A kT-dependent sea-quark distribution for CASCADE

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Based on results obtained with F. Hautmann and H. Jung

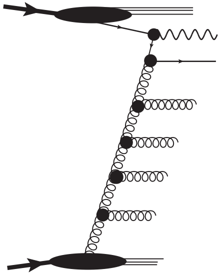
Motivation

CASCADE: Monte-Carlo event generator based on the CCFM evolution equation

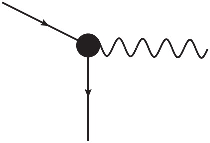
- particularly suitable for dynamics at small x
- provides unintegrated gluon density $\mathcal{A}(x, k_t, \mu^2)$
  - $+$ CCFM parametrization of valence quark distribution
- but no sea quark distribution

Process of interest at LHC: **forward Drell-Yan** production (γ^*, Z, W)

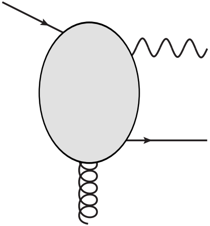
- couples by seaquark to gluon density
- probe proton at very small x, up to $3 \cdot 10^{-6}$
- investigate small x dynamics: BFKL, saturation, ...



Forward DY production



- leading order: $q\bar{q} \to Z$
- quark q: valence quark of proton 1
- anti-quark $\bar{q}$: sea quark, couples to gluon evolution of proton 2



- CASCADE with unintegrated gluon: sea quark by $qg^* \to Zq$ [Ball, Marzani, '09]
- collinear divergence: inclusive Z requires cut-off or finite quark mass

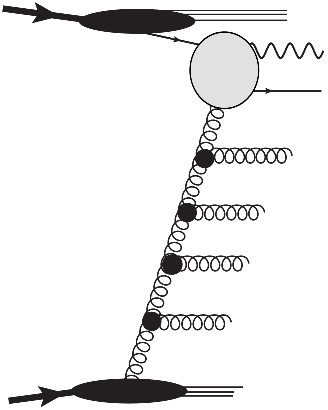
Collinear factorization (DGLAP):

- coll. divergency $\equiv$ non-perturbative contributions to partonic process
- universal: factorize and subtract into seaquark distribution

Goal of this study: do the same, but within the context of CCFM:

→ universal unintegrated sea quark density

gluon splitting: CCFM versus DGLAP versus BFKL

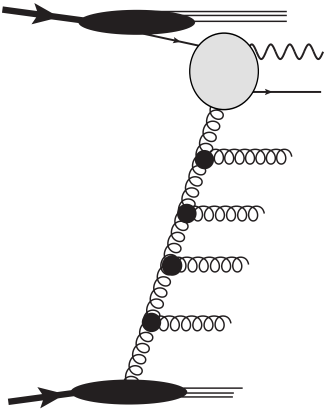


- **DGLAP:** emssion ordered in k_T, evolution in transverse scale Q^2
- splitting function:

$$P_{gg}(z) = 2C_A \left[\frac{1-z}{z} + \frac{z}{1-z} + z(1-z) \right]$$

- k_T of gluon neglected against collinear component xp
- integrated gluon distribution $g(x, \mu)$
- no k_T dependence for partonic cross-section $gq \to Zq$

gluon splitting: CCFM versus DGLAP versus BFKL



- **BFKL:** reggeized gluon formalism, emission ordered in longitudinal momenta
- k_T dependent splitting kernel

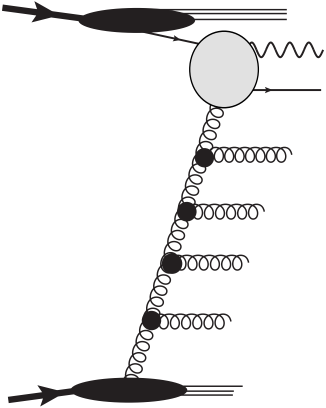
$$\frac{1}{(\boldsymbol{q}-\boldsymbol{k})^2}\frac{1}{x}x^{-\bar{\alpha}_s \ln(\boldsymbol{q}^2/\lambda^2)}$$

- keep k_T dependence for partonic cross-section and unintegrated gluon density $\mathcal{F}(x, \mu^2, \boldsymbol{k}^2)$
- neglect 'small' against 'large' longitudinal momenta; for DGLAP: $z \to 0$, miss $z \to 1$ region and finite terms

reggeized gluon formalism ➡ effective couplings ➡ gauge invariant off-shell continuation ($\boldsymbol{k}^2 \neq 0$) of collinear partonic cross-section $\hat{\sigma}(k_T)$

- Higher accuracy in kinematics: LO k_T catches important $N^m LO$ collinear effects in small x region

gluon splitting: CCFM versus DGLAP versus BFKL

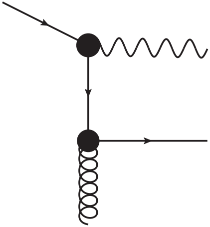


- **CCFM :** based on color coherence $\rightarrow$ angular ordered emssion
- splitting kernel contains both enhanced parats ($z \rightarrow 0, 1$) of DGLAP splitting
- small x: for inclusives observables (allow for $z \rightarrow 0$) $\equiv$ BFKL $\Rightarrow k_T$ dependence!
- $z \rightarrow 1$ region treated correclty $\rightarrow$ essential for exclusive events (Monte-Carlo!), correct DGLAP limit
- defines (as BFKL) unintegrated gluon density $\mathcal{A}(x, \boldsymbol{k}^2, \bar{q})$

$\hat{\sigma}(k_T)$ defined as for BFKL (effective reggeized gluon couplings)

- no longer restricted to very small x
- take care: collinear and soft divergencies!

Factorization of collinear divergency: quark-gluon splitting



- **DGLAP:** contains naturally splitting function $P_{qg}(z) = Tr(z^2 + (1-z)^2)$
- no k_T dependence for seaquark distribution $q(x, \mu^2) = P_{qg}(z) \otimes g(x/z, \mu^2)$ and partonic cross-section $\sigma_{q\bar{q}\to Z}$

$$\hat{\sigma}_{q\bar{q}\to Z}(\nu = \hat{s}) = \underbrace{\sqrt{2}G_F M_Z^2 (V_q^2 + A_q 2)}_{\text{Z-coupling}} \times \frac{\pi}{N_c}\delta(\nu - M_Z^2)$$

- **reggeized quarks** (analogy to BFKL): arises in the limit of high center of mass energies of the $qg^* \to Zq$ process
- gauge invariant definition of q_T dependent partonic process $q\bar{q}^* \to Z$ (with off-shell quark!)

$$\hat{\sigma}_{q\bar{q}^*\to Z}(\nu, \boldsymbol{q}^2) = \underbrace{\sqrt{2}G_F M_Z^2 (V_q^2 + A_q 2)}_{\text{Z-coupling}} \times \frac{\pi}{N_c}\delta(\nu - M_Z^2 - \boldsymbol{q}^2)$$

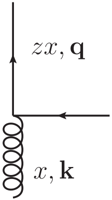
- splitting: $z \to 0$; correct for strict h.e. limit

kT-dep. quark-gluon splitting function

[Catani, Hautmann '94] : high energy resummation within collinear factorization

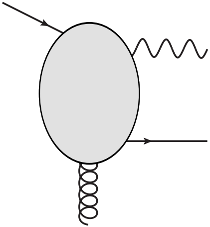
$$P_{qg}\left(z, \frac{\boldsymbol{k}^2}{\boldsymbol{q}^2}\right) = T_R \left(\frac{\boldsymbol{q}^2}{\boldsymbol{q}^2 + z(1-z)\boldsymbol{k}^2}\right)^2 \left[P_{qg}(z) + 4z^2(1-z)^2 \frac{\boldsymbol{k}^2}{\boldsymbol{q}^2}\right]$$

- $\boldsymbol{k}^2 \to 0$: DGLAP splitting, $z \to 0$: reggeized quark splitting
- k_T-dependent splitting function is universal ➡ can use it to define q_T dependent sea-quark density



$$\mathcal{A}^{\text{seaquark}}(x, \boldsymbol{q}^2, \mu^2) := \int_x^1 dz \int_0^{\boldsymbol{q}^2/z} \frac{d\boldsymbol{k}^2}{\boldsymbol{q}^2} P_{qg}\left(z, \frac{\boldsymbol{k}^2}{\boldsymbol{q}^2}\right) \mathcal{A}^{\text{gluon}}_{\text{CCFM}}(x/z, \boldsymbol{k}^2, \boldsymbol{q}^2/z)$$

Forward DY



Catani-Hautmann: exact k_T-dependence of gluon, integrate over $\boldsymbol{q}^2$ ➡ no q_T-dependence for $\hat{\sigma}$

here: keep explicit q_T-dependence for partonic proces $q\bar{q}^* \to Z$

➡ more accurate kinematics : p_T of Z ...

analyze $qg^* \to Zq$ (in k_T-fact.) [Ball, Marzani, '09]; find

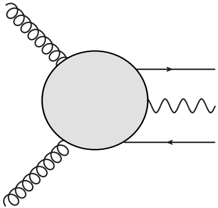
$$\hat{\sigma}_{qg^* \to Zq}(\nu, \boldsymbol{k}^2) = \int_x^1 \frac{dz}{z} \int \frac{d\boldsymbol{q}^2}{\boldsymbol{q}^2} \hat{\sigma}_{q\bar{q}^* \to Z} P_{qg}(z, \frac{\boldsymbol{k}^2}{\boldsymbol{q}^2}) + \text{remainder}$$

- remainder subleading in high energy ($\hat{s}_{qg^*} \to \infty$) and collinear limit
- $\hat{\sigma}_{q\bar{q}^* \to Z}$ agrees with the reggeized quark result, but difference in delta-function of $\hat{\sigma}_{q\bar{q}^* \to Z}$

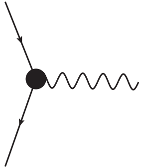
$$\delta(\nu - M_Z^2 - \boldsymbol{q}^2) \leftrightarrow \delta(\nu - M_Z^2 - \frac{\boldsymbol{q}^2}{1-z} - z\boldsymbol{k}^2)$$

- in general: more accurate but not exact kinematics, here: can absorb by redefinition of q_T

Extension: central DY



- $g^* g^* \to q\bar{q}Z$ by [Deak, Schwennsen, '08] and [Baranov, Lipatov, Zotov, '08]
- need massive quarks or cut-off for inclusive production: collinear singularity
- can factorize now with splitting function, requires $\hat{\sigma}_{q^* \bar{q}^* \to Z}$



- extraction from $\hat{\sigma}_{g^* g^* \to Z q\bar{q}}$ possible but difficult
- reggeized quark formalism yields

$$\hat{\sigma}_{q^* \bar{q}^* \to Z}(\boldsymbol{q}_1, \boldsymbol{q}_2) = g^2_{q\bar{q}Z} \frac{\pi}{N_c} \left[\frac{M_Z^2 + \boldsymbol{q}_1^2 + \boldsymbol{q}_2^2}{\nu} \right] \delta \left[\nu - M_Z^2 - (\boldsymbol{q}_1 + \boldsymbol{q}_2)^2 \right]$$

splitting function requires in addition angular averaging

Conclusion and outlook

- Defined q_T dependent seaquark density with correct collinear and high energy limit and correct h.e. resummed gluon-quark splitting
- Partonic cross-sections (off-shell continuation of collinear X-sec.)
  (a) extraction from higher order calculation
  (b) direct: reggeized quark formalism
- explicit: forward and central DY

NOW:

- Numerical implementation into CASCADE is in progress: acuracy of the approximation?

FUTURE:

- Analyze further splittings (gluon - quark, quark - quark)
- soft gluon resummation (?)
- Further process: forward jets