Hard rescattering in exclusive Higgs boson production at the LHC

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Based on recent work done with J. Bartels, S. Bondarenko and K. Kutak

Overview

Motivation

The Durham approach

Hard rescattering

Gluon extrapolation and Results

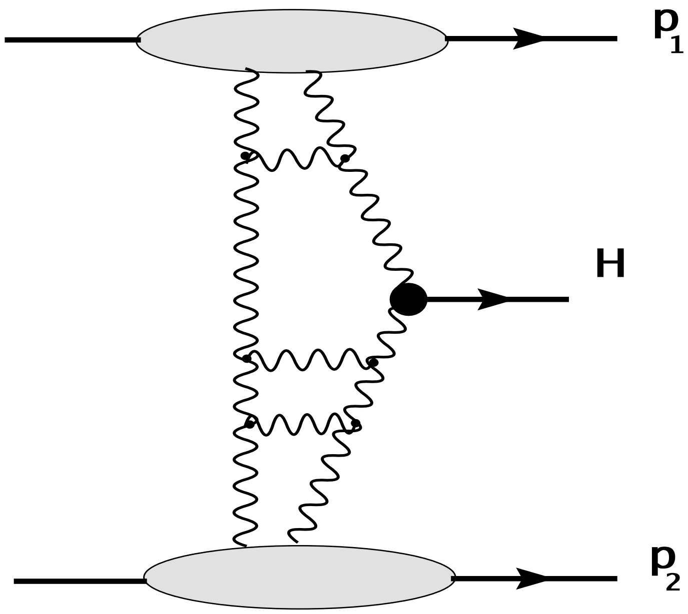
Discussion, Outlook, Conclusions

Definition and Motivation

⟶ The exclusive Higgs boson production in pp: $pp \to pHp$

⟶ The protons stay intact and are detected by forward detectors

⟶ Precise determination of kinematics and mass of the produced system, $\Delta M \sim 1$ GeV



⟶ Possibility to investigate quantum numbers of the produced state e.g. by observing angular correlations of the protons filtering the scalar from the pseudoscalar

⟶ Possible measurements of hypothetical invisible particles in analogous processes

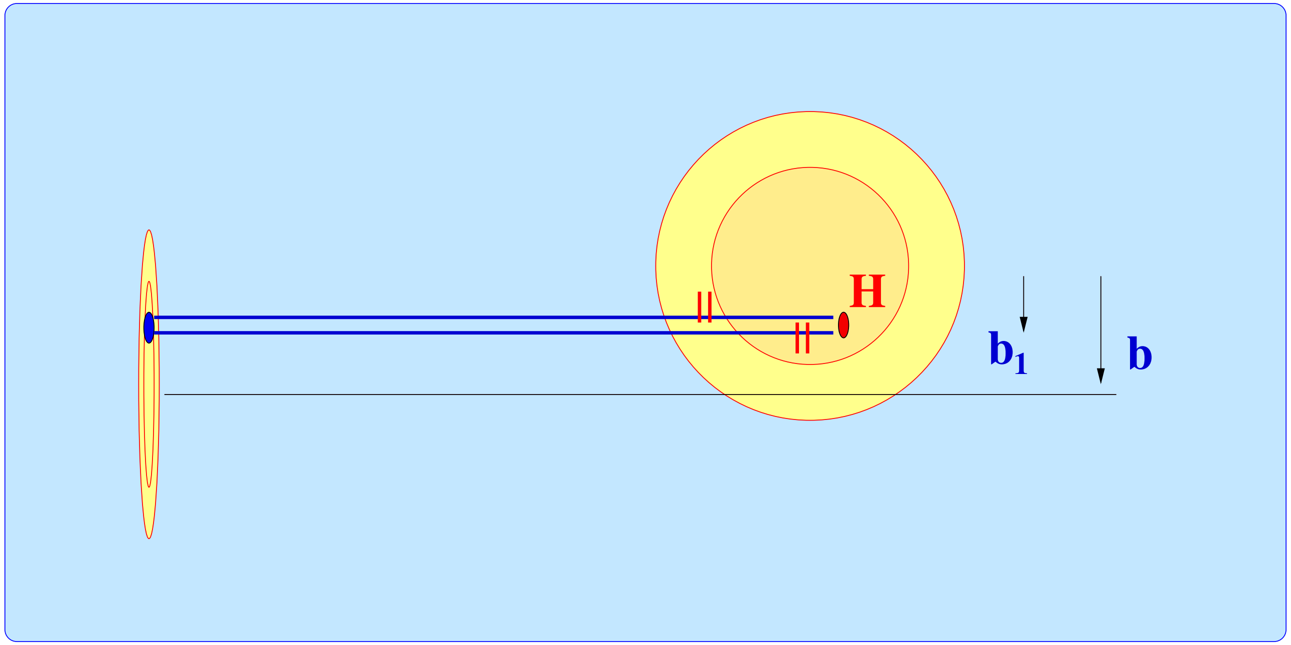
⟶ Numerous papers by V. Khoze, A. Martin, M. Ryskin, A. Kaidalov, J. Stirling

The main idea

Exclusive $pp \to pHp$ $\longrightarrow$ Higgs mass gives hard scale $\longrightarrow$ Sudakov form-factor $\longrightarrow$ fusion of two hard ladders into Higgs

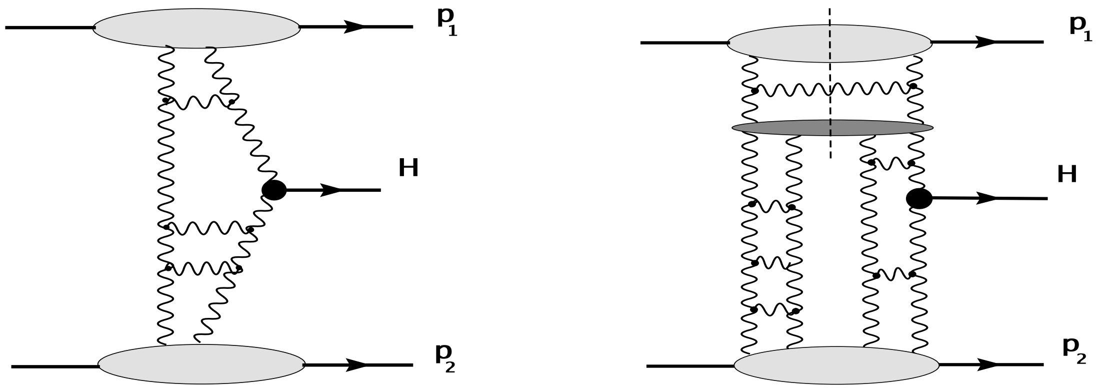
Multiple soft rescattering of the spectator partons (fields) assumed to be independent of the hard production mechanism

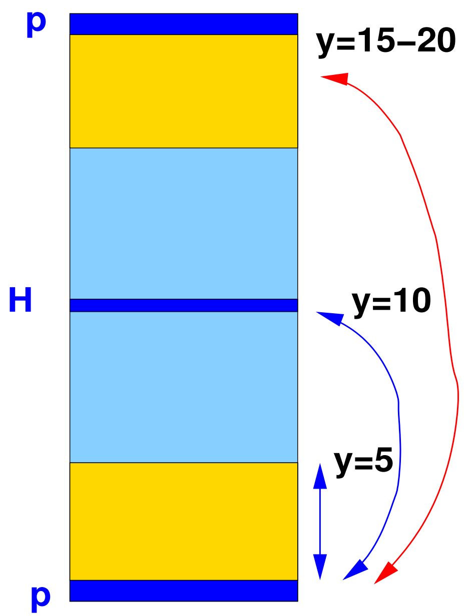
Are hard ladders are small enough to see the protons as colour transparent?



Key issues: hard ladder size, coupling, transverse profiles of matter and impact parameter dependence of scattering $\longrightarrow$ relation of "ladder size" to saturation radius

Kinematics of exclusive production and rescattering





Large rapidity distance $y = 15 - 20$ characterizing the rescattering of the hard ladder $\longrightarrow$ long low-x evolution and enhancement

Two Pomeron Fusion amplitude

Amplitudes to find gluon pair in the proton:

$\longrightarrow$ two-scale off-diagonal unintegrated gluon distributions are introduced:

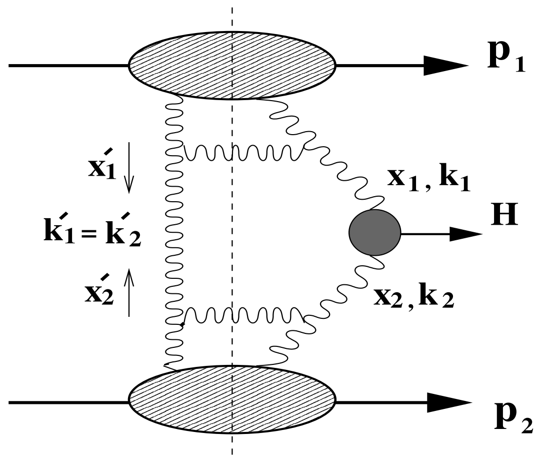
$$f_g(x, x', k, \mu), \qquad xg(x, Q^2) = \int^{Q^2} \frac{dk^2}{k^2} f_g(x, k^2, Q)$$

Sudakov form factor is naturally incorporated in f_g: **[Kimber, Martin, Ryskin]**

$$f_g(x, k^2; \mu) = Q^2 \frac{\partial}{\partial Q^2} \Big[xg(x, Q^2) \cdot T_g(Q, \mu) \Big]_{Q^2 = k^2}$$

$$f_g^{\rm off}(x, k^2; \mu) = R_\xi Q^2 \frac{\partial}{\partial Q^2} \Big[xg(x, Q^2) \cdot \sqrt{T_g(Q, \mu)} \Big]_{Q^2 = k^2}$$

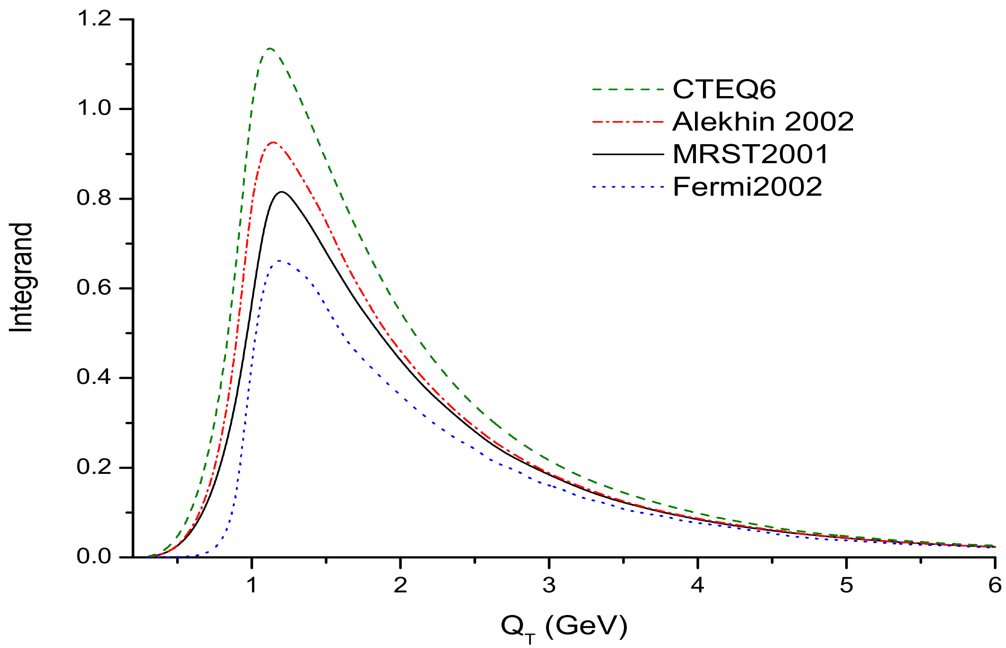
$$\mathrm{Im}\; M_0(y) \sim \int \frac{dk^2}{k^4} f_g^{\rm off}(x_1, k^2; \mu)\, f_g^{\rm off}(x_2, k^2; \mu)$$



Behaviour of the integrand:

$$\mathrm{Im}\ M_0(y) \sim \int \frac{k\,dk}{k^4}\, f_g^{\mathrm{off}}(x_1, k^2; \mu)\, f_g^{\mathrm{off}}(x_2, k^2; \mu)$$

[J. Forshaw]



The integrand is dominated by momenta $Q_T \sim 1 - 2$ GeV

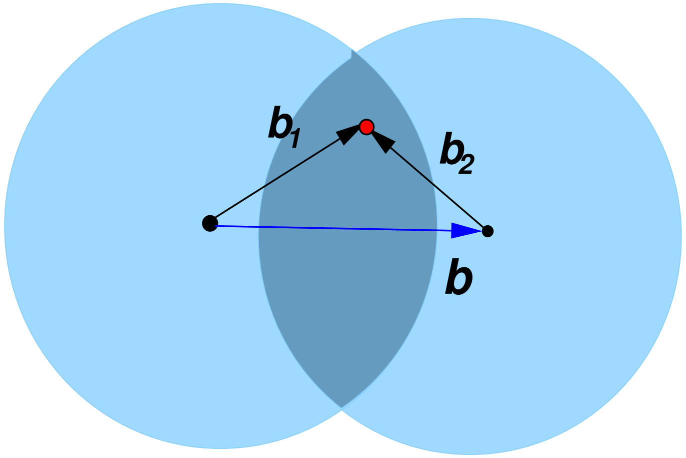
Sudakov form factor reduces the exclusive cross section by two orders of magnitude

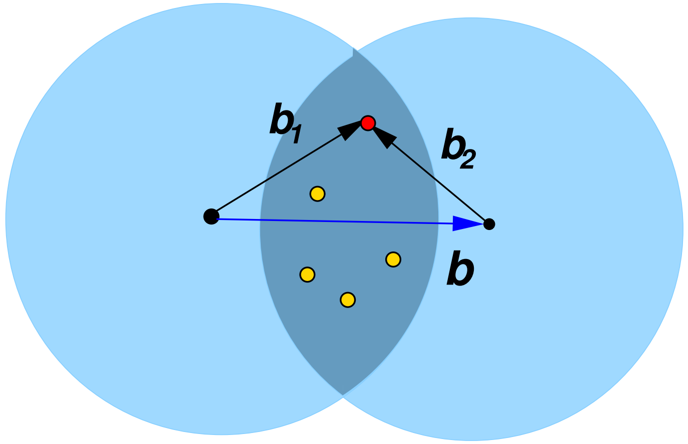
Soft gap survival

Soft rescattering corrections to a hard exclusive scattering process $\longrightarrow$ opacity $\Omega(b)$

Independence of hard production and rescattering is assumed

$$M_{corr}(b) = M_{hard}(b)[1-\Omega(b)/2+(\Omega(b)/2)^2/2!-(\Omega(b)/2)^2/3!+\ldots] = M_0(b)\,\exp(-\Omega(b)/2)$$





Amplitude of matter distribution in the proton

$$S(b_1) \sim \exp(-b_1^2/R^2), \qquad R^2 \sim 8\ \mathrm{GeV}^{-2}$$

$$M_{\mathrm{hard}}(b) \sim M_0 \int d^2b_1\, S(\boldsymbol{b}_1)\, S(\boldsymbol{b}_1 - \boldsymbol{b})$$

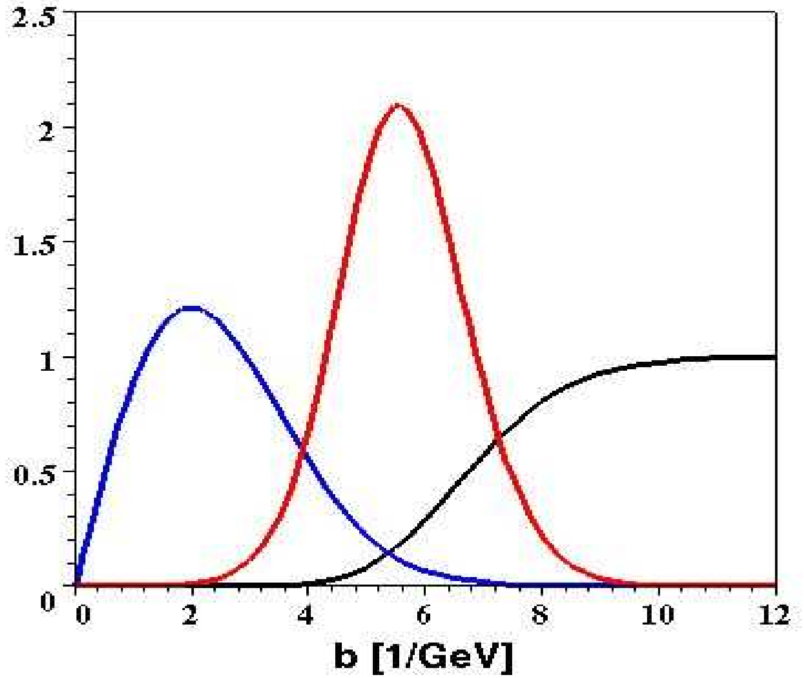
$$\sigma_{\mathrm{excl}} = \int d^2b \int d^2b_1\, |M_0\, S(\boldsymbol{b}_1)\, S(\boldsymbol{b}_1 - \boldsymbol{b})\,|^2 \exp(-\Omega(b))$$

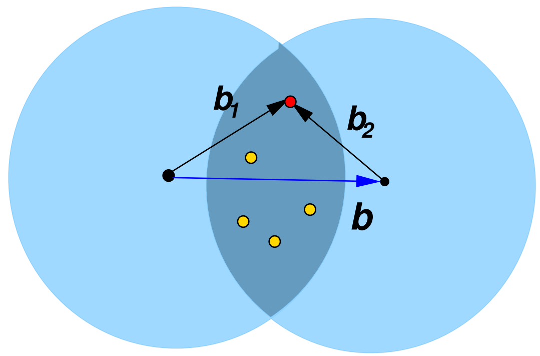
Impact parameter profile of exclusive process

Gap survival factor:
$$S^2 = \frac{\int b\,db\ \exp(-\Omega(b))\,|M_{\rm hard}(b)|^2}{\int b\,db\,|M_{\rm hard}(b)|^2}$$

Exclusive Production = Hard matrix element × Amplitude of no rescattering

Production profile (red) for LHC is magnified by factor of 100

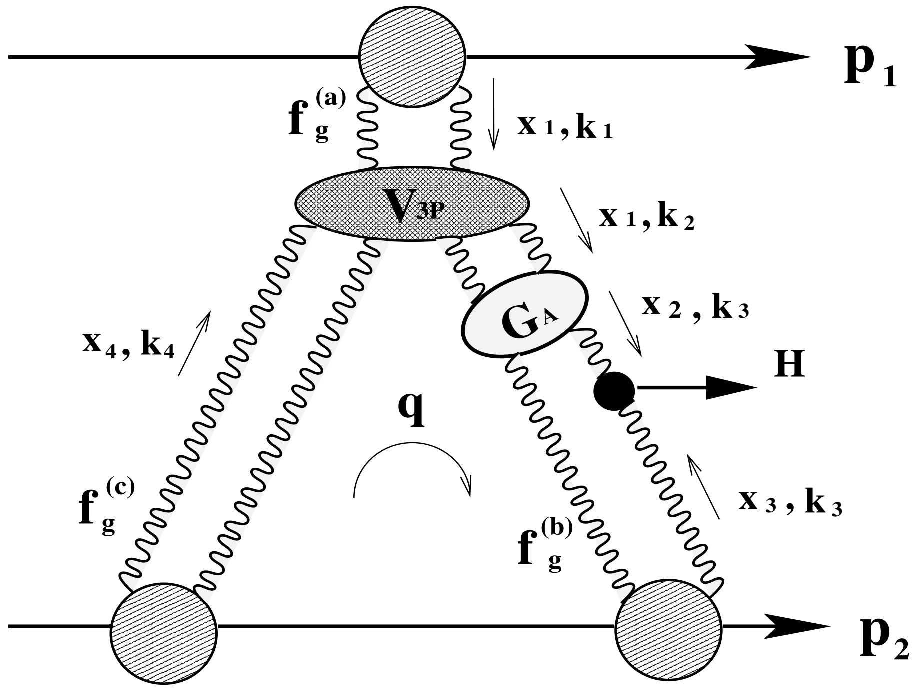


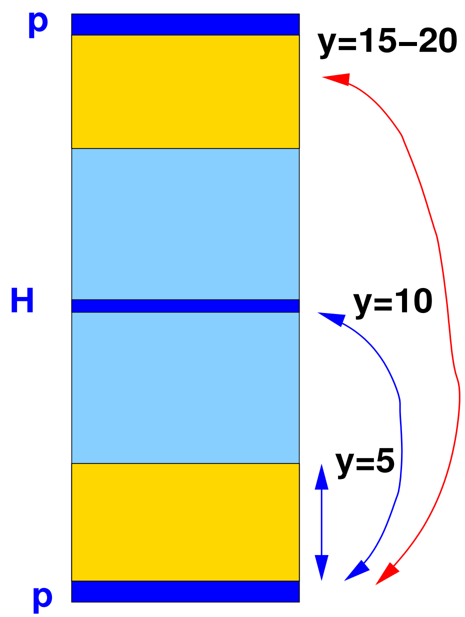


Production dominated by $b \simeq 1.2$ fm and $b_1 \simeq 0.6$ fm

Two-channel eikonal model of gap survival is used that incorporates low-mass diffractive intermediate states. Typically: $S^2 = 0.03$ for exclusive processes at the LHC

Hard rescattering correction





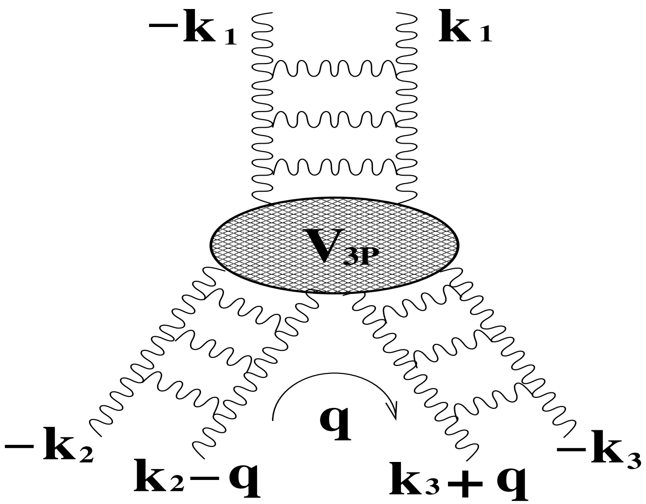
$$\mathrm{Im}\ M^{(1)}_{\mathrm{corr}}(y) \ = \ -\frac{9}{8}\ 16\pi^2\ (2\pi^3 A) \int_{x_a}^{x_b} \frac{dx_4}{x_4} \int \frac{d^2\, q}{(2\pi)^2} \int \frac{d^2 k_2}{2\pi k_2^4} \int \frac{d^2 k_3}{2\pi k_3^4} \int \frac{d^2 k_4}{2\pi k_4^4}$$

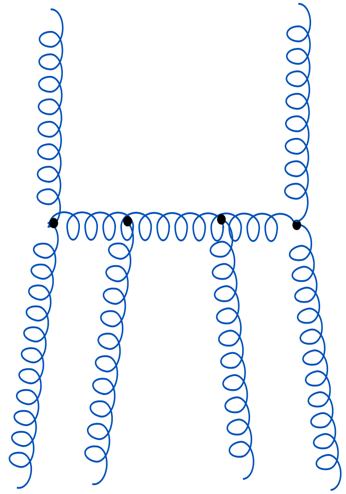
$$\times\ [V_{3P} \otimes f_g^{(a)}(x_1)](\boldsymbol{k}_2,\ \boldsymbol{k}_4)\ G_{\mathrm{A}}(\boldsymbol{k}_2, \boldsymbol{k}_3; x_1, x_2; M_H/2)$$

$$\times\ f_g^{(b)}(x_3, \boldsymbol{k}_3, \boldsymbol{q} - \boldsymbol{k}_3; M_H/2)\ f_g^{(c)}(x_4, \boldsymbol{k}_4, -\boldsymbol{q} - \boldsymbol{k}_4)$$

Triple Pomeron Vertex

[Bartels]





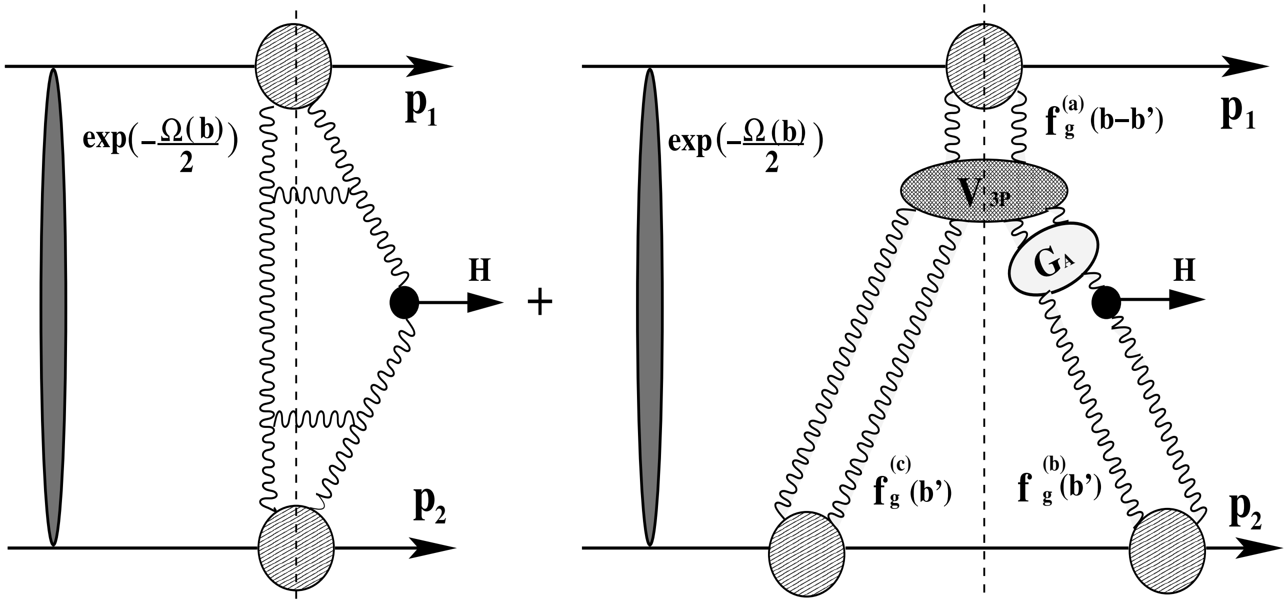
$$[V_{3P} \otimes D](\boldsymbol{k}_2,\, \boldsymbol{k}_3) \;=$$

$$\alpha_s^2\, c_{3P} \int \frac{d^2\boldsymbol{k}_1}{2\pi k_1^2} \Bigg\{ \left(\frac{k_2^2}{(\boldsymbol{k}_1 - \boldsymbol{k}_2)^2} + \frac{k_3^2}{(\boldsymbol{k}_1 + \boldsymbol{k}_3)^2} - \frac{(\boldsymbol{k}_2 + \boldsymbol{k}_3)^2\, k_1^2}{(\boldsymbol{k}_1 - \boldsymbol{k}_2)^2\, (\boldsymbol{k}_1 + \boldsymbol{k}_3)^2} \right) D(k_1)$$

$$- \frac{k_1^2}{(\boldsymbol{k}_1 - \boldsymbol{k}_2)^2} \left(\frac{k_2^2}{(\boldsymbol{k}_1 - \boldsymbol{k}_2)^2 + k_1^2} - \frac{(\boldsymbol{k}_2 + \boldsymbol{k}_3)^2}{(\boldsymbol{k}_1 - \boldsymbol{k}_2)^2 \;+\; (\boldsymbol{k}_1 + \boldsymbol{k}_3)^2} \right) D(k_2)$$

$$- \frac{k_1^2}{(\boldsymbol{k}_1 + \boldsymbol{k}_3)^2} \left(\frac{k_3^2}{(\boldsymbol{k}_1 + \boldsymbol{k}_3)^2 + k_1^2} - \frac{(\boldsymbol{k}_2 + \boldsymbol{k}_3)^2}{(\boldsymbol{k}_1 - \boldsymbol{k}_2)^2 \;+\; (\boldsymbol{k}_1 + \boldsymbol{k}_3)^2} \right) D(k_3) \Bigg\}$$

Exclusive production in position space



$$\mathrm{Im}\ \tilde{M}_{\mathrm{corr}}(y,\boldsymbol{b},\boldsymbol{b}_1) = -\left\{\frac{9}{8}\,16\pi^2\,(2\pi^3 A)\int_{x_a}^{x_b}\frac{dx_4}{x_4}\int\frac{d^2k_2}{2\pi k_2^4}\int\frac{d^2k_3}{2\pi k_3^4}\int\frac{d^2k_4}{2\pi k_4^4}\right.$$

$$\times\,[V_{3P}\otimes\tilde{f}_g^{(a)}(x_1,\boldsymbol{b}-\boldsymbol{b}_1)](\boldsymbol{k}_2,\,\boldsymbol{k}_4)\ G_{\mathrm{A}}(\boldsymbol{k}_2,\boldsymbol{k}_3;x_1,x_2;M_H/2)$$

$$\left.\times\ \tilde{f}_g^{(b)}(x_3,k_3^2,\boldsymbol{b}_1;M_H/2)\ \tilde{f}_g^{(c)}(x_4,k_4^2,\boldsymbol{b}_1)\right\}\ -\ \{y\to -y\}$$

$$\frac{d\sigma^{(0+1),\Omega}_{pp\to pHp}(y)}{dy} = \frac{1}{16\pi}\int d^2b\int d^2b_1\,|S(\boldsymbol{b}_1)S(\boldsymbol{b}-\boldsymbol{b}_1)M_0(y)+M_{\mathrm{corr}}(y,\boldsymbol{b},\boldsymbol{b}_1)|^2\exp(-\Omega(s,\,\boldsymbol{b}))$$

b-dependent Balitsky-Kovchegov equation

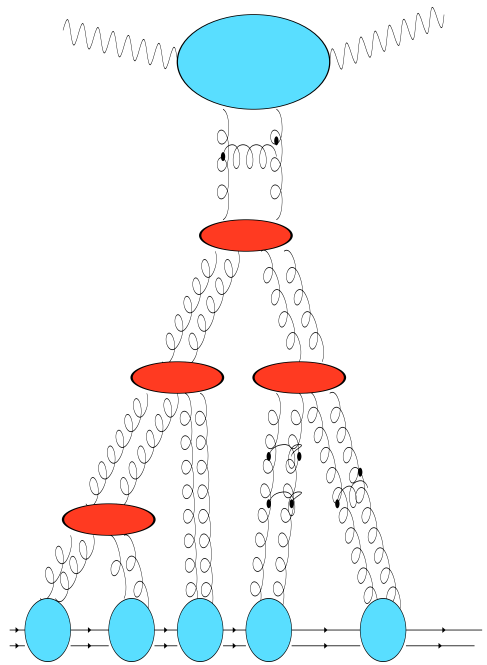
Resummation of BFKL pomeron fan diagrams in the LL approximation with rescattering corrections

$$\frac{\partial \tilde{f}_g(x,k^2,b)}{\partial \log 1/x} = \frac{\alpha_s N_c}{\pi} k^2 \int_{k_0^2} \frac{dk'^2}{k'^2} \left\{ \frac{\tilde{f}_g\left(x,k'^2,b\right) - \tilde{f}_g\left(x,k^2,b\right)}{|k'^2 - k^2|} + \frac{\tilde{f}_g\left(x,k^2,b\right)}{[4k'^4 + k^4]^{\frac{1}{2}}} \right\}$$

$$-\pi\alpha_s^2 \left(1 - k^2 \frac{d}{dk^2}\right)^2 k^2 \left[\int_{k^2}^{\infty} \frac{dk'^2}{k'^4} \log\left(\frac{k'^2}{k^2}\right) \tilde{f}_g(x,k'^2,b) \right]^2$$

Improvements in the linear part: **[Kwieciński, Martin, Staśto, Kutak, LM]**

- collinearly improved NLL corrections to the BFKL kernel
- running coupling constant
- non-singular part of the DGLAP splitting funtion P_{gg} included
- the equation coupled to DGLAP evolution of quarks

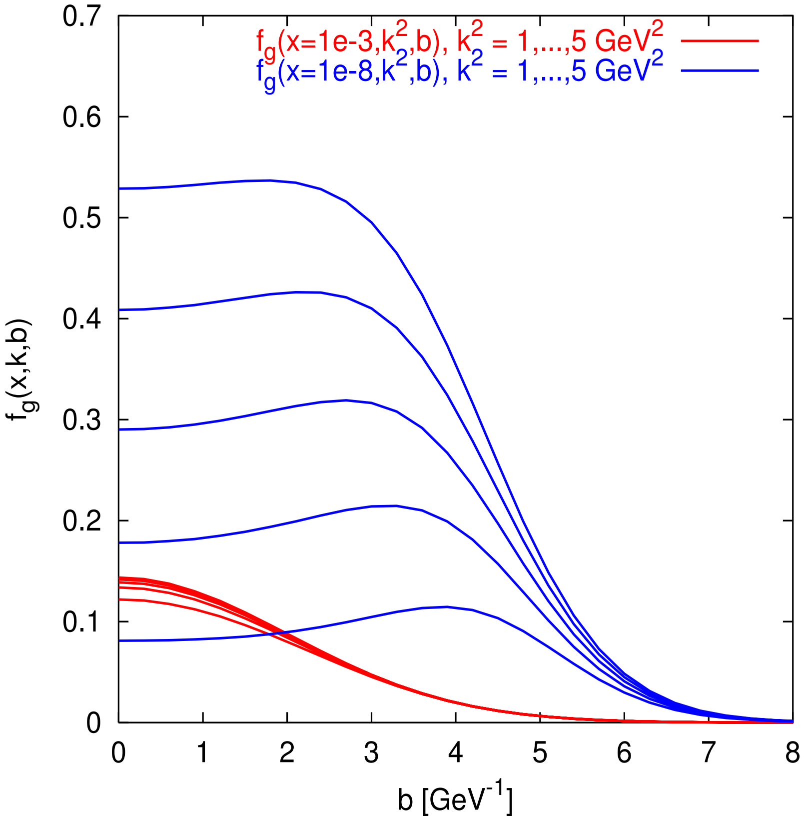


Special features:

- Gluon recombination/ rescattering effects
- Impact parameter dependence in the local approximation

Unintegrated gluon — b-dependence

$\tilde{f}_g(x, k^2, b)$ plotted as a function of b for $k^2 = 1, 2, \ldots, 5$ GeV^2
and for $x = 10^{-3}$ and $x = 10^{-8}$



$$f_g(x, k^2) = \int d^2b \, f_g(x, k^2, b)$$

$$xg(x, Q^2) = \int^{Q^2} \frac{dk^2}{k^2} \, f_g(x, k^2)$$

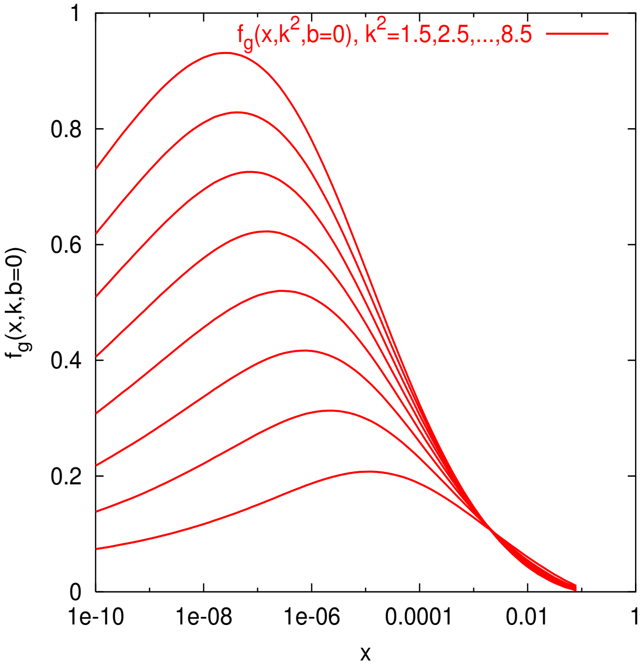
⟶ Broadening and box-like shape of the proton at lower momenta and very low x

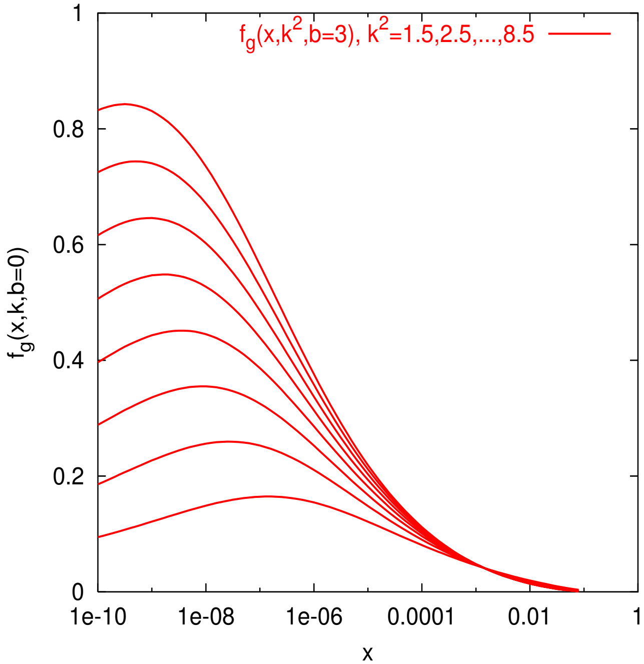
⟶ At very low x – gluon is a non-monotonical function of the distance from the centre

Unintegrated gluon — x-dependence

$\tilde{f}_g(x, k^2, b)$ plotted as a function of x for $k^2 = 1.5, 2.5, \ldots, .5$ GeV^2 and for

$b = 0$ and $b = 0.6$ fm





⟶ The maxima signal that the saturation scale $Q_s(x)$ reached the momentum k

⟶ Decreasing distribution for $k^2 < Q_s^2(x)$

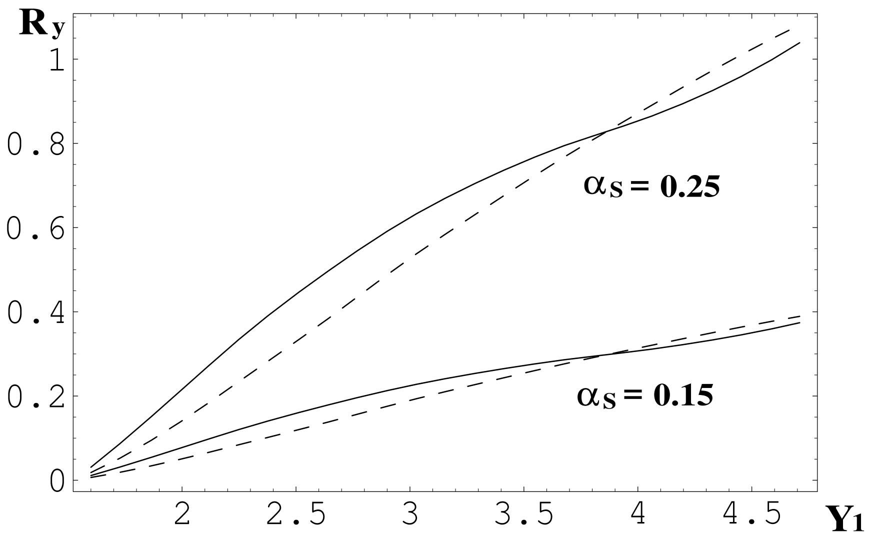
⟶ Saturation scale grows with decreasing x

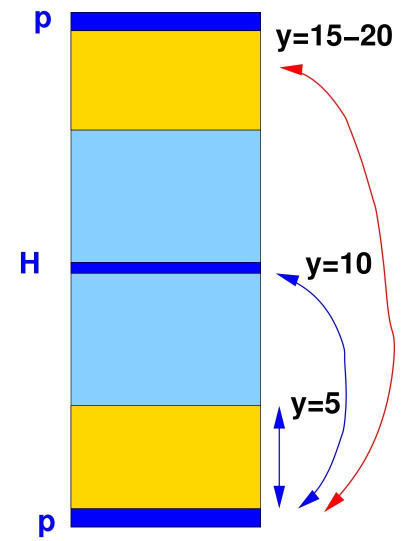
⟶ Saturation scale decreases with growing b

Evaluation of rescattering correction

$Y_1 \longrightarrow$ rapidity distance of the Triple Pomeron Vertex from the *projectile proton* at $b = 0$ and $b_1 = 0$. $M_H = 120$ GeV, the LHC energy

$$R_y(y_1) \;=\; \left[\frac{|d\tilde{M}_{\rm corr}(y,\boldsymbol{b},\boldsymbol{b}_1)/dy_1|}{|\tilde{M}_0(y,\boldsymbol{b},\boldsymbol{b}_1)|}\right]_{b=b_1=0,\,y=0}$$





BFKL Green's function (continuous) and the two gluon exchange (dashed)

$\longrightarrow$ Screening is strongest for rapidities close to the production vertex

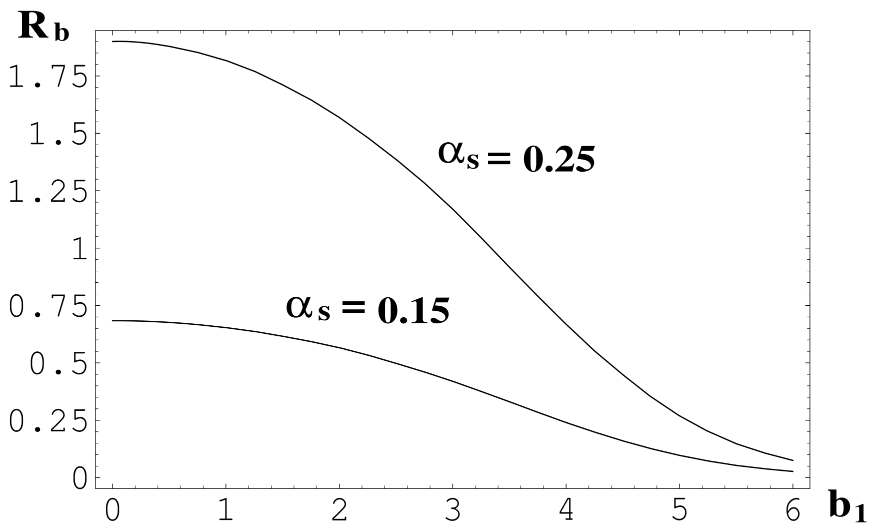
$\longrightarrow$ Multiple scattering of the large mass intermediate state

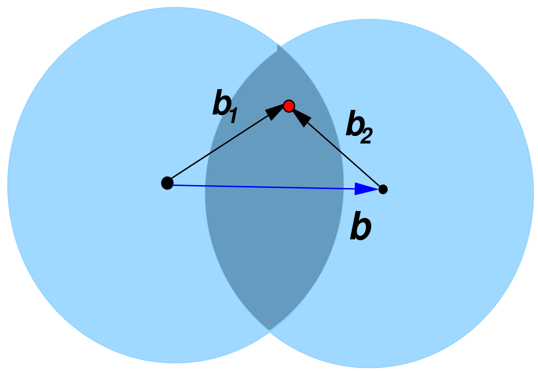
$\longrightarrow$ The correction is large

Evaluation of rescattering correction

Relative correction as a function of the distance of the production vertex from the centre of the target proton – at zero impact parameter of the collision

$$R_b(b_1) = \left[\frac{|\tilde{M}_{\rm corr}(y,b,b_1)|}{|\tilde{M}_0(y,b,b_1)|}\right]_{y=0,\,b=0}$$





⟶ The rescattering correction amplitude is more concentrated close to the centre of proton than the production amplitude

⟶ The correction should experience stronger suppression by the soft rescattering than the production amplitude

Effect of hard rescattering on the cross section

$\left(\frac{d\sigma_{pp\to pHp}}{d\,y}\right)_{y=0}$ (in fb) with hard and soft rescattering corrections included — for $M_H = 120$ GeV at the LHC

TPF	$\alpha_s = 0.15$	$\alpha_s = 0.2$	$\alpha_s = 0.25$
0.4	0.12	0.042	0.14

Hard rescattering correction $\longrightarrow$ soft gap survival probability, $\hat{S}^2$, is modified

TPF)	$\alpha_s = 0.15$	$\hat{S}^2\,(0.2)$	$\hat{S}^2\,(0.25)$
0.024	0.037	0.051	0.016

$\longrightarrow$ Correction amplitude equal to leading term at $\alpha_s = 0.2$

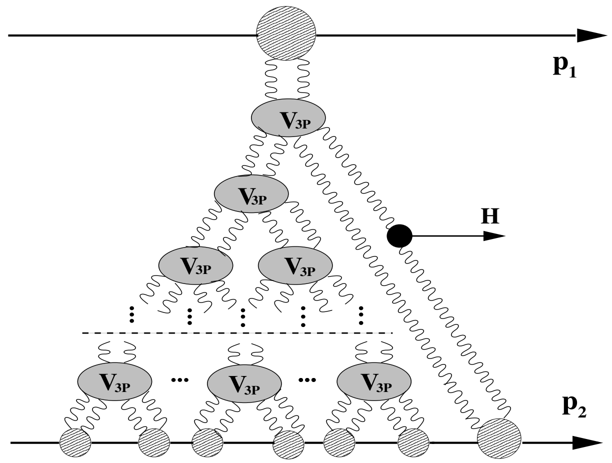
$\longrightarrow$ Important effect, need for higher order contributions

Discussion

The relative magnitude of the correction is large and the sign is negative

Factorisation between hard production amplitude and rescattering is strongly broken

- The magnitude of the higher order unitarity corrections in expected to be large as well
- Theoretical uncertainty of $\sigma_{excl}(pp \to pHp)$ is higher than expected
- Suppression or enhancement?
- Tests of the framework needed



Key ingredients:

- Large rapidity available for the screening pomeron $Y \sim 15 - 20$
- Perturbative momenta and large mass of the rescattering state
- Partial resummation of unitarity corrections

Conclusions

- The hard rescattering correction to the exclusive Higgs boson production was evaluated and found to be large and clearly separated from soft rescattering
- Factorisation of the hard production process from the soft rescattering was found to be broken
- Theoretical uncertainty of the cross section for exclusive Higgs production was broadened
- Resummation of higher order unitarity corrections is necessary
- Practical goal – we want to have better theoretical controll of the exclusive Higgs production
- Theoretical goal – to understand the dynamics of dense gluonic systems and multiple scattering in pp collisions