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Forward jets and energy flow in hadronic collisions

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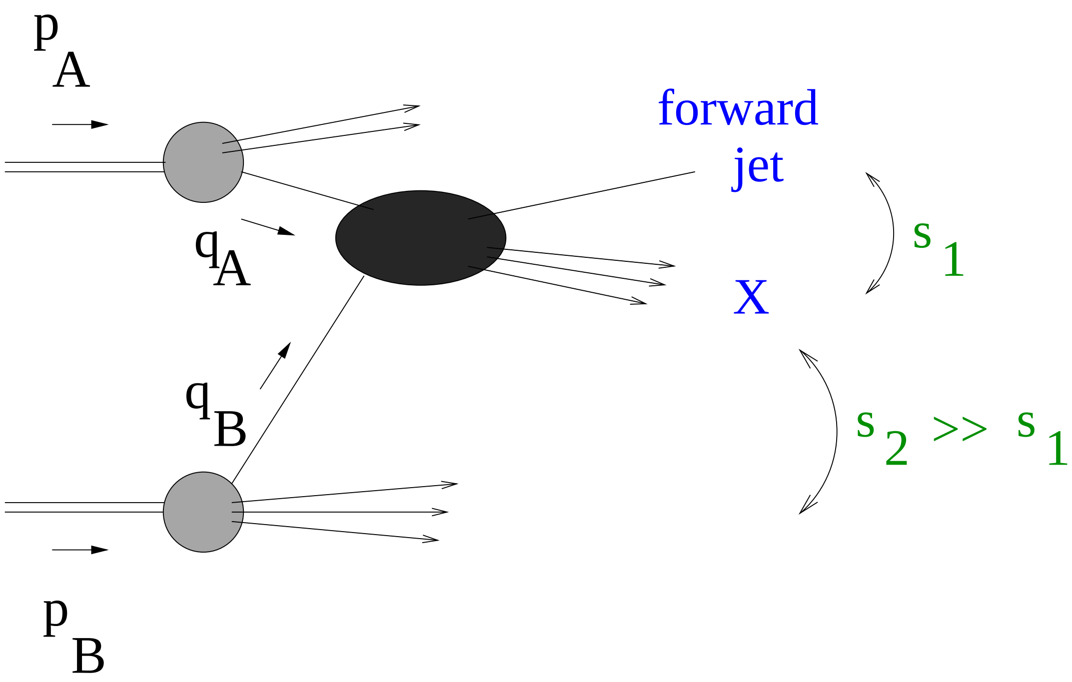
I. Introduction: high-p$_T$ events in the forward region at the LHC

II. Theoretical issues in the QCD treatment of forward hard processes

III. Phenomenology: jet correlations; transverse energy flow

I. High-p_T production in the forward region at the LHC



▷ phase space opening up for large $\sqrt{s}$

▷ unprecedented coverage of large rapidities (calorimeters+proton taggers)

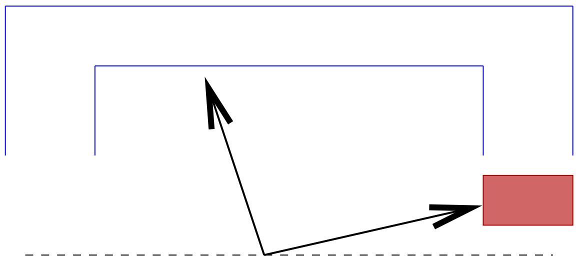
$\Downarrow$

• physics of hard processes with multiple hard scales

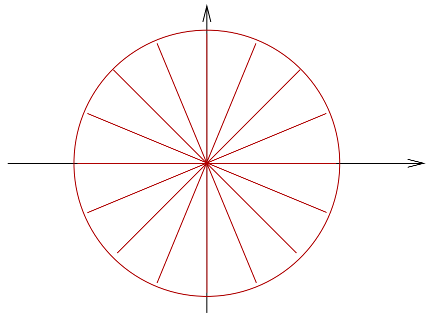
and highly asymmetric parton kinematics $q_A \cdot p_B \gg q_B \cdot p_A$

- polar angles small but far enough from beam axis
- measure azimuthal plane correlations

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



central + forward detectors



azimuthal plane

▷ ATLAS, CMS, LHCb
+ CASTOR experiments

[Z. Ajaltouni et al., HERA-LHC Proc. arXiv:0903.3861;

M. Grothe, arXiv:0901.0998; D. d'Enterria, arXiv:0806.0883;

X. Aslanoglou et al., CERN-CMS-NOTE-2008-022 (2008)]

OPEN QUESTIONS

- How well do current Monte Carlo event generators simulate LHC final states in the forward region

- Are fixed-order QCD calculations reliable in the forward region? Are perturbative resummations to be performed?

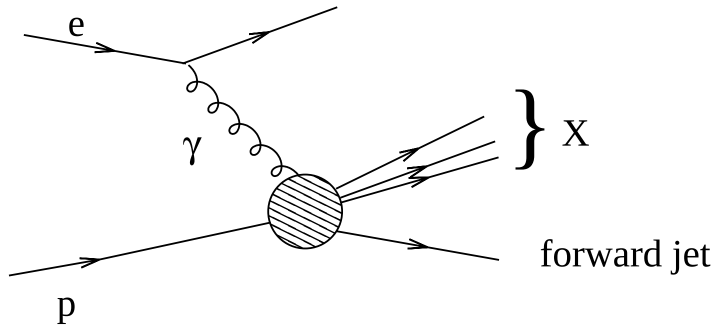
- Do multiple parton interactions become non-negligible in hard processes at forward rapidities?

♠ Multi-scale problem ⇒

⇒ all-order summation of high-energy logarithmic corrections long recognized to be necessary for reliable QCD predictions

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

♠ Note: DIS case ⇒



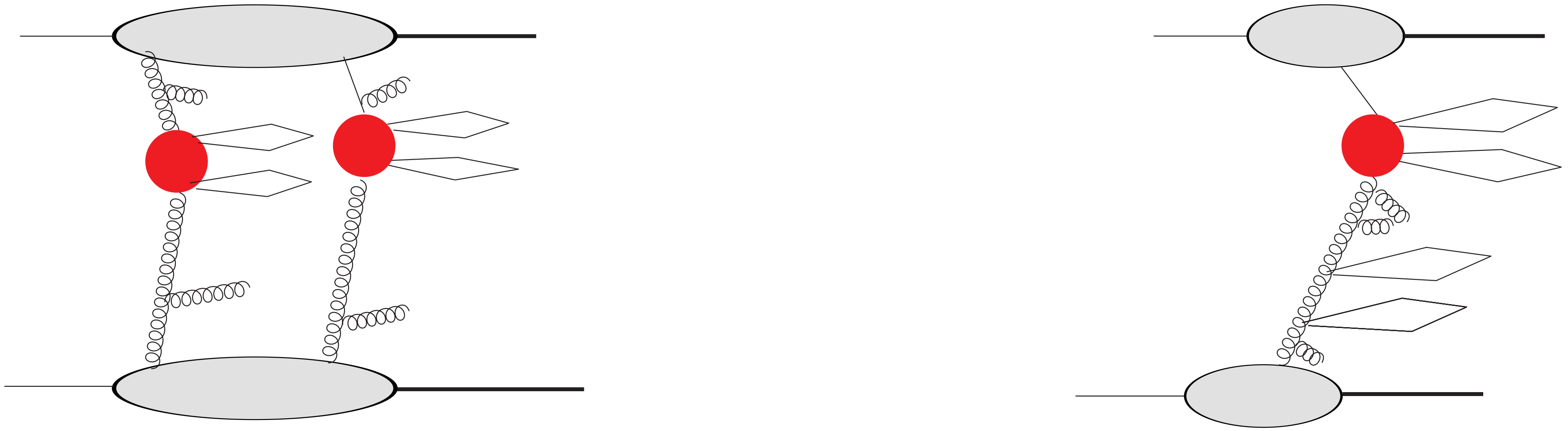
• neither PYTHIA Monte Carlo nor NLO calculations are able to describe forward jet ep data

[A. Knutsson, LUNFD6-NFFL-7225-2007 (2007); L. Jönsson, AIP Conf. Proc. 828 (2006) 175]

♠ Resummation of logarithmic corrections both in the hard scale and in the rapidity interval can be achieved by QCD factorization at fixed transverse momentum

Catani, Ciafaloni & H, 1991

Multiple parton interactions



Multi-jet production by (left) multiple parton chains; (right) single parton chain.

- modeled by shower Monte Carlo generators

  Sjöstrand & Skands, 2006; Gieseke et al., 2008

- expected to contribute significantly to forward production

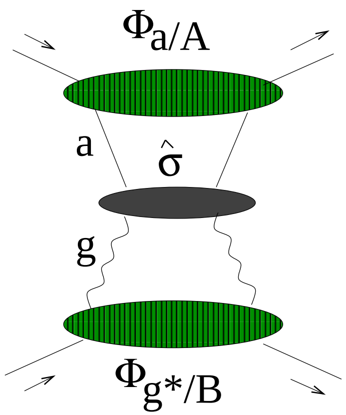
- High-energy factorization at fixed transverse momentum

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

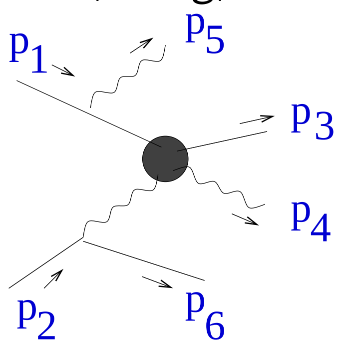
▷ needed to resume consistently both logs of rapidity and logs of hard scale

Catani et al., 1991; Ciafaloni, 1998

Deak, Jung, Kutak & H, arXiv:0908.0538



(a)



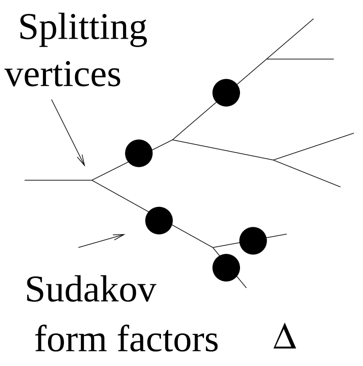
(b)

Figure 1: (a) Factorized structure of the cross section; (b) a typical contribution to the qg channel matrix element.

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

◇ $\widehat{\sigma}$ off-shell continuation of hard-scattering matrix elements

II. QCD EVOLUTION BY PARTON SHOWERING METHODS

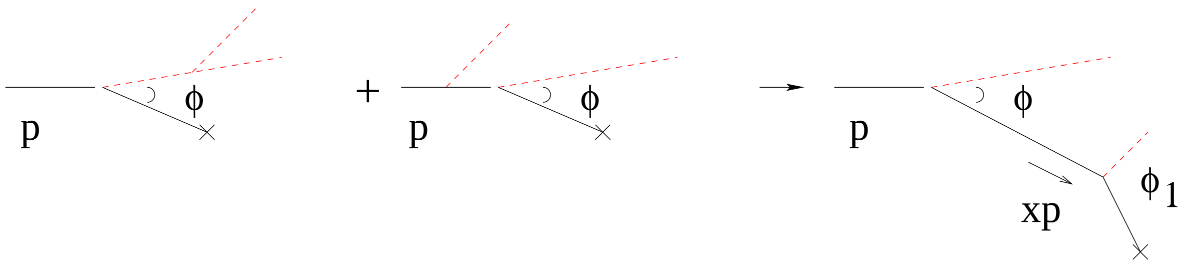


$$d\mathcal{P} = \int \frac{dq^2}{q^2} \int dz \; \alpha_S(q^2) \; P(z) \; \Delta(q^2, q_0^2)$$

$\hookrightarrow$ collinear, incoherent emission

$\diamondsuit$ Soft emission $\longrightarrow$ interferences $\longrightarrow$ ordering in decay angles

$\hookrightarrow$ gluon coherence for $x \sim 1$



- ex.: HERWIG, new PYTHIA

$\diamondsuit$ Gluon coherence for $x \ll 1 \Rightarrow$ corrections to angular ordering:

$\hookrightarrow$ MC based on $k_\perp$-dependent unintegrated pdfs and MEs

COHERENCE IN HIGH-ENERGY LIMIT

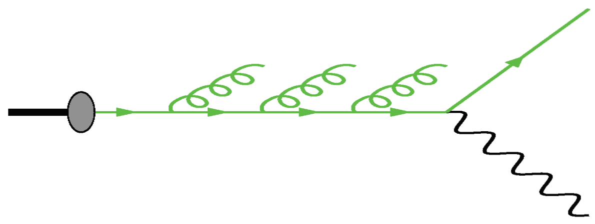
Soft vector-emission current from external legs $\longrightarrow$

• leading IR singularities

[J.C. Taylor, 1980; Gribov-Low (QED)]

• fully appropriate in single-scale hard processes

Dokshitzer, Khoze, Mueller and Troian, RMP (1988); Webber, A. Rev. Nucl. Part. (1986)



multi-scale: $s = q_1^2 \gg \cdots \gg q_n^2 \gg \Lambda^2$
[e.g.: LHC final states with multi-jets]

$\Downarrow$

▷ internal emissions non-negligible

▷ current also factorizable at high-energy: *[Ciafaloni 1998; 1988]*

$$\left|M^{(n+1)}(k,p)\right|^2 = \left\{[M^{(n)}(k+q,p)]^\dagger\, [\mathbf{J}^{(R)}]^2\, M^{(n)}(k+q,p) - [M^{(n)}(k,p)]^\dagger\, [\mathbf{J}^{(V)}]^2\, M^{(n)}(k,p)\right\} \quad .$$

BUT... ▷

▷ ... • **J** depends on total transverse momentum transmitted

⇒ matrix elements and pdf at fixed $k_\perp$ ("unintegrated")

• virtual corrections not fully represented by Δ form factor

⇒ modified branching probability $P(z, k_\perp)$ as well

▷ enhanced terms $\mathcal{O}(\alpha_S^k \ln^m s/p_T^2)$

◇ Note: superleading logs $m > k$ cancel in fully inclusive quantities

e.g: high-energy corrections to anomalous dimensions γ^{ij}

at most single-logarithmic

$$\gamma^{ij}(\alpha_s, \omega) = \frac{\alpha_s}{\omega^p}\; c_0^{ij}\; \left[1 + \sum_{n=1}^{\infty} c_n^{ij}\; \left(\frac{\alpha_s}{\omega}\right)^n + \mathcal{O}\left(\alpha_s\; (\frac{\alpha_s}{\omega})^{n-1}\right) \right]$$

ω - moment conjugate to $\ln s$ *BFKL; Jaroszewicz; Catani et al.*

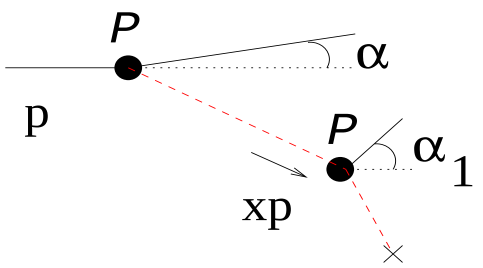
◇ but cancellations do not apply in exclusive final-state correlations

$K_\perp$-DEPENDENT PARTON BRANCHING

- MC for (almost-)NLO QCD evolution at unintegrated level
  proposed in Jadach & Skrzypek, arXiv:0905.1399 [hep-ph]
  arXiv:1002.0010 [hep-ph]

- $\{x \to 0\} \oplus \{x \to 1\}$ gluon branching eq. (leading-logarithms, all orders in α_s)
  CCFM evolution equation [Marchesini et al., 1990's]

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



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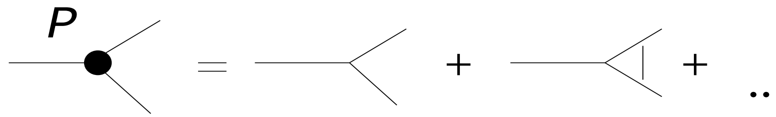


▷ Monte Carlo implementations CASCADE, LDCMC, ...

- unintegrated quark with k_T-dependent branching
  $\hookrightarrow$ ongoing work

Merging PS and ME

Both PS distributions and hard ME depend on $k_\perp$

- Merging in high-energy limit can be done using

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

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

Unintegrated quark evolution

[Jung & H, in progress]

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

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

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

[Catani & H, 1994; Ciafaloni et al., 2005-2006]

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

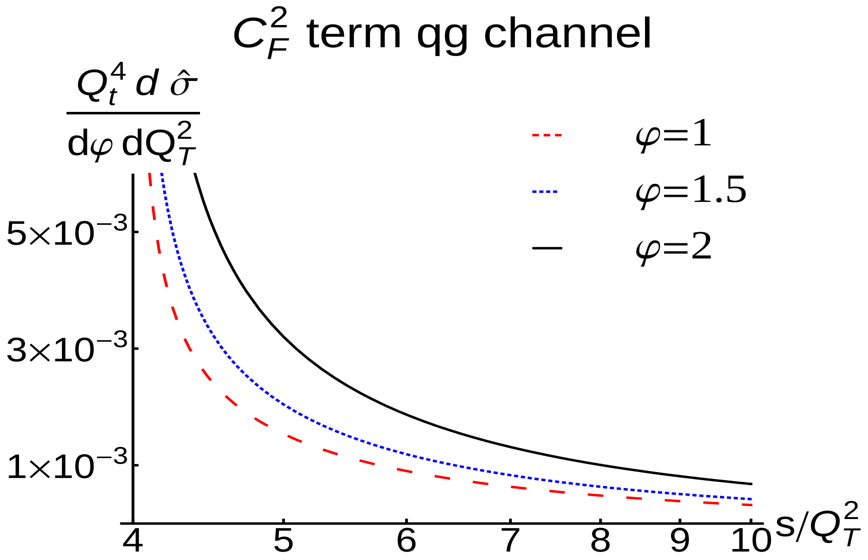
III. FORWARD JET HADRO-PRODUCTION CROSS SECTIONS

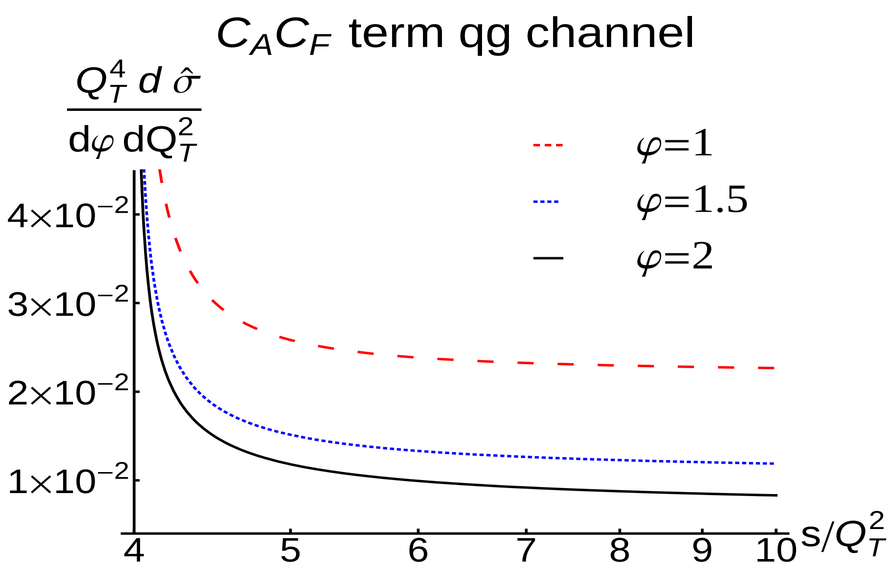
- Matrix elements for fully exclusive events with forward jets

[Deak, Jung, Kutak & H, arXiv:0908.1870 [hep-ph]]

- Both quark and gluon channels found to be important for realistic phenomenology

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



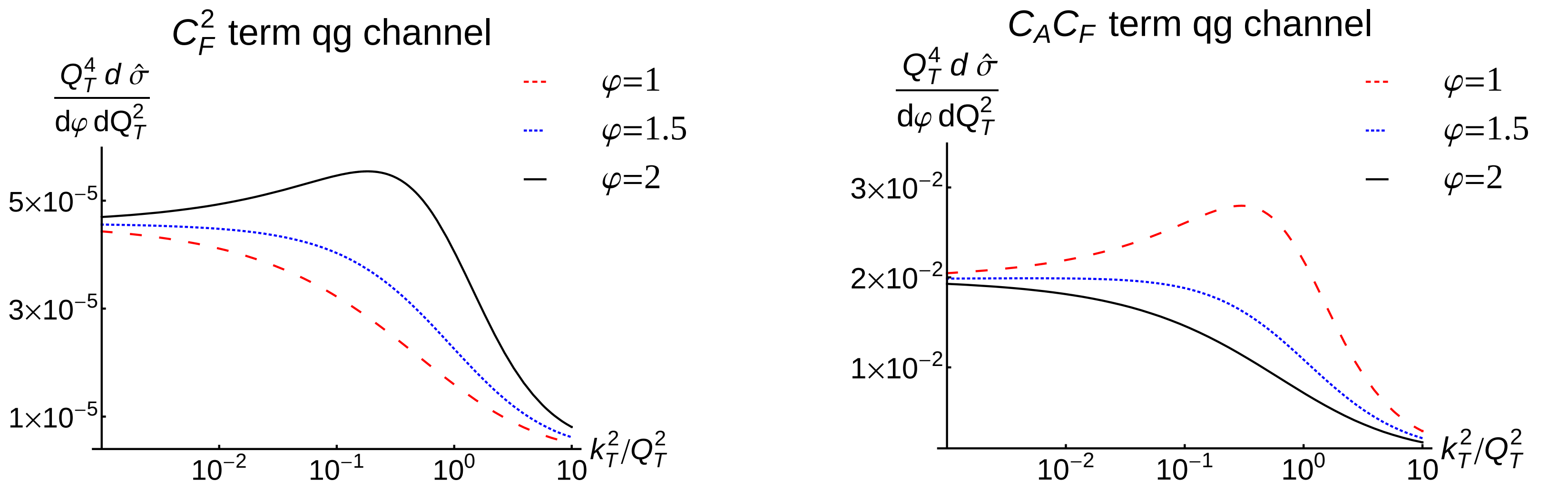


▷ $C_F C_A$ contribution to qg dominates large $\widehat{s}/Q_t^2$ (constant at large energy)

BEHAVIOR AT LARGE $K_\perp$

k_t = transverse momentum carried away by extra jets

$k_t/Q_t \to 0$ leading order process



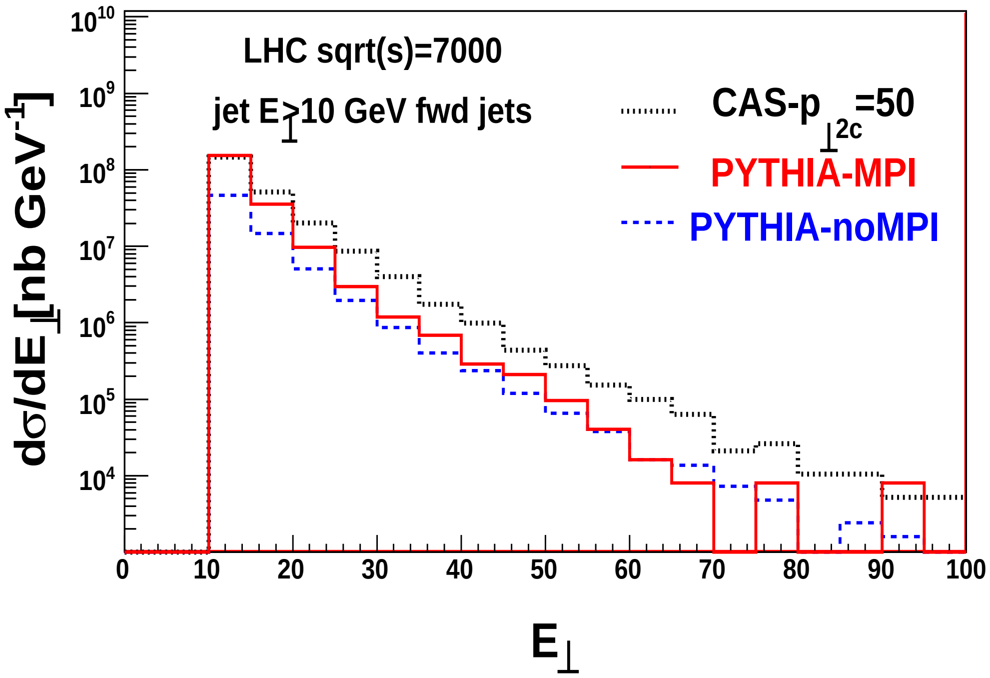
[Deak, Jung, Kutak & H, in progress]

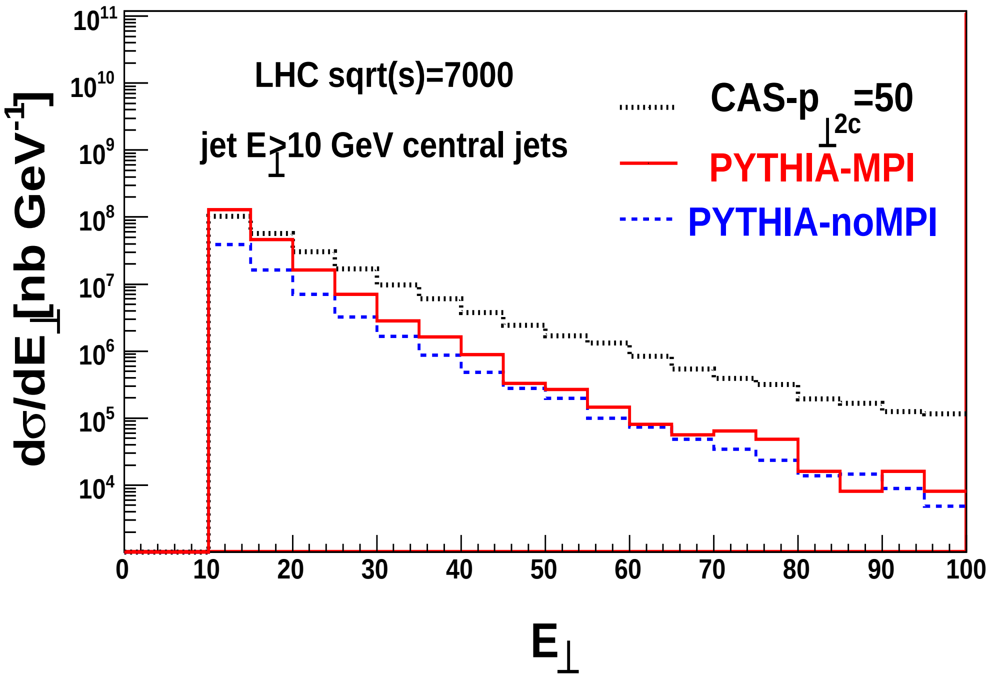
- measures transverse momentum distribution of third jet
  - dynamical cut-off at $k_t \sim Q_t$ set by coherence effects
    - non-negligible terms from finite k_t tail

1 central $\oplus$ 1 forward jet

Transverse momentum spectra: $k_\perp$-shower vs. collinear shower

[Deak et al., in progress]

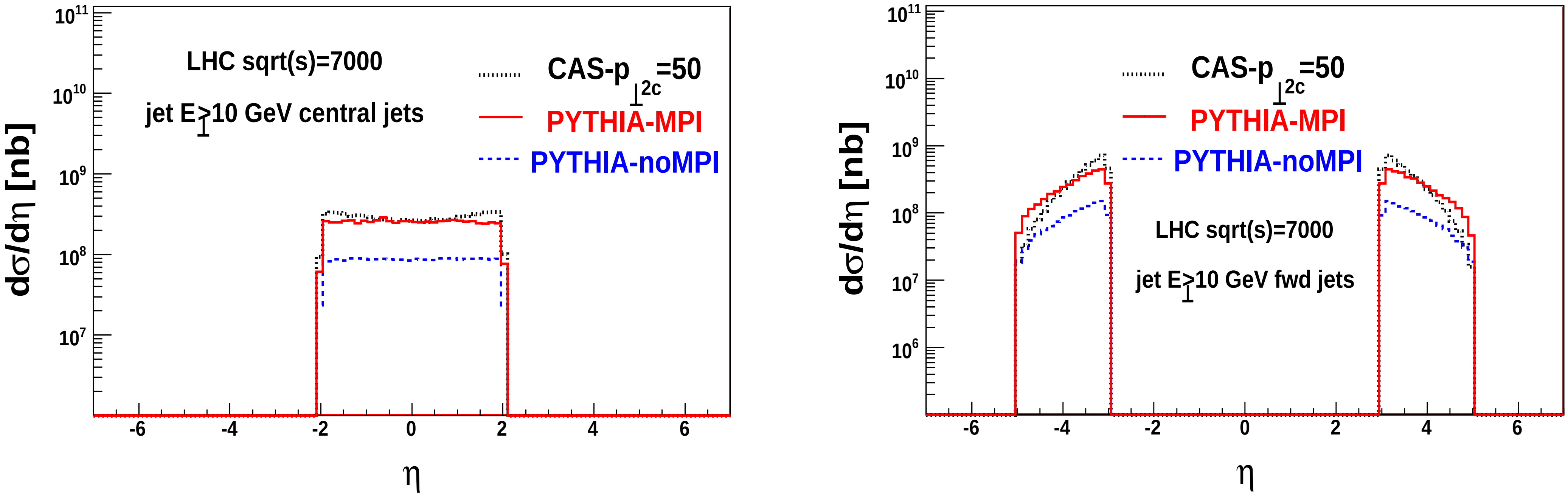




- harder spectrum in central region due to small-x radiation

1 central ⊕ 1 forward jet

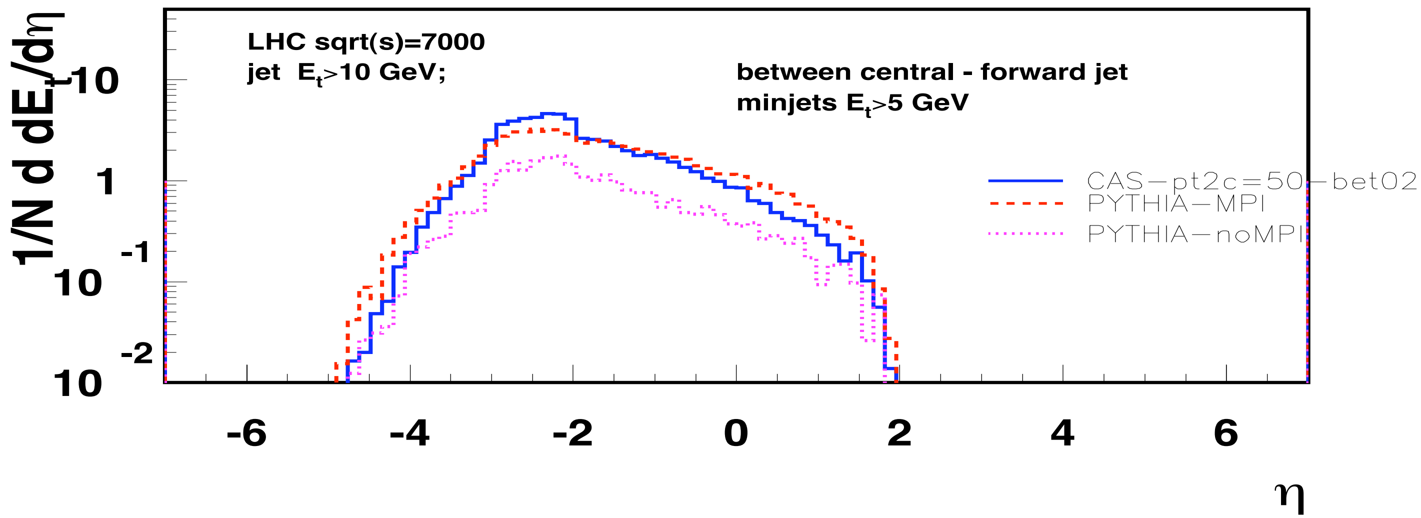
Rapidity spectra of produced jets

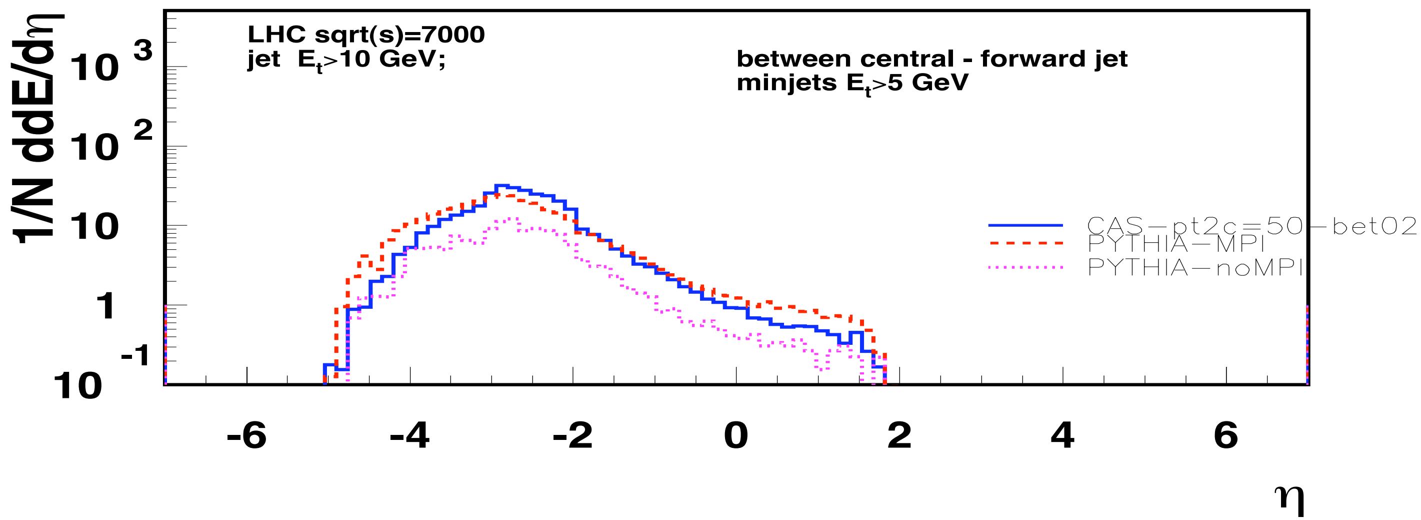


- similar results, but a hint of different slopes in forward jet distributions

Transverse energy flow in the inter-jet region

[Deak et al., in progress]

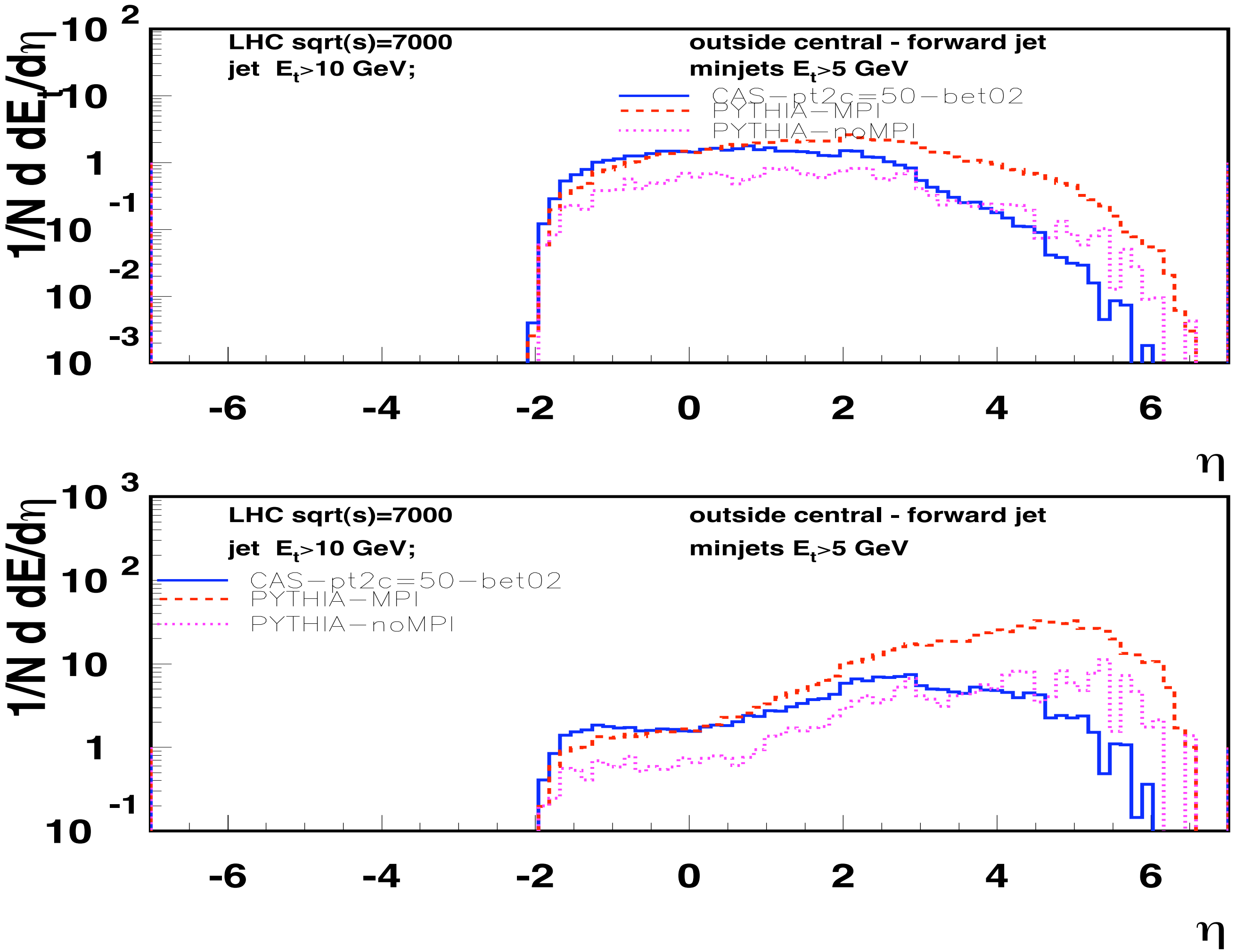




- higher mini-jet activity in the inter-jet region from corrections to collinear ordering

Transverse energy flow in the outside region

[Deak et al., in progress]



- at large (opposite) rapidities, full branching well approximated by collinear ordering
- higher energy flow only from multiple interactions

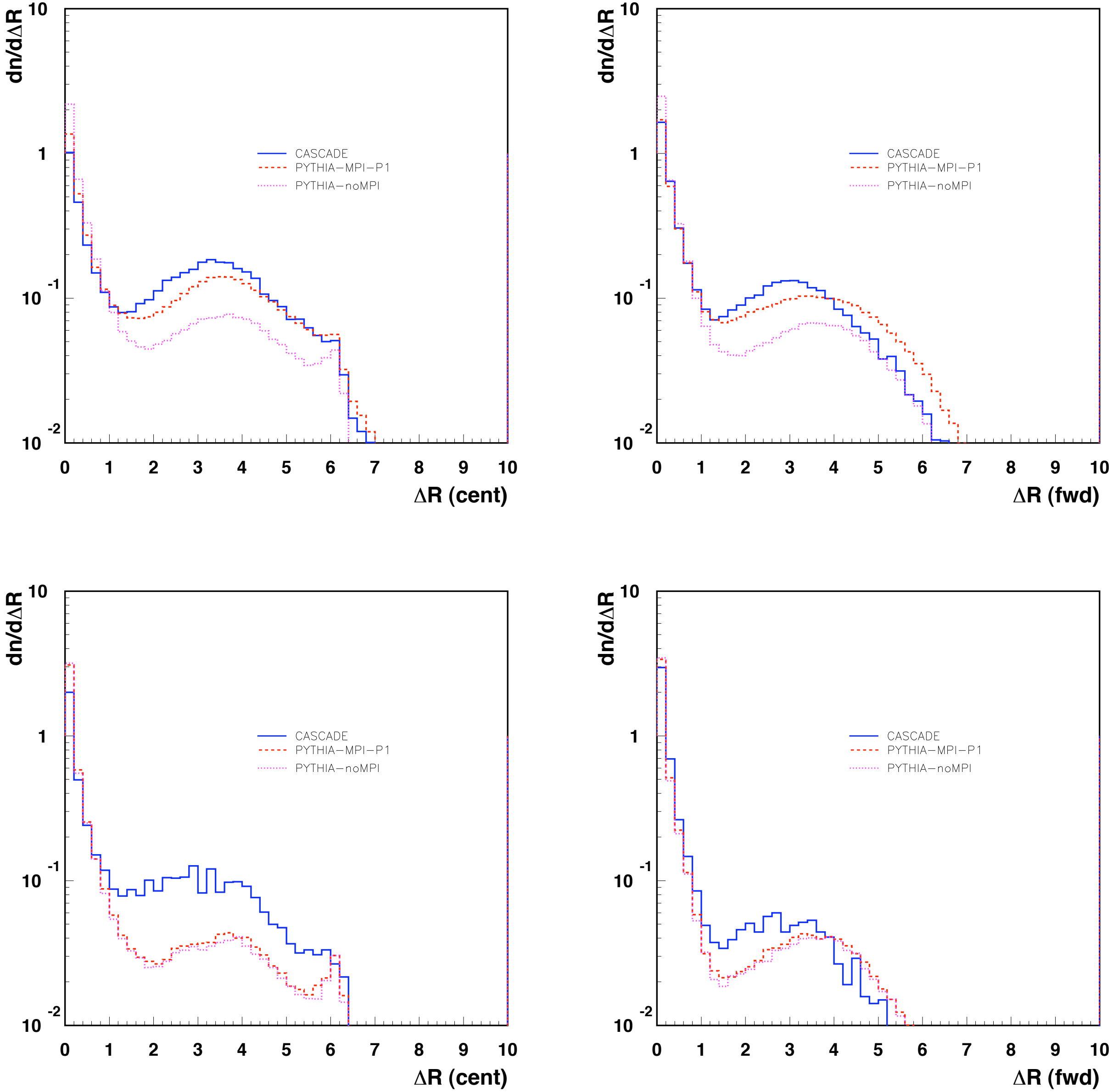
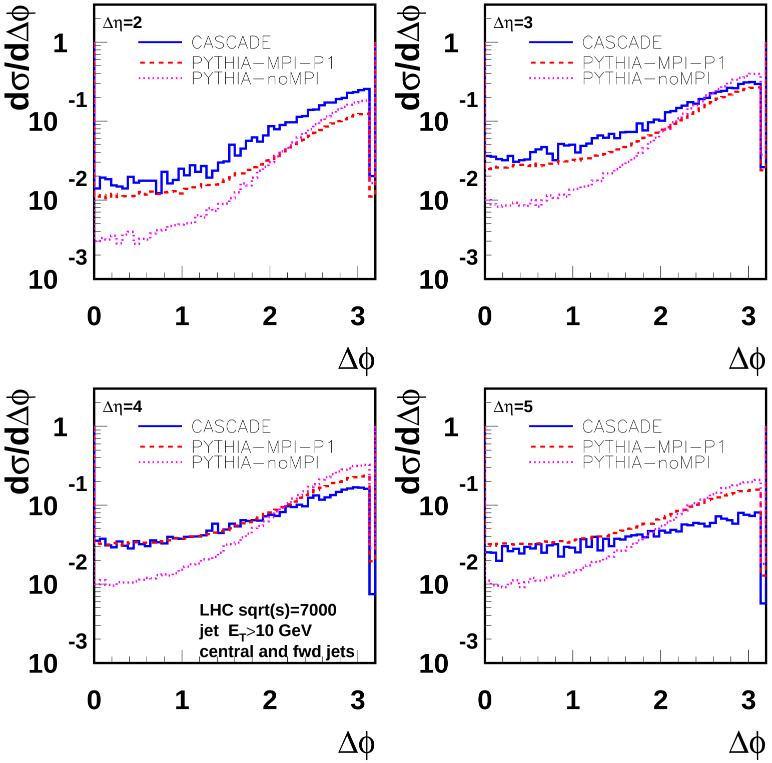
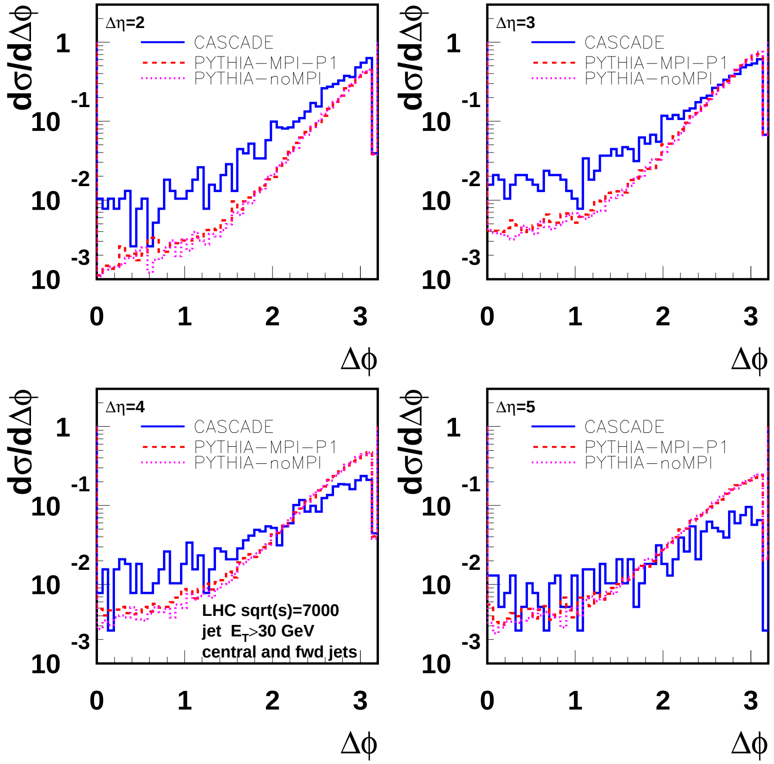


Figure 5: ΔR distribution of the central ($|\eta_c| < 2$, left) and forward jets ($3 < |\eta_f| < 5$, right) for $E_T > 10$ GeV (upper row) and $E_T > 30$ GeV (lower row). The prediction from the $k_\perp$ shower (CASCADE) is shown with the solid blue line; the prediction from the collinear shower (PYTHIA) 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 the central and the forward jet for different rapidity separations





CONCLUSIONS

- For the first time at the LHC, correlations of high-p_T probes can be measured across large rapidity intervals via forward + central detectors

▷ QCD methods required to handle potentially large logarithmic corrections to higher orders both in the hard transverse momentum and in the large rapidity interval:

- resummation techniques for multi-scale processes
- parton-shower algorithms to be combined with perturbative calculations

▷ investigate possibly new effects from QCD physics

▷ backgrounds to new particle searches:

e.g.: forward jets from vector boson fusion search channels