DARK MATTER PRODUCTION THROUGH GLUON FUSION

Omar Rafael Torrijo Gonzalez

In collaboration with,
PhD. Edilson A. Reyes R - PhD. Blanca C. Cañas O.

Departamento de Física y Geología,
G.O.M. - Física Teórica / UDP,
Integral / UDP,
Grupo de Campos y Particulas / UNAL,
Pamplona, Norte de Santander - Colombia

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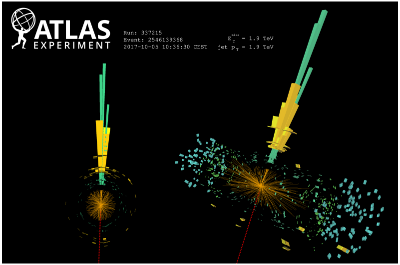


Figure: Event display of a monojet in the signal region of a search for invisible Higgs boson decays.

Atlas Experiment.
Web image associated with Arxiv.org:2102.10874

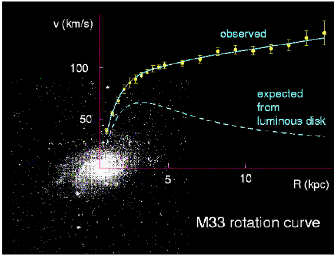


Figure: A superposition of the measurements of the galaxy rotation velocity conducted experimentally with theoretical predictions

Dark matter and dark energy
Lecture Notes in Physics, vol. 653, 03 2004

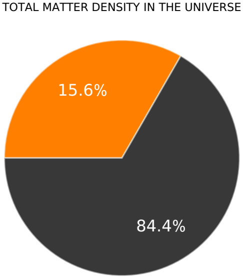


Figure: Distribution of ordinary matter, dark matter, and dark energy in the universe in terms of percentage of density in the universe.

Particle Data Group
pdg.lbl.gov

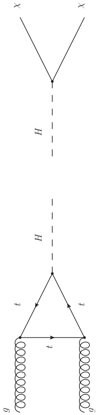


Figure: Feynman diagram for the production of Dark matter through gluon fusion.

Consider the QCD Lagrangian + Yukawa Lagrangian:

$$\mathcal{L} = -\frac{1}{4} G^a_{\mu\nu}(x) G^{\mu\nu}_a(x) + \bar{\psi}_f (i\not{D} - m_f)\psi_f - \frac{1}{2\xi}(\partial^\mu G^a_\mu)^2 + \bar{c}^a \partial^\mu D^{ab}_\mu c^b \dots$$
$$\dots - y_f \bar{\psi}^i(x)\phi(x)\psi_i(x), \quad (1)$$

$$\mathcal{L}_{Int} = g_s \bar{\psi}^i(x)\gamma^\mu G^a_\mu(x) t^a \psi_i(x) - y_f \bar{\psi}^i(x)\phi(x)\psi_i(x) \quad (2)$$

With the identified interaction term, we are going to calculate the S-matrix for scattering $2 \to 1 (gg \to H)$.

$$\langle f|\, S\, |i\rangle = (2\pi)^4 \delta^4\left(k_i - k_f\right) i\mathcal{M}(k_i \to k_f)$$

$$\langle H|\, T\left[\exp\left(-i\int d^4x \mathcal{L}_{Int}\right)\right] |g_1, g_2\rangle \quad (3)$$

$$= \langle k_3|\, T\left[\exp\left(-i\int d^4x \mathcal{L}_{Int}\right)\right] |(k_1,\sigma_1),(k_2,\sigma_2)\rangle \quad (4)$$

$$\langle k_3|\, T\left\{\exp\left[-i\int d^4x\left(g_s\bar{\psi}^i(x)\gamma^\mu G^a_\mu(x)t^a\psi_i(x)\ \ldots\right.\right.\right.$$
$$\left.\left.\left.\ldots -y_f\bar{\psi}^i(x)\phi(x)\psi_i(x)\right)\right]\right\}|(k_1,\sigma_1),(k_2,\sigma_2)\rangle \quad (5)$$

We applied Dyson series expansion and Wick's theorem:

$$\langle k_3|\, T\left(-i^3\int d^4x\int d^4y\int d^4z\left[g_s\bar{\psi}^i(x)\gamma^\mu G^a_\mu(x)t^a\psi_i(x)-y_f\bar{\psi}^i(x)\phi(x)\psi_i(x)\right]\ldots\right.$$
$$\ldots\times\left[g_s\bar{\psi}^j(y)\gamma^\rho G^b_\rho(y)t^b\psi_j(y)-y_f\bar{\psi}^j(y)\phi(y)\psi_j(y)\right]\ldots$$
$$\left.\ldots\times\left[g_s\bar{\psi}^k(z)\gamma^\beta G^c_\beta(z)t^c\psi_k(z)-y_f\bar{\psi}^k(z)\phi(z)\psi_k(z)\right]\right)|(k_1,\sigma_1),(k_2,\sigma_2)\rangle \quad (6)$$

$$i\mathcal{M}(k_i\to k_f)=-i^3(g_s)^2y_f\int d^4x\int d^4y\int d^4z\,\langle k_3|\,T\left[(\bar{\psi}\gamma Gt\psi)_x(\bar{\psi}\gamma Gt\psi)_y\ldots\right.$$
$$\left.\ldots\times(\bar{\psi}\phi\psi)_z\right]|(k_2,\sigma_2),(k_3,\sigma_3)\rangle \quad (7)$$

If we interpret this with Feynman diagrams and apply the corresponding Feynman rules, we get:

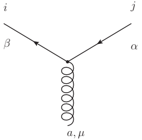


Figure: Quark-Gluon vertex.

$$= -ig_s\gamma^{\mu}_{\beta\alpha}[t^a]_{ji} \tag{8}$$

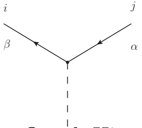


Figure: Quark-Higgs vertex.

$$= -i\frac{y_t\delta_{ij}\delta_{\alpha\beta}}{\sqrt{2}} \tag{9}$$

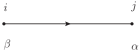


Figure: Fermion propagator.

$$= \frac{i(\not{k} + m)_{\beta\alpha}\delta_{ij}}{k^2 - m^2 + i\varepsilon} \tag{10}$$

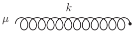


Figure: Incoming Gluon.

$$= \epsilon_{\mu}(k, \sigma) \tag{11}$$

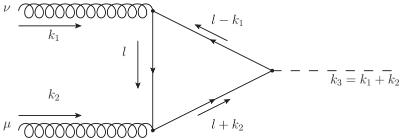


Figure: First contribution $gg \to H$.

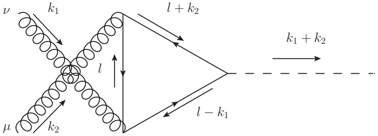


Figure: Second contribution $gg \to H$.

FeynArts
hep-ph/0012260

$$i\mathcal{M} = \int \frac{d^4 l}{(2\pi)^4} \frac{i(\not{l} - \not{k}_1 + m)}{(l^2 - m^2)} \left(-i\frac{y_t}{\sqrt{2}}\right) \frac{i(\not{l} + \not{k}_2 + m)}{[(l-k_1)^2 - m^2]} \dots$$
$$\times (-ig_s \gamma^\mu [t^a]) \frac{i(\not{l} + m)}{[(l+k_2)^2 - m^2]} (-ig_s \gamma^\nu [t^b]) \epsilon_\nu(k_1, \sigma_1) \epsilon_\mu(k_2, \sigma_2) \quad (12)$$

$$i\mathcal{M} = i^3 (-ig_s)^2 \left(-i\frac{y_t}{\sqrt{2}}\right) tr\{t^a t^b\} \epsilon_\nu(k_1, \sigma_1) \epsilon_\mu(k_2, \sigma_2) \dots$$
$$\dots \times \int \frac{d^4 l}{(2\pi)^4} \frac{Tr\{(\not{l} - \not{k}_1 + m)(\not{l} + \not{k}_2 + m)\gamma^\mu (\not{l} + m)\gamma^\nu\}}{(l^2 - m^2)[(l-k_1)^2 - m^2][(l+k_2)^2 - m^2]} \quad (13)$$

So, Apply dimensional regularization $d = 4 - 2\varepsilon$:

$$i\mathcal{M} = i^3(-ig_s)^2\left(-i\frac{y_t}{\sqrt{2}}\right)\mathrm{tr}\{t^a t^b\}\epsilon_\nu(k_1,\sigma_1)\epsilon_\mu(k_2,\sigma_2)\dots$$
$$\dots\times\lim_{\varepsilon\to 0}\mu^{4-d}\int\frac{d^d l}{(2\pi)^d}\frac{Tr\{(\not{l}-\not{k}_1+m)(\not{l}+\not{k}_2+m)\gamma^\mu(\not{l}+m)\gamma^\nu\}}{(l^2-m^2)[(l-k_1)^2-m^2][(l+k_2)^2-m^2]} \tag{14}$$

And we applied the Dirac algebra in d-dimension to the Trace of the loop integral to obtain:

$$\mu^{4-d}\int\frac{d^d l}{(2\pi)^d}\frac{8m[k_1^\mu k_2^\nu - k_1^\nu k_2^\mu + 2k_2^\mu l^\nu - 2k_1^\nu l^\mu + 4l^\mu l^\nu - g^{\mu\nu}k_1\cdot k_2 - g^{\mu\nu}l\cdot l + g^{\mu\nu}m^2]}{(l^2-m^2)[(l-k_1)^2-m^2][(l+k_2)^2-m^2]} \tag{15}$$

We redefine the denominators as:

$$D_0 = l^2 - m^2 \qquad D_1 = (l-k_1)^2 - m^2 \qquad D_2 = (l+k_2)^2 - m^2$$

We write as a set of integrals known as Passarino - Veltman functions.

$$
\begin{aligned}
i\mathcal{M} = i^3(-ig_s)^2\left(-i\frac{y_t}{\sqrt{2}}\right)\mathrm{tr}\{t^a t^b\}\epsilon_\nu(k_1,\sigma_1)\epsilon_\mu(k_2,\sigma_2)\lim_{\varepsilon\longrightarrow 0}\dots \\
\dots\times\mu^{4-d}8m\left(k_1^\mu k_2^\nu\int\frac{d^dl}{(2\pi)^d}\frac{1}{D_0D_1D_2} - k_1^\nu k_2^\mu\int\frac{d^dl}{(2\pi)^d}\frac{1}{D_0D_1D_2}\dots\right. \\
\dots + 2k_2^\mu\int\frac{d^dl}{(2\pi)^d}\frac{l^\nu}{D_0D_1D_2} - 2k_1^\nu\int\frac{d^dl}{(2\pi)^d}\frac{l^\mu}{D_0D_1D_2}\dots \\
\dots + 4\int\frac{d^dl}{(2\pi)^d}\frac{l^\mu l^\nu}{D_0D_1D_2} - g^{\mu\nu}k_1\cdot k_2\int\frac{d^dl}{(2\pi)^d}\frac{1}{D_0D_1D_2}\dots \\
\left.\dots - g^{\mu\nu}\int\frac{d^dl}{(2\pi)^d}\frac{l^2}{D_0D_1D_2} + g^{\mu\nu}m^2\int\frac{d^dl}{(2\pi)^d}\frac{1}{D_0D_1D_2}\right),
\end{aligned}
\tag{16}
$$

tensor integrals of rank 0, 1, 2.

$$i\mathcal{M} = 8mg_f^2\left(\frac{y_t}{\sqrt{2}}\right)\mathrm{tr}\{t^a t^b\}\epsilon_\nu(k_1,\sigma_1)\epsilon_\mu(k_2,\sigma_2)\lim_{\varepsilon\longrightarrow 0}\left(k_1^\mu k_2^\nu C_0 \ldots\right.$$
$$\left.-k_1^\nu k_2^\mu C_0 + 2k_2^\mu C^\nu - 2k_1^\nu C^\mu + 4C^{\mu\nu} - g^{\mu\nu}k_1\cdot k_2 C_0 - g^{\mu\nu}B_0^{(1,2)}\right) \quad (17)$$

We impose the transversality condition, $\epsilon_\mu(k_i,\sigma_i)k_i^\mu = 0$, and color algebra, $\mathrm{tr}\{t^a t^b\} = \frac{\delta^{ab}}{2}$ on the integral:

$$i\mathcal{M} = 4m\frac{g_s^2 y_t\delta^{ab}}{\sqrt{2}}\epsilon_\nu(k_1,\sigma_1)\epsilon_\mu(k_2,\sigma_2)\lim_{\varepsilon\longrightarrow 0}\left[(C^0_{(0,1,2)} + 4C_{23})k_1^\mu k_2^\nu \cdots\right.$$
$$\left.+g^{\mu\nu}\left(4C_{24} - B^0_{(1,2)} - \frac{1}{2}sC^0_{(0,1,2)}\right)\right]. \quad (18)$$

$$i\mathcal{M} = -\frac{imy_t g^2 \delta^{ab}}{16\sqrt{2}\pi^2 m_H^4}\left[m_H^2 \vec{\epsilon}(k_1)\cdot\vec{\epsilon}(k_2) - 2\vec{k}_1\vec{\epsilon}(k_2)\vec{k}_2\vec{\epsilon}(k_1)\right]\cdots$$
$$\cdots\times\left[4m^2\log^2\left(\frac{\sqrt{m_H^4-4m^2m_H^2}-m_H^2+2m^2}{2m^2}\right)\cdots\right.$$
$$\left.\cdots-m_H^2\log^2\left(\frac{\sqrt{m_H^4-4m^2m_H^2}-m_H^2+2m^2}{2m^2}\right)-4m_H^2\right] \quad (19)$$

Now we calculate $|\mathcal{M}|^2$ and summing over all the polarization states.

$$\overline{|\mathcal{M}|}^2 = \frac{g^4}{64\pi^4 m_H^4}\left[my_t m_H^2\log^2\left(\frac{\sqrt{m_H^4-4m^2m_H^2}-m_H^2+2m^2}{2m^2}\right)-4my_t m_H^2\cdots\right.$$
$$\left.\cdots-4m^3y_t\log^2\left(\frac{\sqrt{m_H^4-4m^2m_H^2}-m_H^2+2m^2}{2m^2}\right)\right]^2 \quad (20)$$

With $\tau = \dfrac{4m^2}{M_H^2}$, $\alpha_s^2 = \dfrac{g^4}{16\pi^2}$, $y_t^2 = \dfrac{2m^2}{v^2}$ and considering $\tau \geq 1$

$$\overline{|\mathcal{M}|}^2 = \frac{\alpha_s^2 m_H^4}{32^2\pi^2 v^2}\tau^2\left[1 + (1-\tau)\arcsin^2\left(\frac{1}{\sqrt{\tau}}\right)\right]^2 \tag{21}$$

Then, the cross section is:

$$\sigma(gg \to H)_{SM} = \frac{1}{2s}\int \frac{d^3k_3}{(2\pi)^3 2E_H}(2\pi)^4\delta^4\left(k_3 - \sum_{i=1}^{2} k_i\right)\overline{|\mathcal{M}|}^2 \tag{22}$$

$$\sigma(gg \to H)_{SM} = \frac{\pi}{m_H^2}\delta\left(s - m_H^2\right)\overline{|\mathcal{M}|}^2 \tag{23}$$

$$= \frac{\alpha_s^2 m_H^2}{32^2\pi v^2}\tau^2\delta\left(s - m_H^2\right)\left[1 + (1-\tau)\arcsin^2\left(\frac{1}{\sqrt{\tau}}\right)\right]^2 \tag{24}$$

The difference involves the fragmentation of one gluon.

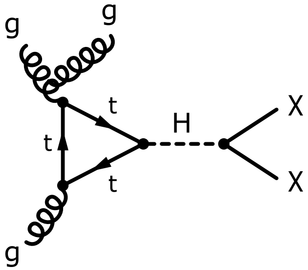


Figure: H+Jet topology - The production of dark matter via gluon fusion with the presence of the $E_{\mathrm{T}}^{\mathrm{miss}}$

Combination of search for invisible decays of the Higgs boson ATLAS
arXiv:2301.10731v2

The creation of a high-precision simulation becomes necessary.

Data samples and simulations

P. P.	Incl.C.S. Precision
ggH	N^3LO(QCD),NLO(EW)
qqH	NNLO(QCD),NLO(EW)
VH	NNLO(QCD),NLO(EW)

Table: Simulation used for the different Higgs boson production process (P.P.) and the accuracy of the inclusive cross section (Incl.C.S.) used for each process is show.

Searches for invisible decay of the Higgs boson in PP collisions CMS
arXiv:1610.09218v2

Statistics consistent with the predictions of the Standard Model become upper limits.

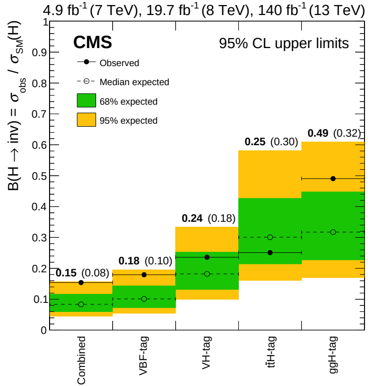


Figure: observed and expected upper limits on $\mathcal{B}(H \to \text{inv})$ at 95% CL. CMS

Dark sector searches with the CMS experiment
arXiv:2405.13778(2024)

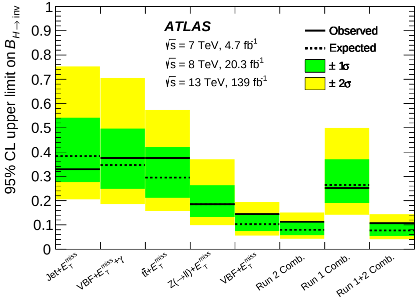


Figure: observed and expected upper limits on $\mathcal{B}(H \to \text{inv})$ at 95% CL. ATLAS

Combination of searches for invisible decays of the Higgs boson..
arxiv.org/2301.10731v2

When exploring theories that extend the standard model (SM) that introduce new particles or interactions connected with dark matter:

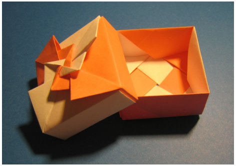
HIGGS-PORTAL MODEL

$$\Delta\mathcal{L}_S = -\frac{1}{2}M_S^2 S^2 - \frac{1}{4}\lambda_S S^4 - \frac{1}{4}\lambda_{HSS}\Phi^\dagger\Phi S^2 \quad (25)$$

$$\Delta\mathcal{L}_V = \frac{1}{2}M_V^2 V_\mu V^\mu + \frac{1}{4}\lambda_V (V_\mu V^\mu)^2 + \frac{1}{4}\lambda_{HVV}\Phi^\dagger\Phi V_\mu V^\mu \quad (26)$$

$$\Delta\mathcal{L}_\chi = -\frac{1}{2}{}_{\chi}\bar{\chi}\chi - \frac{1}{4}\frac{\lambda_{H\chi\chi}}{\Lambda}\Phi^\dagger\Phi\bar{\chi}\chi \quad (27)$$

The POWHEG BOX



powhegbox.mib.infn.it

PYTHIA

pythia.org

THANK YOU SO MUCH.

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