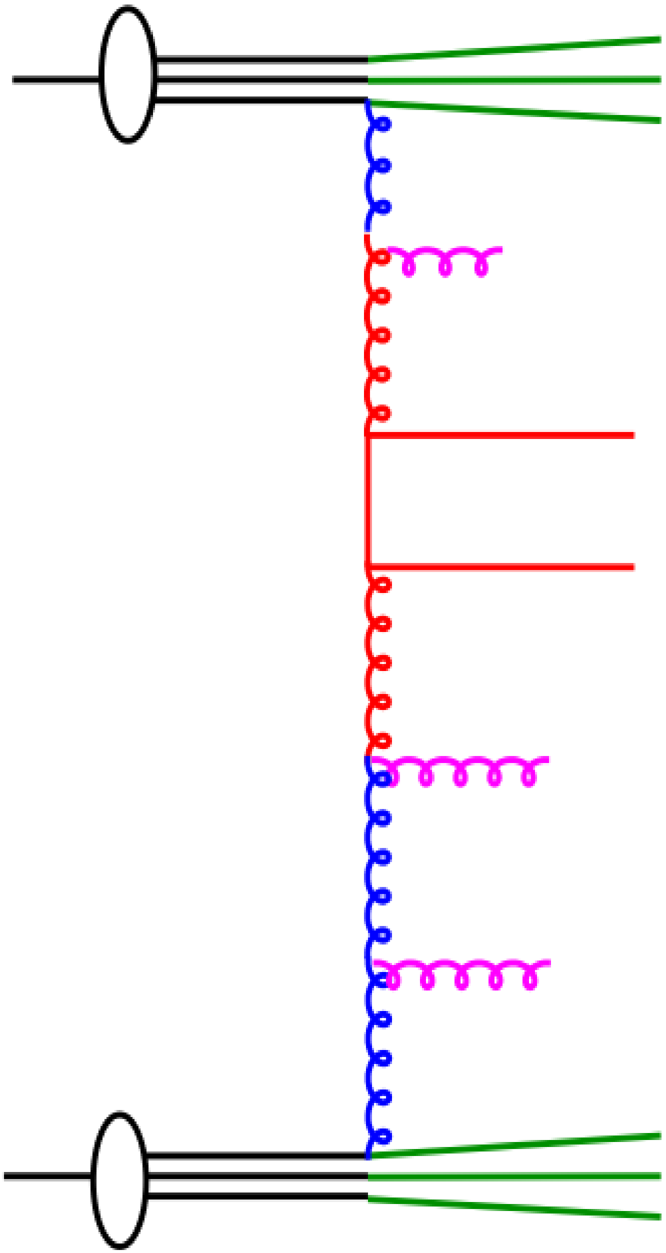
- real parton emission generated, from Sudakov form factor, splitting function and uPDF
- next real emission generated ...



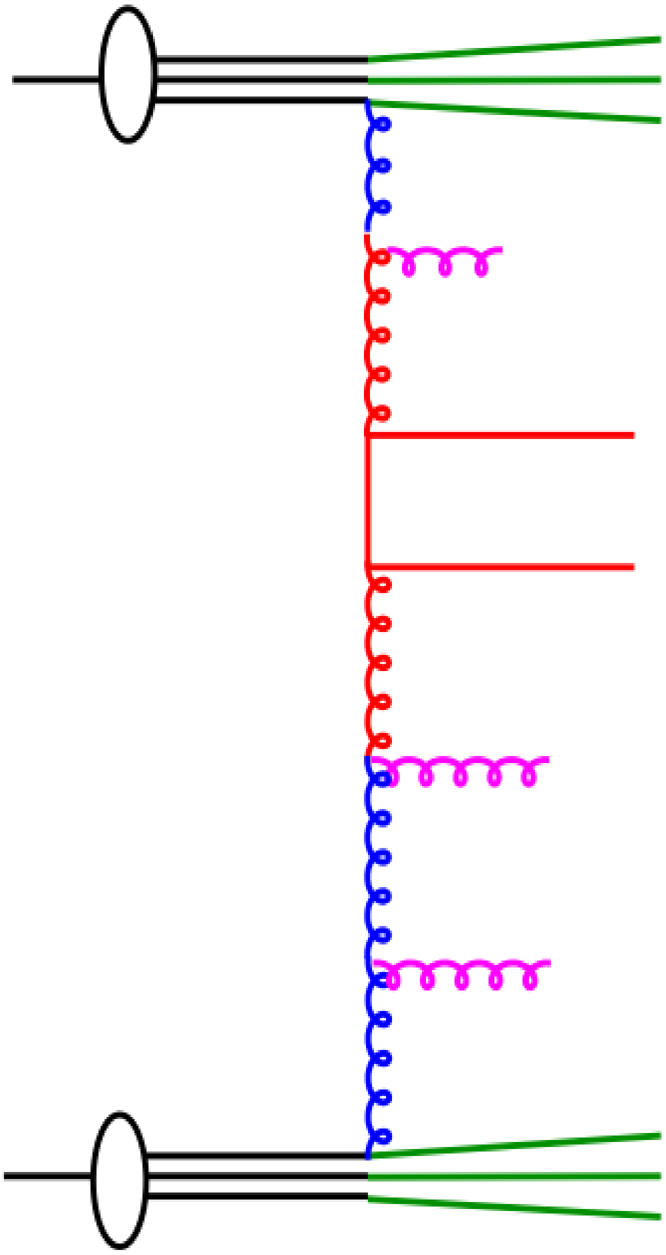
# Constructing the hadronic final state

- use backward evolution, starting from hard scattering.
- kinematics of hard scattering fixed from using uPDF.
- real parton emission generated, from Sudakov form factor, splitting function and uPDF
- next real emission generated ...
- and next and next until cutoff scale $Q_0$



# Constructing the hadronic final state

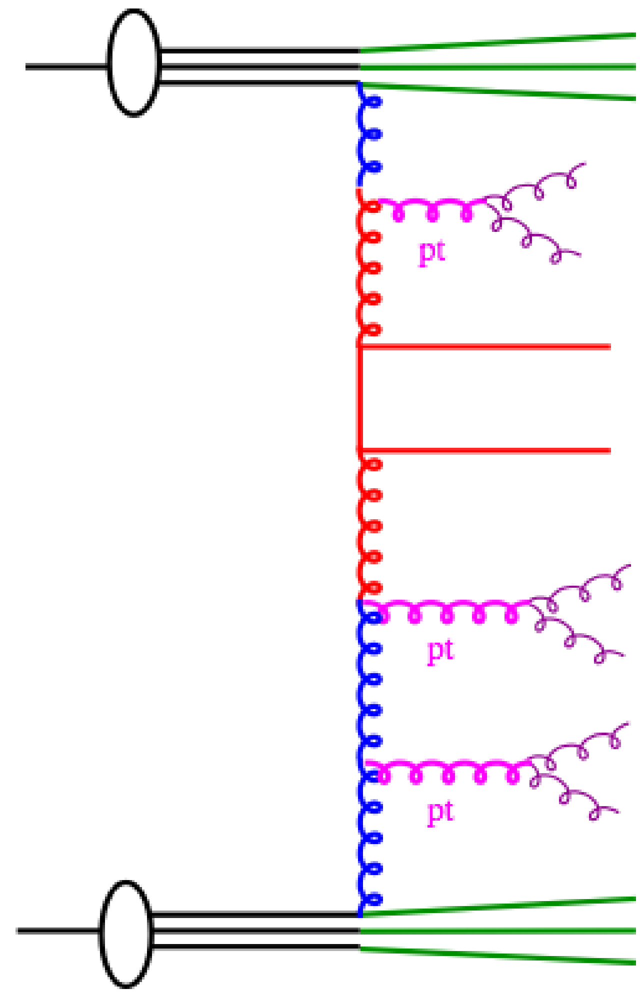
- use backward evolution, starting from hard scattering.
- kinematics of hard scattering fixed from using uPDF.
- real parton emission generated, from Sudakov form factor, splitting function and uPDF
- next real emission generated ...
- and next and next until cutoff scale $Q_0$
- **NO change in kinematics of hard scattering from adding parton showers**



# Further initial state shower issues

- Timelike cascade in initial state radiation
- $p_t$ of gluon taken as maximum scale
  - ➔ kinematics of subsequent emissions changed because of finite virtuality $p^2 = p_t^2$
- does not change hard scattering
- effect seen in soft particle production

NEW



# Further initial state shower issues

- Timelike cascade in initial state radiation
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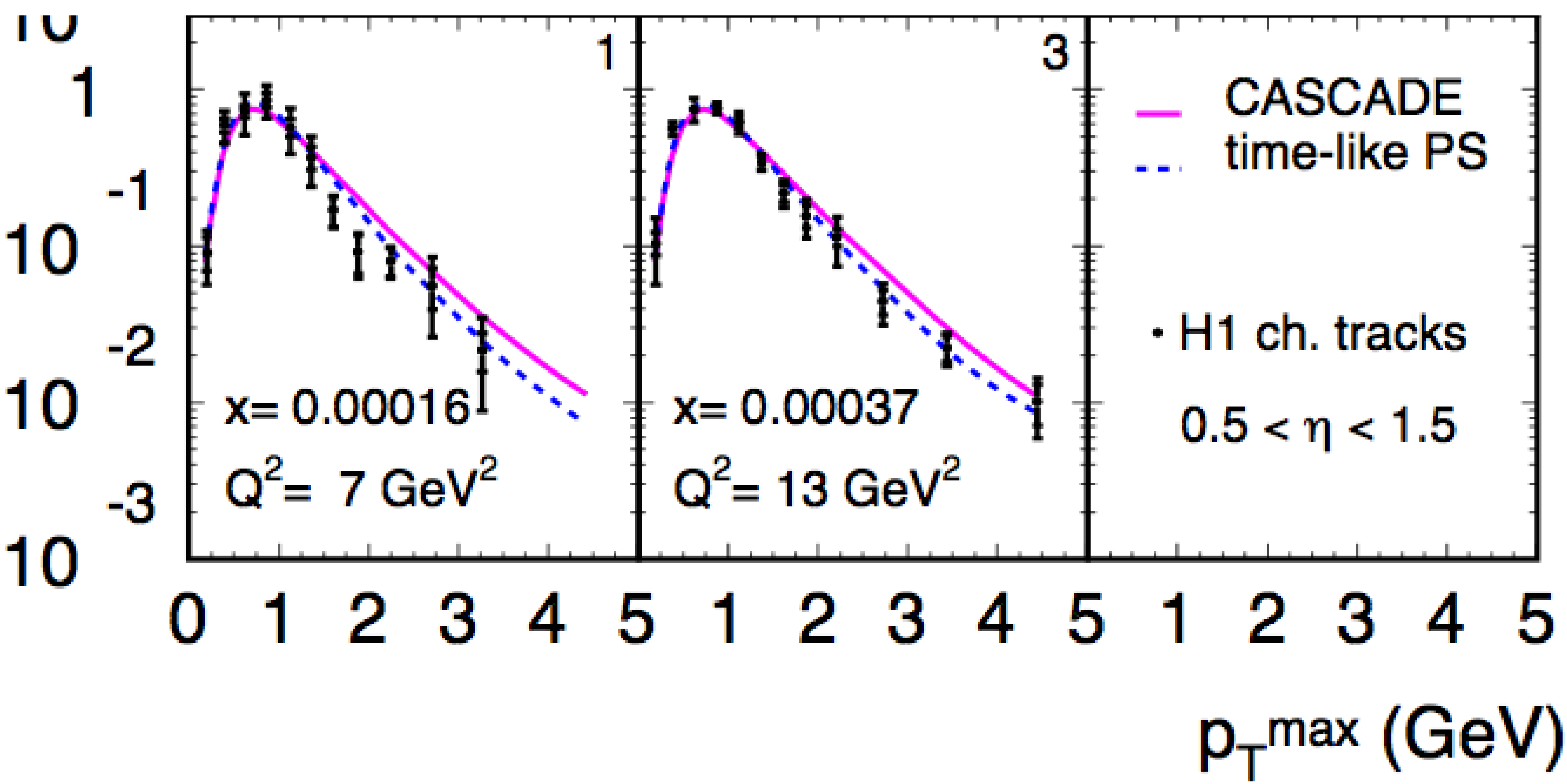
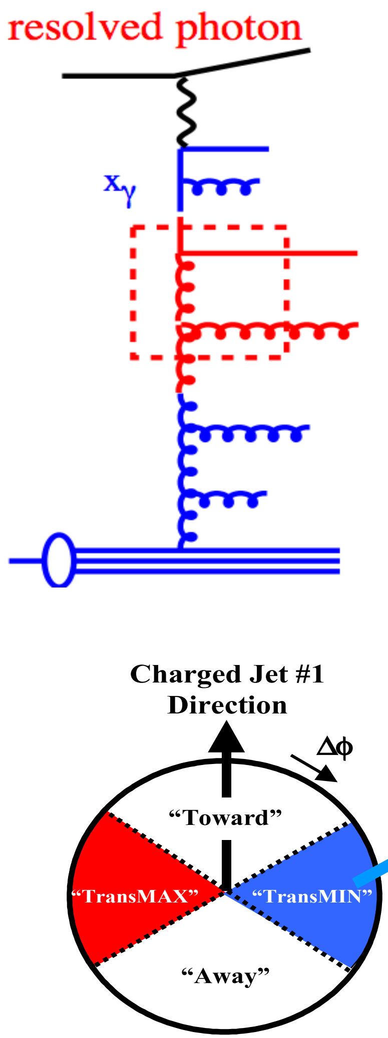
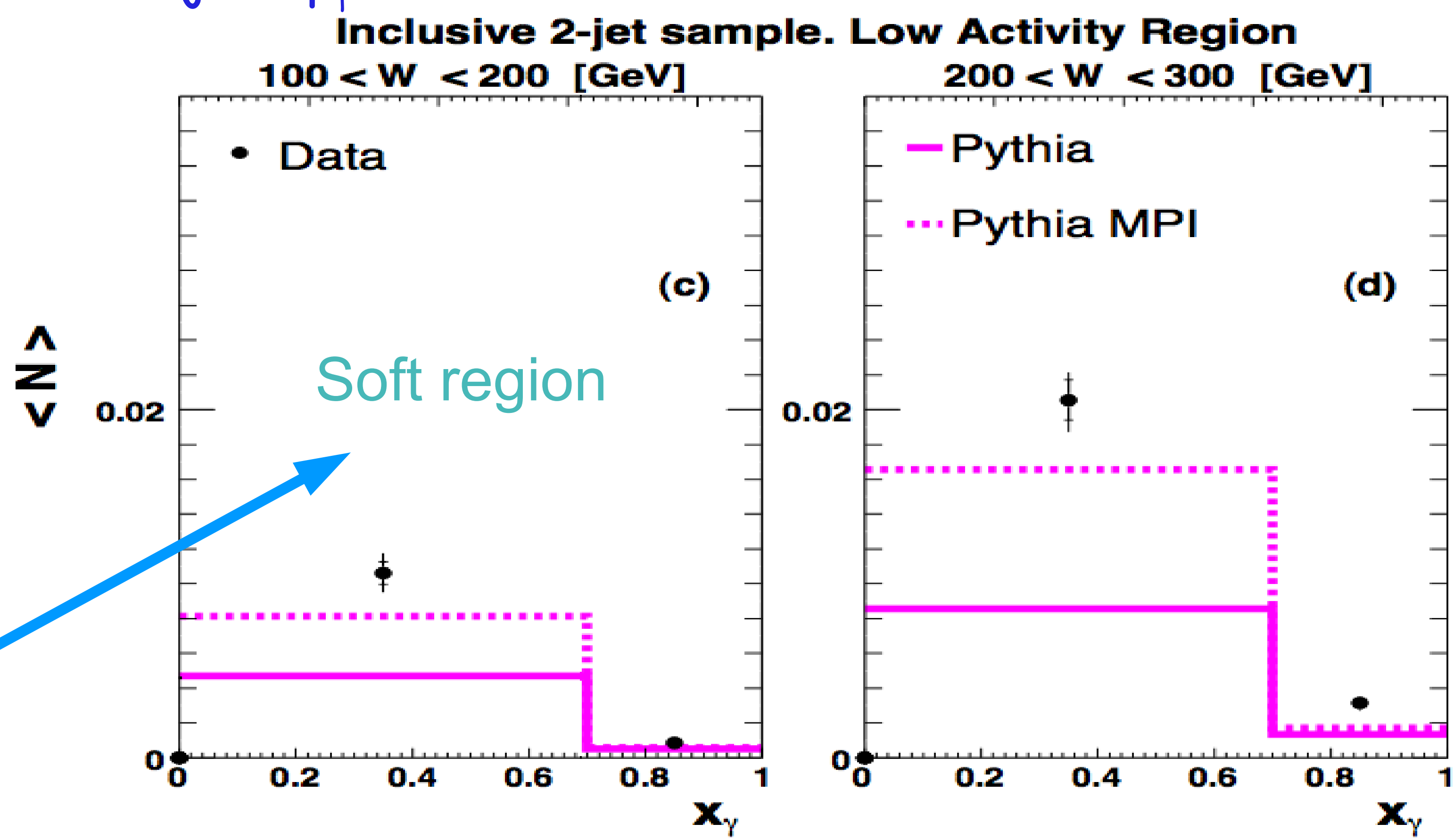


# Studies at HERA: DIS

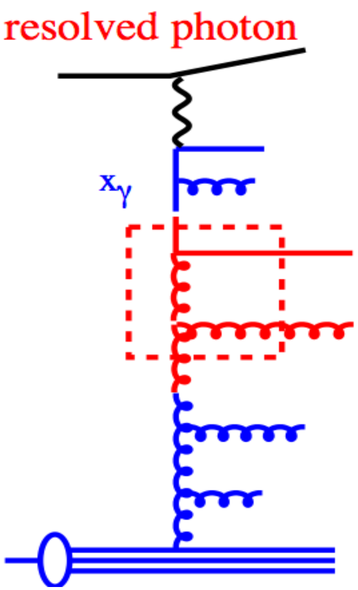



- Underlying events in DIS ($Q^2 > 5$ GeV$^2$): minijets $p_t > 3.5$ GeV




➔ **Minjet multiplicities are not at all described !**

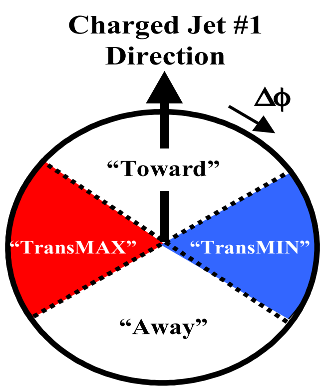
# What if using CCFM in DIS ?

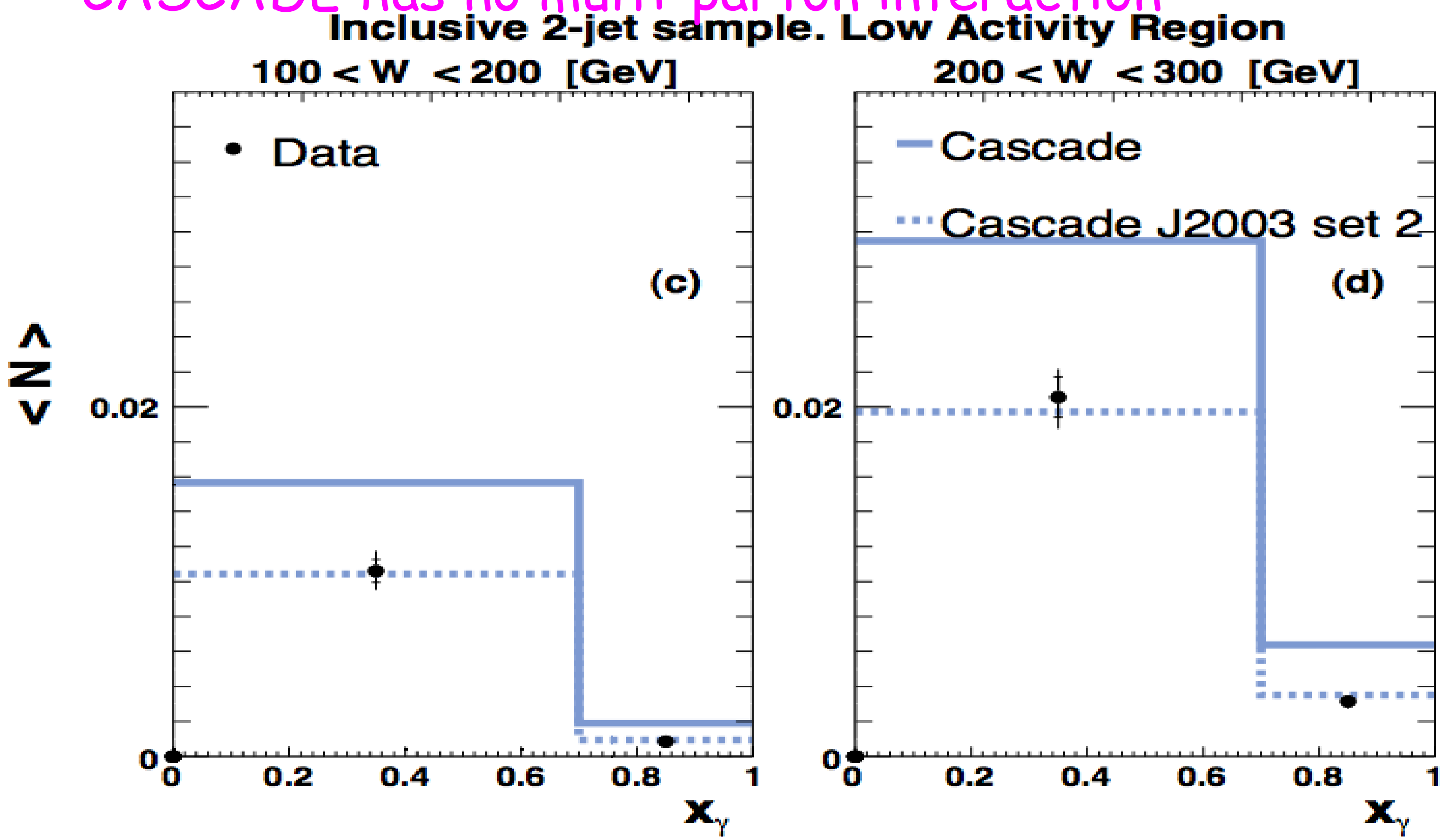



- Underlying events in DIS (Q2 > 5 GeV2): minijets pt > 3.5 GeV

S. Osman, H1 PhD thesis, Lund 2008,h1th-499

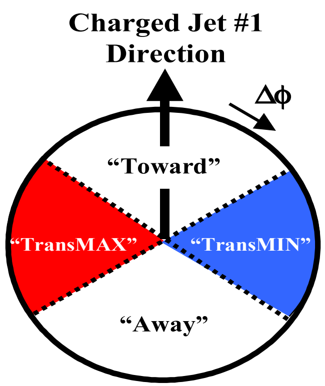
- CASCADE has no multi-parton interaction




➔ **Minjet multiplicities are well described !**

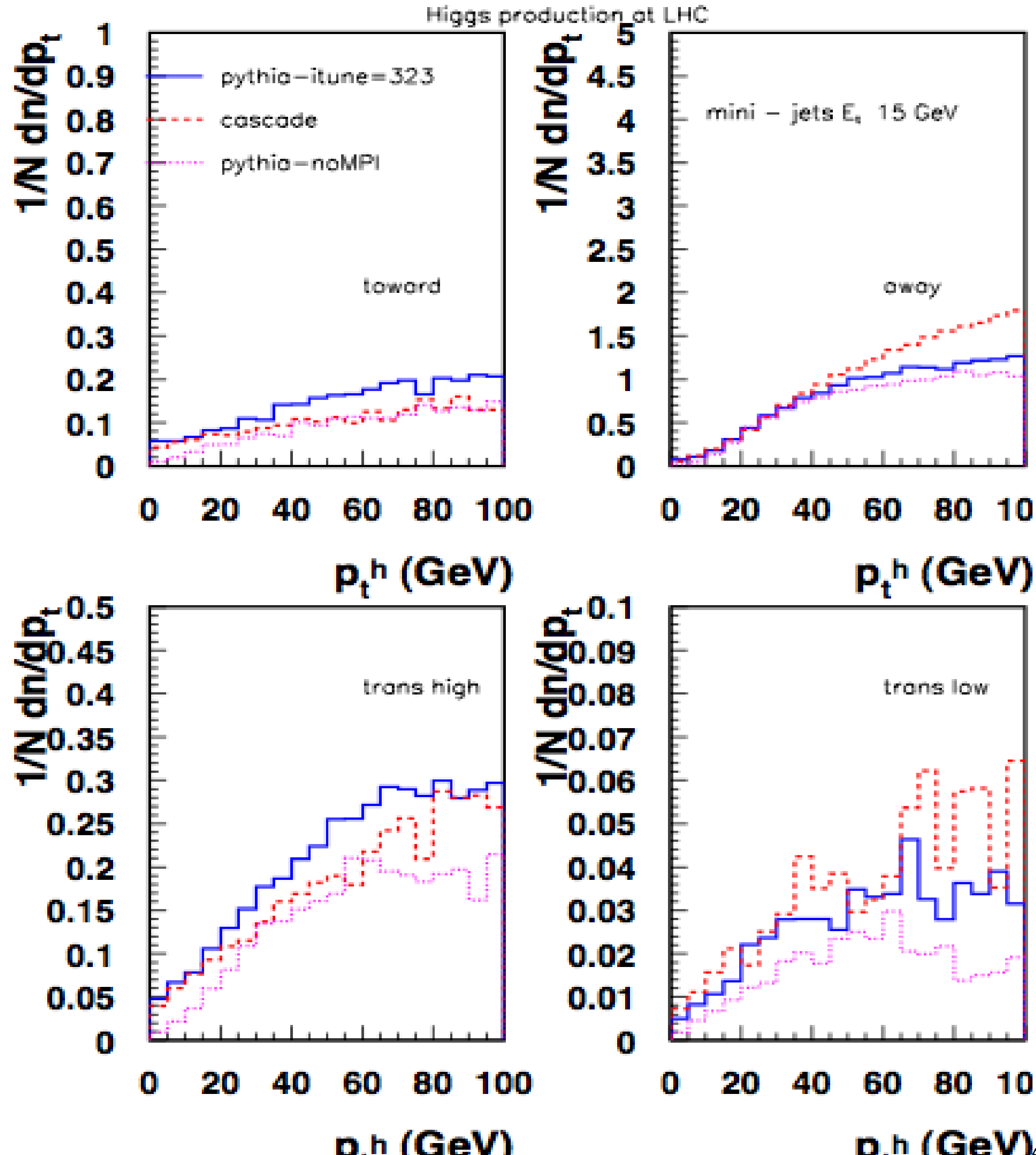
# The underlying event in pp → h X




Mini-jets $E_t$ > 15 GeV

- study underlying event in gluon process
- check $\langle N_{minijet} \rangle$ vrs $p_t^h$

➔ CCFM parton shower produces higher multiplicity w/o multi-parton interactions



# $Z_0$/W production in pp

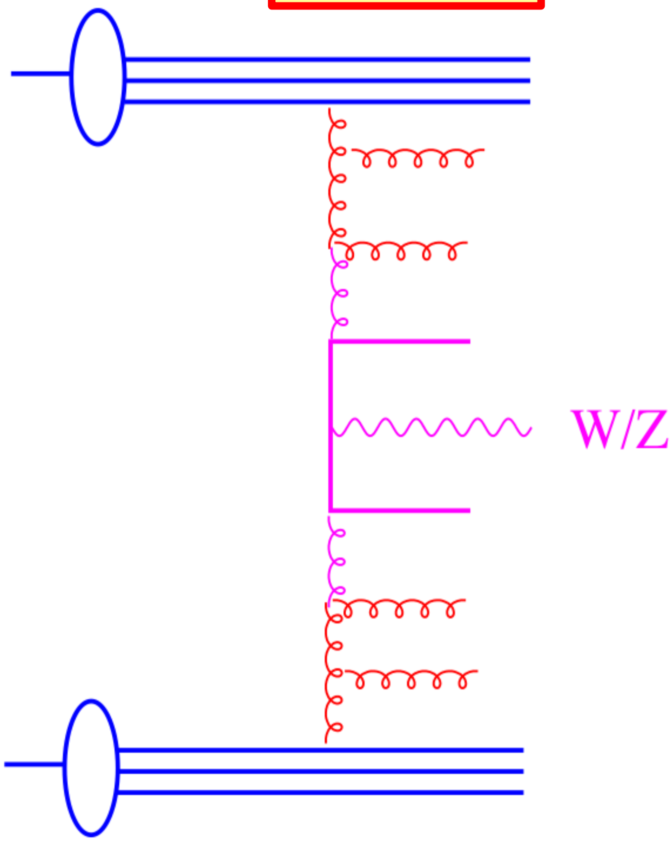
- calculations performed:
  - M. Deak, F. Schwennsen
  - S. Baranov, A. Lipatov, N. Zotov

$$gg \to Z_0/W^{\pm} + q + \bar{q}$$

$$gg \to Z_0/W^{\pm} + Q + \bar{Q}$$

- calculation now finished

NEW




- fully implemented in CASCADE
- allows comparison with collinear calculation, for the first time with W and Z

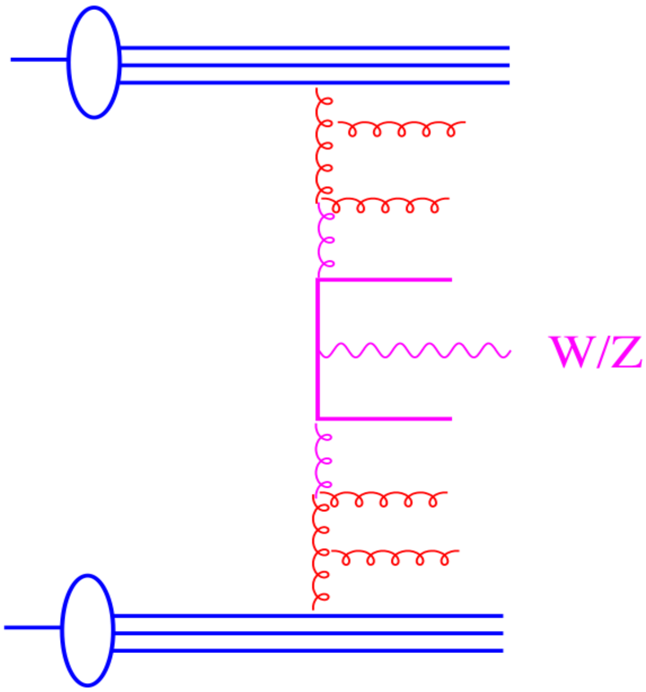
# $Z_0$+jets production in pp

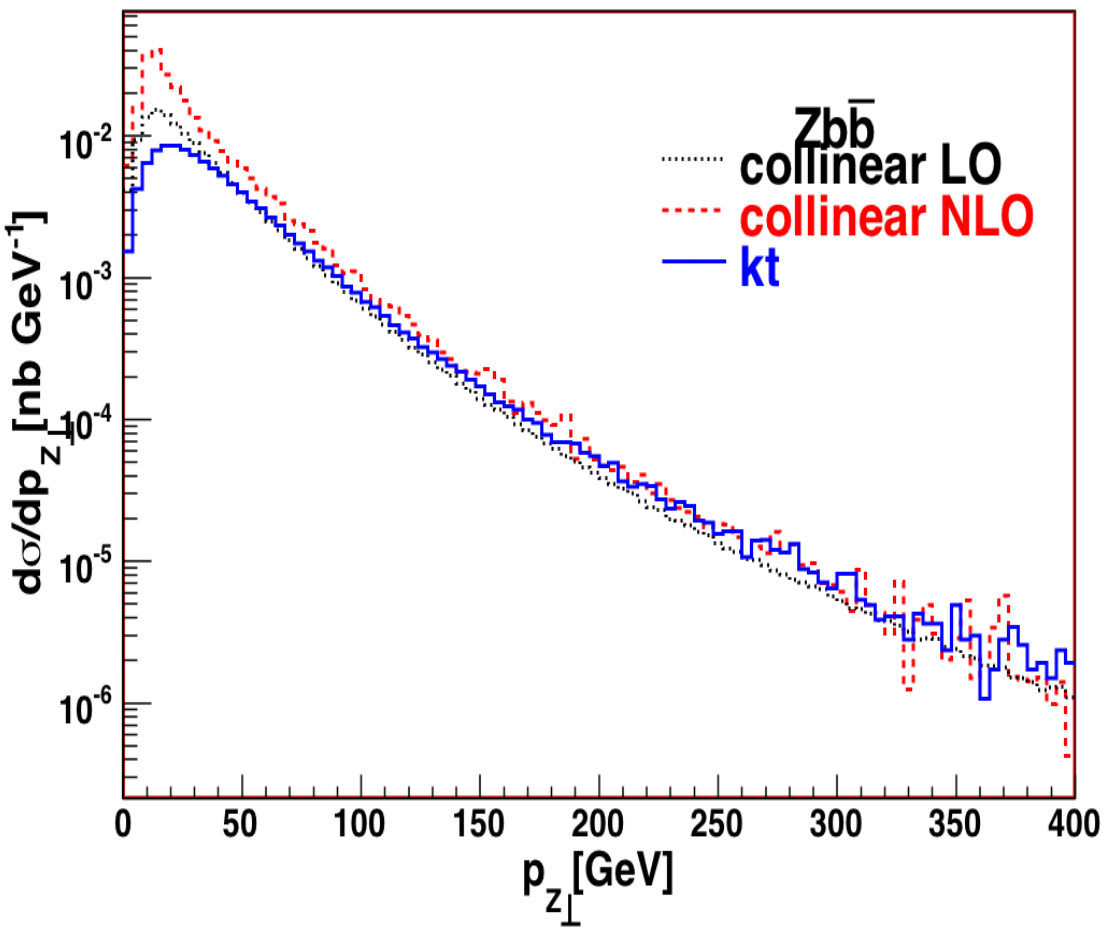
- M. Deak, F. Schwennsen

from hep-ph/0805.3763.

NEW

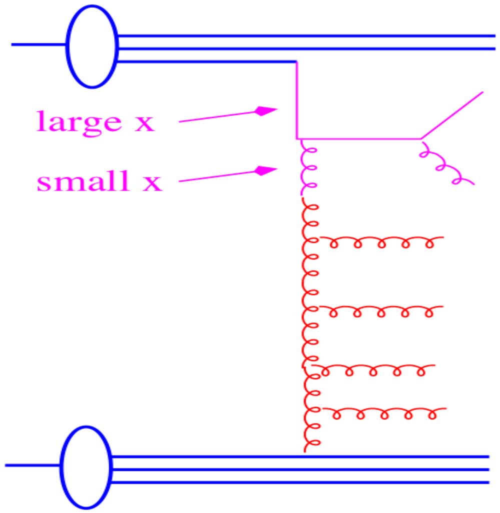
$$gg \to Z_0/W^{\pm} + Q + \bar{Q}$$

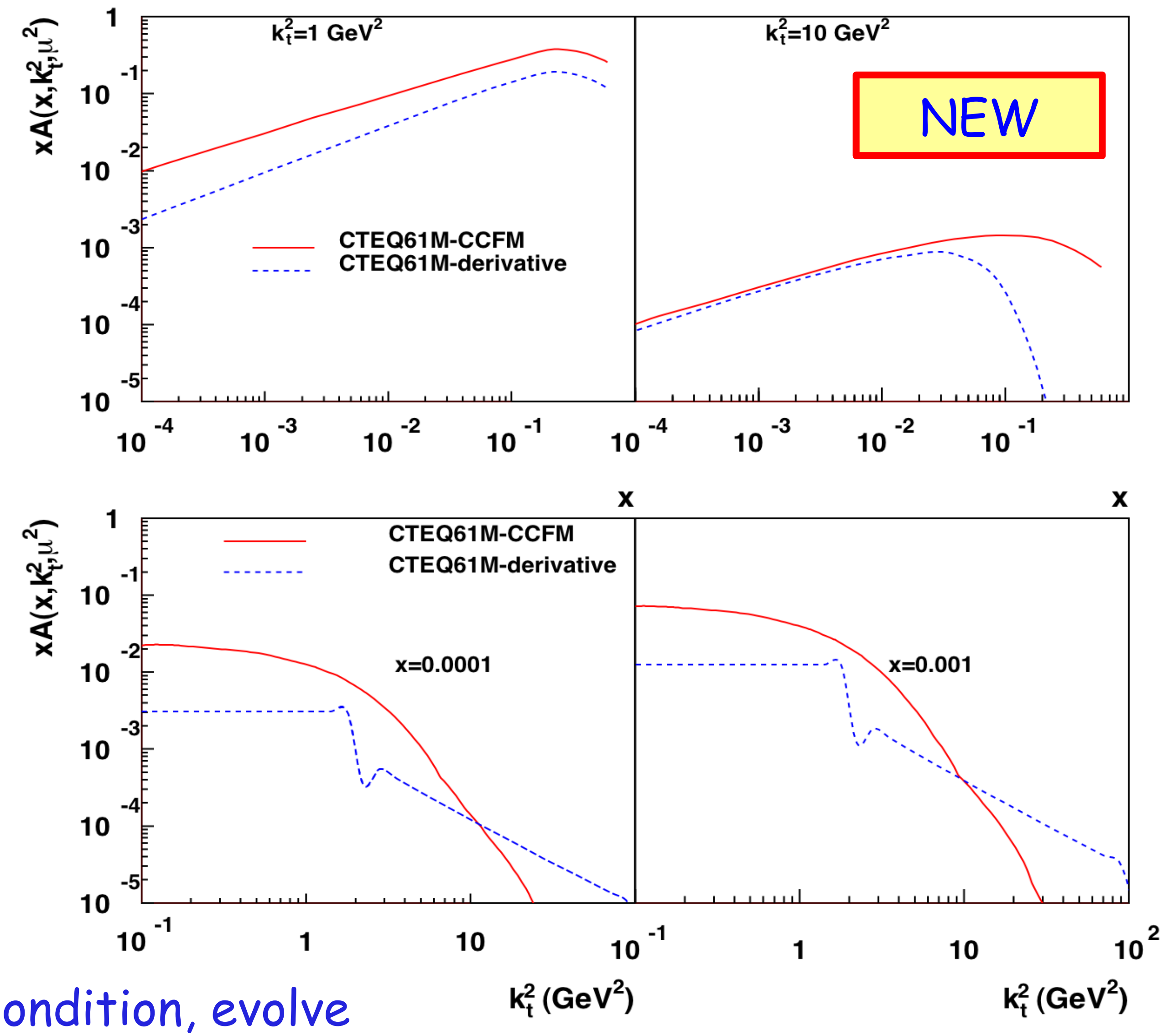


# Including valence quarks

- including $qg \to qg$
- important for forward jets ....




- need unintegrated valence quarks:
  - use CTEQ61 as initial condition, evolve with "CCFM-type" splitting fct