# The CASCADE MC event generator

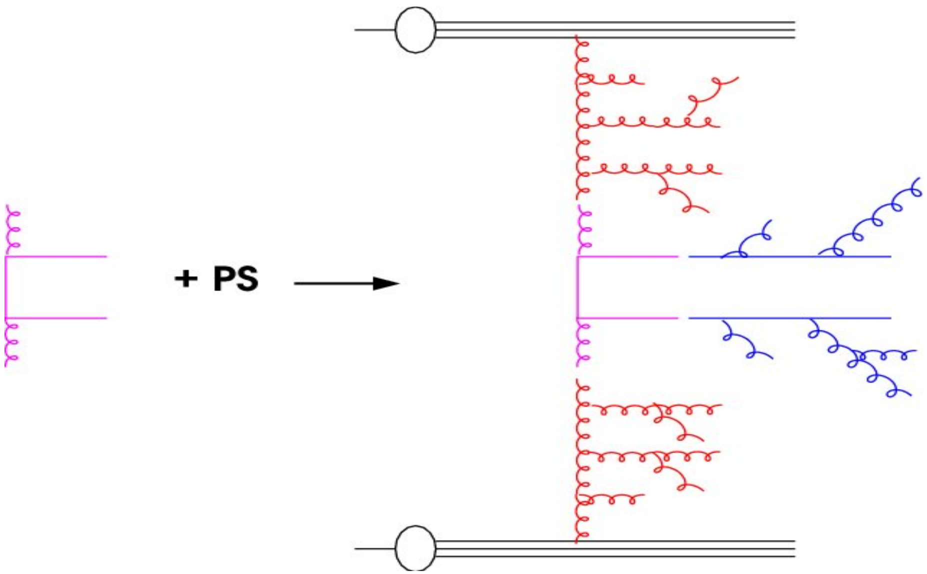
H. Jung (DESY)

- What it is about ....
- Critics of the collinear approach ...
- CASCADE
  - Basic idea
  - applications at the TeVatron
  - applications for LHC
- HowTo run CASCADE
  - topics for the exercises

# CASCADE ...

... is a hadron level
Monte Carlo event generator for
QCD type processes
with emphasis on the
initial state parton evolution

# Collinear ansatz: ME & parton evolution

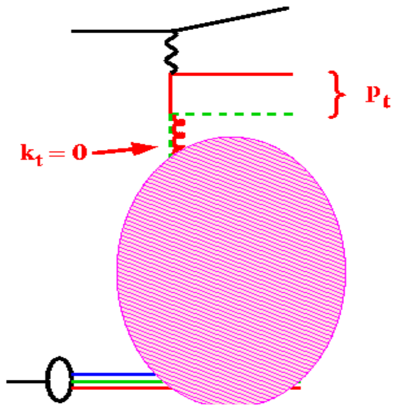


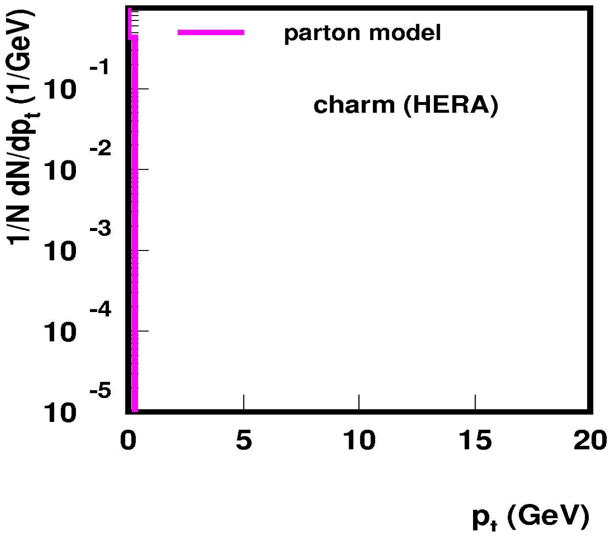

- use LO matrix elements (on-shell, no transverse momentum)
  - cutoffs are needed to avoid divergencies.....
- apply initial and final state parton showers (**PS**)
  - need matching of cutoff in ME with parton showers
- apply hadronization
- obtain cross sections fully differential in any observable
- **BUT:**
  - mainly in LO and a few attempts in NLO: Collins et al, MC@NLO, etc )

# Problems in Collinear Approximation

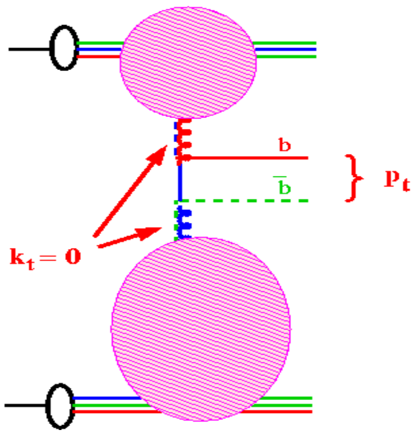
J. Collins, H. Jung hep-ph/0508280

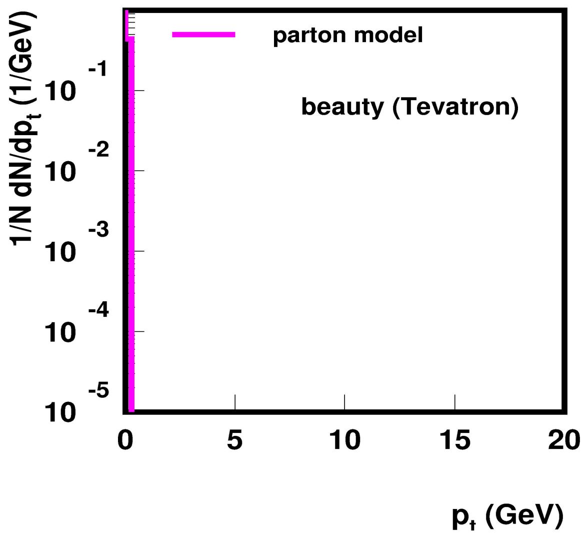
heavy quarks at HERA



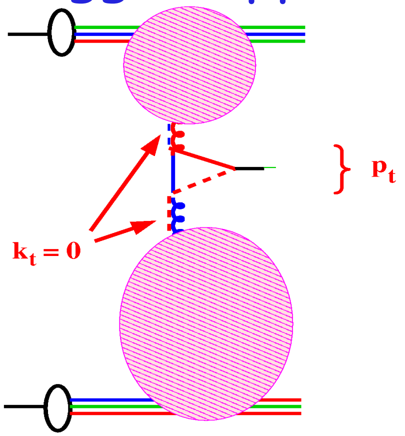



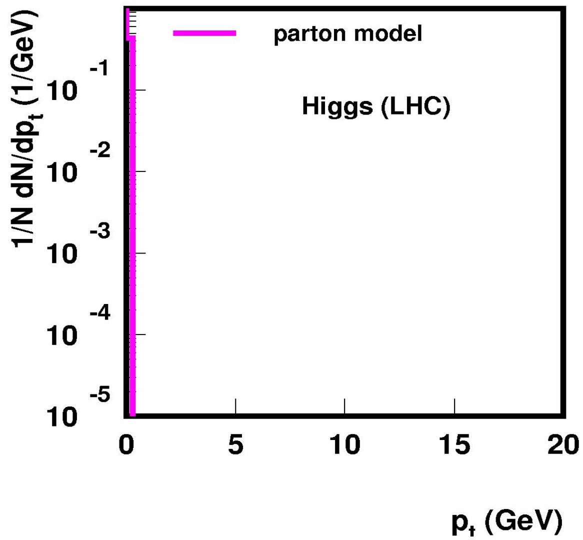

heavy quarks in pp




Higgs in pp



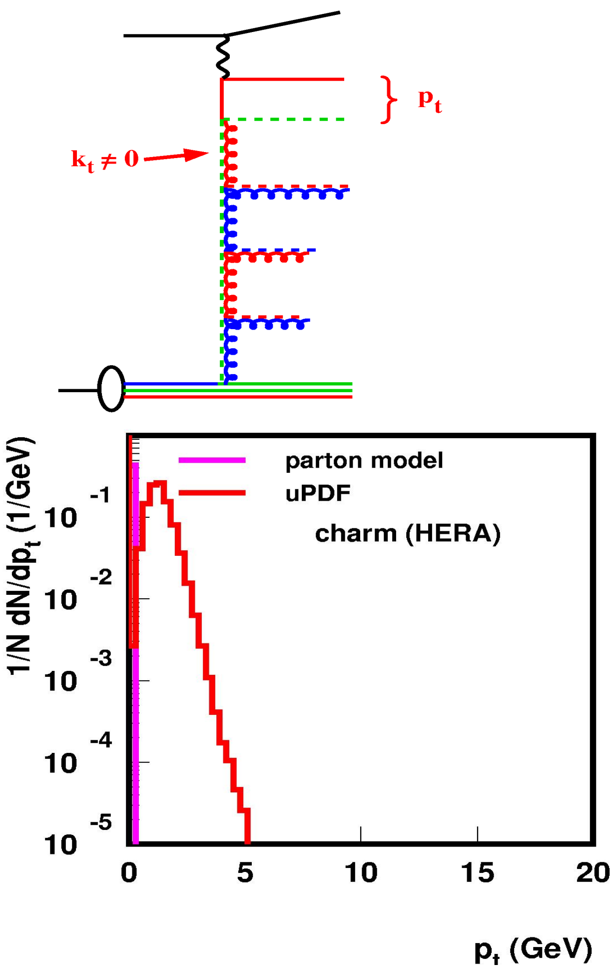




➔ NLO corrections will be very large for these LO processes .....

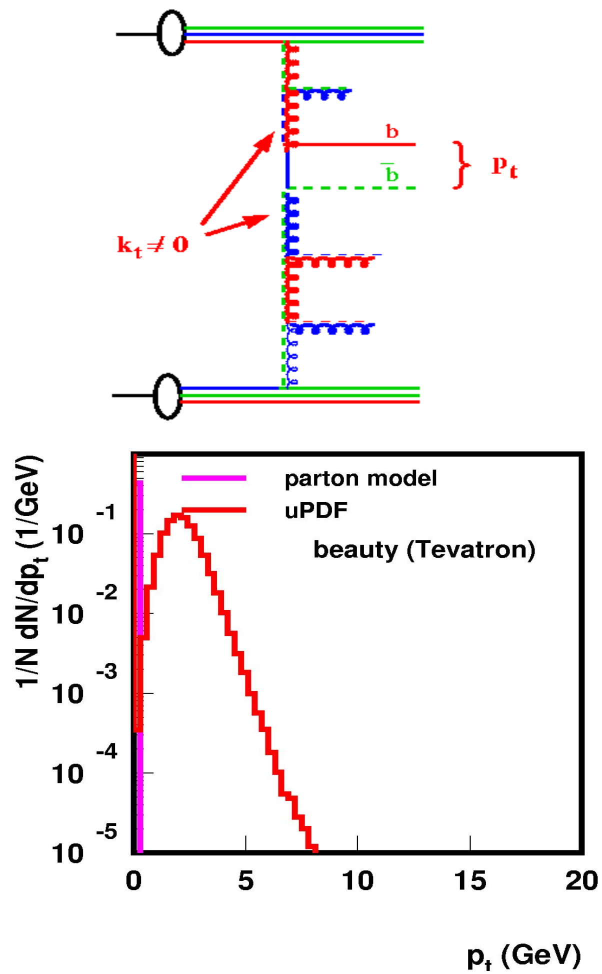
# Doing much better with uPDFs ...

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

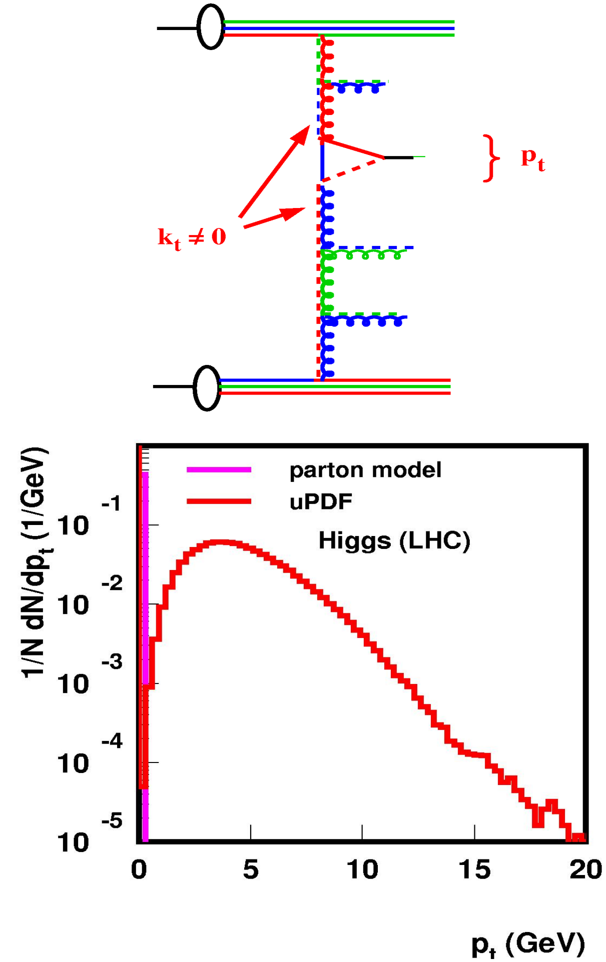
## heavy quarks at HERA




## heavy quarks in pp



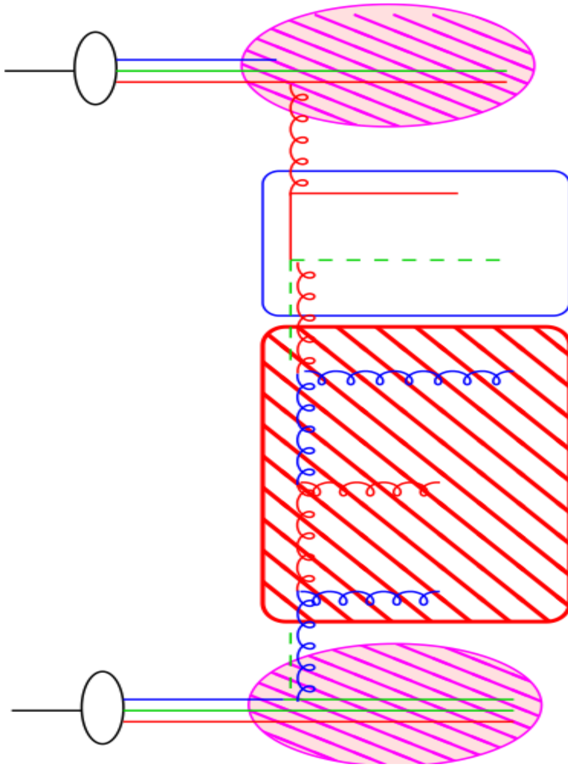

## Higgs in pp




➔ doing kinematics correct at LO, reduces NLO corrections ...

➔ NEED uPDFs !!!!

# CASCADE – basic idea

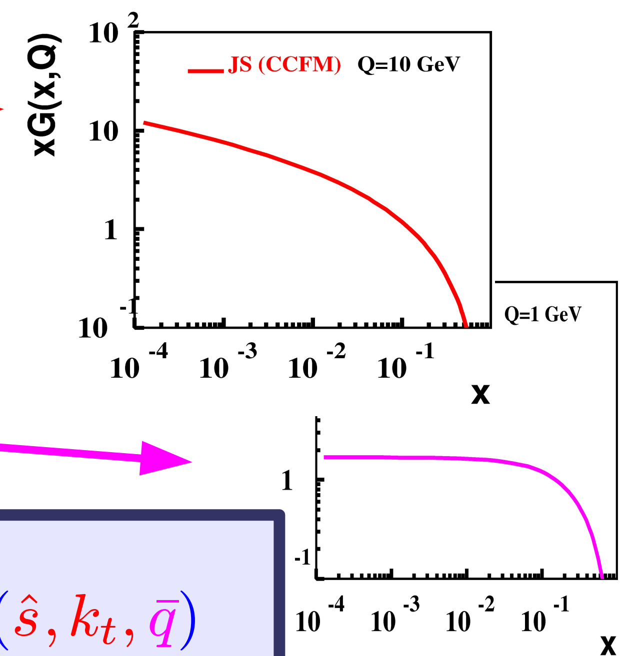


matrix element

evolution of parton cascade:

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

initial distribution
~ flat




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

$$\int d^2k_t x_g \mathcal{A}(x_g, k_t, \bar{q}) = x_g G(x_g, Q^2) \text{ if } \hat{\sigma} = \hat{\sigma}(\hat{s}, 0, \bar{q})$$

# DGLAP and uPDF

- standard DGLAP evolution equation
  PDF as from small to large scale
  evolved:

$$t_0 \ll t_1 \ll t_2 \ll t_3 \cdots \ll \mu^2$$

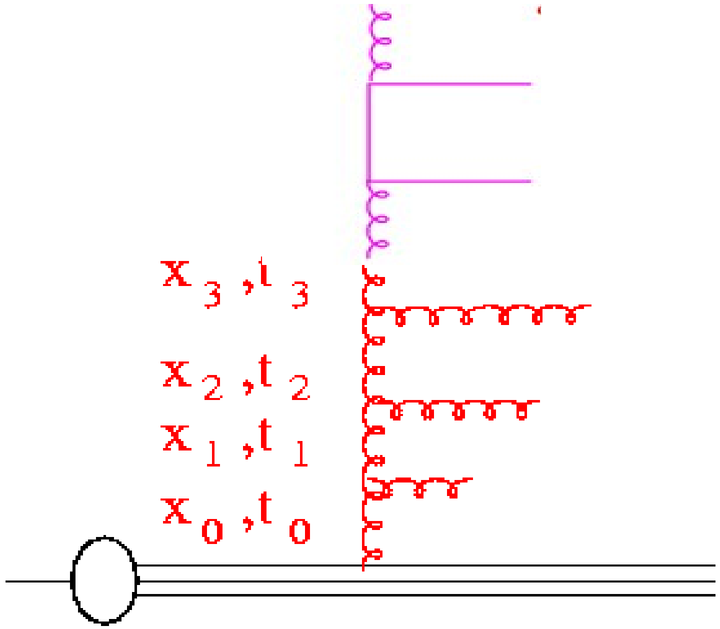
  - in deriving DGLAP splitting functions we assumed:

    $$\hat{t} \ll \hat{s}$$

  - and also in the small $t$ limit:

    $$\hat{t} \sim \frac{-k_\perp^2}{1-z}$$

  - strong ordering: neglect all kinematics of previous branchings...




- implicitly also ordering in x:
  $x_0 > x_1 > x_2 > x_3$
- at hard scattering, parton have a transverse momentum: uPDF

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

# CCFM and angular ordering

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

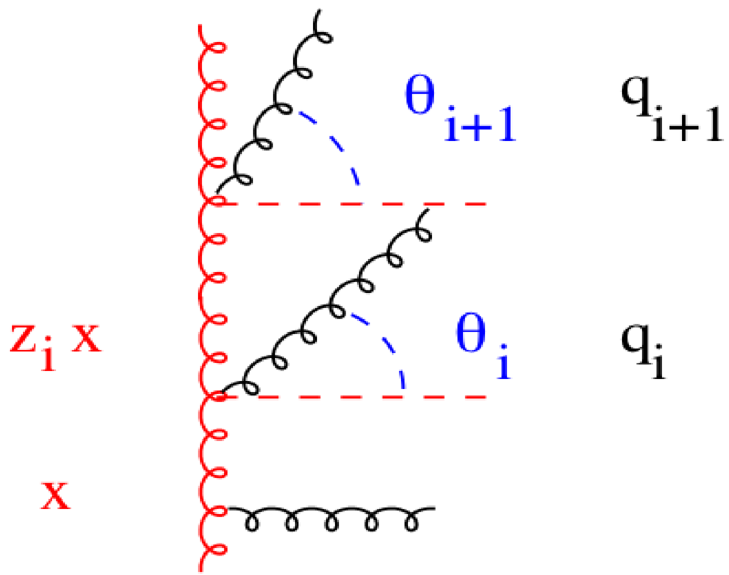
$$\bar{q} > z_n q_n, q_n > z_{n-1} q_{n-1}, ..., q_1 > Q_0$$

angular ordering implies:

➔ recover DGLAP with $q_t$ ordering at medium and large $x$

➔ no restriction on $q_t$ at small $x$:

$$q_i > z_{n-1} q_{n-1}$$

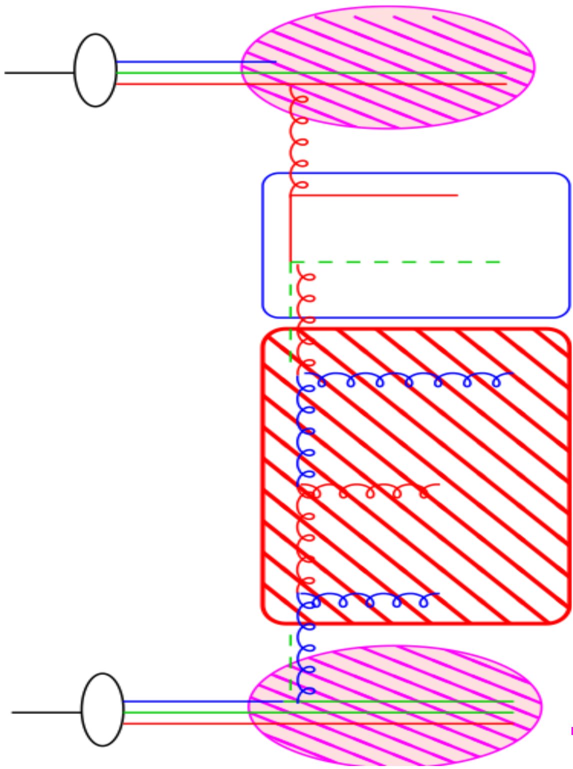



➔ **C**atani**C**iafaloni**F**iorani**M**archesini evolution forms a bridge between DGLAP and BFKL evolution

➔ important for comparison with collinear NLO calculations ...

# CASCADE - C$_{\text{atani}}$C$_{\text{iafaloni}}$F$_{\text{iorani}}$M$_{\text{archesini}}$ evolution

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



matrix element
off shell

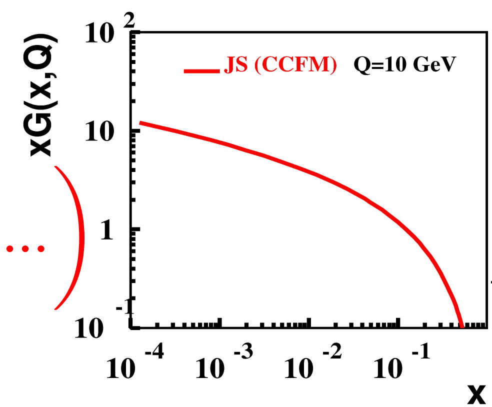
evolution of parton
cascade:

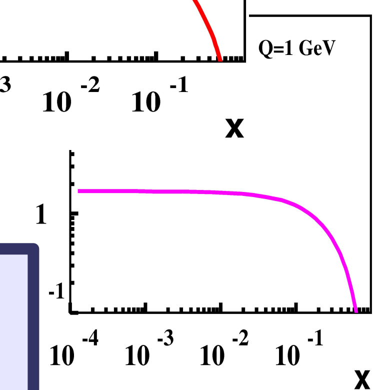
$$\tilde{P} = \bar{\alpha}_s \left( \frac{1}{1-z} + \frac{1}{z}\Delta_{ns} + \ldots \right)$$

initial distribution
~ flat

CCFM (all loops)

- angular ordering
- non - Sudakov$\Delta_{ns}$



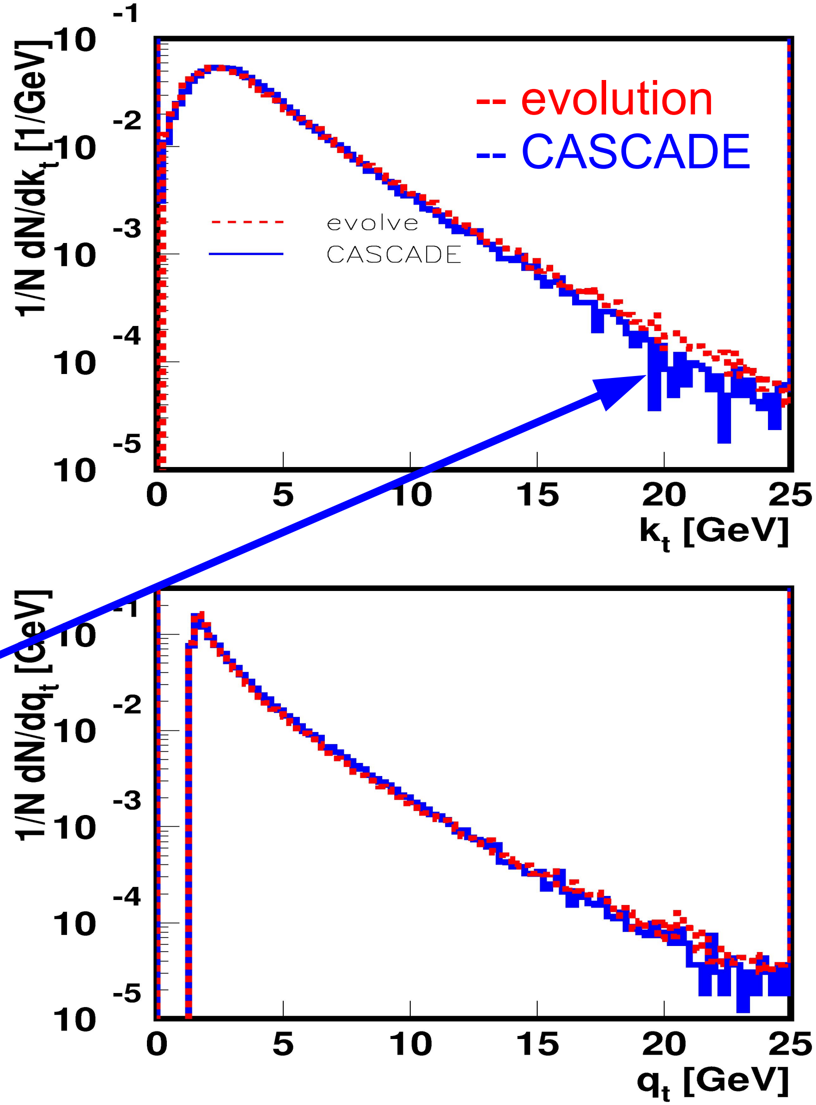

$$\sigma(pp \to q\bar{q} + X) = \int \frac{dx_{g1}}{x_{g1}} \frac{dx_{g2}}{x_{g2}} \int d^2k_{t1} d^2k_{t2} \hat{\sigma}(\hat{s}, k_t, \bar{q})$$
$$\times x_{g1} \mathcal{A}(x_{g1}, k_{t1}, \bar{q}) x_{g2} \mathcal{A}(x_{g2}, k_{t2}, \bar{q})$$

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

# Advantage of explicit 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



# uPDF fit to inclusive HERA data

- fit parameters of starting distribution

  $$xg(x, \mu_0^2) = N x^{-B_g} \cdot (1-x)^4$$

- using $F_2$ data

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

  $$x < 0.05 \quad Q^2 > 5 \text{ GeV}^2$$

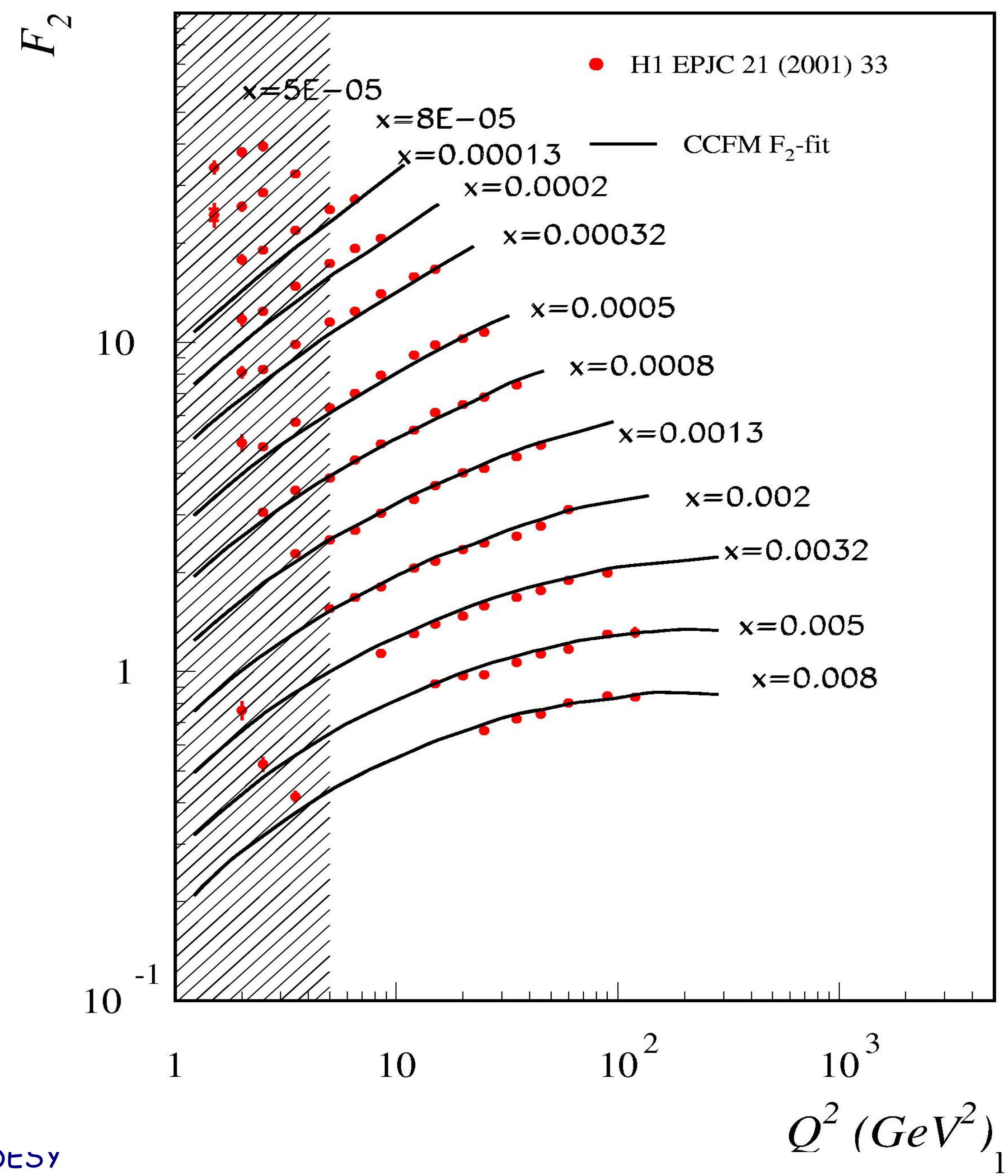
- parameters: $\mu_r^2 = p_t^2 + m_{q,Q}^2$

  $$m_q = 250 \text{ MeV}, m_c = 1.5 \text{ GeV}$$

- Fit (only stat+uncorr):

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

➔ similar to NLO DGLAP fits (~1.5)



# CASCADE MC event generator

- gluon induced processes included
  - ep: $\gamma g^* \to q\bar{q}$, $\gamma^* g^* \to Q\bar{Q}$, $\gamma g^* \to J/\psi g$ at HERA tested well !!!
  - pp: $g^* g^* \to q\bar{q}$, $g^* g^* \to Q\bar{Q}$, $g^* g^* \to h$ HQ at TeVatron tested !!!
- initial state parton shower, backward evolution, according to CCFM
- final state PS
- p-remnant treatment
- Hadronization

→ full PYTHIA final state PS & remnant treatment included

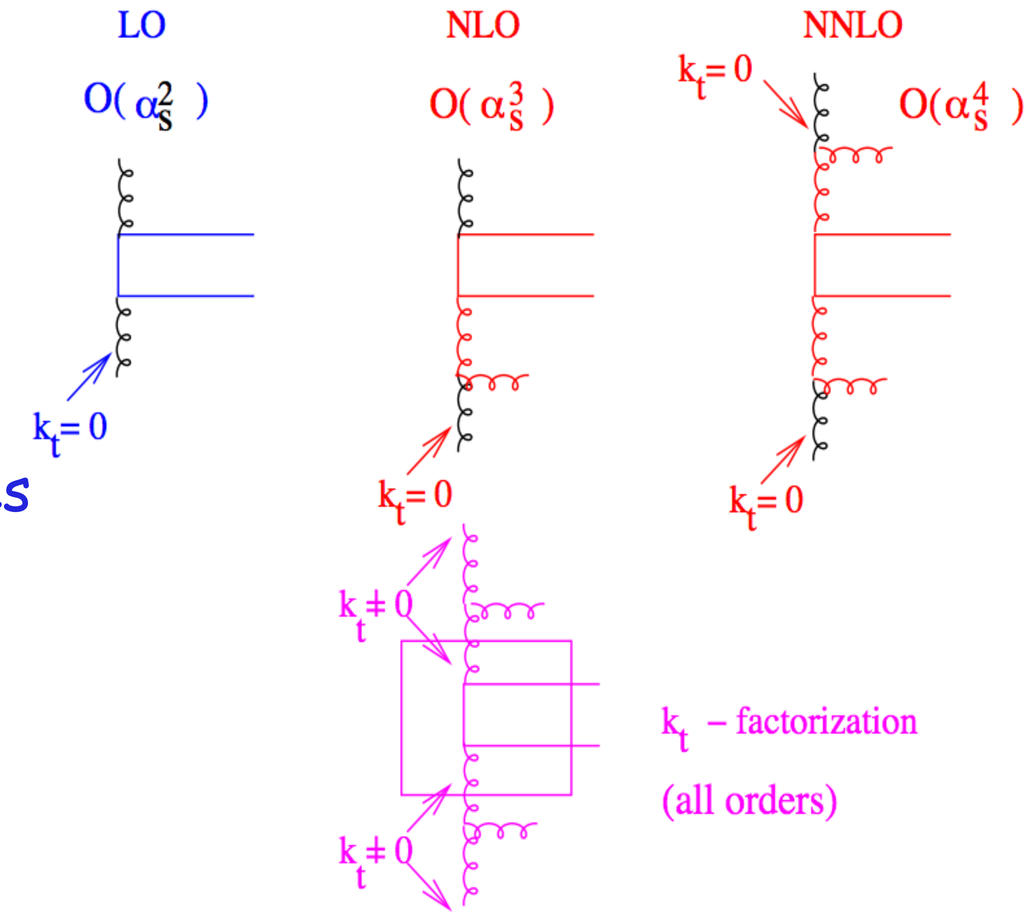
→ applicable for $t\bar{t}$ -production

using LHA interface to
PYTHIA/HERWIG
for
- final state PS
- p-remnant
- hadronization

**use CASCADE in ep and pp**

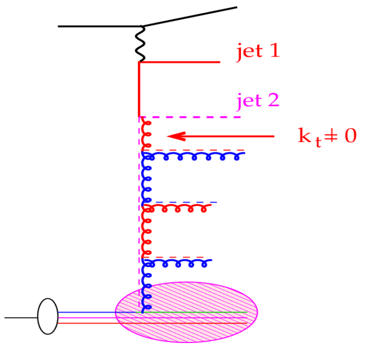
# CASCADE and coll. NLO calculations

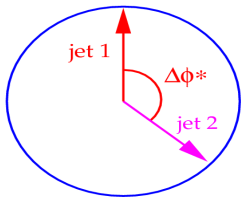
- fit of uPDF to inclusive structure functions /x-sections used to determine normalization
  - ➔ includes "all-orders" !!!!
- off-shell matrix element simulates part of real NLO corrections
  - ➔ study of scale dependence
  - ➔ compare to coll. NLO calculations
  - ➔ check with benchmark x-sections




**uPDFs are THE important ingredient for CASCADE ...**

# The problem with NLO .....

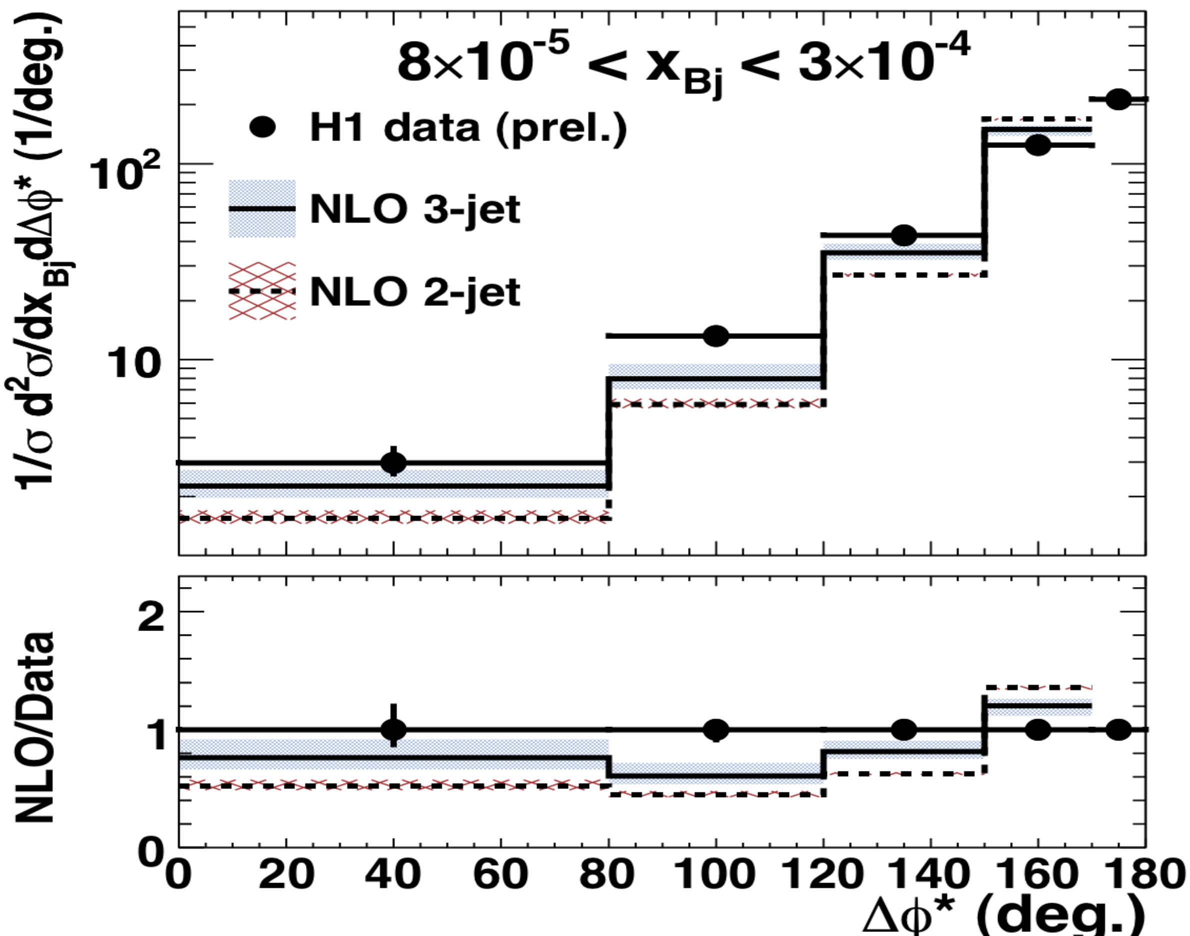



- H1 prel data

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

➔ None of the NLO (2-jet, 3-jet) calculations are enough



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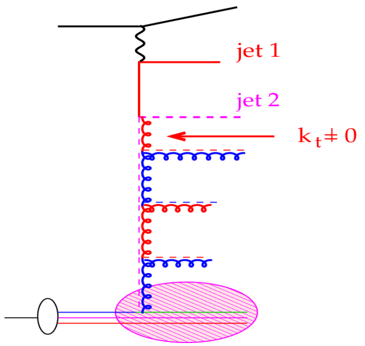


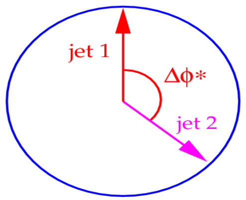


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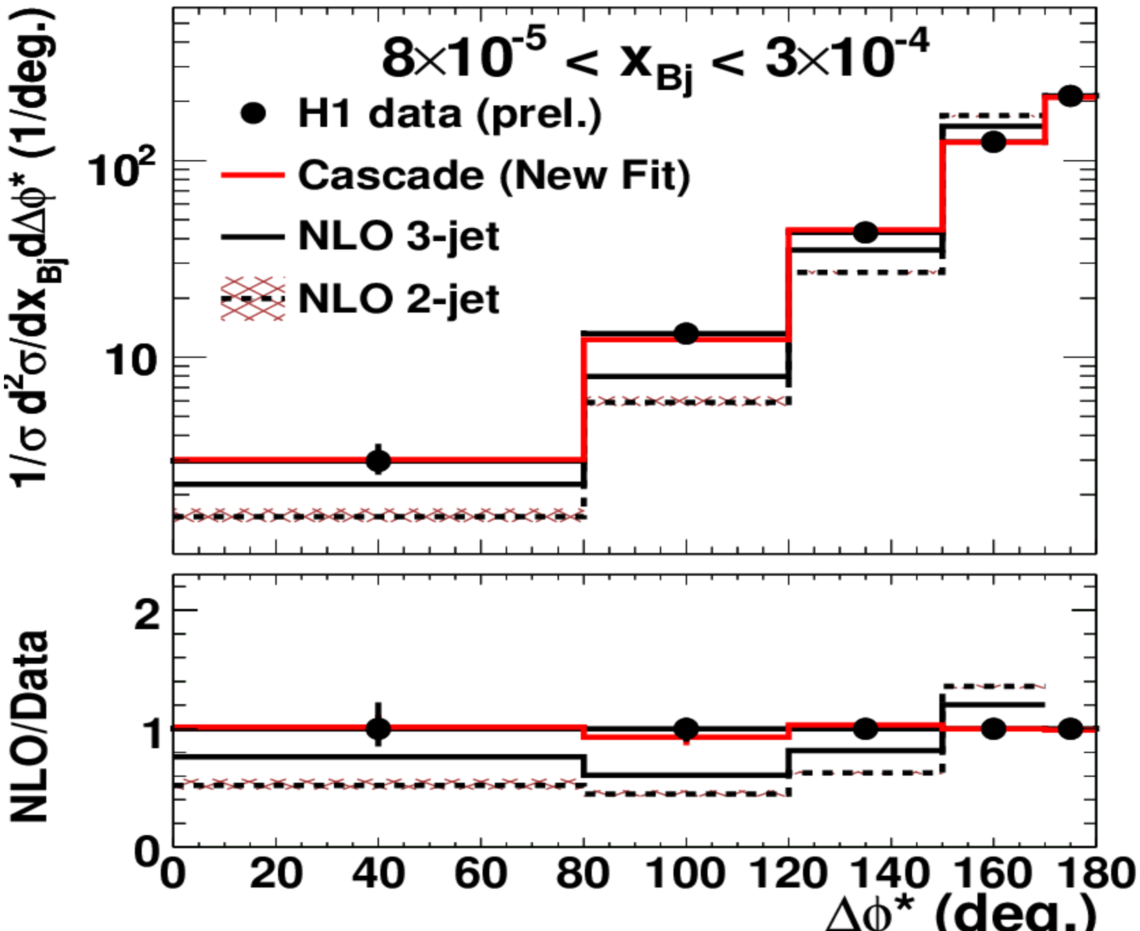


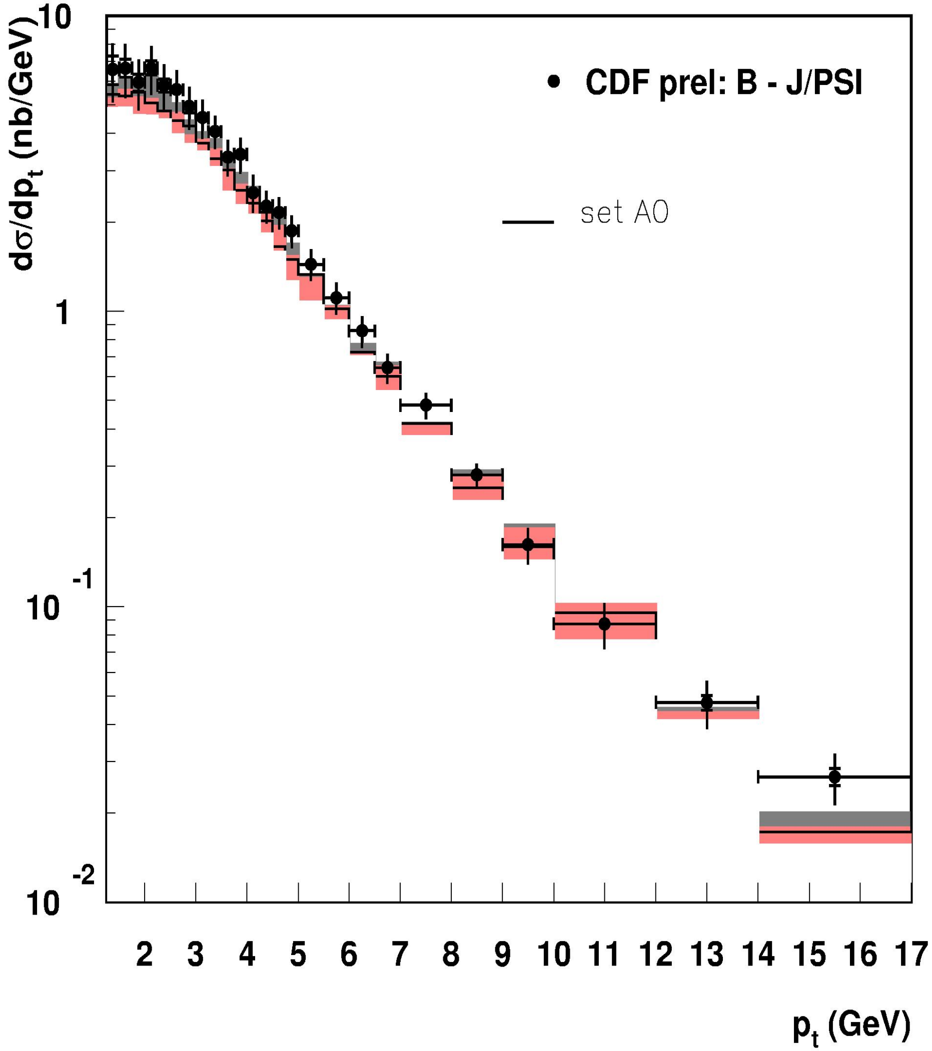

- BUT ....

➔ CASCADE with uPDFs much better !!!

# Bottom at TeVatron

- bottom xsection at CDF

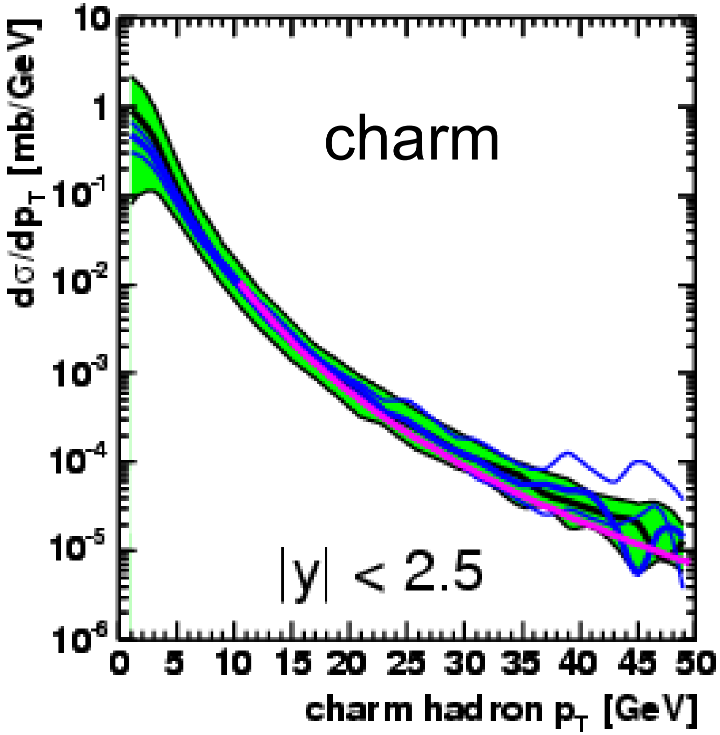
| | $\sigma(b, \lvert y \rvert < 1)$ |
|---|---|
| CASCADE | $24.95\ \mu b$ |
| Cacciari et al (FONLL) | $23.6\ \mu b$ |
| CDF | $24.9 \pm 0.6 \pm 6.2\ \mu b$ |
| | $\sigma(b, \lvert y \rvert < 0.6)$ $BR(B \to J/\psi \to \mu)$ |
| CASCADE | $17.2\ nb$ |
| ... with PYTHIA BR | $15.2 nb$ |
| MC@NLO | $17.2\ nb$ |
| Cacciari et al (FONLL) | $19.0^{+8.4}_{-6.0}\ nb$ |
| CDF | $19.9^{+3.8}_{-3.2}\ nb$ |



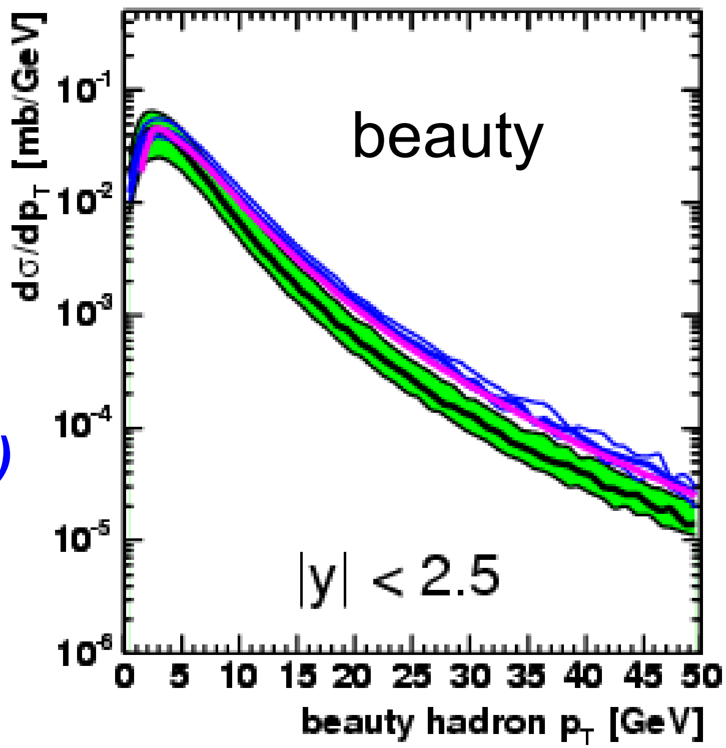

- Remarkable agreement CASCADE and MC@NLO
- Good agreement CASCADE and FONLL

# 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

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

# CASCADE: technical intro

- where to get the source code
  - ➔ http://projects.hepforge.org/cascade
  - ➔ available also in GENSER, both at CERN and DESY mirror
- easy and fast installation using autotools
  - needs PYTHIA/HERWIG for hadronization
- "still" written in FORTRAN..... BUT
  - ➔ all steering of the program is done via steering file
  - ➔ no need for the "normal" user to interact directly with the program code
  - ➔ i.e.: `cascade < steer_pp-top`

# CASCADE: the steering file

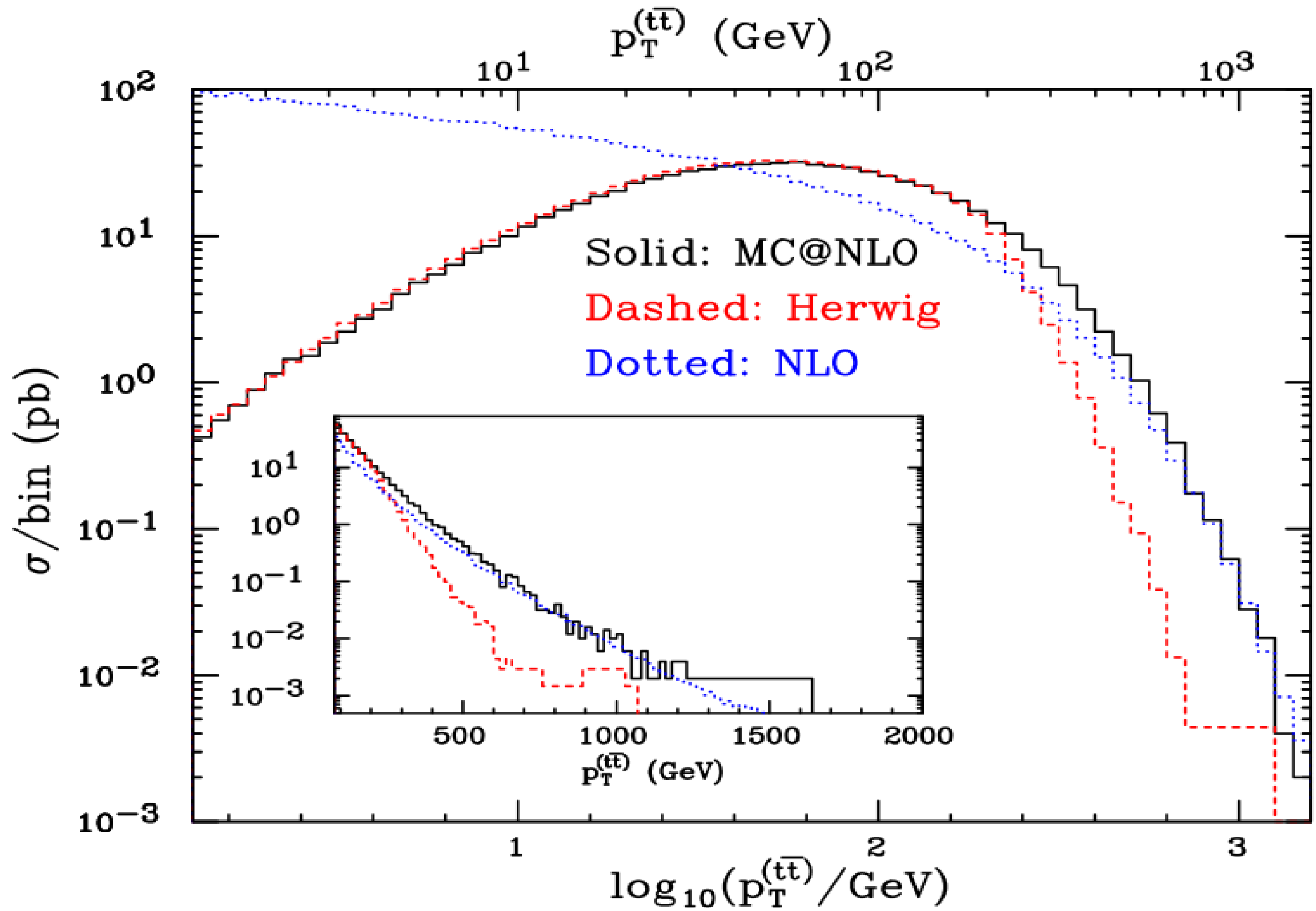
```
 * +++++++++++++++++ Kinematic parameters +++++++++++++++
*
     'PBE1'     1       0       -7000.   ! Beam energy

     'KBE1'     1       0        2212    ! 2212: proton
     'IRE1'     1       0        1       ! 0: beam 1 has no structure
*                                 ! 1: beam 1 has structure
     'PBE2'     1       0        7000.   ! Beam energy
     'KBE2'     1       0        2212    ! 2212: proton
     'IRE2'     1       0        1       ! 0:  beam 2 has no structure
*                                 ! 1: beam 2 has structure
* +++++++++++++++ Hard subprocess selection ++++++++++++++++++
*
     'IPRO'     1       0        11      ! (D=1)
*                                        ! 10: Light quarks
*                                        ! 11: Heavy quarks
*                                        ! 102: g g -> Higgs
*
     'IHFL'     1       0         6      ! (D=4) produced flavour for IPRO=11
*                                        ! 4: charm
*                                        ! 5: bottom
*                                        ! 6: top
*
     'PTCU'     1       0        1000.   ! (D=0) p_t **2 cut for process
*
```

# CASCADE: the steering file (cont'd)

```
* ++++++++++++ Parton shower and fragmentation ++++++++++++
*
     'NFRA'     1       0        1        ! (D=1) Fragmentation on=1 off=0
*
     'IFPS'     1       0        3        ! (D=3) Parton shower
*                                         ! 0: off
*                                         ! 1: initial state PS
*                                         ! 2: final state PS
*                                         ! 3: initial and final state PS
*
*     'IGLU'     1       0        1001    ! (D=1010)Unintegrated gluon density
*                                         !  1: CCFM old set JS2001
*                                         !  1001: CCFM J2003 set 1
*                                         !  1002: CCFM J2003 set 2
*                                         !  1003: CCFM J2003 set 3
*                                         !  1010: CCFM set A0
*                                         !  1011: CCFM set A0+
*                                         !  1012: CCFM set A0-
*                                         !  1013: CCFM set A1
*                                         !  1020: CCFM set B0
*                                         !  1021: CCFM set B0+
*                                         !  1022: CCFM set B0-
*                                         !  1023: CCFM set B1
```

# Exercise – compare to MC@NLO

- compare CASCADE results with corresponding plot of MC@NLO
  (Frixione,Nason,Webber hep-ph/0305252)

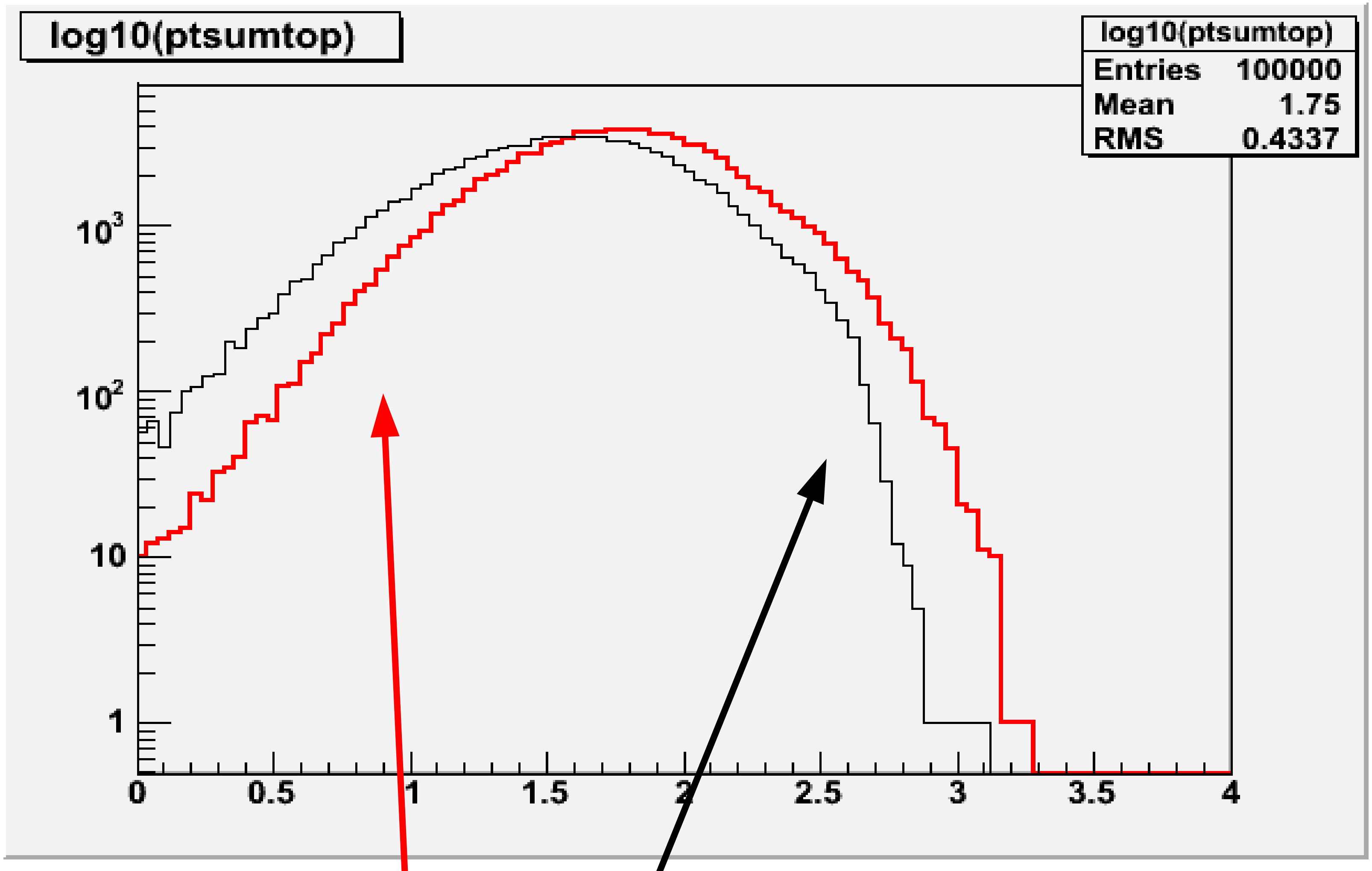



- comparison with DGLAP and CCFM mode ....

➔ CASCADE ~ MC@NLO

# Exercise - compare to MC@NLO

- compare CASCADE results with corresponding plot of MC@NLO




- comparison with CCFM and DGLAP mode ....

➔ CASCADE CCFM ~ MC@NLO ??????

# Conclusions

- CASCADE has many advantages compared to other Monte Carlo event generators:
  - ➔ treats kinematics correct from the beginning
  - ➔ no difference between evolution and parton showering
  - ➔ agrees well with standard NLO calculations, where applicable !!!
  - ➔ includes naturally transition to small x via angular ordering in CCFM
- CASCADE for pp
  - ➔ applicable for standard high $p_t$ processes:
    - ➔ jets, heavy quarks, Higgs, W/Z (coming soon)

**CASCADE treats parton radiation beyond collinear approach**

# Backup Slides

# CASCADE for LHC

- Extension of CASCADE towards a **multipurpose event generator** applying $k_t$-factorization
- Inclusion of new processes ... matrix element calculations needed ...
- Extension of "CASCADE" collaboration:
  - M. Deak, K. Kutak,
  - J. Bartels, F. Schwennsen,
  - S. Baranov, A. Kotikov,
  - A. Lipatov, N. Zotov

- New processes (calculations done recently)

$$
\begin{aligned}
pp &\rightarrow W^{\pm} + jets + X \\
pp &\rightarrow Z^{0} + jets + X \\
pp &\rightarrow \gamma + jets + X
\end{aligned}
$$

- New processes to come:

$$
\begin{aligned}
pp &\rightarrow jets + X \\
pp &\rightarrow \gamma + \gamma + X
\end{aligned}
$$

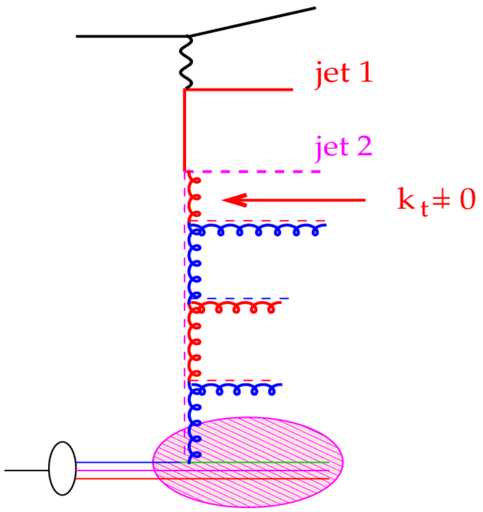
- Multiparton interactions according to AGK including diffraction and saturation ... still to come ...

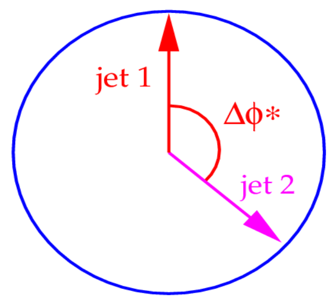
# Other features of CASCADE

- various sets of uPDFs included (but only CCFM/KMR with parton shower):
  - CCFM
  - KMR (Kimber, Martin, Ryskin Phys. Rev. D63 (2001) 114027)
  - KMS (Kwiecinski, Martin, Stasto Phys. Rev. D 56 (1997) 3991)
  - saturation model
  - derivative of integrated gluon
  - ....
  - **Remember: consistent treatment only with uPDF**
    - KMR prescription: one additional radiation ... useful for determination of hadronization corrections for NLO calculations
- Features of CCFM uPDFs: variation of renormalization scale
  - using uPDFs accordingly determined

➔ smaller uncertainty from theory

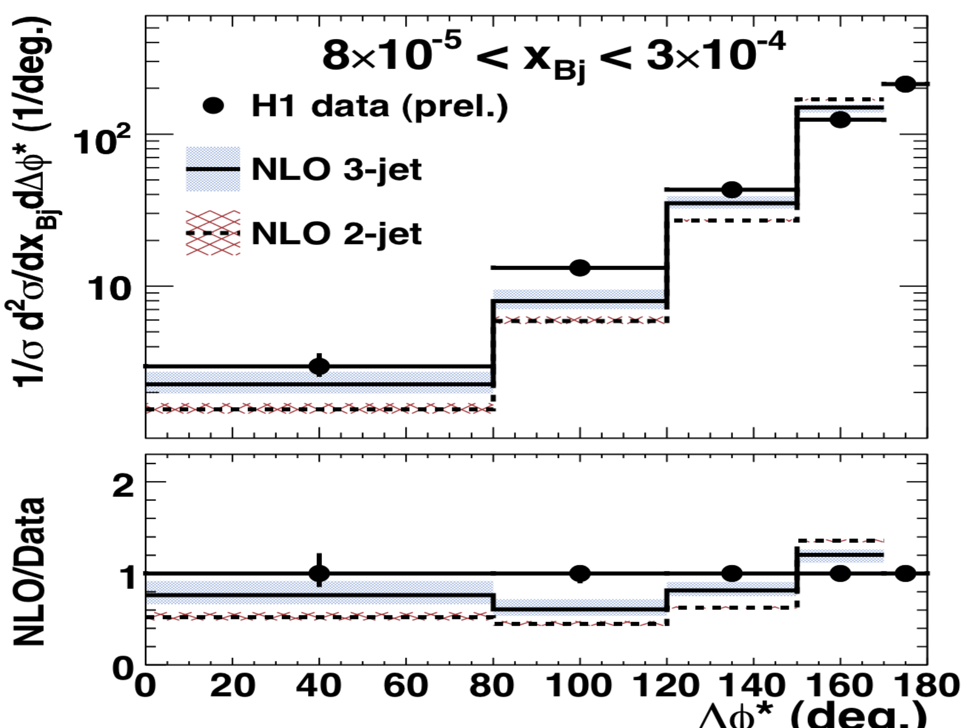
# The problem with NLO ...

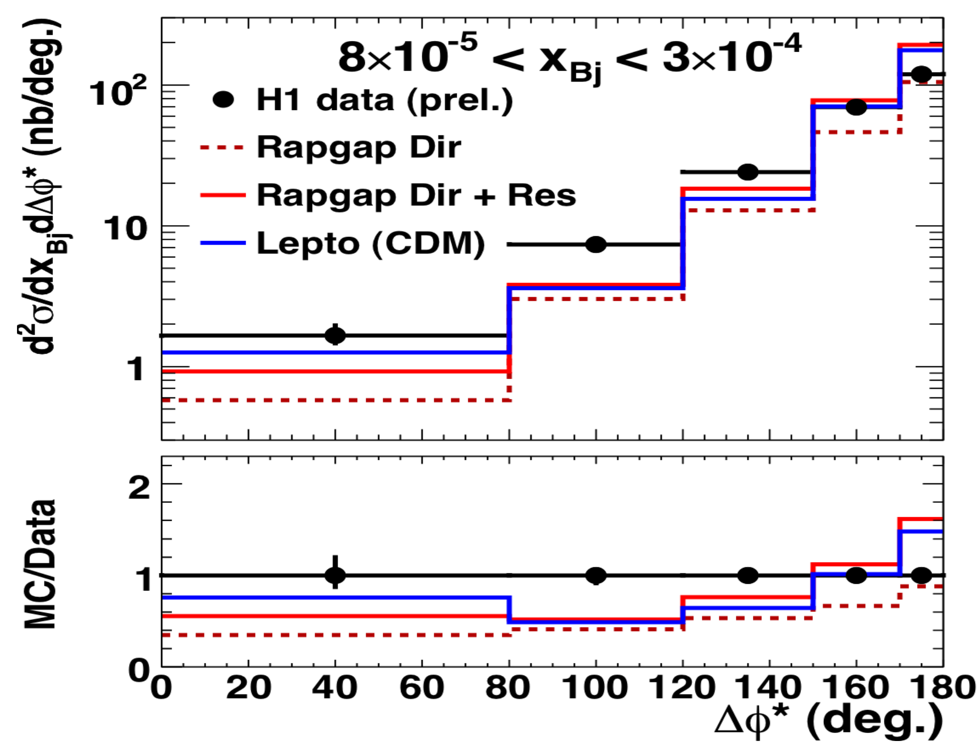



- H1 prel data $5 < Q^2 < 100\ \mathrm{GeV}^2$
  $-1 < \eta < 2.5$
  $E_T > 5\ \mathrm{GeV}$

➔ None of the calculations can describe measurements !!!



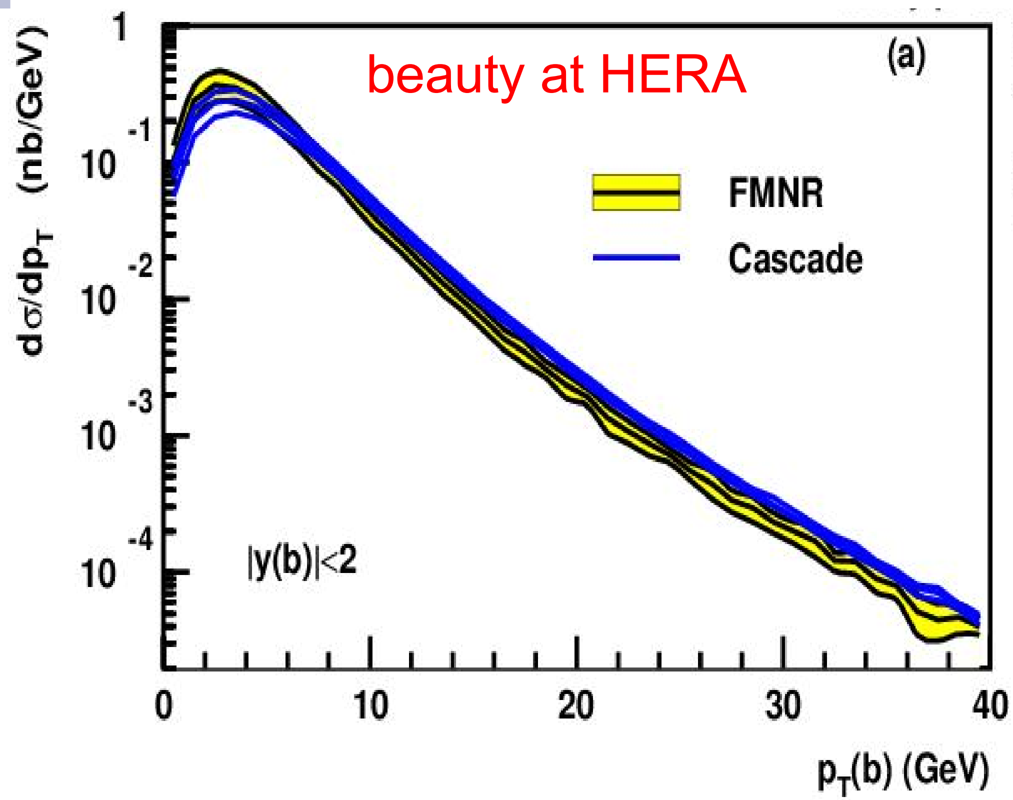



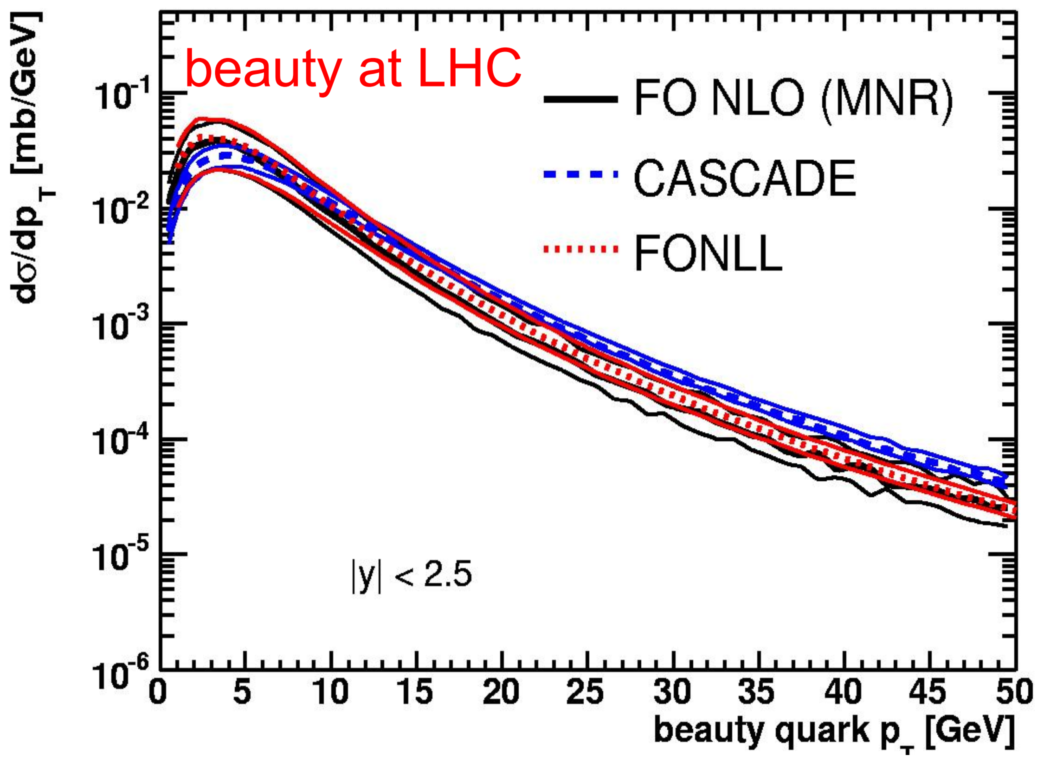
# Benchmarks: beauty at HERA and LHC

from Proceedings of the HERA-LHC workshop hep-ph/0601013

## Cross sections at parton level in central region

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




**"Perfect" agreement of NLO(FMNR) calculation with CASCADE using uPDFs !!!**

# $Z_0/W$ production in pp

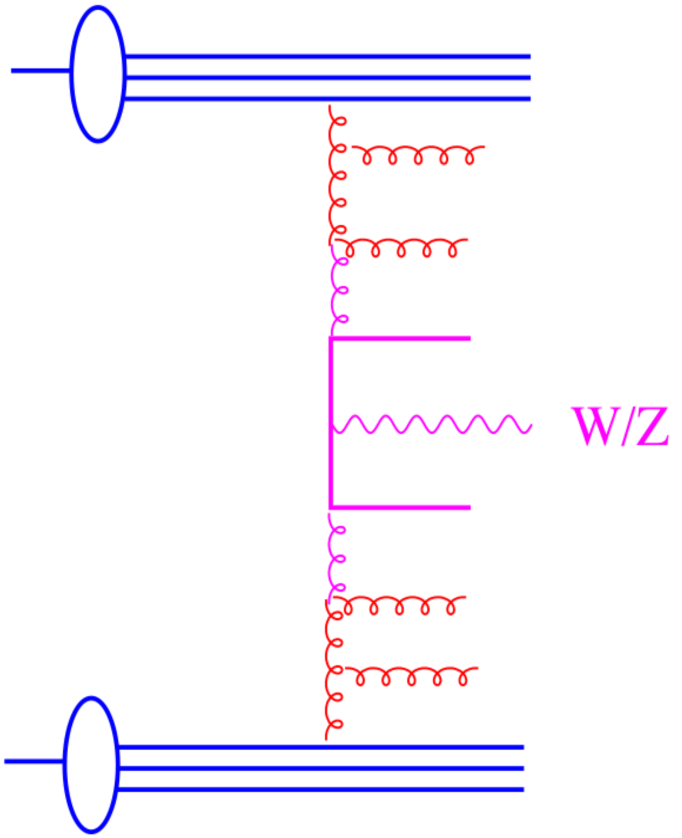
- calculations performed: M. Deak, F. Schwennsen, S. Baranov, A. Lipatov, N. Zotov

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

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

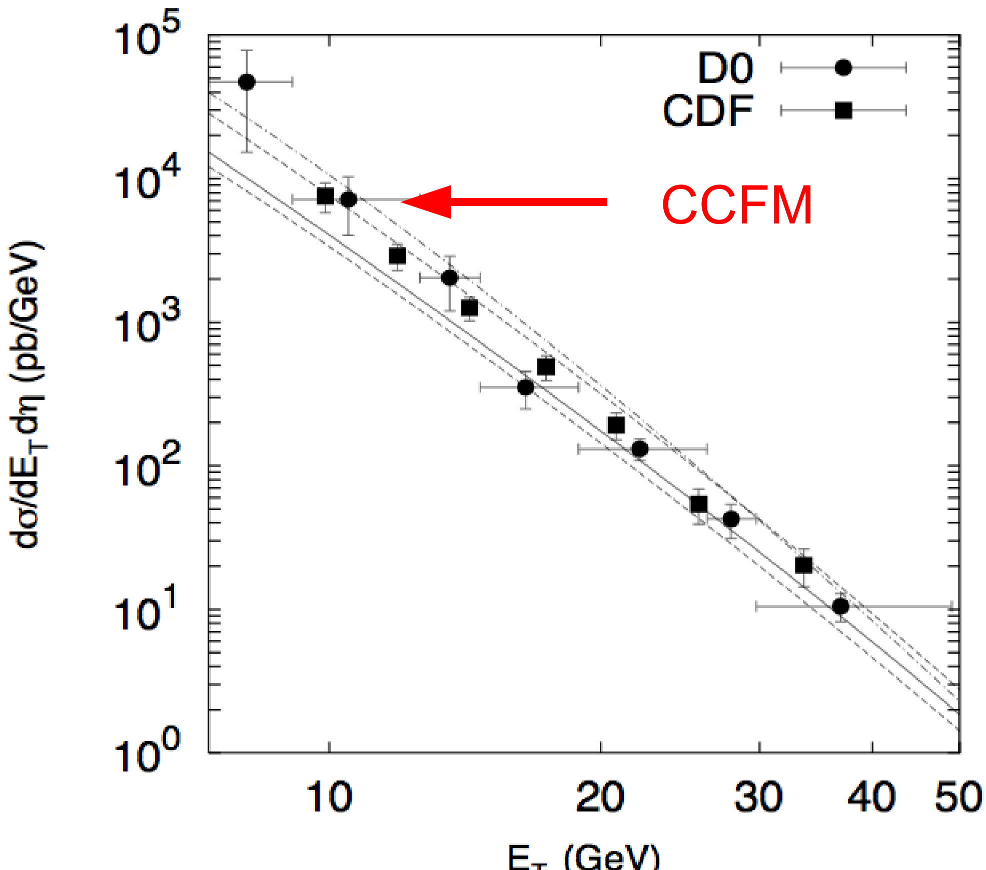
- calculation now finished

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



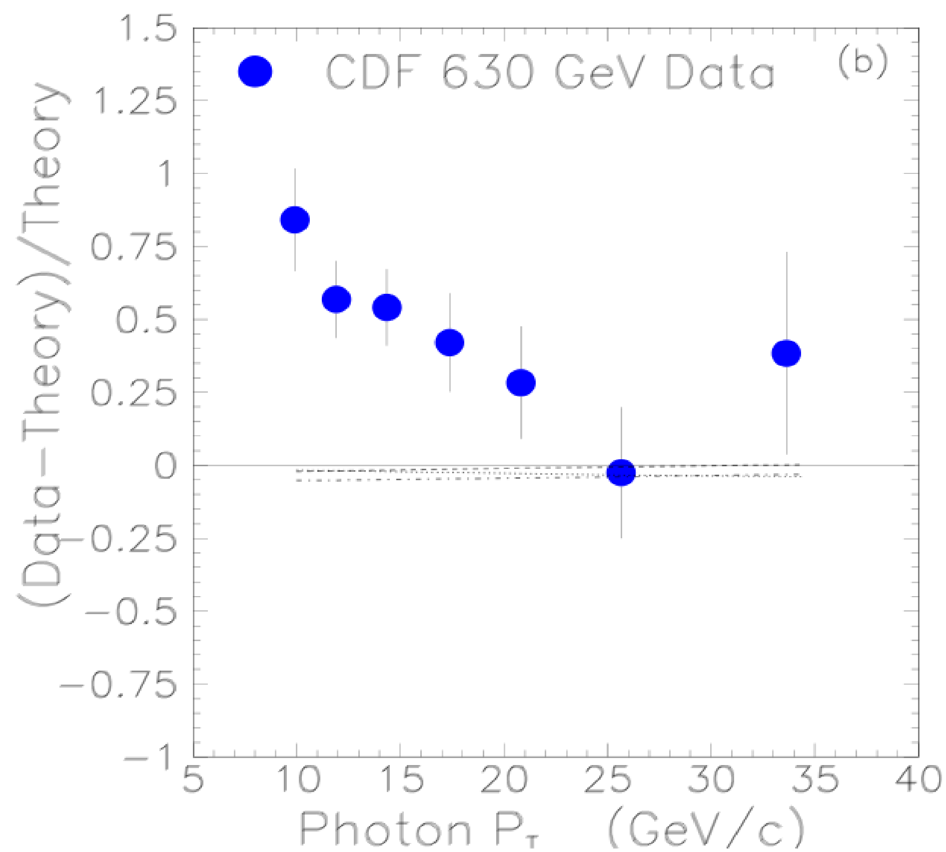
# Prompt photons in pp

- Calculations done by Baranov, Lipatov, Zotov (hep-ph/0708.3560) implemented in CASCADE




➔ good description even at lowest Et

- Compare to collinear NLO result: (hep-ex/0201004)




➔ need 4 GeV intrinsic kt for lowest Et bins !!??!!

# Including valence quarks

- including $qg \to qg$
- important for forward jets ....
- need unintegrated valence quarks
- transition to collinear case
- ➔ calculations by M. Deak, K.Kutak
- ➔ 1st results presented at DIS08