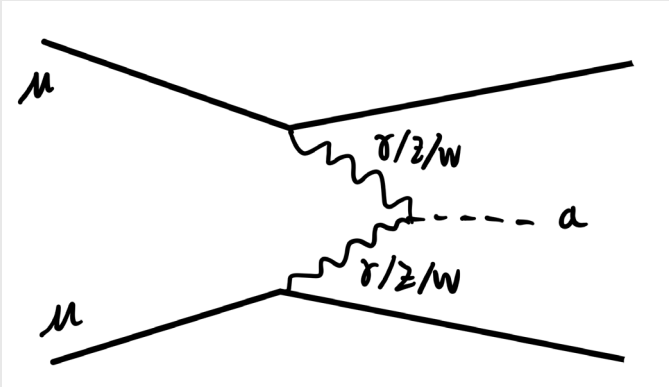
Heavy QCD Axion at Muon Collider



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Collaboration with Ravneet Bedi, Tony Gherghetta,
Soubhik Kumar, Zhen Liu

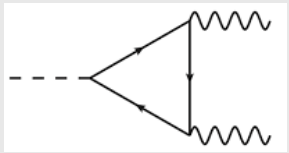
Outline

- How a heavy axion can solve strong-CP problem

- How such heavy axion can be measured at muon collider

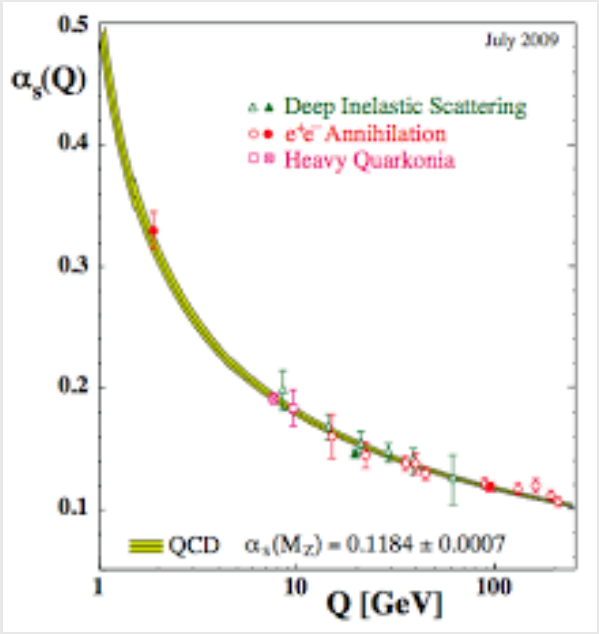
Motivation of heavy QCD axion

- Solving strong-CP problem
  - $\frac{g_3^2}{32\pi^2}\theta G\tilde{G}$ where $\theta \in [0,2\pi)$
  - Experimental measured value $\theta < 10^{-10}$

- $\frac{g_3^2}{32\pi^2}\frac{\phi(x)}{f_a}G\tilde{G}$ 
- $V(\phi) = \Lambda_{QCD}^4\left(1-\cos(\theta+\frac{\phi(x)}{f_a})\right) \rightarrow \delta\phi = a(x) \rightarrow m_a \sim \frac{\Lambda_{QCD}^2}{f_a}$

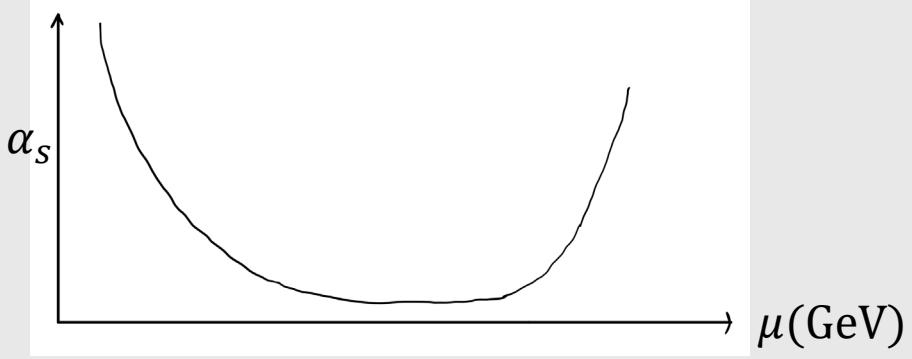
Motivation of heavy QCD axion

- Mirror model:
  - Introduce a full copy of SM sector
  - But the mirror sector has a different vev of Higgs $v_{mirror} \gg v_{SM}$
  - All masses in the mirror sector are heavier
  - The running coupling of mirror-sector QCD will be modified → $\Lambda_{QCD}^{mirror} \gg \Lambda_{QCD}$
  - $m_a \sim \frac{\left(\Lambda_{QCD}^{mirror}\right)^2 + \Lambda_{QCD}^2}{f_a}$



Motivation of heavy QCD axion

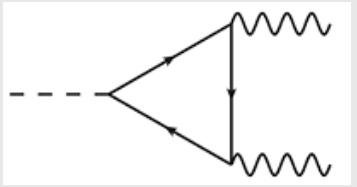
- Extra-dim axion model (4+1d)
  - 5D action: $S \supset -\int_0^L \mathrm{d}y \int \mathrm{d}^4x \left\{ \frac{1}{2g_5^2}\mathrm{tr}\left[G_{MN}G^{MN}\right] + \frac{1}{4g_5^2}F_{MN}F^{MN} - \frac{b_{\mathrm{CS}}}{32\pi^2}\epsilon^{MNRST}B_M \mathrm{tr}[G_{NR}G_{ST}] \right\}$
  - 4D effective Lagrangian : $\mathcal{L} \supset -\frac{1}{2}\mathrm{tr}\left[G_{\mu\nu}G^{\mu\nu}\right] + \frac{1}{2}(\partial_\mu a)^2 + \frac{b_{\mathrm{CS}}Lg_s^3}{32\pi^2} a\,\mathrm{tr}\,G_{\mu\nu}\tilde{G}^{\mu\nu} - \frac{1}{4}F^{\mu\nu}F_{\mu\nu}$
  - $a(x) = \frac{B_5(x)}{g_5/\sqrt{L}}$, seems like: $m_a \sim \frac{\Lambda_{QCD}^2}{f_a}$ still small
  - But, there are small instanton effect from UV scale make the m_a larger again. 2001.05610



Effective coupling of Axion

$$\mathcal{L} \supset c_3 \frac{\alpha_s}{8\pi f_a} aG\tilde{G} + c_2 \frac{\alpha_2}{8\pi f_a} aW\tilde{W} + c_1 \frac{\alpha_1}{8\pi f_a} aB\tilde{B}$$

with $c_3 \sim c_2 \sim c_1 \sim 1$



$\frac{\alpha_s}{8\pi} = 0.0046951, \frac{\alpha_1}{8\pi} = 0.0004058, \frac{\alpha_2}{8\pi} = 0.00135$

Axion mainly couple to gluon.

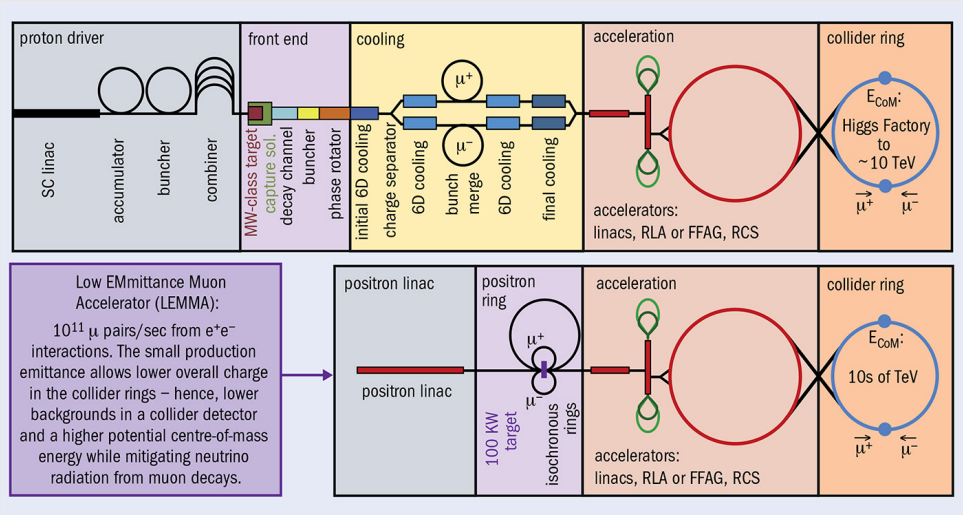
$c_1 = c_2 = c_3 = 1$:

$$Br(a \to gg) \gg Br(a \to WW, ZZ, \gamma\gamma)$$

Why muon collider?

- High energy (3,10 TeV):
  - High mass (low synchrotron radiation)
  - Fundamental particle: full energy collision

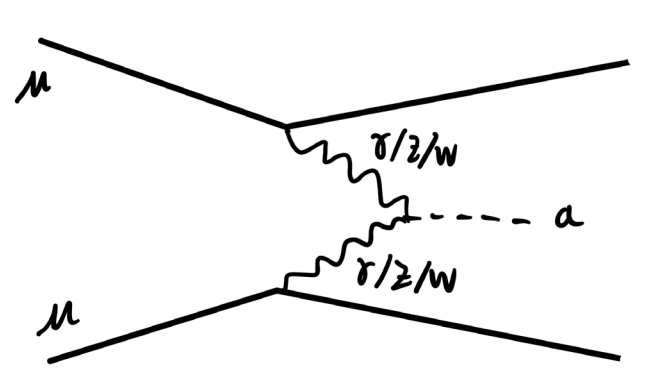
- Clean environment:
  - Known initial state
  - Clean background



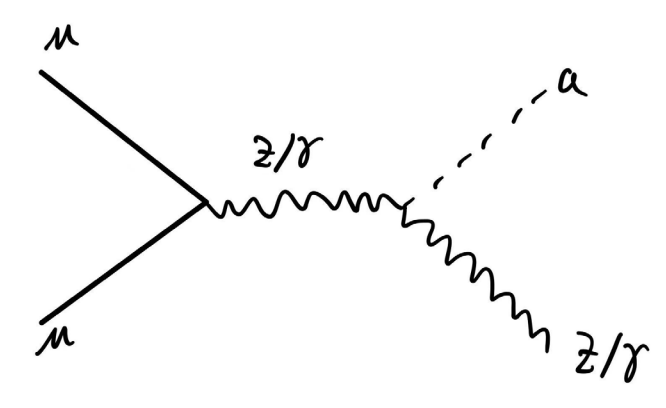
Expect to have great sensitivity.

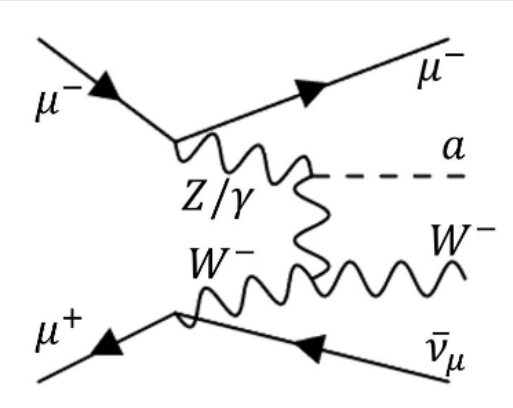
Axion production @ MuC

- Leading channel: VBF production

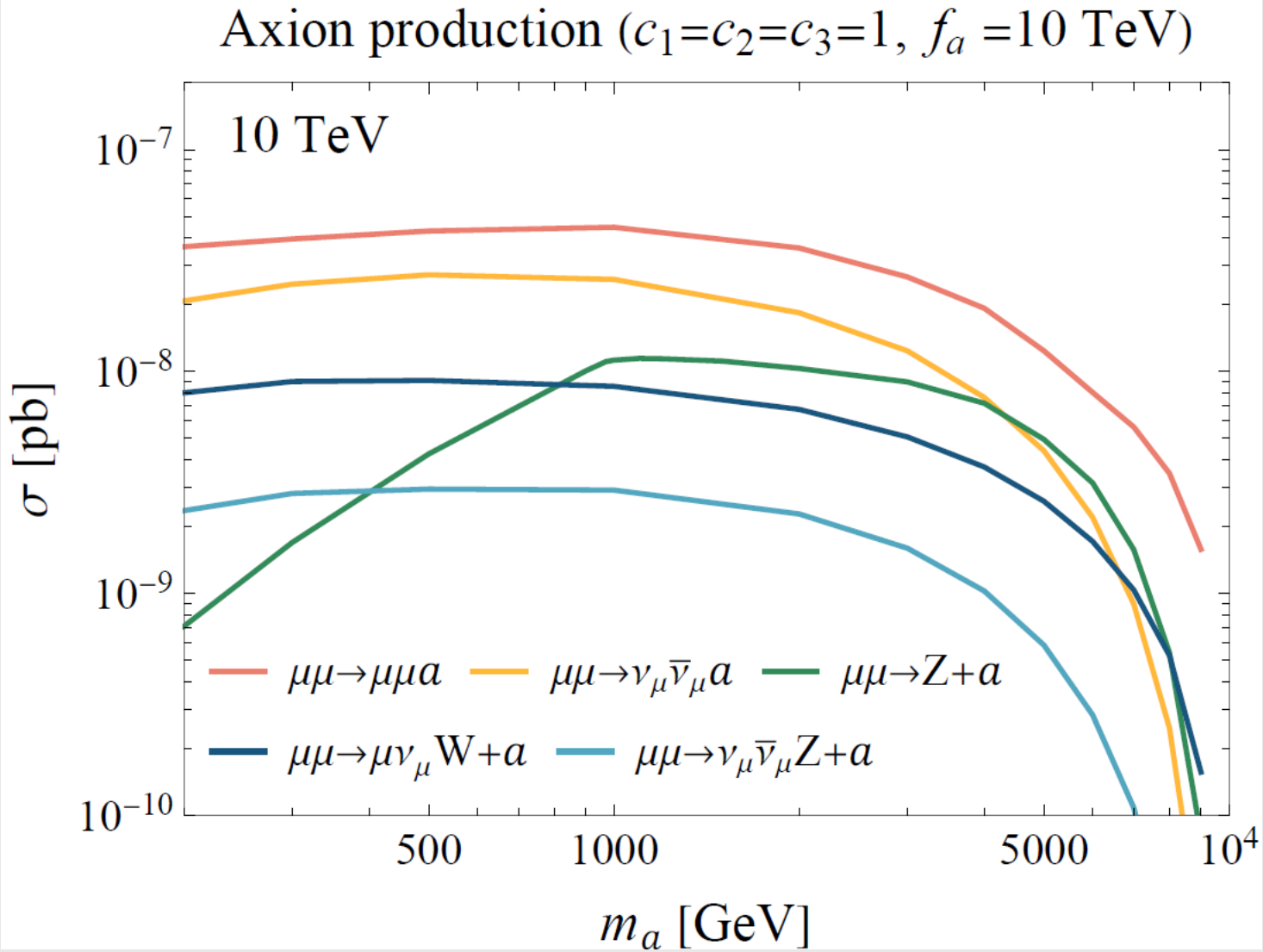


- Subleading channel: associated production and VBS production



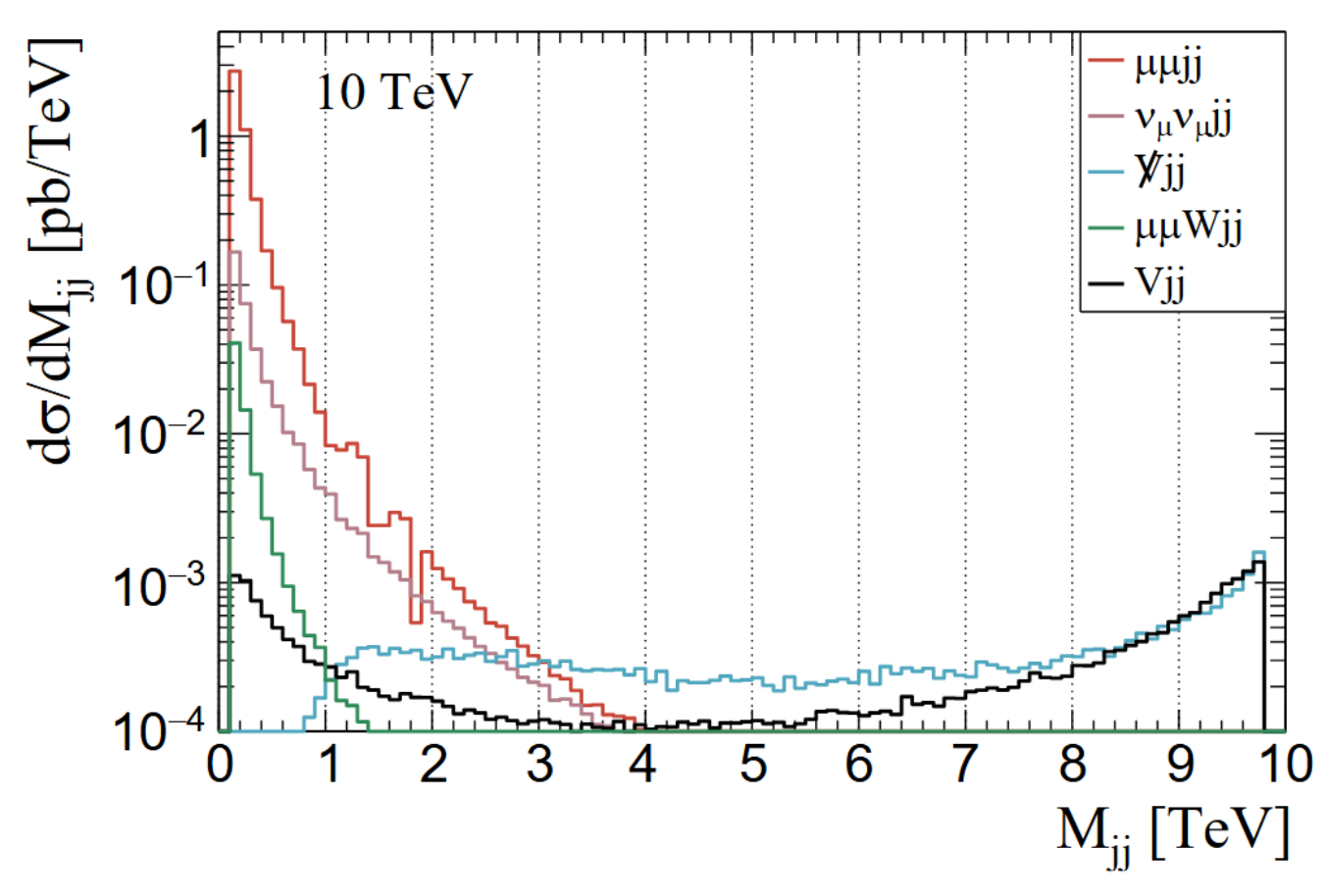


Axion production @ 10 TeV MuC

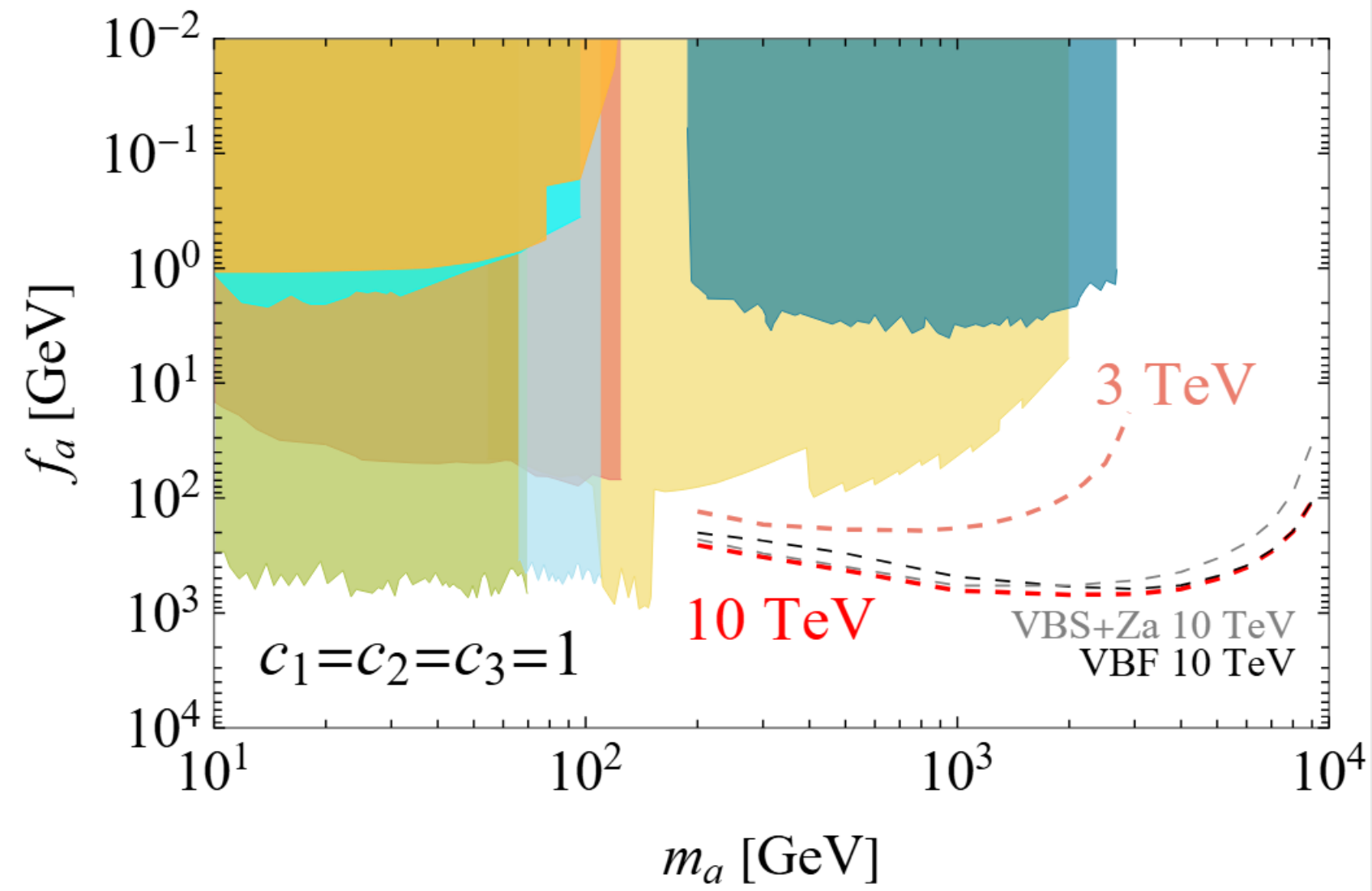


$|\eta(g)| < 2.5, p_T(g) > 10\ \text{GeV}, \Delta R(gg) > 0.4$

Background


10 TeV
μμjj
$\nu_\mu\nu_\mu$jj
$\not{V}$jj
μμWjj
Vjj
$d\sigma/dM_{jj}$ [pb/TeV]
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0 1 2 3 4 5 6 7 8 9 10
M_{jj} [TeV]

Axion search @ MuC



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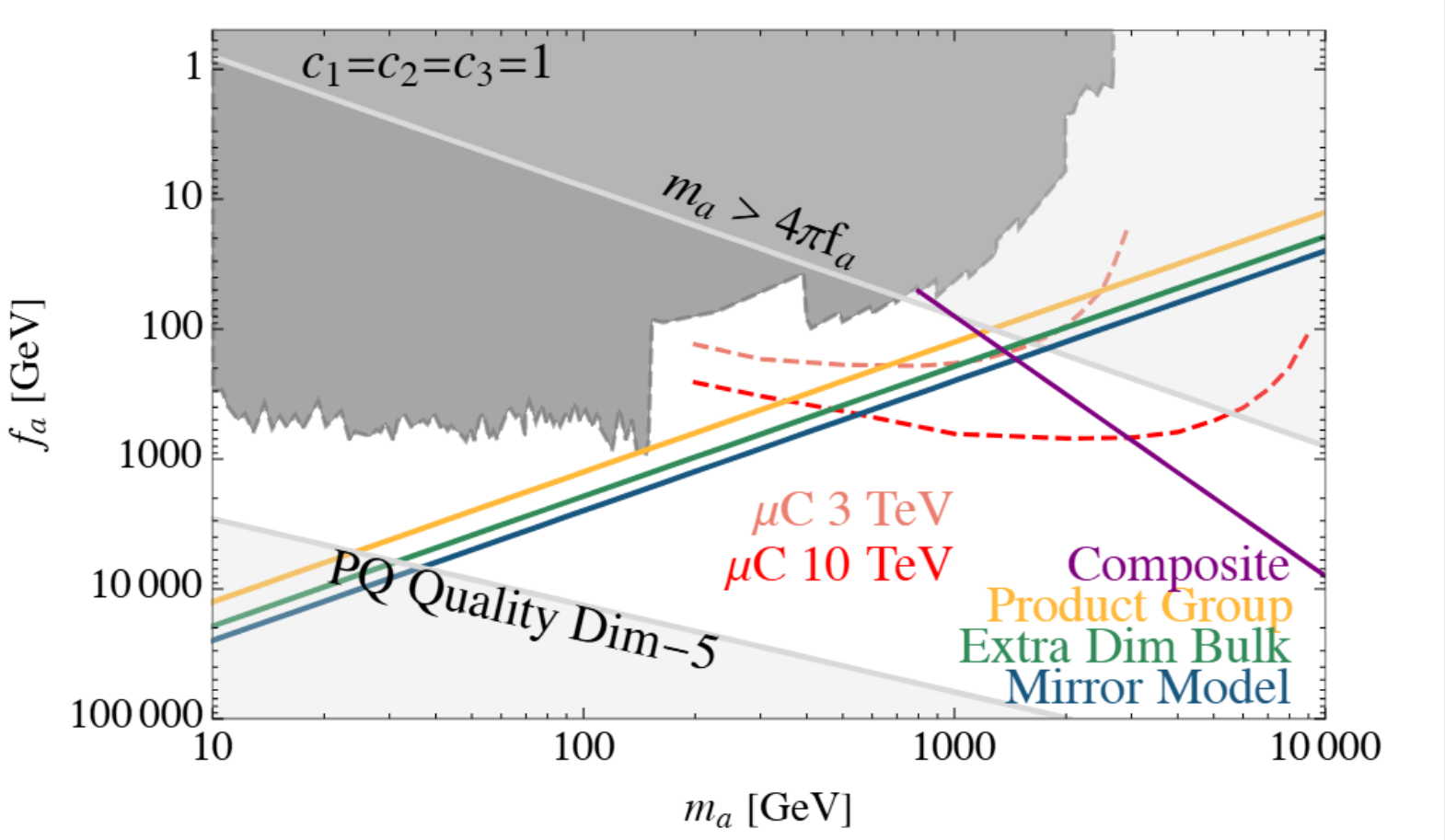
Conclusion

- Heavy QCD axion models can be motivated by strong-CP problem.
- TeV axion can be well explored at MuC with a huge parameter space.

Backup


$c_1=c_2=c_3=1$
$m_a > 4\pi f_a$
μC 3 TeV
μC 10 TeV
PQ Quality Dim−5
Composite
Product Group
Extra Dim Bulk
Mirror Model
f_a [GeV]
m_a [GeV]
1
10
100
1000
10 000
100 000
10
100
1000
10 000

QCD running coupling

$$\frac{1}{g^2} = \frac{1}{g_0^2} - \frac{1}{16\pi^2}\left(\frac{11\,N}{3} - \frac{2}{3}n_f - \frac{1}{6}n_s\right)\log\left(\frac{M_0^2}{\mu^2}\right)$$