New Axion Searches at Flavour Factories

Filippo Sala
DESY Hamburg
BSM: where to go?

1. NO BSM in data

2.
BSM: where to go?

1. NO BSM in data → 2.

This workshop

Deny 1.: Anomalies

Act on 1.: New Observables/More Precision

Act on 2.: Tests from New Theory Connections
BSM: where to go?

1. NO BSM in data  →  2.

THIS TALK: Act on 1.: New Observables
(Most?) **Solid discovery method** at colliders: Look for peaks in invariant mass distributions
BSM resonances: where to look?

Present searches: \[ M_{\gamma\gamma, \tau\tau, \ldots} > O(100) \text{ GeV} \]
BSM resonances: where to look?

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1. Theory bias towards high masses

Why not $M_X < O(100) \text{ GeV}$? 2. “Low-mass already constrained by previous colliders (LEP, …)”

3. “It is very difficult!” Minimal pT cuts, …

Here: demystify 1. 2. and 3., new limits and prospects at LHCb & BelleII
1. Theory bias towards high masses

Why not $M_X < O(100) \text{ GeV}$?
Why low-mass resonances?

LHC is pushing solutions to SM problems (hierarchy, flavour, …) to $M_{BSM} \gg \text{TeV}$

Richer sectors could exist there

How to test them?
Why low-mass resonances?

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Richer sectors could exist there

How to test them?

via ALPs!

$M_{\text{BSM}} \approx g_* f_a$

aka Pseudo Goldstone Bosons (PGBs)

from spontaneous breaking of global symmetry

with a small explicit breaking that controls $m_a \neq 0$
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aka Pseudo Goldstone Bosons (PGBs)

from spontaneous breaking of global symmetry

with a small explicit breaking that controls $m_\alpha \neq 0$

$m_\alpha$ Mass of the ALP naturally lighter than any BSM scale $M_{\text{BSM}}$

(technically natural, unlike Higgs mass)

$f_\alpha$ decay constant controls ALP Couplings

\[ L_{\text{int}} = \frac{a}{4\pi f_\alpha} \left[ \alpha_s c_3 G \tilde{G} + \alpha_2 c_2 W \tilde{W} + \alpha_1 c_1 B \tilde{B} \right] \]
Why low-mass resonances?

LHC is pushing solutions to SM problems (hierarchy, flavour, …) to $M_{BSM} \gg \text{TeV}$

Richer sectors could exist there

**How to test them?**

Richer sectors could exist there

via ALPs!

$M_{BSM} \approx g_* f_a \gtrsim \text{TeV} \sim$ from LHC exclusions

$m_a \sim 1 - 100 \ \text{GeV} \sim$ an unexplored range

$f_a \sim 0.1 - 100 \ \text{TeV}$ of interest for colliders (see rest of talk)

Filippo Sala

New Axion searches at Flavour Factories
ALP$_s$ and BSM: strongly coupled

They already exist: pions from QCD
ALPs and BSM: strongly coupled

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“Just because” strong sector: vector-like confinement

[add gauge group that confines at $\gtrsim$TeV, w/new fermions, vector-like to satisfy EW precision tests]

see e.g. Kilic Okui Sundrum 0906.0577
ALPs and BSM: strongly coupled

They already exist: pions from QCD

“Just because” strong sector: vector-like confinement

[add gauge group that confines at $\gtrsim$TeV, w/new fermions, vector-like to satisfy EW precision tests]

Natural strong sector: composite Higgs models

Example: SO(6)/SO(5) has 5 PGB, the Higgs and a singlet $\eta$

No tuning in $\eta$ potential $\implies m_\eta \sim m_h \times \frac{f}{v} \sim 600$ GeV $\times$ $\sqrt{\frac{0.05}{(v/f)^2}}$

with dependence on top representation

e.g. if only bottom contributes: $m_\eta \sim 10$ GeV $\times$ $\sqrt{\frac{0.05}{(v/f)^2}}$

Larger coset structures have more PGBs
They already exist: pions from QCD

“Just because” strong sector: vector-like confinement

[add gauge group that confines at ~ TeV, w/new fermions, vector-like to satisfy EW precision tests]

**Natural** strong sector: composite Higgs models

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with dependence on top representation

e.g. if only bottom contributes: \( m_\eta \sim 10 \text{ GeV} \times \sqrt{\frac{0.05}{(v/f)^2}} \)

Larger coset structures have more PGBs

**Less natural** composite Higgs models:

give up on little hierarchy and focus on generate EW & DM scales

\( \text{DM & GUT} \)

Bernard+ 1409.7391
\( \text{Antipin+1410.1817} \)
ALPs and BSM: QCD axion

Standard QCD axion points to large $f_a$ and small $m_a$

$$V_a \approx -\Lambda_{QCD}^4 \cos \frac{Na}{f}$$
ALPs and BSM: QCD axion

Standard QCD axion points to large $f_a$ and small $m_a$

$$V_a \simeq -\Lambda_{QCD}^4 \cos \frac{Na}{f} + \frac{1}{2^{\Delta - 1}} \frac{|\lambda_\Delta| f_\Delta}{\Lambda_{UV}^{\Delta - 4}} \cos \left( \alpha_\Delta + \Delta \frac{a}{f} \right)$$

but: “Axion Quality” problem spoils solution to strong CP

$$\Delta V_{PQ} = \lambda_\Delta \frac{\Phi_\Delta}{\Lambda_{UV}^{\Delta - 4}} + \text{h.c.} \quad \Phi = \frac{f_a}{\sqrt{2}} e^{ia/f_a}$$

Kamionkowski March-Russel hep-th/9202003,...
ALPs and BSM: QCD axion

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Example: $\Delta = 6$ (same of SM baryon number)

$$\Lambda_{UV} = M_{Pl} \Rightarrow f \lesssim O(10) \text{ TeV}$$

$$\Lambda_{UV} = M_{GUT} \Rightarrow f \lesssim O(1) \text{ TeV}$$
ALPs and BSM: QCD axion

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$$\Lambda_{UV} = M_{GUT} \Rightarrow f \lesssim O(1) \text{ TeV}$$

1. Push $\Delta$ to much larger values
   ... Redi Sato 1602.05427
   Duerr+ 1712.01841

2. Model building for smaller $f_a$ and larger $m_a$

Rubakov hep-ph/9703409  ……
M.K. Gaillard+ 1805.06465
ALPs and BSM: QCD axion

Standard QCD axion points to large $f_\alpha$ and small $m_\alpha$

$$V_\alpha \simeq -\Lambda_{QCD}^4 \cos \left( \frac{N a}{f} \right) + \frac{1}{2^{\frac{\Delta}{2} - 1}} \left| \lambda_\Delta \right| \frac{f_\Delta}{\Lambda_{UV}^{\Delta-4}} \cos \left( \alpha_\Delta + \Delta \frac{a}{f} \right)$$

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Kamionkowski March-Russel hep-th/9202003,…

strong CP solved here!

2. Model building for smaller $f_\alpha$ and larger $m_\alpha$

Rubakov hep-ph/9703409 ……
M.K. Gaillard+ 1805.06465

Kamionkowski March-Russel hep-th/9202003,…
Pseudoscalar-mediated Dark Matter

\[ \mathcal{L}_{\text{int}} = \frac{a}{4\pi f_a} \alpha_s c_3 G \tilde{G} + g_\ast \Phi \psi \tilde{\psi} \]

\[ \Phi = \frac{f_a e^{ia/f_a}}{\sqrt{2}} \]

\[ m_\psi \simeq 4.6 \text{ TeV} \frac{c_3}{10} \left( \frac{g_\ast}{3} \right)^2 \Rightarrow f \simeq 1.9 \text{ TeV} \frac{3}{g_\ast} \]

Observed relic abundance for
ALPs and BSM: Dark Matter

Pseudoscalar-mediated Dark Matter

\[ \mathcal{L}_{\text{int}} = \frac{a}{4\pi f_a} \alpha_s c_3 G \tilde{G} + g_* \Phi \psi \tilde{\psi} \]

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\[ m_\psi \simeq 4.6 \text{ TeV} \frac{c_3}{10} \left( \frac{g_*}{3} \right)^2 \Rightarrow f \simeq 1.9 \text{ TeV} \frac{3}{g_*} \]

**Direct Detection** completely irrelevant

**Indirect Detection** not yet competitive

(caveat: should compute Sommerfeld)

**Colliders** are needed to test this scenario!
N = 1 SUSY always accompanied by a continuous $U(1)_R = \text{"R-symmetry"}$

$$R : \theta_\alpha \rightarrow e^{i\epsilon} \theta_\alpha \quad [R, Q] = -Q$$

R-charge assignments:

$$\Phi = \phi + \sqrt{2}\theta \psi + \theta^2 F$$

$$r_\phi = r_\Phi$$
$$r_\psi = r_\Phi - 1$$
$$r_F = r_\Phi - 2$$

Vector superfields are real $\Rightarrow$ gauginos have $r_\lambda = 1$

Lagrangian $\mathcal{L}$ R-symmetric $\Rightarrow R(W) = 2$

($\Leftarrow$ if Kahler canonical)

$$\mathcal{L} \ni \int d^2\theta W + \text{c.c.}$$

$W$ superpotential
i) SUSY broken in global minimum

ii) superpotential $W$ “generic”
(i.e. contains all terms not forbidden by symmetries)

$\Rightarrow$ Lagrangian respects a $U(1)_R$

$U(1)_R$ needs to be broken because of

gaugino masses & EW symmetry breaking & Higgsino masses

$\mathcal{L} \supset m_\lambda \lambda \lambda \ [r_\lambda = 1]$ & $\mathcal{L} \supset B_\mu H_u H_d + c.c.$ & $W \supset \mu H_u H_d$

Nelson-Seiberg NPB416 (1994)
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Break $U(1)_R$ spontaneously

Massless Goldstone in the spectrum R-axion $a$
Nelson-Seiberg NPB416 (1994)

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$\mathcal{L} \supset m_\lambda \lambda \lambda$  \hspace{1cm} \hspace{1cm} \hspace{1cm} [r_\lambda = 1]

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$U(1)_R$ spontaneously

Massless Goldstone in the spectrum $\text{R-axion } a$

$\rightarrow$ Tune CC to zero: explicit breaking of $U(1)_R$

$m_a^2 \sim (10 \text{ MeV})^2 \times \frac{M_{\text{SUSY}}}{10 \text{ TeV}} \times \frac{m_{3/2}}{\text{eV}}$ \hspace{1cm} \hspace{1cm} \hspace{1cm} \hspace{1cm} Bagger+

hep-ph/9405345

$\rightarrow$ Metastable vacuum Intriligator Seiberg Shih 2007

\hspace{1cm} \hspace{1cm} \hspace{1cm} \hspace{1cm} $m_a \ll M_{\text{SUSY}}$

light SUSY particle \hspace{1cm} \hspace{1cm} \hspace{1cm} \hspace{1cm} \hspace{1cm} \hspace{1cm} by symmetry
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- EW symmetry breaking
- Higgsino masses

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\[ \mathcal{L} \supset B_\mu H_u H_d + c.c. \quad \& \quad W \supset \mu H_u H_d \]

Break $U(1)_R$ spontaneously

Massless Goldstone in the spectrum $a$

$ma \ll M_{SUSY}$

light SUSY particle by symmetry

→ Tune CC to zero: explicit breaking of $U(1)_R$

$ma \sim (10 \text{ MeV})^2 \times \frac{M_{SUSY}}{10 \text{ TeV}} \times \frac{m_{3/2}}{\text{eV}}$  Bagger+

hep-ph/9405345

→ Metastable vacuum Intriligator Seiberg Shih 2007

Could be first sign of SUSY at colliders!

Bellazzini Mariotti Redigolo FS Serra 1702.02152
R-axion- as Dark Matter mediator

Spectrum à la gauge mediation

Gravitino DM

\[ m_{3/2} = \frac{F}{(\sqrt{3} M_{Pl})} \simeq 11 \text{ meV} \cdot \left(\frac{g_*/3}{f/4 \text{ TeV}}\right)^2 \]

🤔 Cannot make observed DM for these values of parameter

(motivated by naturalness of Fermi scale)

😊 Respects all bounds from cosmology and collider
R-axion- as Dark Matter mediator

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Respects all bounds from cosmology and collider

DM from messenger or SUSY breaking sectors

Dimopoulos Giudice Pomarol hep-ph/9607225

Mardon Nomura Thaler 0905.3749
Fan Thaler Wang 1004.0008

R-axion is natural portal!

Motivated realisation of ALP-portal Dark Matter
Pseudo Goldstone bosons (ALPs) with mass $m_a \sim 1 - 100$ GeV and decay rate $f_a \sim 0.1 - 100$ TeV arise in several motivated models (QCD axion, DM, SUSY, CHM,...)

**Theory** summary

**Pheno** observation

Coupling to gluons $\sim aG\tilde{G}$ often neglected in ALPs pheno but mandatory for QCD axion

natural in CHM (e.g. loops of tops, …)
as well as in SUSY! (e.g. loops of tops, gluinos, …)

1. Theory bias towards high masses

Why not $M_X < O(100)$ GeV ?

2. “Low-mass already constrained by previous colliders (LEP, …)”

3. “It is very difficult!” Minimal pT cuts, …
Why not $M_X < O(100)$ GeV ?

2. “Low-mass already constrained by previous colliders (LEP,...)”
**ALP mass coverage 2017**

\[ \mathcal{L}_{\text{int}} = \frac{a}{4\pi f_a} \left[ \alpha_s c_3 G \tilde{G} + \alpha_2 c_2 W \tilde{W} + \alpha_1 c_1 B \tilde{B} \right] \]

\[ \alpha_1 = \frac{5}{3} \alpha_y \]
ALP production at the LHC

Production cross sections of $\sim 10^5$ pb are still allowed! $[f_a \approx 300 \text{ GeV}]$
**ALP production at the LHC**

Production cross sections of $\sim 10^5$ pb are still allowed! [$f_a \approx 300$ GeV]

LHC could be sitting on a few million diphoton events! 1000 times more ALPs than SM Higgses!!

Production cross sections of $\sim 10^5$ pb are still allowed! [$f_a \approx 300$ GeV]
1. Theory bias towards high masses

Why not $M_X < O(100) \text{ GeV}$?  2. “Low-mass already constrained by previous colliders (LEP,…)”
May our dreams come true?

Why not $M_X < O(100) \text{ GeV}$?

3. “It is very difficult!” Minimal pT cuts, …
Why difficult to go below $\sim 100$ GeV?

\[ M_{\gamma\gamma,jj,...} > \Delta R \sqrt{p_{T1}^{\min} p_{T2}^{\min}} \]

Isolation of photon/jet/… $\Delta R \equiv \sqrt{\Delta \eta^2 + \Delta \phi^2}$

Minimal cuts on transverse momenta

Two ways to lower $M_{\gamma\gamma}$

- Lower $\Delta R$
- Lower $p_T^{\min}$
Why difficult to go below $\sim 100$ GeV?

Low Mariotti Redigolo FS Tobioka
in progress…not in this talk

Rest of this talk

Two ways to lower $M_{\gamma\gamma}$
- Lower $\Delta R$
- Lower $p_T^{\text{min}}$
**Lower $p_T^{\text{min}}$?**

| Experiment | Process | $\sigma_{\gamma\gamma}$ | $p_T$ Cut | Energy |
|------------|---------|--------------------------|------------|--------|
| D0 ($\sigma_{\gamma\gamma}$) | $p\bar{p} \rightarrow a \rightarrow \gamma\gamma$ | 4.2 fb$^{-1}$ | $p_{T1, T2} > 21, 20$ GeV | 1.96 TeV |
| CDF ($\sigma_{\gamma\gamma}$) | $p\bar{p} \rightarrow a \rightarrow \gamma\gamma$ | 5.36 fb$^{-1}$ | $p_{T1, T2} > 17, 15$ GeV | 1.96 TeV |
| ATLAS | $pp \rightarrow a \rightarrow \gamma\gamma$ | 4.9 fb$^{-1}$ | $p_{T1, T2} > 25, 22$ GeV | 7 TeV |
| ATLAS | $pp \rightarrow a \rightarrow \gamma\gamma$ | 20.2 fb$^{-1}$ | $p_{T1, T2} > 40, 30$ GeV | 8 TeV |
| CMS | $pp \rightarrow a \rightarrow \gamma\gamma$ | 5.0 fb$^{-1}$ | $p_{T1, T2} > 40, 25$ GeV | 7 TeV |

**$\Delta R \gtrsim 0.4$**

LHC $p_T$ cuts in diphoton cross section measurements, but LHC diphoton searches do not reach such low masses.
Lower $p_T^{\text{min}}$?

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LHC $p_T$ cuts in diphoton cross section measurements but LHC diphoton searches do not reach such low masses

Why? **Background Shape**

$m_{\gamma\gamma}^{\text{MIN}}$

$\Delta R \geq 0.4$

- 9.4 GeV
- 13.9 GeV
- 14.2 GeV
Lower $p_T^{\text{min}}$?

LHC $p_T$ cuts in diphoton cross section measurements but LHC diphoton searches do not reach such low masses.

Why? Background Shape

\[ m_{\gamma\gamma} \approx 2 p_T^{\text{min}} \]
Below \( p_T \) cuts: Background has a structure, so data-driven estimates are difficult.

### LHC \( p_T \) cuts in diphoton cross section measurements

but LHC diphoton searches do not reach such low masses.

| Experiment | Process | \( p_T \) | Energy | Lower \( m_{\gamma\gamma} \) |
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\( \Delta R \geq 0.4 \)

\( m_{\gamma\gamma}^{\text{MIN}} \)

\( 9.4 \text{ GeV} \)

\( 13.9 \text{ GeV} \)

\( 14.2 \text{ GeV} \)
Starting point: inclusive **diphoton cross section measurements** @ ATLAS7,8 and CMS7

**New Bound** we assume zero knowledge of bkg

\[ N_{\text{signal}, \text{bin}} < N_{\text{meas}, \text{bin}} (1 + 2 \Delta_{\text{bin}}) \]

experimental rel. uncertainty
New $\gamma \gamma$ Bound & Sensitivities

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$$N_{\text{signal}}^{\text{bin}} < N_{\text{meas.}}^{\text{bin}} (1 + 2 \Delta_{\text{bin}})$$

- experimental rel. uncertainty

**Current LHC reach?**

If bump-hunt on steep slope or if Monte Carlos improve:

$$N_{\text{signal}}^{\text{bin}} < N_{\text{meas.}}^{\text{bin}} \times 2 \Delta_{\text{bin}}$$

(we take data = SM prediction, and optimise binning)

**Future LHC Reach** we rescale by simulation of bkg with **same cuts** at **different energies**

[Madgraph+Pythia+Delphes]
Impact on ALP parameter space

\[ \mathcal{L}_{\text{int}} = \frac{a}{4\pi f_a} \left[ \alpha_s c_3 G \tilde{G} + \alpha_2 c_2 W \tilde{W} + \alpha_1 c_1 B \tilde{B} \right] \]

\[ \alpha_1 = \frac{5}{3} \alpha_y \]
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Our simple bound is (by far) the strongest one!
Impact on ALP parameter space

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Our simple **bound** is (by far) the strongest one!

Reach assumes bump hunt on steep slope or improvement in SM prediction

But at least we have been conservative for masses that LHC already explored
Even smaller masses?

**Figure:**

- **$\gamma\gamma$ HL**
- **$\gamma\gamma$ 8TeV 20 fb$^{-1}$**
- **ALP portal DM**
- **QCD axion quality $\Delta=6$**

**Axes:**
- **$f$ [TeV]**
- **$m_a$ [GeV]**
- **$g_{\gamma\gamma} [\text{GeV}^{-1}]$**

**Legend:**
- **Babar $\gamma\to\gamma a(jj)$**
- **ATLAS/CMS $pp\to a(\gamma\gamma)$**
- **CMS boosted $a(jj)$**
- **LEP $Z\to\gamma a(jj)$**
- **$Z$ width**
- **$c_{1,2,3}=10$**

**Graph:**
- The graph shows the relationship between the axion mass ($m_a$) and the coupling constant ($f$), along with various experimental searches and bounds on the axion-photon coupling constant ($g_{\gamma\gamma}$).
LHCb aims at competitive search for $B_s \rightarrow \gamma\gamma$

They published note with search strategy

Table 1: Loose offline selection for $B_s^0 \rightarrow \gamma\gamma$ used as a baseline for the efficiency determination. The fraction of events in each category after this loose selection with respect to the total events that pass it is shown in the last row.

| Variable                  | $0CV$ | $1CV$ LL | $1CV$ DD | $2CV$ |
|---------------------------|-------|----------|----------|-------|
| Calo $\gamma$ CL         | $> 0.3$ | $> 0.3$ | $> 0.3$ | $-$   |
| Calo $\gamma$ $p$ [GeV/c]| $> 6$  | $> 6$    | $> 6$    | $-$   |
| Calo $\gamma$ $E_T$ [GeV]| $> 3$  | $> 3$    | $> 3$    | $-$   |
| Converted $\gamma$ $p_T$ [GeV/c] | $-$ | $> 2.0$ | $> 2.0$ | $> 2.0$ |
| Converted $\gamma$ $M$ [MeV/$c^2$] | $-$ | $< 60$  | $< 60$   | $< 60$ |
| Converted $\gamma$ $\chi^2_T$ | $-$ | $> 4$   | $> 0$    | $> 1$  |
| $\sum p_T, \gamma$ [GeV] | $> 6.5$ | $> 5.5$ | $> 5.5$  | $> 5$  |
| $B_s^0$ $p_T$ [GeV/c]    | $> 3.0$ | $> 3.0$ | $> 3.0$  | $> 3.0$ |
| $B_s^0$ $\chi^2_{vis}$   | $-$     | $-$     | $-$      | $< 20$ |
| $M_{B_s}$ [MeV/$c^2$]    | [4.3, 6.3] | [4.3, 6.3] | [4.3, 6.3] | [4.5, 6.1] |
| Fraction of signal       | $83.4\%$ | $4.3\%$ | $11.7\%$ | $0.6\%$ |

Table 2: L0 efficiencies for each topology with respect to the offline selection.

| Trigger requirement | $\epsilon_{0CV}$ ($\%$) | $\epsilon_{1CV}$ LL ($\%$) | $\epsilon_{1CV}$ DD ($\%$) | $\epsilon_{2CV}$ ($\%$) |
|---------------------|--------------------------|-----------------------------|-----------------------------|--------------------------|
| L0Electron TOS      | $57.61 \pm 0.30$         | $66.9 \pm 1.3$              | $69.3 \pm 0.8$              | $79.0 \pm 2.8$           |
| L0Photon TOS        | $71.68 \pm 0.28$         | $47.7 \pm 1.3$              | $49.9 \pm 0.8$              | $7.8 \pm 1.9$            |
| Total L0 TOS        | $93.20 \pm 0.15$         | $89.7 \pm 0.8$              | $91.2 \pm 0.5$              | $80.0 \pm 2.8$           |

Table 6: Efficiency $\epsilon$ of the BDT classifiers with respect to L0 and HLT1 at the cut values applied in the trigger.

|                | $0CV$ | $1CV$ LL | $1CV$ DD | $2CV$ |
|----------------|-------|----------|----------|-------|
| BDT output     | $> 0.15$ | $> 0.2$  | $> 0.26$ | $> 0.18$ |
| Signal $\epsilon$ ($\%$) | $39.8 \pm 0.5$ | $79.6 \pm 1.8$ | $73.4 \pm 1.8$ | $80.0 \pm 5.0$ |
Even smaller masses? LHCb

LHCb aims at competitive search for $B_s \rightarrow \gamma\gamma$

They published note with search strategy

![Graph showing search strategy and mass distributions for $B_s \rightarrow \gamma\gamma$]
Even smaller masses? Belle-II

**FIG. 5**: 90% CL upper limits on product branching fractions (BF) (left axis) \( B(\Upsilon(3S) \rightarrow \gamma A^0) \cdot B(A^0 \rightarrow \text{hadrons}) \) and (right axis) \( B(\Upsilon(2S) \rightarrow \gamma A^0) \cdot B(A^0 \rightarrow \text{hadrons}) \), for (a) CP- all analysis, and (b) CP-odd analysis. The overlaid curves in red are the limits expected from simulated experiments, while the blue curves are the limits from statistical errors only.
Even smaller masses? Belle-II

Assumes Belle-II produces 100x more \( \Upsilon(3S') \) than BABAR (\( \Upsilon(1S, 2S) \) good as well)

**FIG. 5:** 90% CL upper limits on product branching fractions (BF) (left axis) \( B(\Upsilon(3S) \to \gamma A^0) \cdot B(A^0 \to \text{hadrons}) \) and (right axis) \( B(\Upsilon(2S) \to \gamma A^0) \cdot B(A^0 \to \text{hadrons}) \), for (a) CP-all analysis, and (b) CP-odd analysis. The overlaid curves in red are the limits expected from simulated experiments, while the blue curves are the limits from statistical errors only. The
**Summary**

- **ALPs** at **flavour factories** are well motivated (heavy **QCD axion**, SUSY **R-axion**, …)

- We should look for them!
**Summary**

- **ALPs at flavour factories** are well motivated (heavy QCD axion, SUSY R-axion, …)

- We should look for them!

---

Could be useful to **non-ALP scenarios**!

Light Z' (e.g. as DM mediators)

Extra Higgses  

Delgado+ 1603.00962

….  

Mariotti Redigolo FS Tobioka 1710.01743 + Cid Vidal 1810.09452
Where to go?

- LHC & Belle-II perform the actual searches!

- Other LHC (e.g. coupling with fermions)  Cacciapaglia+1710.11142,…

- Other Belle-II (e.g. ALP → hadrons?)
Back up
More on R-axion
PGB from SUSY: R-symmetry

N = 1 SUSY always accompanied by a continuous $U(1)_R = \text{"R-symmetry"}$

\[ R : \theta_\alpha \rightarrow e^{i\epsilon} \theta_\alpha \quad [R, Q] = -Q \]

R-charge assignments:

\[ \Phi = \phi + \sqrt{2} \theta \psi + \theta^2 F \]

\[ r_\phi = r_\Phi \]
\[ r_\psi = r_\Phi - 1 \]
\[ r_F = r_\Phi - 2 \]

Vector superfields are real $\Rightarrow$ gauginos have $r_\lambda = 1$

Lagrangian $\mathcal{L}$ R-symmetric $\Rightarrow R(W) = 2$

\[ \mathcal{L} \ni \int d^2 \theta W + \text{c.c.} \]

(W superpotential)
A strongly coupled “UV" completion

Very low energy SUSY breaking $F$

motivated by:

- Naturalness + Higgs mass Gherghetta Pomarol 1107.4697
- + LHC exclusions Buckley et al. 1610.08059
- Gravitino cosmology Ibe Yanagida 1608.01610

needs a strongly coupled sector

so that $m_{\chi^i} \sim \frac{g_i^2}{g_*^2} m_*$ OK with LHC bounds

- $m_*$ mass gap of the hidden sector (e.g. mass of messengers in gauge mediation)
- $g_* > 1$ coupling between hidden sector states

SUSY Naive Dimensional Analysis

$M_{\text{SUSY}} \sim m_* \sim g_* f \quad f_a \sim f$

$F \sim g_* f^2 \quad w_R \sim g_* f^3$

$a \rightarrow GG$ saturates the upper bound
The R-axion pheno Lagrangian-I

Tool: constrained superfield formalism

\[ X = \frac{G^2}{2 F_X} + \sqrt{2} \theta G + \theta^2 F_X \]

\[ \mathcal{R} = e^{iA/f_a} = e^{ia/f_a} + O(a G, \ldots) \]

satisfy the constraints

\[ \begin{cases} X^2 = 0 \\ X(R^\dagger R - 1) = 0 \end{cases} \]

~ analogous to ordinary Goldstones

\[ U^\dagger U = 1 \quad U = e^{i\pi} \]

Most general effective Lagrangian:

\[ \mathcal{L}_{G+\alpha} = \int d^4 \theta \, (X^\dagger X + f_a^2 \mathcal{R}^\dagger \mathcal{R}) + \int d^2 \theta \, (FX + w_R \mathcal{R}^2) + \text{c.c.} \]

Absent for any other axion

First pheno prediction (valid for any UV completion!):

R-axion decays to missing energy

\[ \Gamma_{\alpha \rightarrow GG} < \frac{1}{32\pi} \frac{m_\alpha^5}{F^2} \]

\[ w_R < \frac{1}{2} f_a F \]

Dine Festuccia Komargodski 0910.2527

see also Bellazzini 1605.06111
R-axion pheno overview

Tool: constrained superfield formalism

\[
X = \frac{G^2}{2F_X} + \sqrt{2\theta} G + \theta^2 F_X
\]

\[
\mathcal{R} = e^{iA/f_a} = e^{ia/f_a} + O(a G,...)
\]

satisfy the constraints

\[
\begin{cases}
X^2 = 0 \\
X(R^\dagger R - 1) = 0
\end{cases}
\]

\(\sim\) analogous to ordinary Goldstones

\[
U^\dagger U = 1 \quad U = e^{i\pi}
\]

\(r_{\mathcal{R}} = 1 \quad r_X = 2 \quad r_W = 1\)

\[
\mathcal{L}_{\text{gauge}} = \int d^2 \theta \left( \frac{1}{4} - ig_i^2 \frac{c^\text{hid}_i}{16\pi^2} A \right) \mathcal{W}_i^2 - \int d^2 \theta \frac{m_{\lambda_i}}{2F} X \mathcal{R}^{-2} \mathcal{W}_i^2 + \text{c.c.}
\]

\[
\mathcal{L}_{\text{Higgs}} \supset \int d^4 \theta \left( \frac{\mu}{F} X^\dagger H_u H_d \mathcal{R}^{2-R_H} - \frac{B_\mu}{F^2} X^\dagger X H_u H_d \mathcal{R}^{-R_H} + \text{c.c.} \right)
\]

\[-ia R_H \left( c_\beta^2 \frac{m_u}{f_a} \bar{u} \gamma_5 u + s_\beta^2 \frac{m_d}{f_a} \bar{d} \gamma_5 d + s_\beta^2 \frac{m_\ell}{f_a} \bar{\ell} \gamma_5 \ell \right)\]

\[
\delta^2 \frac{v}{\nu} (\partial_{\mu} a)^2 h \quad \delta = R_H \frac{v s_{2\beta}}{f_a}\]
\( \alpha \) from decays of \( h, \gamma \) and \( B \)

\[
\mathcal{L}_{h\alpha^2} = \frac{\delta^2}{\nu} (\partial_\mu \alpha)^2 h
\]

\[
\delta = R_H \frac{\nu}{f_\alpha} \frac{s_{2\beta}}{2}
\]

\[
\text{BR}_{\gamma \rightarrow \gamma \alpha} \simeq 3 - 5 \times 10^{-5} \left( \frac{\text{TeV}}{f_\alpha} \right)^2
\]

since Wilczek PRL39 (1977)

\[
\text{BR}_{B \rightarrow K \alpha, K^* \alpha} \simeq 3 - 5 \times 10^{-4} \left( \frac{\text{TeV}}{f_\alpha} \right)^2
\]

see Hall Wise 1981, Freytsis Ligeti Thaler 0911.5355

experiments: BABAR

Belle-II

LHCb

Belle, Belle-II

LHC, ILC, CLIC
**R axion branching ratios**

Both plots: $t_\beta = 10$

- **No anomaly**
- **Large anomalies**

| BRs | 
|-----|
| $\mu\mu + \tau\tau$ | $\gamma\gamma$, $jj$, $WW + ZZ + Z\gamma$, inv., $\gamma\gamma + \text{MET}$ |

Both plots:

- $c_{hid} = 0, t_\beta = 10$
- $c_{hid} = -10, t_\beta = 10$
R axion branching ratios

Both plots: $t_\beta = 2$

No anomaly

Large anomalies

BRs:  
- $\mu\mu + \tau\tau$,  
- $cc + bb + tt$,  
- $\gamma\gamma$,  
- $jj$,  
- $WW + ZZ + Z\gamma$,  
- inv.,  
- $\gamma\gamma$+MET

\[ c_{hid} = 0, t_\beta = 2 \]

\[ c_{hid} = -10, t_\beta = 2 \]
$$\mathcal{L}_{\text{int}} = \frac{a}{4\pi f_a} \left[ \alpha_s c_3 G \tilde{G} + \alpha_2 c_2 W \tilde{W} + \alpha_1 c_1 B \tilde{B} \right] + i C_f m_f \frac{a}{f_a} \bar{f} \gamma_5 f + C_h v \left( \frac{\partial \mu a}{f_a} \right)^2 h + \cdots$$

\[\sigma_{pp \rightarrow a}^{13\text{TeV}} [\text{fb}]\]

- $\gamma\gamma$, $\gamma\gamma + \text{MET}$
- $\gamma\gamma + \text{MET}$
- $\mu\mu$
- $\tau\tau$
- inv.
- BR$_{h \rightarrow \mu\mu}$

LHC exclusions:
- $pp \rightarrow h \rightarrow aa$
- $pp \rightarrow a \rightarrow \gamma\gamma$
- $pp \rightarrow a \rightarrow tt$
- $pp \rightarrow a \rightarrow \tau\tau$
- $pp \rightarrow a \rightarrow \text{inv}$
- $pp \rightarrow a \rightarrow jj$
- $pp \rightarrow a \rightarrow \gamma\gamma + \text{MET}$

$\sigma_{pp \rightarrow a}^{13\text{TeV}} [\text{fb}]$

- $c_{\text{hid}} = -10$, $t_\beta = 2$
- $10^7$ BR$_{Z \rightarrow \gamma a (\mu\mu)}$
\( \mathcal{L}_{\text{int}} = \frac{a}{4\pi f_a} \left[ \alpha_s c_3 G \tilde{G} + \alpha_2 c_2 W \tilde{W} + \alpha_1 c_1 B \tilde{B} \right] + i C_f m_f \frac{a}{f_a} \bar{f} \gamma_5 f + C h v \left( \frac{\partial_{\mu} a}{f_a} \right)^2 h + \ldots \)

\[ \begin{align*}
\sigma^{\text{GF 13 TeV}}_{\text{pp} \to a} & \quad \text{[fb]} \\
\gamma \gamma, \quad \text{tt}, \quad \tau \tau, \quad \text{inv.}, \quad \text{BR}_{h \to a a}, \quad 10^7 \text{BR}_{Z \to \gamma a(j)}
\end{align*} \]

\( c^{\text{hid}} = -10, \quad t_\beta = 10 \)

LHC exclusions:
- \( pp \to h \to a a \)
- \( pp \to a + \gamma \gamma \)
- \( pp \to a + t t \)
- \( pp \to a + \tau \tau \)
- \( pp \to a + \text{inv} \)
- \( pp \to a + j j \)
- \( pp \to a + \gamma \gamma + \text{MET} \)
More on low-mass γγ
What if different couplings?

\[ \mathcal{L}_{\text{eff}} \supset \frac{N\alpha_3}{4\pi} \frac{a}{f} G_{\mu\nu} \tilde{G}^{\mu\nu} + \frac{E\alpha_{\text{em}}}{4\pi} \frac{a}{f} F_{\mu\nu} \tilde{F}^{\mu\nu} \]

Cid-Vidal Mariotti Redigolo FS Tobioka 1810.09452
What if different couplings?

\[ \mathcal{L}_{\text{eff}} \supset \frac{N \alpha_3}{4\pi} \frac{a}{f} G_{\mu\nu} \tilde{G}^{\mu\nu} + \frac{E \alpha_{\text{em}}}{4\pi} \frac{a}{f} F_{\mu\nu} \tilde{F}^{\mu\nu} \]

---

**ATLAS:** $Z \rightarrow \gamma a(\gamma\gamma)$

**LEP:** $Z \rightarrow \gamma a(jj)$

**ATLAS/CMS 20 fb$^{-1}$**

**LHCb 300 fb$^{-1}$**

**ATLAS/CMS sens. 20 fb$^{-1}$**

**HL ATLAS/CMS 3 ab$^{-1}$**

$m_a = 15$ GeV
So, what should ATLAS & CMS do?

Study so far shows clearly an unexplored potential, but

**Challenge:** need improvement in Monte Carlo to predict the backgrounds or being able to hunt bumps on steep data

\[ M_{\gamma\gamma,jj,...} > \Delta R \sqrt{p_{T_1}^{min} p_{T_2}^{min}} \]

- Lower \( \Delta R \)
  - and look for resonances recoiling against a jet (or any ISR)

**Background is smooth** and one does not need Monte Carlos!
Lower $\Delta R$: The Present

| CMS     | $pp \rightarrow a \rightarrow jj$ | 18.8 fb$^{-1}$ | 8 TeV  | 500 GeV | [38] |
|---------|----------------------------------|----------------|--------|---------|------|
| ATLAS   | $pp \rightarrow a \rightarrow jj$ | 20.3 fb$^{-1}$ | 8 TeV  | 350 GeV | [39] |
| CMS     | $pp \rightarrow a \rightarrow jj$ | 12.9 fb$^{-1}$ | 13 TeV | 600 GeV | [40] |
| ATLAS   | $pp \rightarrow a \rightarrow jj$ | 3.4 fb$^{-1}$  | 13 TeV | 450 GeV | [41] |
| CMS     | $pp \rightarrow j a \rightarrow j j j$ | 35.9 fb$^{-1}$ | 13 TeV | 50 GeV  | [42] |

Done recently in **dijet**, tremendous improvement in mass reach!

CMS 1710.00159
ATLAS 1801.08769

Look for **boosted** resonance in jet substructure

Extra hard object to pass the trigger

CMS

95% CL upper limits

- Observed
- Expected
- ± 1 std. deviation
- ± 2 std. deviation
- Theory, $g_q = 0.08$
- Theory, $g_q = 0.17$

Z' mass (GeV)

$p_{T}$ (GeV)
Lower $\Delta R$: The Future

They managed with jets, why not with photons?

Diphotons boosted vs a hard jet $p_T^a > 500$ GeV

Photons get collimated $\Delta R \simeq \frac{2m_a}{p_T^a}$

Standard isolation rejects signal

$$\sum_{i \neq \gamma_{test}} p_{T,i} < \# \quad \sum_{i \neq \gamma_{test}} p_{T,i}/E_{T,\gamma_{test}} < \#$$
They managed with jets, why not with photons?

Diphotons boosted vs a hard jet \( p_T^\gamma > 500 \text{ GeV} \)

Photons get collimated \( \Delta R \simeq \frac{2m_a}{p_T^\gamma} \)

Standard isolation rejects signal

\[
\Delta R < R_{\text{iso}} \quad \sum_{i \neq \gamma_{\text{test}}} p_T^i < \# \quad \sum_{i \neq \gamma_{\text{test}}} p_T^i / E_{T,\gamma_{\text{test}}} < \#
\]

**Modify isolation!** (NB: simpler than photon-jet substructures…)

It works!

final checks and optimisations in progress
They managed with jets, why not with photons?

Diphotons boosted vs a hard jet \( p_T^a > 500 \text{ GeV} \)

Photons get collimated \( \Delta R \simeq \frac{2m_a}{p_T^a} \)

Standard isolation rejects signal

\[
\sum_{i \neq \gamma_{\text{test}}} p_T,i < \# \quad \text{and} \quad \sum_{i \neq \gamma_{\text{test}}} \frac{p_T,i}{E_{T,\gamma_{\text{test}}}} < \#
\]

Modify isolation! (NB: simpler than photon-jet substructures…)

It works!

final checks and optimisations in progress
Other ways to low-mass resonances?

$m_{\gamma\gamma} < 10$ GeV at the LHCb?

work in progress…

Big hole for $4$ GeV $\lesssim m_a \lesssim 10$ GeV

Difermions, e.g. ditaus?

Cacciapaglia Ferretti Flacke Serodio 1710.11142

NB. sensitivities not based on data definitely worth investigating
New $\gamma\gamma$ Bound & Sensitivities

Starting point: inclusive diphoton cross section measurements @ ATLAS7,8 and CMS7

1. New Bound  we assume zero knowledge of bkg

\[ N_{\text{signal}}^{\text{bin}} < N_{\text{bin}}^{\text{meas.}} (1 + 2 \Delta_{\text{bin}}) \]

experimental rel. uncertainty

2. Reach  we assume data = SM prediction

\[ N_{\text{signal}}^{\text{bin}} < N_{\text{bin}}^{\text{meas.}} \times 2 \Delta_{\text{bin}} \]

3. Reach with smarter bins  (= 2., where we reduce ~ 10 GeV bins to mass resolution of ~ 3 GeV)

4. Reach we simulate bkg with same cuts at different energies  [Madgraph+Pythia+Delphes]

Reach of 3.  Simulated bkg cross sections

Starting point: inclusive diphoton cross section measurements @ ATLAS7,8 and CMS7
### Low-mass analyses we found

| Experiment | Process                                                                 | Lumi       | √s          | low mass reach | ref.  |
|------------|-------------------------------------------------------------------------|------------|-------------|----------------|-------|
| LEPI       | $e^+e^- \rightarrow Z \rightarrow \gamma a \rightarrow jj$          | 12 pb$^{-1}$| Z-pole      | 10 GeV         | [29]  |
| LEPI       | $e^+e^- \rightarrow Z \rightarrow \gamma a \rightarrow \gamma\gamma$ | 78 pb$^{-1}$| Z-pole      | 3 GeV          | [30]  |
| LEPII      | $e^+e^- \rightarrow Z^*, \gamma^* \rightarrow \gamma a \rightarrow jj$ | 9.7 pb$^{-1}$| Z-pole      | 60 GeV         | [31]  |
| LEPII      | $e^+e^- \rightarrow Z^*, \gamma^* \rightarrow \gamma a \rightarrow \gamma\gamma$ | 9.7 pb$^{-1}$| Z-pole      | 60 GeV         | [31]  |
| LEPII      | $e^+e^- \rightarrow Z^*, \gamma^* \rightarrow Z a \rightarrow jj\gamma\gamma$ | 9.7 pb$^{-1}$| Z-pole      | 60 GeV         | [31]  |
| D0/CDF     | $p\bar{p} \rightarrow a \rightarrow \gamma\gamma$                    | 7/8.2 fb$^{-1}$| 1.96 TeV    | 100 GeV        | [33]  |
| ATLAS      | $p p \rightarrow a \rightarrow \gamma\gamma$                         | 20.3 fb$^{-1}$| 8 TeV       | 65 GeV         | [34]  |
| CMS        | $p p \rightarrow a \rightarrow \gamma\gamma$                         | 19.7 fb$^{-1}$| 8 TeV       | 80 GeV         | [35]  |
| CMS        | $p p \rightarrow a \rightarrow \gamma\gamma$                         | 19.7 fb$^{-1}$| 8 TeV       | 150 GeV        | [36]  |
| CMS        | $p p \rightarrow a \rightarrow \gamma\gamma$                         | 35.9 fb$^{-1}$| 70 GeV      | 70 GeV         | [37]  |
| CMS        | $p p \rightarrow a \rightarrow jj$                                    | 18.8 fb$^{-1}$| 8 TeV       | 500 GeV        | [38]  |
| ATLAS      | $p p \rightarrow a \rightarrow jj$                                    | 20.3 fb$^{-1}$| 8 TeV       | 350 GeV        | [39]  |
| CMS        | $p p \rightarrow a \rightarrow jj$                                    | 12.9 fb$^{-1}$| 13 TeV      | 600 GeV        | [40]  |
| ATLAS      | $p p \rightarrow a \rightarrow jj$                                    | 3.4 fb$^{-1}$| 13 TeV      | 450 GeV        | [41]  |
| CMS        | $p p \rightarrow a \rightarrow jj$                                    | 35.9 fb$^{-1}$| 13 TeV      | 50 GeV         | [42]  |
| UA2        | $p\bar{p} \rightarrow a \rightarrow \gamma\gamma$                    | 13.2 pb$^{-1}$| 0.63 TeV    | 17.9 GeV       | [43]  |
| D0         | $p\bar{p} \rightarrow a \rightarrow \gamma\gamma$                    | 4.2 fb$^{-1}$| 1.96 TeV    | 8.2 GeV        | [44]  |
| CDF        | $p\bar{p} \rightarrow a \rightarrow \gamma\gamma$                    | 5.36 fb$^{-1}$| 1.96 TeV    | 6.4 GeV        | [45, 46]|
| ATLAS      | $p p \rightarrow a \rightarrow \gamma\gamma$                         | 4.9 fb$^{-1}$| 7 TeV       | 9.4 GeV        | [8]   |
| CMS        | $p p \rightarrow a \rightarrow \gamma\gamma$                         | 5.0 fb$^{-1}$| 7 TeV       | 14.2 GeV       | [10]  |
| ATLAS      | $p p \rightarrow a \rightarrow \gamma\gamma$                         | 20.2 fb$^{-1}$| 8 TeV       | 13.9 GeV       | [9]   |
Signal efficiencies and cross section

\[
\epsilon_S(m_a) = \frac{\sigma_{\gamma\gamma}^{\text{MC cuts}}(m_a, s)}{C_s \sigma_{\gamma\gamma}^{\text{LO}}(m_a, s)}
\]

where we work in the approximation \(\Gamma_{\text{tot}} \simeq \Gamma_{gg}\) (which is excellent in the parameter space that we have studied), and where

\[
\sigma_{\gamma\gamma}^{\text{th}}(m_a, s) = \frac{K_\sigma}{K_g} \cdot \sigma_{\gamma\gamma}^{\text{LO}}(m_a, s),
\]

\[
\sigma_{\gamma\gamma}^{\text{LO}}(m_a, s) = \frac{1}{m_a s} C_{gg}(m_a^2/s) \cdot \Gamma_{\gamma\gamma},
\]

\[
C_{gg} = \frac{\pi^2}{8} \int_{m_a^2/s}^{1} \frac{dx}{x} f_g(x) f_g\left(\frac{m_a^2}{sx}\right),
\]

\(K_\sigma = 3.7\) from ggHiggs v3.5

\(K_g = 2.1\)

| \(m_a\) in GeV | 10  | 20  | 30  | 40  | 50  | 60  | 70  | 80  | 90  | 100 | 110 | 120  |
|----------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|------|
| \(\epsilon_S\) for \(\sigma_{7\text{TeV}}\) ATLAS [8] | 0   | 0.008 | 0.022 | 0.040 | 0.137 | 0.293 | 0.409 | 0.465 | 0.486 | 0.533 | 0.619 | 0.637 |
| \(\epsilon_S\) for \(\sigma_{7\text{TeV}}\) CMS [10] | 0   | 0.002 | 0.010 | 0.020 | 0.030 | 0.058 | 0.156 | 0.319 | 0.424 | 0.499 | 0.532 | 0.570 |
| \(\epsilon_S\) for \(\sigma_{8\text{TeV}}\) ATLAS [9] | 0   | 0.007 | 0.008 | 0.014 | 0.024 | 0.037 | 0.071 | 0.233 | 0.347 | 0.419 | 0.452 | 0.484 |
| \(\epsilon_S\) for \(\sigma_{2\text{TeV}}\) CDF [45, 46] | 0.001 | 0.007 | 0.026 | 0.143 | 0.212 | 0.241 | 0.276 | 0.275 | 0.283 | 0.3 | 0.319 | 0.327 |
| \(\epsilon_S\) for \(\sigma_{2\text{TeV}}\) D0 [44] | 0   | 0.002 | 0.008 | 0.018 | 0.114 | 0.169 | 0.208 | 0.21 | 0.217 | 0.234 | 0.244 | 0.252 |

\(C_s^{\text{MC cuts}}\) Simulated w/Madgraph+Pythia+Delphes matched up to 2 extra jets

\(\sigma_{\gamma\gamma}^{\text{LO}}\) reproduces up to a constant factor \(C_s\) the shape of \(\sigma_{\gamma\gamma}^{\text{MC tot}}\) for \(m_{\gamma\gamma} \gtrsim 60\) GeV (i.e. sufficiently far from the sum of the minimal detector \(p_T\) cuts on the photons). A constant factor \(C_s \equiv \sigma_{\gamma\gamma}^{\text{MC tot}}(s)/\sigma_{\gamma\gamma}^{\text{LO}}(s)\) is hence included in Eq. (5) and we obtain \(C_{7\text{TeV}} \approx C_{8\text{TeV}} \approx 0.85\) while \(C_{2\text{TeV}} \approx 1\) at the Tevatron center of mass energy.
Validation

$fa = 1 \text{ TeV}$
$c_3 = 10 = c_\gamma / 2$

$\sigma_{\gamma \gamma \rightarrow h, \gamma \gamma}$ [pb]

$m_a$ [GeV]

$\sigma_{\text{MCtot}}$
$C_5 \sigma^{\text{LO}}$

$\sigma_{\text{Valt,LO}}$ [pb]

$m_{\gamma \gamma}$ [GeV]

$\text{SM } \gamma \gamma \text{ ATLAS7}$
$\text{SM } \gamma \gamma \text{ MadGraph}$
Validation

\[ \sigma \rightarrow \gamma \gamma \]

\[ f_a = 1 \text{ TeV} \]
\[ c_3 = 10 = c_\gamma / 2 \]

\[ m_a \text{ [GeV]} \]

\[ \sigma_{-\gamma-\gamma} \text{ [pb]} \]

- FCC–hh
- LHC27
- LHC14

\[ C_{14} = 0.85 \]
\[ C_{27} = 0.73 \]
\[ C_{100} = 0.67 \]
Interplay of LHC and Tevatron

![Graph showing the interplay of LHC and Tevatron with various datasets and significance levels.](image-url)
**FCC ee** reach computed rescaling
LEP limits on $\text{BR}[Z \to \gamma a(jj)]$
and assuming $10^{12}$ Z bosons

If $aG\tilde{G}$ switched on
HL-LHC wins over FCC ee

**FCC hh** reach computed like LHC14 one
[from simulations, Lumi= 3 ab$^{-1}$]

NB. pT cuts as in ATLAS8 (30, 40 GeV)

Still, speculative even for FCC standards!

this search has not even been performed at 8 TeV
at 100 TeV game could be very different (larger boosts,…)

Thoughts in progress…
ALPs without gluons
A selected example: Higgs decays to 4 photons

$$\mathcal{L}_{\text{eff}}^{D \geq 6} = \frac{C_{ah}}{\Lambda^2} (\partial_\mu a)(\partial^\mu a) \phi^\dagger \phi$$

$$\mathcal{L}_{\text{eff}}^{D \leq 5} \ni e^2 C_{\gamma \gamma} \frac{a}{\Lambda} F_{\mu \nu} \tilde{F}^{\mu \nu}$$

For more on ALP at colliders see e.g.

Mimasu Sanz 1409.4792, ...., Bauer+1808.10323
FCC-ee with no gluon coupling

\[ \mathcal{L}_{\text{int}} = \frac{a}{4\pi f_a} \left[ \alpha_s G G + \alpha_2 c_2 W W + \alpha_1 c_1 B \bar{B} \right] \]

\[ \alpha_1 = \frac{5}{3} \alpha_y \]

To compare with previous slides:

\[ \Lambda_{aBB} = \frac{\pi}{c_1 \alpha_1} f_a \approx 20 f_a \frac{10}{c_1} \]

For Tera Z

\[ \text{BR}[Z \to \gamma a(\gamma\gamma)] \lesssim 3 \times 10^{-9} \]

[current LEP limit \( \lesssim 5 \times 10^{-6} \)]

FCC ee could reach \( f_a \lesssim 100 \) TeV

FCC hh VBF?

Associated production?

Photon fusion?

???