A ubiquitous pseudo-scalar in composite Higgs models

Lara Mason
work in progress with Alan Cornell, Aldo Deandrea, Benjamin Fuks

12 September 2019

LFC19: Strong dynamics for physics within and beyond the Standard Model at LHC and Future Colliders
ECT*

CH models and this talk

- Light scalars in composite Higgs models
- Result from breaking of U(1) symmetry and occur ubiquitously
- New implementation using FeynRules/Madgraph
- Full LO treatment including quark loops in couplings to gauge bosons
- Should not ignore b quark contributions
- A case for targeted searches in the low mass region at the LHC

Introduction

- Composite Higgs models will be accompanied by light states generated by the same dynamics
- First signs of compositeness?
- Possibility to use partial compositeness for (top) mass generation

- We are interested in a theory with an **underlying fermion-gauge completion**
- Motivations: origin of EWSB and addressing the hierarchy problem

This talk: pseudo-scalar which is **always present in models** of this nature due to U(1) breaking

Composite Higgs theories

- Extend the SM
- Introduce strongly coupled gauge fermion sector
- Avoid fundamental scalars (no SO(5)/SO(4)!)

ψ, χ

- Underlying theory in terms of gauge and fermion DOF that confine at low energies
- Higgs bound state arises due to the breaking of flavour symmetry
- Choose scenario where Higgs is a pNGB of the broken symmetry
- How to provide mass to fermions?
- Provides masses to gauge bosons as usual

Global symmetries in the effective low energy model are determined (QCD, U(1)..)

pNGB Higgs

- Consequence of broken global symmetry

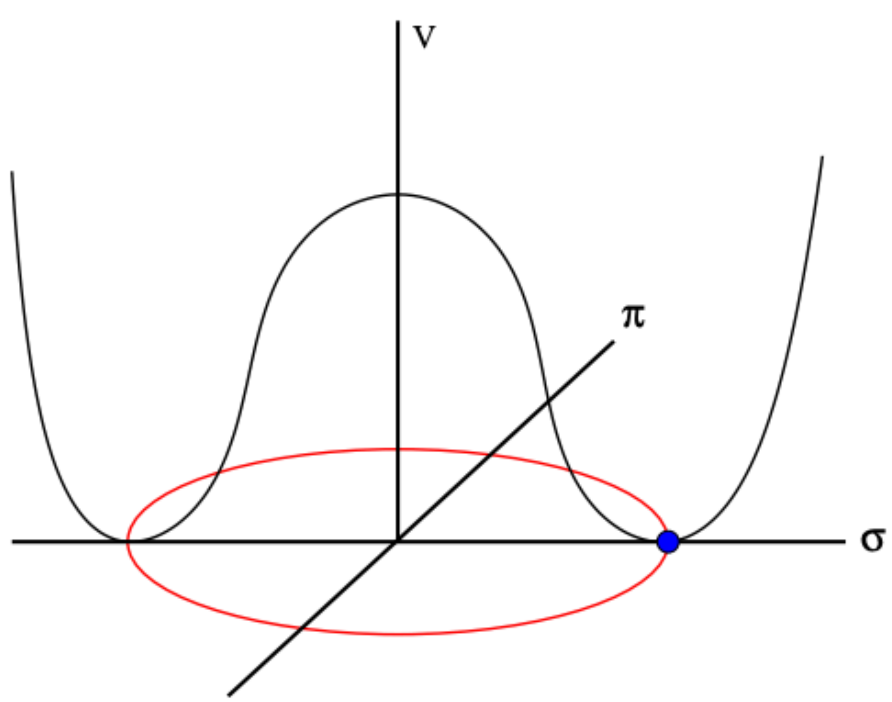
Coset: G_F/H_F

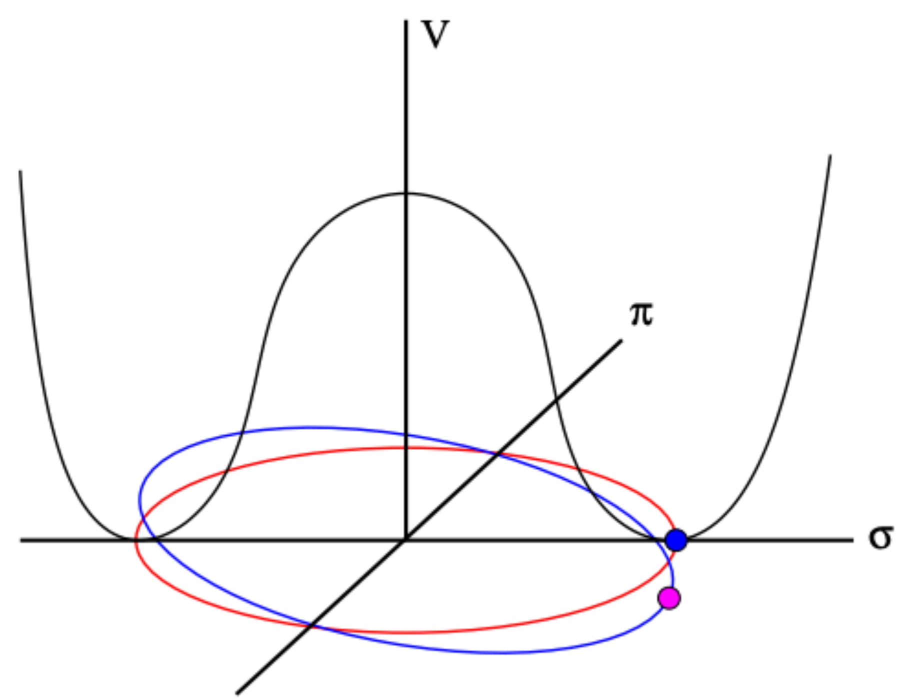
$$H_F \supset G_{cus} \supset G_{SM}$$

$$G_{cus} = SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_X$$

$$G_{SM} = SU(3)_C \times SU(2)_L \times U(1)_Y$$

- Explicit breaking of the global sector by, for example, bare masses for the hyperquarks





This model (+ new implementation)

Eur. Phys. J. C (2018) 78:724
https://doi.org/10.1140/epjc/s10052-018-6183-4

THE EUROPEAN PHYSICAL JOURNAL C

CrossMark

Regular Article - Theoretical Physics

Revealing timid pseudo-scalars with taus at the LHC

Giacomo Cacciapaglia[1,2,a], **Gabriele Ferretti**[3,b], **Thomas Flacke**[4,c], **Hugo Serôdio**[5,d]

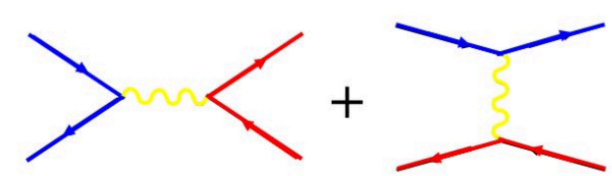
[1] Université de Lyon, Lyon, France
[2] Université Lyon 1, CNRS/IN2P3, UMR5822, IPNL, 69622 Villeurbanne Cedex, France
[3] Department of Physics, Chalmers University of Technology,, Fysikgården 41296 Göteborg, Sweden
[4] Center for Theoretical Physics of the Universe, Institute for Basic Science (IBS), Daejeon 34126, Korea
[5] Department of Astronomy and Theoretical Physics, Lund University, SE-223 62 Lund, Sweden

Received: 17 April 2018 / Accepted: 23 August 2018 / Published online: 6 September 2018

FEYNRULES 2.0- A complete toolbox for tree-level phenomenology

Adam Alloul[a], Neil D. Christensen[b], Céline Degrande[c,d], Claude Duhr[d], Benjamin Fuks[e,f]

MadGraph + MadEvent



Automated Tree-Level Feynman Diagram, Helicity Amplitude, and Event Generation

arXiv.org > hep-ph > arXiv:1902.06890

High Energy Physics – Phenomenology

Light scalars in composite Higgs models

G.Cacciapaglia, G.Ferretti, T.Flacke, H.Serôdio

(Submitted on 19 Feb 2019)

This model: SM loops, full LO

Underlying fermions

We have ψ, χ in two different irreps of the hypercolour group

EW-charged ψ: generate the Higgs and EW symmetry breaking upon condensation
multiplicity matches minimal coset

QCD χ: partial compositeness
carry QCD colour and hypercharge

Once the underlying dynamics are specified, we may only have the following patterns

$$SU(N_f)/Sp(N_f)$$

$$SU(N_f)/SO(N_f)$$

$$SU(N_f) \times SU(N_f)/SU(N_f)$$

And we find that our minimal cosets are $SU(4)/Sp(4), \quad SU(5)/SO(5)$ and $SU(4) \times SU(4)/SU(4)$

Partial Compositeness

$$\mathcal{L} \supseteq y_L \bar{q}_L \Psi_{q_L} + y_R \bar{\Psi}_{t_R} t_R + h.c$$

- Cannot accommodate enough partners to realise PC for all fermions:
- Spin-1/2 top partners
- Top quark mixes with a composite state of the new strong sector with the same quantum numbers: suppresses FCNC and CP-violating terms

$$\psi\chi\chi \qquad \psi\psi\chi$$

Chimera baryons - tend to be heavy and beyond the reach of the LHC

Models

- M1-M12 including partial compositeness for the top
- Varying group structures
- Limit number of fermions so we don't lose asymptotic freedom
- HC: confining gauge interactions
- Custodial symmetry preserved
- Coefficients are computable: determined by the dimension of the underlying fermionic representation.

Ingredients: HC group, choice of fermion representations, EW coset, QCD coset

Models

Coset	HC	ψ	χ	$-q_\chi/q_\psi$	Baryon	Name	Lattice
$\frac{SU(5)}{SO(5)} \times \frac{SU(6)}{SO(6)}$	SO(7)	$5 \times \mathbf{F}$	$6 \times \mathbf{Sp}$	5/6	$\psi\chi\chi$	M1	
	SO(9)			5/12		M2	
	SO(7)	$5 \times \mathbf{Sp}$	$6 \times \mathrm{F}$	5/6	$\psi\psi\chi$	M3	
	SO(9)			5/3		M4	
$\frac{SU(5)}{SO(5)} \times \frac{SU(6)}{Sp(6)}$	Sp(4)	$5 \times \mathbf{A}_2$	$6 \times \mathbf{F}$	5/3	$\psi\chi\chi$	M5	$\surd$
$\frac{SU(5)}{SO(5)} \times \frac{SU(3)^2}{SU(3)}$	SU(4)	$5 \times \mathbf{A}_2$	$3 \times (\mathbf{F}, \overline{\mathbf{F}})$	5/3	$\psi\chi\chi$	M6	$\surd$
	SO(10)	$5 \times \mathbf{F}$	$3 \times (\mathbf{Sp}, \overline{\mathbf{Sp}})$	5/12		M7	
$\frac{SU(4)}{Sp(4)} \times \frac{SU(6)}{SO(6)}$	Sp(4)	$4 \times \mathbf{F}$	$6 \times \mathbf{A}_2$	1/3	$\psi\psi\chi$	M8	$\surd$
	SO(11)	$4 \times \mathbf{Sp}$	$6 \times \mathbf{F}$	8/3		M9	
$\frac{SU(4)^2}{SU(4)} \times \frac{SU(6)}{SO(6)}$	SO(10)	$4 \times (\mathbf{Sp}, \overline{\mathbf{Sp}})$	$6 \times \mathbf{F}$	8/3	$\psi\psi\chi$	M10	
	SU(4)	$4 \times (\mathbf{F}, \overline{\mathbf{F}})$	$6 \times \mathbf{A}_2$	2/3		M11	$\surd$
$\frac{SU(4)^2}{SU(4)} \times \frac{SU(3)^2}{SU(3)}$	SU(5)	$4 \times (\mathbf{F}, \overline{\mathbf{F}})$	$3 \times (\mathbf{A}_2, \overline{\mathbf{A}_2})$	4/9	$\psi\psi\chi$	M12	

G. Cacciapaglia, G. Ferretti, T. Flacke, and H. Serôdio *Front.in Phys.*, vol. 7, p. 22, 2019.

Particle Spectrum

Various EW/QCD resonances are possible

Rich spectrum due to fermions with two representations

$$< \chi\chi >$$

$$< \psi\psi >$$

$< \psi\chi >$ never forms so HC group remains unbroken

U(1) singlets: mass eigenstates $\{a, \eta'\}$

Coupling to gluons via the Wess-Zumino-Witten anomaly term

Two types of fermions in the underlying theory

$\Longrightarrow$ there is always a combination of the two U(1)'s

which is non anomalous with respect to the HC group

$\Longrightarrow$ the associated pseudo-scalar will be light

Ubiquitous U(1) scalars

We will always have singlet pseudo-scalars associated to global U(1) symmetries, (and a coloured octet arising from the presence of coloured underlying fermions)

$$a, \eta', \pi_8$$

a, η' non trivial mixing

$$\sin \alpha_{dec} = -\frac{1}{\sqrt{1 + \frac{q_\psi^2 N_\psi f_\psi^2}{q_\chi^2 N_\chi f_\chi^2}}}$$

The pNGB $\tilde{a}$ is naturally **lighter** than the typical confinement scale, and the orthogonal $\tilde{\eta}$ is heavier

ψ condensing: the axial $U(1)_\psi$ would be spontaneously broken, but also explicitly broken by a ABJ anomaly $\Longrightarrow$ heavy Goldstone.
Also have χ fermions condensing $\Longrightarrow$ additional axial $U(1)_\chi$ spontaneously broken.
Possible to construct an ABJ anomaly free linear combination $U(1)_a$: associated pseudo-scalar will be light

U(1) pseudo-scalar *a*

- Light: mass up to 100 GeV
- Small couplings to SM particles
- Singlet under SM symmetries
- Couples directly to SM fermions

$$\mathcal{L} = \frac{1}{2}\left(\partial_\mu a\right)\left(\partial^\mu a\right) - \frac{1}{2} m_a^2 a^2 - \Sigma_f \frac{i C_f m_f}{f_a} a \bar{\Psi}_f \gamma^5 \Psi_f + \frac{g_s^2 K_g}{16\pi^2 f_a} a G^a_{\mu\nu} \tilde{G}^{a\mu\nu} + \frac{g^2 K_W}{16\pi^2 f_a} a W^i_{\mu\nu} \tilde{W}^{i\mu\nu} + \frac{g'^2 K_B}{16\pi^2 f_a} a B_{\mu\nu} \tilde{B}^{\mu\nu},$$

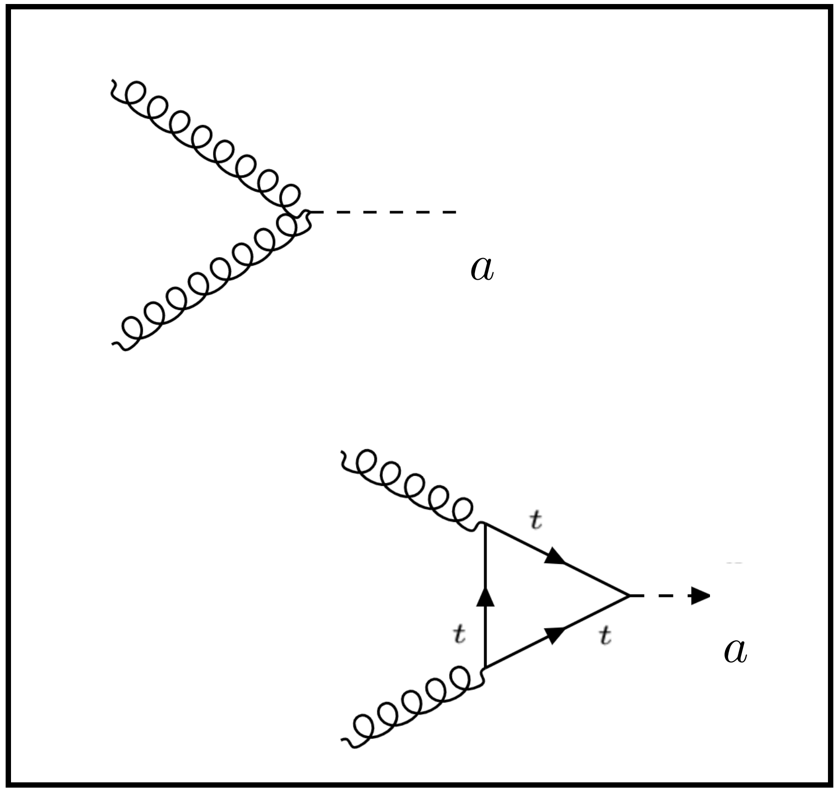
$$f_a = \sqrt{\frac{q_\psi^2 N_\psi f_\psi^2 + q_\chi^2 N_\chi f_\chi^2}{q_\psi^2 + q_\chi^2}}$$

$$C_t^a = c_5 \left(\frac{n_\psi}{\sqrt{N_\psi}} \cos\alpha + \frac{f_\psi}{f_\chi} \frac{n_\chi}{\sqrt{N_\chi}} \sin\alpha \right)$$

$$\mathcal{L}_{haa} = \frac{3 C_t^2 m_t^2 \kappa_t}{8\pi^2 f_a^2 v} \log \frac{\Lambda^2}{m_t^2} h \left(\partial_\mu a\right)\left(\partial^\mu a\right),$$

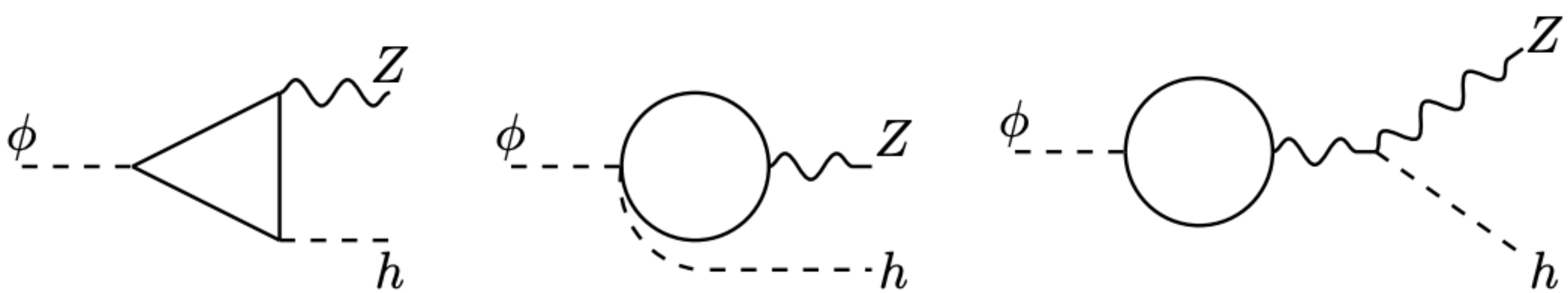
$$\mathcal{L}_{hZa} = \frac{3 C_t m_t^2 g_A}{2\pi^2 f_a v} \left(\kappa_t - \kappa_V\right) \log \frac{\Lambda^2}{m_t^2} h \left(\partial_\mu a\right) Z^\mu .$$

Coupling to bosons

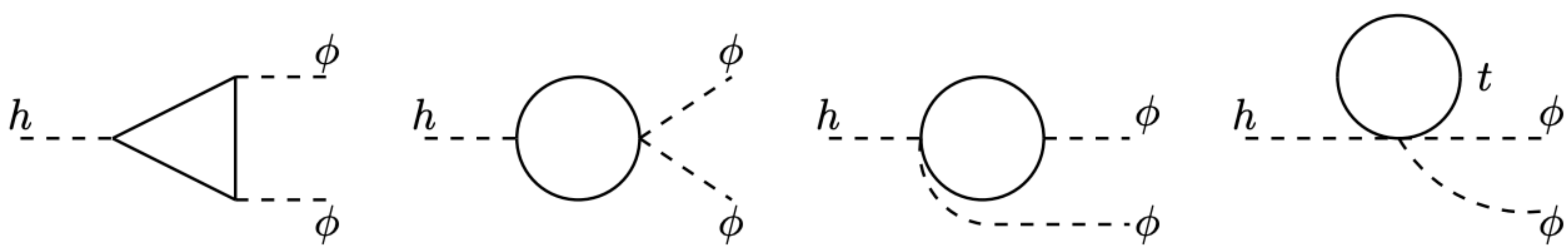


$$K_V^a = c_5 \left(\frac{C_V^\psi}{\sqrt{N_\psi}} \cos\alpha + \frac{f_\psi}{f_\chi} \frac{C_V^\chi}{\sqrt{N_\chi}} \sin\alpha \right)$$

- Anomalous couplings to gauge bosons



- Loop couplings with the Higgs and Z



G. Cacciapaglia, G. Ferretti, T. Flacke, and H. Serôdio *Front.in Phys.*, vol. 7, p. 22, 2019.

Coupling to gauge bosons: loops

There will be a contribution to the coupling to gauge bosons thanks to loops of quarks

$$\tau = \frac{4m_f^2}{M_a^2} \longrightarrow \sigma_0 = \frac{\sqrt{2}G_F}{256\pi}\alpha_s^2 \left|\kappa_g + \sum_f A(\tau_f)\right|^2$$

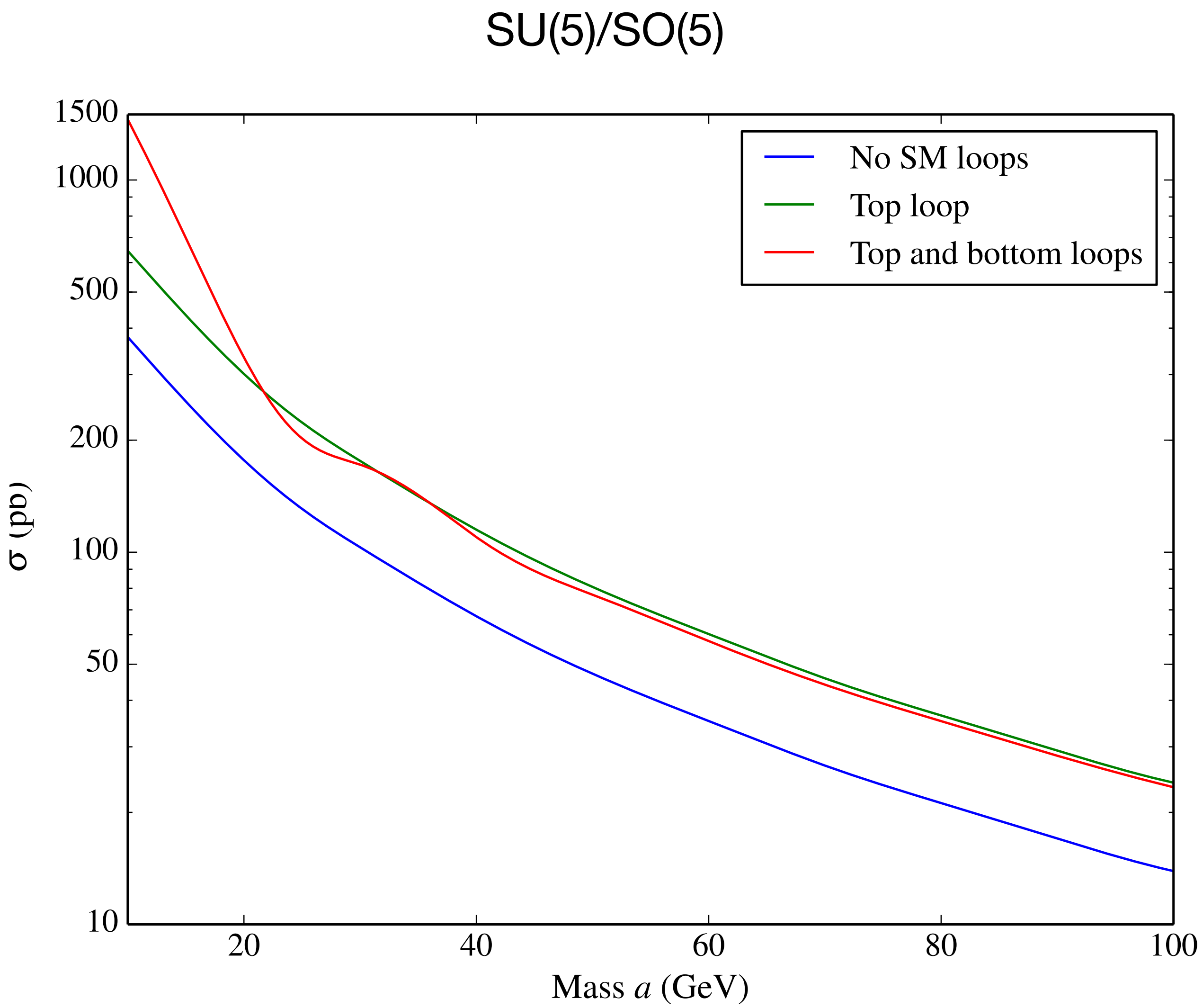
$$A(\tau) = \tau f(\tau)$$ Differs from Higgs result as now we are dealing with a pseudo-scalar

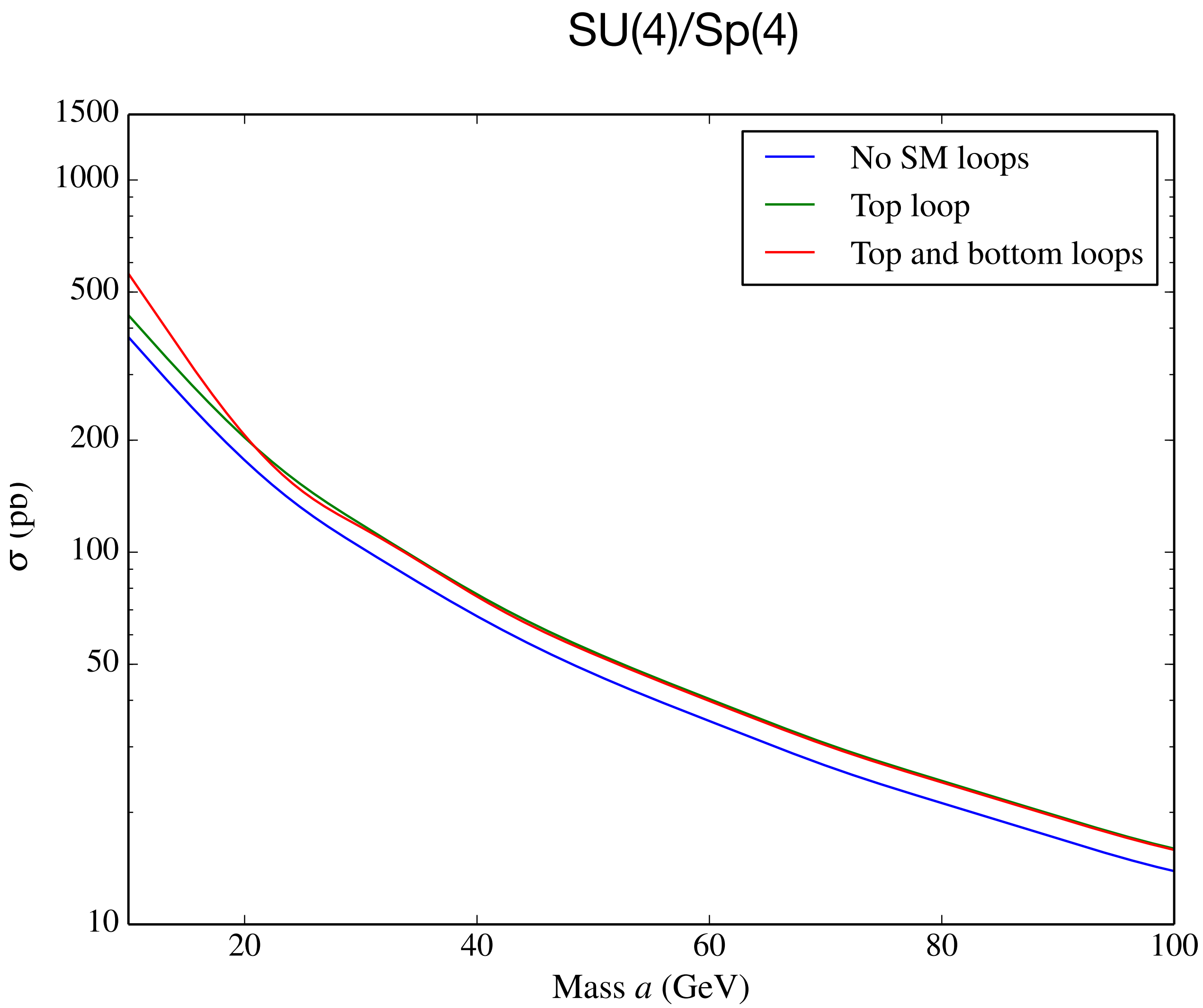
$$f(\tau) = \begin{cases} -\frac{1}{4}\left[\log\left(\frac{1+\sqrt{1-\tau}}{1-\sqrt{1-\tau}}\right) - i\pi\right]^2 & \text{if } \tau < 1 \\ \arcsin^2\left(\frac{1}{\sqrt{\tau}}\right) & \text{if } \tau \geq 1 \end{cases}$$

$\tau < 1$ ← **bottom**

$\tau \geq 1$ ← **top**

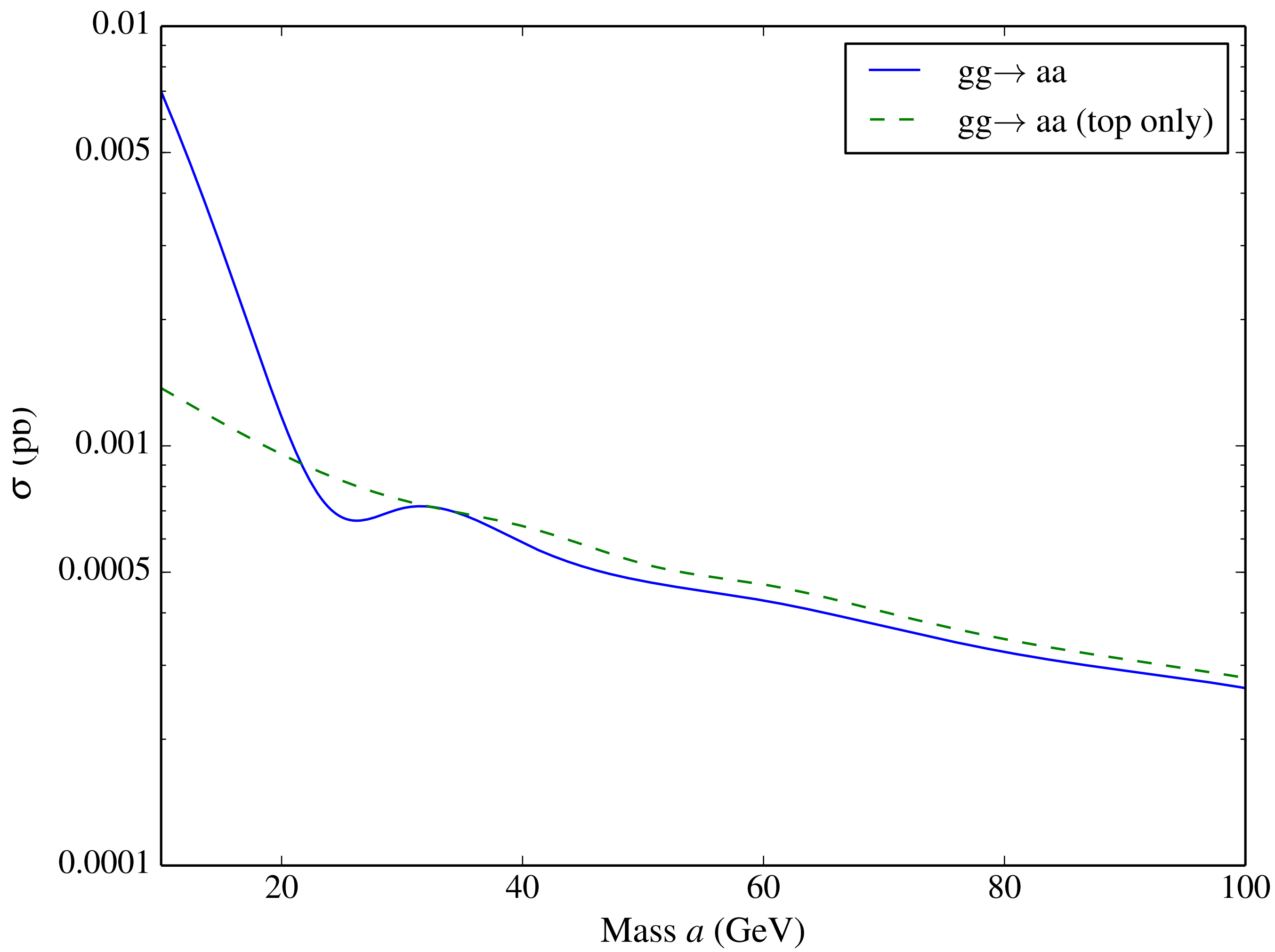
Production Modes: ggF single production

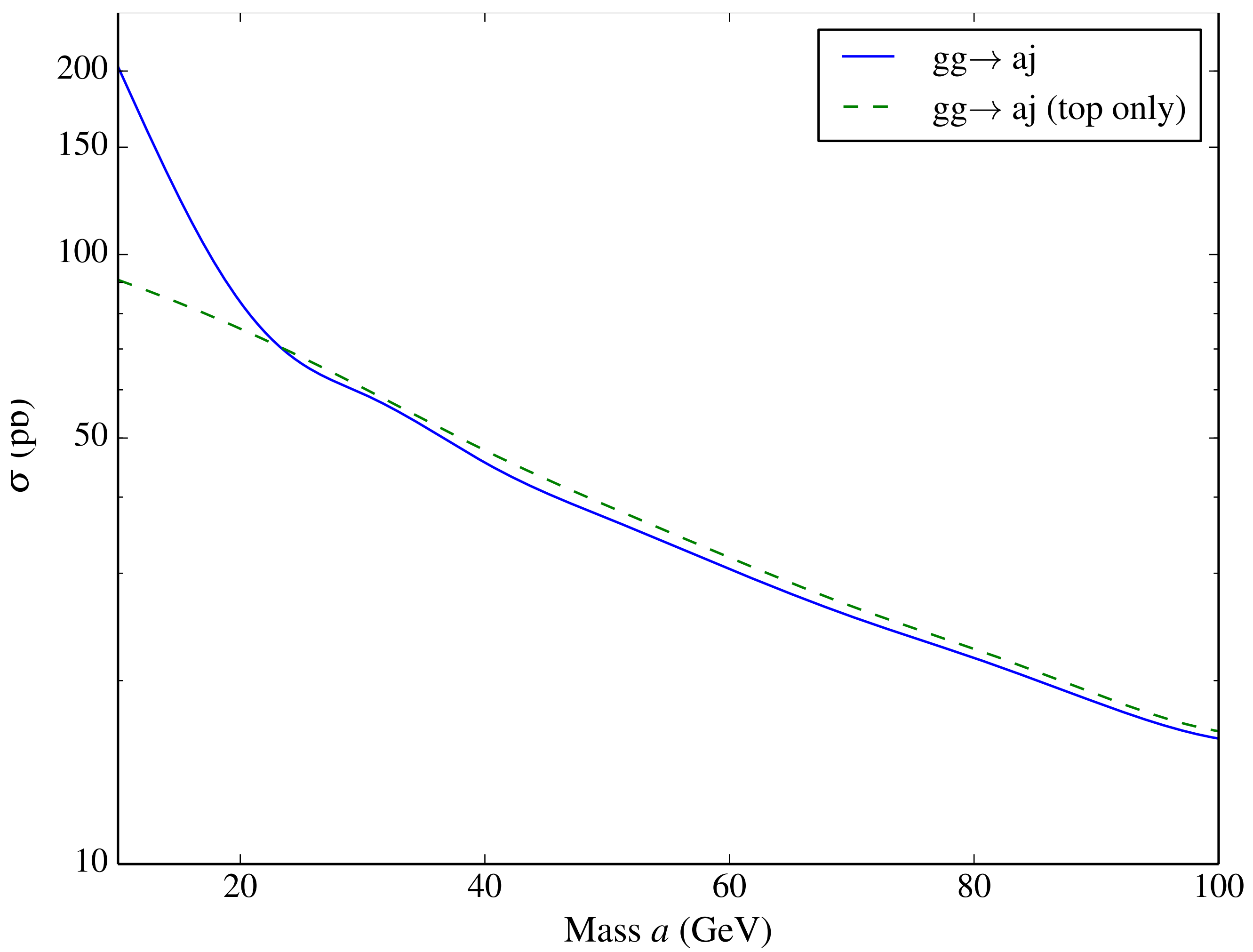




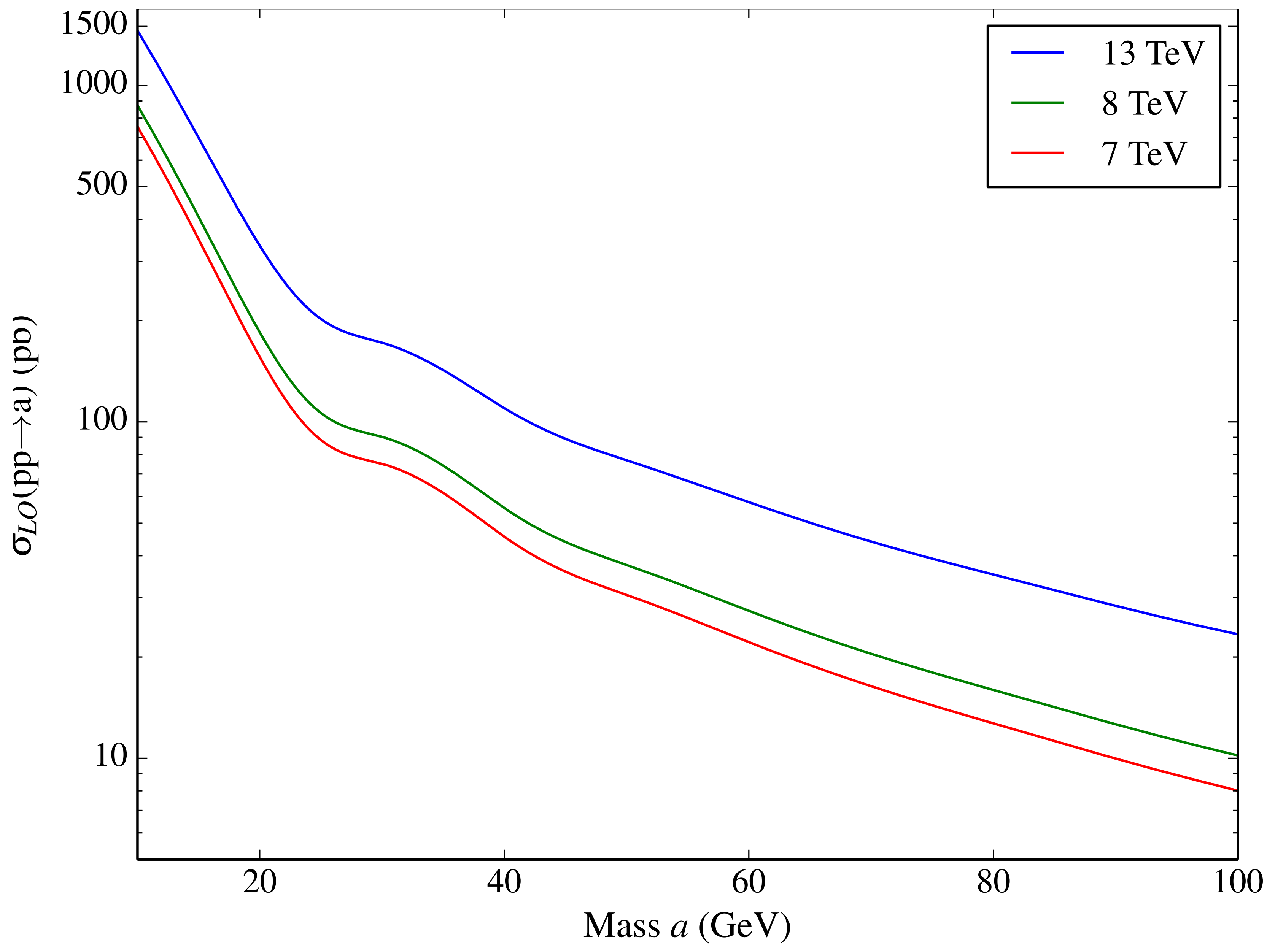
Production Modes

Gluon-gluon fusion alternative production modes

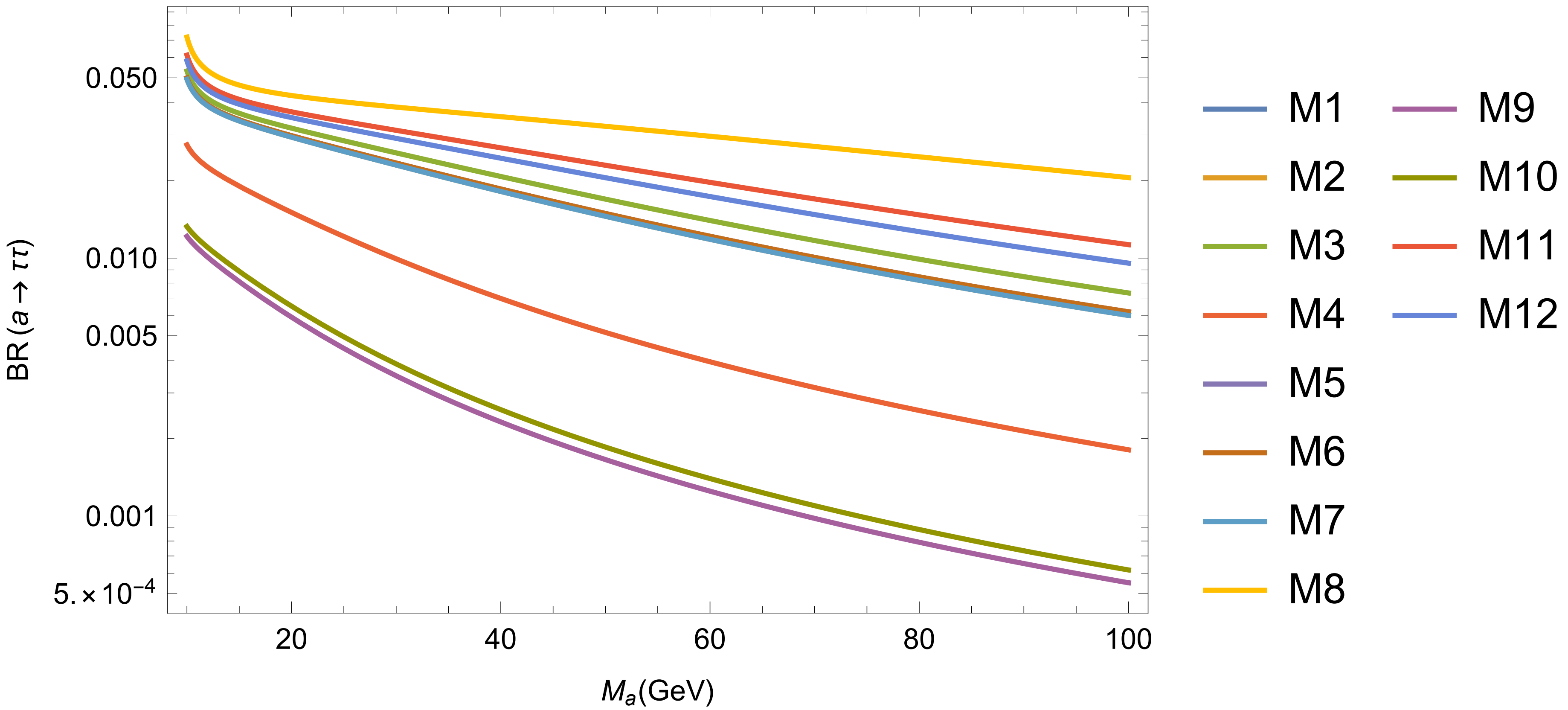




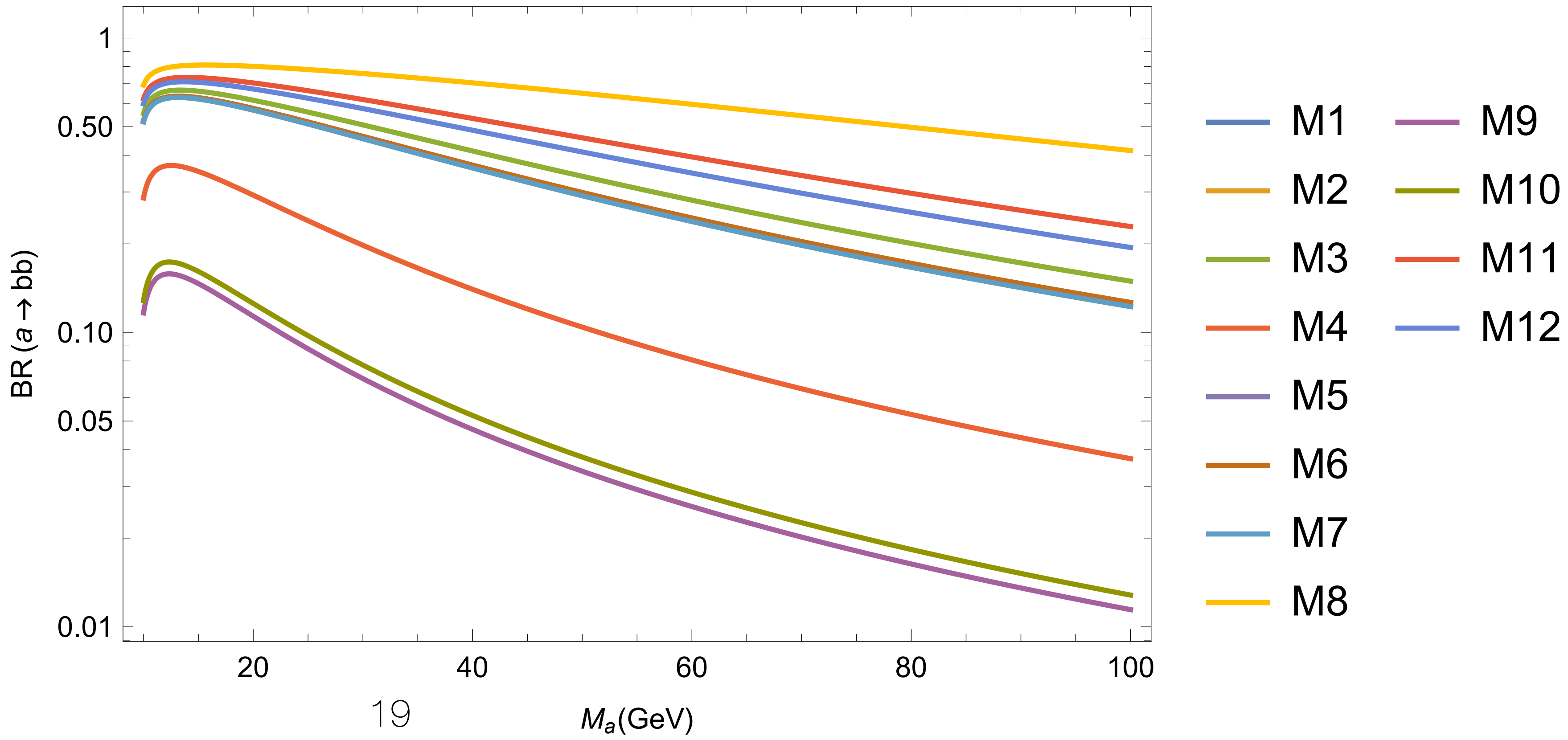
LHC Production Modes



Decay modes

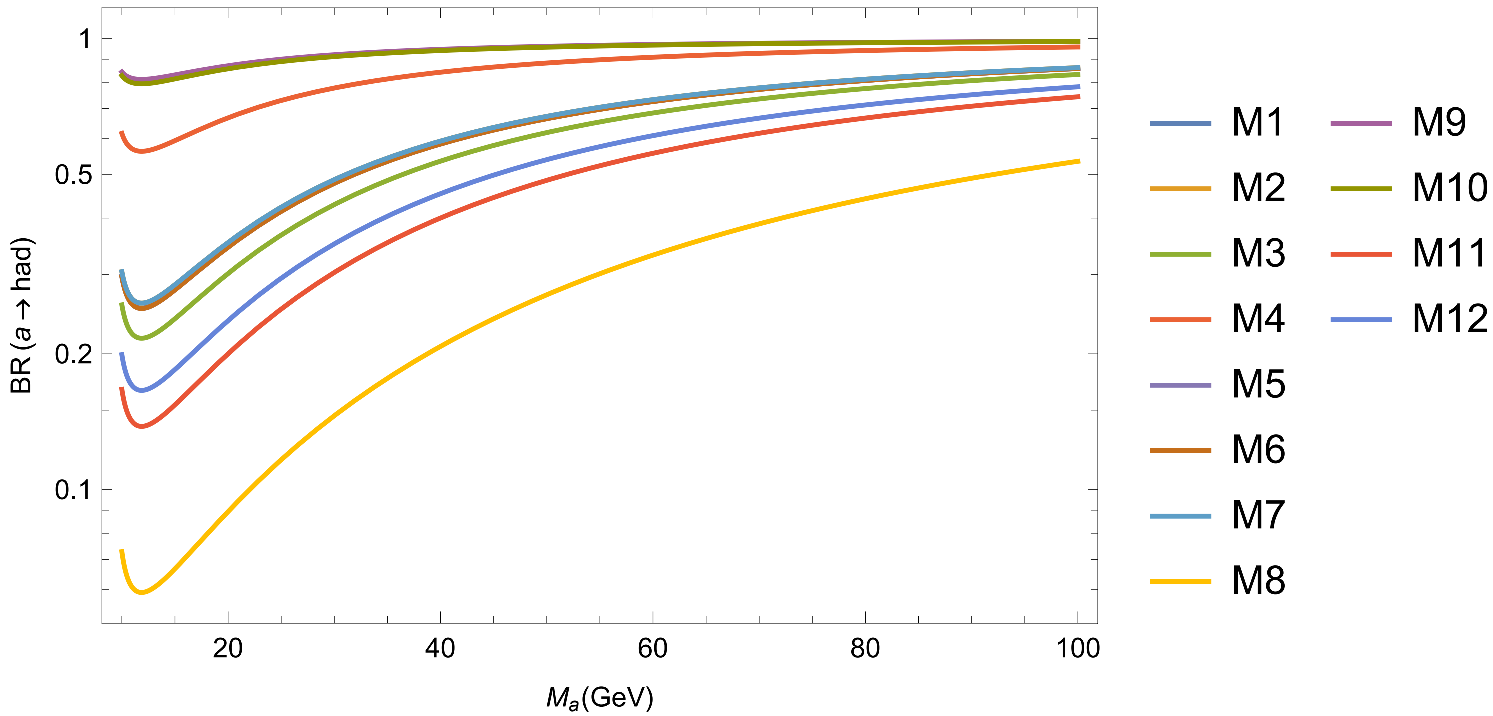


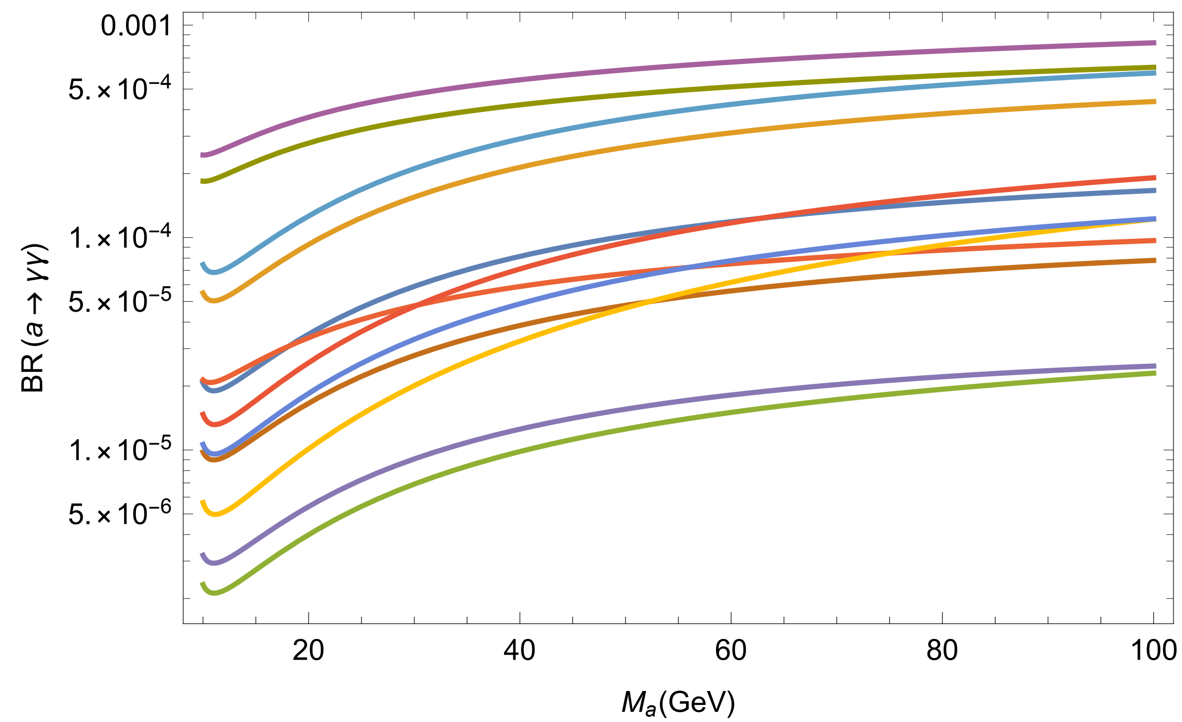
BR (a → ττ)
0.050
0.010
0.005
0.001
5. × 10^-4
20
40
60
80
100
M_a(GeV)
M1
M2
M3
M4
M5
M6
M7
M8
M9
M10
M11
M12

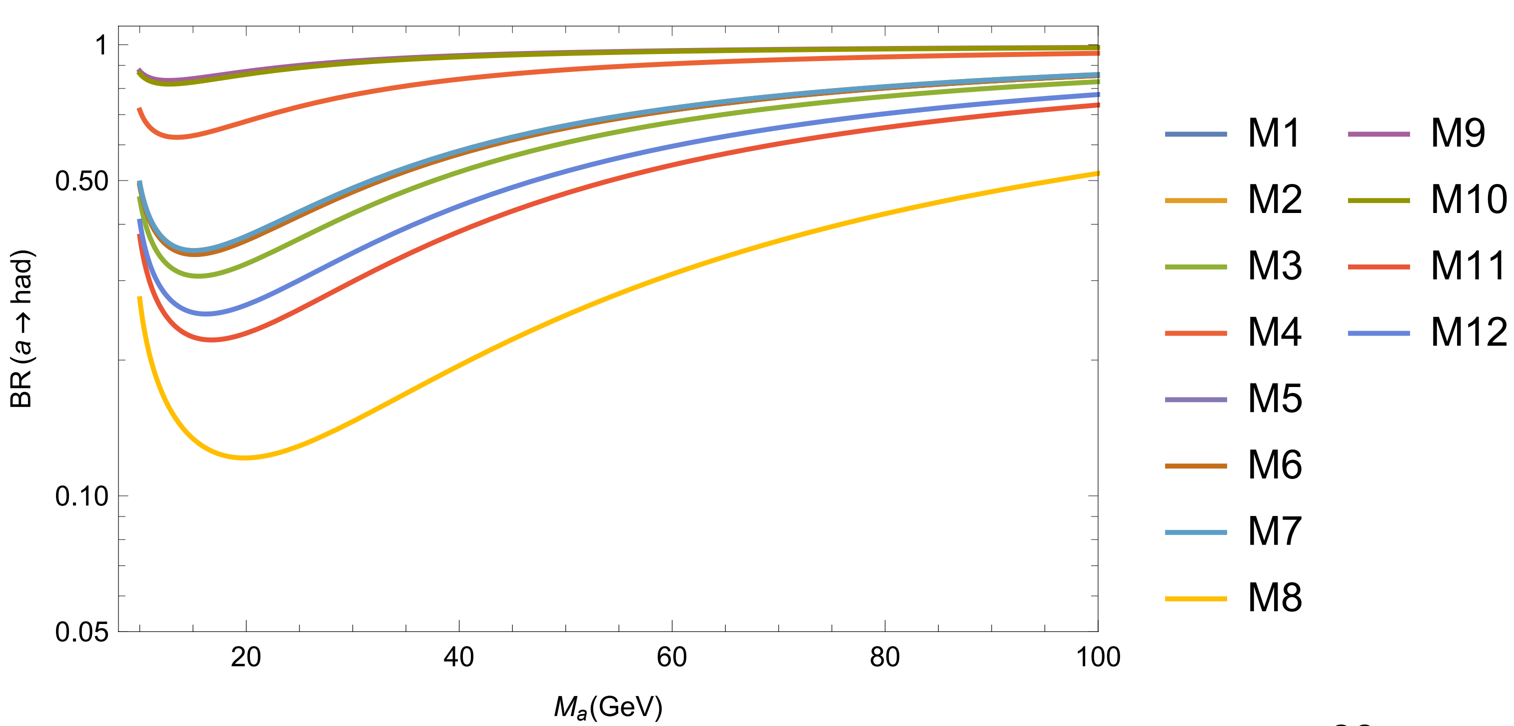


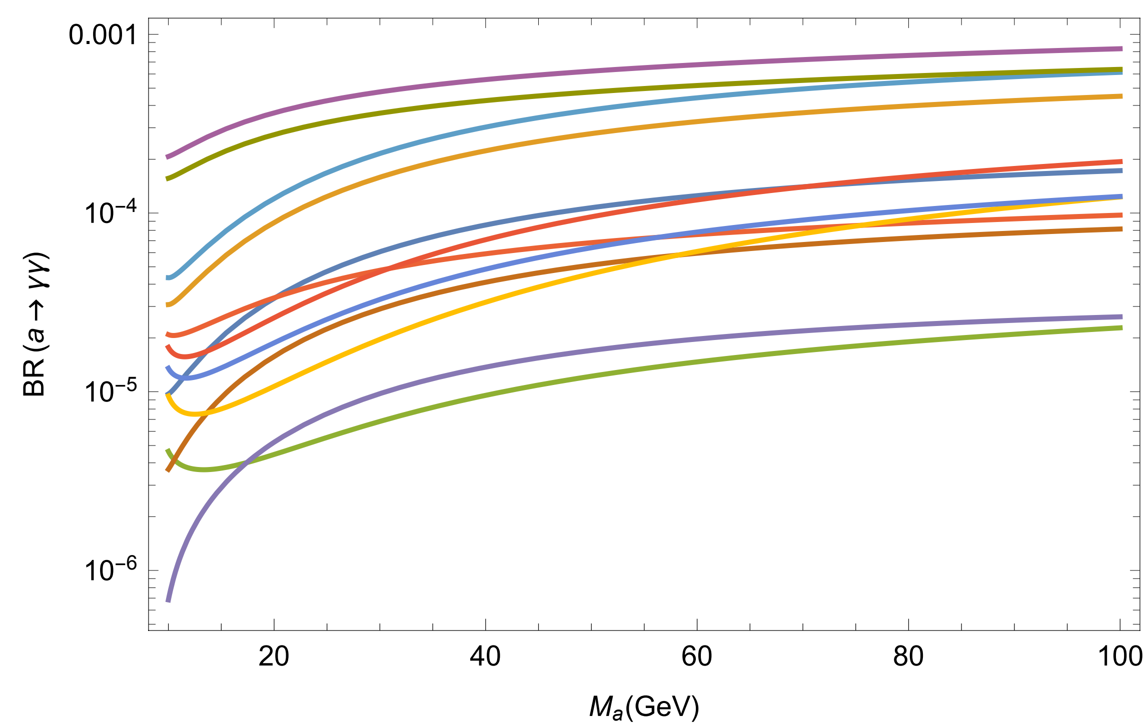
BR (a → bb)
1
0.50
0.10
0.05
0.01
20
40
60
80
100
M_a(GeV)
M1
M2
M3
M4
M5
M6
M7
M8
M9
M10
M11
M12

The case for including b quarks

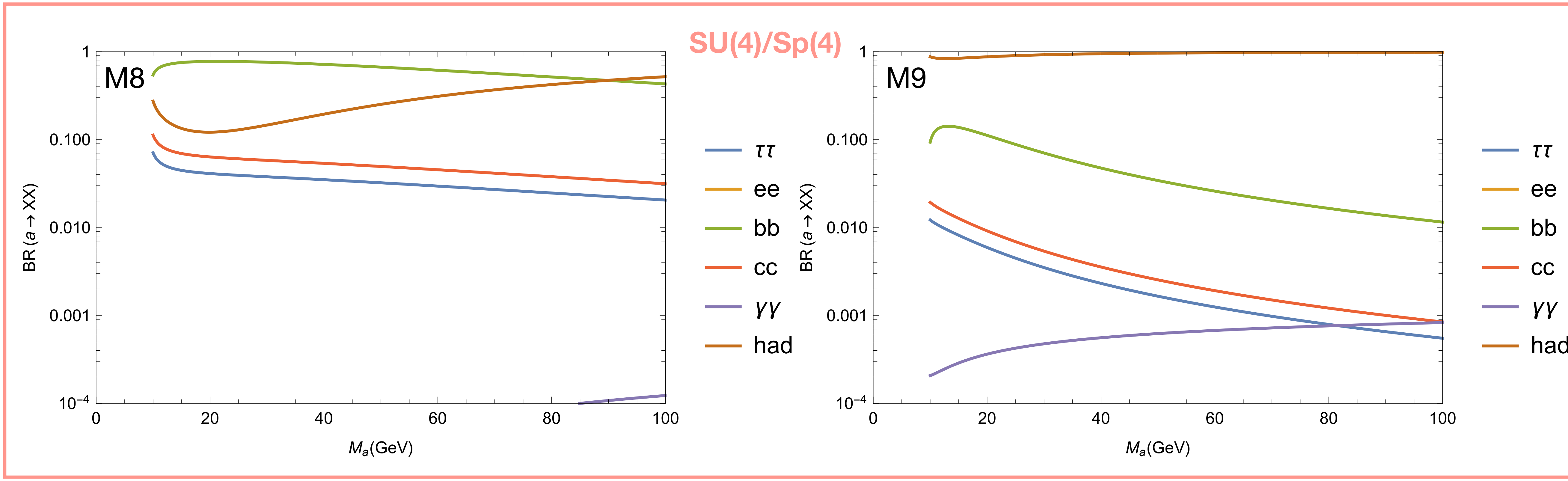


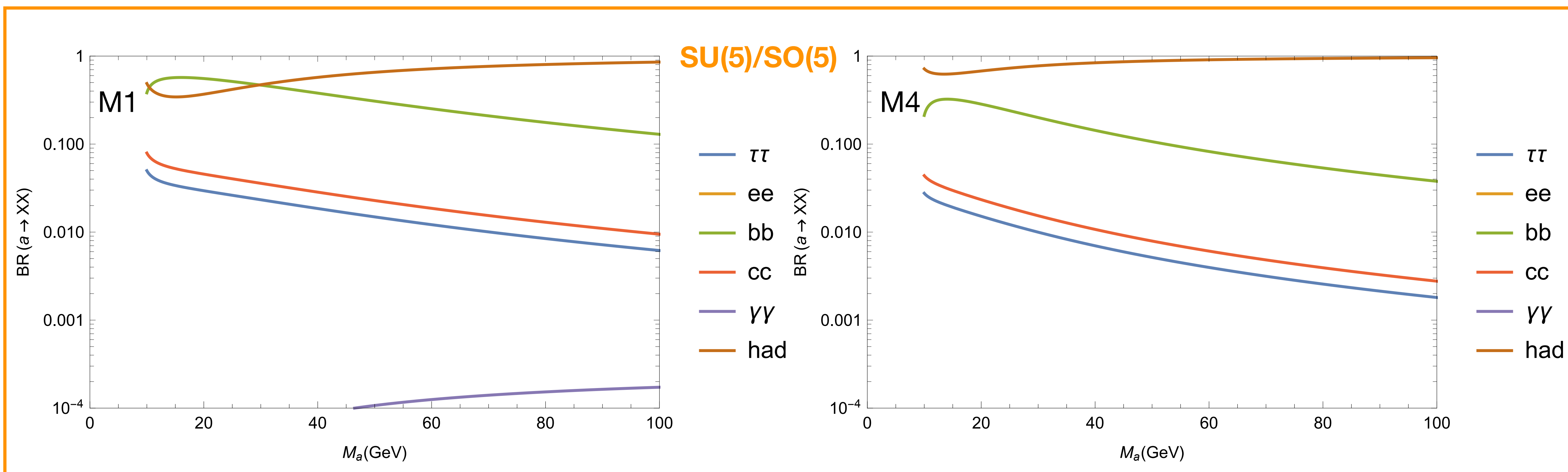






A model comparison

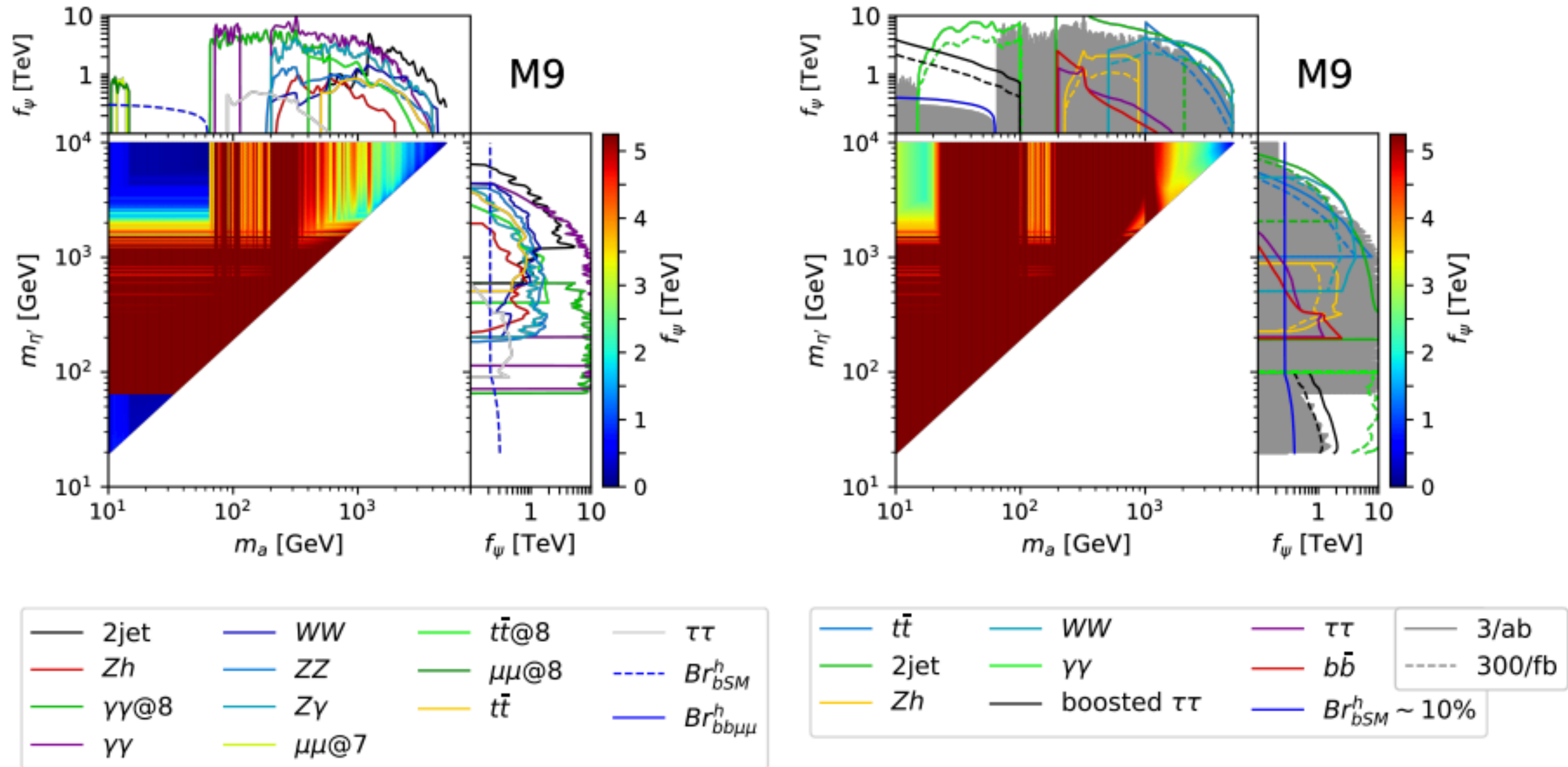




Future Searches

Light scalars - are they still viable?

We can use the large amount of data to be processed from the LHC to look at these lower mass windows



G. Cacciapaglia, G. Ferretti, T. Flacke, and H. Serôdio *Front.in Phys.*, vol. 7, p. 22, 2019.

Thank you

Couplings

	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	M11	M12
K_g	−7.2	−8.7	−6.3	−11.	−4.9	−4.9	−8.7	−1.6	−10.	−9.4	−3.3	−4.1
K_W	7.6	12.	8.7	12.	3.6	4.4	13.	1.9	5.6	5.6	3.3	4.6
K_B	2.8	5.9	−8.2	−17.	0.40	1.1	7.3	−2.3	−22.	−19.	−5.5	−6.3
C_f	2.2	2.6	2.2	1.5	1.5	1.5	2.6	1.9	0.70	0.70	1.7	1.8
$\frac{f_a}{f_\psi}$	2.1	2.4	2.8	2.0	1.4	1.4	2.4	2.8	1.2	1.5	3.1	2.6

G. Cacciapaglia, G. Ferretti, T. Flacke, and H. Serôdio *Front.in Phys.*, vol. 7, p. 22, 2019.