On the impact of the Higgs boson on the production of exotic particles at the LHC

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arXiv:1408.0983 [hep-ph]

Outline

1 Introduction

2 Scalar and fermionic particle production at the LHC

3 Scalar multiplet production at the LHC

4 Fermion multiplet production at the LHC

5 Perspectives for a $\sqrt{s} = 100$ TeV proton-proton collider

6 Conclusions

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Many Standard Model extensions containing new sectors provide numerous ways to connect these sectors to the SM sector:

- Higgs portal;
- Neutrino portal ('sterile neutrinos');
- Lepton/quark portal DM containing additional messengers;
- Vector portal (U(1)', gauge portal, ...);
- Axion portal;
- ...

Analyse a simple scenario:

- Add **one** new uncolored scalar S or fermionic particle ψ to SM particle spectrum.
- Assign quantum numbers.
- Compare and quantify importance of Higgs portal and electroweak gauge portal for the production of states containing the new particles.
- Consider p-p CM energies of 8 TeV and 14 TeV (100 TeV).

Analyse a simple scenario:

- Add **one** new uncolored scalar S or fermionic particle ψ to SM particle spectrum.
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Additional SCALAR $\rightarrow$ Any quantum number assignment

Additional FERMION $\rightarrow$
- New singlet/doublet/triplet
  Break $\mathrm{U}(1)_{\mathrm{L}}$, both chiralities $\rightarrow$ Vectorlike leptons under $\mathrm{SU}(2)_{\mathrm{L}} \otimes \mathrm{U}(1)_{Y}$.
- Choice $(1,0)$ and $(3,0)$ are the type-I and type-III seesaw scenarios (for R chirality).

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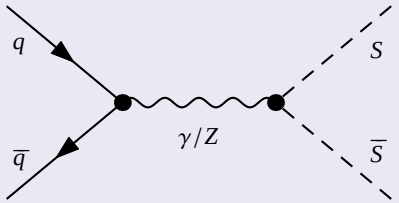
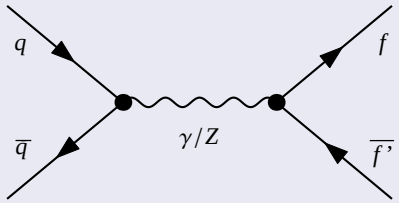
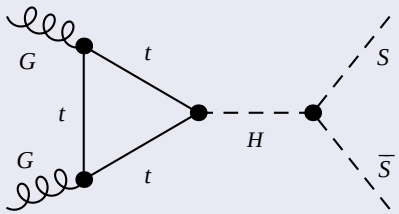
Contributing LO processes for parton-parton $\to f\bar{f}' \,/\, S\bar{S}$

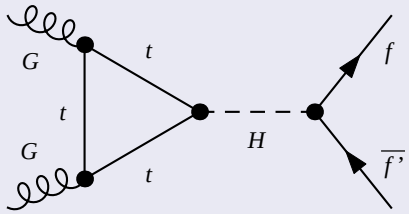
Drell-Yan:



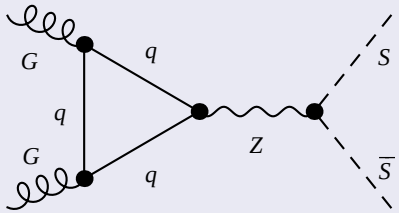


Gluon fusion via H:

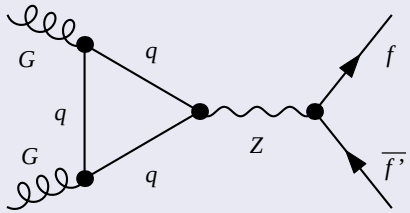




Gluon fusion via Z:



vanishes[#]



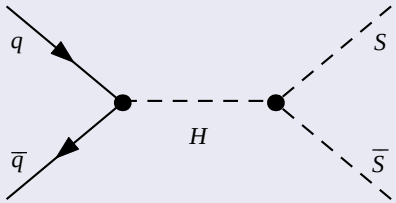
not considered here[†]

[#] F. del Aguila, L. Ametller, Phys. Lett. B261 326-333 (1991)

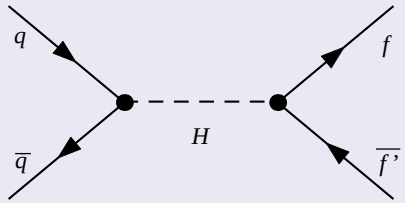
[†] C. Liu, S. Yang, Phys. Rev. D81, 093009 (2010)

Contributing LO processes for parton-parton $\to f\bar{f}\,/\,S\bar{S}$

Yukawa:



neglect



neglect

Others: Higgs- and Z-mediated processes along with other particles in the final state (neglect all)

Drell-Yan

Cross section:

$$\sigma\left(p\,p \to X_1 X_2;\, s\right) = \sum_{q=u,d} \int_{\tau_s}^{1} \frac{d\mathcal{L}^{q\bar{q}}}{d\tau}\, \sigma\left(q\bar{q} \to X_1 X_2; \hat{s} = \tau s\right)\, d\tau$$

Quark luminosity function:

$$\frac{d\mathcal{L}^{q\bar{q}}}{d\tau} = \int_{\tau}^{1} \frac{q\left(x, \mu_F\right) \bar{q}\left(\frac{\tau}{x}, \mu_F\right) + q\left(\frac{\tau}{x}, \mu_F\right) \bar{q}\left(x, \mu_F\right)}{x}\, dx$$

Gluon fusion

Cross section:

$$\sigma\left(p\,p \to X_1 X_2;\, s\right) = \int_{\tau_s}^{1} \frac{d\mathcal{L}^{gg}}{d\tau}\, \sigma\left(gg \to X_1 X_2;\, \hat{s} = \tau s\right)\, d\tau$$

Gluon luminosity function:

$$\frac{d\mathcal{L}^{gg}}{d\tau} = \int_{\tau}^{1} \frac{g\left(x, \mu_F\right) g\left(\frac{\tau}{x}, \mu_F\right)}{x}\, dx$$

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Benchmark model

New vev-less uncolored scalar: $S = (S_1, \ldots, S_n)^T, \qquad n = 2\,T + 1, \qquad T^3 S_1 = -T S_1, \ldots, T^3 S_n = T S_n$

U(1)-invariant Lagrangian: $\mathcal{L}_S = c\,(D_\mu\,S)^\dagger\,(D^\mu\,S) - V(S,H), \quad c = 1,\ 1/2$

$$\begin{aligned} V(S,H) \;=\; & \mu_H^2\,H^\dagger H + f_1\left(H^\dagger H\right)^2 + \mu_S^2\,S^\dagger S + f_2\left(S^\dagger S\right)^2 + f_3\left(H^\dagger H\right)\left(S^\dagger S\right) \\ & + f_4\left(H^\dagger \tau^a H\right)\left(S^\dagger T^a S\right) + f_5\left(S^\dagger T^a S\right)\left(S^\dagger T^a S\right) \end{aligned}$$

Effective $h\,S\,S$ coupling: $\Lambda_Q = -\,2\,f_3 \,+\, f_4\,T^3 \;=\; -\,2\,f_3 \,+\, f_4\left(Q - \frac{Y}{2}\right)$

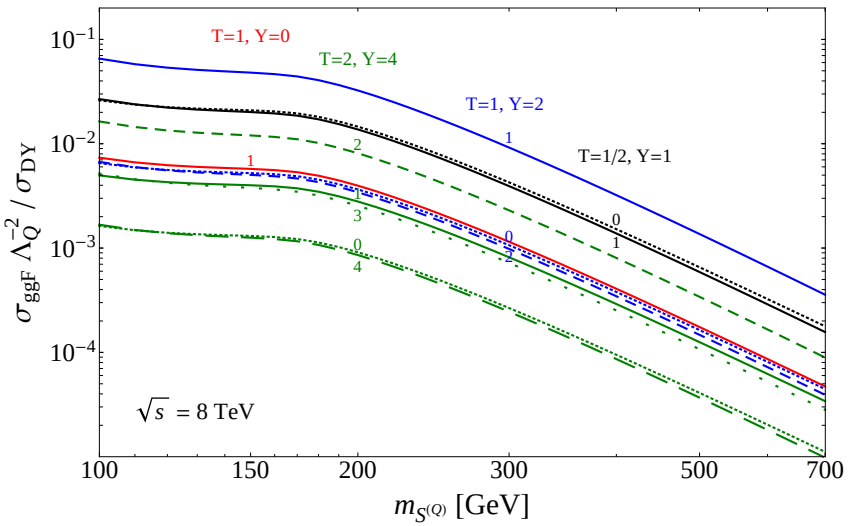
$m^2_{S(Q)} = \mu_S^2 \,-\, \frac{1}{4}\,\Lambda_Q\,v^2 \quad \Longrightarrow$ Mass splitting due to f_4

Constraints

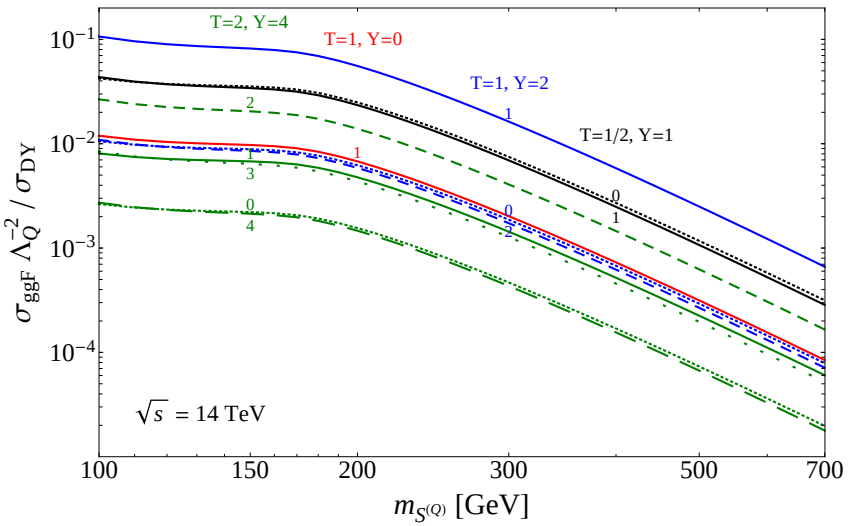
- ☐ Perturbativity ($f_i \leq 4\pi$)
- ☐ Vacuum stability
- ☐ Unitarity of scattering amplitudes (constrain couplings and multiplet size)
- ☐ Electroweak precision observables (S, T, U)
- ☐ $h \to \gamma\gamma$ signal strength
- ☐ Z width ($\Longrightarrow$ $m_{S(Q)} \gtrsim m_Z/2 \simeq 45$ GeV)

Contribution of ggH to $pp \to S^{(Q)}\bar{S}^{(Q)}$ relative to DY

$\sigma_{\mathrm{ggF}}\Lambda_Q^{-2}/\sigma_{\mathrm{DY}}$ @ 8 TeV



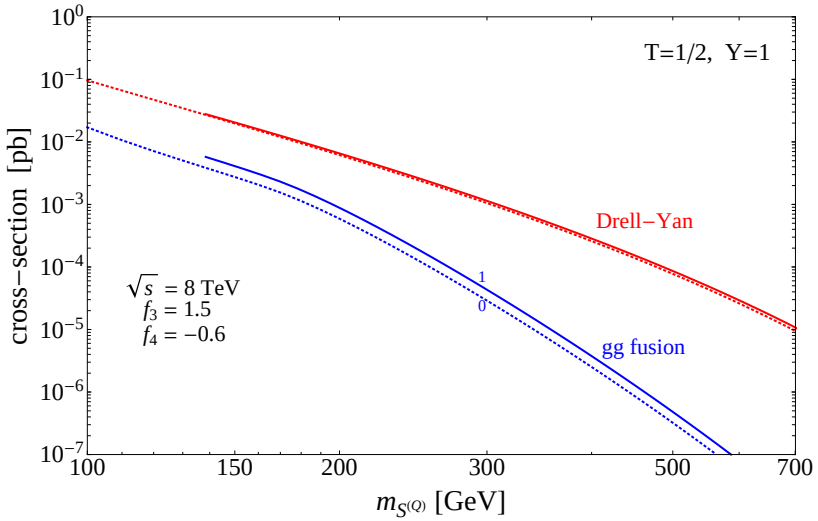
$\sigma_{\mathrm{ggF}}\Lambda_Q^{-2}/\sigma_{\mathrm{DY}}$ @ 14 TeV

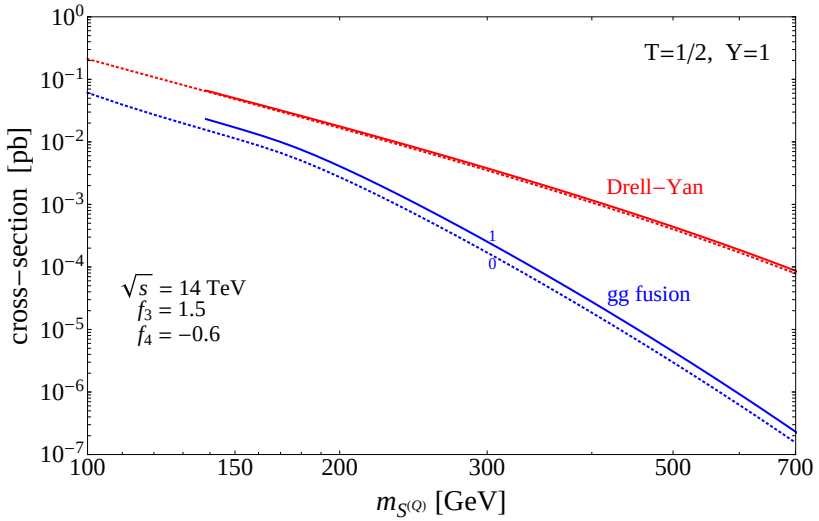


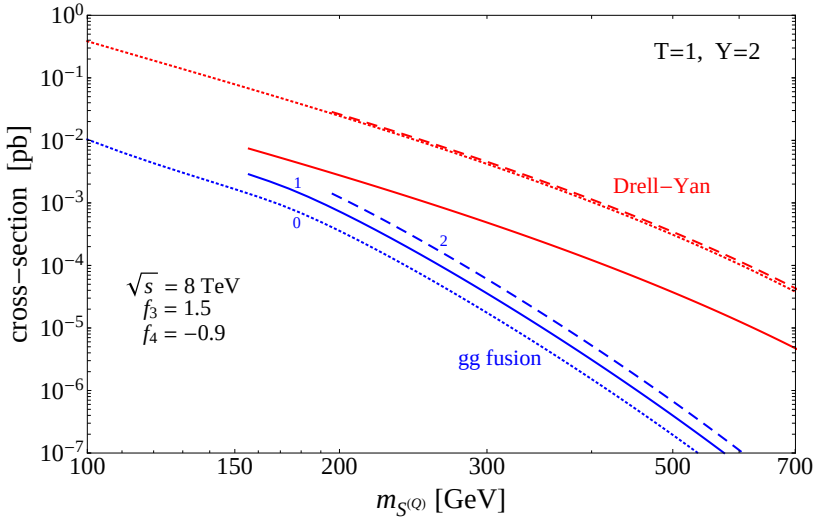
On-shell H production: $K \equiv \sigma_{\mathrm{NNLO+NNLL}}/\sigma_{\mathrm{LO}} \sim 3$ at 14 TeV. #

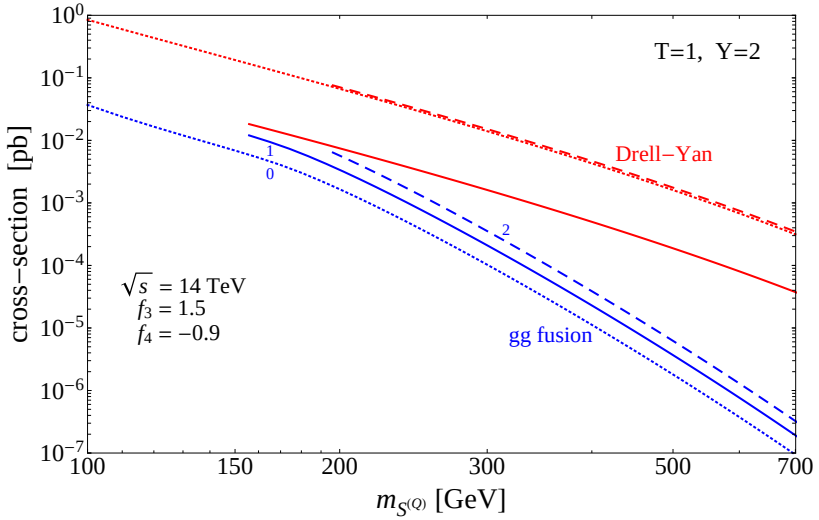
[https://twiki.cern.ch/twiki/bin/view/LHCPhysics/CrossSections]

$pp \to S^{(Q)}\bar{S}^{(Q)}$ for doublet $(T = 1/2,\ Y = 1)$ and triplet $(T = 1,\ Y = 2)$









DOUBLET: $\Lambda_{+1} = -3.3,\ \Lambda_0 = -2.7$; TRIPLET: $\Lambda_{+2} = -3.9,\ \Lambda_{+1} = -3,\ \Lambda_0 = -2.1$.

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Benchmark model

Generally: $\mathcal{L}_\psi = c\bar{\psi}\left(i\not{\partial} - m_\psi\right)\psi + \mathcal{L}_Y\left(H, \psi, L, E\right), \quad c = 1,\, 1/2, \quad \psi$ uncolored

Focus on low-scale Type I/III seesaw

Seesaw I & III:

$$\mathcal{L}_{NC}^{\mathcal{N}} = -\frac{g}{4\,c_w}\,\overline{\nu_{\alpha L}}\,\gamma_\mu\,\Theta_{\alpha k}\,(1-\gamma_5)\,\mathcal{N}_k\,Z^\mu + \text{h.c.}$$

$$\mathcal{L}_{H}^{\mathcal{N}} = -\frac{g\,M_k}{4\,m_W}\,\overline{\nu_{\alpha L}}\,\Theta_{\alpha k}\,(1+\gamma_5)\,\mathcal{N}_k\,h + \text{h.c.}$$

Seesaw III:

$$\mathcal{L}_{NC}^{\mathcal{E}} = -\frac{g}{2\sqrt{2}\,c_w}\,\overline{\ell_\alpha}\,\gamma_\mu\,\Theta_{\alpha k}(1-\gamma_5)\,\mathcal{E}_k\,Z^\mu + \text{h.c.}$$

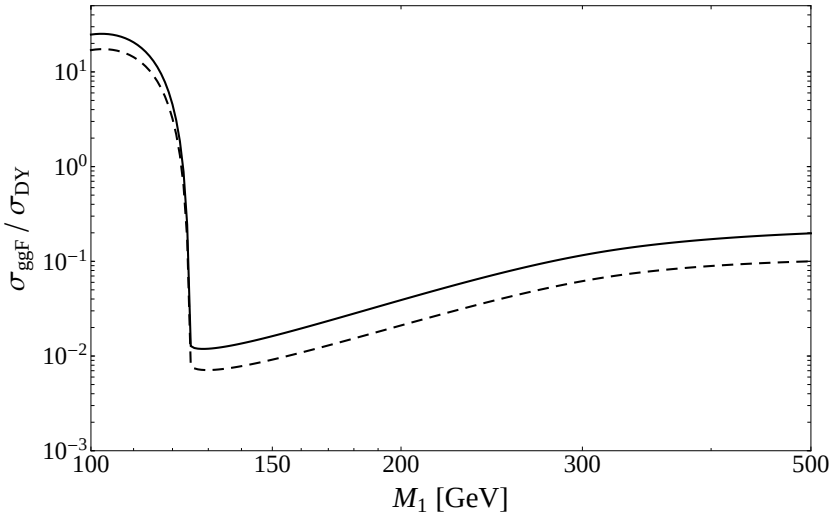
$$\mathcal{L}_{H}^{\mathcal{E}} = -\frac{g\,M_k}{2\sqrt{2}\,m_W}\,\overline{\ell_\alpha}\,\Theta_{\alpha k}\,(1+\gamma_5)\,\mathcal{E}_k\,h + \text{h.c.}$$

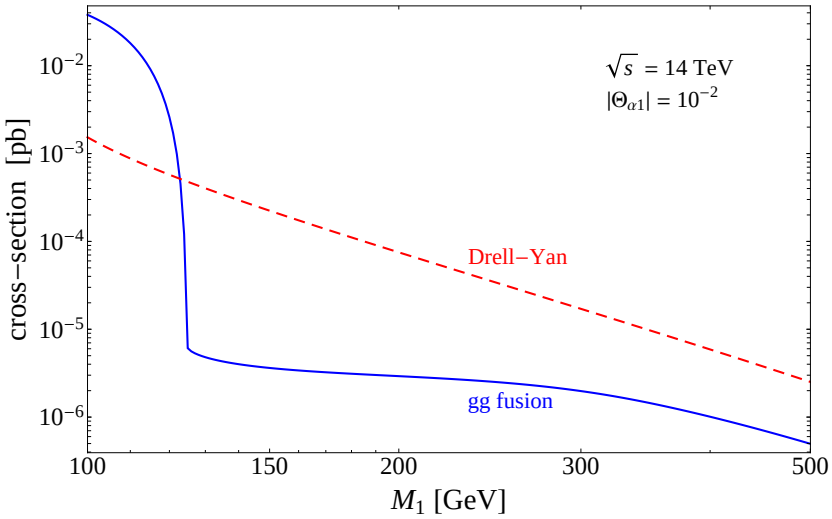
- SS-I: $|\Theta_{\alpha k}| \lesssim 10^{-2}$ for $M_k \sim 100$ GeV, SS-III: generally smaller [#]
- For SS-III, $M_k \gtrsim 300$ GeV from $\mathcal{E}\mathcal{N}$ searches [†]

[#] D. N. Dinh, A. Ibarra, E. Molinaro, S. T. Petcov, JHEP **08** (2012) 125
R. Alonso, M. Dhen, M. B. Gavela, T. Hambye, JHEP **01** (2013) 118

[†] ATLAS-CONF-2013-019

Contribution of ggF to $pp \to \mathcal{N}_k \nu_\alpha / \mathcal{E}_k \bar{\ell}_\alpha$ relative to DY [#]





- Possibility to test SS-I via $h \to \nu\mathcal{N}$, with $\mathcal{N} \to \ell W, \nu Z$ [#]
- For discovery of SS-III, heavy fermion pair production via W better suited. [†]

[#] C. G. Cely, A. Ibarra, E. Molinaro, S. T. Petcov, Phys. Lett. B **718** (2013) 957
P. S. Bhupal, R. Franceschini, R. N. Mohapatra, Phys. Rev. D **86**, 093010
[†] F. del Aguila, J. A. Aguilar-Saavedra, Phys. Lett. B **672** (2009) 158-165

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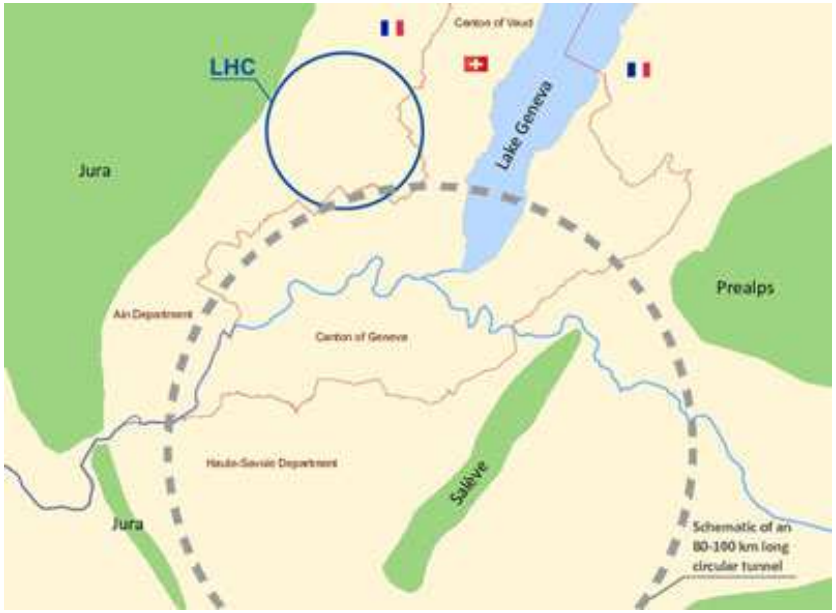
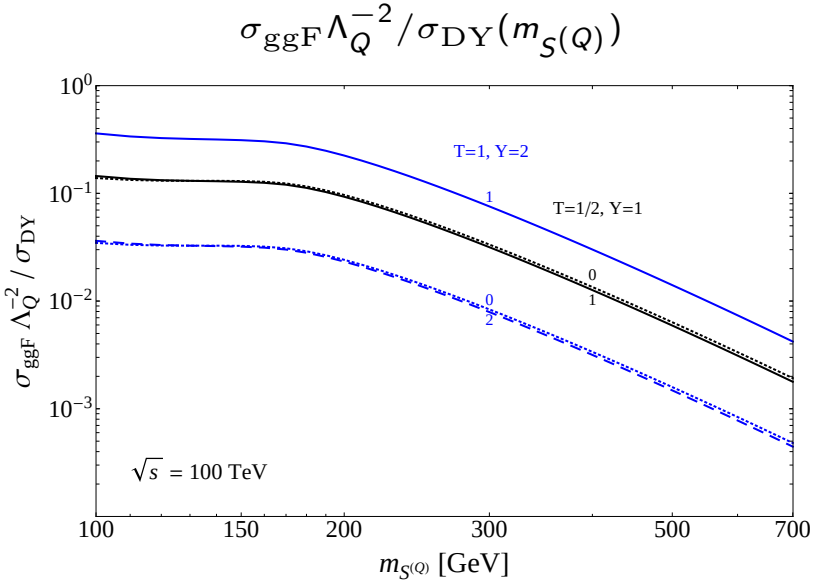
Post-LHC era → Discussion about hypothetical future machines, such as HE-LHC (33 TeV)[#], TLEP or a 100 TeV collider[†].

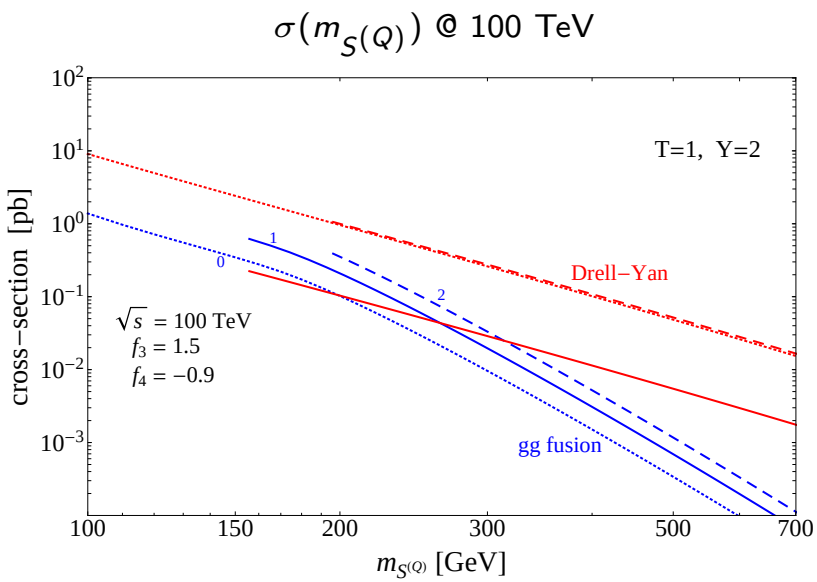


Study impact of gluon fusion on production of new particles at a 100 TeV collider

[#] BSM physics opportunities at 100 TeV, http://indico.cern.ch/event/284800/overview

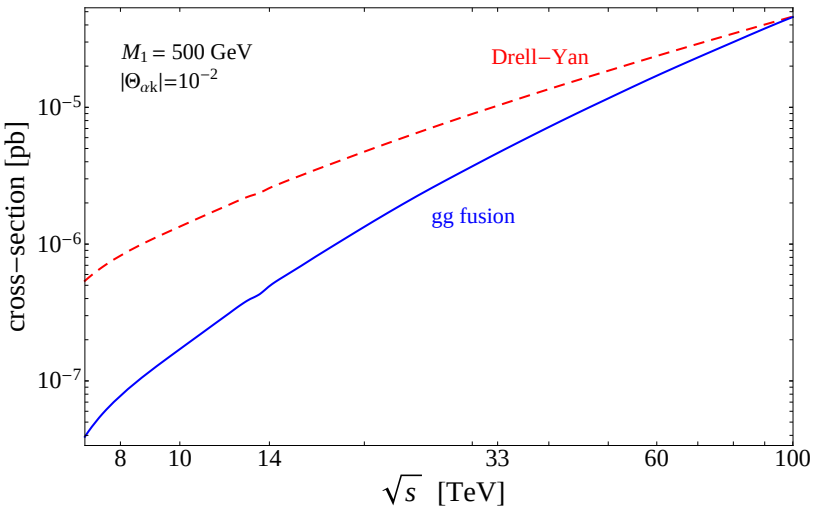
[†] E. Todesco, F. Zimmermann, arXiv:1111.7188 [physics.acc-ph]



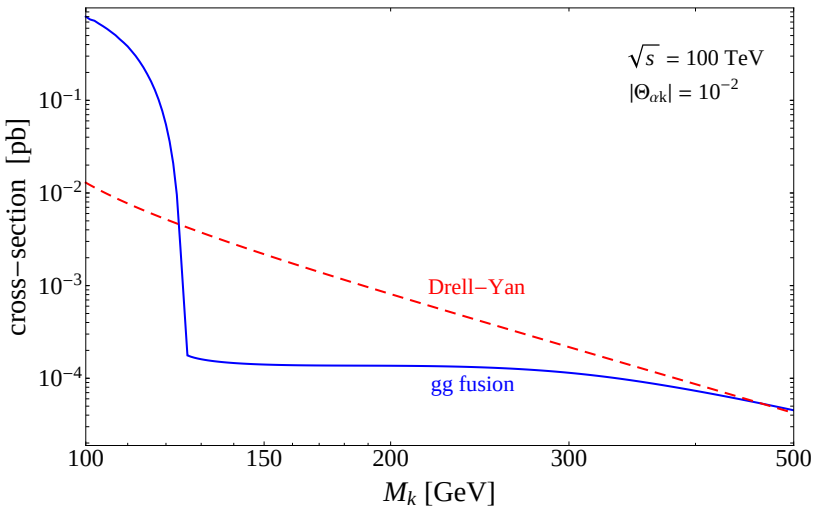


- σ_{ggF} increases about two orders of magnitude compared to 14 TeV, while σ_{DY} increases by about one order of magnitude.
- ggF is dominant for $m_{S(1)}$ up to $\sim$280 GeV.
- Expect copious production of exotic scalars: 10^7 to 10^4 singly charged pairs for masses in the range 100 to 700 TeV and $\int \mathcal{L} = 10$ ab^{-1}.

$\sigma_{\mathrm{SSIII}}(\sqrt{s})$



$\sigma_{\mathrm{SSIII}}(M_k)$ @ 100 TeV



- Relative importance of ggF w.r.t. DY increases by one order of magnitude; Equality at $\sqrt{s} = 100$ TeV.
- ggF is non-negligible for currently allowed range of masses of $\mathcal{E}_k$, $M_k \gtrsim 300$ GeV.
- Expect hundreds of events for $\int \mathcal{L} = 10$ ab^{-1} and $M_k \lesssim 500$ GeV.

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- We investigated the production of exotic scalars and fermions at the LHC via ggF in minimal BSM scenarios.
- Considered in particular U(1)-invariant vev-less scalar models and Seesaw type I and III fermionic models.
- ggF contributes significantly to scalar pair production for $\Lambda_Q \gtrsim \mathcal{O}(1)$.
- In the considered heavy fermion mass range, ggF dominates by far in the resonant region and is non-negligible for large masses.
- In both cases, Higgs mediation can constitute 10% or more at 14 TeV.
- Contribution of Higgs-mediated channel in a 100 TeV collider is generally non-negligible.
- Expect inclusion of correct K factors to strengthen these assertions.

BACKUP SLIDES

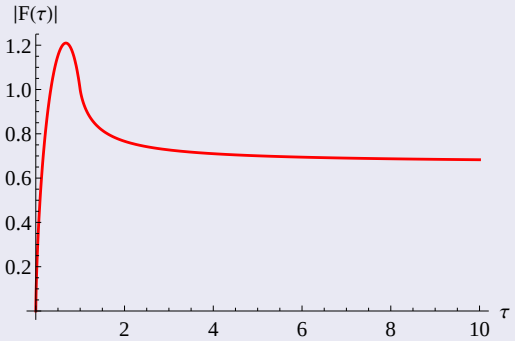
Production via gluon fusion

Effective G-G-H Lagrangian: $\mathcal{L}_{\text{eff}} = \frac{1}{4v} G_H G^a_{\mu\nu} G^{a\,\mu\nu} h$

Effective G-G-H coupling: $G_H = \frac{\alpha_s}{2\pi} \left| \sum_Q F(\tau_Q) \right| \rightarrow \frac{\alpha_s}{2\pi} |F(\tau_t)|, \quad \tau_Q = \frac{4m_Q^2}{P^2}$

Loop function[#]: $F(\tau) = \tau[1 + (1-\tau) f(\tau)]$

$$f(\tau) = \begin{cases} \arcsin^2 \frac{1}{\sqrt{\tau}} & \text{if } \tau \geq 1 \\ -\frac{1}{4}\left[\log\left(\frac{1+\sqrt{1-\tau}}{1-\sqrt{1-\tau}}\right) - i\pi\right]^2 & \text{if } \tau < 1 \end{cases}$$



$\rightarrow \frac{2}{3}$

[#] [H. M. Georgi, S. L. Glashow, M. E. Machacek, D. V. Nanopoulos, PRL **40**, 692 (1978)]

Some models with new scalar multiplets

Minimal Dark Matter	$n \geq 5 \rightarrow$ Accidental global U(1) or Z_2 always present in potential at the renormalizable level. $\Longrightarrow$ Lightest member automatically stable if unbroken. $Y = 2T \rightarrow$ Global U(1) with neutral lightest component of complex multiplet. $Y = 0 \rightarrow$ Global $Z_2 \rightarrow$ Impose U(1) by hand to have a 'next-to-minimal' DM candidate.
VEV hierarchy	Higgs Triplet Model: Global U(1) equivalent to $U(1)_L$, softly broken by μ term (neutrino masses in SS-II). Two-Higgs Doublet Models with soft U(1)-breaking term $\mu^2 \phi_1^\dagger \phi_2$ generated by small vev of additional singlet ϕ_3: $\mu^2 = \mu' \langle \phi_3 \rangle$.
Little Higgs Models	Larger scalar multiplets spontaneously break larger gauge group to SM gauge group $\rightarrow$ Higgs mass stabilization.

☐ parton-parton $\to S^{(Q)}\bar{S}^{(Q)}$

$$\sigma\left(g\,g \to S^{(Q)}\bar{S}^{(Q)};\,\hat{s}\right) = \frac{\Lambda_Q^2\, G_H^2\, \sqrt{\hat{s}}\,\sqrt{\hat{s}-4\,m^2_{S(Q)}}}{4096\,\pi\,\left(m_h^2-\hat{s}\right)^2}$$

$$\sigma\left(u\,\bar{u} \to S^{(Q)}\bar{S}^{(Q)};\,\hat{s}\right) = \frac{\pi\,\alpha_{\rm em}^2\,\hat{s}\,\left(1-4\,m^2_{S(Q)}/\hat{s}\right)^{3/2}}{288\,c_w^4\,s_w^4\,\left(m_Z^2-\hat{s}\right)^2}\left[4\,Q^2\,c_w^4\left(\frac{16\,m_Z^4 s_w^4}{9\,\hat{s}^2}-1\right)+4\left(Q\,c_w^2-\frac{2\,Y\,s_w^2}{3}\right)^2\right.$$
$$\left.+\left(2\,Q\,c_w^2\left(1-\frac{4\,m_Z^2 s_w^2}{3\,\hat{s}}\right)-Y\left(1-\frac{8\,s_w^2}{3}\right)\right)^2+\frac{8}{3}\,Y^2\,s_w^2\left(c_w^2-s_w^2\right)\right]$$

☐ parton-parton $\to \mathcal{N}_k\nu_\alpha/\mathcal{E}_k\bar{\ell}_\alpha$

$$\sigma\left(g\,g \to \mathcal{N}_k\,\nu_\alpha\,;\,\hat{s}\right) = \sigma\left(g\,g \to \mathcal{E}_k\,\overline{\ell_\alpha}\,;\,\hat{s}\right) = \frac{\alpha_{\rm em}\,\left|\Theta_{\alpha k}\right|^2\,G_H^2\,M_k^2\,\left(M_k^2-\hat{s}\right)^2}{512\,s_w^2\,m_W^2\,\left(\left(m_h^2-\hat{s}\right)^2+m_h^2\Gamma_h^2\right)\,v^2}$$

$$\sigma\left(u\,\bar{u} \to \mathcal{N}_k\,\nu_\alpha\,;\,\hat{s}\right) = \sigma\left(u\,\bar{u} \to \mathcal{E}_k\,\overline{\ell_\alpha}\,;\,\hat{s}\right)$$
$$= \frac{\pi\,\alpha_{\rm em}^2\,\left|\Theta_{\alpha k}\right|^2\left(\hat{s}-M_k^2\right)^2\left(M_k^2+2\,\hat{s}\right)}{1296\,c_w^4\,s_w^4\,\left(\hat{s}-m_Z^2\right)^2\,\hat{s}^2}\left(9\,c_w^4-6\,c_w^2\,s_w^2+17\,s_w^4\right)$$