Production of Magnetic Monopoles Via Photon Fusion - Implementation in MadGraph

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Introduction:

- In previous analyses, only Drell-Yan (DY, $pp \to mm^+ mm^-$) magnetic monopole production was considered (both in ATLAS and MoEDAL).
- DY was implemented in MadGraph using Fortran code setup.
  - Only three-particle vertex.
- Presently we are looking at modeling photon fusion process through MadGraph.
- Need to move on from Fortran models:
  - Future MadGraph models will be usable only through python, hence old models need to be transferred to python.
  - Fortran code was inadequate to describe four-particle vertex as required in bosonic monopole production through photon fusion ($\gamma\gamma \to mm^+ mm^-$).
- Solution: implement photon fusion as a **UFO** model written in python.

UFO: Universal FeynRules Output

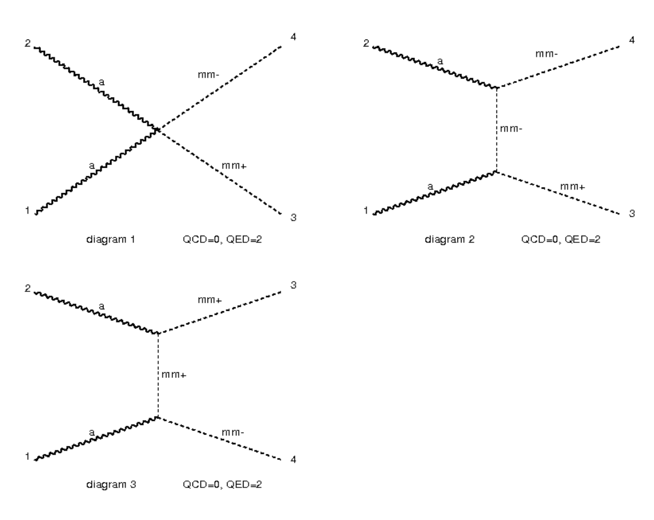
- FeynRules: Mathematica package for describing Feynman rules.
- Based on Python objects.
- Requires the model Lagrangian as an input in Mathematica format.
- Model parameters (mass, spin, coupling etc) are kept in a text file.

- For β-dependent coupling, it is introduced as a Fortran form factor.
  - Used the definition of $\beta = \sqrt{1 - 4M^2/\hat{s}}$ with $\hat{s} = 2P_1 \cdot P_2$ for LHC collision of quarks, where P_1 and P_2 are the four momenta of the incoming colliding particles.
  - $\beta \to 0$ when $\hat{s} \to (2M)^2$.
- With the help from Stephanie Baines on theoretical calculations and Mathematica.

- Validation of the UFO models

Feynman Diagrams for Spin 0, $\gamma\gamma \to mm^+ mm^-$

- $\mathcal{L}^{S=0} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + (\partial - ig(\beta)\mathcal{A}_\mu)\phi^\dagger(\partial + ig(\beta)\mathcal{A}_\mu)\phi - M^2\phi^\dagger\phi$



Cross-section for $\gamma\gamma \to mm^+ mm^-$, β-independent coupling, spin 0 monopole, charge 1 g_D

- No PDF used in MadGraph to compare with the theoretical value.

Mass (GeV)	σ (pb) $\gamma\gamma \to mm^+ mm^-$ (UFO model)	σ (pb) $\gamma\gamma \to mm^+ mm^-$ (Theory values)	Ratio UFO model/Theory
1000.0	1.518×10^4	1.5039×10^4	1.009
2000.0	1.202×10^4	1.1945×10^4	1.006
3000.0	9218	9108.09	1.012
4000.0	7366	7218.79	1.020
5000.0	6558	6519.68	1.006
6000.0	5378	5325.76	1.010

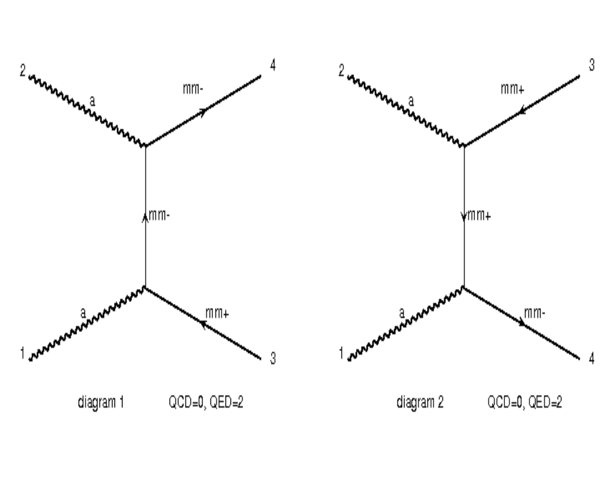
Cross-section for $\gamma\gamma \to mm^+ mm^-$, β-dependent coupling, spin 0 monopole, charge 1 g_D

- No PDF used in MadGraph to compare with the theoretical value.

Mass (GeV)	σ (pb) $\gamma\gamma \to mm^+ mm^-$ (UFO model)	σ (pb) $\gamma\gamma \to mm^+ mm^-$ (Theory values)	Ratio UFO model/Theory	β	Ratio β-dep/β-ind (UFO model)
1000	1.4493×10^4	1.4336×10^4	0.99	0.9881	0.9547 ($\sim 0.9881^4$)
2000	9.851×10^3	9.791×10^3	1.006	0.9515	0.8196 ($\sim 0.9515^4$)
3000	5.685×10^3	5.640×10^3	1.007	0.8871	0.6167 ($\sim 0.8871^4$)
4000	2847	2810.5	1.013	0.7882	0.3866 ($\sim 0.7882^4$)
5000	1094	1087	1.006	0.639	0.1658 ($\sim 0.639^4$)
6000	117.8	116.53	1.011	0.3846	0.022 ($\sim 0.3846^4$)

Feynman diagrams for Spin 1/2, $\gamma\gamma \to mm^{+}mm^{-}$

- $\mathcal{L}^{S=1/2} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \bar{\psi}(i\partial\!\!\!/ - M)\psi - g(\beta)\bar{\psi}\gamma^{\mu}\psi\mathcal{A}_{\mu}$



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MoEDAL

Cross-section for $\gamma\gamma \to mm^+ mm^-$, β-independent coupling, spin 1/2 monopole, charge 1 g_D

Mass (GeV)	σ (pb) $\gamma\gamma \to mm^+ mm^-$ (UFO model)	σ (pb) $\gamma\gamma \to mm^+ mm^-$ (Theory values)	Ratio UFO model/Theory
1000	1.431×10^5	1.425×10^5	1.004
2000	1.018×10^5	1.007×10^5	1.010
3000	7.755×10^4	7.679×10^4	1.010
4000	5.830×10^4	5.7404×10^4	1.016
5000	3.817×10^4	3.797×10^4	1.005
6000	1.691×10^4	1.6705×10^4	1.012

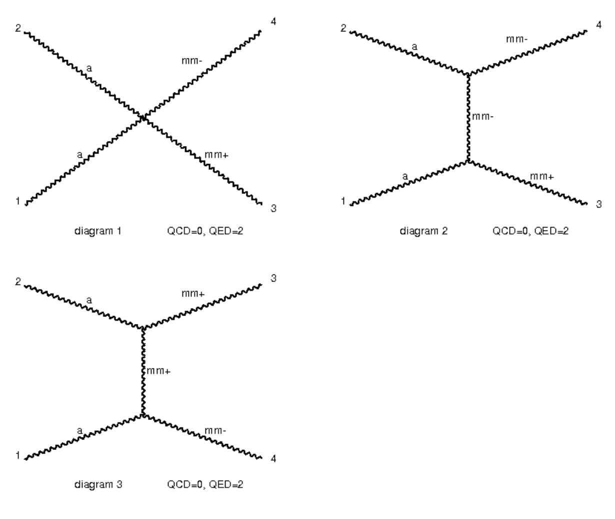
Cross-section for $\gamma\gamma \to mm^+ mm^-$, β-dependent coupling, spin 1/2 monopole, charge 1 g_D

- No PDF used in MadGraph to compare with the theoretical value.

Mass (GeV)	σ (pb) $\gamma\gamma \to mm^+ mm^-$ (UFO model)	σ (pb) $\gamma\gamma \to mm^+ mm^-$ (Theory values)	Ratio UFO model/Theory	β	Ratio β-dep/β-ind (UFO model)
1000	1.364×10^5	1.358×10^5	1.004	0.9881	0.9531 ($\sim 0.9881^4$)
2000	8.341×10^4	8.2551×10^4	1.010	0.9515	0.8193 ($\sim 0.9515^4$)
3000	4.803×10^4	4.7554×10^4	1.010	0.8871	0.6193 ($\sim 0.8871^4$)
4000	2.251×10^4	2.2156×10^4	1.012	0.7882	0.3861 ($\sim 0.7882^4$)
5000	6362	6331	1.005	0.639	0.1667($\sim 0.639^4$)
6000	370	365.5	1.012	0.3846	0.0219($\sim 0.3846^4$)

Feynman Diagrams for Spin 1

- $\mathcal{L}^{S=1} = -\frac{1}{2}\left(\frac{\partial \mathcal{A}_\mu}{\partial x_\nu}\right)\left(\frac{\partial \mathcal{A}_\nu}{\partial x_\mu}\right) - \frac{1}{2}\mathcal{G}^\dagger_{\mu\nu}\mathcal{G}_{\mu\nu} - M^2 W^\dagger_\mu W^\mu - ig(\beta)\kappa F_{\mu\nu} W^\dagger_\mu W_\nu$



Cross-section for $\gamma\gamma \rightarrow mm^+mm^-$, β-independent coupling, spin 1 monopole, charge 1 g_D

Mass (GeV)	σ (pb) $\gamma\gamma \rightarrow mm^+mm^-$ (UFO model)	σ (pb) $\gamma\gamma \rightarrow mm^+mm^-$ (Theory values)	Ratio UFO model/Theory
1000	1.131×10^7	1.131×10^7	1.000
2000	2.765×10^6	2.747×10^6	1.007
3000	1.164×10^6	1.151×10^6	1.011
4000	5.879×10^5	5.835×10^5	1.008
5000	3.161×10^5	3.109×10^5	1.017
6000	1.39×10^5	1.378×10^5	1.009

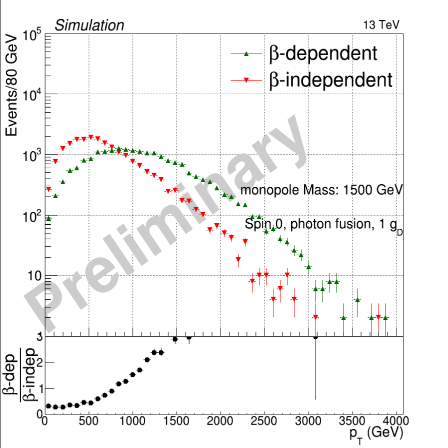
Cross-section for $\gamma\gamma \to mm^+ mm^-$, β-dependent coupling, spin 1 monopole, charge 1 g_D

- No PDF used in MadGraph to compare with the theoretical value.

Mass (GeV)	σ (pb) $\gamma\gamma \to mm^+ mm^-$ (UFO model)	σ (pb) $\gamma\gamma \to mm^+ mm^-$ (Theory values)	Ratio UFO model/Theory	β	Ratio β-dep/β-ind (UFO model)
1000	1.078×10^7	1.0781×10^7	0.999	0.9881	0.9531 ($\sim 0.9881^4$)
2000	2.277×10^6	2.2520×10^6	1.011	0.9515	0.8235 ($\sim 0.9515^4$)
3000	7.214×10^5	7.1290×10^5	1.012	0.8871	0.6198 ($\sim 0.8871^4$)
4000	2.275×10^5	2.2523×10^5	1.010	0.7882	0.3870 ($\sim 0.7882^4$)
5000	5.256×10^4	5.1833×10^4	1.014	0.639	0.1663($\sim 0.639^4$)
6000	3.034×10^3	3.014×10^3	1.007	0.3846	0.0218($\sim 0.3846^4$)

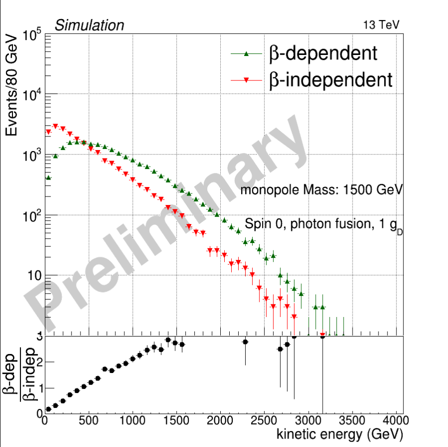
- Kinematic distribution plots: Comparison between β-dependent and independent couplings.
- For photon fusion process, LUXqed is used as PDF.

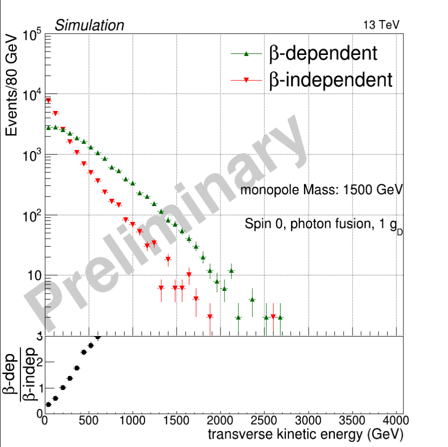
Spin 0 monopoles, charge 1 g_D, monopole mass 1500 GeV



- p_T of β-dependent coupling case is right shifted.

Spin 0 monopoles, charge 1 g_D, monopole mass 1500 GeV





- kinetic energy of β-dependent coupling case is right shifted.
- transverse kinetic energy of β-dependent coupling case is right shifted.

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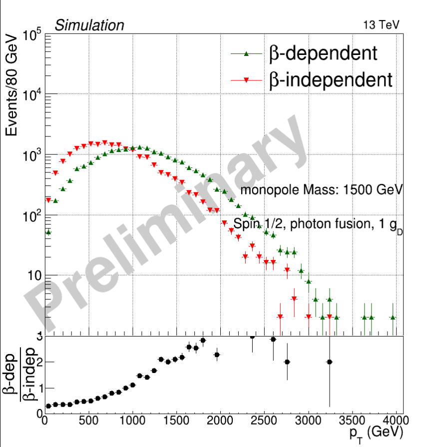
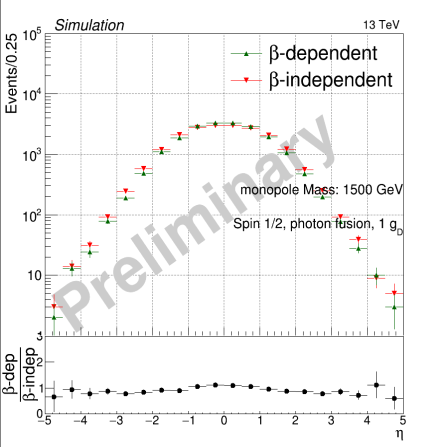
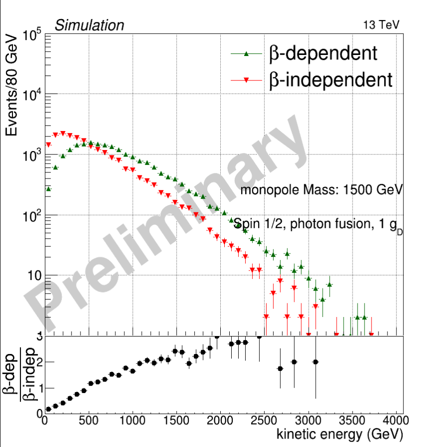
Spin 1/2 monopoles, charge 1 g_D, monopole mass 1500 GeV

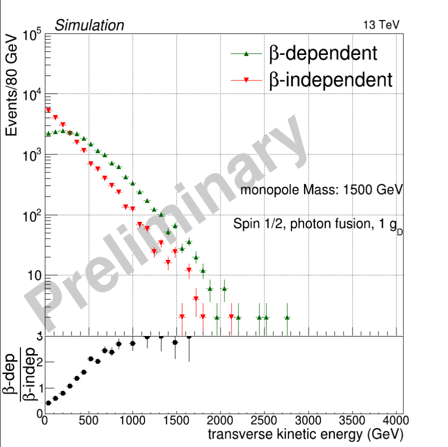




- p_T of β-dependent coupling case is right shifted.
- η of β-dependent coupling case is more or less the same with the β-independent case.

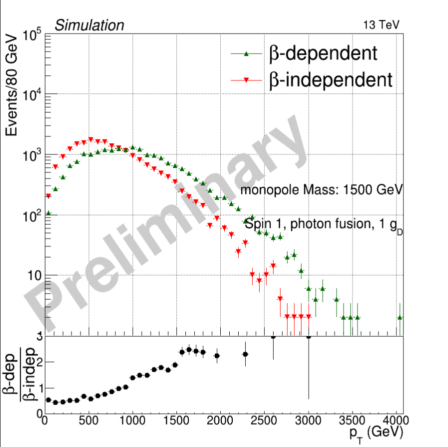
Spin 1/2 monopoles, charge 1 g_D, monopole mass 1500 GeV

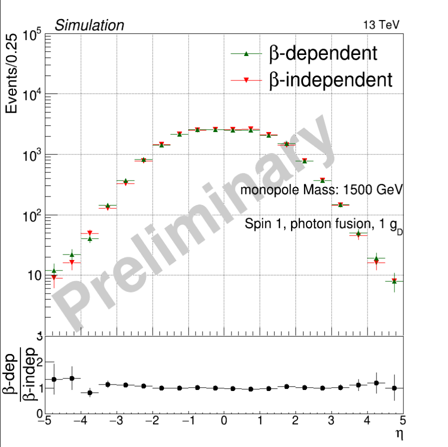




- kinetic energy of β-dependent coupling case is right shifted.
- transverse kinetic energy of β-dependent coupling case is right shifted.

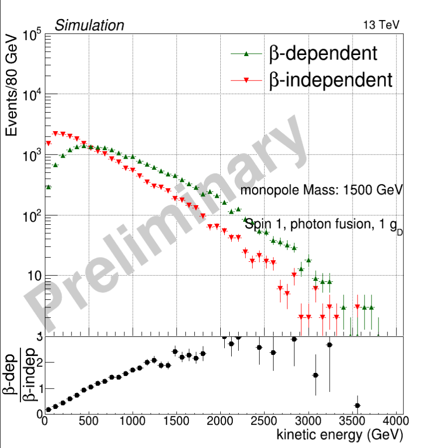
Spin 1 monopoles, charge 1 g_D, monopole mass 1500 GeV

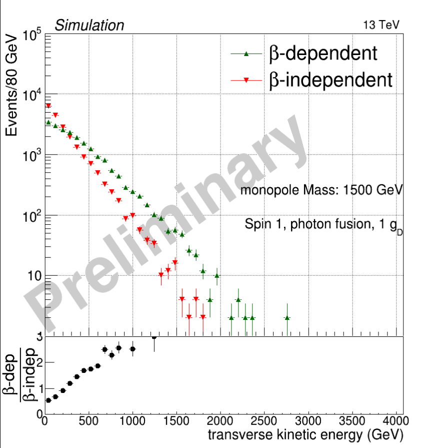




- p_T of β-dependent coupling case is right shifted.
- η of β-dependent coupling case is the same with the β-independent case.

Spin 1 monopoles, charge 1 g_D, monopole mass 1500 GeV

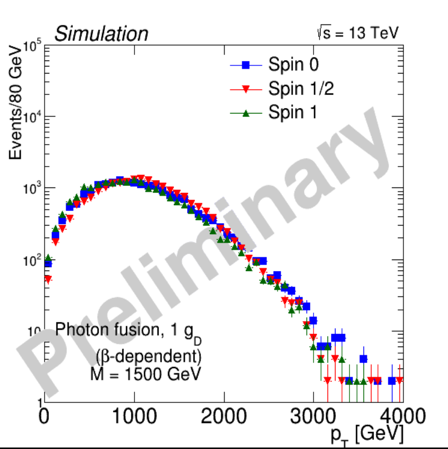


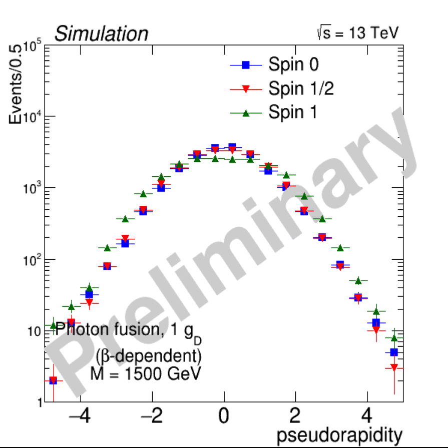


- kinetic energy of β-dependent coupling case is right shifted.
- transverse kinetic energy of β-dependent coupling case is right shifted.

- Kinematic distribution comparison among three spins.
- β-dependent coupling for photon fusion, with LUXqed PDF.

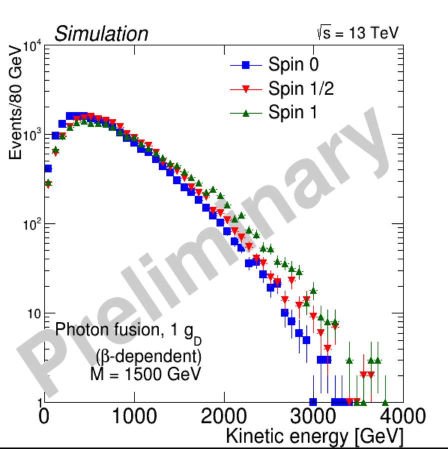
All spins, charge 1 g_D, β-dependent coupling, monopole mass 1500 GeV

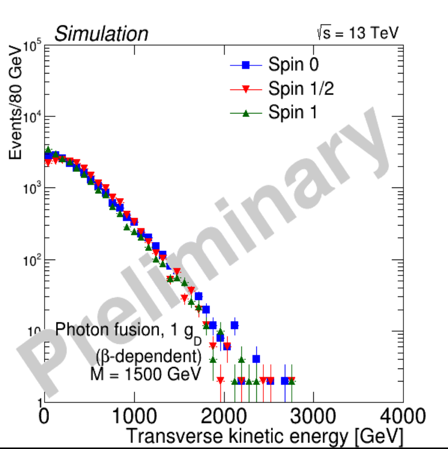




- p_T of spin 1/2 case is slightly right shifted.
- η of spin 1 case is slighly low at $\eta = 0$.

All spins, charge 1 g_D, β-dependent coupling, monopole mass 1500 GeV

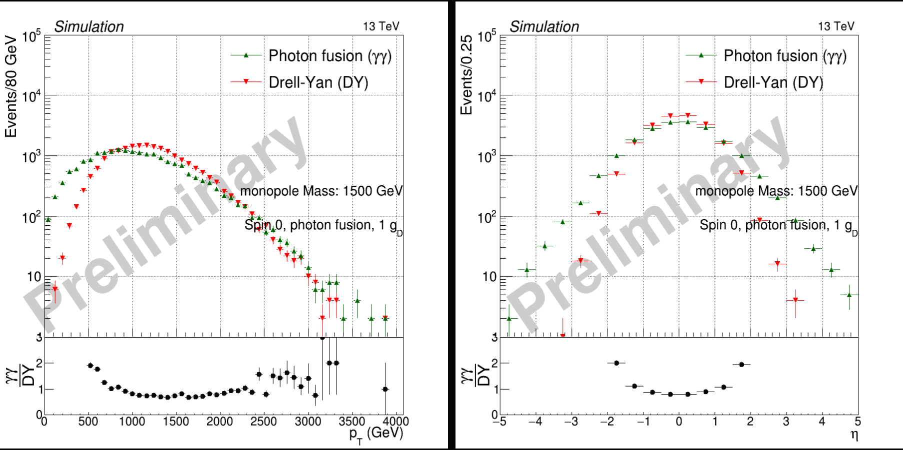




- kinetic energy of spin 1 case is right shifted.
- transverse kinetic energy of all spins are same.

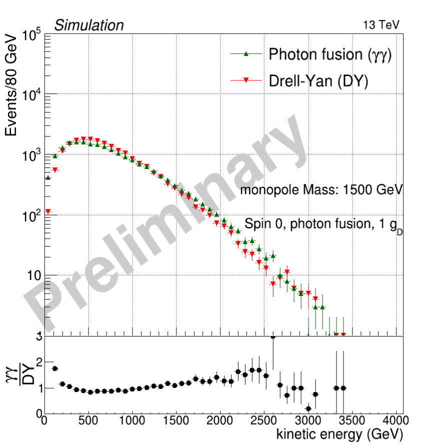
- Kinematic distribution plots: Comparison between photon fusion and DY production mechanism, β-dependent coupling.
- For photon fusion, LUXqed is used as the PDF.
- For DY, NNLOPDF23 is used as the PDF.

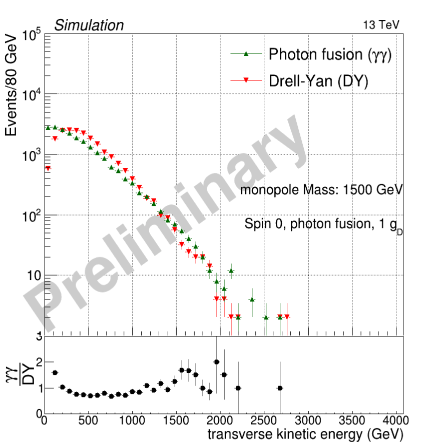
Spin 0 monopoles, charge 1 g_D, monopole mass 1500 GeV



- For spin 0 monopoles, DY p_T distribution is slightly higher than the photon fusion.
- η distributions are different.

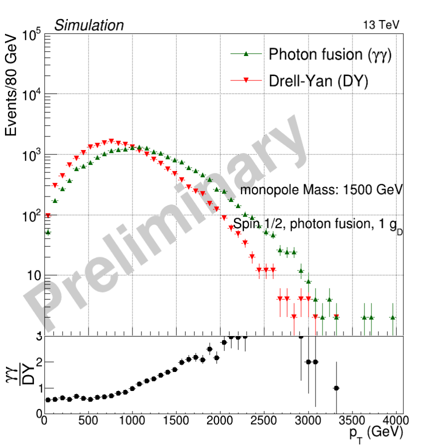
Spin 0 monopoles, charge 1 g_D, monopole mass 1500 GeV

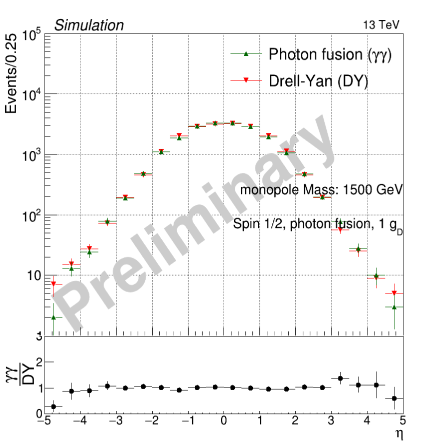




- kinetic energy distribution of DY process is slightly higher than photon fusion.
- transverse kinetic energy distribution of DY process is slightly higher than photon fusion.

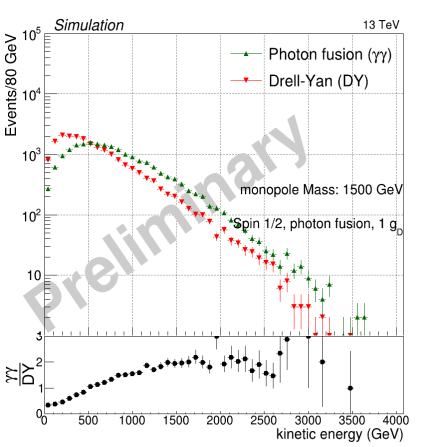
Spin 1/2 monopoles, charge 1 g_D, monopole mass 1500 GeV

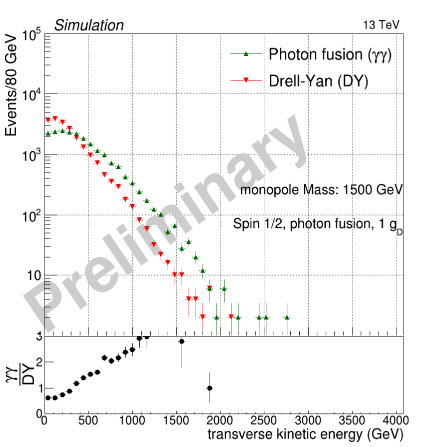




- For spin 1/2 monopoles, DY p_T distribution is lower than the photon fusion.
- η of photon fusion case is more or less the same with the DY case.

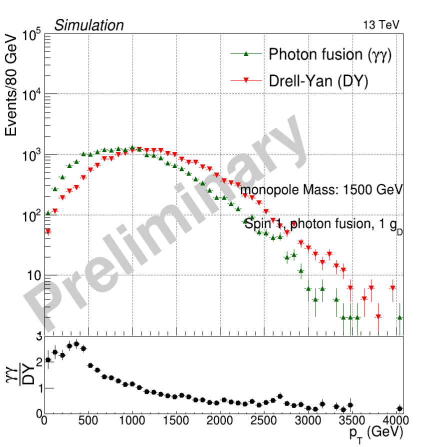
Spin 1/2 monopoles, charge 1 g_D, monopole mass 1500 GeV

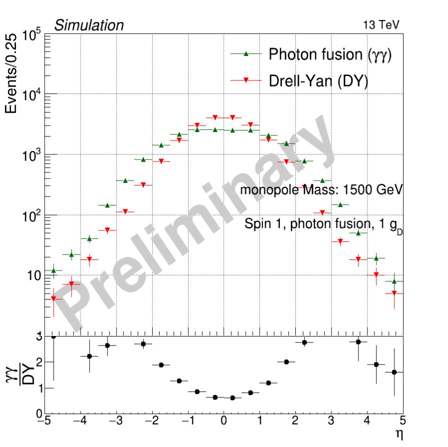




- kinetic energy of photon fusion process is right shifted.
- transverse kinetic energy of photon fusion process is right shifted.

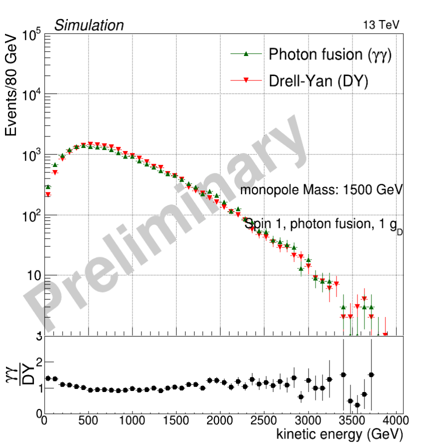
Spin 1 monopoles, charge 1 g_D, monopole mass 1500 GeV

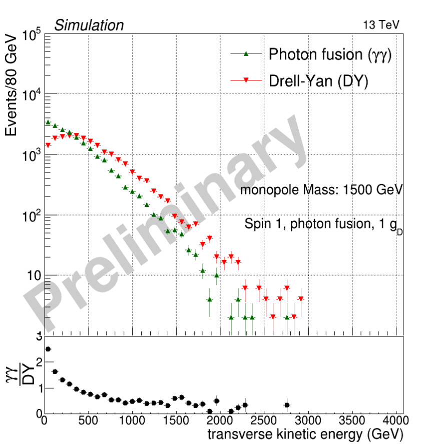




- For spin 1 monopoles, DY p_T distribution is higher than the photon fusion.
- η of photon fusion is different than DY.

Spin 1 monopoles, charge 1 g_D, monopole mass 1500 GeV





- kinetic energy of DY is slightly right shifted.
- Transverse kinetic energy of DY is right shifted.

- Playing with the parameter magnetic moment (κ) for spin 1/2 and 1 monopoles

Cross-section of spin 1/2 monopoles with different magnetic moments, $\gamma\gamma \to mm^+mm^-$:

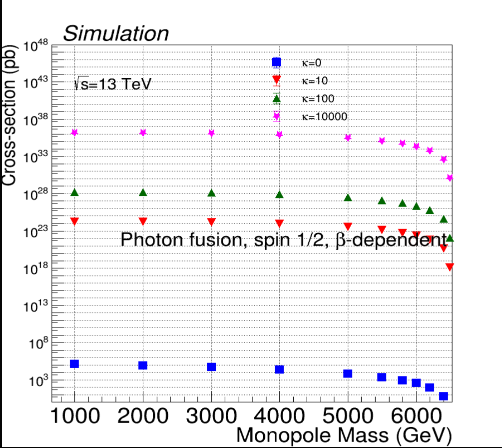
- The Lagrangian with κ:

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \bar{\psi}(i\not{D} - m)\psi - i\frac{1}{4}g(\beta)\,\kappa\,F_{\mu\nu}\bar{\psi}[\gamma^{\mu},\gamma^{\nu}]\psi$$

- β-dependent coupling
- No PDF was used.

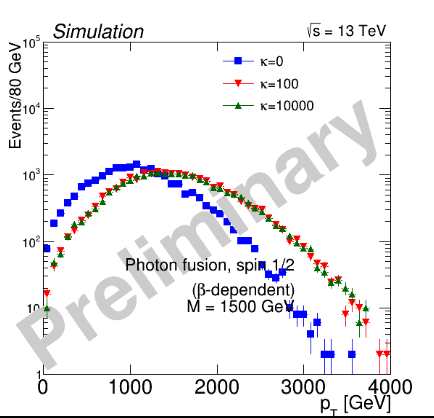
Mass (GeV)	β	σ (pb) $\gamma\gamma \to mm^+mm^-$ $\kappa = 0$	σ (pb) $\gamma\gamma \to mm^+mm^-$ $\kappa = 10$	σ (pb) $\gamma\gamma \to mm^+mm^-$ $\kappa = 100$	σ (pb) $\gamma\gamma \to mm^+mm^-$ $\kappa = 10000$
1000	0.9881	$1.37 \times 10^{+05} \pm 4.6 \times 10^{+02}$	$1.639 \times 10^{+24} \pm 3.3 \times 10^{+21}$	$1.639 \times 10^{+28} \pm 3.3 \times 10^{+25}$	$1.639 \times 10^{+36} \pm 3.3 \times 10^{+33}$
2000	0.9515	$8.303 \times 10^{+04} \pm 4.5 \times 10^{+02}$	$1.61 \times 10^{+24} \pm 3.1 \times 10^{+21}$	$1.61 \times 10^{+28} \pm 3.1 \times 10^{+25}$	$1.61 \times 10^{+36} \pm 3.1 \times 10^{+33}$
3000	0.8871	$4.78 \times 10^{+04} \pm 3.5 \times 10^{+02}$	$1.356 \times 10^{+24} \pm 2.5 \times 10^{+21}$	$1.356 \times 10^{+28} \pm 2.5 \times 10^{+25}$	$1.356 \times 10^{+36} \pm 2.5 \times 10^{+33}$
4000	0.7882	$2.237 \times 10^{+04} \pm 1.9 \times 10^{+02}$	$8.612 \times 10^{+23} \pm 2.1 \times 10^{+21}$	$8.613 \times 10^{+27} \pm 2.1 \times 10^{+25}$	$8.613 \times 10^{+35} \pm 2.1 \times 10^{+33}$
5000	0.639	6396 ± 61	$3.154 \times 10^{+23} \pm 1.1 \times 10^{+21}$	$3.154 \times 10^{+27} \pm 1.1 \times 10^{+25}$	$3.154 \times 10^{+35} \pm 1.1 \times 10^{+33}$
5500	0.5329	2256 ± 22	$1.247 \times 10^{+23} \pm 4.5 \times 10^{+20}$	$1.247 \times 10^{+27} \pm 4.5 \times 10^{+24}$	$1.247 \times 10^{+35} \pm 4.5 \times 10^{+32}$
5800	0.4514	886.5 ± 7.8	$5.28 \times 10^{+22} \pm 2.5 \times 10^{+20}$	$5.28 \times 10^{+26} \pm 2.5 \times 10^{+24}$	$5.28 \times 10^{+34} \pm 2.5 \times 10^{+32}$
6000	0.3846	367.2 ± 3	$2.294 \times 10^{+22} \pm 7.6 \times 10^{+19}$	$2.294 \times 10^{+26} \pm 7.6 \times 10^{+23}$	$2.294 \times 10^{+34} \pm 7.6 \times 10^{+31}$
6200	0.3003	97.19 ± 0.77	$6.43 \times 10^{+21} \pm 3.3 \times 10^{+19}$	$6.43 \times 10^{+25} \pm 3.3 \times 10^{+23}$	$6.43 \times 10^{+33} \pm 3.3 \times 10^{+31}$
6400	0.1747	5.846 ± 0.025	$4.065 \times 10^{+20} \pm 1.5 \times 10^{+18}$	$4.065 \times 10^{+24} \pm 1.5 \times 10^{+22}$	$4.065 \times 10^{+32} \pm 1.5 \times 10^{+30}$
6490	0.0554	$0.017 \pm 2.27 \times 10^{-5}$	$1.27 \times 10^{18} \pm 8.74 \times 10^{14}$	$1.27 \times 10^{22} \pm 8.74 \times 10^{18}$	$1.27 \times 10^{30} \pm 8.74 \times 10^{26}$

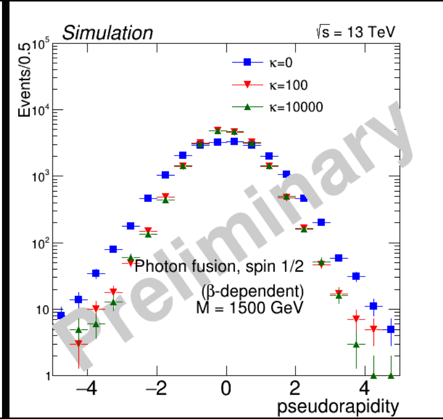
Cross-section of spin 1/2 monopoles with different magnetic moments, $\gamma\gamma \to mm^{+}mm^{-}$:



- The higher the κ value, the slower the cross-section goes to zero at $\beta \to 0$ (M$\to \sqrt{s}/2$).

Kinematic distribution plots of spin 1/2 monopoles with different magnetic moments, $\gamma\gamma \to mm^+ mm^-$, LUXqed PDF





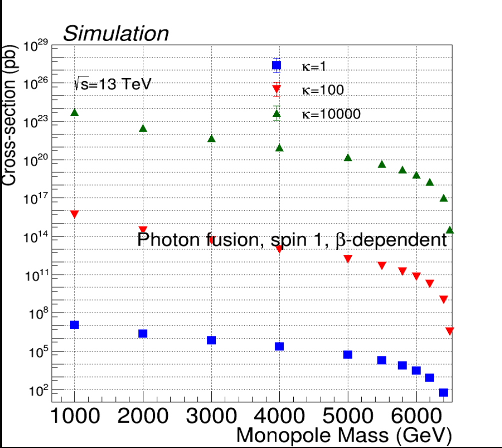
- The p_T distributions of non-zero κ are very different from the distribution of $\kappa = 0$.
- The η distributions of non-zero κ are very different from the distribution of $\kappa = 0$.

Cross-section of spin 1 monopoles with different magnetic moments, $\gamma\gamma \to mm^+mm^-$:

- β-dependent coupling
- No PDF was used.

Mass (GeV)	β	σ (pb) $\gamma\gamma \to mm^+mm^-$ $\kappa = 1$	σ (pb) $\gamma\gamma \to mm^+mm^-$ $\kappa = 100$	σ (pb) $\gamma\gamma \to mm^+mm^-$ $\kappa = 10000$
1000	0.9881	$1.086 \times 10^{+07} \pm 1.4 \times 10^{+05}$	$4.939 \times 10^{+15} \pm 1 \times 10^{+13}$	$5.033 \times 10^{+23} \pm 2.1 \times 10^{+21}$
2000	0.9515	$2.275 \times 10^{+06} \pm 1.6 \times 10^{+04}$	$2.844 \times 10^{+14} \pm 4.9 \times 10^{+11}$	$2.879 \times 10^{+22} \pm 9.8 \times 10^{+19}$
3000	0.8871	$7.198 \times 10^{+05} \pm 6.6 \times 10^{+03}$	$4.518 \times 10^{+13} \pm 1.5 \times 10^{+11}$	$4.536 \times 10^{+21} \pm 1.2 \times 10^{+19}$
4000	0.7882	$2.273 \times 10^{+05} \pm 2.2 \times 10^{+03}$	$9.079 \times 10^{+12} \pm 2.7 \times 10^{+10}$	$9.002 \times 10^{+20} \pm 3.2 \times 10^{+18}$
5000	0.639	$5.232 \times 10^{+04} \pm 4.9 \times 10^{+02}$	$1.513 \times 10^{+12} \pm 9.2 \times 10^{+09}$	$1.5 \times 10^{+20} \pm 9.3 \times 10^{+17}$
5500	0.5329	$1.785 \times 10^{+04} \pm 1.6 \times 10^{+02}$	$4.49 \times 10^{+11} \pm 1.7 \times 10^{+09}$	$4.466 \times 10^{+19} \pm 2.9 \times 10^{+17}$
5800	0.4514	7118 ± 62	$1.658 \times 10^{+11} \pm 1.1 \times 10^{+09}$	$1.624 \times 10^{+19} \pm 8.4 \times 10^{+16}$
6000	0.3846	3025 ± 24	$6.72 \times 10^{+10} \pm 2.5 \times 10^{+08}$	$6.627 \times 10^{+18} \pm 3.7 \times 10^{+16}$
6200	0.3003	836.9 ± 6.3	$1.764 \times 10^{+10} \pm 1 \times 10^{+08}$	$1.733 \times 10^{+18} \pm 1 \times 10^{+16}$
6400	0.1747	53.42 ± 0.23	$1.066 \times 10^{+09} \pm 3.9 \times 10^{+06}$	$1.05 \times 10^{+17} \pm 3.8 \times 10^{+14}$
6490	0.0554	0.1694 ± 0.00065	$3.293 \times 10^{+06} \pm 5.6 \times 10^{+03}$	$3.244 \times 10^{+14} \pm 5.6 \times 10^{11}$

Cross-section of spin 1 monopoles with different magnetic moments, $\gamma\gamma \rightarrow mm^{+}mm^{-}$:



- The higher the κ value, the slower the cross-section goes to zero at $\beta \rightarrow 0$ (M$\rightarrow \sqrt{s}/2$).

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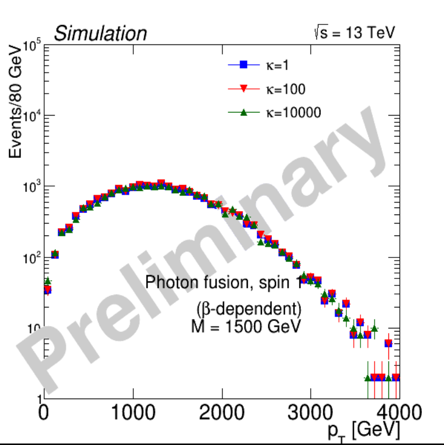
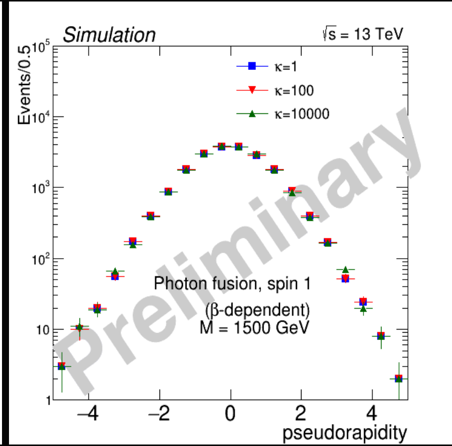
Kinematic distribution plots of spin 1 monopoles with different magnetic moments, $\gamma\gamma \to mm^+ mm^-$, LUXqed PDF





- No difference in the p_T distributions.
- No difference in the pseudo-rapidity (η) distributions.

Summary:

The UFO model:

- The UFO models for spin 0, 1/2 and 1 are behaving well.
- The cross-sections from MadGraph for photon fusion process are almost the same with the theoretical predictions (DY values in the backup).
- The β-dependent cross-sections are $\sim \beta^4$ times the β-independent cross-section, as expected. So the β-dependence has also been modeled perfectly.
- The kinematic distributions also look okay.

A new parameter κ for spin 1/2 and 1

- Modeled in the MadGraph for the first time!
- Checked the cross-sections with different κ values.
- Cross-section for the high κ goes to 0 slowly at $\hat{s} \to 4M^2$ (or $\beta \to 0$).
- The kinematic distribution plots are not very different among non-zero κ.
- How does κ affect the energy loss of monopoles? κ may also affect the stopping power.

- Back up

$pp \to mm^+mm^-$ Spin 0: No PDF, β-dependent

Mass (GeV)	σ (pb) $pp \to mm^+mm^-$ (Fortran model)	σ (pb) $pp \to mm^+mm^-$ (UFO model)	Ratio Fortran/UFO	Theory (first 2 generations of quark)	Ratio Theory/UFO
1000	0.4212	0.4223	0.997	0.4184	0.991
2000	0.3485	0.3484	1.000	0.3465	0.995
3000	0.2448	0.2463	0.994	0.2441	0.991
4000	0.1375	0.1361	1.010	0.1352	0.993
5000	0.04812	0.04724	1.019	0.0473	1.001
6000	0.003809	0.003745	1.017	0.00373	0.996

- Fortran and UFO model cross-sections match very well.
- They also match with the theoretical predictions.

$pp \to mm^{+}mm^{-}$ Spin 1/2: No PDF, β-dependent

Mass (GeV)	σ (pb) $pp \to mm^{+}mm^{-}$ (Fortran model)	σ (pb) $pp \to mm^{+}mm^{-}$ (UFO model)	Ratio Fortran/UFO	Theory (first 2 generations of quark)	Ratio Theory/UFO
1000	1.747	1.747	1.000	1.735	0.993
2000	1.629	1.614	1.009	1.603	0.993
3000	1.377	1.373	1.003	1.373	1.000
4000	1.054	1.039	1.014	1.0352	0.996
5000	0.6082	0.6029	1.009	0.601	0.997
6000	0.1465	0.1454	1.008	0.1442	0.992

- Fortran and UFO model cross-sections match very well.
- They also match with the theoretical predictions.

$pp \to mm^+mm^-$ Spin 1: No PDF, β-dependent

Mass (GeV)	σ (pb) $pp \to mm^+mm^-$ (Fortran model)	σ (pb) $pp \to mm^+mm^-$ (UFO model)	Ratio Fortran/UFO	Theory (first 2 generations of quark)	Ratio Theory/UFO
1000	3367	3362	1.001	3343.05	0.994
2000	231.2	230.6	1.003	228.872	0.993
3000	45.31	45.43	0.997	45.173	0.994
4000	11.52	11.38	1.012	11.3162	0.994
5000	2.326	2.299	1.012	2.282	0.993
6000	0.1209	0.1206	1.002	0.1196	0.992

- Fortran and UFO model cross-sections match very well.
- They also match with the theoretical predictions.

$pp \to mm^{+}mm^{-}$ calculations (β independent):

Mass (GeV)	β	Spin 0 σ (pb) Theory (first 2 generations of quark)	Spin 1/2 σ (pb) Theory (first 2 generations of quark)	Spin 1 σ (pb) Theory (first 2 generations of quark)
1000.0	0.9881	0.4287	1.777	3424.091
2000.0	0.9515	0.3827	1.771	252.8063
3000.0	0.8871	0.3042	1.7446	57.3999
4000.0	0.7882	0.2176	1.6661	18.2137
5000.0	0.639	0.1159	1.4716	5.590
6000.0	0.3846	0.0253	0.9748	0.8085

Mass (GeV)	β	Spin 0 σ (pb) MadGraph(first 2 generations of quark) (no PDF)	Spin 1/2 σ (pb) MadGraph(first 2 generations of quark) (no PDF)	Spin 1 σ (pb) MadGraph(first 2 generations of quark) (no PDF)
1000.0	0.9881	0.4324	1.787	3454
2000.0	0.9515	0.3851	1.781	254.4
3000.0	0.8871	0.312	1.756	57.7
4000.0	0.7882	0.2186	1.673	18.25
5000.0	0.639	0.1158	1.482	5.588
6000.0	0.3846	0.0254	0.9838	0.8142

Rusakovich's calculations:

$$\sigma_{\gamma\gamma}^{s=0}(\hat{s}) = \frac{4\pi\alpha_g^2}{\hat{s}}\beta\left[2-\beta^2-\frac{1-\beta^4}{2\beta}\ln\left(\frac{1+\beta}{1-\beta}\right)\right] \quad (1)$$

$$\sigma_{\gamma\gamma}^{s=1/2}(\hat{s}) = \frac{4\pi\alpha_g^2}{\hat{s}}\beta\left[-2+\beta^2+\frac{3-\beta^4}{2\beta}\ln\left(\frac{1+\beta}{1-\beta}\right)\right] \quad (2)$$

$$\sigma_{\gamma\gamma}^{s=1}(\hat{s}) = \frac{\pi\alpha_g^2}{\hat{s}}\beta\left[2\frac{22-9\beta^2+3\beta^4}{1-\beta^2}-3\frac{1-\beta^4}{\beta}\ln\left(\frac{1+\beta}{1-\beta}\right)\right] \quad (3)$$

where

$$\alpha_g = g^2\beta^2,\ \beta = \sqrt{1-4M^2/\hat{s}},\ \hat{s} = z_1 z_2 s \quad (4)$$

.

1. $g = \sqrt{137/4} = 5.85$
2. $\alpha_g = 34.25$
3. form factor $= 1.0$
4. $z_1 = z_2 = 1$
5. $\sqrt{s} = 13$ TeV
6. 1 pb $= 2.5819 \times 10^{-9}$ GeV^{-2}
7. $\hat{s} = 13 \times 13$ TeV^2

Conditions for MadGraph

- Spin 0, Spin 1/2 and Spin 1, Kinematic distributions.
- Photon fusion, elastic.
- β-dependent coupling
- total kinetic energy, E_{kin} = total energy, E − mass, M
- transverse kinetic energy, $E_{kint} = \sqrt{p_T^2 + M^2} - M$.
- longitudinal kinetic energy, $E_{kinl} = E_{kin} - E_{kint}$

Argument against β-dependent coupling:

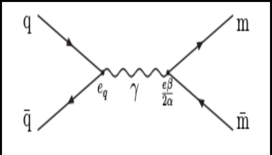
ATLAS 'shrugged':

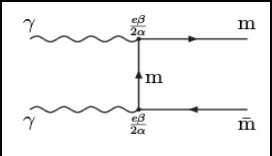
- ATLAS has moved from β-dependent coupling (7 TeV, arXiv:1207.6411) to β-independent coupling (8 TeV, arXiv:1509.08059) following an argument by Roman Koniuk (York).

- Milton (arXiv:hep-ex/0602040) derived the electron-monopole scattering cross-section for small scattering angle : $\frac{d\sigma}{d\Omega} = \frac{1}{(2\mu v_0)^2}\left[\left(\frac{eg}{c}\right)^2\right]\frac{1}{(\theta/2)^4}$ where g is the magnetic charge of the monopole.
- Rutherford scattering formula: $\frac{d\sigma}{d\Omega} = \frac{1}{(2\mu v_0)^2}\left[\left(\frac{e_1 e_2}{v_0}\right)^2\right]\frac{1}{(\theta/2)^4}$ can be obtained from Milton's calculation if $\frac{e_2}{v_0} \to \frac{g}{c}$ or $e_2 \to \frac{g v_0}{c} = g\beta$.
- This leads to $\alpha = \frac{e^2}{\hbar c} \to \alpha_m = \frac{(g\beta)^2}{\hbar c}$.
- The Lorentz Force law: $\vec{F} = e\vec{E} + e\beta\vec{c} \times \vec{B}$; even though the interaction with the magnetic field depends on β, the QED coupling depends only on e: $\alpha = \frac{e^2}{\hbar c}$.
- Force on the monopole: $\vec{F} = g\vec{B} - g\beta\vec{c} \times \vec{E}$.
- This does not necessarily imply that the photon-monopole coupling should be β-dependent.

Symmetry argument between electricity and magnetism:

- There is no velocity dependent coupling for photon-electron, will there be any for photon-monopole?





- The ratio of couplings in photon fusion and DY process in the monopole production is given by: $r_m = \frac{e_q^4(\frac{e\beta}{2\alpha})^4}{e_q^2(\frac{e\beta}{2\alpha})^2}$ (S.D. Eur. Phys. J. A (2009) **39**: 213).
- The ratio of couplings in photon fusion and DY process in the lepton production is given by: $r_l = \frac{e_q^4 e^4}{e_q^2 e^2} = \bar{\eta}^2\alpha^2$. Here $\bar{\eta}$ is the average fractional quark charge contributing to the cross-section.
- Change in the $\gamma\gamma$/DY cross-section ratio expected for monopole versus lepton production is given by: $R = \frac{r_m}{r_l} = \frac{\beta^2/4}{\alpha^2} \sim 4700$ when $\beta \sim 1$.
- Dress et al found that $r_l \sim 0.01$, hence $r_m \sim 47$ when $\beta \sim 1$.

Details of Milton's calculations:

- Milton derived the electron-monopole scattering cross-section for small scattering angle: $\frac{d\sigma}{d\Omega} = \frac{1}{(2\mu v_0)^2}\left[\left(\frac{e_1 g_2 - e_2 g_1}{c}\right)^2 + \left(\frac{e_1 e_2 - g_2 g_1}{v_0}\right)^2\right]\frac{1}{(\theta/2)^4}$, where e_i and g_i are the electric and magnetic charge for dyon i.
- For electron and monopole $e_1 = e$, $g_1 = 0$, $e_2 = 0$, $g_2 = 1$.
- Hence $\frac{d\sigma}{d\Omega} = \frac{1}{(2\mu v_0)^2}\left[\left(\frac{eg}{c}\right)^2\right]\frac{1}{(\theta/2)^4}$
- Rutherford scattering formula: $\frac{d\sigma}{d\Omega} = \frac{1}{(2\mu v_0)^2}\left[\left(\frac{e_1 e_2}{v_0}\right)^2\right]\frac{1}{(\theta/2)^4}$ can be obtained from Milton's calculation if $\frac{e_2}{v_0} \to \frac{g}{c}$ or $e_2 \to \frac{g v_0}{c}$.
- This leads to $\alpha = \frac{e^2}{\hbar c} \to \alpha_m = \frac{(g\beta)^2}{\hbar c}$

Details of the argument against β-dependent coupling:

- The Bethe-Bloch formula of energy loss: $-\frac{dE}{dx} = K\frac{Z}{A}\frac{z^2}{\beta^2}\left[\ln\frac{2m_e c^2\beta^2\gamma^2}{I} - \beta^2 - \delta/2\right]$.
- If we replace z by $g\beta$, then (Ahlen, Phys.Rev. D14 (1976) 2935-2940):
  $-\frac{dE}{dx} = K\frac{Z}{A}g^2\left[\ln\frac{2m_e c^2\beta^2\gamma^2}{I} + \frac{k(|g|)}{2} - \frac{1}{2} - \delta/2 - B(|n|)\right]$.
- The β factor appears in the electron-monopole scattering formula because of the Lorentz force interaction of monopoles with the electric field.
- It also appears in the formula of $-\frac{dE}{dx}$, but it is not justified for the photon-monopole coupling.