EDS09, CERN, June 2009

Theoretical Aspects of High-$p_\perp$ Production at Forward Rapidities

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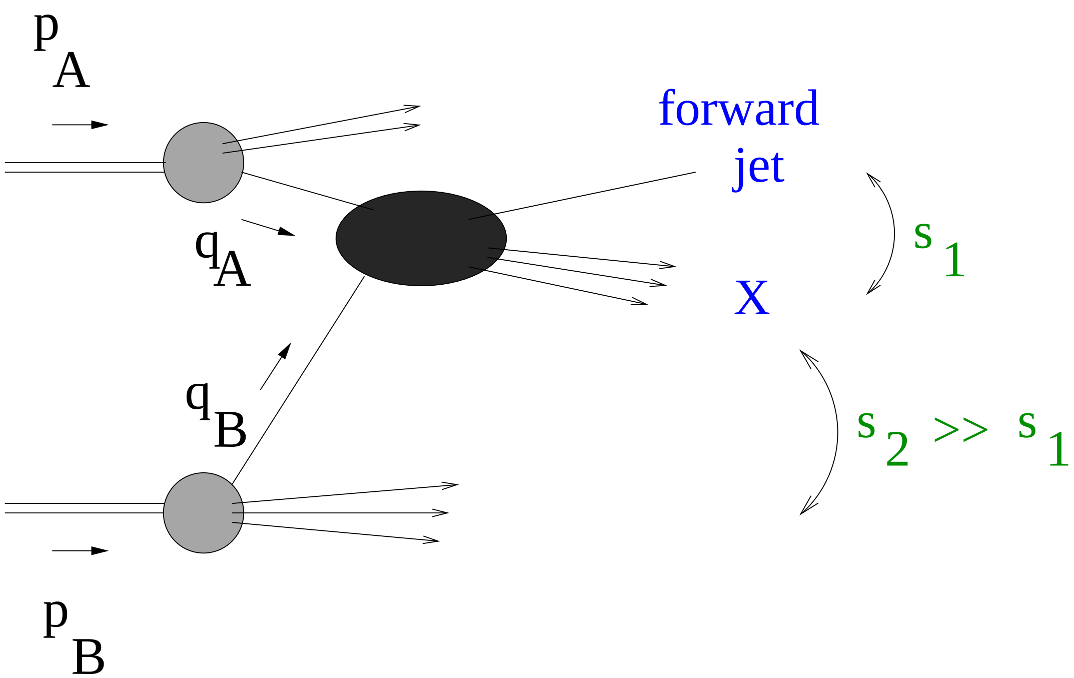
1. Forward jet production: introductory remarks

2. Recent results on using QCD high-energy factorization for LHC forward region

3. Studies from ep and $p\bar{p}$ multi-jet correlations

I. 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)

$\Downarrow$

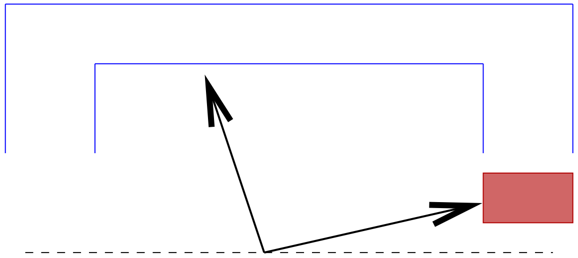
• physics of hard processes with multiple hard scales

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

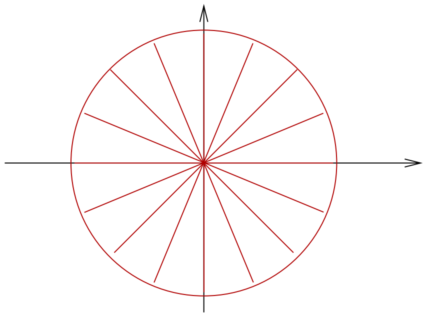
• polar angles small but far enough from beam axis

• measure azimuthal plane correlations

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



central + forward detectors



azimuthal plane

▷ see experiments' talks
in Fwd-Physics session

[H. Jung 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)]

▷ 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, Peskin & Tang, 1993; Stirling, 1994

⇒ efforts toward improved Monte Carlos / semi-analytic approaches

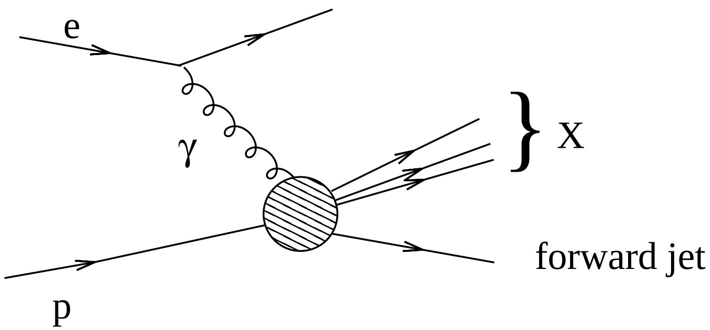
Andersen, arXiv:0906.1965; Andersen and Sabio Vera, 2003;

Andersen, Del Duca, Frixione, Schmidt and Stirling, 2001;

Schwennsen, hep-ph/0703198; Bartels, Sabio Vera and Schwennsen, 2006;

Ewerz, Orr, Stirling and Webber, 2000; Orr and Stirling, 1998

- 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]

- 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

Catani et al., 1991; Ciafaloni, 1998

Deak, Jung, Kutak & H, in progress

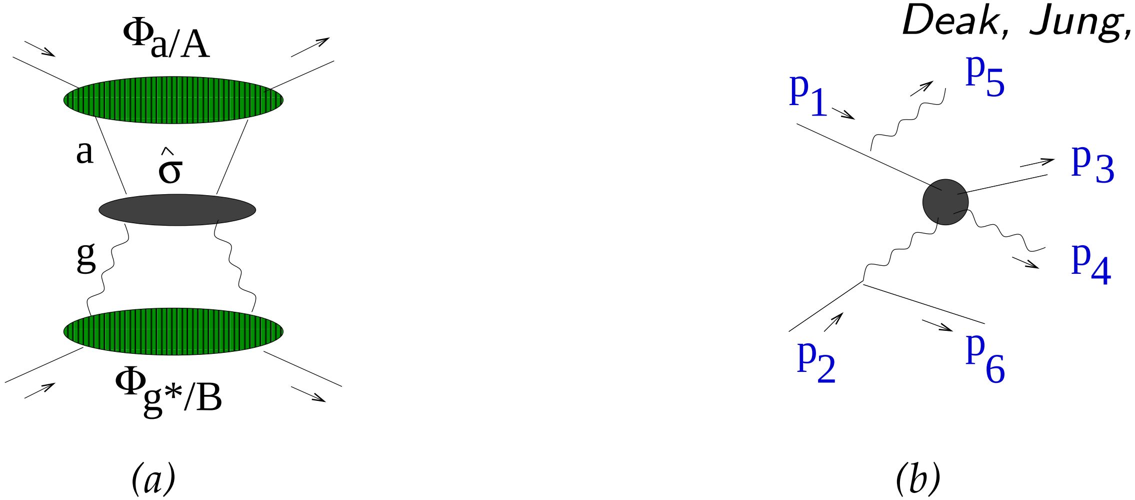
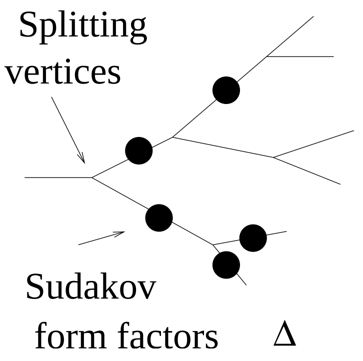


Figure 1: (a) Factorized structure of the cross section; (b) a typical contribution to the qg channel matrix element.

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

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

II. PARTON DISTRIBUTIONS BY SHOWERING METHODS

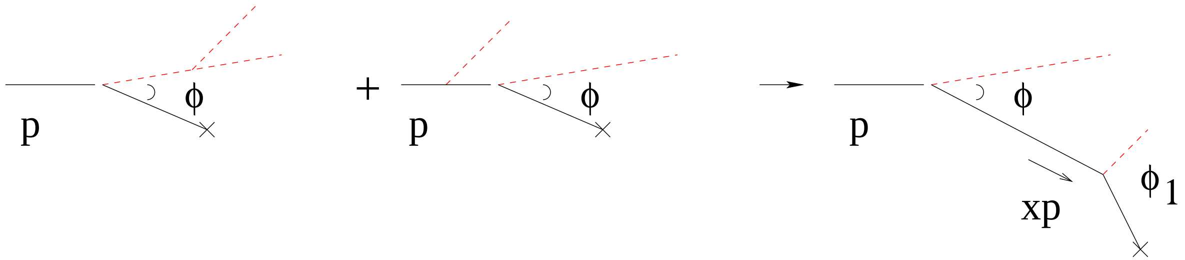


$$d\mathcal{P} = \int \frac{dq^2}{q^2} \int dz \; \alpha_S(q^2) \; P(z) \; \Delta(q^2, q_0^2)$$

$\hookrightarrow$ 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:

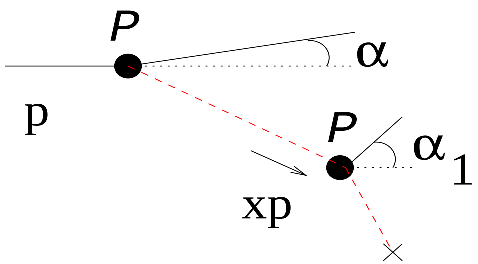
$\hookrightarrow$ MC based on $k_\perp$-dependent unintegrated pdfs and MEs

K$_\perp$-DEPENDENT PARTON BRANCHING

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

- $\{x \to 0\} \oplus \{x \to 1\}$ gluon branching eq. (leading-logarithmic)

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



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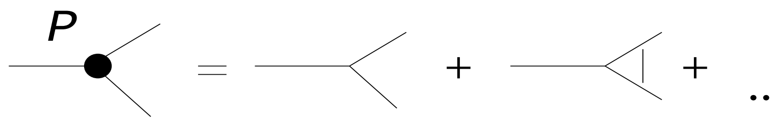


▷ implemented in CASCADE MC

- unintegrated quark with k_T-dependent branching
  $\hookrightarrow$ ongoing work (next slide)

Unintegrated quark evolution

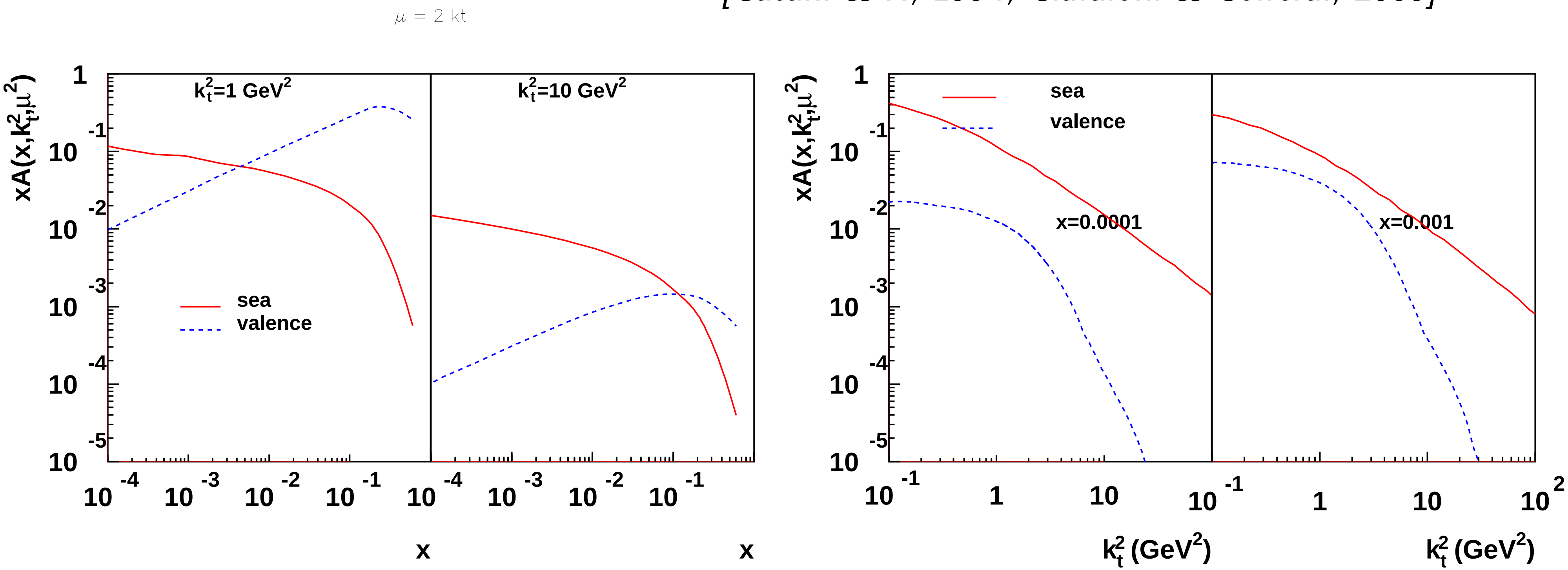
[H. Jung et al., in progress]

- 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)

[Catani & H, 1994; Ciafaloni & Colferai, 2005]



- valence: independent evolution (dominated by soft gluons x → 1)

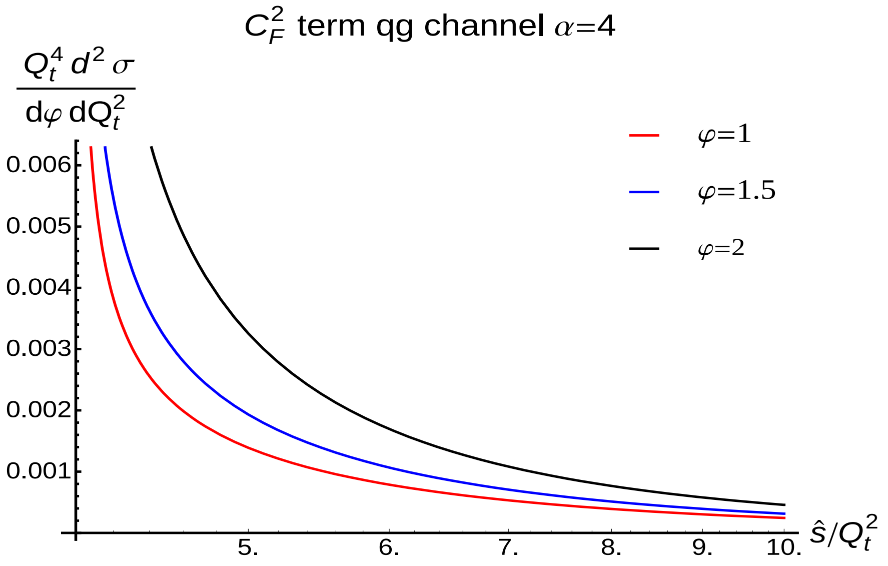
III. HARD SCATTERING CROSS SECTIONS

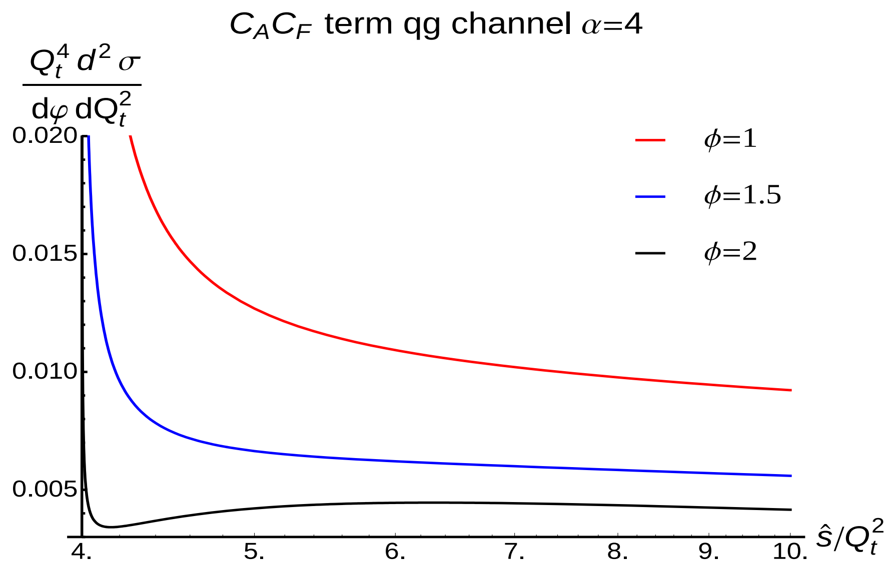
- Matrix elements for fully exclusive events with forward jets

[Deak, Jung, Kutak & H, 2009]

- 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)



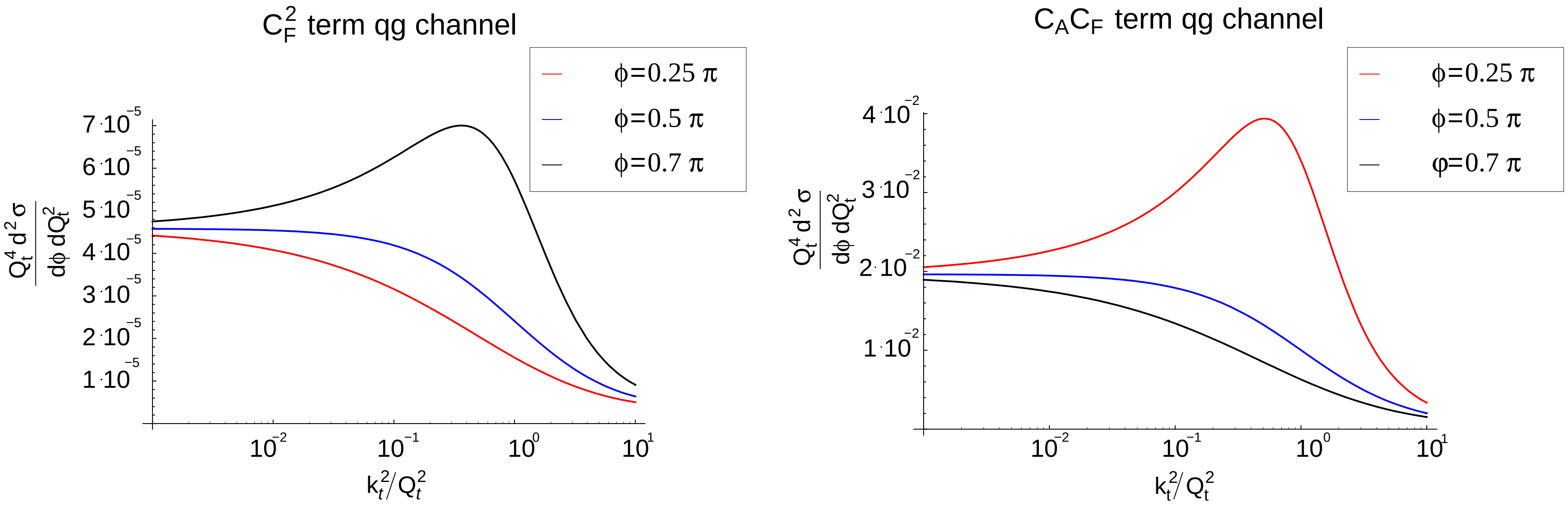


▷ $C_F C_A$ contribution to qg dominates large $\hat{s}/Q_t^2$ (constant at large energy)

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

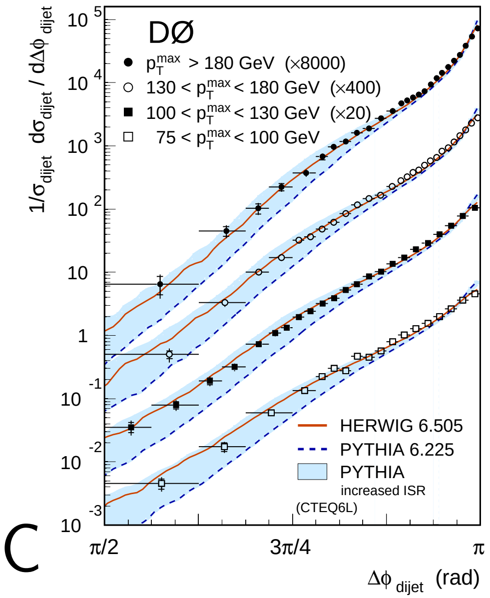
IV. COMMENTS ON $\mathrm{P\overline{P}}$ AND EP MULTI-JETS

$\Delta\phi$ 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

[M.G. Albrow et al., TEV4LHC Proc., hep-ph/0610012]



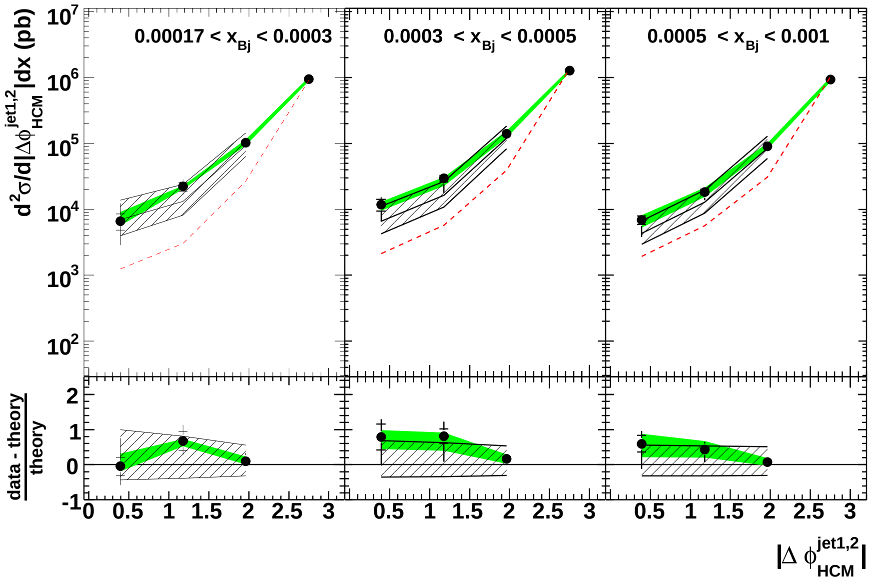
▷ HERA $\Delta\phi$ not well described by standard MC

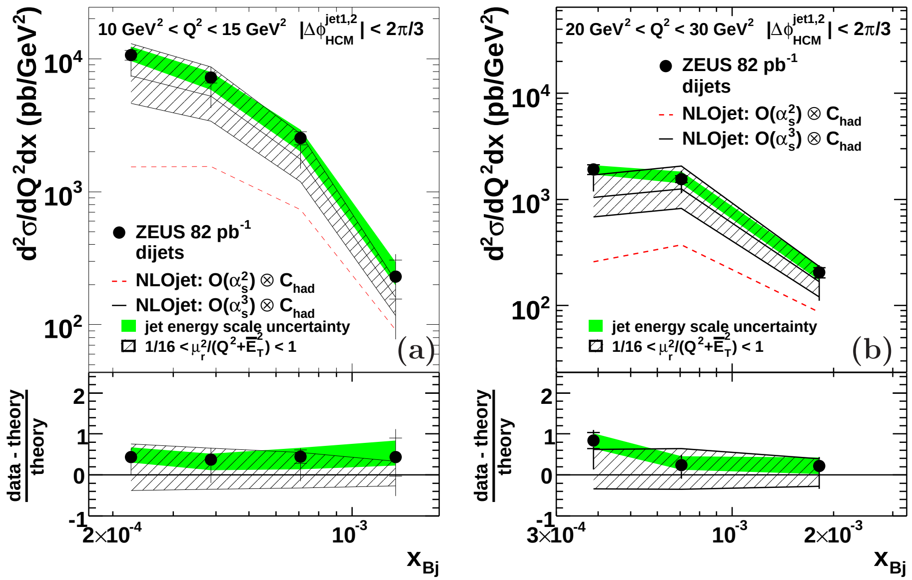
[S. Chekanov et al., arXiv:0705.1931] ↪ see next

▷ accessible at the LHC relatively early

↪ how do MC describe multiple radiation?

DI-JET EP CORRELATIONS: COMPARISON WITH NLO RESULTS





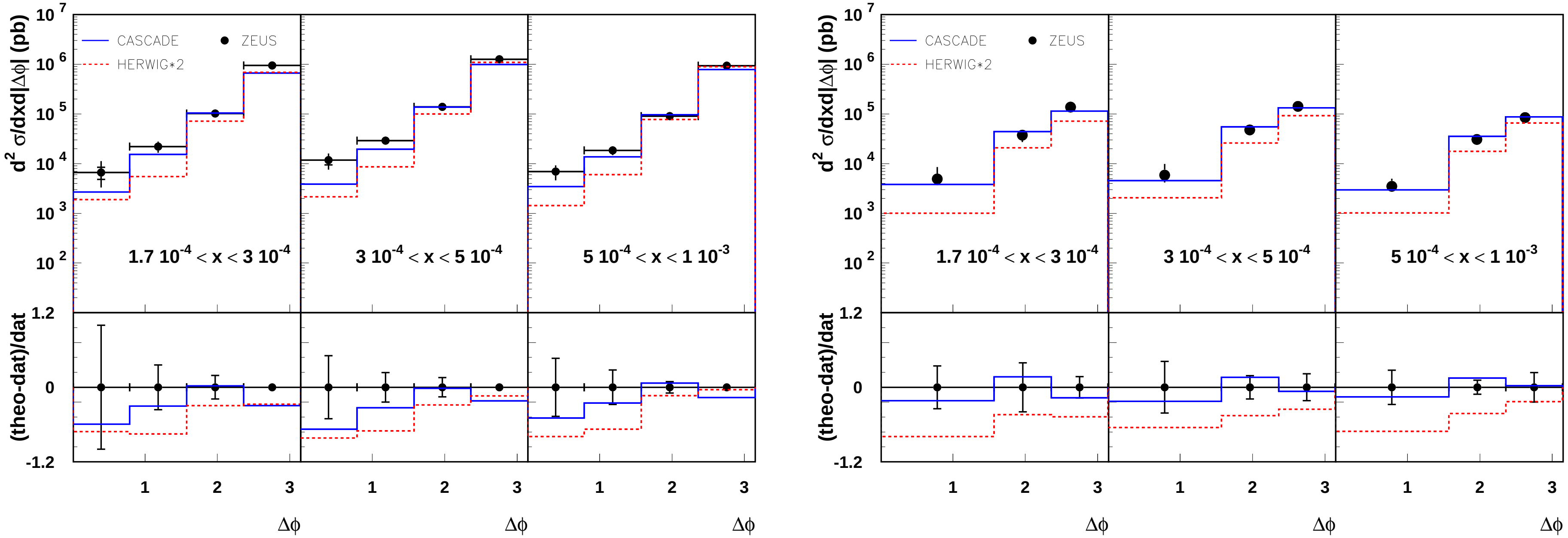
(left) Azimuth dependence and (right) Bjorken-x dependence of di-jet distributions

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

[S. Chekanov et al., arXiv:0705.1931]

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

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

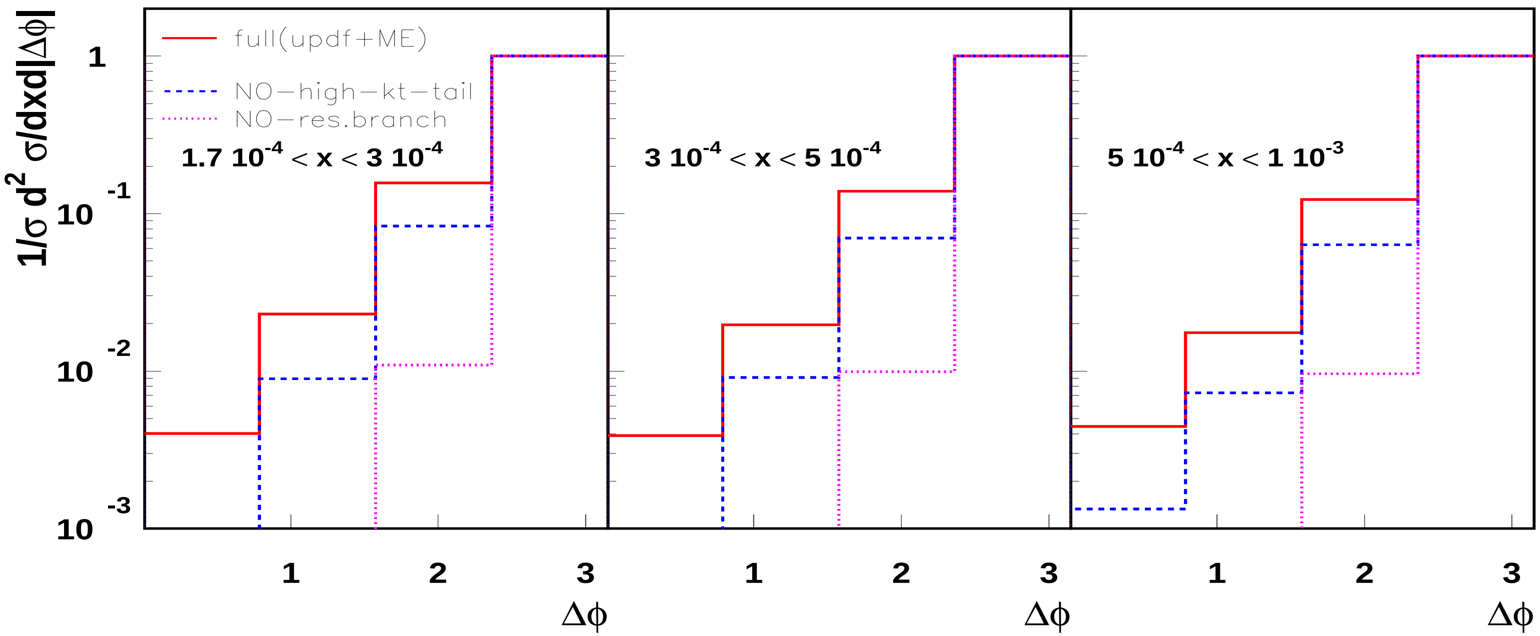


(left) di-jet cross section; (right) three-jet cross section

Jung & H, JHEP 0810 (2008) 113

- quantitative effects of small-x coherence sizeable
- largest differences at small $\Delta\phi$
- good description of shapes by $k_\perp$-shower
- HERWIG normalized to 2-jet region by K-factor

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, EPJC 58 (2008) 17*:
u-pdf but no ME correction)

V. FURTHER ISSUES AND CONCLUSIONS

- Tevatron b-jets angular correlations

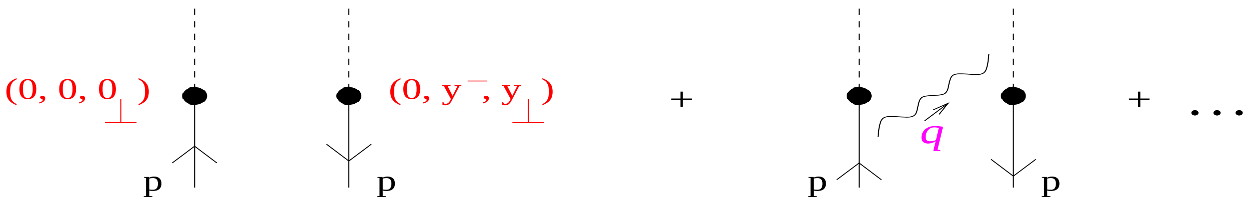
($\hookrightarrow$ CDF $\Delta\phi$ data)

- asymmetric parton kinematics $\Rightarrow$

$\Rightarrow$ $x \rightarrow 1$ endpoint behavior at fixed $k_\perp$

phen. relevant to LHC forward jets?

$n = (0, 1, 0_\perp)$



Collins, arXiv:0808.2665

H, arXiv:0708.1319

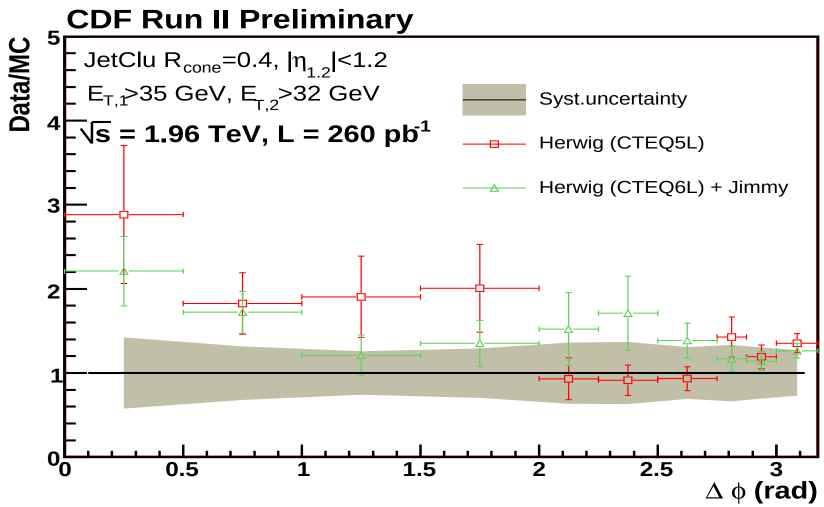
- High parton density questions

via unintegrated pdf evolution?

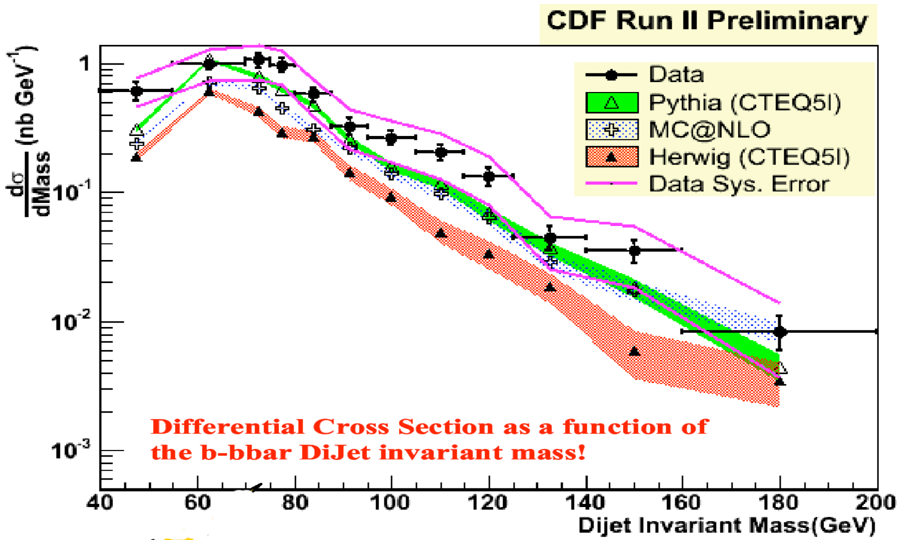
Iancu, Kugeratski, Triantafyllopoulos, 2008

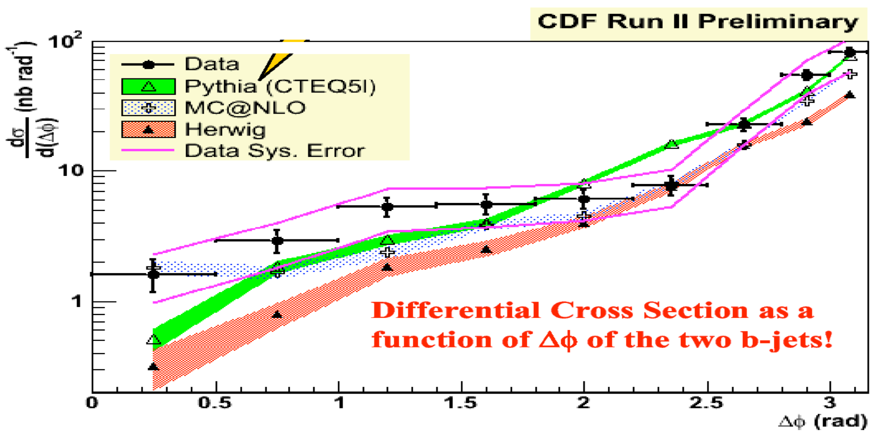
Avsar's talk

Tevatron b-jets correlations



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





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

Conclusions

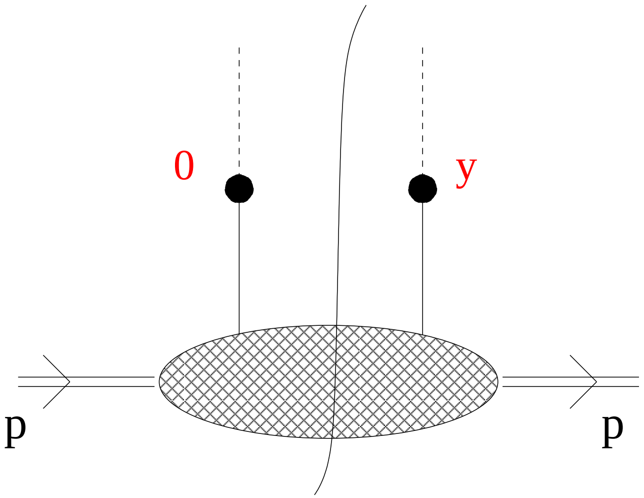
- Correlations of high-p_T probes across large rapidity intervals
  will be explored with forward detectors at the LHC
  to unprecedented level

- 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

EXTRA SLIDES

Example 2: General operator matrix elements:



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

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

$V_y(n) = \mathcal{P} \exp\left(ig_s \int_0^\infty d\tau\ n \cdot A(y + \tau\ n)\right)$ eikonal Wilson line in direction n

- works at tree level [Mulders, 2002; Belitsky et al., 2003]
- subtler at level of radiative corrections [Collins & Zu; H; Cherednikov et al.]

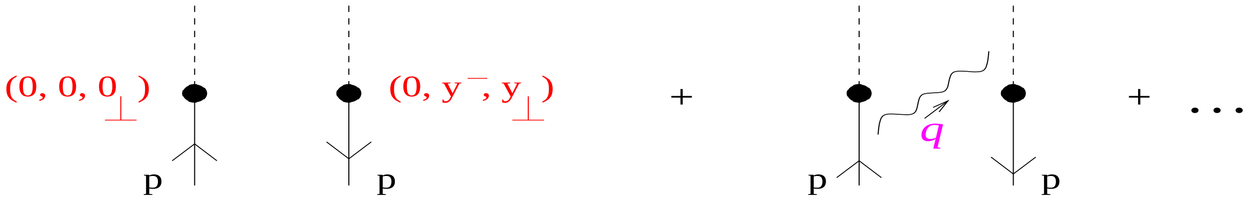
  $\hookrightarrow x \to 1 \Rightarrow$ explicit regularization method (unlike inclusive case)
- non-abelian Coulomb phase $\longrightarrow$ spectator effects possibly non-decoupl.?

  [Mulders, Bomhof; Collins, Qiu; Brodsky et al]

III.A LIGHTCONE DIVERGENCES

$n = (0, 1, 0_\perp)$

◇ Suppose a gluon is absorbed or emitted by eikonal line:



$$f_{(1)} = P_R(x, k_\perp) - \delta(1-x)\,\delta(k_\perp) \int dx' dk'_\perp P_R(x', k'_\perp)$$

where $\quad P_R = \frac{\alpha_s C_F}{\pi^2} \left[\frac{1}{1-x} \frac{1}{k_\perp^2 + \rho^2} + \{\text{regular at } x \to 1\} \right]$ $\qquad \rho$=IR regulator

↑ *endpoint singularity* $(q^+ \to 0, \ \forall \ k_\perp)$ $\qquad$ [Brodsky et al, 2001; Collins, 2002]

◇ Physical observables:

$$\mathcal{O} = \int dx\, dk_\perp\, f_{(1)}(x, k_\perp)\, \varphi(x, k_\perp)$$

$$= \int dx\, dk_\perp\, [\varphi(x, k_\perp) - \varphi(1, 0_\perp)]\, P_R(x, k_\perp)$$

inclusive case: φ independent of $k_\perp \Rightarrow 1/(1-x)_+$ from real + virtual

general case: endpoint divergences (incomplete KLN cancellation)

• Distributions at fixed $k_\perp$ are no longer protected by KLN mechanism against uncancelled lightcone divergences

• Only after supplying matrix element with a regularization prescription is distribution well defined.

• Note: regularization of endpoint divergences may also affect distributions integrated over $k_\perp$ and UV subtractions

$$\text{Ex.}: \quad \int dk_\perp \; f(x, k_\perp, \mu) \; \Theta(\mu - k_\perp) \; \stackrel{?}{=} \; f^{\overline{\rm MS}}(x, \mu)$$

$=$ holds only at tree level: full relation involves coefficient function R

$$\int^\mu dk_\perp \; f(x, k_\perp, \mu) \; = \; R(x) \; \otimes \; f^{\overline{\rm MS}}(x, \mu)$$

$\diamondsuit$ R calculable as a power series in α_s, $R(x) = \delta(1-x) + \sum_k \; r_k \; \alpha_s^k$:

— $(\phi^3)_6$ *[Collins & Zu, 2005]*

— $f_g(x \to 0)$ *[Catani et al, 1994]*

• Applications: Cut-off regularization vs. Subtractive regularization

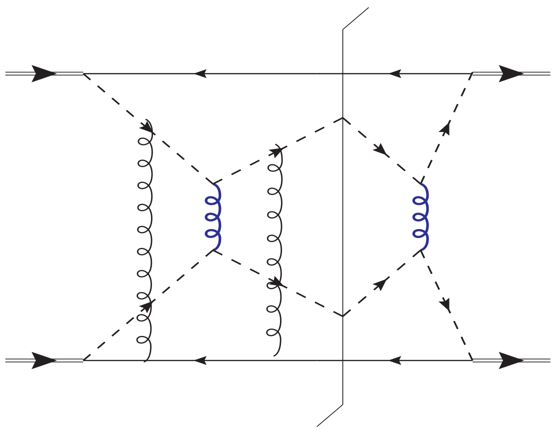
III.C COULOMB PHASE EFFECTS

- soft gluon exchange with spectator partons

Mert Aybat & Sterman, PLB671 (2009) 46

Boer, Brodsky & Hwang, PRD 67 (2003) 054003

⇒ factorization breaking in higher loops?



Collins, arXiv:0708.4410

Vogelsang and Yuan, arXiv:0708.4398

Bomhof and Mulders, arXiv:0709.1390

♢ likely suppressed for small-x, small-$\Delta\phi$

♢ could affect physical picture near large x, back-to-back region

- Note: Coulomb/radiative mixing terms also appear to break coherence in di-jet cross sections with gap in rapidity

Forshaw & Seymour, arXiv:0901.3037

Forshaw, Kyrieleis & Seymour, hep-ph/0604094