DIS 2012 Workshop, Bonn, March 2012

Forward Jets and Small-x Physics at the LHC

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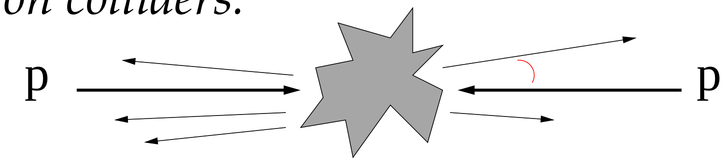
collaboration with M. Deak, H. Jung and K. Kutak

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

II. QCD factorization at high energy and parton showers

III. Forward jet observables 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

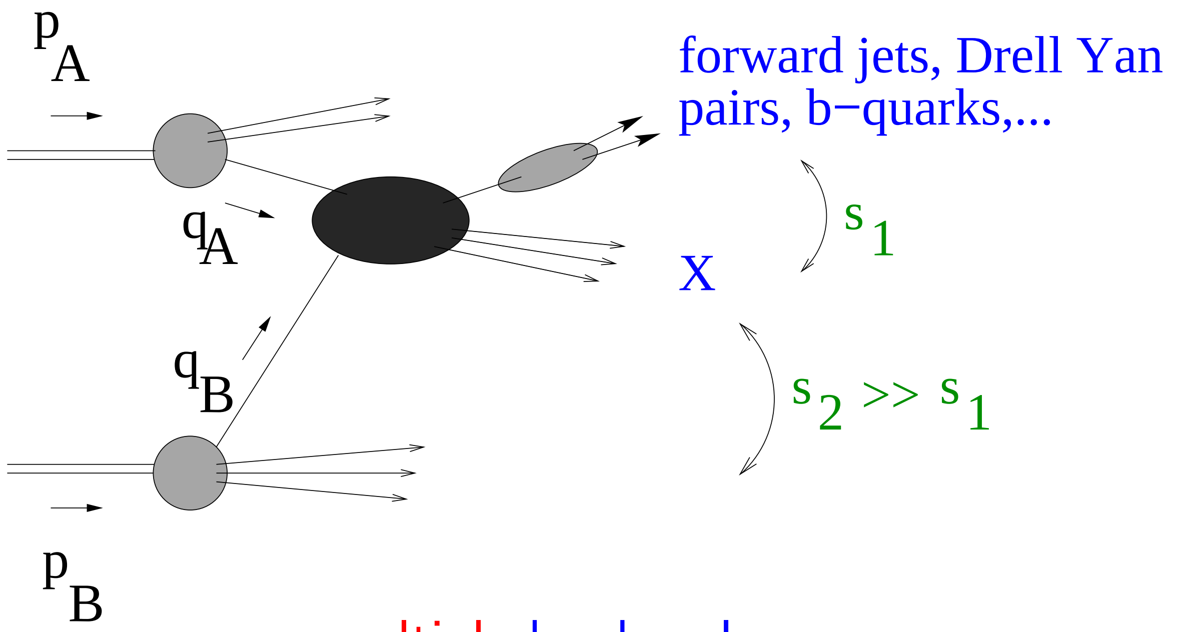
new particle discovery processes, e.g.

- 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

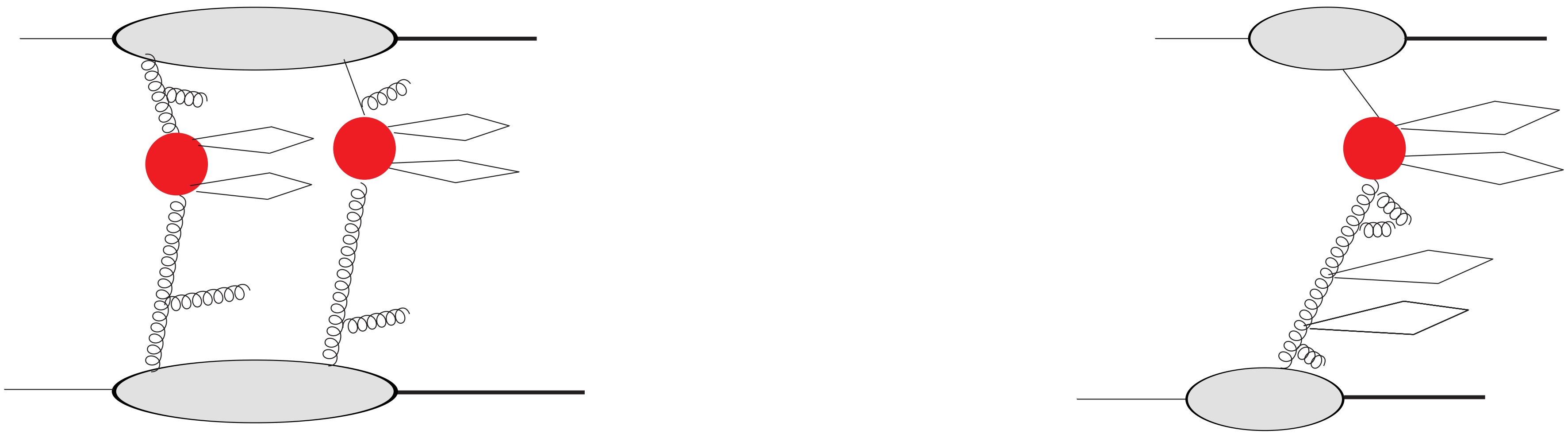
II. High-p_T production in the forward region



- multiple hard scales
- asymmetric parton kinematics $x_A \to 1, \ x_B \to 0$

$\diamondsuit$ Are fixed-order QCD calculations reliable in the forward region?

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

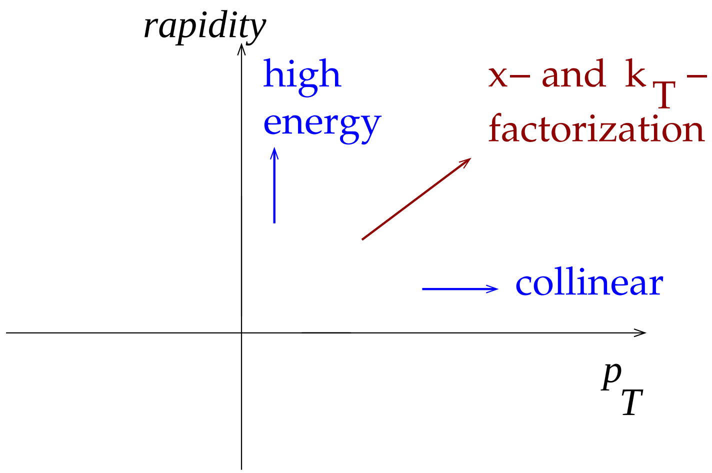
♢ Do multiple parton interactions become non-negligible in hard processes at forward rapidities?

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



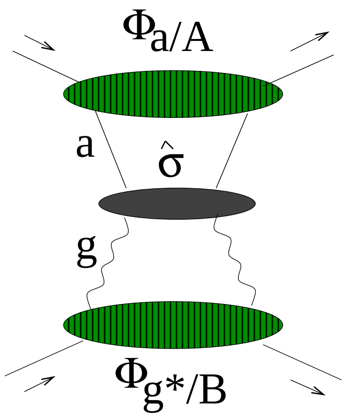
$\longrightarrow$ Both kinds of log contributions can be summed consistently to all orders of perturbation theory via QCD factorization at fixed k_T

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

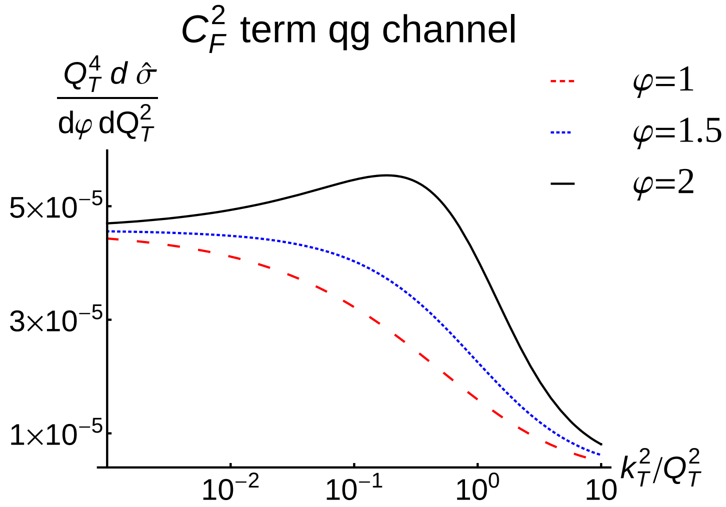
♢ $\widehat{\sigma}$ off-shell (but gauge-invariant) continuation of hard-scattering matrix elements *[Catani et al., 1991; Ciafaloni, 1998]*

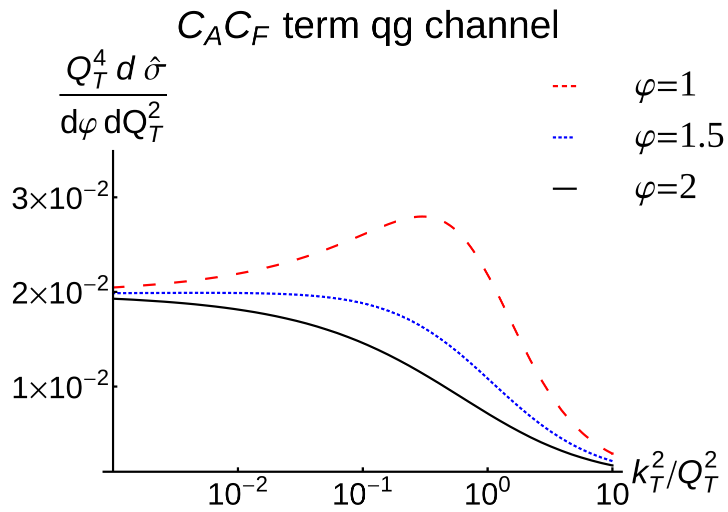
FULLY EXCLUSIVE MATRIX ELEMENTS: BEHAVIOR AT LARGE $K_\perp$

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

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

k_t = transverse momentum carried away by extra jets





- Matrix elements factorize for high energy

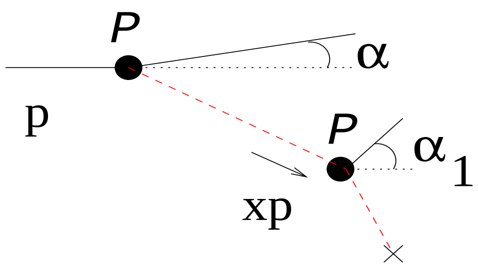
not only in collinear region but also at finite angle

$\Rightarrow$ effects of coherence across large rapidity intervals not associated with small angles

- Coupling to parton showers via merging scheme defined by factorization at high energy

▷ 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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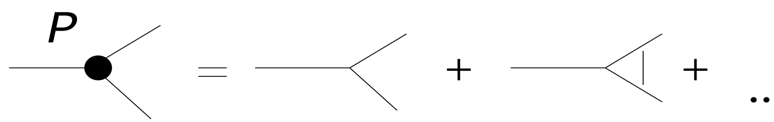


▷ CCFM evolution equation

▷ Monte Carlo implementations CASCADE, LDC, ...

Merging PS and ME

- Merging in high-energy limit can be done using

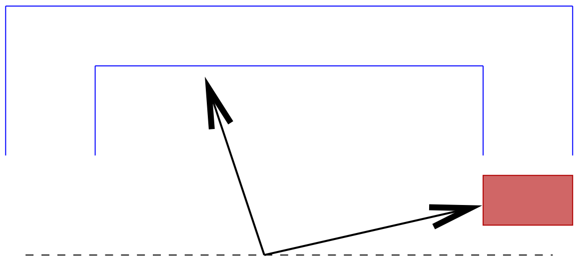
$$\gamma \frac{1}{k_\perp^2} \left(\frac{k_\perp^2}{\mu^2}\right)^\gamma \overset{\gamma \ll 1}{=} \delta(k_\perp^2) + \gamma \left(\frac{1}{k_\perp^2}\right)_{\rm R} + \gamma^2 \left(\frac{1}{k_\perp^2} \ln \frac{k_\perp^2}{\mu^2}\right)_{\rm R} + \dots$$

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

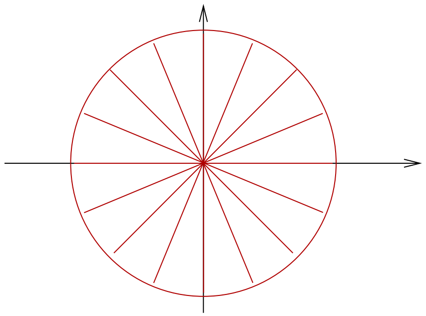
III. FORWARD JETS AT THE LHC

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

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

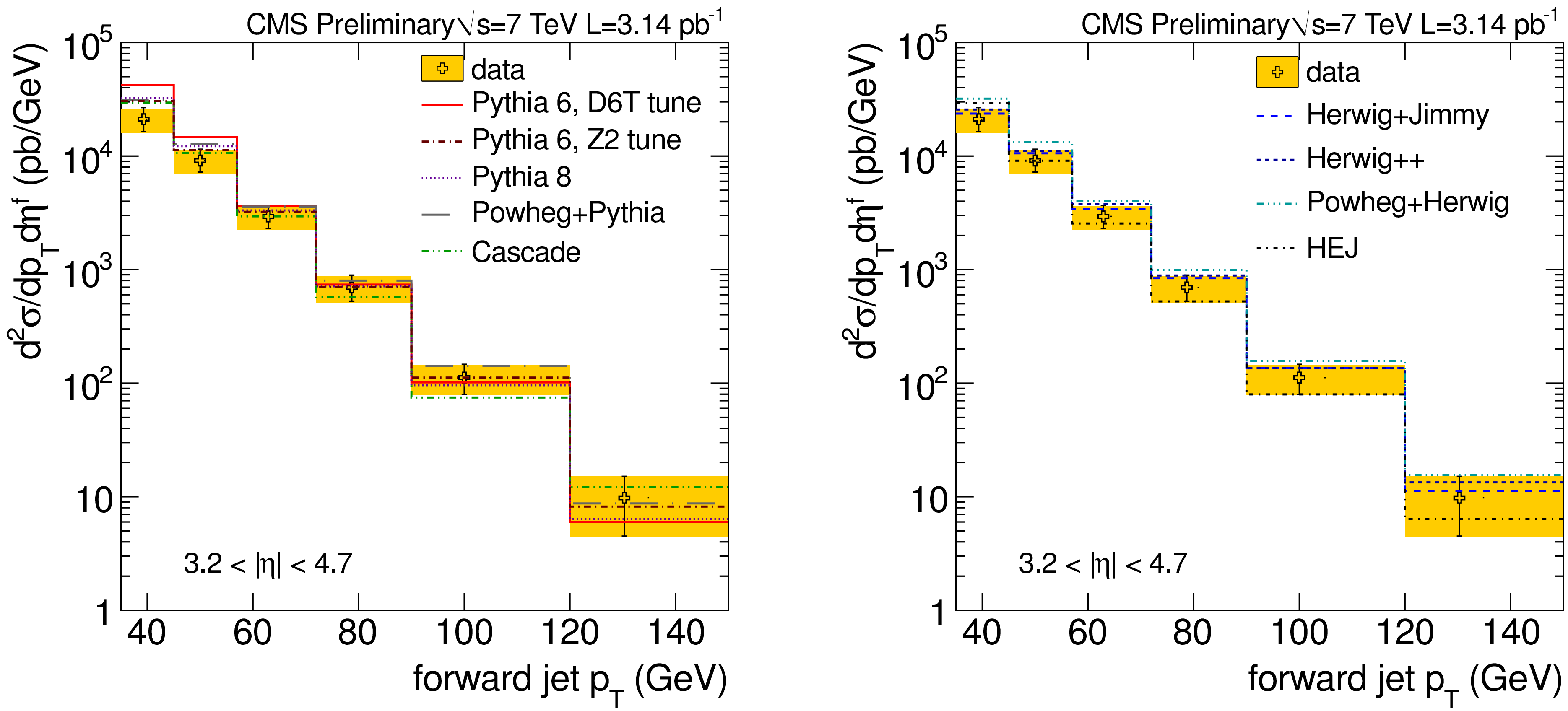


central + forward detectors



azimuthal plane

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



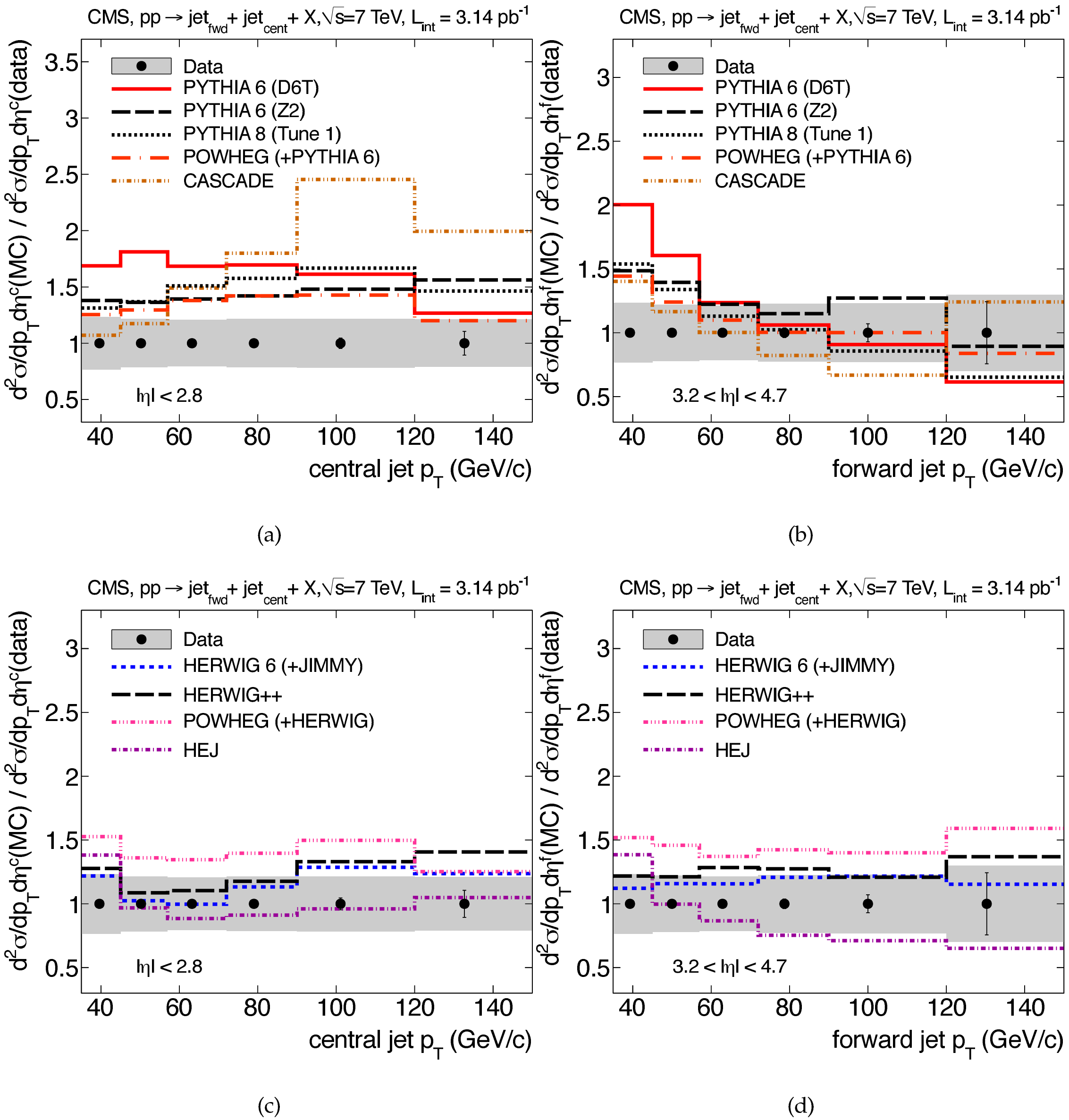
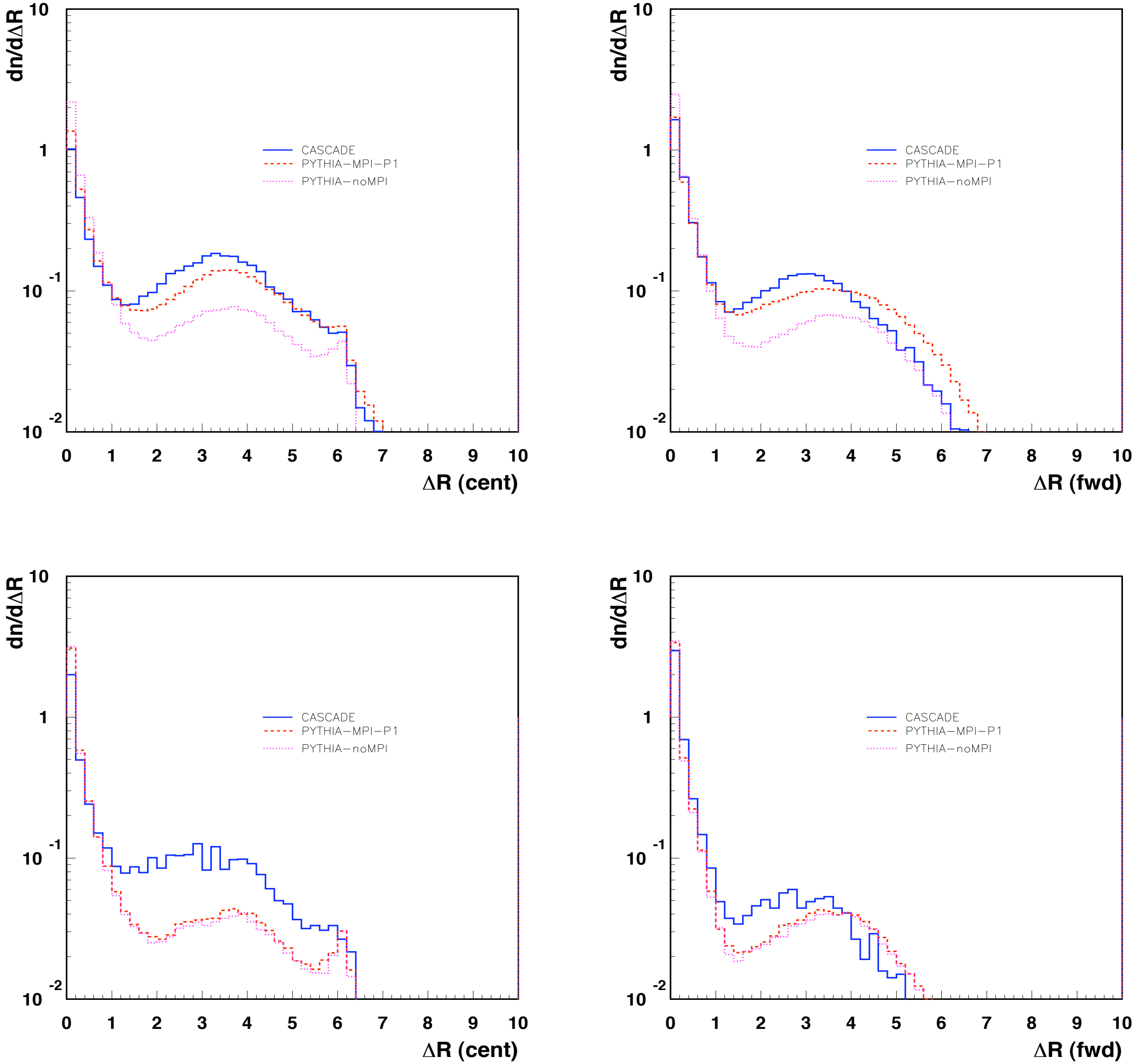


Figure 8: Ratio of theory to data for differential cross sections as a function of p_T, for central ((a) and (c)) and forward ((b) and (d)) jets produced in dijet events. The error bars on all data points reflect just statistical uncertainties, with systematic uncertainties plotted as grey bands.

[CMS Coll., arXiv:1202.0704]

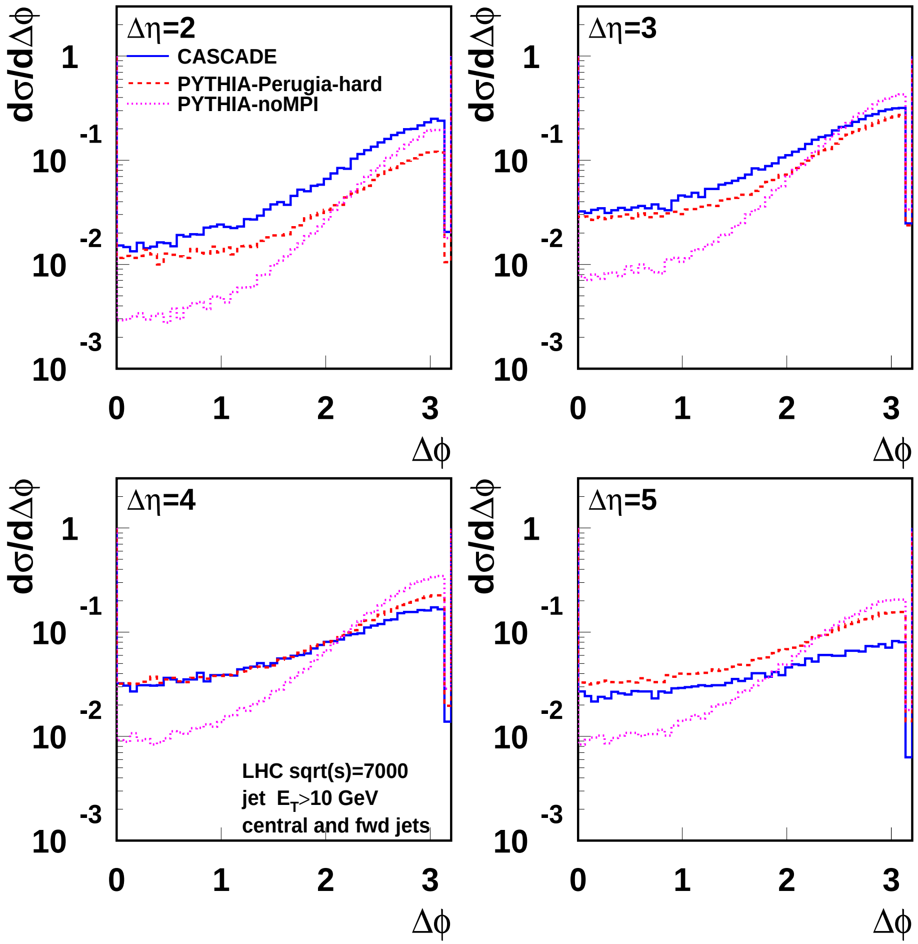


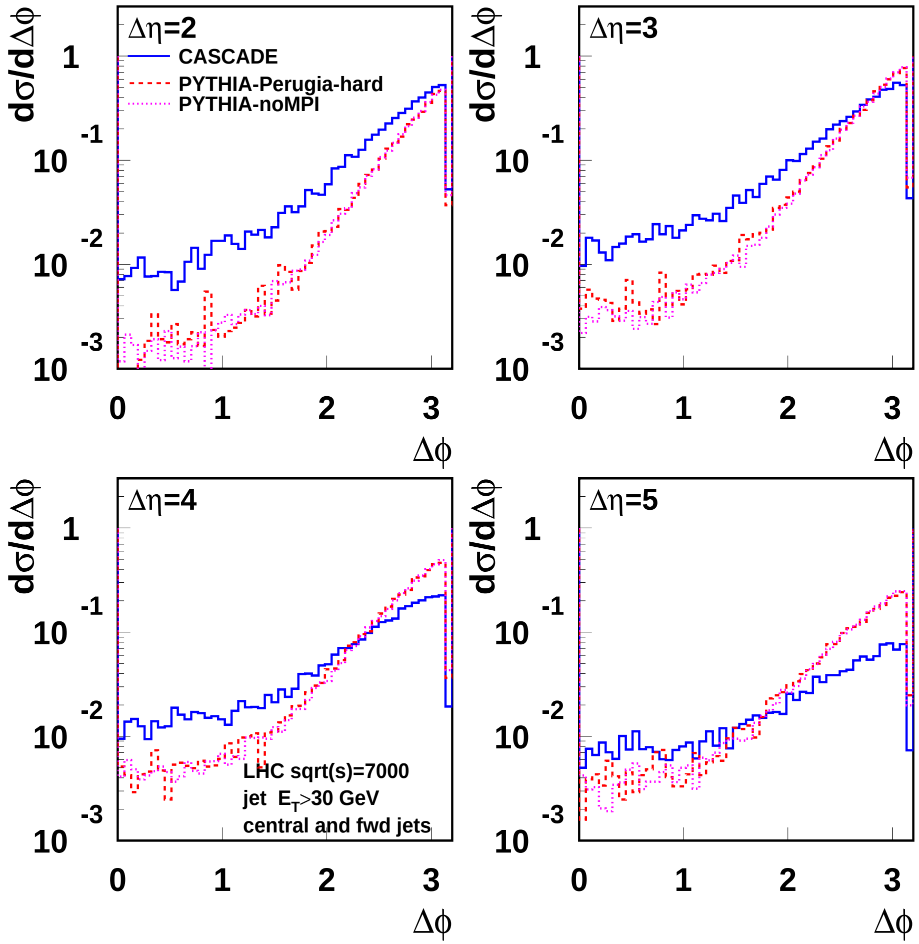
[Deak et al., arXiv:1012.6037]

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 central and forward jet for different rapidity separations

[Deak et al., arXiv:1012.6037]



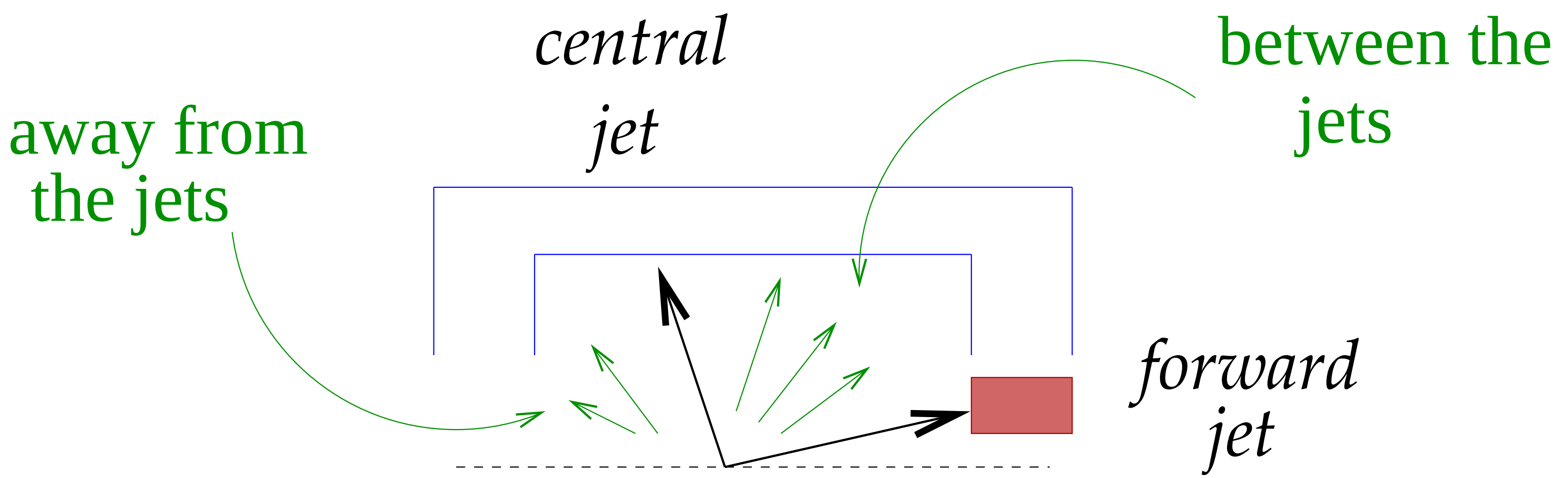


MC models: • CASCADE: non-collinear radiative corrections to single parton chain

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

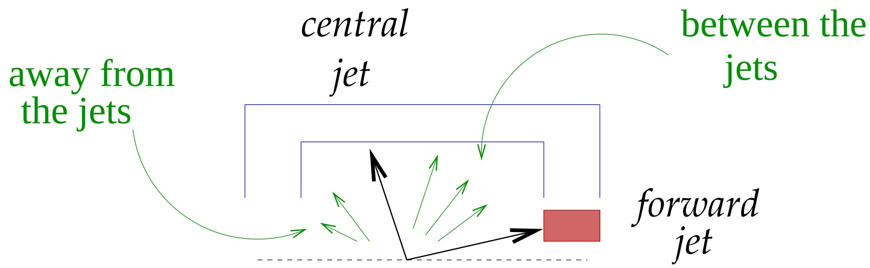
1 central + 1 forward jet:

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



Transverse energy flow as a function of rapidity

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



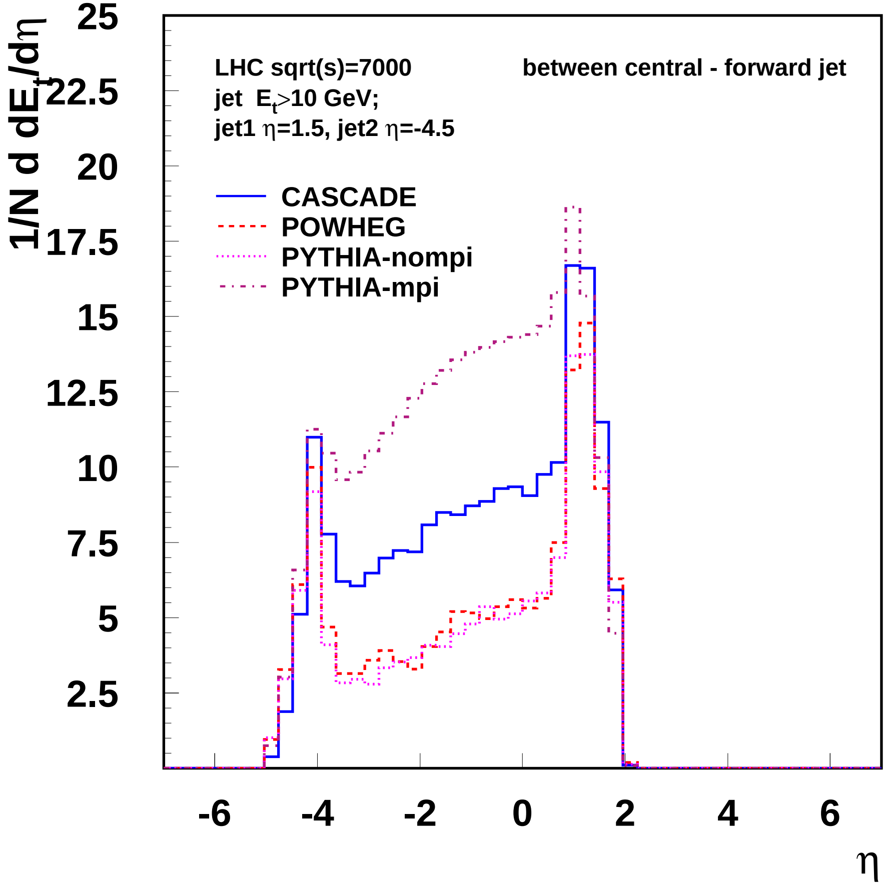
$$\frac{dE_\perp}{d\eta} = \frac{1}{\sigma} \int dq_\perp \ q_\perp \ \frac{d\sigma}{dq_\perp \ d\eta}$$

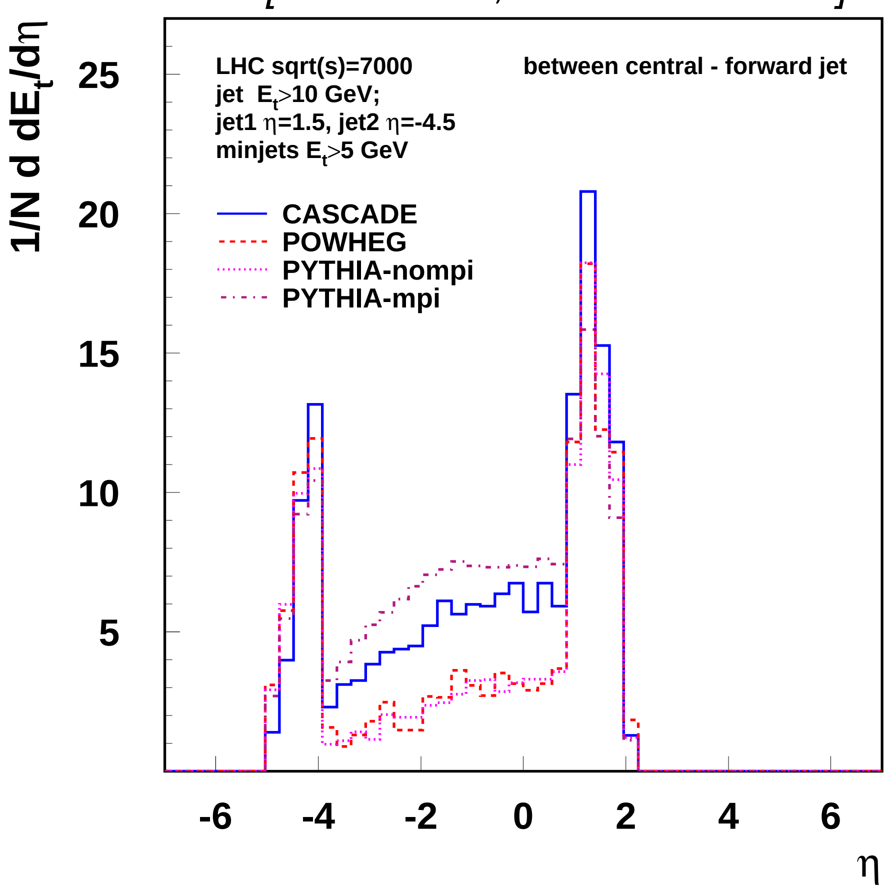
"Minijet" energy flow

- 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]



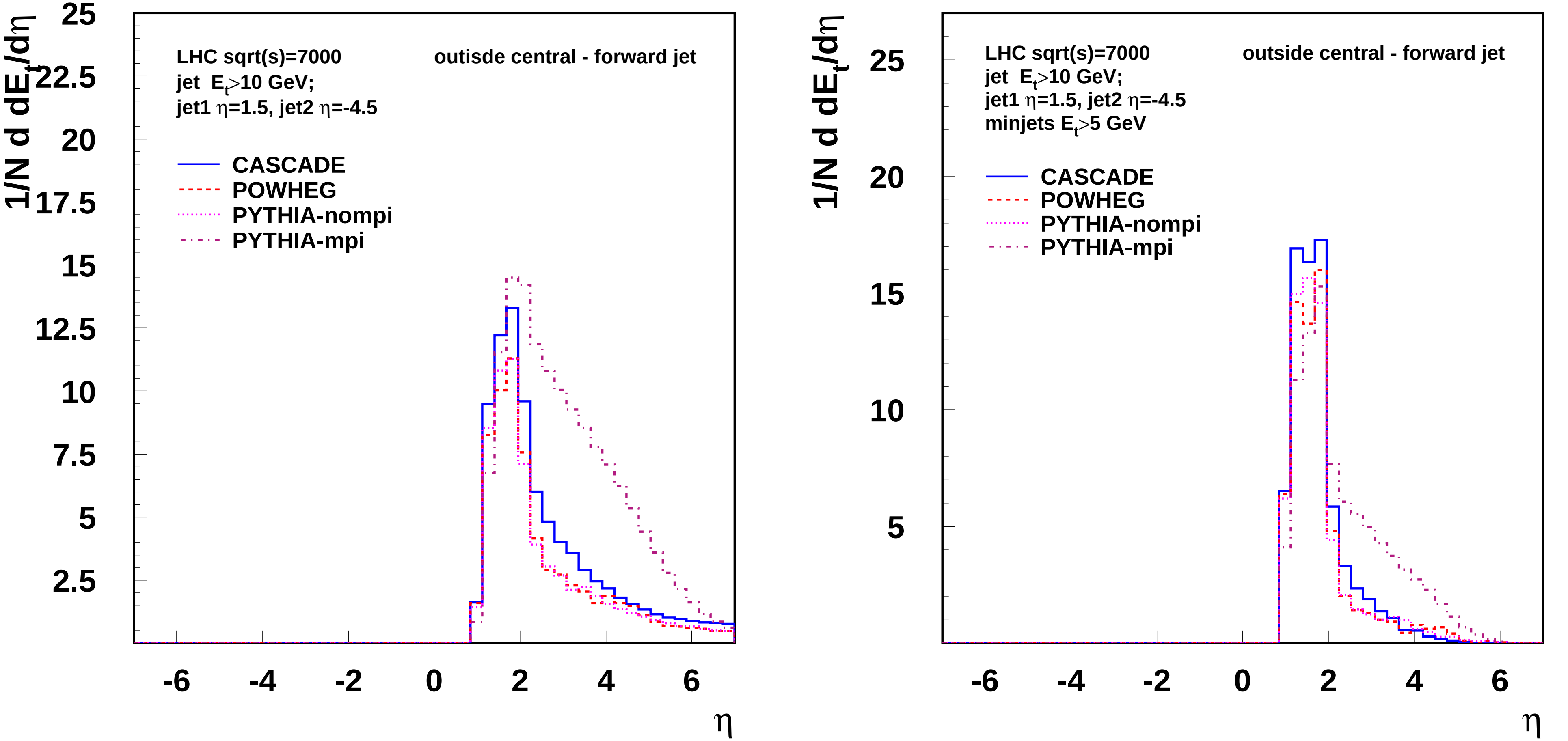


(left) particle flow; (right) minijet flow

▷ 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

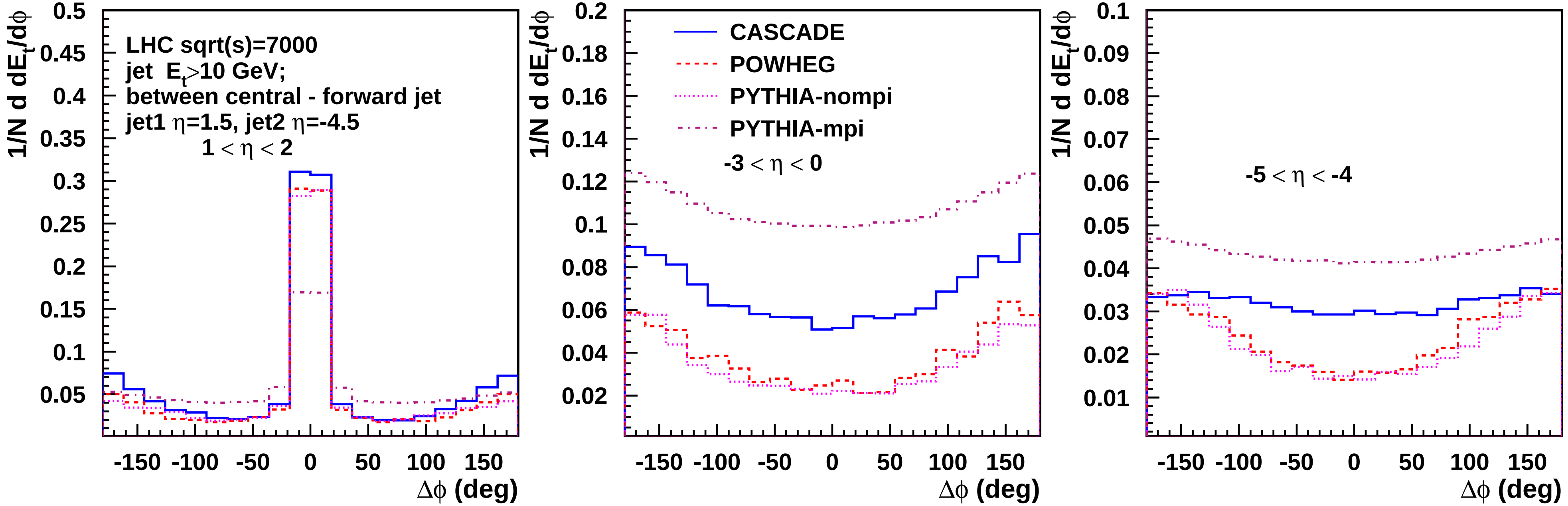


▷ at large (opposite) rapidities, full branching well approximated by collinear ordering

▷ higher energy flow only from multiple interactions

Azimuthal dependence of transverse energy flow

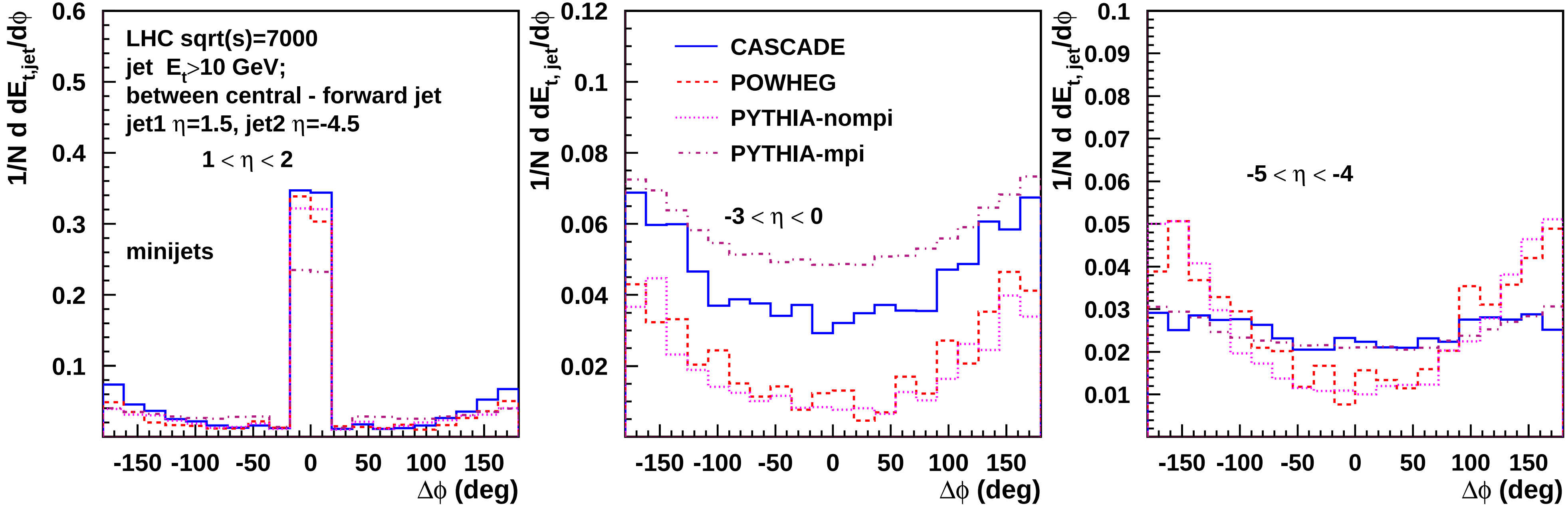
(left) central-jet; (middle) intermediate; (right) forward-jet rapidities



- 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

Toward higher $p_\perp$

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

$\Rightarrow$ subleading perturbative corrections from both shower evolution and matrix element

♠ u-pdf's asymptotic behavior

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

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

♢ NLO corrections to hard matrix element matched with showers

[see M. Deak's talk at this workshop]

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

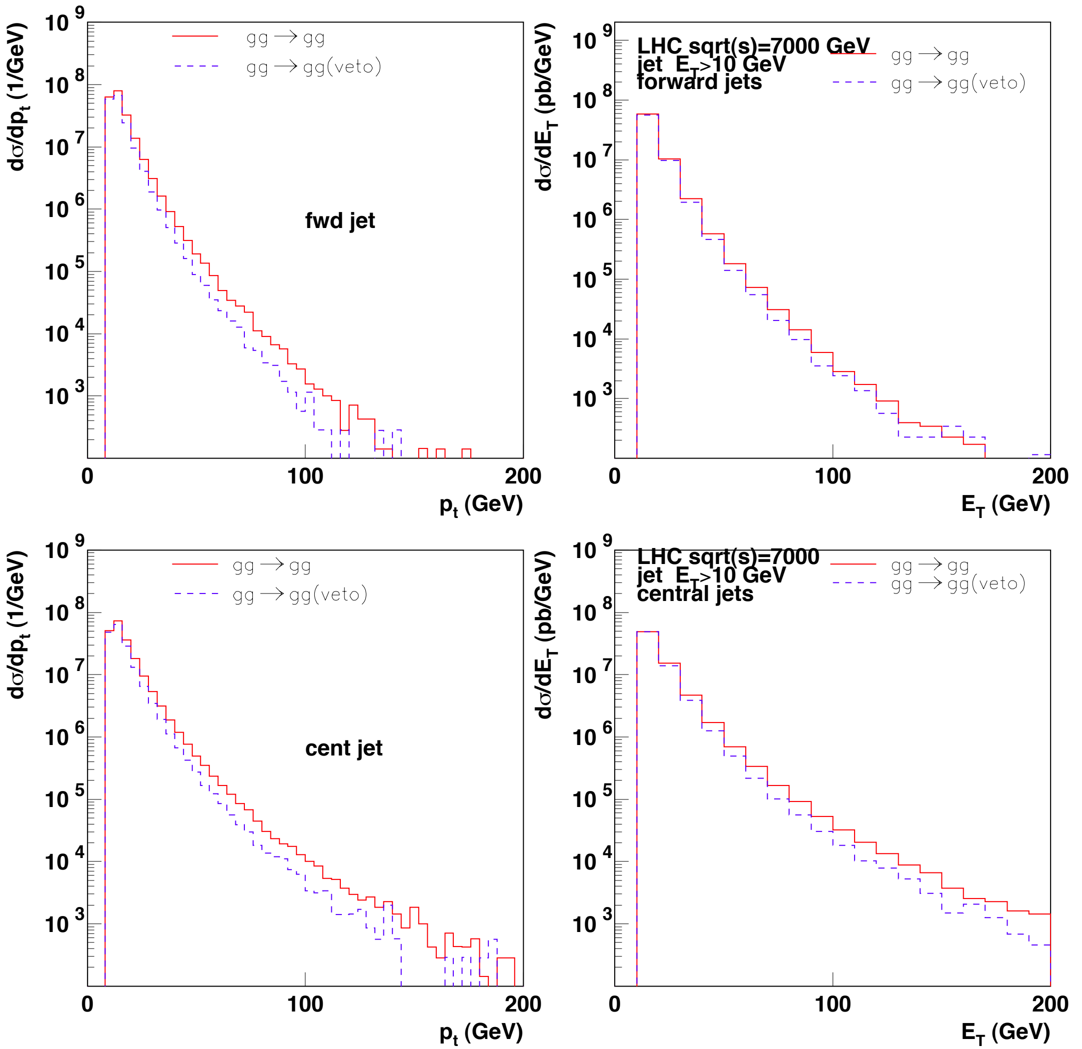
♣ full doubly off-shell matrix elements

$\Rightarrow$ further re-arranging of shower kinematics and suppression at high $p_\perp$

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

$\Rightarrow$ subtractive procedure to avoid double counting

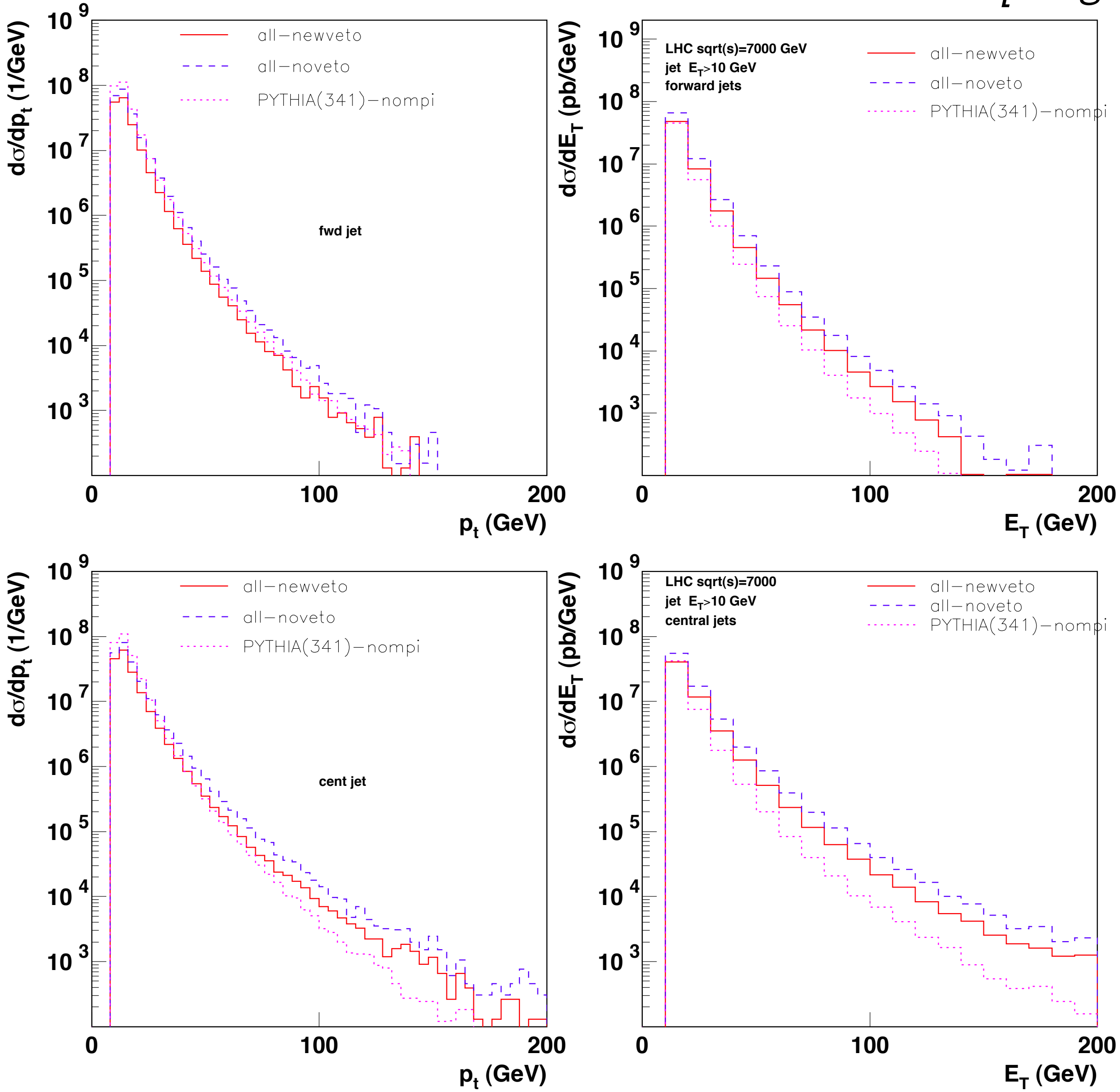
Ex.: $gg \to qq$ from direct production and from $gg \to gg \otimes g \to qq$



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

Comparison of transverse momentum spectra

[Jung & H, in progress]



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

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 its interplay 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 exp.'l observations in only rough agreement with current Monte Carlo's

- CCFM parton showers coupled to high energy factorized matrix elements

▷ color coherence for both $x \to 0$ and $x \to 1$

▷ increased azimuthal decorrelation with forward-central jets

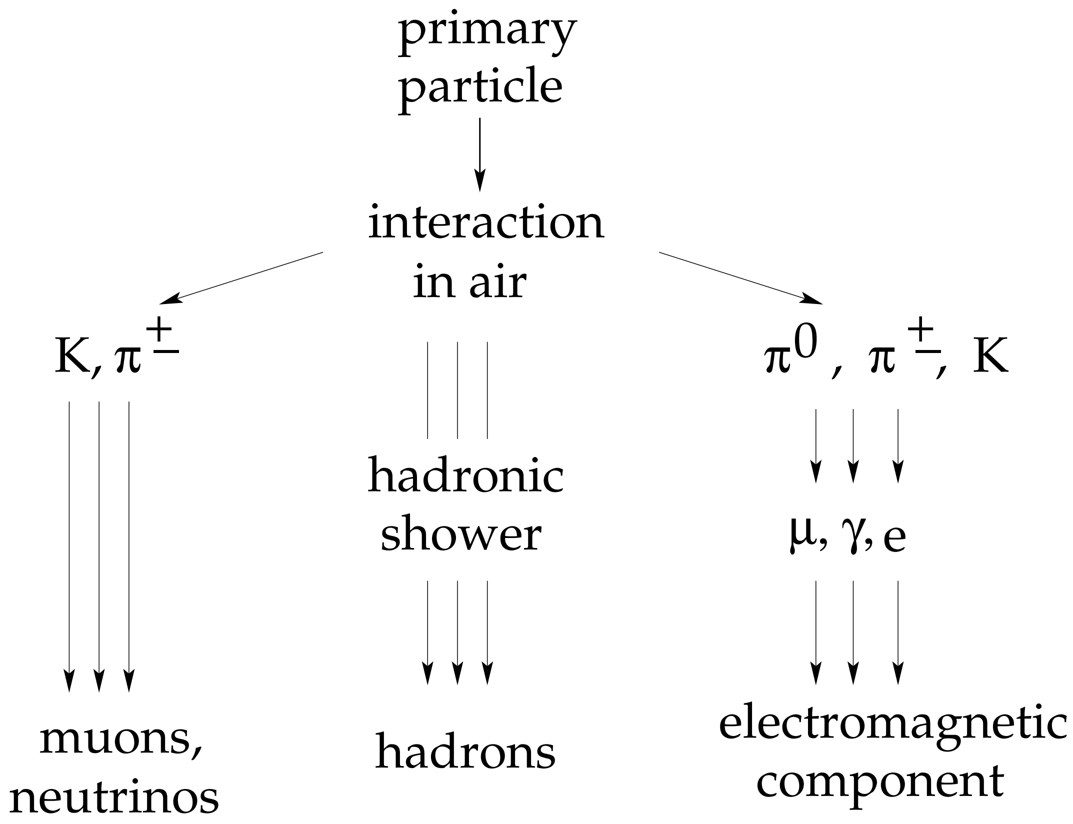
▷ increased particle and mini-jet energy flow in inter-jet region

▷ subleading corrections beyond collinear approximation?

▷ MPI effects?

EXTRA SLIDES

• Measurements of forward particle production (soft and hard)
at the LHC serve as input to
Monte Carlo models of high-energy showers in cosmic ray physics



• Fixed target collision in air with 10^{17} eV corresponds to pp interaction at LHC

♠ Nearly all topics in forward hard production processes at the LHC imply new experimental areas

♠ Theoretical issues: LHC forward physics dominated by QCD at small x

$\Downarrow$

- Factorization/resummation for large rapidity separations
- Parton evolution / showering beyond collinear ordering
- High parton density effects

♠ Phenomenology: How well do current Monte Carlo generators simulate LHC final states in the forward region?

Remarks

◇ Note difference from classic Mueller-Navelet approach

$$\sigma^{(MN)} = \sum_a \int \phi_{a/A} \otimes V_{jet1} \otimes \mathcal{G}_{gg} \otimes V_{jet2} \otimes \phi_{b/B}$$

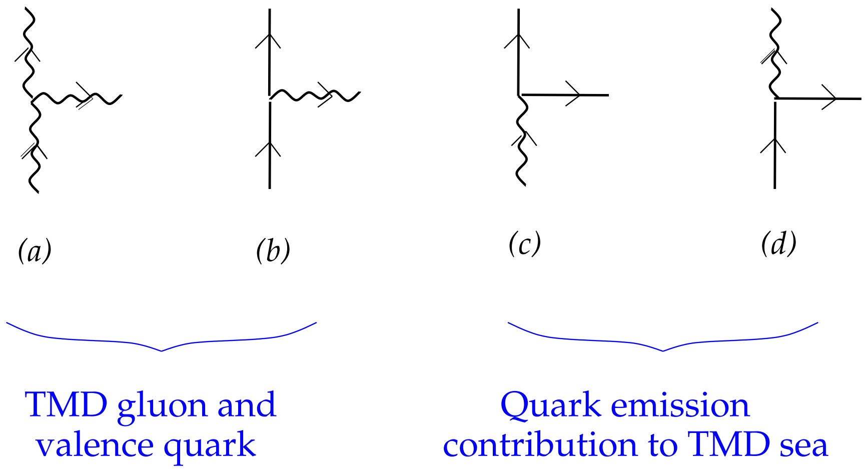
[Colferai, Schwennsen, Szymanowski and Wallon, JHEP 12 (2010) 026]

[D'Enterria, arXiv:0911.1273]

- non-collinear corrections to ϕ distributions
- no "vertex jet function" V_{jet}
- jets produced by either hard ME or parton shower (taking account of $k_\perp$)

Beyond quenched approximation: unintegrated quark evolution

[Hentschinski, Jung & H, in progress]



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

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

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

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

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

COHERENCE IN HIGH-ENERGY LIMIT

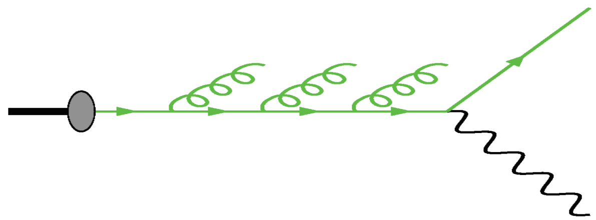
Soft vector-emission current from external legs $\rightarrow$

• 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]*

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

BUT... ▷

▷ …   • $\mathbf{J}$ depends on total transverse momentum transmitted

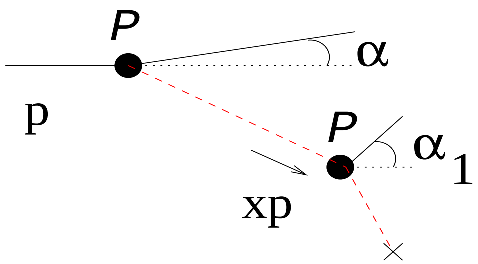
$\Rightarrow$ matrix elements and pdf at fixed $k_\perp$ ("unintegrated")

• virtual corrections not fully represented by Δ form factor

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

▷ $K_\perp$-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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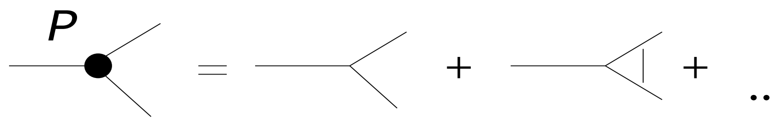

▷ CCFM evolution equation

▷ Monte Carlo implementations: CASCADE, LDC, …