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Jet Correlations, Coherence Effects and High-p_T Physics in the Forward Region at the LHC

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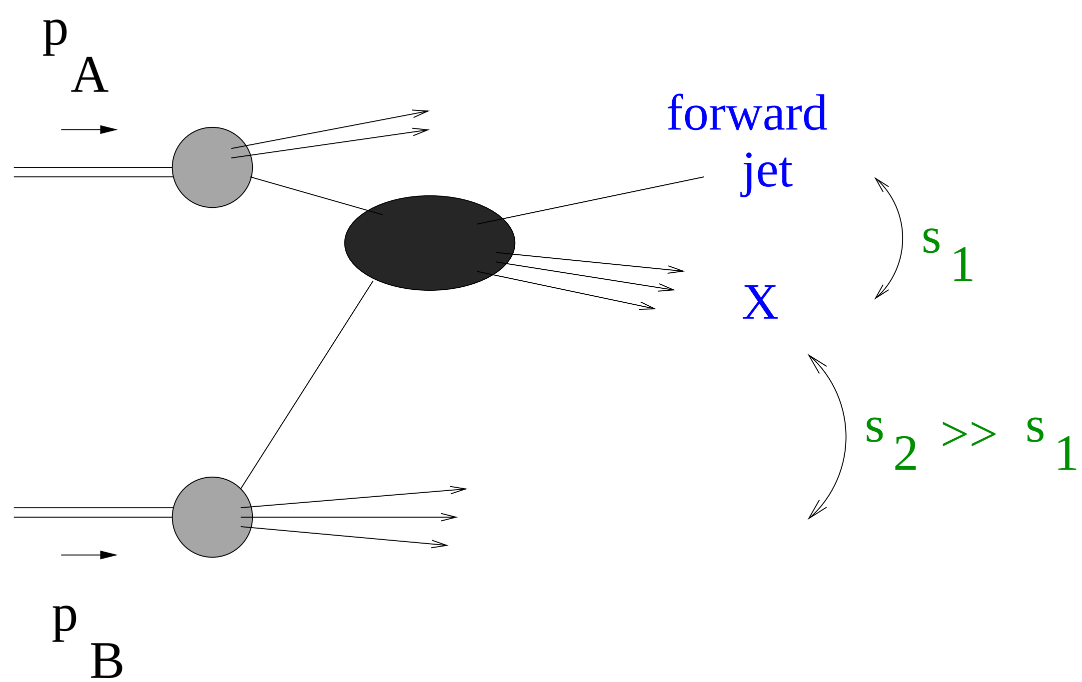
- Motivation — hard processes at forward rapidities at the LHC
- Theoretical issues on space-like parton showers and coherent gluon radiation
- What do we learn from ep and $p\bar{p}$ jets

INTRODUCTION

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 $x_A \to 1, \ x_B \to 0$

◇ MULTI-GLUON COHERENCE IN THIS KINEMATIC REGION

- not included AT ALL in standard shower Monte Carlo generators
- included ONLY partially in NLO multi-jet calculations
- present to all orders and potentially enhanced by logs of $\sqrt{s}/p_T$

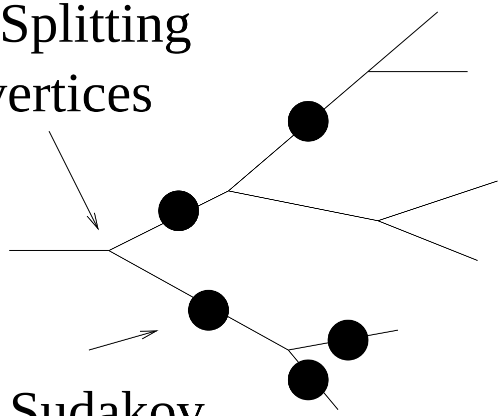
OUTLINE

I. QCD coherence effects (quick review)

II. Issues on unintegrated matrix elements

III. Applications to jets: LHC prospects + $p\bar{p}$ and ep data

I. MULTI-PARTON EMISSION BY PARTON BRANCHING METHODS



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

- based on dominance of collinear evolution of jets

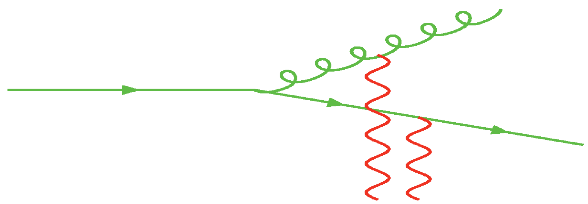
- Factorization of QCD cross sections in collinear limit
  $\longrightarrow$ probabilistic (Markov) picture

- summation of logarithmically enhanced radiative contributions
  $(\alpha_S \; \ln p_T/\Lambda)^n$

- soft gluon radiation by coherent branching [e.g.: HERWIG, new PYTHIA]

$\hookrightarrow$

▷ soft gluons radiated over long times $\longrightarrow$ quantum interferences



$\swarrow$ factorization in soft limit

$$|M_{n+1}^{a_1 \ldots a_n a}(p_1, p_n, q)\rangle = \mathbf{J}^a |M_n^{a_1 \ldots a_n}(p_1, p_n)\rangle \ , \quad \mathbf{J}^{a\mu} = \sum_i \mathbf{Q}_i^a \, \frac{p_i^\mu}{p_i \cdot q} \ , \quad \mathbf{Q} = \text{color charge}$$

interference terms $\downarrow$

$$d\sigma_{n+1} = d\sigma_n \, \frac{d^3 q}{(q^0)^3} \, \sum_{i,j} \mathbf{Q}_i \cdot \mathbf{Q}_j \ w_{ij} \quad , \quad w_{ij} = \frac{(q^0)^2 \ p_i \cdot p_j}{(p_i \cdot q)(p_j \cdot q)}$$

— not positive definite, non-Markov..?

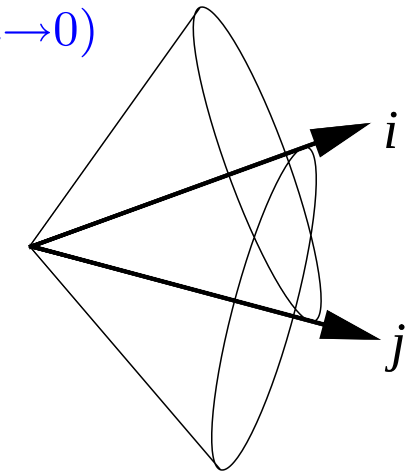
$\longrightarrow$ spoils probabilistic picture? NO, owing to soft-gluon coherence $\hookrightarrow$

- single-emission: separate singularities along emitters' directions

$$\frac{(q^0)^2 p_i \cdot p_j}{(p_i \cdot q)(p_j \cdot q)} \equiv \frac{\zeta_{ij}}{\zeta_{iq}\zeta_{jq}}$$

$$= \frac{1}{2}\left(\frac{\zeta_{ij}}{\zeta_{iq}\zeta_{jq}} - \frac{1}{\zeta_{jq}} + \frac{1}{\zeta_{iq}}\right) + \frac{1}{2}\left(\frac{\zeta_{ij}}{\zeta_{iq}\zeta_{jq}} - \frac{1}{\zeta_{iq}} + \frac{1}{\zeta_{jq}}\right)$$

$$\text{where } \zeta_{nk} \equiv \frac{p_n \cdot p_k}{p_n^0 p_k^0} \simeq 1 - \cos\theta_{nk} \quad (m \to 0)$$



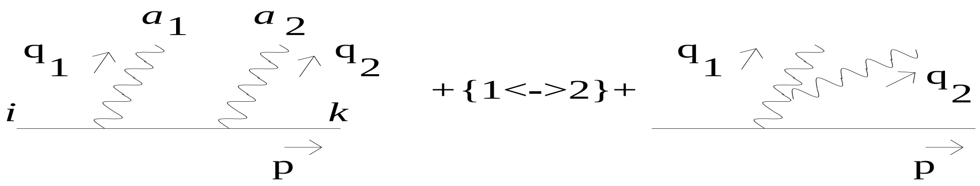
$\longrightarrow$ by azimuthal average

$$\langle \frac{\zeta_{ij}}{\zeta_{iq}\zeta_{jq}} \rangle = \frac{1}{\zeta_{iq}}\Theta(\zeta_{ij} - \zeta_{iq}) + \frac{1}{\zeta_{jq}}\Theta(\zeta_{ij} - \zeta_{jq})$$

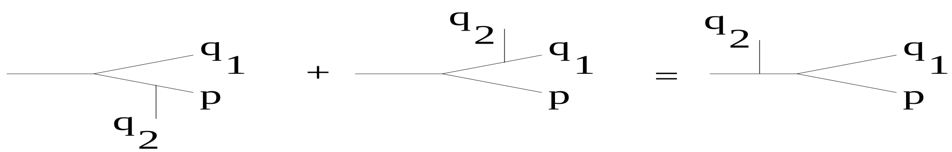
$\diamondsuit$ large-angle emissions of soft gluons sum coherently outside angular-ordered cones

- multiple emission: $(q_1,\ q_2$ with $q_2^0 \ll q_1^0)$

$$\mathbf{J}_1^{\mu a_1} = \mathbf{Q}_p^{a_1} \frac{p^\mu}{p \cdot q_1} \quad , \quad \mathbf{J}_2^{\mu a_2} = \mathbf{Q}_p^{a_2} \frac{p^\mu}{p \cdot q_2} + \mathbf{Q}_{q_1}^{a_2} \frac{q_1^\mu}{q_1 \cdot q_2}$$



(a)



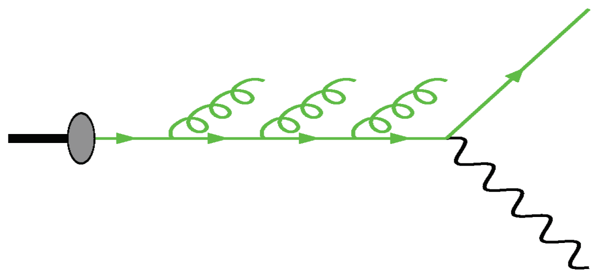
(b)

$$\begin{aligned}\mathcal{M}_{ki}^{a_1 a_2} &= g_s^2 \ \langle a_1 \ k | \ \mathbf{J}_2 \cdot \varepsilon_2 \ | a' \ i' \rangle \ \langle \ i' \ | \mathbf{J}_1 \cdot \varepsilon_1 | \ i \ \rangle \\ &= g_s^2 \ \frac{p \cdot \varepsilon_1}{p \cdot q_1} \ \left(\frac{p \cdot \varepsilon_2}{p \cdot q_2} \ t^{a_2} t^{a_1} + \frac{q_1 \cdot \varepsilon_2}{q_1 \cdot q_2} \ [t^{a_1}, t^{a_2}] \right)_{ki}\end{aligned}$$

- small angle: bremsstrahlung cones
- large angle $(\theta_{pq_2} \gg \theta_{pq_1})$: sees total charge $\mathbf{Q}_p + \mathbf{Q}_{q_1}$

II. COHERENCE IN HIGH-ENERGY, SMALL-X PARTON SHOWERS

- Arguments used above rely on soft vector emission current from external legs $\longrightarrow$ leading IR singularities
  - appropriate in single-scale hard processes



multi-scale: $s = q_1^2 \gg \cdots \gg q_n^2 \gg \Lambda^2$

[e.g.: LHC forward hard processes]

$\Downarrow$

▷ internal emissions non-negligible

▷ current also factorizable at high-energy:

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

▷ 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

♢ radiative enhancements $\alpha_S^k \ln^m s/p_T^2$

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

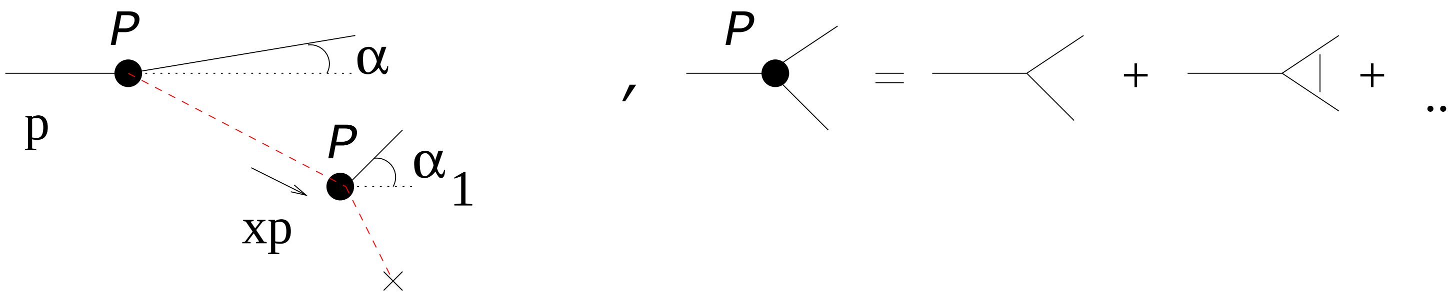
(e.g: corrections $\mathcal{O}(\alpha_s^k)$ to space-like splitting functions)

♢ but not in exclusive final-state correlations

$\mathrm{K}_\perp$-DEPENDENT PARTON BRANCHING

- implement all-order summation of $(\alpha_S \ln s/p_T^2) \oplus$ IR $x \to 1$ behavior

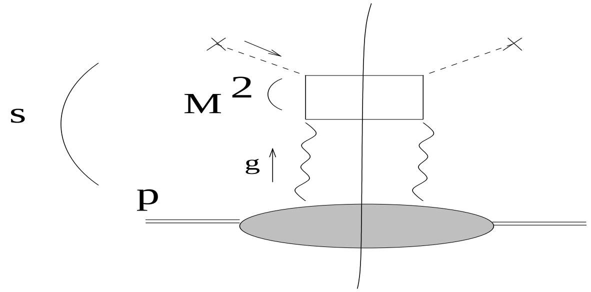
- branching eq. :
$$\mathcal{G}(x, k_T, \mu) \;=\; \mathcal{G}_0(x, k_T, \mu) + \int \frac{dz}{z} \int \frac{dq^2}{q^2}\, \Theta(\mu - zq) \times \underbrace{\Delta(\mu, zq)}_{\mathrm{Sudakov}} \;\; \underbrace{\mathcal{P}(z, q, k_T)}_{\mathrm{unintegr.\,splitting}} \;\; \mathcal{G}(\frac{x}{z}, k_T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



(left) Coherent radiation in the space-like parton shower for $x \ll 1$;
(right) the unintegrated splitting function $\mathcal{P}$, including small-x virtual corrections.

$$\alpha/x > \alpha_1 > \alpha \quad (\mathrm{small-x\ \ coherence\ \ region})$$

HOW TO CHARACTERIZE UNINTEGRATED PDF's WITH PRECISION



♢ single gluon polarization dominates $s \gg M^2 \gg \Lambda^2_{\rm QCD}$

$\hookrightarrow$ gauge invariance rescued (despite gluon off-shell)

[Lipatov; Ciafaloni; Catani, H; Collins et al.]

• corrections down by $1/\ln s$ rather than $1/Q$

$\hookrightarrow$ NLO to BFKL ($+$ its variants)

• can go to ARBITRARILY HIGH $k_\perp$

$\Rightarrow$ UV scaling violation correctly reproduced

[Altarelli et al.; Ciafaloni et al.]

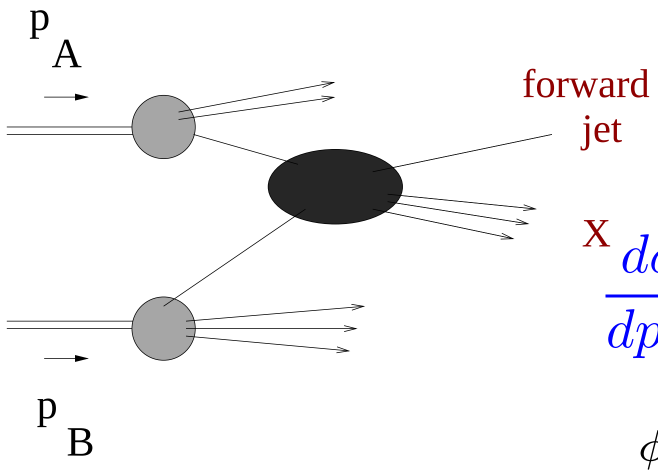
$\Rightarrow$ well-defined summation of higher-order logarithmic corrections

$\Rightarrow$ suitable for simulations of jet physics at the LHC

III. APPLICATIONS TO JET PHYSICS

A) JETS IN THE FORWARD REGION AT THE LHC:

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



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

ϕ_A quasi-collinear , ϕ_B $k_\perp$-dependent

- $d\widehat{\sigma}/dp_T^2$ from perturbative off-shell amplitudes

- $k_\perp$-dependent shower from branching equation + data fits

▷ OBTAIN AZIMUTHAL-PLANE CORRELATIONS BETWEEN JETS ACROSS RAPIDITY INTERVALS $\Delta\eta \gtrsim 4 \div 6$

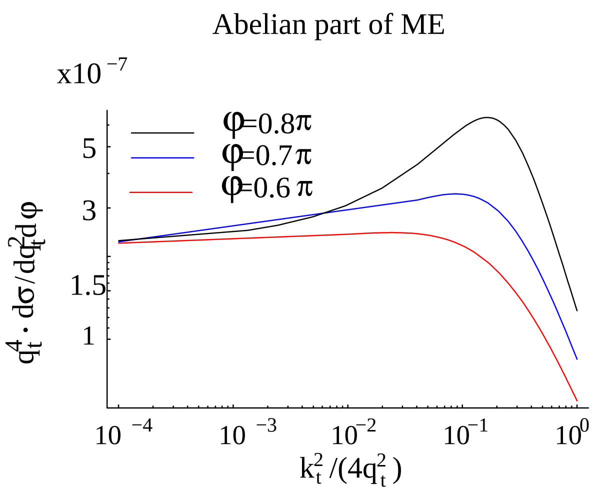
COHERENT MATRIX ELEMENTS FOR HARD EVENT

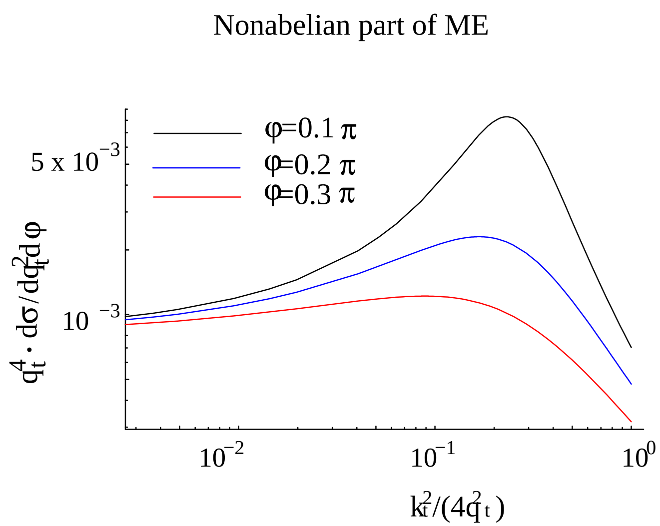
[M. Ciafaloni 1998]

- Note: dynamical cut-off on next-to-hardest jet going to largest η

Ex.: $q_T =$ weighted final-state transverse energy

[M. Deak, K. Kutak (2009)]





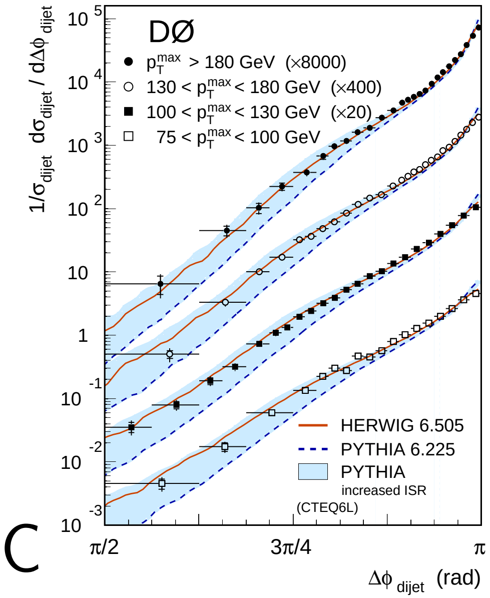
- measures transverse momentum distribution of third jet
- large k_T tail ($=$ higher orders) set by coherence effects

B) WHAT DO WE LEARN FROM P$\overline{\text{P}}$ AND EP JET FINAL STATES

Ex.: azimuthal $\Delta\phi$ correlation between two hardest jets

▷ Tevatron $\Delta\phi$ dominated by leading-order processes

- good description by HERWIG as well as by NLO
  - used for MC parameter tuning in PYTHIA



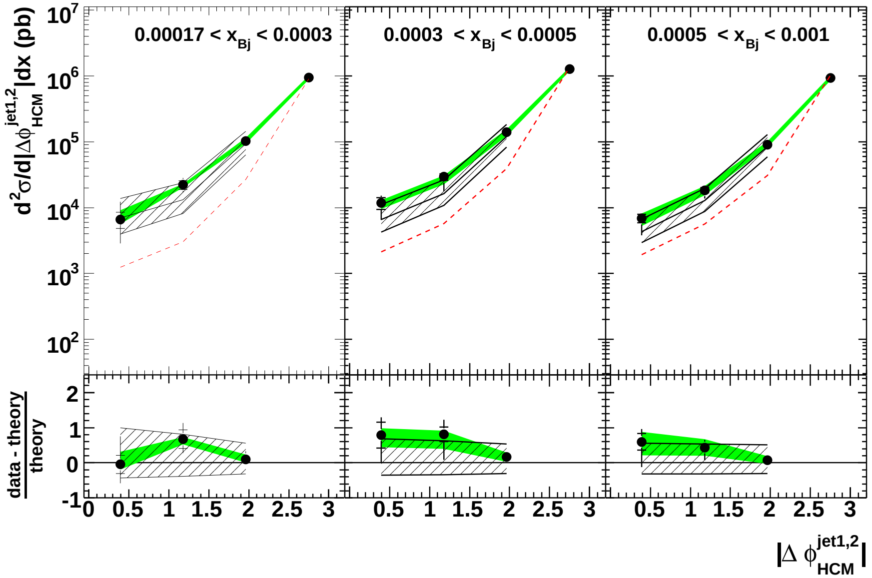
▷ HERA $\Delta\phi$ not well described by standard MC

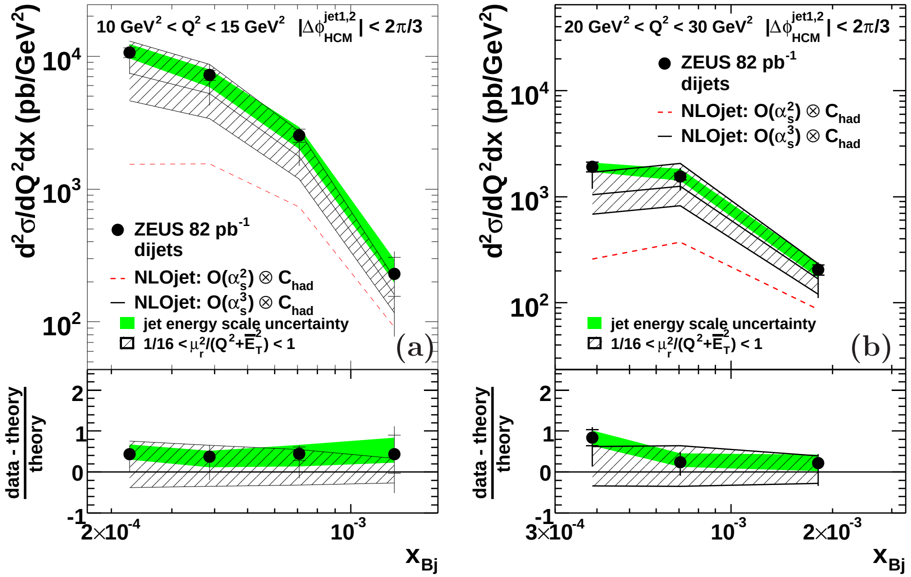
$\hookrightarrow$ see next

▷ accessible at the LHC relatively early

$\hookrightarrow$ how do MC describe multiple radiation?

DI-JET EP CORRELATIONS: COMPARISON WITH NLO RESULTS



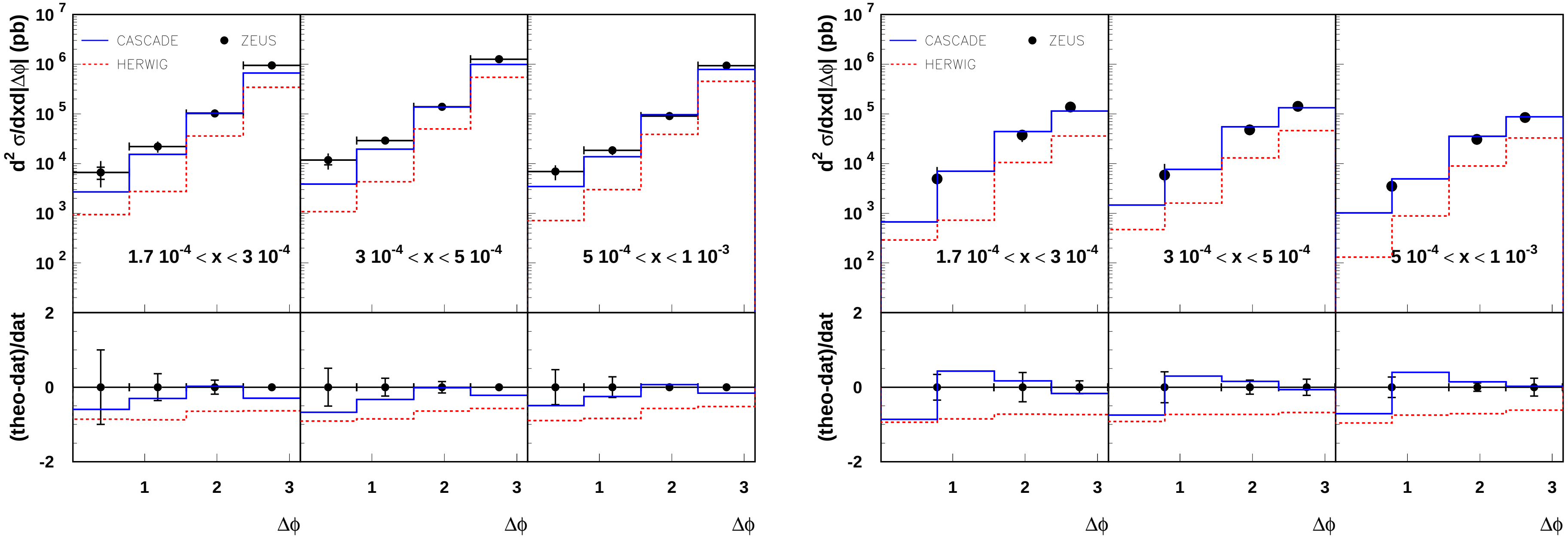


(left) Azimuth dependence and (right) Bjorken-x dependence of di-jet distributions

$$Q^2 > 10 \text{ GeV}^2 \quad , \qquad 10^{-4} < x < 10^{-2}$$

◇ large variation from order-α_s^2 to order-α_s^3 prediction as $\Delta\phi$ and x decrease
$\Rightarrow$ sizeable theory uncertainty at NLO (underestimated by "μ error band")

ANGULAR JET CORRELATIONS FROM $k_\perp$-SHOWER (CASCADE) AND COLLINEAR-SHOWER (HERWIG)

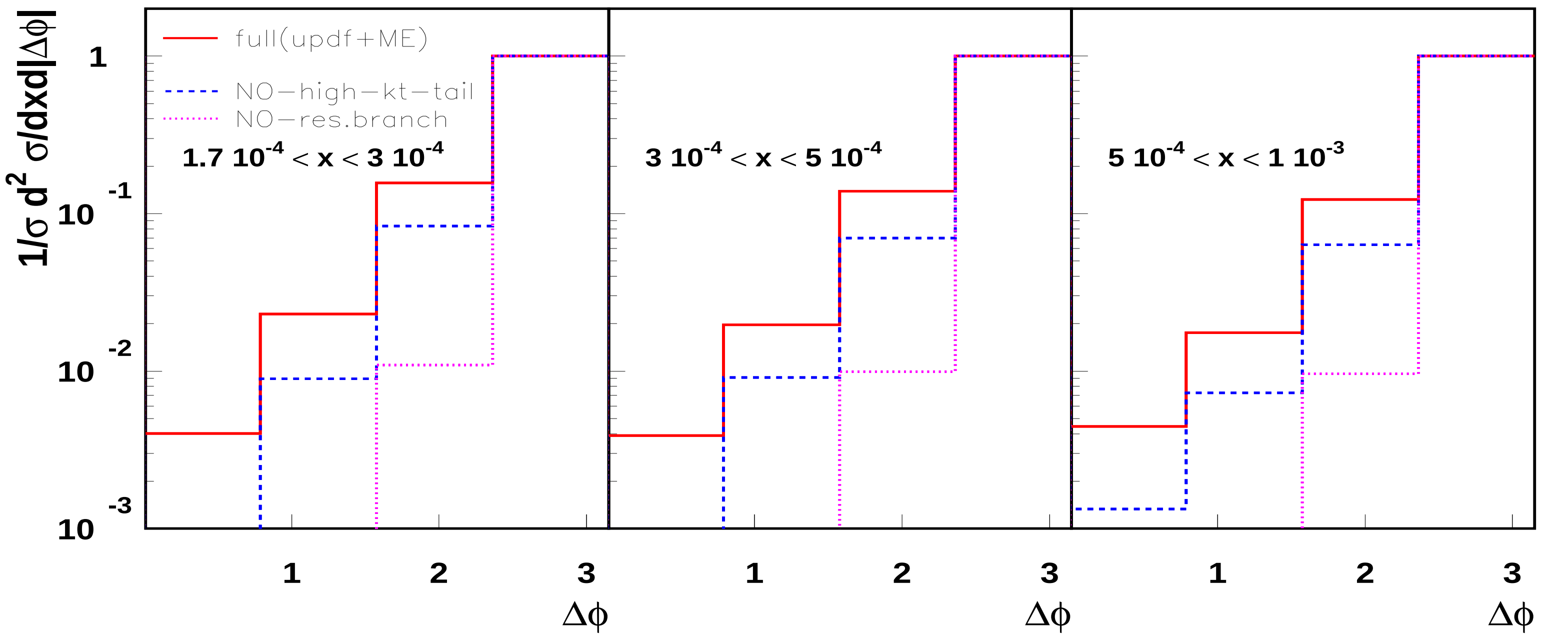


(left) di-jet cross section; (right) three-jet cross section

Jung & H, arXiv:0805.1049 [hep-ph]

- largest differences at small $\Delta\phi$
- good description of measurement by $k_\perp$-shower
- collinear shower insufficient to describe shapes

Normalize to the back-to-back cross section:



updf $\oplus$ ME

- - - updf $\oplus$ ME$_{collin.}$: $\mathcal{M} \to \mathcal{M}_{collin.}(k_T) = \mathcal{M}(0_\perp)\ \Theta(\mu - k_T)$

· · · · · · no resolved branching : $\mathcal{A} \to \mathcal{A}_{no-res.}(x, k_T, \mu) = \mathcal{A}_0(x, k_T, Q_0)\ \Delta(\mu, Q_0)$

▷ high-k$_\perp$, coherent effect essential for correlation at small $\Delta\phi$

(cfr., e.g., MC by Höche, Krauss & Teubner, arXiv:0705.4577: u-pdf but no ME correction)

IV. PROSPECTS FOR FURTHER FINAL STATES AND CONCLUSIONS

- production of b, c — what size NLO uncertainties at LHC energies?

  [see MC@NLO; Nason et al.]

  ▷ sizeable corrections from $g \to b\bar{b}$ coupling to spacelike jet

  ▷ coherence effects to $b\bar{b} + 2\ jets$ for $m_b \ll p_T^{(b\bar{b})} \ll p_T^{(jet)}$

- even more complicated multi-scale effects in $b\bar{b} + W/Z$ production

  [HERA-LHC Proc. arXiv:0903.3861; Mangano, 1993]

- Tevatron b-jets angular correlations

  ($\hookrightarrow$ CDF $\Delta\phi$ data)

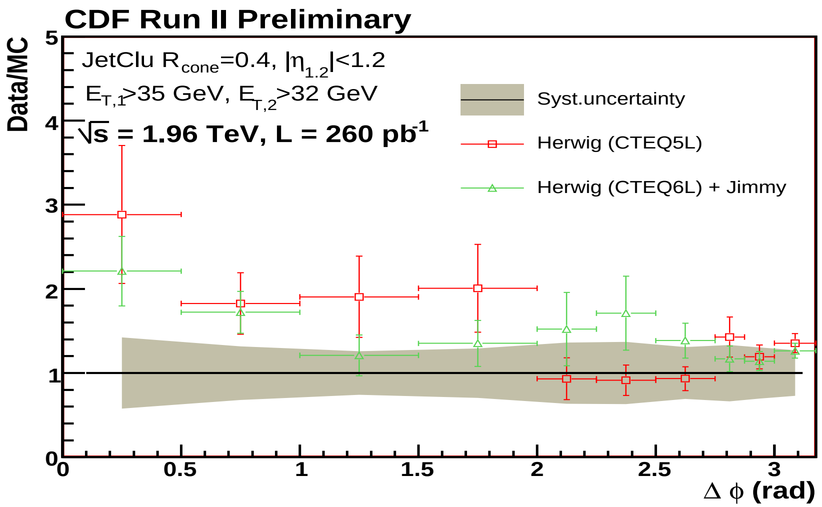
- final states with Higgs

  $\rightarrow$ possibly 10 $\div$ 20 % effects in p_T spectrum from $x \ll 1$ terms?

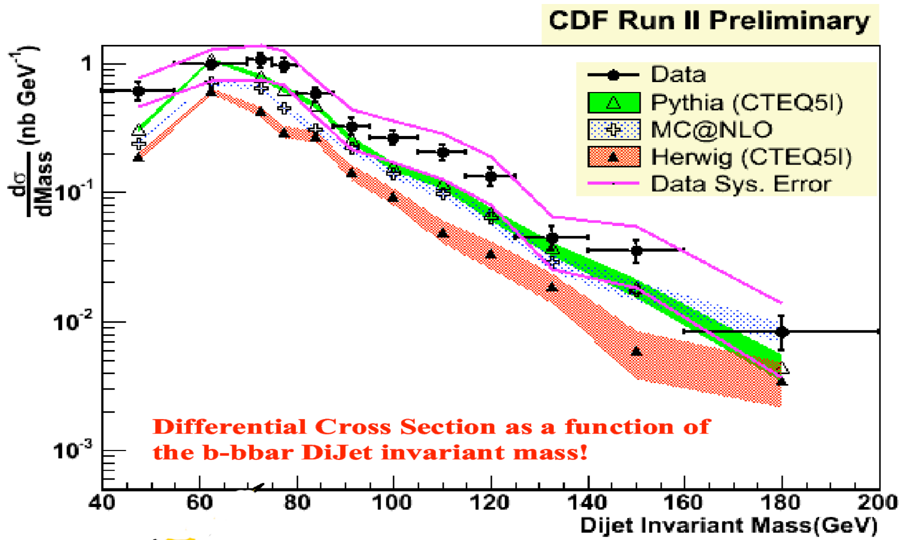
  [Kulesza, Sterman & Vogelsang, 2004]

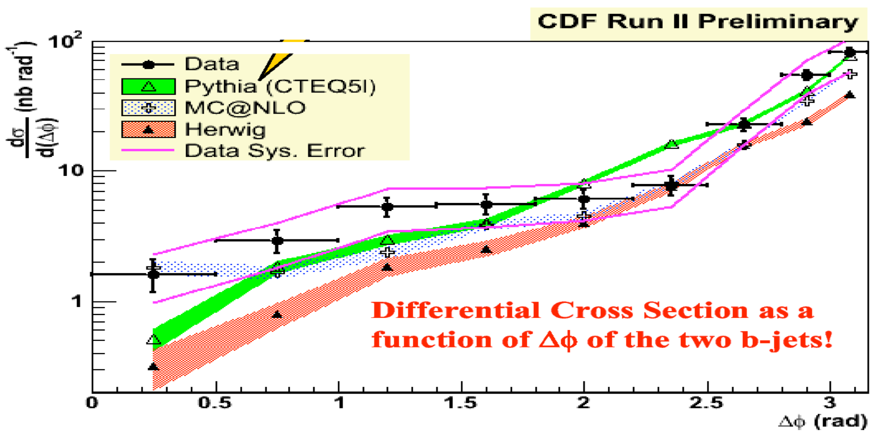
  see also: Marzani, Ball, Del Duca et al., 2008; H, 2002

Tevatron b-jets correlations



[CDF Coll., FNAL-8939 (2007)]





- Herwig description not satisfactory
- $k_\perp$ distribution of underlying event?

Conclusions

- Correlations of high-p_T probes across large rapidity intervals will be explored with forward detectors at the LHC to unprecedented level

- Branching methods based on u-pdfs and $k_\perp$-MEs useful to
  - ▷ simulate high-energy parton showers
  - ▷ investigate possibly new effects from QCD physics

- Systematic theoretical studies of u-pdf's ongoing
  ▷ relevant to turn these Monte-Carlo's into general-purpose tools