Higgsstrahlung at forward rapidities

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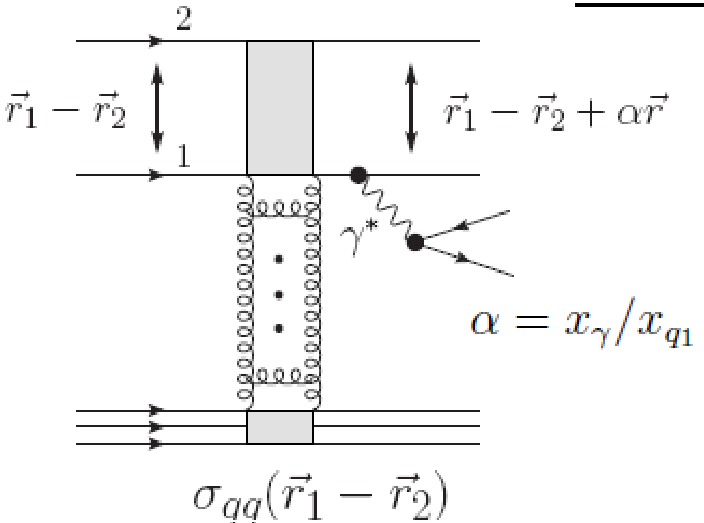
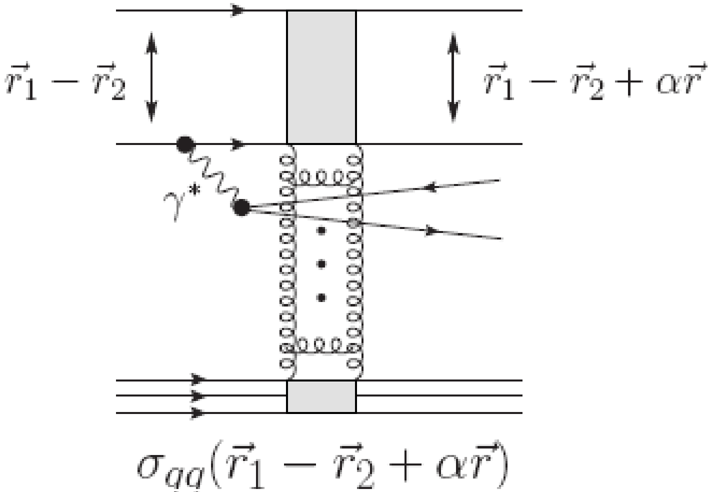
- Single diffractive Higgs production
- Inclusive vs diffractive Higgsstrahlung
- Conclusions

DY example: Abelian Bremsstrahlung off a dipole

...due to transverse motion of partons





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

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

DDY in the dipole-target scattering

dipoles with different sizes interact differently!

The fundamental reason for diffraction!

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

destructive interference

one of the reasons for diffractive factorisation breaking!

Elastic amplitude and gap survival

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

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

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

nearly imaginary at high energies!

Diffractive amplitude is proportional to

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

another source of QCD factorisation breaking

Exactly the soft survival probability amplitude

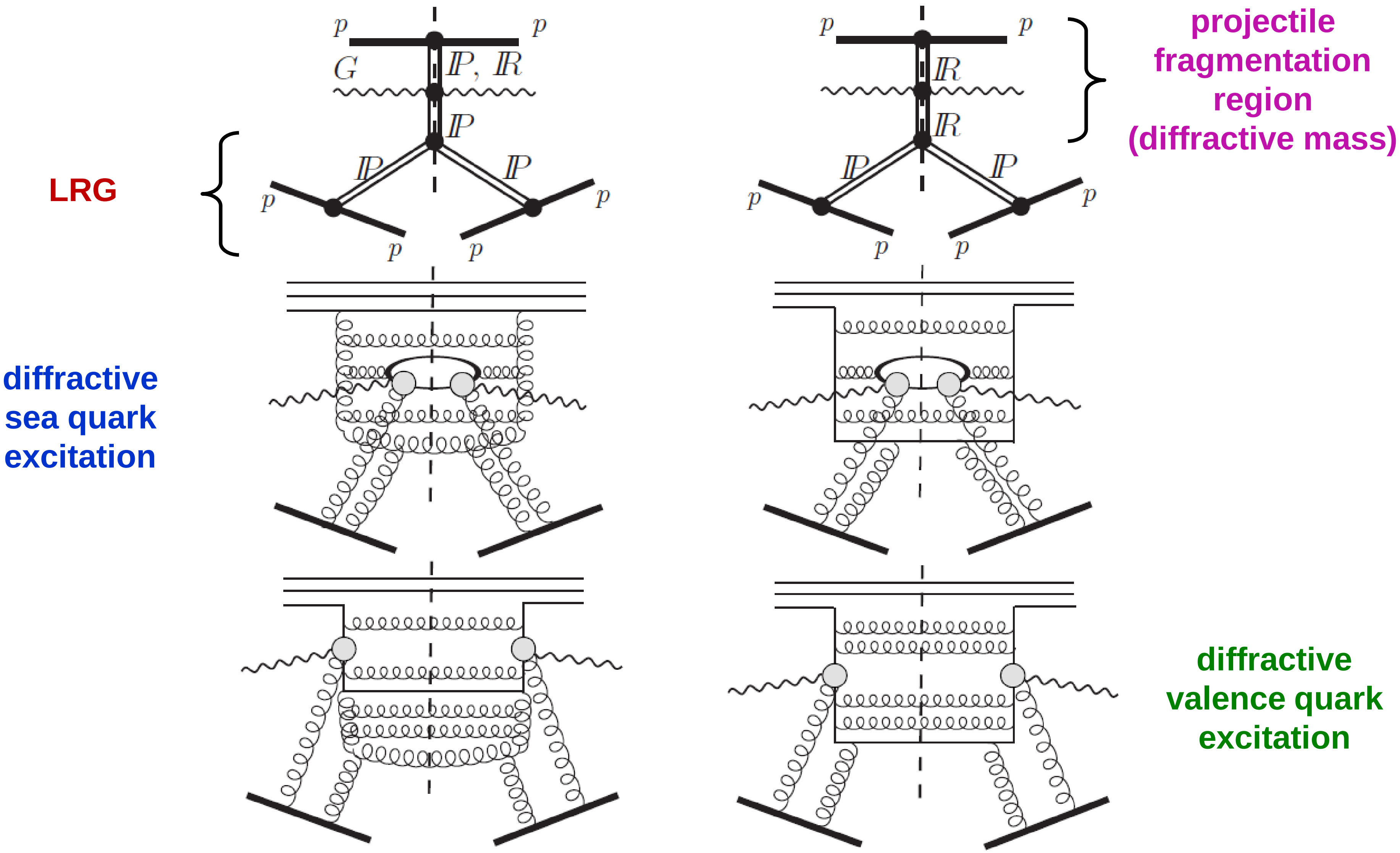
controlled by soft spectator partons

vanishes in the black disc limit!

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

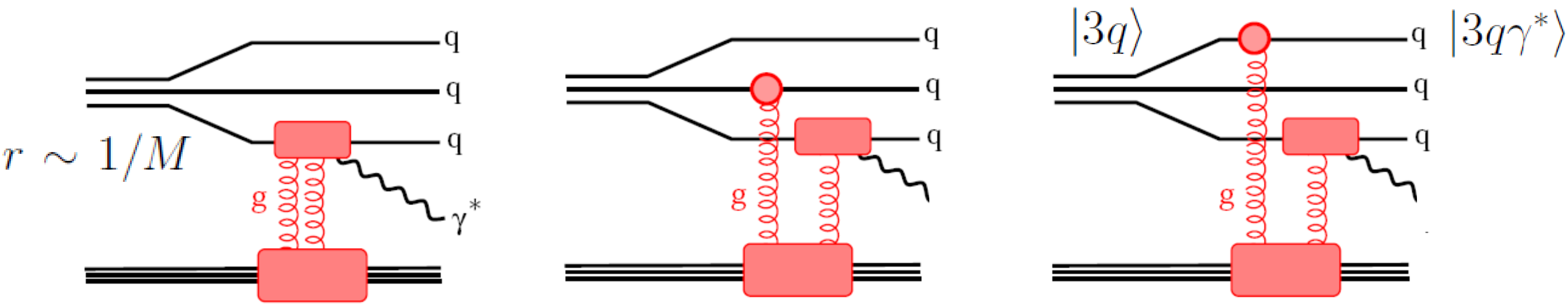
DY example: Regge picture of diffractive excitations

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



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



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

Interplay between hard and soft scales

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 $\propto r^2$

diffractive factorization holds!

diffractive factorization is broken!

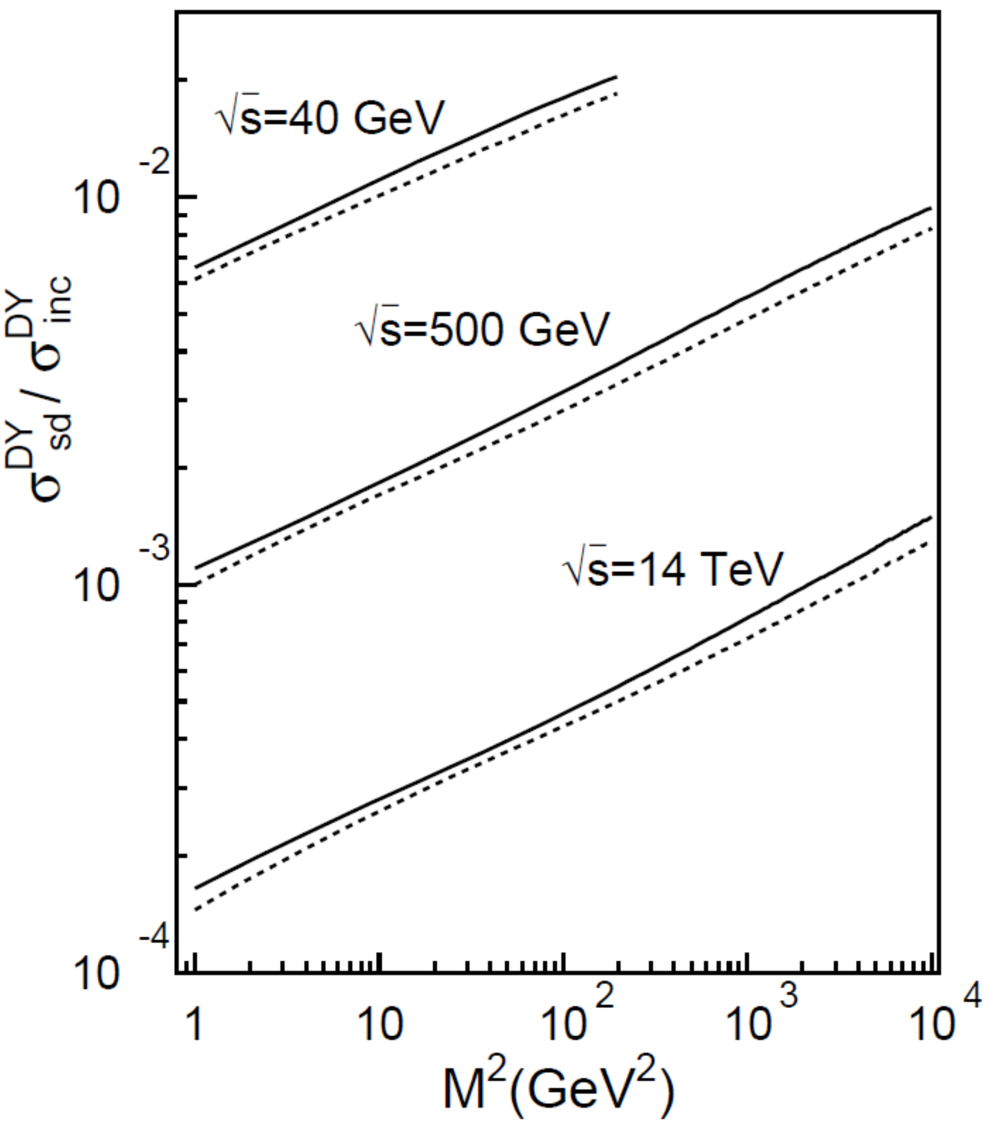
Higher twist effect!

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 factorization-based results (like Ingelman-Schlein)

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

Non-Abelian diffraction

- Larger single diffractive cross sections than heavy QQ CEP/Abelian mechanisms (dominates the diffractive heavy flavor production)

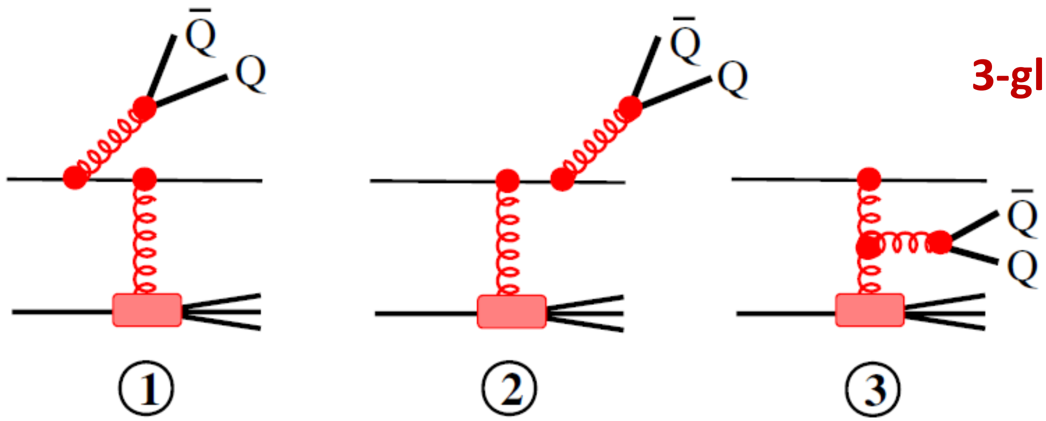
- One more promising test of QCD diffraction mechanisms and, in particular, diffractive factorisation breaking effects

- An 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

Non-Abelian Bremsstrahlung off a quark and gg-fusion

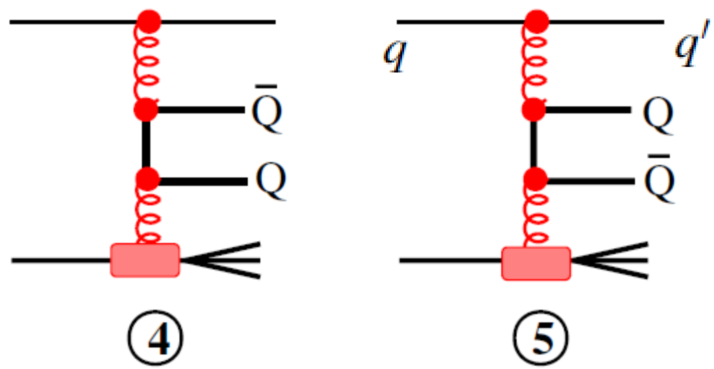


3-gluon coupling

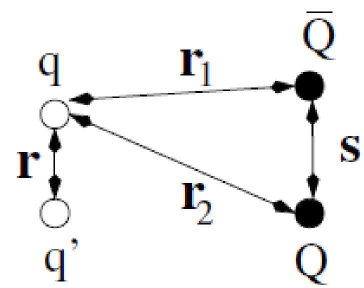
Bremsstrahlung component

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

Extra QQ production terms



Impact parameters



Production component

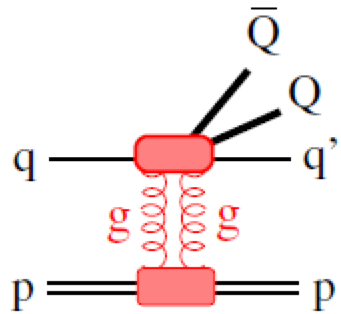
$$M^T_{\rm Pr} = \frac{M^2}{M^2 + Q^2} M^T_3 + M^T_4 + M^T_5$$

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)

QQ production: diffractive parton-proton scattering

Quark-proton scattering
(diffractive quark excitation)



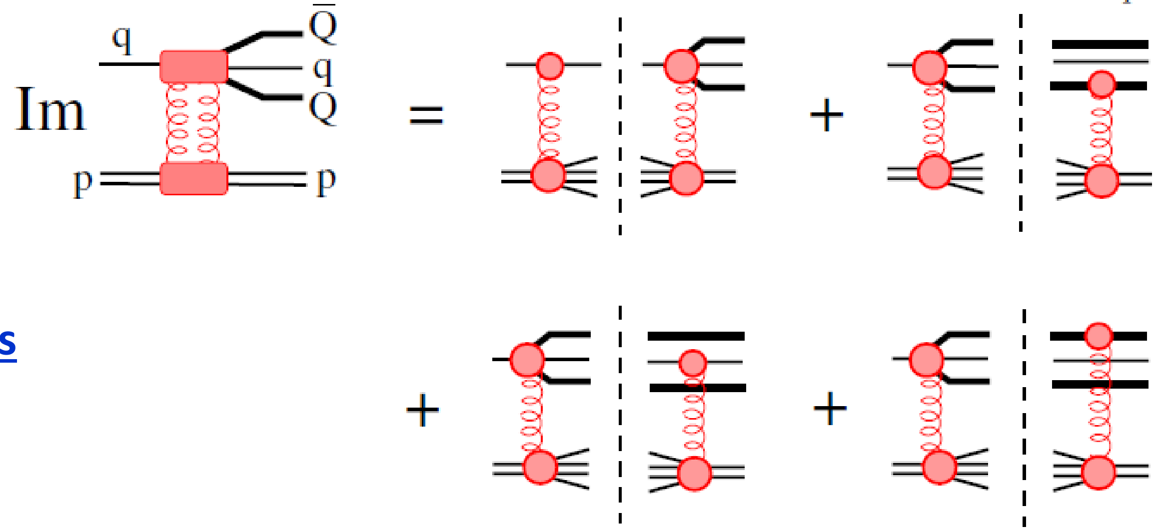
...dominant at forward rapidities

Imaginary amlitude

Cutting rules

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

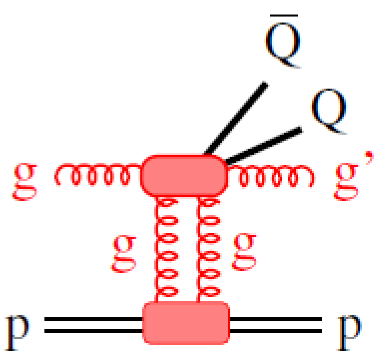
$$\langle s^2\rangle \sim 1/m_Q^2$$
$$\langle\rho^2\rangle \sim 1/m_q^2$$



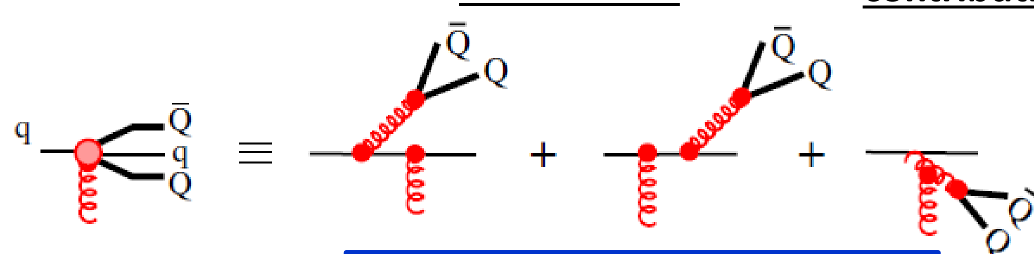
"Bremsstrahlung" contribution

"Production" contribution

Gluon-proton scattering
(diffractive gluon excitation)

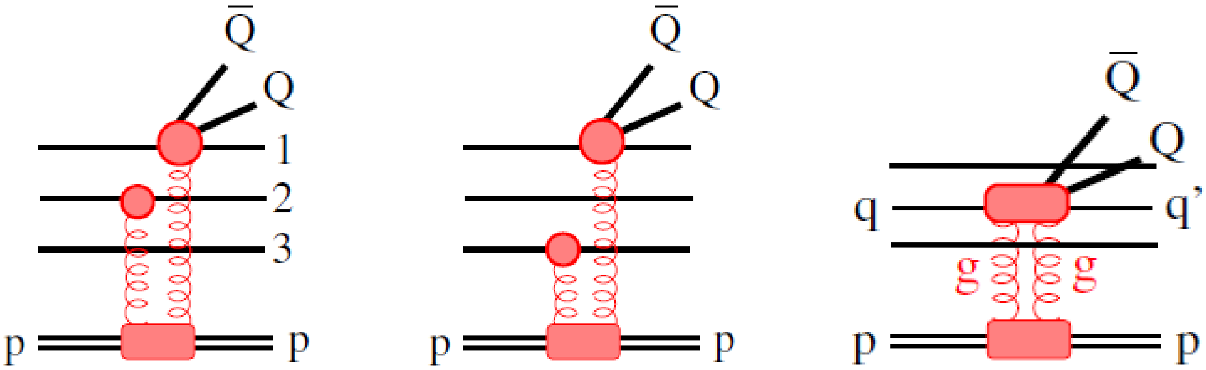


...vanishes at forward rapidities



Does not vanish
in the forward scattering!

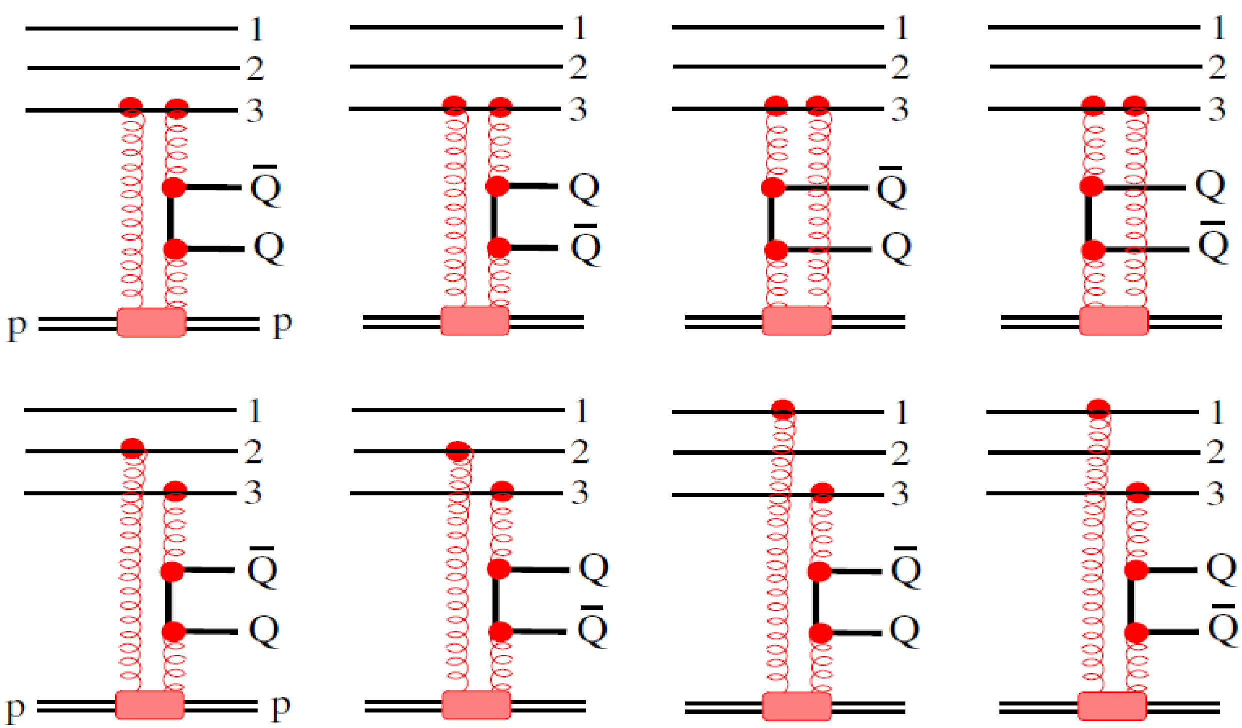
QQ production: diffractive proton-proton scattering



and sea gluons/quarks must be included!

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

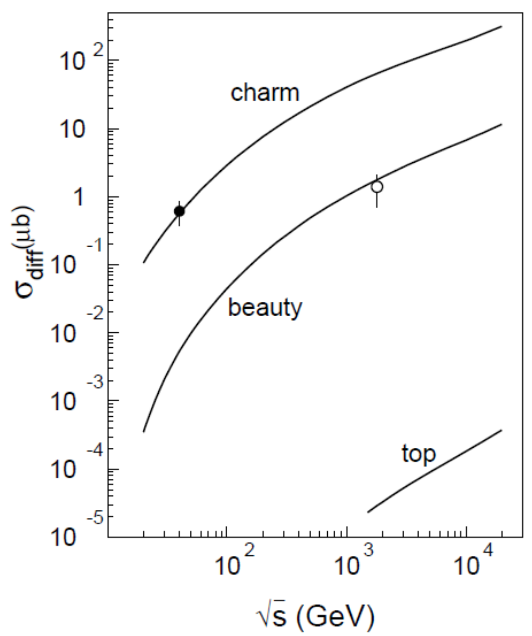
Production component strongly dominates the diffractive cross section!

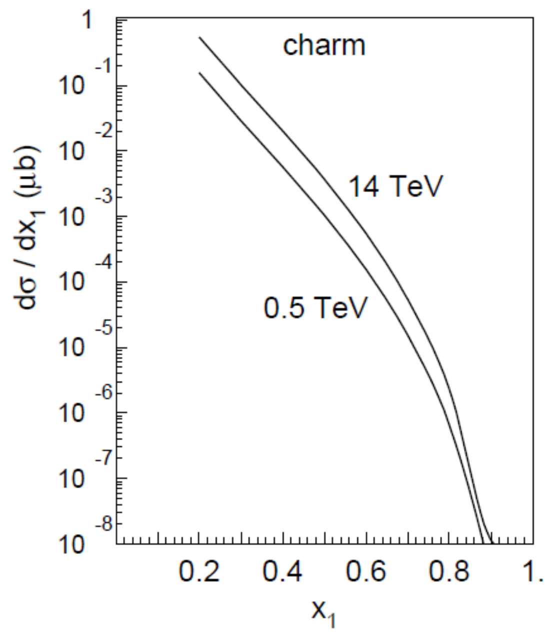


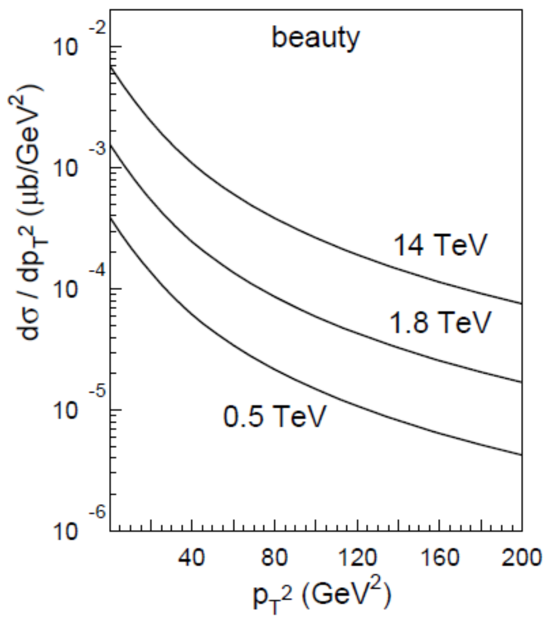
the largest leading-twist contribution

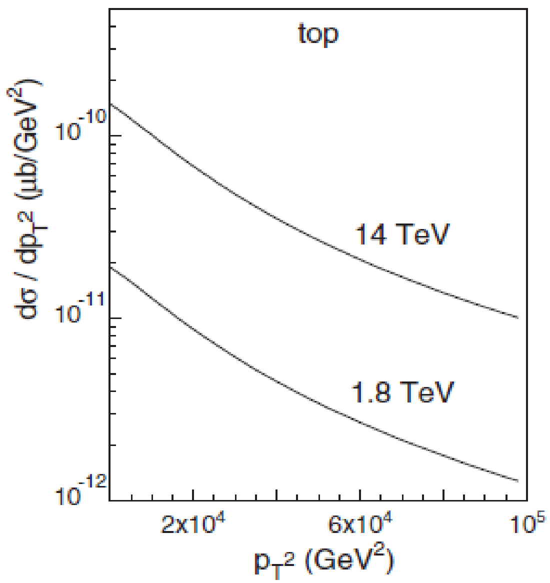
$$\sim \; 1/m_Q^2$$

Forward diffractive heavy flavor: cross sections









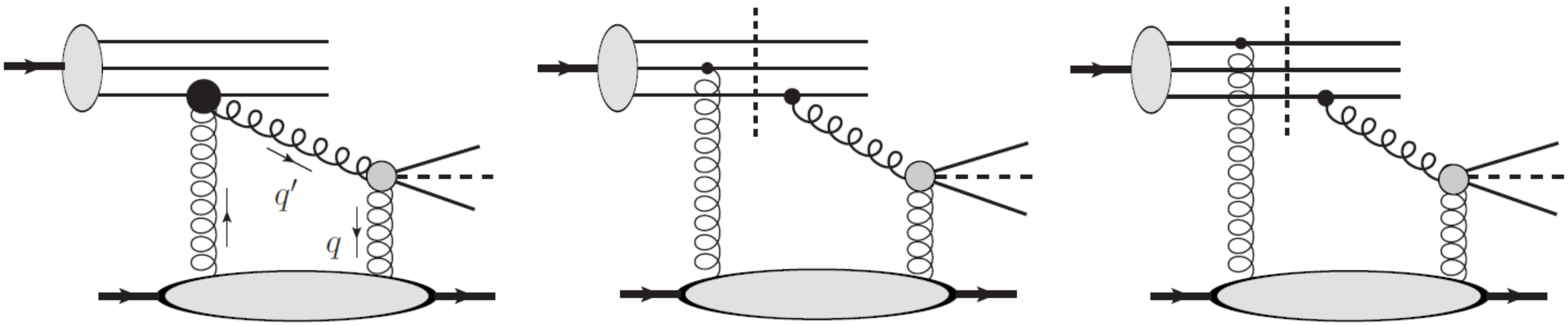
B. Kopeliovich et al, Phys.Rev.D76, 034019 (2007)

Leading-twist diffractive excitations are proven to be dominated!

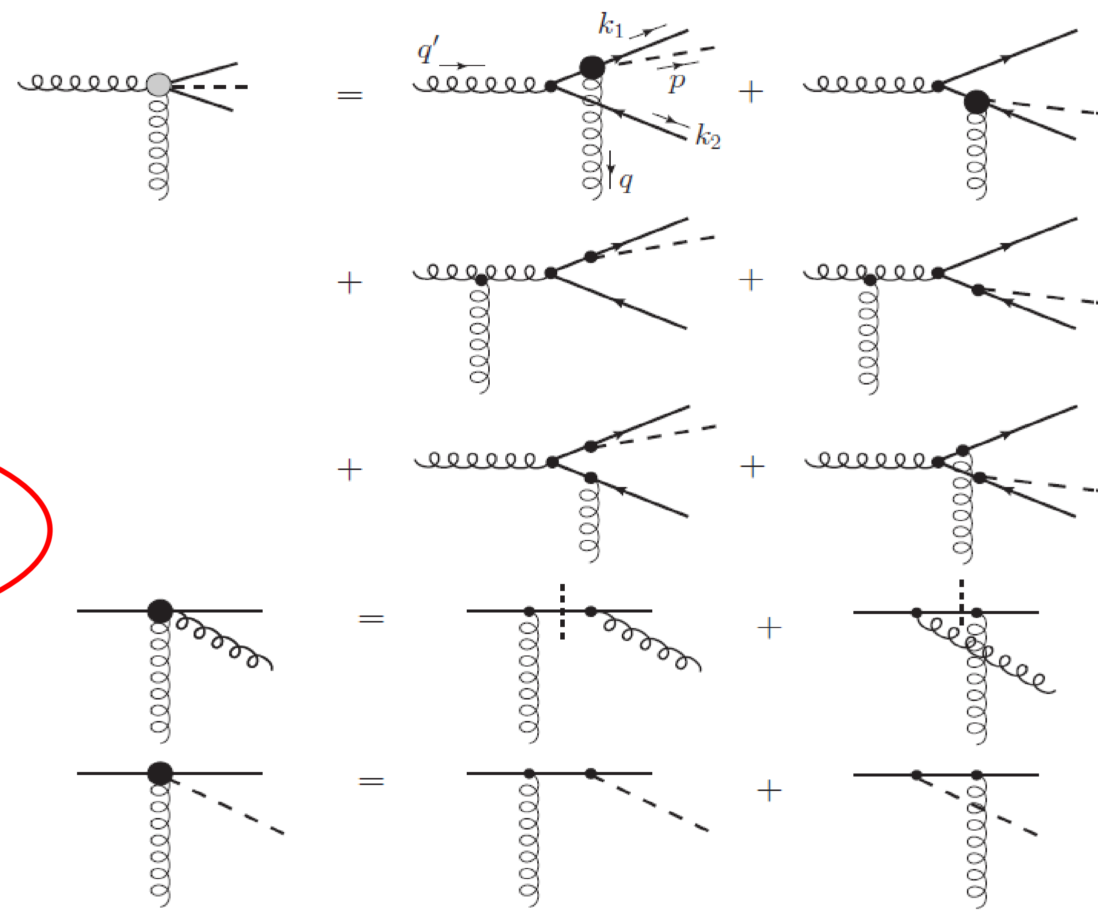
cf. *factorisation-based approach* by

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:

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

$$\frac{d\sigma^{L,T}(pp \to p(Q\bar{Q}h)X)}{d^2\vec{\kappa}\, d^2\vec{r}\, d\ln\alpha\, d\ln\beta\, d\ln\xi\, d^2\delta_\perp}\Big|_{\delta_\perp \to 0} = \frac{1}{(2\pi)^4}\frac{9}{256\pi^2}$$
$$\times \sum_{l=q,g}\; \sum_{q=val,sea} \int d^2\vec{r}_1 d^2\vec{r}_2 d^2\vec{r}_3\, d^2\vec{\omega}\, d^2\vec{\rho}_1 d^2\vec{\rho}_2\, d^2\vec{\sigma}_1 d^2\vec{\sigma}_2\, dx_q \prod_{j\neq 1} dx_q^j \prod_k dx_g^k\, e^{i\vec{\kappa}\cdot(\vec{\rho}_1-\vec{\rho}_2)}$$
$$\times\, e^{i\vec{r}\cdot(\vec{\sigma}_1-\vec{\sigma}_2)}\, \Sigma_l^{L,T}(\vec{r}_1,\vec{r}_2,\vec{r}_3;\alpha,\vec{\omega};\beta,\vec{\rho}_1;\xi,\vec{\sigma}_1)\, \Sigma_l^{L,T*}(\vec{r}_1,\vec{r}_2,\vec{r}_3;\alpha,\vec{\omega};\beta,\vec{\rho}_2;\xi,\vec{\sigma}_2)$$
$$\times\, |\Psi_i(\vec{r}_1,\vec{r}_2,\vec{r}_3;x_q,\{x_q^{2,3,\dots}\},\{x_g^{1,2,\dots}\})|^2\,,$$

diffractive amplitude of QQh production in parton-proton scattering

Incoming proton wave function

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

…in terms of valence/sea (anti)quark distribution

an immediate access to the quark PDFs at large x!

Diff. Higgsstrahlung is of the higher twist

$$\sigma(pp \to Q\bar{Q}h + X) \propto r_{\rm hard}^4$$

Single diffractive amplitude: Higgsstrahlung

Effective wave function

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

$$\underbrace{\times\int d^2b\Big\{\Big[2\mathrm{Im}\, f_{el}(\vec b,(1-\alpha)\,\vec\omega-\xi\vec\sigma)-2\mathrm{Im}\, f_{el}(\vec b,(1-\alpha)\,\vec\omega)\Big] - \Big[2\mathrm{Im}\, f_{el}(\vec b,(1-\alpha)\,\vec\omega-\beta\vec\rho-\xi\vec\sigma)-2\mathrm{Im}\, f_{el}(\vec b,(1-\alpha)\,\vec\omega-\beta\vec\rho)\Big]\Big\}}_{\text{Effective dipole cross section}}$$

+ a lot more...

Effective dipole cross section

Soft scale: $\langle\omega^2\rangle \sim 1/m_q^2 \sim \langle R\rangle^2$

Hard scales: $\left\{\begin{array}{l}\langle\rho^2\rangle\sim 1/m_Q^2\\ \langle\sigma^2\rangle \sim 1/M_h^2\end{array}\right.$

The source of the higher-twist Higgsstrahlung:

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

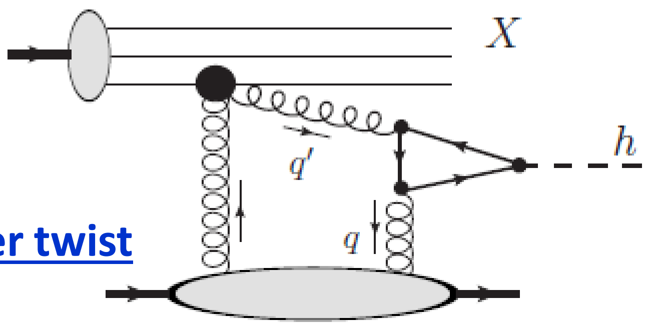
$$\simeq A\,B\,\frac{\partial^2\mathrm{Im}\, f_{el}(\vec b,\vec x)}{\partial x_i\partial x_j}\Big|_{\vec x=\vec R}\,\rho_i\,\sigma_j,$$

the principal source of diffractive factorisation breaking

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

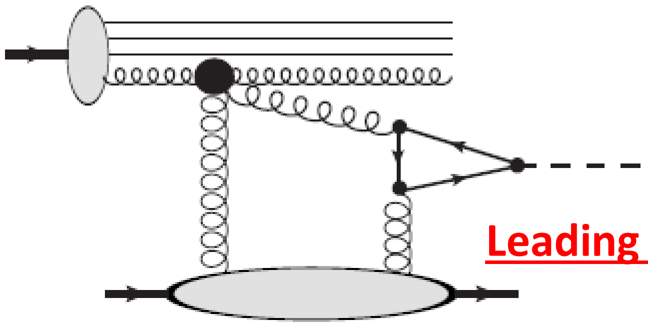
Loop-induced single diffractive Higgs: the dipole picture

Diffractive quark excitation:



Higher twist

Diffractive gluon excitation:



Leading twist..

BUT! ..suppressed in the forward region of large x!

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

$$\left.\frac{d\sigma_q(pp\to phX)}{d^2\vec{p}\,d\ln\alpha\,d^2\vec{\delta}_\perp}\right|_{\delta_\perp\to 0} = \frac{1}{(2\pi)^2}\frac{1}{64\pi^2}\sum_q \int d^2\vec{\omega}d^2\vec{\omega}\,'\,dx_q\left[\rho_q(x_q)+\rho_{\bar{q}}(x_q)\right]$$

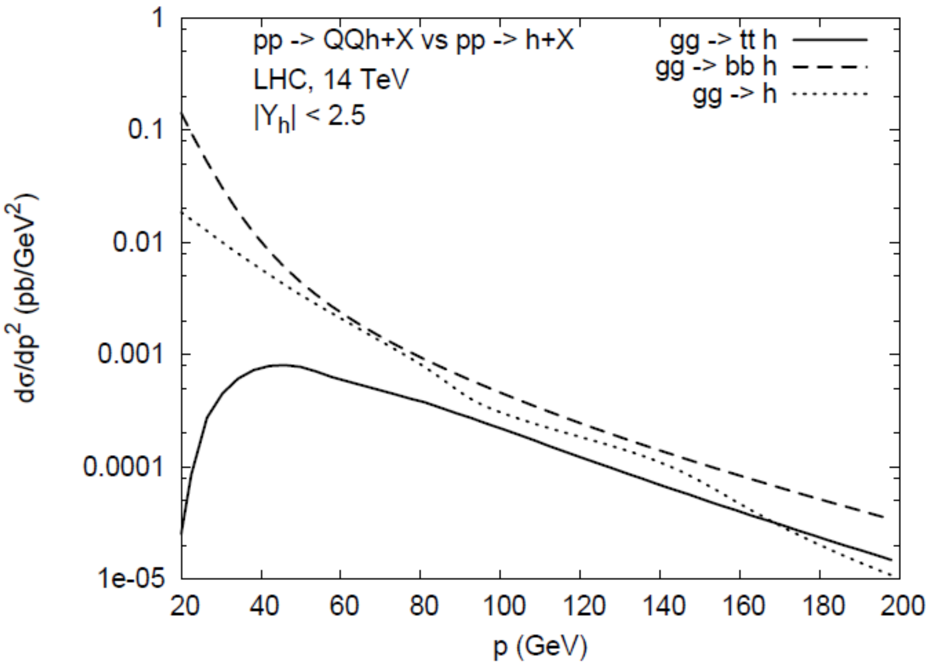
$$\times\,\Phi^q_\triangle(\alpha,\vec{\omega})\Phi^{q*}_\triangle(\alpha,\vec{\omega}\,')\,\Sigma_\triangle(\alpha,\vec{\omega})\Sigma_\triangle(\alpha,\vec{\omega}\,')\,e^{i\vec{p}\cdot(\vec{\omega}-\vec{\omega}\,')},$$

The hard scale

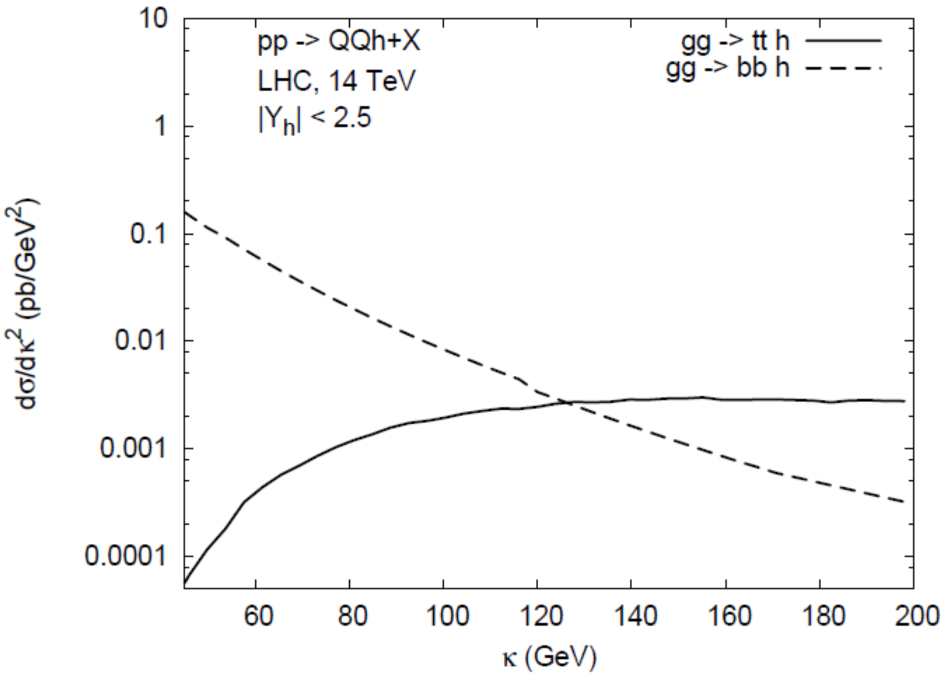
$$\Sigma_\triangle = \frac{3}{2}\Big[\sigma(\vec{\omega}) - \sigma\big((1-\alpha)\vec{\omega}\big)\Big] \simeq \frac{3\sigma_0}{2R_0^2}\alpha(2-\alpha)\omega^2 \qquad \omega \ll r_{ij} \sim R$$

Inclusive Higgsstrahlung vs loop-induced contribution

<u>in Higgs transverse momentum</u>



<u>in heavy quark transverse momentum</u>

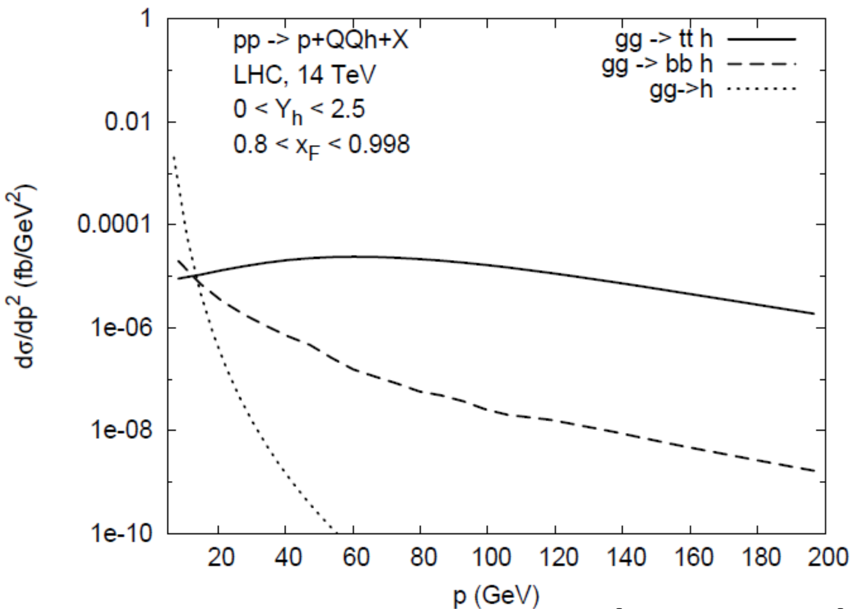


<u>Higgsstrahlung is important at all Higgs pT's!</u>

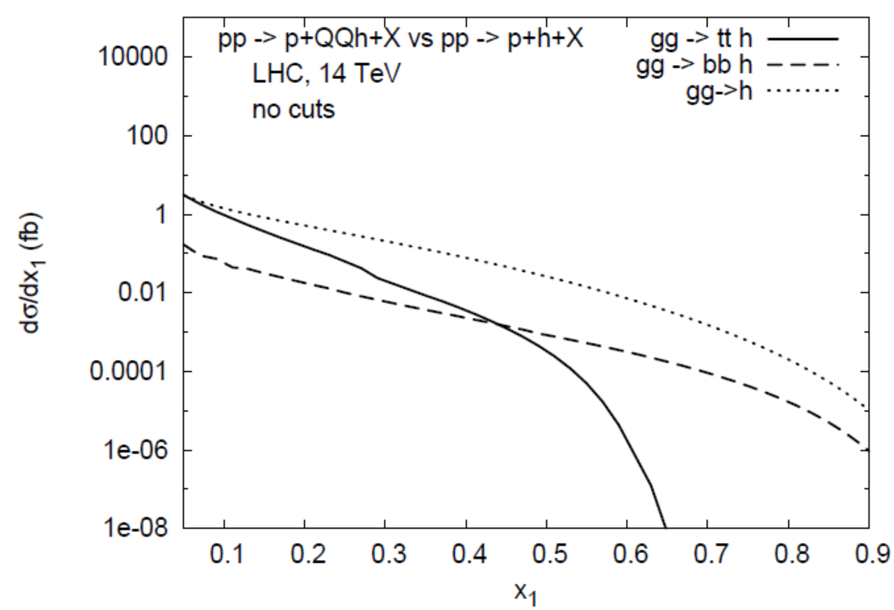
<u>Higgsstrahlung off top quarks dominates at at large quark pT's!</u>

Single diffractive Higgsstrahlung vs loop-induced contribution

in Higgs transverse momentum

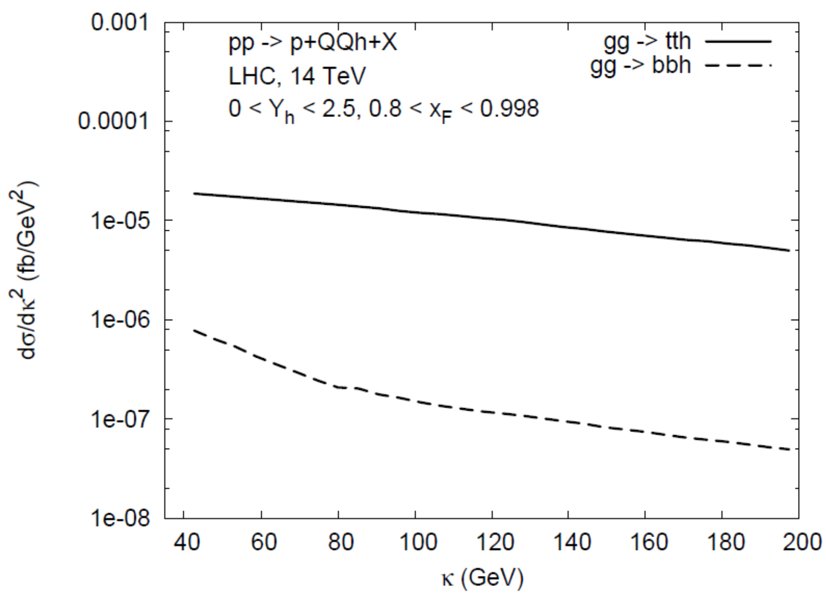


in QQh momentum fraction



in heavy quark transverse momentum

Diffractive Higgsstrahlung off tops dominates at Higgs pT > 20 GeV



Loop mechanism dominates at large x1

Conclusion

- The diffractive 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

- The observation of DHF production **provides a good tool for studies of intrinsic heavy flavors**

- The **diffractive Higgsstrahlung** off heavy quarks is enhanced at large Higgs pT's w.r.t. the loop-induced 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