Odd Features of Hard Diffraction

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In collaboration with
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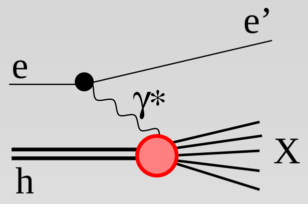
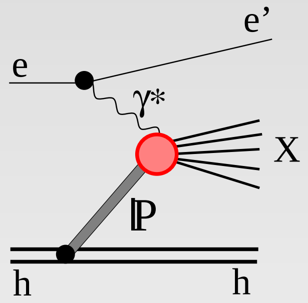
QCD factorization in Diffraction

Ingelman-Schlein picture of diffraction.

DIS on a proton (inclusive $\gamma^* + p \longrightarrow X$) provides the distribution of partons in the proton.



Therefore, DIS on the Pomeron (diffraction $\gamma^* + p \longrightarrow X + p$) provides the distribution of partons in the Pomeron.



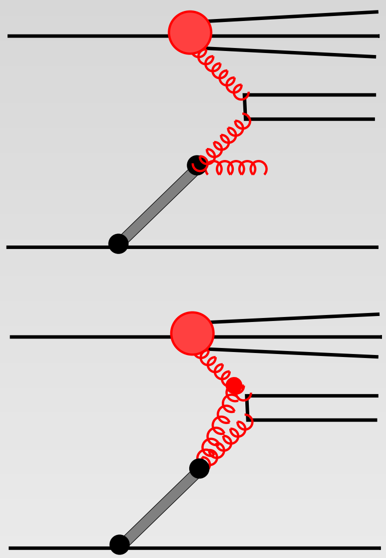
Once the parton densities in the Pomeron are known, one can predict the cross section of any hard hadronic reaction.
For instance (A.Donnachie & P.Landshoff),

$$\sigma_{sd}^{DY}(pp \longrightarrow \bar{l}l\, X\, p) = G_{\mathbb{P}/p} \otimes F_{\bar{q}/\mathbb{P}} \otimes F_{q/p} \otimes \hat{\sigma}(\bar{q}q \longrightarrow \bar{l}l).$$

QCD factorization in Diffraction

Breakdown of factorization.

This naive picture fails due to compositeness of the Pomeron (J.Collins, L.Frankfurt & M.Strikman). The usual assumption that only one parton participates in the hard interaction, while other partons in the hadron are spectators, apparently is not correct for the Pomeron which may interact as a whole.



The full calculation of relevant graphs (F.Yuan & K.-T.Chao) misses, however, the interaction with the spectator partons which leads to:

- Dependence of Drell-Yan diffraction on the hadronic size;
- Leading twist behavior, $1/Q^4 \Rightarrow 1/Q^2$.

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Quantum Mechanics of Diffraction

Diffractive excitation happens due to compositeness of hadrons

R. Glauber (1955)

Feinberg&Pomeranchuk (1956)

Good & Walker (1964)

Since hadrons can be excited, they are not eigenstates of interaction. However, a hadron can be expanded over the complete set of eigen states:

$$|h\rangle = \sum_{\alpha=1} C^h_\alpha \, |\alpha\rangle \; ,$$

where $|\alpha\rangle$ are eigenstates of interaction, $\hat{f}_{el}|\alpha\rangle = f_\alpha \, |\alpha\rangle$.

Quantum Mechanics of Diffraction

Employing completeness one can calculate the forward single diffraction cross section with no knowledge of the properties of $|h'\rangle$:

$$\sum_{h'\neq h} \left.\frac{d\sigma_{sd}^{h\to h'}}{dt}\right|_{t=0} = \frac{1}{4\pi}\sum_{h'}\left(|f_{sd}^{hh'}|^2 - |f_{sd}^{hh}|^2\right)$$

$$= \frac{1}{4\pi}\left[\sum_{\alpha=1}|C_\alpha^h|^2\,|f_\alpha|^2 - \left|\sum_{\alpha=1}|C_\alpha^h|^2 f_\alpha\right|^2\right]$$

$$= \langle|f_\alpha|^2\rangle_h - |\langle f_\alpha\rangle_h|^2$$

Thus, the diffractive dissociation cross section is given by the dispersion of the α-distribution.

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Quantum Mechanics of Diffraction

In the Froissart regime all the partial eigen-amplitudes reach the unitarity limit, $\mathrm{Im}\, f_\alpha = 1$. Then, according to the completeness conditions,

$$f_{el}^{hh} \Rightarrow \sum_{\alpha=1} |C_\alpha^h|^2 = 1$$

$$f_{sd}^{hh'} \Rightarrow \sum_{\alpha=1} (C_\alpha^{h'})^* C_\alpha^h = 0$$

Diffraction is impossible within a black disc, but only on its periphery, $b \sim R$.

In the Froissart regime $R \propto \ln(s)$, therefore

$$\underline{\sigma_{sd}/\sigma_{tot} \propto 1/\ln(s)}$$

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Color Dipole Description

Which hadronic components are the eigenstates of interaction at high energies?

Color dipoles with a definite transverse separation $\vec{r}_T$ cannot be excited and can experience only elastic diffractive scattering. Indeed, the dipoles have no definite mass, but only separation $\vec{r}_T$ which cannot be altered during soft interaction.

Color transparency: $\sigma_{dipole}(r_T) \propto r_T^2$

B.K., L.Lapidus & A.Zamolodchikov (1981)

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Color Dipole Description

The total and single diffractive cross sections read,

$$\sigma_{tot}^{hp} = \sum_{\alpha=1} |C_{\alpha}^{h}|^2 \, \sigma_{\alpha} = \int d^2 r_T \, |\Psi_h(r_T)|^2 \, \sigma(r_T)$$

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Color Dipole Description

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$$16\pi \sum_{h' \neq h} \left. \frac{d\sigma_{sd}^{h \to h'}}{dt} \right|_{t=0} = \langle \sigma^2(r_T) \rangle - \langle \sigma(r_T) \rangle^2$$

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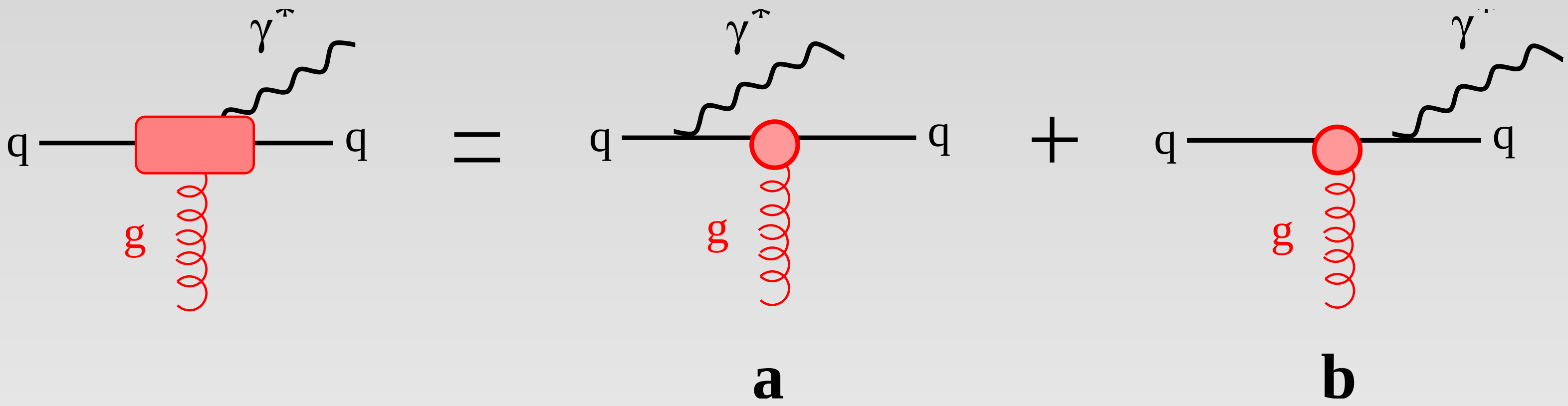
Drell-Yan reaction via Dipoles

In the rest frame of the target Drell-Yan Reaction looks like radiation of a heavy photon decaying into a dilepton.



The cross section is expressed via the dipoles similar to DIS,

$$\frac{d\sigma_{inc}^{DY}(qp \to \gamma^* X)}{d\alpha\, dM^2} = \int d^2r \; \left|\Psi_{q\gamma^*}(\vec{r},\alpha)\right|^2 \; \sigma\left(\alpha r, x_2\right)$$

$$\alpha = \frac{p^+_{\gamma^*}}{p^+_q}$$

(B.K. 1995)

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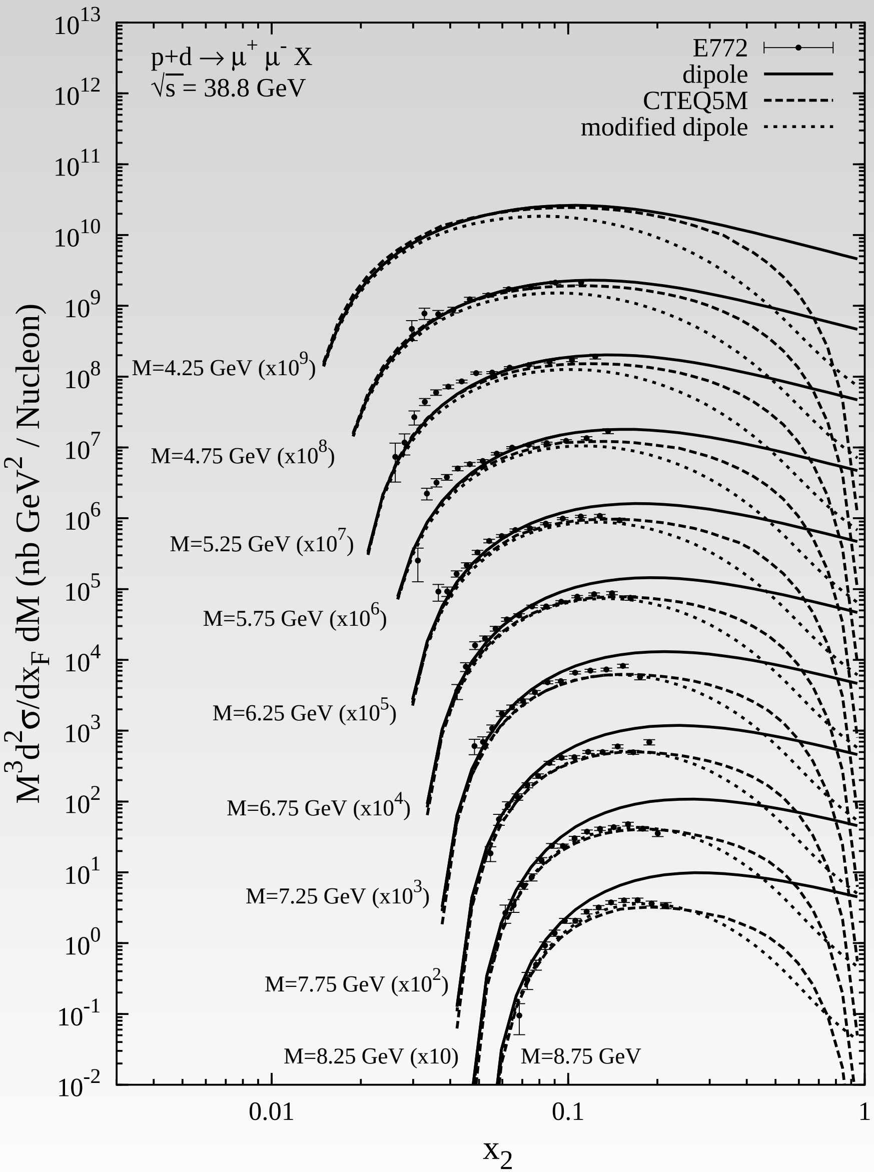
Drell-Yan reaction via Dipoles

$$\frac{d\sigma_{inc}^{DY}}{dx_1\,dM^2} = \frac{1}{M^2\,x_1}\,\frac{\alpha_{em}^2}{3\pi}\int_{x_1}^{1}\frac{d\alpha}{\alpha}\,F_2(x_1/\alpha)$$
$$\times\int d^2r\left|\Psi_{q\gamma^*}^{L,T}(\vec{r},\alpha)\right|^2\sigma\left(\alpha r, x_2\right)$$

E772 $\sqrt{s} = 40\,\mathrm{GeV}$

J.Raufeisen, J.C.Peng, G.Nayak



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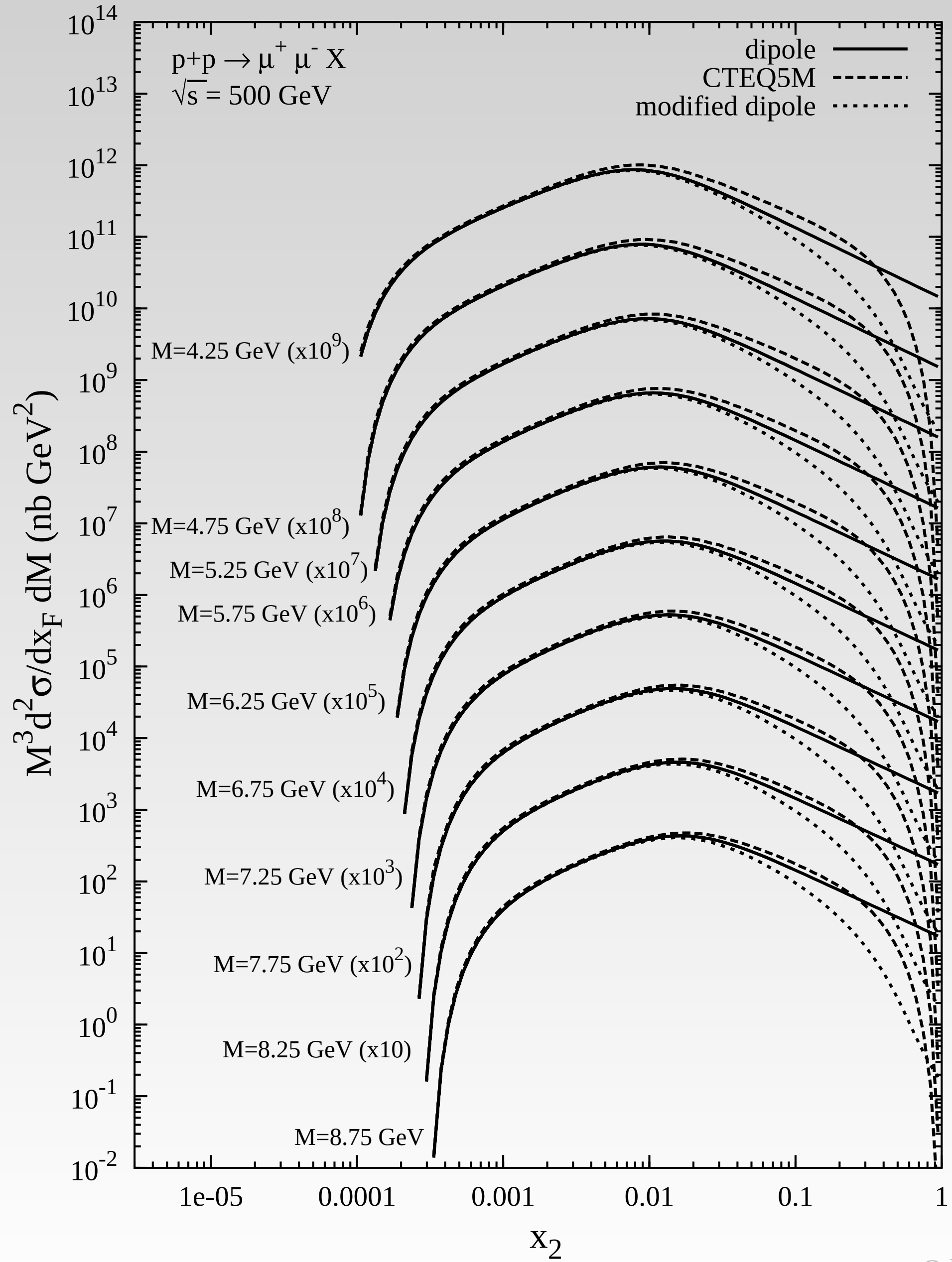
Drell-Yan reaction via Dipoles

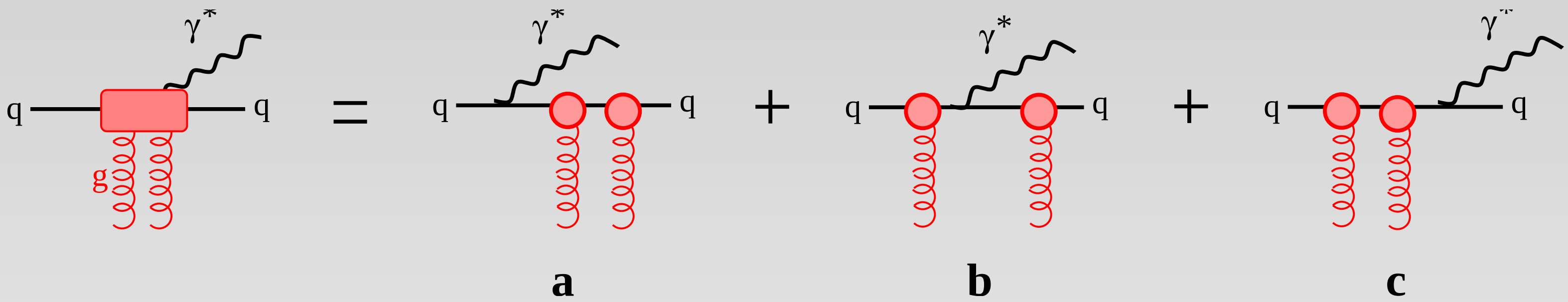
RHIC
$\sqrt{s} = 500\,\text{GeV}$

J. Raufeisen,
J.C. Peng,
G.C. Nayak



Diffractive Drell-Yan

Diffractive radiation of a dilepton by a quark



$$\left.\frac{d\sigma_{inc}^{DY}(qp \to \gamma^* qp)}{d\alpha\, dM^2}\right|_{p_T=0} = 0 \quad \textbf{!!!}$$

In both Fock components of the quark, $|q\rangle$ and $|q\gamma^*\rangle$ only quark interacts. No dispersion $\Rightarrow$ no diffraction.

This conclusion holds for any abelian diffractive radiation, like **W, Z bosons, Higgs, etc.**

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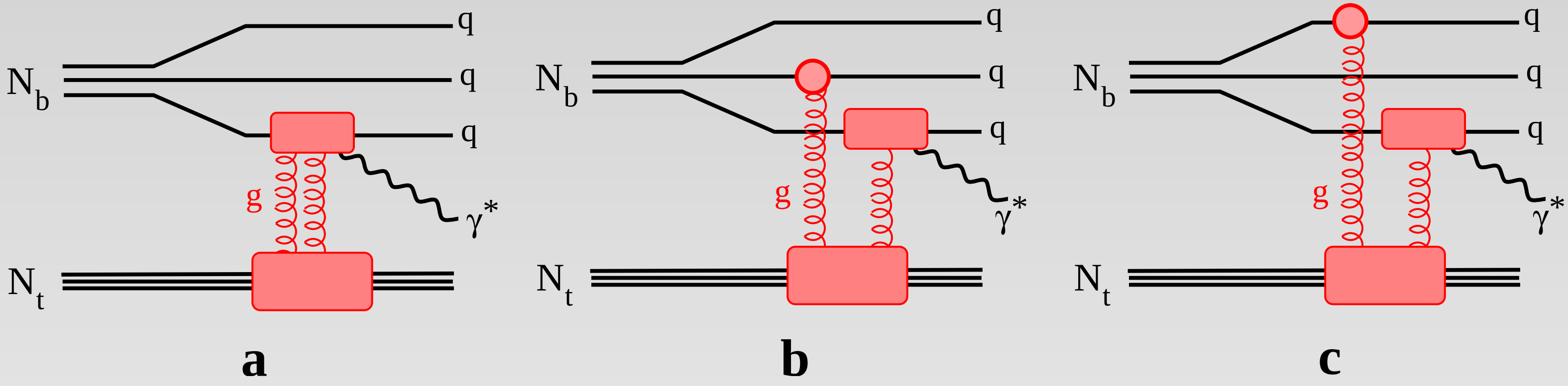
Diffractive Drell-Yan

Diffractive radiation of a dilepton by a proton



$$\left.\frac{d\sigma^{DY}_{inc}(pp \to \gamma^* X p)}{d\alpha\, dM^2}\right|_{p_T=0} \neq 0$$

In both Fock components of the proton, $|3q\rangle$ and $|3q\gamma^*\rangle$ only the quark dipoles interact. However these dipoles have different sizes, since the recoil quark gets a shift in impact parameters. So the dipoles interact differently giving rise to diffraction.

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Diffractive Drell-Yan

On the contrary to DIS, Drell-Yan diffraction is not soft dominated. Indeed,

$$\boldsymbol{\sigma}(\vec{R}) - \boldsymbol{\sigma}(\vec{R} - \alpha\vec{r}) \ \propto \ \vec{r} \cdot \vec{R}$$

Thus, the diffractive amplitude is not quadratic in $\boldsymbol{r}$ like in DIS, but linear. Therefore, the soft part of the interaction is not enhanced in Drell-Yan diffraction, which turns out to be as hard/soft as the inclusive cross section is.

- If gluon density saturates and the dipole cross section has the form $\boldsymbol{\sigma}(\boldsymbol{r_T}) = \boldsymbol{\sigma_0}(\mathbf{1} - \boldsymbol{e}^{-\boldsymbol{r_T^2}/\boldsymbol{R_0^2}})$, the Drell-Yan diffraction is suppressed at $R > R_0$ where the cross section is leveling off. This suppression is stronger at higher energies, since $\boldsymbol{R_0}$ decreases.

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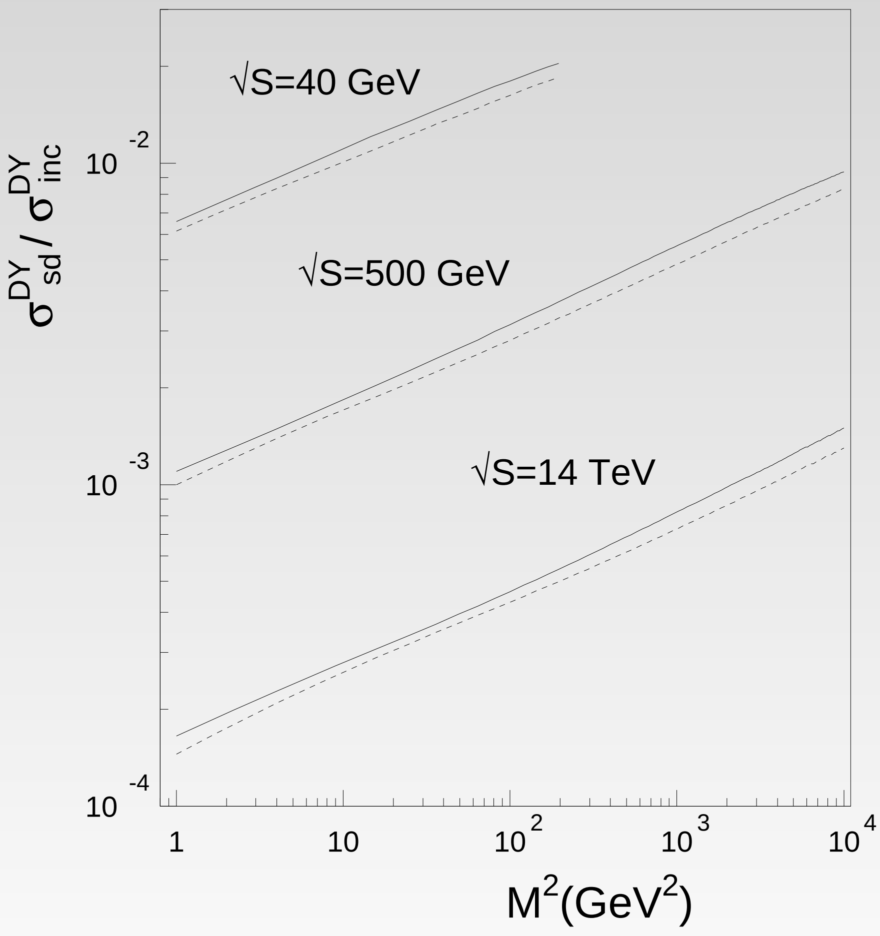
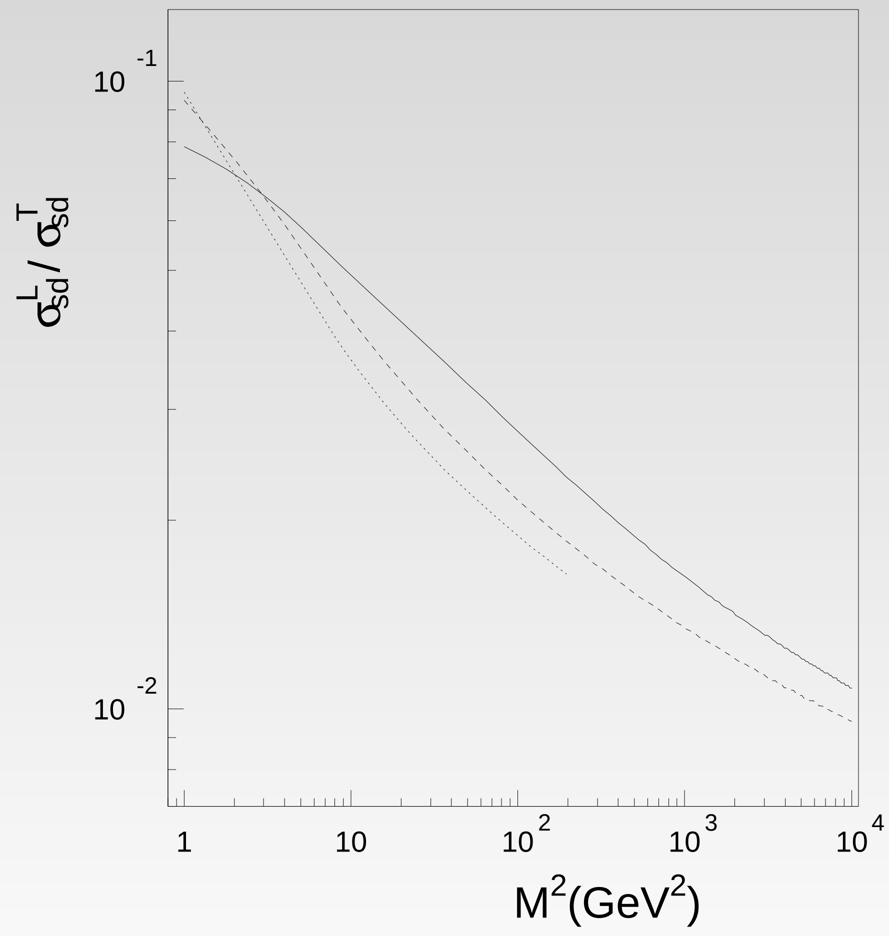
Diffractive Drell-Yan: Results





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Diffractive Drell-Yan: Results

Why does the fraction of diffraction in the total Drell-Yan cross section rises with scale?

Why does the fraction of diffraction in the total Drell-Yan cross section steeply fall with energy?

- Data for $F_2^p(x, Q^2)$ suggest a saturated shape for the dipole cross section (Golec-Biernat & Wüsthoff),

$$\sigma(r, x) = \sigma_0 \left(1 - e^{-r^2/R_0^2(x)}\right)$$

where $R_0(x)$ decreases at high energies, or at small x.

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Diffractive Drell-Yan: Results

$$\frac{\sigma_{sd}^{DY}}{\sigma_{inc}^{DY}} \propto \frac{1}{R_0^2(x_2)}\, e^{-2R^2/R_0^2(x_2)}$$

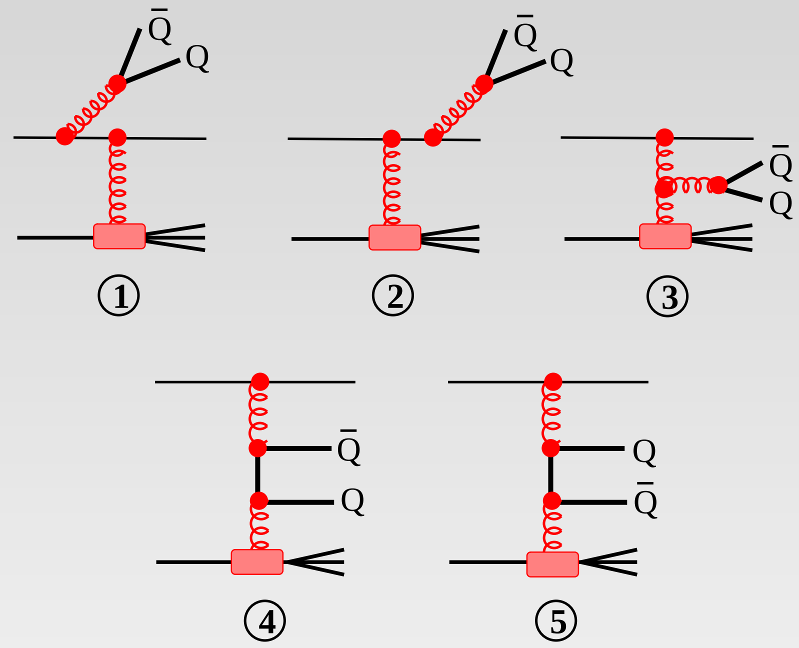
With rising energy at fixed scale the Bjorken $x_2 = M^2/x_1/s$ decreases and $R_0(x_2)$ shrinks causing a fall of the cross section.

On the contrary, with rising scale at fixed energy x_2 rises and the fraction of diffraction increases.

These unusual features of Drell-Yan diffraction are directly related to the phenomenon of saturation, which is still under debate. Thus, diffractive Drell-Yan process is a very sensitive probe for saturation.

Heavy Flavors

Bremsstrahlung and Production mechanisms in inclusive production of heavy flavors by a projectile parton (quark or gluon)

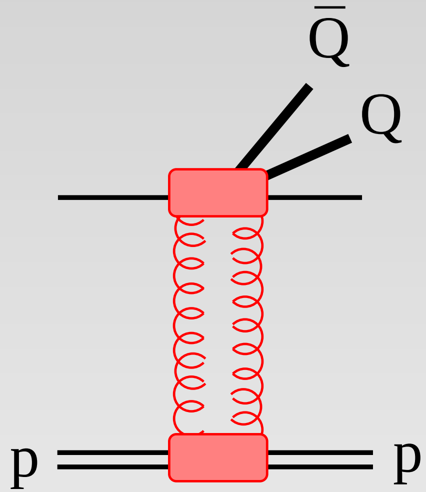


$$M_{Br} = M_1 + M_2 + \frac{Q^2}{M^2+Q^2} M_3$$

$$M_{Pr} = \frac{M^2}{M^2+Q^2} M_3 + M_4 + M_5$$

Diffractive Heavy Flavors

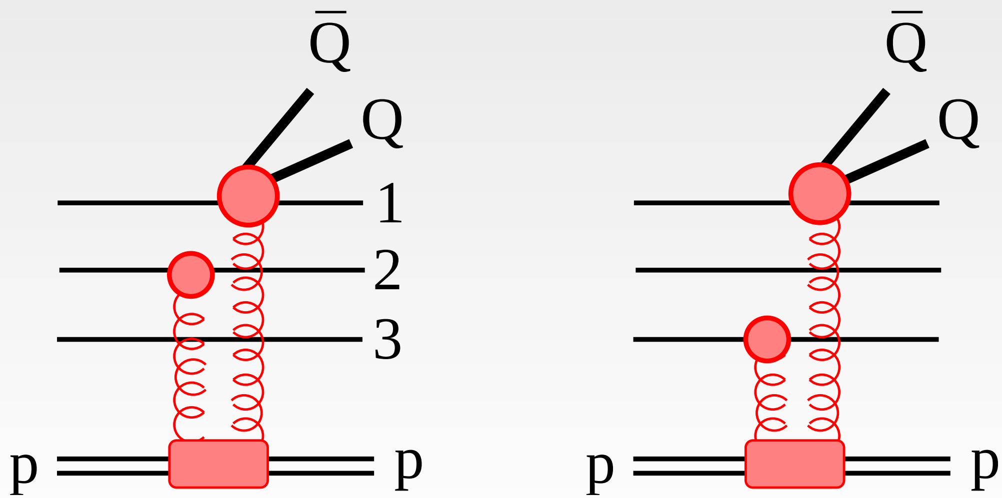
Higher twist bremsstrahlung mechanism in diffraction: radiation of a $\bar{Q}Q$ pair by an isolated parton.



$\sigma \sim 1/m_Q^4$

Higher twist

Leading twist bremsstrahlung mechanism in diffraction:



$\sigma \sim 1/m_Q^2$

Leading twist

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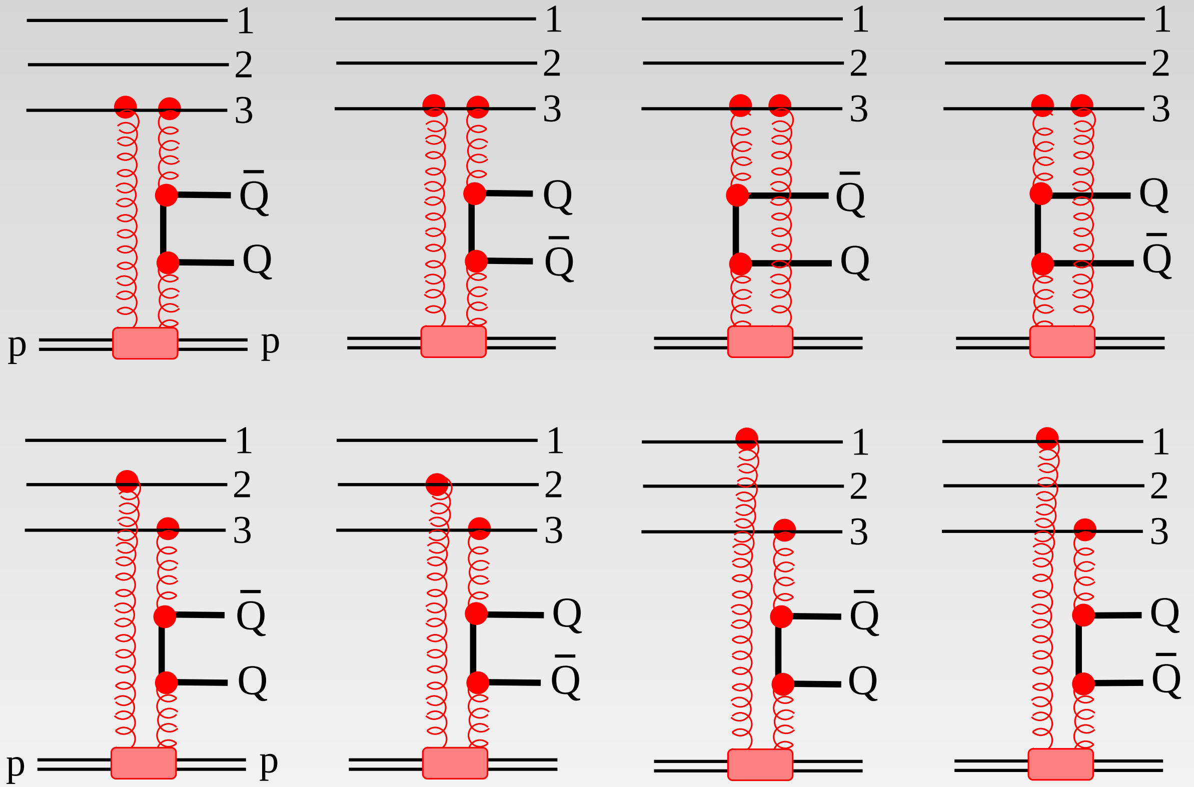
Diffractive Heavy Flavors

Production mechanism in diffraction:



$$\sigma \propto 1/m_Q^2$$

Leading twist

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Data

- Measurements at ISR led to an amazingly large (probably incorrect) cross section of diffractive charm production (K.L.Giboni et al. 1979), $\sigma \sim 10 - 60\,\mu$b. This experiment was order of magnitude above the subsequent data for inclusive charm production.

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- The E690 experiment reported the diffractive charm cross section at $\boldsymbol{\sigma = 0.61 \pm 0.12 \pm 0.11}\ \boldsymbol{\mu}$b at $800\,\mathrm{GeV}$. Agrees well with our calculations.

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Data

- The CDF experiment measured the fraction of diffractively produced beauty, $\boldsymbol{R^{\bar{b}b}_{diff/tot}} = (\mathbf{0.62 \pm 19 \pm 16})\%$, at $\sqrt{s} = 1.8\,$TeV. The total cross section of beauty production at this energy has not been measured so far. If to rely on the theoretical prediction (J.Raufeisen & J.C.Peng) $\boldsymbol{\sigma^{\bar{b}b}_{tot}} = \mathbf{200}\,\mathrm{mb}$, then $\boldsymbol{\sigma^{\bar{b}b}_{diff}} \approx \mathbf{1.2}\,\mathrm{mb}$. This estimate agrees rather well with our results, but contradicts by an order of magnitude the higher twist mass dependence $\boldsymbol{\sigma^{\bar{b}b}_{diff}} \propto \mathbf{1}/\boldsymbol{m_Q^4}$.

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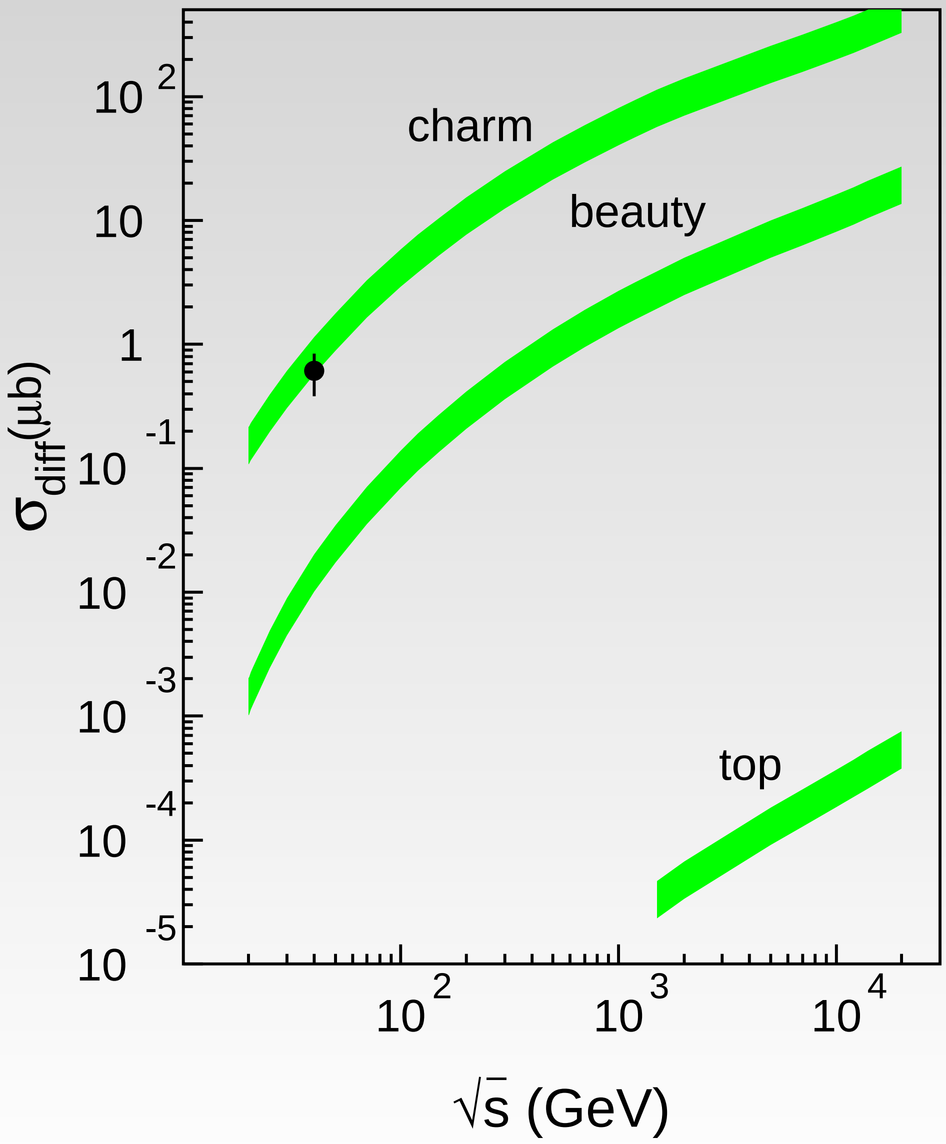
Diffractive Heavy Flavors

Results and data



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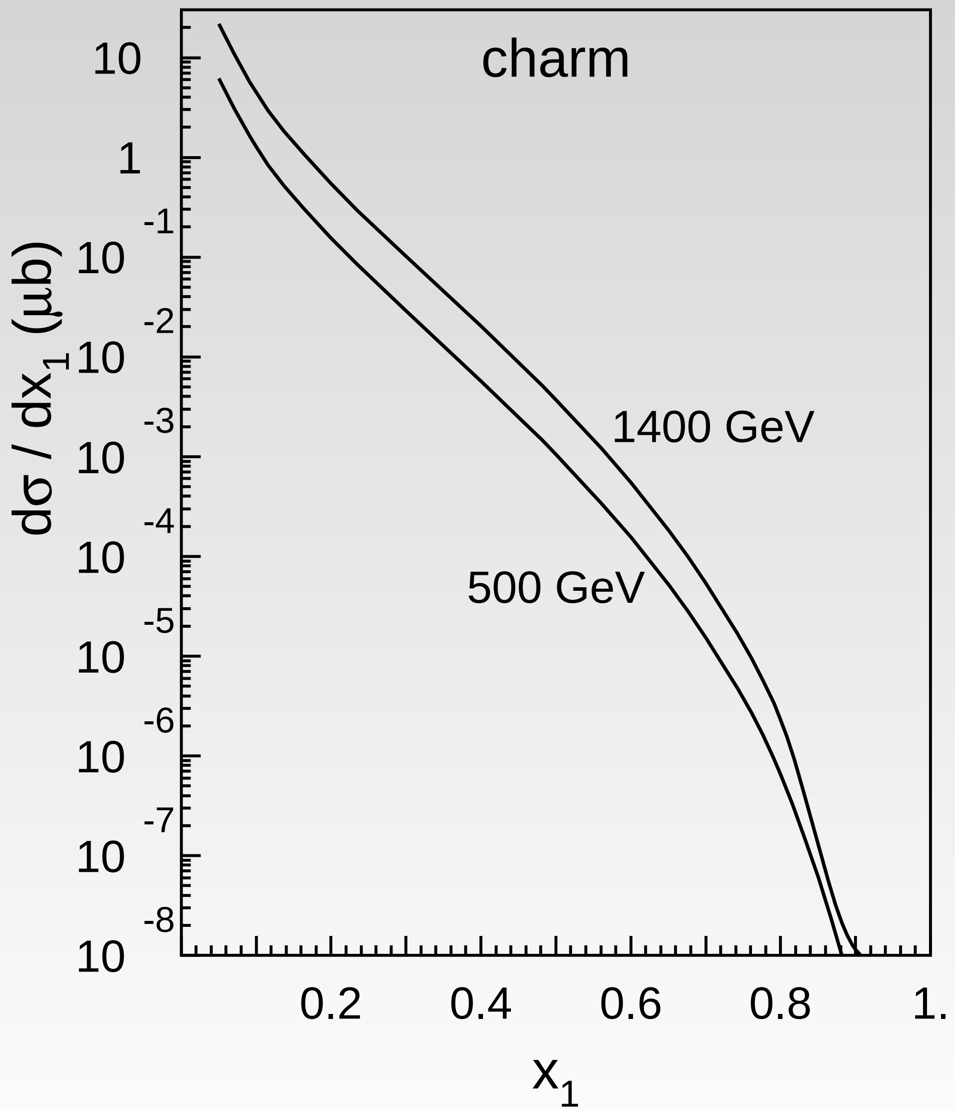
Diffractive Heavy Flavors

Results



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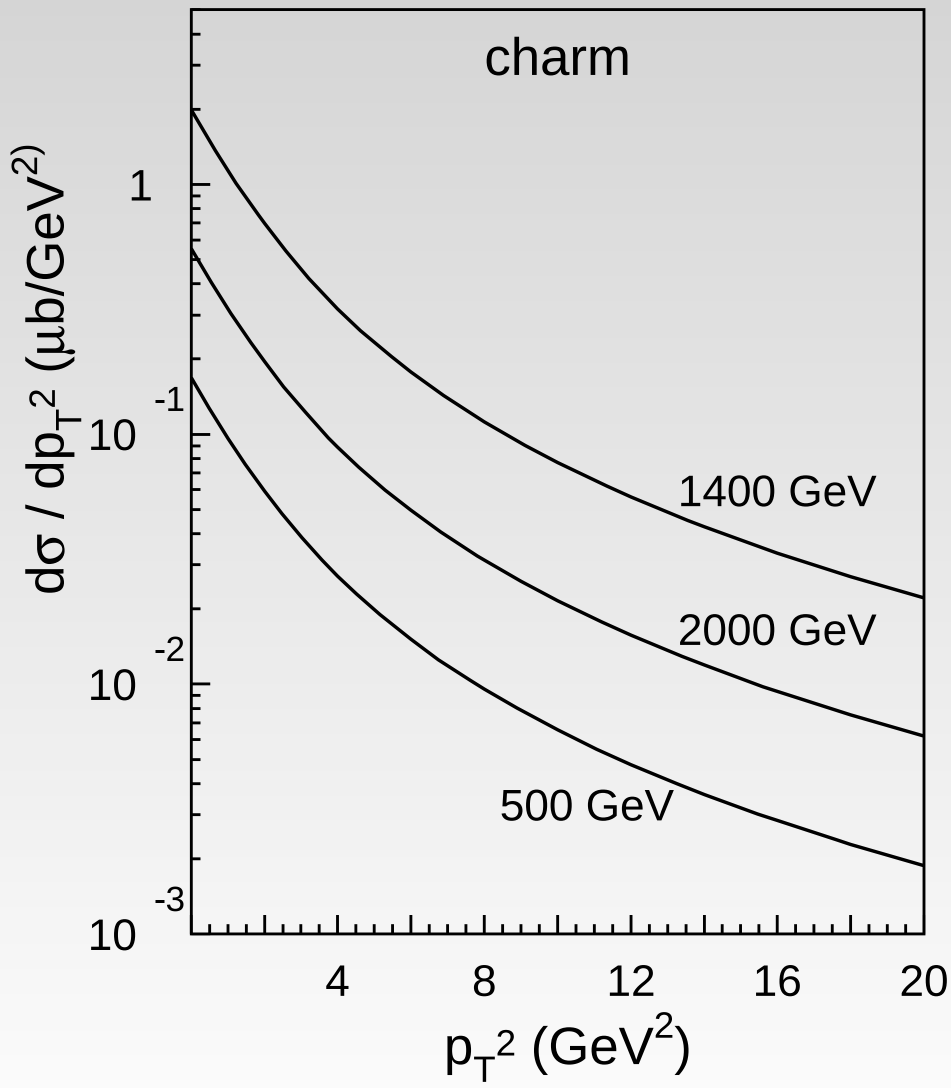
Diffractive Heavy Flavors

Results



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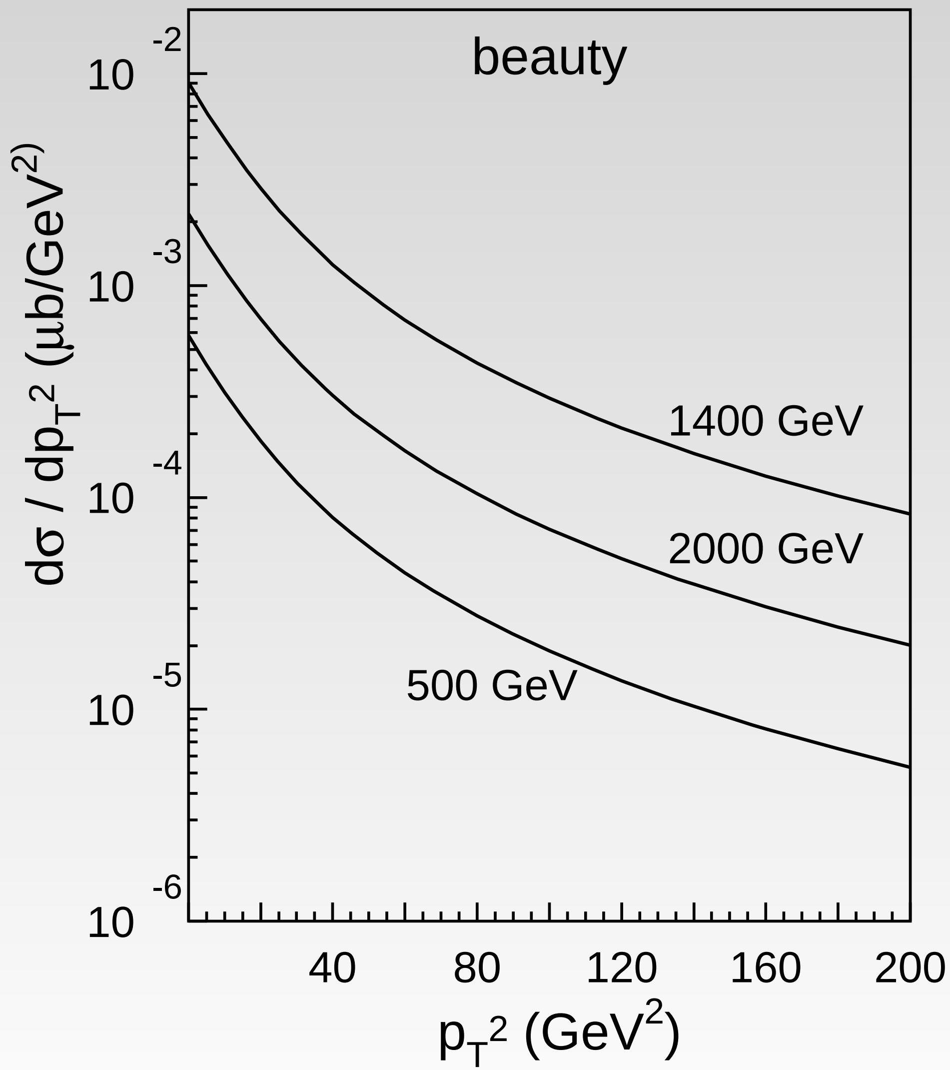
Diffractive Heavy Flavors

Results



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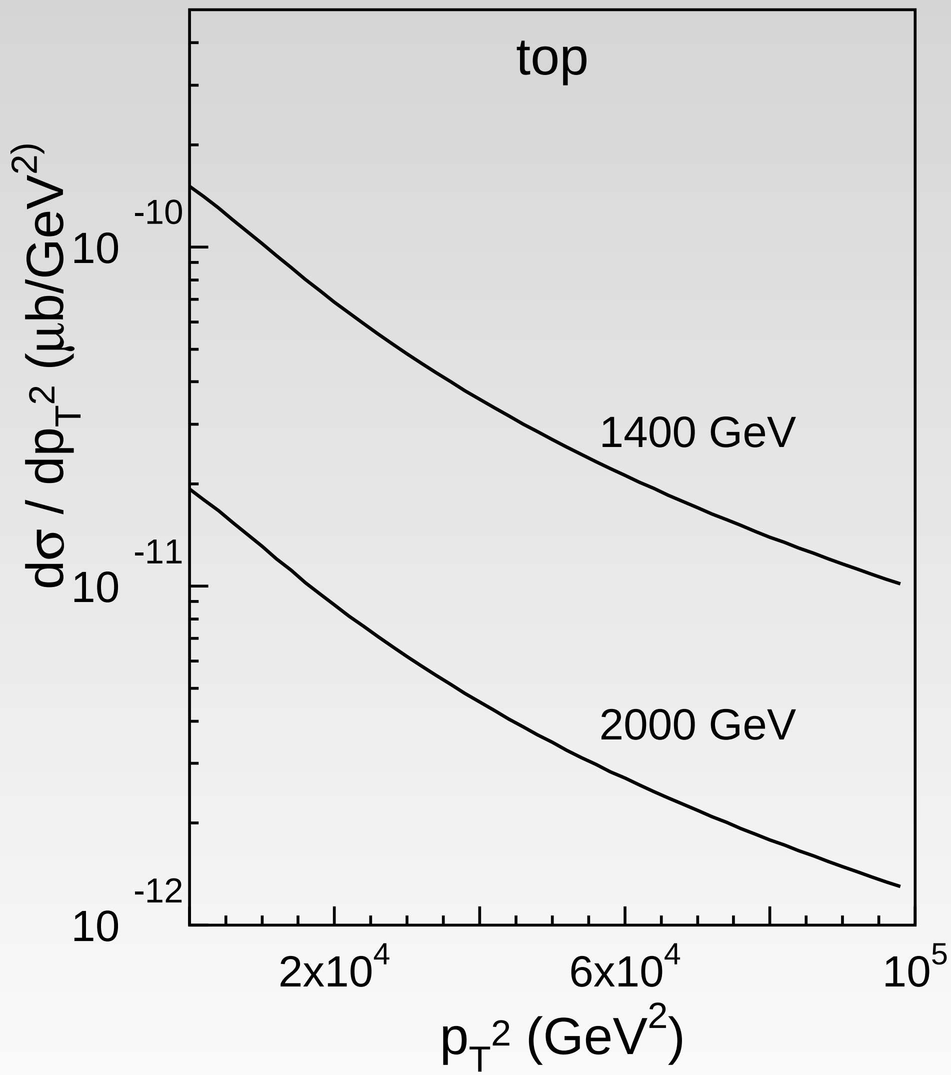
Diffractive Heavy Flavors

Results



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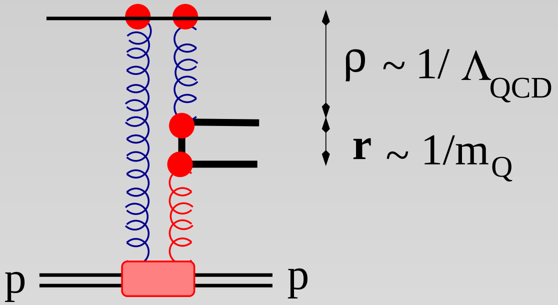
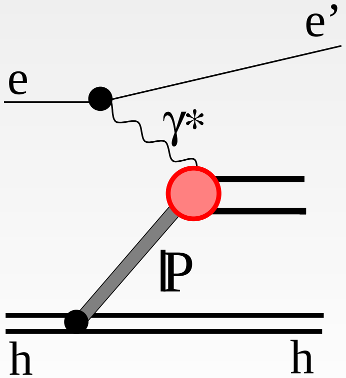
Diffractive Heavy Flavors

Previous calculations missed the leading twist contribution $\sigma \propto 1/m_Q^2$, resulting from interaction with spectator partons.



The distance between the spectator parton and the heavy pair is large, $\vec{\rho} \sim 1/\Lambda_{QCD}$, while the the $\bar{Q}Q$ separation is very small $r \sim 1/m_Q$. Thus, two gluons (blue) in the figure are soft, and only one (red) is hard. The leading twist behavior results from interference of the two sizes.
The main uncertainty is due to a poor knowledge of the infra-red limit $\alpha_s(\Lambda_{QCD}) \sim 0.4 - 0.8$

Similar situation occurs in heavy flavor production in diffractive DIS: the heavy quarks are created far away from the electron.



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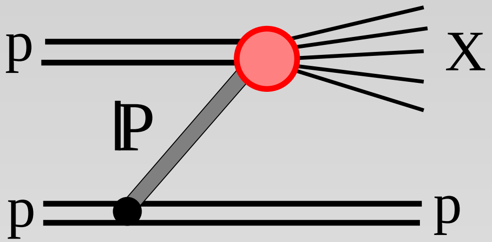
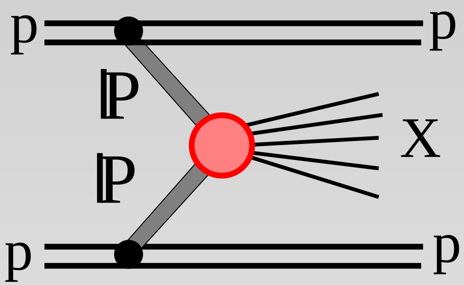
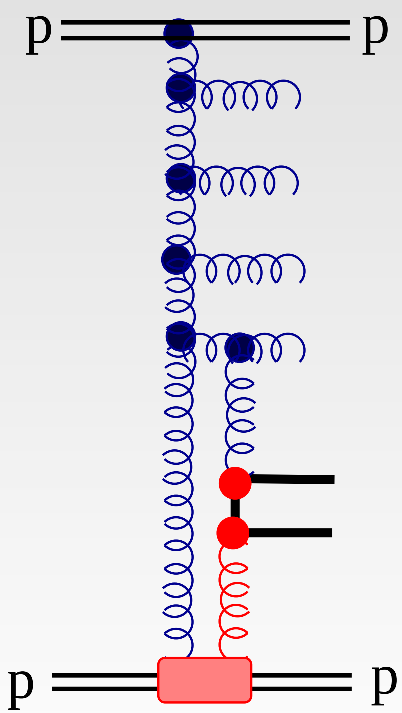
Single and Double Diffraction





The main contribution to single diffractive production of heavy flavors at small $\boldsymbol{x_1}$ comes from semi-hard/semi-soft graphs like this:.



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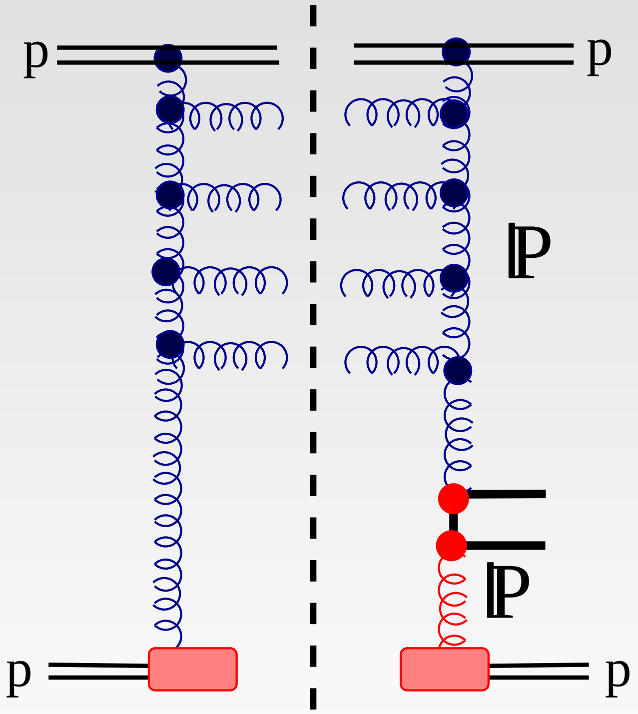
Single and Double Diffraction

The projectile Fock component of the proton consisted of quarks and many gluons has a good chance to fold back to the proton, since it get only a soft kick from the hard process.

We arrive at a double Pomeron production of heavy flavor, one Pomeron is hard, but one is soft.



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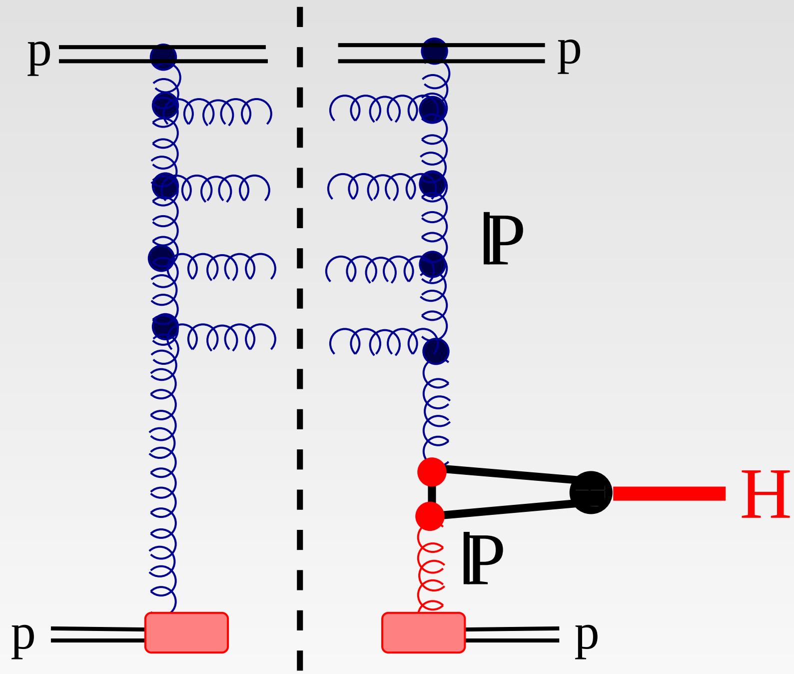
Double Diffractive Higgs Production

One of the promising processes to search for Higgs is the double-Pomeron production. This process contains two contributions: soft-hard and hard-soft Pomerons. This leads to the leading twist effect $\sigma \propto 1/m_H^2$ (it has been believed to be $1/m_H^4$ so far).



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Summary

The Ingelman-Schlein QCD factorization is broken in hard hadronic diffraction not only due to the composite structure of the Pomeron, but also due to possibility of interaction with the projectile spectator partons. The latter effect is huge. It makes diffraction a leading twist process.

Data for diffractive production of charm and beauty support this prediction. No data are available for diffractive Drell Yan so far.

Effects similar to diffractive Drell Yan are expected for other abelian radiation processes: Z, W and Higgs diffractive production. High-p_T diffractive jets can be calculated with the same technique as heavy flavors.

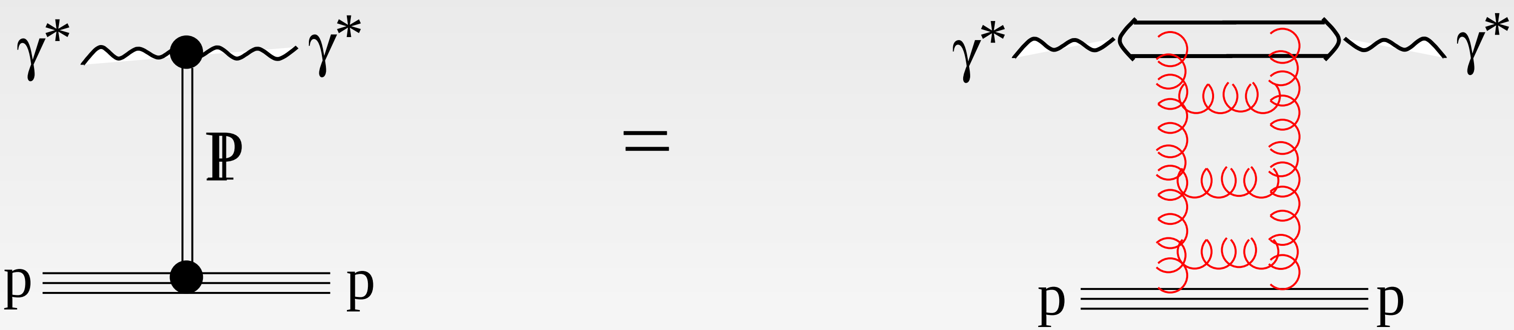
The double-Pomeron production of Higgs turns out to be a leading twist effect.

Backup slides

Color Dipole Description

The lowest Fock component of a meson is just a $\bar{q}q$ pair. Calculation of the universal dipole cross section $\sigma_{\bar{q}q}(r_T)$ is still a theoretical challenge. However, it can be fitted to data.

A rich source of information about $\sigma_{\bar{q}q}(r_T)$ is DIS. At small x_{Bj} the virtual photon exposes hadronic properties



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Backup slides

$$\sigma_{tot}^{\gamma^* p}(x_{Bj}, Q^2) = \int d^2 r_T \int_0^1 d\alpha \left|\Psi_{\gamma^*}(r_T, \alpha, Q^2)\right|^2 \sigma_{\bar{q}q,}(r_T, x_{Bj})$$

One controls the effective size and energy of the dipole via the photon wave function $\Psi_{\gamma^*}(r_T, x, Q^2)$, varying $Q^2,\ x_{Bj}$.

A remarkable feature of the dipole cross section is Color Transparency (CT): for small dipoles, $r_T \longrightarrow 0$, the cross section vanishes as $\sigma_{\bar{q}q}(r_T) \propto r_T^2 \propto 1/Q^2$. Indeed, a point-like colorless object cannot interact with external color fields. The quadratic r_T-dependence is a consequence of the nonabelian dynamics.

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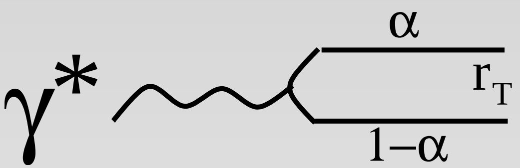
Backup slides

The light-cone distribution amplitude of a $\bar{q}q$ pair in the photon can be calculated perturbatively.



J.Bjorken, J.Kogut & D.Soper (1971)

$$\Psi^{T,L}_{\gamma^*}(\vec{r}_T,\alpha) = \frac{\sqrt{\alpha_{em}}}{2\,\pi}\,\bar{\chi}\,\widehat{O}^{T,L}\,\chi\,K_0(\epsilon r_T)$$

where $\epsilon^2 = \alpha(1-\alpha)Q^2 + m_q^2$;

$$\begin{aligned}
\widehat{O}^{T} &= m_q\,\vec{\sigma}\vec{e} + i(1-2\alpha)\,(\vec{\sigma}\vec{n})\,(\vec{e}\vec{\nabla}_{r_T}) + (\vec{\sigma}\times\vec{e})\vec{\nabla}_{r_T}\ ; \\
\widehat{O}^{L} &= 2\,Q\,\alpha(1-\alpha)\,\vec{\sigma}\vec{n}
\end{aligned}$$

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Backup slides

The mean transverse separation is

$$\langle r_T^2 \rangle \sim \frac{1}{\epsilon^2} = \frac{1}{Q^2\alpha(1-\alpha)+m_q^2} \, ,$$

i.e. the separation is about as small as $1/Q^2$, except the endpoints $\alpha \to 0, 1$

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Backup slides

Is DIS $\gamma^* p \to X$ hard or soft? - both

Is diffraction $\gamma^* p \to Xp$ hard or soft? - only soft

	$\lvert C_\alpha\rvert^2$	σ_α	$\sigma_{tot} = \sum_{\alpha=soft}^{hard} \lvert C_\alpha\rvert^2 \sigma_\alpha$	$\sigma_{sd} = \sum_{\alpha=soft}^{hard} \lvert C_\alpha\rvert^2 \sigma_\alpha^2$
Hard	~ 1	$\sim \frac{1}{Q^2}$	$\sim \frac{1}{Q^2}$	$\sim \frac{1}{Q^4}$
Soft	$\sim \frac{m_q^2}{Q^2}$	$\sim \frac{1}{m_q^2}$	$\sim \frac{1}{Q^2}$	$\sim \frac{1}{m_q^2 Q^2}$

($m_q \sim \Lambda_{QCD}$ plays role of an infra-red cut off)

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Backup slides

Hard fluctuations of the photon have large weight, but vanishing $1/Q^2$ cross section, while soft fluctuations have a small, m_q^2/Q^2 weight, but interact strongly, $\sigma \sim 1/m_q^2$. The latter factor compensates the smallness of the probability in the case of DIS, and over-compensates it for diffraction.

Thus, diffraction is predominantly soft.

Diffractive Drell-Yan

The diffractive amplitude has the form,

$$A_{if}^{(1)}\Big|_{(p_T)_{N_t}=0} = \frac{i}{8\pi}\int d^2r_1 d^2r_2 d^2r_3 d^2r\, dx_{q_1} dx_{q_2} dx_{q_3}$$
$$\times\Psi_i(\{\vec{r}_i\};\{x_{q_i}\})\Psi_f^*(\vec{r}_1+\alpha\vec{r},\vec{r}_2,\vec{r}_3;x_{q_1}-x_\gamma,x_{q_2},x_{q_3})$$
$$\times\Sigma^{(1)}(\vec{r}_1,\vec{r}_2,\vec{r}_3,\vec{r},\alpha)\,\Phi(\vec{r},\alpha)\,e^{-i\vec{k}\cdot\vec{r}},$$

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$$\times \Sigma^{(1)}(\vec{r}_1,\vec{r}_2,\vec{r}_3,\vec{r},\alpha)\,\Phi(\vec{r},\alpha)\,e^{-i\vec{k}\cdot\vec{r}},$$

where the dipole amplitude reads,

$$\begin{aligned}\Sigma^{(1)}(\vec{r}_1,\vec{r}_2,\vec{r}_3,\vec{r},\alpha) &= \sigma(\vec{r}_1-\vec{r}_2)-\sigma(\vec{r}_1-\vec{r}_2-\alpha\vec{r}) \\ &+ \sigma(\vec{r}_1-\vec{r}_3)-\sigma(\vec{r}_1-\vec{r}_3-\alpha\vec{r})\end{aligned}$$

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