Introducción computacional a MadGraph5 para dos modelos

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Resumen

Actualmente el conocimiento de la programación física computacional ha ido aumentando con el tiempo, y en su mayoría por programas que hacen posible este desarrollo, en este trabajo destacaremos lo que han sido Madgrafths y Cross-Section en los procesos de interacción de partículas dentro del lenguaje Linux. Los cuales bajo estos conceptos obtendremos los resultados correspondientes, teniendo en cuenta las variaciones que esto pudiera tener en caso de que no se utilice el modelo habitual (Modelo Estándar de partículas), por el modelo HEFT.

Palabras Clave
Madgrafths, Linux, Cross-Section, modelo

1 Metodología

1.1 MadGraph5-aMC@NLO

Es un marco que tiene como objetivo proporcionar todos los elementos necesarios para la fenomenología SM y BSM, como los cálculos de secciones transversales, la generación de eventos duros y su combinación con los generadores de eventos, y el uso de una variedad de herramientas relevantes para manipulación y análisis de eventos.[3] Considerado el primer código público que realiza el cálculo de NLO y hace coincidir el resultado de NLO de orden fijo con la parton shower (con formalismo MC@NLO) de forma automática; entre ellos destacan las correcciones QCD y EW para procesos SM. Todos los cálculos de orden fijo se basan en el marco MadGraph5.[1,3]

MadGraph5-aMC@NLO es la nueva versión de MadGraph5 y aMC@NLO que unifica las líneas LO y NLO de desarrollo de herramientas automatizadas dentro de la familia MadGraph.

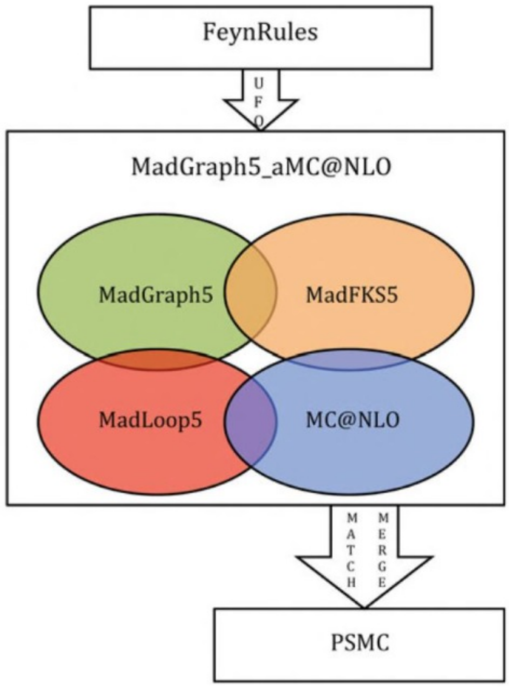

Fig. 1. Estructura del MadGraph5-aMC@NLO. El PSMC sería la interfaz del Parton Shower Monte Carlo.[1]

En breve mostraré cómo ejecutar el código para realizar un análisis fenomenológico de forma básica. Para el cálculo de una sección transversal por Madgraph5-aMC@NLO consta principalmente de tres fases: generation, output, and running.
La ejecución del código viene dada por:

```
> ./bin/mg5_aMC
```

Luego, el usuario verá el aviso interactivo.

```
MG5_aMC>
```

La sintaxis de los tres pasos es:

```
MG5_aMC> generate PROCESS
MG5_aMC> output (output file)
MG5_aMC> launch (options)
```

, donde PROCESS es el proceso interesado, *(options)* en el último paso son las opciones opcionales especificadas por el usuario para el comando *launch*, y *(output file)* es el archivo opcional que el usuario le dice al programa dónde generar el código numérico.[1]

1.2 Cross-Section en partículas

La Cross-Section, en física de partículas nos referimos a la probabilidad de que dos partículas colisionen y reaccionen de cierta manera, es decir, cuando medimos la sección transversal “protón-protón a top-antitop”, estamos contando cuántos pares top-antitop se crearon cuando se disparó un número determinado de protones entre sí. Además, la Cross-Section es independiente de la intensidad y el foco de los haces de partículas, por lo que los números de sección transversal medidos en un acelerador se pueden comparar directamente con los números medido en otro, independientemente de la potencia de los aceleradores.[2] Este concepto se utilizará dentro del Madgraph para diferentes chorros de partículas dentro del modelo que estudiamos, en este caso serían dos modelos: Modelo Estándar (SM) y Higgs y Teoría de Campo Efectivo (HEFT).

2 Resultados

Se mostrará los resultados de la Cross-Sections obtenidos para ambos modelos basados en el **H + 2 jets**, cada uno para 25000 eventos, y su diagrama de Feynman principal respectivo.

2.1 Para el SM

Cross-Section del proceso p p >h j j

s= 3.3761 ± 0.00545 (pb)

Graph	Cross-Section ↓	Error	Events (K)	Unwgt	Luminosity
/home/hep/Programs/MG5_aMC_v2_7_2/bin/smhjj3/SubProcesses/P1_qq_hqq	3.376	0.00545	1940.877	69365.0	0

s= 3.3761 ± 0.00545 (pb)

Graph	Cross-Section ↓	Error	Events (K)	Unwgt	Luminosity
G3	1.923	0.00382	1350.18	43736.0	2.28e+04
G1	0.672	0.00261	450.06	14035.0	2.09e+04
G6.7	0.5083	0.00208	98.741	8129.0	1.6e+04
G4.7	0.2346	0.00188	27.876	2243.0	9.56e+03
G6.8	0.02618	0.000592	7.01	633.0	2.42e+04
G4.8	0.01159	0.000237	7.01	589.0	5.08e+04

Tabla 1. Se obtuvo un valor de 3.3761±0.00545 (pb).

Diagrama de Feynman del proceso p p > h j j

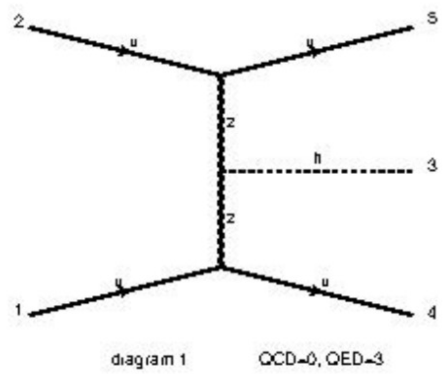

Fig. 2. Diagrama de Feynman principal.

Cabe mencionar que solo se escogió un solo diagrama, ya que el mismo proceso nos arroja una cantidad inmensa de 152 diagramas (43 independientes).

2.2 Para el HEFT

Cross-Section del proceso p p > h j j

s= 7.8619 ± 0.0156 (pb)

Graph	Cross-Section ↓	Error	Events (K)	Unwgt	Luminosity
/home/hep/Programs/MG5_aMC_v2_7_2/bin/hefthjj3/SubProcesses/P1_gg_hgg	4.908	0.013	2329.861	34527.0	0
/home/hep/Programs/MG5_aMC_v2_7_2/bin/hefthjj3/SubProcesses/P1_gq_hgq	2.569	0.00837	899.839	21827.0	0
/home/hep/Programs/MG5_aMC_v2_7_2/bin/hefthjj3/SubProcesses/P1_gg_hqq	0.1927	0.00185	113.863	1728.0	0
/home/hep/Programs/MG5_aMC_v2_7_2/bin/hefthjj3/SubProcesses/P1_qq_hqq	0.1857	0.00145	82.014	2492.0	0
/home/hep/Programs/MG5_aMC_v2_7_2/bin/hefthjj3/SubProcesses/P1_qq_hgg	0.005948	0.000103	28.083	1264.0	0

s= 4.9082 ± 0.013 (pb)

Graph	Cross-Section ↓	Error	Events (K)	Unwgt	Luminosity
G8	1.581	0.00495	764.544	13540.0	8.55e+03
G7	0.886	0.00544	220.04	5867.0	6.63e+03
G4	0.8819	0.00348	1260.04	6574.0	7.47e+03
G6	0.5936	0.00516	29.616	2855.0	4.81e+03
G13	0.5882	0.00784	21.972	2528.0	4.29e+03
G9	0.1815	0.00252	8.051	851.0	4.69e+03
G14	0.1814	0.0027	11.572	1175.0	6.48e+03
G3	0.01388	0.000432	7.016	547.0	3.94e+04
G1	0.0001392	2.78e-06	7.01	590.0	4.24e+06

s= 0.19266 ± 0.00185 (pb)

Graph	Cross-Section ↓	Error	Events (K)	Unwgt	Luminosity
G7	0.06858	0.000978	48.733	274.0	4e+03
G4	0.06686	0.000965	39.826	443.0	6.63e+03
G5	0.0286	0.000805	7.01	855.0	2.99e+04
G2	0.02788	0.000939	11.278	114.0	4.09e+03
G1	0.0007438	2.03e-05	7.016	42.0	5.65e+04

s= 2.5695 ± 0.00837 (pb)

Graph	Cross-Section ↓	Error	Events (K)	Unwgt	Luminosity
G1	1.136	0.00481	175.075	8598.0	7.58e+03
G4	0.5335	0.00302	185.046	6201.0	1.16e+04
G2	0.4524	0.00522	39.684	2310.0	5.11e+03
G3	0.2757	0.00189	470.024	2506.0	9.09e+03
G7	0.1686	0.00264	15.982	981.0	5.82e+03
G5	0.002929	4.46e-05	7.015	658.0	2.25e+05
G6	0.0004332	1.35e-05	7.013	573.0	1.32e+06

s= 0.0059477 ± 0.000103 (pb)

Graph	Cross-Section ↓	Error	Events (K)	Unwgt	Luminosity
G1	0.002789	6.5e-05	7.035	487.0	1.75e+05
G2	0.001592	6.86e-05	7.017	17.0	1.07e+04
G3	0.001543	3.98e-05	7.018	241.0	1.56e+05
G4	2.294e-05	4.99e-07	7.013	519.0	2.26e+07

s= 0.18569 ± 0.00145 (pb)

Graph	Cross-Section ↓	Error	Events (K)	Unwgt	Luminosity
G1	0.1848	0.00145	75.001	1694.0	9.17e+03
G3	0.0008942	1.48e-05	7.013	798.0	8.92e+05

Tabla 2. Se obtuvo un valor de 7.8619±0.0156 (pb).

Diagrama de Feynman del proceso p p > h j j

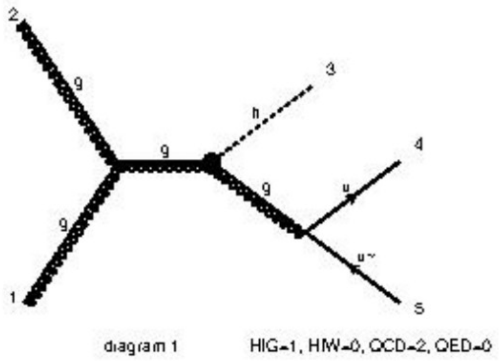

Fig. 3. Diagrama de Feynman principal.

Al igual que el anterior, solo se escogió un solo diagrama, ya que el mismo proceso nos arroja 354 diagramas (68 independientes).

3 Discusión de resultados

Los resultados obtenidos por la sección transversal nos dan una visión general de lo que se puede encontrar modificando el número de eventos de cada proceso, y dado que éste es diferente para los distintos modelos [Fig. 1-2], normalmente lo habitual sería para centrarnos en el modelo estándar actual y más conocido, pero a modo de comparación, desarrollamos dicho proceso p p > h j j en un modelo diferente, como es el HEFT, que nos proporcionaría un mayor número de diagramas, subprocesos y diferentes rangos de luminosidad debido a la cantidad de particulas incidentes.

Conclusiones

En este trabajo hemos encontrado el diagrama de Feynman y la sección transversal para distintos modelos. Hemos observado la variación que se puede obtener gracias al programa Madgraft. Cabe mencionar que el programa puede ofrecernos más resultados dependiendo del estudio que estemos realizando, pero en esta ocasión solo nos enfocamos en las secciones transversales. Esperamos que este trabajo inspire académicamente al lector a profundizar sus conocimientos en física computacional de partículas, ya que estamos seguros que servirá de base para futuros análisis en diferentes modelos, modelos más allá del modelo estándar.

Agradecimientos

Primero que nada agradezcer al comité organizador por hacer posible este evento a pesar de la situación actual del país, y de la misma manera al Dr. Nhell Cerna, por sus enseñanzas a lo largo de esta semana, sabiendo que es un curso complejo, pero se logró condensar satisfactoriamente.

Referencias

[1] Hua-Sheng S. (2016).*Heavy Quarkonium Production Phenomenology and Automation of One-Loop Scattering Amplitude Computations.* Springer Theses, pág. 139. DOI:10.1007/978-981-10-1624-0

Cibernéticas

[2] https://cms.cern/news/what-do-we-mean-cross-section-particle-physics

[3] https://launchpad.net/mg5amcnlo

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SOLUCIÓN AL TRABAJO FORMATIVO

1. A partir del lagrangiano de Proca para un campo vectorial de spin 1:

$$L = \frac{-1}{16\pi}\left(\partial^{\mu}A^{\nu} - \partial^{\nu}A^{\mu}\right)\left(\partial_{\mu}A_{\nu} - \partial_{\nu}A_{\mu}\right) + \frac{1}{8\pi}\left(\frac{mc}{\hbar}\right)^2 A^{\nu}A_{\nu}$$

Nos piden la ecuación de E-L de este lagrangiano:

$$\frac{\partial L}{\partial A_{\nu}} - \partial_{\mu}\left(\frac{\partial L}{\partial\left(\partial_{\mu}A_{\nu}\right)}\right) = 0 \tag{1}$$

Operamos por sectores de la ecuación, por un lado tenemos a $\frac{\partial L}{\partial A_{\nu}}$, que llamaremos como la parte **I**, y por otro tenemos a $\frac{\partial L}{\partial\left(\partial_{\mu}A_{\nu}\right)}$, que sería la parte **II**.

Resolviendo **(I)**:

$$\frac{\partial L}{\partial A_{\nu}} = \frac{1}{8\pi}\left(\frac{mc}{\hbar}\right)^2 A^{\nu} \tag{2}$$

Resolviendo **(II)**:

$$\frac{\partial L}{\partial\left(\partial_{\mu}A_{\nu}\right)} = -\frac{1}{8\pi}\left(\partial^{\mu}A^{\nu} - \partial^{\nu}A^{\mu}\right) \tag{3}$$

Reemplazando **(I)** y **(II)** en la ecuación principal:

$$\frac{1}{8\pi}\left(\frac{mc}{\hbar}\right)^2 A^{\nu} - \partial_{\mu}\left(-\frac{1}{8\pi}\left(\partial^{\mu}A^{\nu} - \partial^{\nu}A^{\mu}\right)\right) = 0 \tag{4}$$

, despejando

$$\left(\frac{mc}{\hbar}\right)^2 A^{\nu} + \partial_{\mu}\left(\partial^{\mu}A^{\nu} - \partial^{\nu}A^{\mu}\right) = 0 \tag{5}$$

$\therefore$ De esta forma, podemos deducir la ecuación de E-L en la Ec. (5).

2. Tal como está, el Lagrangiano de Dirac:

$$L = i\left(\hbar c\right)\overline{\psi}\gamma^{\mu}\partial_{\mu}\psi - \left(mc^2\right)\overline{\psi}\psi$$

Aplicando la E-L en $\overline{\psi}$:

$$\frac{\partial L}{\partial\overline{\psi}} - \partial_{\mu}\left(\frac{\partial L}{\partial\left(\partial_{\mu}\overline{\psi}\right)}\right) = 0 \tag{6}$$

Operamos por sectores de la ecuación, por un lado tenemos a $\frac{\partial L}{\partial\overline{\psi}}$, que llamaremos como la parte **I**, y por otro tenemos a $\frac{\partial L}{\partial\left(\partial_{\mu}\overline{\psi}\right)}$, que sería la parte **II**.

Resolviendo **(I)**:

$$\frac{\partial L}{\partial\overline{\psi}} = i\hbar c\gamma^{\mu}\partial_{\mu}\psi - mc^2\psi \tag{7}$$

Resolviendo **(II)**:

$$\frac{\partial L}{\partial\left(\partial_{\mu}\overline{\psi}\right)} = 0 \tag{8}$$

Reemplazando **(I)** y **(II)** en la ecuación principal:

$$i\hbar c\gamma^{\mu}\partial_{\mu}\psi - mc^2\psi - \partial_{\mu}\left(0\right) = 0 \tag{9}$$

, despejando

$$i\gamma^{\mu}\partial_{\mu}\psi - \left(\frac{mc}{\hbar}\right)\psi = 0 \tag{10}$$

De esta manera obtuvimos la ecuación de E-L para el caso de $\overline{\psi}$.

Ahora nos faltaría, ψ:

$$\frac{\partial L}{\partial \psi} - \partial_\mu \left(\frac{\partial L}{\partial\left(\partial_\mu \psi\right)} \right) = 0 \tag{11}$$

Operamos por sectores de la ecuación, por un lado tenemos a $\frac{\partial L}{\partial \psi}$, que llamaremos como la parte **I**, y por otro tenemos a $\frac{\partial L}{\partial\left(\partial_\mu \psi\right)}$, que sería la parte **II**.

Resolviendo **(I)**:

$$\frac{\partial L}{\partial \psi} = -mc^2\overline{\psi} \tag{12}$$

Resolviendo **(II)**:

$$\frac{\partial L}{\partial\left(\partial_\mu \psi\right)} = i\hbar c\overline{\psi}\gamma^\mu \tag{13}$$

Reemplazando **(I)** y **(II)** en la ecuación principal:

$$-mc^2\overline{\psi} - \partial_\mu \left(i\hbar c\overline{\psi}\gamma^\mu\right) = 0 \tag{14}$$

, despejando

$$i\partial_\mu\overline{\psi}\gamma^\mu + \left(\frac{mc}{\hbar}\right)\overline{\psi} = 0 \tag{15}$$

$\therefore$ De esta forma, deducimos la ecuación de E-L para el ψ en la Ec. (15).

3. El lagrangiano de Klein-Gordon para un campo complejo sería

$$L = \frac{1}{2}\left(\partial_\mu\phi^*\right)\left(\partial^\mu\phi\right) - \frac{1}{2}\left(\frac{mc}{\hbar}\right)^2\phi^*\phi$$

Aplicando la E-L en ϕ:

$$\frac{\partial L}{\partial \phi} - \partial_\mu \left(\frac{\partial L}{\partial\left(\partial_\mu \phi\right)} \right) = 0 \tag{16}$$

Operamos por sectores de la ecuación, por un lado tenemos a $\frac{\partial L}{\partial \phi}$, que llamaremos como la parte **I**, y por otro tenemos a $\frac{\partial L}{\partial\left(\partial_\mu \phi\right)}$, que sería la parte **II**.

Resolviendo **(I)**:

$$\frac{\partial L}{\partial \phi} = -\frac{1}{2}\left(\frac{mc}{\hbar}\right)^2\phi^* \tag{17}$$

Resolviendo **(II)**:

$$\frac{\partial L}{\partial\left(\partial_\mu \phi\right)} = \frac{1}{2}\partial^\mu\phi^* \tag{18}$$

Reemplazando **(I)** y **(II)** en la ecuación principal:

$$-\frac{1}{2}\left(\frac{mc}{\hbar}\right)^2\phi^* - \partial_\mu\left(\frac{1}{2}\partial^\mu\phi^*\right) = 0 \tag{19}$$

, despejando

$$\phi^* + \left(\frac{\hbar}{mc}\right)^2\partial_\mu\left(\partial^\mu\phi^*\right) = 0 \tag{20}$$

De esta manera obtuvimos la ecuación de E-L para el ϕ.

Ahora nos faltaría, ϕ^*:

$$\frac{\partial L}{\partial \phi^*} - \partial_\mu \left(\frac{\partial L}{\partial\left(\partial_\mu \phi^*\right)} \right) = 0 \tag{21}$$

Operamos por sectores de la ecuación, por un lado tenemos a $\frac{\partial L}{\partial \phi^*}$, que llamaremos como la parte **I**, y por otro tenemos a $\frac{\partial L}{\partial\left(\partial_\mu \phi^*\right)}$, que sería la parte **II**.

Resolviendo **(I)**:

$$\frac{\partial L}{\partial \phi^*} = -\frac{1}{2}\left(\frac{mc}{\hbar}\right)^2\phi \tag{22}$$

Resolviendo **(II)**:

$$\frac{\partial L}{\partial\left(\partial_\mu \phi^*\right)} = \frac{1}{2}\partial^\mu \phi \tag{23}$$

Reemplazando **(I)** y **(II)** en la ecuación principal:

$$-\frac{1}{2}\left(\frac{mc}{\hbar}\right)^2 \phi - \partial_\mu \left(\frac{1}{2}\partial^\mu \phi\right) = 0 \tag{24}$$

, despejando

$$\phi + \left(\frac{\hbar}{mc}\right)^2 \partial_\mu \left(\partial^\mu \phi\right) = 0 \tag{25}$$

$\therefore$ De esta forma, obtenemos la ecuación de E-L para el ϕ^* en la Ec. (25), además podemos comprobar con la Ec.(20) que existe una consistencia en relación a sus campos complejos conjugados.

4. Aplicar las ecuaciones de Euler – Lagrange a la ecuación:

$$L = \left[i\hbar c\overline{\psi}\gamma^\mu \partial_\mu \psi - mc^2 \overline{\psi}\psi\right] - \left(q\overline{\psi}\gamma^\mu \psi\right) A_\mu$$

Aplicando la E-L en ψ:

$$\frac{\partial L}{\partial \psi} - \partial_\mu \left(\frac{\partial L}{\partial\left(\partial_\mu \psi\right)}\right) = 0 \tag{26}$$

Operamos por sectores de la ecuación, por un lado tenemos a $\frac{\partial L}{\partial \psi}$, que llamaremos como la parte **I**, y por otro tenemos a $\frac{\partial L}{\partial\left(\partial_\mu \psi\right)}$, que sería la parte **II**.

Resolviendo **(I)**:

$$\frac{\partial L}{\partial \psi} = -mc^2 \overline{\psi} - \left(q\overline{\psi}\gamma^\mu\right) A_\mu \tag{27}$$

Resolviendo **(II)**:

$$\frac{\partial L}{\partial\left(\partial_\mu \psi\right)} = i\hbar c\overline{\psi}\gamma^\mu \tag{28}$$

Reemplazando **(I)** y **(II)** en la ecuación principal:

$$-mc^2 \overline{\psi} - \left(q\overline{\psi}\gamma^\mu\right) A_\mu - \partial_\mu \left(i\hbar c\overline{\psi}\gamma^\mu\right) = 0 \tag{29}$$

, despejando

$$i\hbar c\partial_\mu \overline{\psi}\gamma^\mu + mc^2 \overline{\psi} + \left(q\overline{\psi}\gamma^\mu\right) A_\mu = 0 \tag{30}$$

De esta manera obtuvimos la ecuación de E-L para el caso de ψ.

Ahora nos faltaría, $\overline{\psi}$:

$$\frac{\partial L}{\partial \overline{\psi}} - \partial_\mu \left(\frac{\partial L}{\partial\left(\partial_\mu \overline{\psi}\right)}\right) = 0 \tag{31}$$

Operamos por sectores de la ecuación, por un lado tenemos a $\frac{\partial L}{\partial \overline{\psi}}$, que llamaremos como la parte **I**, y por otro tenemos a $\frac{\partial L}{\partial\left(\partial_\mu \overline{\psi}\right)}$, que sería la parte **II**.

Resolviendo **(I)**:

$$\frac{\partial L}{\partial \overline{\psi}} = i\hbar c\gamma^\mu \partial_\mu \psi - mc^2 \psi - \left(q\gamma^\mu \psi\right) A_\mu \tag{32}$$

Resolviendo **(II)**:

$$\frac{\partial L}{\partial\left(\partial_\mu \overline{\psi}\right)} = 0 \tag{33}$$

Reemplazando **(I)** y **(II)** en la ecuación principal:

$$i\hbar c\gamma^\mu \partial_\mu \psi - mc^2 \psi - \left(q\gamma^\mu \psi\right) A_\mu - \partial_\mu (0) = 0 \tag{34}$$

, despejando

$$i\hbar c\gamma^\mu \partial_\mu \psi - mc^2 \psi - \left(q\gamma^\mu \psi\right) A_\mu = 0 \tag{35}$$

$\therefore$ De esta forma, deducimos la ecuación de E-L para el ψ en la Ec. (35).

5. Produzca las siguientes colisiones e interprete sus resultados (cross – sección y diagramas de Feynman adjuntos)

a. Generate p p > e+ e-

- Diagramas de Feynman

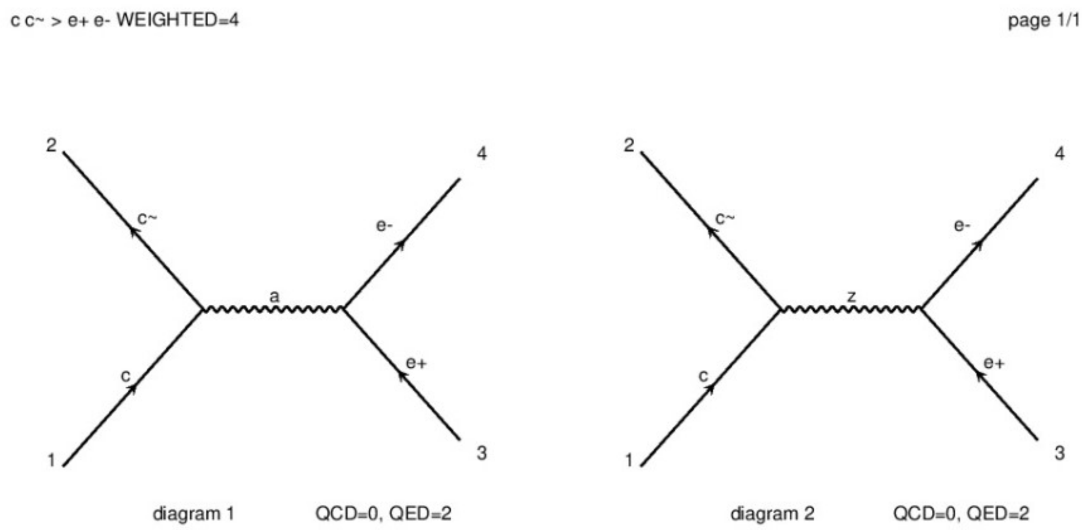

Figura 1

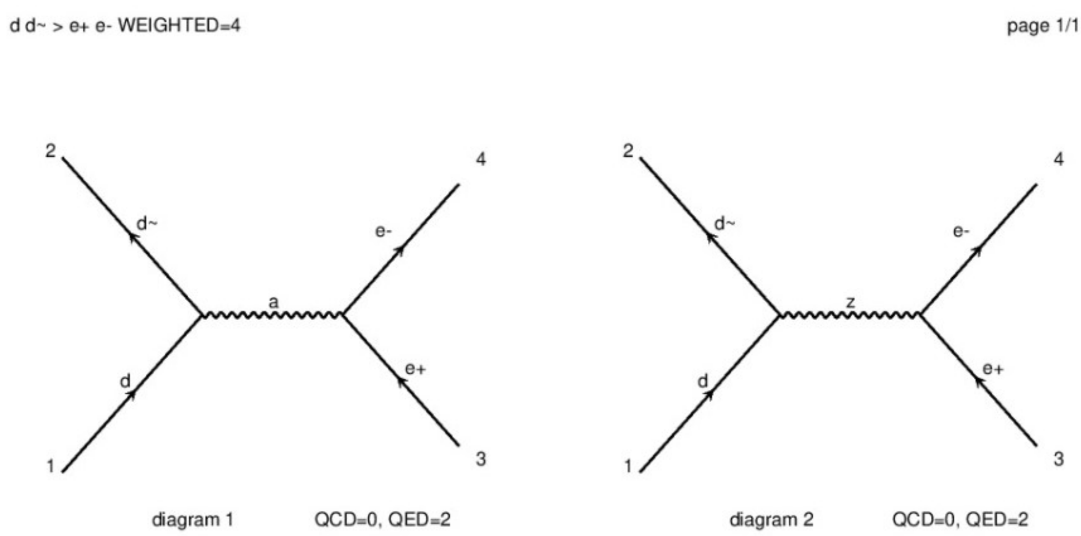

Figura 2

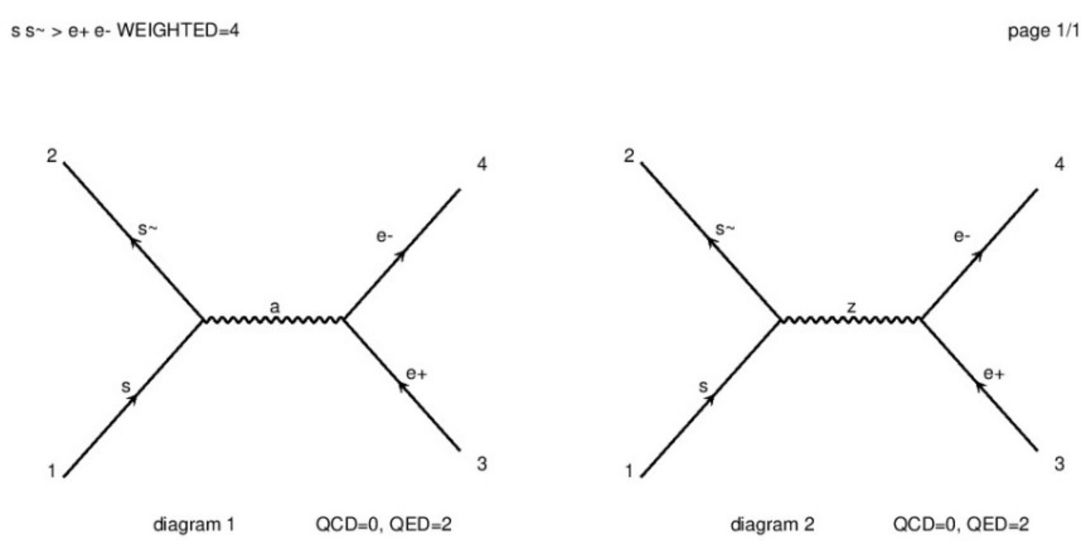

Figura 3

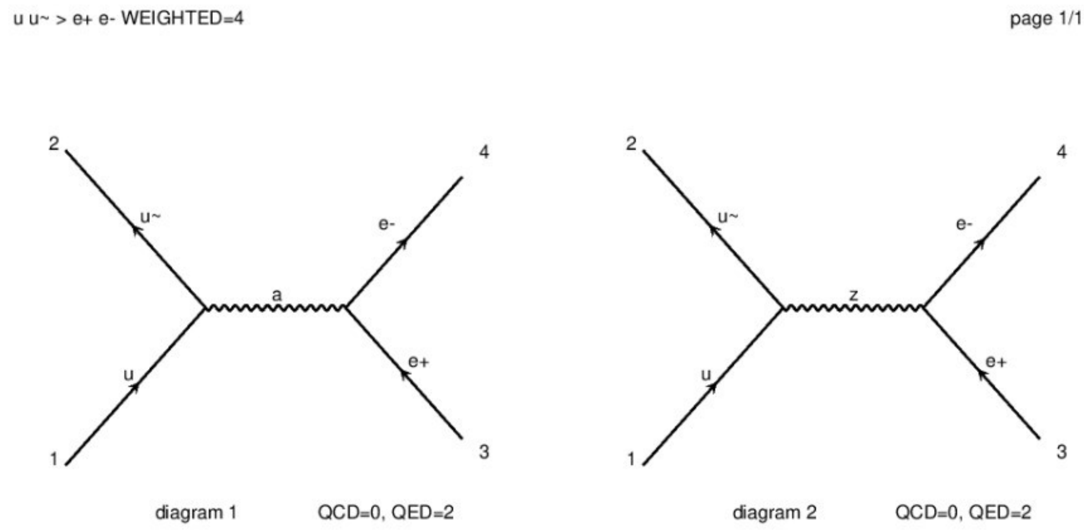

Figura 4

- Cross-Section

s= 836.58 ± 5.22 (pb)

Graph	Cross-Section ↓	Error	Events (K)	Unwgt	Luminosity
/home/hep/Programs/MG5_aMC_v2_7_2/bin/e+e-/SubProcesses/P1_qq_ll	836.6	5.22	19.896	1941.0	0

s= 836.58 ± 5.22 (pb)

Graph	Cross-Section ↓	Error	Events (K)	Unwgt	Luminosity
G2	631.8	4.62	12.881	977.0	1.55
G1	204.8	2.44	7.015	964.0	4.71

Figura 5

b. Generate p p > z, z > e+ e-

- Diagramas de Feynman

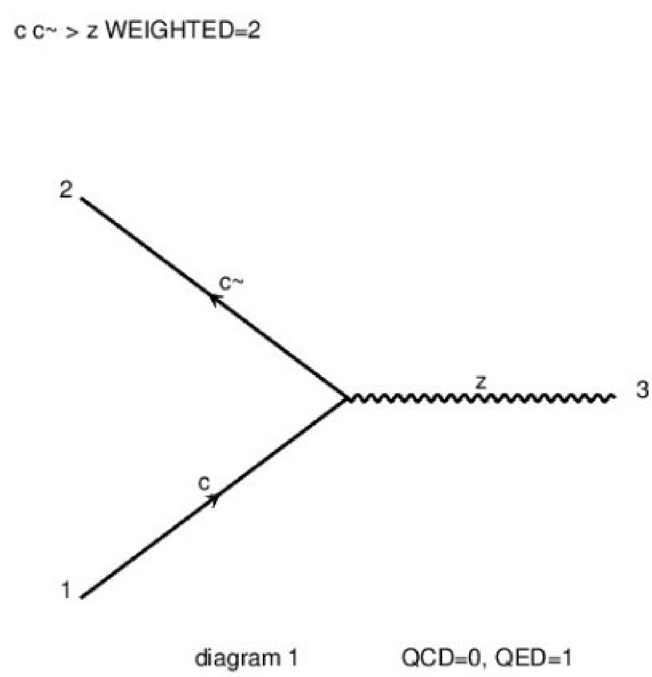

Figura 6

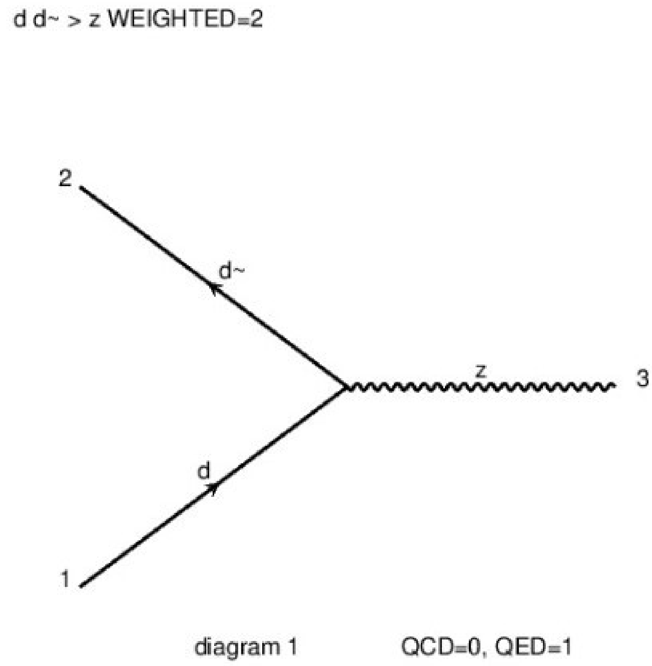

Figura 7

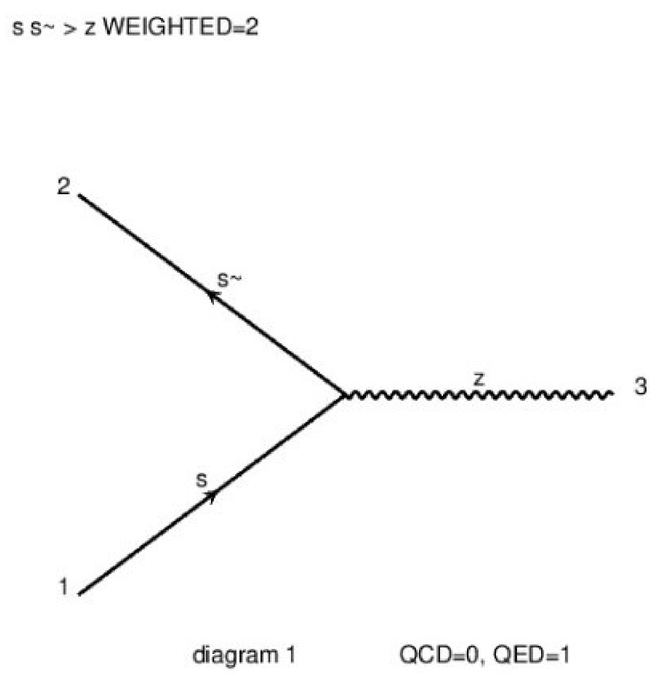

Figura 8

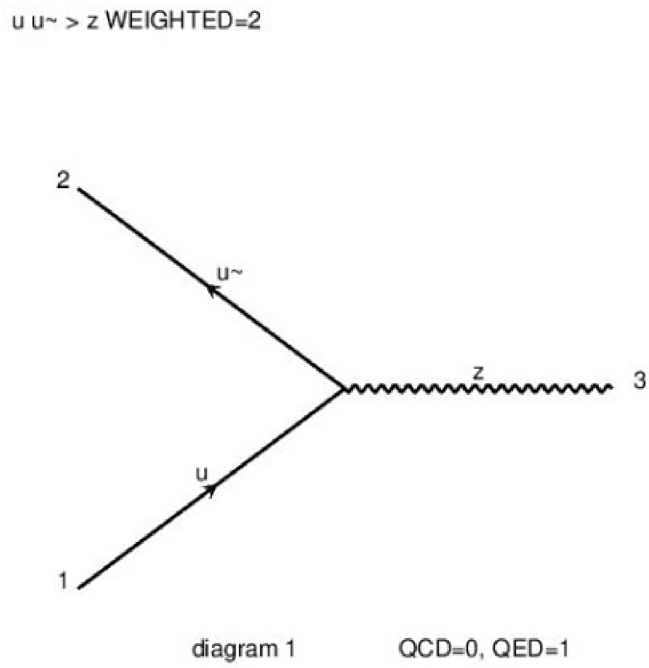

Figura 9

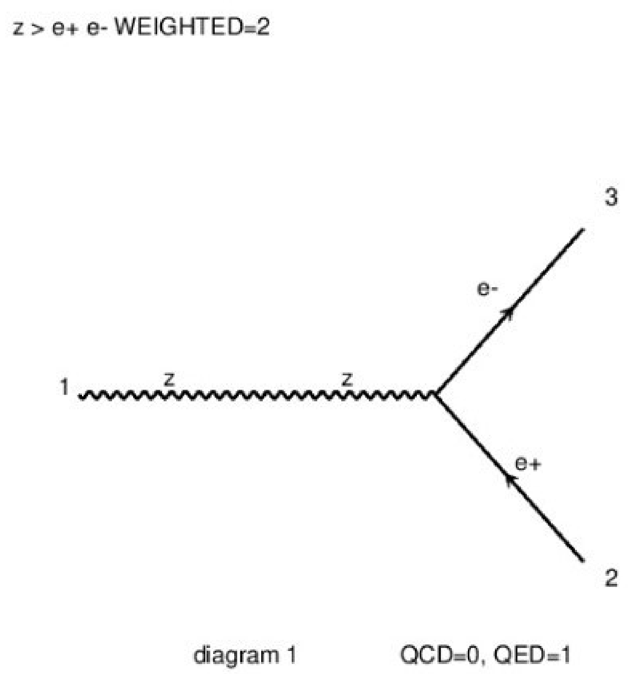

Figura 10

- Cross-Section

s= 1420.3 ± 4.5 (pb)

Graph	Cross-Section ↓	Error	Events (K)	Unwgt	Luminosity
/home/hep/Programs/MG5_aMC_v2_7_2/bin/z,/SubProcesses/P1_qq_z_z_ll	1420	4.5	33.93	1875.0	0

s= 1420.3 ± 4.5 (pb)

Graph	Cross-Section ↓	Error	Events (K)	Unwgt	Luminosity
G1	1420	4.5	33.93	1875.0	1.32

Figura 11

c. Generate p p > e+ e- z

- Diagramas de Feynman

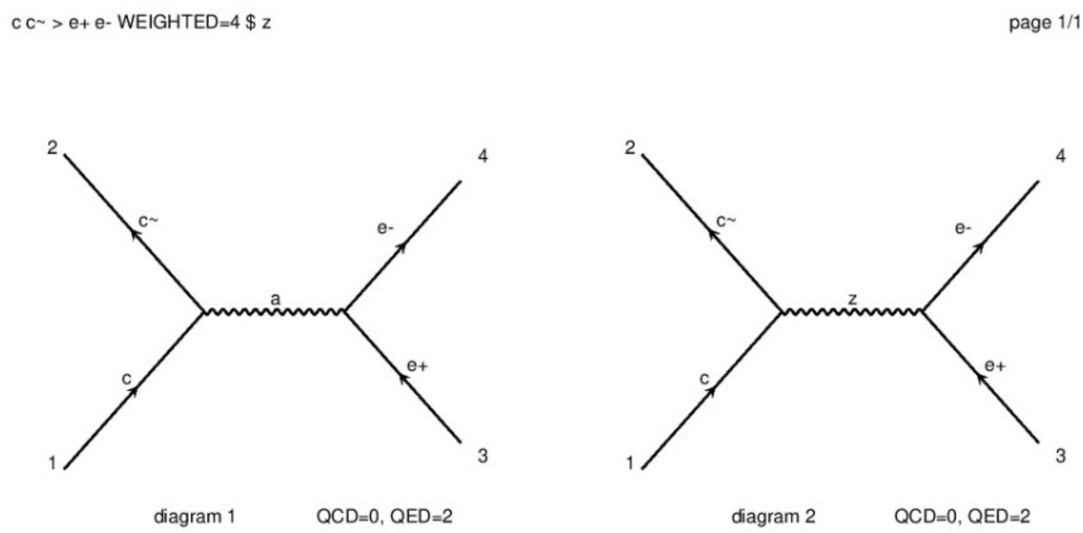

Figura 12

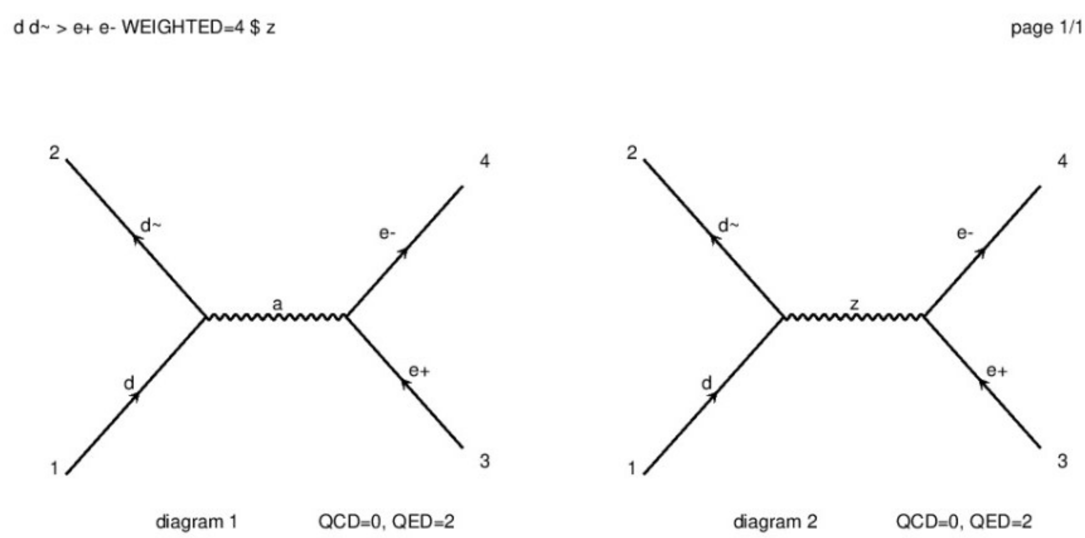

Figura 13

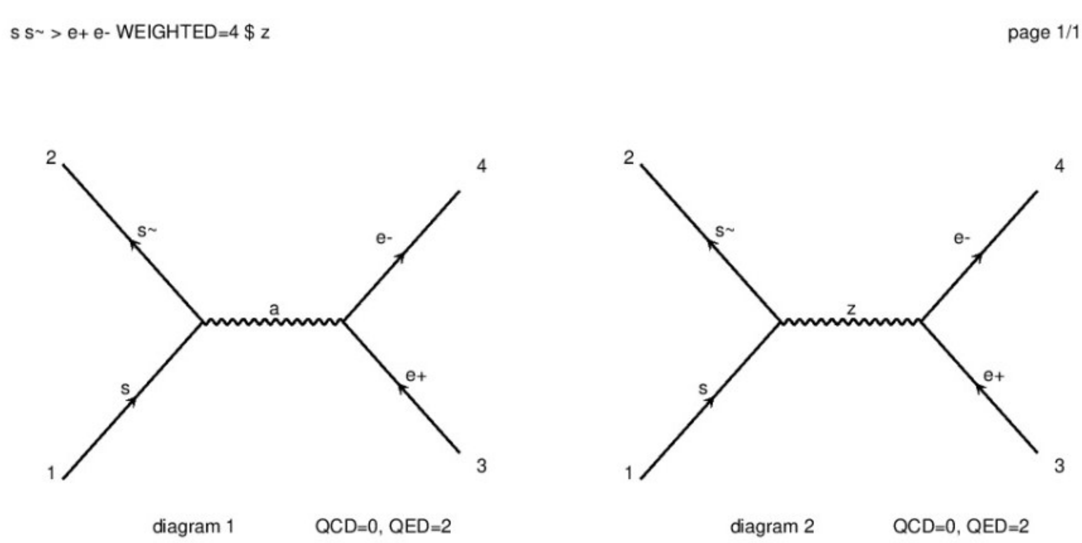

Figura 14

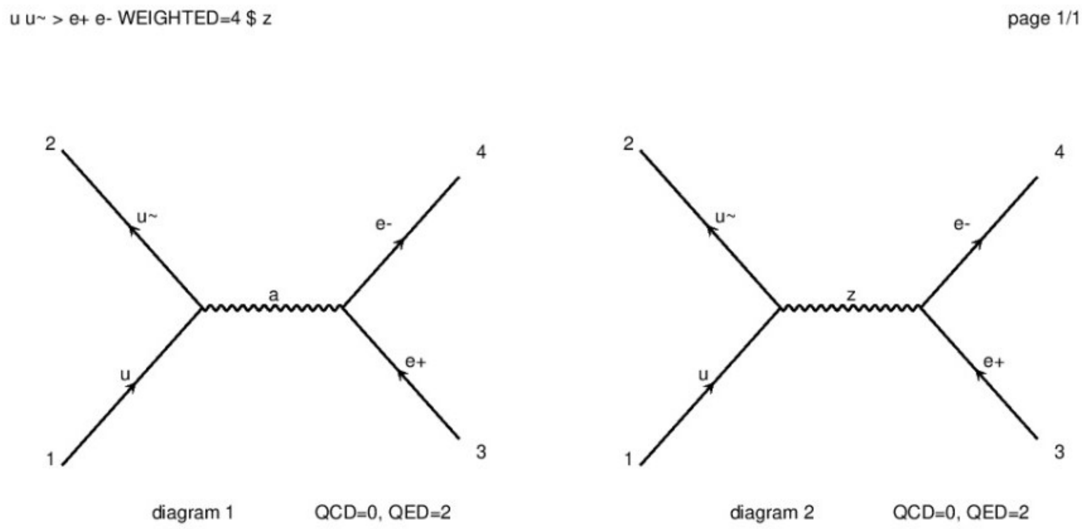

Figura 15

Cross-Section

s= 213.18 ± 1.72 (pb)

Graph	Cross-Section ↓	Error	Events (K)	Unwgt	Luminosity
/home/hep/Programs/MG5_aMC_v2_7_2/bin/e+/SubProcesses/P1_qq_ll	213.2	1.72	21.042	2753.0	0

s= 213.18 ± 1.72 (pb)

Graph	Cross-Section ↓	Error	Events (K)	Unwgt	Luminosity
G1	205.7	1.72	14.028	1924.0	9.35
G2	7.441	0.102	7.014	829.0	111

Figura 16

d. Generate p p > e+ e- / z

- Diagramas de Feynman

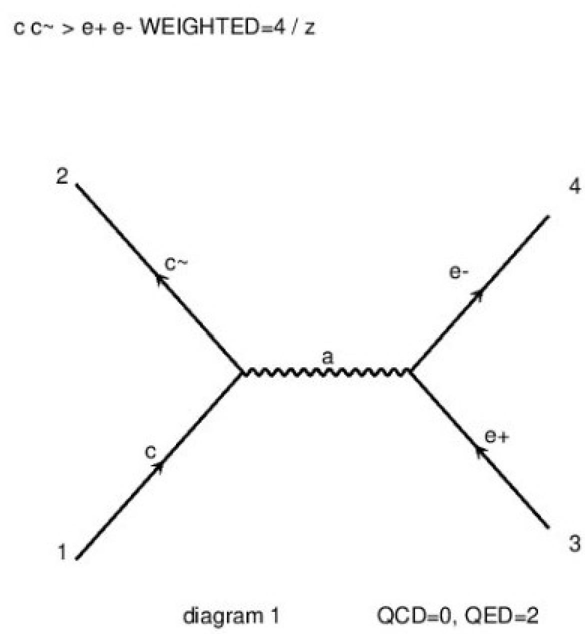

Figura 17

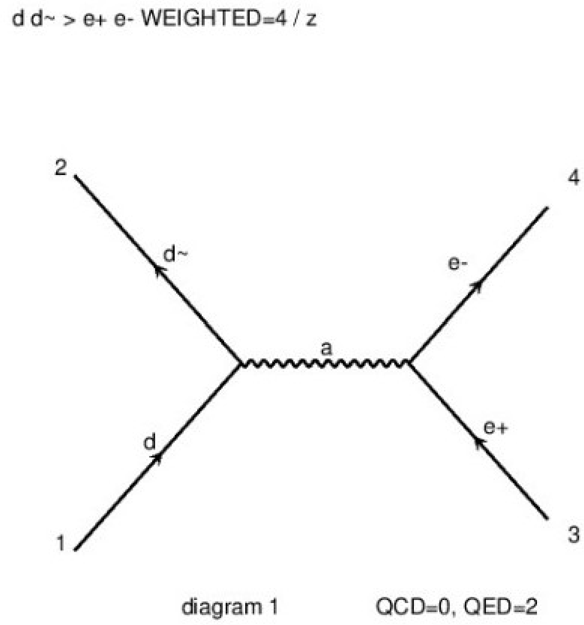

Figura 18

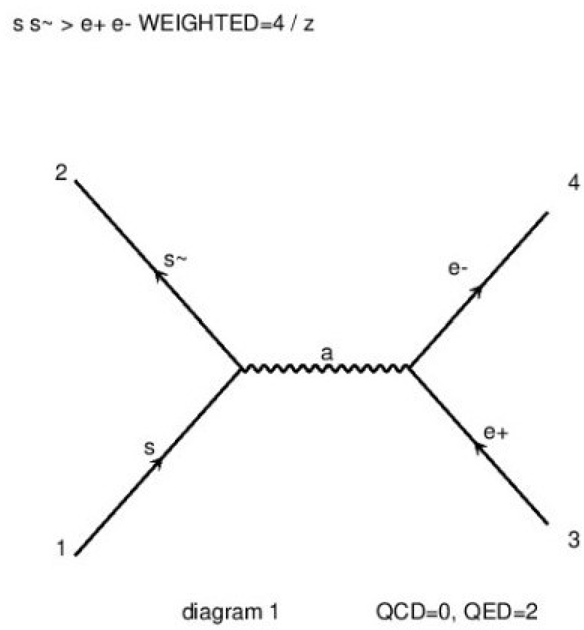

Figura 19

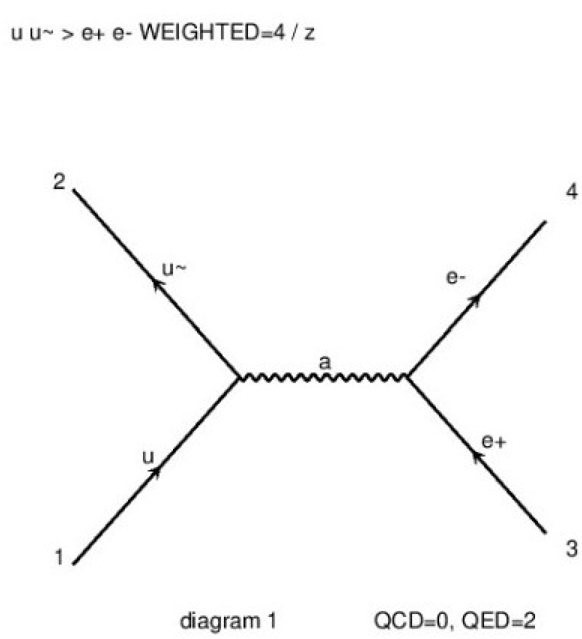

Figura 20

- Cross-Section

s= 206.67 ± 1.72 (pb)

Graph	Cross-Section ↓	Error	Events (K)	Unwgt	Luminosity
/home/hep/Programs/MG5_aMC_v2_7_2/bin/e+/SubProcesses/P1_qq_ll	206.7	1.72	14.031	1826.0	0

s= 206.67 ± 1.72 (pb)

Graph	Cross-Section ↓	Error	Events (K)	Unwgt	Luminosity
G1	206.7	1.72	14.031	1826.0	8.84

Figura 21

e. Generate p p > e+ e- / a

- Diagramas de Feynman

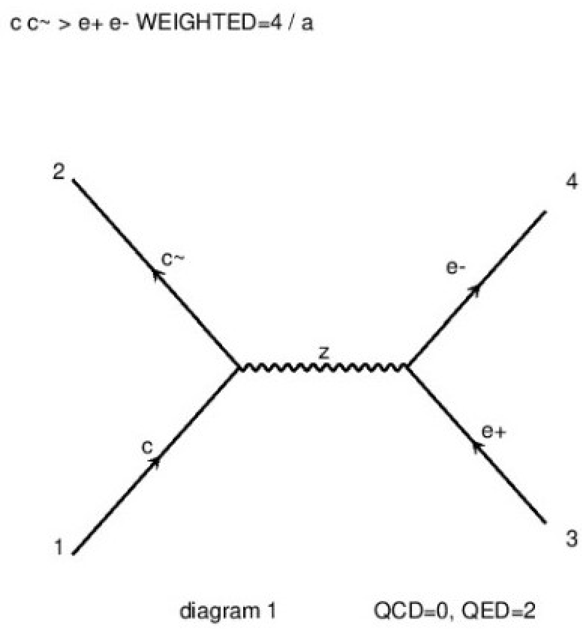

Figura 22

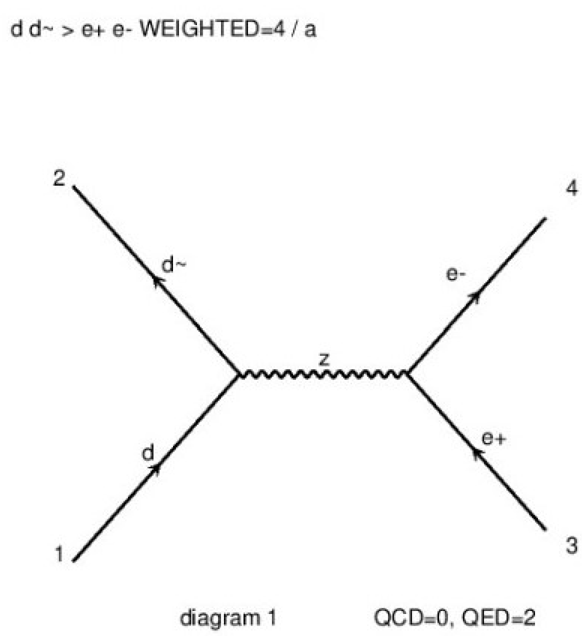

Figura 23

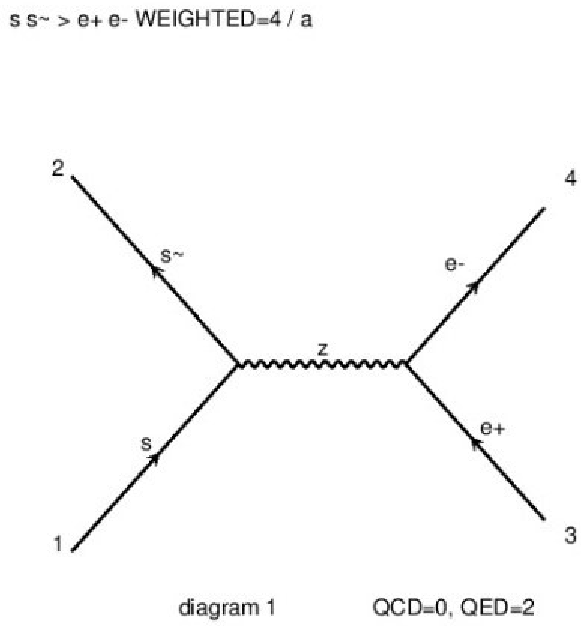

Figura 24

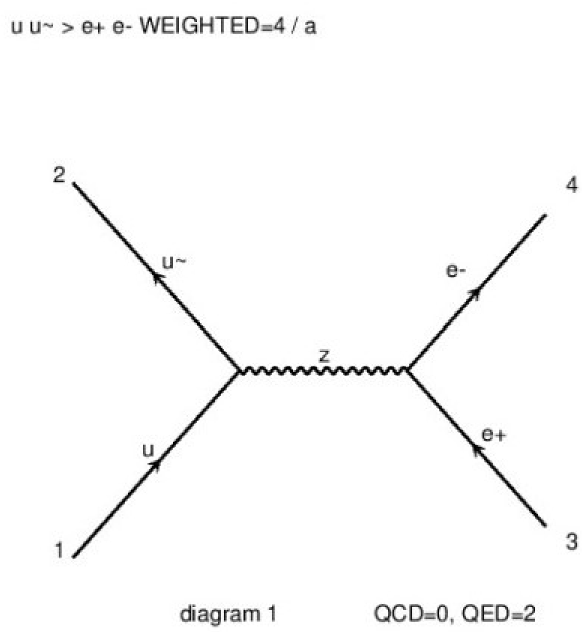

Figura 25

- Cross-Section

s= 636.83 ± 3.29 (pb)

Graph	Cross-Section ↓	Error	Events (K)	Unwgt	Luminosity
/home/hep/Programs/MG5_aMC_v2_7_2/bin/e+/SubProcesses/P1_qq_ll	636.8	3.29	24.137	1834.0	0

s= 636.83 ± 3.29 (pb)

Graph	Cross-Section ↓	Error	Events (K)	Unwgt	Luminosity
G1	636.8	3.29	24.137	1834.0	2.88

Figura 26

6. En la siguiente tabla se muestran los siguientes procesos para los modelos standard model (SM) y Higgs and Effective Field Theory (HEFT).

I. Modelo Estándar (H + 2 jets)
Se presentará la Cross-Section del proceso **p p > h j j** con respecto al número de eventos realizados.

- Para 1000 eventos

s= 3.3522 ± 0.0216 (pb)

Graph	Cross-Section ↓	Error	Events (K)	Unwgt	Luminosity
/home/hep/Programs/MG5_aMC_v2_7_2/bin/smhjj/SubProcesses/P1_qq_hqq	3.352	0.0216	138.042	5045.0	0

s= 3.3522 ± 0.0216 (pb)

Graph	Cross-Section ↓	Error	Events (K)	Unwgt	Luminosity
G3	1.898	0.0156	75.001	1676.0	883
G1	0.6912	0.0124	35.001	991.0	1.43e+03
G6.7	0.4924	0.00714	7.01	616.0	1.25e+03
G4.7	0.2331	0.00411	7.01	540.0	2.32e+03
G6.8	0.02618	0.000592	7.01	633.0	2.42e+04
G4.8	0.01159	0.000237	7.01	589.0	5.08e+04

Figura 27

- Para 10000 eventos

s= 3.3689 ± 0.00752 (pb)

Graph	Cross-Section ↓	Error	Events (K)	Unwgt	Luminosity
/home/hep/Programs/MG5_aMC_v2_7_2/bin/smhjj2/SubProcesses/P1_qq_hqq	3.369	0.00752	819.468	29594.0	0

s= 3.3689 ± 0.00752 (pb)

Graph	Cross-Section ↓	Error	Events (K)	Unwgt	Luminosity
G3	1.92	0.00593	525.07	17225.0	8.98e+03
G1	0.6737	0.00333	225.03	6686.0	9.92e+03
G6.7	0.5064	0.00248	44.21	3564.0	7.04e+03
G4.7	0.2309	0.0019	11.138	897.0	3.88e+03
G6.8	0.02618	0.000592	7.01	633.0	2.42e+04
G4.8	0.01159	0.000237	7.01	589.0	5.08e+04

Figura 28

- Para 25000 eventos

s= 3.3761 ± 0.00545 (pb)

Graph	Cross-Section ↓	Error	Events (K)	Unwgt	Luminosity
/home/hep/Programs/MG5_aMC_v2_7_2/bin/smhjj3/SubProcesses/P1_qq_hqq	3.376	0.00545	1940.877	69365.0	0

s= 3.3761 ± 0.00545 (pb)

Graph	Cross-Section ↓	Error	Events (K)	Unwgt	Luminosity
G3	1.923	0.00382	1350.18	43736.0	2.28e+04
G1	0.672	0.00261	450.06	14035.0	2.09e+04
G6.7	0.5083	0.00208	98.741	8129.0	1.6e+04
G4.7	0.2346	0.00188	27.876	2243.0	9.56e+03
G6.8	0.02618	0.000592	7.01	633.0	2.42e+04
G4.8	0.01159	0.000237	7.01	589.0	5.08e+04

Figura 29

II. Higgs y la Teoría del Campo Efectivo (H + 2 jets)
Se presentará la Cross-Section del proceso **p p > h j j** con respecto al número de eventos realizados.

- Para 1000 eventos

s= 7.7747 ± 0.0652 (pb)

Graph	Cross-Section ↓	Error	Events (K)	Unwgt	Luminosity
/home/hep/Programs/MG5_aMC_v2_7_2/bin/hefthjj/SubProcesses/P1_gg_hgg	4.813	0.0568	102.248	4333.0	0
/home/hep/Programs/MG5_aMC_v2_7_2/bin/hefthjj/SubProcesses/P1_gq_hgq	2.594	0.0288	85.887	2847.0	0
/home/hep/Programs/MG5_aMC_v2_7_2/bin/hefthjj/SubProcesses/P1_gg_hqq	0.186	0.00331	35.068	1211.0	0
/home/hep/Programs/MG5_aMC_v2_7_2/bin/hefthjj/SubProcesses/P1_qq_hqq	0.176	0.0137	14.023	879.0	0
/home/hep/Programs/MG5_aMC_v2_7_2/bin/hefthjj/SubProcesses/P1_qq_hgg	0.005948	0.000103	28.083	1264.0	0

s= 4.8131 ± 0.0568 (pb)

Graph	Cross-Section ↓	Error	Events (K)	Unwgt	Luminosity
G8	1.52	0.0424	7.01	335.0	220
G7	0.8807	0.015	18.159	452.0	513
G4	0.8719	0.0163	35.001	144.0	165
G6	0.5841	0.0257	7.016	526.0	901
G13	0.5666	0.0155	7.016	688.0	1.21e+03
G14	0.1913	0.00442	7.01	440.0	2.3e+03
G9	0.1849	0.0034	7.01	611.0	3.3e+03
G3	0.01388	0.000432	7.016	547.0	3.94e+04
G1	0.0001392	2.78e-06	7.01	590.0	4.24e+06

s= 0.18598 ± 0.00331 (pb)

Graph	Cross-Section ↓	Error	Events (K)	Unwgt	Luminosity
G7	0.06445	0.00205	7.016	156.0	2.42e+03
G4	0.0642	0.00205	7.016	92.0	1.43e+03
G5	0.0286	0.000805	7.01	855.0	2.99e+04
G2	0.02798	0.00137	7.01	66.0	2.36e+03
G1	0.0007438	2.03e-05	7.016	42.0	5.65e+04

s= 2.5937 ± 0.0288 (pb)

Graph	Cross-Section ↓	Error	Events (K)	Unwgt	Luminosity
G1	1.136	0.0156	15.821	827.0	728
G4	0.5479	0.0187	7.013	102.0	186
G2	0.4707	0.0107	7.012	316.0	671
G3	0.2731	0.00642	35.001	101.0	370
G7	0.1621	0.00892	7.012	270.0	1.67e+03
G5	0.002929	4.46e-05	7.015	658.0	2.25e+05
G6	0.0004332	1.35e-05	7.013	573.0	1.32e+06

s= 0.0059477 ± 0.000103 (pb)

Graph	Cross-Section ↓	Error	Events (K)	Unwgt	Luminosity
G1	0.002789	6.5e-05	7.035	487.0	1.75e+05
G2	0.001592	6.86e-05	7.017	17.0	1.07e+04
G3	0.001543	3.98e-05	7.018	241.0	1.56e+05
G4	2.294e-05	4.99e-07	7.013	519.0	2.26e+07

s= 0.17597 ± 0.0137 (pb)

Graph	Cross-Section ↓	Error	Events (K)	Unwgt	Luminosity
G1	0.1751	0.0137	7.01	81.0	463
G3	0.0008942	1.48e-05	7.013	798.0	8.92e+05

Figura 30

- Para 10000 eventos

s= 7.8612 ± 0.0243 (pb)

Graph	Cross-Section ↓	Error	Events (K)	Unwgt	Luminosity
/home/hep/Programs/MG5_aMC_v2_7_2/bin/hefthjj2/SubProcesses/P1_gg_hgg	4.917	0.0177	1036.094	14296.0	0
/home/hep/Programs/MG5_aMC_v2_7_2/bin/hefthjj2/SubProcesses/P1_gq_hgq	2.567	0.016	336.938	8371.0	0
/home/hep/Programs/MG5_aMC_v2_7_2/bin/hefthjj2/SubProcesses/P1_gg_hqq	0.186	0.00331	35.068	1211.0	0
/home/hep/Programs/MG5_aMC_v2_7_2/bin/hefthjj2/SubProcesses/P1_qq_hqq	0.185	0.00287	30.023	1111.0	0
/home/hep/Programs/MG5_aMC_v2_7_2/bin/hefthjj2/SubProcesses/P1_qq_hgg	0.005948	0.000103	28.083	1264.0	0

s= 4.9169 ± 0.0177 (pb)

Graph	Cross-Section ↓	Error	Events (K)	Unwgt	Luminosity
G8	1.588	0.00719	287.405	4681.0	2.95e+03
G7	0.8786	0.00991	70.02	1643.0	1.87e+03
G4	0.8775	0.0048	630.02	3190.0	3.64e+03
G6	0.6085	0.00709	11.831	1463.0	2.4e+03
G13	0.574	0.00759	8.772	1131.0	1.97e+03
G14	0.1913	0.00442	7.01	440.0	2.3e+03
G9	0.1849	0.0034	7.01	611.0	3.3e+03
G3	0.01388	0.000432	7.016	547.0	3.94e+04
G1	0.0001392	2.78e-06	7.01	590.0	4.24e+06

s= 0.18598 ± 0.00331 (pb)

Graph	Cross-Section ↓	Error	Events (K)	Unwgt	Luminosity
G7	0.06445	0.00205	7.016	156.0	2.42e+03
G4	0.0642	0.00205	7.016	92.0	1.43e+03
G5	0.0286	0.000805	7.01	855.0	2.99e+04
G2	0.02798	0.00137	7.01	66.0	2.36e+03
G1	0.0007438	2.03e-05	7.016	42.0	5.65e+04

s= 2.5673 ± 0.016 (pb)

Graph	Cross-Section ↓	Error	Events (K)	Unwgt	Luminosity
G1	1.135	0.00744	70.033	3829.0	3.38e+03
G4	0.5331	0.00462	75.001	1170.0	2.19e+03
G2	0.4554	0.00928	15.863	1127.0	2.47e+03
G3	0.2788	0.00387	155.001	744.0	2.67e+03
G7	0.1621	0.00892	7.012	270.0	1.67e+03
G5	0.002929	4.46e-05	7.015	658.0	2.25e+05
G6	0.0004332	1.35e-05	7.013	573.0	1.32e+06

s= 0.0059477 ± 0.000103 (pb)

Graph	Cross-Section ↓	Error	Events (K)	Unwgt	Luminosity
G1	0.002789	6.5e-05	7.035	487.0	1.75e+05
G2	0.001592	6.86e-05	7.017	17.0	1.07e+04
G3	0.001543	3.98e-05	7.018	241.0	1.56e+05
G4	2.294e-05	4.99e-07	7.013	519.0	2.26e+07

s= 0.18503 ± 0.00287 (pb)

Graph	Cross-Section ↓	Error	Events (K)	Unwgt	Luminosity
G1	0.1841	0.00287	23.01	313.0	1.7e+03
G3	0.0008942	1.48e-05	7.013	798.0	8.92e+05

Figura 31

- Para 25000 eventos

s= 7.8619 ± 0.0156 (pb)

Graph	Cross-Section ↓	Error	Events (K)	Unwgt	Luminosity
/home/hep/Programs/MG5_aMC_v2_7_2/bin/hefthjj3/SubProcesses/P1_gg_hgg	4.908	0.013	2329.861	34527.0	0
/home/hep/Programs/MG5_aMC_v2_7_2/bin/hefthjj3/SubProcesses/P1_gq_hgq	2.569	0.00837	899.839	21827.0	0
/home/hep/Programs/MG5_aMC_v2_7_2/bin/hefthjj3/SubProcesses/P1_gg_hqq	0.1927	0.00185	113.863	1728.0	0
/home/hep/Programs/MG5_aMC_v2_7_2/bin/hefthjj3/SubProcesses/P1_qq_hqq	0.1857	0.00145	82.014	2492.0	0
/home/hep/Programs/MG5_aMC_v2_7_2/bin/hefthjj3/SubProcesses/P1_qq_hgg	0.005948	0.000103	28.083	1264.0	0

s= 4.9082 ± 0.013 (pb)

Graph	Cross-Section ↓	Error	Events (K)	Unwgt	Luminosity
G8	1.581	0.00495	764.544	13540.0	8.55e+03
G7	0.886	0.00544	220.04	5867.0	6.63e+03
G4	0.8819	0.00348	1260.04	6574.0	7.47e+03
G6	0.5936	0.00516	29.616	2855.0	4.81e+03
G13	0.5882	0.00784	21.972	2528.0	4.29e+03
G9	0.1815	0.00252	8.051	851.0	4.69e+03
G14	0.1814	0.0027	11.572	1175.0	6.48e+03
G3	0.01388	0.000432	7.016	547.0	3.94e+04
G1	0.0001392	2.78e-06	7.01	590.0	4.24e+06

s= 0.19266 ± 0.00185 (pb)

Graph	Cross-Section ↓	Error	Events (K)	Unwgt	Luminosity
G7	0.06858	0.000978	48.733	274.0	4e+03
G4	0.06686	0.000965	39.826	443.0	6.63e+03
G5	0.0286	0.000805	7.01	855.0	2.99e+04
G2	0.02788	0.000939	11.278	114.0	4.09e+03
G1	0.0007438	2.03e-05	7.016	42.0	5.65e+04

s= 2.5695 ± 0.00837 (pb)

Graph	Cross-Section ↓	Error	Events (K)	Unwgt	Luminosity
G1	1.136	0.00481	175.075	8598.0	7.58e+03
G4	0.5335	0.00302	185.046	6201.0	1.16e+04
G2	0.4524	0.00522	39.684	2310.0	5.11e+03
G3	0.2757	0.00189	470.024	2506.0	9.09e+03
G7	0.1686	0.00264	15.982	981.0	5.82e+03
G5	0.002929	4.46e-05	7.015	658.0	2.25e+05
G6	0.0004332	1.35e-05	7.013	573.0	1.32e+06

s= 0.0059477 ± 0.000103 (pb)

Graph	Cross-Section ↓	Error	Events (K)	Unwgt	Luminosity
G1	0.002789	6.5e-05	7.035	487.0	1.75e+05
G2	0.001592	6.86e-05	7.017	17.0	1.07e+04
G3	0.001543	3.98e-05	7.018	241.0	1.56e+05
G4	2.294e-05	4.99e-07	7.013	519.0	2.26e+07

s= 0.18569 ± 0.00145 (pb)

Graph	Cross-Section ↓	Error	Events (K)	Unwgt	Luminosity
G1	0.1848	0.00145	75.001	1694.0	9.17e+03
G3	0.0008942	1.48e-05	7.013	798.0	8.92e+05

Figura 32

Tanto para el **SM** y **HEFT**, mientras exista mayor número de eventos, mayor será la sección transerval aunque esto sea lo más ligero posible. Y la luminosidad debido a la cantidad de particulas incidentes.

III. Modelo Estándar (W + up to 3 jets)
Se presentará secuencialmente la Cross-Section para el proceso **p p > e- ve**~ y los procesos añadidos cada uno con **25000** eventos realizados.

- Generate p p > e- ve~

s= 3761.9 ± 5.9 (pb)

Graph	Cross-Section ↓	Error	Events (K)	Unwgt	Luminosity
/home/hep/Programs/MG5_aMC_v2_7_2/bin/ppe-ve-/SubProcesses/P1_qq_lvl	3762	5.9	416.854	32483.0	0

s= 3761.9 ± 5.9 (pb)

Graph	Cross-Section ↓	Error	Events (K)	Unwgt	Luminosity
G1	3762	5.9	416.854	32483.0	8.63

Figura 33

- Generate p p > e- ve~
  add process p p > e- ve~ j

s= 4530.3 ± 7.71 (pb)

Graph	Cross-Section ↓	Error	Events (K)	Unwgt	Luminosity
/home/hep/Programs/MG5_aMC_v2_7_2/bin/ppe-ve-j/SubProcesses/P1_qq_lvl	3762	6.19	345.092	26933.0	0
/home/hep/Programs/MG5_aMC_v2_7_2/bin/ppe-ve-j/SubProcesses/P2_gq_lvlq	610.8	4.31	83.88	7756.0	0
/home/hep/Programs/MG5_aMC_v2_7_2/bin/ppe-ve-j/SubProcesses/P2_qq_lvlg	157.6	1.63	20.242	1914.0	0

s= 610.81 ± 4.31 (pb)

Graph	Cross-Section ↓	Error	Events (K)	Unwgt	Luminosity
G2	463.3	4.13	48.879	4704.0	10.1
G1	147.5	1.2	35.001	3052.0	20.7

s= 157.56 ± 1.63 (pb)

Graph	Cross-Section ↓	Error	Events (K)	Unwgt	Luminosity
G1	84.45	1.28	7.032	727.0	8.61
G2	73.12	1.01	13.21	1187.0	16.2

s= 3761.9 ± 6.19 (pb)

Graph	Cross-Section ↓	Error	Events (K)	Unwgt	Luminosity
G1	3762	6.19	345.092	26933.0	7.16

Figura 34

- Generate p p > e- ve~
  add process p p > e- ve~ j
  add process p p > e- ve~ j j

s= 4801.2 ± 7.87 (pb)

Graph	Cross-Section ↓	Error	Events (K)	Unwgt	Luminosity
/home/hep/Programs/MG5_aMC_v2_7_2/bin/ppe-ve-jj/SubProcesses/P1_qq_lvl	3756	6.5	325.604	25571.0	0
/home/hep/Programs/MG5_aMC_v2_7_2/bin/ppe-ve-jj/SubProcesses/P2_gq_lvlq	609.7	3.82	119.534	6014.0	0
/home/hep/Programs/MG5_aMC_v2_7_2/bin/ppe-ve-jj/SubProcesses/P3_gq_lvlgq	197.3	1.43	144.384	3326.0	0
/home/hep/Programs/MG5_aMC_v2_7_2/bin/ppe-ve-jj/SubProcesses/P2_qq_lvlg	156.9	1.53	17.201	1159.0	0
/home/hep/Programs/MG5_aMC_v2_7_2/bin/ppe-ve-jj/SubProcesses/P3_qq_lvlqq	46.72	0.67	75.382	1460.0	0
/home/hep/Programs/MG5_aMC_v2_7_2/bin/ppe-ve-jj/SubProcesses/P3_gg_lvlqq	23.35	0.448	28.04	1463.0	0
/home/hep/Programs/MG5_aMC_v2_7_2/bin/ppe-ve-jj/SubProcesses/P3_qq_lvlgg	11.12	0.124	63.094	1114.0	0

s= 23.35 ± 0.448 (pb)

Graph	Cross-Section ↓	Error	Events (K)	Unwgt	Luminosity
G3	14.23	0.412	7.01	385.0	27.1
G4	4.477	0.157	7.01	28.0	6.25
G7	4.407	0.0814	7.01	709.0	161
G1	0.2326	0.00579	7.01	341.0	1.47e+03

s= 197.3 ± 1.43 (pb)

Graph	Cross-Section ↓	Error	Events (K)	Unwgt	Luminosity
G1	70.8	0.65	72.766	758.0	10.7
G2	63.59	1.08	8.611	614.0	9.66
G3	22.6	0.326	21.099	578.0	25.6
G7	13.94	0.343	12.216	442.0	31.7
G8	10.29	0.209	8.653	255.0	24.8
G4	9.591	0.363	7.012	263.0	27.4
G5	5.846	0.208	7.012	140.0	23.9
G6	0.6431	0.0174	7.015	276.0	429

s= 11.124 ± 0.124 (pb)

Graph	Cross-Section ↓	Error	Events (K)	Unwgt	Luminosity
G3	4.762	0.0654	35.001	756.0	159
G6	2.039	0.0584	7.014	101.0	49.5
G4	1.527	0.0699	7.012	37.0	24.2
G2	1.5	0.0429	7.035	46.0	30.7
G1	1.296	0.0296	7.032	174.0	134

s= 46.717 ± 0.67 (pb)

Graph	Cross-Section ↓	Error	Events (K)	Unwgt	Luminosity
G1	15.73	0.525	7.01	103.0	6.55
G2	14.96	0.325	26.307	471.0	31.5
G7	7.428	0.204	7.01	118.0	15.9
G8	5.424	0.155	7.01	225.0	41.5
G11	1.185	0.0323	7.013	251.0	212
G9	0.9395	0.0251	7.011	36.0	38.3
G10	0.8899	0.0237	7.011	41.0	46.1
G5	0.1575	0.00519	7.01	215.0	1.37e+03

s= 609.67 ± 3.82 (pb)

Graph	Cross-Section ↓	Error	Events (K)	Unwgt	Luminosity
G2	461.9	3.63	44.533	4264.0	9.25
G1	147.8	1.18	75.001	1750.0	11.8

s= 156.87 ± 1.53 (pb)

Graph	Cross-Section ↓	Error	Events (K)	Unwgt	Luminosity
G1	83.87	1.09	8.331	600.0	7.15
G2	73	1.07	8.87	559.0	7.66

s= 3756.2 ± 6.5 (pb)

Graph	Cross-Section ↓	Error	Events (K)	Unwgt	Luminosity
G1	3756	6.5	325.604	25571.0	6.81

Figura 35

- Generate p p > e- ve~
  add process p p > e- ve~ j
  add process p p > e- ve~ j j
  add process p p > e- ve~ j j j

s= 4902 ± 8 (pb)

Graph	Cross-Section ↓	Error	Events (K)	Unwgt	Luminosity
/home/hep/Programs/MG5_aMC_v2_7_2/bin/ppe-ve-jjj/SubProcesses/P1_qq_lvl	3758	6.44	322.46	25507.0	0
/home/hep/Programs/MG5_aMC_v2_7_2/bin/ppe-ve-jjj/SubProcesses/P2_gq_lvlq	613.3	3.99	82.889	5317.0	0
/home/hep/Programs/MG5_aMC_v2_7_2/bin/ppe-ve-jjj/SubProcesses/P3_gq_lvlgq	199.2	1.87	113.998	2437.0	0
/home/hep/Programs/MG5_aMC_v2_7_2/bin/ppe-ve-jjj/SubProcesses/P2_qq_lvlg	157.2	1.38	28.019	2777.0	0
/home/hep/Programs/MG5_aMC_v2_7_2/bin/ppe-ve-jjj/SubProcesses/P4_gq_lvlggq	55.5	0.731	270.869	2203.0	0
/home/hep/Programs/MG5_aMC_v2_7_2/bin/ppe-ve-jjj/SubProcesses/P3_qq_lvlqq	46.5	0.608	84.77	1876.0	0
/home/hep/Programs/MG5_aMC_v2_7_2/bin/ppe-ve-jjj/SubProcesses/P3_gg_lvlqq	22.66	0.384	28.04	1324.0	0
/home/hep/Programs/MG5_aMC_v2_7_2/bin/ppe-ve-jjj/SubProcesses/P4_qq_lvlgqq	20.44	0.342	373.142	2286.0	0
/home/hep/Programs/MG5_aMC_v2_7_2/bin/ppe-ve-jjj/SubProcesses/P4_gg_lvlgqq	11.19	0.147	201.603	3366.0	0
/home/hep/Programs/MG5_aMC_v2_7_2/bin/ppe-ve-jjj/SubProcesses/P3_qq_lvlgg	11.03	0.139	35.116	816.0	0
/home/hep/Programs/MG5_aMC_v2_7_2/bin/ppe-ve-jjj/SubProcesses/P4_gq_lvlqqq	5.89	0.115	112.16	1641.0	0
/home/hep/Programs/MG5_aMC_v2_7_2/bin/ppe-ve-jjj/SubProcesses/P4_qq_lvlggg	1.197	0.0207	112.24	1134.0	0

s= 11.191 ± 0.147 (pb)

Graph	Cross-Section ↓	Error	Events (K)	Unwgt	Luminosity
G17	1.99	0.0826	7.01	29.0	14.6
G9	1.904	0.0646	8.373	125.0	65.6
G10	1.632	0.0757	31.01	21.0	12.9
G18	1.618	0.0491	7.01	168.0	104
G40	0.4929	0.022	7.01	97.0	197
G24	0.4734	0.0119	7.01	294.0	621
G35	0.439	0.0252	7.01	60.0	137
G15	0.4063	0.0179	7.01	85.0	209
G13	0.3842	0.0153	7.01	92.0	239
G33	0.3665	0.0134	7.01	159.0	434
G20	0.3001	0.00883	7.01	83.0	277
G19	0.2811	0.00888	7.01	173.0	616
G39	0.2151	0.0056	7.01	225.0	1.05e+03
G23	0.2122	0.0145	7.01	20.0	94.3
G46	0.1181	0.00445	7.01	308.0	2.61e+03
G45	0.1158	0.00316	7.01	268.0	2.31e+03
G22	0.08305	0.00541	7.01	159.0	1.91e+03
G38	0.07839	0.00289	15.01	149.0	1.9e+03
G21	0.02904	0.00063	7.01	385.0	1.33e+04
G37	0.02866	0.00135	7.01	61.0	2.13e+03
G5	0.01132	0.000349	7.01	281.0	2.48e+04
G6	0.009747	0.00052	7.01	23.0	2.36e+03
G1	0.001437	6.85e-05	7.01	38.0	2.65e+04
G3	0.0009852	5.85e-05	7.01	63.0	6.39e+04

s= 55.497 ± 0.731 (pb)

Graph	Cross-Section ↓	Error	Events (K)	Unwgt	Luminosity
G5	8.654	0.392	7.01	56.0	6.47
G7	6.65	0.303	8.359	65.0	9.77
G2	6.561	0.178	20.651	109.0	16.6
G1	6.441	0.304	7.01	54.0	8.38
G8	5.176	0.108	34.567	131.0	25.3
G34	4.938	0.182	31.012	73.0	14.8
G6	3.926	0.22	7.01	77.0	19.6
G33	3.788	0.165	7.027	66.0	17.4
G3	1.711	0.174	7.01	20.0	11.7
G4	1.268	0.0656	7.01	72.0	56.8
G39	1.051	0.0427	7.01	92.0	87.5
G17	0.7373	0.0219	7.017	159.0	216
G19	0.649	0.0325	7.01	32.0	49.3
G40	0.6438	0.0305	7.01	28.0	43.5
G20	0.6041	0.0425	7.01	108.0	179
G18	0.5991	0.0373	7.014	206.0	344
G35	0.3509	0.023	7.014	4.0	11.4
G38	0.3336	0.0112	7.01	99.0	297
G37	0.3201	0.012	7.01	65.0	203
G42	0.2927	0.0174	7.01	44.0	150
G36	0.2476	0.0189	7.014	81.0	327
G21	0.1638	0.00583	7.01	49.0	299
G27	0.1226	0.011	7.01	2.0	16.3
G26	0.1015	0.00494	15.012	71.0	700
G41	0.0837	0.00205	7.01	216.0	2.58e+03
G25	0.05433	0.00292	7.012	20.0	368
G28	0.02712	0.000961	7.01	157.0	5.79e+03
G29	0.003922	0.00023	7.01	47.0	1.2e+04

s= 1.1972 ± 0.0207 (pb)

Graph	Cross-Section ↓	Error	Events (K)	Unwgt	Luminosity
G28	0.1362	0.00759	7.01	39.0	286
G7	0.1339	0.00473	7.01	68.0	508
G20	0.1234	0.00956	7.01	36.0	292
G5	0.116	0.00505	7.01	45.0	388
G6	0.101	0.0121	7.018	39.0	386
G8	0.09394	0.00384	7.016	317.0	3.37e+03
G19	0.07262	0.00307	7.013	36.0	496
G27	0.06351	0.00294	7.012	25.0	394
G26	0.05218	0.0016	7.04	124.0	2.38e+03
G29	0.05194	0.00276	7.01	26.0	501
G18	0.04768	0.0032	7.041	28.0	587
G21	0.0439	0.00239	7.01	34.0	775
G4	0.04294	0.00336	7.01	41.0	955
G1	0.03955	0.00148	7.01	149.0	3.77e+03
G3	0.03949	0.00138	7.01	112.0	2.84e+03
G2	0.03892	0.00304	7.01	15.0	385

s= 5.8895 ± 0.115 (pb)

Graph	Cross-Section ↓	Error	Events (K)	Unwgt	Luminosity
G5	1.605	0.0796	7.01	182.0	113
G6	1.297	0.0652	7.009	24.0	18.5
G42	0.4671	0.0269	7.01	51.0	109
G26	0.3786	0.0257	7.01	18.0	47.5
G41	0.3743	0.011	7.01	213.0	569
G17	0.3712	0.026	7.01	132.0	356
G25	0.36	0.0119	7.01	131.0	364
G19	0.3274	0.0145	7.01	28.0	85.5
G29	0.2341	0.0063	7.011	212.0	906
G30	0.2146	0.0087	7.01	88.0	410
G43	0.09459	0.00798	7.01	114.0	1.21e+03
G44	0.08661	0.00402	7.01	22.0	254
G37	0.03163	0.00138	7.01	64.0	2.02e+03
G7	0.02442	0.000582	7.01	309.0	1.27e+04
G38	0.02027	0.00174	7.01	21.0	1.04e+03
G1	0.003078	0.000151	7.01	32.0	1.04e+04

s= 20.437 ± 0.342 (pb)

Graph	Cross-Section ↓	Error	Events (K)	Unwgt	Luminosity
G5	2.242	0.121	10.578	31.0	13.8
G13	1.9	0.16	15.01	20.0	10.5
G8	1.602	0.0811	31.01	26.0	16.2
G7	1.32	0.0723	7.01	64.0	48.5
G1	1.305	0.117	7.01	23.0	17.6
G14	1.098	0.104	7.011	42.0	38.3
G18	1.079	0.0483	8.177	59.0	54.7
G6	0.9998	0.0356	7.01	105.0	105
G40	0.9871	0.0341	7.01	85.0	86.1
G17	0.9757	0.107	15.011	85.0	87.1
G2	0.8924	0.0898	7.01	10.0	11.2
G38	0.8433	0.0404	7.01	23.0	27.3
G41	0.5581	0.0233	7.01	93.0	167
G37	0.5138	0.0229	7.01	30.0	58.4
G19	0.5103	0.0689	15.01	22.0	43.1
G42	0.4406	0.0293	7.01	100.0	227
G39	0.4236	0.0165	7.01	211.0	498
G43	0.4019	0.0416	7.01	14.0	34.8
G45	0.3878	0.0398	7.01	16.0	41.3
G20	0.3835	0.0178	7.01	47.0	123
G44	0.3783	0.0563	31.01	24.0	63.4
G46	0.3217	0.0196	15.01	34.0	106
G47	0.1908	0.00795	7.01	63.0	330
G48	0.1752	0.00759	7.01	102.0	582
G55	0.08096	0.00344	7.011	33.0	408
G51	0.07092	0.00264	7.01	32.0	451
G56	0.07071	0.00217	7.011	61.0	863
G52	0.06855	0.00329	15.011	82.0	1.2e+03
G49	0.04644	0.00212	7.01	42.0	904
G50	0.03996	0.00238	7.013	86.0	2.15e+03
G60	0.0217	0.00081	7.011	125.0	5.76e+03
G57	0.01839	0.000986	7.01	15.0	816
G59	0.01793	0.000626	7.009	78.0	4.35e+03
G25	0.01738	0.000664	7.01	66.0	3.8e+03
G27	0.01664	0.000964	7.009	25.0	1.5e+03
G58	0.01576	0.000835	7.01	61.0	3.87e+03
G29	0.0116	0.000585	7.01	76.0	6.55e+03
G30	0.008293	0.000735	7.01	19.0	2.29e+03
G35	0.0008744	4.32e-05	7.01	73.0	8.35e+04
G33	0.0005049	2.38e-05	7.01	83.0	1.64e+05

s= 22.664 ± 0.384 (pb)

Graph	Cross-Section ↓	Error	Events (K)	Unwgt	Luminosity
G3	13.16	0.353	7.01	255.0	19.4
G4	4.669	0.118	7.01	263.0	56.3
G7	4.614	0.0937	7.01	418.0	90.6
G1	0.2242	0.00556	7.01	388.0	1.73e+03

s= 199.21 ± 1.87 (pb)

Graph	Cross-Section ↓	Error	Events (K)	Unwgt	Luminosity
G1	71.24	0.91	35.001	623.0	8.75
G2	66.01	1.19	8.793	491.0	7.44
G3	22.19	0.571	9.01	172.0	7.75
G7	14.31	0.287	33.132	191.0	13.4
G8	9.674	0.413	7.012	234.0	24.2
G4	9.114	0.288	7.012	195.0	21.4
G5	6.022	0.761	7.017	159.0	26.4
G6	0.6606	0.0167	7.021	372.0	563

s= 11.031 ± 0.139 (pb)

Graph	Cross-Section ↓	Error	Events (K)	Unwgt	Luminosity
G3	4.691	0.112	7.015	53.0	11.3
G6	1.958	0.0531	7.014	135.0	69
G4	1.561	0.0425	7.015	217.0	139
G2	1.517	0.0352	7.034	329.0	217
G1	1.305	0.0327	7.038	82.0	62.9

s= 46.503 ± 0.608 (pb)

Graph	Cross-Section ↓	Error	Events (K)	Unwgt	Luminosity
G1	15.34	0.48	8.527	387.0	25.2
G2	15.06	0.279	34.182	227.0	15.1
G7	7.279	0.194	7.01	147.0	20.2
G8	5.763	0.15	7.01	234.0	40.6
G11	1.107	0.0275	7.011	196.0	177
G9	0.9212	0.0225	7.011	178.0	193
G10	0.8699	0.0181	7.009	365.0	420
G5	0.169	0.00602	7.01	142.0	840

s= 613.32 ± 3.99 (pb)

Graph	Cross-Section ↓	Error	Events (K)	Unwgt	Luminosity
G2	464.1	3.66	47.888	4245.0	9.15
G1	149.3	1.59	35.001	1072.0	7.18

s= 157.24 ± 1.38 (pb)

Graph	Cross-Section ↓	Error	Events (K)	Unwgt	Luminosity
G1	83.44	0.675	20.986	2197.0	26.3
G2	73.8	1.2	7.033	580.0	7.86

s= 3757.8 ± 6.44 (pb)

Graph	Cross-Section ↓	Error	Events (K)	Unwgt	Luminosity
G1	3758	6.44	322.46	25507.0	6.79

Figura 36

7. Compare la cross-section de H + 2 jets para el modelo SM y HEFT, para 10000 eventos.

Para el modelo SM, obtuvimos una Cross-Section total de 3.3689±0.00752, y para el modelo HEFT, se obtuvo 7.8612±0.0243, en el que podemos notar de este último modelo una mayor cantidad de colisiones.

8. Para la colisión (W + up to 3 jets) produzca las siguientes colisiones:
Los resultados obtenidos de la Cross-Section fueron mostrados anteriormente en la pregunta 6, pero no los diagramas, es por eso que en esta parte mostraré el diagrama principalde cada proceso.

- Generate p p > e- ve~

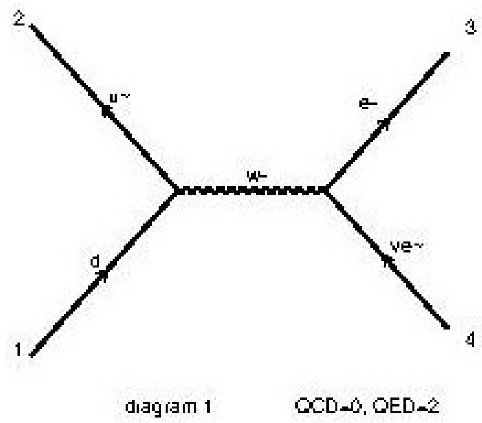

Figura 37

- Generate p p > e- ve~
  add process p p > e- ve~ j

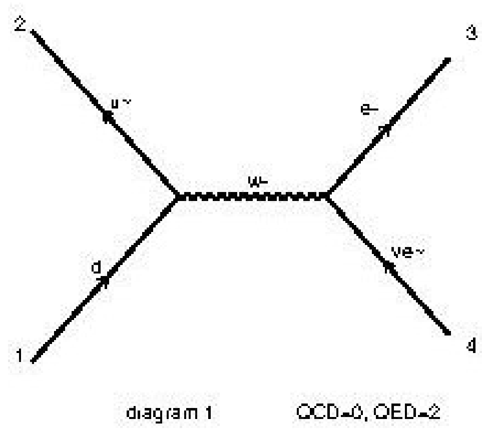

Figura 38

- Generate p p > e- ve~
  add process p p > e- ve~ j
  add process p p > e- ve~ j j

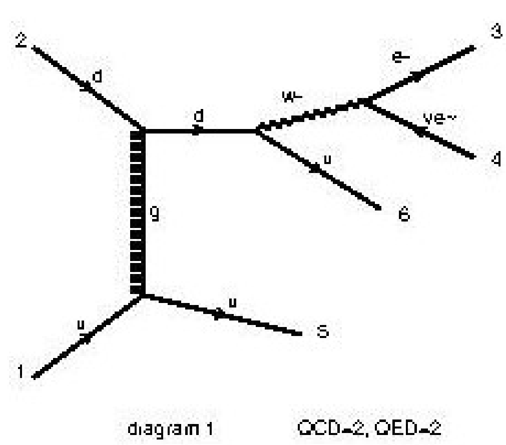

Figura 39

- Generate p p > e- ve~
  add process p p > e- ve~ j
  add process p p > e- ve~ j j
  add process p p > e- ve~ j j j

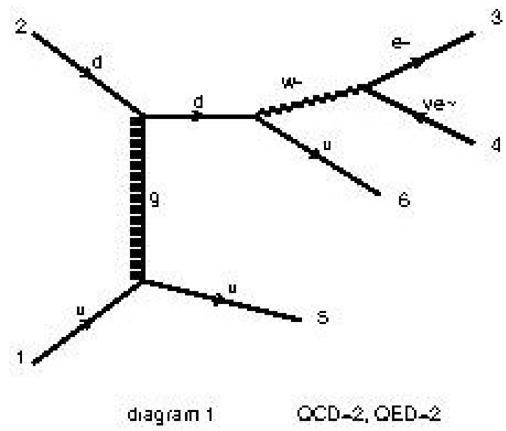

Figura 40

En este link encontrarán el trabajo realizado:
https://es.overleaf.com/project/62157ef8a4acf9683c5378e0

En las siguientes páginas mostraré mi desarrollo a mano de las primeras 4 preguntas, por si mis operaciones son muy simples. **(Opcional)**

1)

$$\mathcal{L} = -\frac{1}{16\pi}(\partial^\mu A^\nu - \partial^\nu A^\mu)(\partial_\mu A_\nu - \partial_\nu A_\mu) + \frac{1}{8\pi}\left(\frac{mc}{\hbar}\right)^2 A^\nu A_\nu$$

E-L

$$\underbrace{\frac{\partial \mathcal{L}}{\partial A_\nu}}_{I} - \partial_\mu \underbrace{\frac{\partial \mathcal{L}}{\partial(\partial_\mu A_\nu)}}_{II} = 0$$

I:

$$\frac{\partial \mathcal{L}}{\partial A_\nu} = \frac{\partial}{\partial A_\nu}\left[-\frac{1}{16\pi}(\partial^\mu A^\nu - \partial^\nu A^\mu)(\partial_\mu A_\nu - \partial_\nu A_\mu) + \frac{1}{8\pi}\left(\frac{mc}{\hbar}\right)^2 A^\nu A_\nu\right]$$

$$= \frac{\partial}{\partial A_\nu}\left[-\frac{1}{16\pi}(\eta^{\mu\nu}\partial^\mu A^\nu - \partial^\nu A^\mu)(\partial_\mu A_\nu - \partial_\nu A_\mu)\right]^{=0} + \frac{\partial}{\partial A_\nu}\left[\frac{1}{8\pi}\left(\frac{mc}{\hbar}\right)^2 A^\nu A_\nu\right]$$

$$\boxed{\frac{\partial \mathcal{L}}{\partial A_\nu} = \frac{1}{8\pi}\left(\frac{mc}{\hbar}\right)^2 A^\nu}$$

II:

$$\frac{\partial \mathcal{L}}{\partial(\partial_\mu A_\nu)} = \frac{\partial}{\partial(\partial_\mu A_\nu)}\left[\left(\quad\right)\partial_\mu A_\nu - \left(\quad\right)\partial_\nu A_\mu\right) + \frac{\partial}{\ldots}$$

$$= \frac{\partial}{\partial(\partial_\mu A_\nu)}\left[-\frac{1}{16\pi}\left(\partial^\mu A^\nu \partial_\mu A_\nu - \partial^\nu A^\mu \partial_\mu A_\nu - \partial^\mu A^\mu \partial_\mu A_\nu + \partial^\nu A^\mu \partial_\nu A_\mu\right) + \frac{1}{8\pi}\left(\frac{mc}{\hbar}\right)^2 A^\nu A_\nu\right]$$

$$\frac{\partial x^2}{\partial x} = 2x$$

$$= \left(-\frac{1}{16\pi}\right)\frac{\partial}{\partial(\partial_\mu A_\nu)}\left[\partial^\mu A^\nu \partial_\mu A_\nu - \partial^\nu A^\mu \partial_\nu A_\mu - \partial^\mu A^\mu \partial_\mu A_\nu + \partial^\nu A^\mu \partial_\nu A_\mu\right]$$

$$= \left(-\frac{1}{16\pi}\right)\frac{\partial}{\partial(\partial_\mu A_\nu)}\left[\eta^{\mu\nu}\partial_\nu(\eta^{\mu\nu}A_\mu)\partial_\mu A_\nu - (\partial_\nu A_\mu)^2 - (\partial_\mu A_\nu)^2 + 0 + \partial_\mu A_\nu \partial_\nu A_\mu\right]$$

$$= \left(\frac{-1}{16\pi}\right) \frac{\partial}{\partial(\partial_\mu A_\nu)} \left[\partial_\nu A_\mu \partial_\mu A_\nu - (\partial_\nu A_\mu)^2 - (\partial_\mu A_\nu)^2 + \partial_\mu A_\nu \partial_\nu A_\mu \right]$$

$$= \left(\frac{-1}{16\pi}\right) \left[\partial_\nu A_\mu - 0 - 2\partial_\mu A_\nu + \partial_\nu A_\mu \right]$$

$$\mathrm{II} = -\frac{1}{8\pi} \left[\underbrace{\partial_\nu A_\mu}_{\partial^\mu A^\nu} - \underbrace{\partial_\mu A_\nu}_{\partial^\nu A^\mu} \right]$$

E-L: $(\mathrm{I}) - (\mathrm{II}) = 0$

$$\cancel{\frac{1}{8\pi}}\left(\frac{mc}{\hbar}\right)^2 A^\nu + \partial_\mu\left(\cancel{\frac{1}{8\pi}}(\partial^\mu A^\nu - \partial^\nu A^\mu)\right) = 0$$

$$\partial_\mu(\partial^\mu A^\nu - \partial^\nu A^\mu) + \left(\frac{mc}{\hbar}\right)^2 A^\nu = 0$$

2

$$\mathcal{L} = i(\hbar c)\bar{\Psi}\gamma^\mu \partial_\mu \Psi - (mc^2)\bar{\Psi}\Psi$$

Aplicando E-L en $\bar{\Psi}$:

$$\underbrace{\frac{\partial \mathcal{L}}{\partial \bar{\Psi}}}_{\mathrm{I}} - \partial_\mu \underbrace{\left(\frac{\partial \mathcal{L}}{\partial(\partial_\mu \bar{\Psi})}\right)}_{\mathrm{II}} = 0$$

$$\mathrm{I} = \frac{\partial \mathcal{L}}{\partial \bar{\Psi}} = \frac{\partial}{\partial \bar{\Psi}}(\quad) = i\hbar c\gamma^\mu \partial_\mu \Psi - mc^2 \Psi$$

$$\mathrm{II}: \frac{\partial \mathcal{L}}{\partial(\partial_\mu \bar{\Psi})} = \frac{\partial}{\partial(\partial_\mu \bar{\Psi})}(\quad) = 0$$

$$\mathrm{I} - \partial_\mu(\mathrm{II}) = 0$$

$$i\hbar \cancel{c}\gamma^\mu \partial_\mu \Psi - mc^{\cancel{2}}\Psi - \cancel{\partial_\mu}(0) = 0$$

$$i\gamma^\mu \partial_\mu \Psi - \left(\frac{mc}{\hbar}\right)\Psi = 0$$

Su adjunto: $\bar{\Psi}$ " ψ ":

E.-L: $$\underbrace{\frac{\partial \mathcal{L}}{\partial \psi}}_{\mathrm{I}} - \partial_\mu \Big(\underbrace{\frac{\partial \mathcal{L}}{\partial(\partial_\mu \psi)}}_{\mathrm{II}} \Big) = 0$$

I: $$\frac{\partial \mathcal{L}}{\partial \psi} = \frac{\partial}{\partial \psi}\left(i(\hbar c)\bar{\Psi}\gamma^\mu \partial_\mu \psi - (mc^2)\bar{\Psi}\psi \right)$$

$$= \cancel{\partial} \; 0 - mc^2\bar{\Psi}$$

$$= -mc^2\bar{\Psi}$$

II: $$\frac{\partial \mathcal{L}}{\partial(\partial_\mu \psi)} = i\hbar c\bar{\Psi}\gamma^\mu - 0$$

$$= i\hbar c\bar{\Psi}\gamma^\mu$$

Entonces: $$(\mathrm{I}) - \partial_\mu(\mathrm{II}) = 0$$

$$-mc^2\bar{\Psi} - \partial_\mu(i\hbar c\bar{\Psi}\gamma^\mu) = 0$$

$$\cancel{+}\, m\cancel{c^2}\bar{\Psi} \cancel{+}\, i\hbar\cancel{c}\,\partial_\mu\bar{\Psi}\gamma^\mu = 0$$

$$i\partial_\mu\bar{\Psi}\gamma^\mu + \left(\frac{mc}{\hbar}\right)\bar{\Psi} = 0$$

3

$$\mathcal{L} = \frac{1}{2}\underbrace{(\partial_\mu \phi)^* (\partial^\mu \phi)}_{\partial^\mu \phi^* \partial_\mu \phi} - \frac{1}{2}\underbrace{\left(\frac{mc}{\hbar}\right)^2}_{\text{parametro de masa}} \phi^* \phi$$

E-L
Para un ϕ

$$\underbrace{\frac{\partial \mathcal{L}}{\partial \phi}}_{\mathrm{I}} - \partial_\mu \underbrace{\left(\frac{\partial \mathcal{L}}{\partial(\partial_\mu \phi)}\right)}_{\mathrm{II}} = 0$$

$$\mathrm{I}: \frac{\partial \mathcal{L}}{\partial \phi} = -\frac{1}{2}\left(\frac{mc}{\hbar}\right)^2 \phi^*$$

$$\mathrm{II}: \frac{\partial \mathcal{L}}{\partial(\partial_\mu \phi)} = \frac{\partial}{\partial(\partial_\mu \phi)}\left(\frac{1}{2}\partial_\mu \phi \, \partial^\mu \phi^* - \frac{1}{2}\left(\frac{mc}{\hbar}\right)^2 \phi^* \phi\right)$$

$$= \frac{1}{2}\partial^\mu \phi^* - 0$$

Entonces.

$$\mathrm{I} - \partial_\mu(\mathrm{II}) = 0$$

$$-\cancel{\frac{1}{2}}\left(\frac{mc}{\hbar}\right)^2 \phi^* - \partial_\mu\left(\cancel{\frac{1}{2}}\partial^\mu \phi^*\right) = 0$$

$$\phi^* + \left(\frac{\hbar}{mc}\right)^2 \partial_\mu(\partial^\mu \phi^*) = 0$$

Ambas ecuaciones de campo son consistentes.

Para ϕ^*:

$$\underbrace{\frac{\partial \mathcal{L}}{\partial \phi^*}}_{\mathrm{I}} - \partial_\mu \underbrace{\left(\frac{\partial \mathcal{L}}{\partial(\partial_\mu \phi^*)}\right)}_{\mathrm{II}} = 0$$

$$\mathrm{I}: \frac{\partial \mathcal{L}}{\partial \phi^*} = -\frac{1}{2}\left(\frac{mc}{\hbar}\right)^2 \phi$$

$$\mathrm{II}: \frac{\partial \mathcal{L}}{\partial(\partial_\mu \phi^*)} = \frac{1}{2}\partial^\mu \phi$$

$$(\mathrm{I}) - \partial_\mu(\mathrm{II}) = 0$$

$$-\cancel{\tfrac{1}{2}}\left(\frac{mc}{\hbar}\right)^2 \phi - \partial_\mu\left(\cancel{\tfrac{1}{2}}\partial^\mu \phi\right)$$

$$\rightarrow \phi + \left(\frac{\hbar}{mc}\right)^2 \partial_\mu(\partial^\mu \phi) = 0$$

4

$$\mathcal{L} = \left[i\hbar c \bar{\Psi} \gamma^{\mu} \partial_{\mu} \Psi - mc^2 \bar{\Psi} \Psi \right] - (q \bar{\Psi} \gamma^{\mu} \Psi) A_{\mu}$$

Para Ψ:

$$\underbrace{\frac{\partial \mathcal{L}}{\partial \Psi}}_{\mathrm{I}} - \partial_{\mu} \underbrace{\left(\frac{\partial \mathcal{L}}{\partial(\partial_{\mu} \Psi)} \right)}_{\mathrm{II}} = 0$$

$$\mathrm{I}: \frac{\partial \mathcal{L}}{\partial \Psi} = -mc^2 \bar{\Psi} - q \bar{\Psi} \gamma^{\mu} A_{\mu}$$

$$\mathrm{II}: \frac{\partial \mathcal{L}}{\partial(\partial_{\mu} \Psi)} = \left[i\hbar c \bar{\Psi} \gamma^{\mu} - 0 \right] - 0$$

$$= i\hbar c \bar{\Psi} \gamma^{\mu}$$

$$\mathrm{I} - \partial_{\mu}(\mathrm{II}) = 0$$

$$-mc^2 \bar{\Psi} - q \bar{\Psi} \gamma^{\mu} A_{\mu} - \partial_{\mu} (i\hbar c \bar{\Psi} \gamma^{\mu}) = 0$$

$$-mc^2 \bar{\Psi} - q \bar{\Psi} \gamma^{\mu} A_{\mu} - i\hbar c \partial_{\mu} \bar{\Psi} \gamma^{\mu} = 0$$

$$\boxed{i\hbar c \partial_{\mu} \bar{\Psi} \gamma^{\mu} + mc^2 \bar{\Psi} + q \bar{\Psi} \gamma^{\mu} A_{\mu} = 0}$$

Para $\bar{\Psi}$

$$\underbrace{\frac{\partial \mathcal{L}}{\partial \bar{\Psi}}}_{\mathrm{I}} - \partial_{\mu} \underbrace{\left(\frac{\partial \mathcal{L}}{\partial(\partial_{\mu} \bar{\Psi})} \right)}_{\mathrm{II}} = 0$$

$$\mathrm{I}: \frac{\partial \mathcal{L}}{\partial \bar{\Psi}} = \left[i\hbar c \gamma^{\mu} \partial_{\mu} \Psi - mc^2 \Psi \right] - (q \gamma^{\mu} \Psi) A_{\mu}$$

$$\mathrm{II}: \frac{\partial \mathcal{L}}{\partial(\partial_{\mu} \bar{\Psi})} = 0$$

$$(\mathrm{I}) - \cancel{\partial_{\mu} (\mathrm{II})}^{\,0} = 0$$

$$\boxed{i\hbar c \gamma^{\mu} \partial_{\mu} \Psi - mc^2 \Psi - (q \gamma^{\mu} \Psi) A_{\mu} = 0}$$