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A global analysis of ALP-mediated multiboson production at the LHC

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based on
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Axion-Like Particles (ALPs)

- ALPs appear as pseudo Goldstone bosons in many SM extensions with a spontaneous breaking of an approximate global symmetry at scale f_a
- they naturally arise in a broad class of UV completions, e.g. string compactifications, composite Higgs models
- in contrast to the axions, their mass and couplings are free parameters!
- ALPs inherit the approximate shift symmetry $a \to a + c$, their couplings are momentum dependent, distinct scaling with $\sqrt{\hat{s}}$
- ALP associated with a heavy new scale $f_a \gg v \Rightarrow$ EFT approach

Linear ALP EFT

- As in SMEFT, start from a linear realisation of EW symmetry, i.e. with a Higgs doublet H

$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_a$$

- Expand in powers of a/f_a , NLO has one insertion

$$\mathcal{L}_a = \frac{1}{2}\left(\partial_\mu a\right)\left(\partial^\mu a\right) + \frac{1}{2}m_a^2 a^2 + \sum_{f=Q,u,d,L,e} c_f \frac{\partial_\mu a}{f_a}\bar{f}\gamma^\mu f$$
$$- c_{\tilde{G}}\frac{a}{f_a}G^a_{\mu\nu}G^{a,\mu\nu} - c_{\tilde{W}}\frac{a}{f_a}W^I_{\mu\nu}W^{I,\mu\nu} - c_{\tilde{B}}\frac{a}{f_a}B_{\mu\nu}B^{\mu\nu}$$

- The couplings to fermions are proportional to the fermion mass (using EOM)

  ⇒ Singles out the top quark $\quad \mathcal{L} \supset -ic_t \frac{m_t a}{2f_a}\left(\bar{t}\gamma^5 t\right)$

- Multiboson final states are rare within the SM and sensitive to new physics. The structure of ALP-gauge couplings leads to irreducible contact interactions that directly generate multiboson vertices

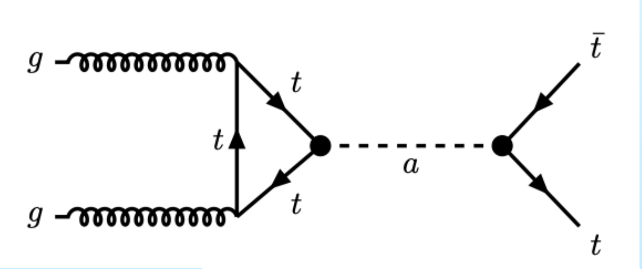
Constraining ALP couplings at the LHC

ALPs can be searched for at colliders in a large mass range, using both **resonant signatures** and **non-resonant production of light ALPs**

Previous works have focused on individual ALP signatures at the LHC, e.g.

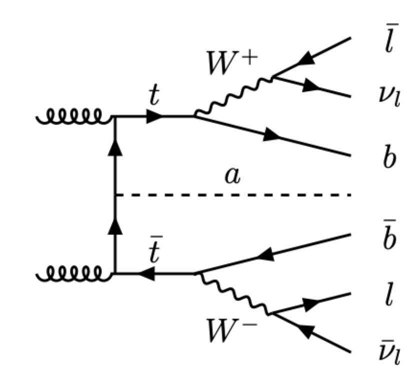
- diphoton, massive diboson, vector-boson scattering

  [Brivio, Gavela, Merlo, Mimasu, No, del Rey, Sanz '17]
  [Bauer, Neubert, Thamm, '17]
  [Gavela, No, Sanz, Trocóniz,'19]
  [Feng, Mao, Wang '25]



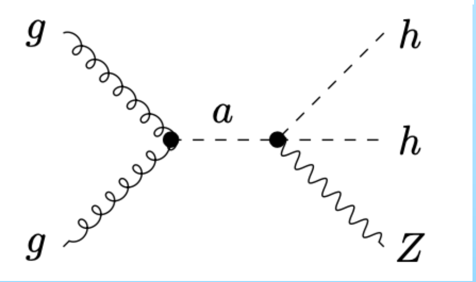
- top-quark

  [FE, Madigan, Sanz, Ubiali '23],
  [Hosseini, Mohammadi Najafabad '24]
  [Barbosa, Coelho, Fichet, da Silveira, M. Machado, '25]
  [Butterworth, Cullingworth, Egan, FE, Sanz, Ubiali, '25]



- gluons
- di-Higgs

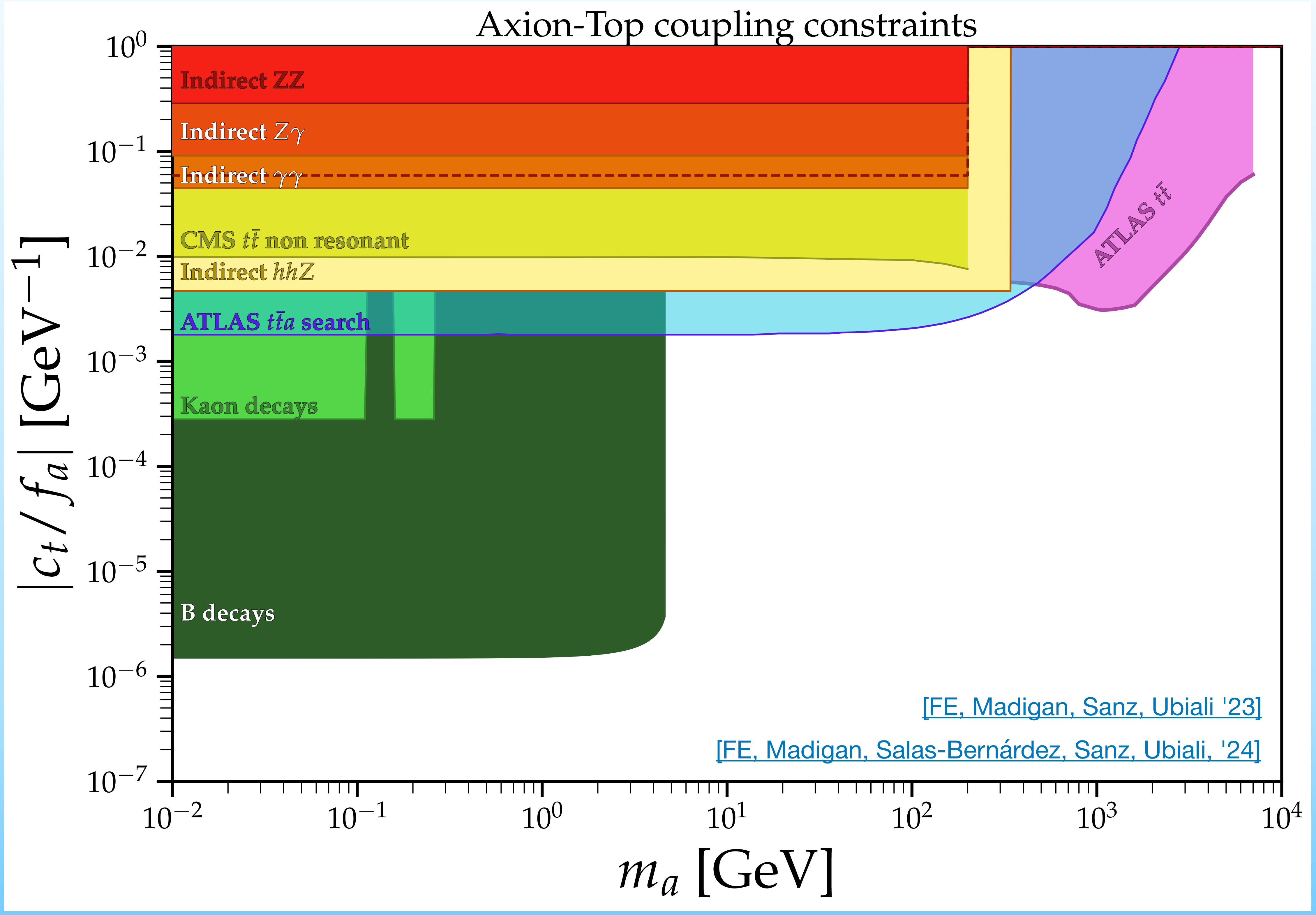
  [FE, Madigan, Salas-Bernárdez, Sanz, Ubiali, '24]



A comprehensive treatment of ALP-mediated multiboson production with independent couplings and combing different channels is missing

⇒ A global analysis is essential, only combining complementary observables can disentangle the underlying parameter space

ALP-top coupling



Multiboson production in linear ALP EFT

Vertex	Feynman rule (linear ALP EFT)
$a\gamma\gamma$	$-\frac{4i}{f_a}\left(\cos^2\theta_W\, \mathbf{c}_{\tilde{\mathbf{B}}} + \sin^2\theta_W\, \mathbf{c}_{\tilde{\mathbf{W}}}\right)\epsilon^{\mu\nu\rho\sigma}(p_{\gamma 1})_\rho (p_{\gamma 2})_\sigma$
$a\gamma Z$	$\frac{2i}{f_a}\sin(2\theta_W)(\mathbf{c}_{\tilde{\mathbf{B}}} - \mathbf{c}_{\tilde{\mathbf{W}}})\epsilon^{\mu\nu\rho\sigma}(p_Z)_\rho (p_\gamma)_\sigma$
aZZ	$-\frac{4i}{f_a}\left(\sin^2\theta_W\, \mathbf{c}_{\tilde{\mathbf{B}}} + \cos^2\theta_W\, \mathbf{c}_{\tilde{\mathbf{W}}}\right)\epsilon^{\mu\nu\rho\sigma}(p_{Z1})_\rho (p_{Z2})_\sigma$
aW^+W^-	$-\frac{4i}{f_a}\mathbf{c}_{\tilde{\mathbf{W}}}\,\epsilon^{\mu\nu\rho\sigma}(p_{W^+})_\rho (p_{W^-})_\sigma$
agg	$-\frac{4i}{f_a}\mathbf{c}_{\tilde{\mathbf{G}}}\,\delta_{ab}\epsilon^{\mu\nu\rho\sigma}(p_{g1})_\rho (p_{g2})_\sigma$
$a\gamma W^+W^-$	$\frac{4ie}{f_a}\mathbf{c}_{\tilde{\mathbf{W}}}\,\epsilon^{\mu\nu\rho\sigma}(p_{WW\gamma})_\sigma$
aZW^+W^-	$\frac{4ie}{f_a}\frac{\cos\theta_W}{\sin\theta_W}\mathbf{c}_{\tilde{\mathbf{W}}}\,\epsilon^{\mu\nu\rho\sigma}(p_{WWZ})_\sigma$
$aggg$	$\frac{4}{f_a}g_s\mathbf{c}_{\tilde{\mathbf{G}}}\,f_{abc}\,\epsilon^{\mu\nu\rho\sigma}(p_{ggg})_\sigma$

Assume ALP couplings at leading order exclusively to the gauge sector, no couplings to fermions or Higgs portals

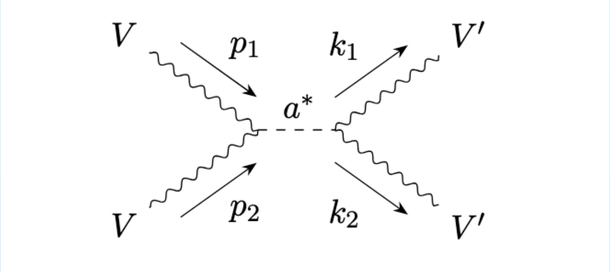
2-boson vertices currently provide the strongest sensitivity. They probe different combinations of the WCs.

Channels with 3 gauge bosons are not yet competitive, but will gain relevance with the increase of luminosity

Off-shell ALP mediation

- **Resonant searches:** search for a narrow peak around the ALP mass in the invariant mass distribution, relies heavily on kinematic cuts around the ALP mass m_a
- Here: **The ALP is exchanged off-shell**, it enters as a virtual mediator and modifies the tails of the SM distribution

  $\Rightarrow$ Probe light ALPs that would otherwise evade conventional resonance searches due to selection cuts



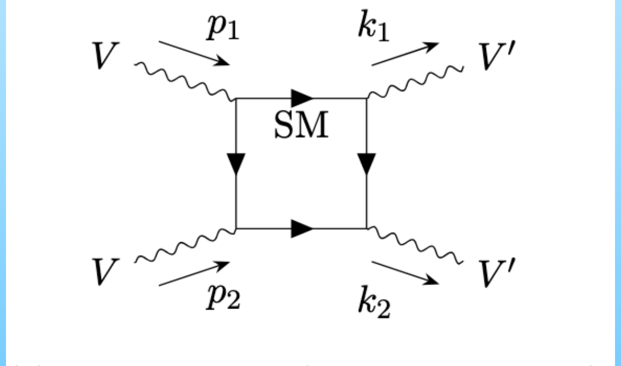
(b) Off-shell ALP exchange in the s-channel

$$\mathcal{M}_a \sim \frac{1}{\hat{s} - m_a^2 + i m_a \Gamma_a} \left(\frac{4}{f_a} c_{V_1 V_2}\, \epsilon_{\mu\nu\rho\sigma}\, p_1^\rho p_2^\sigma \varepsilon_1^\mu \varepsilon_2^\nu \right) \left(\frac{4}{f_a} c_{V_3 V_4}\, \epsilon_{\alpha\beta\lambda\kappa}\, k_1^\lambda k_2^\kappa \varepsilon_3^\alpha \varepsilon_4^\beta \right)$$

$$|\mathcal{M}_a|^2 \propto \frac{(c_{V_1 V_2}\, c_{V_3 V_4})^2}{f_a^4} \frac{\hat{s}^4}{(\hat{s} - m_a^2)^2 + m_a^2 \Gamma_a^2}$$

$$\hat{\sigma}(V_1 V_2 \to V_3 V_4) \propto \frac{1}{\hat{s}} |\mathcal{M}_a|^2 \propto \frac{(c_{V_1 V_2}\, c_{V_3 V_4})^2}{f_a^4}\, \hat{s}$$

For $m_a \ll \sqrt{\hat{s}}$, the ALP exchange leads to boosted gauge boson final states, the sensitivity depends primarily on the effective couplings and not on the ALP mass.



(a) SM continuum (no ALP resonance)

The growth with $\hat{s}$ is a generic feature of ALP-mediated processes and reflects the derivative nature of the couplings

The sensitivity of the LHC measurements is driven by high-energy tails of the kinematic distribution, distinct scaling than the SM background

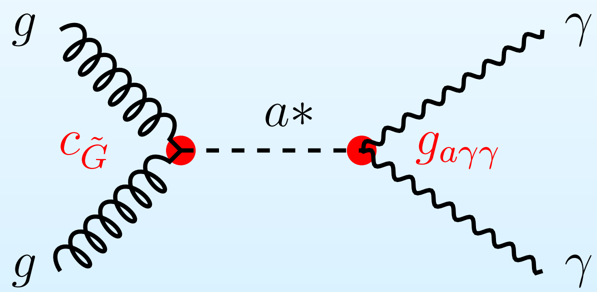
Global analysis of LHC Run II measurements

final state	experiment	$\sqrt{s}$ (TeV)	luminosity	observables	reference and data
$\gamma\gamma$	CMS	7	$5\,\mathrm{fb}^{-1}$	$d\sigma_{\gamma\gamma}/dm_{\gamma\gamma}$	[28] HepData
	ATLAS	13	$139\,\mathrm{fb}^{-1}$	$d\sigma_{\gamma\gamma}/dm_{\gamma\gamma}$	[29] Analysis HepData Rivet
ZZ	CMS	13	$137\,\mathrm{fb}^{-1}$	$d\sigma/m_{ZZ}$, $d\sigma/p_T^l$	[30]Analysis HepData
	ATLAS	13.6	$29\,\mathrm{fb}^{-1}$	$d\sigma/dm_{4l}$	[31] HepData
W^+W^-	CMS	13	$34.8\,\mathrm{fb}^{-1}$	total cross section	[32] HepData
	ATLAS	13	$36.1\,\mathrm{fb}^{-1}$	$d\sigma_{WW}/dm_{e\mu}$	[33] HepData Rivet
dijet (gg)	**ATLAS**	13	$3.2\,\mathrm{fb}^{-1}$	$d^2\sigma_{jj}/dm_{jj}dy*$	[34] HepData Rivet
	CMS	13	$2.3\,\mathrm{fb}^{-1}$	$d^2\sigma_{jj}/dm_{jet}dp_T$	[35] HepData Rivet
	CMS	13	$2.6\,\mathrm{fb}^{-1}$	$1/\sigma d^2\sigma_{jj}/d\chi dm_{jj}$	[36] HepData Rivet
	CMS	13	$35.9\,\mathrm{fb}^{-1}$	$1/\sigma d^2\sigma_{jj}/d\chi dm_{jj}$	[37] HepData
γZjj (VBF)	**CMS**	13	$139\,\mathrm{fb}^{-1}$	$\mathbf{d\sigma/dp_T^{\gamma}}$, $d\sigma/dp_T^{\mathrm{lead,l}}$, $d\sigma/p_T^{\mathrm{lead,j}}$, $d^2\sigma/dy_{jj}dm_{jj}$	[38] HepData
$ZZjj, W^+W^-jj$ (VBF)	**ATLAS**	13	$140\,\mathrm{fb}^{-1}$	Events/ 200 GeV in m_{VV} bins	[39] Additional material

Analysis strategy:

- generate signal events in **MadGraph5_aM@NLO** at LO, using **NNPDF4.0**, 4-flavour scheme and *ALP_linear_UFO* [Brivio, Gavela, Merlo, Mimasu, No, del Rey, Sanz '17]
- **set $m_a = 1$ MeV** (signal roughly independent of m_a as long as $m_a \ll \sqrt{\hat{s}}$)
- **set $f_a = 1$ TeV**. We are only sensitive to ratios $\frac{c_{\tilde{X}}}{f_a}$, quote limits for $f_a = 1$ TeV, can be easily rescaled
- follow fiducial cuts and binning as given by in the ATLAS/CMS analysis
- focus on **pure quadratic signal** contribution and no interference with the SM

Diphoton channel



$$g_{a\gamma\gamma} = \frac{4}{f_a}\left(c_\theta^2 \mathbf{c_{\tilde{B}}} + s_\theta^2 \mathbf{c_{\tilde{W}}}\right)$$

Generate events for a benchmark
$(c_{\tilde{G}} = 1, c_{\tilde{W}} = 1, c_{\tilde{B}} = 0)$,
the distribution for any other choices can be obtained from the Feynman rules:

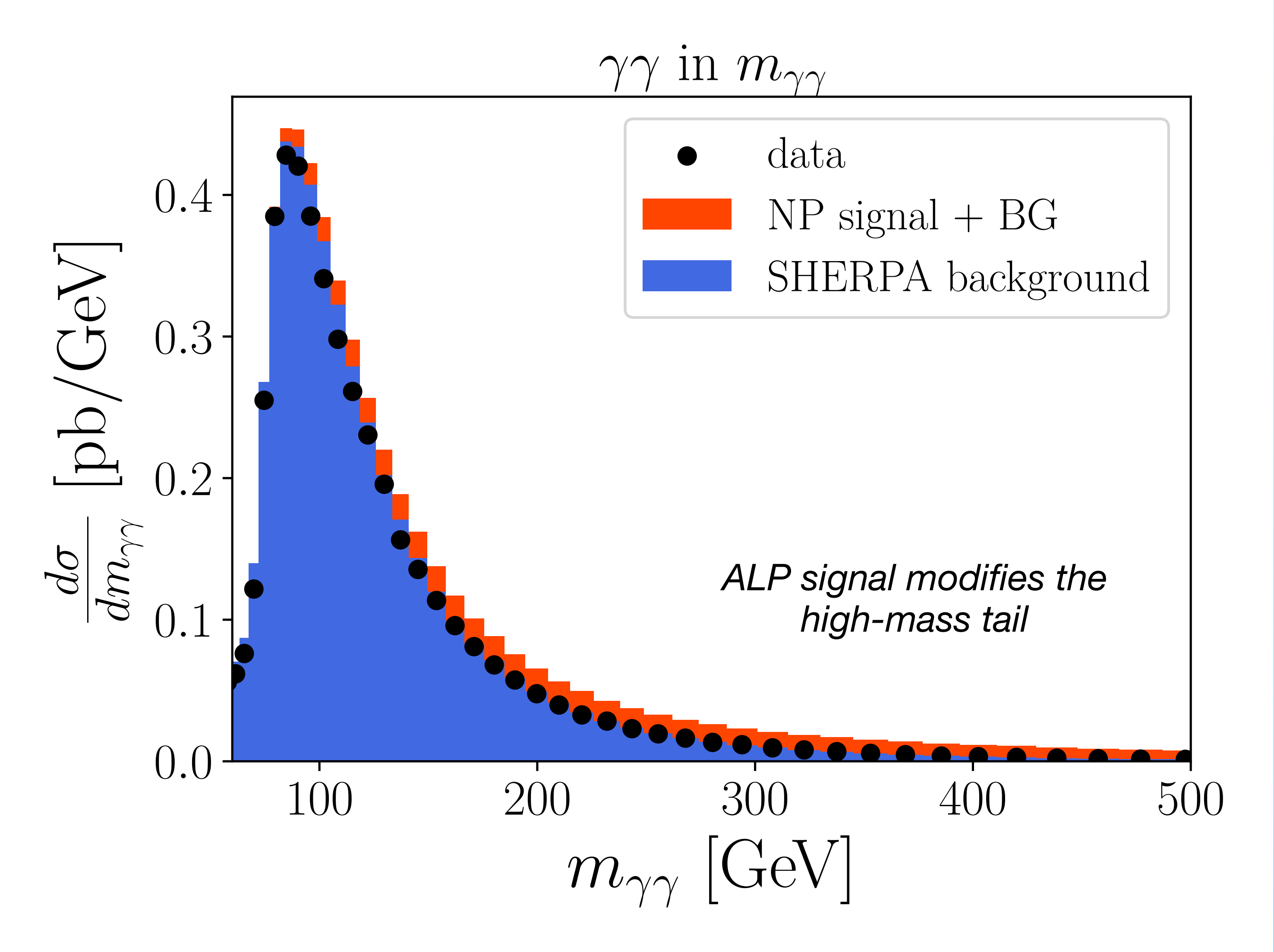
$$N_i^{\text{th}} = N_i^{BG} + N_i^{\text{ALP}}(c_{\tilde{G}} = 1,\, c_{\tilde{W}} = 1,\, c_{\tilde{B}} = 0)\left(\frac{c_{\tilde{G}}}{f_a}\right)^2\left(\frac{g_{a\gamma\gamma}}{4s_\theta^2}\right)^2$$

This holds as long as there is no interference with the SM. For diboson final states it is tiny because $gg \to VV$ has no tree-level SM contribution

$$\chi^2 = \sum_i \left(\frac{N_i^{\text{data}} - N_i^{\text{th}}}{\sigma_i}\right)^2$$

calculate χ^2 for each channel, only diagonal uncertainties provided

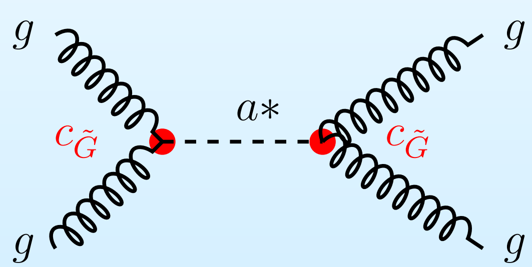
Binned analysis in $m_{\gamma\gamma}$, data and background from ATLAS [2107.09330]



Analyses for ZZ and WW very similar!

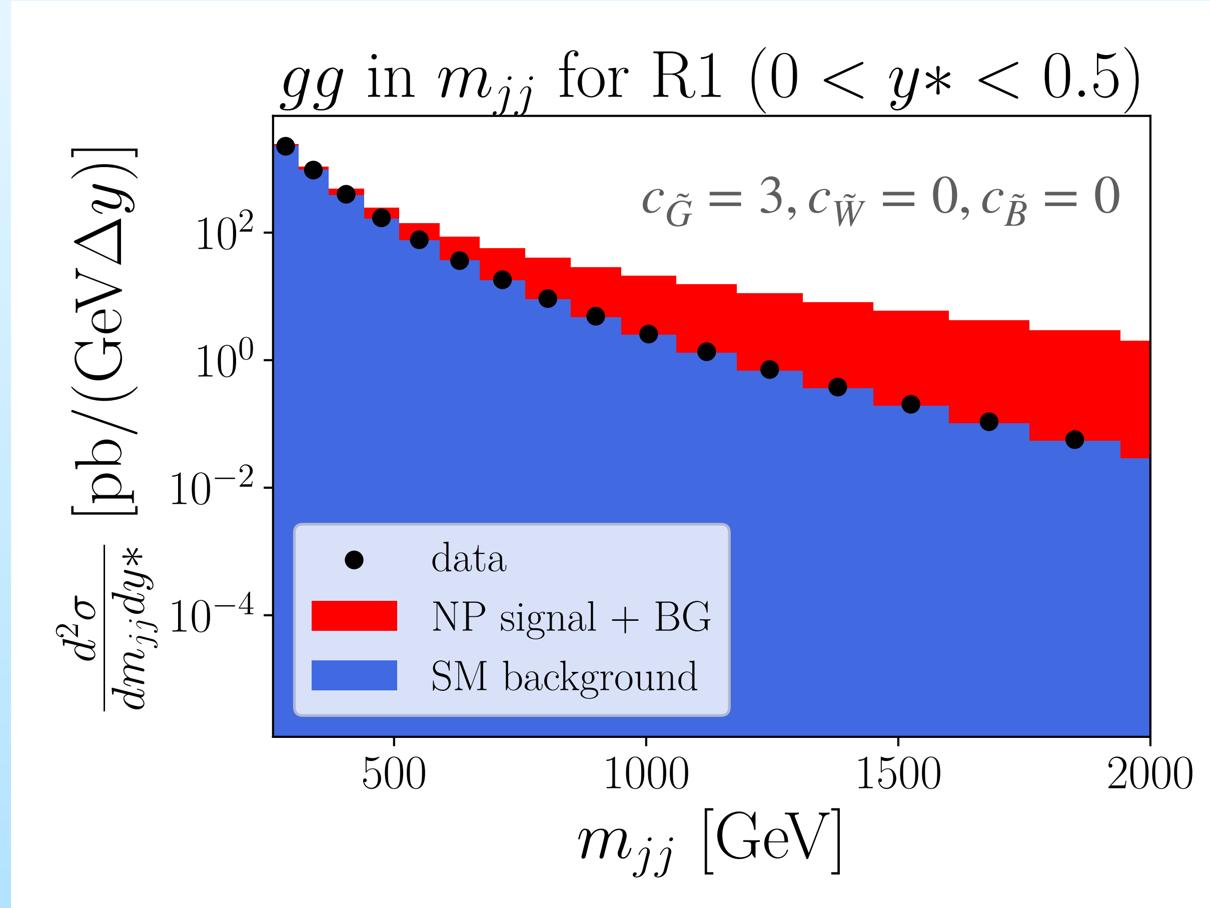
Dijet

ATLAS provides double differential dijet cross section $\dfrac{d^2\sigma}{dm_{jj}dy^*}$, half-rapidity separation $y^* = \dfrac{1}{2}|y_{j_1} - y_{j_2}|$ [1711.02692]



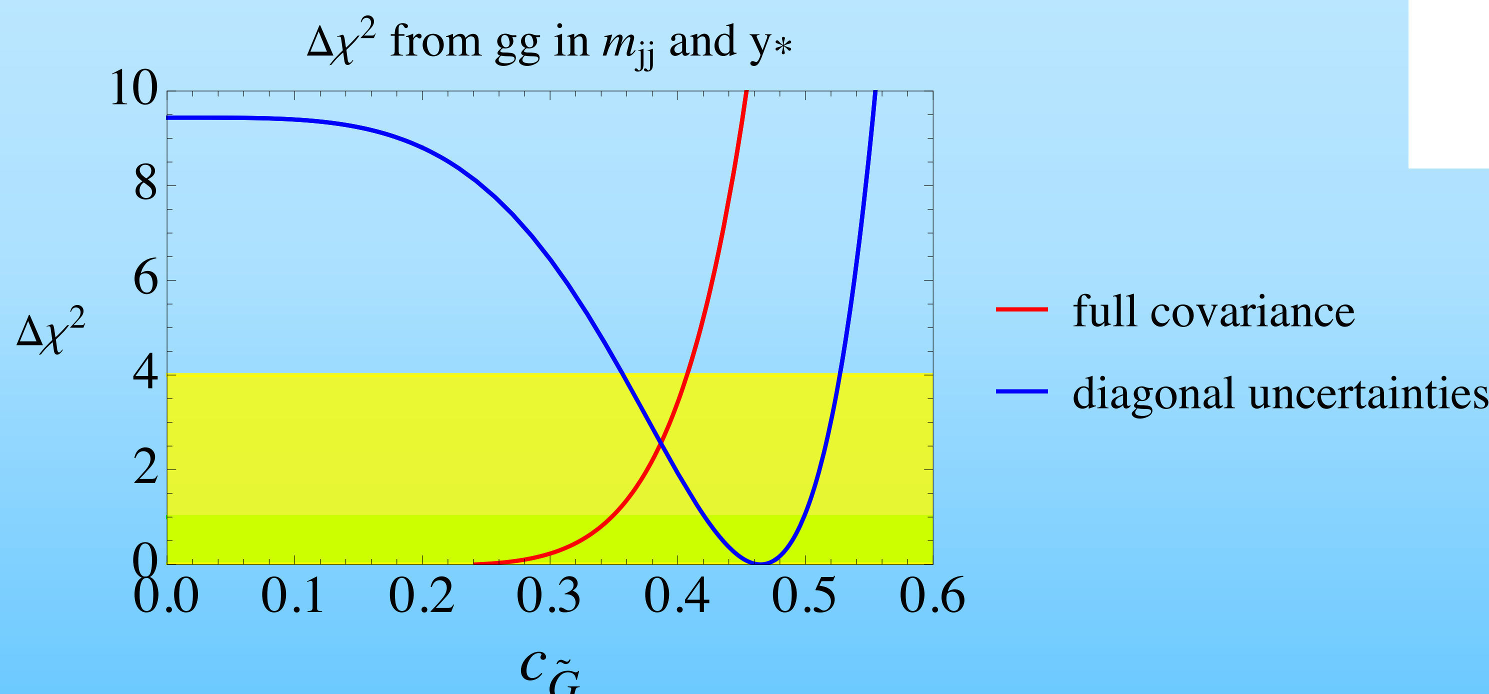
depends only on $c_{\tilde{G}}$!

$$N_i^{\text{th}} = N_i^{BG} + \left(\frac{c_{\tilde{G}}}{f_a}\right)^4 N_i^{\text{ALP}}(c_{\tilde{G}} = 1)$$



Split in 6 regions of y^* (136 bins in total)
Background from NNLOJET code [NNLOJET collaboration '25]
Utilise the full experimental covariance matrix

$$\chi^2 = \left(N^{\text{data}} - N^{\text{th}}\right)^T \Sigma^{-1} \left(N^{\text{data}} - N^{\text{th}}\right)$$

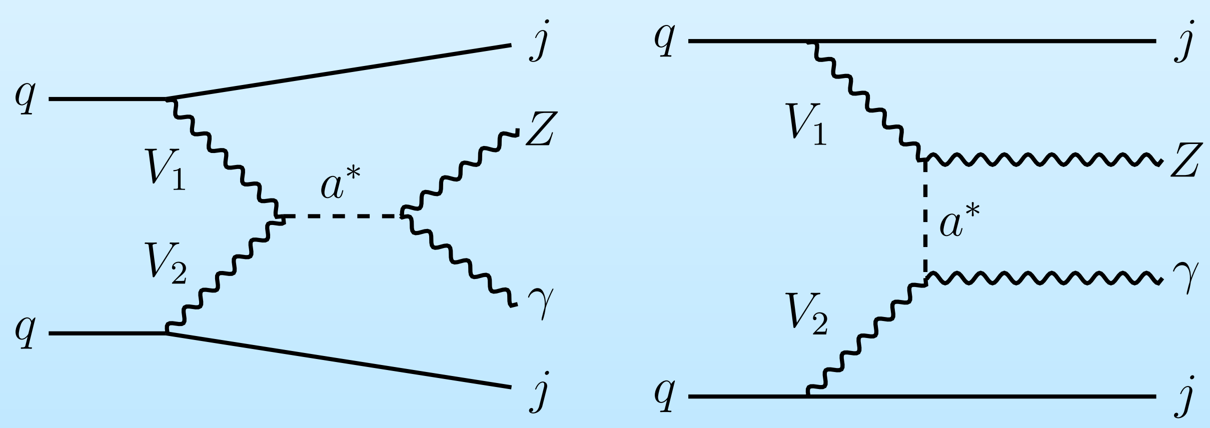


Ignoring the correlations even prefers a non-zero $c_{\tilde{G}}$!

$\Rightarrow$ shows the importance of the covariance!

Vector boson fusion (VBF) γZjj

All other channels so far depend on $c_{\tilde{G}}$, VBF enables us to constrain couplings in $\left(c_{\tilde{W}}, c_{\tilde{B}}\right)$ independently of $c_{\tilde{G}}$

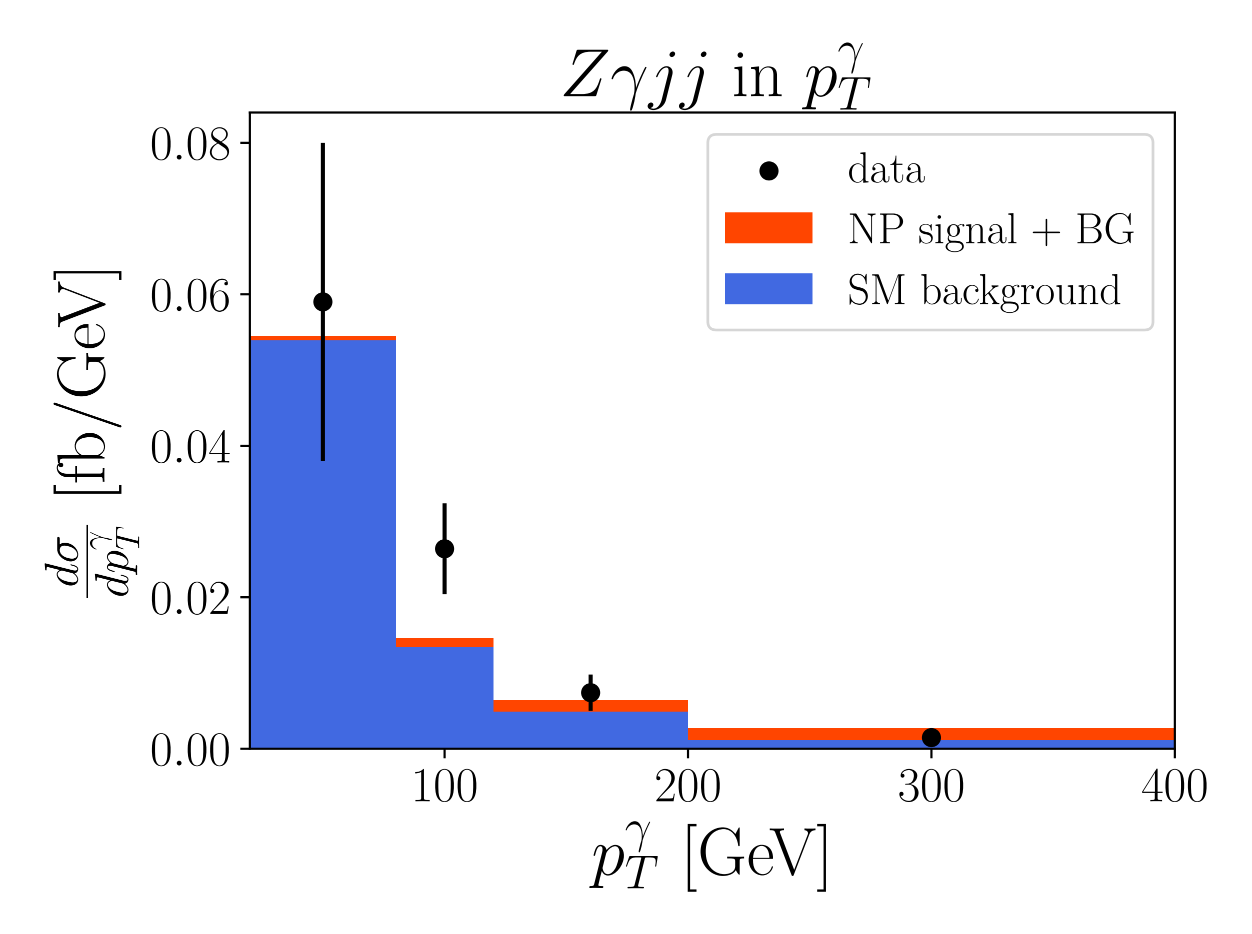


Fit the cross section

$$\sigma_{Z\gamma jj}(c_{\tilde{W}}, c_{\tilde{B}}) = \sum_{m,n=0}^{4, m+n\leq 4} \alpha_{mn}\, c_{\tilde{W}}^{m} c_{\tilde{B}}^{n}$$

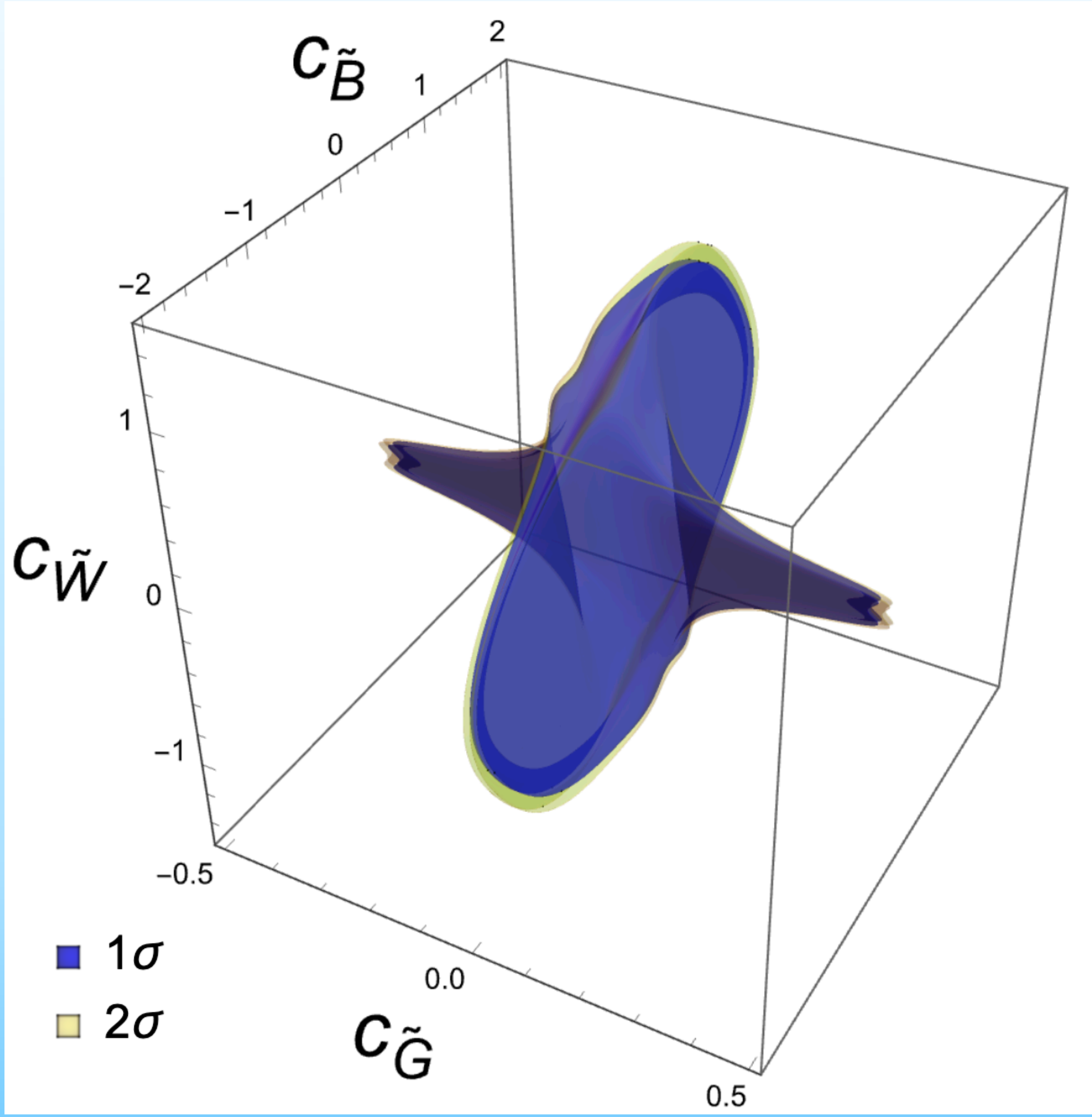
CMS measurement of $pp \to Z\gamma jj,\, Z \to l^+l^-$

Best distribution $\dfrac{d\sigma}{dp_T^\gamma}$ [2106.11082]

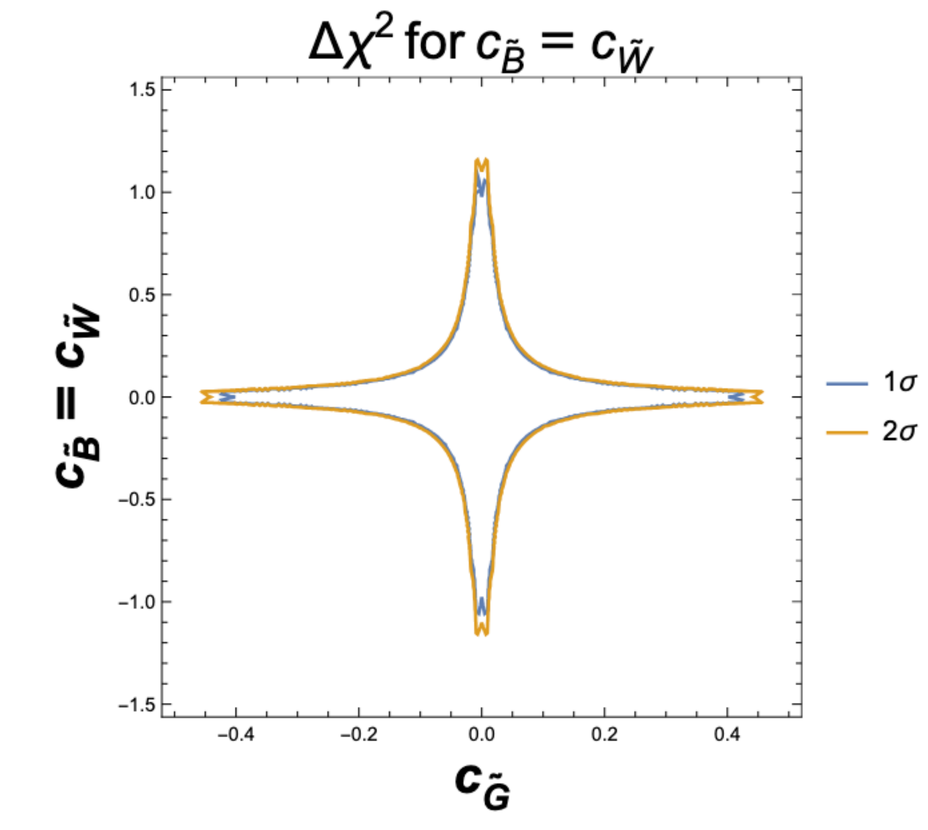


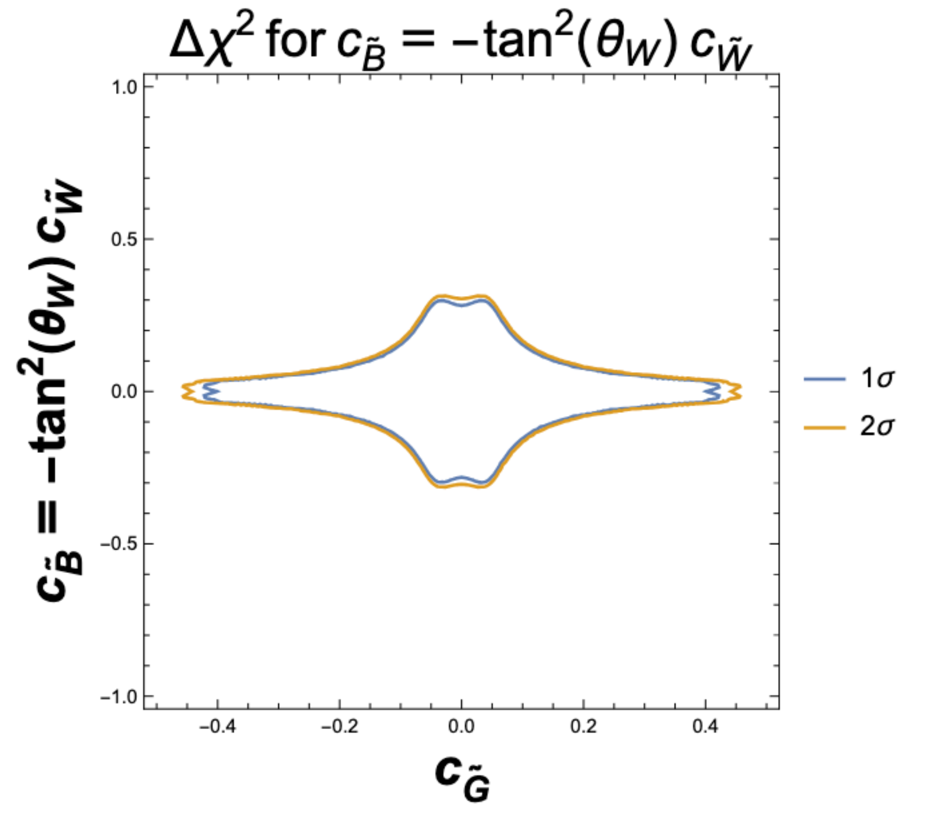
Similar for VBF channels $pp \to ZZjj$ and $pp \to W^+W^-jj$,
they probe different combinations of $\left(c_{\tilde{W}}, c_{\tilde{B}}\right)$

Global fit results

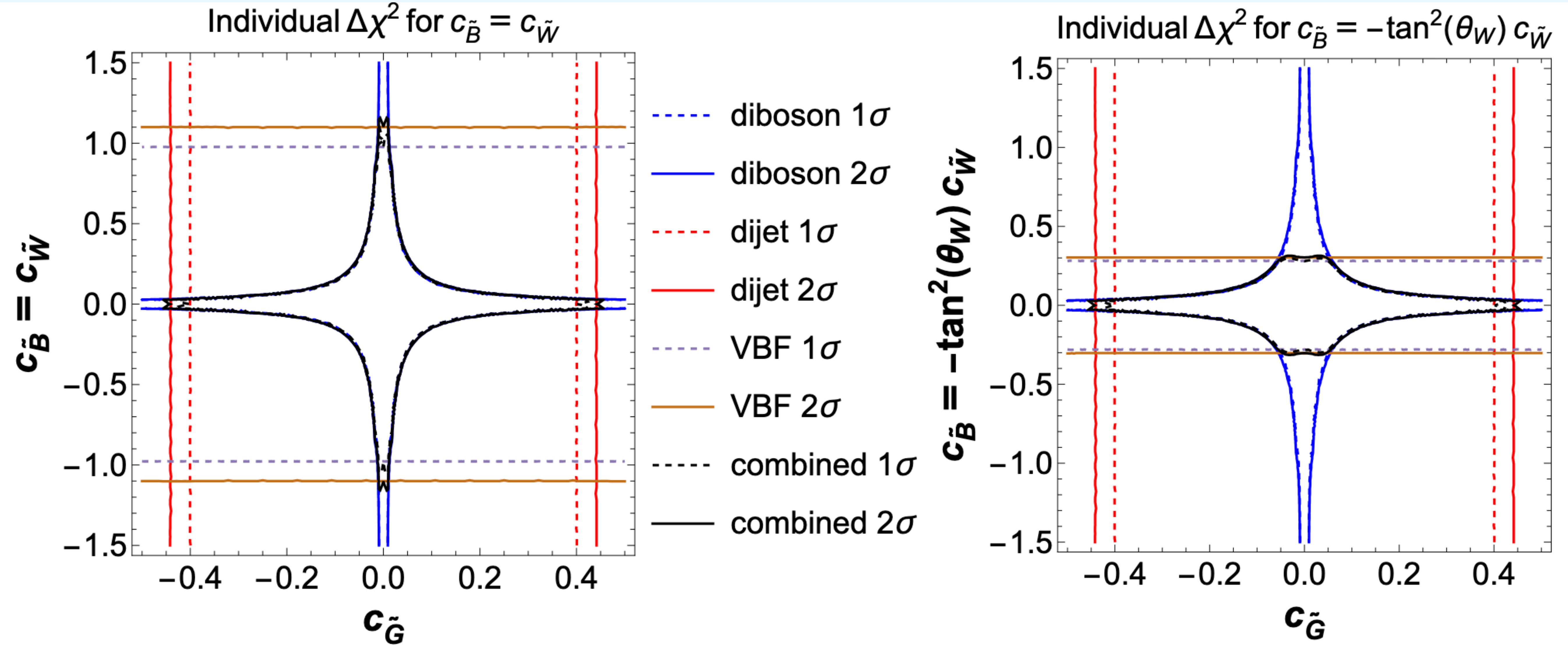


$f_a = 1$ TeV





Importance of each channel



Dijet channel dominates the sensitivity to ALP couplings and determines the limits on $c_{\tilde{G}}$, diboson and VBF give complementary constraints on $\left(c_{\tilde{W}}, c_{\tilde{B}}\right)$.

VBF is crucial to access the parameter space near $c_{\tilde{G}} = 0$.

Projected, profiled and marginalised limits

Projected/individual:
slicing the 3D likelihood along one axis while setting the other coefficients to zero

Profiled:
minimise χ^2 wrt the other two coefficients, limits from effective 1D likelihood

Marginalised:
extremal values of each coefficient on the 1σ/ 2σ surface of the 3D fit

	Projected		Profiled		3D marginalised	
	1σ	2σ	1σ	2σ	1σ	2σ
$c_{\tilde{G}}$	0.40	0.44	0.35	0.41	0.46	0.48
$c_{\tilde{B}}$	1.77	1.89	1.60	1.78	1.92	2.00
$c_{\tilde{W}}$	1.07	1.16	0.85	1.09	1.26	1.33

$f_a = 1$ TeV

To be read: We exclude values of $c_{\tilde{X}}$ above the given limit at $1\sigma/2\sigma$.
Profiled limits are the strongest.

Conclusion & Outlook

- Linear ALP EFT offers a model-independent formulation of ALP couplings to the SM
- Multiboson final states can be produce through momentum-dependent dim-5 contact operators
- We combined Run 2 LHC measurements of $\gamma\gamma$, ZZ, WW, dijet (gg), and VBF final states and performed a global analysis in $\left(c_{\tilde{G}}, c_{\tilde{W}}, c_{\tilde{B}}\right)$
- The highest sensitivity comes form dijet measurements, the other channels are crucial to constrain the electroweak couplings
- The analysis would profit from a fuller use of the unfolded covariance matrix (currently only provided for dijet)
- High-luminosity measurements are expected to improve the constraints, WW/ZZ measurements and additional electroweak channels ($Z\gamma$, $W\gamma$, $\gamma\gamma$+jet, 3 bosons, …) will sharpen especially the $\left(c_{\tilde{W}}, c_{\tilde{B}}\right)$ constraints


Chi miigwech!

Back-up slides

The (Peccei-Quinn) Axion

- Strong CP problem: QCD allows for theta term, why is it so small?

$$\mathcal{L}_\theta = \theta \frac{\alpha_s}{8\pi} G^a_{\mu\nu} \tilde{G}^{a,\mu\nu}$$

- Introduce global $U(1)_{PQ}$ Peccei-Quinn symmetry that is spontaneously broken at scale f_a, the axions is the associated NG boson

$$\Phi = \frac{f_a + \rho}{\sqrt{2}} e^{\frac{ia}{f_a}}$$

- At the classical level, the axion potential is completely degenerate and the axion massless
- At the quantum level, sectors with different topological charges give rise to an axion potential

$$V(a) = \chi \left[1 - \cos\left(\bar{\theta} + \frac{a}{f_a}\right)\right]$$

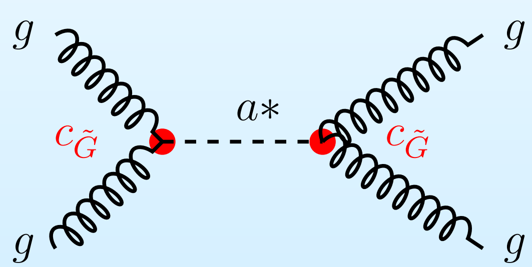
- The axion mass m_a and the axion couplings to SM particles are fixed by f_a and QCD

$$m_a^2 = \frac{\chi}{f_a^2}$$

$$\chi = \frac{m_u m_d}{(m_u + m_d)^2} m_\pi^2 f_\pi^2$$

Dijet with PDF uncertainty

ATLAS provides double differential dijet cross section $\frac{d^2\sigma}{dm_{jj}dy^*}$, half-rapidity separation $y^* = \frac{1}{2}|y_{j_1} - y_{j_2}|$ [1711.02692]

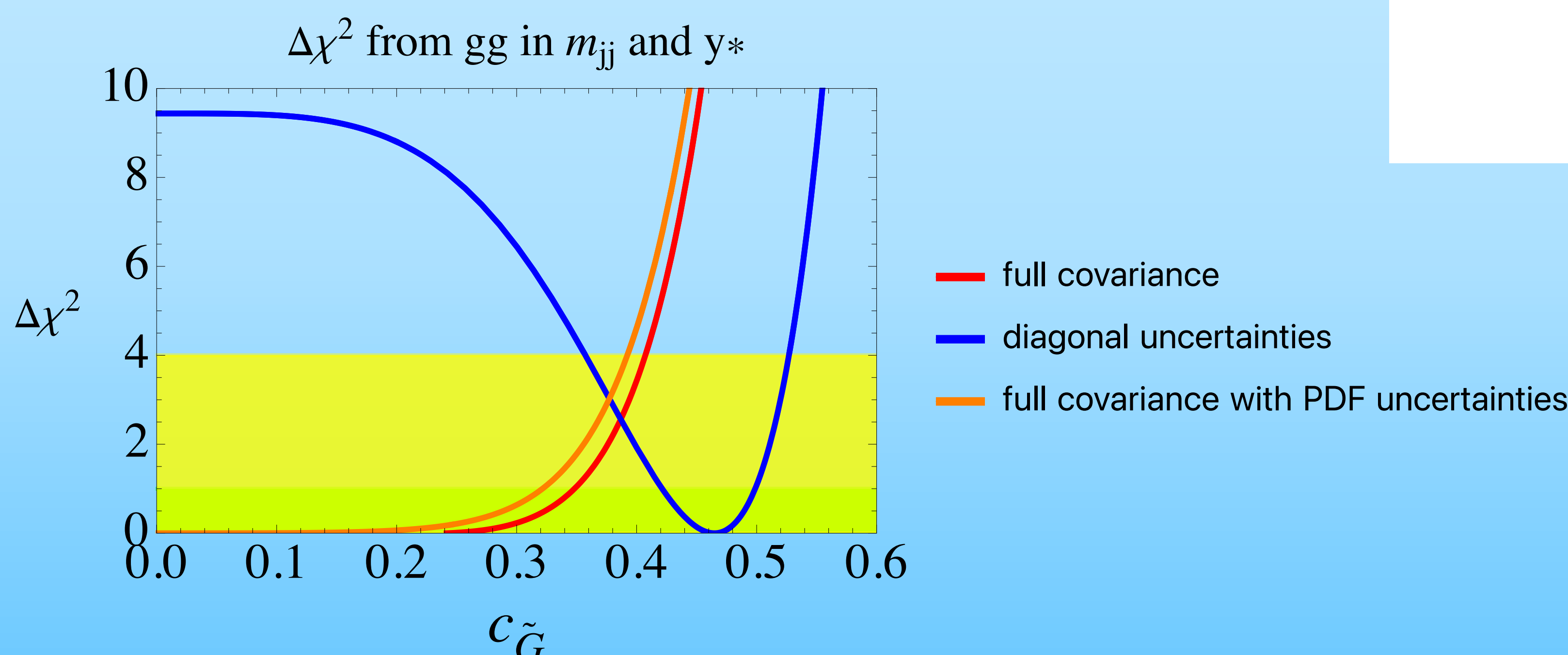


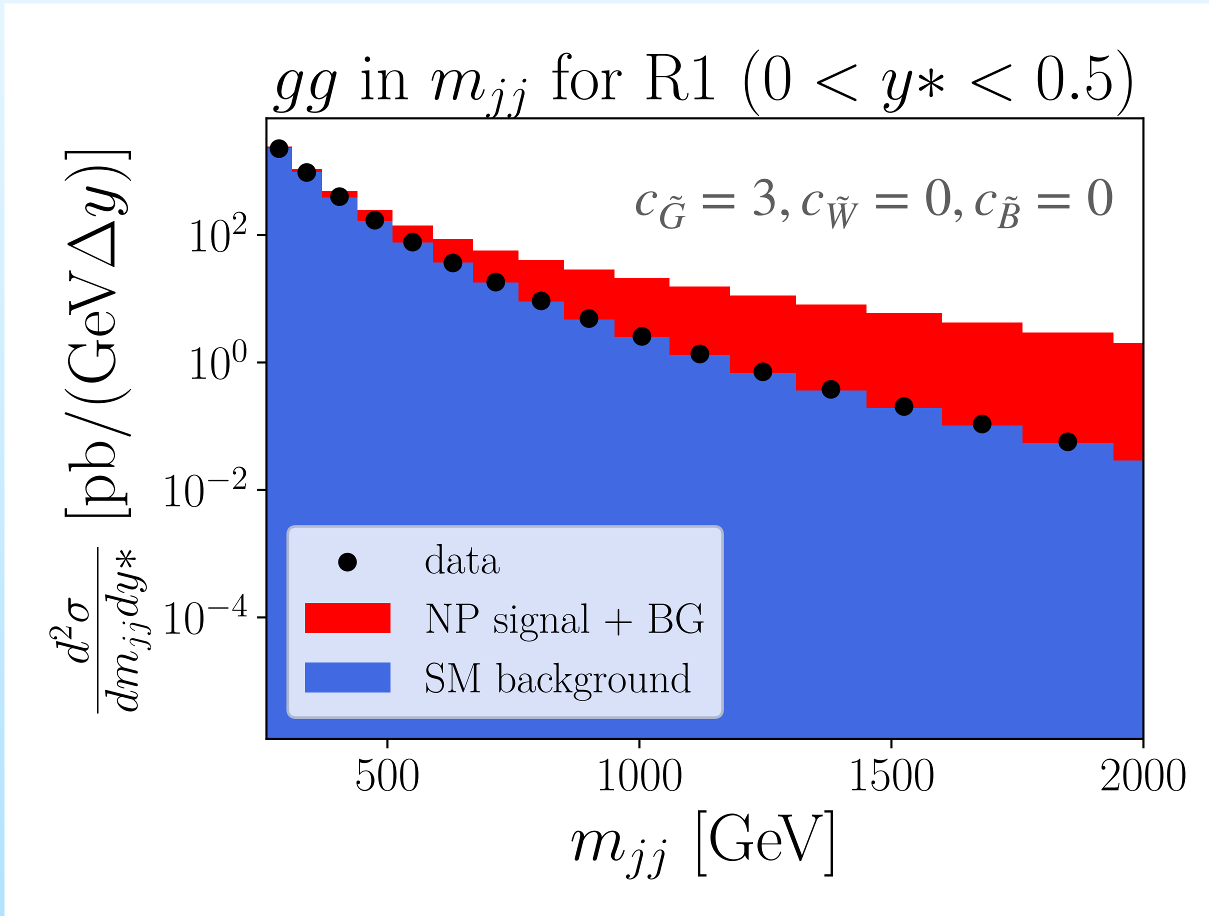
depends only on $c_{\tilde{G}}$!

$$N_i^{\text{th}} = N_i^{BG} + \left(\frac{c_{\tilde{G}}}{f_a}\right)^4 N_i^{\text{ALP}}(c_{\tilde{G}} = 1)$$

Split in 6 regions of y^* (136 bins in total)
Background from NNLOJET code [NNLOJET collaboration '25]
Utilise the full experimental covariance matrix

$$\chi^2 = \left(N^{\text{data}} - N^{\text{th}}\right)^T \Sigma^{-1} \left(N^{\text{data}} - N^{\text{th}}\right)$$





Include PDF uncertainties as main theory uncertainty.

Ignoring the correlations even prefers a non-zero $c_{\tilde{G}}$, shows importance of covariance!

Limits with PDF uncertainties are slightly stronger due to negative interference.

EFT validity?

NDA estimate: EFT valid if the relevant hard scale $\sqrt{\hat{s}} \lesssim \dfrac{4\pi f_a}{\max |c_i|}$

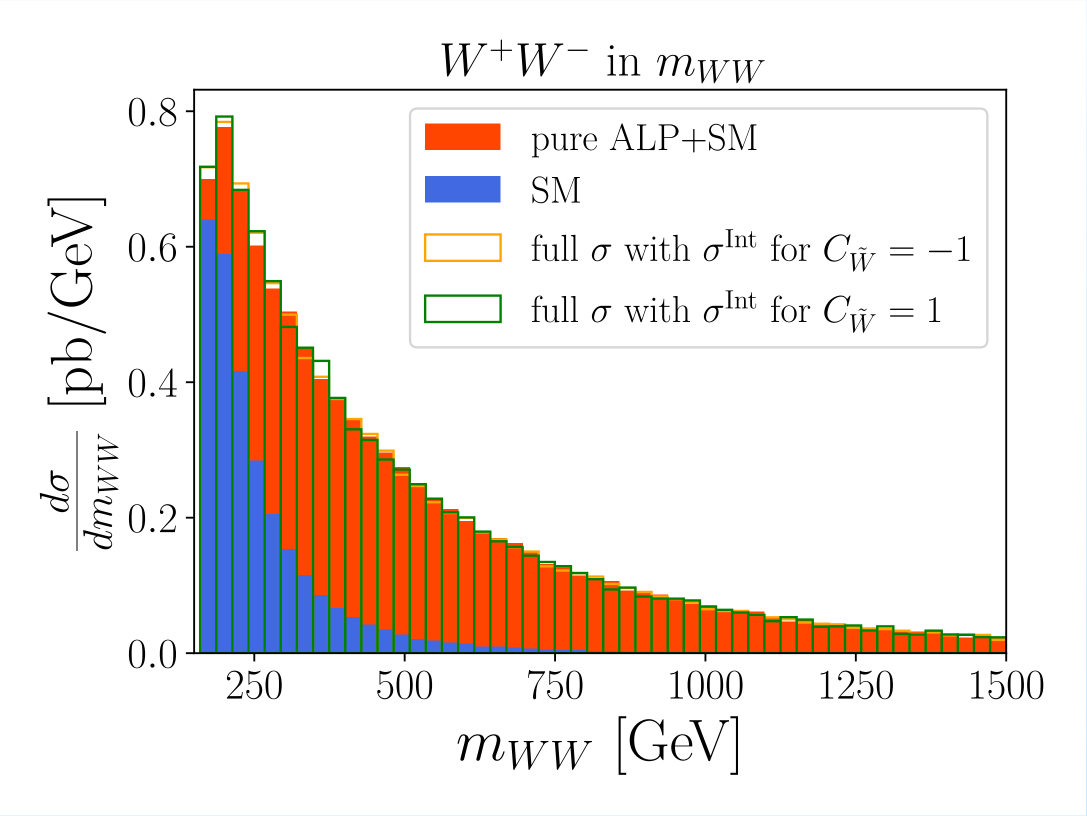
$\Rightarrow$ EFT indicative consistency window: $|c_i| = \dfrac{4\pi f_a}{\sqrt{\hat{s}_{\max}}}$

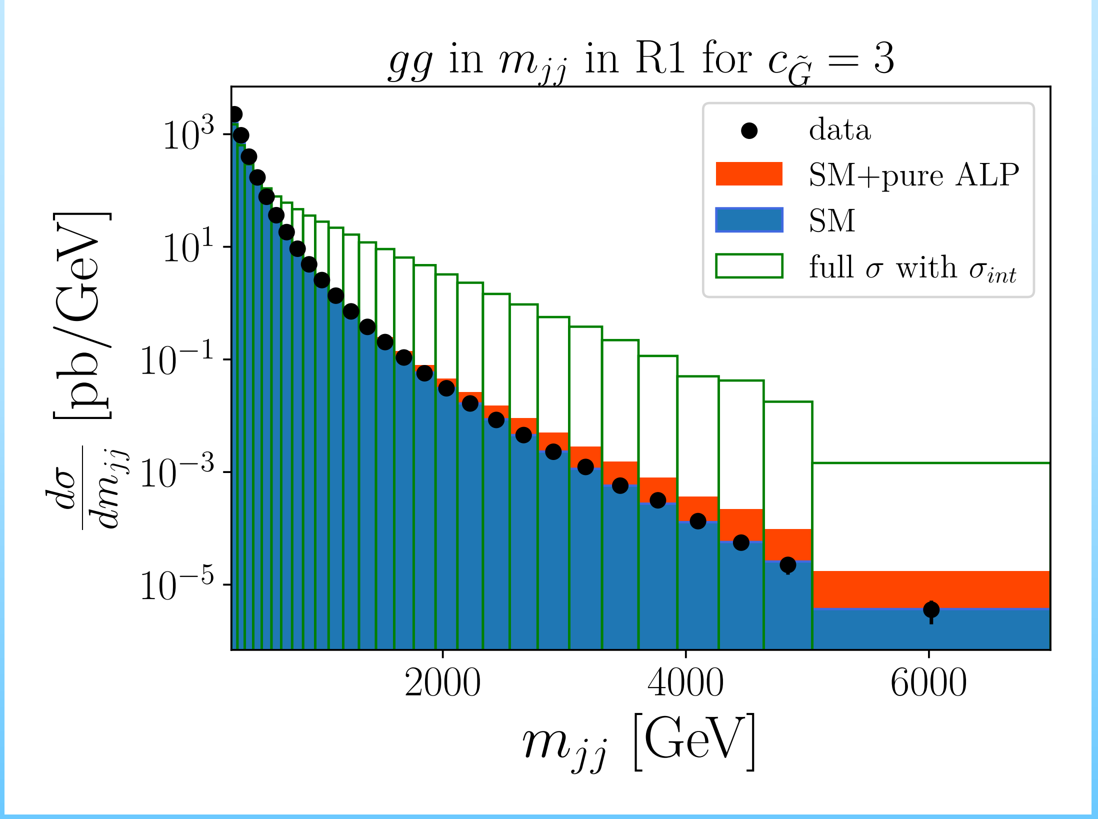
diboson ($\sqrt{\hat{s}_{\max}} \sim 1.5$ TeV):	$|c_i| \approx 8.4$
VBF ($\sqrt{\hat{s}_{\max}} \sim 1$ TeV):	$|c_i| \approx 12.6$
dijets ($\sqrt{\hat{s}_{\max}} \sim 8$ TeV):	$|c_i| \approx 1.6$

Our 95% CL bounds lie well within this NDA range.

We checked that the limits are robust under truncating the bins for which $\sqrt{\hat{s}} > f_a$.

ALP-SM interference?





For a pure quadratic ALP signal we know the scaling of the signal events with the WCs.

$$N_i^{\text{th}} = N_i^{BG} + N_i^{\text{ALP}}(c_{\tilde{G}} = 1,\, c_{\tilde{W}} = 1)\left(\frac{c_{\tilde{G}}}{f_a}\right)^2 \left(\frac{c_{\tilde{W}}}{f_a}\right)^2$$

Including interference effects, this analytic traceability is lost.

For di-boson ($\gamma\gamma$, ZZ, WW), no interference arises at partonic level and the total interference is small.

$$\sigma_{WW}^{\text{SM}} = 76.74\,\text{pb}, \quad \sigma_{WW}^{\text{ALP}} = 181.13\,\text{pb}, \quad \sigma_{WW}^{\text{Int}} = -0.02\,\text{pb}$$

Additional problem for dijet: Large NLO QCD effects are included in the NNLOJET background, but hard to simulate in MadGraph

$\Rightarrow$ Unreliable background estimation dominates χ^2

The dijet signal depends quartically on $c_{\tilde{G}}$

$$N_i^{\text{th}} = N_i^{BG} + \left(\frac{c_{\tilde{G}}}{f_a}\right)^4 N_i^{\text{ALP}}(c_{\tilde{G}} = 1)$$

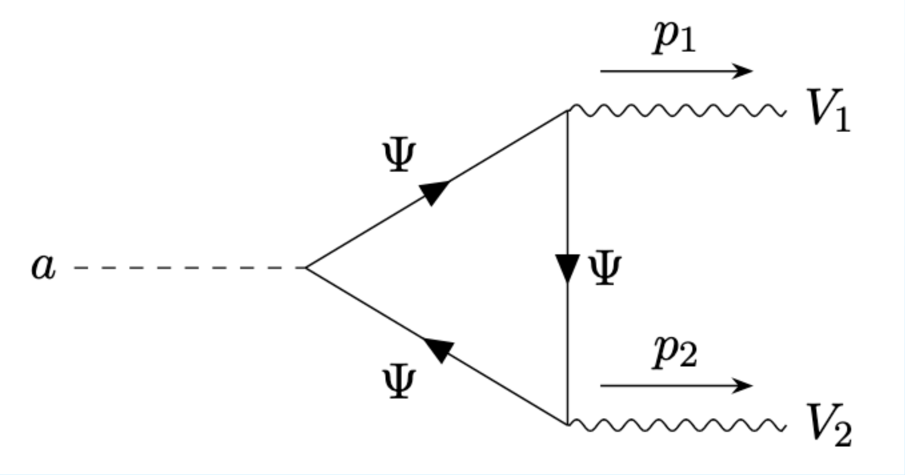
$\Rightarrow$ The interference in this channel is always positive

Our bounds can be seen as a conservative upper bound

UV motivation

$U(1)_X$ that is spontaneously broken at f_a,
vector-like fermions with charge q_X^Ψ under $U(1)_X$ and representations R_3^Ψ, R_2^Ψ and Y_Ψ under the SM.
In the UV theory, the ALP couples to the $U(1)_X$ current.

$$\mathcal{L} \supset \frac{\partial_\mu a}{f_a} J_X^\mu, \qquad J_X^\mu = \sum_\Psi q_X^\Psi \, \bar{\Psi}\gamma^\mu \Psi$$



Idea: create mixed anomalies with SM gauge groups and $U(1)_X$

The $U(1)_X$ current is anomalous with the SM gauge groups

$$\partial_\mu J_X^\mu = \sum_\Psi \left[\frac{g_s^2}{16\pi^2} 2\, q_X^\Psi \, T\left(R_3^\Psi\right) \, G^a_{\mu\nu}\tilde{G}^{a\,\mu\nu} + \frac{g^2}{16\pi^2} 2\, q_X^\Psi \, T\left(R_2^\Psi\right) \, W^i_{\mu\nu}\tilde{W}^{i\,\mu\nu} + \frac{g'^2}{16\pi^2} 2\, q_X^\Psi \, \mathcal{Y}_\Psi^2 \, B_{\mu\nu}\tilde{B}^{\mu\nu} \right]$$

NB: The scenario with only $c_{\tilde{X}} \neq 0$ should rather be seen as a benchmark than the most general EFT. In a realistic model, ALP-fermion and ALP-Higgs couplings are present and generated, e.g. through RGE running, and contribute at low energies.
However, they are not quantitatively important in multiboson processes at the LHC

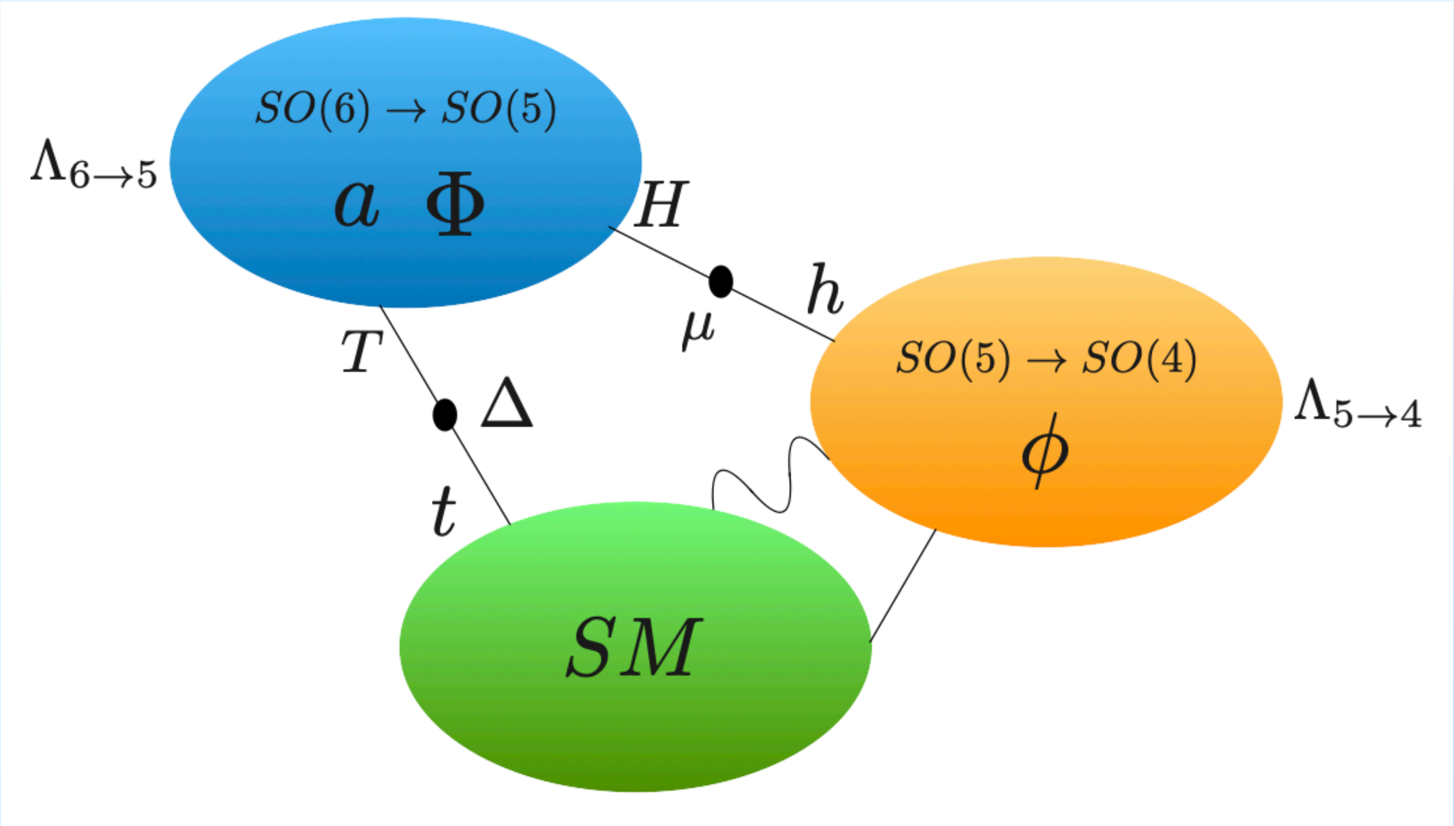
Integrating out the VLFs yields the correct structure

$$\mathcal{L}_{\rm WZ} = \frac{a}{f_a} \left[\frac{g_s^2}{16\pi^2} \mathcal{A}_3 \, G^a_{\mu\nu}\tilde{G}^{a\,\mu\nu} + \frac{g^2}{16\pi^2} \mathcal{A}_2 \, W^i_{\mu\nu}\tilde{W}^{i\,\mu\nu} + \frac{g'^2}{16\pi^2} \mathcal{A}_1 \, B_{\mu\nu}\tilde{B}^{\mu\nu} \right], \mathcal{A}_X \equiv 2 \sum_\Psi q_X^\Psi \, \mathcal{I}_X^\Psi,$$

Assuming the SM fields neutral under $U(1)_X$ avoids ALP-fermion and ALP-Higgs couplings

c_t from model building

ALP-top coupling natural for example in models with partial compositeness:



- see-saw Composite Higgs: Higgs doublets mix pGB from both symmetry breakings
- ALPs are pGB associated with heavy scale $f_a \sim \Lambda_{6\to5}$
- EWSB involves new fermionic composites, the top partners T with $m_T \sim \Lambda_{6\to5}$
- T couples to a via
$$\mathscr{L} \supset -c_T \frac{\partial_\mu a}{\Lambda_{6\to5}} (\bar{T}\gamma^\mu T)$$
- T mixes with top quarks through mass mixing $-\Delta \bar{t}_R T + h.c.$

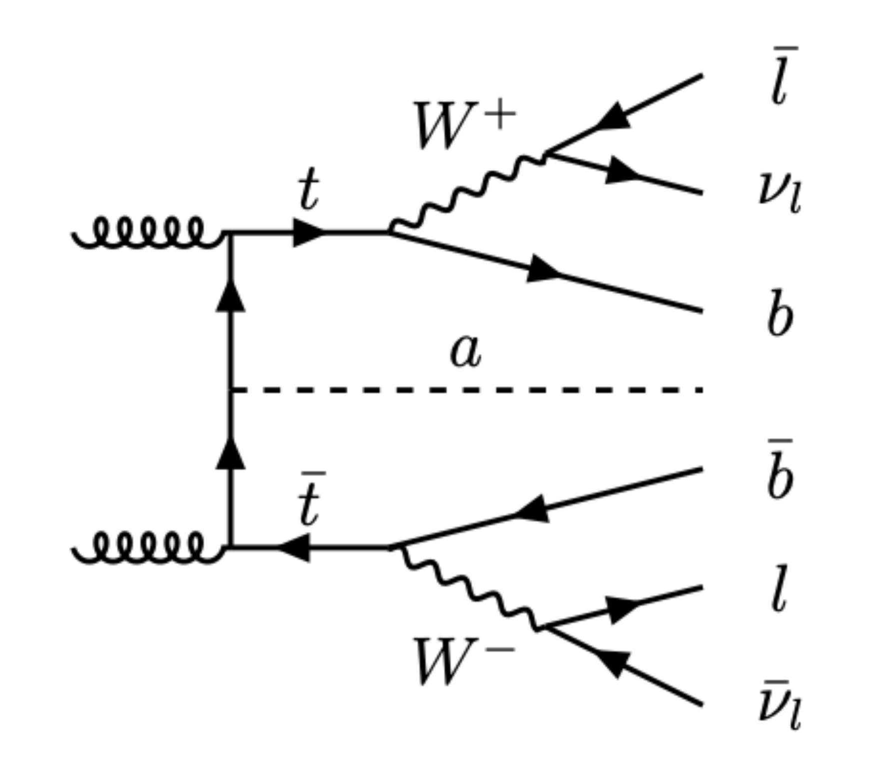
→ induces an ALP top coupling $c_t \propto c_T \dfrac{\Delta^2}{m_T^2}$

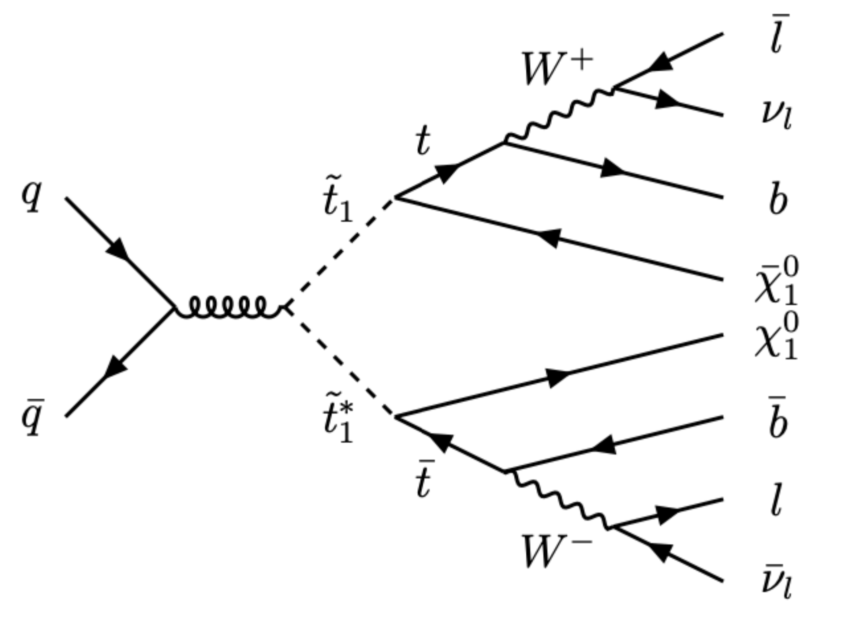
Direct constraints on c_t

- signal process: $t\bar{t} + a$ production with leptonic top decay
- assume ALP collider stable, escapes the detector as missing transverse energy (MET)
- Reinterpret a Run II **ATLAS SUSY search for top squarks** in events with 2 leptons, 2 b-jets and MET at $\sqrt{s} = 13$ TeV, $\mathcal{L} = 139$ fb^{-1} [2102.134929]
- SUSY benchmark: pair production of stops with prompt decay into top quarks and neutralinos
- **same final state topology** of $2l + 2j + MET$

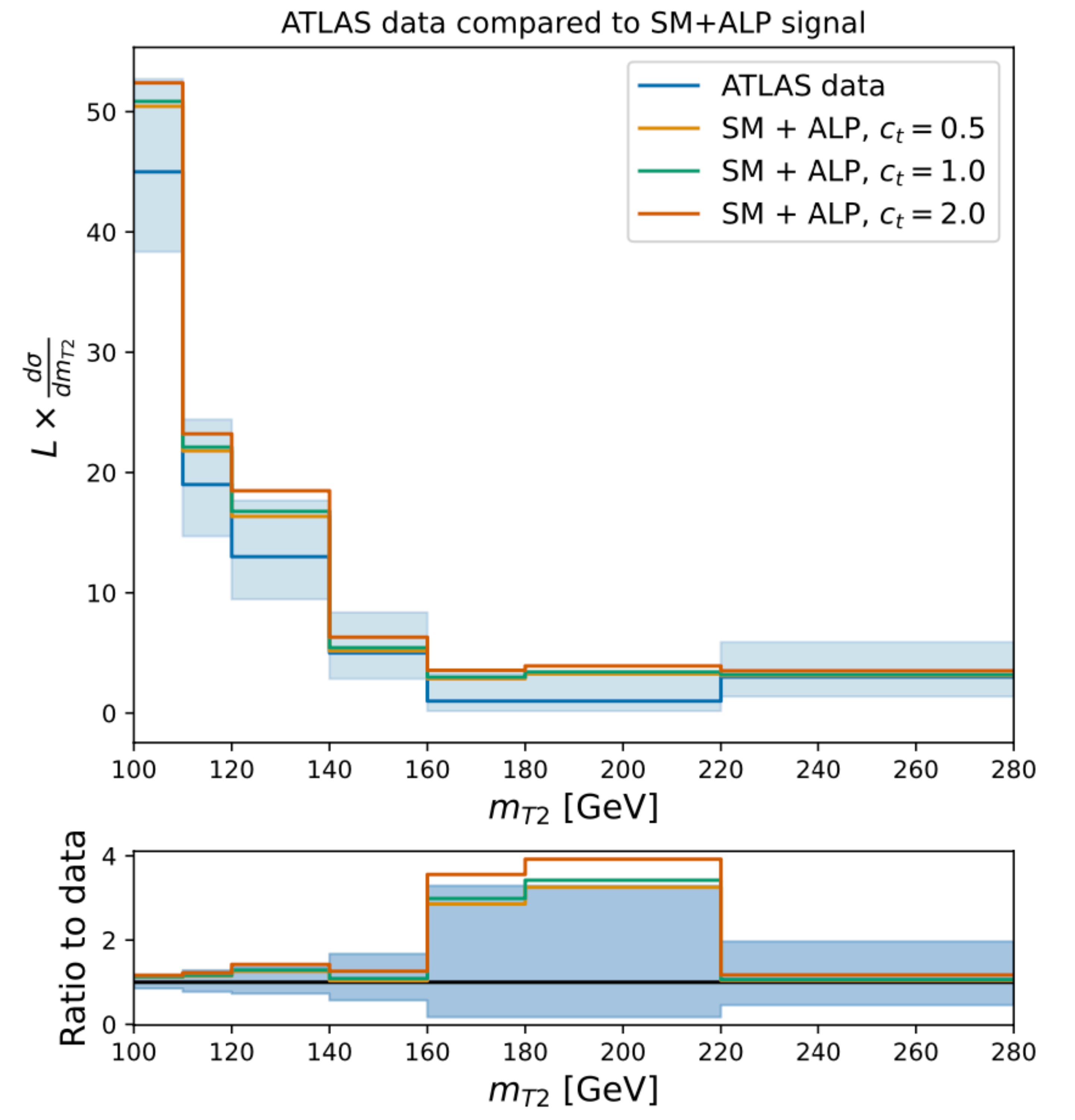
with $MET = \begin{cases} \nu & SM \\ \nu + a & ALP \\ \nu + \tilde{\chi}^0 & SUSY \end{cases}$

- use ALP EFT UFO file and MadGraph5 to generate events





ALP signal



- compare ALP signal + SM background for different c_t to data
- MadGraph and SM background uncertainties negligible compared to experimental uncertainties
- $t\bar{t}a$ vertex proportional to c_t/f_a, global factor $\left(c_t/f_a\right)^2$ in the signal events
- Assume a Poisson likelihood

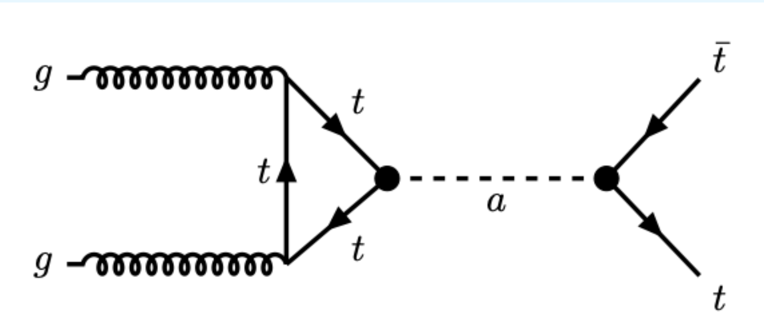
$$\mathcal{L}(c_t) = \prod_{k=1}^{N_{\rm bins}} \frac{\exp\left(-\left(\left(\frac{c_t}{f_a}\right)^2 s_k + b_k\right)\right)\left(\left(\frac{c_t}{f_a}\right)^2 s_k + b_k\right)^{n_k}}{n_k!}$$

- use the profile likelihood ratio to obtain limits on c_t:

$$\boxed{\left|\frac{f_a}{c_t}\right| > 550 \text{ GeV at 95\% CL}}$$

Indirect constraints on c_t

A. ALP mediated $t\bar{t}$ production:



light off-shell ALP contributing non-resonantly to $gg \to a \to t\bar{t}$,
calculate at tree-level with effective coupling $c_{agg}^{eff} = -\dfrac{\alpha_s}{8\pi} c_t$

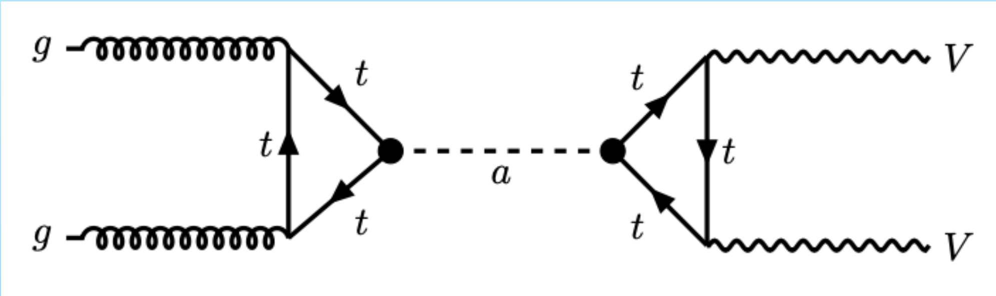
1. **CMS**: $m_{t\bar{t}}$ **distribution** in the lepton + jets channel, Run-II data [2108.02803]

$$\left|\frac{f_a}{c_t}\right| > 103.1 \text{ GeV at 95\% CL}$$

2. **ATLAS:** p_T **spectrum** of the boosted hadronically decaying top-quark [2202.12134]

$$\left|\frac{f_a}{c_t}\right| > 169.5 \text{ GeV at 95\% CL}$$

B. ALP mediated diboson production

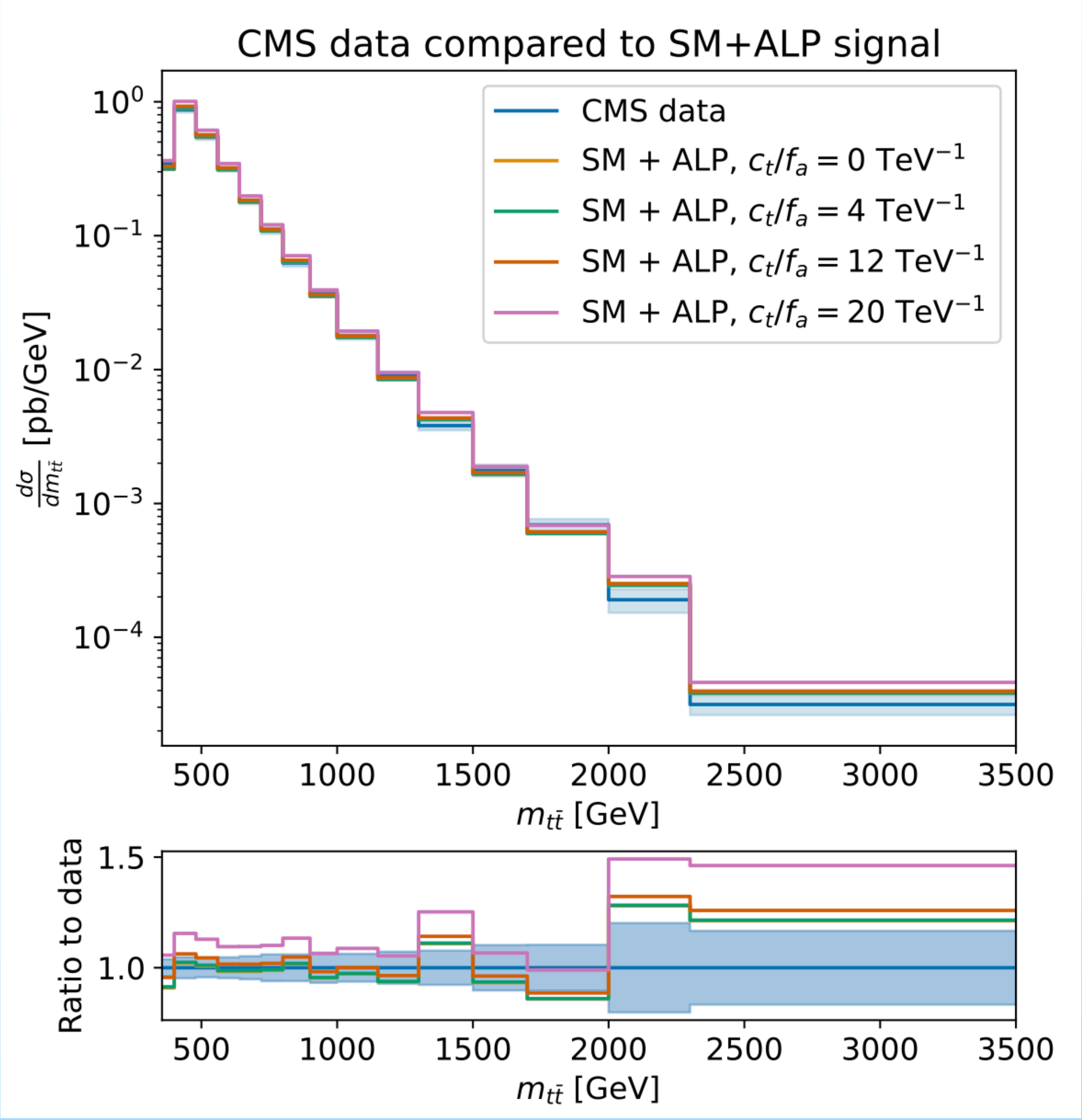


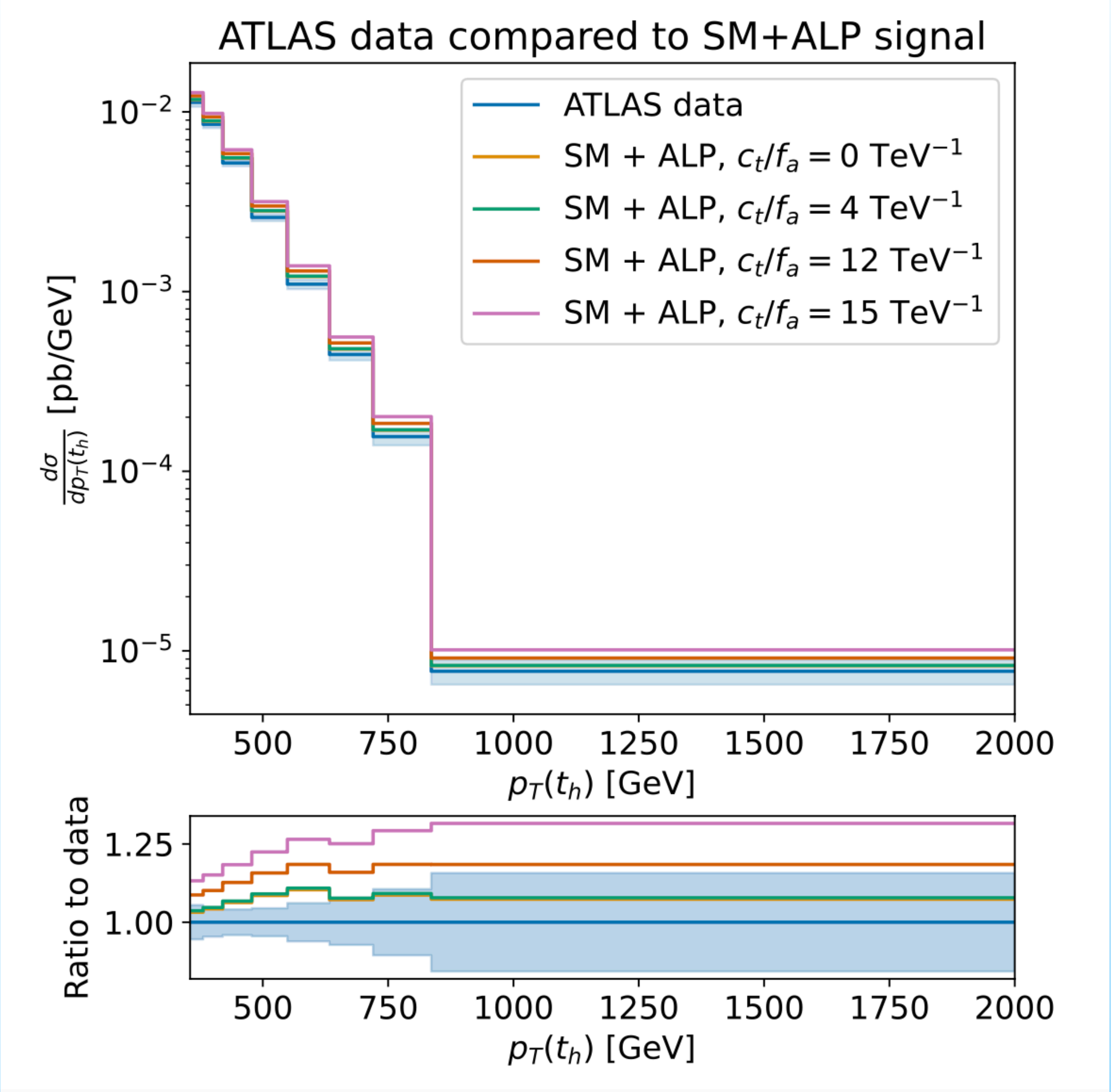
Non-resonant searches with ALP as off-shell mediator of a 2→2 scattering process

Constraints on g_{aVV} through $gg \to VV$ diboson production, data from CMS search at $\sqrt{s} = 13$ TeV [Gavela, No, Sanz, Trocóniz, 2019] [Carra et al., 2021]

VV	lower limit on $\frac{f_a}{c_t}$
ZZ	3.5 GeV
$\gamma\gamma$	22.5 GeV
$Z\gamma$	11.0 GeV

ALP mediated $t\bar{t}$ production





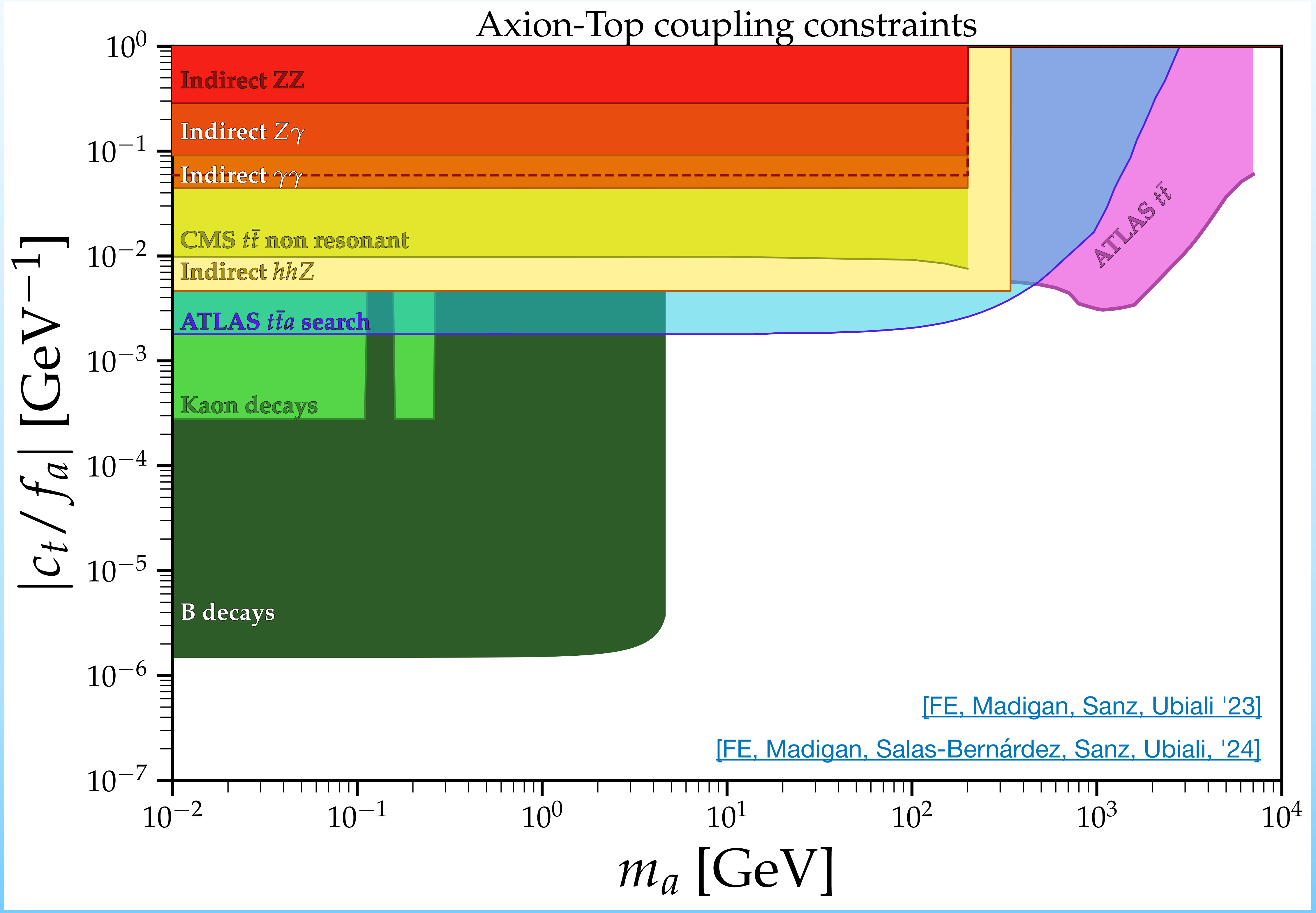
CMS: $\left|\frac{f_a}{c_t}\right| > 103.1$ GeV at 95% CL,

low $m_{t\bar{t}}$ bins and ALP-SM interference dominate

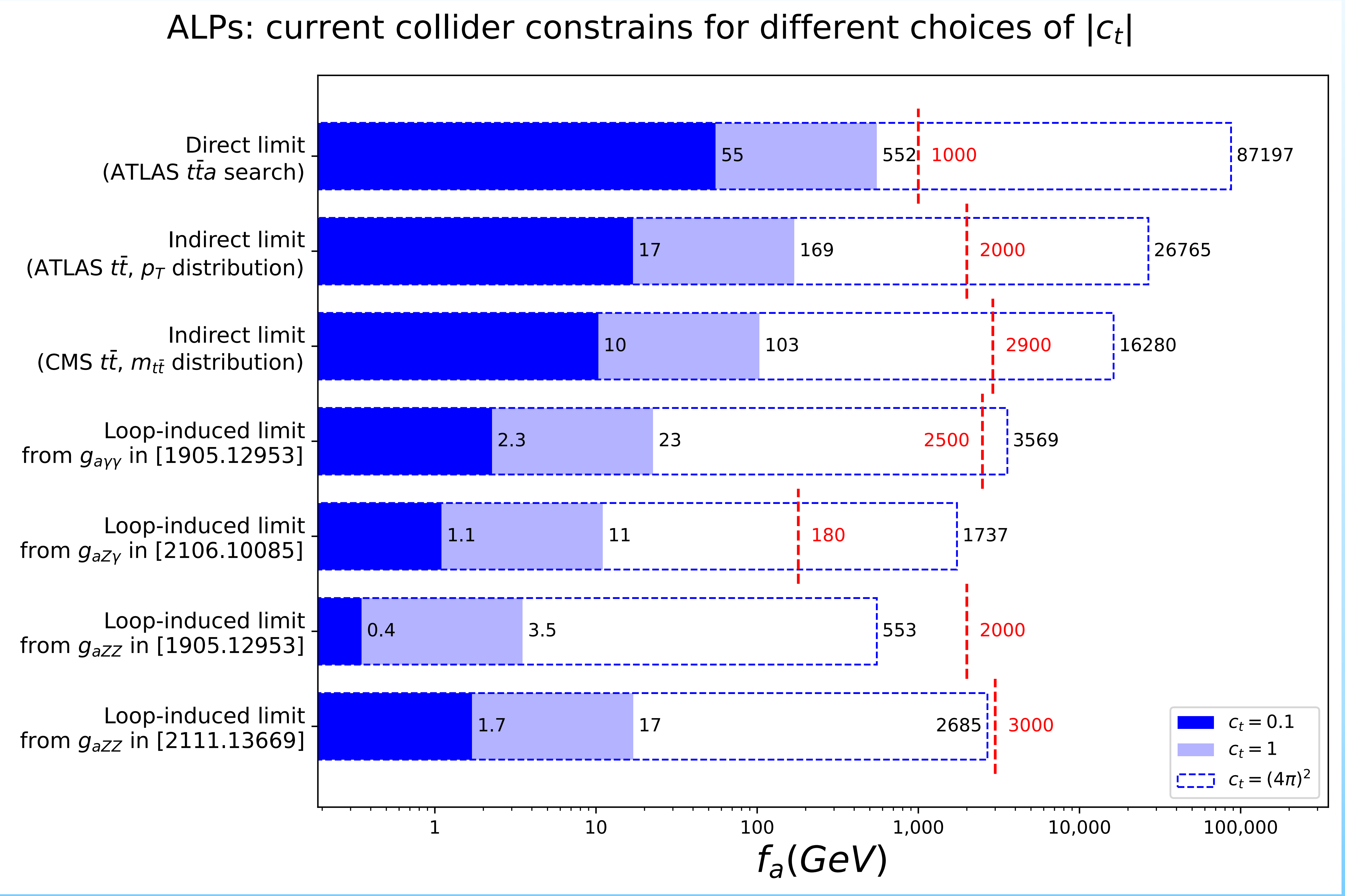
ATLAS: $\left|\frac{f_a}{c_t}\right| > 169.5$ GeV at 95% CL,

high p_T bins and pure ALP dominate

ALP-top coupling



Summary of constraints from Run-II data



red dashed lines: EFT validity limits