Diffractive Higgs boson photoproduction in $pp$ collisions

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- Summary
Motivation

- LHC will allow to study a new kinematic region:
  - CM energy: 14 TeV → 7x Tevatron energy
  - Luminosity: 10-100 fb\(^{-1}\) → \(\sim\)10x Tevatron luminosity
  - Higgs physics: it is expected that the \(pp\) collisions will be able to produce the Higgs boson.

- Some hadron-hadron collisions will occur with no strong interaction.
  - The peripheral collisions are a new way to study the Higgs boson production in \(pp(AA)\) collisions.

- Other processes of Higgs production are under study to allow its detection in hadron colliders.
  - DPE allows the Higgs boson production through the leading \(ggH\) vertex mainly in the mass range \(M_H \sim 115 - 200\) GeV.

- Evidences show another mass range excluded for Higgs boson production.
New results from the Tevatron


\[ 160 \text{ GeV} < M_H < 170 \text{ GeV} \]

- EW fits: \[ M_H = 116.3^{+15.6}_{-1.30} \text{ GeV} \] Goebel, arXiv:0905.2488[hep-ph]

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GFPAE talks — Sept '09
Deeply Virtual Compton Scattering (DVCS)

- **1997**: Ji
  - $\gamma^* p \rightarrow \gamma p$ by Pomeron exchange in $ep$ collisions.

- **2001**: Munier, Staśto and Mueller
  - Vector meson production $\gamma^* p \rightarrow Vp$ with GBW model.

- **2008**: Motyka and Watt
  - Vector particle production $\gamma p \rightarrow Ep$ in Peripheral Collisions.

\[ \gamma^*, \gamma, \gamma, \omega, J/\psi, \rho^0 \]
\[ J/\psi, \gamma, Z^0 \]

**MW**: $Z^0$ boson production

\[
y = 0 \begin{cases} 
\sigma_{\gamma p} = 4.2 \text{ fb}, \text{Tevatron} \\
\sigma_{\gamma p} = 37 \text{ fb}, \text{LHC}
\end{cases}
\]
Electromagnetic Higgs production

- **1990**: Cahn and Jackson
  Müller and Schramm

  Peripherial heavy-ion collision $\rightarrow \gamma\gamma$ annihilation

- **2007**: Miller

  Contribution from Electroweak boson loops to the $\gamma\gamma \rightarrow H$.

\[ p, A \rightarrow \gamma \rightarrow H \rightarrow p, A \]

- \[ M_H = 150 \text{ GeV} \quad \sqrt{s} = 3.5 \text{ TeV/A} \quad \begin{cases} \text{CJ: } \sigma_{\text{PbPb}} = 7.0 \text{ pb} \\ \text{MS: } \sigma_{\text{AA}} \sim 100 \text{ pb} \end{cases} \]

- \[ M_H = 120 \text{ GeV} \quad \sqrt{s} = 14 \text{ TeV} \quad M: \sigma_{\text{pp}} = 0.1 \text{ fb} \]
Diffractive Higgs production in $pp$ and $AA$ collisions

- **1991**: Bialas and Landshoff

  - Regge Theory $\rightarrow$ **non-perturbative gluons**

- **1997**: Khoze, Martin and Ryskin

- **2007**: Levin and Miller

  - QCD Pomeron $\rightarrow$ **hard-gluon exchange**

\[ \begin{align*}
M_H &= 150 \text{ GeV} \\
\sqrt{s} &= 16 \text{ TeV} \\
\text{BL} : \sigma_{pp} &= 0.1 \text{ pb}
\end{align*} \]

\[ \begin{align*}
M_H &= 120 \text{ GeV} \\
\sqrt{s} &= 14 / 8.8 (5.5) \text{ TeV/A} \\
\text{KMR} : \sigma_{pp}^{\text{exc/inc}} &\approx 1 \text{ fb}/300 \text{ fb} \\
\text{LM} : \sigma_{pA(AA)} &= 0.64 \text{ pb} (3.9 \text{ nb})
\end{align*} \]
Diffractive Higgs photoproduction

- **Proposal:** $\gamma p$ process by DPE in $pp$ collision.

The loop is treated in **impact factor formalism** at $t = 0$. 

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Scattering amplitude

- **Partonic process:** $\gamma q \rightarrow \gamma + H + q$

\[
\begin{align*}
\gamma(q^\mu) & \rightarrow \gamma(q^\mu) \\
q(\ell^\mu) & \rightarrow \bar{q}(q^\mu - \ell^\mu) \\
g(k^\mu) & \rightarrow \bar{q}(q^\mu - \ell^\mu) \\
q(p^\mu) & \rightarrow \bar{q}(q^\mu - \ell^\mu)
\end{align*}
\]

- The scattering amplitude is obtained by the **Cutkosky Rules**

\[
\text{Im } \mathcal{A} = \frac{1}{2} \int d(PS)_3 \mathcal{A}_{(\text{left})} \mathcal{A}_{(\text{right})}
\]
Photon impact factor

- The color dipole is composed of two effective vertices to the $\gamma g$ coupling

$$
\chi^\mu_\nu_L = -ig_s ee_q t^a \left\{ \gamma^\mu \left[ \frac{f_1 - q}{(l_1 - q)^2} \right] \gamma^\nu - \gamma^\nu \left[ \frac{f_1 - k}{(l_1 - k)^2} \right] \gamma^\mu \right\}
$$

$$
\chi^\lambda_\eta_R = -ig_s ee_q t^b \left\{ \gamma^\lambda \left[ \frac{k - f_2}{(k - l_2)^2} \right] \gamma^\eta - \gamma^\eta \left[ \frac{q - f_2}{(q - l_2)^2} \right] \gamma^\lambda \right\}
$$

- Photon polarization vectors for $t = 0$:

$$
\epsilon^L_\mu \epsilon^L_\nu = \frac{4Q^2}{s} \frac{p_\mu p_\nu}{s}
$$

and

$$
\sum \epsilon^T_\mu \epsilon^{T*}_\nu = -g_{\mu\nu} + \frac{4Q^2}{s} \frac{p_\mu p_\nu}{s}
$$

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Applying the rules

- Performing the product of the two sides of the cut one gets

$$\mathcal{A}_L \mathcal{A}_R = (4\pi)^3 \alpha_s^2 \alpha \left( \sum_q e_q^2 \right) \left( \frac{\epsilon_\mu \epsilon_\lambda^*}{k^6} \right) \frac{V_{ba}^{\sigma \eta}}{N_c} \left( t^b t^a \right) \left( \frac{2}{4\pi^2} \right)$$

$$\text{eikonal} \times 4p_\nu p^\sigma$$

- For a non-heavy Higgs ($M_H \lesssim 200$ GeV), the $ggH$ vertex reads

$$V_{\mu \nu}^{ab} \approx \frac{2}{3} \frac{M_H^2 \alpha_s}{4\pi v} \left( g_{\mu \nu} - \frac{k_{2 \mu} k_{1 \nu}}{k_1 \cdot k_2} \right) \delta^{ab}$$

Forshaw, hep-ph/0508274
Updates on $gg \rightarrow H$ cross section

- Most recent advances taken into account:
  - NNLL soft-gluon resummation;
  - NLO bottom-quark contribution;
  - 2-loop EW effects.

- Significant improvements in LHC.

**TEVATRON**

\[
\begin{align*}
+9\% & \rightarrow M_H = 115 \text{ GeV} \\
-9\% & \rightarrow M_H = 200 \text{ GeV}
\end{align*}
\]

**LHC**

\[
\begin{align*}
+30\% & \rightarrow M_H = 115 \text{ GeV} \\
+9\% & \rightarrow M_H = 300 \text{ GeV}
\end{align*}
\]
The amplitude in parton level

- The imaginary part of the amplitude has the form

\[
\frac{\text{Im} \mathcal{A}}{s} = -\frac{4}{9} \left( \frac{M_H^2 \alpha_s^2 \alpha}{N_c \nu} \right) \left( \sum_q e_q^2 \right) \left( \frac{\alpha_s C_F}{\pi} \right) \int \frac{d\mathbf{k}^2}{k^6} \int_0^1 d\tau \int_0^1 d\rho \, \mathcal{X}(k^2, Q^2),
\]

with

\[
\mathcal{X}(k^2, Q^2) = \frac{k^2 [\tau^2 + (1 - \tau)^2] [\rho^2 + (1 - \rho)^2]}{Q^2 \rho(1 - \rho) + k^2 \tau(1 - \tau)}.
\]

- **First remark**: dependence on \( k^{-6} \) due to the presence of the color dipole.

- Computing the event rate in central rapidity

\[
\frac{d\sigma}{dy_H dp^2 dt}\bigg|_{y_H, t=0} = \frac{1}{2} \left( \frac{\alpha_s^2 \alpha M_H^2}{9\pi^2 N_c \nu} \right)^2 \left( \sum_q e_q^2 \right)^2 \left[ \frac{\alpha_s C_F}{\pi} \int \frac{d\mathbf{k}^2}{k^6} \mathcal{X}(k^2, Q^2) \right]^2.
\]

- Only the **quark contribution** → extension to the hadron coupling.
Parton $\rightarrow$ Hadron

- The hadron coupling is represented by a non-diagonal PDF

$$\frac{\alpha_s C_F}{\pi} \rightarrow f_g(x, k^2) = \mathcal{K} \left( \frac{\partial [xg(x, k^2)]}{\partial \ln k^2} \right)$$

- The non-diagonality is approximated by a multiplicative factor

$$\mathcal{K} = (1.2) \exp(-Bp^2/2)$$

where $B = 5.5 \text{ GeV}^{-2}$ is the slope of the gluon-proton form factor.

- To correctly compute the pomeron coupling to the proton: $x \sim 0.01$. 

Khoze, Martin and Ryskin
PLB 401 (1997) 330

Shuvaev et al
PRD 60 (1999) 014015
Phenomenology inside

Gluon Radiation

- The real gluon emission from the $ggH$ vertex needs to be suppressed.
  - Sum the virtual graphs that include terms like $\ln \left( \frac{M_H}{k^2} \right)$.
  - The emission probability of 1-gluon is computed by Sudakov form factors

$$S(k^2, M_H^2) = \frac{N_c}{\pi} \int_{k^2}^{M_H^2/4} \frac{\alpha_s(\hat{p}^2)}{\hat{p}^2} d\hat{p}^2 \int_{p_T}^{M_H/2} \frac{d\hat{E}}{\hat{E}} = \frac{3\alpha_s}{4\pi} \ell n^2 \left( \frac{M_H^2}{4k^2} \right)$$

- Real emissions are not suppressed if the gluon color neutralization fails.

- Suppressing many gluons emission:
  - It is included a factor $e^{-S}$ to the cross section.
  - Emissions below $k^2$ are forbidden.
  - As $k^2 \to 0$ the non-emission probability goes to zero faster than any power of $k$, like $k^{-6}$. 
**Phenomenology inside**

**Rapidity Gaps**  

- The **Rapidity Gap Survival Probability** is calculated by

\[
S_{\text{gap}}^2 = \frac{\int |A(s, b)|^2 e^{-\Omega(b)} d^2 b}{\int |A(s, b)|^2 N d^2 b} = \begin{cases} 
5\% \quad \text{Tevatron} \\
2.7\% - 3\% \quad \text{LHC} 
\end{cases}
\]

where \( N = e^{-\Omega_0} \) is the relevant opacity at \( \Omega = 0 \).

- **Pomeron loops**: Higgs boson production with \( S_{\text{gap}}^2 = 0.4\% \)

Miller  
EPJC 56 (2008) 39  
Cross section for central rapidity

Gay Ducati and Silveira PRD 78 (2008) 113005

The cross section is calculated for central rapidity ($y_H = 0$)

$$\frac{d\sigma}{dy_H dt} \bigg|_{y_H,t=0} = \frac{S_{gap}^2}{2\pi B} \left( \frac{\alpha_s^2 \alpha M_H^2}{3 N_c \pi v} \right)^2 \left( \sum_q e_q^2 \right)^2 \left[ \int_{k_0^2}^{\infty} \frac{dk^2}{k^6} e^{-S(k^2, M_H^2)} f_g(x, k^2) \chi(k^2, Q^2) \right]^2$$

- Proton content$^1$: $\alpha_s C_F / \pi \rightarrow f_g(x, k^2) = K \left( \ell n k^2 \right)^x g(x, k^2)$

- Gap Survival Probability$^2$: $S_{gap}^2 \rightarrow 3\% (5\%)$ for LHC (Tevatron)

- Gluon radiation suppression$^3$: Sudakov factor $S(k^2, M_H^2) \sim \ell n^2 \left( M_H^2 / 4k^2 \right)$

- Cutoff $k_0^2$: Necessary to avoid infrared divergencies :: $k_0^2 = 1$ GeV$^2$.

- Electroweak vacuum expectation value: $v = 246$ GeV

- Gluon-proton form factor: $B = 5.5$ GeV$^{-2}$

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$^1$Khoze, Martin, Ryskin, EJPC 14 (2000) 525

$^2$Khoze, Martin, Ryskin, EJPC 18 (2000) 167

$^3$Forshaw, hep-ph/0508274
Results: predictions for the $\gamma p$ process

- The predictions for different PDF’s are close in LHC
- **Tevatron**: restricted to $M_H < 140$ GeV (reason: $x > 0.01$)
Results: gluon PDF parametrizations

- All parametrizations start the distribution evolution from
  \[ k_0^2 \sim 1.25 \text{ GeV}^2 \]

- One can extrapolate the distribution for \( k^2 \to 0 \)
  \[ k_0^2 \sim k^{4+2(\gamma+2)} k^2 \]

- For each parametrization one needs to compute the parameters to match the function and its derivative in the correct value.

\[ \text{MRST2001lo} \to \gamma = 1.987455222 \]
Higgs production in Peripheral Collisions

- The $\gamma p$ process is a subprocess in peripheral $pp$ collisions

Hencken et al
Phys. Rept. 458 (2008) 1

- Impact parameter: $|\vec{b}| > 2R \rightarrow \text{NO STRONG INTERACTION!}$
- Only EM force acts in the second proton $\rightarrow \text{REAL PHOTONS}$
Peripheral photons

- The photon virtuality is related to the nucleus radius: coherent action of the charged particles
  
  \[ Q^2 \lesssim 1/R^2 \]

  - In the proton case: \( Q^2 \lesssim 10^{-2} \text{ GeV}^2 \).

- Uncertainty principle: upper limit to the photon transverse momentum
  
  \[ Q \lesssim \frac{1}{R} \approx \begin{cases} 
    28 \text{ MeV}, \text{ Pb beam} \\
    330 \text{ MeV}, \text{ proton beam}
  \end{cases} \]
Photon spectra

- The energy fraction of the photon related to the incident nucleus obey the **coherence condition**

\[ x_\gamma = \frac{\text{photon energy}}{\text{beam energy}} = \frac{\omega}{E} \left\{ \begin{array}{c} x_\gamma \lesssim 10^{-3}, \text{Ca} \\ x_\gamma \lesssim 10^{-4}, \text{Pb} \end{array} \right\} \]

- The photon distribution is **strongly** suppressed at high energies.
Hadronic cross section

For $pp$ collisions, $\sigma_{\gamma p}$ is convoluted with the photon flux

$$\sigma(pp \rightarrow p + H + p) = 2 \int_{\omega_0}^{\sqrt{s}/2} \frac{dn}{d\omega} \sigma_{\gamma p}(\omega, M_H) \ d\omega,$$

where the photon flux is given by

$$\frac{dn}{dk} = \frac{\alpha_{em}}{2\pi \omega} \left[ 1 + \left( 1 - \frac{2k}{\sqrt{s}} \right)^2 \right] \left( \ell nA - \frac{11}{6} + \frac{3}{A} - \frac{3}{2A^2} + \frac{1}{3A^2} \right).$$

with $A \simeq 1 + (0.71 \text{ GeV}^{-2}) \sqrt{s}/2\omega^2$.

The parametrization allows one to write the virtuality as

$$Q^2 = -\omega^2/(\gamma_L^2/\beta_L^2) - q_\perp^2$$

with $\gamma_L = (1 - \beta_L^2)^{-1/2} = \sqrt{s}/2m_p$.

The $\gamma p$ center-of-mass energy: $W^2 = 2\omega\sqrt{s}$. 
Results: Higgs boson in UPCs

- Similar to those from $\gamma\gamma$ process ($10^{-1}$ fb).
- Clear distinction among the predictions in LHC for different PDF’s.
- The event rate is obtained from the relation $\frac{d\sigma_{\text{pp}}}{dy_H} = 2\int_{\omega_0}^{\sqrt{s}/2} d\omega \frac{dn}{d\omega} \frac{d\sigma_{\gamma p}}{dy_H} d\omega$. 

![Graph showing event rate vs. Higgs mass](image)

![Graph showing predicted rates](image)
Results: Cutoff sensitivity

- The main contribution comes from the range $k_0^2 < 30 \text{ GeV}^2$.

- Sensitivity: almost the same behavior than the direct $pp$ process.
Summary

- We compute the event rate for Higgs boson production in Peripheral Collisions at LHC:

\[ \sigma_{pp} \sim 0.1 \text{ fb} \]

- The computed total cross section is lower than the direct \( pp \) process, however,
  - The Rapidity Gap Survival Probability (GSP) is not appropriated to the \( \gamma p \) process (3%).
  - We must compute the GSP for the \( \gamma p \) collisions.

<table>
<thead>
<tr>
<th>Subprocess</th>
<th>GSP (%)</th>
<th>( \sigma_{pp} ) (fb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IPIP</td>
<td>2.3</td>
<td>2.7</td>
</tr>
<tr>
<td>IPIP</td>
<td>0.4</td>
<td>0.47</td>
</tr>
<tr>
<td>( \gamma \gamma )</td>
<td>100</td>
<td>0.1</td>
</tr>
<tr>
<td>( \gamma p )</td>
<td>3.0</td>
<td>\textbf{0.08}</td>
</tr>
</tbody>
</table>

- The predictions can be analysed in a data sample of non-central collisions.
  - Will be less competitive than direct \( pp \) processes if analysed separately.
Perspectives

- Study this approach in nucleus-nucleus collisions: $pA$ and $AA$.

- More phenomenology:
  - More precise predictions for the GSP;
  - Include updates on the $ggH$ cross section;
  - ...

- Inclusion of QCD and Electroweak-theory corrections:
  - Compute the impact factor for $\gamma \to \gamma^*$;
  - ...

- and more.