

Electroweak ALP Searches at a Muon Collider

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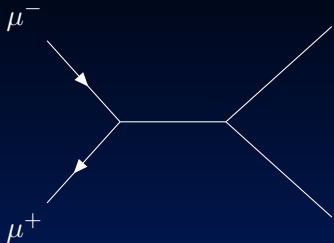
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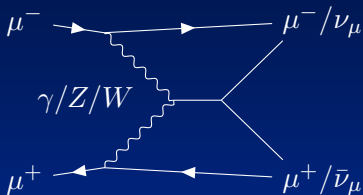
Why Muon Collider?

- Hadron colliders
 - HL-LHC
 - FCC-hh
 - SPPC
 - ...
- Circular e^+e^- colliders
 - CEPC
 - FCC-ee
 - ...
- Linear e^+e^- colliders
 - ILC
 - CLIC
 - ...
- Large hadronic background
- Complicated partonic content
- Large synchrotron radiation
- Bunch wasted after the first crossing (low luminosity)

Muon Collider = $\mu^+ \mu^-$ Collider + Vector Boson Collider



$$\sigma \sim \frac{1}{s},$$



$$\sigma \sim \frac{1}{\Lambda^2} \ln^n \left(\frac{s}{\Lambda^2} \right).$$

[Ali et al., 2103.14043], [Han et al., 2007.14300], [Ruiz et al., 2111.02442], ...

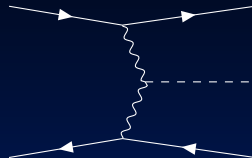
Axion-like Particle (ALP) Effective Lagrangian

$$\begin{aligned}\mathcal{L}_{\text{ALP}} = & \frac{1}{2}(\partial a)^2 - \frac{1}{2}m_a^2 a^2 + \left(\frac{g_1}{4\pi}\right)^2 \frac{C_{BB}}{f_a} a B_{\mu\nu} \widetilde{B}^{\mu\nu} \\ & + \left(\frac{g_2}{4\pi}\right)^2 \frac{C_{WW}}{f_a} a W_{\mu\nu}^i \widetilde{W}^{i;\mu\nu} \\ & + \left(\frac{g_1}{4\pi}\right) \left(\frac{g_2}{4\pi}\right) \frac{C_{BW}}{f_a} a B_{\mu\nu} \widetilde{W}^{3;\mu\nu},\end{aligned}\tag{1}$$

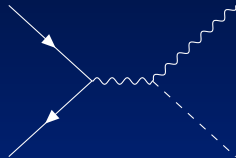
$$m_a \sim \mathcal{O}(1 \text{ TeV}), \quad C_{VV'}/f_a \sim \mathcal{O}(1 \text{ TeV}^{-1}).$$

Production Channels

1. Vector boson fusion (VBF) resonance

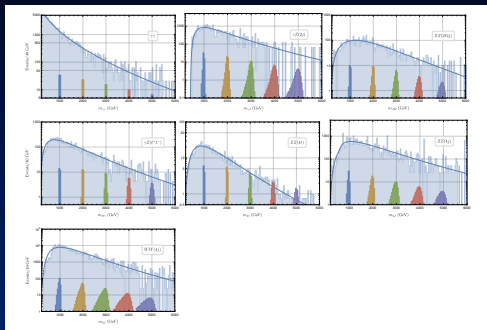


2. Associated production (Va)

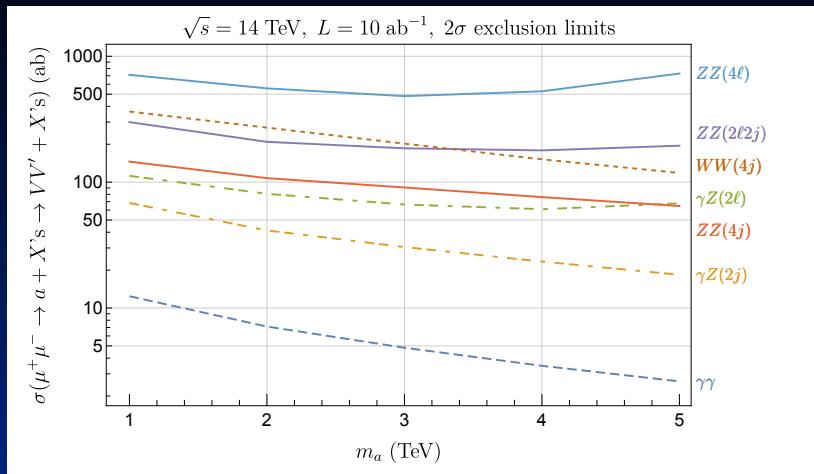


Detection Channels

1. $a \rightarrow \gamma\gamma$
2. $a \rightarrow \gamma Z$
 - $a \rightarrow \gamma Z(2\ell)$
 - $a \rightarrow \gamma Z(2j)$
3. $a \rightarrow ZZ$
 - $a \rightarrow ZZ(4\ell)$
 - $a \rightarrow ZZ(2\ell 2j)$
 - $a \rightarrow ZZ(4j)$
4. $a \rightarrow W^+W^-$
 - $a \rightarrow W^+W^-(4j)$

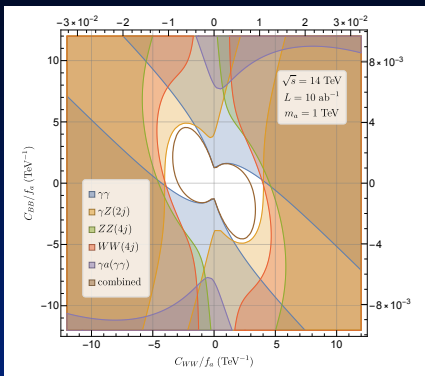


VBF Resonance Exclusion Reach

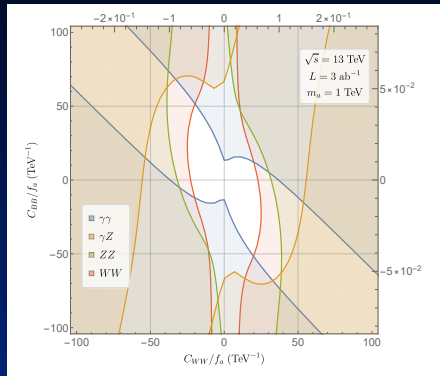


Constraints on Wilson Coefficients

Muon Collider



HL-LHC (reprojected)



Conclusions

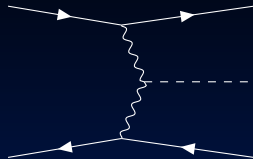
- “Muon collider = $\mu^+\mu^-$ collider + VV' collider”;
- All detection channels jointly constrain the parameter space;
- “Muon collider > HL-LHC” .

⇒ Exciting possibilities
at muon collider

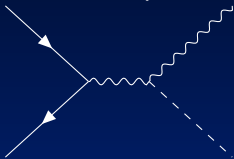
Thank you.

Production Channels

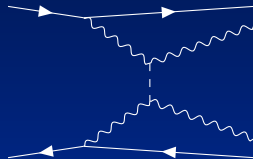
1. Vector boson fusion (VBF) resonance !!



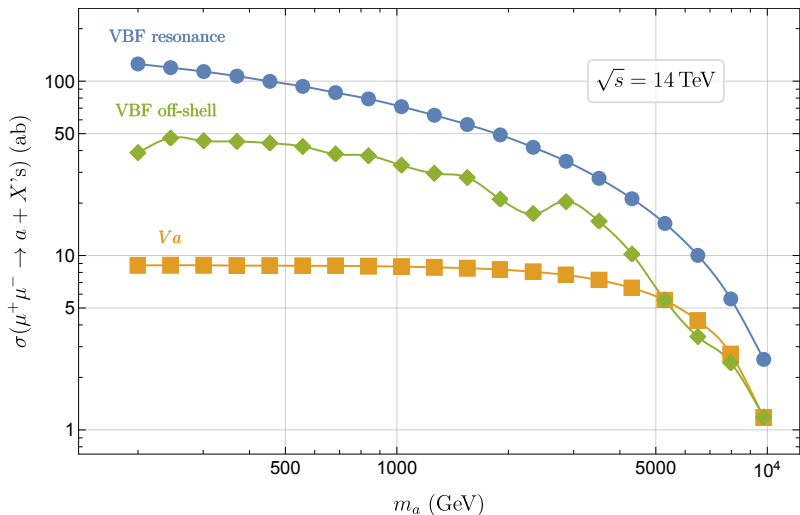
2. Associated production (also called, ALP-strahlung) !



3. VBF off-shell (indirect) production



Production Cross Sections



$$C_{WW}/f_a = C_{BB}/f_a = 1 \text{ TeV}^{-1}$$

Model Independence

12 sets of Wilson coefficients

Percentage variations of exclusion reaches are small.

m_a (TeV)	$\gamma\gamma$	$\gamma Z(2\ell)$	$\gamma Z(2j)$	$ZZ(4\ell)$
1	5	10.5	16.4	11
2	1.7	10.7	4.7	10.3
3	1.3	12.4	1.4	11.5
4	1	12.7	1.8	13.3
5	1.3	14.5	2.7	13.3
m_a (TeV)	$ZZ(2\ell 2j)$	$ZZ(4j)$	$WW(4j)$	
1	12.8	3.2	5.5	
2	11.6	2.1	4.1	
3	10.8	2.4	2.3	
4	12.5	2.3	3.3	
5	14.7	2.7	1.2	

Other Energy and Luminosity Benchmarks

