Diffractive heavy flavor production and Higgsstrahlung in the color dipole picture

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- Color Dipole Picture of diffraction
- Abelian vs non-Abelian diffractive production
- Diffractive factorisation breaking
- Forward diffractive heavy quarks production
- Diffractive Higgsstrahlung off heavy quarks
- Single diffractive Higgs production
- Conclusions

Reminder: dipole picture of diffractive excitations

R. J. Glauber, Phys. Rev. 100, 242 (1955).
E. Feinberg and I. Ya. Pomeranchuk, Nuovo. Cimento. Suppl. 3 (1956) 652.
M. L. Good and W. D. Walker, Phys. Rev. 120 (1960) 1857.

A hadron can be excited – it is not an eigenstate of interaction!

Eigenstates of interaction are color dipoles

$$|h\rangle = \sum_{\alpha=1} C_\alpha^h |\alpha\rangle \qquad \langle h'|h\rangle = \sum_{\alpha=1} (C_\alpha^{h'})^* C_\alpha^h = \delta_{hh'}$$

$$\hat{f}_{el}|\alpha\rangle = f_\alpha |\alpha\rangle \qquad \langle\beta|\alpha\rangle = \sum_{h'} (C_\beta^{h'})^* C_\alpha^{h'} = \delta_{\alpha\beta}$$

Elastic and single diffractive amplitudes

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

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

Single diffractive cross section

$$\sum_{h'} \left.\frac{d\sigma_{sd}^{h\to h'}}{dt}\right|_{t=0} = \sum_{\alpha=1} |C_\alpha^h|^2 \frac{\sigma_\alpha^2}{16\pi} =$$

$$\int d^2 r_T\, |\Psi_h(r_T)|^2 \frac{\sigma^2(r_T)}{16\pi} = \frac{\langle\sigma^2(r_T)\rangle}{16\pi}$$

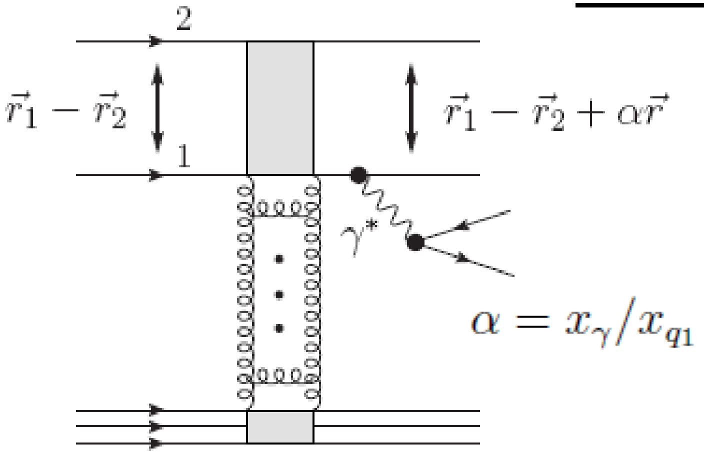
Dipole:

- cannot be excited
- experience only elastic scattering
- have no definite mass, but only separation
- universal – elastic amplitude can be extracted in one process and used in another

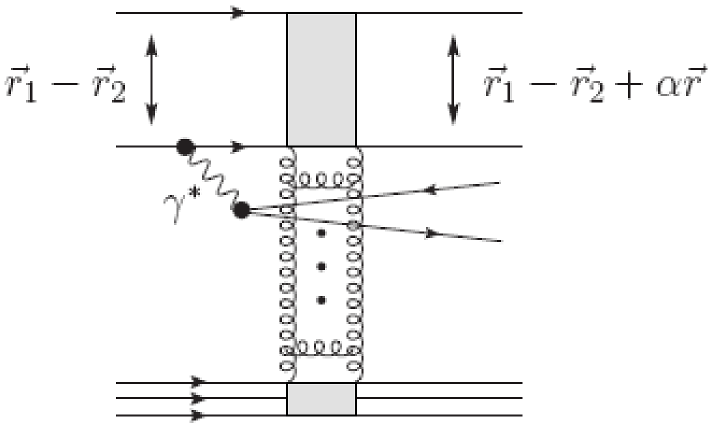
⇒ **Any diffractive amplitude is a superposition of different elastic dipole amplitudes!**

DY example: Abelian Bremsstrahlung off a dipole

...due to transverse motion of partons



$\sigma_{qq}(\vec{r}_1 - \vec{r}_2)$



$\sigma_{qq}(\vec{r}_1 - \vec{r}_2 + \alpha\vec{r})$

$$2i\,\mathrm{Im}\,f_{el}(\vec{b},\vec{r}_p) = \frac{i}{N_c}\sum_X \sum_{c_f c_i} \left|V_q(\vec{b}) - V_q(\vec{b}+\vec{r}_p)\right|^2$$

$$\sigma_{\bar{q}q}(r_p) = \int d^2b\, 2\,\mathrm{Im} f_{el}(\vec{b},\vec{r}_p)$$

DDY in the dipole-target scattering

dipoles with different sizes interact differently!

The fundamental reason for diffraction!

$$M^{(1)}_{qq}(\vec{b},\vec{r}_p,\vec{r},\alpha) = -2ip_i^0\sqrt{4\pi}\,\frac{\sqrt{1-\alpha}}{\alpha^2}\,\Psi^\mu_{\gamma^* q}(\alpha,\vec{r})\left[2\mathrm{Im}\,f_{el}(\vec{b},\vec{r}_p) - 2\mathrm{Im}\,f_{el}(\vec{b},\vec{r}_p+\alpha\vec{r})\right]$$

destructive interference ⇒ **one of the reasons for diffractive factorisation breaking!**

Elastic amplitude and gap survival

Complete dipole elastic amplitude has **eikonal form**:

$$\mathrm{Im}\, f_{el}(\vec{b}, \vec{r}_1 - \vec{r}_2) = 1 - \exp\left[i\chi(\vec{r}_1) - i\chi(\vec{r}_2)\right],$$

$$\chi(b) = -\int_{-\infty}^{\infty} dz\, V(\vec{b}, z),$$

nearly imaginary at high energies!

Diffractive amplitude is proportional to

$$\mathrm{Im}\, f_{el}(\vec{b}, \vec{r}_1 - \vec{r}_2 + \alpha\vec{r}) - \mathrm{Im}\, f_{el}(\vec{b}, \vec{r}_1 - \vec{r}_2) = \boxed{\exp\left[i\chi(\vec{r}_1) - i\chi(\vec{r}_2)\right]} \exp\left[i\alpha\, \vec{r}\cdot\vec{\nabla}\chi(\vec{r}_1)\right]$$

another source of QCD factorisation breaking

Exactly the soft survival probability amplitude

controlled by soft spectator partons

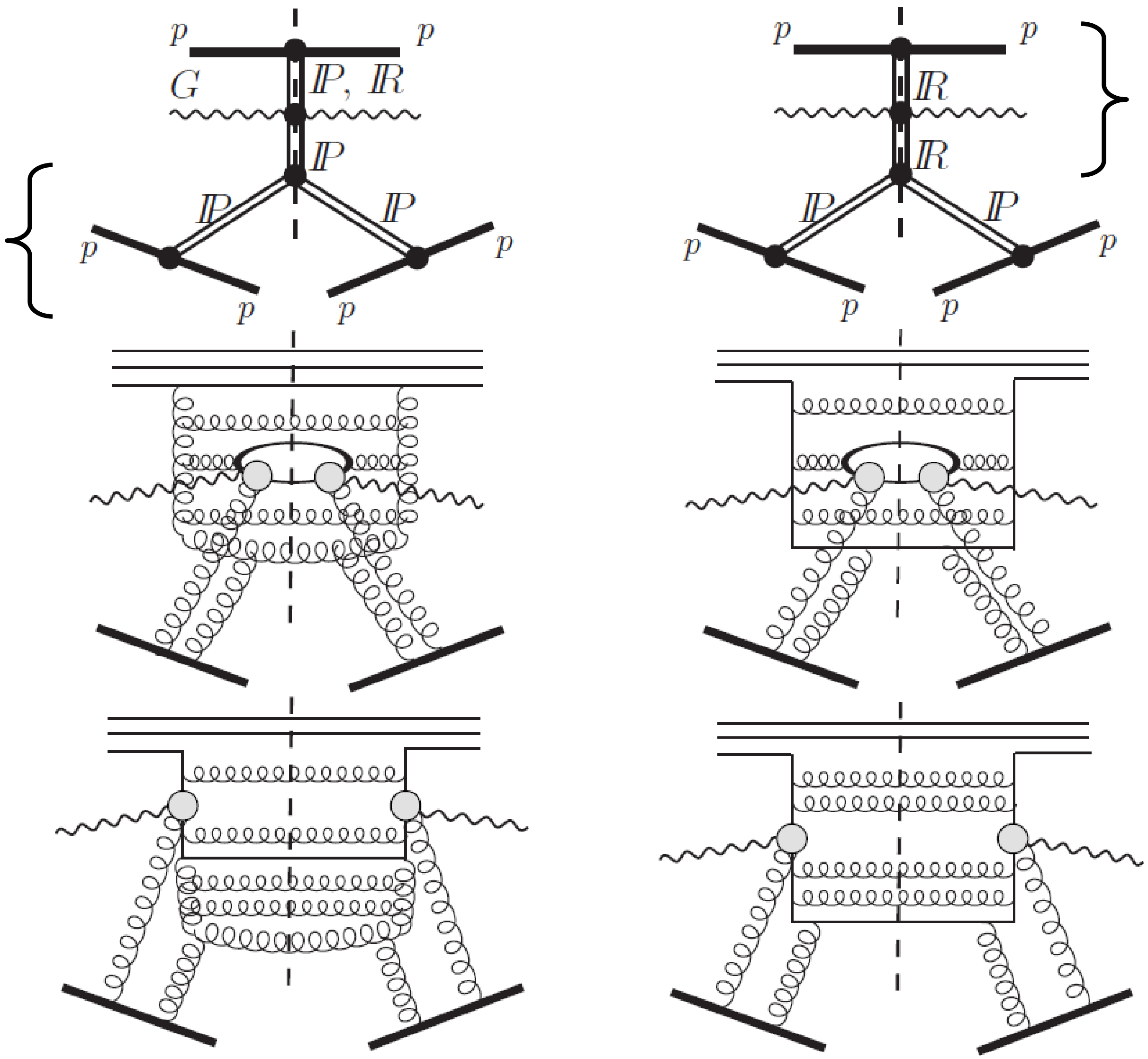
vanishes in the black disc limit!

Absorption effect should be included into elastic amplitude parameterization (at the amplitude level)

DY example: Regge picture of diffractive excitations

$$\xi = 1 - x_F = \frac{M_X^2}{s} \ll 1$$

LRG



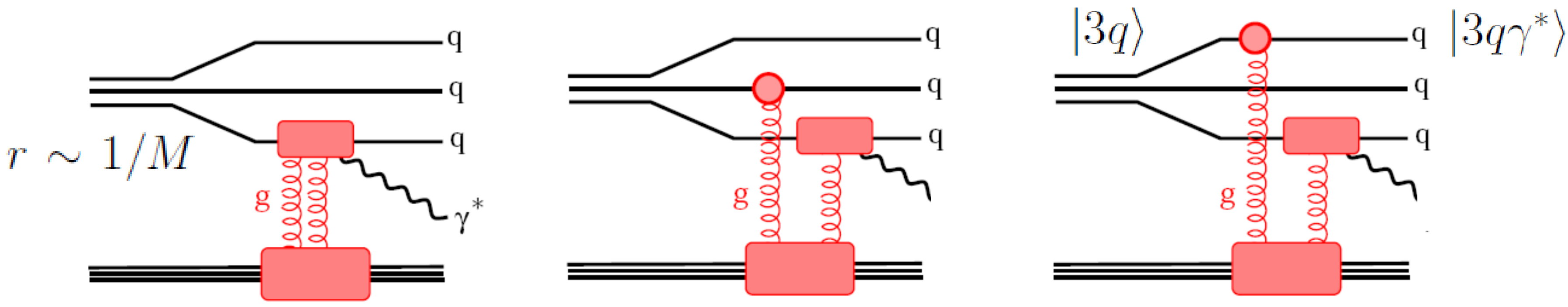
projectile fragmentation region (diffractive mass)

diffractive sea quark excitation

diffractive valence quark excitation

DY example: Probing large distances in the proton…

R. Pasechnik, B. Kopeliovich, I. Potashnikova, Phys. Rev. D86, 114039, 2012
R. Pasechnik, B. Kopeliovich, Eur. Phys. J. C71: 1827, 2011
B. Kopeliovich, I. Potashnikova, I. Schmidt and A. Tarasov, Phys. Rev. D74: 114024, 2006



Interplay between hard and soft scales

GBW dipole (ex.) $\sigma(r) = \sigma_0 \left(1 - e^{-r^2/R_0^2}\right)$

Amplitude $\propto \sigma(\vec{R}) - \sigma(\vec{R} - \alpha\vec{r}) = \frac{2\alpha\,\sigma_0}{R_0^2(x_2)} e^{-R^2/R_0^2(x_2)} \left(\vec{r}\cdot\vec{R}\right) + O(r^2)$

Diffractive DIS $\propto r^4$

Diffractive DY $\propto r^2$

QCD factorization holds!

QCD factorization is broken!

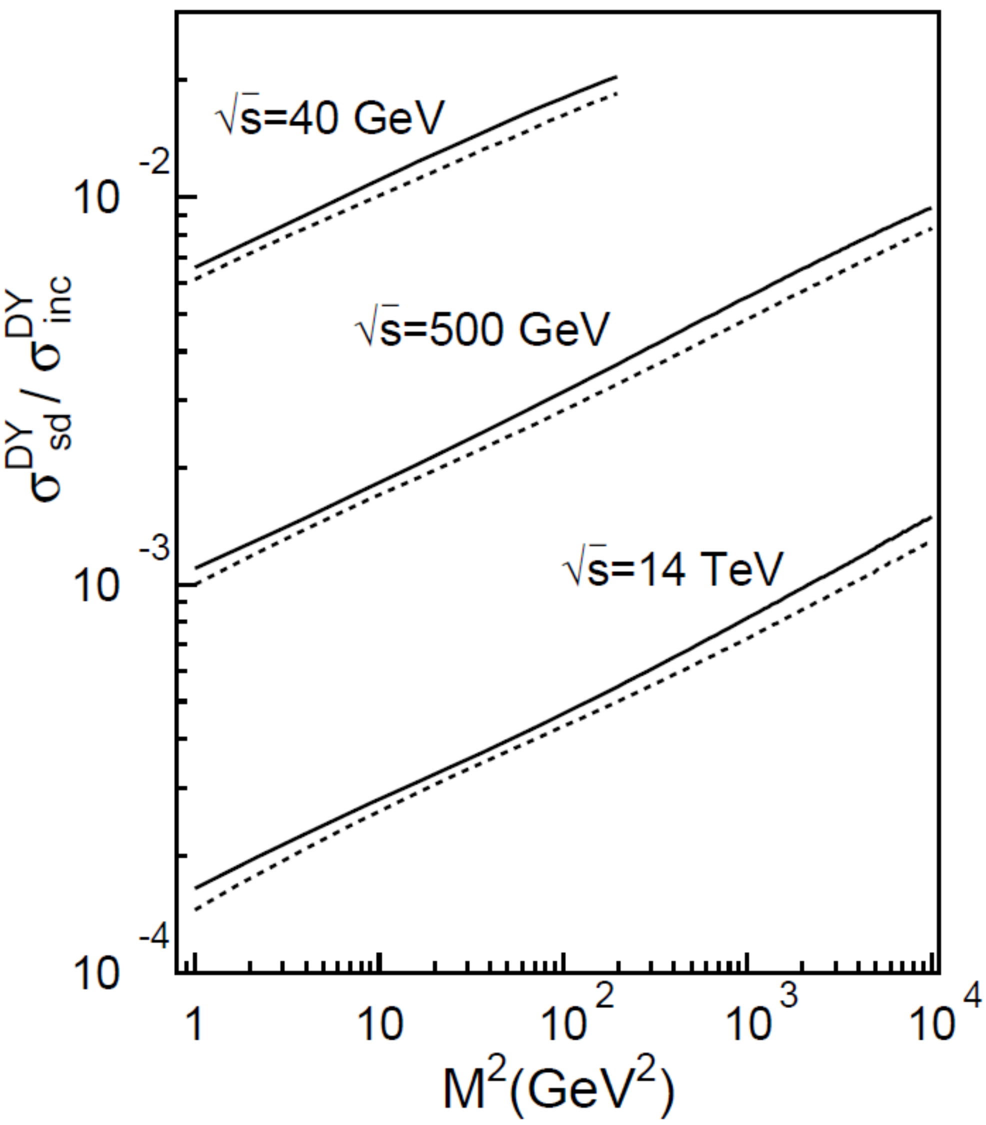
Higher twist effect!

Leading twist effect!

Diffraction is dominated by soft fluctuations!

Diffraction is dominated by semisoft-semihard fluctuations!

DY example: signatures for QCD factorisation breaking



saturated shape of the dipole CS

+

unitarity corrections

Fraction of diffractive events

- **steeply falls with energy**
- **grows with the hard scale**

Opposite to QCD factorization-based results (like Ingelman-Schlein)

See QCD factorisation-based calculations by

G. Kubasiak, A. Szczurek, Phys.Rev.D84:014005,2011

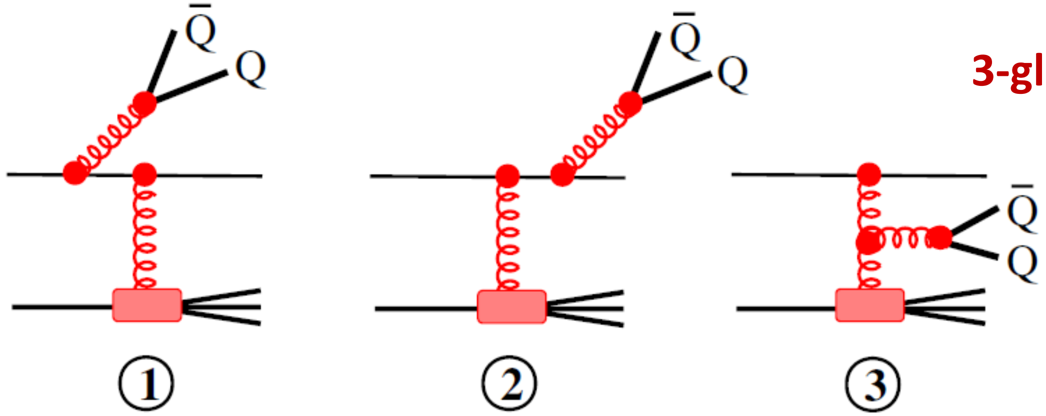
Why go non-Abelian?

- Higher single diffractive cross sections than heavy QQ CEP/Abelian mechanisms (dominates the diffractive heavy flavor production)
- One more promising test of QCD diffraction mechanisms and, in particular, QCD factorisation breaking effects
- More complicated than Abelian but enables to test non-Abelian mechanisms of heavy flavor production vs Abelian ones
- The most important background for intrinsic heavy flavor studies via diffraction
- An important playground for forward Higgsstrahlung studies off heavy flavor/gauge bosons (Brodsky et al ’06, ‘07)
- One of the ways of direct Higgs-bottom/Higgs-top Yukawa couplings studies via diffraction

BUT! The pile-up and backgrounds yet need to be taken under control at high energies!

Non-Abelian Bremsstrahlung off a quark and gg-fusion

Non-Abelian couplings

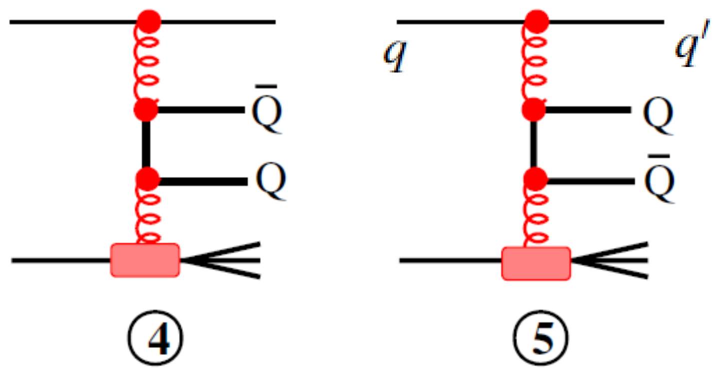


3-gluon coupling

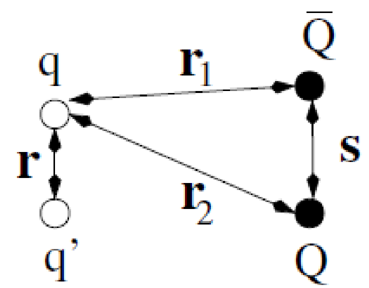
Bremsstrahlung component

$$M^T_{\rm Br} = M^T_1 + M^T_2 + \frac{Q^2}{M^2+Q^2} M^T_3$$

Extra QQ production terms



Impact parameters



Production component

$$M^T_{\rm Pr} = \frac{M^2}{M^2+Q^2} M^T_3 + M^T_4 + M^T_5$$

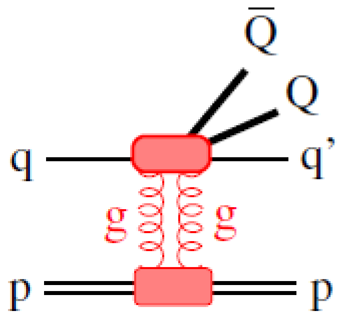
q'-(QQ) distance: $\vec{\rho} = \vec{r} - \beta \vec{r}_1 - (1-\beta)\vec{r}_2$

B. Kopeliovich et al, Phys.Rev.D76, 034019 (2007)

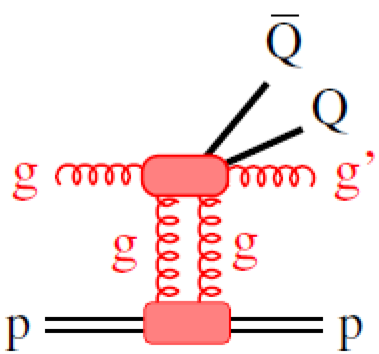
Does not vanish in the forward scattering!

QQ production: diffractive parton-proton scattering

Quark-proton scattering
(diffractive quark excitation)



Gluon-proton scattering
(diffractive gluon excitation)

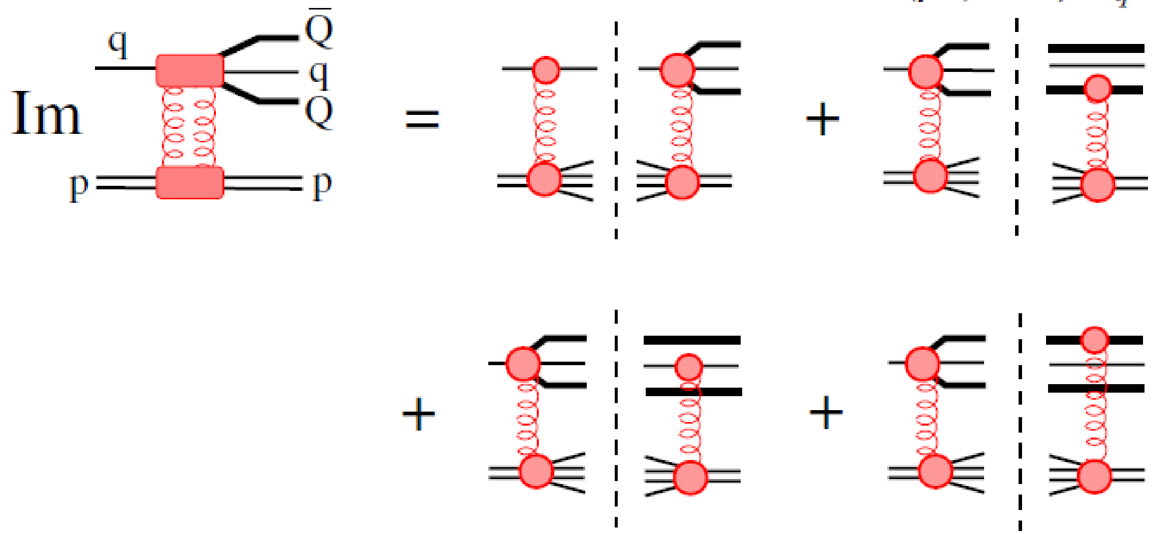


Imaginary amlitude

Cutting rules

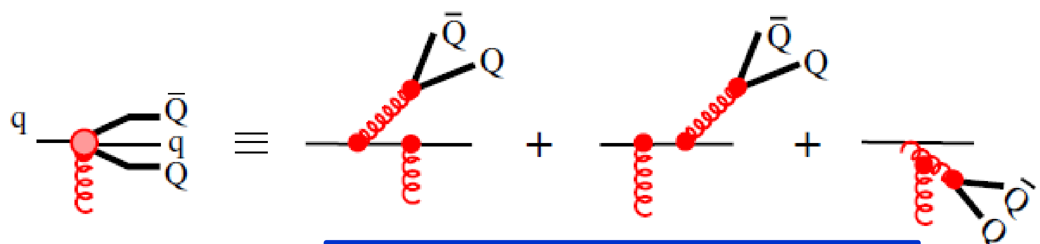
$$\langle\rho^2\rangle \sim \langle s^2\rangle \sim \frac{1}{m_Q^2}$$

$$\langle s^2\rangle \sim 1/m_Q^2$$
$$\langle \rho^2\rangle \sim 1/m_q^2$$



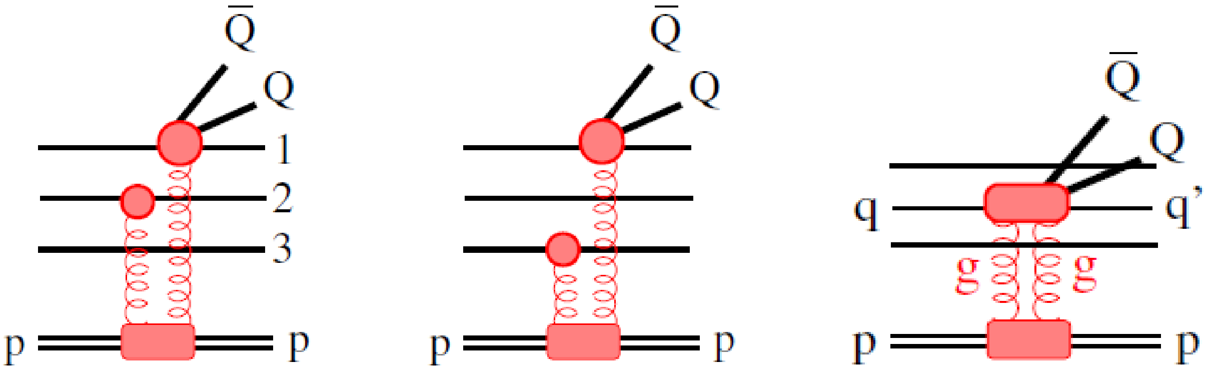
“Bremsstrahlung” contribution

“Production” contribution



Does not vanish in the forward scattering!

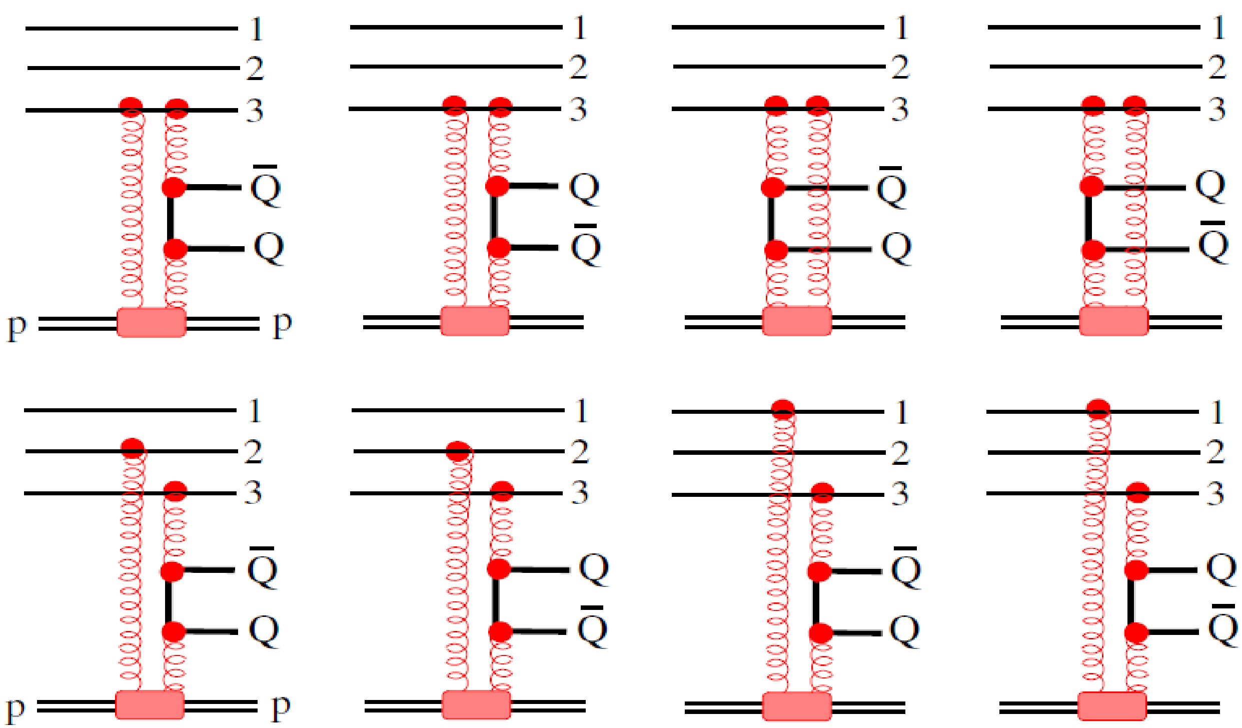
QQ production: diffractive proton-proton scattering



and sea gluons/quarks must be included!

$$|\Psi_{\text{in}}(\vec{r}_i, x_i)|^2 \Rightarrow \frac{1}{3}\left[\sum_q q(x) + \bar{q}(x) + \frac{81}{16} g(x)\right]$$

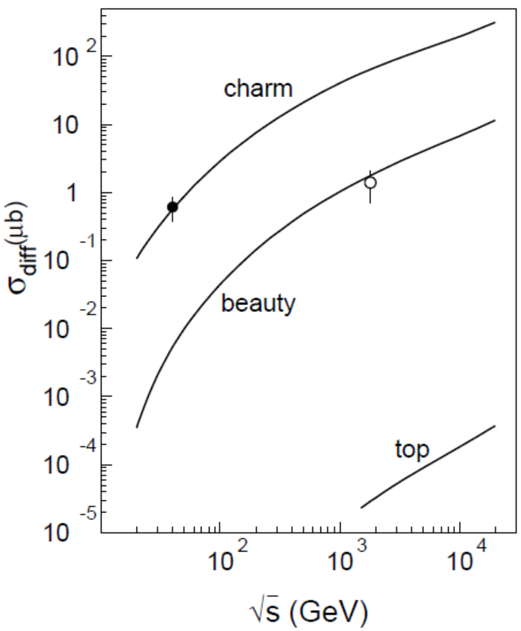
Production component strongly dominates the diffractive cross section!

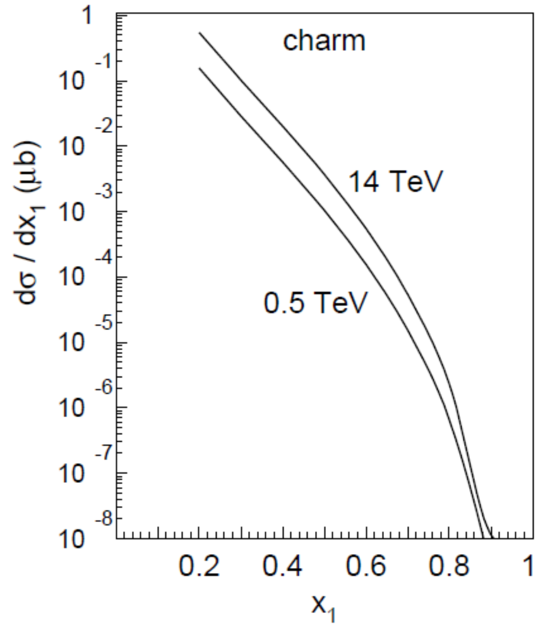


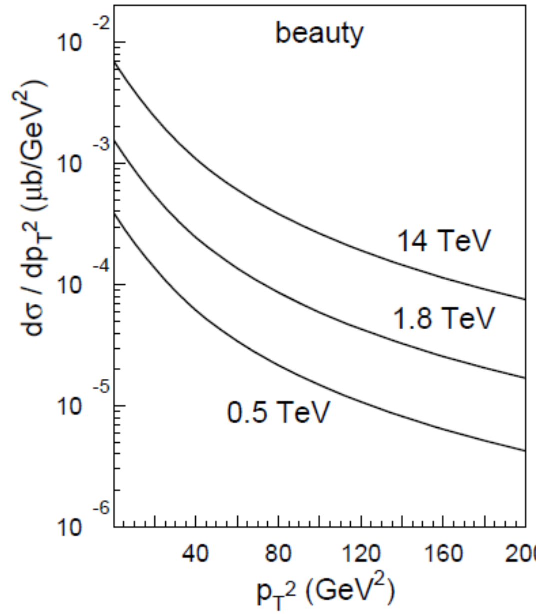
the largest leading-twist contribution

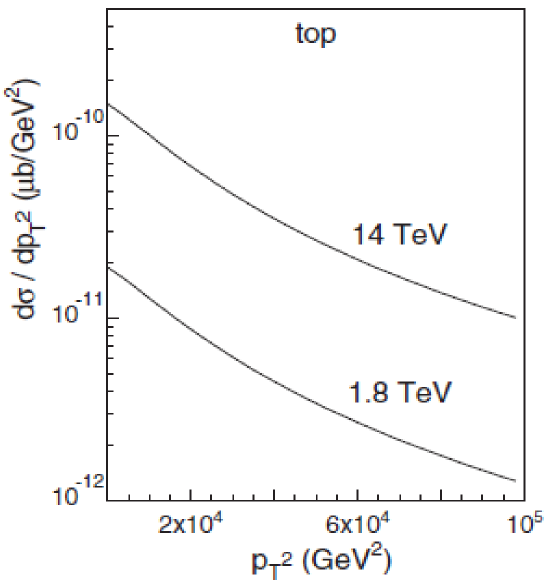
$$\sim\ 1/m_Q^2$$

Forward diffractive heavy flavor: cross sections









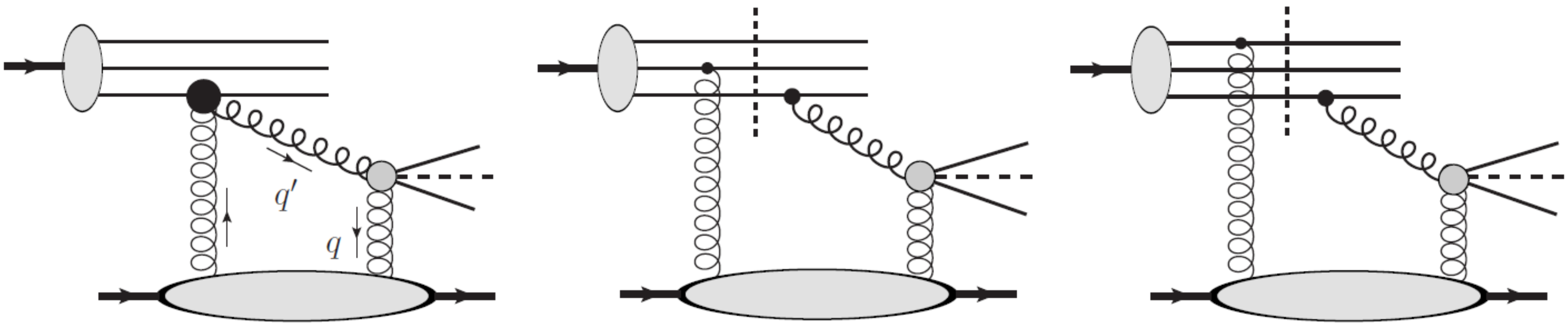
B. Kopeliovich et al, Phys.Rev.D76, 034019 (2007)

Leading-twist diffractive excitations are proven to be dominated!

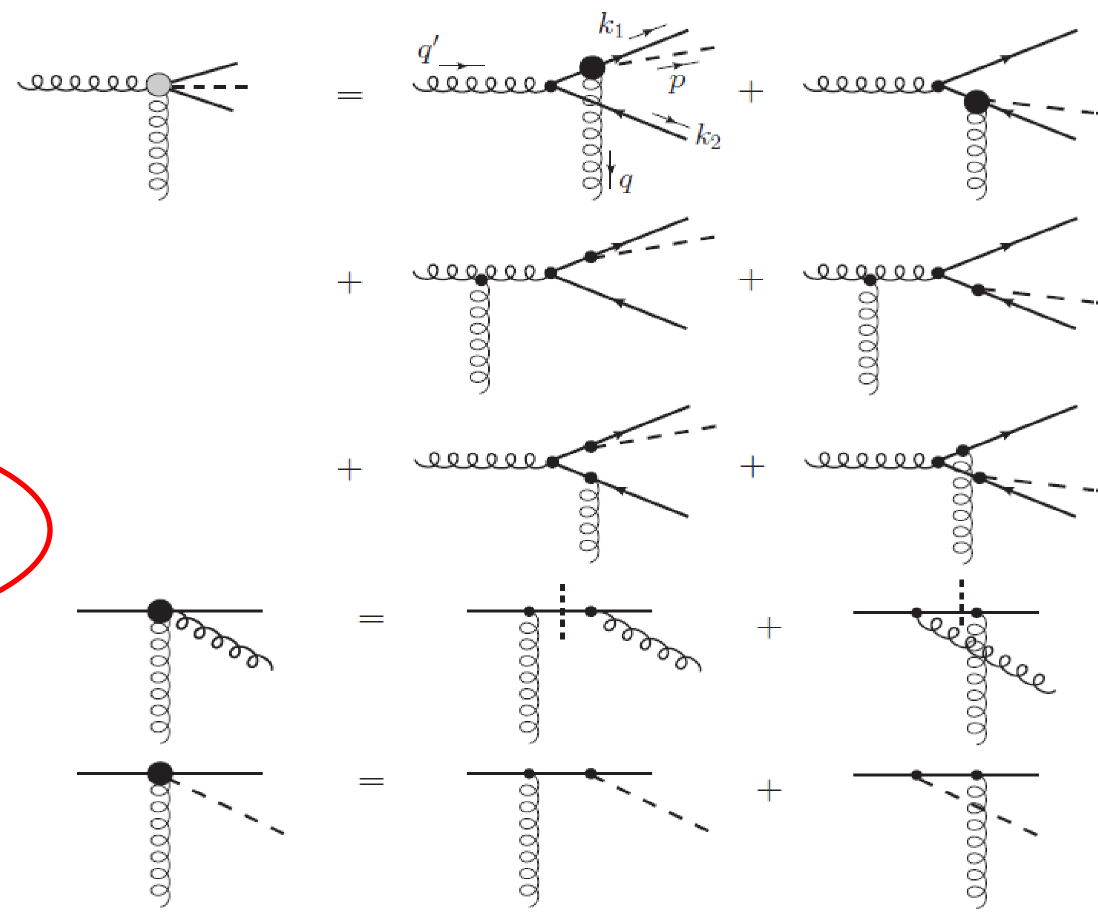
cf. *QCD factorisation-based approach* by

M. Luszczak, W. Schafer and A.Szczurek, arXiv:1305.4727 [hep-ph]

Diffractive Higgsstrahlung off heavy flavor



$$p + p \to \bar{Q}Qh + X + p$$



Gluon-Gluon fusion strongly dominates over gluon Bremsstrahlung!

Single diffractive cross section: Higgsstrahlung

The general result:

$$\frac{d\sigma^{L,T}(pp\to p(Q\bar{Q}h)X)}{d^2\vec{\kappa}\,d^2\vec{r}\,d\ln\alpha\,d\ln\beta\,d\ln\xi\,d^2\delta_\perp}\Big|_{\delta_\perp\to 0} = \frac{1}{(2\pi)^4}\frac{9}{256\pi^2}$$

$$\times\sum_{l=q,g}\sum_{q=val,sea}\int d^2\vec{r}_1 d^2\vec{r}_2 d^2\vec{r}_3\,d^2\vec{\omega}\,d^2\vec{\rho}_1 d^2\vec{\rho}_2\,d^2\vec{\sigma}_1 d^2\vec{\sigma}_2\,dx_q\prod_{j\neq 1}dx_q^j\prod_k dx_g^k\,e^{i\vec{\kappa}\cdot(\vec{\rho}_1-\vec{\rho}_2)}$$

$$\times\, e^{i\vec{r}\cdot(\vec{\sigma}_1-\vec{\sigma}_2)}\,\Sigma_l^{L,T}(\vec{r}_1,\vec{r}_2,\vec{r}_3;\alpha,\vec{\omega};\beta,\vec{\rho}_1;\xi,\vec{\sigma}_1)\,\Sigma_l^{L,T*}(\vec{r}_1,\vec{r}_2,\vec{r}_3;\alpha,\vec{\omega};\beta,\vec{\rho}_2;\xi,\vec{\sigma}_2)$$

$$\times\,|\Psi_i(\vec{r}_1,\vec{r}_2,\vec{r}_3;x_q,\{x_q^{2,3,\dots}\},\{x_g^{1,2,\dots}\})|^2\,,$$

diffractive amplitude of QQh production in parton-proton scattering

Incoming proton wave function

$$|\Psi_i(\vec{r}_1,\vec{r}_2,\vec{r}_3;x_q,x_{q_2},x_{q_3})|^2 = \frac{3a^2}{\pi^2}e^{-a(r_1^2+r_2^2+r_3^2)}\rho(x_q,x_{q_2},x_{q_3}) \times\,\delta(\vec{r}_1+\vec{r}_2+\vec{r}_3)\delta(1-x_q-x_{q_2}-x_{q_3})$$

$$a = \langle r_{ch}^2\rangle^{-1}$$

Valence quark distribution

$$x_q = \frac{x_1}{\alpha}\,,\qquad x_1 = \frac{q'^+}{P_1^+}$$

$$\int dx_{q_2}dx_{q_3}\,\delta(1-x_q-x_{q_2}-x_{q_3})\rho(x_q,x_{q_2},x_{q_3}) = \rho_q(x_q)$$

+ sea quarks and antiquarks!

an immediate access to the quark PDFs at large x!

Single diffractive amplitude: Higgsstrahlung

<u>*Effective wave function*</u>

$$\Sigma^{L,T}_{q(1)}(\vec r_1,\vec r_2,\vec r_3;\alpha,\vec\omega;\beta,\vec\rho;\xi,\vec\sigma) = \frac{1}{2}(\tau^{q_1}_b\tau^{q_1}_a)(\tau^Q_a\tau^Q_b)\left\{\tilde\Phi^{T,L}_q(\alpha,\vec\omega;\beta,\vec\rho;\xi,\vec\sigma)\right.$$

$$\times\int d^2b\left\{\left[2\mathrm{Im}\,f_{el}(\vec b,(1-\alpha)\,\vec\omega-\xi\vec\sigma)-2\mathrm{Im}\,f_{el}(\vec b,(1-\alpha)\,\vec\omega)\right]\right.$$

$$\left.\left.-\left[2\mathrm{Im}\,f_{el}(\vec b,(1-\alpha)\,\vec\omega-\beta\vec\rho-\xi\vec\sigma)-2\mathrm{Im}\,f_{el}(\vec b,(1-\alpha)\,\vec\omega-\beta\vec\rho)\right]\right\}\right\}$$

+ a lot more...

<u>*Effective dipole cross section*</u>

<u>**Soft scale:**</u> $\langle\omega^2\rangle\sim 1/m_q^2\sim\langle R\rangle^2$

<u>***Hard scales:***</u> $\begin{cases}\langle\rho^2\rangle\sim 1/m_Q^2\\ \langle\sigma^2\rangle\sim 1/M_h^2\end{cases}$

The source of the higher-twist Higgsstrahlung:

$$\left[\mathrm{Im}\,f_{el}(\vec b,\vec R+A\vec\rho+B\vec\sigma)-\mathrm{Im}\,f_{el}(\vec b,\vec R+A\vec\rho)\right]-\left[\mathrm{Im}\,f_{el}(\vec b,\vec R+B\vec\sigma)-\mathrm{Im}\,f_{el}(\vec b,\vec R)\right]$$

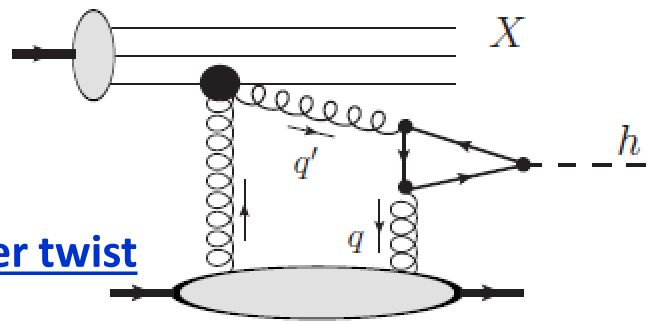
$$\simeq A\,B\,\frac{\partial^2\mathrm{Im}\,f_{el}(\vec b,\vec x)}{\partial x_i\partial x_j}\Big|_{\vec x=\vec R}\,\rho_i\,\sigma_j,$$

the principal source of diffractive factorisation breaking

$$\int d^2b\,\frac{\partial^2\mathrm{Im}\,f_{el}(\vec b,\vec x)}{\partial x_i\partial x_j}\Big|_{\vec x=\vec R}\equiv C_{ij}(\vec R)\,,\quad C_{ij}(\vec R)=\frac{\sigma_0(s)}{R_0^2(s)}\,e^{-R^2/R_0^2(s)}\left[\delta_{ij}-\frac{2R_iR_j}{R_0^2(s)}\right]$$

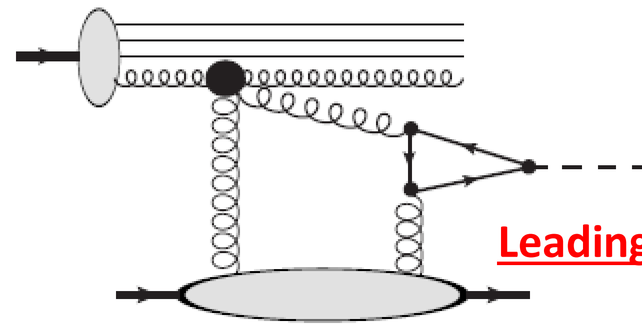
Loop-induced single diffractive Higgs: the dipole picture

Diffractive quark excitation:



Higher twist

Diffractive gluon excitation:



Leading twist

Gluon-gluon fusion via a heavy top loop

$$T^f_{\mu\nu}(q,q') \simeq i\frac{\sqrt{\alpha_s}}{2\pi}\frac{1}{v}\left[(qq')g_{\mu\nu} - q_\mu q'_\nu\right] G^f_1\left(\frac{M_h^2 + i\epsilon}{4m_f^2}\right) \qquad G^f_1 \to 2/3$$

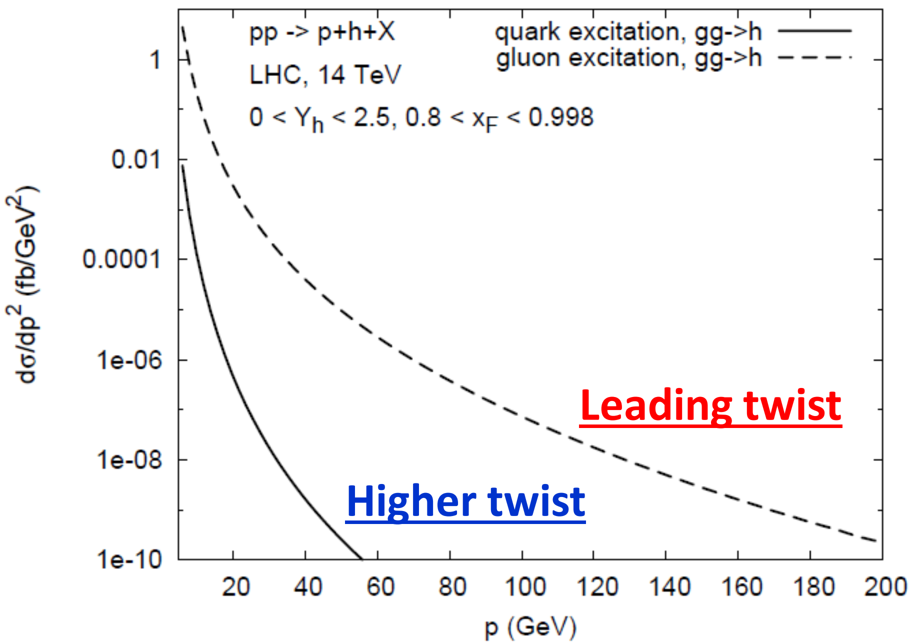
The cross section

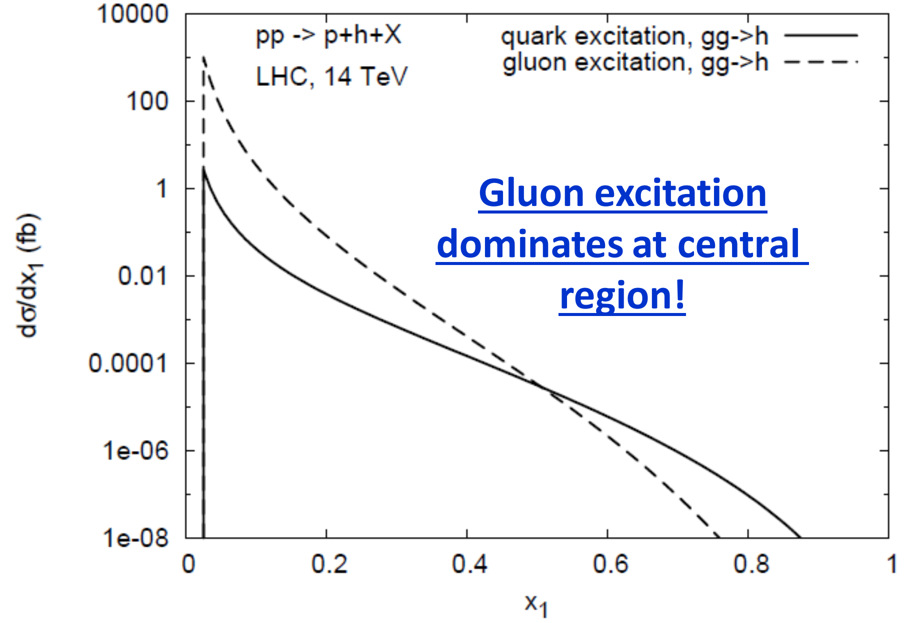
$$\frac{d\sigma_q(pp\to phX)}{d^2\vec{p}\,d\ln\alpha\, d^2\vec{\delta}_\perp}\Big|_{\delta_\perp\to 0} = \frac{1}{(2\pi)^2}\frac{1}{64\pi^2}\sum_q \int d^2\vec{\omega}d^2\vec{\omega}\,'\,dx_q\left[\rho_q(x_q) + \rho_{\bar{q}}(x_q)\right]$$
$$\times\,\Phi^q_\triangle(\alpha,\vec{\omega})\Phi^{q*}_\triangle(\alpha,\vec{\omega}\,')\,\Sigma_\triangle(\alpha,\vec{\omega})\Sigma_\triangle(\alpha,\vec{\omega}\,')\,e^{i\vec{p}\cdot(\vec{\omega}-\vec{\omega}\,')}\,,$$

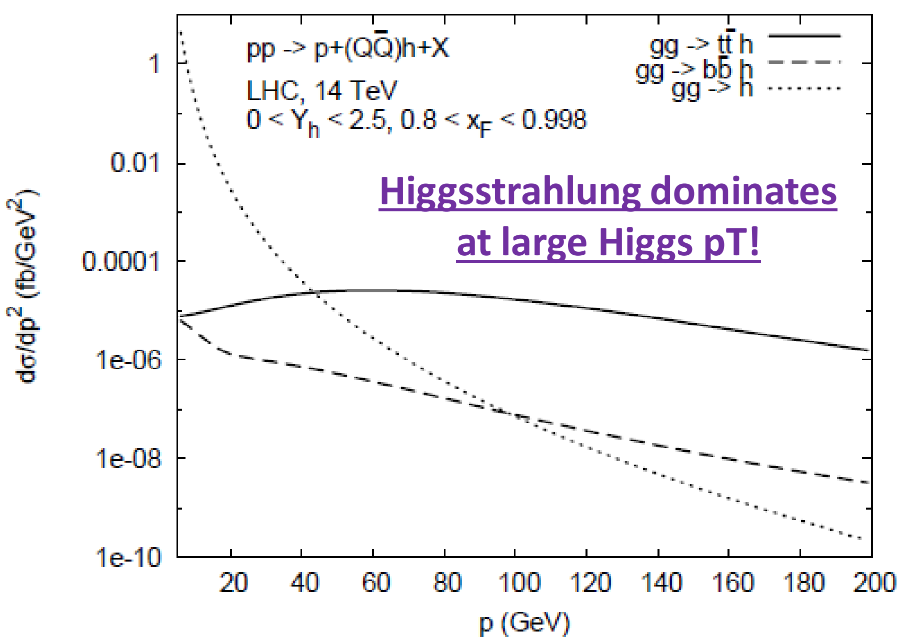
The hard scale

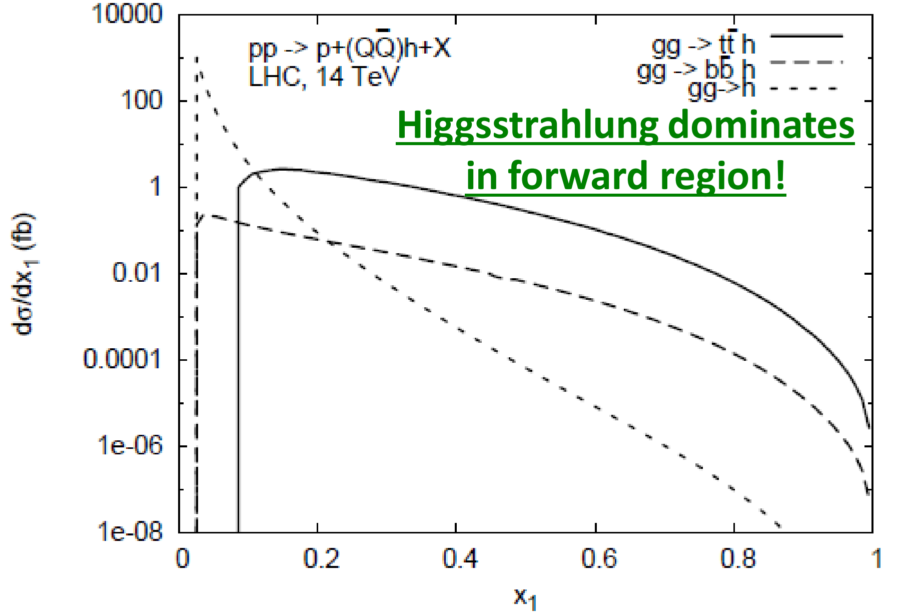
$$\Sigma_\triangle = \frac{3}{2}\Big[\sigma(\vec{\omega}) - \sigma\big((1-\alpha)\vec{\omega}\big)\Big] \simeq \frac{3\sigma_0}{2R_0^2}\alpha(2-\alpha)\omega^2 \qquad \omega \ll r_{ij} \sim R$$

Numerical results









Conclusion

- The QCD factorisation is **broken by the presence of transverse motion of spectator quarks at large separations**. The same effect is responsible for the absorption.
- Hard/soft interactions and interplay leads to **dominance of leading-twists mechanisms** in the diffractive heavy flavor (DHF) production
- Experimental measurements of DHF would allow to probe directly the dipole cross section **at large separations**, as well as **the proton structure** function at soft and semi-hard scales, and large x
- The observation of DHF production **provides a good tool for studies of intrinsic heavy flavors**
- The **diffractive Higgsstrahlung** off heavy quarks is enhanced at forward rapidities compared to the single diffractive Higgs boson production
- The **major background** for the diffractive Higgsstrahlung comes from (ttbar)+(bbbar) final states at large Y's is expected to come **multiparton interactions** and needs to be analyzed at the next step