Workshop *QCD at Cosmic Energies - V*, Paris, June 2012

Forward Jets at Colliders and Small-x Physics

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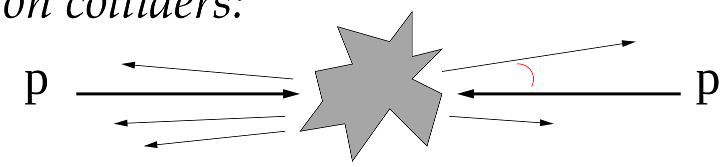
I. Introduction: high-p_T events in the forward region

II. Issues on QCD factorization and parton showers

III. Jet production at high rapidities at the LHC

Particle production in the forward region at hadron colliders:



small polar angles, i.e. large rapidities

♢ Historically:

- fairly specialized subject: e.g., measurements of σ(total) and σ(elastic)
- dominated by soft, small-p$_T$ processes

♢ At the LHC:

- both soft and hard production
- phase space opening up for large $\sqrt{s}$ $\Rightarrow$ multiple-scale processes
- unprecedented coverage of large rapidities (calorimeters + proton taggers)

$\Rightarrow$ forward high-p$_T$ production

♠ Forward high-p_T production at the LHC involves both

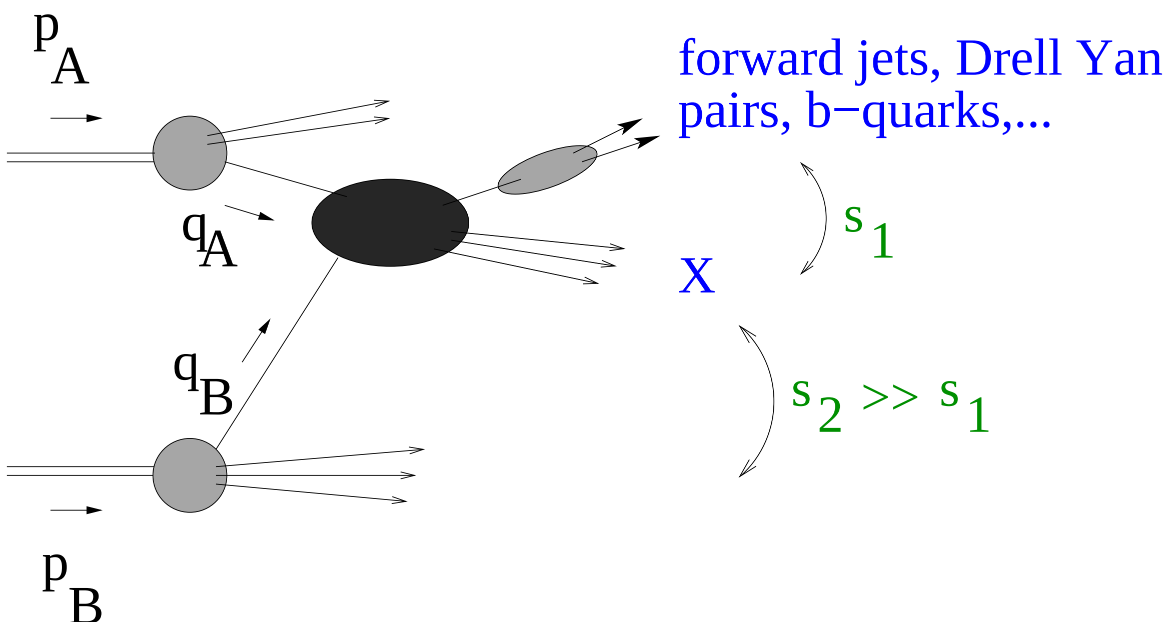
new particle discovery processes, e.g.

- Higgs searches in vector boson fusion channels
- jet studies in decays of highly boosted heavy states

and new aspects of Standard Model physics, e.g.

- QCD at small x and its interplay with cosmic ray physics
- new states of strongly interacting matter at high density

High-p_T production in the forward region



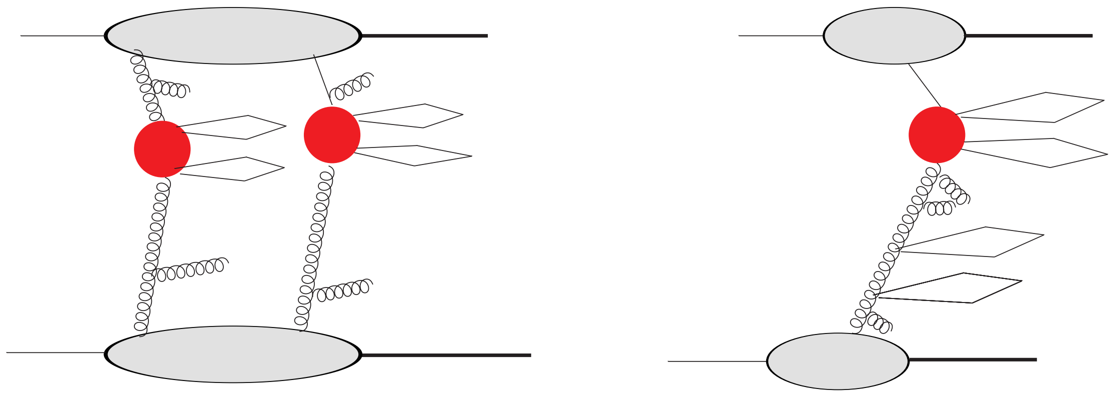
- multiple hard scales

- asymmetric parton kinematics $x_A \to 1, \; x_B \to 0$

♢ Are finite-order QCD calculations reliable in the forward region?

♢ Perturbative QCD resummations?

Multiple parton interactions



Multi-jet production by *[talk by B. Blok]*

(left) multiple parton chains; (right) single parton chain

- modeled in shower Monte Carlo event generators

[talks by A. Siódmok, L. Lönnblad]

- increasingly important as parton density grows

♢ non-negligible in forward hard processes?

- contribute primarily to highly differential cross sections

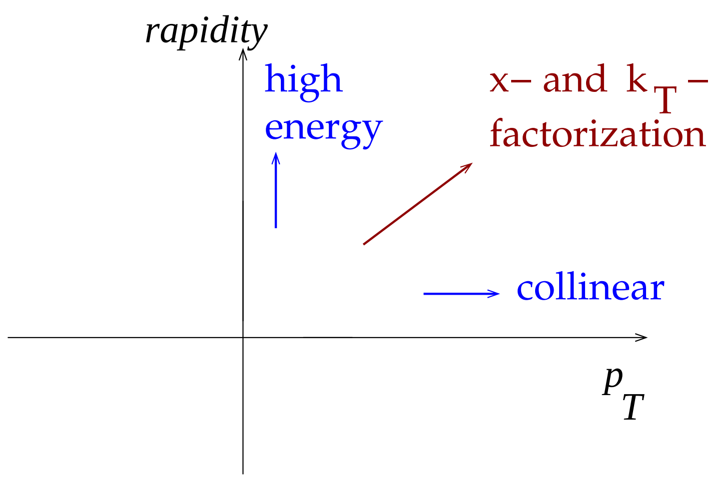
♢ dependence on detailed distribution of states produced by parton evolution?

II . Forward jet production as a multi-scale problem

• summation of high-energy logarithmic corrections long recognized to be necessary for reliable QCD predictions
$\Rightarrow$ BFKL calculations

Mueller & Navelet, 1987; Del Duca et al., 1993; Stirling, 1994; Colferai et al., arXiv:1002.1365

• Large logarithmic corrections are present both in the hard p_T and in the rapidity interval



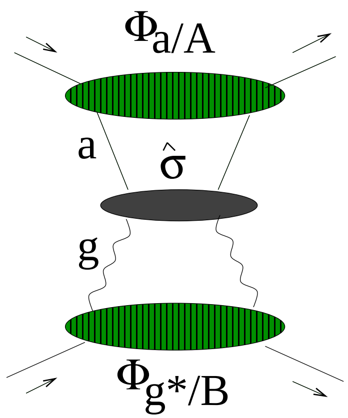
$\longrightarrow$ Both kinds of log contributions can be summed consistently to all orders of perturbation theory via QCD factorization at fixed k$_T$

Forward jets:

- High-energy factorization at fixed transverse momentum

$$\frac{d\sigma}{dQ_t^2 d\varphi} = \sum_a \int \phi_{a/A} \otimes \frac{d\widehat{\sigma}}{dQ_t^2 d\varphi} \otimes \phi_{g^*/B}$$

▷ needed to resum consistently both logs of rapidity and logs of hard scale *Deak, Jung, Kutak & H, JHEP 09 (2009) 121*



(a)

Figure 1: Factorized structure of the cross section.

♢ ϕ_a near-collinear, large-x; ϕ_{g^*} $k_\perp$-dependent, small-x

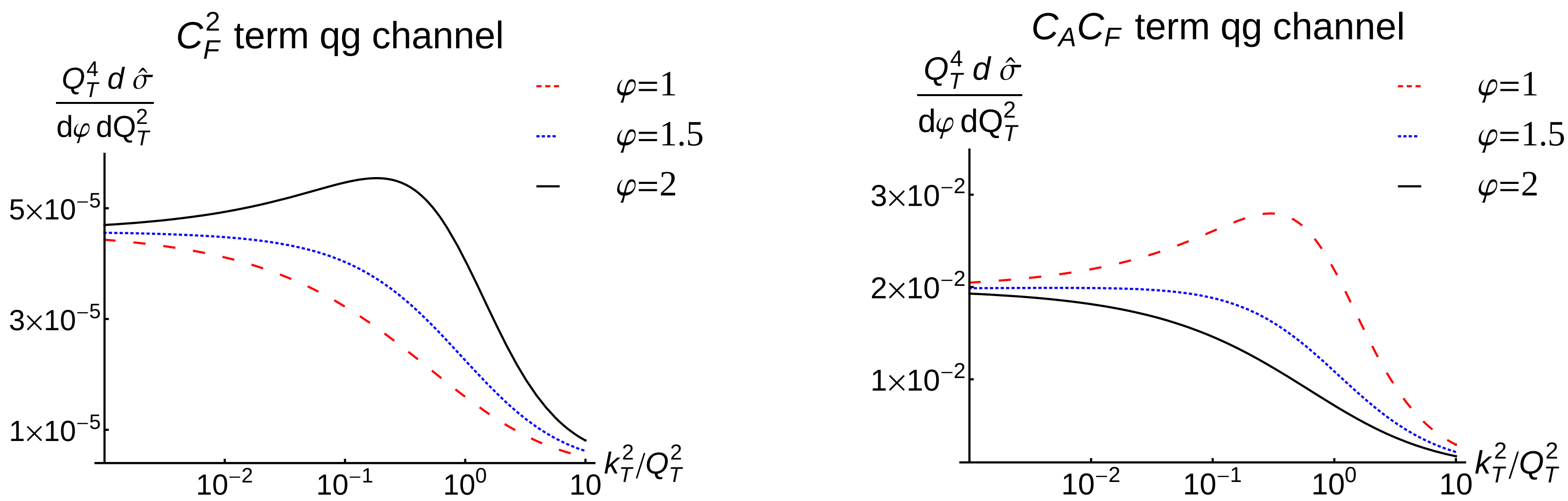
♢ $\widehat{\sigma}$ off-shell (but gauge-invariant) continuation of hard-scattering matrix elements *[Catani et al., 1991; Ciafaloni, 1998]*

FULLY EXCLUSIVE MATRIX ELEMENTS: BEHAVIOR AT LARGE K$_\perp$

Deak, Jung, Kutak & H, JHEP 09 (2009) 121

Q_t = final-state transverse energy (in terms of two leading jets p_t and y)

k_t = transverse momentum carried away by extra jets



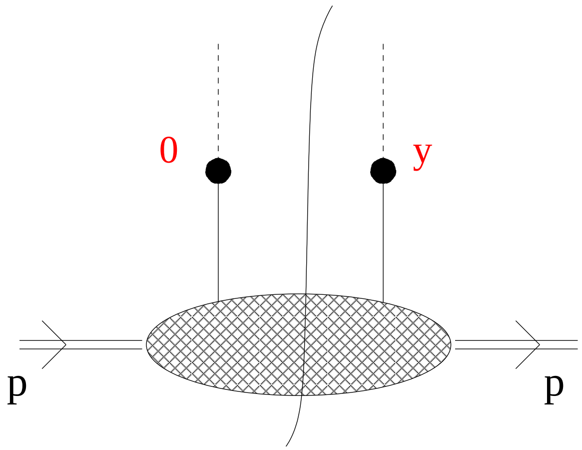
- Matrix elements factorize for high energy

not only in collinear region but also at finite angle

- Couple to k$_\perp$-dependent parton showers

⇒ *coherence* from gluon emission across large rapidity intervals (not small-angle)

UNINTEGRATED (OR TRANSVERSE MOMENTUM DEPENDENT) PARTON DISTRIBUTIONS



$p = (p^+ ,\ m^2 / 2\, p^+ ,\ 0_\perp)$

$$\widetilde{f}(y) = \langle\ P \mid \overline{\psi}(y)\ V_y^\dagger(n)\ \gamma^+\ V_0(n)\ \psi(0) \mid P\ \rangle \quad , \qquad\qquad y = (0, y^-, y_\perp)$$

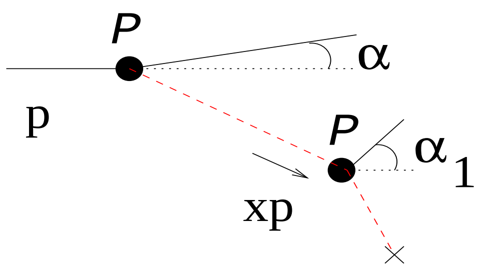
$$V_y(n) = \mathcal{P} \exp \left(i g_s \int_0^\infty d\tau\ n \cdot A(y + \tau\ n) \right)$$

correlation of parton fields ('dressed' with gauge links) at distances y, $y_\perp \neq 0$

- Sudakov region ⇒ resummation $\alpha_S^n \ln^k (M/q_T)$ [J.-W. Qiu talk]
  - high energy region ⇒ resummation $\alpha_S^n \ln^k (\sqrt{s}/E_T)$

▷ $K_\perp$-DEPENDENT PARTON BRANCHING

$$\mathcal{G}(x,k_T,\mu) = \mathcal{G}_0(x,k_T,\mu) + \int \frac{dz}{z} \int \frac{dq^2}{q^2}\,\Theta(\mu - zq) \times \underbrace{\Delta(\mu,zq)}_{\text{Sudakov}} \; \underbrace{\mathcal{P}(z,q,k_T)}_{\text{unintegr. splitting}} \; \mathcal{G}(x/z, k_T + (1-z)q, q)$$



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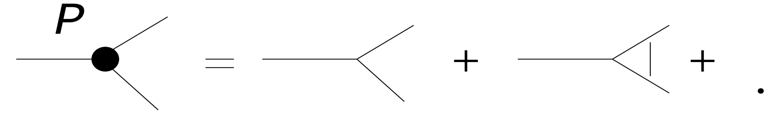


▷ CCFM evolution equation

▷ Monte Carlo implementations: CASCADE [Jung et al.]

LDC [Gustafson et al.]

Merging PS and ME

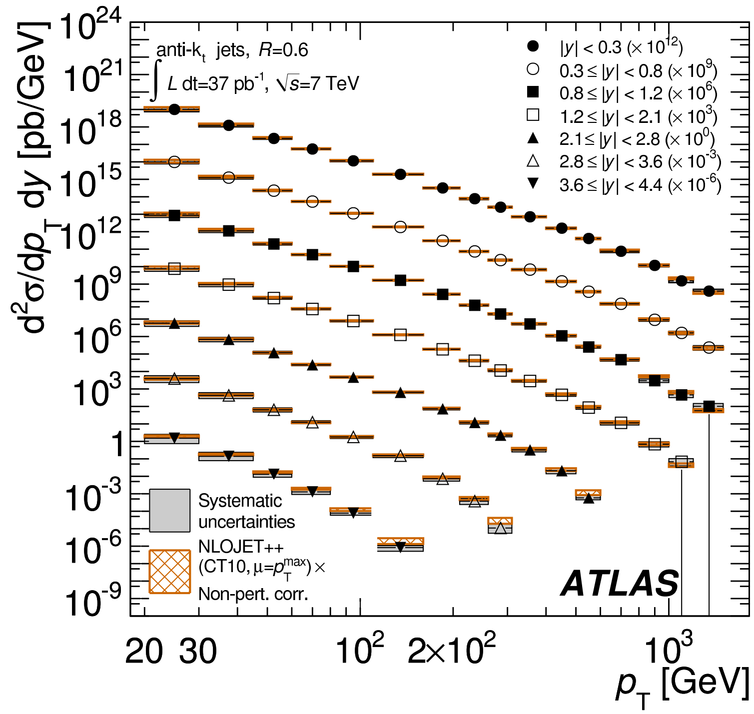
- Merging in high-energy limit uses

$$(\gamma/k_\perp^2)\ \left(k_\perp^2/\mu^2\right)^{\gamma} \stackrel{\gamma \ll 1}{=} \delta(k_\perp^2) + \gamma\ \left(1/k_\perp^2\right)_{\rm R} + \gamma^2\ \left(k_\perp^{-2}\ln k_\perp^2/\mu^2\right)_{\rm R} + \dots$$

$$\text{where} \int dk_\perp\ \left(G(k_\perp,\mu)\right)_{\rm R}\ \varphi(k_\perp) = \int dk_\perp\ G(k_\perp,\mu)[\varphi(k_\perp) - \Theta(\mu - k_\perp)\ \varphi(0)]$$

III . Jets at the LHC

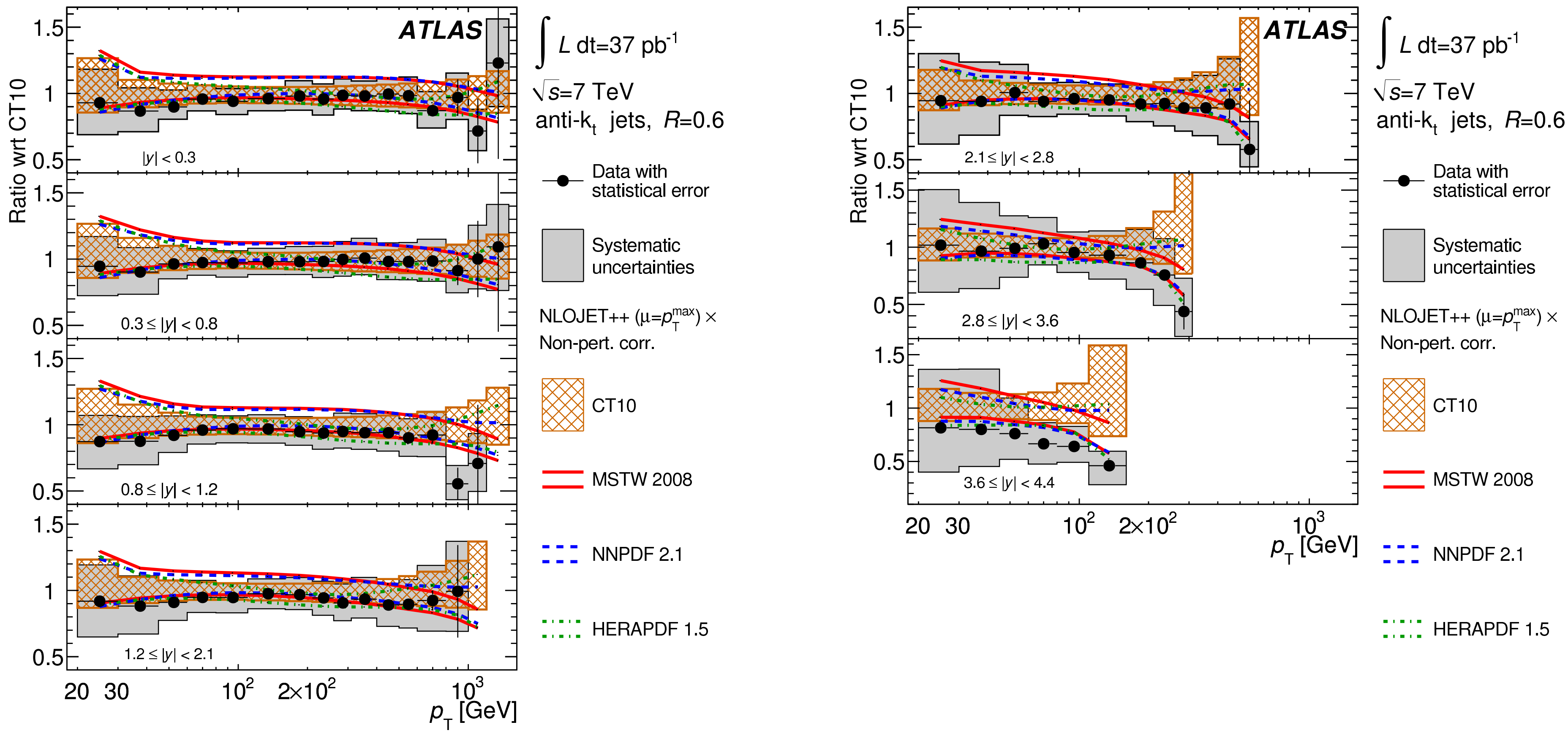
- Measurements presented in talks by G. Brandt, L. Kheyn



ATLAS, arXiv:1112.6297

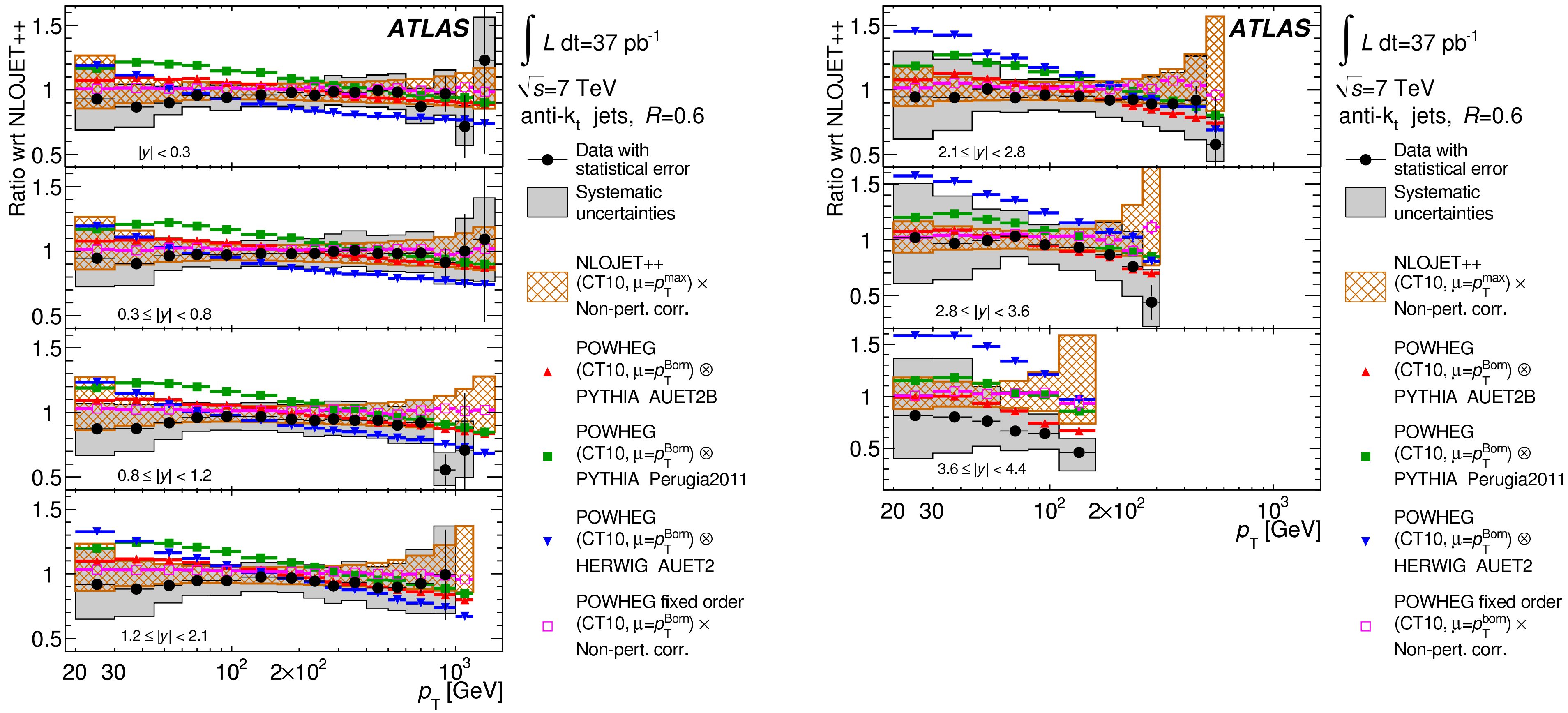
- comparisons with NLO QCD calculations — supplemented by “nonperturbative” [NP] corrections — and with NLO-matched shower event generators (e.g., Powheg)
- large kinematic range explored for the first time at colliders

Inclusive jets *[ATLAS, arXiv:1112.6297]*



- NLO calculation agrees at central rapidities
- increasing deviations with increasing y for large p_T

Inclusive jets *[ATLAS, arXiv:1112.6297]*

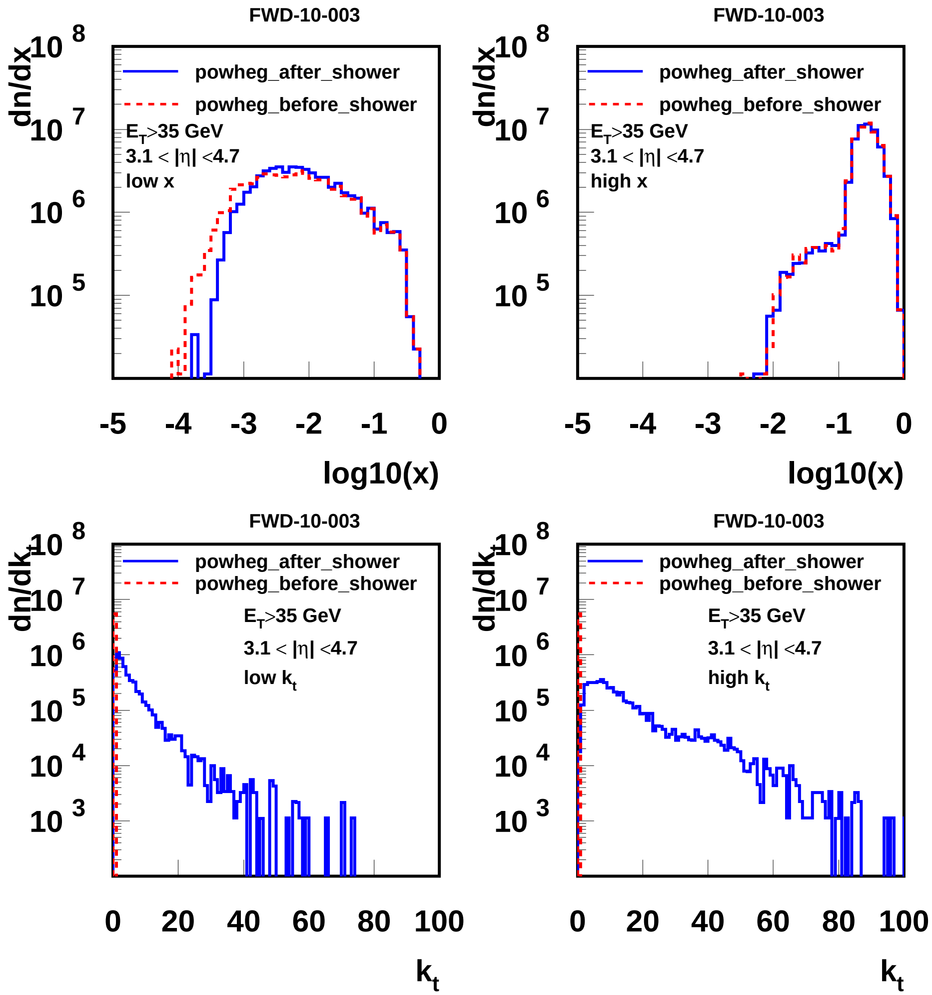


- higher order radiation from parton shower in POWHEG significant
- large differences between POWHEG/ PYTHIA and POWHEG/ HERWIG in forward region

Collinear shower kinematics

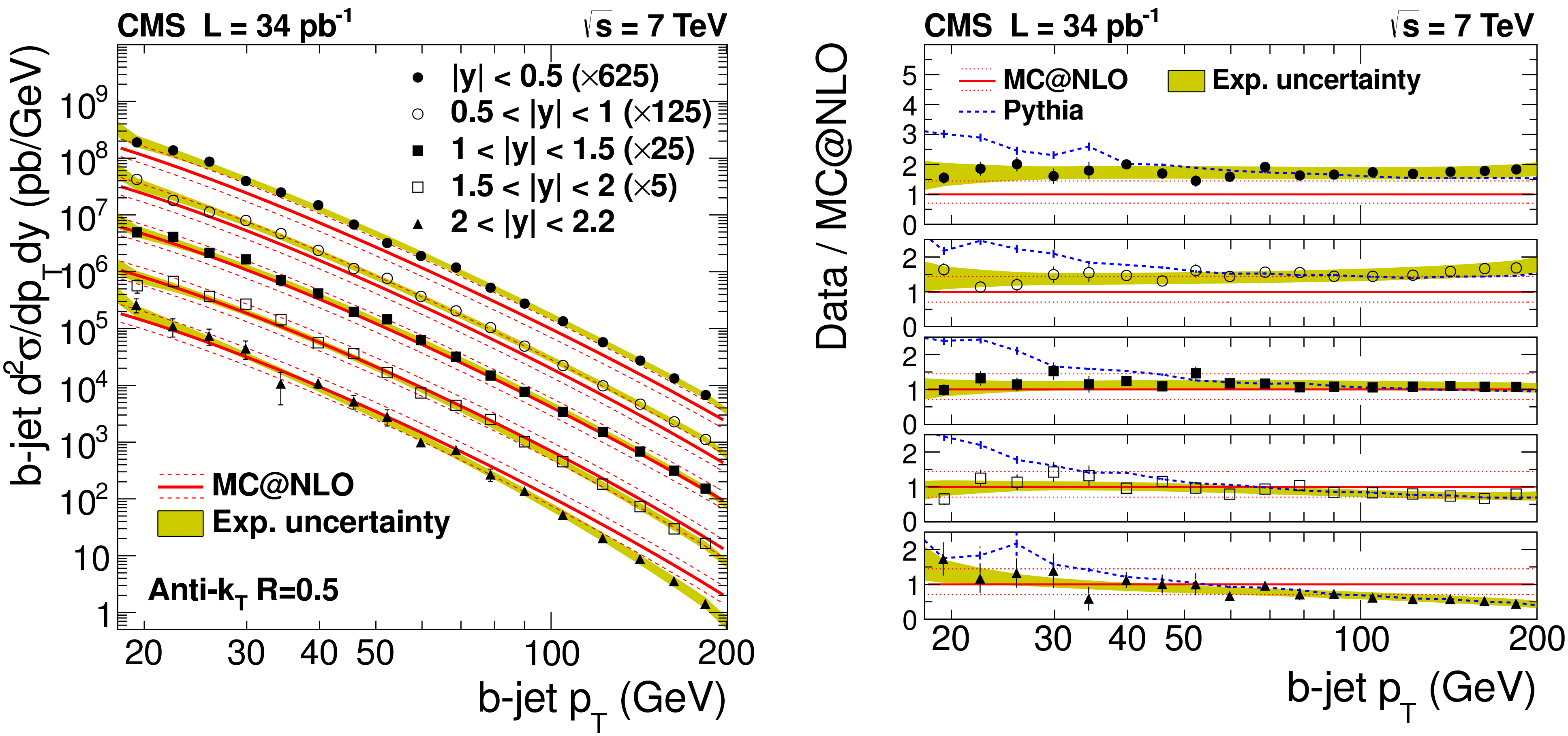
change in x distribution due to showering

[H. Jung, talk at "Event generators and resummation", DESY, May 2012]



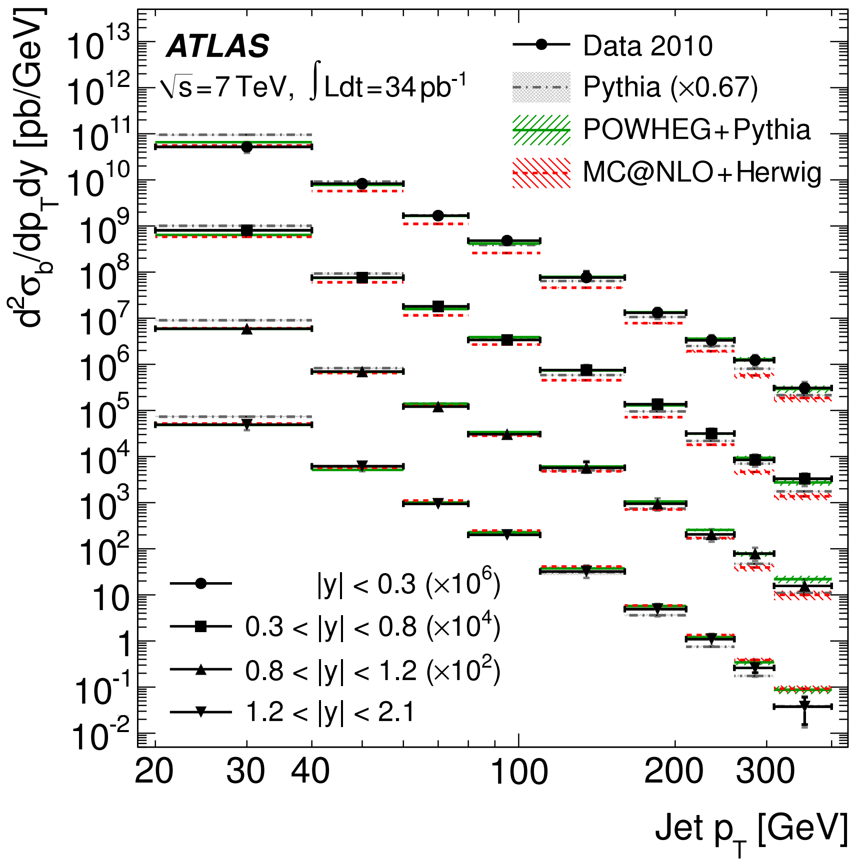
▷ non-negligible effect for high rapidity

Inclusive b-jets *[CMS, arXiv:1202.4617]*



- reasonable description by NLO-matched shower MC@NLO at central rapidities
  - data below the prediction at large y and large p_T

Inclusive b-jets *[ATLAS, arXiv:1109.6833]*

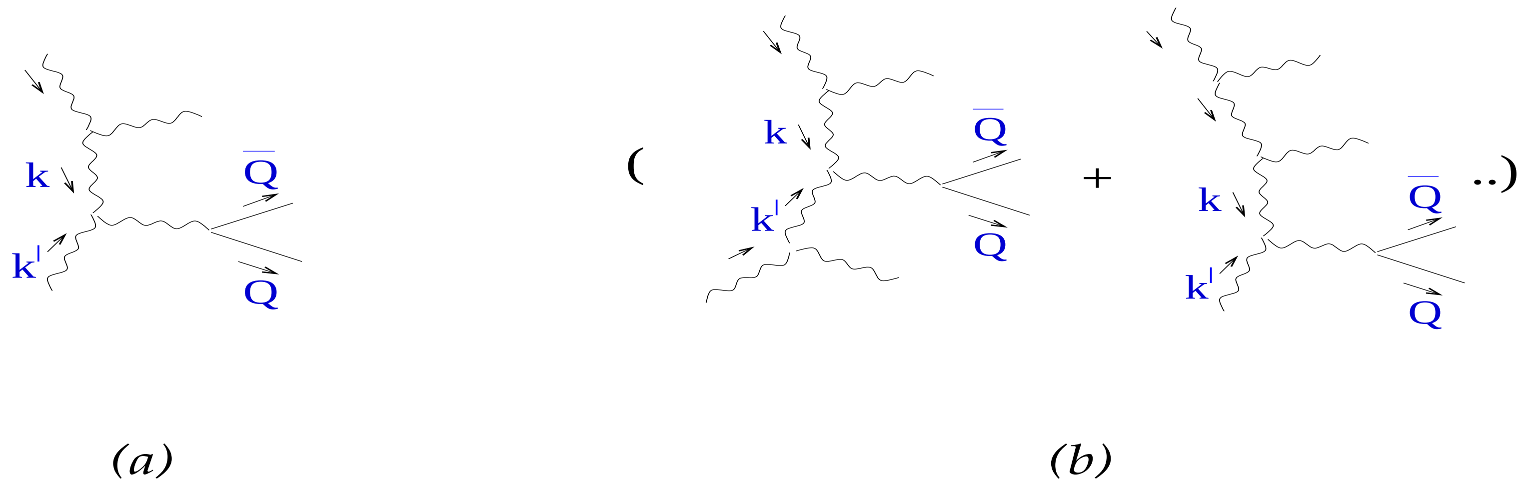


- data below NLO-matched calculations POWHEG and MC@NLO at large y and large p_T

Heavy flavor production: high-energy behavior

$$\sigma_{gg,N} \simeq C \left(\frac{m_Q^2}{K_T^2}\right)^{N+1} \ln(1 + K_T^2/(4m_Q^2))$$

$\Rightarrow$ strong triple-pole singularity in moments conjugate to k_T
from $m_Q^2 \ll (k_T + k'_T)^2 \ll k_T^2 \simeq k'^2_T$



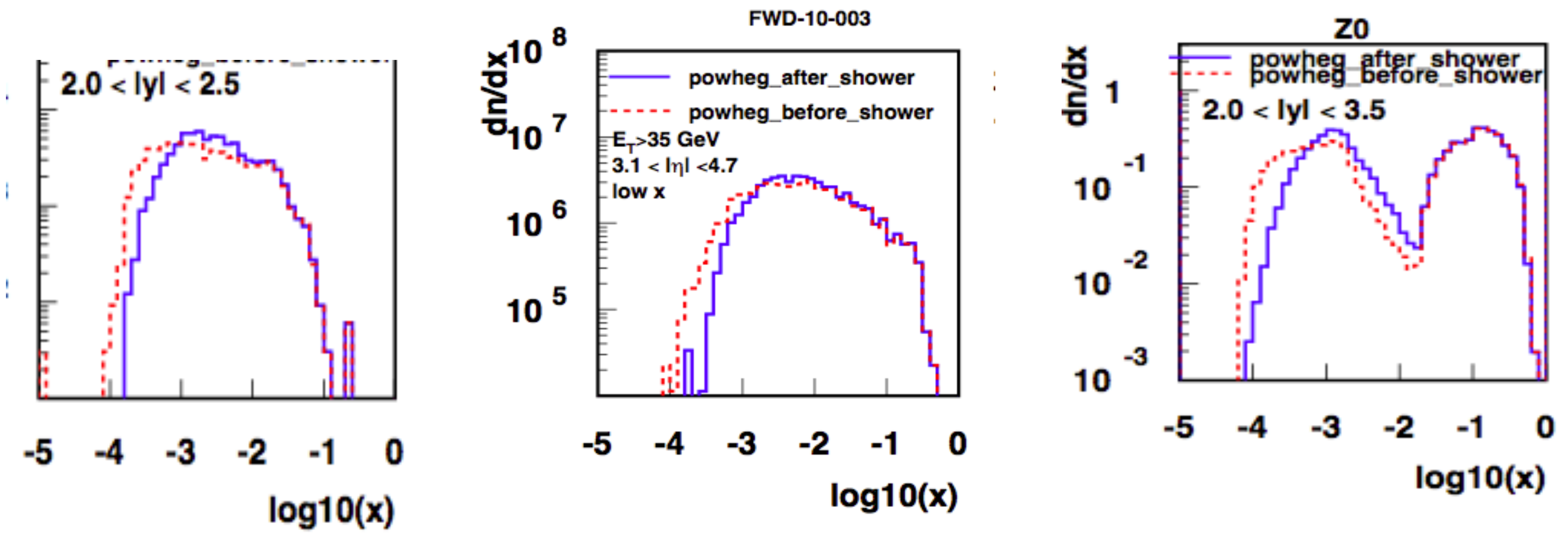
(a) heavy quark hadroproduction from gluon showering;

(b) next correction from extra jet emission

- not included by collinear showers (even at NLO [MC@NLO])
- obtainable by $k_\perp$-shower

Collinear shower kinematics

x distribution from POWHEG in
b-jets before and after showering

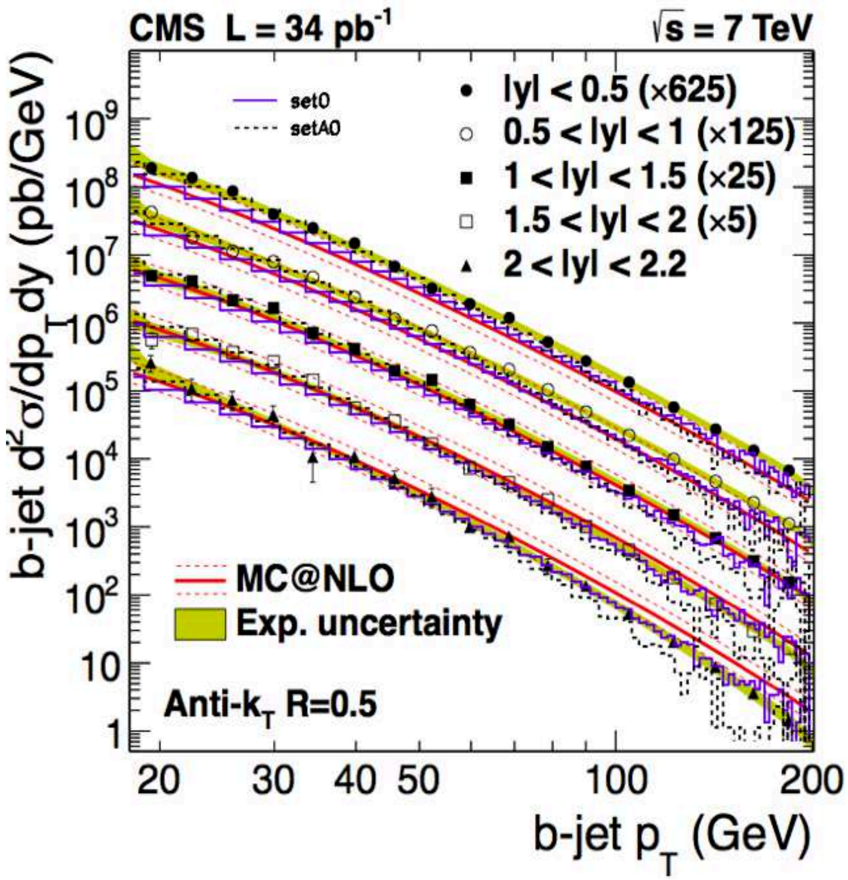


• reshuffling in momentum fractions x after showering
due to emitted $k_\perp$ and energy-momentum conservation

▷ non-negligible effect at large y

b-jets using k$_\perp$-dependent showers

[H. Jung et al., arXiv:1206.1796]



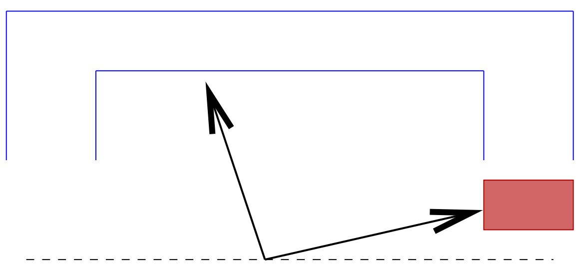
- similar description to MC@NLO at central rapidities
- shape in p_T closer to data at large y

♢ Is this effect of small-x resummation or mainly kinematics?

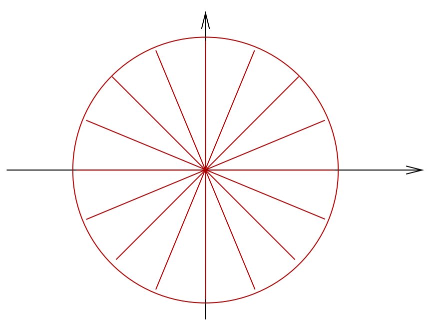
ASSOCIATED FORWARD AND CENTRAL JETS

- polar angles small but far enough from beam axis
  - measure correlations in azimuth, rapidity, p_T

$$p_\perp \gtrsim 20 \text{ GeV} \,,\ \Delta\eta \gtrsim 4 \div 6$$

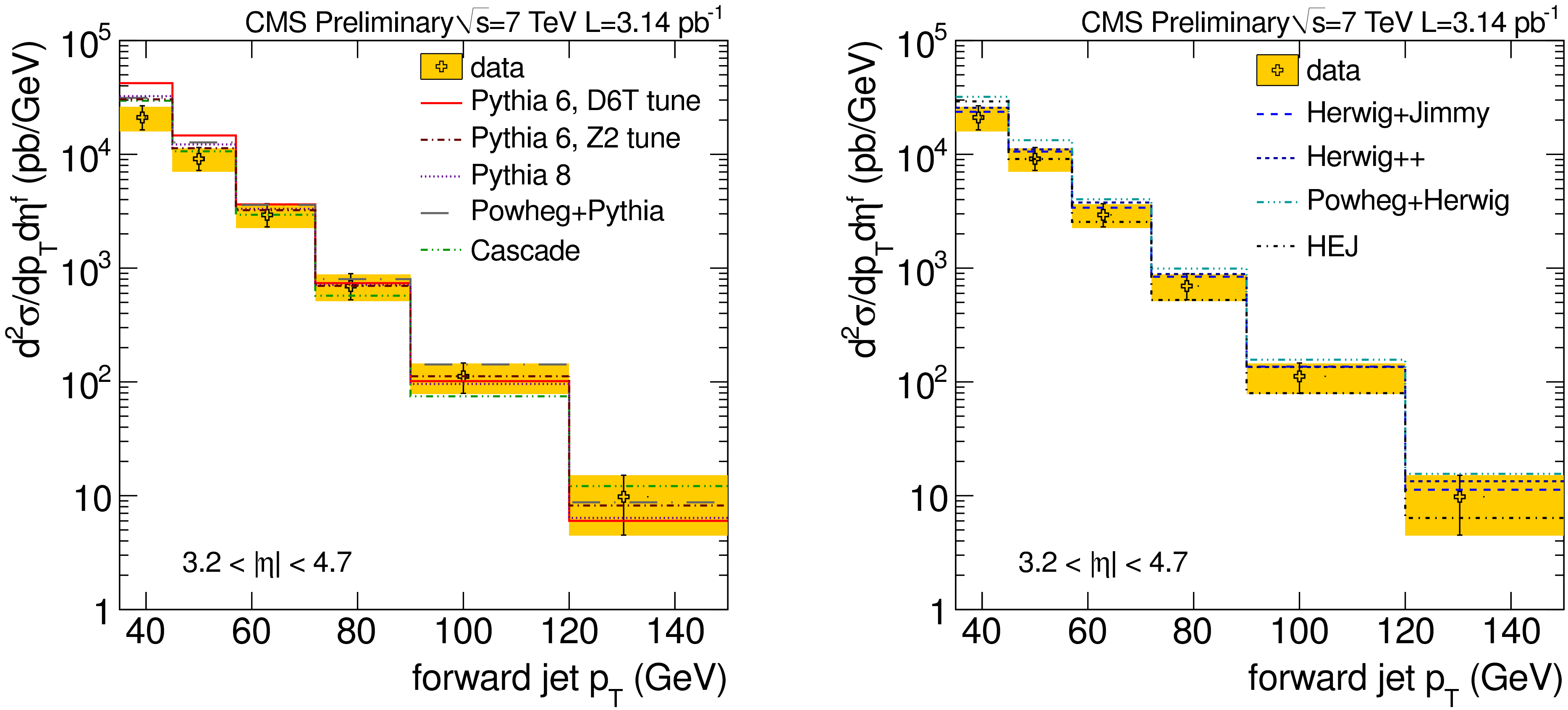


central + forward detectors



azimuthal plane

Forward jet spectrum *[CMS, arXiv:1202.0704]*



- spectrum in rough agreement with Monte Carlo results
  - but detailed forward-central correlations are not $\hookrightarrow$

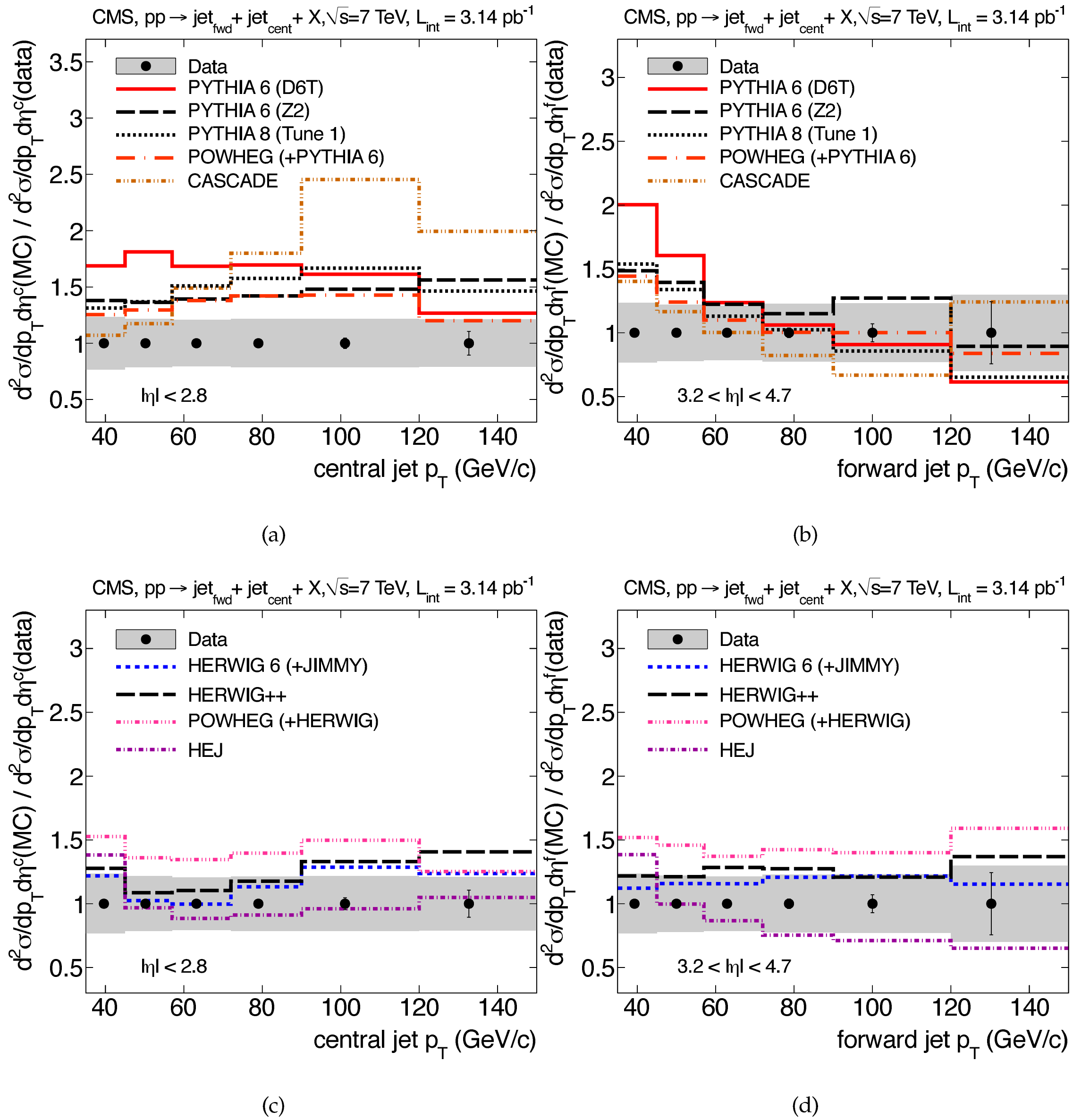
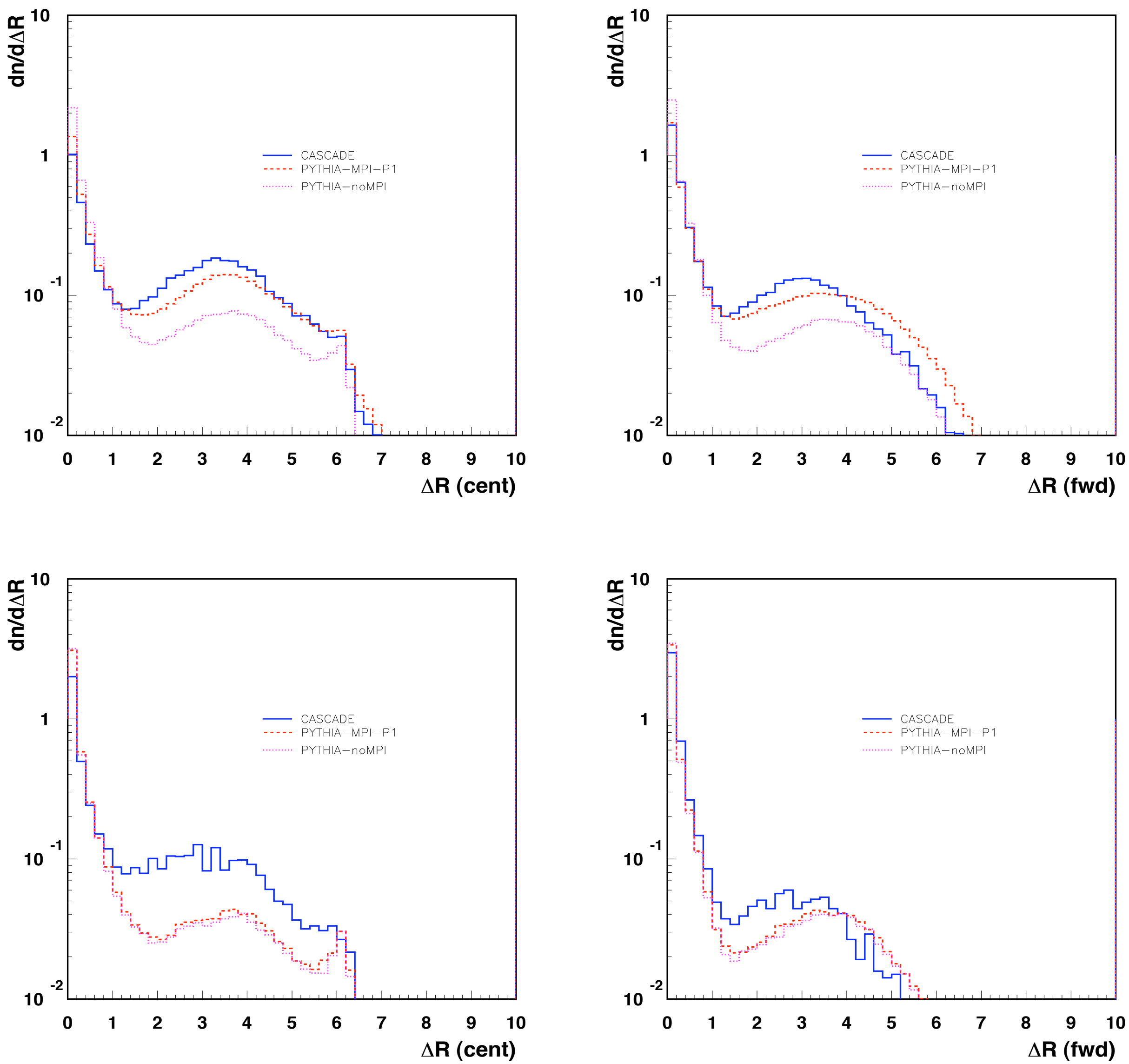


Figure 8: Ratio of theory to data for differential cross sections as a function of p_{T}, for central ((a) and (c)) and forward ((b) and (d)) jets produced in dijet events. The error bars on all data points reflect just statistical uncertainties, with systematic uncertainties plotted as grey bands.

[CMS Coll., arXiv:1202.0704]

- large differences between POWHEG/ PYTHIA and POWHEG/ HERWIG



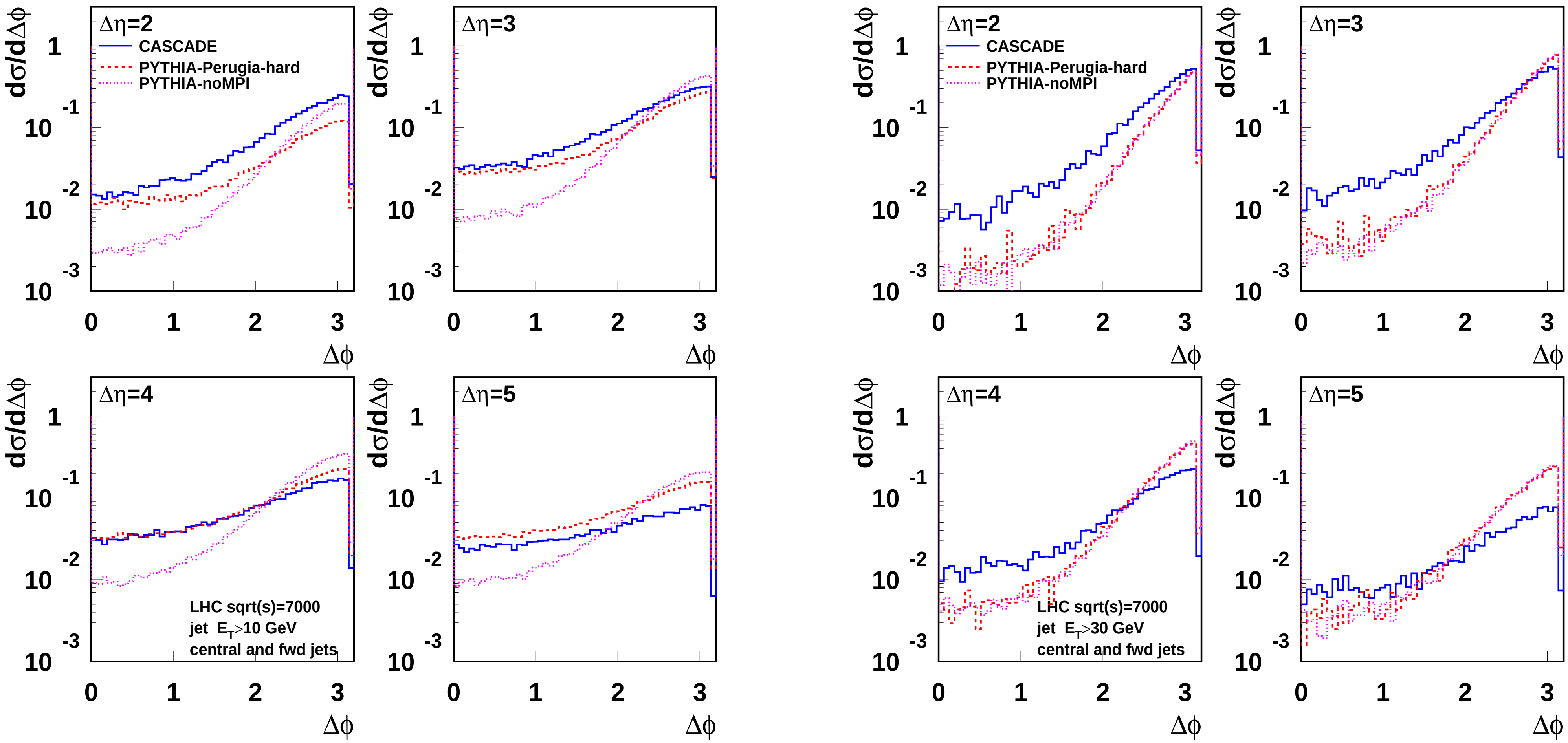
[Deak et al., arXiv:1012.6037]

- sizeable contributions to jets from showers (large-ΔR)

Figure 5: ΔR distribution of the central ($|\eta_c| < 2$, left) and forward jets ($3 < |\eta_f| < 5$, right) for $E_T > 10$ GeV (upper row) and $E_T > 30$ GeV (lower row). The prediction from the $\text{k}_\perp$ shower (CASCADE) is shown with the solid blue line; the prediction from the collinear shower (PYTHIA) including multiple interactions and without multiple interactions is shown with the red and purple lines. $\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2}$, where $\Delta\phi = \phi_{jet} - \phi_{part}$, $\Delta\eta = \eta_{jet} - \eta_{part}$

Cross section as a function of the azimuthal difference $\Delta\phi$ between central and forward jet for different rapidity separations

[Deak et al., arXiv:1012.6037]

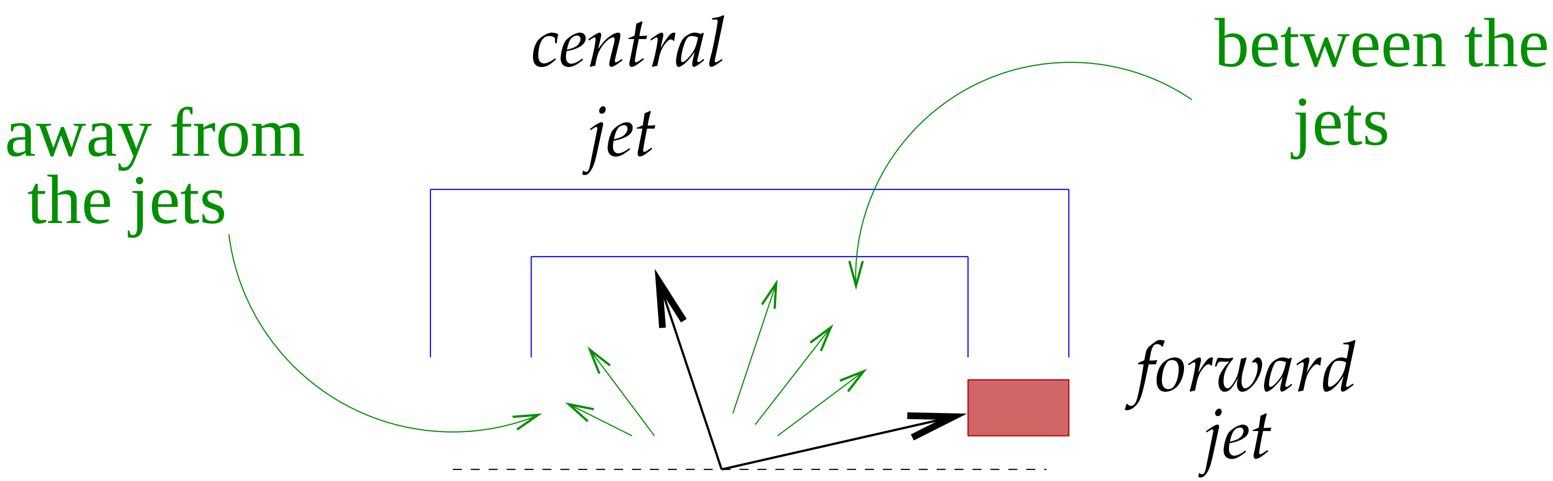


MC models: • CASCADE: non-collinear corrections to single parton chain

• PYTHIA: multiple parton interactions, no corrections to collinear approximation

1 central $+$ 1 forward jet:

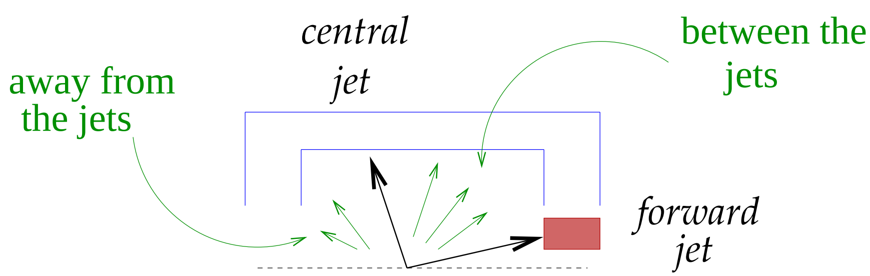
particle and energy flow in the inter-jet and outside regions



[complementary to measurements by CMS in L. Kheyn's talk on
forward energy flow in minimum bias and dijet events]

Transverse energy flow as a function of rapidity and azimuthal angle

$$1 < \eta_c < 2 \quad , \qquad -5 < \eta_f < -4$$



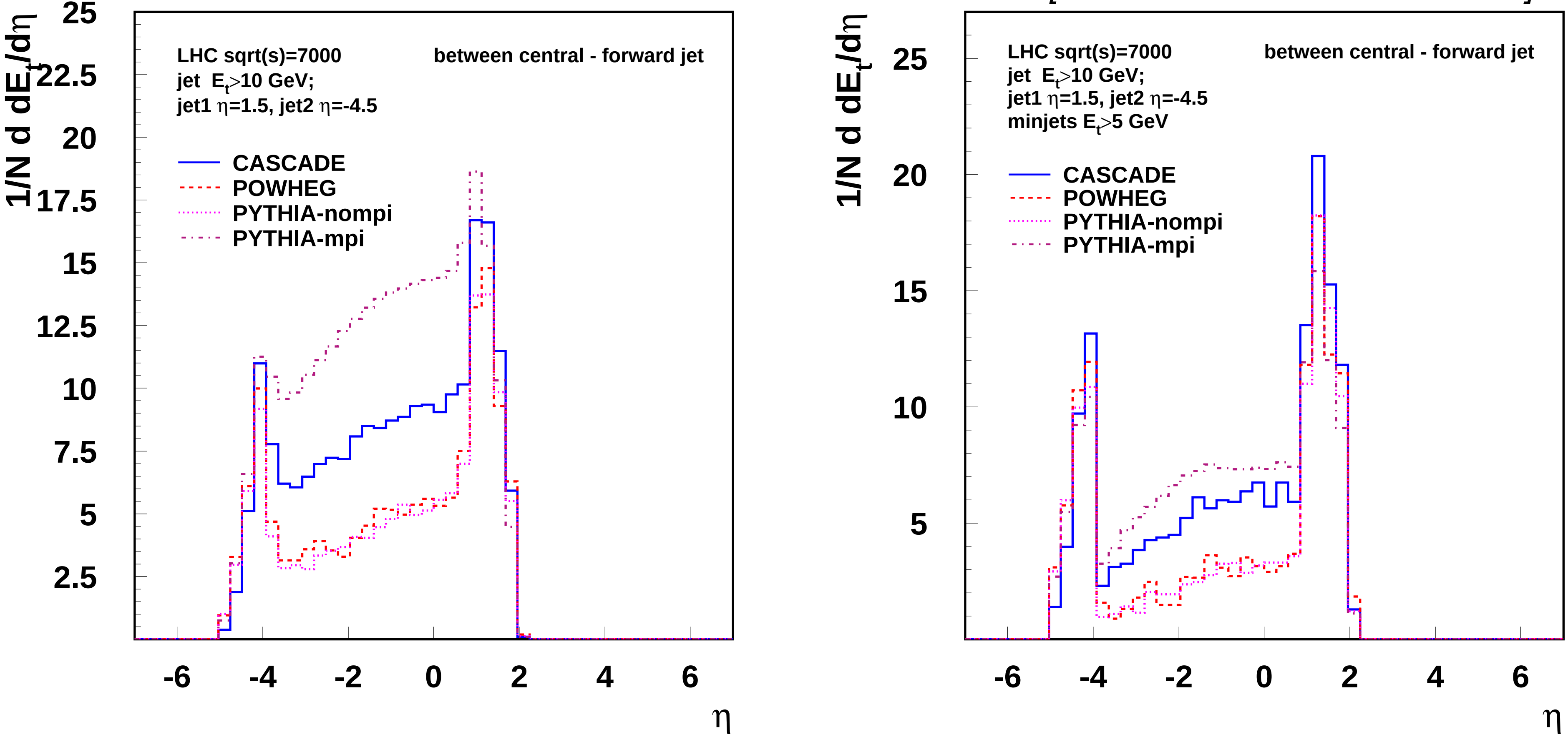
$$\frac{dE_\perp}{d\eta} = \frac{1}{\sigma} \int dq_\perp \; q_\perp \; \frac{d\sigma}{dq_\perp \; d\eta}$$

"Minijet" energy flow

- merge particles into jets via jet algorithm
- construct energy flow from jets with $q_\perp > q_0$
- $q_0 = \mathcal{O}(\text{a few GeV})$ feasible at the LHC

Transverse energy flow in the inter-jet region

[Deak et al., arXiv:1112.6354]

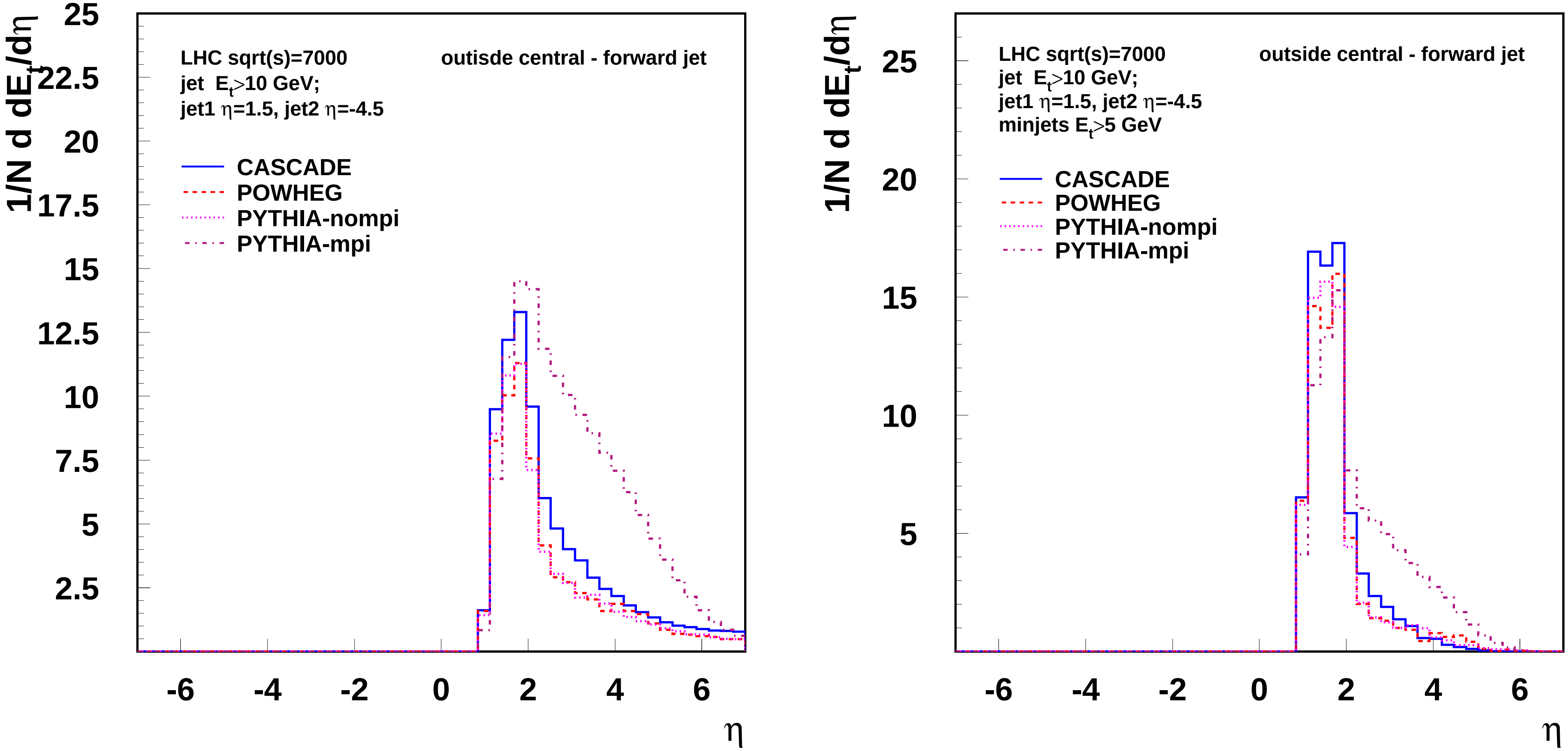


(left) particle flow; (right) minijet flow

▷ higher mini-jet activity in the inter-jet region from corrections to collinear ordering and from MPI

▷ little effect from NLO hard correction in POWHEG

Transverse energy flow in the outside region

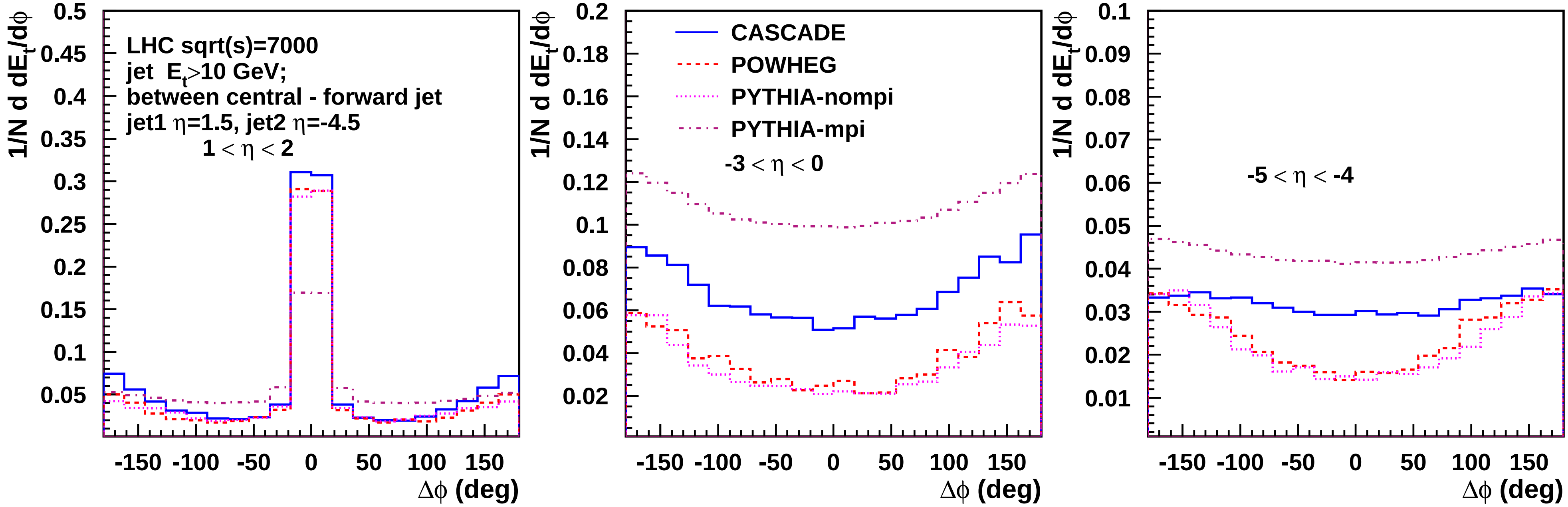


▷ at large (opposite) rapidities, full branching well approximated by collinear ordering

▷ higher energy flow only from multiple interactions

Azimuthal dependence of transverse energy flow

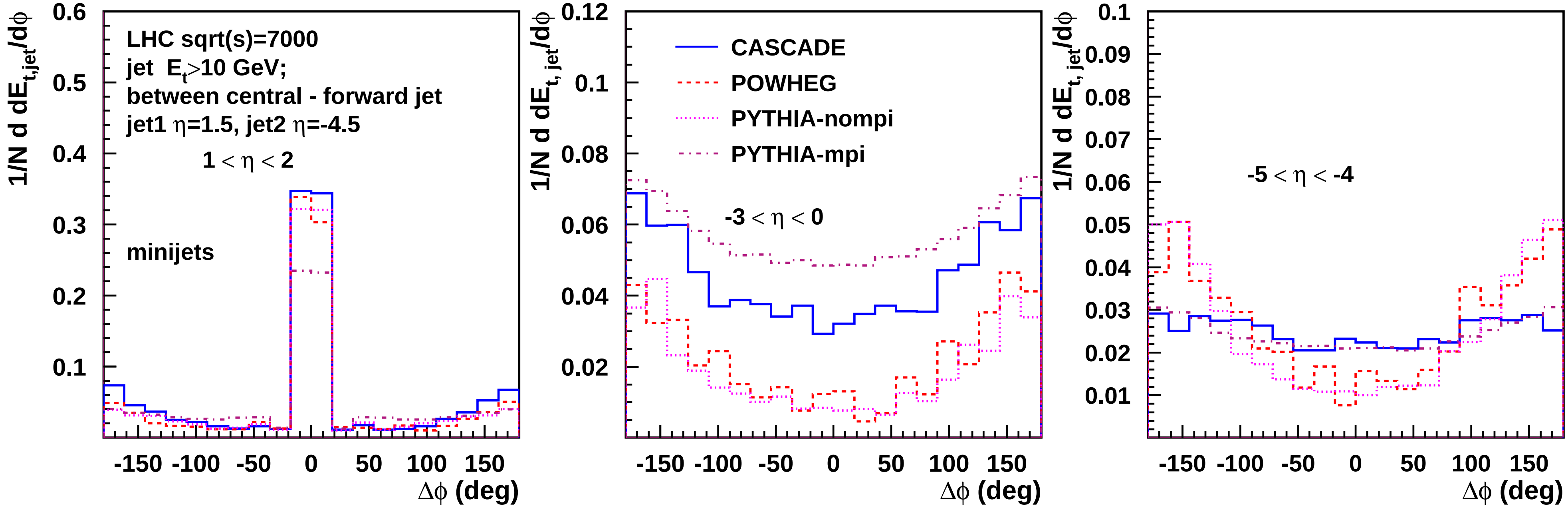
(left) central-jet; (middle) intermediate; (right) forward-jet rapidities



- more pronounced flattening of the $\Delta\phi$ distribution from CASCADE and PYTHIA-mpi compared to POWHEG and PYTHIA-nompi

Azimuthal dependence of transverse energy flow

(left) central-jet; (middle) intermediate; (right) forward-jet rapidities



- mini-jet energy flow

Extension to forward-backward kinematics

$\diamondsuit$ search for Mueller-Navelet effects

$\diamondsuit$ background to searches in vector boson fusion channels

$\diamondsuit$ large-Δy dijet data poorly understood

[CMS, arXiv:1204.0696]

[ATLAS, arXiv:1107.1641]

Toward higher $p_\perp$

- High energy factorization can be used to describe arbitrarily large $p_\perp$

$\Rightarrow$ "preasymptotic" corrections from both shower evolution and matrix element

♠ u-pdf's asymptotic UV behavior

$$G(k_\perp, \mu) \sim \exp \int_\mu^{k_\perp} \frac{dq_\perp}{q_\perp} \gamma(\alpha_s(q_\perp)) \quad , \qquad \gamma(\alpha_s) = \gamma_{LL} + \gamma_{NLL} + \ldots$$

$\gamma_{NLL} < 0$ reduces growth from multi-gluon emission at high $k_\perp$

♢ NL corrections to hard matrix element matched with showers

[M. Deak, talk at Moriond 2012]

$\Rightarrow$ likely to reduce dependence on cut-off scale μ

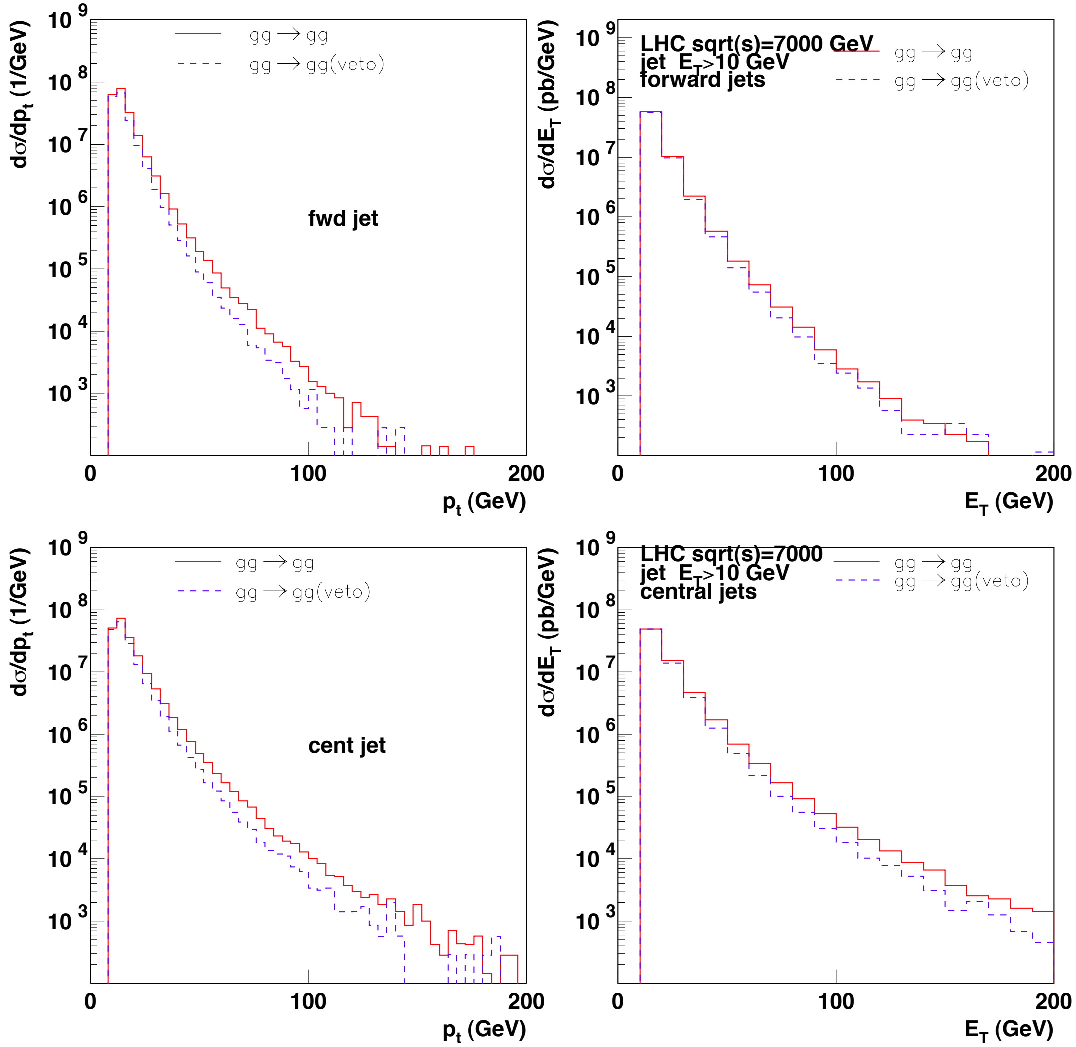
♠ gluon u-pdf at high x

- poorly determined at present by fits to data
- relevant for high-p_T jets

◇ $k_\perp$-shower contains radiative corrections beyond leading order

⇒ veto procedure to avoid double counting

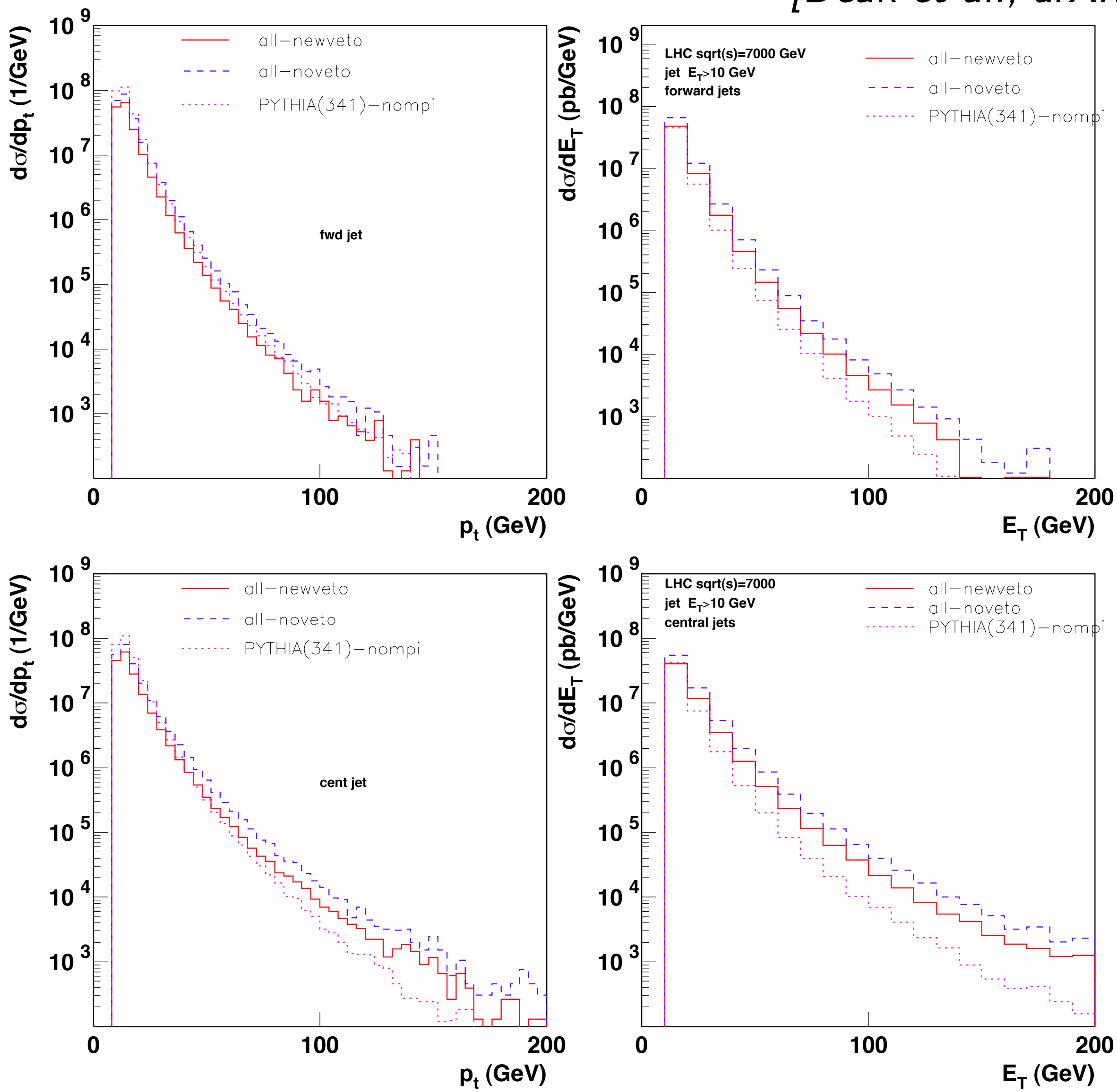
Ex.: $gg \to qq$ from direct production and from $gg \to gg \otimes g \to qq$



(left) parton-level; (right) jet-level

Comparison of transverse momentum spectra

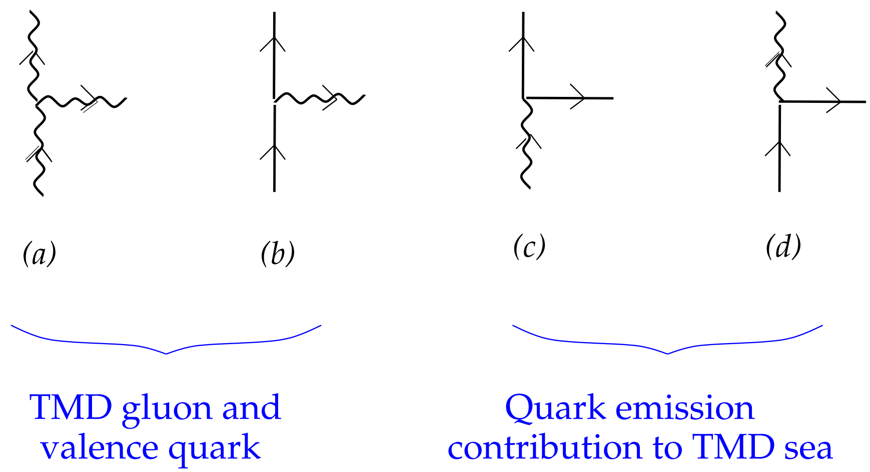
[Deak et al., arXiv:1206.1745]



(left) parton-level; (right) jet-level

Beyond quenched approximation: unintegrated quark evolution

[Hentschinski, Jung & H, arXiv:1205.1759]



- sea: flavor-singlet evolution coupled to gluons at small x via

$$\mathcal{P}_{g\to q}(z;q,k) = P_{qg,\mathrm{DGLAP}}(z)\ \left(1 + \sum_{n=0}^{\infty}\ b_n(z)(k^2/q^2)^n\right)$$

all b_n known; $\mathcal{P}_{g\to q}$ computed in closed form (positive-definite)

in *[Catani & H, 1994; Ciafaloni et al., 2005-2006]* by small-x factorization

- valence: independent evolution (dominated by soft gluons x $\to$ 1)

Conclusions

- Forward high $p_\perp$ physics — largely new field at the LHC
  - ▷ jet studies in decays of boosted massive states
  - ▷ Higgs searches in vector boson fusion
  - ▷ QCD at small x and relationship with cosmic ray physics

- New challenges to theory
  - ▷ multiple hard scales $\Rightarrow$ QCD corrections beyond finite-order perturbation theory and/or beyond single parton interaction

- First experimental observations
  - ▷ deviations from NLO (+ shower) at high rapidity
  - ▷ di-jet correlations at large rapidity separations not yet understood

- TMD branching and pdfs may be necessary for proper treatment of kinematics
  - ▷ influence on treatment of MPI?
  - ▷ small-x dynamical effects?