Associated production of one particle and a Drell-Yan pair

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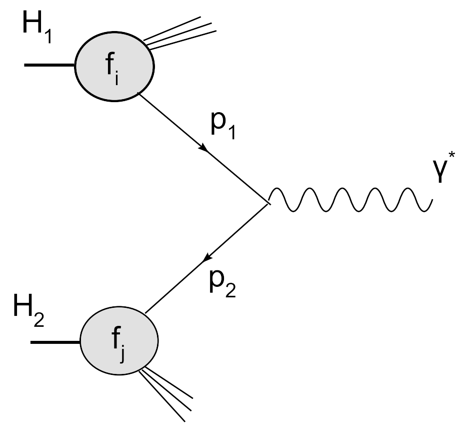
Outline

- The Drell-Yan process : theoretical status
- Associated production of one particle and a Drell-Yan pair
- Factorization of collinear singularities and finite cross-section
- Application : Single diffractive Drell-Yan production
- Application : Double parton scattering in DY+hadron.

The Drell-Yan process : theoretical status

- Consider the Drell-Yan process $H_1(P_1) + H_2(P_2) \to \gamma^*(q) + X$:



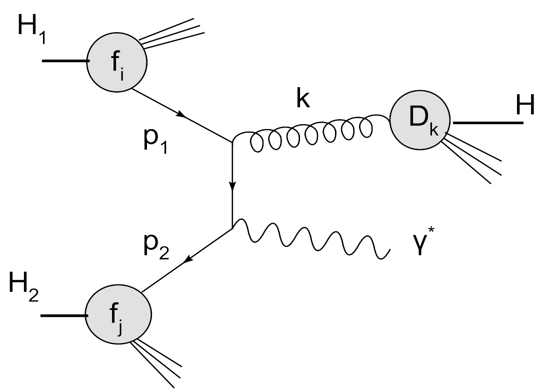
$$\frac{d\sigma^{(0)}}{dQ^2} = \sigma_0 \sum_{i,j} \left[f_i^{[1]} \otimes f_j^{[2]} + f_i^{[2]} \otimes f_j^{[1]} \right] \otimes \frac{d\widehat{\sigma}^{ij}}{dQ^2} \,, \quad \sigma_0 = \frac{4\pi\alpha_{em}^2}{9 S_h Q^2}$$

- Factorization proven at soft+collinear level

- soft gluon resummation NLL for $d\sigma/dq_t$, $d\sigma/dY\,dQ^2$ up to NNLO

$\mathcal{O}(\alpha_s)$ Associated production

- Consider now the process: $H_1(P_1) + H_2(P_2) \to \gamma^*(q) + H(h) + X$
- lepton pair of invariant mass $Q^2 \gg \Lambda^2_{QCD}$
- hadron H detected in the final state with $z = 2E_H/\sqrt{S_h}$
- $\mathcal{O}(\alpha_s)$ production : the observed hadron H results from the fragmentation of a final state parton :



$$\frac{d\sigma^{H,C}(\tau)}{dQ^2dz} = \sigma_0 \sum_q e_q^2 \int \frac{d\rho}{\rho} \int \frac{dx_1}{x_1} \int \frac{dx_2}{x_2} f_q(x_1) f_{\bar{q}}(x_2) D_g^H(z/\rho) \frac{d\hat{\sigma}^g_{q\bar{q}}}{dQ^2 d\rho} \, .$$

- $\rho = 2E_k/\sqrt{S_h}$ is the partonic analogue of z, being E_k the energy of the outgoing gluon.

$\mathcal{O}(\alpha_s)$ corrections, Central region

- $q\bar{q}$ channel : $q(p_1) + \bar{q}(p_2) \longrightarrow \gamma^*(q) + g(k)$

$\Rightarrow$ Perform an ϵ-expansion in two disjoint singular limits, *i.e.* for $y \to 0, 1$:

$$\frac{d\sigma^{H,C}(\tau)}{dQ^2 dz} = \sigma_0 \int_0^1 dy \int_{r_1}^1 \frac{dx_1}{x_1} \int_{r_2}^1 \frac{dx_2}{x_2} \sum_q e_q^2 \Big[f_q^{[1]}(x_1)\, f_{\bar{q}}^{[2]}(x_2) + (q \leftrightarrow \bar{q}) \Big]\, D_g^H(z/\rho) \cdot$$
$$\Bigg[-\frac{1}{\rho}\frac{\alpha_s}{2\pi}\frac{c_0}{\epsilon}\widehat{P}_{qq}(w)\Big[\delta(y) + \delta(1-y)\Big] + \frac{\alpha_s}{2\pi} K_{q\bar{q}}\Big(y, x_1, x_2, w, \frac{\mu_F^2}{Q^2}\Big)\Bigg] .$$

- Extra collinear divergences proportional to the unregularized $\widehat{P}_{qq}(w) = \frac{1+w^2}{1-w}$ splitting functions.

- They do correspond to configurations in which the parent parton k of the observed hadron H is collinear to the incoming parton p_1 $(y \to 0)$ or p_2 $(y \to 1)$.

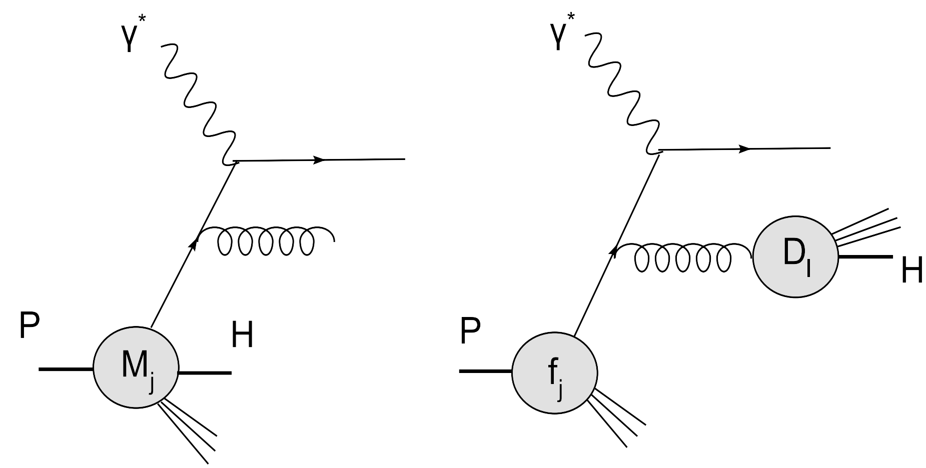
$\Rightarrow$ at vanishing p_t, pQCD looses predictive power $\longrightarrow$ transverse momentum Cut-off.

Fracture functions

• Missing ingridient in the approach:

⇒ Fracture functions M parametrize soft QCD dynamics in forward semi-inclusive processes.

• $M_i^{H/P}(x, z, Q^2)$ give the conditional probability that a parton i with a fractional momentum x of the incoming nucleon momentum P enters the hard scattering while an hadron H with fractional momentum z is detected in the target fragmentation region of P.



• They obey a DGLAP-type inhomogeneous evolution equations:

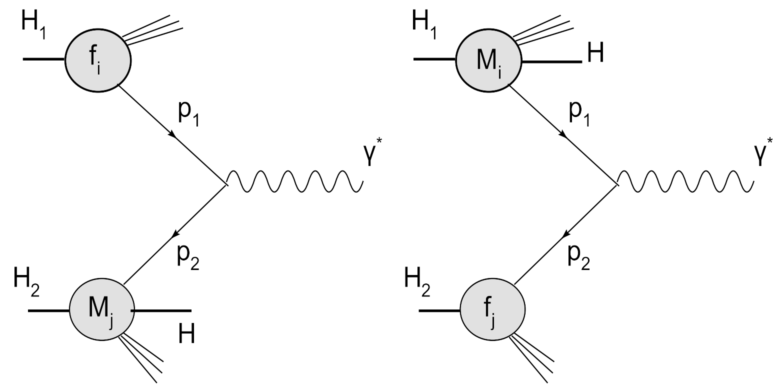
$$Q^2 \frac{dM_i^{H/P}}{dQ^2} = \frac{\alpha_s}{2\pi} P_{ji} \otimes M_j^{H/P} + \frac{\alpha_s}{2\pi} \widehat{P}_{ji}^l \otimes f_j D_l^H \, .$$

• L. Trentadue, G. Veneziano, PLB323 (1994) 201

The parton model formula

• "Bare" fracture functions M describe hadron production at $\theta_{\rm cm} = 0, \pi$, where $\theta_{\rm cm}$ is the relative angle between H and H_1 in the HCMS.

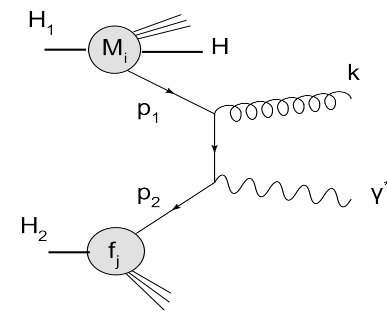
• To $\mathcal{O}(\alpha_s^0)$ hadron H is non-perturbatively produced by a fracture functions:



• The "conjectured" parton model formula is:

$$\frac{d\sigma^{H,T,(0)}}{dQ^2dz} = \sigma_0 \sum_{i,j} \left[M_i^{[1]} \otimes f_j^{[2]} + M_i^{[2]} \otimes f_j^{[1]} \right] \otimes \frac{d\widehat{\sigma}^{ij}}{dQ^2}$$

$\mathcal{O}(\alpha_s)$ corrections, Target region



- Real NLO radiation must be integrated over and virtual corrections added.

- In the $q\bar{q}$ channel the cross-section reads:

$$\begin{aligned}
\frac{d\sigma^{H,T}(\tau)}{dQ^2 dz} \quad = \quad & \sigma_0 \int_\tau^{1-z} \frac{dx_1}{x_1} \int_{\frac{\tau}{x_1}}^1 \frac{dx_2}{x_2} \sum_q e_q^2 \Big[M_q^{[1]}(x_1, z) f_{\bar{q}}^{[2]}(x_2) + (q \leftrightarrow \bar{q}) \Big] \cdot \\
& \Big[\delta(1-w) - \frac{2}{\epsilon} \frac{\alpha_s}{2\pi} P_{qq}(w)\, c_0 + \frac{\alpha_s}{2\pi} C_{q\bar{q}}\Big(w, \frac{\mu_F^2}{Q^2}\Big) \Big] + \\
& + \sigma_0 \int_{\frac{\tau}{1-z}}^1 \frac{dx_1}{x_1} \int_{\frac{\tau}{x_1}}^{1-z} \frac{dx_2}{x_2} \sum_q e_q^2 \Big[M_q^{[2]}(x_2, z) f_{\bar{q}}^{[1]}(x_1) + (q \leftrightarrow \bar{q}) \Big] \cdot \\
& \Big[\delta(1-w) - \frac{2}{\epsilon} \frac{\alpha_s}{2\pi} P_{qq}(w)\, c_0 + \frac{\alpha_s}{2\pi} C_{q\bar{q}}\Big(w, \frac{\mu_F^2}{Q^2}\Big) \Big] .
\end{aligned}$$

- The $\mathcal{O}(\alpha_s)$ coefficient functions C_{ij} in the target fragmentation region are the same as for inclusive DY

Factorization of collinear singularities

- The subtraction of singular terms in the partonic cross-sections is performed by absorbing the divergences in the definitions of bare distributions.

- In the $\overline{\mathrm{MS}}$ scheme the subtraction for parton distributions f reads:

$$f_i(\xi) = \int_{\xi}^{1} \frac{du}{u}\Big[\delta_{ij}\delta(1-u) + \frac{1}{\epsilon}\frac{\alpha_s}{2\pi}\frac{\Gamma(1-\epsilon)}{\Gamma(1-2\epsilon)}\Big(\frac{4\pi\mu_R^2}{\mu_F^2}\Big)^{\epsilon} P_{ij}(u)\Big] f_j\Big(\frac{\xi}{u}, \mu_F^2\Big)$$

- An analogous $\overline{\mathrm{MS}}$ the subtraction formula holds also for fracture functions:

$$M_i^H(\xi,\zeta) = \int_{\frac{\xi}{1-\zeta}}^{1} \frac{du}{u}\Big[\delta_{ij}\delta(1-u) + \frac{1}{\epsilon}\frac{\alpha_s}{2\pi}\frac{\Gamma(1-\epsilon)}{\Gamma(1-2\epsilon)}\Big(\frac{4\pi\mu_R^2}{\mu_F^2}\Big)^{\epsilon} P_{ij}(u)\Big] M_j^H\Big(\frac{\xi}{u}, \zeta, \mu_F^2\Big)$$

$$+ \int_{\xi}^{\frac{\xi}{\xi+\zeta}} \frac{du}{u}\frac{1}{1-u}\frac{u}{\xi}\frac{1}{\epsilon}\frac{\alpha_s}{2\pi}\frac{\Gamma(1-\epsilon)}{\Gamma(1-2\epsilon)}\Big(\frac{4\pi\mu_R^2}{\mu_F^2}\Big)^{\epsilon} \widehat{P}_{(k)i\leftarrow j}(u)\, f_j\Big(\frac{\xi}{u}\Big)\, D_k^H\Big(\frac{\zeta u}{\xi(1-u)}\Big)$$

- D. Graudenz, NPB432 (1994) 351

Factorization of collinear singularities

- Now rewrite the parton model formula in terms of renormalized quantity;

√ Singularities in the target frag. region cancelled by the f and the homogeneous M renorm. term.

√ Singularities in the central frag. region cancelled by the f and the inhomogeneous M renorm. term.

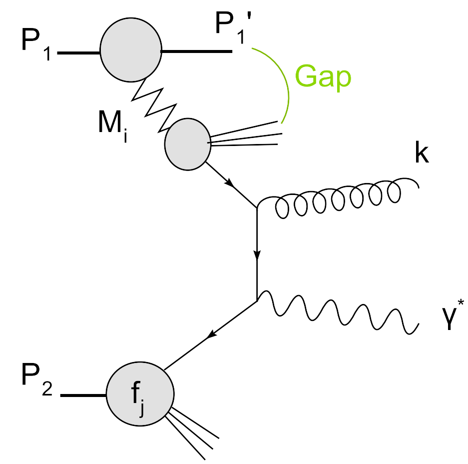
$$\frac{d\sigma^H}{dQ^2dz}\sigma_0 \sum_{i,j} \left[M_i^{[1]} \otimes f_j^{[2]} + (1 \leftrightarrow 2)\right] \left(1 + \frac{\alpha_s}{2\pi} C^{ij}\right) + \frac{\alpha_s}{2\pi} \sum_{i,j,k} f_i^{[1]} \otimes f_j^{[2]} \otimes D^{H/k} \otimes K_k^{ij}$$

- F.A.C. and Luca Trentadue, PLB668 (2008) 319

- All bare distributions are replaced by renormalized ones ⇒ Cross-sections infrared finite;
- Coefficient functions $K_{q\bar{q}}^{g}$ and K_{gq}^{q} have been calculated

Single diffractive DY

- For very forward proton production, central term suppressed
- Use NLO inclusive DY rapidity $d\sigma/dQ^2dY$ with diffractive PDF.
- Kinematics : $x^0_{1,2} = \sqrt{\frac{Q^2}{S_h}} \exp^{\pm Y}$, $x_P \simeq 1 - z$

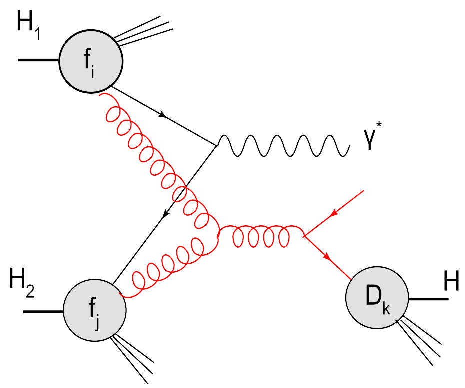


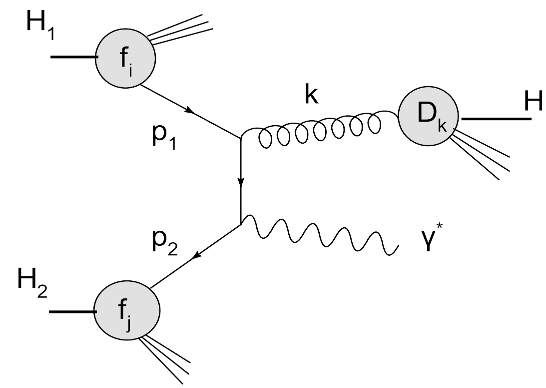
$$\begin{aligned}\frac{d^3\sigma}{dQ^2 dx_P dY} &= \sigma_0 \sum_q \int_{x_1^0}^{x_P} dx_1 \int_{x_2^0}^{1} dx_2 \Big\{ \Big[D^{(0)}_{q\bar{q}} + \frac{\alpha_s}{2\pi} D^{(1)}_{q\bar{q}} \Big] M_q^{[1]}(x_1, x_P, Q^2) f_{\bar{q}}^{[2]}(x_2, Q^2) \\ &+ \frac{\alpha_s}{2\pi} D^{(1)}_{gq} M_g^{[1]}(x_1, x_P, Q^2) \Big[f_{\bar{q}}^{[2]}(x_2, Q^2) + f_{\bar{q}}^{[2]}(x_2, Q^2) \Big] \\ &+ \frac{\alpha_s}{2\pi} D^{(1)}_{qg} \Big[M_q^{[1]}(x_1, x_P, Q^2) + M_{\bar{q}}^{[1]}(x_1, x_P, Q^2) \Big] f_g^{[2]}(x_2, Q^2) \Big\}\end{aligned}$$

- Tests factorization breaking as a function of x,x_P and Q^2 in a region covered by HERA diffractive PDFs.

DPS studies in DY+hadron

- At non-vanishing hadron $p_T \simeq \mathcal{O}(GeV)$, studies of double parton scattering are possible





- Assuming collinear fragmentation ($y_{\text{parton}} = y_{\text{hadron}}$) and changing variables to hadronic p_T^2 and η:

$$p_T^2 = z^2 S_h \, y\,(1-y)\,, \eta = \frac{1}{2}\log\frac{1-y}{y}$$

$\Rightarrow$ The (background) single parton scattering cross-section is

$$\frac{d\sigma^{H,C}(\tau)}{dQ^2 dp_T^2 d\eta} = \frac{\sigma_0}{zS_h}\int_{r_1}^1 \frac{dx_1}{x_1}\int_{r_2}^1 \frac{dx_2}{x_2}\sum_i e_i^2 f_i^{[1]}(x_1)\, f_j^{[2]}(x_2)\, D_k^H(z/\rho)\frac{d\hat{\sigma}_{ij}^k}{dQ^2 d\eta}$$

- Studies of DPS in terms of double parton distributions as a function of Q^2.

Conclusions

- We have proven to $\mathcal{O}(\alpha_s)$ in perturbative QCD a collinear factorization formula for the associated production of one particle and a Drell-Yan pair.
- The use of fracture functions is essential for the factorization of additional collinear singularities appearing in the calculation.
- The corresponding cross-section is therefore infrared finite
- Large collinear logarithms $\alpha_s \ln Q^2/\mu_F^2$ are removed from coefficient functions C and K and resummed by using fracture functions evolution equations.
- The p_t-integrated cross-section does not require any p_t cut on the observed hadron since it is present an additional scale Q^2 which makes the process "perturbative"
- Tests factorization breaking in single diffractive DY production by using HERA diffractive PDFs
- At non vanishing p_T, formalism can be used to "produce" SPS background to DY+hadron
  $\Rightarrow$ Studies of DPS, test Q^2 dependence of double parton distributions.