CASCADE vrs pp data at LHC

H. Jung (CERN, DESY & Antwerp)

- basic ideas of the CASCADE MC generator
- first comparison with pp data
  - min bias
  - heavy flavor (open & hidden)
- prospects for forward jets

CASCADE basic idea

- CASCADE elements are:

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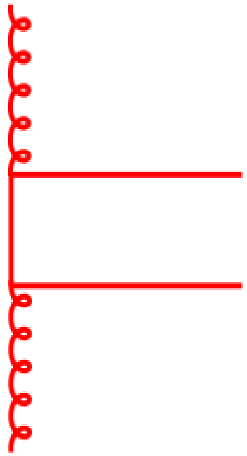
  - Matrix Elements:



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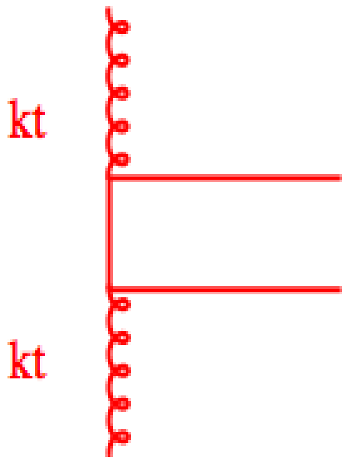

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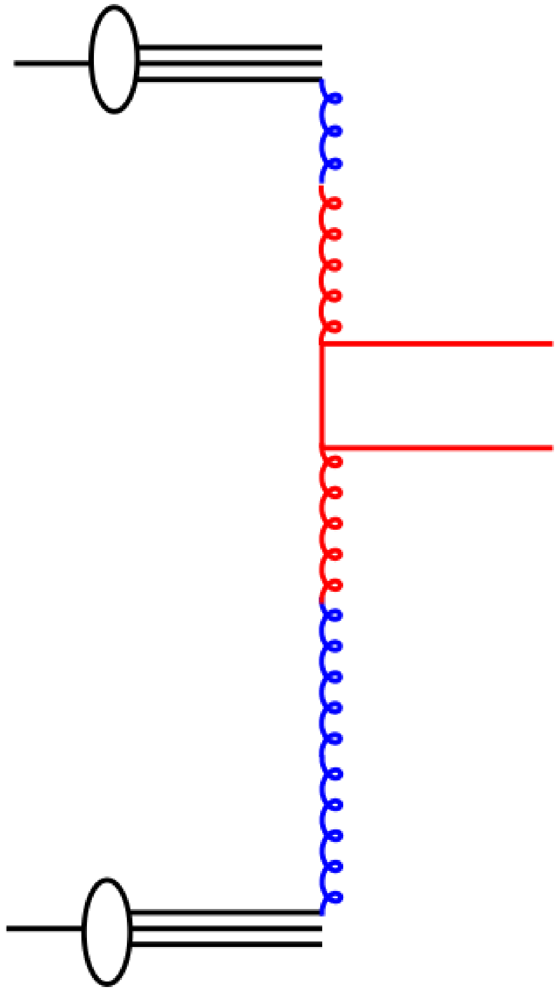
  - PDFs



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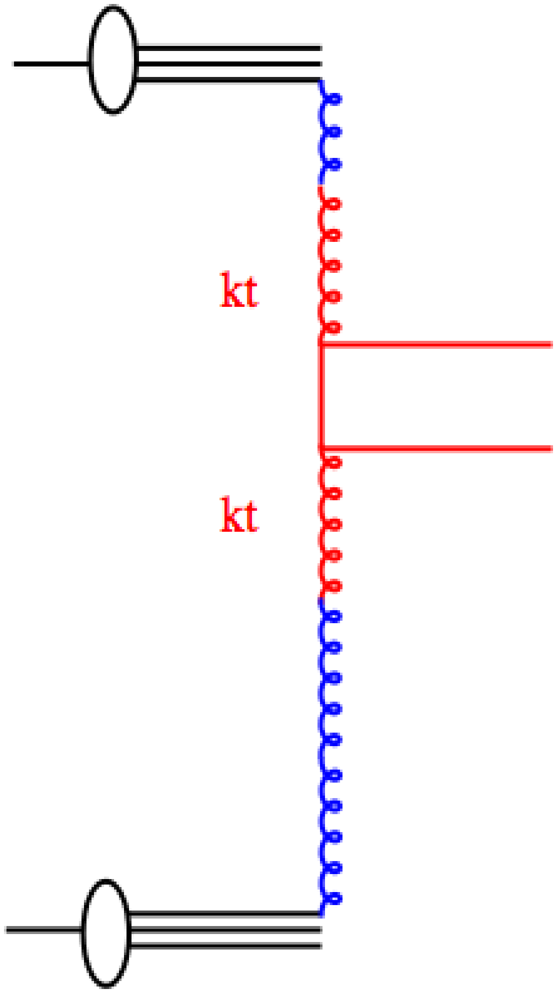

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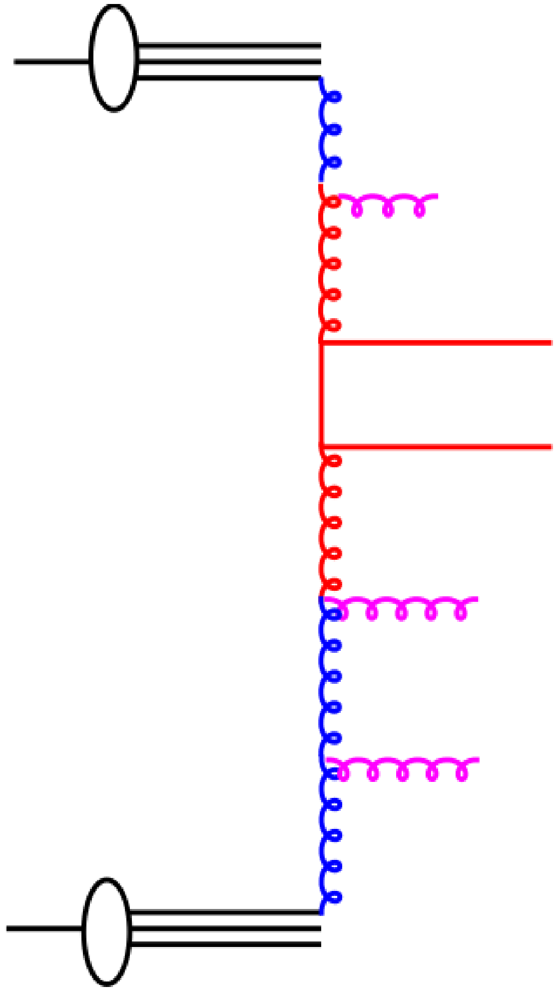

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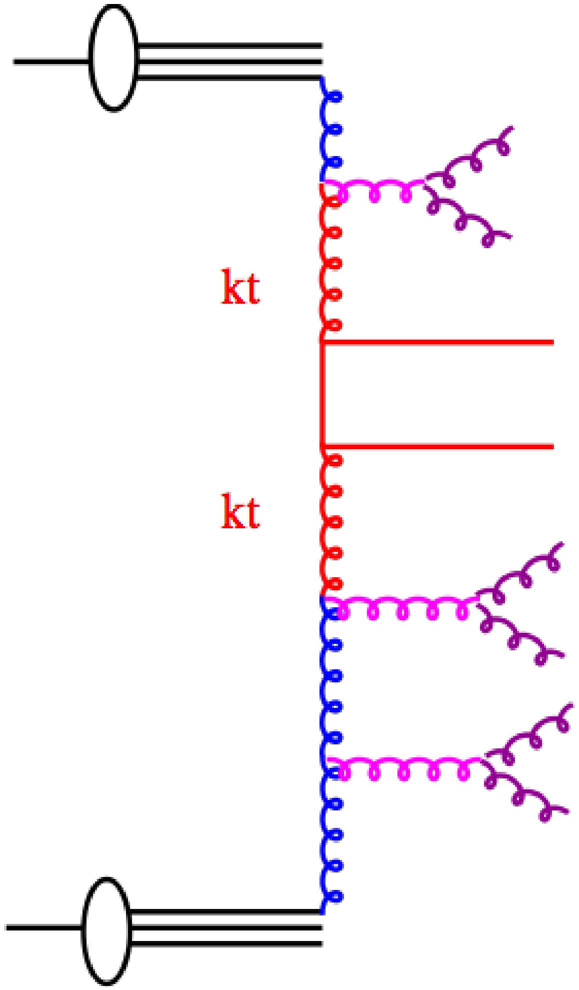
    - ➔ angular ordering (CCFM)



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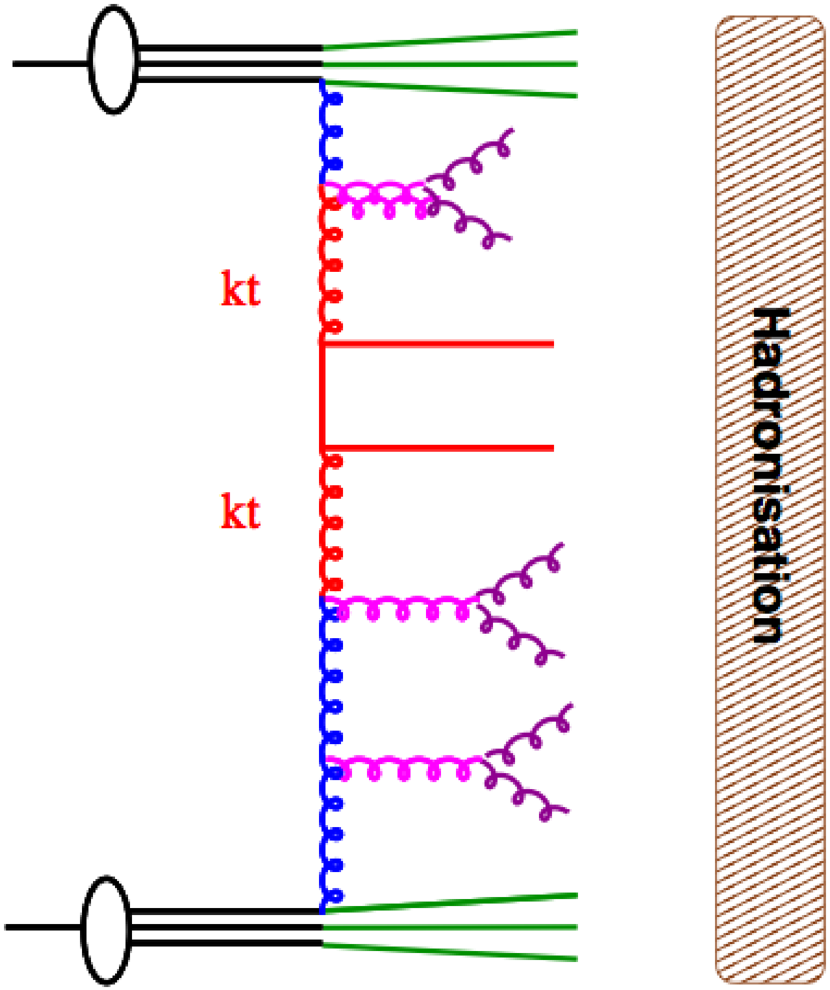
- Proton remnant and hadronization handled by standard hadronization program, e.g. PYTHIA



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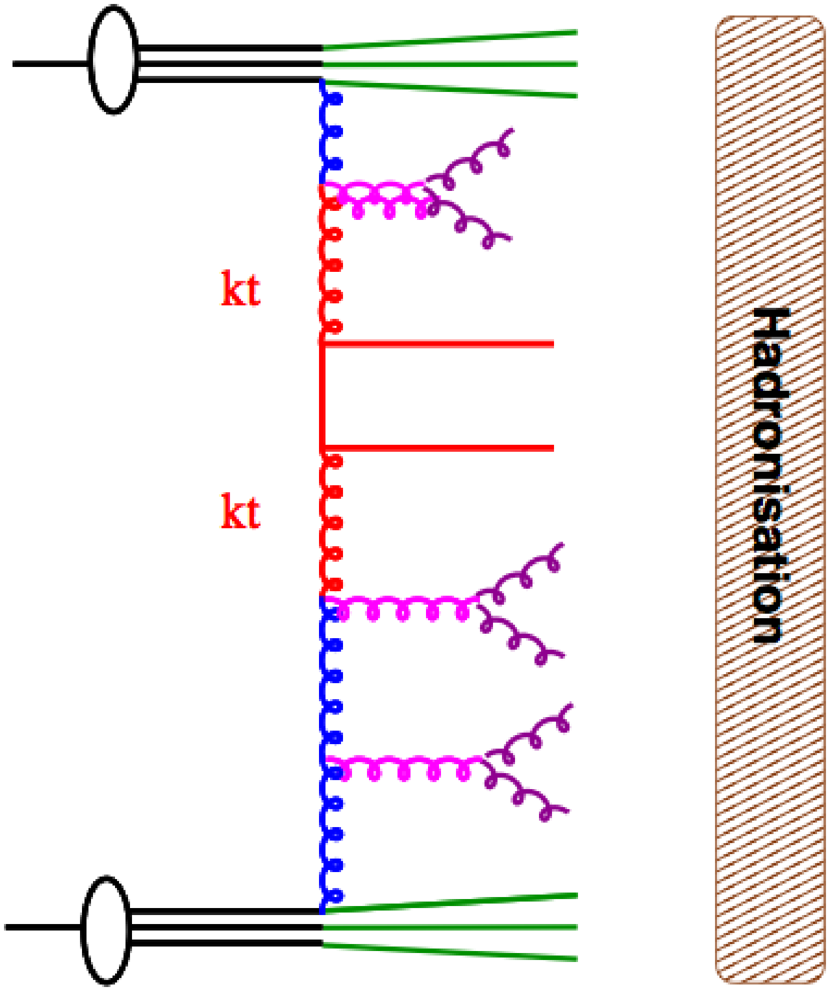


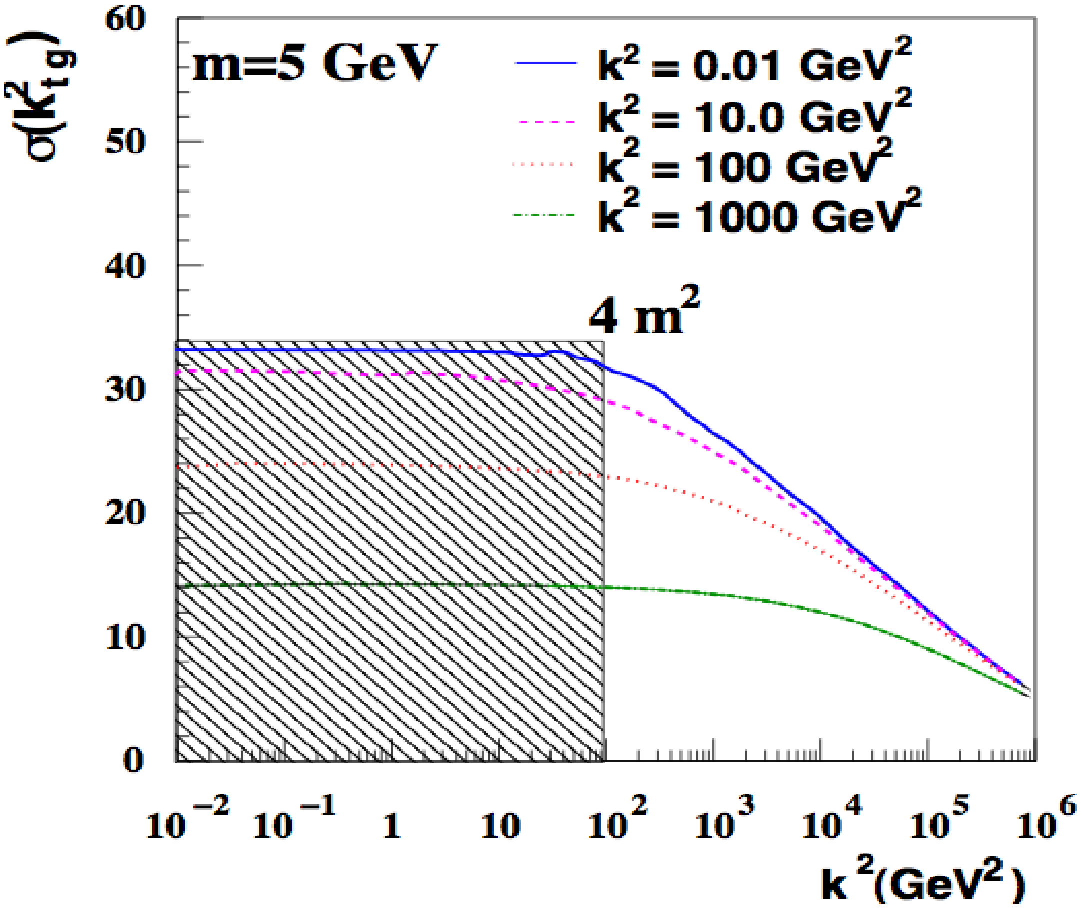
$$\sigma(pp \to q\bar{q} + X) = \int \frac{dx_{g1}}{x_{g1}} \frac{dx_{g2}}{x_{g2}} \int d^2 k_{t1} d^2 k_{t2} \hat{\sigma}(\hat{s}, k_t, \bar{q})$$
$$\times x_{g1} \mathcal{A}(x_{g1}, k_{t1}, \bar{q}) x_{g2} \mathcal{A}(x_{g2}, k_{t2}, \bar{q})$$

Why off-shell matrix elements ?

- Example: $g^* g^* \to Q\bar{Q}$
  - 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 $\mu^2 \sim 4m^2$



Which off-shell matrix elements ?

- heavy quarks

  NEW

  including excited states:
  - 1S, 2S, 3S
  - 1P, 2P

$$g^* g^* \rightarrow Q\bar{Q}$$
$$g^* g^* \rightarrow J/\psi(\Upsilon) g$$
$$g^* g^* \rightarrow \chi_c(\chi_b)$$

- Gauge boson & Higgs

  NEW

$$g^* g^* \rightarrow h$$
$$g^* g^* \rightarrow Z + Q\bar{Q}$$
$$g^* g^* \rightarrow W + q_i q_j$$
$$q g^* \rightarrow Z q$$

- QCD processes – forward jets

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

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:

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

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

- appropriate for 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

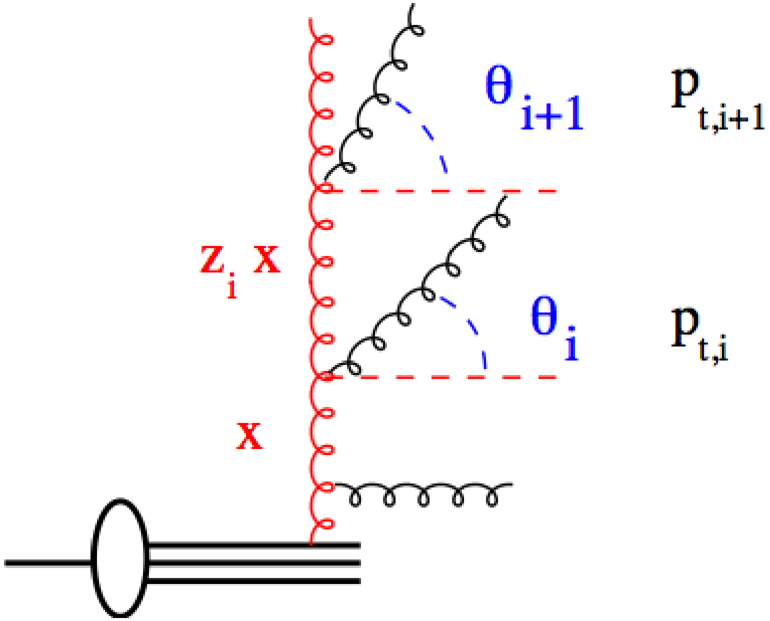
at medium and large x

➔ 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 distributic

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

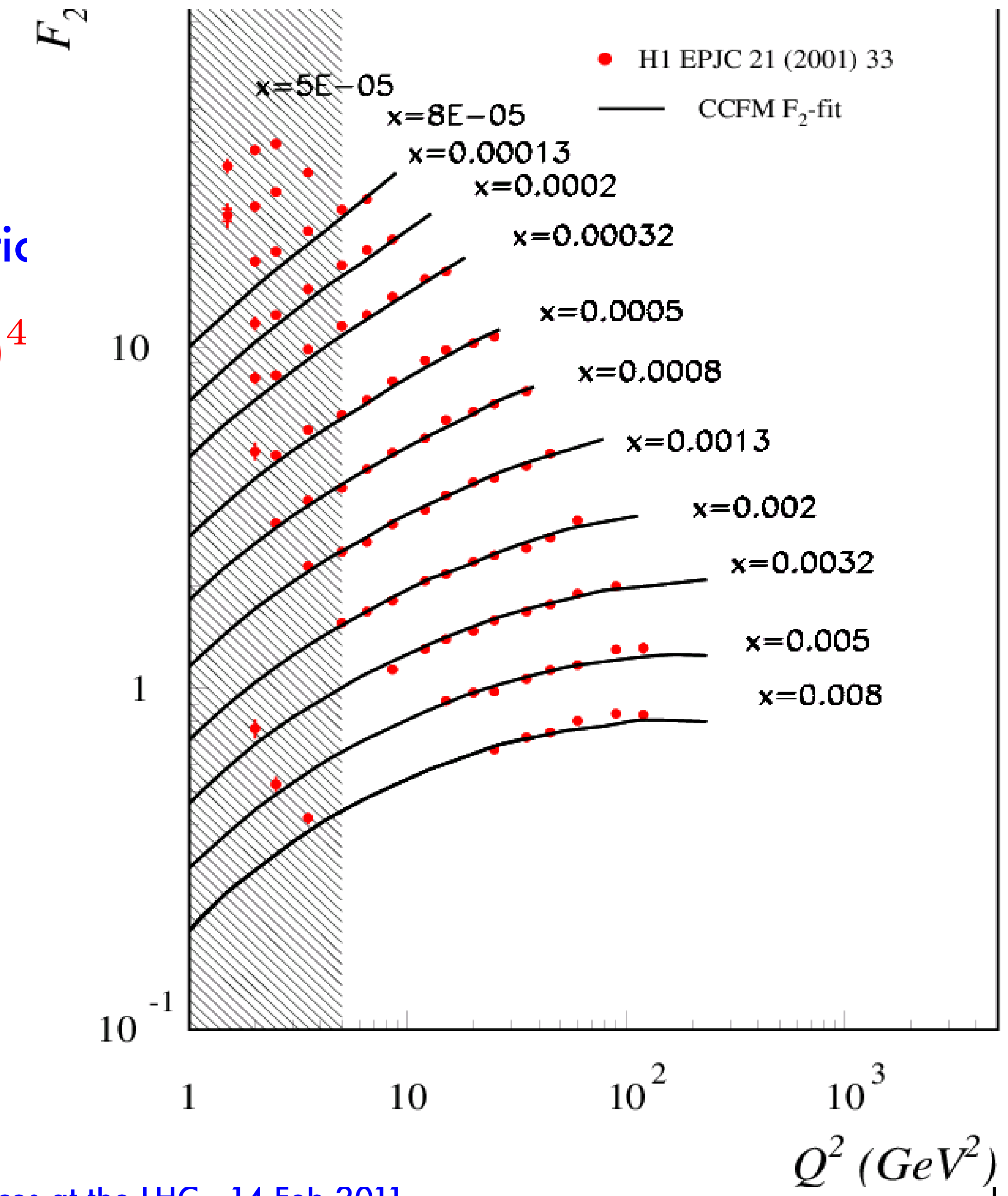
  (H1 Eur. Phys. J. C21 (2001) 33-61, DESY 00-181)

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

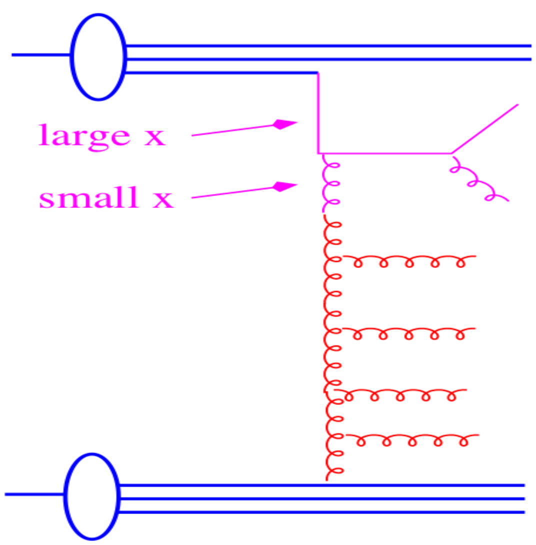
  $$\frac{\chi^2}{\text{ndf}} = \frac{111.8}{61} = 1.83$$

  $$B_g = 0.028 \pm 0.003$$

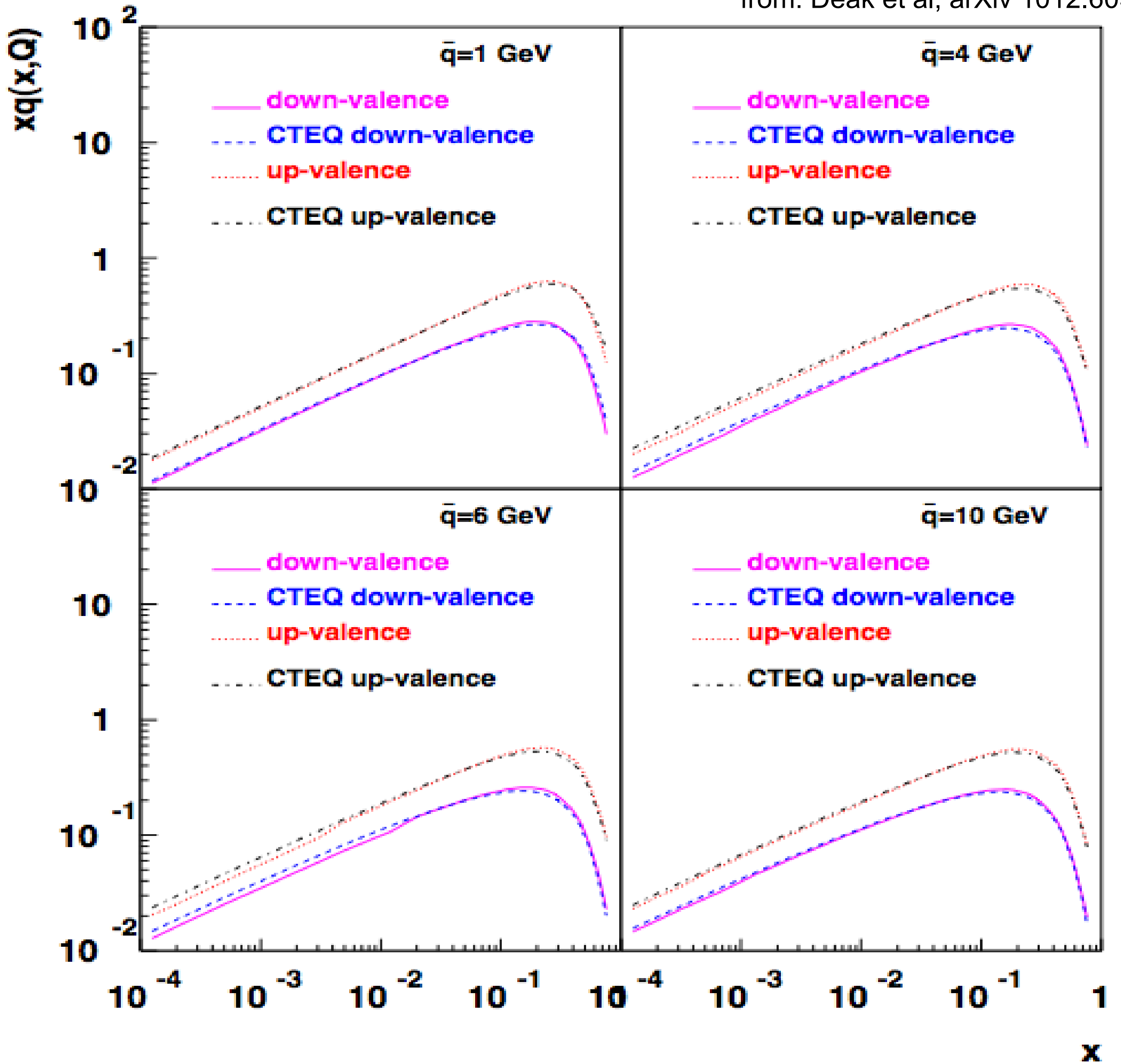


unintegrated valence quarks

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



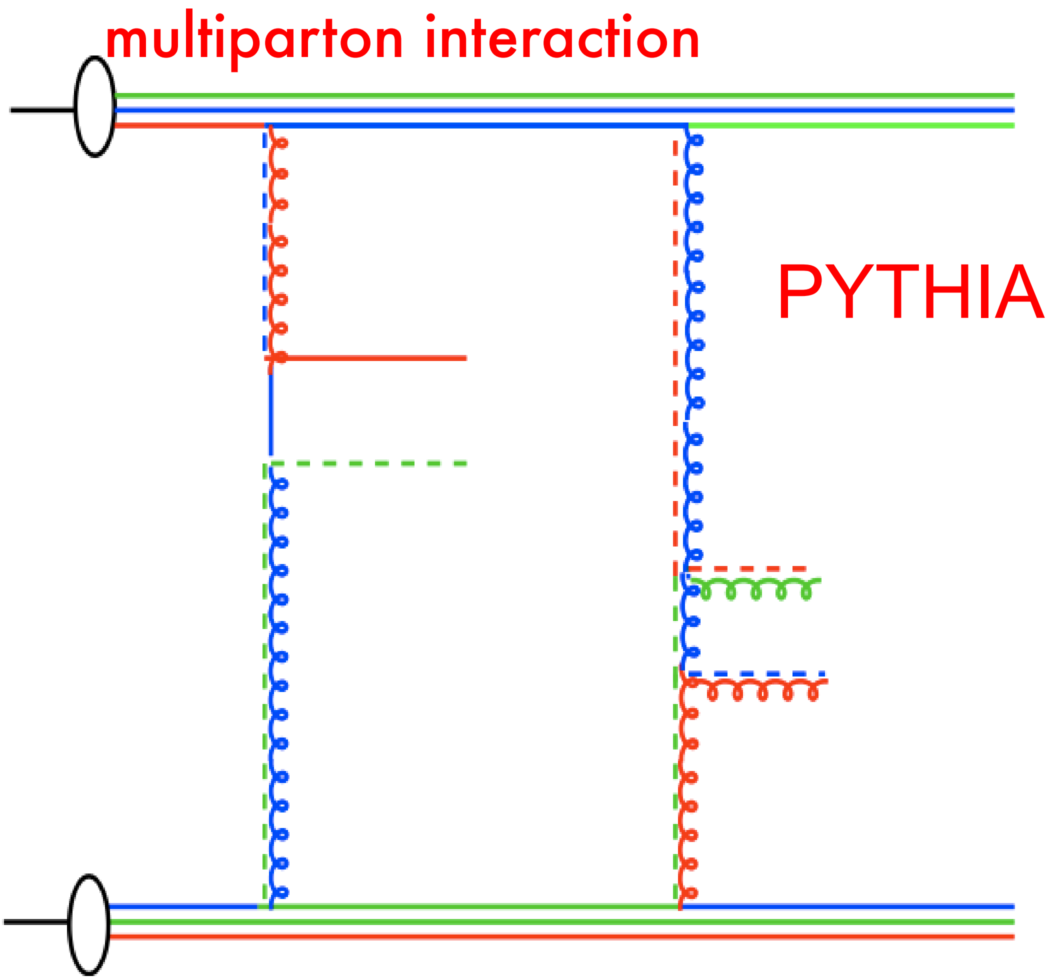
from: Deak et al, arXiv 1012.6037

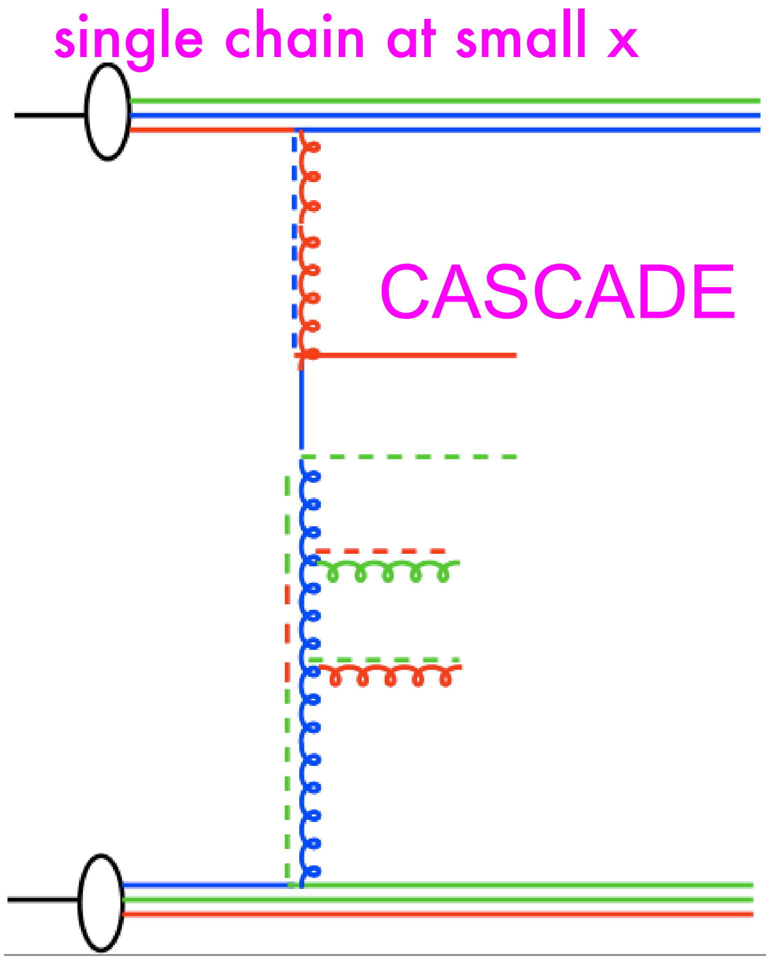


Comparison to pp data:
Minimum Bias

How well do we know soft parton radiation?

- soft parton radiation:

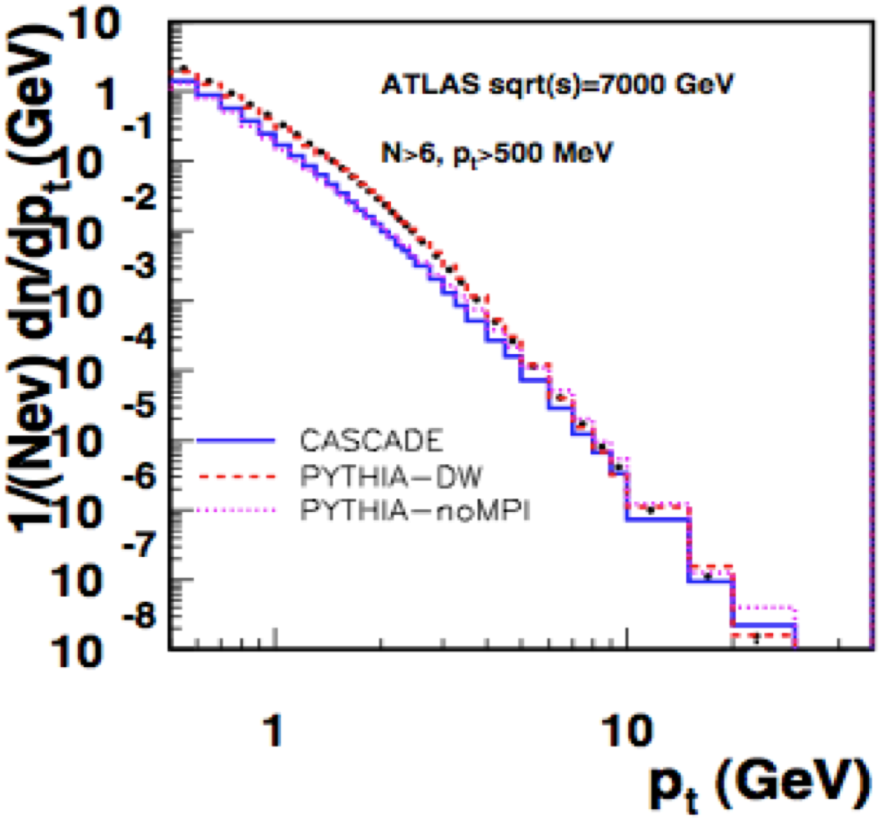


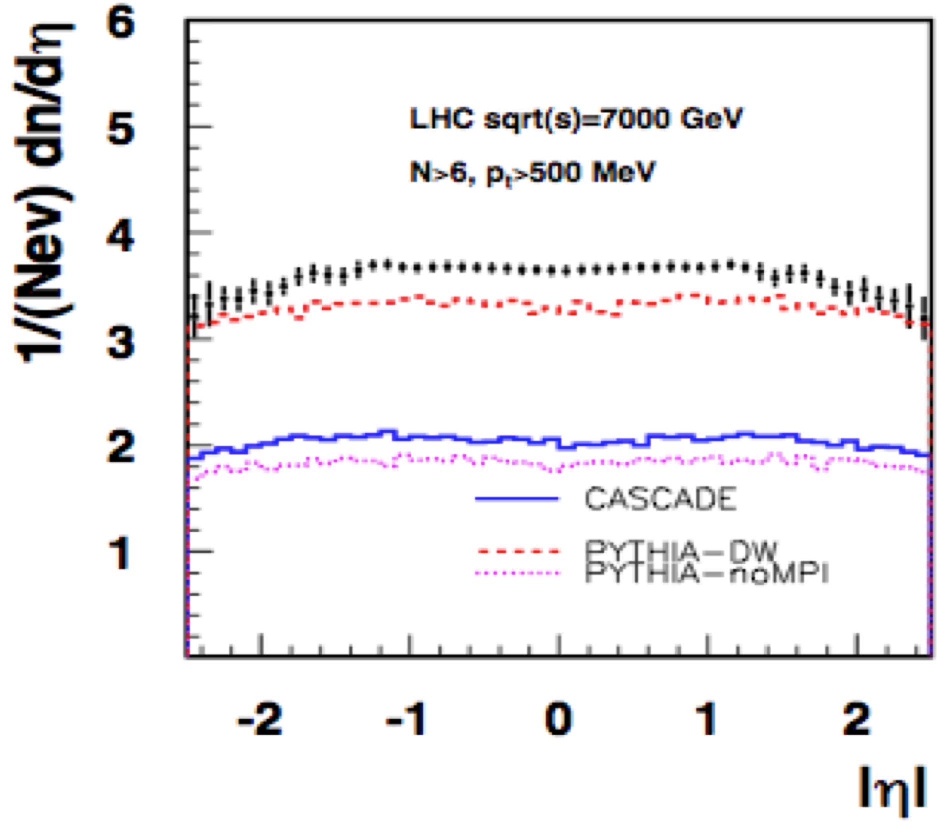


- which of the two is correct or are they both describing the same ... ???

Charged particle spectra in Minbias

$$g^* g^* \to q\bar{q},\ g^* g \to gg,\ g^* q \to qg$$



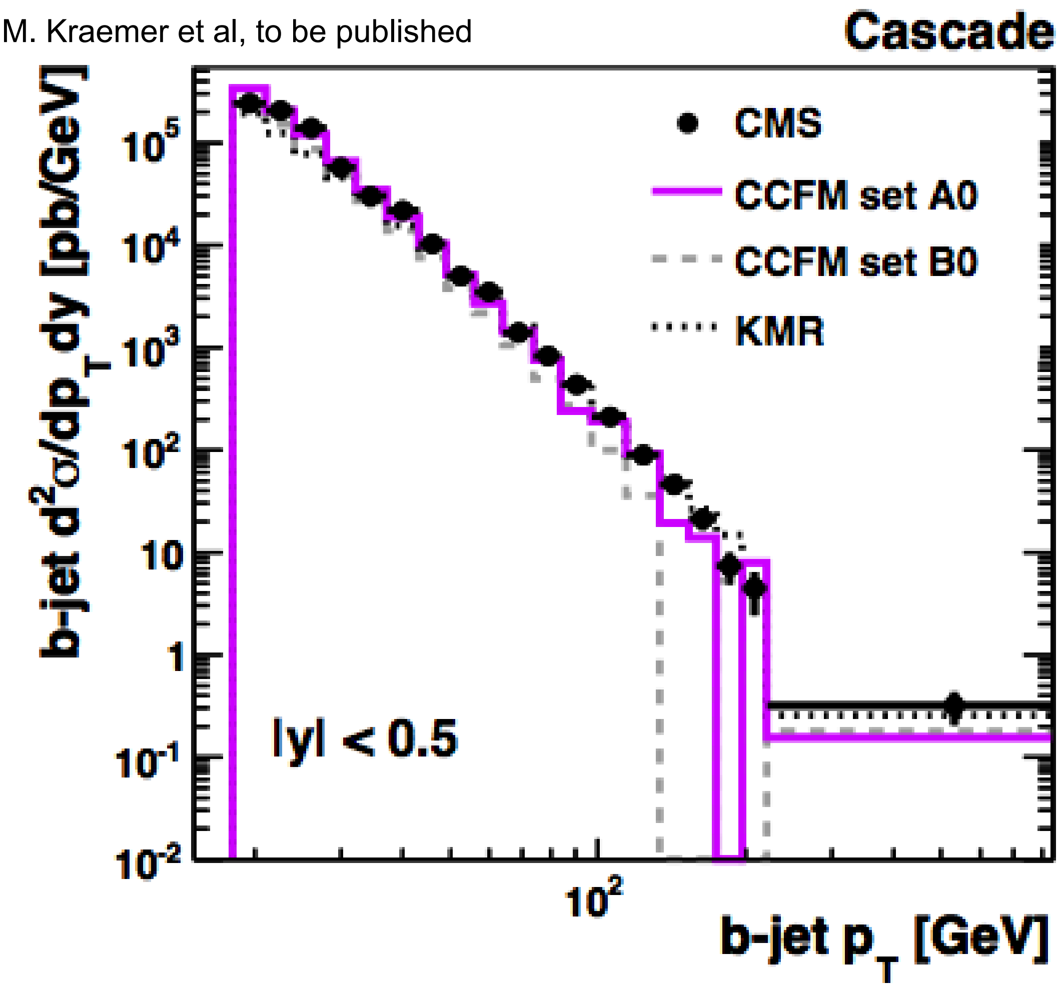


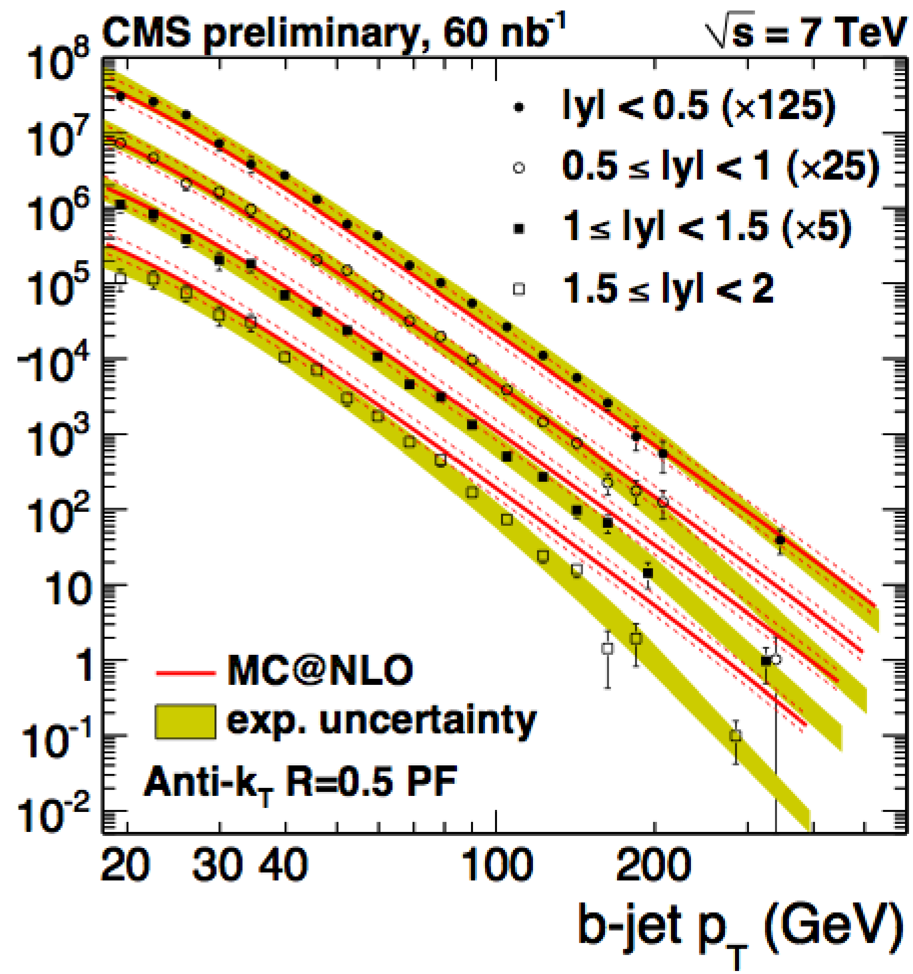
- clear deficit of particle production in the soft region
  - region where multiparton interactions play dominant role
  - CASCADE larger than PYTHIA w/o MPI

Comparison to pp data:
hard processes - heavy flavors

Open Heavy Flavor production

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

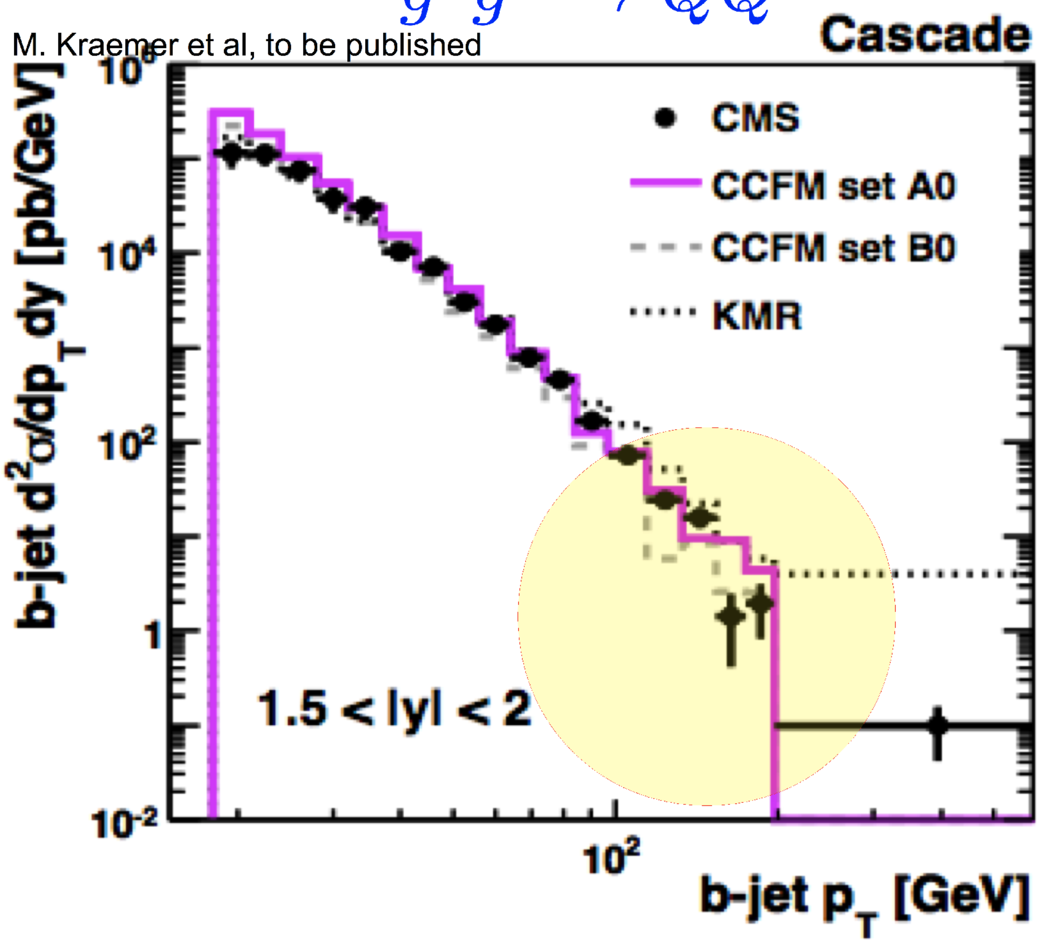


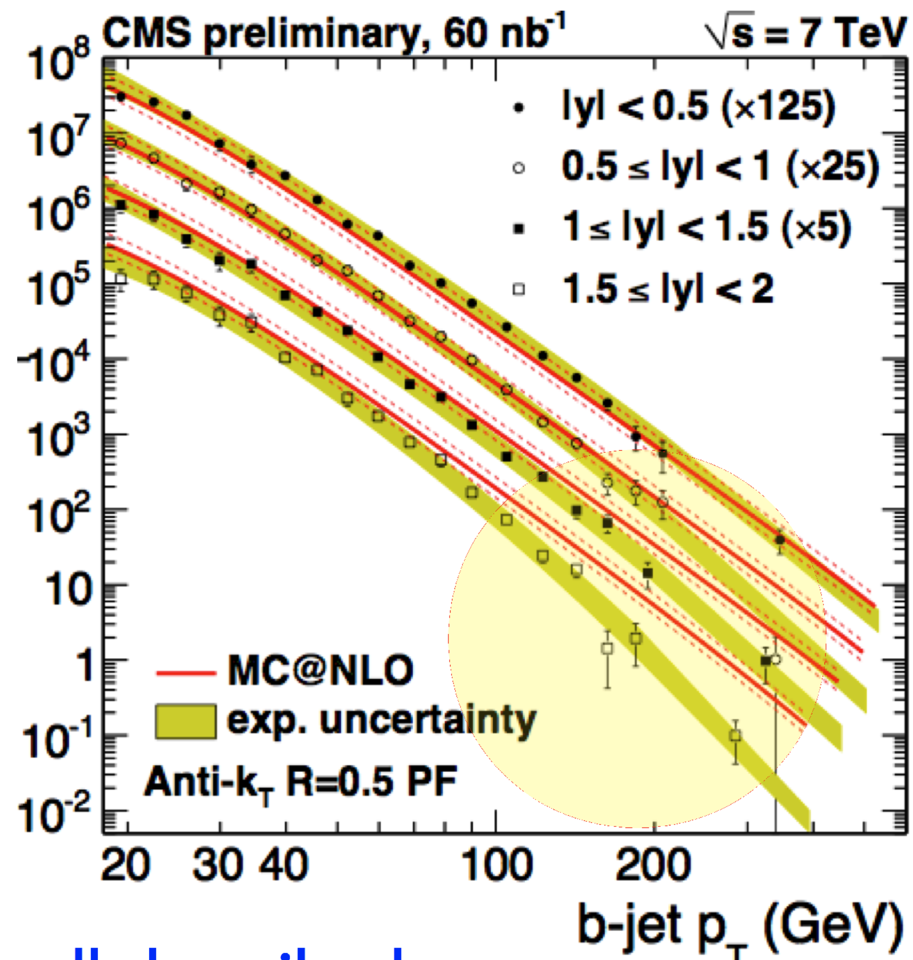


- at small |y|xsection well described (similar to MC@NLO)

Open Heavy Flavor production

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

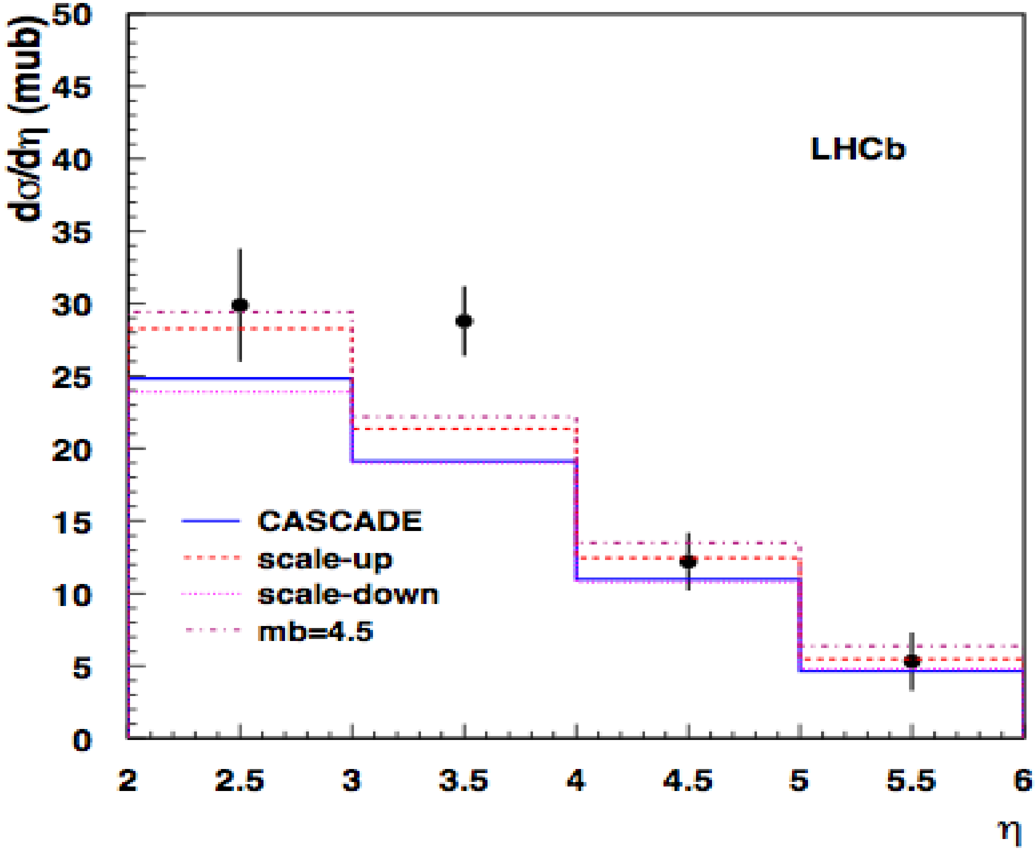


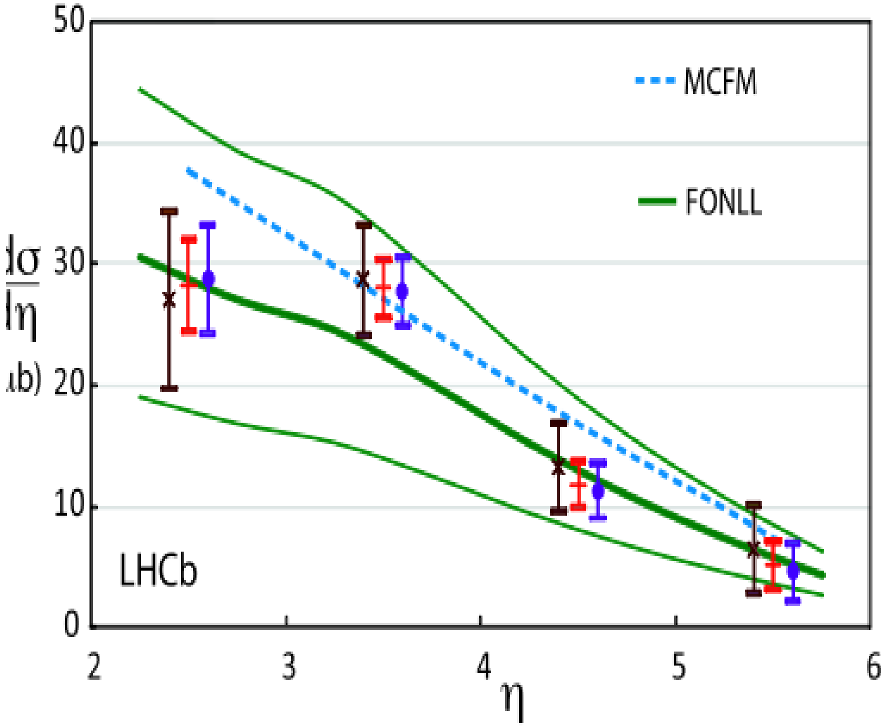


- at large 1.5 < |y| <2.0 x-section well described
  - effect of suppression in off-shell ME ?
  - note: MC@NLO is too large at large pt ...

Forward B – production (LHCb)

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

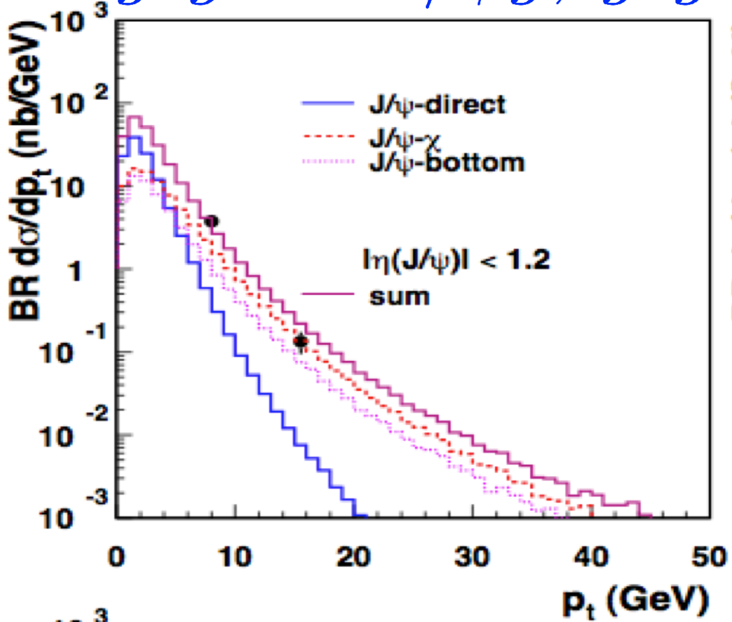


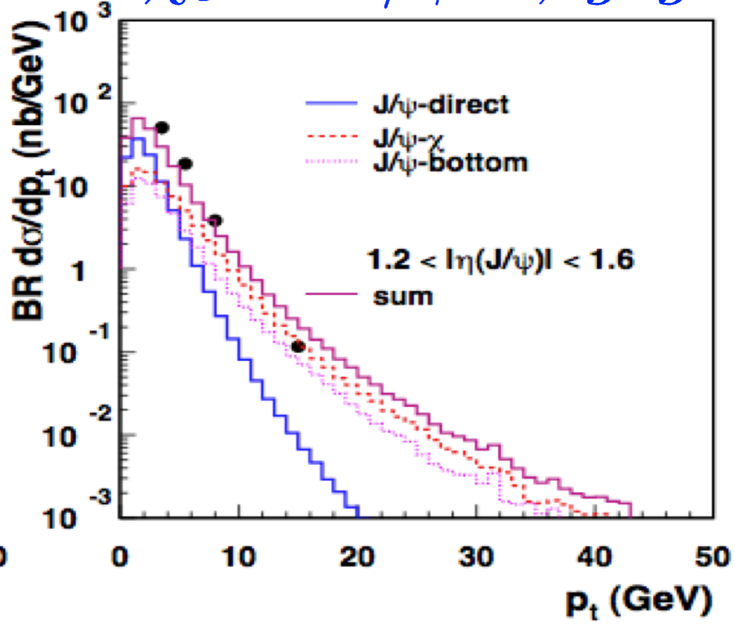


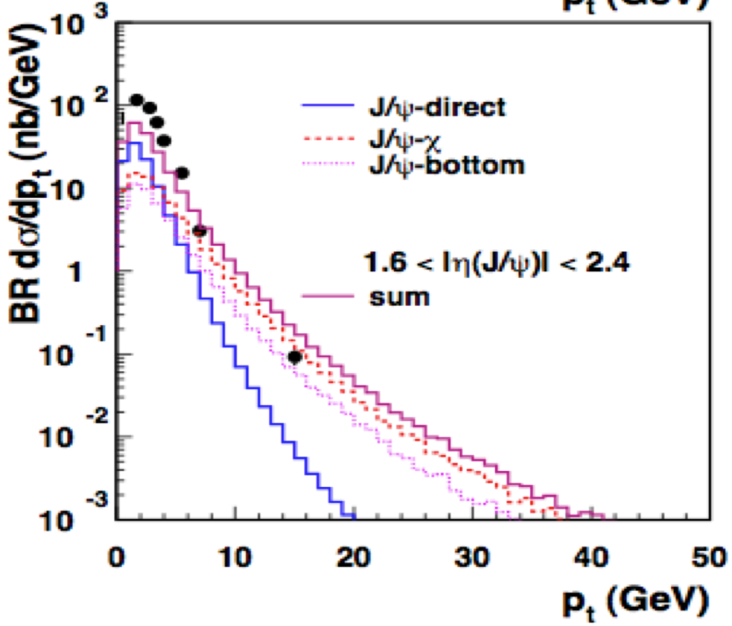
- Forward B-hadron production described well
  - "small" uncertainties from uPDF and b-mass

Inelastic J/ ψ production

$$g^*g^* \to J/\psi g,\ g^*g^* \to \chi_c \to J/\psi X,\ g^*g^* \to b\bar{b} \to J/\psi X$$



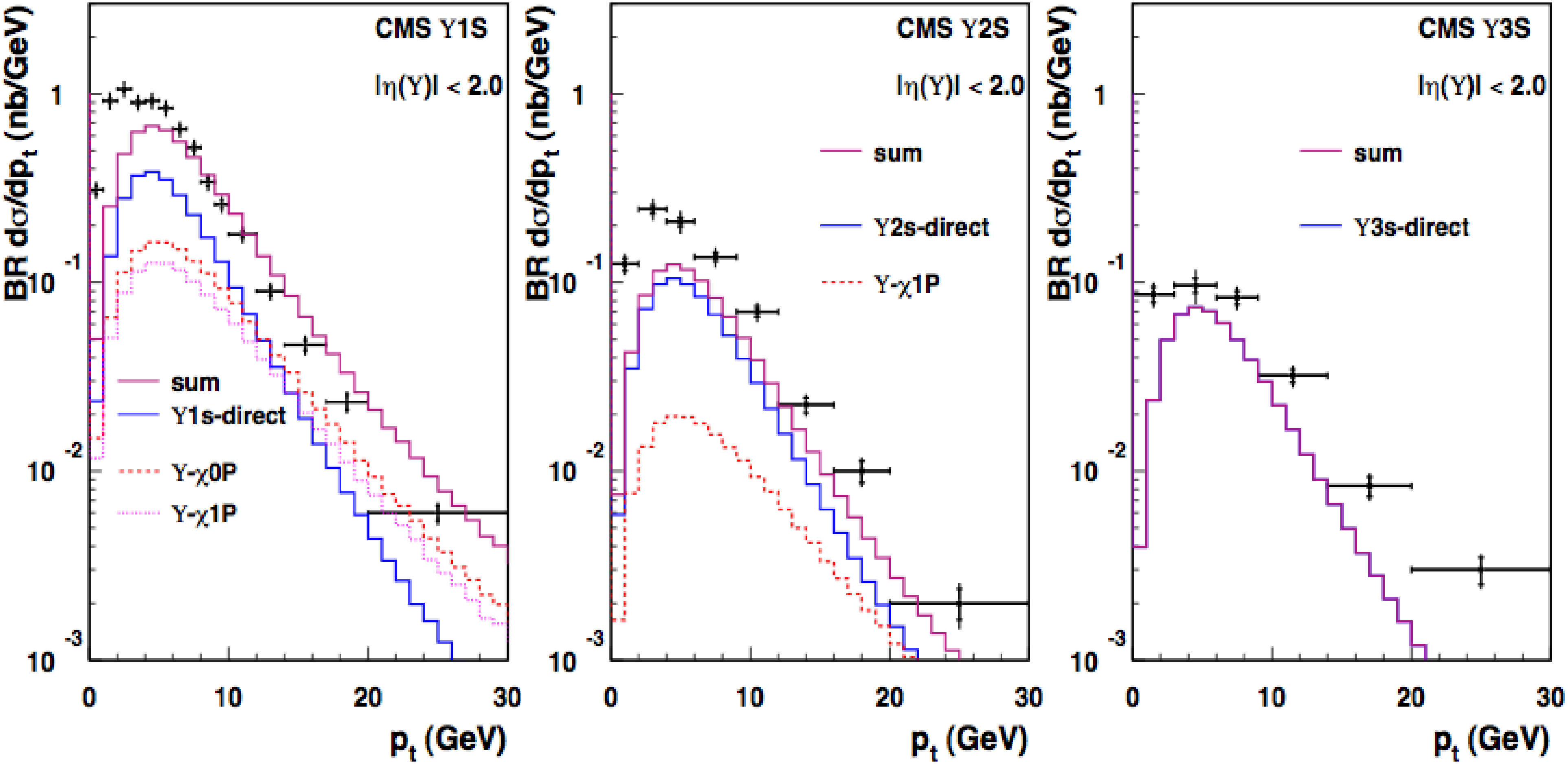




- only CSM contributions included
- cross section depends on wave function
- no free tunable parameters
  - possible contribution from color octet processes expected to be very small

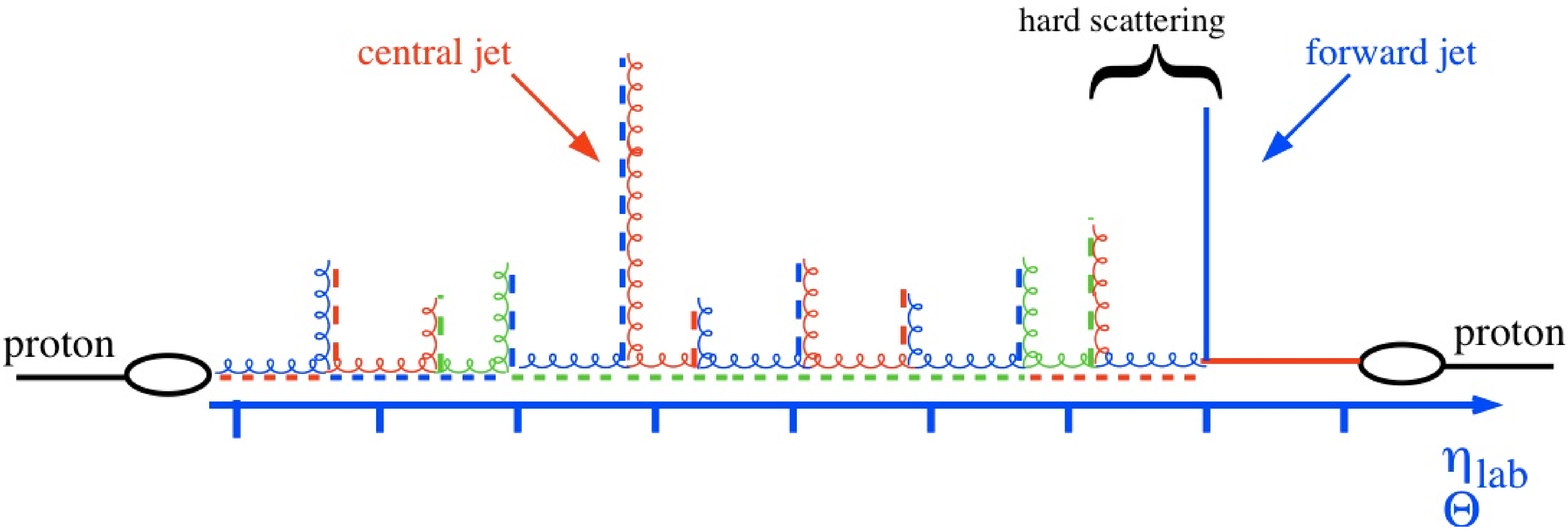
Inelastic Upsilon production

$g^*g^* \to \Upsilon g,\ g^*g^* \to \chi_b \to \Upsilon + X$



- Only color singlet model contributions included
- excited states calculated explicitly including proper wavefunctions
- NO tunable parameters, except uPDF, scales in α_s

Associated forward jet production



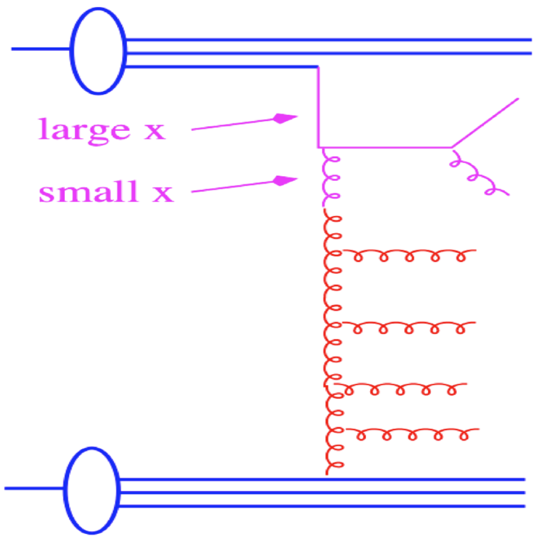
- **forward jet** $E_t > 10(30)\ GeV,\ \ 3 < |\eta| < 5$
- **central jet** $E_t > 10(30)\ GeV,\ \ |\eta| < 2$

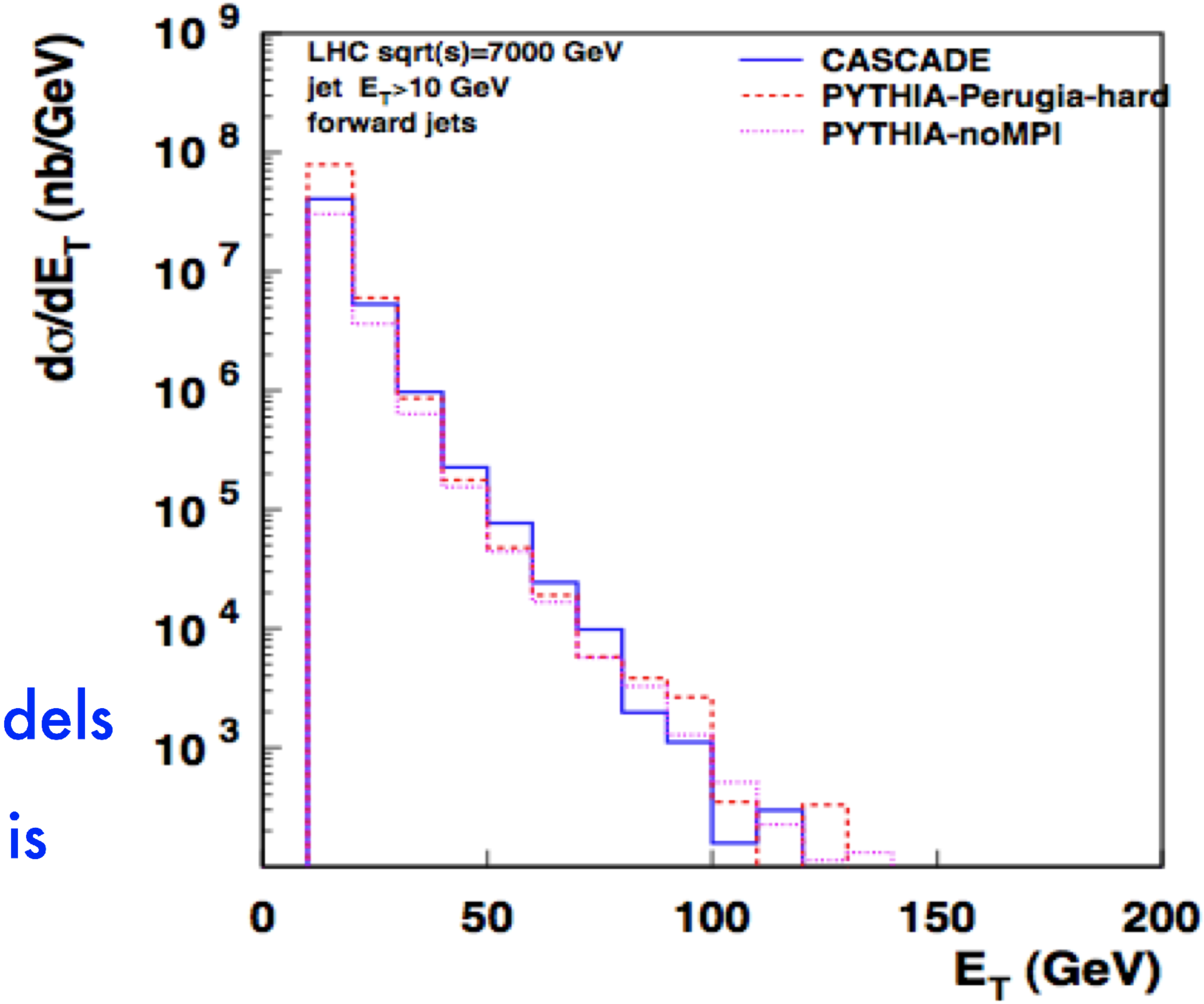
Hard processes: forward jets

Forward – central jets

$$g^*g^* \to q\bar{q},\ g^*g \to gg,\ g^*q \to qg$$

from: Deak et al, arXiv 1012.6037





- pt spectra are similar in CASCADE and MPI models
  - consistent with what is observed in data

Azimuthal correlations in fwd-cent jets

$$g^* g^* \to q\bar{q},\ g^* g \to gg,\ g^* q \to qg$$

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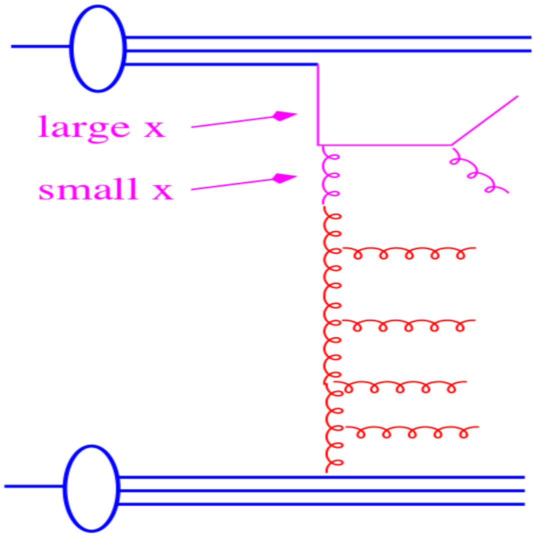

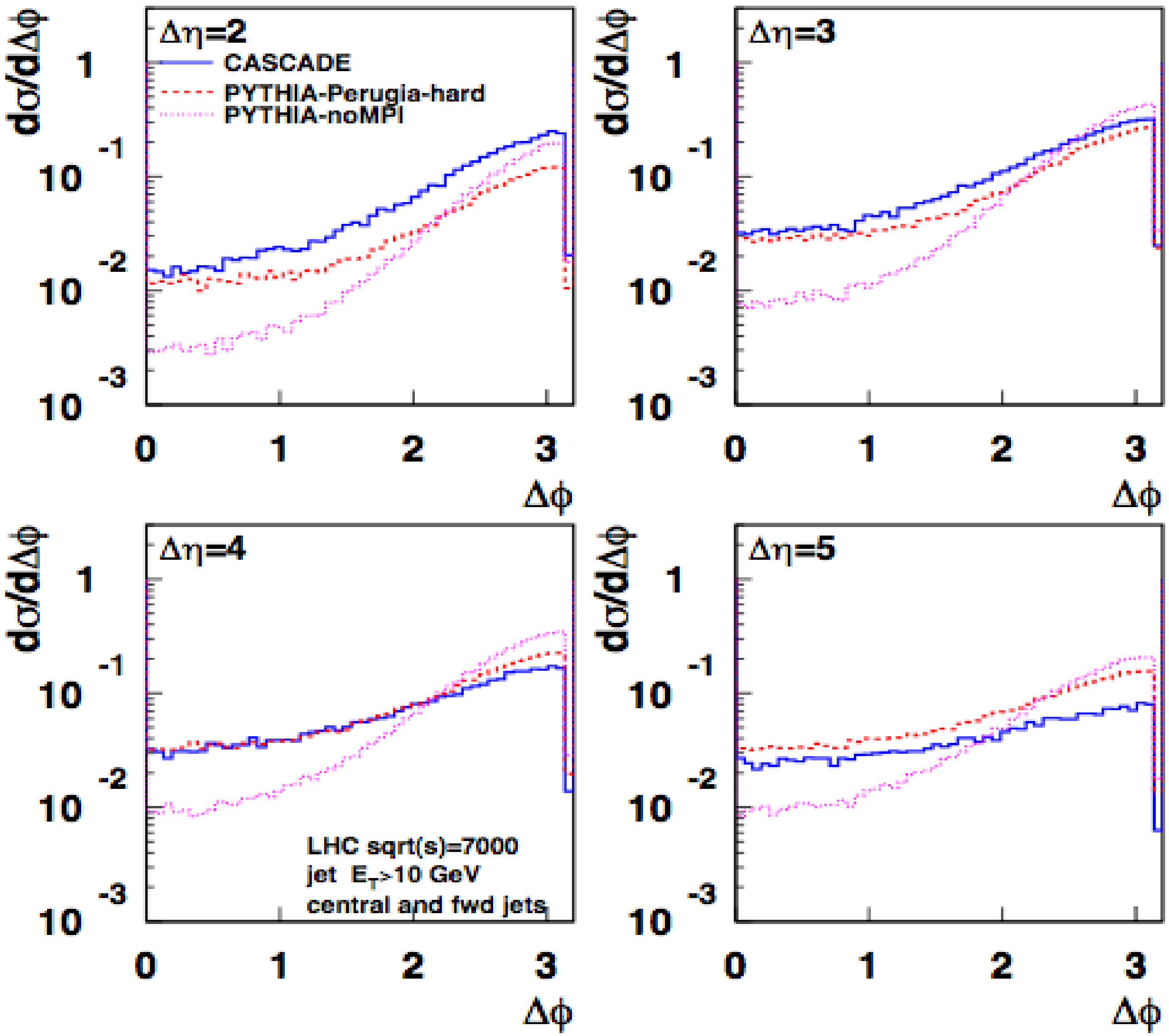

- significant differences between CASCADE and MPI models

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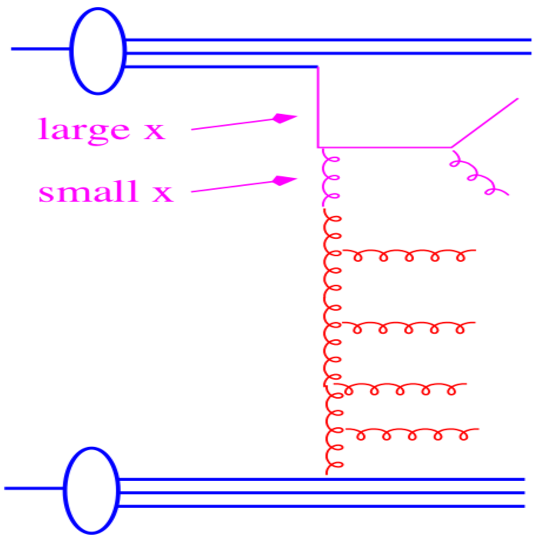

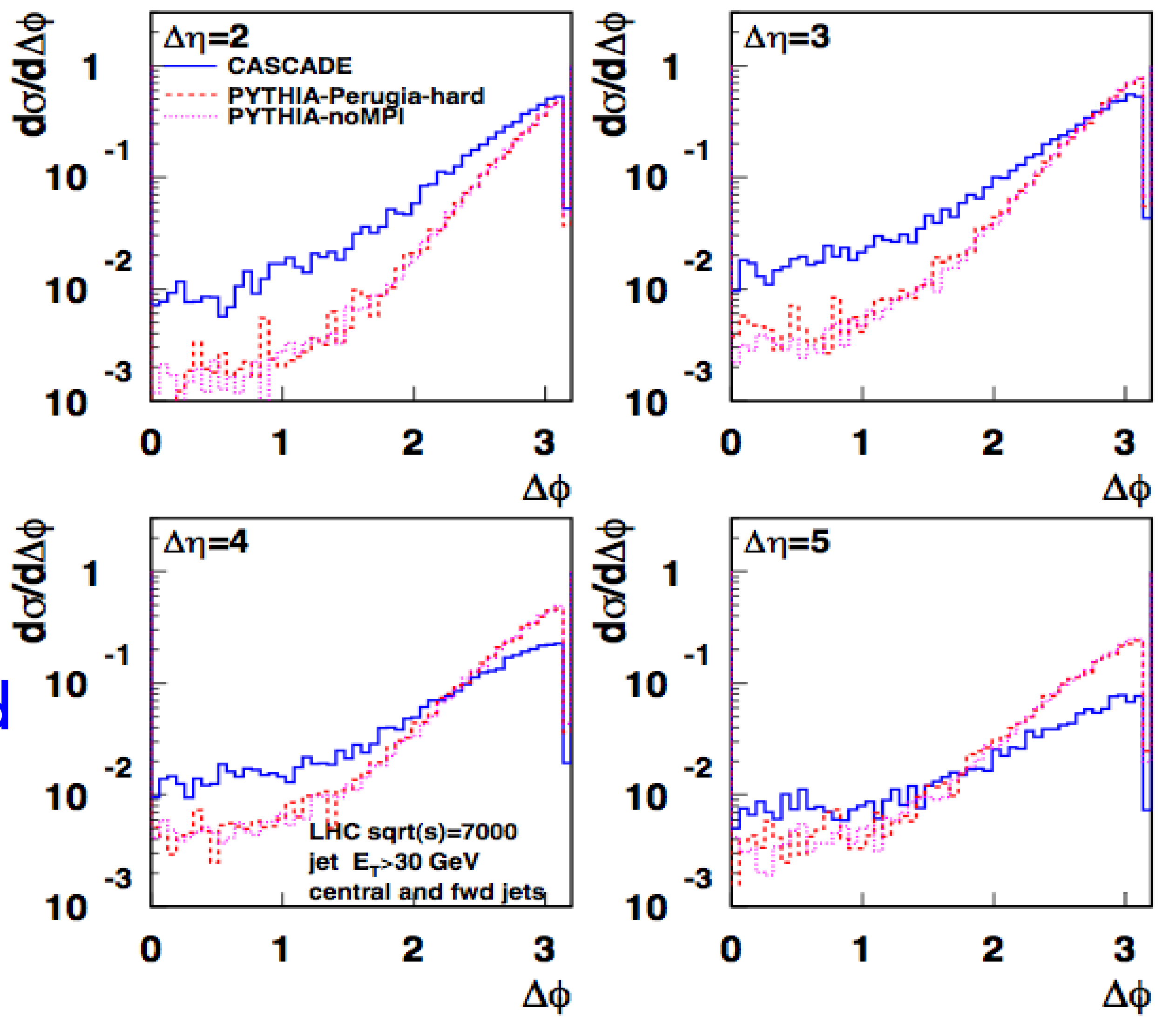

- significant differences between CASCADE and MPI models
- differences also at $E_t > 30$ GeV

Azimuthal correlations in fwd-cent jets

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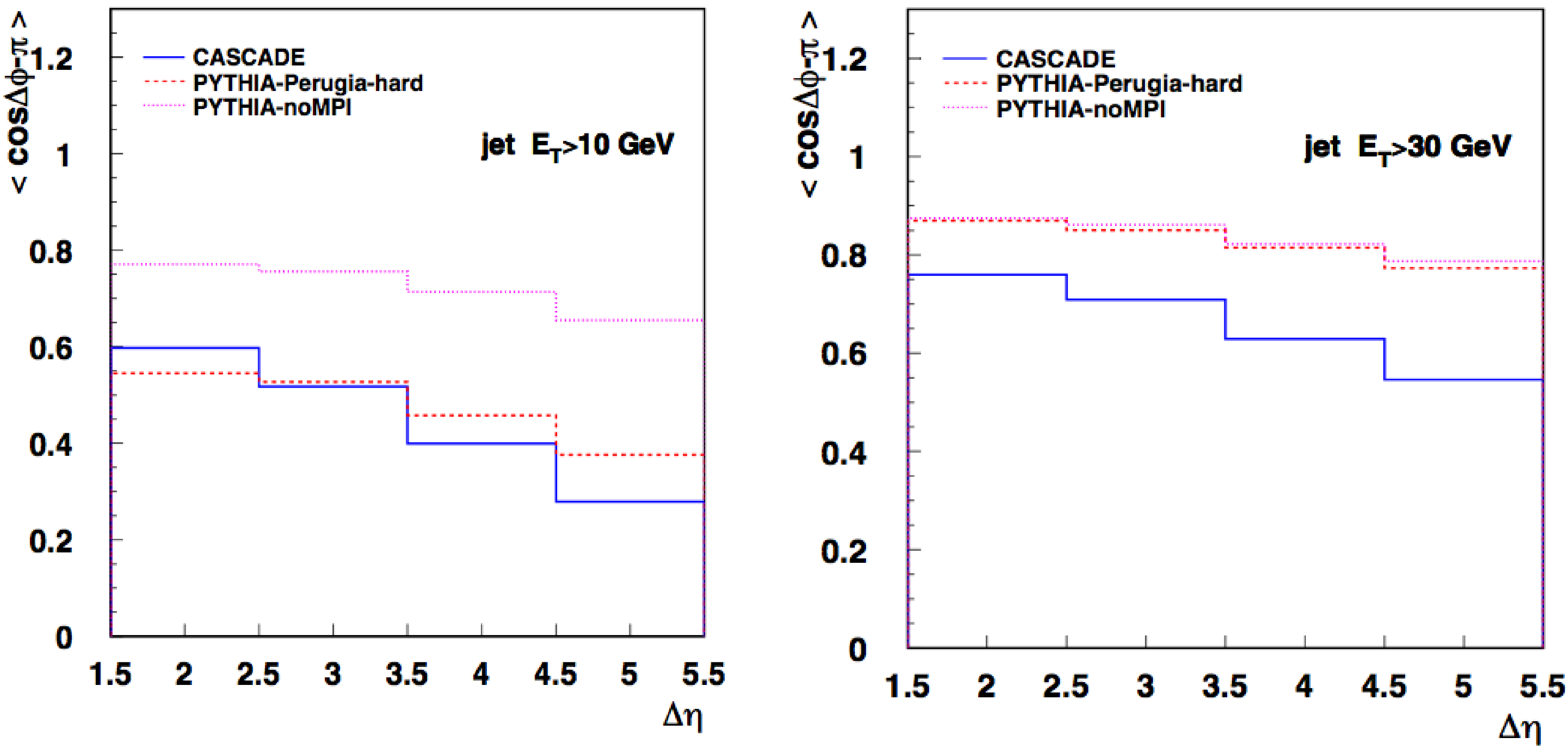

- significant de-correlation effects observable
- BUT, differential distributions has discriminate better !

Conclusions

- CASCADE works promising well in pp
  - specialities are (up to now):
    - heavy flavors (open and hidden)
    - forward (& central) jets
  - even does not too bad for min – bias
- CASCADE has essentially NO free parameters
  - all parameters are fixed by uPDF
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You are most welcome to use CASCADE for your analysis !

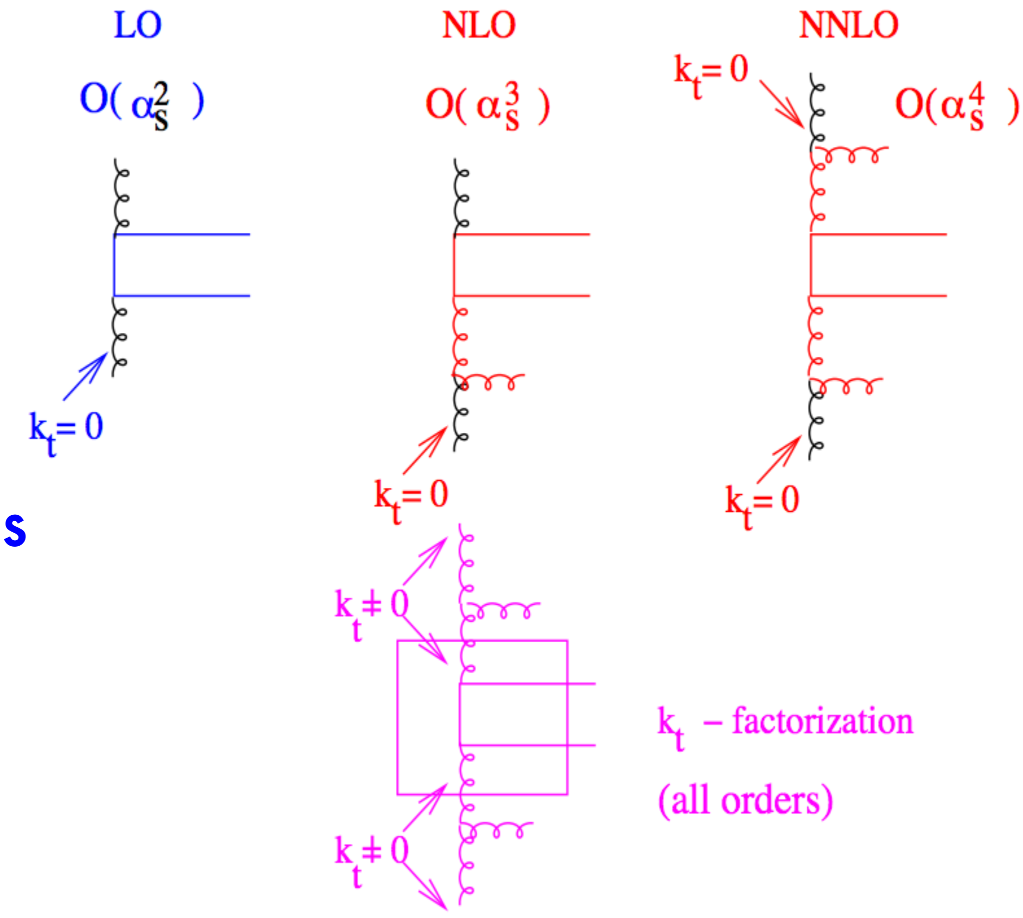
Backup slides

CASCADE and coll. NLO calculations

- fit of uPDF to inclusive structure functions /x-sections used to determine normalization

  ➔ includes "all-orders" !!!!

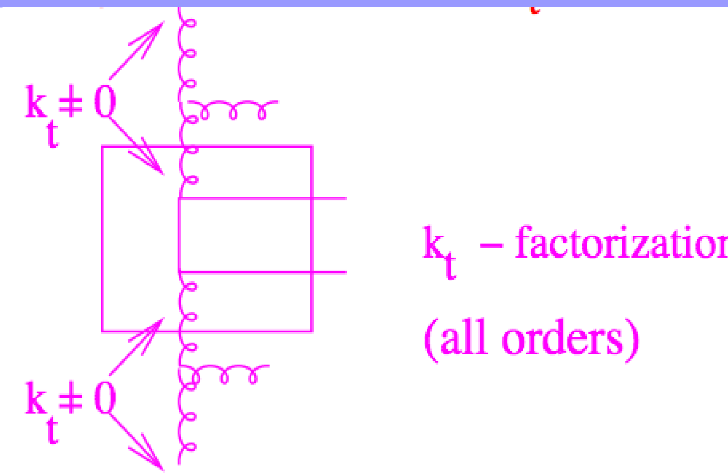
- off-shell matrix element simulates part of real NLO corrections



uPDFs are important....

CASCADE and NLO: 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