Models of Composite Higgs at the Future Circular Collider

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Based on a work in Physical Review D

(10.1103/PhysRevD.102.035030)

in collaboration with Aldo Deandrea, Benjamin Fuks, and Lara Mason

In this talk

A theoretical motivation

- The Standard model Higgs and why might it be composite?
- Composite Higgs models (BSM) predict the existence of a light particle a, produced in association with the Higgs
- How we might search for such a new resonance?
- In order to search, we will define 12 models (fundamental fermions)

Analysis outline

- Targeted low mass search for BSM physics:
- Consider $m_a \in [10,60]$ GeV:

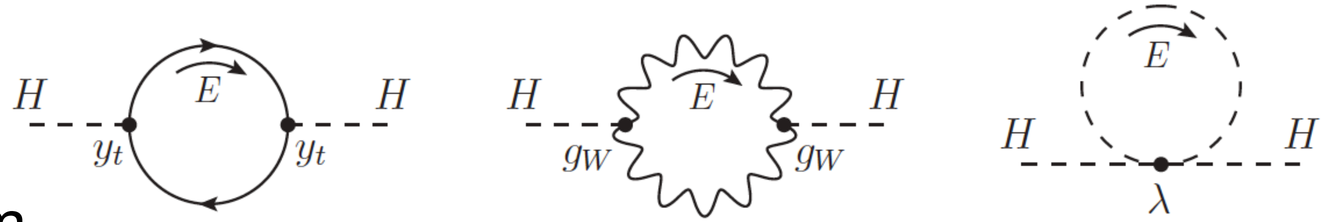
  deficiency of (LHC) searches thus far
- Possible search avenue at lepton colliders (FCC-ee)

  with low c.m. + high integrated luminosity = possibility

  for detection of weakly interacting particles
- Machine learning using boosted decision trees

Theoretical motivation

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

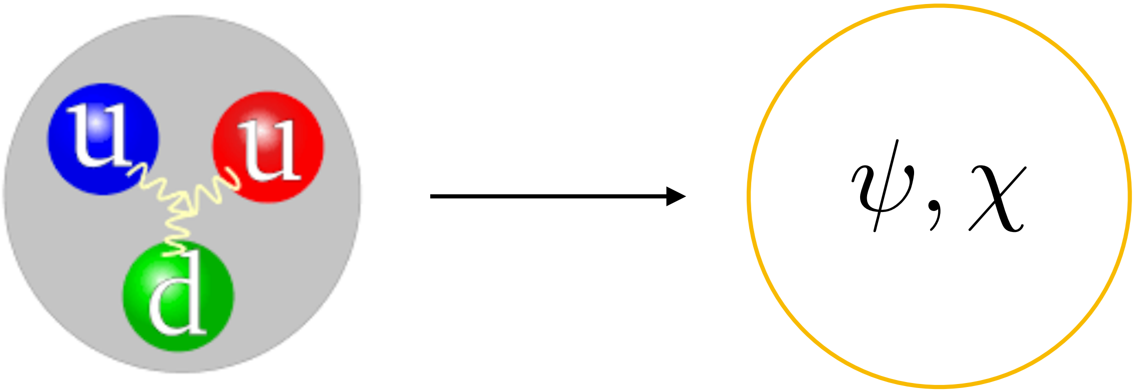


Unstable due to quantum corrections to the Higgs mass at high scales

Composite models remove this tension: quadratic divergences allowed only up to some compositeness scale

Finite size effects screen quadratic growth

- Composite Higgs models: high scale fundamental gauge dynamics + new strong sector
- Higgs is a bound state of fermions (but not the ones we know)
- If the Higgs *is* composite, it's hard to detect that from direct measurements, but..
- It will be accompanied by light states arising from same dynamics
- These light states may be the first signs of compositeness!

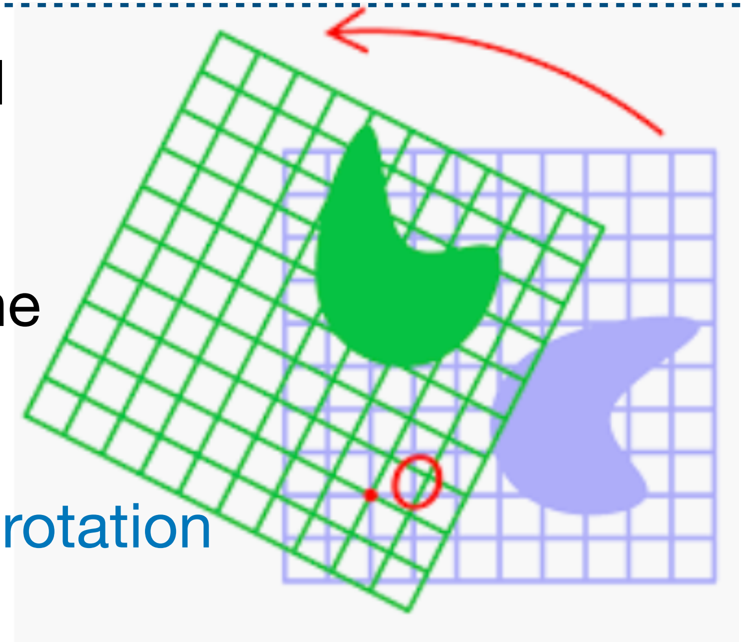


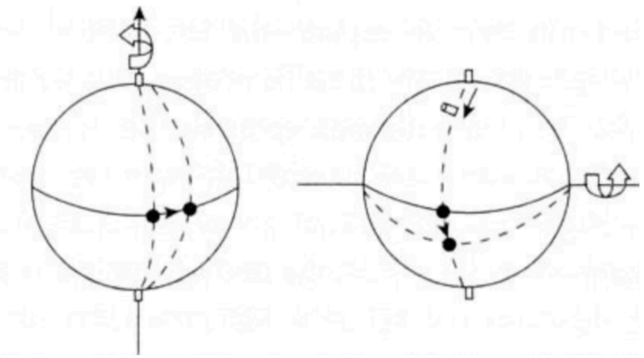
"Same" idea as QCD! (new fermions take the place of quarks)

A quick interlude: symmetry groups

The understanding of symmetries is crucial in both SM and CH models

- Whenever there is a symmetry of a physical system, we talk about a group
- The elements of the group correspond to the symmetry transformations
- Eg rotations in physical space, where each rotation is described by some matrix

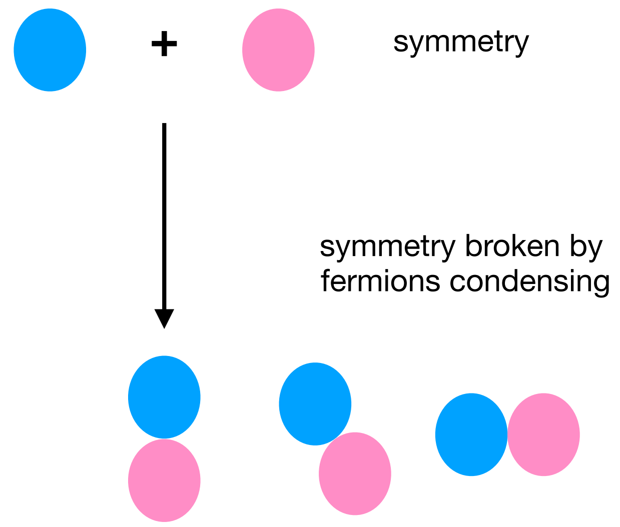




- Symmetries leave our system unchanged
- The SM is governed by the symmetry groups

$$SU(3) \times SU(2) \times U(1)$$

- Many BSM theories will go to larger symmetry groups
- In composite Higgs theories, there is some larger symmetry group which is spontaneously broken to produce our Higgs (and other Goldstones)



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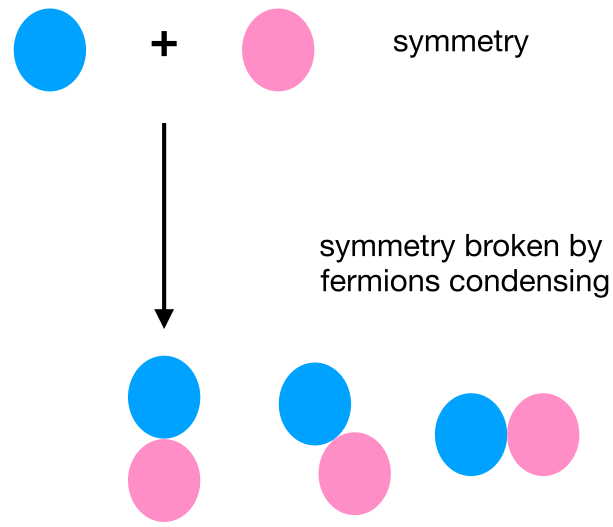


- Extend the SM
- Introduce strongly coupled gauge fermion sector
- Avoid fundamental scalars (no $SO(5)/SO(4)$!)

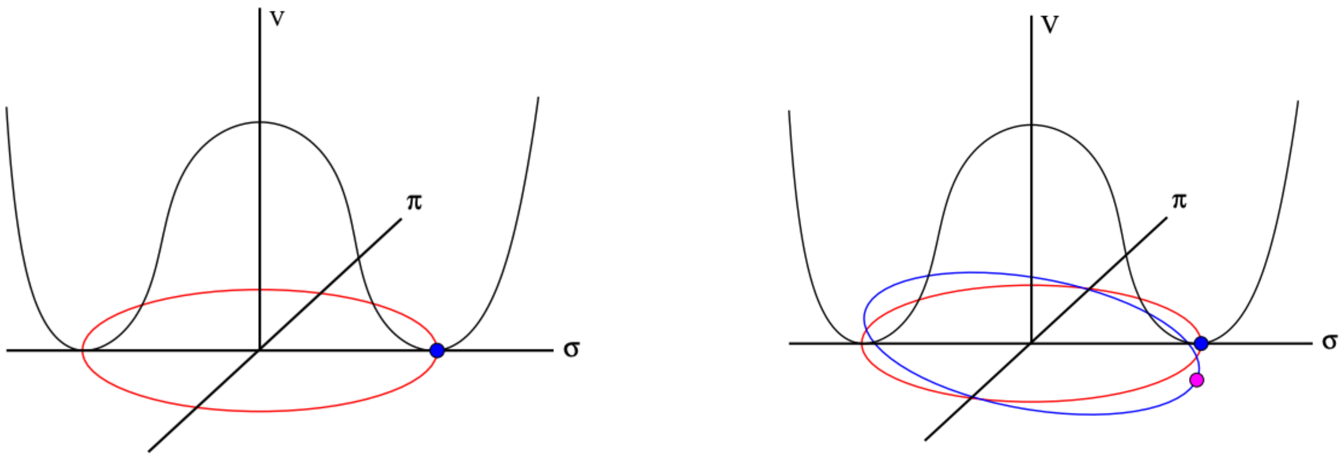
pNGB Higgs

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

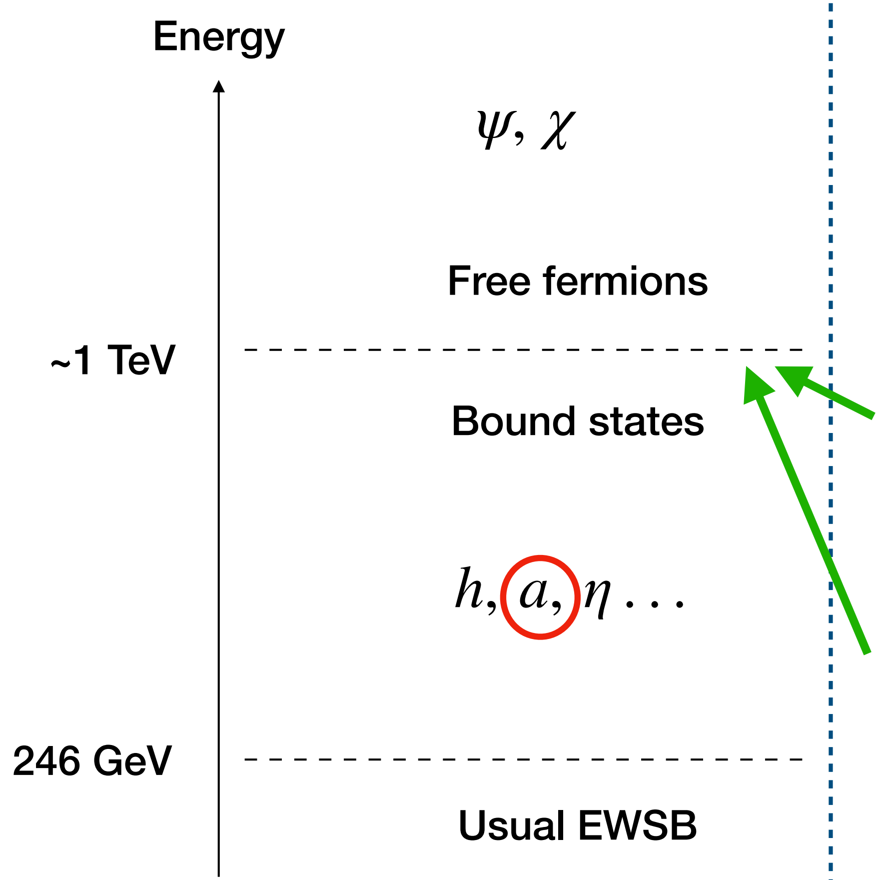
Goldstone's theorem: pNGB produced in the breaking

$$G \rightarrow H$$

when G was initially explicitly broken by some small amount.



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



- A given model has a hypercolour gauge group (unbroken), and ψ, χ in two different irreps of the hypercolour group
- Global (flavour) symmetries of ψ, χ are broken on the order of 1 TeV
- Also broken (by the same mechanism) is a ubiquitous non-anomalous $U(1)$ symmetry

- We have to make choices for these higher dimensional symmetries
- We will employ a set of 12 models (M1-M12) spanning a variety of HC and flavour groups
- Varying group structures
- Coefficients determined

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1312.5330/1610.06591

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This talk: pseudo-scalar a which is **always present in models** of this nature

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

- Fermion condensate breaks EW symmetry
- Higgs identified with lightest scalar excitation of the condensate

COMPOSITE HIGGS

- Fermion condensate breaks global symmetry group G
- Higgs identified with pNGB

A CH 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 and condensation forming Higgs.
In the technicolour limit, $\xi = 1$.
In limit $f \rightarrow \infty$, new physics decouples leaving SM ($\xi = 0$)

Underlying fermions

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

EW-charged ψ : generate Higgs and EWSB 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

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

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

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

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

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

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

Ubiquitous U(1) scalars

Always have singlet pseudo-scalars assoc. to global U(1) symm,
(and a coloured octet from 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 $U(1)_\psi$ spontaneously broken, but also explicitly broken by a ABJ anomaly $\Longrightarrow$ heavy Goldstone.
Also have χ fermions condensing $\Longrightarrow$ additional axial $U(1)_\chi$ SB.
Possible to construct an ABJ anomaly free linear combination $U(1)_a$: associated pseudo-scalar will be light

A $U(1)$ pseudo-scalar emerges

How has it evaded detection so far?

- Needs to be weakly coupled - no strong or electric charge
- Small couplings
- Low mass

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How has it evaded detection so far?

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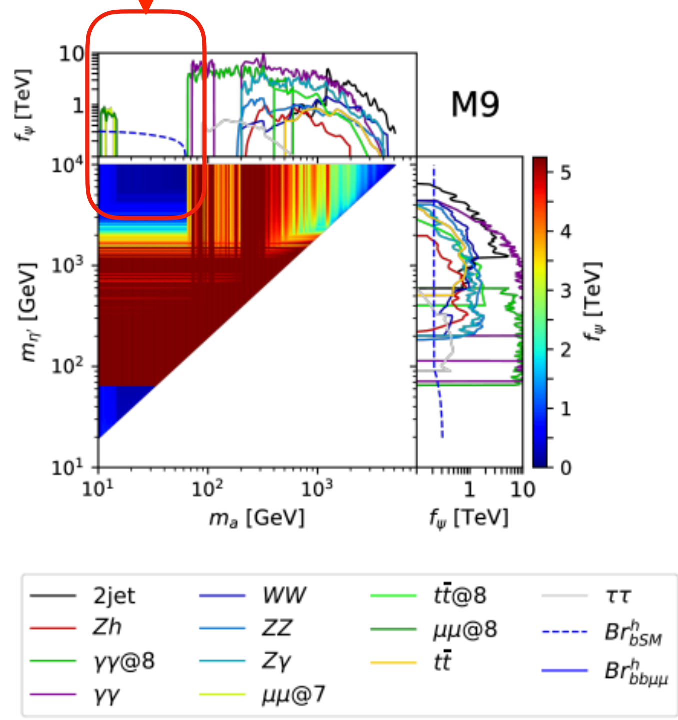
- Low mass

- Previous searches (di-j/di-μ/di-γ/di-τ) yield poor constraints in low pseudo-scalar mass region
- QCD backgrounds play a role in low mass searches at hadron colliders (therefore difficult to search there)

Minimal constraints region in the lower mass region



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(Top band: bounds from a.
Side band: bounds from η.
Bounds on f_ψ computed individually and then most stringent bound chosen)

U(1) pseudo-scalar

$$\mathcal{L} = \frac{1}{2}\left(\partial_\mu a\right)\left(\partial^\mu a\right) - \frac{1}{2}m_a^2 a^2 - \Sigma_f \frac{iC_f m_f}{f_a} a\bar{\Psi}_f \gamma^5 \Psi_f +$$

$$\frac{g_s^2 K_g}{16\pi^2 f_a} a G^a_{\mu\nu}\tilde{G}^{a\mu\nu} + \frac{g^2 K_W}{16\pi^2 f_a} a W^i_{\mu\nu}\tilde{W}^{i\mu\nu} + \frac{g'^2 K_B}{16\pi^2 f_a} a B_{\mu\nu}\tilde{B}^{\mu\nu},$$

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

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Previous phenomenology in 1710.11142, 1902.06890, focusing on LHC searches

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

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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)

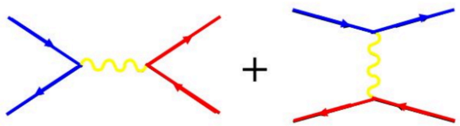
This model: SM loops, full LO

Model implementation tools: simulation

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

DELPHES
fast simulation

We will examine FCC (not built yet!)

Using a simulation of the collider and detector to create data:

FeynRules for model building:

Define all particles and how they interact with each other

MG5_aMC for simulation of signal and background processes:

Model collisions at detector

Pythia for parton showering and hadronisation

Delphes (+ FastJet) for detector response:

Simulate how the particles would be detected

Analysis:

MadAnalysis: cut and count

XGBoost: machine learning

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

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.

Recall: minimal cosets are

$SU(4)/Sp(4), SU(5)/SO(5),$
$SU(4) \times SU(4)/SU(4)$

A variety of hypercolour groups

F: fundamental rep

A: antisymmetric rep

Sp: spinorial rep

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$q_{\psi(\chi)}$: charges of fermions under non-anomalous $U(1)$

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

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$U(1)$ pseudo-scalar a

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- Light: mass up to 100 GeV
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- Couples directly to SM fermions

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

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

	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

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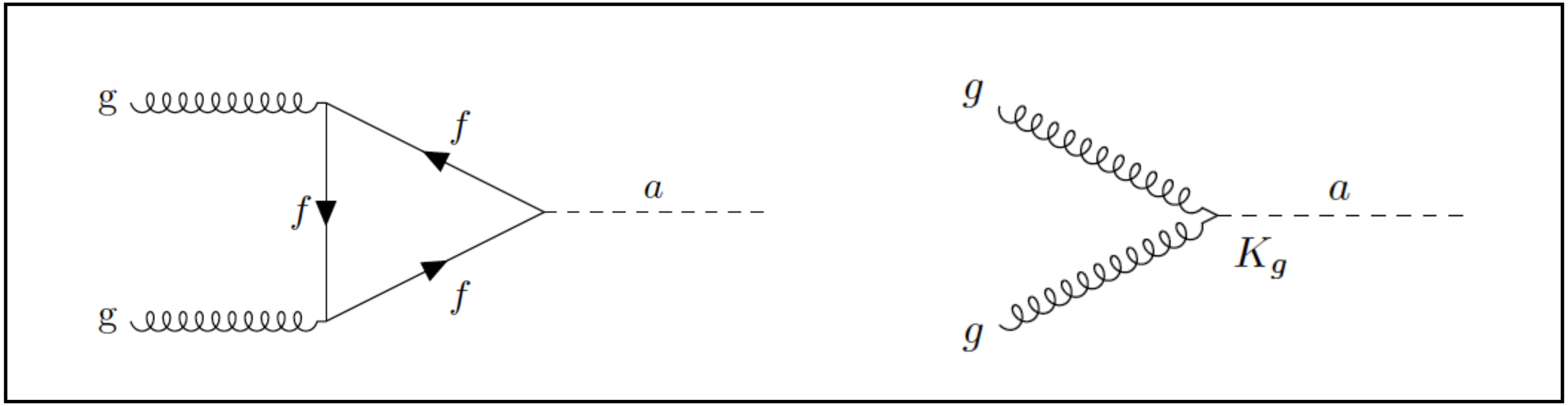
Anomalous coupling to bosons

Couplings of the form aXX', XX' are gauge bosons, proceed via the Wess-Zumino-Witten anomaly.

Coupling can be broken into a BSM component (effective vertex) and an SM component (loop of SM fermions)

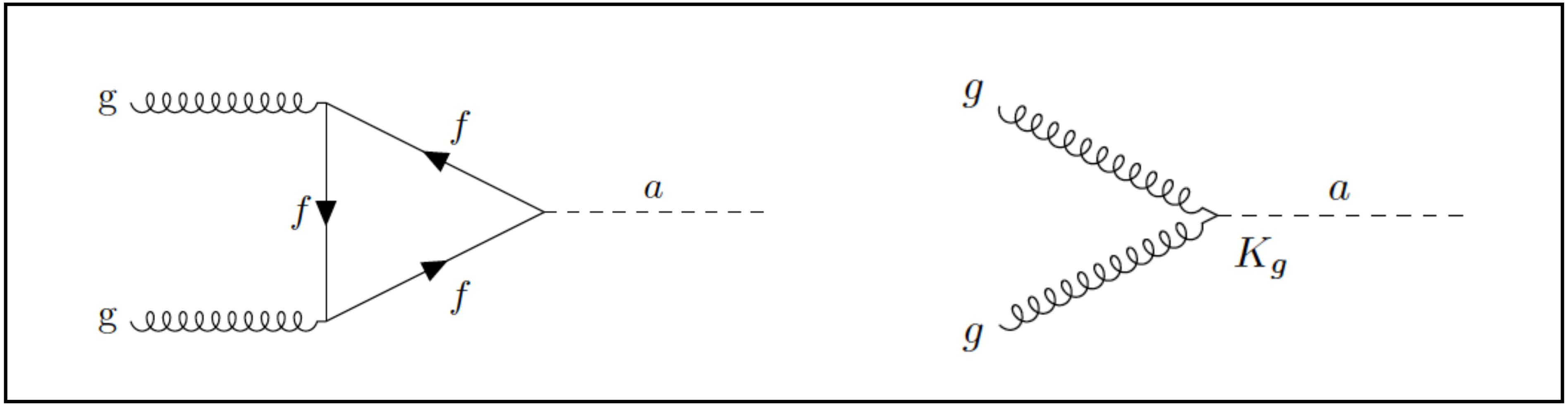
$$K_V^a = c_5 \left(\frac{C_V^\psi}{\sqrt{N_\psi}} \cos\alpha + \frac{f_\psi}{f_\chi} \frac{C_V^\chi}{\sqrt{N_\chi}} \sin\alpha \right)$$



$C_V^{\psi(\chi)}$: - anomaly coefficients of the singlets assoc. with $U(1)_{\psi(\chi)}$
- fully determined by SM charges of underlying fermions.

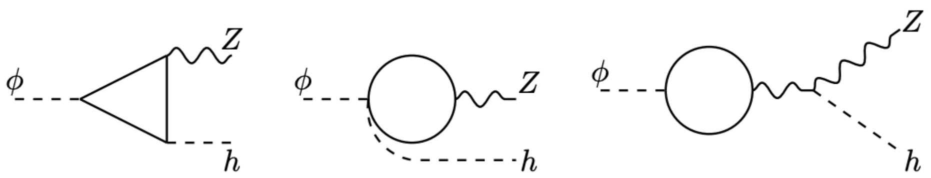
Only dependence on the mixing angle α remains: determined by the masses of the two states.

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

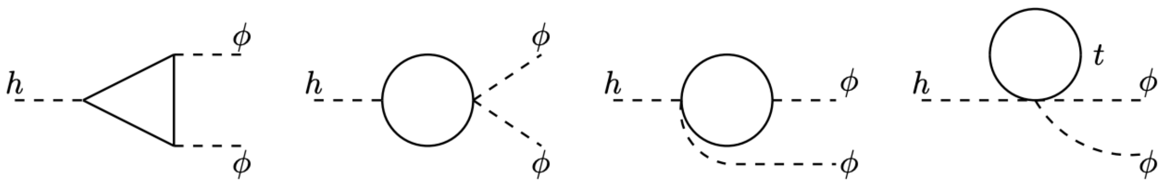


Coupling to bosons

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



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



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

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

Coupling to gauge bosons: quark loops

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

$A(\tau) = \tau f(\tau)$ Differs from Higgs result as now have a pseudo-scalar

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

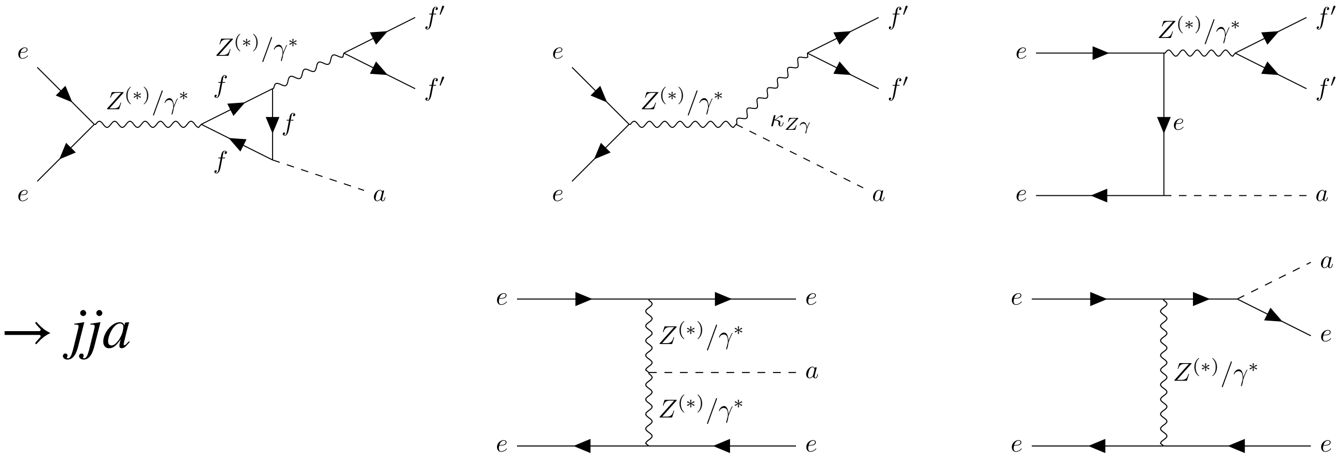
← **bottom** ($\tau < 1$)

← **top** ($\tau \geq 1$)

Production at lepton colliders

Consider production in association with a (virtual or real) boson:

$$e^+e^- \to \ell^+\ell^- a \; , \qquad e^+e^- \to jja$$



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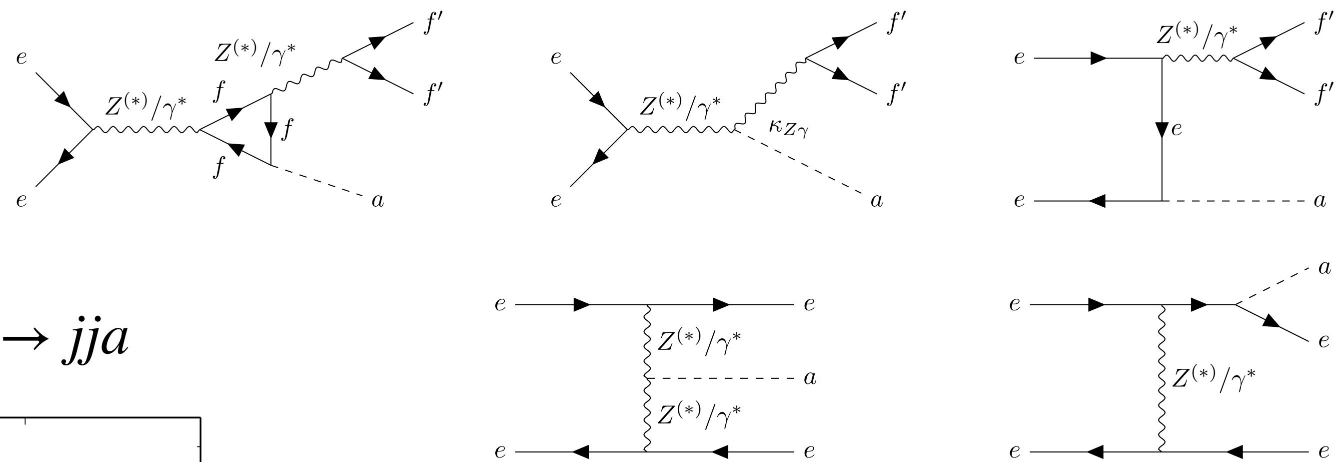
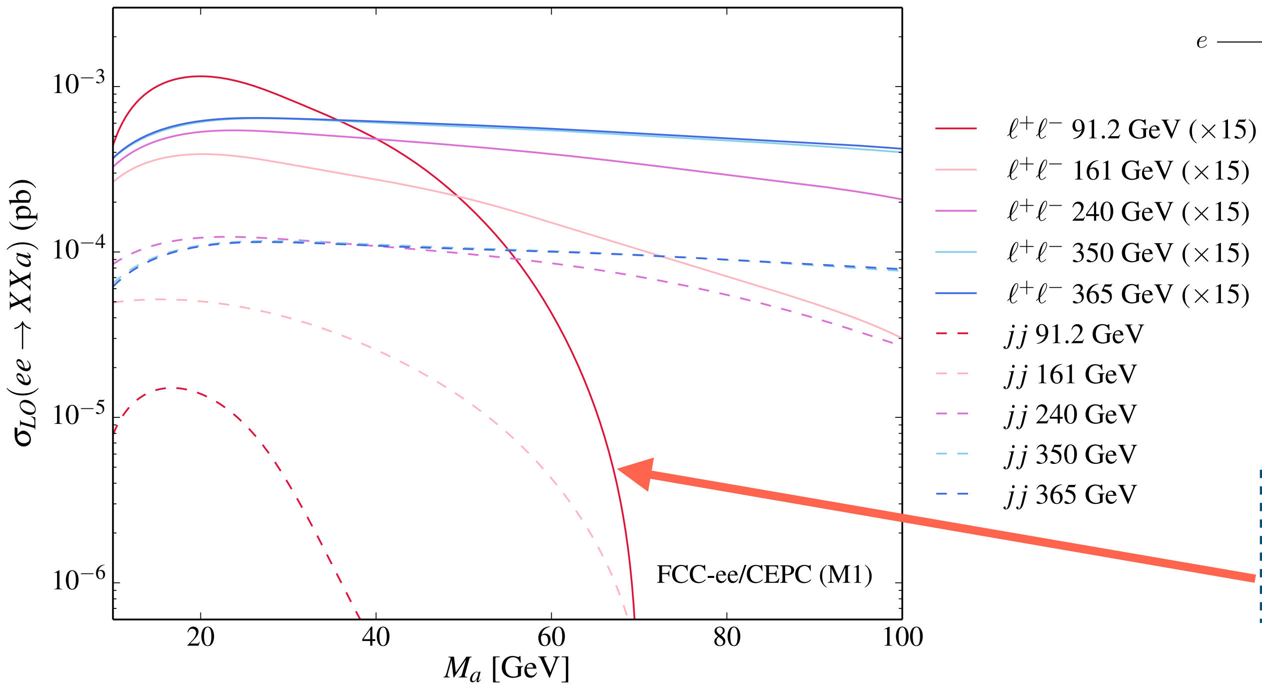
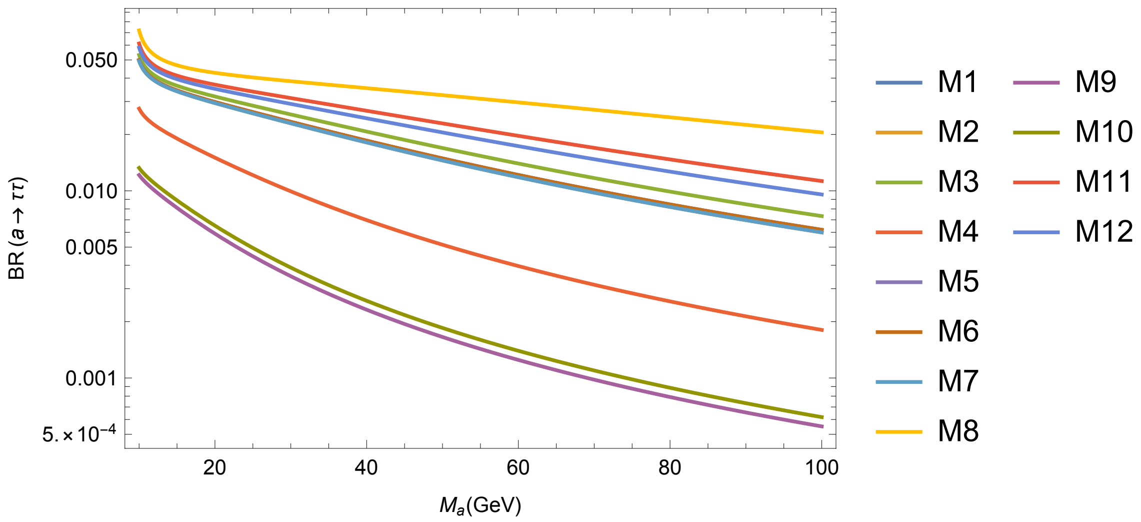




Mass range of interest is relatively well covered, even at the Z pole

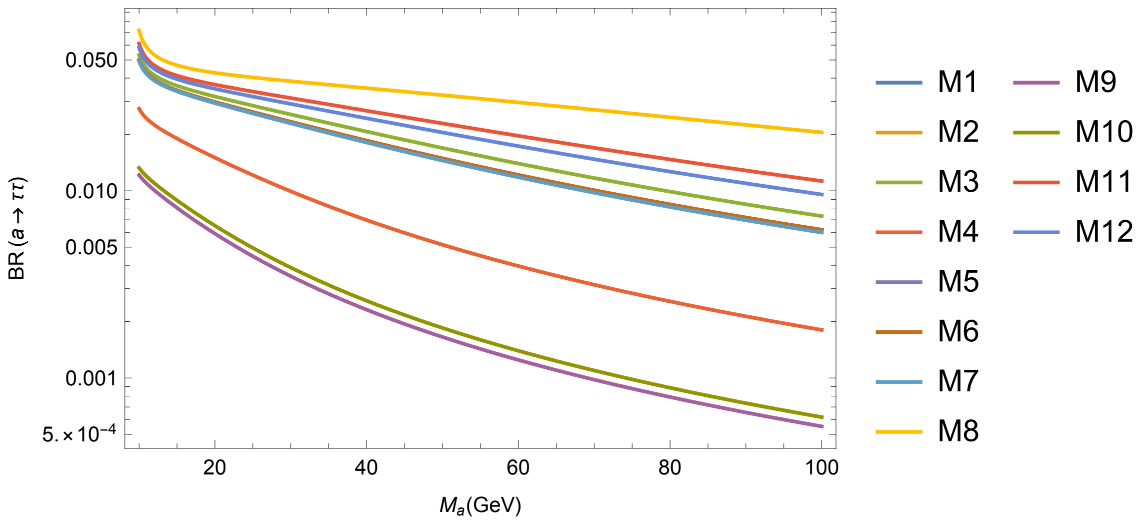
FCC-ee: $\tau\tau$ decay



Branching to τ's and b's highest (coupling proportional to mass)

We choose τ decay mode

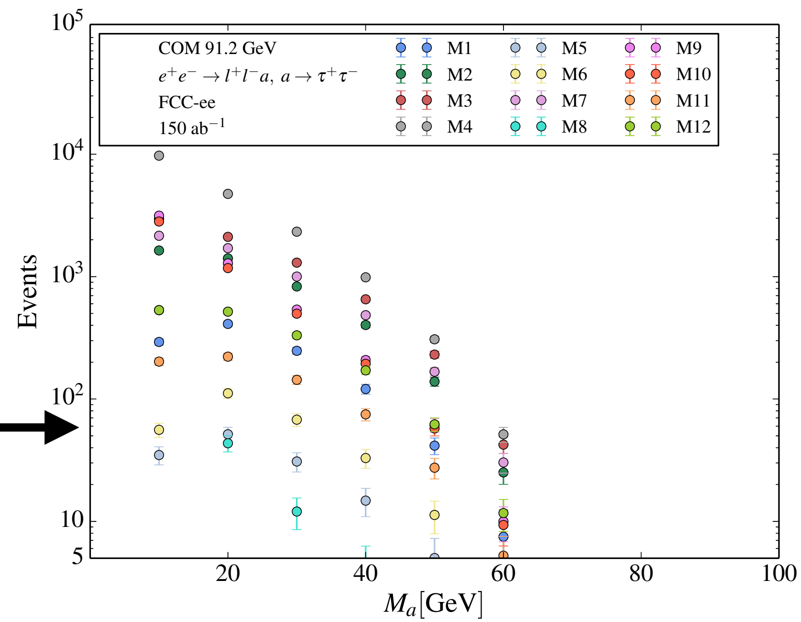
FCC-ee: $\tau\tau$ decay



Branching to τ's and b's highest (coupling proportional to mass)

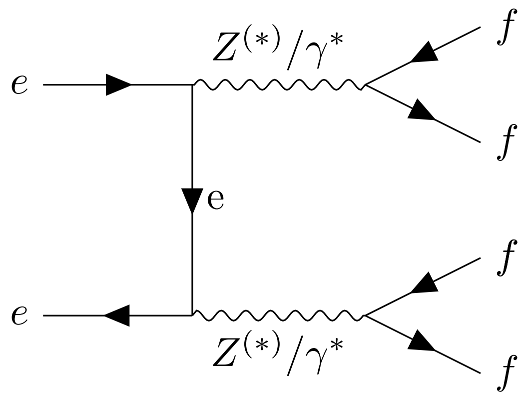
We choose τ decay mode

- Consider a produced with a pair of OS leptons (avoid multi jet bg)
- Signal events expected for subsequent decay to hadronic $\tau\tau$
- Sensitivity depends on model



Analysis

- Signal: $e^+e^- \to a\ \ell^+\ell^-,\ a \to \tau^+\tau^-$ (hadronic taus)
- Z pole: low c.m energy means fewer background processes
- Background resulting from (virtual) Z/γ events: look like our signal, but don't contain our a
- We simulate background to make the data realistic



And others!

Preselection: ensure objects are good quality when reconstructing

$N_\ell \geq 2$ with $p_T(\ell) > 10$ GeV; $N_\tau \geq 2$ with $p_T(\tau) > 5$ GeV; $M_{\ell\ell} > 12$ GeV; $M_{\tau\tau} > 10$ GeV .

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- Following preselection, we expect about 50,000 background events and up to 40 signal events (maximal production at $M_a = 20/30$ GeV)
- Signal looks swamped by background - it will be hard to see
- In the following analysis we will compare a cut and count with ML
- Choose a sample of models with varying group structures for illustrative purposes

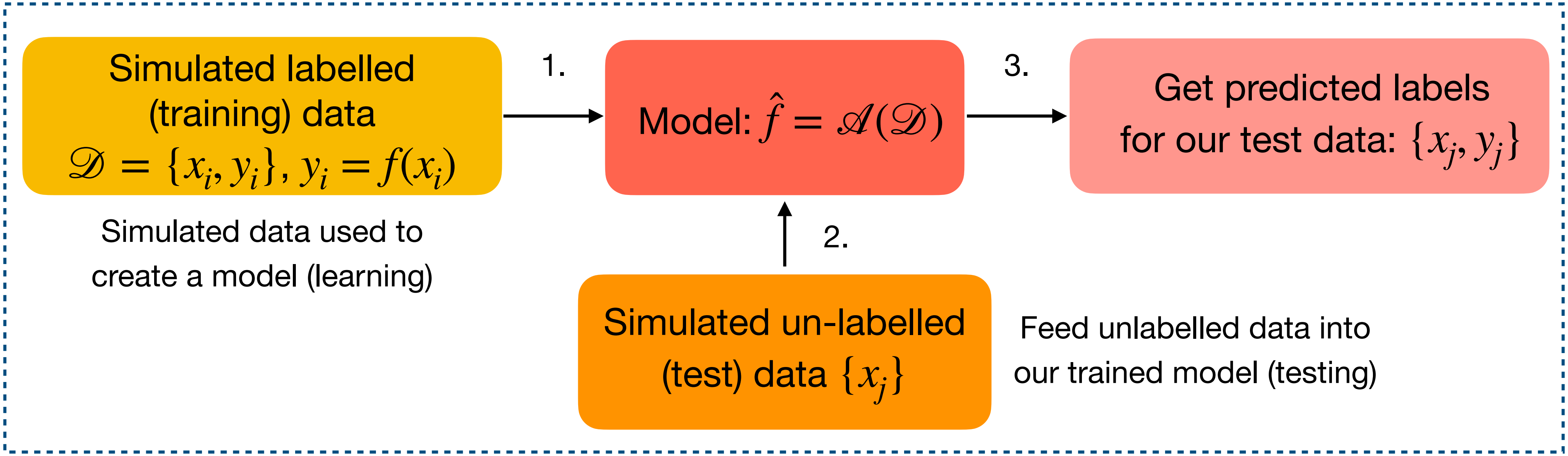
Machine learning

- The simple cuts in variables aren't enough
- What if we can build an algorithm to differentiate the signal from background?
- Make a big matrix of both signal and background, label them, and ask the machine to learn how to identify the signal

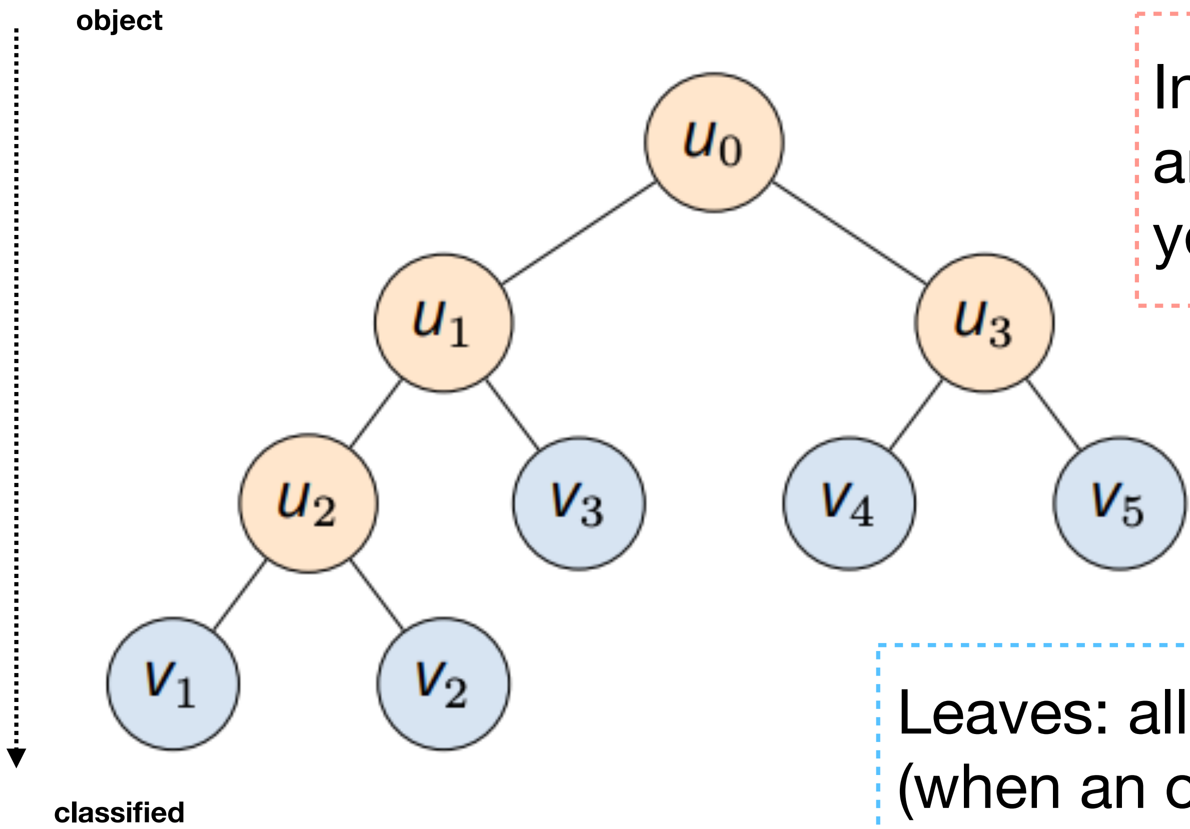
features →

$$X = \begin{bmatrix} x_1^1 & x_1^2 & \cdots & x_1^d \\ x_2^1 & x_2^2 & \cdots & x_2^d \\ \vdots & \vdots & \ddots & \vdots \\ x_N^1 & x_N^2 & \cdots & x_N^d \end{bmatrix}$$

↓ *objects*


Simulated labelled
(training) data
$\mathscr{D} = \{x_i, y_i\}, y_i = f(x_i)$
Simulated data used to
create a model (learning)
1.
Model: $\hat{f} = \mathscr{A}(\mathscr{D})$
3.
Get predicted labels
for our test data: $\{x_j, y_j\}$
2.
Simulated un-labelled
(test) data $\{x_j\}$
Feed unlabelled data into
our trained model (testing)

Decision trees: the basis of our algorithm



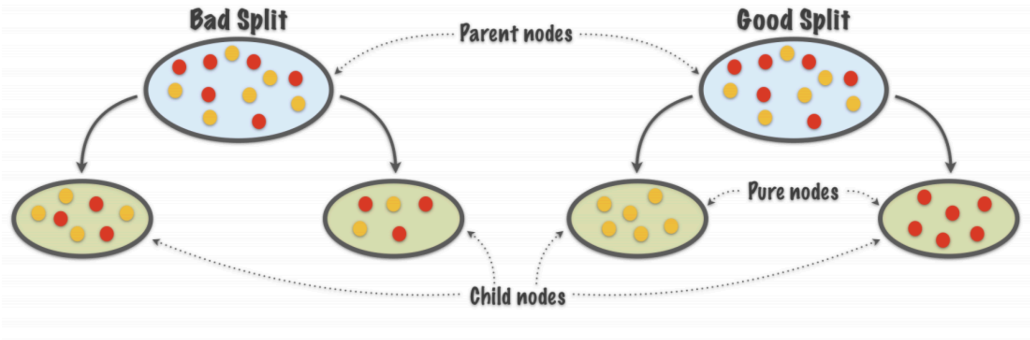
Internal nodes: check value and compare to a threshold ('if yes, go left, if no, go right")

Leaves: allow us to make predictions (when an object lands on a leaf, it is assigned the classification of that leaf)

While decision trees are interpretable, they are often not very powerful and can be unstable.

A more advanced class of algorithms builds on this idea..

- We want to train our tree so that at each node we split our data in a sensible way.
- Once the tree is trained, a given object will traverse the tree until it hits a leaf and is classified.



Picture credit: https://alanjeffares.wordpress.com/tutorials/decision-tree/

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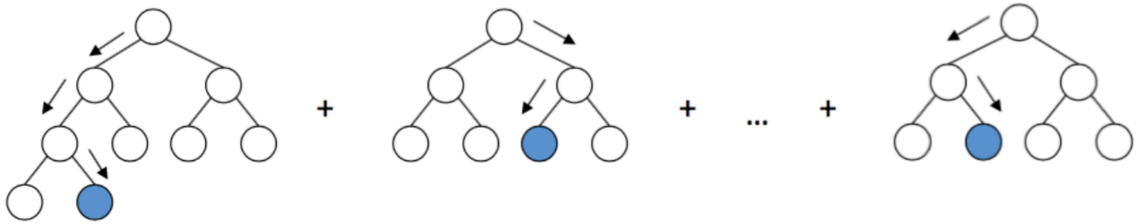
Machine learning: XGBoost

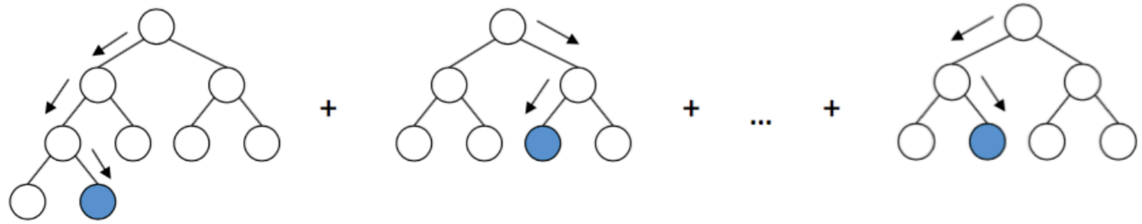


XGBoost:

- Gradient boosting ML algorithm: combines many decision trees
- Classify S or B: Logistic regression for binary classification

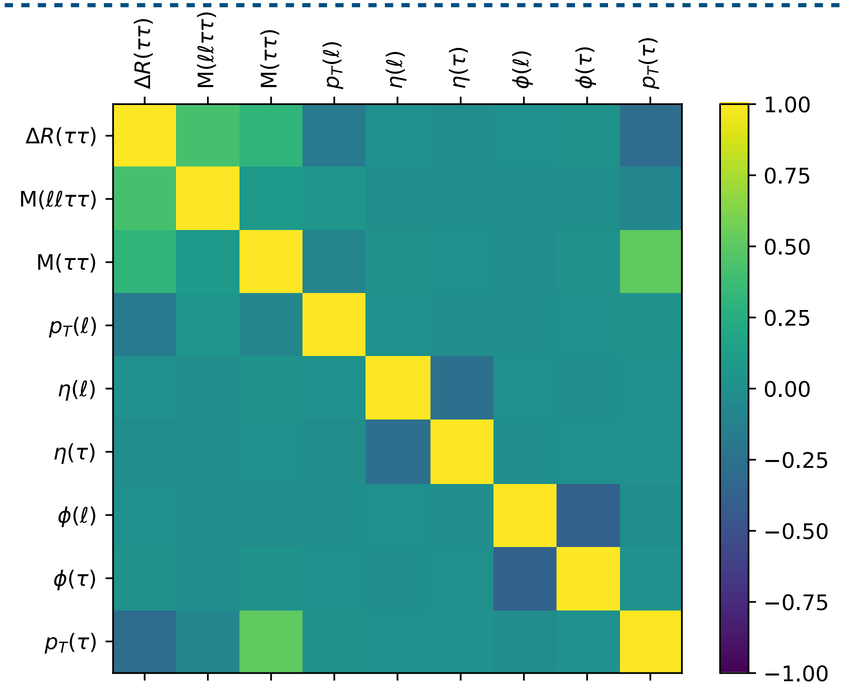
Machine learning: XGBoost

XGBoost:



- Gradient boosting ML algorithm: combines many decision trees
- Classify S or B: Logistic regression for binary classification

- Features optimised to maximise performance without being too correlated
- 1:5 test/train split
- Hyperparameters: *learning rate, maximum depth, minimum child weight*
- Trained by maximising *auc,* then calculated significance



- Variation across models, maximal significance for $M_a = 20$ GeV
- Lowest mass m_a destroyed by preselection, higher m_a low cross-sect

Model	Metric	$M_a = 10$ GeV	$M_a = 20$ GeV	$M_a = 30$ GeV	$M_a = 40$ GeV	$M_a = 50$ GeV
M2	*auc*	0.98 ± 0.003	0.87 ± 0.006	0.84 ± 0.0013	0.94 ± 0.0058	0.95 ± 0.0066
	ams	0.22	2.96	2.41	0.29	0.11
M4	*auc*	0.98 ± 0.0045	0.95 ± 0.0029	0.87 ± 0.020	0.88 ± 0.042	0.89 ± 0.061
	ams	1.16	2.83	1.69	0.54	0.15
M7	*auc*	0.98 ± 0.0018	0.86 ± 0.0082	0.88 ± 0.0011	0.90 ± 0.0012	0.94 ± 0.019
	ams	0.22	3.20	2.58	0.27	0.14
M10	*auc*	0.98 ± 0.003	0.92 ± 0.0057	0.90 ± 0.019	0.96 ± 0.0078	0.96 ± 0.0050
	ams	0.37	4.08	2.35	0.14	0.042
M12	*auc*	0.98 ± 0.0075	0.92 ± 0.003	0.92 ± 0.013	0.95 ± 0.0044	0.96 ± 0.0082
	ams	0.066	1.26	0.98	0.11	0.046

Cf. cut and count significances:

Model	$M_a = 10$ GeV	$M_a = 20$ GeV	$M_a = 30$ GeV	$M_a = 40$ GeV	$M_a = 50$ GeV
M2	0.0015	0.13	0.090	0.049	0.020
M4	0.0013	0.42	0.26	0.12	0.040
M7	0.0024	0.14	0.11	0.061	0.023
M10	0.0042	0.11	0.055	0.023	0.0078
M12	0.00061	0.047	0.035	0.021	0.017

Future prospects and conclusion

What luminosities are needed for us to reach 2 or 3 sigma?

Model	M_a (GeV)	Cut and Count		Machine Learning	
		2σ	3σ	2σ	3σ
M2	10	2.67×10^8	6.00×10^8	1.24×10^4	2.79×10^4
	20	3.55×10^4	7.99×10^4	68.5	154
	30	7.41×10^4	1.67×10^5	103	232
	40	2.50×10^5	5.62×10^5	7.13×10^3	1.61×10^4
	50	1.50×10^6	3.38×10^6	4.96×10^4	1.12×10^5
M4	10	3.55×10^8	7.99×10^8	446	1.00×10^3
	20	3.40×10^3	7.65×10^3	74.9	169
	30	8.88×10^3	2.00×10^4	210	473
	40	4.17×10^4	9.38×10^4	2.06×10^3	4.63×10^3
	50	3.75×10^5	8.44×10^5	2.67×10^4	6.00×10^4
M7	10	1.04×10^8	2.34×10^8	1.24×10^4	2.79×10^4
	20	3.06×10^4	6.89×10^4	58.5	132
	30	4.96×10^4	1.12×10^5	90.1	203
	40	1.61×10^5	3.63×10^5	8.23×10^3	1.85×10^4
	50	1.13×10^6	2.55×10^6	3.06×10^4	6.89×10^4
M10	10	3.40×10^7	7.65×10^7	4.38×10^3	9.86×10^3
	20	4.96×10^4	1.12×10^5	36.0	81.1
	30	1.98×10^5	4.46×10^5	109	244
	40	1.13×10^6	2.55×10^6	3.06×10^4	6.89×10^4
	50	9.86×10^6	2.22×10^7	3.40×10^5	7.65×10^5
M12	10	1.61×10^9	3.63×10^9	1.38×10^5	3.10×10^5
	20	2.72×10^5	6.11×10^5	378	850
	30	4.90×10^5	1.10×10^6	624	1.41×10^3
	40	1.36×10^6	3.06×10^6	4.96×10^4	1.12×10^5
	50	2.08×10^6	4.67×10^6	2.84×10^5	6.38×10^5

- Significant gains by gradient boosting methods over traditional cut and count
- At the FCC-ee we are expecting around 150 ab^{-1}
- Highest masses remain out of reach, as does $M_a = 10$ GeV
- Possibility to achieve 2σ or even 3σ for several models

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- A direct search for a light composite pseudo-scalar at high integrated luminosity lepton colliders should be considered
- Could be separately optimised for the heavier configurations by considering higher c.m. energies.

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Thank-you all for your attention