Azimuthal decorrelation of dijets in QCD hard processes

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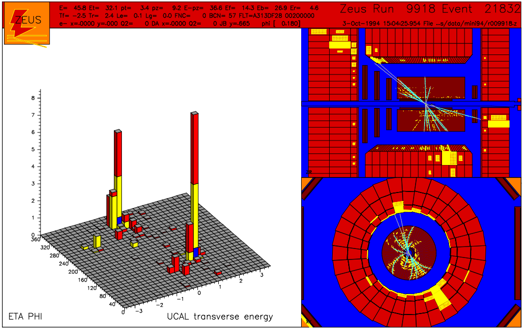
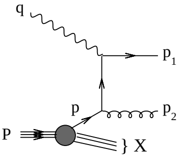
Hard events in QCD and jets

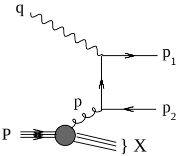
Jet events ⇔ signals for a hard scattering in QCD



Cluster final state particles into jets ⇒ Direct access to partonic cross sections

$$d\sigma_{PQ\to j_1 j_2} = d\sigma_{PQ\to cd} + \mathcal{O}(1/Q^p)$$

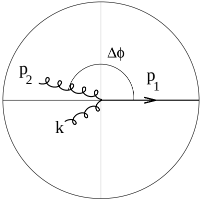




Dijet azimuthal decorrelations are directly sensitive to QCD radiation

- Test fixed order QCD predictions and tune Monte Carlo event generators
- Explore new features of QCD dynamics (BFKL effects, unintegrated pdfs)

[Hautmann Jung 08]



Dijet azimuthal decorrelations as a QCD probe

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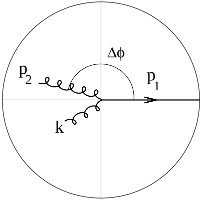

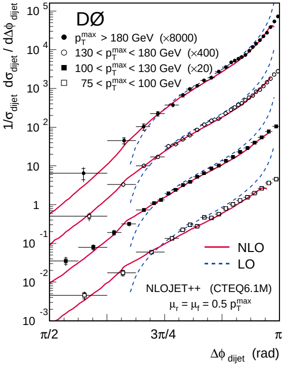

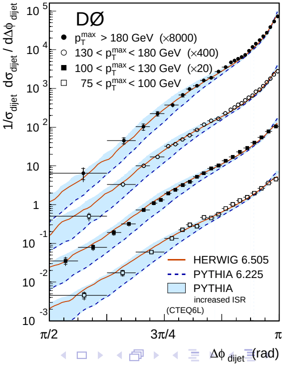

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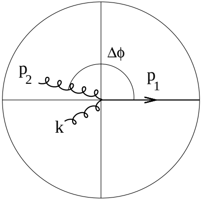
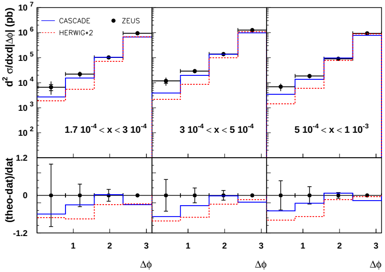
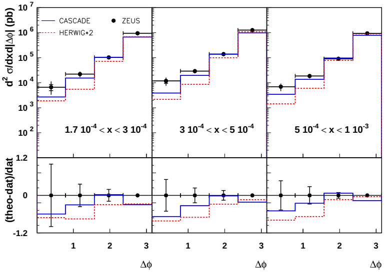
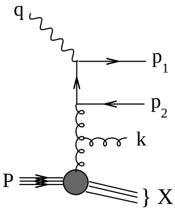


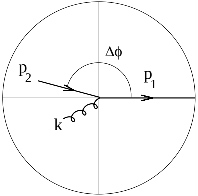




Dijet azimuthal correlations: beyond fixed order

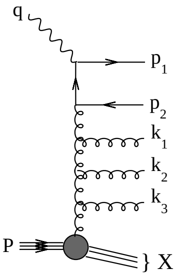
Back-to-back region: sensitivity to multiple soft-collinear emissions

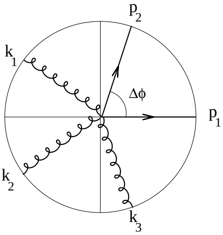




$$\Delta\phi \simeq \pi - \frac{|\vec{k}_t \times \vec{p}_{t,1}|}{p_{t,1}^2}$$

Small-x regime: large phase space for multiple initial-state hard gluons





$$\Delta\phi = \frac{2}{5}\pi \lesssim 1$$

Complementary theoretical approaches

All-order resummation of multiple emission effects to dijet $\Delta\phi$ distribution

Soft-collinear resummation

- Flattening of the distribution (random walk) around $\Delta\phi = \pi$
- Hard emission effects only at fixed order
- Described by HERWIG and PYTHIA at Tevatron (large x) but not at HERA (small x)
- Analytical calculations at NLL+NLO

Small-x resummation

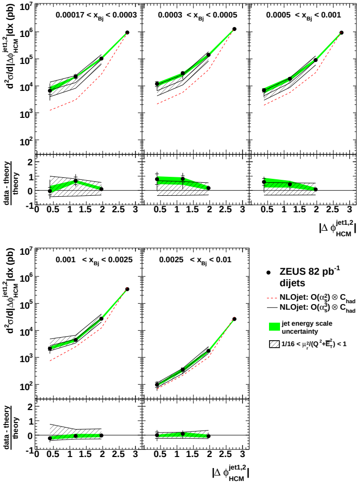
- Unintegrated parton distributions around $\Delta\phi = \pi$
- Multiple hard emissions ordered in rapidity via BFKL or CCFM
- Described at HERA by CASCADE, no extension to hadron-hadron collision yet
- No analytical control over MC simulation

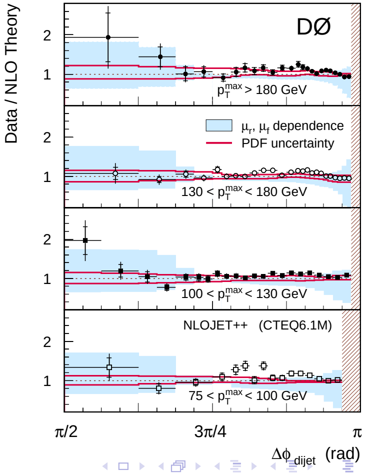
Extrapolating MC results to the LHC (small x) may require combination of multiple soft-collinear and hard gluon effects

Motivation for soft-collinear gluon resummation

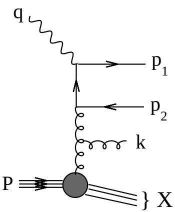
1. NLO calculations describe the $\Delta\phi$ distribution except for $\Delta\phi \simeq \pi$, even at small x $\Rightarrow$ few extra hard gluons are enough? [Nagy Trocsanyi 01]

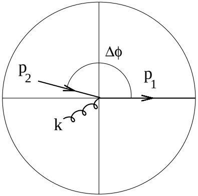
2. $\Delta\phi = \pi$ from secondary gluon transverse momentum cancellation $\Rightarrow$ no need for intrinsic k_t?





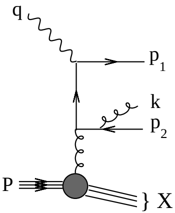
Radiation outside the jets ⇔ $p_{jet,1} = p_1$ and $p_{jet,2} = p_2$

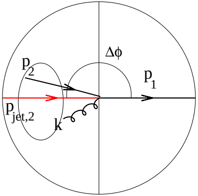




$$\Delta\phi \simeq \pi - \frac{k_t}{p_{t,1}} |\sin\phi|$$

Radiation inside one of the two jets ⇔ $p_{jet,1} = p_1$ but $p_{jet,2} \neq p_2$





In a vectorial recombination

$$\Delta\phi = \pi$$

problems with globalness

[Dasgupta Salam 01]

In a p_t-weighted scheme extra in-jet contribution ⇒ observable is global

$$\phi_{\text{jet},2} = \frac{p_{t,2}\phi_2 + k_t\phi}{p_{t,2} + k_t} \quad \Rightarrow \quad \Delta\phi = \pi - \frac{k_t}{p_{t,1}} |\sin\phi - (\pi - \phi)|$$

After multiple soft-collinear emissions $\{k_1, \ldots, k_n\}$ and $p_t \simeq p_{t,1} \simeq p_{t,2}$

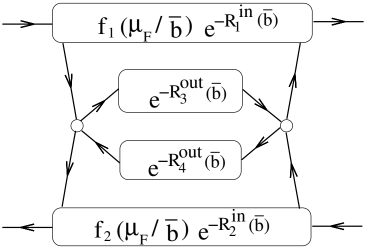
$$|\pi - \Delta\phi| \simeq \left| \sum_{i \notin \text{jets}} \frac{k_{t,i}}{p_t} \sin\phi_i - \sum_{i \in \text{jet1}} \frac{k_{t,i}}{p_t} [\phi_i - \sin\phi_i] - \sum_{i \in \text{jet2}} \frac{k_{t,i}}{p_t} [(\pi - \phi_i) - \sin\phi_i] \right|$$

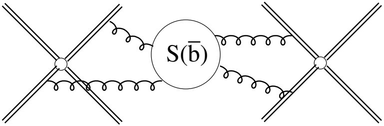
Fourier transform for $\Sigma(\Delta) = \mathrm{Prob}(|\pi - \Delta\phi| < \Delta)$ (here $\bar{b} = b\, e^{-\gamma_E}$)

$$\Sigma(\Delta) = \frac{2}{\pi} \int_0^\infty \frac{db}{b} \sin(b\Delta) \cdot \left[\prod_{a=1}^{n_{\text{in}}} \frac{f_a(\mu_F/\bar{b})}{f_a(\mu_F)} e^{-R^a_{\text{in}}(\bar{b})} \right] \cdot \left[\prod_{a=n_{\text{in}}+1}^{n_{\text{out}}} e^{-R^a_{\text{out}}(\bar{b})} \right] \cdot S(\bar{b})$$

This picture is valid at NLL accuracy $\Rightarrow$ resum $\alpha_s^n \ln^{n+1} b$ and $\alpha_s^n \ln^n b$

[Banfi Delenda Dasgupta 08]



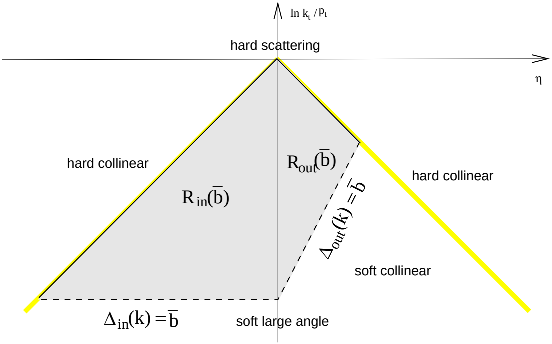


Radiation from incoming legs ($\ell = 1, n_{\rm in}$) $\Leftrightarrow$ inclusive $\vec{k}_t$ distribution

$$\Delta_{\rm in}(k) = \frac{k_t^{(\ell)}}{p_t}|\sin\phi^{(\ell)}| \quad \Rightarrow \quad R_{\rm in}(\bar{b}) \simeq C_{\rm in}\frac{\alpha_s}{\pi}\ln^2\bar{b}$$

Radiation from outgoing legs ($\ell = n_{\rm in}+1, n_{\rm out}$) $\Leftrightarrow$ new inclusive distribution

$$\Delta_{\rm out}(k) = \frac{2}{3}\left(\frac{E_\ell}{p_t}\right)^2\frac{k_t^{(\ell)}}{p_t}e^{-2\eta^{(\ell)}}|\sin^3\phi^{(\ell)}| \Rightarrow R_{\rm out}(\bar{b}) \simeq \frac{C_{\rm out}}{3}\frac{\alpha_s}{\pi}\ln^2\bar{b}$$



Prescriptions for standard resummation

$$\Sigma(\Delta) = \frac{2}{\pi}\int_0^\infty \frac{db}{b}\sin(b\Delta)\cdot\left[\prod_{a=1}^{n_{\rm in}}\frac{f_a(\mu_F/\bar{b})}{f_a(\mu_F)}e^{-R^a_{\rm in}(\bar{b})}\right]\cdot\left[\prod_{a=1}^{n_{\rm out}}e^{-R^a_{\rm out}(\bar{b})}\right]\cdot S(\bar{b})$$

Large-b region

- $R_{\rm in}(\bar{b}), R_{\rm out}(\bar{b}), S(\bar{b})$ contain integrals of $\alpha_s(k_t)$ up to $k_t \sim p_t/\bar{b}$, hitting the Landau pole
  $\Rightarrow$ Cut all b integrals at at $\bar{b} = p_t/\Lambda_{\rm QCD}$
- The factorization scale $\mu_F/\bar{b}$ can reach $1\text{GeV} \sim R_p^{-1}$: can we still trust collinear factorization?
  $\Rightarrow$ Freeze pdf's below 1 GeV

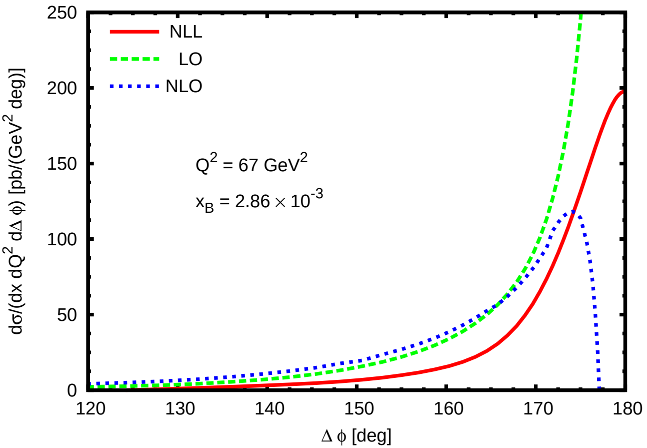
Small-b region

- $b = 0$ corresponds to total cross section, $R_{\rm in}(0) = R_{\rm out}(0) = \ln S(0) = 0$
  $\Rightarrow$ Force $R_{\rm in}, R_{\rm out}, \ln S$ to vanish for $\bar{b} < 1$

Other prescriptions are possible, having all a certain degree of arbitrariness

Azimuthal decorrelation in DIS

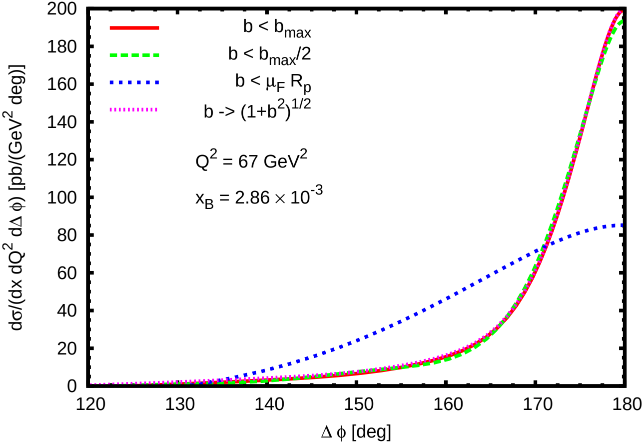
Two jets with $p_{t,\text{jet}}^{\text{HCM}} > 5\text{GeV}$ and $-1 < \eta_{\text{jet}}^{\text{lab}} < 2.5$, with $\mu_F^2 = \mu_R^2 = \langle (p_{t,\text{jet}}^{\text{HCM}})^2 \rangle$



Full phenomenological analysis requires

1. Evaluation of resummation uncertainties (prescriptions, impact of NNLL)
2. Matching to fixed-order for full theoretical uncertainties (μ_R, μ_F variation)

Varying resummation prescriptions



- Small impact from Landau pole ($\bar{b} \to p_t/\Lambda_{\rm QCD}$) and unitarity ($b \to 0$)
- Huge effect from the region $\bar{b} > \mu_F R_p$ $\Rightarrow$ intrinsic k_t needed?

Matching to fixed order

Consider the all-order azimuthal decorrelation in DIS for an incoming gluon

$$\Sigma_g(\Delta) = \frac{2}{\pi}\int_0^\infty \frac{db}{b}\sin(b\Delta)\cdot C^{(g)}(\alpha_s)\cdot\left[\frac{g(\mu_F/\bar{b})}{g(\mu_F)}e^{-R_{\rm in}^{(g)}(\bar{b})}\right]\cdot e^{-2\,R_{\rm out}^{(q)}(\bar{b})}\cdot S_{qqg}(\bar{b})$$

The first order coefficient C_1 gives a contribution $\alpha_s^{2n}\ln^{2n-2} b$, same size as genuine NLL contributions $\alpha_s^n \ln^n b$

$$C_1^{(g)}e^{-\frac{\alpha_s}{\pi}(C_A+\frac{2}{3}C_F)\ln^2 b} + C_1^{(q)}e^{-\frac{\alpha_s}{\pi}(\frac{4}{3}C_F+\frac{1}{3}C_A)\ln^2 b}$$

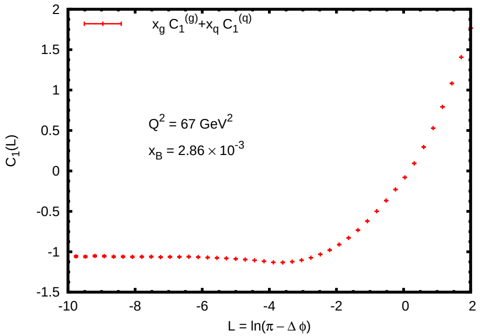
But NLO programs give only a linear combination of $C_1^{(g)}$ and $C_1^{(q)}$ $\Rightarrow$ Need to extract flavour information from NLO code NLOJET++

[AB in collaboration with M. Brambilla]

- ✓ Born and virtual matrix elements
- ✓ Real matrix elements
- ✓ Dipole subtraction terms
- ✗ Dipole finite terms

Calculate C_1 by subtracting logs from exact $\Sigma_1(\Delta)$

$$C_1(L) = \Sigma_1(\Delta) - H_{12}L^2 - H_{11}L \qquad \Sigma_{\rm res}(\Delta) = 1 + H_{12}L^2 + H_{11}L + \mathcal{O}(\alpha_s^2)$$



Negative coefficient $1+C_1$, something has to be exponentiated

- ✓ Large π^2 terms from Coulomb phases [Eynck Laenen Magnea 03]
- ✓ Azimuthal integration in $R_{\rm in}(\bar{b})$ gives another π^2
- ✗ Symmetric E_t-cut enhancement $\Rightarrow$ vanishing for $\Delta\phi \to \pi$?
- ✗ Large $\ln 1/x_B$ from virtual corrections?

Summary and conclusions

Azimuthal decorrelations are intriguing observables

- Complementary to event-shapes for studies of multiple QCD radiation
- At small-x may be sensitive to BFKL effects

A pure PT resummation at NLL gives

- Flattening of distribution around $\Delta\phi = \pi$, as seen in the data
- Need for suitable extension of pdf's for scales below 1GeV

Before matching to exact NLO

- Study PT resummation uncertainties $\Rightarrow$ impact of missing NNLL?
- Understand sources of large coefficient function

Possible research directions

- Address theoretical uncertainties in the simpler case of vector-boson a_T distribution. . . [see Rosa Delgado's talk]
- Compute coefficient functions in DIS and hadron-hadron collisions
- Analytical calculation of $\Delta\phi$ distribution in the hard limit (BFKL, CCFM)
- NP issues: unintegrated parton densities, higher twist, . . .