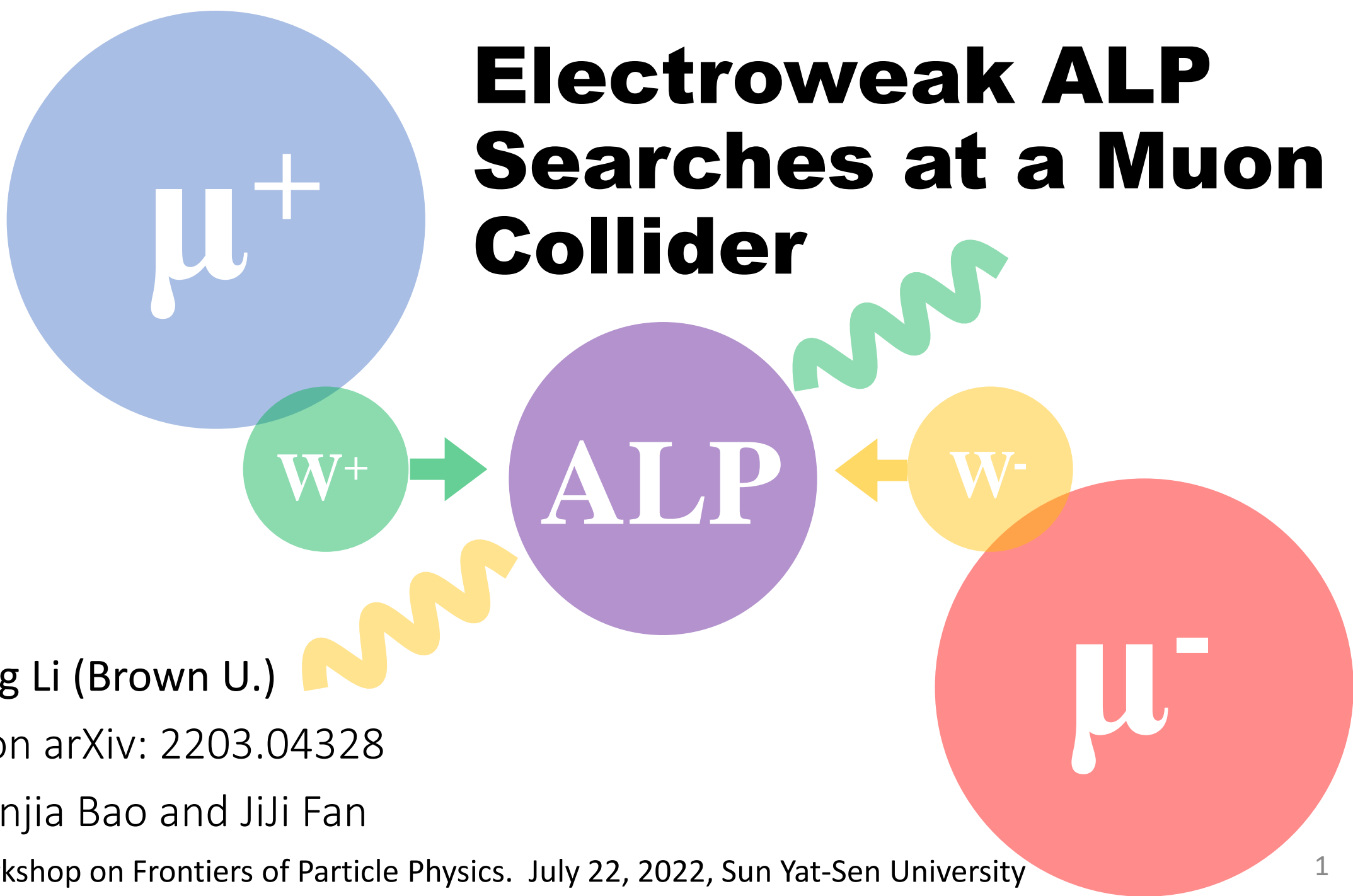


Electroweak ALP Searches at a Muon Collider

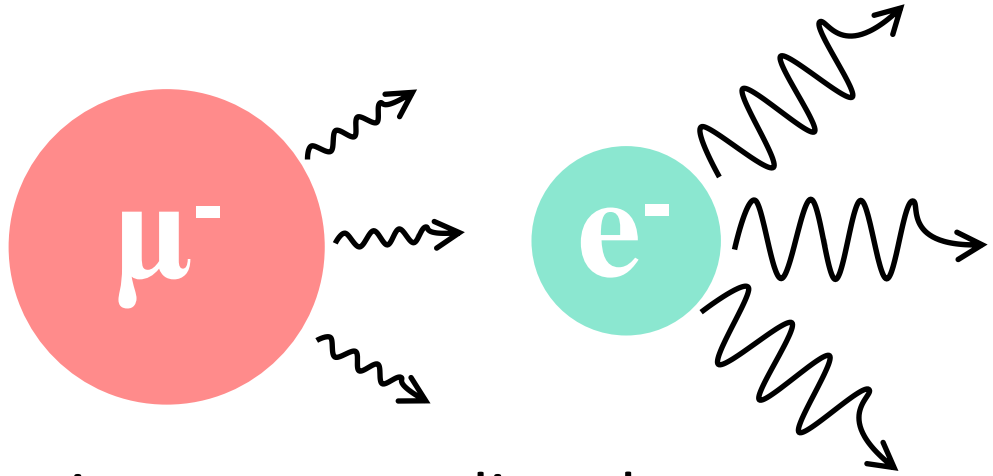


Lingfeng Li (Brown U.)

Based on arXiv: 2203.04328

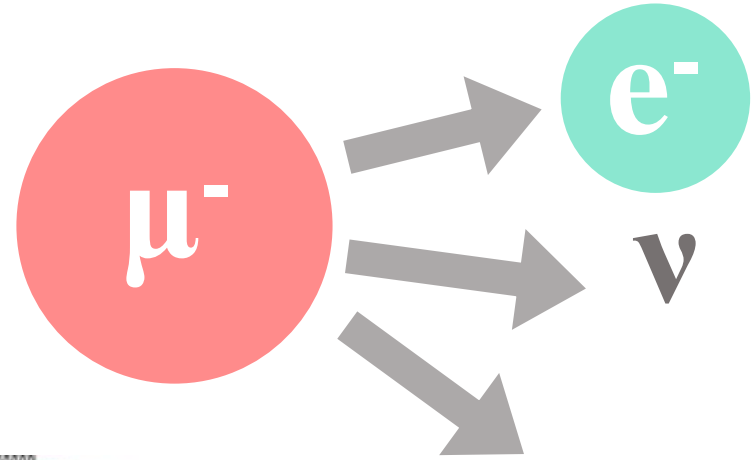
with Yunjia Bao and Jiji Fan

Muon Collider: why & why not yet



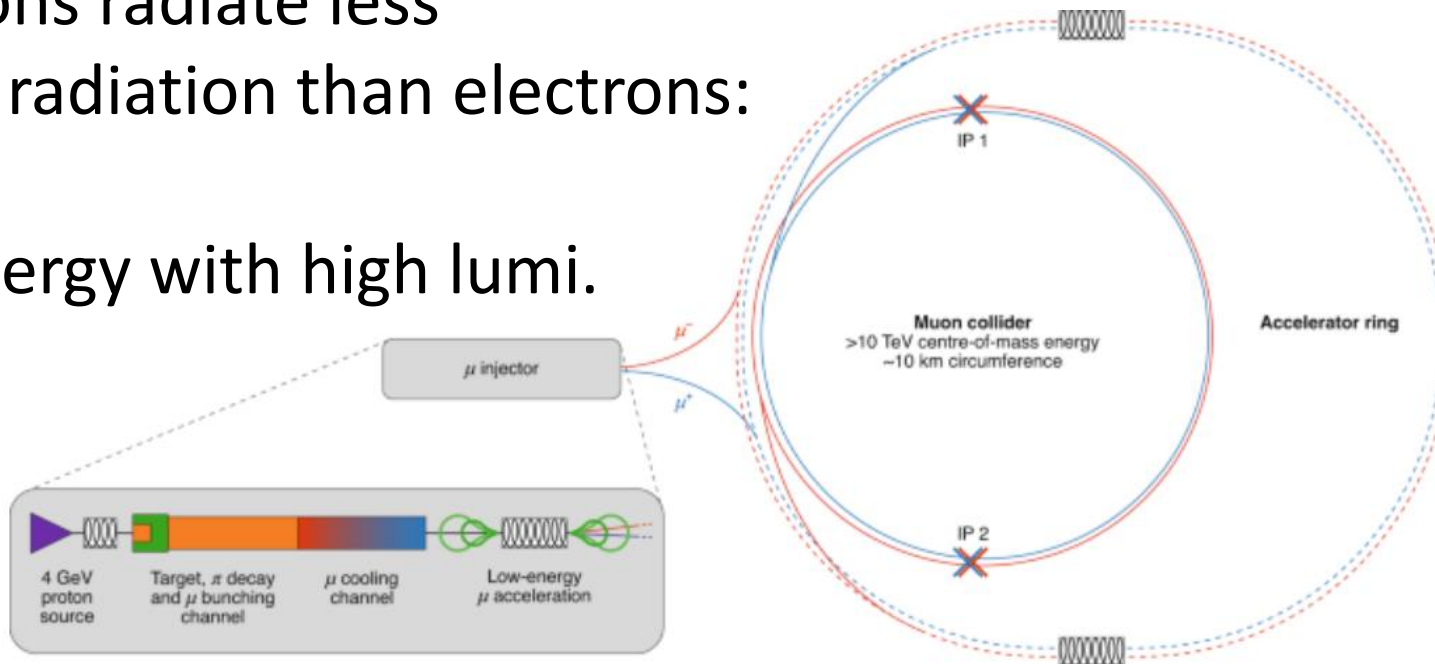
Heavier muons radiate less synchrotron radiation than electrons:

TeV-scale energy with high lumi. possible



Muons DECAY!
Lifetime is 2ms:

Extreme challenges in the design

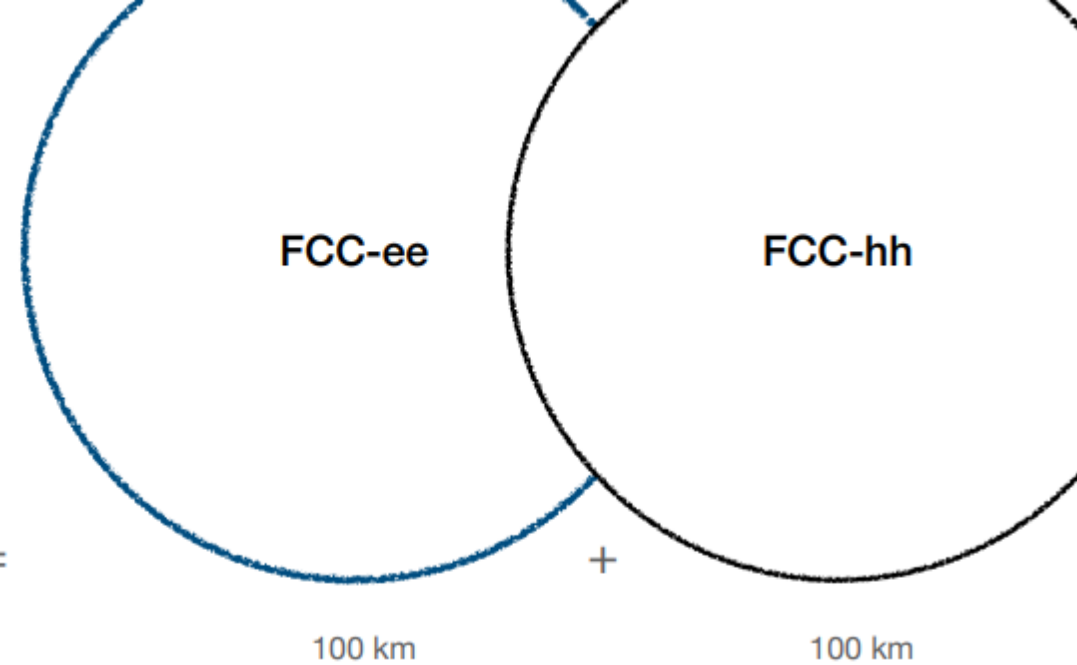


Muon collider physics

The essentials

1) O(10) TeV Energy small two-in-one collider:

MuC
 =
 10 km



X

t

2) Luminosity growing with energy:

5 years



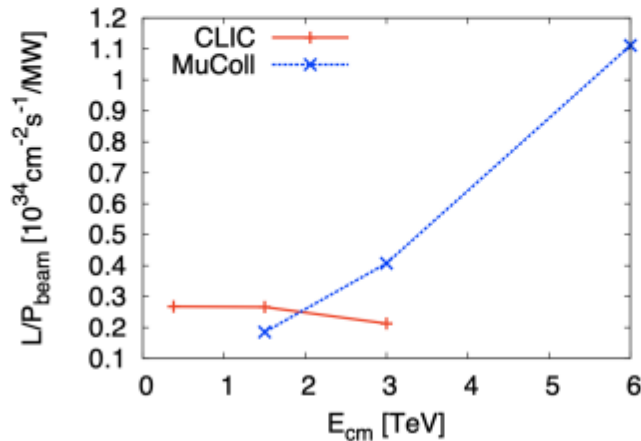
=

15 years



+

25 years



From Fabio Maltoni's talk during the Snowmass EF workshop

⇒ **MuC is an SSTC = Space-Time Compact Collider**

MuC10: 10 TeV, 10 iab, 10 times smaller and 10 times quicker than the FCC

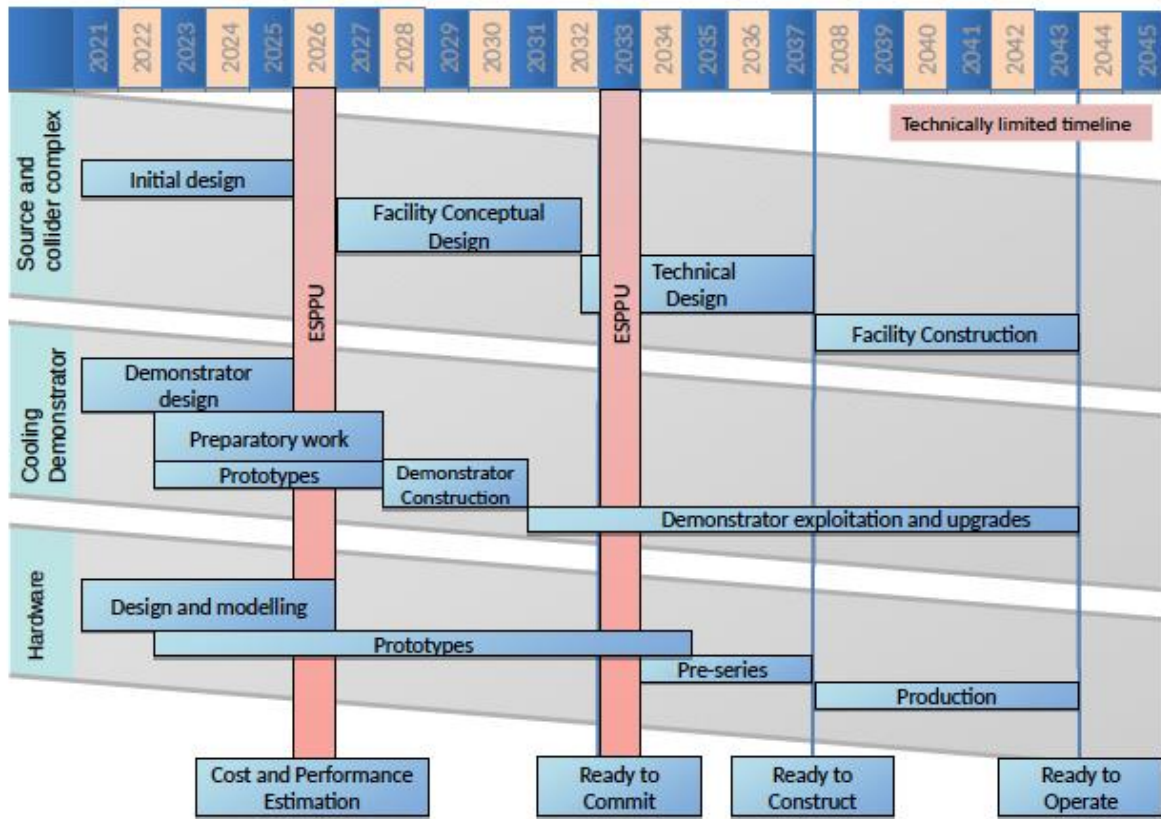


Fig. 5.3: A technically limited timeline for the muon collider R&D programme.

Currently at technology readiness level 2 at most (out of 9 total levels)!

From Mark Palmer's talk during the Snowmass EF workshop

Still futuristic, need very long time and substantial investment for the R&D:

The best candidate for the next-to-next-generation collider?

| Relative Level of Technology Development | Technology Readiness Level | Brief Description |
|--|----------------------------|--|
| Research to prove feasibility | 3 | Analytical and experimental critical function and/or characteristic proof of concept |
| | 2 | Technology concept and/or application formulated |
| Basic technology research | 1 | Basic principles observed and reported |

Axion and ALP

(QCD) axion: a (pseudo) goldstone boson coming from a breaking global (PQ) symmetry at a scale f_a .
Motivated by the strong CP problem.

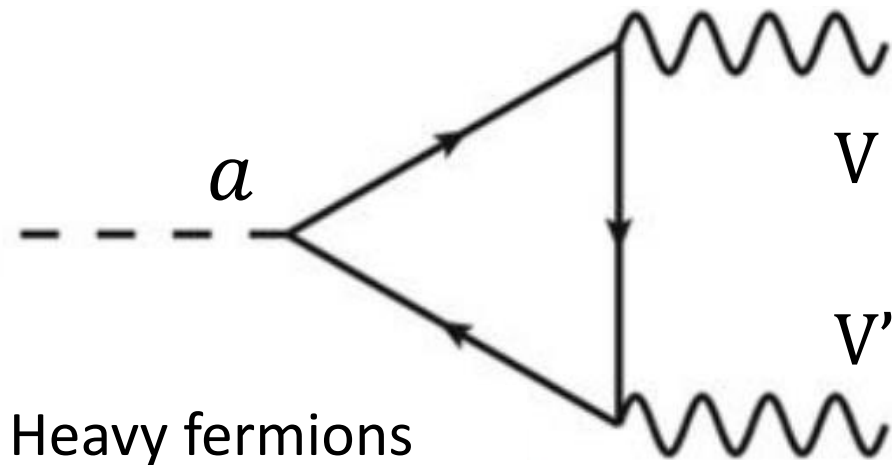
Axion-like-particle (ALP): similar but not directly related to QCD, can show up anywhere.

Heavy electroweak ALP

$$\mathcal{L} = \frac{1}{2} \left[(\partial a)^2 - m_a^2 a^2 \right] + \left(\frac{g_1}{4\pi} \right)^2 C_{BB} \frac{a}{f_a} B_{\mu\nu} \tilde{B}^{\mu\nu} \\ + \left(\frac{g_2}{4\pi} \right)^2 C_{WW} \frac{a}{f_a} W_{\mu\nu}^i \tilde{W}^{i;\mu\nu} + \left(\frac{g_1}{4\pi} \right) \left(\frac{g_2}{4\pi} \right) C_{BW} \frac{a}{f_a} B_{\mu\nu} \tilde{W}^{3;\mu\nu},$$

Similar to Higgs $\rightarrow Z\gamma$, can arise from a dim-7 EFT operator.

$$\left(\frac{g_1}{4\pi} \right) \left(\frac{g_2}{4\pi} \right) C_{BW} \frac{a}{f_a} B_{\mu\nu} \tilde{W}^{3;\mu\nu},$$

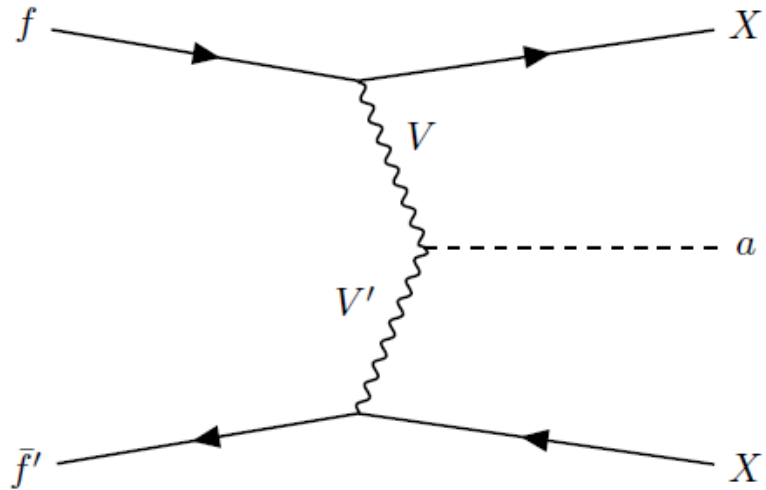


➤ m_a : O(TeV), compatible with the muon collider energy.

➤ $\frac{g_{1,2}^2}{(4\pi)^2}$: The coupling & loop factor

Heavy & Elusive: The Right target for a muon collider!

Primary ALP production rates

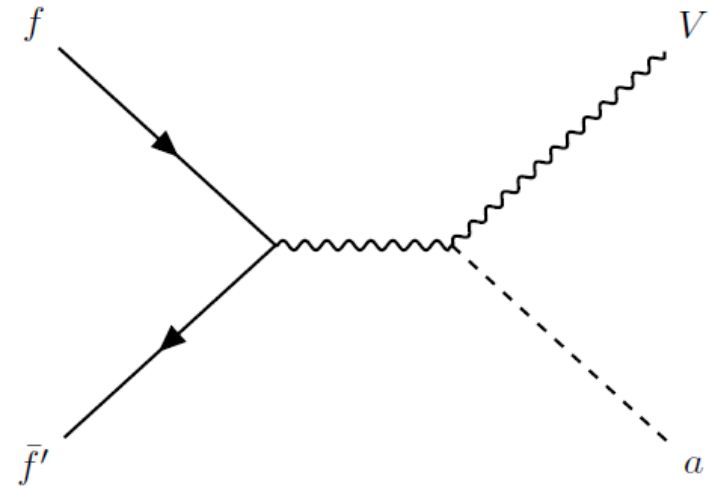


The VBF process:

“Muon collider is also a vector boson collider”

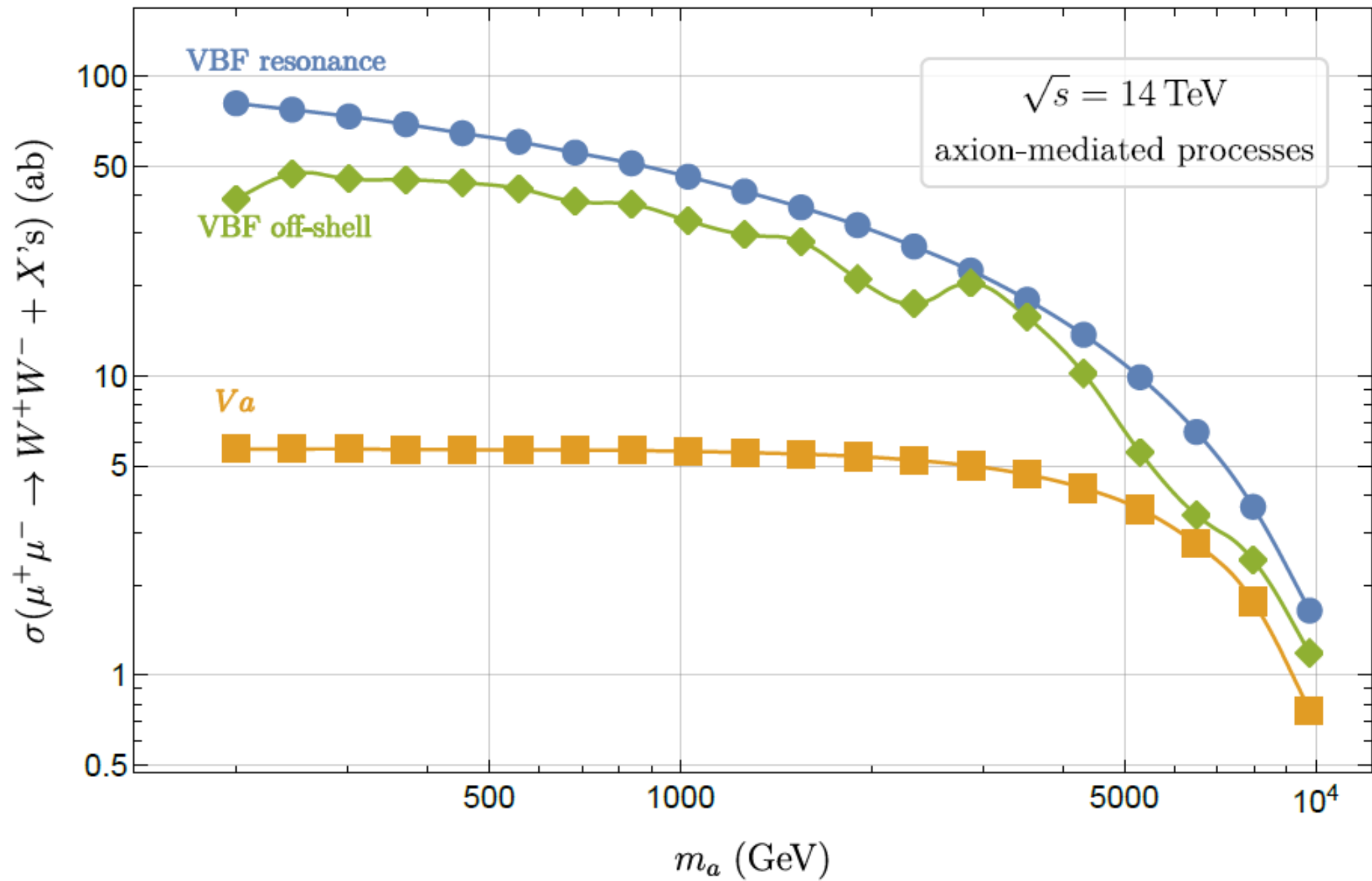
- Large Xsec, grows with \sqrt{s}

[A. Costantini, F. De Lillo, F. Maltoni, L. Mantani, O. Mattelaer, R. Ruiz et al., 2005.10289](#) & [T. Han, Y. Ma and K. Xie, 2007.14300](#)

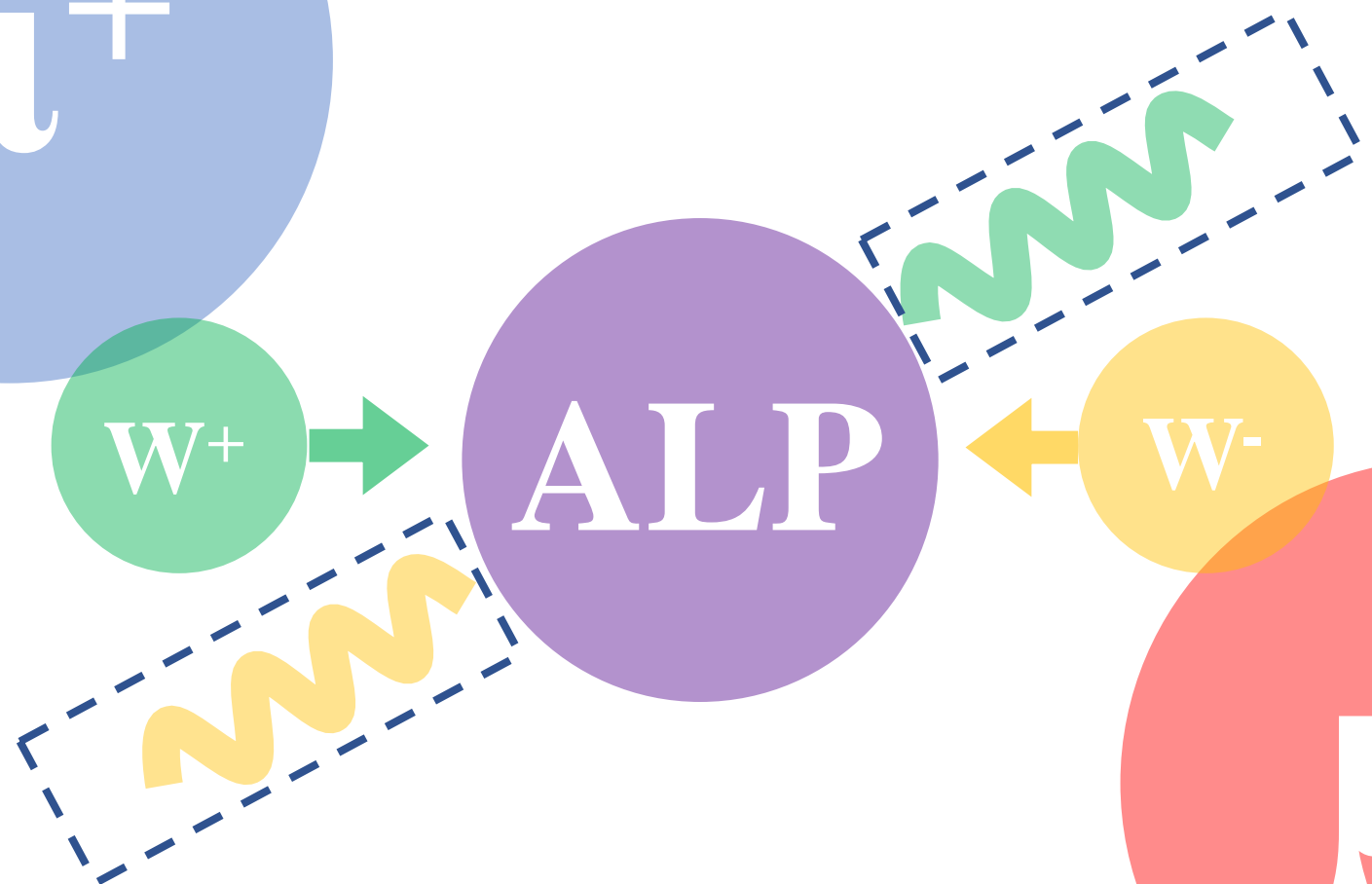
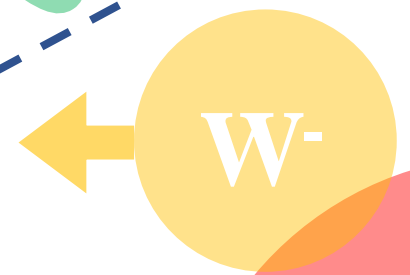
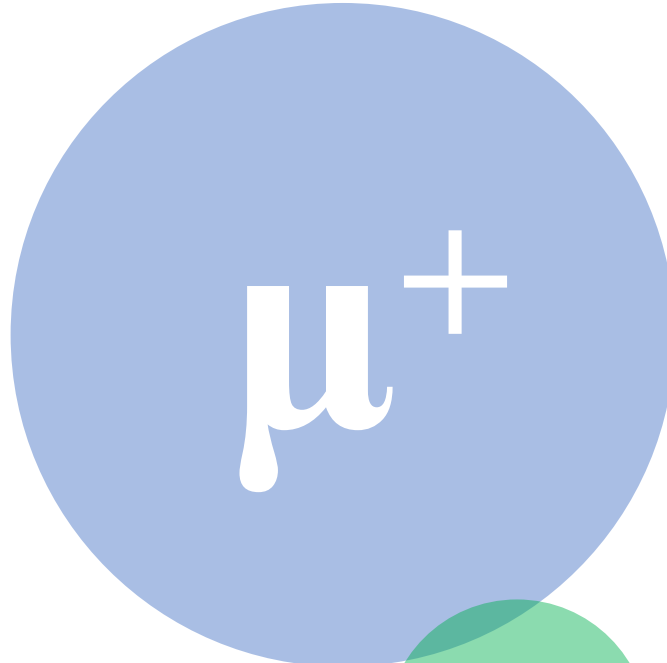


The associated production:

- Xsec drops with \sqrt{s}
- Produces heavy ALP upto $m_a \approx \sqrt{s}$



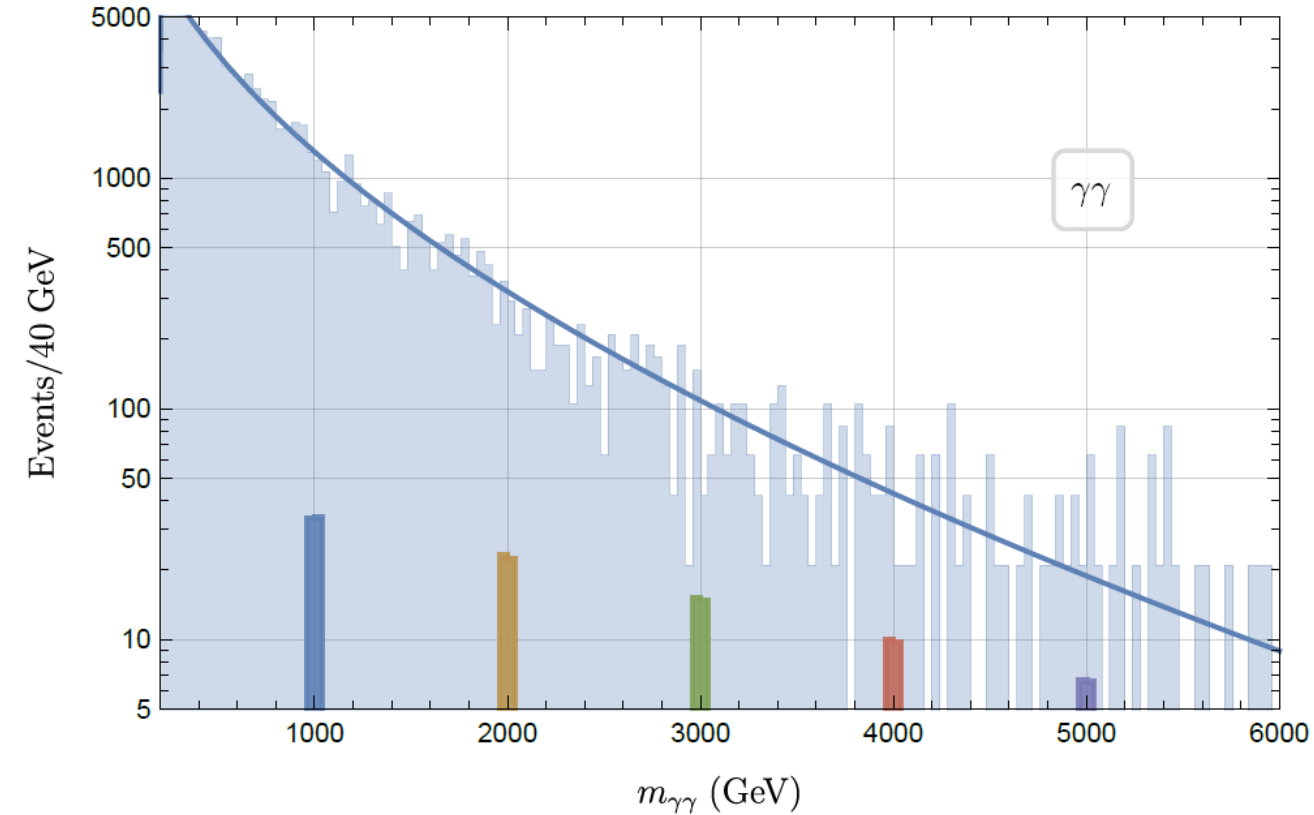
Diboson Resonances



7 channels in total:

- $\gamma\gamma$
- $Z(2\text{ lep})\gamma$
- $Z(2j)\gamma$
- $ZZ(4\text{ lep})$
- $ZZ(2j + 2\text{ lep})$
- $ZZ(4j)$
- $WW(4j)$

VBF Resonance Search

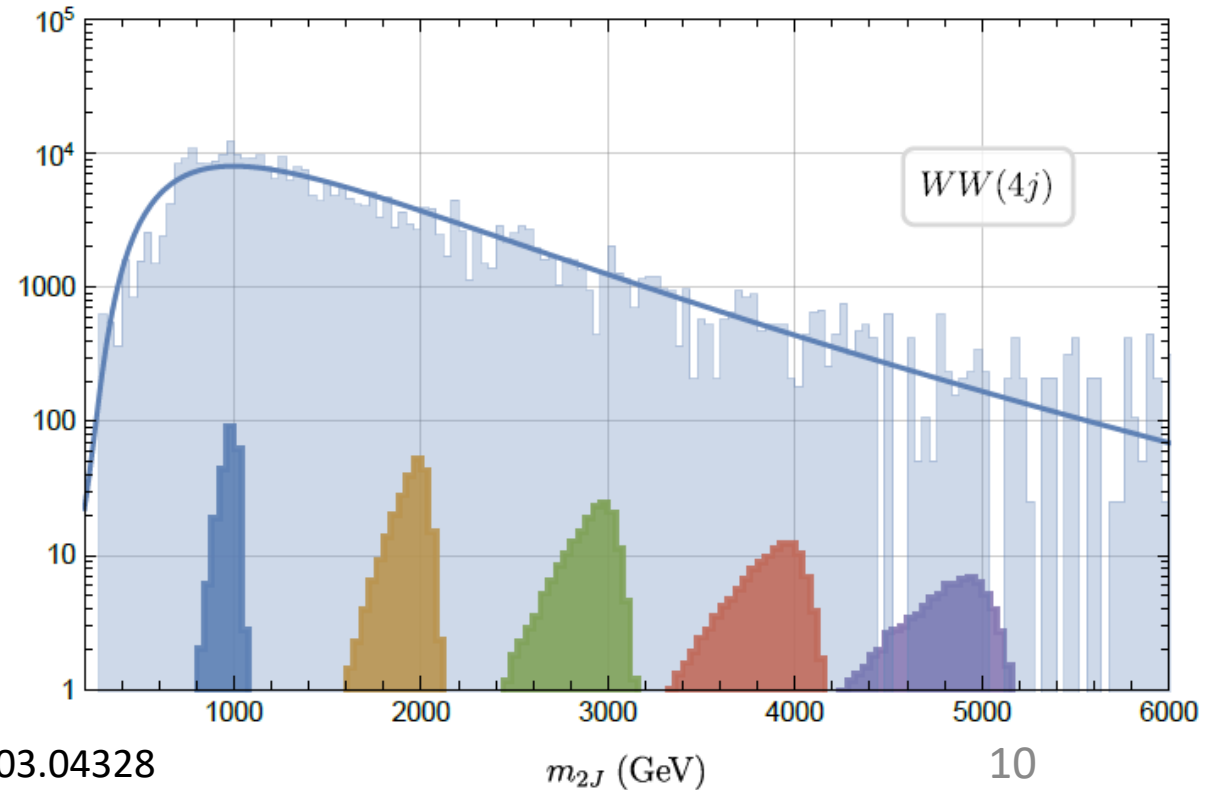


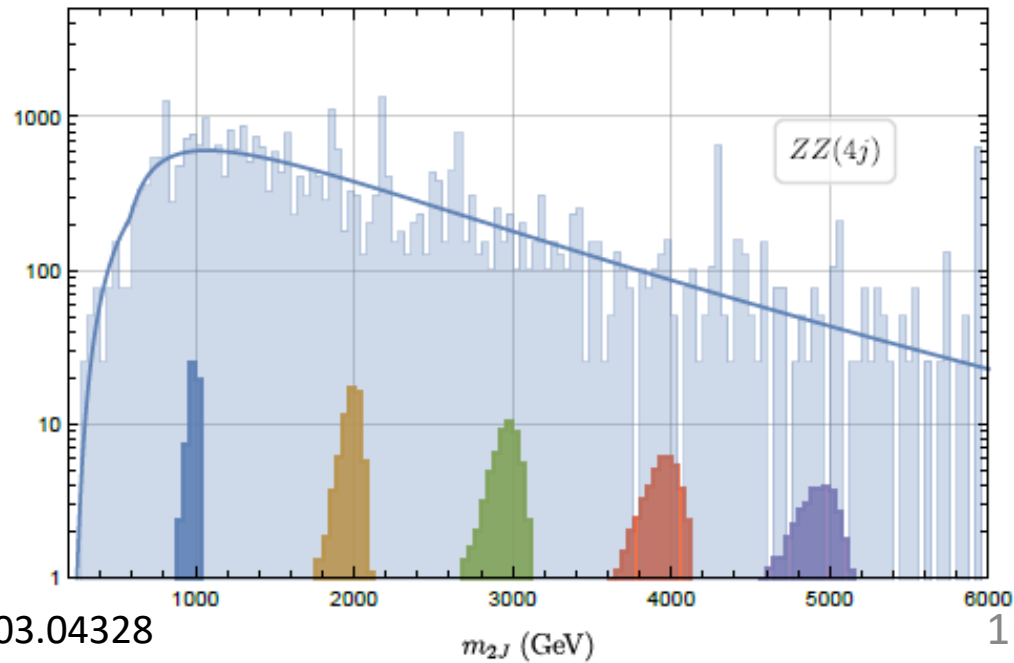
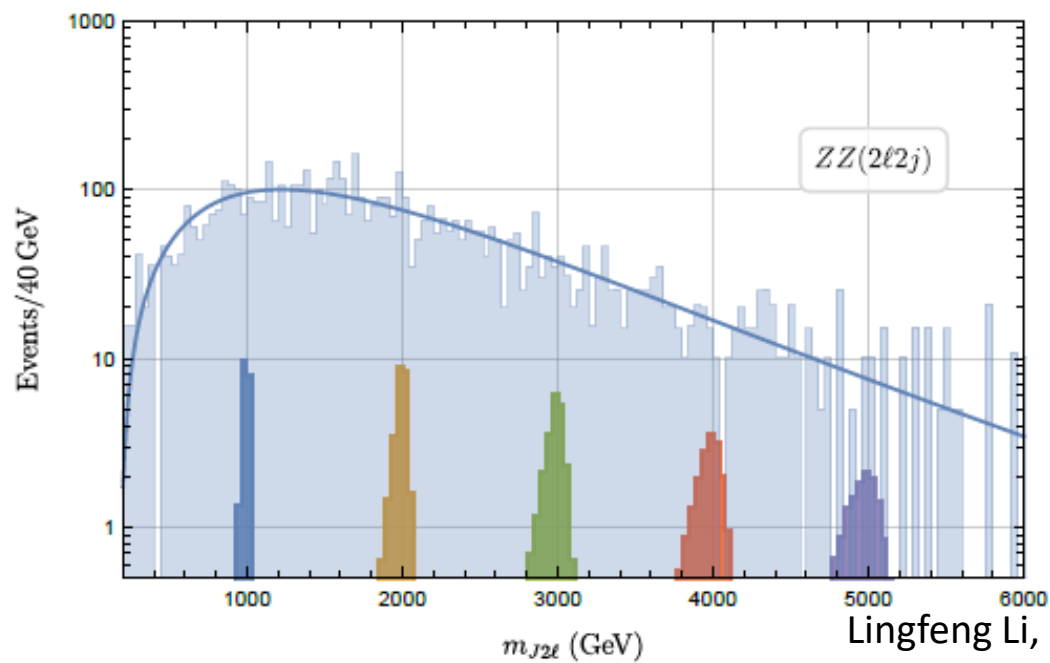
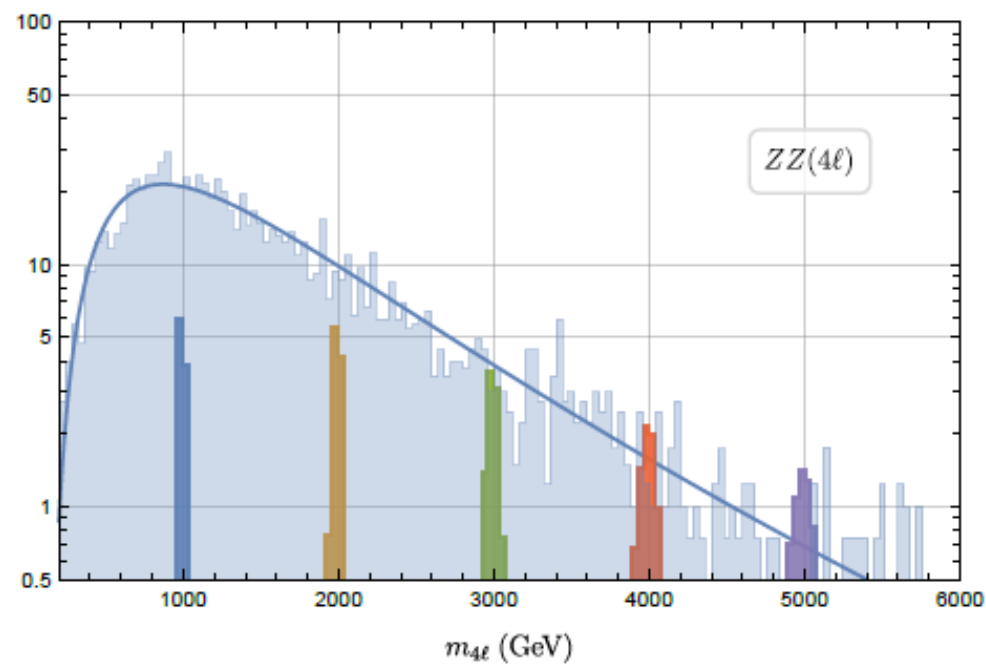
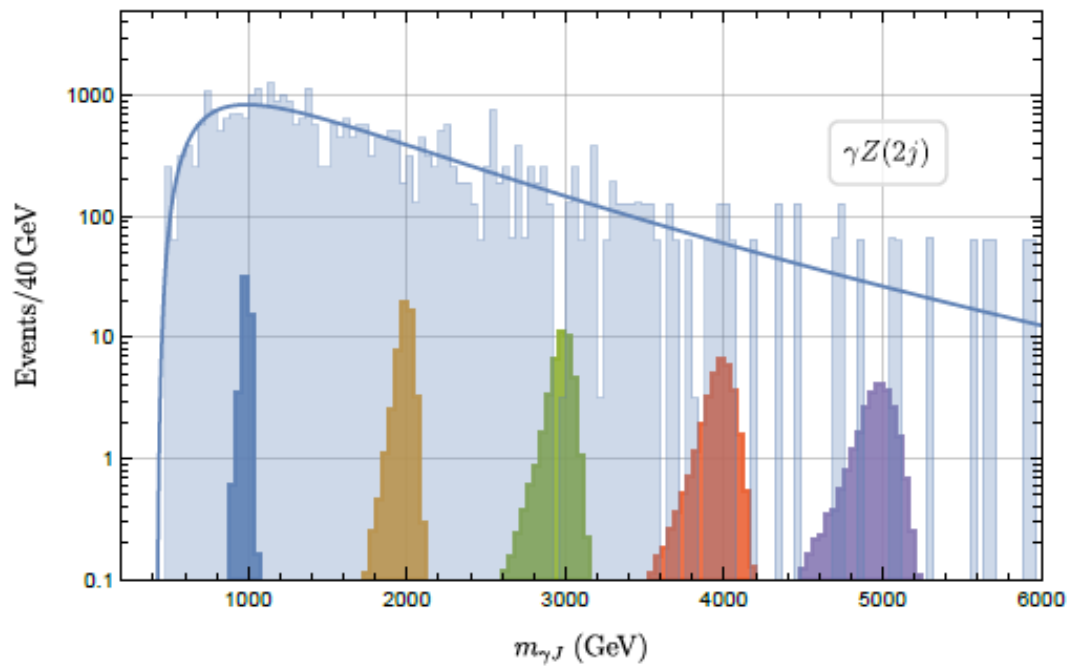
↑: Diphoton

- Cleanest background (VBF $WW \rightarrow \gamma\gamma$)
- Sharpest resonance peaks

↓: $WW(4j)$

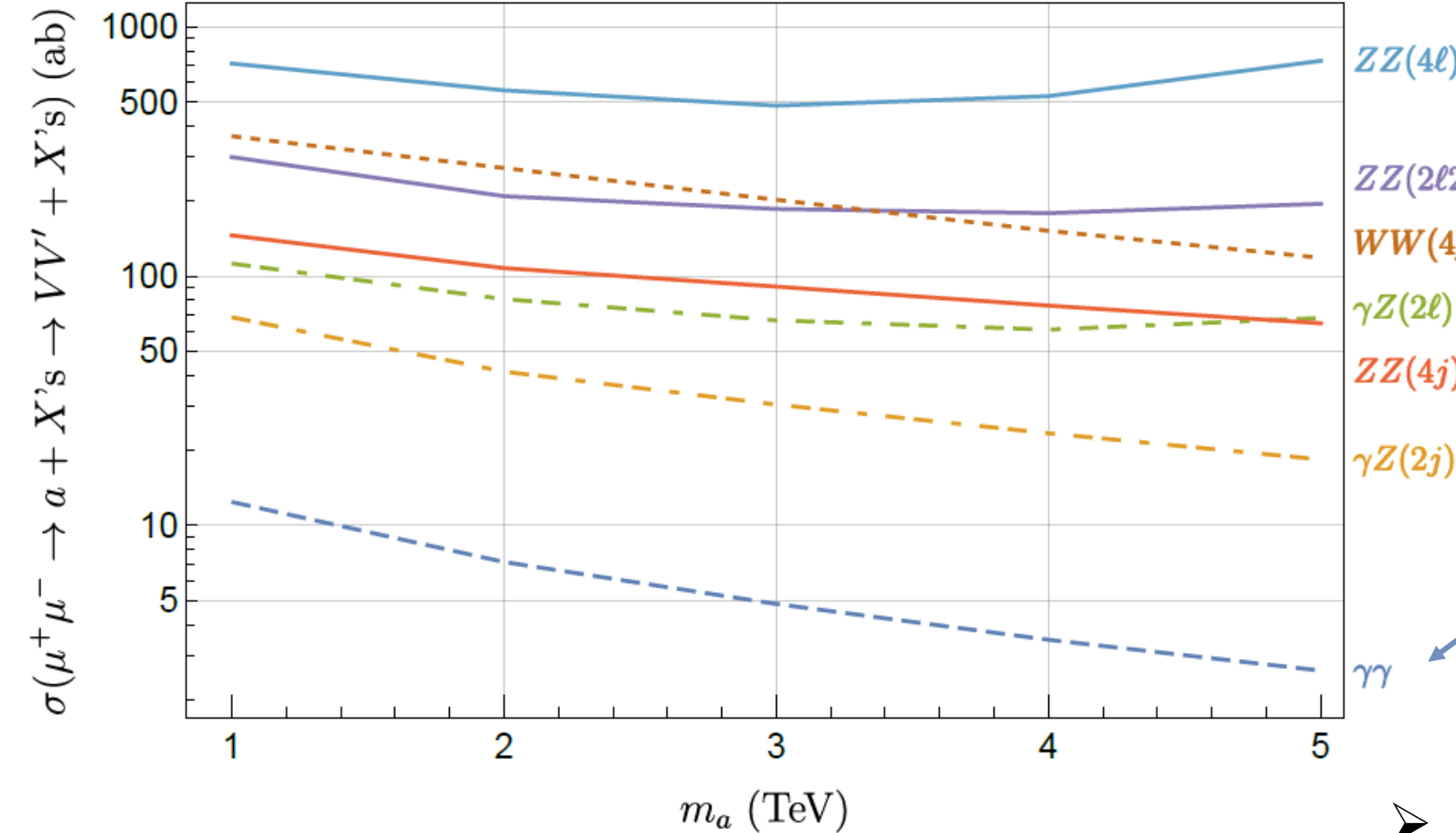
- Highest background (VBF $\gamma\gamma \rightarrow WW$)
- Wide peaks due to jet resolution





Xsec Limits Always < 1 fb!

$\sqrt{s} = 14 \text{ TeV}$, $L = 10 \text{ ab}^{-1}$, 2σ exclusion limits



Very clean, but also very small $\text{BR}(Z \rightarrow \ell\ell)^2$

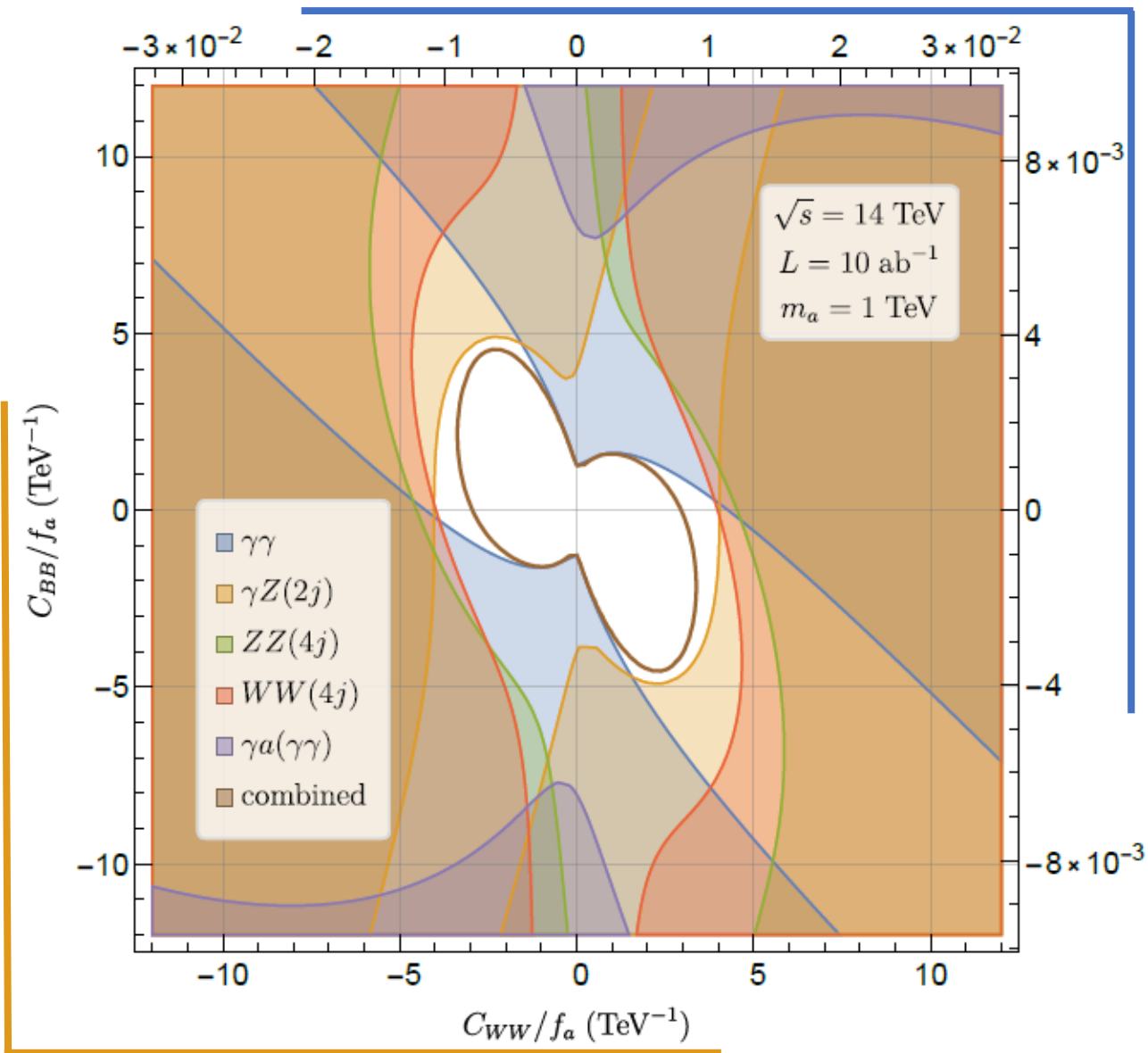
High BR and good reconstruction, next to the best

Best Channel

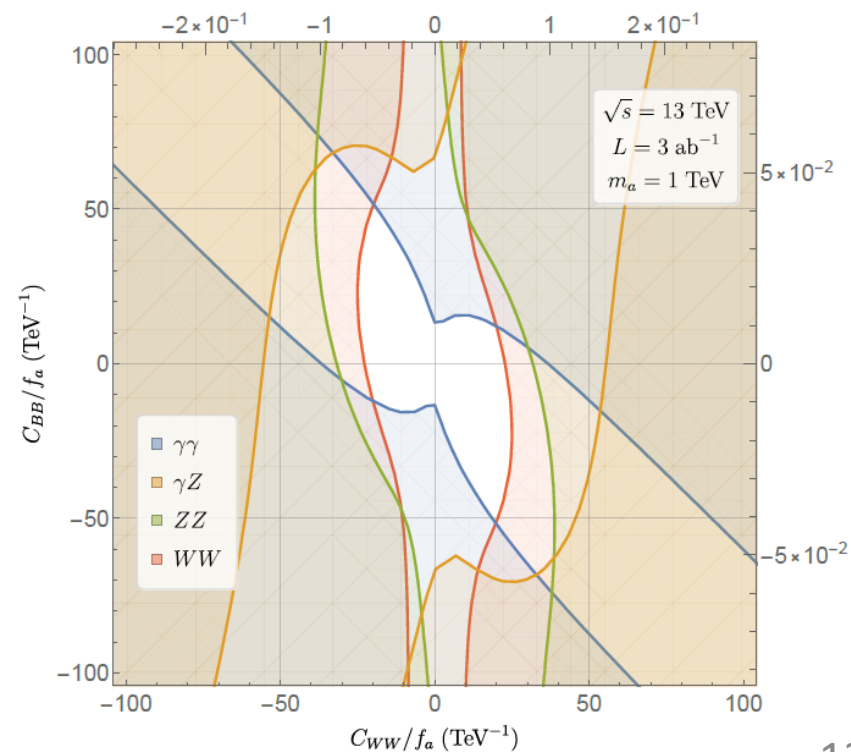
Good for Any Diboson Resonance

- Varying model parameters, signal efficiencies change <20 %
- Works for different CP (e.g. heavy Higgs) and spin (e.g. Z's)

“Popular” parameterization

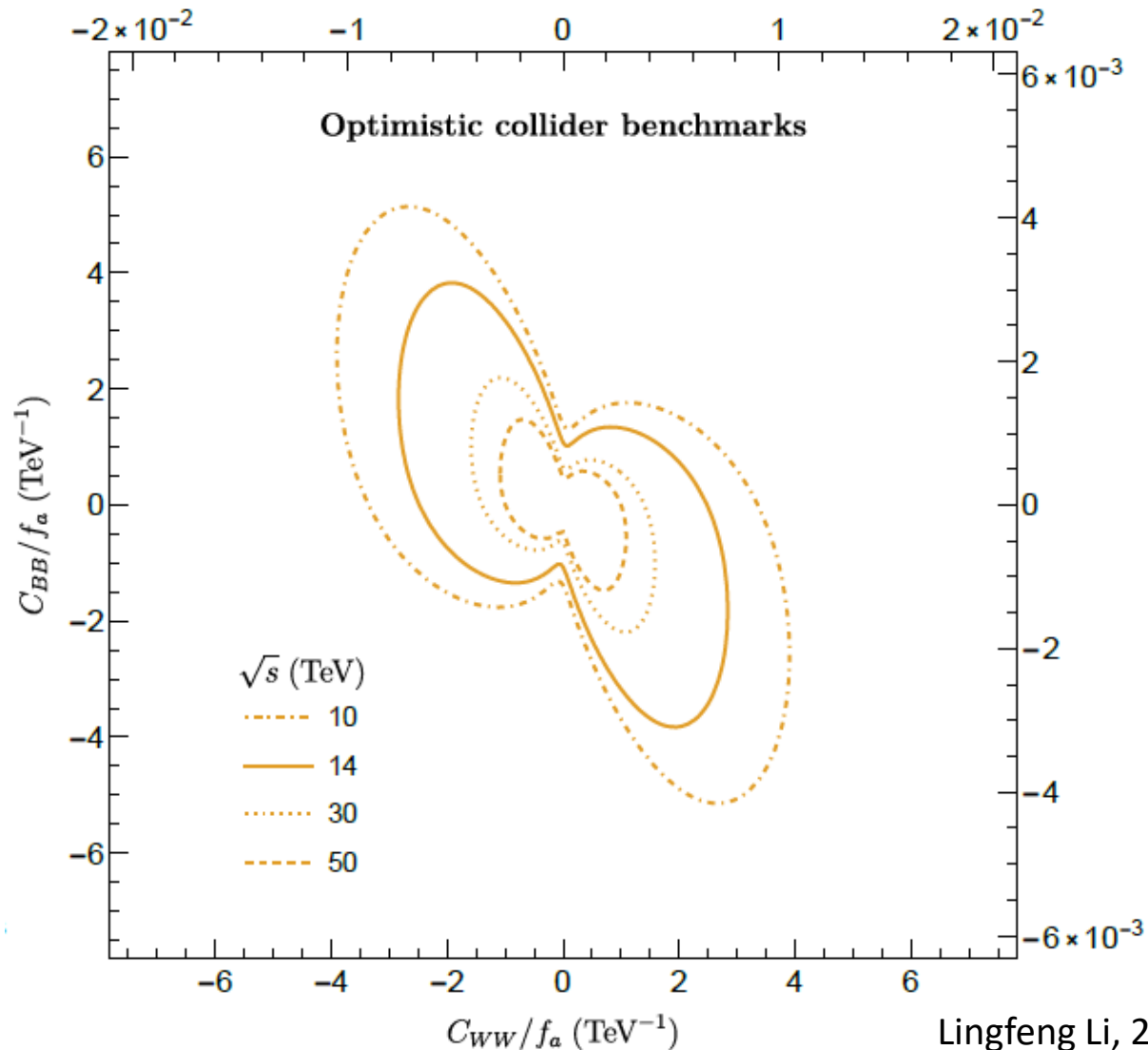


- Lead by two best VBF channels
- ALP + associated photon is subdominant
- Orders of magnitude better than HL-LHC



“Honest” parameterization

Different Benchmarks



- Larger Xsec with improved energy
- Luminosity also increases
- Reach to higher masses

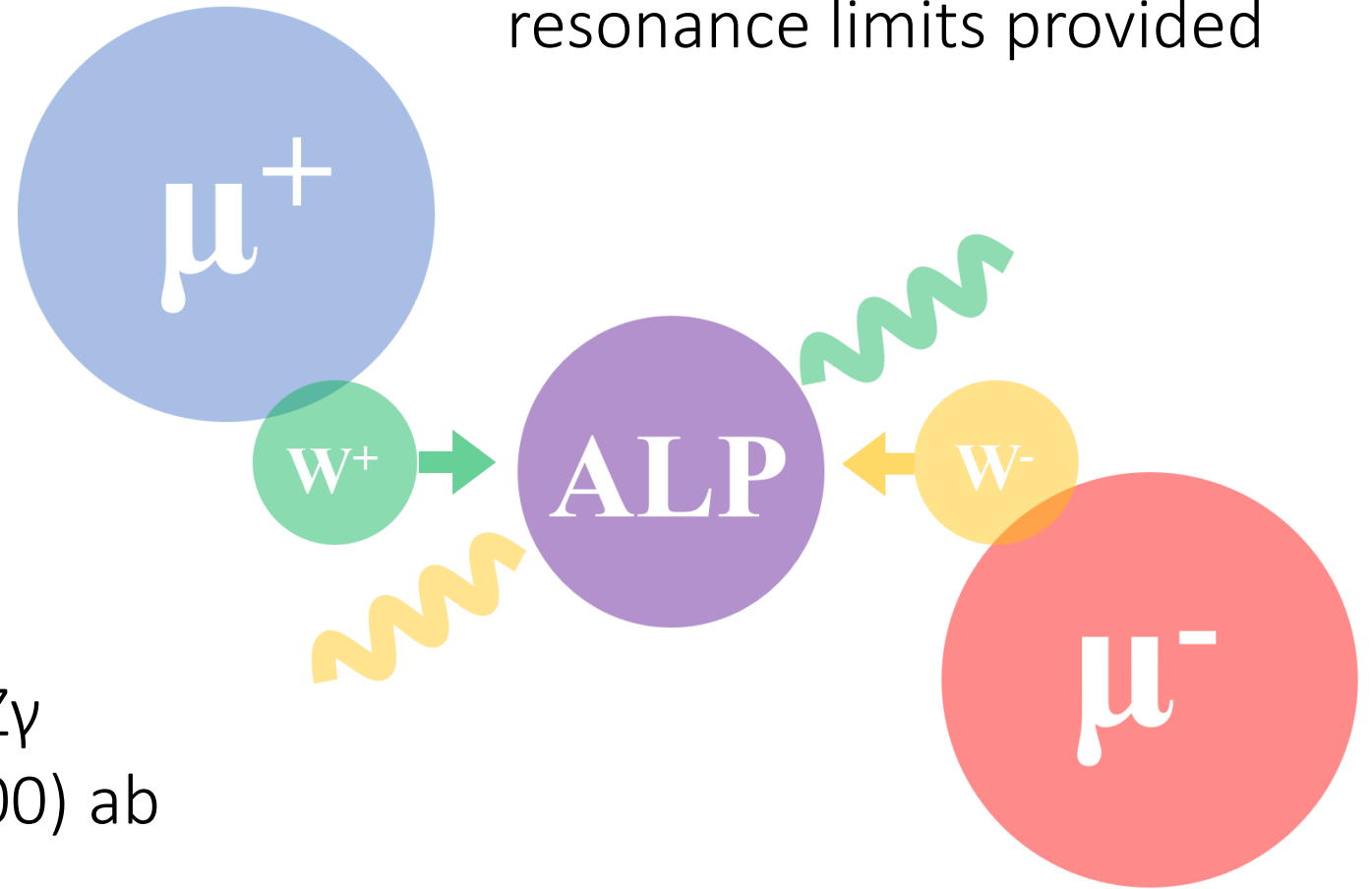
$$\sqrt{s} = 10, 14, 30, 50 \text{ TeV},$$
$$L_{\text{con}} = 10, 10, 10, 10 \text{ ab}^{-1},$$
$$L_{\text{opt}} = 10, 20, 90, 250 \text{ ab}^{-1}.$$

Summary

A high-energy muon collider is also a boson collider with large production rates

Clean channels as $\gamma\gamma$ and $Z\gamma$
constraint σ_{sec} to $O(10-100)$ ab

Reaches the elusive TeV-scale
ALP efficiently



*: Model independent diboson
resonance limits provided