IFIC INSTITUT DE FÍSICA CORPUSCULAR

CSIC CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS

VNIVERSITAT DE VALÈNCIA

MINISTERIO DE CIENCIA E INNOVACIÓN

GENERALITAT VALENCIANA

UNIÓN EUROPEA Fondo Europeo de Desarrollo Regional

Revisiting experimental mass limits on HECOs using Dyson-Schwinger resummation

Emanuela Musumeci (IFIC, Valencia)

in collaboration with

J.Alexandre , N.E. Mavromatos, V. A. Mitsou

Based on Phys. Rev. D 109, 036026

PoS LHCP2023 (2024) 261

ICHEP 2024 PRAGUE

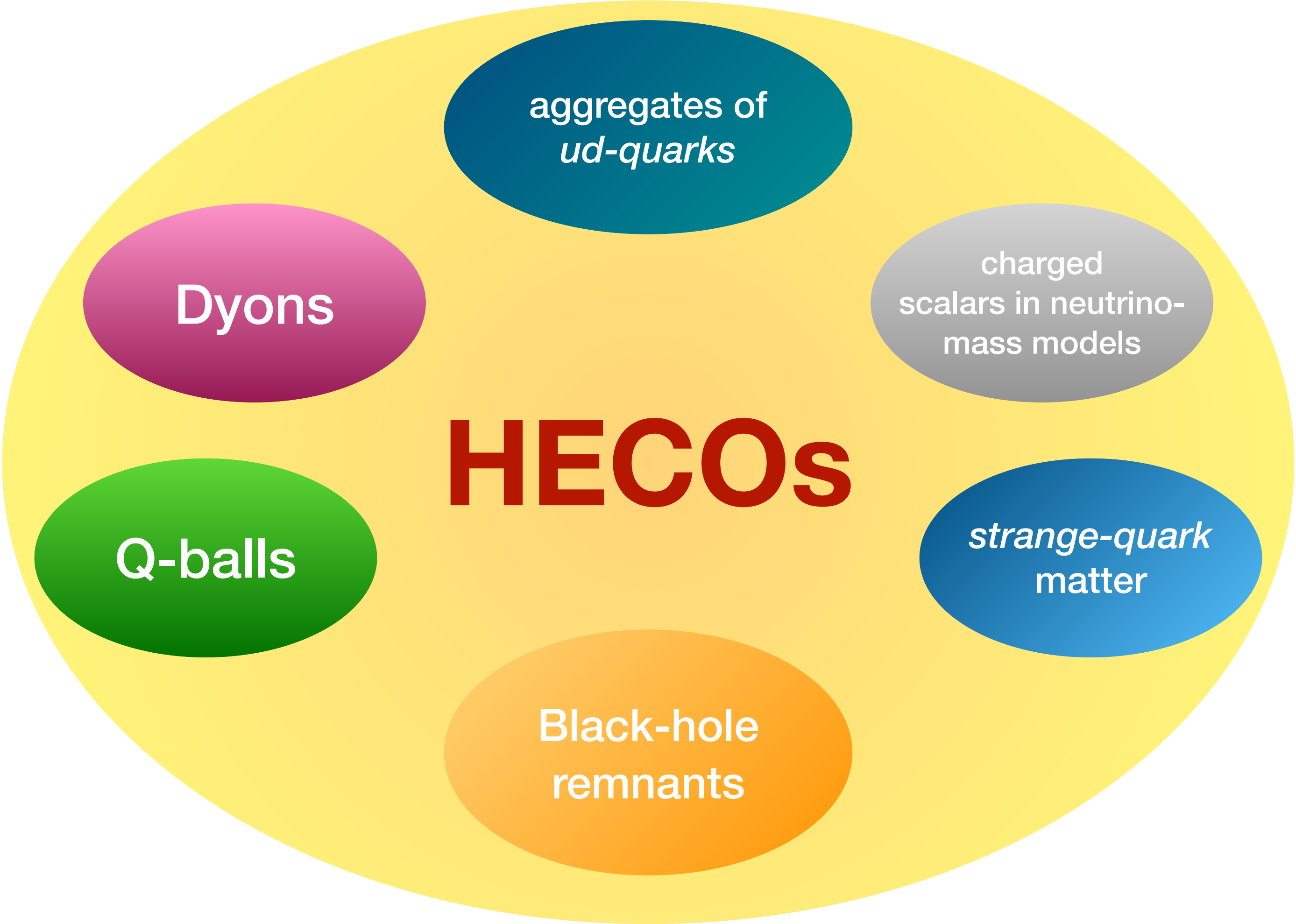
42nd International Conference on High Energy Physics

18-24 July 2024 Prague Czech Republic

19 July 2024

High **E**lectric **C**harge **O**bjects

Predicted by various theories Beyond the Standard Model

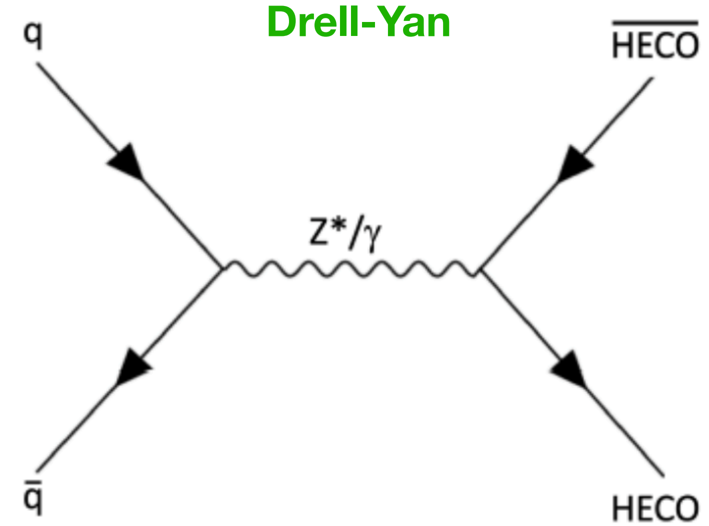


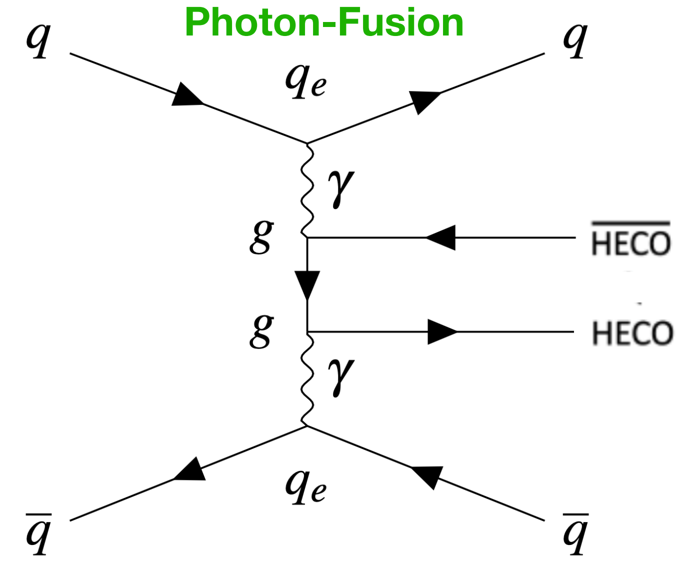
- **Q=** $ne, \; n \in \mathbb{Z}$
- High Ionisation
- Mass and Spin *free parameters*

High Electric Charge Objects

SPIN 1/2

Production mechanisms at colliders





High Electric Charge Objects

SPIN 1/2

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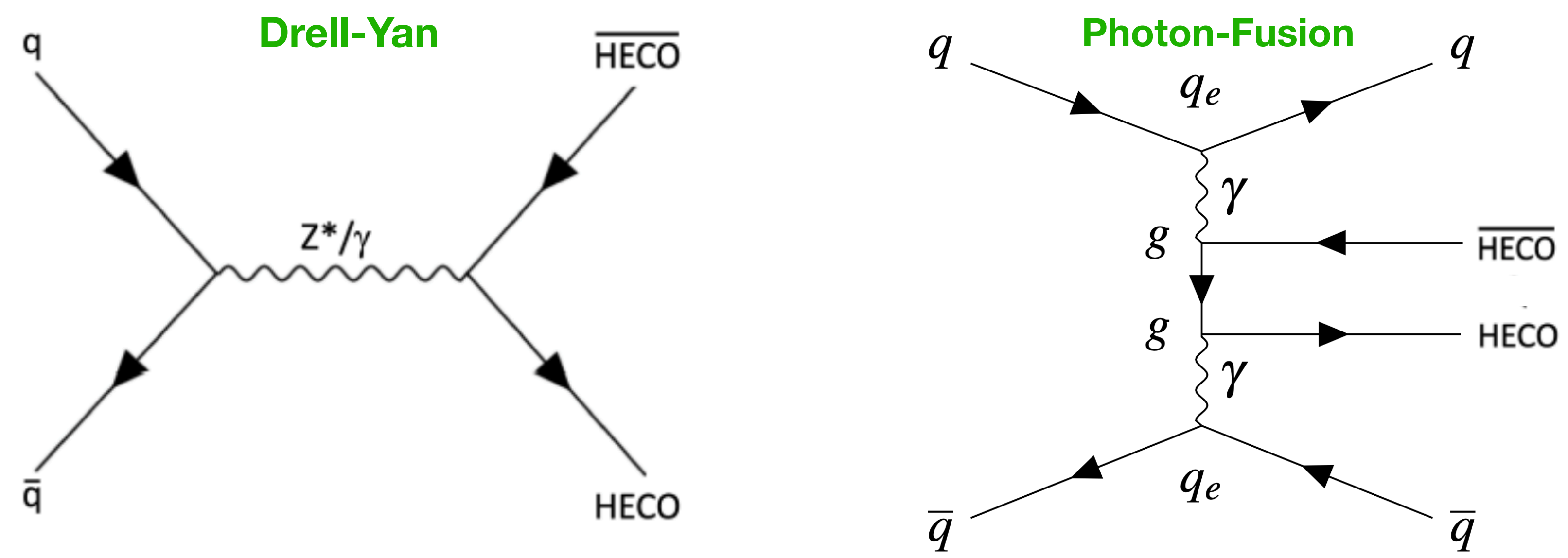


Recent searches at the LHC

ATLAS

PRL 124, (2020) 3, 031802
JHEP 11 (2023) 112

MoEDAL

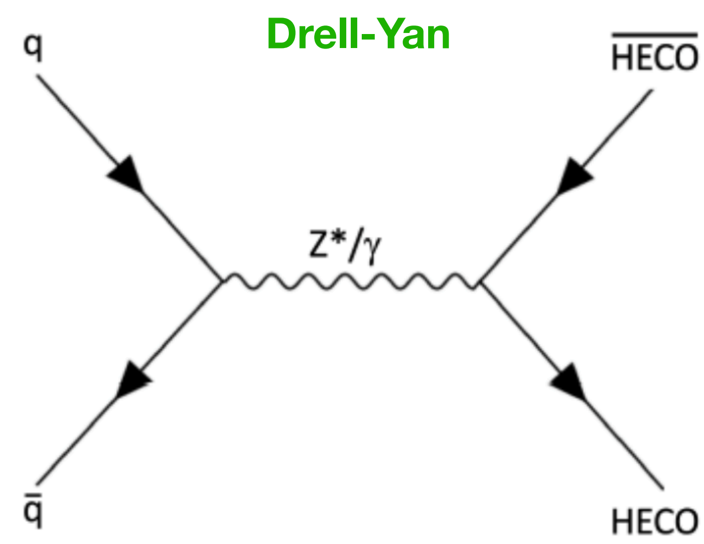
EPJ C**82**,694 (2022)
2311.06509

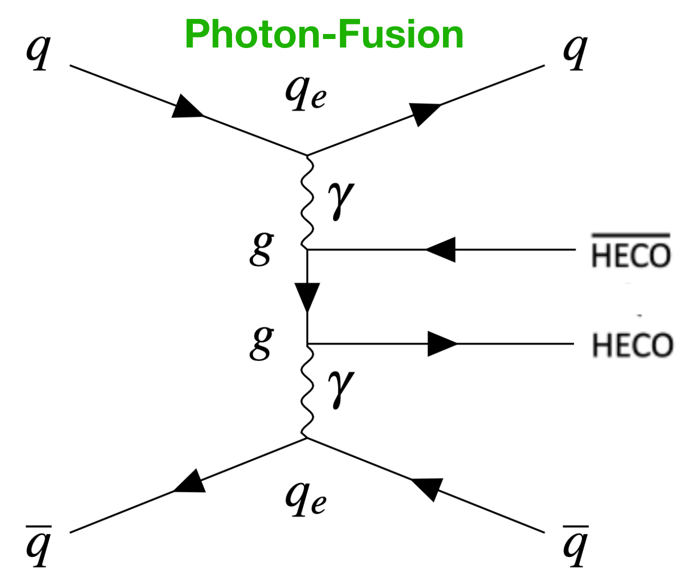
See A.Upreti's talk

High Electric Charge Objects

SPIN 1/2

Production mechanisms at colliders





Recent searches at the LHC

⚠ **At tree level**

ATLAS

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MoEDAL

*EPJ C**82**,694 (2022)*
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See A.Upreti's talk

⚠ Large coupling g → Perturbation theory breaks down → **Resummation needed!**

or, in general, some non-perturbative (e.g. Lattice) treatment

RESUMMATION

Electromagnetic Interactions - QED-like Lagrangian

Photon

$$\mathcal{L}_{\text{bare}} = -\frac{1}{4} F_{\mu\nu}\, F^{\mu\nu} + \overline{\psi}\left(i\partial\!\!\!/ + g A\!\!\!/ - m\right)\psi$$

HECO fermion

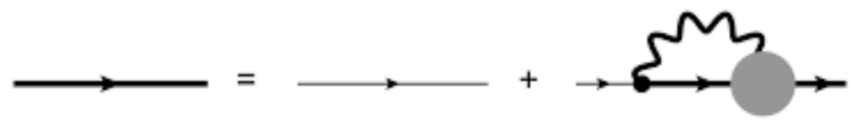
HECO charge
g= ne

Bare mass

$n \geq 11$

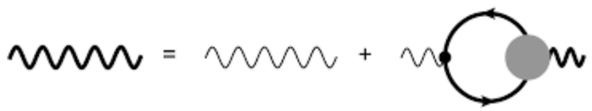
Fermion dressed propagator

$$G \;=\; i\,\frac{Z p\!\!\!/ + M}{Z^2 p^2 - M^2}$$



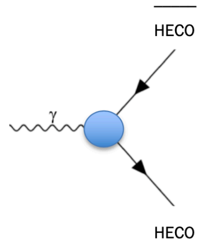
Photon dressed propagator

$$\Delta_{\mu\nu} \;=\; \frac{-i}{(1+\omega)q^2}\left(\eta_{\mu\nu} + \frac{1+\omega-\lambda}{\lambda}\frac{q_\mu q_\nu}{q^2}\right)$$



HECO-γ dressed vertex

* $$\Gamma_\mu \;=\; g Z \gamma_\mu$$



Z, ω, M quantum corrections

* This is due to the fact that the basic effect of the resummation is equivalent to a gauge-fixed free QED Lagrangian in which the standard Ward identity is not valid, leading to the above result, assuming naturally that the coupling renormalisation function is of the same order as the resummation. (see preprint version of Alexandre et al., e-Print:2310.17452 [hep-ph] (*Phys.Rev.D 109 (2024) 3, 3*)

J. Alexandre, N. E. Mavromatos
Phys.Rev.D 100 (2019) 9

RESUMMATION

Electromagnetic Interactions - QED-like Lagrangian

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HECO fermion   HECO charge g= ne   Bare mass

$n \geq 11$

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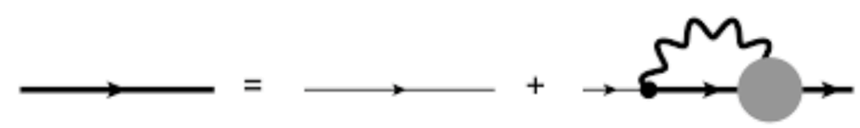

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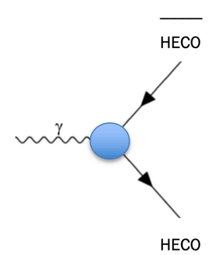

Z, ω, M quantum corrections

- The aim is to solve Dyson-Schwinger equations for HECO and γ self-energies without assuming $g^2 \ll 1$

$$Z \;=\; 1 + \frac{g^2}{8\pi^2\lambda}\ln\left(\frac{Zk}{M}\right)$$

$$Z\omega \;=\; \frac{g^2}{6\pi^2}\ln\left(\frac{Zk}{M}\right)$$

$$Z\left(1-\frac{m}{M}\right) \;=\; \frac{g^2}{8\pi^2\lambda}\,\frac{1+3\lambda+\omega}{1+\omega}\ln\left(\frac{Zk}{M}\right)$$

UV Fixed-point solution

$$\lim_{k\to\infty}(Z,\omega,\tilde{M}) = (Z^\star,\omega^\star,\tilde{M}^\star)$$

such that $\displaystyle\lim_{k\to\infty}\frac{kZ}{M} = \text{finite}$

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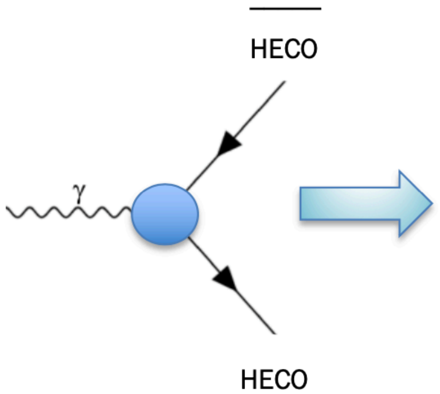
RESUMMATION



Lagrangian based on the running effective parameters

$$\mathcal{L}_{eff} = \frac{1}{2}A_\mu\Big((1+\omega)\eta^{\mu\nu}\Box - \omega\partial^\mu\partial^\nu\Big)A_\nu \; + \bar{\psi}\Big(Zi\partial\!\!\!/ + Zg A\!\!\!/ - M\Big)\psi$$

$A_\mu \to A_\mu/\sqrt{1+\omega}$ and $\psi \to \psi/\sqrt{Z}$ rescaling

$$\mathcal{L}_{eff} \to \frac{1}{2}A_\mu\left(\eta^{\mu\nu}\Box - \frac{\omega}{1+\omega}\partial^\mu\partial^\nu\right)A_\nu \; + \bar{\psi}\left(i\partial\!\!\!/ + \frac{g}{\sqrt{1+\omega}}A\!\!\!/ - \frac{M}{Z}\right)\psi$$

Shifted covariant gauge parameter $\lambda_{eff} = \dfrac{1}{1+\omega}$

Running coupling: $\alpha(k) = \dfrac{g^2/(4\pi)}{1+\omega(k)}$ with g= n e, $\omega(k) > 0$

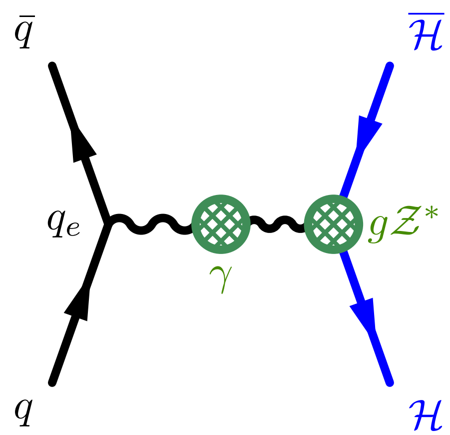
Effective HECO Mass: $\mathcal{M}(k) = \dfrac{M(k)}{Z(k)} = k\exp\left(-\dfrac{2\pi}{\alpha(k)}(Z(k)-1)\right)$

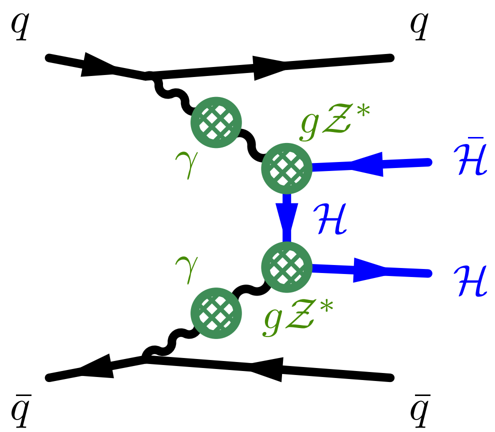
@ UV fixed point $(Z^\star, \omega^\star, M^\star)$

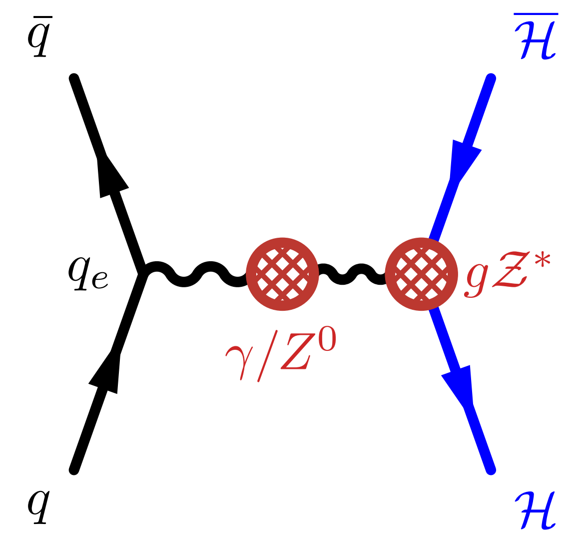
$$\lim_{k\to\Lambda} M(k) \equiv M(\Lambda) = \Lambda\exp\left(-\frac{2\pi}{\alpha^\star}(Z^\star - 1)\right), \; \Lambda \gg m$$

RESUMMATION

Feynman Rules







γ-only exchange

Running mass: $\mathcal{M}(\Lambda) = \Lambda \exp\left(-\frac{2\pi}{\alpha^\star}(Z^\star - 1)\right)$

HECO-fermion propagator: $G^{\text{eff}} = i\frac{\not{p}+\mathcal{M}(\Lambda)}{p^2-\mathcal{M}(\Lambda)^2}$

Photon propagator: $\Delta^{\text{eff}}_{\mu\nu} = \frac{-i}{q^2}\left(\eta_{\mu\nu} + \omega^\star \frac{q_\mu q_\nu}{q^2}\right)$

Photon-HECO vertex: $\Gamma^{\text{eff}}_\mu = g\, Z^\star \gamma_\mu$

with $\hat{\alpha}^\star$ is the rescaled electric coupling $\hat{\alpha}^\star = \frac{g^2/4\pi}{1+\hat{\omega}^\star}$, $Z^\star = 1.477$

the wavefunction renormalization and $\omega^\star = \frac{4}{3}\left(1 - \frac{1}{Z^\star}\right) \simeq 0.431$

Z^0 inclusion SU(2) singlet

Same procedure as for photon with the replacement:

$g^2 \to \hat{g}^2 \equiv g^2 + 3g'^2/4$ where g' is the Z_0-HECO coupling

$\mathcal{M}(\Lambda) = \Lambda \exp\left(-\frac{2\pi}{\hat{\alpha}^\star}(\hat{Z}^\star - 1)\right)$

$\hat{Z}^\star = \hat{Z}_+ = \frac{2}{9}(3+\eta)\left(1 + \sqrt{1 - \frac{9\eta}{(3+\eta)^2}}\right)$

$\hat{\omega}^\star = \frac{4}{3}\eta\left(1 - \frac{1}{\hat{Z}^\star}\right)$ with $\eta \equiv g^2/\hat{g}^2 < 1$.

UNIVERSAL FEYNRULES OUTPUT

SPIN 1/2

Two *UFO* models created:

i) γ-HECO only interaction

ii) Including Z^0 boson

Tested on Madgraph!

Available on the FeynRules model database >Simple extensions of the SM

General 2HDM	The most general 2HDM, including all flavor violation and mixing terms.	C. Duhr, M. Herquet	Availa
Heavy Scalar Effective Model	A model with one heavy scalar with effective couplings to the vector bosons.	Y. Wu, Y. Xu, X. Chen	Availa
Heavy Neutrino	The SM with three heavy Majorana neutrinos that couple to SM fields through mixing with active neutrinos.	R. Ruiz	Availa
Heavy Neutral Leptons	The SM with heavy neutrinos interacting with mesons.	P. Coloma, E. Fernández-Martínez, M. González-López, J. Hernández-García	Availa
Hidden Abelian Higgs Model	A Z' model where the Z' interacts with the SM through mixings, leading to very small non-SM like Z' couplings.	D. Curtin	Availa
HECO	High Electric Charge Objects (HECOs) pair production by including resummation effects	E. Musumeci	Availa
Hill Model	A model with an unusual extension of the SM Higgs sector.	P. de Aquino, C. Duhr	Availa
Inert Doublet Model	A model with an additional complex scalar SU(2)L doublet and an unbroken Z2 symmetry under which all SM particles are even while the extra doublet is odd.	A. Goudelis, B. Herrmann, O. Stal	Availa
Flavor-violating KK gluon	A Kaluza-Klein Gluon Model with FCNC Decay to a Single Top Quark	E. Drueke, R. Schwienhorst, N. Vignaroli, J. Nutter, D. Walker, J.-H. Yu, R. S. Chivukula, E. Simmons	Availa
Simplified Freeze-in models	LHC-friendly minimal freeze-in models with a charged parent	A. Goudelis	Availa
Leptoquarks + dark matter	Minimal model including dark matter and leptoquarks	B. Fuks	Availa
Minimal Zp models	The minimal Z' extension of the SM.	L. Basso	Availa
Minimal Dilaton Model	Minimal Dilaton Model	J. Cao, X. Hao, Z. Heng, L. Shang, Y. Zhang	Availa

Two new input parameters:

i) Multiplicity of the electric charge $\boldsymbol{n}$ (Q= **n** e)

ii) Cut-off Λ

UNIVERSAL FEYNRULES OUTPUT

SPIN 1/2

Two new input parameters:

i) Multiplicity of the electric charge n (Q= n e)

ii) Cut-off Λ

Commands for MadGraph5_aMC@NLO

1. γ-only exchange

- Drell-Yan

```
import model heco_spinhalf_photononly
generate p p > heco heco~
output DY_HECO
```

- Photon-Fusion

```
import model heco_spinhalf_photononly
generate a a > heco heco~
output PF_HECO
```

2. γ/Z0 exchange

- Drell-Yan

```
import model heco_spinhalf_withZ0
generate p p > heco heco~
output DY_HECO_Z0
```

Set run card and parameters

```
launch name_of_theoutput  ### replace name_of_theoutput accordingly, i.e. DY_HECO_Z0
set ebeam1 6500 ### beam 1 energy in GeV
set ebeam2 6500 ### beam 2 energy in GeV
set lpp1 1   ###   beam 1 type (1=proton)
set lpp2 1   ###   beam 2 type (1=proton)
set pdlabel lhapdf ### set the pdlabel argument
set lhaid 82000    ### set the pdf set
set nevents 10000   ### number of events

set n 20 ### set the multiplicity of the charge
set lambda 1000  ### set the cutoff energy scale in GeV
```

VALIDATION OF UFO MODELS

SPIN 1/2

- ☑ Calculation of the analytical cross section (Wolfram Mathematica)
- ☑ Comparison results from Madgraph with those obtained from Mathematica

DRELL-YAN

DY with resummation $u\bar{u} \to \mathcal{H}\overline{\mathcal{H}}$ @ $\sqrt{s} = 13$ TeV, $\Lambda = 2$ TeV — NO PDF

Q (e)	γ-only exchange			γ/Z^0 exchange		
	σ_{MadGraph} (pb)	$\sigma_{\text{Mathematica}}$ (pb)	UFO/Theory	σ_{MadGraph} (pb)	$\sigma_{\text{Mathematica}}$ (pb)	UFO/Theory
20	0.0762	0.0758	1.005	0.0659	0.0655	1.006
40	0.3048	0.3027	1.007	0.2632	0.2616	1.006
60	0.6837	0.6807	1.004	0.5919	0.5886	1.005
80	1.2151	1.2097	1.004	1.0508	1.0462	1.004
100	1.8976	1.8898	1.004	1.6460	1.6345	1.007
120	2.7372	2.7210	1.006	2.3682	2.3537	1.006
140	3.7261	3.7032	1.006	3.2251	3.2035	1.006
160	4.8712	4.8366	1.007	4.2083	4.1843	1.005
180	6.1548	6.1210	1.006	5.3224	5.2955	1.005
200	7.5927	7.5568	1.004	6.5758	6.5379	1.006

PHOTON FUSION

PF with resummation $\gamma\gamma \to \mathcal{H}\overline{\mathcal{H}}$ @ $\sqrt{s} = 13$ TeV, $\Lambda = 2$ TeV — NO PDF

Q (e)	σ_{MadGraph} (pb)	$\sigma_{\text{Mathematica}}$ (pb)	UFO/Theory
20	7.438×10^{3}	7.398×10^{3}	1.005
40	7.732×10^{4}	7.692×10^{4}	1.004
60	3.539×10^{5}	3.528×10^{5}	1.003
80	1.082×10^{6}	1.076×10^{6}	1.006
100	2.596×10^{6}	2.580×10^{9}	1.006
120	5.327×10^{6}	5.300×10^{6}	1.005
140	9.814×10^{6}	9.761×10^{6}	1.005
160	1.668×10^{7}	1.659×10^{7}	1.005
180	2.663×10^{7}	2.651×10^{7}	1.004
200	4.052×10^{7}	4.033×10^{7}	1.005

IMPACT ON PRODUCTION CROSS SECTIONS

DRELL-YAN

DY $pp \to \gamma \to \mathcal{H}\overline{\mathcal{H}}$ @ $\sqrt{s} = 13$ TeV, $\Lambda = 2$ TeV			NNPDF23
Q (e)	$\sigma_{\text{tree-level}}$ (fb)	σ_{resum} (fb)	M (TeV)
20	7.75×10^2	1.692×10^3	0.507
60	4.959	10.79	1.717
100	5.949	12.95	1.893
140	9.134	19.86	1.945
180	13.67	29.71	1.966
220	19.31	42.08	1.977

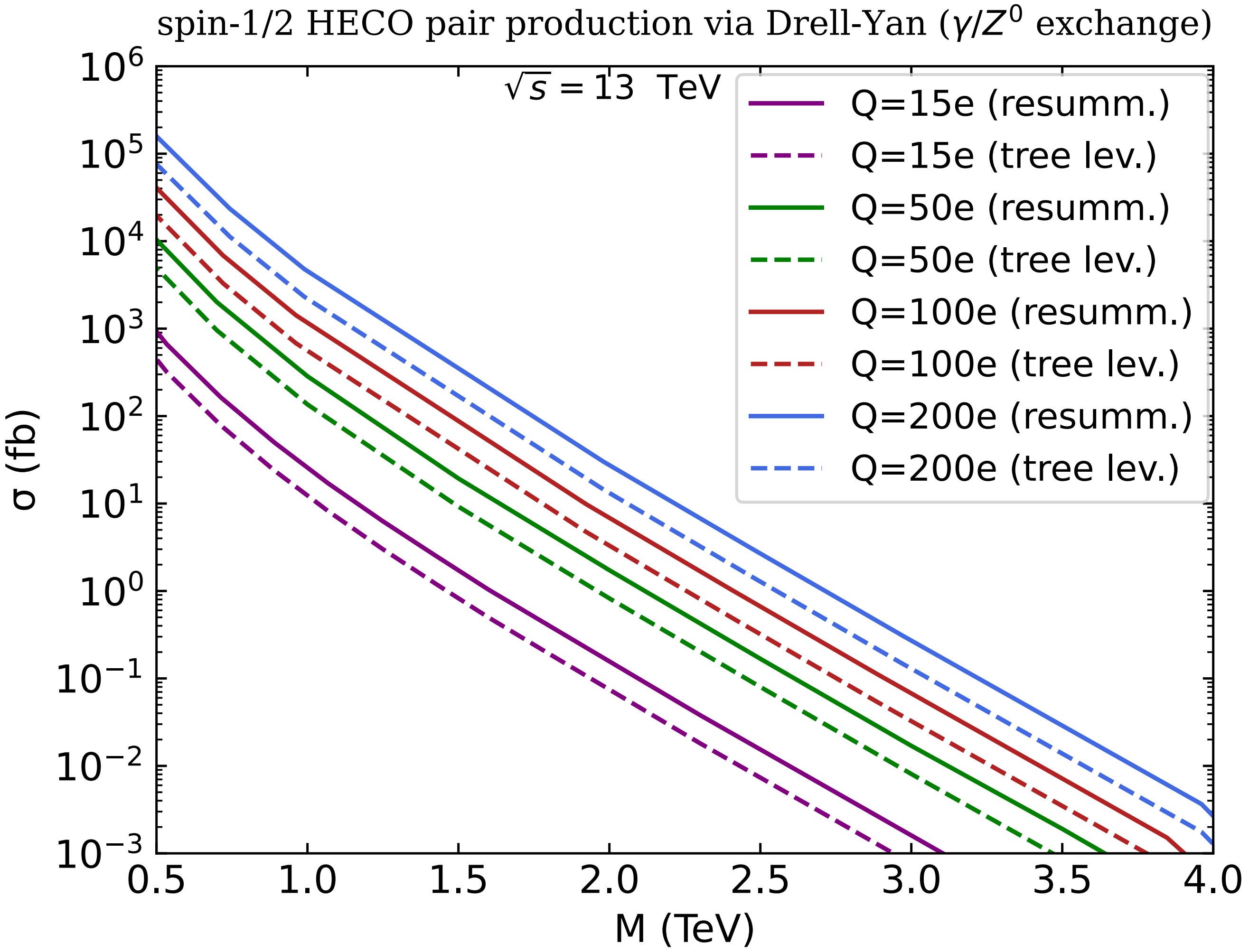
DY $pp \to \gamma/Z^0 \to \mathcal{H}\overline{\mathcal{H}}$ @ $\sqrt{s} = 13$ TeV, $\Lambda = 2$ TeV			
Q (e)	$\sigma_{\text{tree-level}}$ (fb)	σ_{resum} (fb)	M (TeV)
20	1.014×10^2	2.118×10^2	0.798
60	3.367	6.527	1.780
100	4.722	9.835	1.924
140	7.752	16.25	1.961
180	11.95	24.92	1.976
220	17.22	35.94	1.984

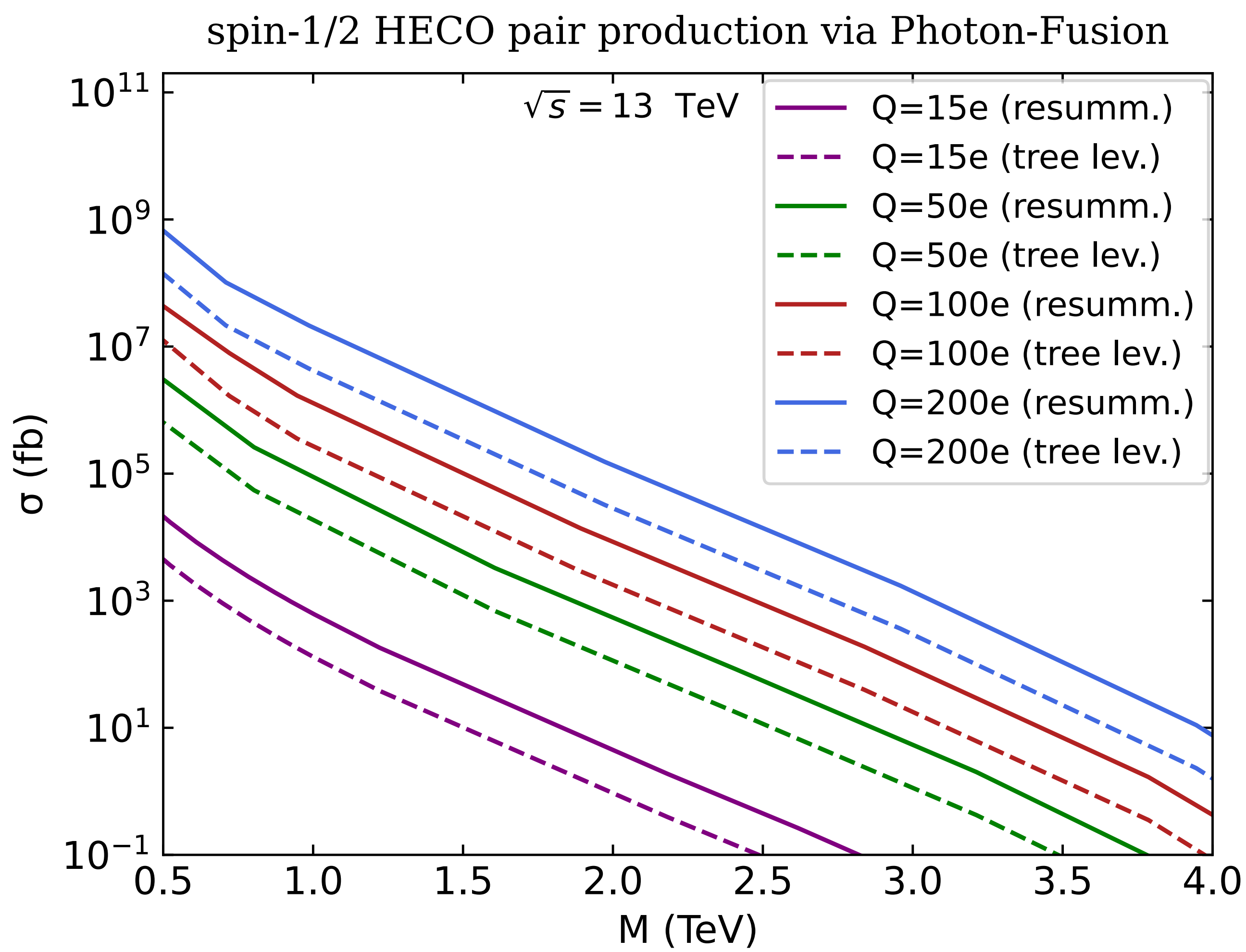
PHOTON FUSION

PF $pp \to \mathcal{H}\overline{\mathcal{H}}$ @ $\sqrt{s} = 13$ TeV, $\Lambda = 2$ TeV			LUXqed17
Q (e)	$\sigma_{\text{tree-level}}$ (fb)	σ_{resum} (fb)	M (TeV)
20	1.321×10^4	6.271×10^4	0.507
60	8.466×10^2	4.025×10^3	1.717
100	2.895×10^3	1.372×10^4	1.893
140	8.753×10^3	4.170×10^4	1.945
180	2.175×10^4	1.030×10^5	1.966
220	4.612×10^4	2.184×10^5	1.977

IMPACT ON PRODUCTION CROSS SECTIONS

SPIN-1/2

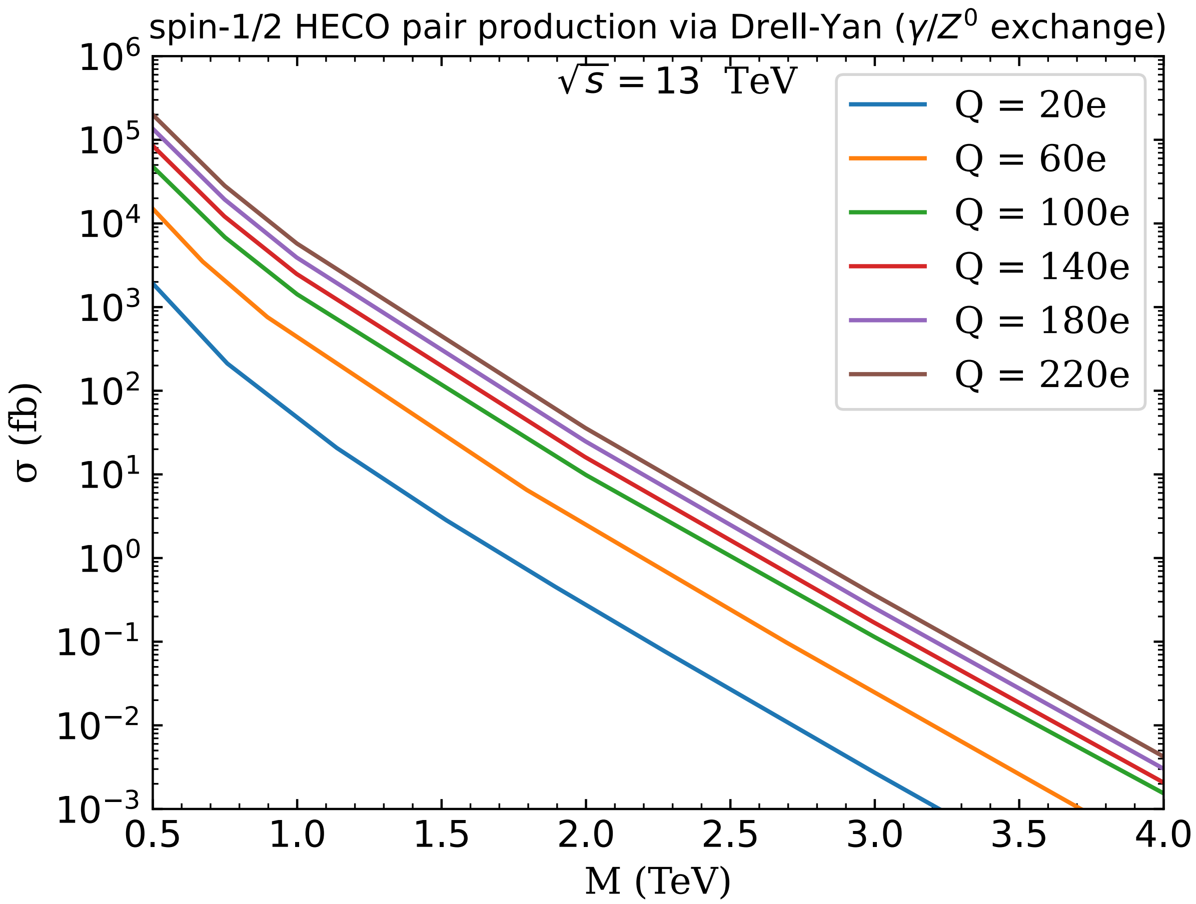


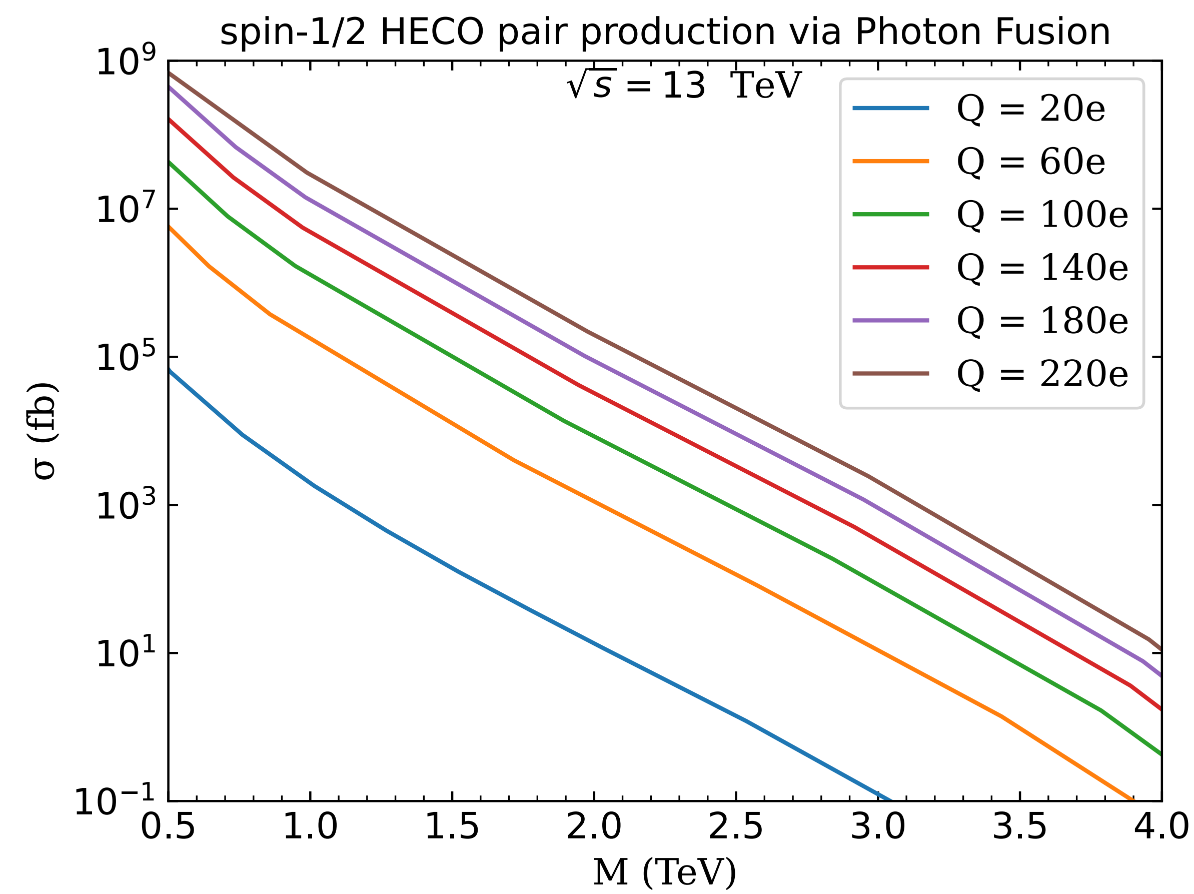


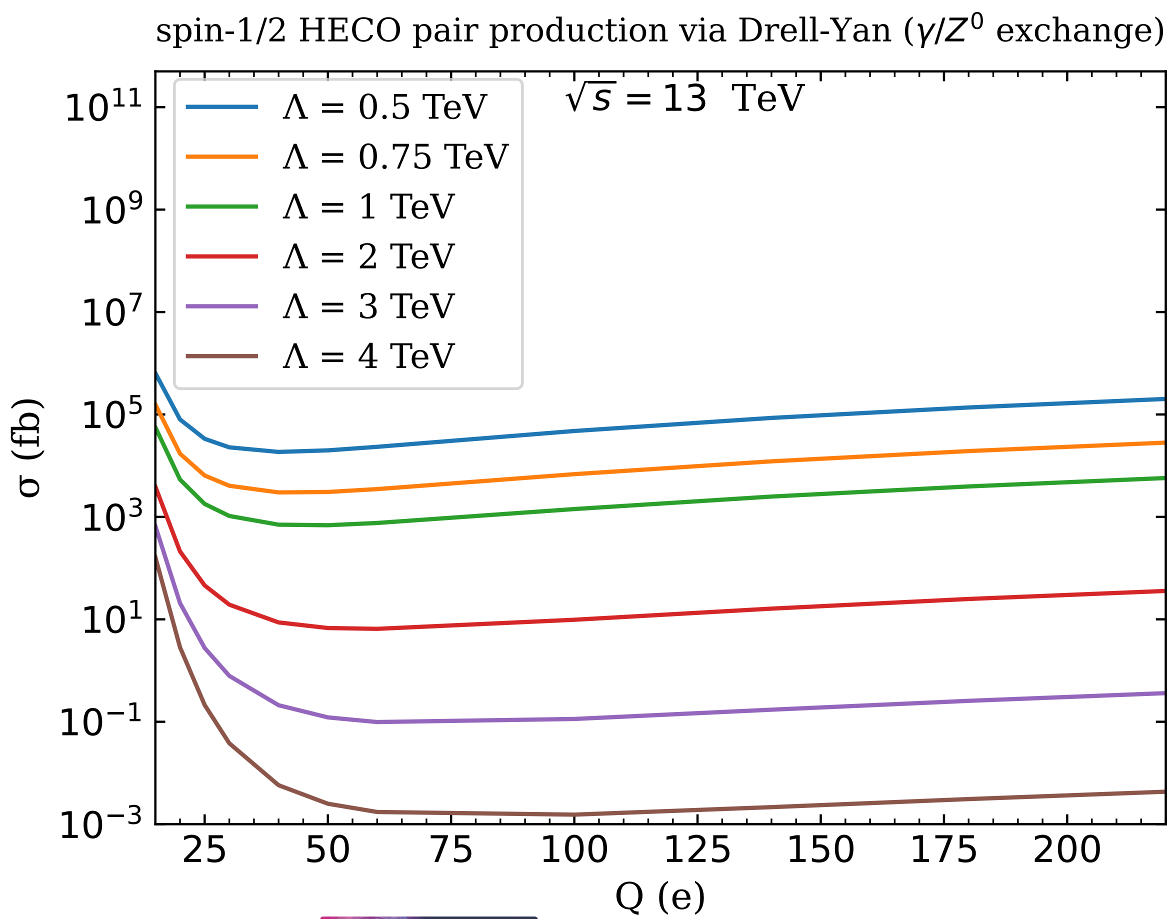
After resummation…

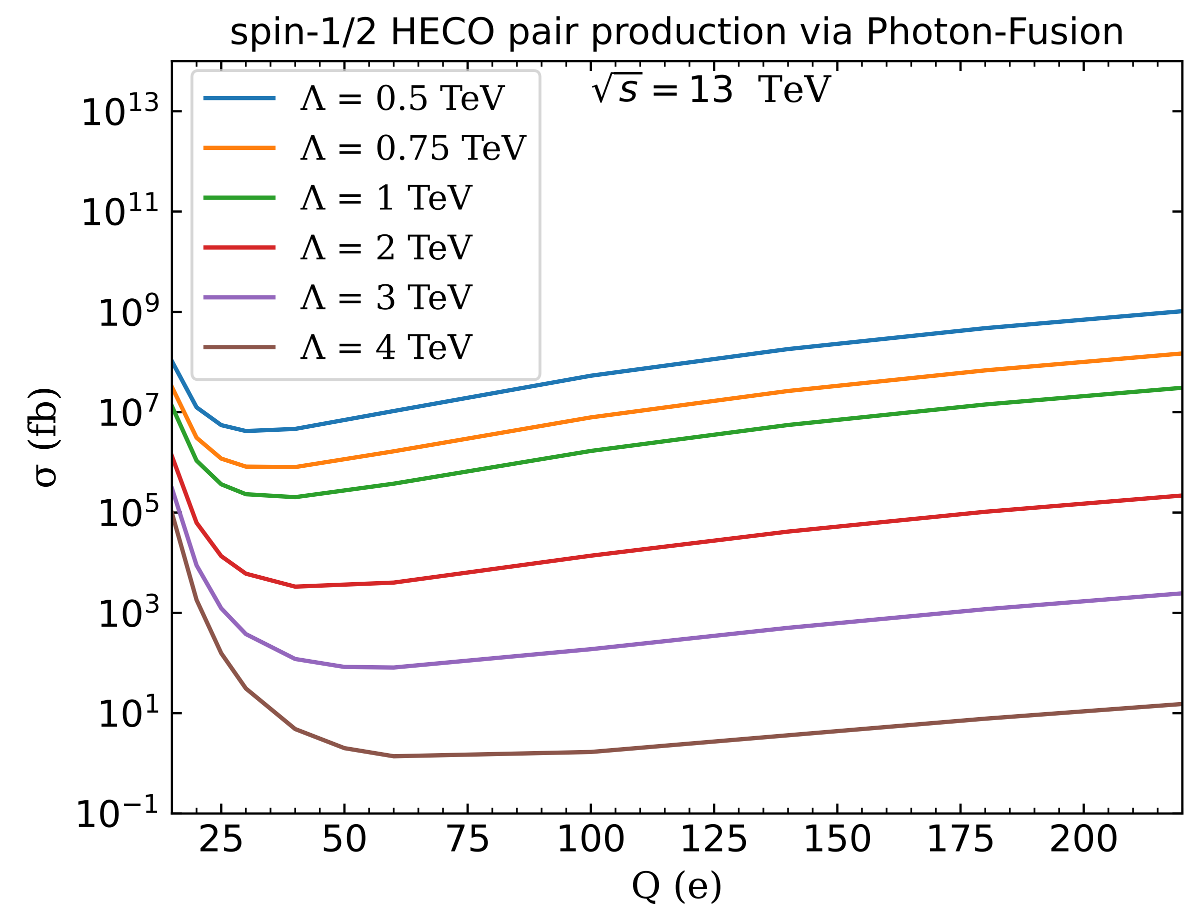
- the production via Dell-Yan cross section increases by a factor of ~ 1.66
- the production via Photon-Fusion cross section increases by a factor of ~ 2.76

IMPACT ON PRODUCTION CROSS SECTIONS





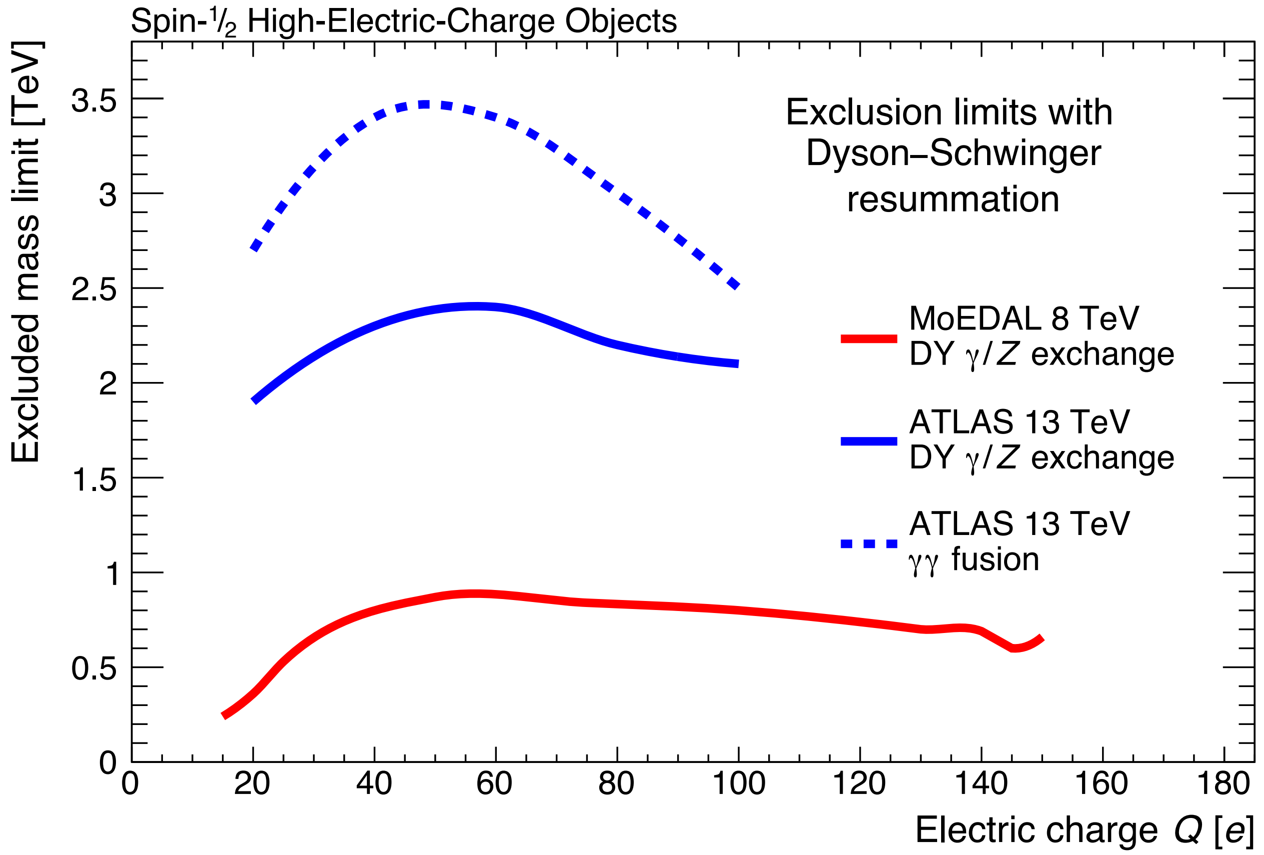




NEW MASS LIMITS

Experimental lower limits at 95% CL on spin-1/2 HECO mass (TeV)

Experiment/ energy	Q (e)	DY γ exchange LO	DY γ exchange DS	DY γ/Z^0 exchange LO	DY γ/Z^0 exchange DS	$\gamma\gamma$ fusion LO	$\gamma\gamma$ fusion DS
MoEDAL [14] $\sqrt{s} = 8$ TeV	15	0.18	0.24	0.17	0.24	–	–
	20	0.28	0.36	0.31	0.36	–	–
	25	0.44	0.55	0.44	0.53	–	–
	50	0.78	0.88	0.78	0.87	–	–
	75	0.78	0.88	0.78	0.84	–	–
	100	0.73	0.84	0.71	0.80	–	–
	125	0.66	0.75	0.64	0.72	–	–
	130	0.64	0.74	0.62	0.70	–	–
	140	0.58	0.68	0.62	0.69	–	–
	145	0.52	0.66	0.51	0.60	–	–
	150	0.50	0.63	0.58	0.66	–	–
ATLAS [11] $\sqrt{s} = 8$ TeV	10	0.78	0.78[a]	–	–	–	–
	20	1.05	1.14	–	–	–	–
	40	1.16	1.25	–	–	–	–
	60	1.07	1.15	–	–	–	–
ATLAS [12, 13] $\sqrt{s} = 13$ TeV	20	1.83	2.02	1.8	1.9	2.5	2.7
	40	2.05	2.22	2.2	2.3	3.1	3.4
	60	2.00	2.18	2.2	2.4	3.1	3.4
	80	1.86	2.02	2.1	2.2	3.0	3.0[b]
	100	1.65	1.80	1.9	2.1	2.5	2.5[b]



The increase in the mass limits spans a wide range of values up to 30%!!

NOTE: The latest MoEDAL results @ 13 TeV are not included here!

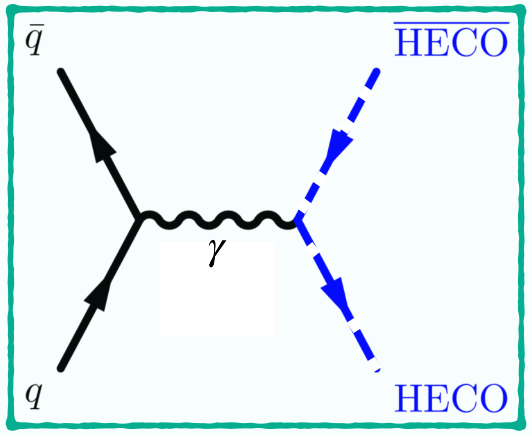
High Electric Charge Objects

WORK IN PROGRESS

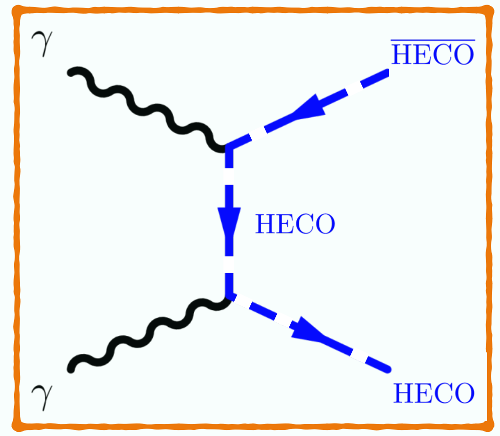
SPIN-0

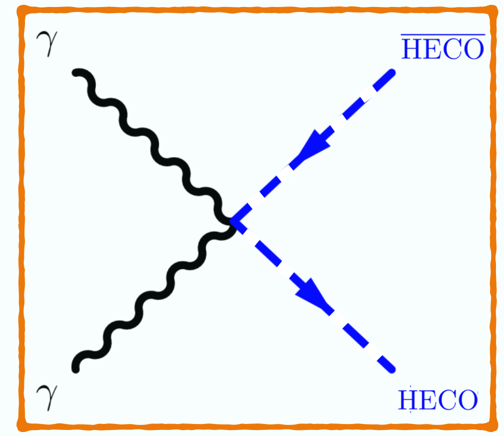
Production mechanisms at colliders

Drell-Yan



Photon-Fusion





Feynman Rules @ UV fixed-point

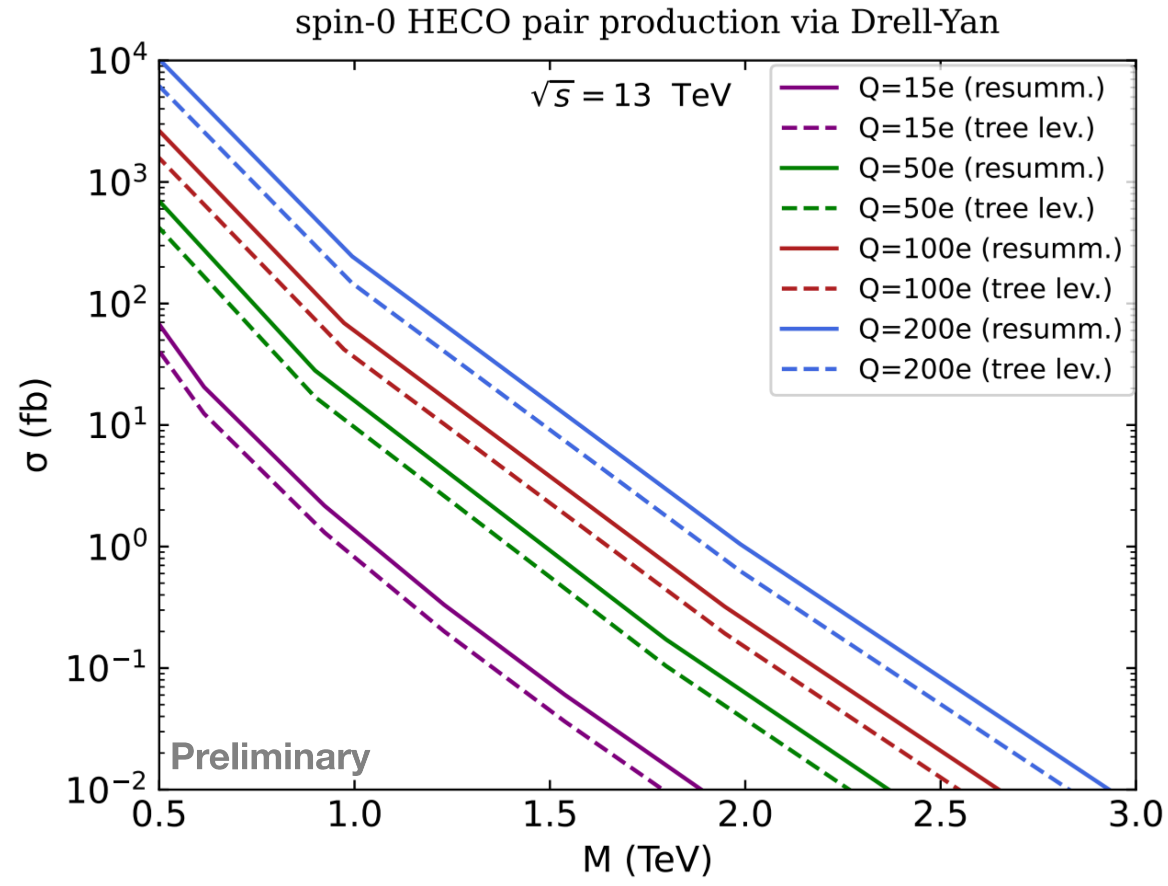
- **Scalar-γ vertex:** $-i\tilde{g}Z^\star \simeq -ig\sqrt{1+\frac{8g^2}{h}}\,, \quad \left(\frac{g^2}{h} \lesssim 0.0825\right)$
- **Self-interaction vertex:** $-i\frac{H^\star}{Z^{\star 4}} \simeq -i\frac{h}{4}\left(1+\frac{8g^2}{h}\right)^{-2}$
- **Running mass:** $\tilde{M} \simeq \Lambda\,\exp\left(-\frac{32\pi^2}{h}\right) \lesssim \Lambda\,\exp\left(-\frac{2.64\,\pi^2}{n^2\,e^2}\right)$
- **Gauge Boson propagator:** $\frac{i}{p^2 - i\epsilon}\left(-\eta_{\mu\nu} + \frac{4g^2}{3h}\right),\ \epsilon \to 0^+$
- **Charged scalar propagator:** $\frac{i}{p^2 - \tilde{M}^2 + i\epsilon},\ \epsilon \to 0^+$

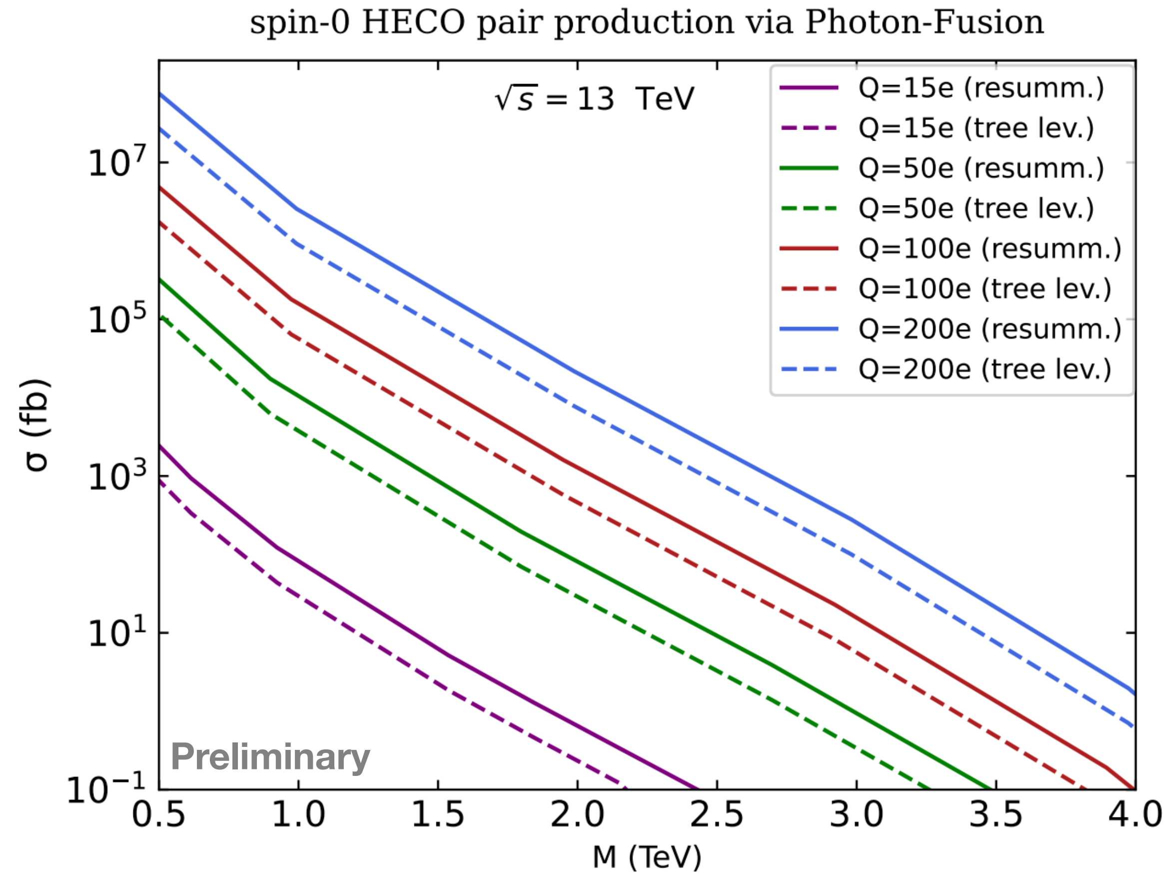
High Electric Charge Objects

WORK IN PROGRESS

SPIN-0

- ☑ Implementation of the UFO model
- ☑ Calculation of the analytical cross section (Wolfram Mathematica)
- ☑ Comparison Madgraph vs Mathematica
- ☑ Studying resummation effects on cross-sections





After resummation...

- the production via Dell-Yan cross section improves by a factor of ~ 2.1
- the production via Photon-Fusion cross section improves by a factor of ~ 4.75

CONCLUSIONS

- Dyson–Schwinger resummation performed
- UFO models available for experimental HECOs searches
- Reliable results compared to those obtained at tree-level
- Ongoing project:
  - ➡ resummation for *spin-0* HECOs (Alexandre, Mavromatos, Mitsou, Musumeci)
- Future project:
  - ➡ resum. for Magnetic Monopoles (based on Alexandre & Mavromatos *Phys.Rev.D 100(2019),9*)

Thank you for your attention!:)

RESUMMATION

Dyson-Schwinger Resummation

$$
\begin{aligned}
Z &= 1 + \frac{g^2}{8\pi^2\lambda}\frac{1}{\epsilon}\left(\frac{Zk}{M}\right)^{\epsilon} + \text{finite} \\
\omega &= \frac{g^2}{6\pi^2 Z}\frac{1}{\epsilon}\left(\frac{Zk}{M}\right)^{\epsilon} + \text{finite} \\
1 - \frac{m}{M} &= \frac{g^2}{8\pi^2\lambda Z}\frac{1+3\lambda+\omega}{1+\omega}\frac{1}{\epsilon}\left(\frac{Zk}{M}\right)^{\epsilon} + \text{finite}
\end{aligned}
$$

k is an energy scale

g and m are independent of k

The aim is to solve the full set of equations without assuming $g^2 \ll 1$

Boundary conditions:

$(Z,\, \omega,\, M) = (1,\, 0,\, m) \quad \text{when} \quad k = m \quad \Longrightarrow$

$$
\begin{aligned}
Z &= 1 + \frac{g^2}{8\pi^2\lambda}\ln\left(\frac{Zk}{M}\right) \\
Z\omega &= \frac{g^2}{6\pi^2}\ln\left(\frac{Zk}{M}\right) \\
Z\left(1 - \frac{m}{M}\right) &= \frac{g^2}{8\pi^2\lambda}\frac{1+3\lambda+\omega}{1+\omega}\ln\left(\frac{Zk}{M}\right)
\end{aligned}
$$

Usual one-loop results for $g^2 \ll 1$

Feynman gauge λ=1

$$\lim_{k\to\infty}\frac{kZ}{M} = \text{finite}$$

$$
\begin{aligned}
Z &= 1 + \frac{g^2}{8\pi^2}\ln\left(\frac{Zk}{M}\right) \\
\omega &= \frac{4}{3}\left(1 - \frac{1}{Z}\right) \\
1 - \frac{m}{M} &= 4\,\frac{4Z-1}{7Z-4}\left(1 - \frac{1}{Z}\right)
\end{aligned}
$$

$$\lim_{k\to\infty}(Z, \omega, \tilde{M}) = (Z^\star, \omega^\star, \tilde{M}^\star)$$

UV Fixed-point

$$\frac{k}{m} = \frac{(7Z-4)}{9(Z_+ - Z)(Z - Z_-)}\;\exp\left(\frac{8\pi^2}{g^2}(Z-1)\right)$$

$$Z_\pm = \frac{8}{9}\left(1 \pm \frac{\sqrt{7}}{4}\right) \simeq \begin{cases} 1.477 = Z^\star \\ 0.301 \end{cases}$$

$$\omega \to \omega^\star = \frac{4}{3}\left(1 - \frac{1}{Z^\star}\right) \simeq 0.431\;,$$

$$\tilde{M} \equiv \frac{M}{k} \to Z^\star \exp\left(-\frac{8\pi^2}{g^2}(Z^\star - 1)\right)$$

Z^0 boson inclusion

SPIN-1/2

$$\mathscr{L}_{\text{int}} = -\frac{e}{\sin(2\,\theta_W)}\bar{H}\gamma^\mu Z^0_\mu\Big(c_L\frac{1}{2}(1-\gamma^5)+c_R\,\frac{1}{2}(1+\gamma^5)\Big)H = -\frac{e}{\sin(2\,\theta_W)}\,\bar{H}\,\gamma^\mu Z^0_\mu\left[\frac{1}{2}(c_L+c_R)-\frac{1}{2}(c_L-c_R)\,\gamma^5\right]H$$

with

$$c_L = t^3 - |n|\,\sin^2\theta_W \qquad c_R = -|n|\,\sin^2\theta_W$$

SU(2) singlet

$$\mathscr{L}_{\text{int}} = \frac{1}{2}e\,|n|\tan\theta_W\bar{H}\gamma^\mu Z^0_\mu H$$

In the Feynman gauge, in the high energy limit, the Z^0 boson behaves as a second photon

$$\Delta^{Z^0}_{\mu\nu} = -\frac{i}{p^2-M_Z^2+i\epsilon}\left(\eta_{\mu\nu}+\frac{\omega_{Z^0}}{1+\omega_{Z^0}}\frac{p_\mu p_\nu}{M_Z^2}\right), \quad \epsilon\to 0^+$$

In the unitary gauge, for $M_Z \neq 0$, leads to the standard massive (Proca) Z^0 boson bare propagator

$$\Delta^{Z^0}_{\mu\nu} = -\frac{i}{p^2-M_Z^2+i\epsilon}\left(\eta_{\mu\nu}-\frac{p_\mu p_\nu}{M_Z^2}\right)-\frac{p_\mu p_\nu}{M_Z^2}\frac{i}{p^2-\xi_Z m_Z^2+i\epsilon}, \quad \epsilon\to 0^+$$