Future collider prospects for a ubiquitous composite pseudo-scalar

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

HEPP: January 2020

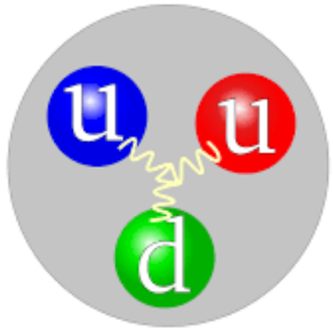
CH models and this talk

CH models:

- BSM
- A new strongly coupled sector which extends the SM
- Higgs emerges as a bound state of a broken global flavour symmetry
- Additional resonances generated by the same dynamics

- Full LO treatment including quark loops in couplings to gauge bosons
- A case for targeted searches in the low mass region at the LHC/ future lepton colliders

A composite Higgs model



(Think QCD!)

10^{19} GeV — **the Planck scale**

Free fermions

$G \to H$

~1000 GeV — **the compositeness scale** — Phase transition 1

Bound states

246 GeV — **the EW scale** — Phase transition 2

A composite Higgs model

Global hyper colour group: G_{HC}

$\downarrow$

Global flavour symmetry of fermion ψ **:** G

$\downarrow$

$G \to H$

A composite Higgs model

Global hyper colour group: G_{HC}

$\downarrow$

Global flavour symmetry of fermion ψ **:** G

$\downarrow$

$G \to H$

Goldstone's theorem $\to$

pNGB produced in the breaking when G was initially explicitly broken by some small amount

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

$$SU(2N_f) \to SO(2N_f)$$

$$SU(2N_f) \to Sp(2N_f)$$

$$SU(N_f) \times SU(N_f) \to SU(N_f)$$

Global symmetries

Global symmetries in the effective low-energy model are determined:

1. There always exists a non-anomalous $U(1)$ charge

- Acts on both species of fermions
- Broken by (at least) the chiral condensate in the EW (Higgs) sector of the theory

Results in a light pNGB, singlet under all SM gauge symmetries

Direct searches may provide first evidence of new physics

Mass generation for fermions

In a general composite Higgs model, mass is generated for SM fermions through four fermion interactions or partial compositeness.

Requires fermions in two different irreps of HC group (ψ, χ)

- Cannot accommodate enough partners to realise PC for all fermions

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

Spin-1/2 top partners:

- Fermions in multiple representations
- Composite states mixing linearly with top
- Tend to be heavy

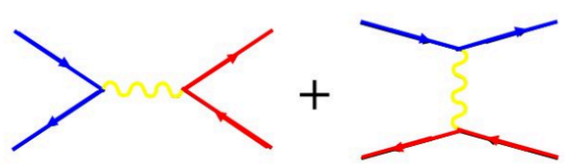
$\psi\psi\chi$
$\psi\chi\chi$

This model (+ new implementation)

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

FeynRules:

-a Mathematica-based package

-implements particle physics models

- Input: a list of fields, parameters and a Lagrangian (any model you like)
- Calculates the Feynman rules
- Output: for MC generators (like MadGraph)

This model: SM loops, full LO

Models

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

Structure determined by the HC irreps of the fermions

A nice feature: all coefficients in this model are completely computable! Based entirely on characteristics of underlying fermions

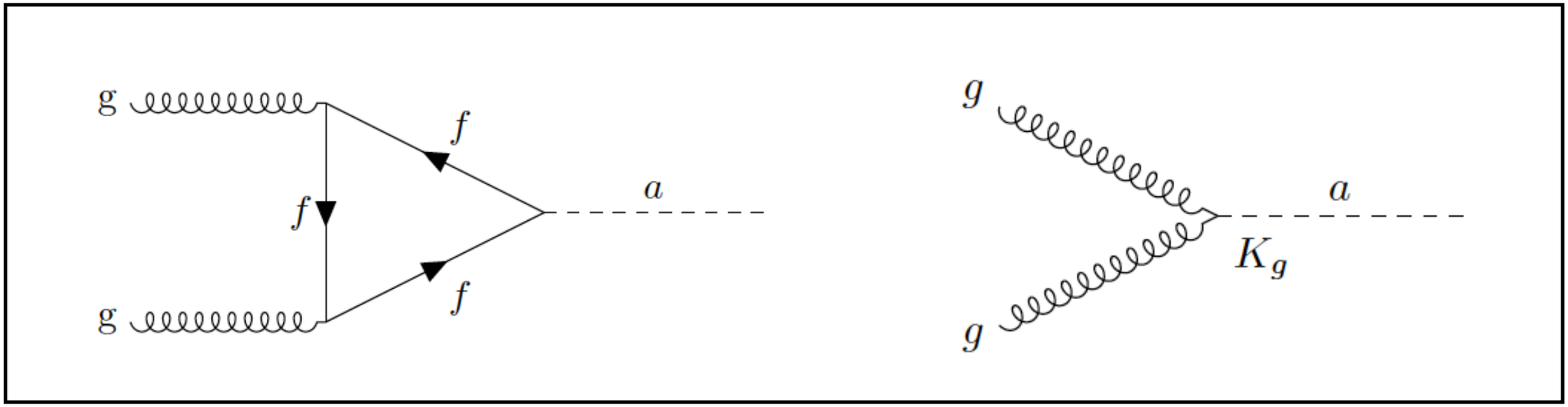
Coset	HC	ψ	χ	$-q_\chi/q_\psi$	Baryon	Name	Lattice
$\frac{SU(5)}{SO(5)} \times \frac{SU(6)}{SO(6)}$	SO(7)	$5 \times \mathbf{F}$	$6 \times \mathbf{Sp}$	5/6	$\psi\chi\chi$	M1	
	SO(9)			5/12		M2	
	SO(7)	$5 \times \mathbf{Sp}$	$6 \times \mathrm{F}$	5/6	$\psi\psi\chi$	M3	
	SO(9)			5/3		M4	
$\frac{SU(5)}{SO(5)} \times \frac{SU(6)}{Sp(6)}$	Sp(4)	$5 \times \mathbf{A}_2$	$6 \times \mathbf{F}$	5/3	$\psi\chi\chi$	M5	✓
$\frac{SU(5)}{SO(5)} \times \frac{SU(3)^2}{SU(3)}$	SU(4)	$5 \times \mathbf{A}_2$	$3 \times (\mathbf{F}, \overline{\mathbf{F}})$	5/3	$\psi\chi\chi$	M6	✓
	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	✓
	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	✓
$\frac{SU(4)^2}{SU(4)} \times \frac{SU(3)^2}{SU(3)}$	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.

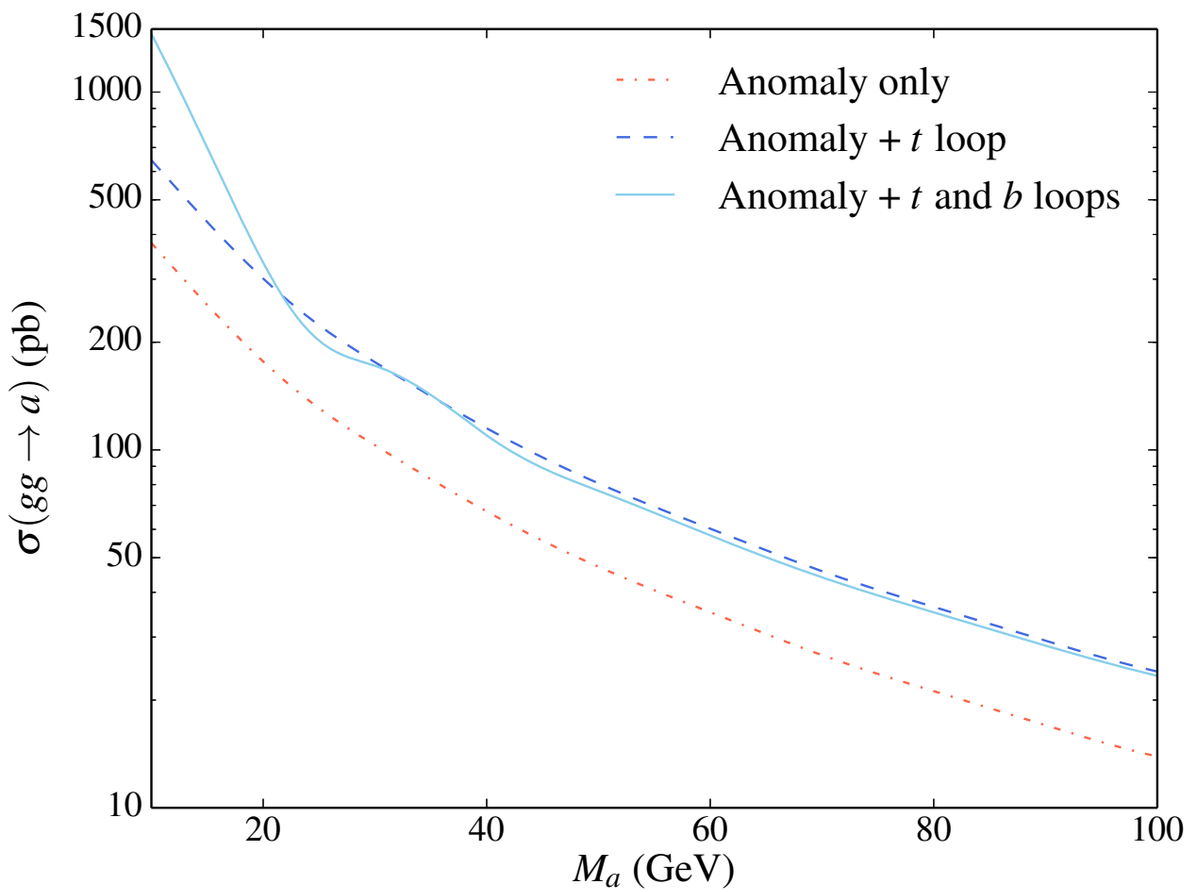
$U(1)$ pseudo-scalar a

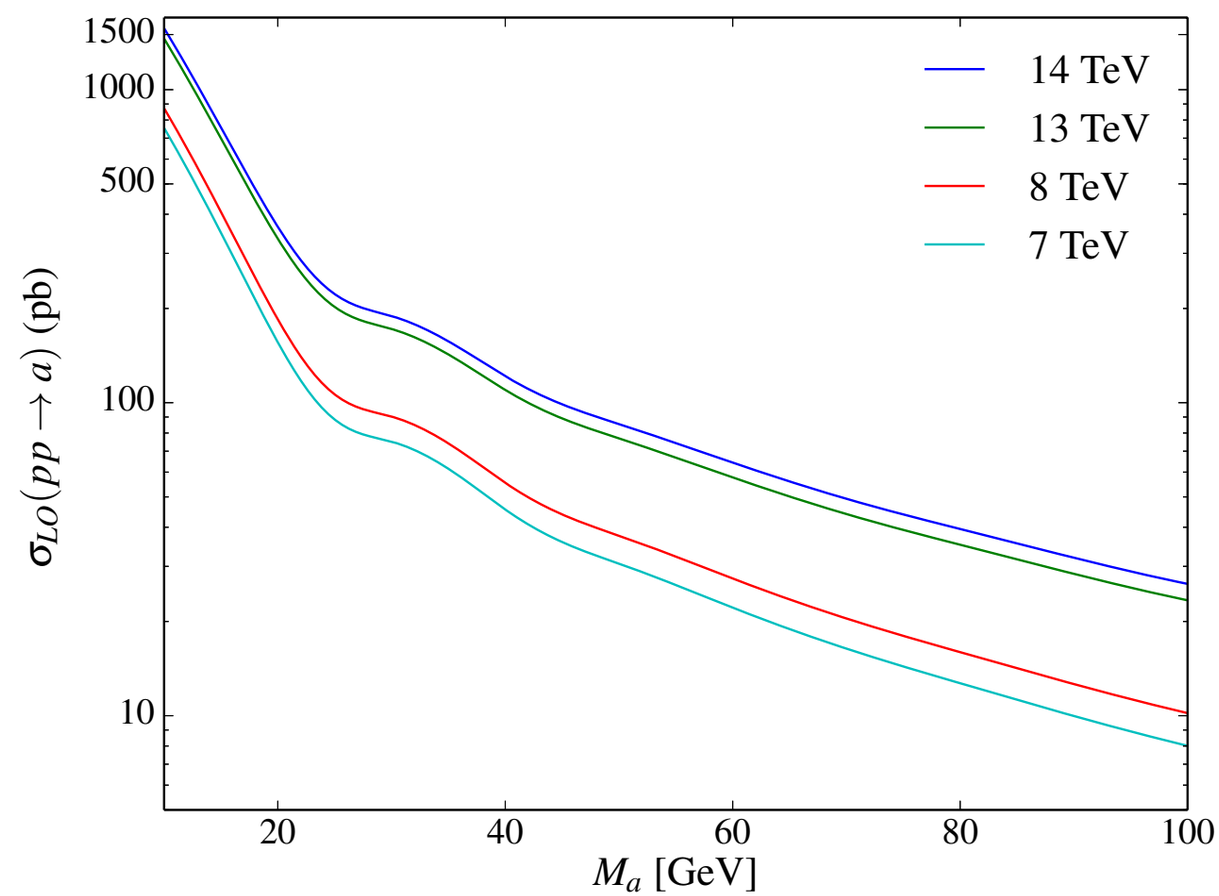
$$\mathcal{L} = \frac{1}{2}\left(\partial_\mu a\right)\left(\partial^\mu a\right) - \frac{1}{2}m_a^2 a^2 - \Sigma_f \frac{iC_f m_f}{f_a} a\bar{\Psi}_f \gamma^5 \Psi_f + \frac{g_s^2 K_g}{16\pi^2 f_a} a G^a_{\mu\nu}\tilde{G}^{a\mu\nu} + \frac{g^2 K_W}{16\pi^2 f_a} a W^i_{\mu\nu}\tilde{W}^{i\mu\nu} + \frac{g'^2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

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



LHC Production Modes



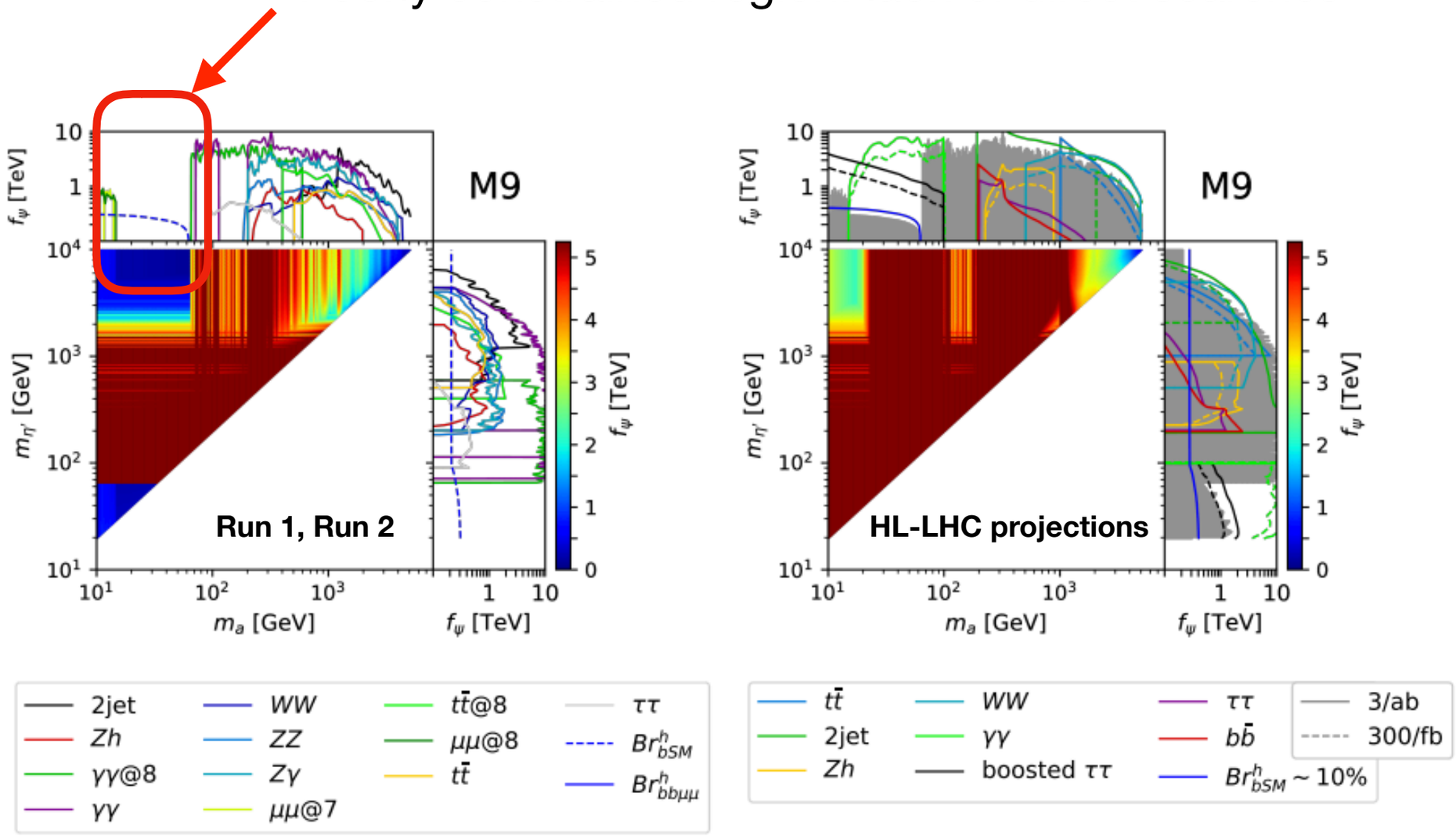


Future Searches

Top band: bounds from a.

Bounds on f_ψ computed individually and then most stringent bound chosen

Poorly constrained region: lack of direct searches



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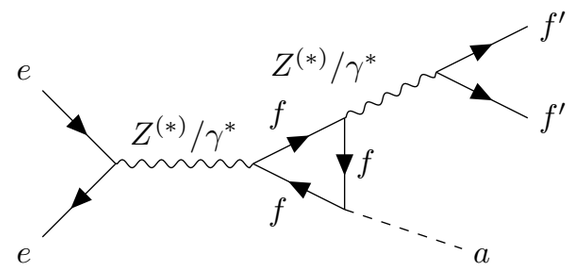
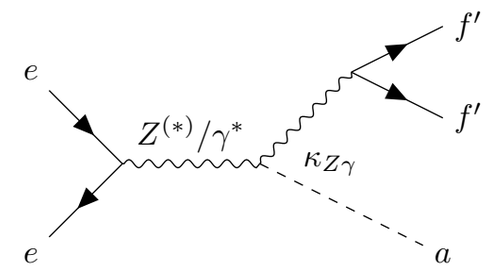
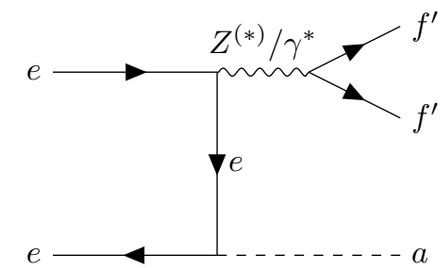
Future lepton colliders

Collider	Energy (GeV)	Int. Lumi (ab^{-1})	Pol.
CEPC	91.2	8	-
	161	2.6	-
	240	5.6	-
FCC-ee	91.2	150	-
	161	10	-
	240	5	-
	350	0.2	-
	365	1.5	-
ILC	250	2	-
		1	(80%,0%)
		1	(-80%,0%)
		0.9	(-80%,30%)
		0.9	(80%,-30%)
	350	0.2	-
		0.05	(80%,0%)
		0.15	(-80%,0%)
		0.135	(-80%,30%)
		0.045	(80%,-30%)
	500	4	-
		2	(80%,0%)
		2	(-80%,0%)
		1.6	(-80%,30%)
		1.6	(80%,-30%)
CLIC	1500	2	(-80,0)
		0.5	(80,0)
	3000	4	(-80,0)
		1	(80,0)

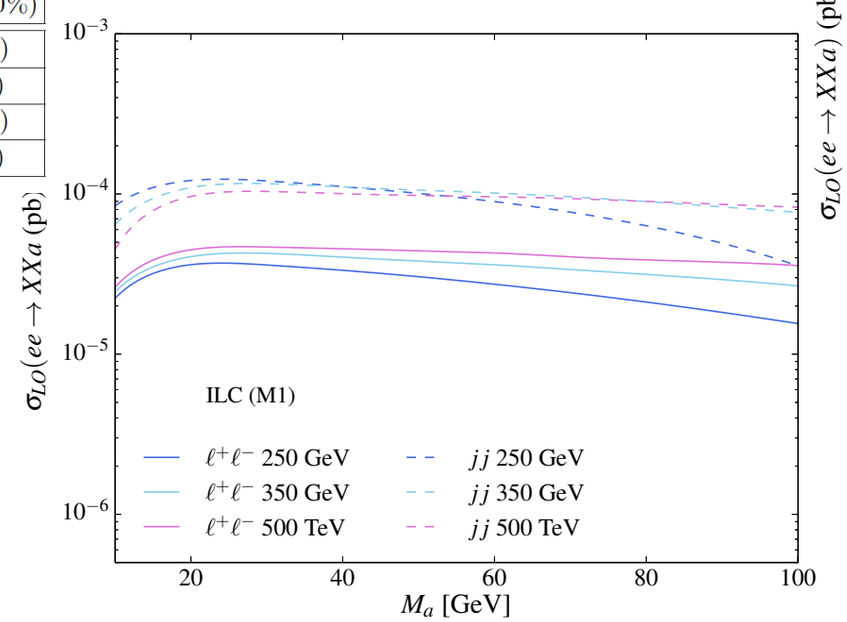
We will consider associated production of a: choose process $e^+e^- \to \ell^+\ell^- a$

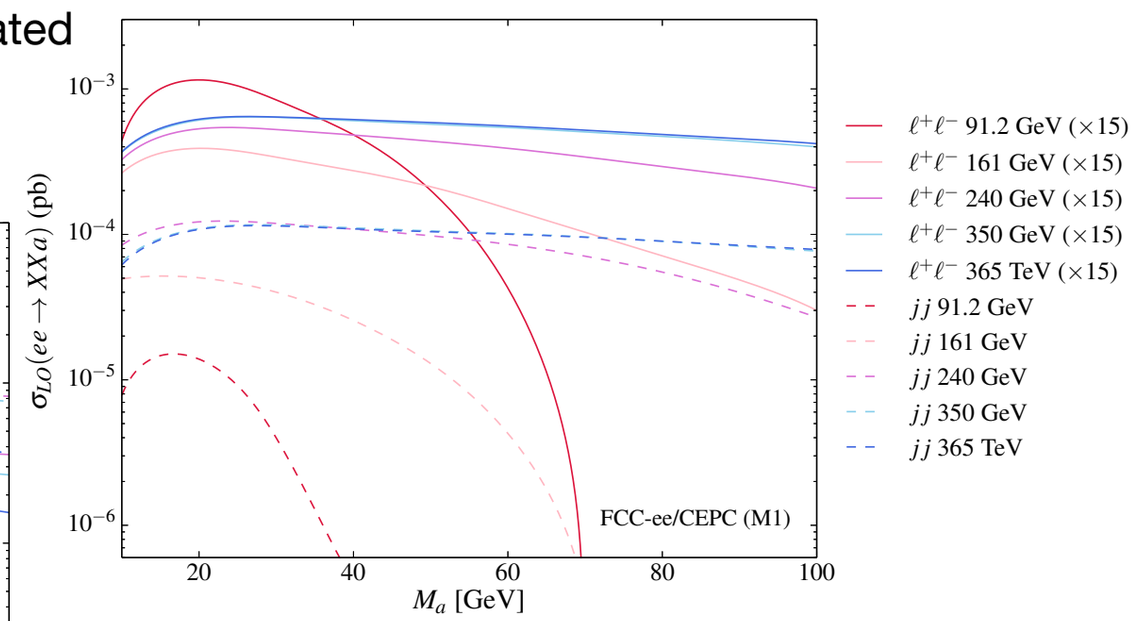






Comparing jet and lepton associated production of a





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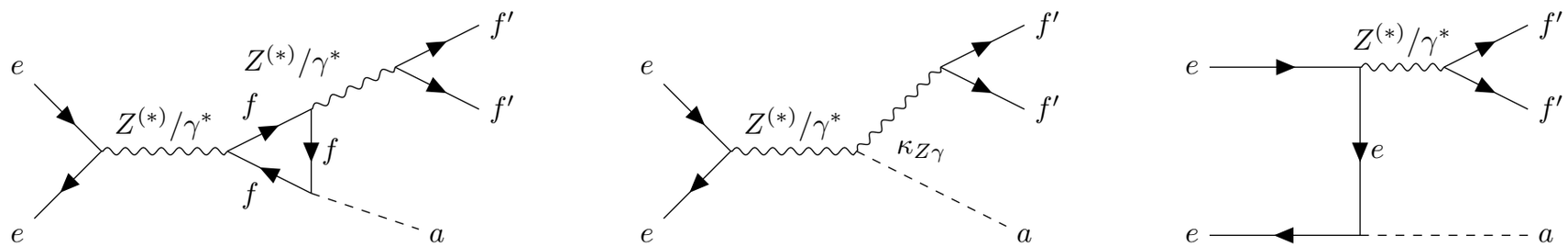

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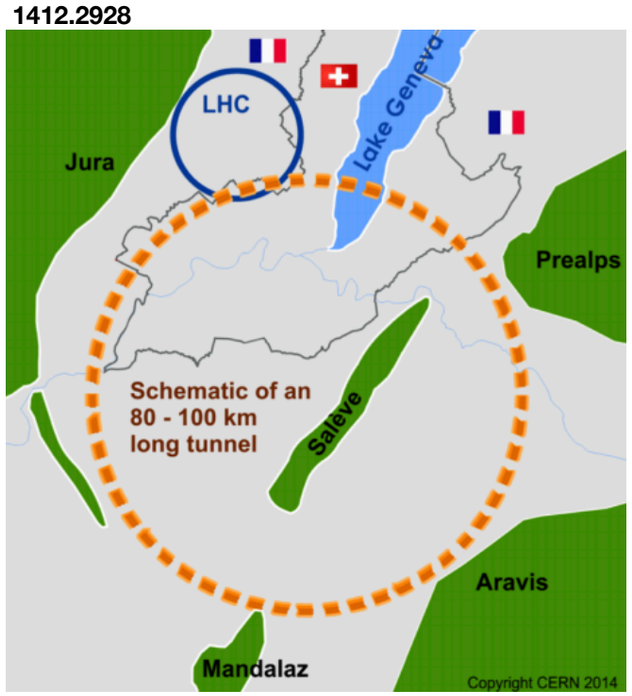
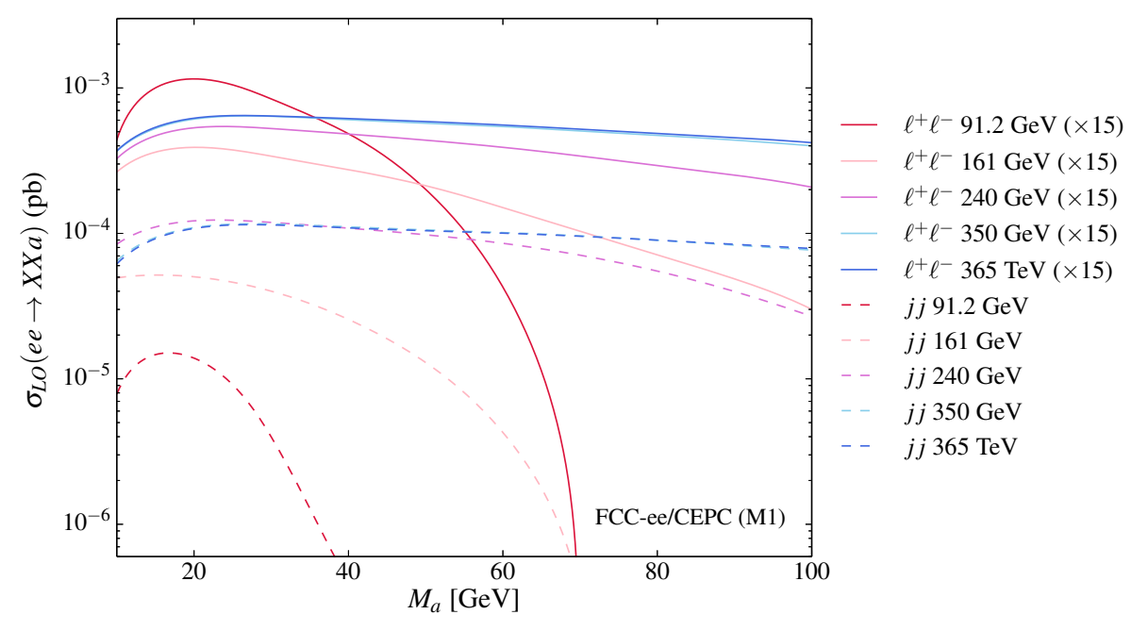
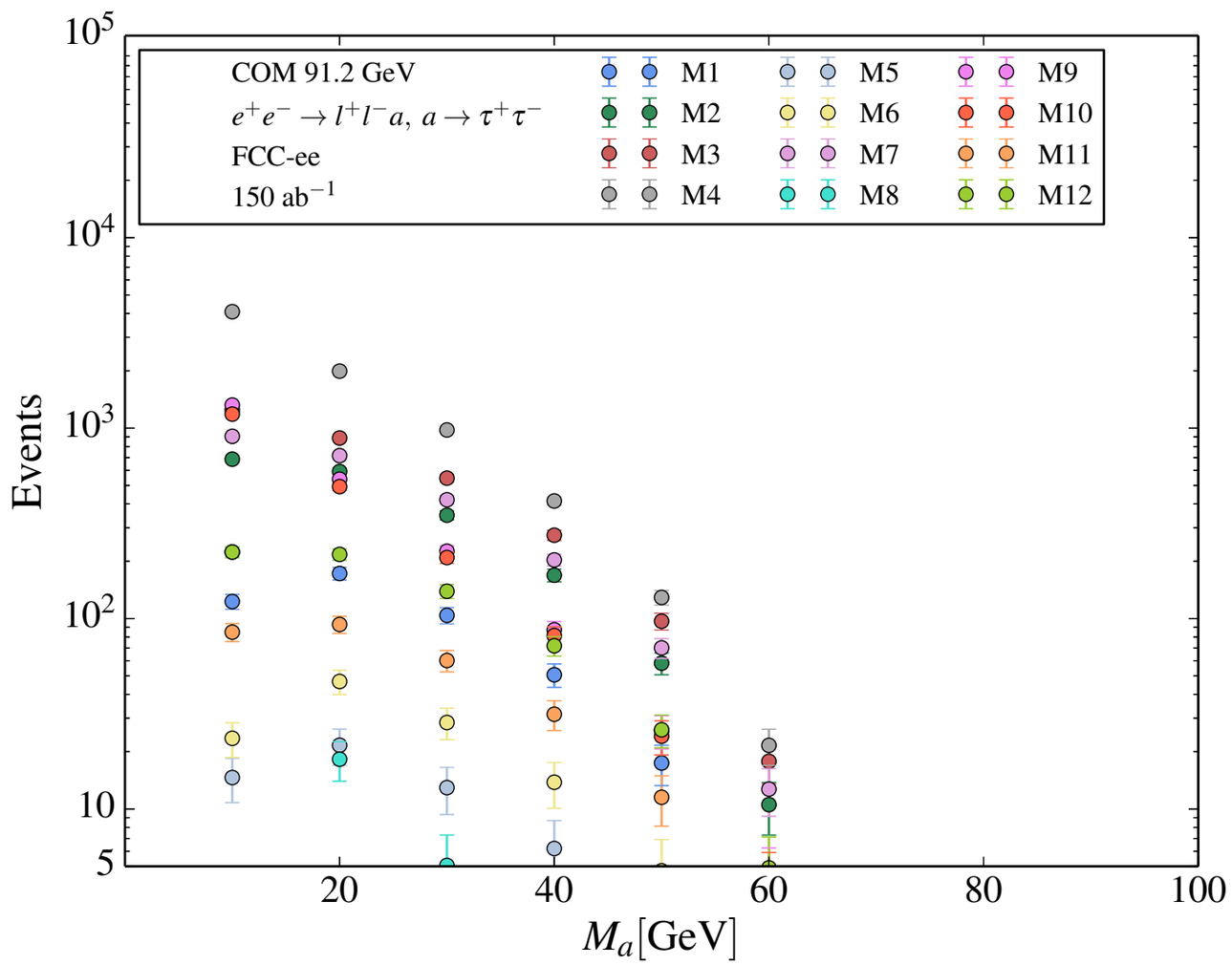
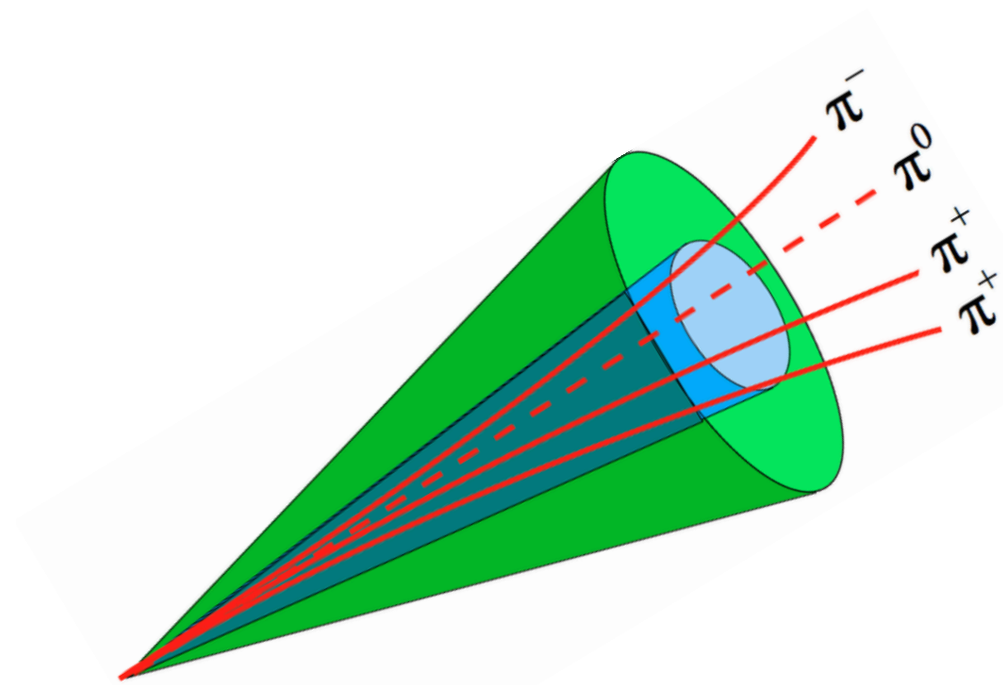




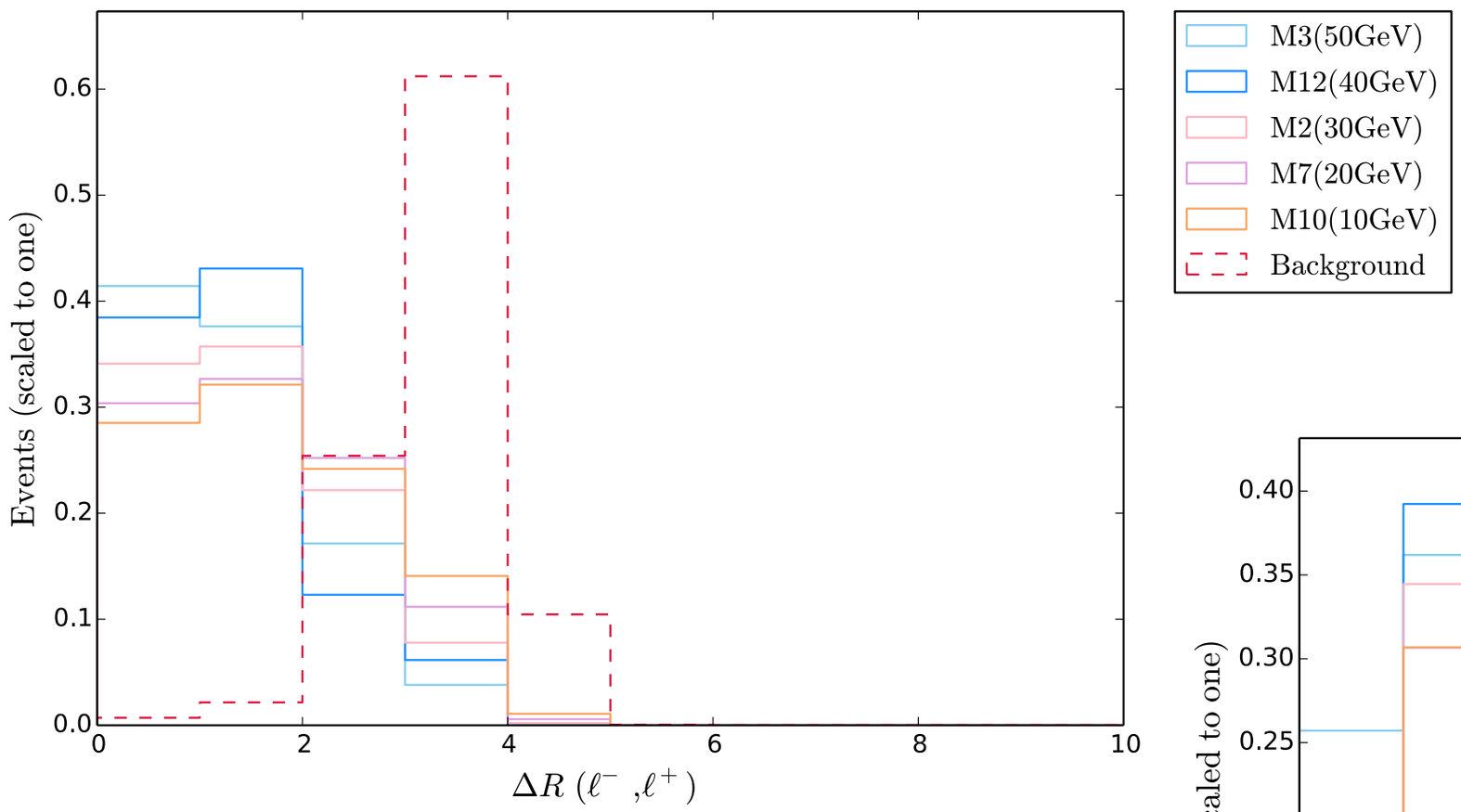
$a \to \tau^+\tau^-$

Hadronic tau decay

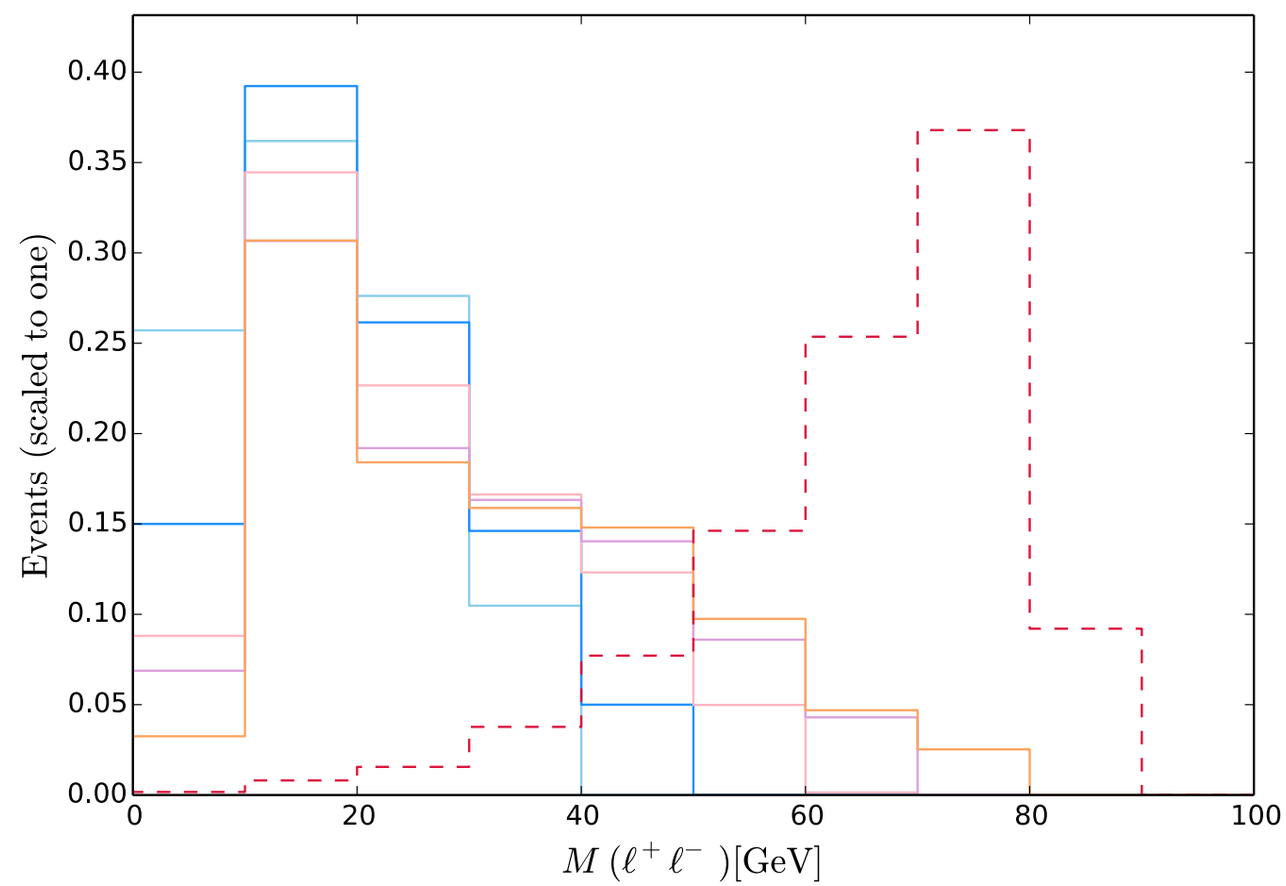




$e^+e^- \to \ell^+\ell^-\tau^+\tau^-$



$Z^{(*)}/\gamma^*$ background discrimination



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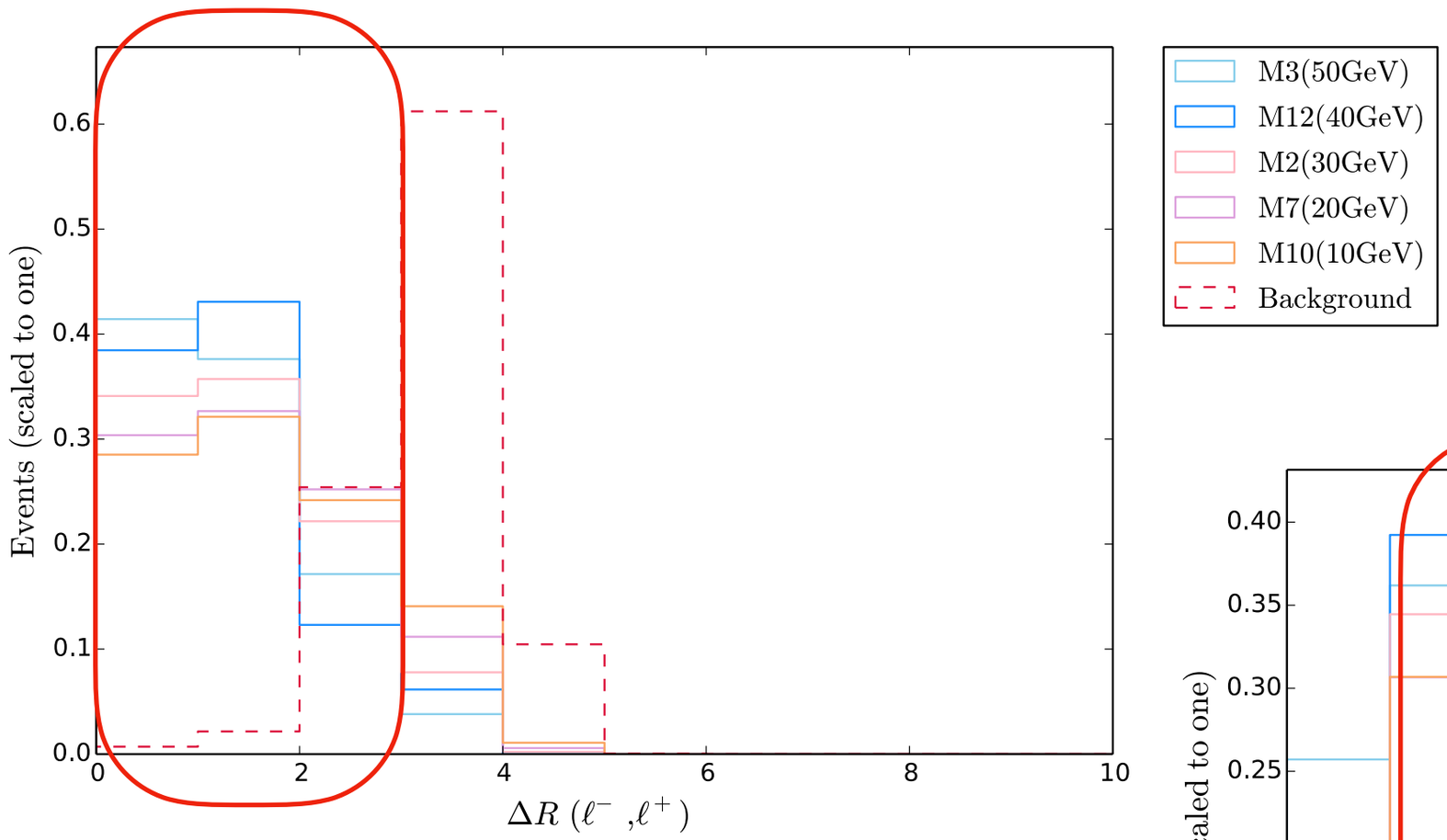

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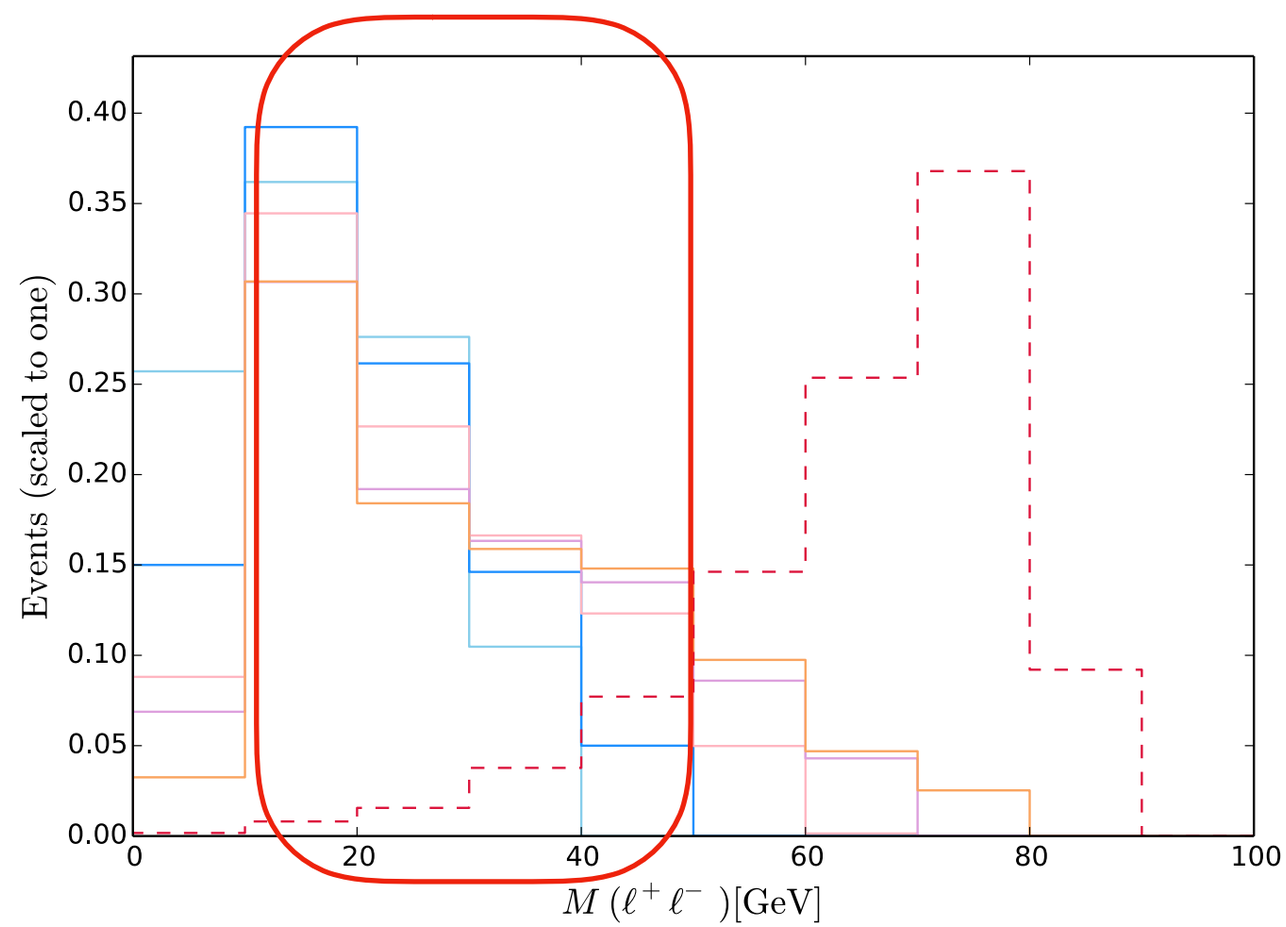

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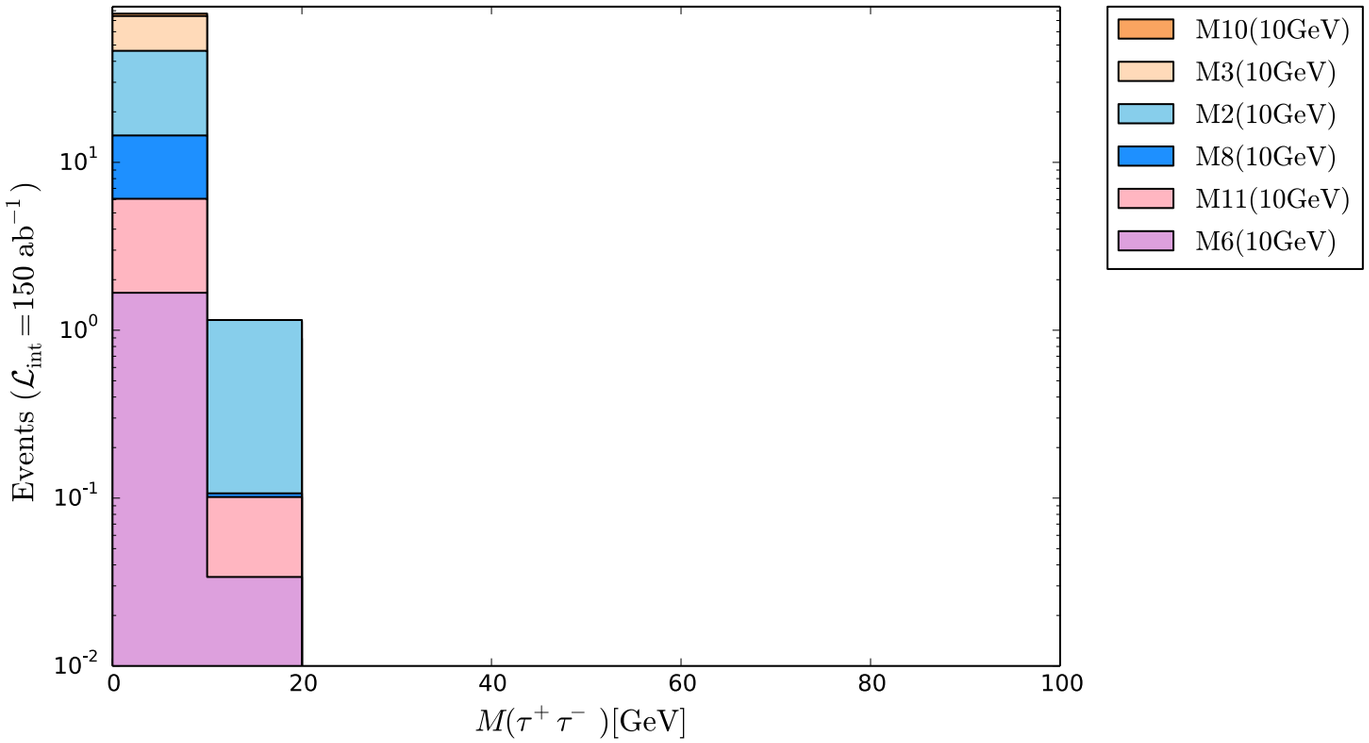
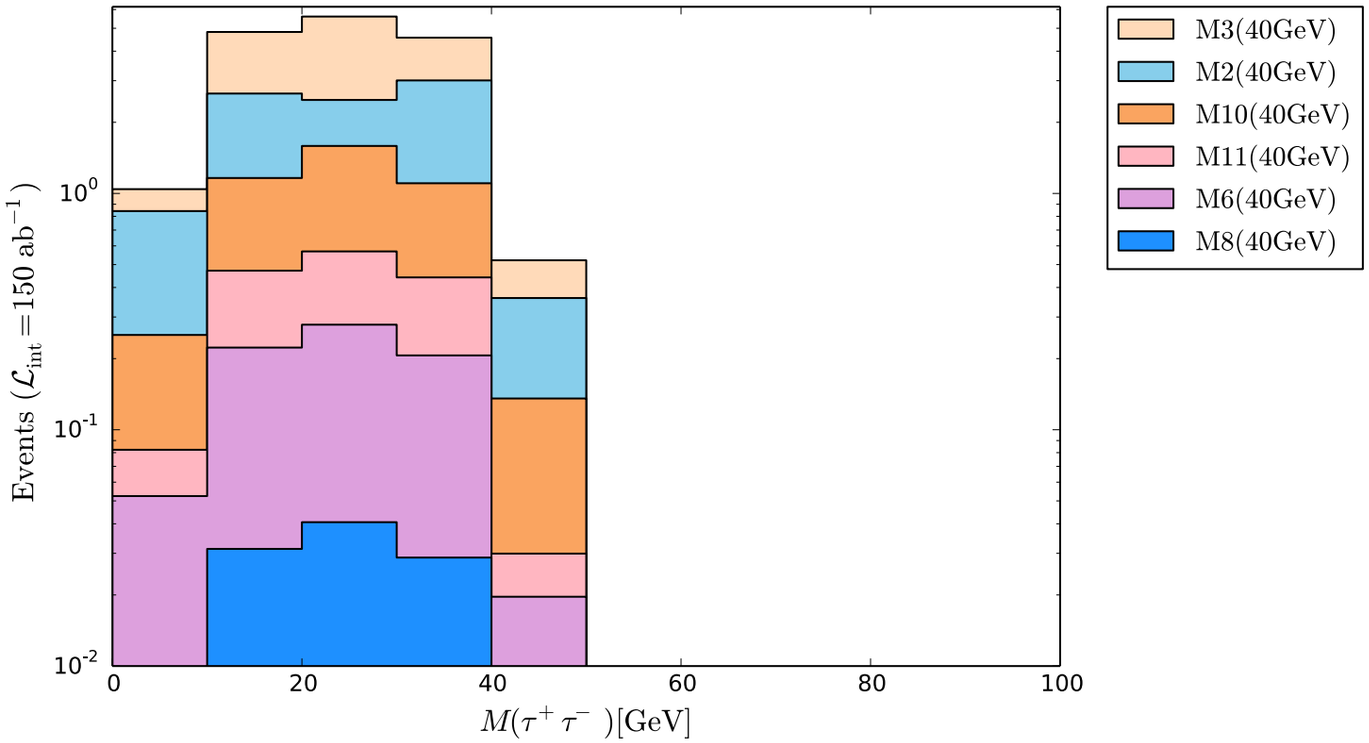
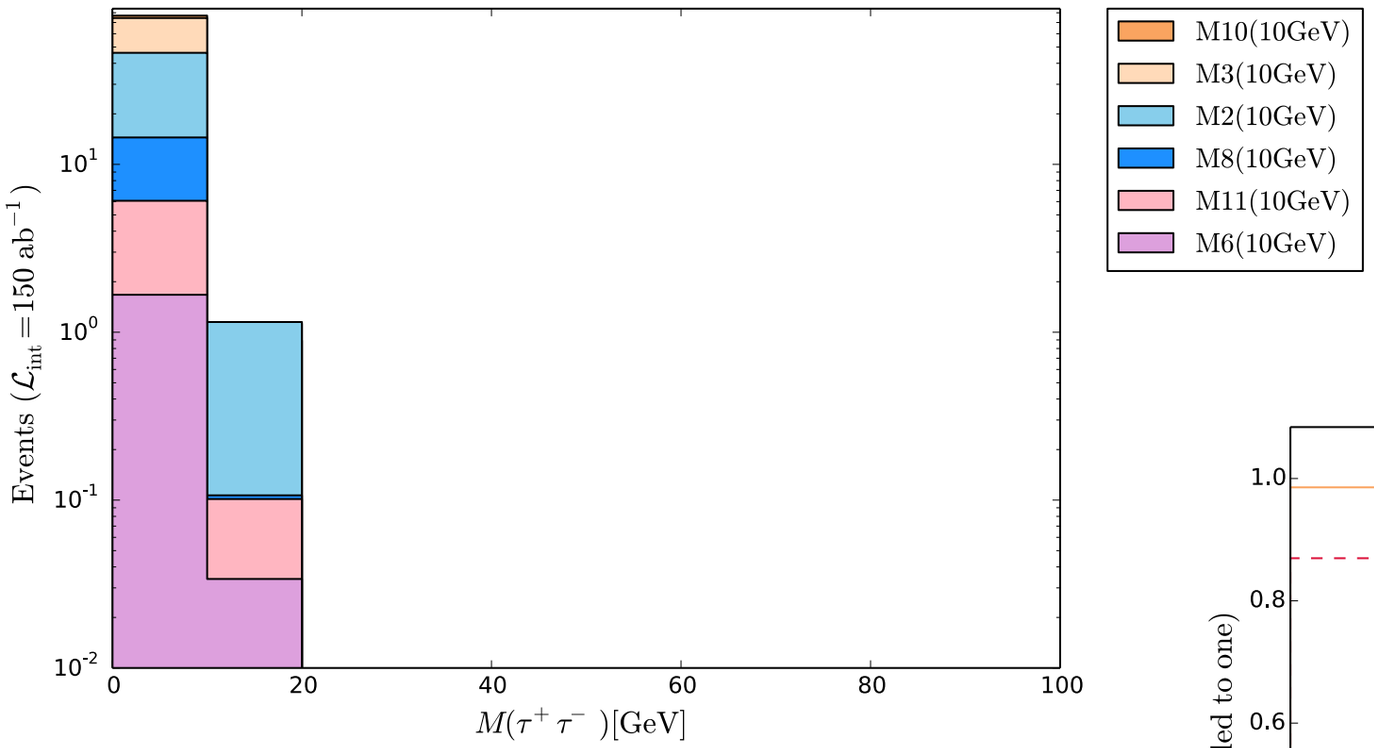


Model behaviour



$e^+e^- \to \ell^+\ell^-\tau^+\tau^-$



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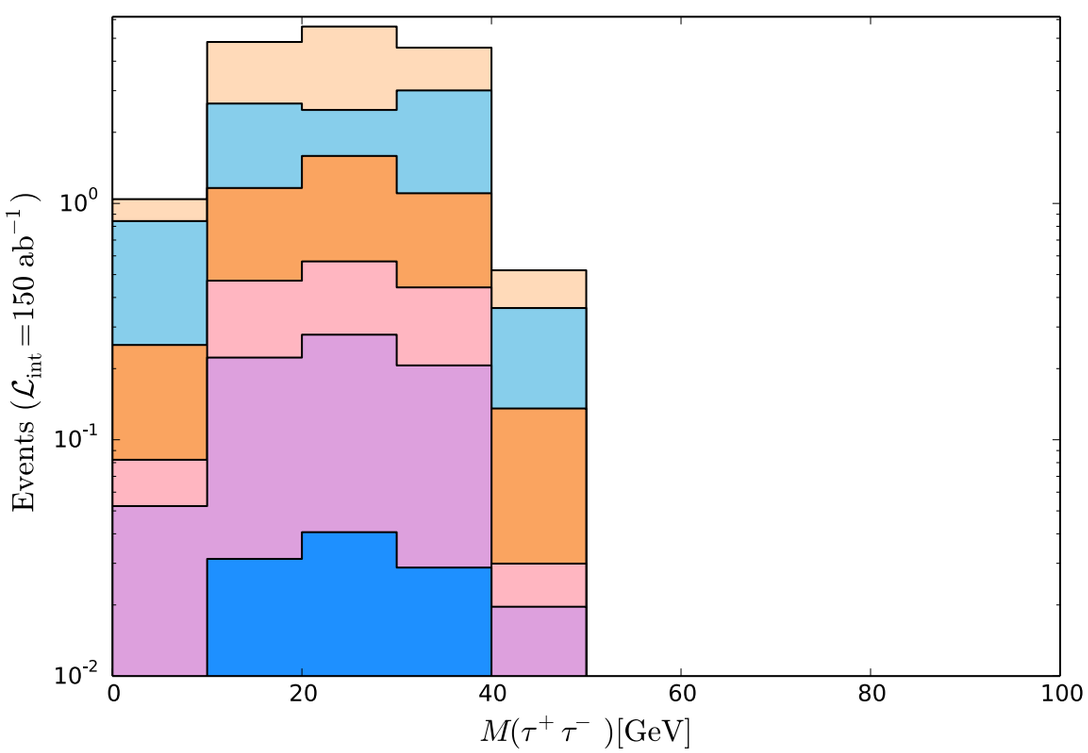
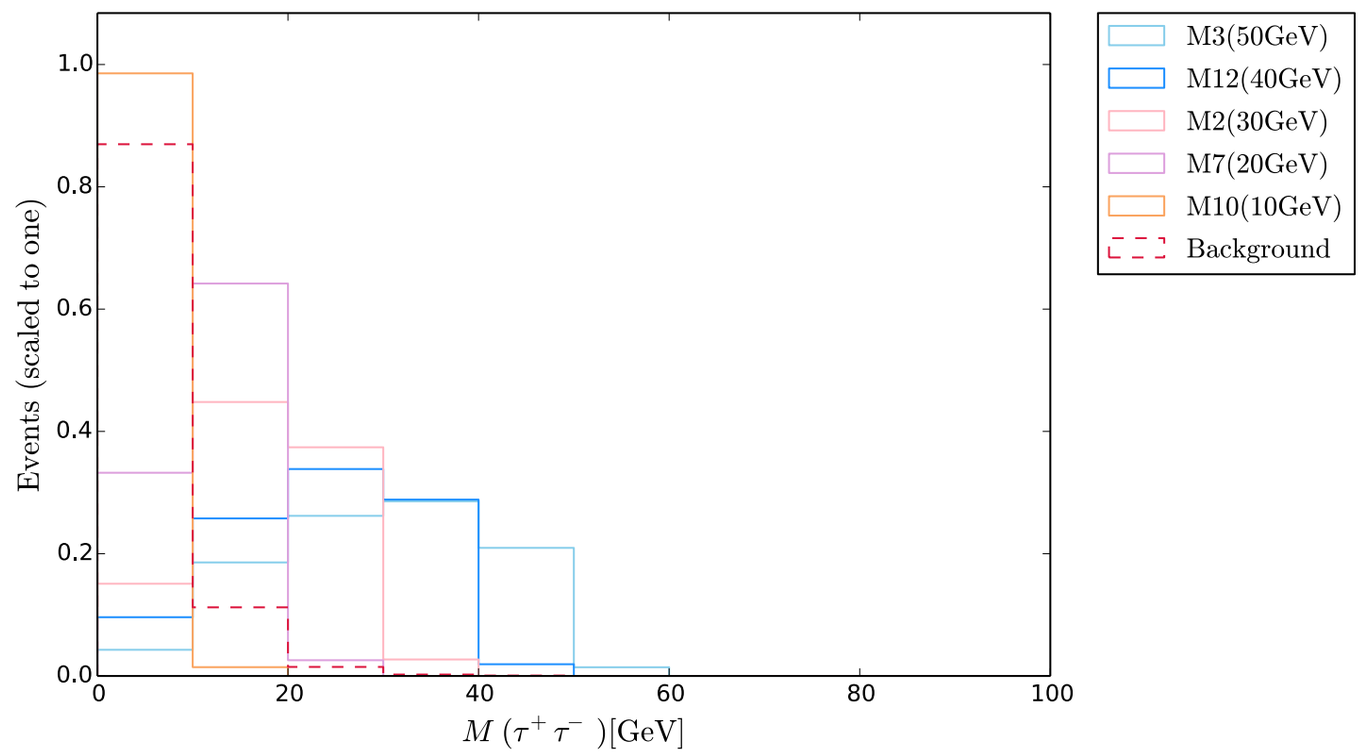


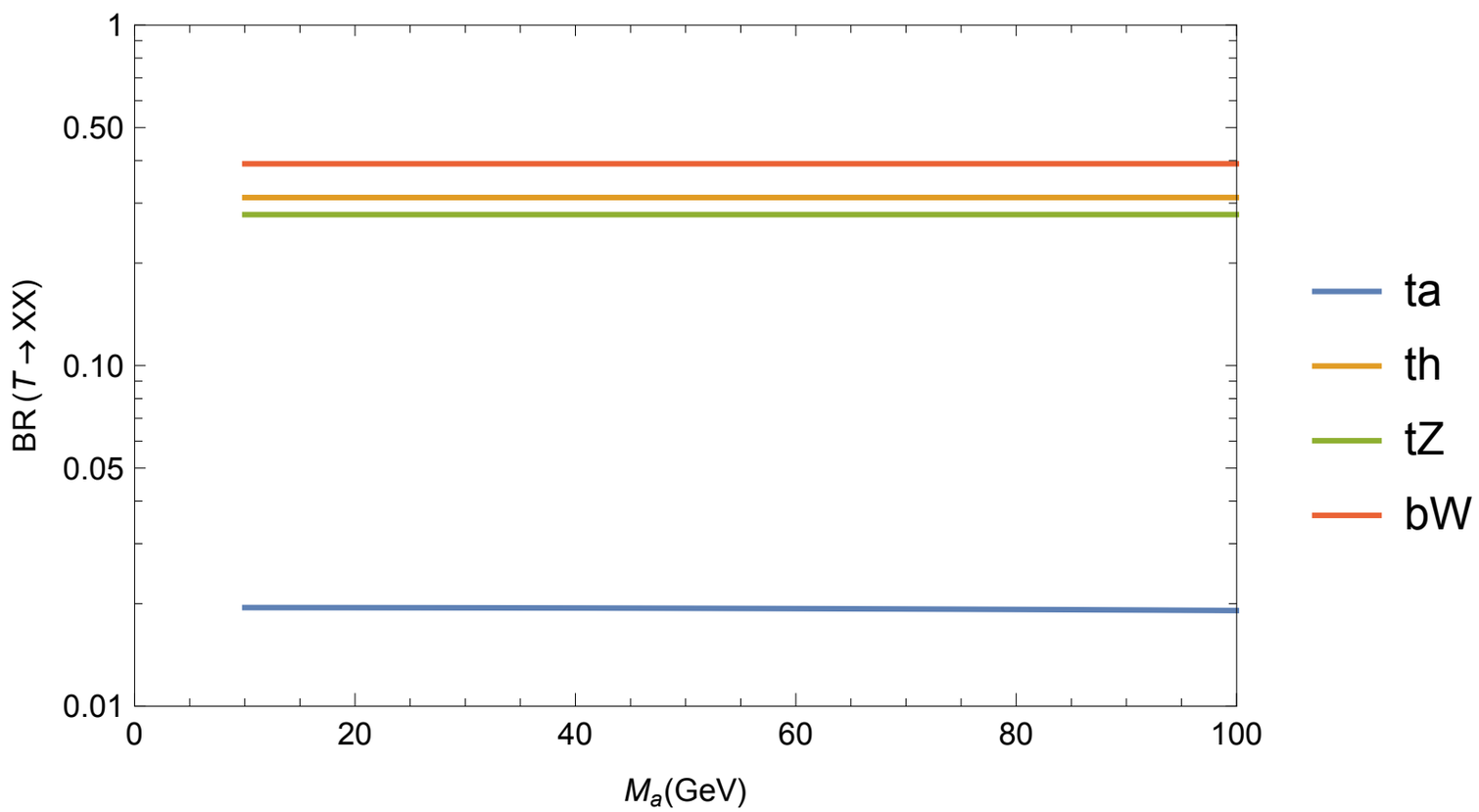


VLQs (T, B, X, Y)

- Composite fermions generating mass for the top (for now) via partial compositeness
- VLQs mix with the SM quarks through the Yukawa Lag.
- Couple to the light scalar a

Q = 5/3: X
Q = 2/3: T
Q = -1/3: B
Q = -4/3: Y

$T \to ta$ or $B \to ba$ an independent test of the models since the couplings do not rely on the composite model structure, and are largely independent of the mass of a in this region.



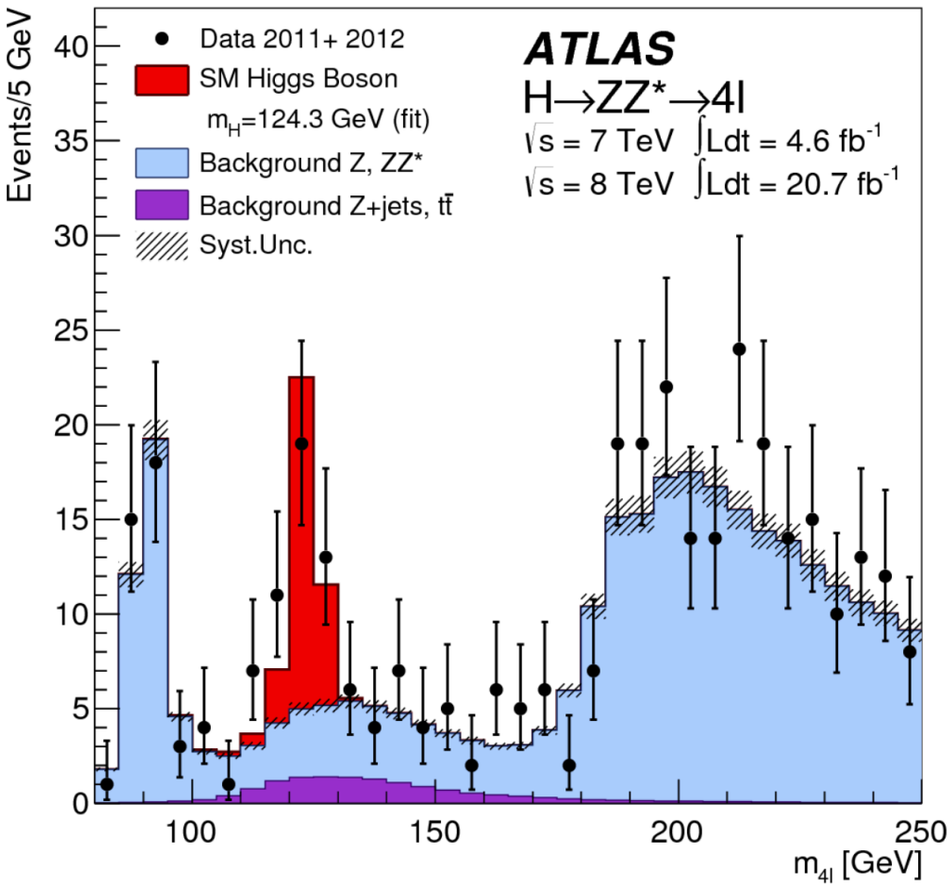
Conclusion

- Additional light scalars may provide first signs of compositeness
- Masses between 10 GeV and 60 GeV poorly constrained thus far
- Possibility of low mass searches for the pseudo-scalar at future lepton colliders in $\ell^+\ell^-\tau^+\tau^-$ channel
- We have constructed a potential search channel at the FCC-ee running at Z pole using the hadronic tau decay channel.
- Dominant di-boson background may be reduced
- VLQs as future additional check

Thank you

BACKUP

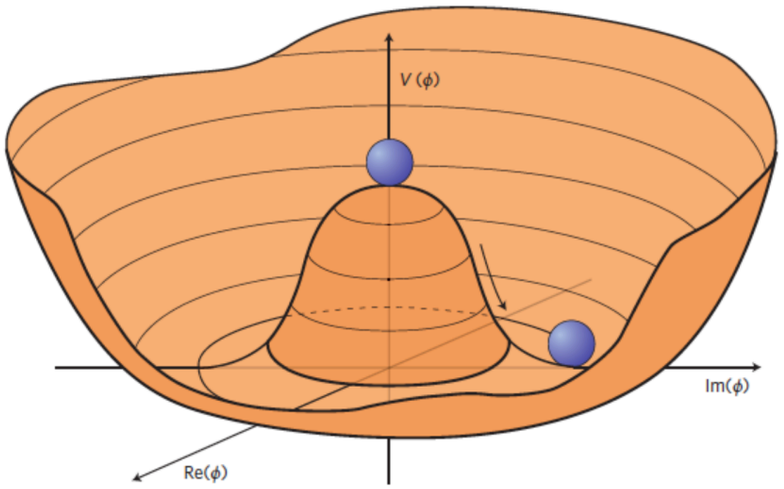
The scalar sector



In 2012, ATLAS and CMS announced the discovery of the SM Higgs at 125 GeV.
All Standard Model particles now accounted for.

However:

- origin of EWSB?
- lightness of the Higgs?



$$V = -\mu^2 |H|^2 + \lambda |H|^4$$

$$\langle H \rangle = v/\sqrt{2}$$

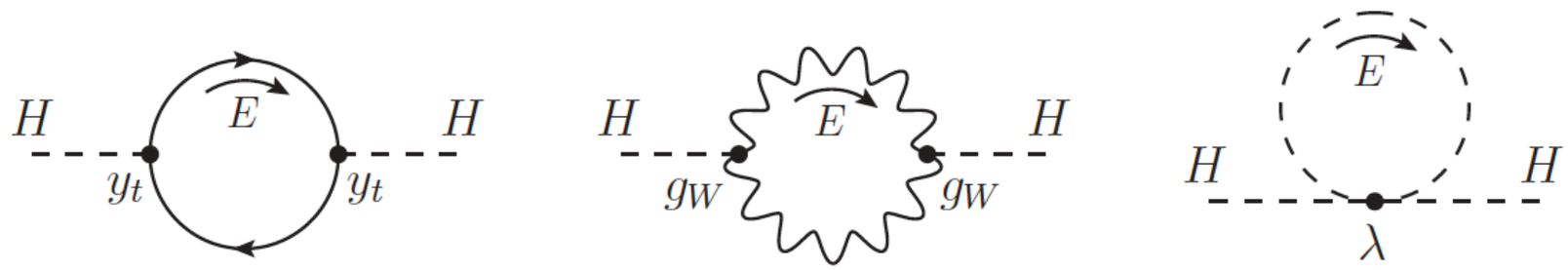
$$v = 246 \ GeV$$

We need the Higgs for gauge invariance:
$m(\bar{\psi}_R \psi_L + \text{h.c})$

The hierarchy problem

The Standard Model is an effective theory: Λ_{SM}

Ambient quantum energy pushes the Higgs mass towards the Planck scale



CH models remove the tension: quadratic divergences allowed only up to some compositeness scale

Finite size effects screen quadratic growth

Symmetry breaking

We must have the Higgs doublet be produced, so we require that $SU(2) \times U(1)$ be embeddable within H.

Coset: G_F/H_F tells you how many Goldstones you have:
$n = dim(G) - dim(H)$

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

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

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

Pattern of chiral symmetry breaking depends on underlying gauge dynamics, governed by

1. dimension of gauge group (number of fermionic matter fields)
2. subgroup to which symmetry breaks

pNGB Higgs

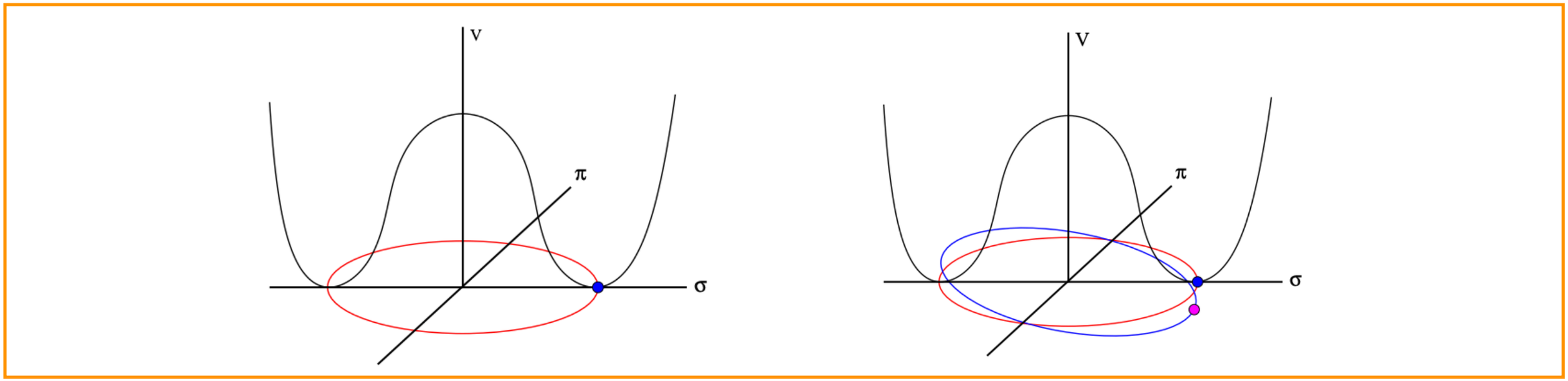
CH models are based on a confining HC gauge group, with fundamental fermions in different irreps of the HC group. A global (flavour) symmetry of the fermions is broken, leading to the production of the Higgs.

Goldstone's theorem: pNGB produced in the breaking

$$G \to H$$

when G was initially explicitly broken by some small amount (analogy with QCD).

- Explicit breaking of the global sector by, for example, bare masses for the hyperquarks, gives mass to NGB which becomes pNGB



Composite Higgs vs technicolour

Both: Higgs sector replaced with fundamental gauge dynamics featuring fermionic matter fields

Gauge dynamics break a symmetry of the theory

Both need a separate sector to provide mass to fermions

TECHNICOLOUR	COMPOSITE HIGGS
Fermion condensate breaks EW symmetry	Fermion condensate breaks global symmetry group G
Higgs identified with lightest scalar excitation of the condensate	Higgs identified with pNGB

Composite Higgs vs technicolour

A composite Higgs model is characterised by some scale f at which condensation of fundamental fermions leads to the formation of the Higgs.

- In technicolour, this scale is equal to the scale of electroweak symmetry breaking, $v = 246\ GeV$ (condensate breaks the EW symmetry and creates the Higgs all at once)

- In composite Higgs models, the vev of the Higgs breaks EW symmetry

$\rightarrow$ system characterised by $\xi = v/f$: indicates difference in energy between scale of EWSB v and condensation leading to formation of Higgs f.

In the technicolour limit, $\xi = 1$.
In limit $f \rightarrow \infty$, new physics decouples and we are left with the SM ($\xi = 0$)

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

This model (+ new implementation)

Built on recent works:

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

THE EUROPEAN PHYSICAL JOURNAL C

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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

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di-tau searches for light pseudo-scalar including only top loops

Description of $U(1)$ scalars

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

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' undergo non-trivial mixing. In the decoupling limit,

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

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

Coupling to gauge bosons: quark loops

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

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

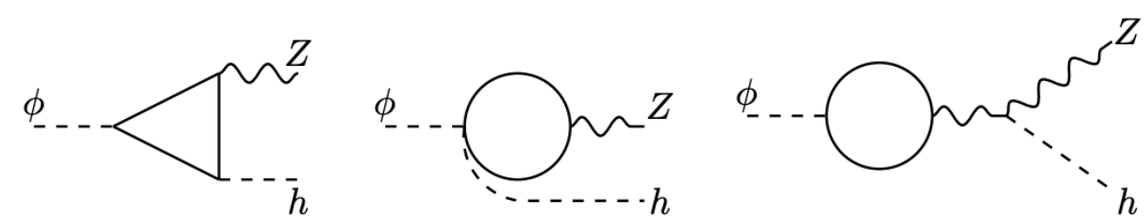
$$f(\tau) = \begin{cases} -\frac{1}{4}\left[\log\left(\frac{1+\sqrt{1-\tau}}{1-\sqrt{1-\tau}}\right) - i\pi\right]^2 & \text{if } \tau < 1 \\ \arcsin^2\left(\frac{1}{\sqrt{\tau}}\right) & \text{if } \tau \geq 1 \end{cases}$$

← **bottom**

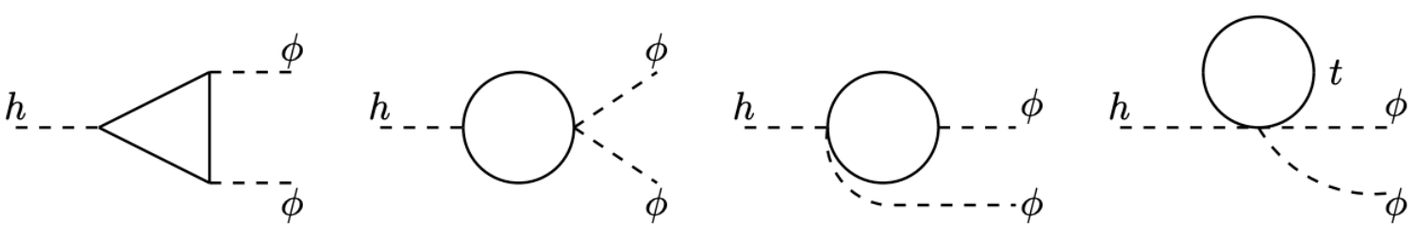
← **top**

Coupling to bosons

$$\mathscr{L}_{gauge} \supset \frac{a}{16\pi^2 f_a}\Big(g_s^2\kappa_{gg}G_{\mu\nu}\tilde{G}^{\mu\nu} + g^2\kappa_{WW}W^+_{\mu\nu}\tilde{W}^{-\mu\nu} + e^2\kappa_{\gamma\gamma}F_{\mu\nu}\tilde{F}^{\mu\nu} + \frac{e^2}{s_W^2 c_W^2}\kappa_{ZZ}Z_{\mu\nu}\tilde{Z}^{\mu\nu} + \frac{2e^2}{s_W c_W}\kappa_{Z\gamma}F_{\mu\nu}\tilde{Z}^{\mu\nu}\Big),$$



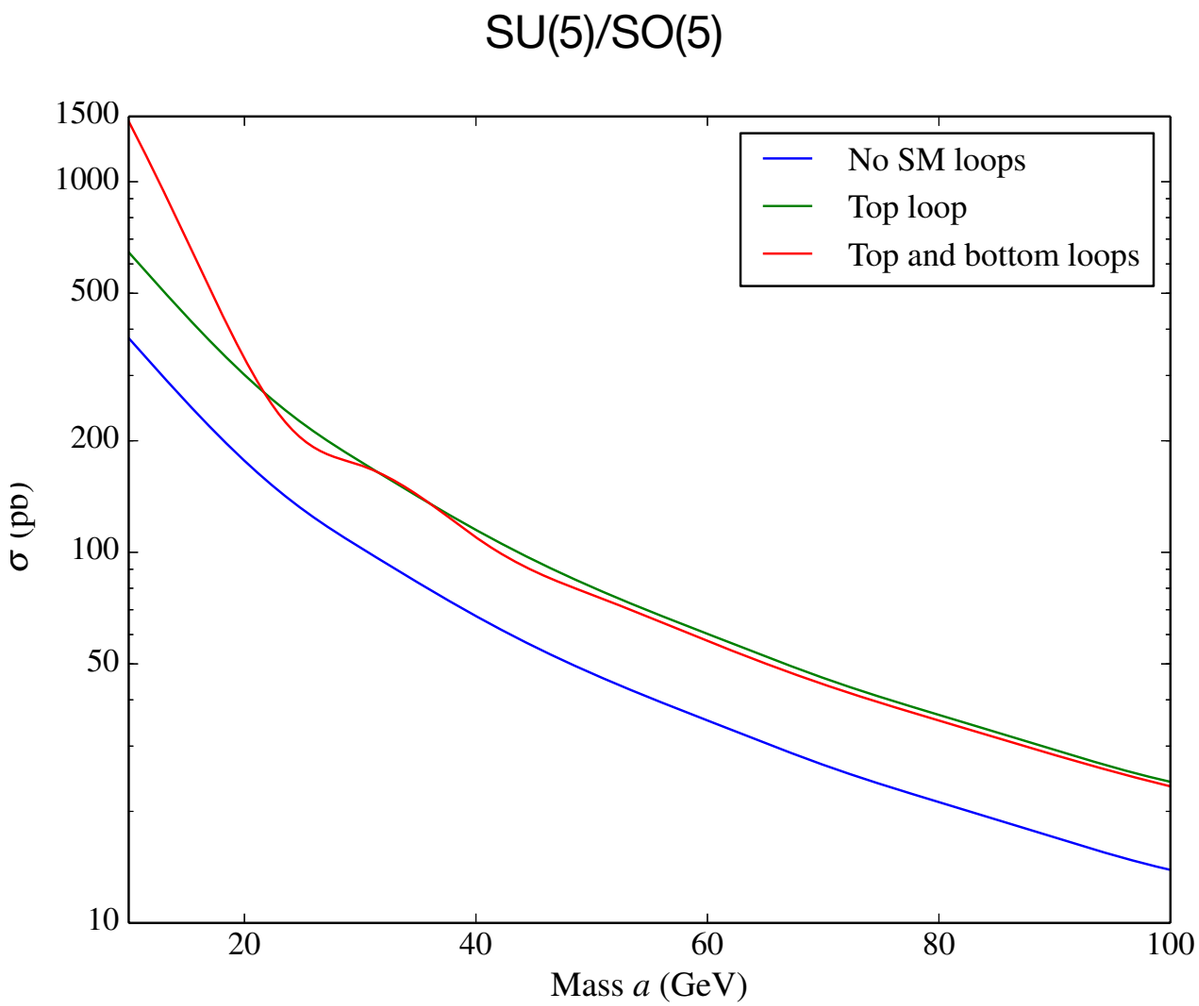
$$\mathcal{L}_{hZa} = \frac{3C_t m_t^2 g_A}{2\pi^2 f_a v}\left(\kappa_t - \kappa_V\right)\log\frac{\Lambda^2}{m_t^2}h\left(\partial_\mu a\right)Z^\mu.$$

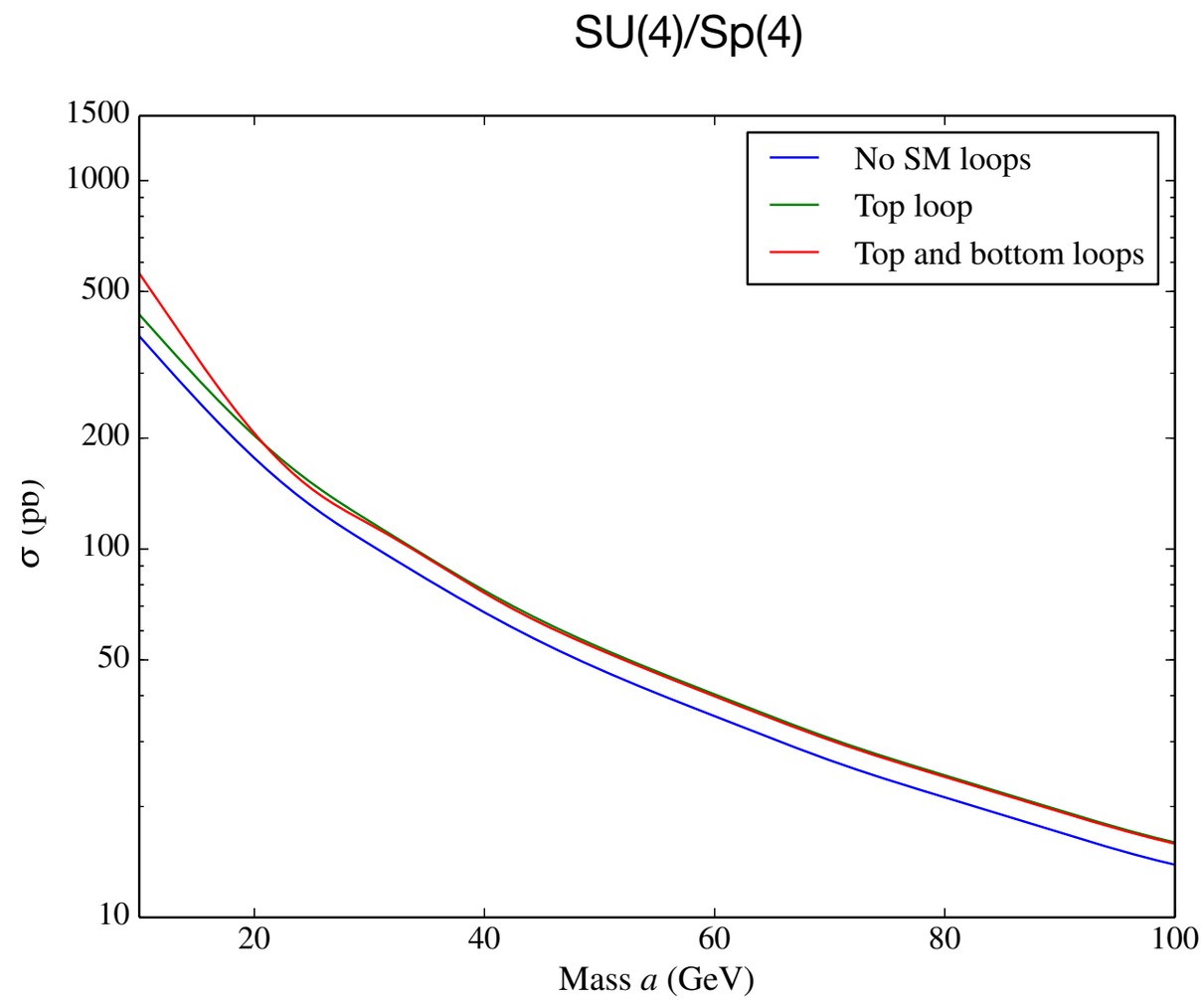


$$\mathcal{L}_{haa} = \frac{3C_t^2 m_t^2 \kappa_t}{8\pi^2 f_a^2 v}\log\frac{\Lambda^2}{m_t^2}h\left(\partial_\mu a\right)\left(\partial^\mu a\right),$$

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

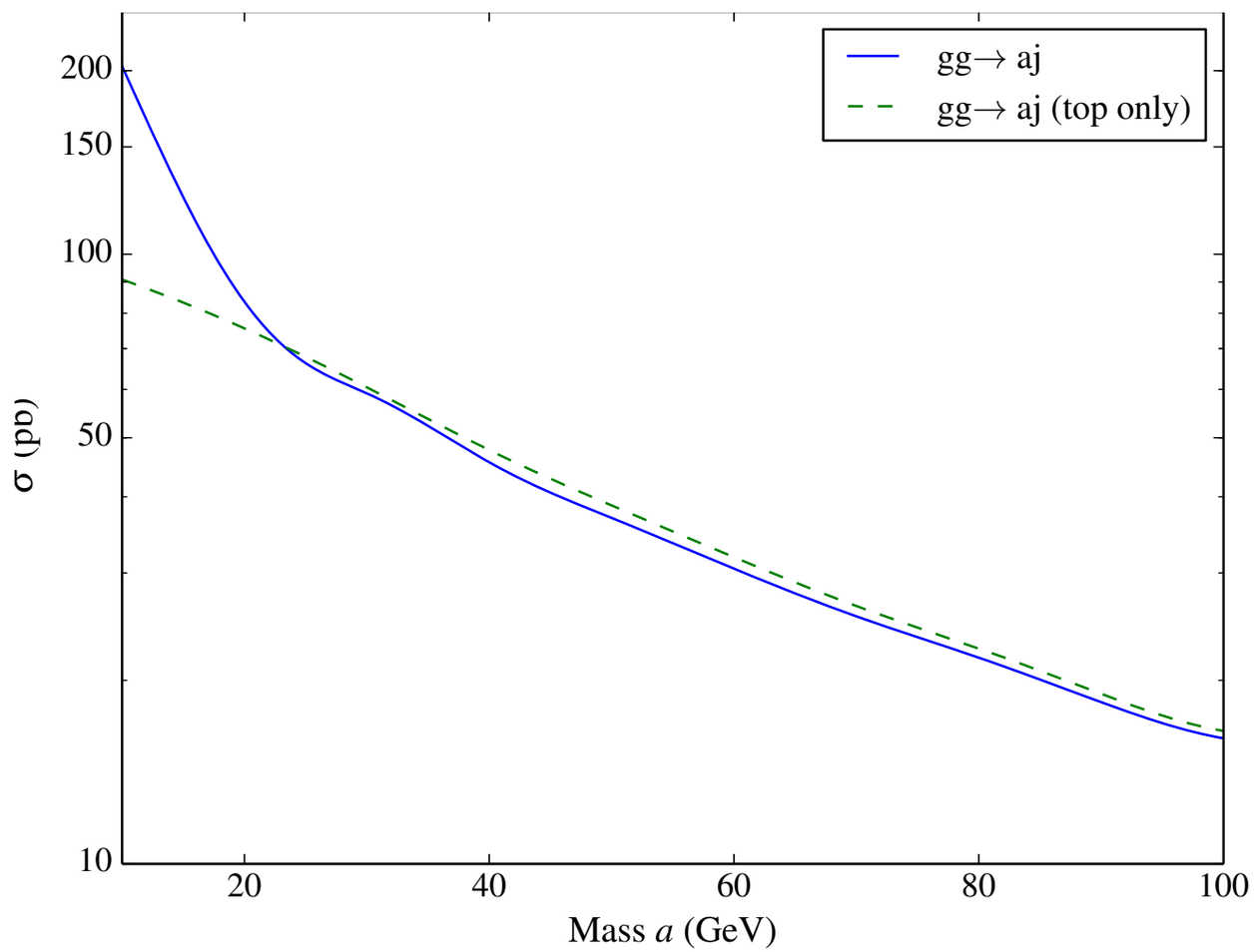
Production Modes: ggF single production

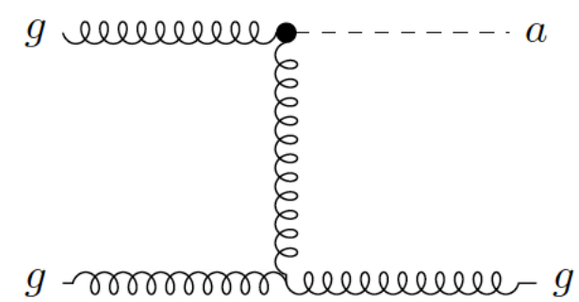


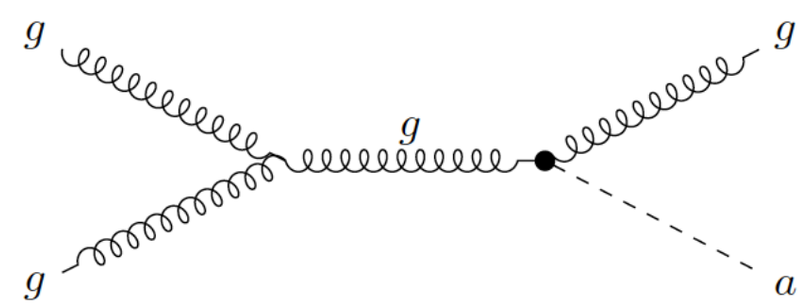


Production Modes

Gluon-gluon fusion alternative production modes

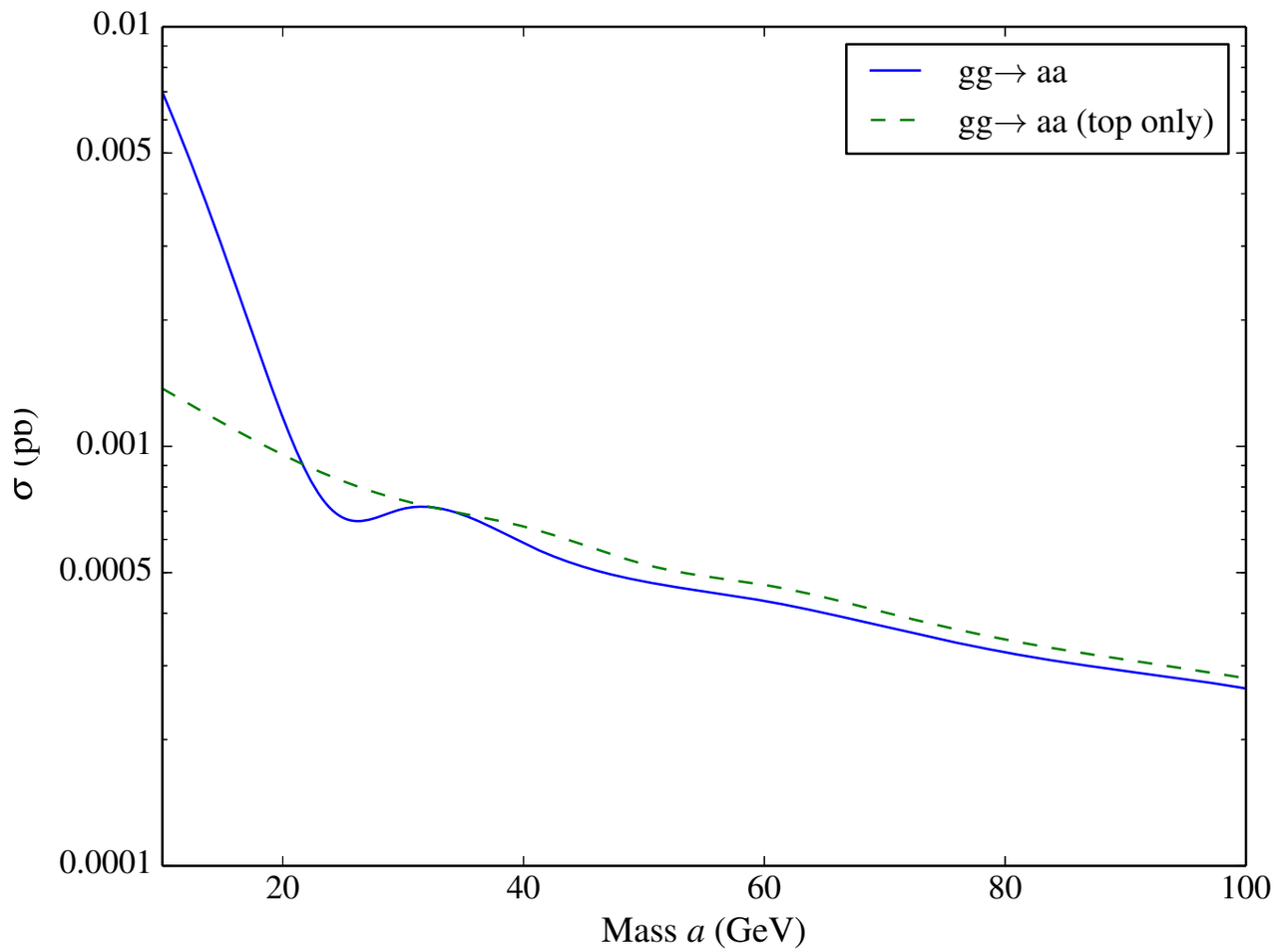


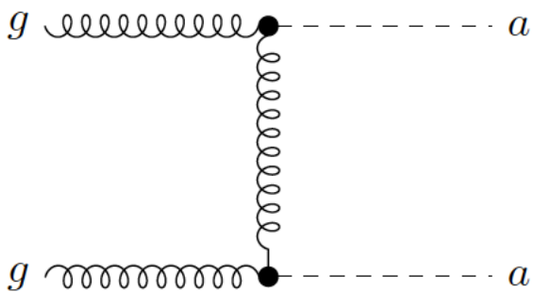




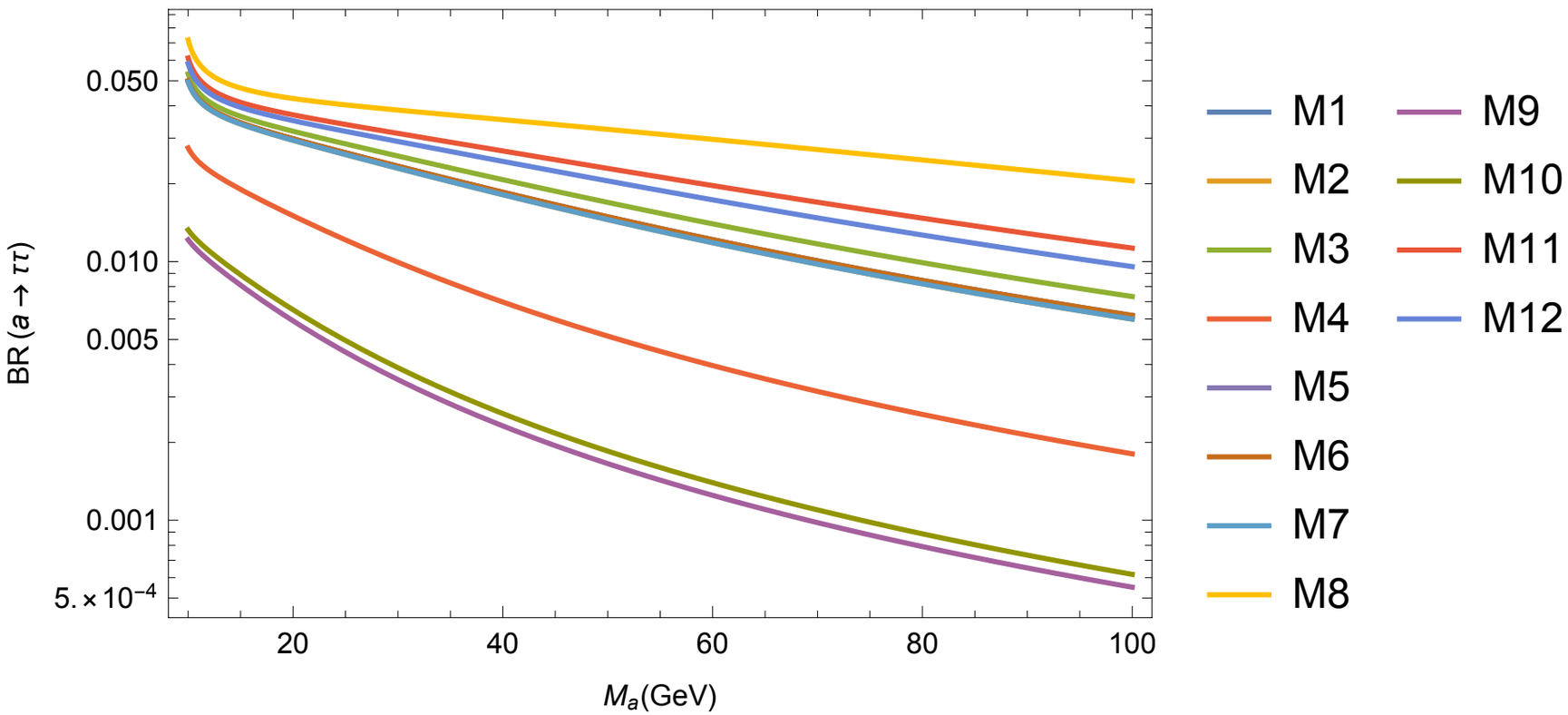
Production Modes

Gluon-gluon fusion alternative production modes



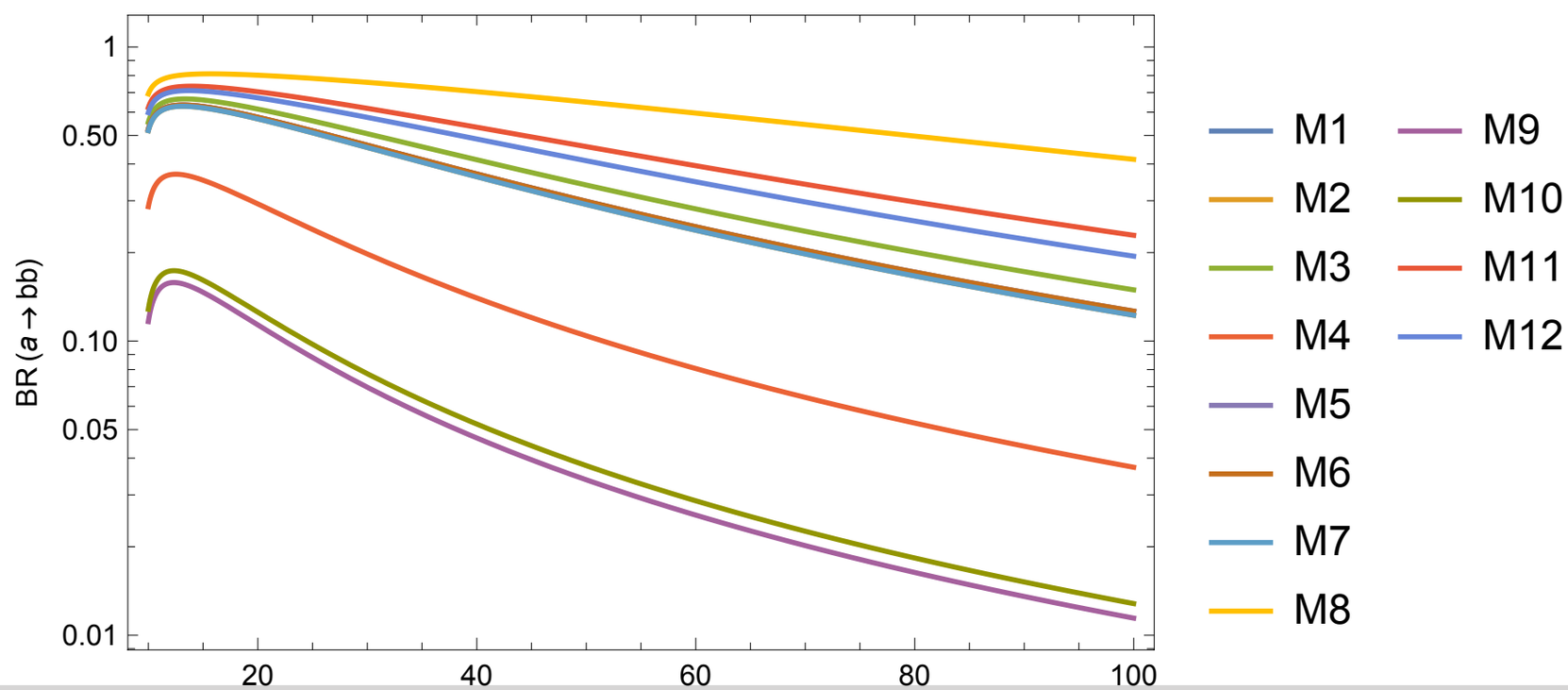


Decay modes

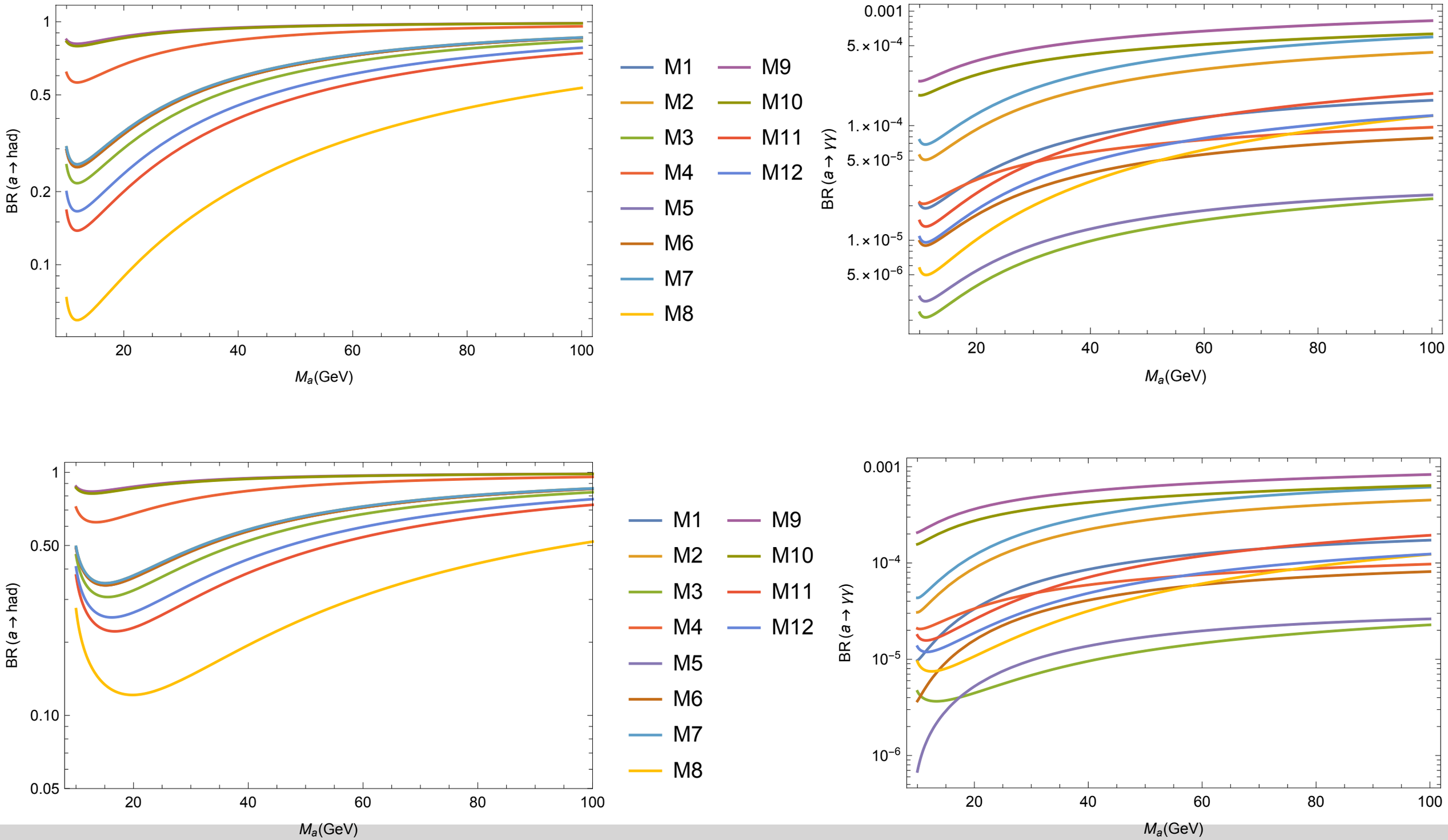
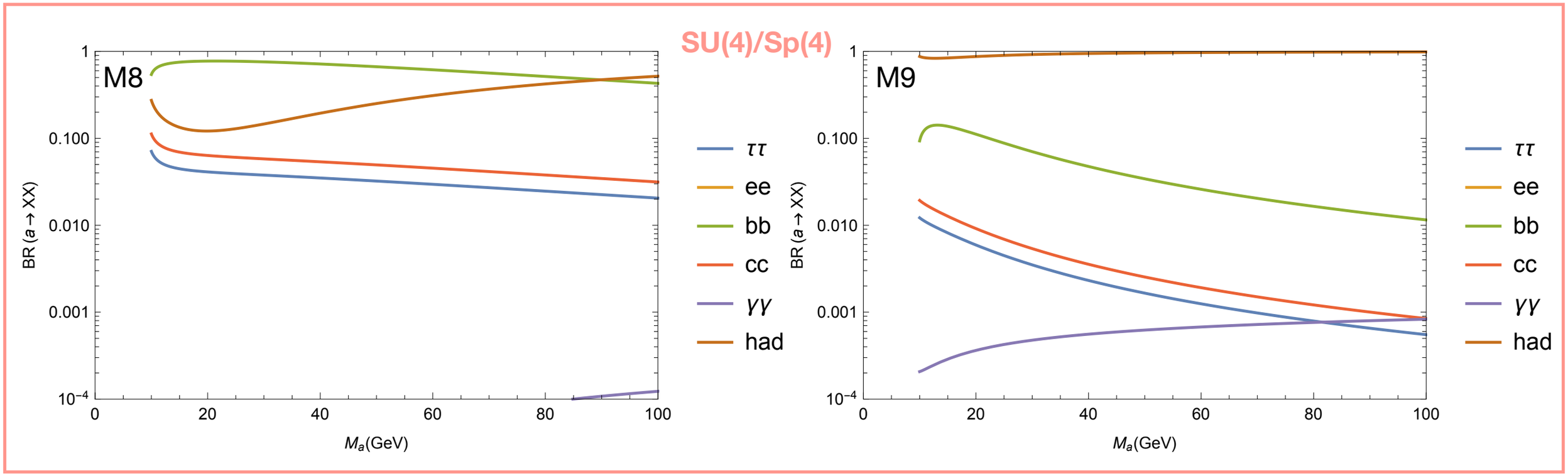
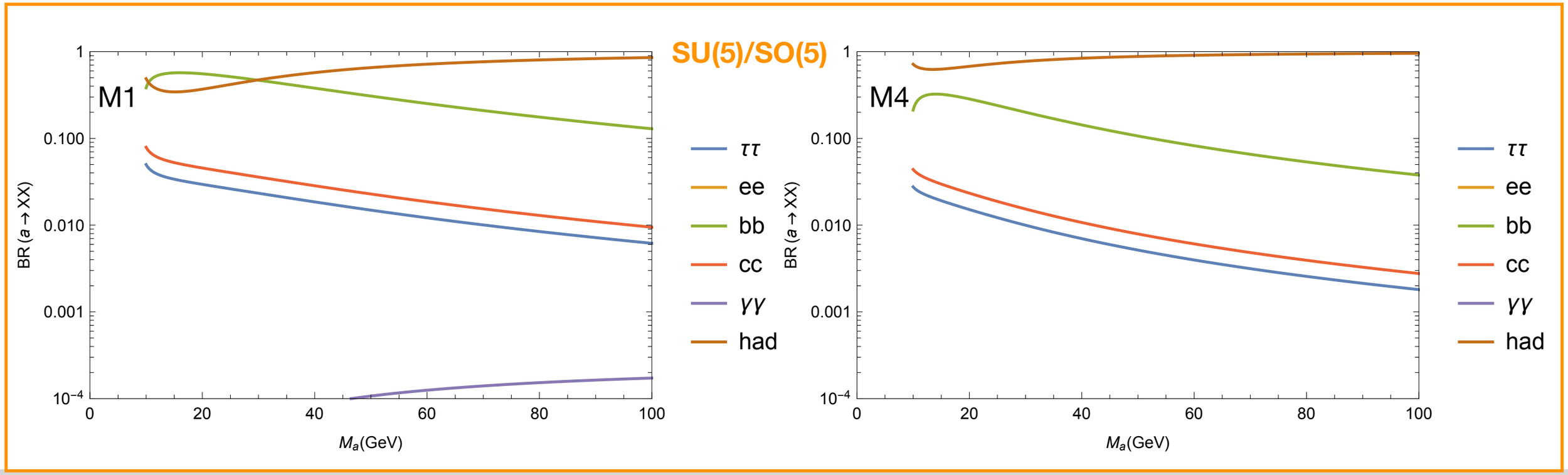


b and tau: dominant fermion decay modes

- Variation across models
- Any dependence on the decay constant vanishes in the branching ratios due to cancellation



The case for including b quarks



A model comparison