New Probes for Axion-like Particles at Hadron Colliders

Based on arXiv:1901.03061

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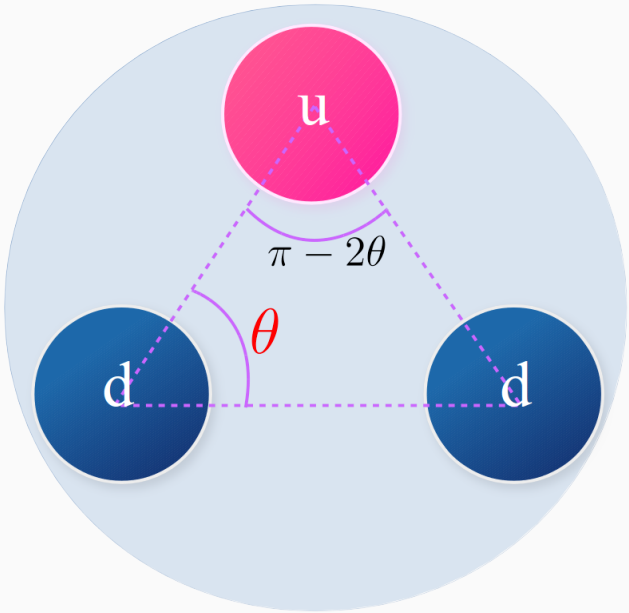
Introduction

Strong CP Problem (Classical)

Neutron EDM (Quark model)

$$\text{EDM:} \quad \vec{d} = \sum_i Q_i \vec{r}_i$$

$$d_N = 2 \times \frac{1}{3} e \times \frac{1}{m_\pi} \sqrt{\frac{1 - \cos(2\theta)}{2}}$$
$$\approx 10^{-13} |\sin\theta| \text{ e.cm}$$



Current Measurements

[C. A. Baker et al., PRL, 2006, hep-ex/0602020.]

$$d_N < 2.9 \times 10^{-26} \text{ e.cm (90\%CL)}$$

Bounds on θ

$$\theta < 10^{-12}$$

QFT: $\theta_{QCD}\, G\tilde{G}$

Why?

Strong CP Problem (Classical)

Neutron EDM (Quark model)

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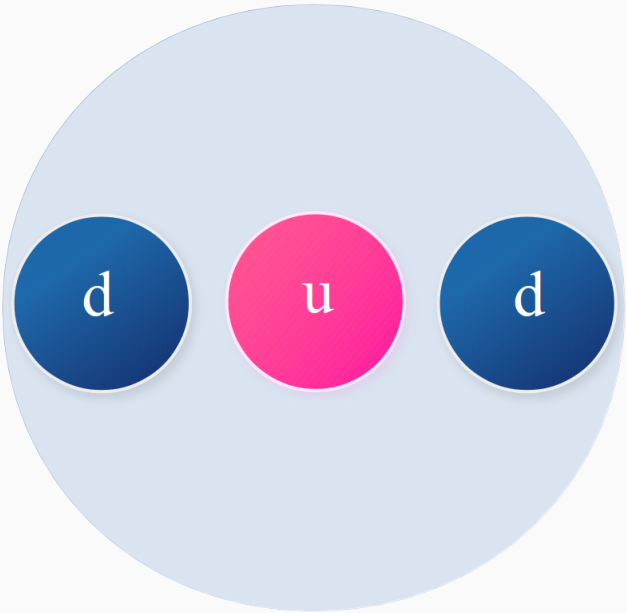

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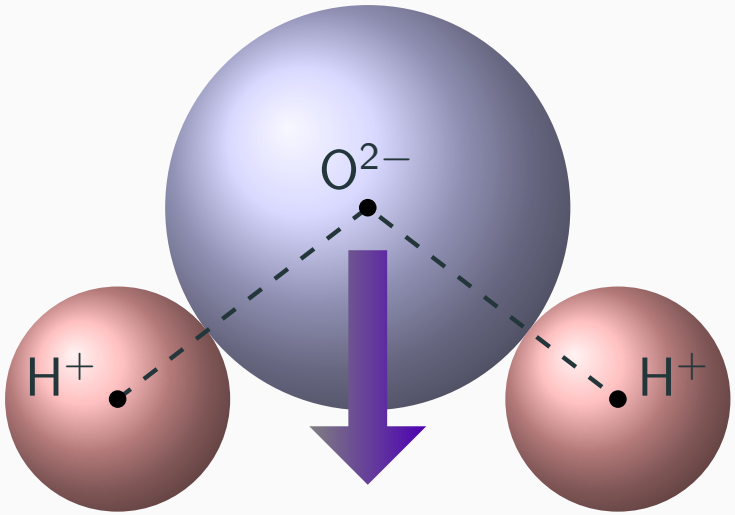
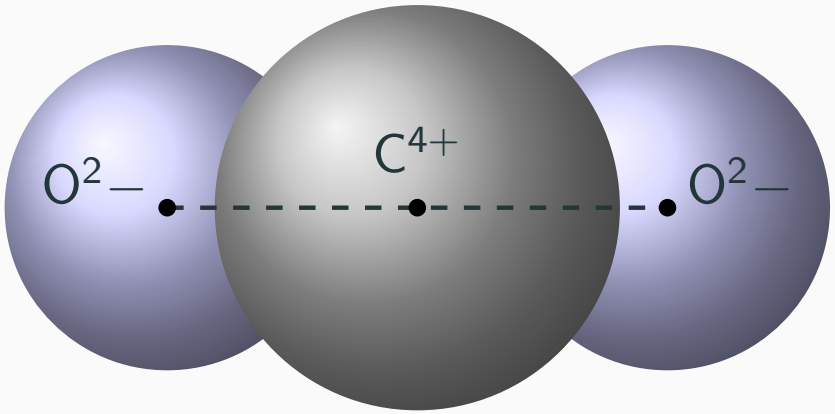
Why θ is so small?

Strong CP Problem (Classical)



Water: H_2O

Electric Dipole Moment(EDM)
$= 3.8 \times 10^{-9}$ e.cm



Carbon Dioxide: CO_2

Electric Dipole Moment(EDM)
$\approx 0 \times 10^{-9}$ e.cm

Question: How the EDMs are different?

Answer: Dynamics of the system

Axions and Axion-like Particles

QCD Axion

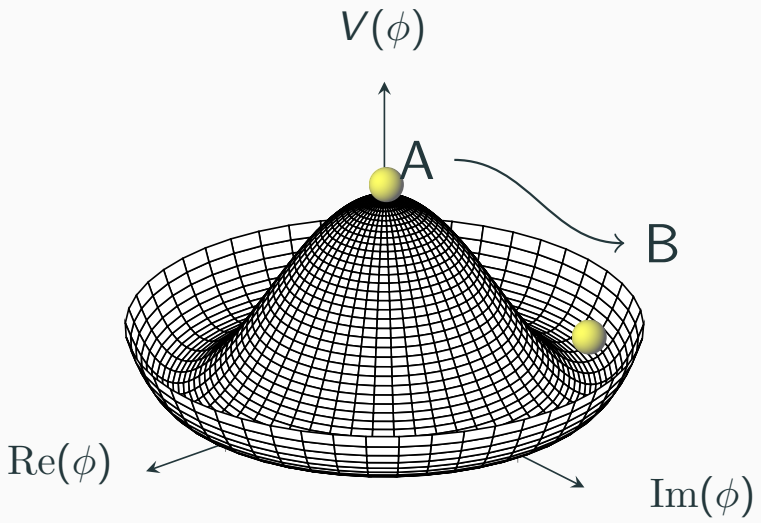
Axion model

- A global $U(1)_{\mathrm{PQ}}$ symmetry
- A new complex scalar ϕ charged under $U(1)_{\mathrm{PQ}}$

$$\phi = \frac{1}{\sqrt{2}}(v_{\mathrm{PQ}} + \sigma)e^{ia/f_a}$$

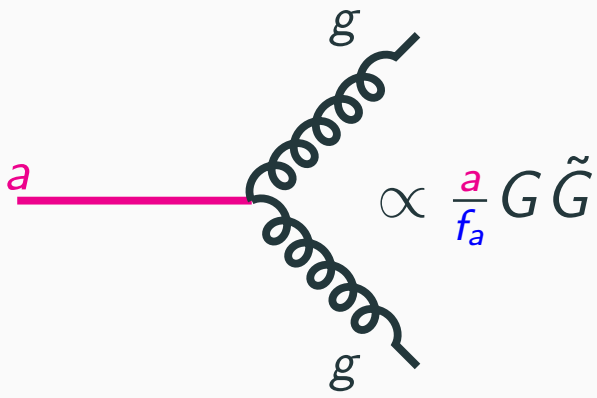
- Tangential excitation (a): pseudo Nambu-Goldstone boson (axion)

axion potential

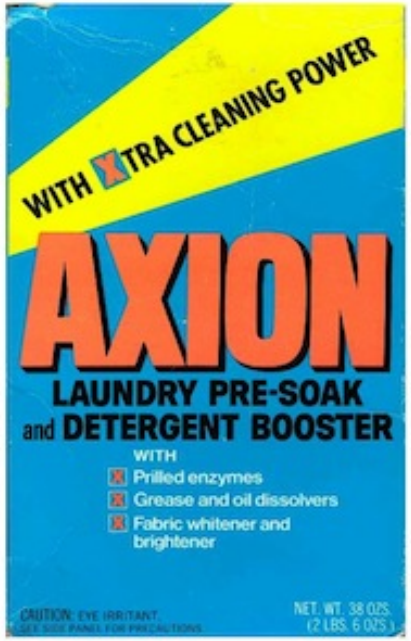


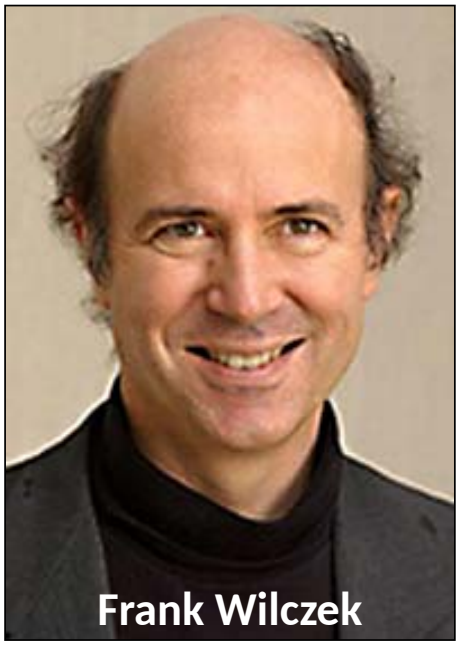
Solving Strong CP

- Global symmetry breaking $\rightarrow$ shift symmetry ($a \rightarrow a + c$)
- Absorb θ in a
- Potential is minimized when $\theta = 0$



The Cleansing Axion





"I named them after a laundry detergent, since they clean up a problem with an axial current."
(Nobel lecture 2004)

Axion-like Particles (ALP)

Axion (QCD axion)

- The QCD axion mass due to strong interaction [S. Weinberg, PRL, 1977]

$$m_a \approx \frac{m_\pi f_\pi}{f_a} \approx 6 \times 10^{-6}\text{eV}\frac{10^{12}\text{GeV}}{f_a}$$

- The mass of axion is a function of its decay constant (1 parameter)

The QCD axion is for solving strong CP, but there are other axion models

Axion-like Particles (ALP)

- Generic prediction of many high energy physics model with spontaneous global symmetry breaking
- Appear in phenomenological models of string theory
- The ALPs can be dark matter candidates [J. Redondo, 2019]
- The ALP can help to solve baryogenesis [hep-ph/1901.02031]
- The mass of ALP is independent of its decay constant (2 parameters)

EFT for ALP

Effective field theory for ALP(a)

- No new CP violation source
- ALP(a): CP-odd scalar, singlet of SM gauge group
- ALP is a pseudo-Nambu-Goldstone boson of a broken global symmetry
  Up to dimension 5 [H. Georgi, et.al, PLB, 1986]

$$\begin{aligned}\mathcal{L}_{eff}^{D\leq 5} &= \mathcal{L}_{SM} + \frac{1}{2}(\partial^\mu a)(\partial_\mu a) - \frac{1}{2}{m_a}^2 a^2 \\ &+ c_{a\Phi}\frac{\partial^\mu a}{f_a}(\Phi^\dagger i \overleftrightarrow{D}_\mu \Phi) + \frac{\partial^\mu a}{f_a}\sum_F \bar{\Psi}_F \mathbf{C}_F \Psi_F \\ &- c_{GG}\frac{a}{f_a}G^A_{\mu\nu}\tilde{G}^{\mu\nu,a} - c_{BB}\frac{a}{f_a}B_{\mu\nu}\tilde{B}^{\mu\nu} - c_{WW}\frac{a}{f_a}W^a_{\mu\nu}\tilde{W}^{\mu\nu,a},\end{aligned}$$

- We probe c_{GG}, c_{WW}, c_{BB} at the LHC

Phenomenology at the LHC

Phenomenology at the LHC

Sensitive couplings at the LHC

- $\frac{c_{GG}}{f_a}$
- $\frac{c_{WW}}{f_a}$
- $\frac{c_{BB}}{f_a}$
- $\frac{c_{\gamma\gamma}}{f_a} = \frac{c_{BB}}{f_a}\cos\theta_W^2 + \frac{c_{WW}}{f_a}\sin\theta_W^2$
  Based on low-energy experiments:
  $c_{BB} = -\tan\theta_W^2 c_{WW}$

ALP signatures at the LHC

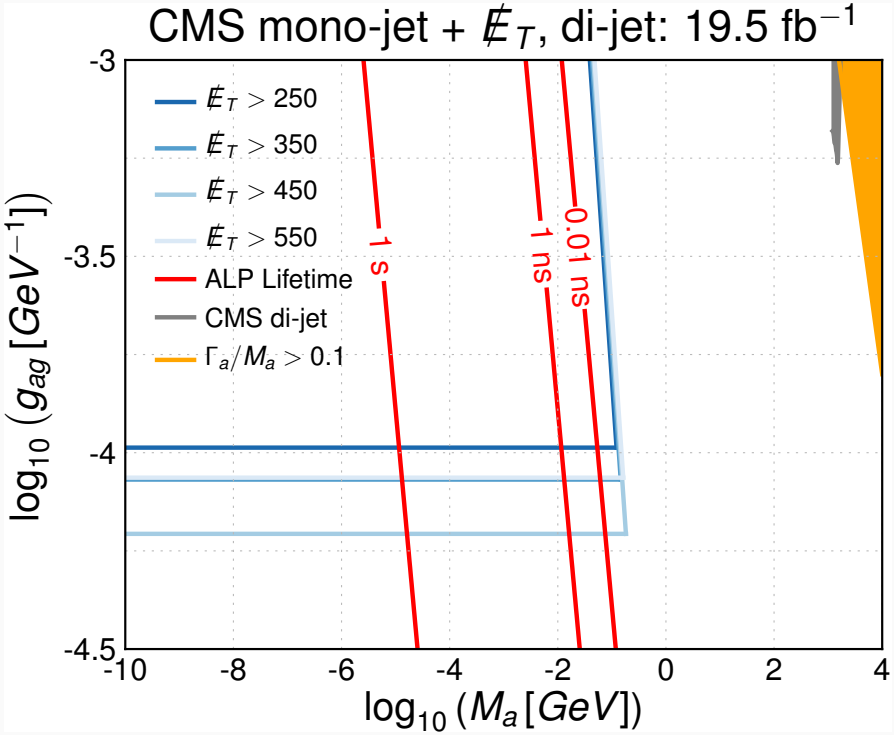
- ALP is prodcued on-shell and escapes the detector (Mono-X)
- ALP in S-channel (Di-X)
- ALP is produced on-shell and then decays (Tri-X)

Channels at the LHC

- Mono-jet
- Mono-photon
- Mono-W
- Mono-Z
- Mono-Higgs
- Di-jet
- Di-photon
- Tri-jet
- Tri-photon
- Jet + photon + MET
- $t\bar{t}$ + MET
- Single top + MET

Coupling of ALP to gluons $\frac{c_{GG}}{f_a}$ via mono-jet at the LHC

- jet + ALP (missing energy) $\Rightarrow$ mono-jet
- S-channel jet production $\Rightarrow$ di-jet



[Ken Mimasu and Verónica Sanz,JHEP, 2015, hep-ph/1409.4792]

CMS mono-jet selection

Trigger

- $\not{E}_T > 120$ GeV

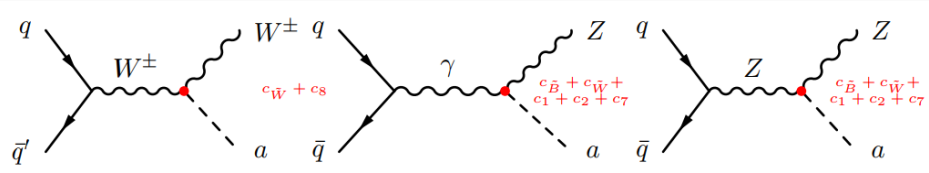
Vetos

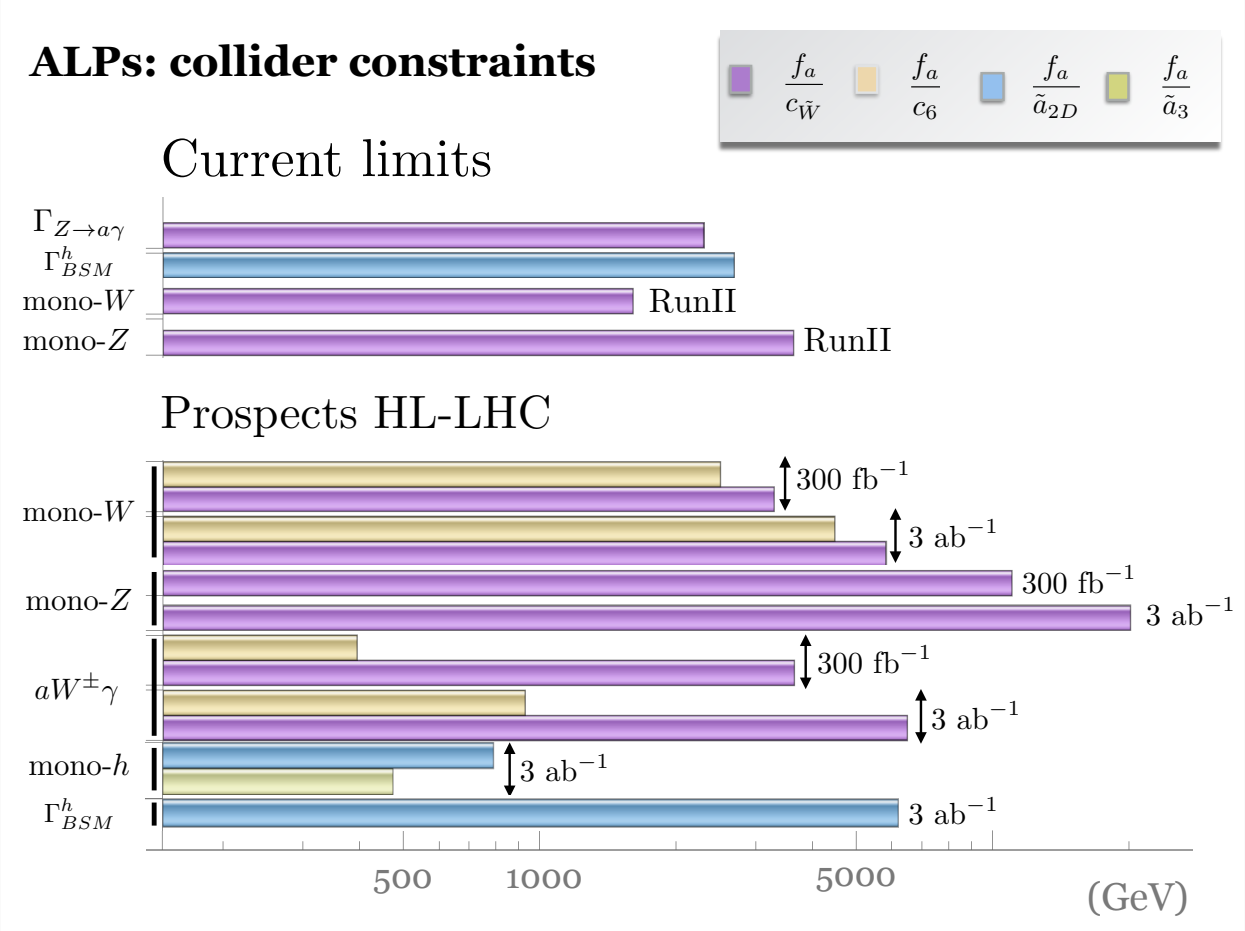
- More than two jets with $p_T > 30$ GeV and $|\eta| < 4.3$
- A second jet with $\Delta\phi(j_1, j_2) > 2.5$
- Well reconstructed electrons or muons with $p_T > 10$ GeV
- Well reconstructed taus with $p_T > 20$ GeV and $|\eta| < 2.3$

Selection

- Hardest jet with $p_T > 110$ GeV and $|\eta| < 2.4$
- $\not{E}_T$ cut for each signal region

Coupling of ALP to W bosons $\frac{c_{WW}}{f_a}$ at the LHC

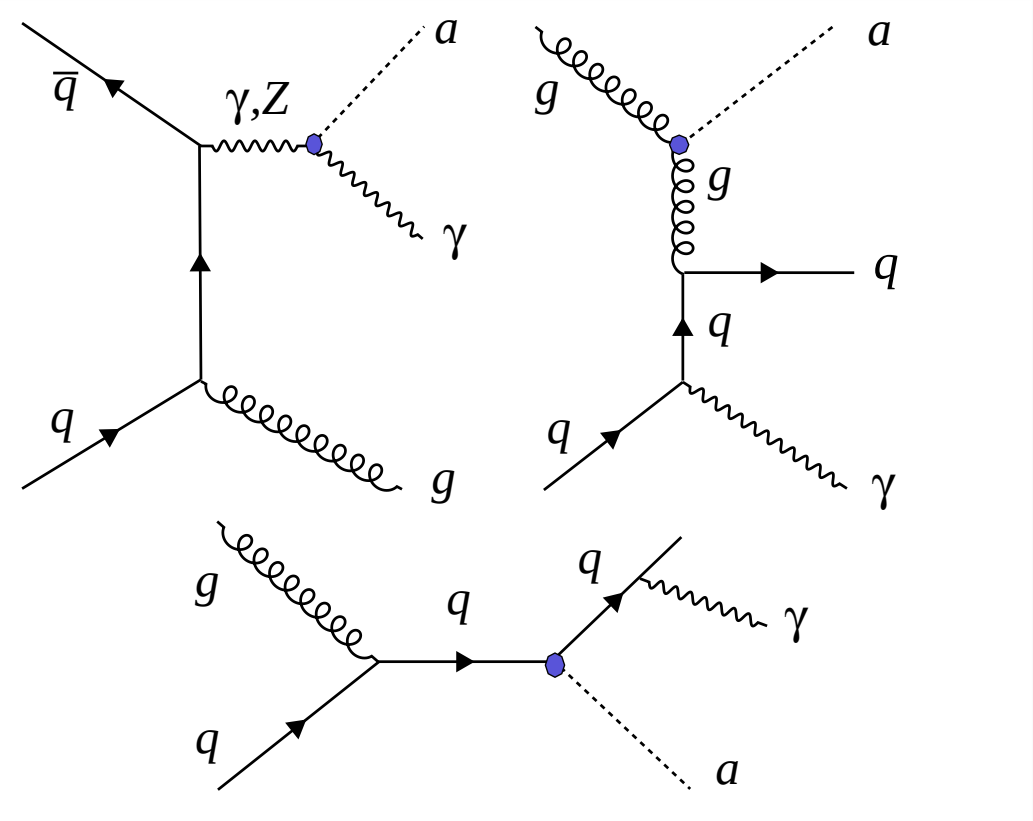




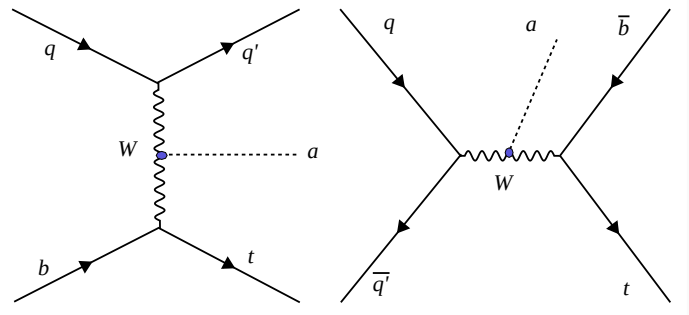
[Brivio, I. et. al., EPJC, 2017, hep-ph/1701.05379]

ALP channels

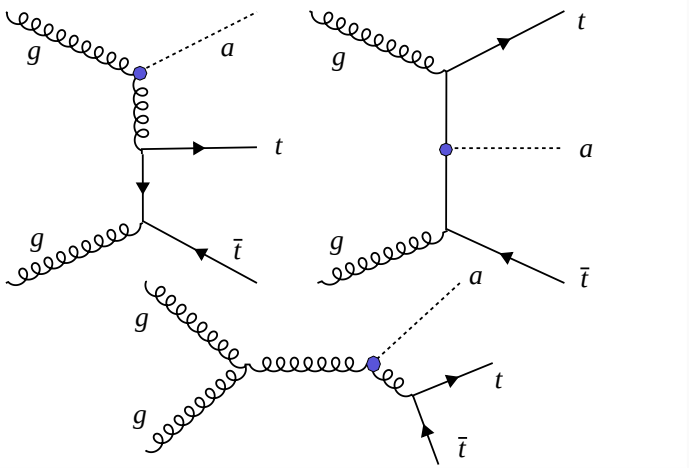
jet + photon $+a$



single top + a



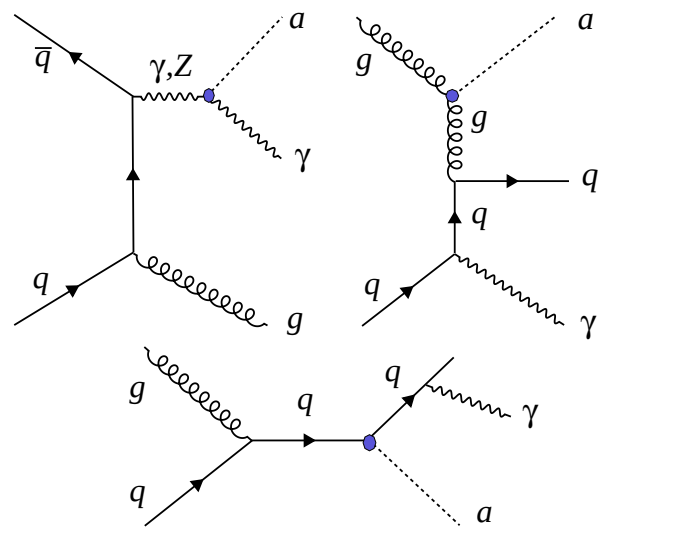
$t\bar{t} + a$



- Massive a can decay to SM
- Light a appears as MET in the detector

ALP + jet + photon

- $\sigma(pp \to j\gamma a) = 30.0 \times \left(\frac{c_{GG}}{f_a}\right)^2$ pb
- $\sigma(pp \to j\gamma a) = 13.9 \times \left(\frac{c_{WW}}{f_a}\right)^2$ pb
- The cross section is independent of the m_a
- The m_a is set to 1MeV



Main backgrounds

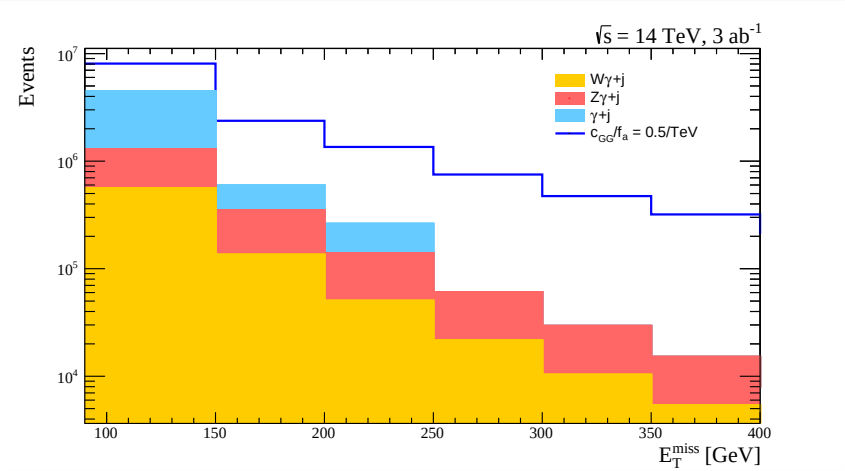
- $j\gamma$
- $Z(\to \nu\bar{\nu})j\gamma$
- $W(\to l\bar{\nu}_l)j\gamma$

Cut	c_{gg}	c_{ww}	$Zj\gamma$	$Wj\gamma$	$j\gamma$
Photon and Jet	0.591	0.728	0.636	0.28	0.7
$\Delta\phi(\gamma, j) < 2.7$	0.503	0.402	0.464	0.163	0.087
$E_T^{\text{miss}} > 50$GeV	0.462	**0.147**	0.370	0.084	3.3×10^{-4}
$E_T^{\text{miss}} > 90$GeV	**0.365**	0.031	0.216	0.033	3.7×10^{-5}

ALP + jet + photon

Histogram of MET at the HL-LHC

- $Z \to \nu\bar{\nu}$ using $Z \to \mu^+\mu^-$
  Interpret pair of muons as a pair of missing neutrinos Correct for acceptance, efficiencies and branching fraction
  $R(Z \to \nu\bar{\nu})/R(Z \to \mu^+\mu^-) = 5.95$



The 95% CL Limits:

$$\frac{c_{GG}}{f_a} < 0.012\text{TeV}^{-1} \quad L = 3000\text{fb}^{-1}, \sqrt{s} = 14\text{TeV}$$

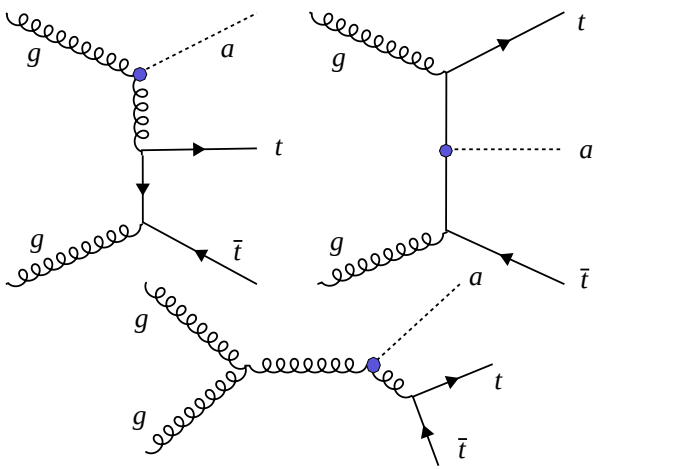
$$\frac{c_{WW}}{f_a} < 0.041\text{TeV}^{-1} \quad L = 3000\text{fb}^{-1}, \sqrt{s} = 14\text{TeV}$$

ALP + ttbar

- $\sigma(pp \to t\bar{t}a) = 3.9 \times \left(\frac{c_{GG}}{f_a}\right)^2$ pb
- Dark Matter + $t\bar{t}$ (2.2fb^{-1}) [CMS-EXO-16-005]
- Semi-leptonic decay of $t\bar{t}$
- 95% Limits:

$$\frac{c_{GG}}{f_a} < 0.44\text{TeV}^{-1} \quad L = 2.2\text{fb}^{-1}, \sqrt{s} = 13\text{TeV}$$
$$\frac{c_{GG}}{f_a} < 0.15\text{TeV}^{-1} \quad L = 100\text{fb}^{-1}, \sqrt{s} = 13\text{TeV}$$
$$\frac{c_{GG}}{f_a} < 0.11\text{TeV}^{-1} \quad L = 3000\text{fb}^{-1}, \sqrt{s} = 13\text{TeV}$$
$$\frac{c_{GG}}{f_a} < 0.063\text{TeV}^{-1} \quad L = 3000\text{fb}^{-1}, \sqrt{s} = 14\text{TeV}$$

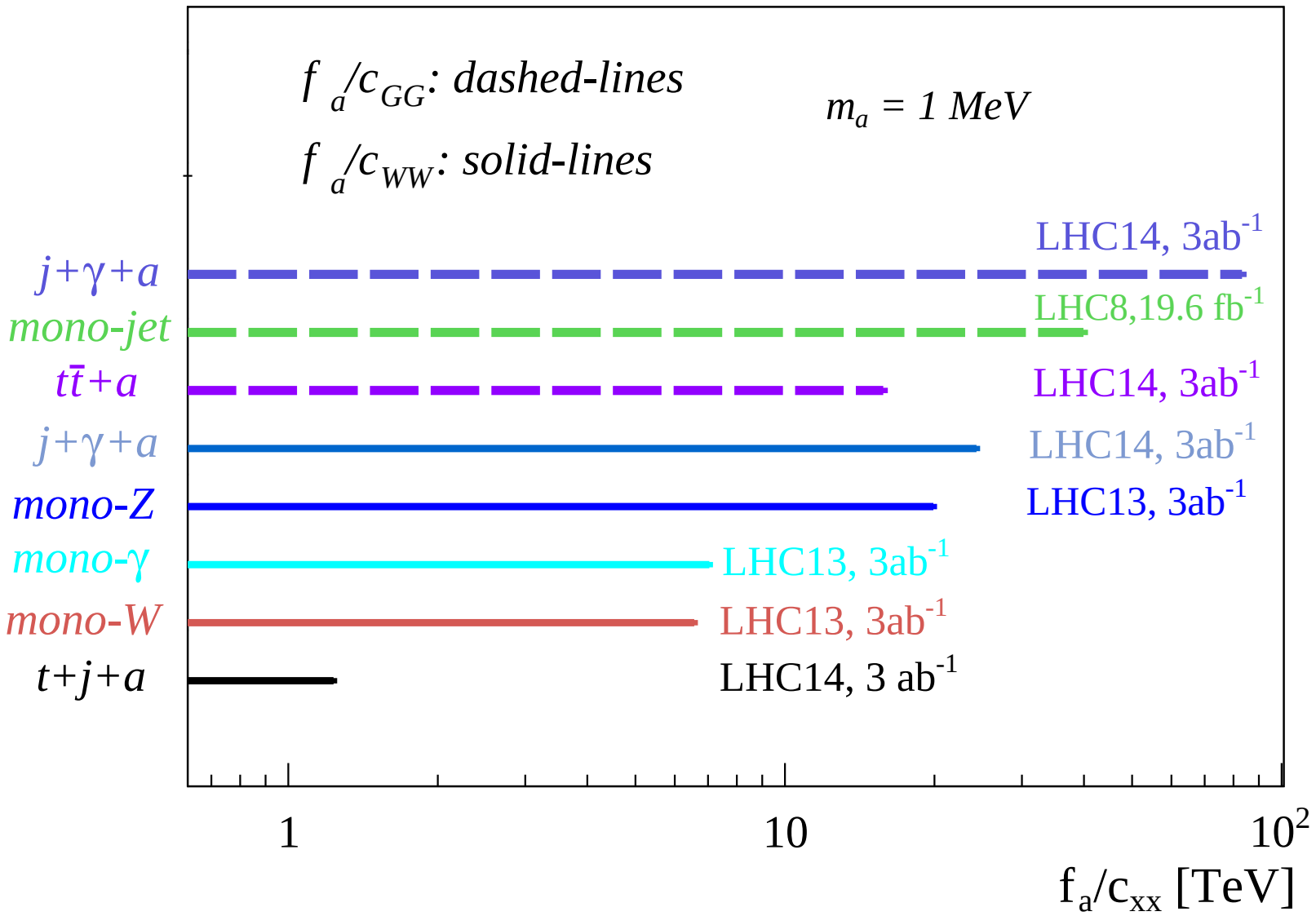
Channel	**# @2.2fb^{-1}**
$t\bar{t}$	24.6 ± 2.2
W + jets	6.4 ± 1.6
Z + jets	0.10 ± 0.04
Single t	7.0 ± 2.0
Diboson	1.7 ± 0.4
Background	39.8 ± 3.4



Signal regions	Leptons	Jets	b jets	p_T^{miss}	Other selection
ℓ+jets $t\bar{t} + p_T^{\text{miss}}$	e or μ	≥ 3	≥ 1	≥ 160GeV	$M_T > 160$GeV and $M_{T2}^W > 200$GeV $min\Delta\phi(p_T^{\text{jet}_i}, p_T^{\text{miss}}) > 1.2$rad

Bound on gluon-ALP coupling (c_{gg}/f_a)

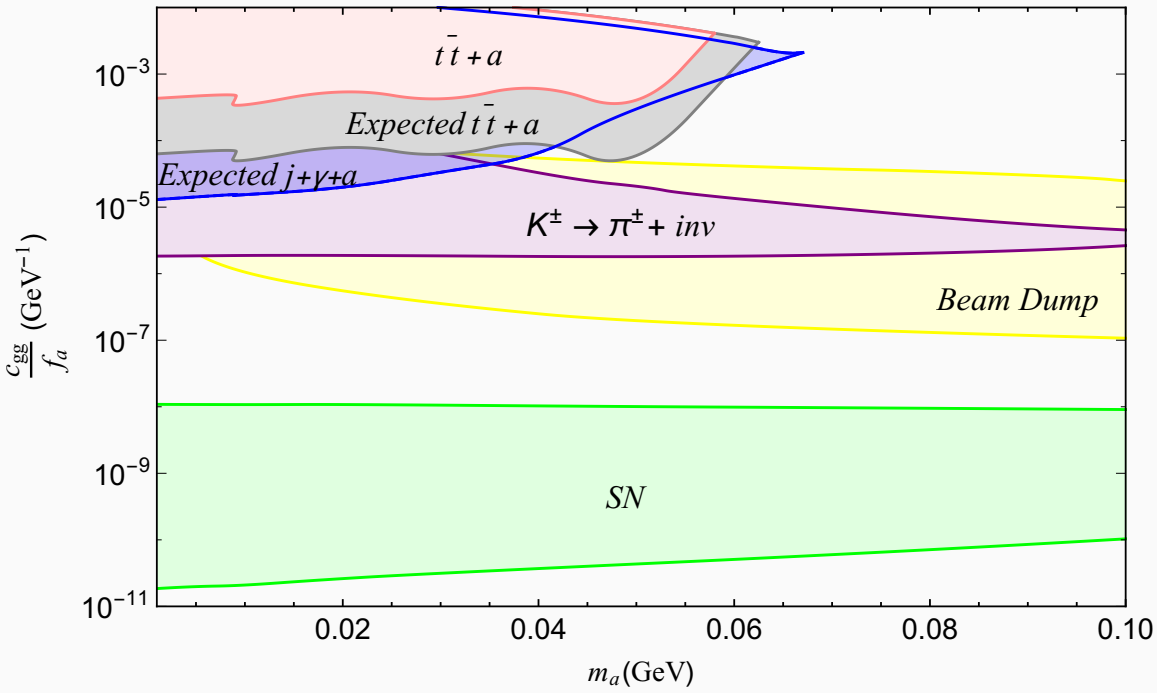
Prospect of bounds for low mass ALP at the LHC



Decay rate of ALP and Bounds on gluon-ALP coupling (c_{gg}/f_a)

ALP decay rate

- pQCD ($m_a > 2$GeV) and ChPT ($m_a < 0.5$GeV)
- $\frac{\Gamma_{a\to gg}(m_a=2\,\mathrm{GeV})}{\Gamma_{a\to 3\pi}(m_a=0.5\,\mathrm{GeV})} \approx \mathcal{O}(10^5)$!
  [D. Aloni et al.,CERN-TH-2018-237, 2018, hep-ph/1811.03474.]



Summary and Conclusions

Summary

- Axions and ALPs are well motivated particles.
- Searching for ALPs in colliders is a complementary for low energy searches
- Light ALPs at the LHC would appear as a missing energy in detectors
- We found bounds and expected bounds for ALP using $t\bar{t} + a$ and single top $+$ a channel
- The jet $+$ photon $+$ a is a promising channel to constrain c_{GG} and c_{WW} couplings

Thank you for your attention

Backup

Strong CP Problem (Quantum Filed Theory)

- The QCD Lagrangian (with one flavor of massless quarks):

$$\mathcal{L} = \int d^4x \Big[-\frac{1}{4} G^a_{\mu\nu} G^{\mu\nu}_a + \bar{\psi}(i\gamma^\mu D_\mu - m_j)\psi - \frac{g^2 \theta_{\text{QCD}}}{32\pi^2} G^{\mu\nu}_a \tilde{G}^a_{\mu\nu} \Big]$$

$$G^{\mu\nu}_a \tilde{G}^a_{\mu\nu} \equiv \frac{1}{2} \epsilon_{\mu\nu\alpha\beta} G^{\mu\nu}_a G^{\alpha\beta}_a$$

- Neutron EDM (QCD, Chiral Perturbation Theory):

$$d_N = 3.2 \times 10^{-26} \theta_{\text{QCD}} \text{e.cm}$$

- Neutron EDM (QCD + EW):

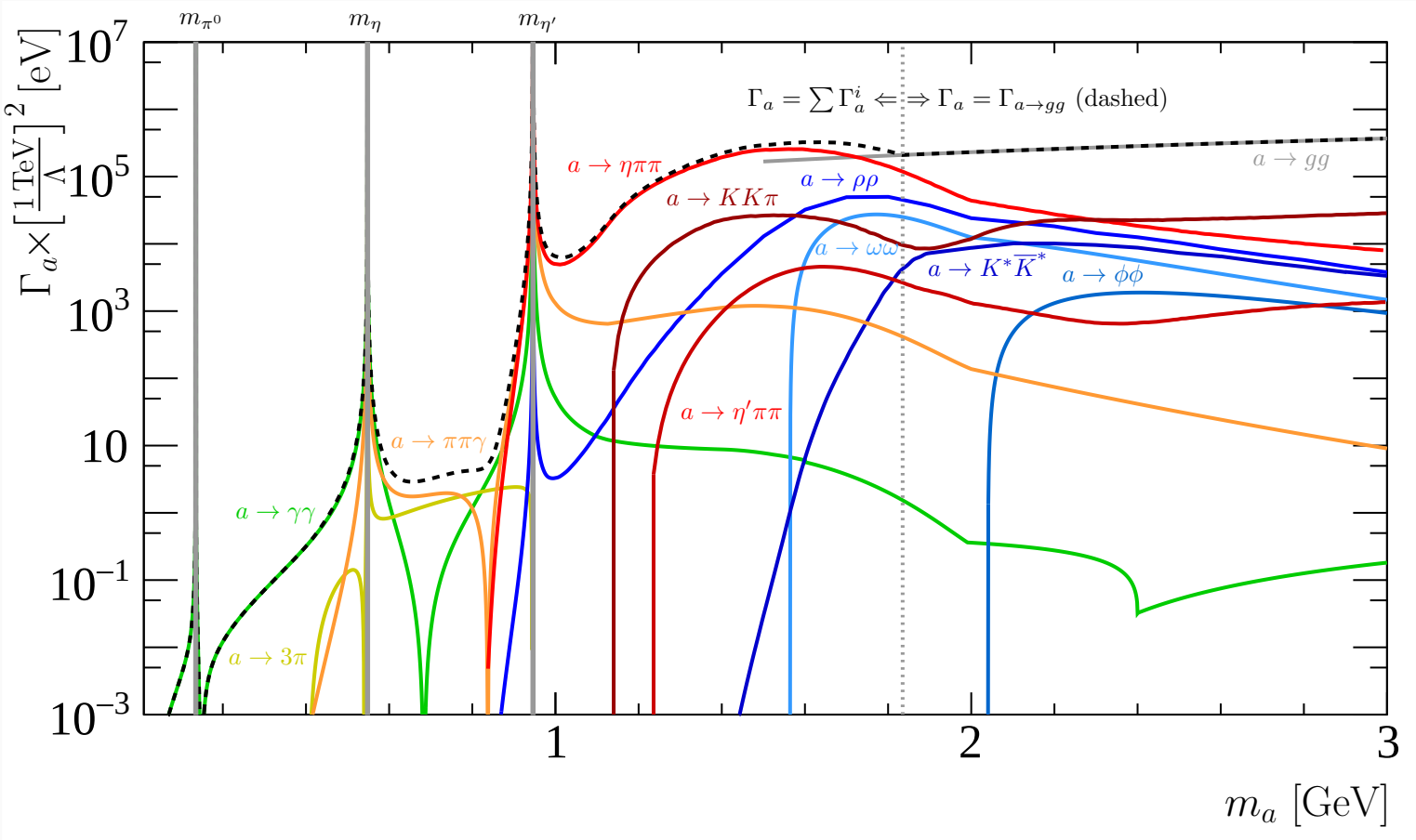
$$d_N = 3.2 \times 10^{-26} (\theta_{\text{QCD}} + \det[M_u M_d]) \text{e.cm}$$

- If CP is a symmetry of the Nature: $\theta_{\text{QCD}} + \det[M_u M_d] = 0$ but, CP is not a symmetry of the Nature.

The Strong CP problem

$$\theta = \theta_{\text{QCD}} + \det[M_u M_d] < 10^{-10}$$

ALP decay rate



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