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Diffractive Higgs boson photoproduction in Ultraperipheral Collisions

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Defense of dissertation to fulfill the requeriments for the degree of *Doctor in Science* at the Physics Institute, Universidade Federal do Rio Grande do Sul

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High Energy Physics Phenomenology Group

Outline

- Motivation
- Electroweak theory and the Higgs search
- Particle Diffraction
- Photoproduction mechanism of the Higgs boson
  - Production mechanisms review
  - γp subprocess
  - Phenomenology inside
  - Results for the Tevatron and the LHC — **Phys. Rev. D78 (2008) 113005**
- Application to Ultraperipheral Collisions
  - Results for *pp* and *pA* collisions — **Phys. Rev. D82 (2010) 073004**
- Diffractive factorization
  - Single Diffractive production — **Phys. Rev. D83 (2011) 074005**
  - Double Pomeron Exchange — **Submitted to Phys. Rev. D**
- The scenario for the exclusive Higgs production
- Conclusions

Motivation

- The Higgs boson is the ultimate particle to be detected for the consolidation of the Standard Model;
- LHC is expected to discover the Higgs boson in the beginning of its operation;
  - The **low luminosity** regime is favorable to the diffractive production;
  - The estimation for the S/B ratio is higher than the direct production.
    - The $J_z = 0$ spin selecting rule allows the suppression of many background signals.
- Diffractive processes have very clear experimental signatures;
  - The Double Pomeron Exchange allows the Higgs boson production by the ggH vertex in the mass range of $M_H \sim 115 - 160$ GeV;
- Some of the hadron-hadron collisions will **not** experience strong interactions;
  - **Ultraperipheral collisions**: due to the long separation of the colliding particles, only electromagnetic interactions will take place.
- **This dissertation is devoted to explore a new production mechanism for the Higgs boson in the LHC kinematical regime.**

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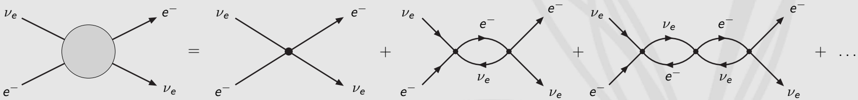
Weak interactions

- **First proposal**: Relativistic theory by Fermi for the neutron decaying

$$\mathcal{H} = \mathcal{H}^0 + \frac{G}{\sqrt{2}} \int d^3x \, J_\mu^{(L)\dagger}(x) J^\mu_{(L)}(x)$$

$$J_\mu^{(L)} = \sum \bar{u}_L(x)\gamma_\mu(1-\gamma_5)u_{\nu_L}(x)$$

- **Problem #1**: Cross section for the $\nu\ell$ processes grows with energy;
  - Calculation in higher orders in perturbation theory are necessary.



- QED: vacuum polarization diagrams yields **divergencies**:
  - It is fundamental to consider a Quantum Field Theory for the description of the interaction by the exchange virtual massless particle.
- **Problem #2**: The Weak Interaction demands a massive mediator particle:

non-renormalizable theory

Spontaneous symmetry breaking

- The **Higgs field** is defined as

$$\varphi(x) = \frac{1}{\sqrt{2}}\left[\varphi_1(x) + \imath\varphi_2(x)\right] \qquad \varphi^*(x) = \frac{1}{\sqrt{2}}\left[\varphi_1(x) - \imath\varphi_2(x)\right]$$

which obeys the Lagrangian invariant to the SO(2) symmetry group

$$\mathcal{L}_H = (\partial^\mu\varphi)^*\,(\partial_\mu\varphi) - \left(\mu^2|\varphi|^2 + \frac{\lambda}{3!}|\varphi|^4\right)$$

- Essential feature: **local** symmetry transformation

$$\tilde{\varphi}(x) = T(x)\varphi(x) = e^{\imath g\theta(x)}\varphi(x)$$

- The Lagrangian that satisfies this feature and is invariant to SU(2) is given by

$$\mathcal{L}_H = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} + (D^\mu\varphi)^*\,(D_\mu\varphi) - \mu^2|\varphi|^2 - \frac{\lambda}{3!}|\varphi|^4$$

where $F^{\mu\nu} = \partial^\nu a^\mu(x) - \partial^\mu a^\nu(x)$ and $D^\mu = \partial^\mu + \imath g\, a^\mu(x)$.

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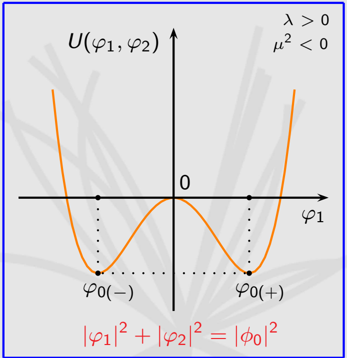

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where $F^{\mu\nu} = \partial^\nu a^\mu(x) - \partial^\mu a^\nu(x)$ and $D^\mu = \partial^\mu + \imath g\, a^\mu(x)$.

Higgs mechanism

- Selecting a vacuum state, the Lagrangian is changed through $\varphi_1' = \varphi_1 - \phi_0$;
- Performing the following transformations

$$\begin{aligned} \varphi(x) &= \frac{1}{\sqrt{2}}\left[\rho(x) + a\right] \exp[\imath g \omega(x)/a] \\ a_\mu(x) &= C_\mu - \frac{1}{a}\partial_\mu \omega(x) \end{aligned}$$

one finds

$$\begin{aligned} \mathcal{L}_H &= -\frac{1}{4} C^{\mu\nu} C_{\mu\nu} + \frac{1}{2} m_C^2 C^\mu C_\mu \\ &- \frac{1}{2}(\partial^\mu \rho)^* (\partial_\mu \rho) + \frac{1}{2} m_\rho^2 |\rho|^2 - \frac{\lambda}{4!}|\rho|^4 - \frac{\lambda \phi_0}{3!} + \frac{g^2}{2} C^\mu C_\mu \left(|\rho|^2 + 2|\rho||\phi_0|\right) \end{aligned}$$

- The spurious field $\omega(x)$ is subtracted $\rightarrow$ **Goldstone boson**;
- The other fields acquire mass: C_μ: $m_C = g|\phi_0| \rightarrow$ gauge boson

  ρ: $m_\rho = \sqrt{-2\mu^2} \rightarrow$ **Higgs boson**

renormalizable theory with a **massive propagator**

Electroweak theory

- **60-70's**: Unification of QED + Weak Interactions

Symmetry group $SU(2)_L \otimes U(1)_Y$

- The Electroweak Lagrangian for leptons has the form

$$\mathcal{L}_{EW} = -\frac{1}{4} B_a^{\mu\nu} B^a_{\mu\nu} - \frac{1}{4} F^{\mu\nu} F_{\mu\nu} - \mu^2 \varphi^\dagger \varphi - \frac{\lambda}{3!} \left(\varphi^\dagger \varphi\right)^2 + \left(D_\mu \varphi\right)^\dagger \left(D^\mu \varphi\right)$$

$$+ \sum_\ell \left[\bar{L}_\ell \left(\imath \gamma^\mu D_\mu\right) L_\ell + \bar{R}_\ell \left(\imath \gamma^\mu D_\mu\right) R_\ell - G_\ell \left(\bar{L}_\ell \varphi R_\ell + \bar{R}_\ell \varphi^\dagger L_\ell \right) \right]$$

- The Higgs mechanism allows one to obtain the mass of the physical fields;

$$m_e \sim |\phi_0| G_e \qquad m_\mu \sim |\phi_0| G_\mu \qquad m_\tau \sim |\phi_0| G_\tau$$

$$M_Z = 90 \text{ GeV} \qquad M_W = 80 \text{ GeV}$$

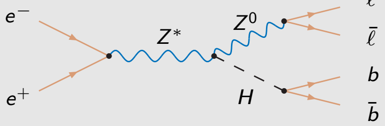
$$M_H = \sqrt{-2\mu^2}$$

- **1983**: CERN detects the massive electroweak bosons

$$M_W = 80.5 \pm 0.5 \text{ GeV} \qquad M_Z = 95.6 \pm 1.4 \text{ GeV}$$

LEP results

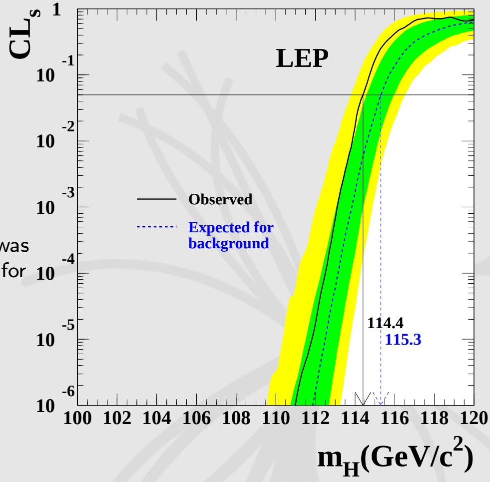
- **Final step**: detect the **Higgs boson**!
- The Higgs boson production was investigated with the LEP data for the production mechanism



- With the analysis of the results, it was possible to estimate a lower bound for the Higgs mass

$$M_H \geq \ 114.4 \text{ GeV}$$

with 95% of confidence level.



New analysis from the Tevatron

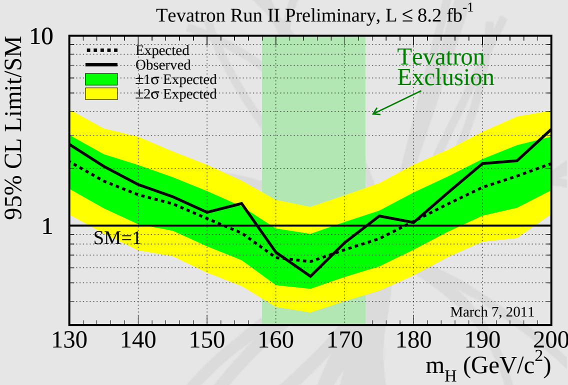
- The analyses of the data from the CDF and D0 experiments excluded the possibility for the Higgs boson detection in the range

$$158 \text{ GeV} < M_H < 173 \text{ GeV}$$

with 95% of confidence level;

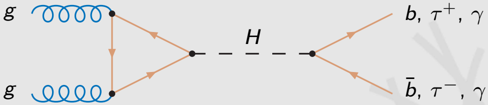
- An estimative for the Higgs mass can be obtained with the study of EW processes

$$M_H = 120^{+12}_{-5} \text{ GeV}$$

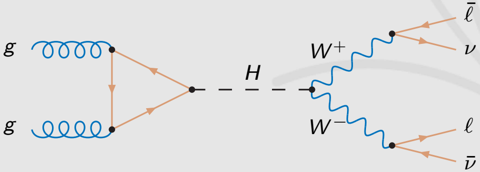


Searches in the LHC

- Different production mechanisms can be studied in the LHC kinematical regime;
- Most expected: **gluon fusion production** + **lepton decay channel**
  - $M_H < 135$ GeV: Gluon fusion with decay into a $b\bar{b}$ pair



  - $M_H > 135$ GeV: Gluon fusion with decay into a W^+W^- pair



- The LHC detectors have different acceptances for the decay channels, leading to different analysis.

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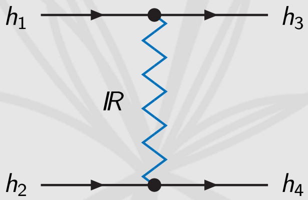
Regge theory

- **50's**: First phenomenological approach to study the hadronic collisions in high energies (before QCD);
- This theory predicted the interactions in the t-channel as the exchange of a **family of ressonances** $\to$ **Reggeon**

$$\alpha(t) = \alpha(0) + \alpha' t$$

- The cross section for hadron-hadron scattering with the exchange of a *reggeized* particle is given by

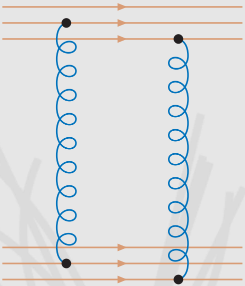
$$\sigma_{tot} \sim s^{\alpha(0)-1}$$



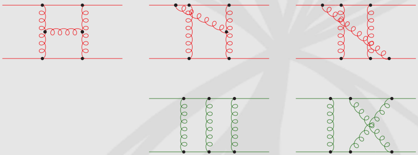
- **1960**: the behavior of the hadronic cross section is constant for $\sqrt{s} = 10$–20 GeV;
- **Pomeron**: particle with intercept $\alpha(0) \approx 1$;
  - Little grow for $\sqrt{s} \sim 2$ TeV;
  - Current data show that $\alpha(0) = 1.0808$.
- **Essential feature**: the Pomeron has the **vacuum quantum numbers**.

BFKL/QCD Pomeron

- Description of Regge theory through the degrees of freedom of QCD;
- Pomeron exchange: gluon pair to recover vacuum quantum numbers;
  - **Minimal** configuration to introduce the Pomeron exchange.



- Study of qq scattering by gluon exchange;
- The diagrams that contribute are:
  - One-loop diagram;
  - Radiative correction;
    - **Real gluon emission**;
    - **Virtual gluon emission**.



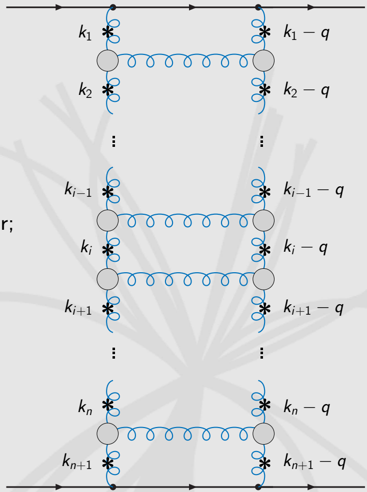
BFKL gluon ladder

- Accounting for all orders in perturbative theory: **gluon ladder**;
  - The propagator of a reggeized gluon is

$$D_{\mu\nu}(s_i, k_i^2) = -\imath \, \frac{g_{\mu\nu}}{k_i^2} \left(\frac{s}{\vec{k}^2} \right)^{\alpha_g(t)-1}$$

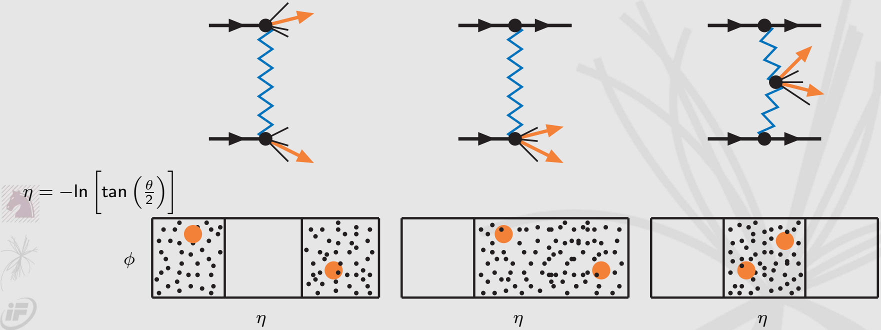
where $\alpha_g(t)$ is seen as its trajectory;

- This results in the **BFKL evolution equation**;
  - Describes the evolution of the gluon ladder;
  - The parton densities $f_i(x, Q^2)$ are evolved in the momentum fraction x.
- **Diffractive particle Physics**: Interactions governed by the exchange of Pomerons;
- However, the nature of the Pomeron its unknown yet as well as a formal theory for the Pomeron interactions.



Particle Diffraction

- Diffractive processes are characterized by the exchange of Pomerons;
  - **Exclusive** processes: the initial state is **not** changed after the interaction.
- The **experimental signature** of these processes are the **rapidity gaps**

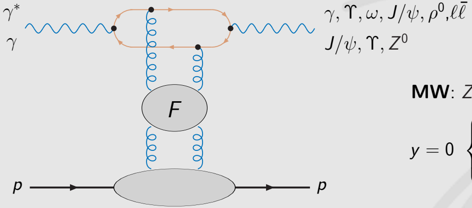


- **The goal**: **study the Higgs boson production in Single Diffractive events and by Double Pomeron exchange in γp processes**.

Outline

Deeply Virtual Compton Scattering (DVCS)

- **1997**: Ji — PRD **55** (1997) 7114
  - $\gamma^* p \to \gamma p$ by **Pomeron exchange** in *ep* collisions.
- **2001**: Munier, Staśto and Mueller — NPB **603** (2001) 427
  - Vector meson production $\gamma^* p \to Vp$ with **GBW model**.
- **2008**: Motyka and Watt — PRD **78** (2008) 014023
  2009: Cisek, Schafer and Szczurek — PRD **80** (2009) 074013
  2009: Kopeliovich, Schmidt and Siddikov — PRD **80** (2009) 054005
  2011: Cisek, Lebiedowicz, Schäfer and Szczurek — arXiv:1101.4874 [hep-ph]
  - Vector particle production $\gamma p \to Ep$ in **Ultraperipheral Collisions**.
- **2010**: Kopeliovich, Schmidt and Siddikov — PRD **82** (2010) 014017
  - Dilepton production in **Double Deeply Virtual Compton Scattering**.

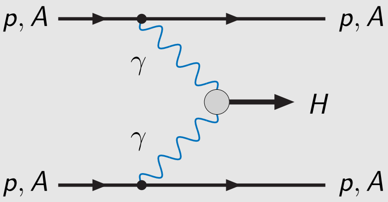


MW: Z^0 boson production

$$y = 0 \begin{cases} \sigma_{\gamma p} = \textbf{4.2 fb}, \text{ Tevatron} \\ \sigma_{\gamma p} = \textbf{37. fb}, \text{ LHC} \end{cases}$$

Electromagnetic Higgs boson production

- **1990**: Cahn and Jackson — PRD **42** (1990) 3690
  Müller and Schramm — PRD **42** (1990) 3699
  - Peripheral heavy-ion collision $\rightarrow \gamma\gamma$ **annihilation**
- **2002**: Khoze, Martin and Ryskin — EPJC 23 (2002) 311
  2007: Miller — arXiv:0704.1985[hep-ph]
  2008: Levin and Miller — arXiv:0801.3593[hep-ph]
  - Contribution from **Electroweak boson loops** to the $\gamma\gamma \rightarrow H$.
- **2010**: D'Enterria and Lansberg — PRD **81** (2010) 014004
  - **Photon fluxes** and **Higgs effective Theory** in $\gamma\gamma$ processes.

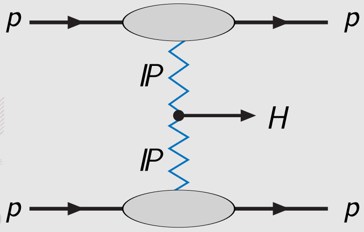


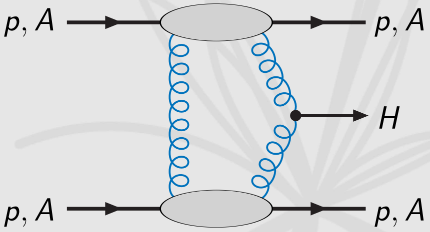
$M_H = 150$ GeV, $\sqrt{s} = 3.5$ TeV/A:
- **CJ**: $\sigma_{\text{PbPb}} = 7.0$ pb
- **MS**: $\sigma_{\text{AA}} \sim 100$ pb

$M_H = 120$ GeV, $\sqrt{s} = 14$ TeV:
- **KMR/M**: $\sigma_{\text{pp}} =$ **0.1 fb/0.12 fb**
- **LM**: $\sigma_{\text{pAu(AuAu)}} =$ **0.6 pb (3.9 nb)**
- **DL**: $\sigma_{\text{pp}} =$ **0.18 fb**

Diffractive Higgs production in pp and AA collisions

- **1991**: Bialas and Landshoff — PLB **256** (1991) 540
  - Regge Theory $\rightarrow$ **non-perturbative gluons**
- **1997**: Khoze, Martin and Ryskin — PLB **401** (1997) 330
  2007: Levin and Miller — arXiv:0801.3593[hep-ph]
  - QCD Pomeron $\rightarrow$ **hard-gluon exchange**



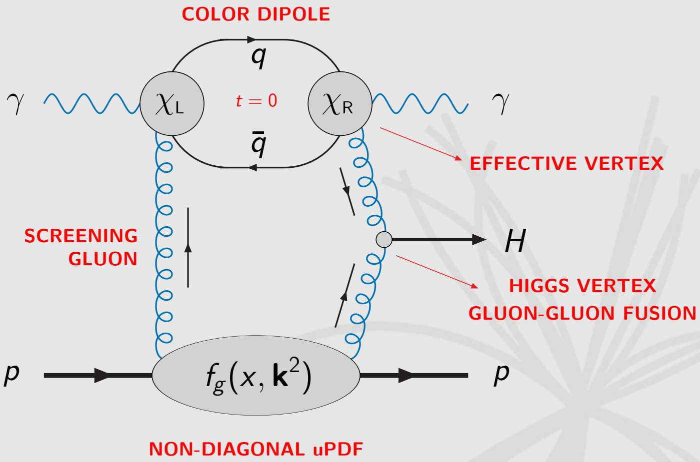


$M_H = 150$ GeV, $\sqrt{s} = 16$ TeV $\left\{\ \textbf{BL} : \sigma_{pp} = 0.1 \text{ pb}\right.$

$M_H = 120$ GeV, $\sqrt{s} = 14$ / 8.8 (5.5) TeV/A $\left\{\begin{array}{ll}\textbf{KMR}: & \sigma^{exc/inc}_{pp} \sim \textbf{3 fb}/300 \text{ fb} \\ \textbf{LM}: & \sigma_{pA(AA)} = \textbf{0.1 pb} \ (3.9 \text{ pb})\end{array}\right.$

Photoproduction mechanism

- **Proposal**: γp process by **DPE** in *pp* collisions[a]

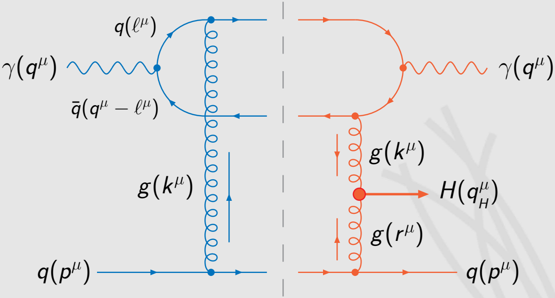


- The dipole amplitude is computed in the **Impact Factor Formalism**.

[a] Gay Ducati, GGS; Phys. Rev. **D78** (2008) 113005

Scattering amplitude

- **Process at partonic level**: $\gamma q \to \gamma + H + q$



- The scattering amplitude is obtained through the **Cutkosky rules**

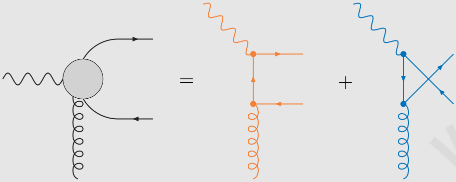
$$\Im \mathcal{A} = \frac{1}{2} \int \mathrm{d}(PS)_3 \, \mathcal{A}_L \, \mathcal{A}_R$$

where $\mathrm{d}(PS)_3$ is the diferential volume element of the three-body phase space;

- It is necessary to check for **all possibilities** for the diagrams of the color dipole.

Effetive vertices

- There are **four** possibilities for the formation of the color dipole



- The calculation is performed through the Feynman rules for each coupling

$$\chi^{\mu\nu} = \imath g_s e e_q\, t^A \left\{ \gamma^\mu \left[\frac{\not l_1 - \not q}{(l_1 - q)^2} \right] \gamma^\nu + \gamma^\nu \left[\frac{\not l_1 - \not k}{(l_1 - k)^2} \right] \gamma^\mu \right\}$$

$$\chi^{\alpha\beta} = \imath g_s e e_q\, t^B \left\{ \gamma^\beta \left[\frac{\not k - \not l_2}{(k - l_2)^2} \right] \gamma^\alpha + \gamma^\alpha \left[\frac{\not q - \not l_2}{(q - l_2)^2} \right] \gamma^\beta \right\}$$

- For the polarizations of the photons, the sum of each configuration implies

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

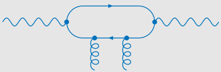
Applying the rules

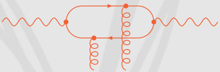
- Performing the scalar products in both sides of the cutting, one finds

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

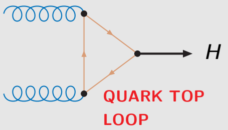
$$\times\ 2\left\{\frac{\mathrm{Tr}\left[(\not{q}-\not{l})\gamma^\mu\not{l}\gamma^\lambda(\not{k}+\not{l})\gamma^\eta\not{l}\gamma^\nu\right]}{l^4}+\frac{\mathrm{Tr}\left[(\not{q}-\not{l})\gamma^\lambda(\not{k}+\not{l}-\not{q})\gamma^\mu(\not{k}+\not{l})\gamma^\eta\not{l}\gamma^\nu\right]}{l^2(k+l+q)^2}\right\}$$

OTHER POSSIBILITIES





- For the production of a **not so heavy** Higgs boson ($M_H \lesssim 200$ GeV), one are able to approximate the ggH vertex like



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

Amplitudes

- It is possible to integrate over $\vec{l}$, resulting in the polarized amplitudes

$$(\Im\mathcal{A})_T = \frac{M_H^2\alpha_s^3\alpha}{6\pi v}\sum_q e_q^2\left(\frac{2C_F}{N_c}\right)\int\frac{d\vec{k}^2}{\vec{k}^6}\left[\frac{20s}{3} - 4Q^2 s\int\frac{-1+2\alpha_\ell+4\alpha_\ell^2-8\alpha_\ell^3+4\alpha_\ell^4}{\vec{k}^2(\tau-\tau^2)+Q^2\alpha_\ell(1-\alpha_\ell)}\,d\alpha_\ell\,d\tau\right]$$

$$(\Im\mathcal{A})_L = -\frac{M_H^2\alpha_s^3\alpha}{6\pi v}\sum_q e_q^2\left(\frac{2C_F}{N_c}\right)\int\frac{d\vec{k}^2}{\vec{k}^6}\left[\frac{8s}{3} - 16Q^2 s\int\frac{\alpha_\ell^2-2\alpha_\ell^3+4\alpha_\ell^4}{\vec{k}^2(\tau-\tau^2)+Q^2\alpha_\ell(1-\alpha_\ell)}\,d\alpha_\ell\,d\tau\right]$$

- **PhD: Extension of the calculations to $Q^2 \neq 0$;**

- For the photoproduction case: **real photons** with $Q^2 \simeq 0$;
  - Only the polarization in **transverse mode** is considered.

- The transverse-polarized scattering amplitude can be rewritten as

$$(\Im\mathcal{A})_T = -\frac{s}{3}\left(\frac{M_H^2}{\pi v}\right)\alpha_s^3\,\alpha\sum_q e_q^2\left(\frac{2C_F}{N_c}\right)\int\frac{d\mathbf{k}^2}{\mathbf{k}^6}\left\{\int_0^1\frac{[\tau^2+(1-\tau)^2][\alpha_\ell^2+(1-\alpha_\ell)^2]\mathbf{k}^2}{\mathbf{k}^2\tau(1-\tau)+Q^2\alpha_\ell(1-\alpha_\ell)}\,d\alpha_\ell\,d\tau\right\}$$

which is known from the **Impact Factor Formalism**.

Cross section for the γq process

- The imaginary part of the scattering amplitude has the form

$$\frac{\Im\mathcal{A}}{s} = -\frac{1}{9\pi}\frac{M_H^2\alpha_s}{N_c v}\int\frac{d\mathbf{k}^2}{\mathbf{k}^6}\left(\frac{\alpha_s C_F}{\pi}\right)\Phi_{\gamma\gamma}(\mathbf{k}^2, Q^2)$$

where $\Phi_{\gamma\gamma}$ is the impact factor of the color dipole with the exchange of two gluons in the t-channel;

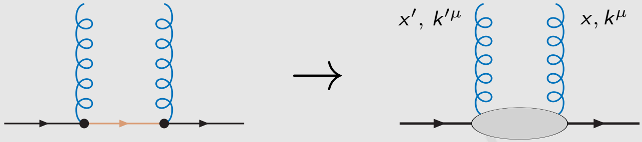
- **First remark**: dependence on $\mathbf{k}^{-6}$ due to the addition of the color dipole.

- This result allows one to obtain the event rate in central rapidity

$$\left.\frac{d\sigma}{dy_H\, d\mathbf{p}^2\, dt}\right|_{y_H,t=0} = \frac{8}{9}\left(\frac{\alpha_s M_H^2}{\pi^3 N_c v}\right)^2\left[\int\frac{d\mathbf{k}^2}{\mathbf{k}^6}\Phi_{\gamma\gamma}(\mathbf{k}^2, Q^2)\,\frac{\alpha_s C_F}{\pi}\right]^2.$$

- This is the result at **partonic level** (qq scattering):
  - It is necessary to introduce the contribution of the proton content;
  - Replacement of one **quark** by the **proton** partonic structure.

Phenomenology: proton partonic content



- The two-gluon coupling to the proton is represented by an **unintegrated density**

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

  which represents the emission of two gluons off the proton;

- The non-diagonality is approximated by a multiplicative factor like

$$\mathcal{K} \simeq (1.2)\exp(-B\mathbf{p}^2/2)$$

  where $B = 5.5\ \text{GeV}^{-2}$ is form factor of the $I\!\!Pp$ coupling;

- The use of f_g demands that the gluon momentum fraction must be $x \sim 0.01$;

Phenomenology: Parametrizations

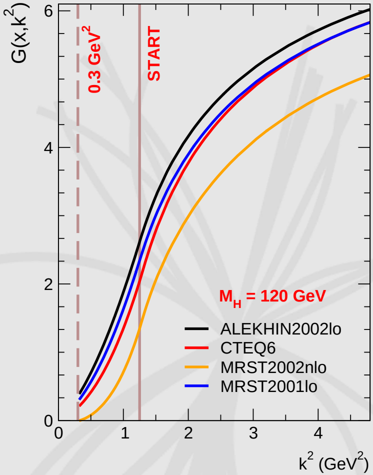
- It is **not** possible to account for the proton content: **non-perturbative regime**;
- Using the available data, one can make a parametrization over x and $\hat{Q}^2$;
- The DGLAP evolution equations are used to evolve the distributions on $\hat{Q}^2$;
  - Each parametrization has an initial scale of evolution:

    MRST :: $\hat{Q}_0^2 = 1.25\ \text{GeV}^2$.
- We extend the distributions to lower values of $\hat{Q}^2$ using the parametrization

$$G(x, \hat{Q}^2) \sim \hat{Q}^{4+2(\gamma+2)\hat{Q}^2}$$

- **The contributions are included to the cross section from the initial scale**

$$\mathbf{k}_0^2 \geq 0.3\ \text{GeV}^2$$

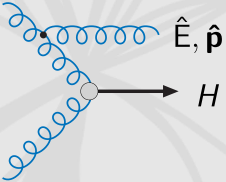


Phenomenology: Gluon radiation at DLLA

- Real gluons can be emitted form the ggH vertex and have to be **suppressed**;
  - **These terms will regulate the infrared region**;
  - Account for the virtual diagrams that include terms like $\ln\left(M_H^2/\mathbf{k}^2\right)$.
- The probability for the emission of one gluon → **Sudakov form factors**

$$S_{\text{sud}}(\mathbf{k}^2, M_H^2) = \frac{N_c \alpha_s}{\pi} \int_{\mathbf{k}^2}^{M_H^2/4} \frac{d\hat{\mathbf{p}}^2}{\hat{\mathbf{p}}^2} \int_{\hat{\mathbf{p}}}^{M_H/2} \frac{d\hat{\mathrm{E}}}{\hat{\mathrm{E}}} = \frac{3\alpha_s}{4\pi} \ln^2\left(\frac{M_H^2}{4\mathbf{k}^2}\right)$$

- If the neutralizing gluon **fails**, the real emissions are **not suppressed**;
- It is necessary to suppress the emission of **multiples** gluons, for which the probability of non-emission exponentiates;
  - A factor of $e^{-S_{\text{sud}}}$ is included to the cross section;
  - The emissions below of $\mathbf{k}^2$ are **suppressed**;
  - If $\mathbf{k}^2 \to 0$, the probability of non-emission goes **faster** to zero than any power of $\mathbf{k}$.



Phenomenology: Gluon radiation at LLA

- The **single** logarithm contributions were forgotten and have to be included;
- The probability of emission from gluons and quarks is rewritten as

$$T(\mathbf{k}^2,\mu^2) = \int_{\mathbf{k}^2}^{\mu^2} \frac{\alpha_s(\hat{\mathbf{p}}^2)}{2\pi}\frac{d\hat{\mathbf{p}}^2}{\hat{\mathbf{p}}^2}\int^{1-\Delta} dz \left[zP_{gg}(z) + \sum_q P_{qg}(z)\right]$$

  - The P_{ij} functions are the DGLAP splitting functions;
  - Δ parameter: the integration over the emission angle of the gluons;
  - In this work, we had use $\mu = M_H/2$.

- The unintegrated gluon distribution function has the final form

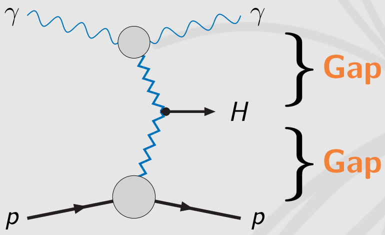
$$\tilde{f}(x,\mathbf{k}^2,\mu^2) = \mathcal{K}\frac{\partial}{\partial \ln \mathbf{k}^2}\left[\sqrt{T(\mathbf{k}^2,\mu^2)}\, G(x,\mathbf{k}^2)\right]$$

where the square-root is added to correct account for the single logarithm terms.

Phenomenology: Rapidity gaps

- The rapidity gaps are the main **signature** for diffractive processes in accelerators;
- Soft interactions produce other particle that will **contaminate** the rapidity gap;
- **Rapidity Gap Survival Probability**: we use two models:
  - KKMR: 2-channel model with enhanced diagrams $\langle S^2 \rangle = 2.6\%(1.5\%)$;
  - GLM: 3-channel model with N=4 SYM and QCD $\langle S^2 \rangle = 3 - 5\%$.

  which account for the fraction of events with gaps;
- Central dijet production at HERA: diffractive ratio of **10%**.



Photoproduction mechanism

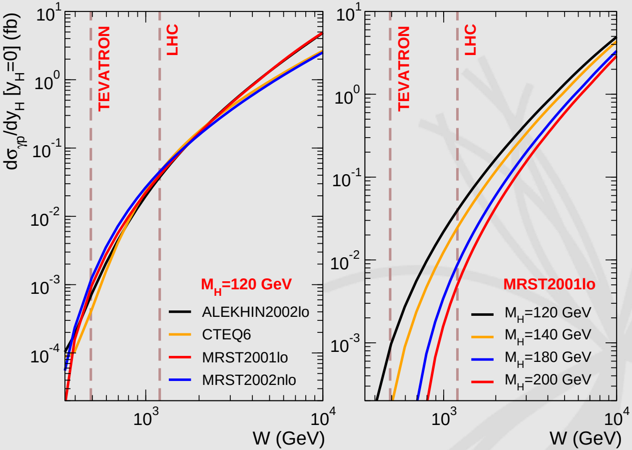
- The cross section is calculated for central rapidity ($y_H = 0$)

$$\left.\frac{d\sigma}{dy_H\,dt}\right|_{y_H,t=0} = \langle S^2\rangle \frac{K_{NLO}}{288\pi^5 B}\,\alpha_s^4 \left(\frac{M_H^2}{N_c \upsilon}\right)^2 \left[\int_{\mathbf{k}_0^2}^{\mu^2} \frac{d\mathbf{k}^2}{\mathbf{k}^6}\,\tilde{f}_g(x,\mathbf{k}^2,\mu^2)\,\Phi^T_{\gamma\gamma}(\mathbf{k}^2,Q^2)\right]^2$$

- Proton content: $\alpha_s C_F/\pi \;\rightarrow\; \tilde{f}_g(x,\mathbf{k}^2,\mu^2) = \mathcal{K}\,\partial_{(\ln \mathbf{k}^2)}\left[\sqrt{T(\mathbf{k}^2,\mu^2)}\,xg(x,\mathbf{k}^2)\right]$;
- Sudakov form factor: $T(\mathbf{k}^2,\mu^2) = \left[\alpha_s(\mathbf{k}^2)/\alpha_s(\mu^2)\right] e^{-S}$, $S \sim \ln^2(\mu^2/\mathbf{k}^2)$;
- Gap Survival Probability: $\langle S^2\rangle \rightarrow$ 3% and 10% for LHC;
- Cutoff $\mathbf{k}_0^2$ to regulate the infrared divergences: $\mathbf{k}_0^2 = 0.3$ GeV^2;
- NLO corrections: $K_{NLO} = 1.5$ for the entire mass range;
- Electroweak vacuum expectation value: $\upsilon = 246$ GeV;
- Slope of the $I\!Pp$ coupling: $B = 5.5$ GeV^{-2}.
- Scale to evolve the Sudakov form factors: $\mu = M_H/2$.

Results: predictions for the photoproduction mechanism[b]

- The predictions using a set of parametrizations for the proton PDF show distinct behaviors considering the CM energy of the subprocess;
- **Tevatron**: restriction for $M_H < 140$ GeV.



[b] Gay Ducati, GGS; arXiv:0910.2595 [hep-ph]

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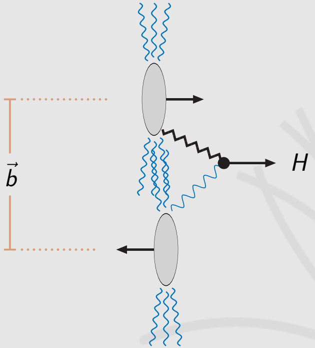
Ultraperipheral Collisions

- The γp interaction is a subprocess that occurs in **Ultraperipheral Collisions**



- These collisions allow interactions with impact parameter $b \geq 2R$;
  - The interactions are purely electromagnetic.
- The photons emitted from the EM field around the hadrons are **real photons**.

Hadronic cross section

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

$$\sigma_{tot} = 2\int_{\omega_{min}}^{\omega_{max}} d\omega\, \frac{dn_i}{d\omega}\, \sigma_{\gamma p}(\omega, M_H),$$

with $\omega_{min} = M_H^2/2x\sqrt{s_{NN}}$ and $\omega_{max} = \sqrt{Q^2\gamma_L^2\beta_L^2}$, and the flux is given by

$$\frac{dn_p}{d\omega} = \frac{\alpha_{em}}{2\pi\omega}\left[1 + \left(1 - \frac{2\omega}{\sqrt{s}}\right)^2\right]\left(\ln\mu_p - \frac{11}{6} + \frac{3}{\mu_p} - \frac{3}{2\mu_p^2} + \frac{1}{3\mu_p^2}\right).$$

for the emission off **protons**, with $A \simeq 1 + (0.71\ \mathrm{GeV}^{-2})\sqrt{s}/2\omega^2$, and

$$\frac{dn_A}{d\omega} = \frac{2Z^2\,\alpha_{em}}{\pi\omega}\left[\mu_A K_0(\mu_A)K_1(\mu_A) - \frac{\mu_A^2}{2}[K_1^2(\mu_A) - K_0^2(\mu_A)]\right].$$

for **nuclei**, with $\mu = b_{min}\omega/\gamma_L$, onde $b_{min} = R_p + R_A$;

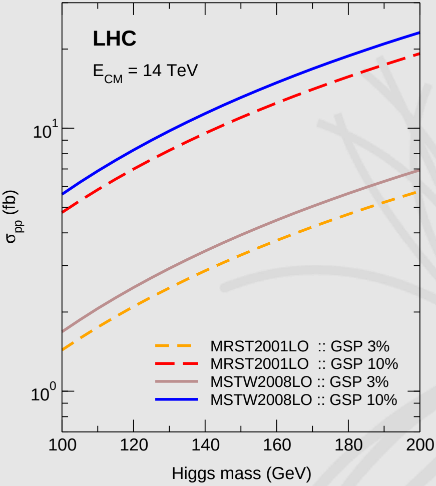
- The photon virtuality have to be decomposed in the form

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

where $\gamma_L = (1 - \beta_L^2)^{-1/2} = \sqrt{s}/2m_i$ is the Lorentz factor of one beam.

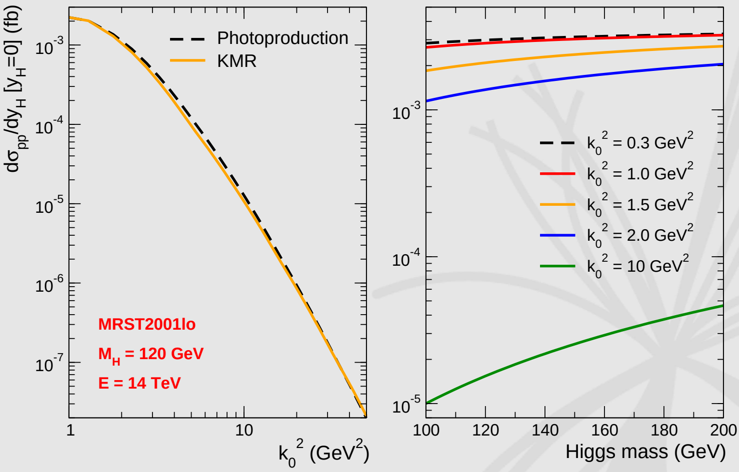
Results: *pp* in UPC

- σ_{pp}: one order higher than the results from $\gamma\gamma$ processes (0.10–0.18 fb).
- An optimistic approach for the GSP provides a cross section of $\sim$**6 fb**.



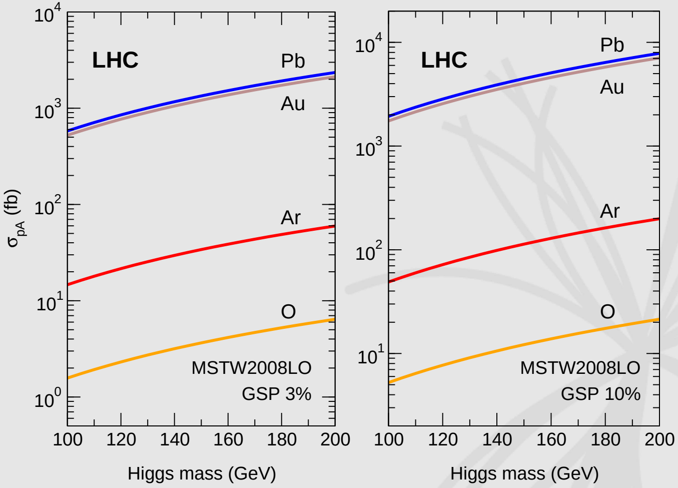
Results: sensibility

- Nearly the same behavior than the results of the Durham group;
- The main contribution comes from the $\mathbf{k}_0^2 < 30\ \mathrm{GeV}^2$.



Results: *pA* in UPC

- $\sigma_{pAu} \sim$ 800 fb: competitive with the $\gamma\gamma$ process;
- σ_{pPb}: **4x** higher than the approach with an **Effective Field Theory**.



Event rates[c]

- Taking the Branching ratio for $\text{BR}(H \to b\bar{b}) \approx 72\ \%$, the event rate for the Higgs boson production can be predicted for LHC;
  - Little chance to observe $b\bar{b}$ decay in LHC: $\gamma\gamma$ and $\tau^+\tau^-$ expected.

	σ (fb)	BR $\times\,\sigma$	$\mathcal{L}$ (fb^{-1})	events/yr
pp	1.77	1.27	1(30)	**1 (30)**
pp	5.92	4.26	1(30)	**6 (180)**
pPb	617	444	0.035	**21**
pPb	2056	1480	0.035	**72**

- There was an one-month run in last November for heavy-ions collisions.
  - New data for *AA* collisions may be available in 2011.

[c] Gay Ducati, GGS; Physical Review D **82** (2010) 074003

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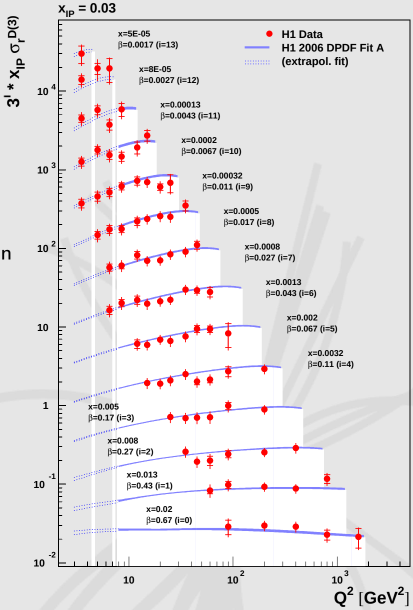
Pomeron partonic content

- An alternative is a phenomenological view of **partons** being the **constituent** of the Pomeron;
  - There would have a **partonic distribution** for quarks and glouns inside de Pomeron.
- To be correct, it was necessary the detection of an **additional jet** coming from the diffractive event;
- The SPS data **confirmed** this expectation;
- In the HERA collider, this ideia allows to study of the **Diffractive DIS**;
- There is a limitation in this approach, which works for the HERA kinematical regime, but not for the Tevatron one.



Diffractive factorization

- This alternative approach is called **Ingelman-Schlein model**, which considers the factorization of the total cross section

$$\sigma_{SD}(AB \to AH + B) = \mathcal{F}_{a/IP/A}(x_{IP}, \beta, \mu_F^2) \otimes \sigma(ab \to H) \otimes f_{b/B}(x, \mu_F^2)$$

$$\sigma_{CED}(AB \to A + H + B) = \mathcal{F}_{a/IP/A}(x_{IP}, \beta, \mu_F^2) \otimes \sigma(ab \to H) \otimes \mathcal{F}_{b/IP/B}(x_{IP}, \beta, \mu_F^2)$$

being known as the **diffractive factorization**;

- The Pomeron Structure Function is described by a two-step process

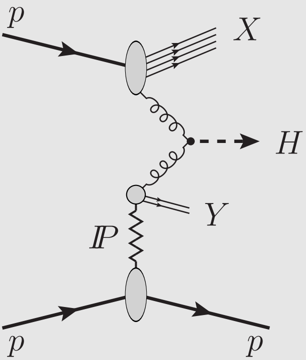
$$\mathcal{F}_{i/IP/A}(x_{IP}, \beta, \mu_F^2) = F_{i/IP}\left(\frac{x}{x_{IP}}, \mu_F^2\right) f_{IP/A}(x_{IP}, t)$$

1. Emission of a soft Pomeron from the colliding hadron, expressed by the Pomern flux $f_{IP/A}(x_{IP}, t)$;
2. Probability of find a parton a in the Pomeron, which is given by the diffractive parton density $F_{i/IP}\left(\beta, \mu_F^2\right)$.

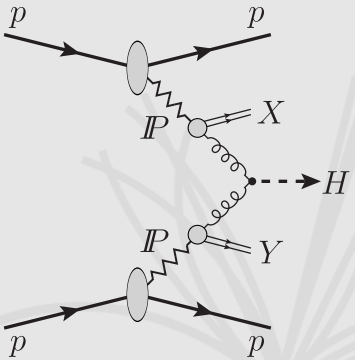
- The **dPDF** is provided by the analyses of the data from the **H1 detector** at HERA and the **Pomeron flux** is computed with **Regge theory**.

Diffractive processes

Single Diffractive[d]



Central Exclusive Diffractive[e]



Purpose: **verify the uncertainties related to predictions of the CED Higgs boson production at the LHC**

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[d] Gay Ducati, Machado, GGS; Physical Review D **83** (2011) 074005

[e] Gay Ducati, GGS; arXiv:1104.3458 [hep-ph]

NLO corrections

- The corrections to the $gg \to H$ processes are represented by the processes

$$gg \to H(g) \qquad qg \to Hq \qquad q\bar{q} \to Hg$$

- The NLO inclusive cross section for $pp \to pHp$ can be computed by

$$\sigma_{NLO} = \frac{d\mathcal{L}^{ij}}{d\tau_H}\sigma_0\tau_H\left[1+\alpha_s(\mu_R^2)\frac{\mathcal{C}}{\pi}\right] + \Delta\sigma_{gg} + \Delta\sigma_{gq} + \Delta\sigma_{q\bar{q}}$$

being the functions definied in the **heavy-quark mass limit** $\tau_Q = M_H^2/4M_t^2$

  - $d\mathcal{L}^{ij}/d\tau$ the parton-parton luminosity;
  - $\tau_H = M_H^2/s$ is the Drell-Yan variable;
  - $\sigma_0 = G_f\alpha_s(\mu_R^2)\left|\frac{3}{4}\,2[\tau_Q + (\tau_Q - 1)\arcsin^2\sqrt{\tau_Q}]/\tau_Q^2\right|^2/288\pi\sqrt{2}.$

- The singular virtual corrections are included in the factor $\mathcal{C}$;
- The non-singular ones in the $\Delta\sigma_{ij}$ terms.

Parton-parton luminosities

- The **modified** parton-parton luminosity for the **SD** process reads

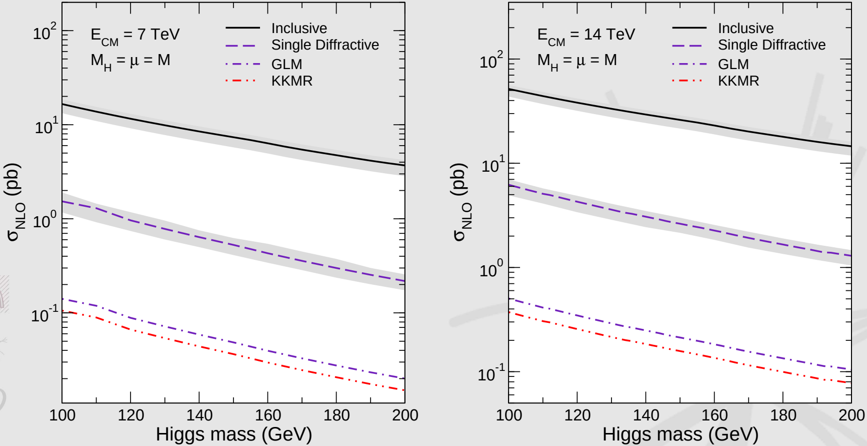
$$\frac{d\mathcal{L}^{gi}_{SD}}{d\tau} = \int_\tau^1 \frac{dx}{x} \int_x^{0.05} \frac{dx_{IP}}{x_{IP}} \mathcal{F}_{i/IP/p}\left(x_{IP}, \frac{x}{x_{IP}}, \mu_F^2\right) g(\tau/x, \mu_F^2) + \int_\tau^1 \frac{dx}{x} \int_{\tau/x}^{0.05} \frac{dx_{IP}}{x_{IP}} g(x, \mu_F^2)\, \mathcal{F}_{i/IP/p}\left(x_{IP}, \frac{\tau}{x_{IP}x}, \mu_F^2\right)$$

- In the case of **CED** production, the luminosity is given by

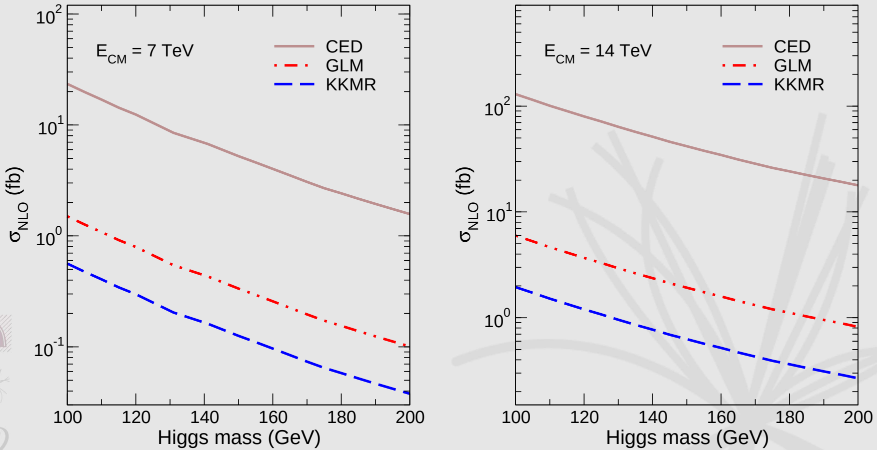
$$\frac{d\mathcal{L}^{ij}_{CED}}{d\tau} = \int_\tau^1 \frac{dx}{x} \int_x^{0.05} \frac{dx_{IP}^1}{x_{IP}^1} \mathcal{F}_{i/IP/p}\left(x_{IP}^1, \frac{x}{x_{IP}^1}, \mu_F^2\right) \times \int_{\tau/x}^{0.05} \frac{dx_{IP}^2}{x_{IP}^2} \mathcal{F}_{j/IP/p}\left(x_{IP}^2, \frac{\tau}{x_{IP}^2 x}, \mu_F^2\right)$$

- The **factorization breaking** occurs for hadron-hadron collisions;
  - **Soft interactions** between hadrons are not included;
  - The **GSP** is a way to introduce such effects and reduce the predictions.

Results: SD production



Results: CED production



- Different **shape** between the curves for NLO and LO calculations;
- Uncertainties in use of a **multiplicative factor** to account for NLO corrections.

Rapidity Gap Survival Probability

- The scenario of all predictions for the exclusive production is competitive[f];

Subprocess	GSP (%)	σ_{pp} (fb)
$I\!PI\!P$	2.6	3.00
$I\!PI\!P$	0.4	0.47
$I\!PI\!P_{\text{IS}}$	4.0	3.20
$\gamma\gamma$	100.	0.10-0.18
γp	3.0	**1.77**
γp	10.	**5.92**

- The GSP is **not** computed for the Higgs boson production in the photoproduction mechanism;
  - The models for the soft interactions depends on the amplitude of the process to estimate the GSP.
- Based on previous evidences from HERA: $\langle S^2 \rangle = \mathbf{10\%}$;
- The diffractive factorization does not include the soft interactions by Pomeron exchange.

[f] Gay Ducati, GGS; Phys. Rev. **D82** 073004 (2010)

Conclusions

- Thesis: **original** approach for a production mechanism and **improvements** to the exclusive production of the Higgs boson;
- We have computed the production cross section for the **Higgs boson** in UPC at the LHC:

$$\sigma_{\text{pp}} \sim 1 - 6 \text{ fb} \qquad \sigma_{\text{pA}} \sim 0.8 - 2.0 \text{ pb}$$

- The *p*A collisions provide a cleaner final state to discover the Higgs boson at the LHC;
  - The luminosity and pile-up in such processes will be favorable for the Higgs boson detection in LHC;
  - A reasonably event rate predicted for future *p*A runs in LHC.
- Low sensitivity to the input parameter: infrared region under control;
- Taking the specific GSP for the photoproduction processes, the predictions may be **higher** than the ones from other approaches;
- The results obtained in the diffractive factorization agree with previous estimations.
  - It allows to include higher-order corrections, **reducing** uncertanties.