Z' MODELS AT A MUON COLLIDER

Mass reach and model discrimination
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Early Career Researchers & Muon Colliders, 28 Aug 2024

HELMHOLTZ

DESY.

Motivation

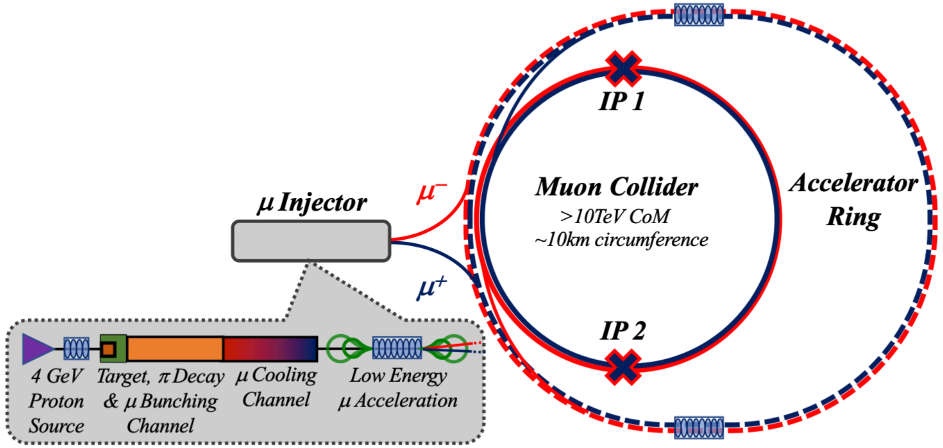
- Despite success of SM, open questions remain: dark matter, matter-antimatter asymmetry, **unification beyond electroweak**
- Multitude of well-motivated UV-complete models for **SM gauge group extensions**
- Naturally come with **additional neutral gauge boson Z′**
- Study large set of models in terms of **effective Lagrangian** with different **axial** and **vector** couplings to SM fermions:

$$-\mathscr{L}_{NC} = eA_\mu {J_A}^\mu + g_Z Z_\mu {J_Z}^\mu + g_{Z'} Z'_\mu {J_{Z'}}^\mu$$

$${J_A}^\mu = \sum_f \bar{f}\gamma^\mu q_f f, \quad {J_Z}^\mu = \sum_f \bar{f}\gamma^\mu (v_f^{SM} - \gamma_5 a_f^{SM}) f, \quad {J_{Z'}}^\mu = \sum_f \bar{f}\gamma^\mu (v_f - \gamma_5 a_f) f,$$

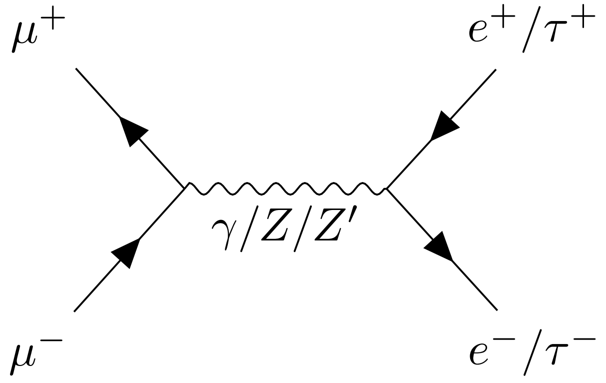
- Muon collider has a great potential to study this
- **Collider options we discuss:**
  $E_{CM} = \{3{,}10\}\,\mathrm{TeV}, \quad \mathscr{L}_{int} = 10\,\mathrm{ab}^{-1}(E/10\,\mathrm{TeV})^2$

Model	$g_{Z'}$	$2v_l$	$2a_l$
SSM	$\frac{e}{s_W c_W}$	$2s_W^2 - \frac{1}{2}$	$-\frac{1}{2}$
E_6	$\frac{e}{c_W}$	$\frac{2\cos\beta}{\sqrt{6}}$	$\frac{\cos\beta}{\sqrt{6}} + \frac{\sqrt{10}\sin\beta}{6}$
LR	$\frac{e}{c_W}$	$\frac{1}{\alpha} - \frac{\alpha}{2}$	$\frac{\alpha}{2}$
ALR	$\frac{e}{s_W c_W \sqrt{1-2s_W^2}}$	$\frac{5}{2}s_W^2 - 1$	$-\frac{1}{2}s_W^2$
LH	$\frac{e}{s_W}$	$-\frac{c}{4s}$	$-\frac{c}{4s}$
USLH	$\frac{e}{c_W \sqrt{3-4s_W^2}}$	$\frac{1}{2} - 2s_W^2$	$\frac{1}{2}$
$U(1)_X$	$\frac{e}{4c_W}$	-8	2



Setup

What do we study?

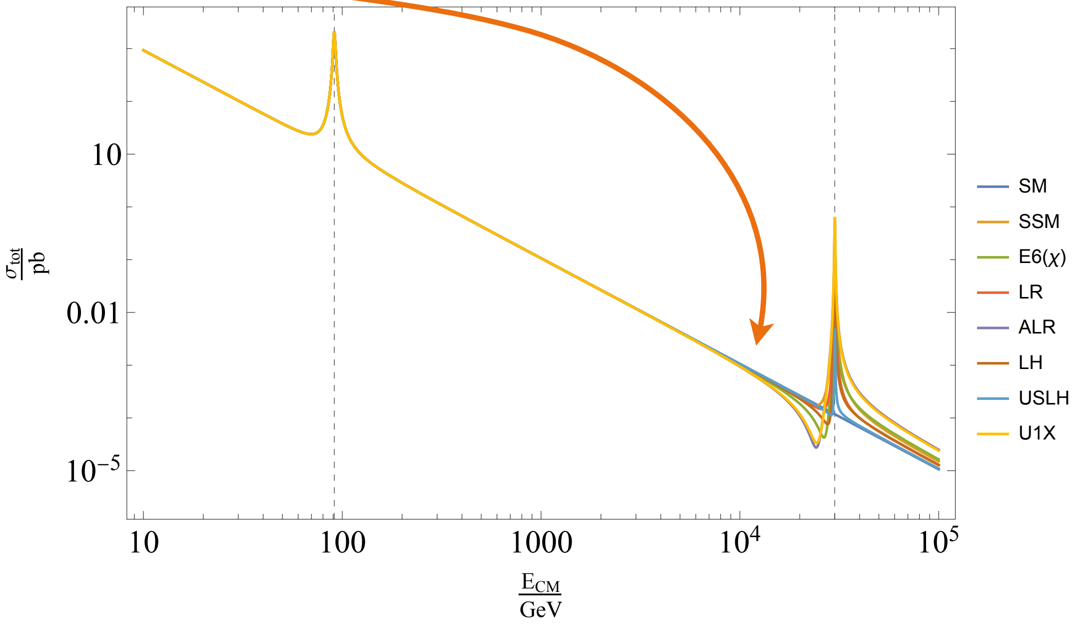


- Study **s-channel** lepton production at a muon collider
- Born approximation gives reliable results in **off-peak region**

  $\Rightarrow$ **Particularly simple analysis**

- Discuss statistical significance in terms of χ^2 w.r.t. reference observables $\hat{O}_i$ and uncertainties $\Delta\hat{O}_i$:

$$\chi^2(a_l, v_l, M_{Z'}) = \sum_{i=1}^{n_{ob}} \left[\frac{\hat{O}_i - O_i(a_l, v_l, M_{Z'})}{\Delta \hat{O}_i} \right]^2$$



Observables

Input for the χ^2

- **Total cross-section** σ_f
- **Forward-backward asymmetry:**

$$A^f_{FB} = \frac{\sigma^f_F - \sigma^f_B}{\sigma^f}$$

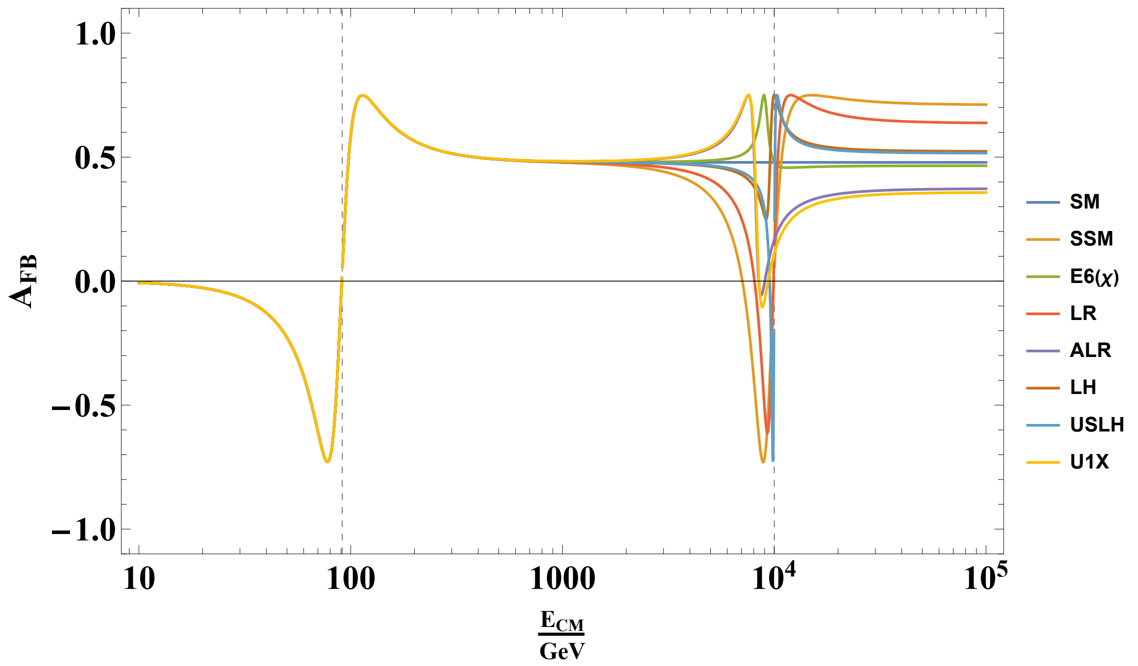
- **Left-right asymmetry** (initial state):

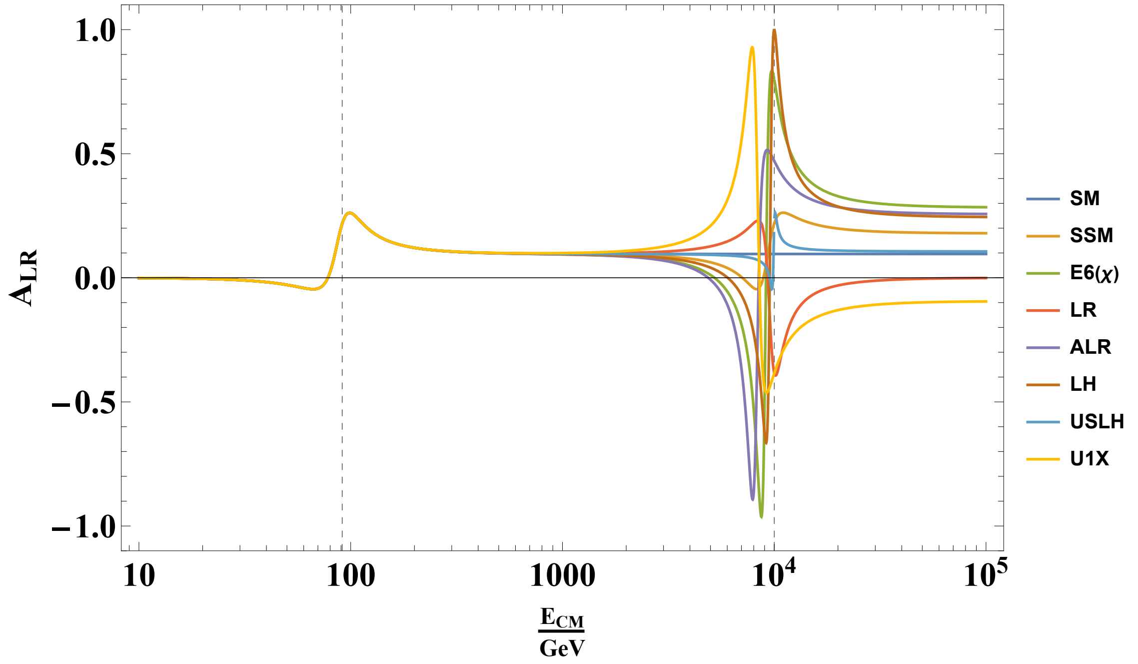
$$A^f_{LR} = \frac{\sigma^f_{LR} - \sigma^f_{RL}}{\sigma^f}$$

- **Polarisation asymmetry** (final state):

$$A_{pol} = \frac{\sigma^f_{lr} - \sigma^f_{rl}}{\sigma^f} \quad (= A_{LR} \text{ for massless fermions})$$

- Signal strengths can be significant even far off-peak
  $\Rightarrow$ **yields a high reach/discrimination power**



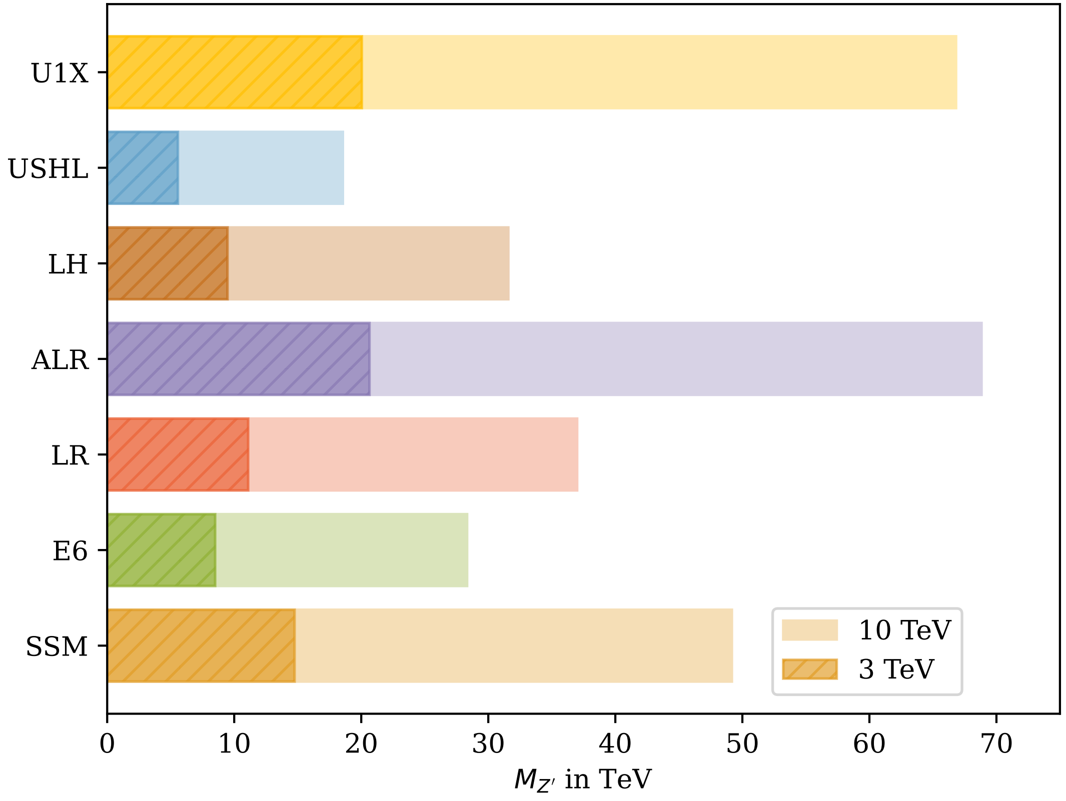


Results

Mass reach

$$\chi^2_{model}(M_{Z'}) = \sum_{i=1}^{n_{ob}} \left[\frac{\hat{O}_i - O_{i,model}(M_{Z'})}{\Delta \hat{O}_i} \right]^2$$

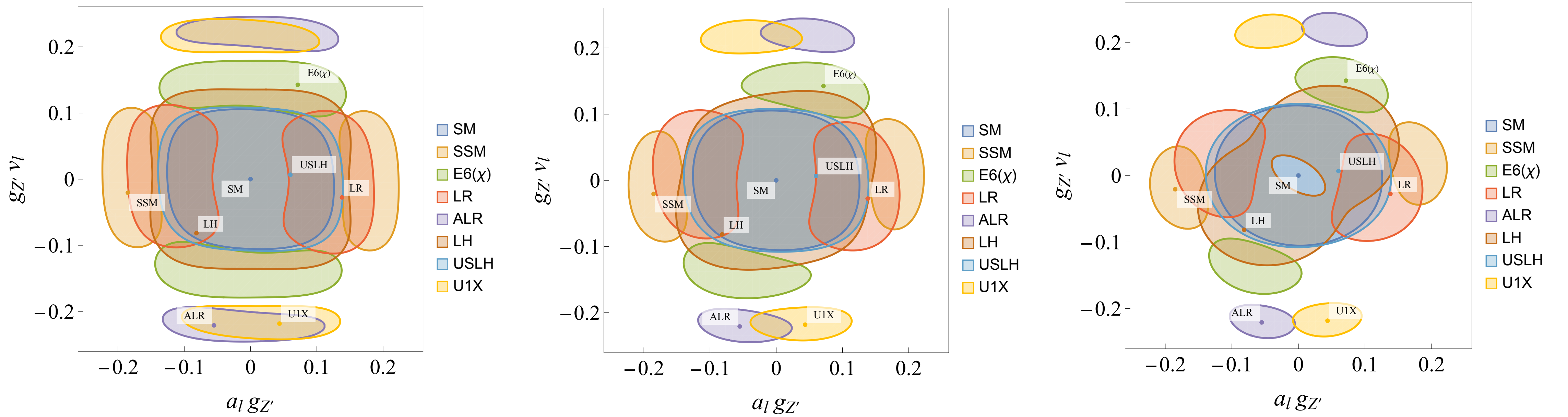
- Use $\chi^2_{model}(M_{Z'})$ for fixed couplings and vary $M_{Z'}$
- **We find limits up to $M_{Z'} \sim 70$ TeV**
  (Note: current LHC limits up to ~ 5 TeV)
- Reach depends on magnitude of couplings
- Extension to hadronic observables **could push reach by up to $\sim 50\,\%$**, depending on the model
  (see LEP-discussion [arXiv:hep-ph/9607306])



Results

Resolving power

- Use $\chi^2_{M_{Z'}}(a_l, v_l)$ for fixed mass and vary couplings w.r.t. reference models: $$\chi^2_{M_{Z'}}(a_l, v_l) = \sum_{i=1}^{n_{ob}} \left[\frac{\hat{O}_i - O_{i,M_{Z'}}(a_l, v_l)}{\Delta \hat{O}_i} \right]^2$$
- Test influence of **polarized beams** or final state **polarization measurement**
- Setup: $\mathscr{L}_{int} = 10\,\text{ab}^{-1}$, $E_{CM} = 10$ TeV, $M_{Z'} = 30$ TeV



$P_{eff} = 0\,\%$, $\Delta_{sys}(A_{Pol}) = 5\,\%$

$P_{eff} = 30\,\%$, $\Delta_{sys}(A_{Pol}) = 5\,\%$

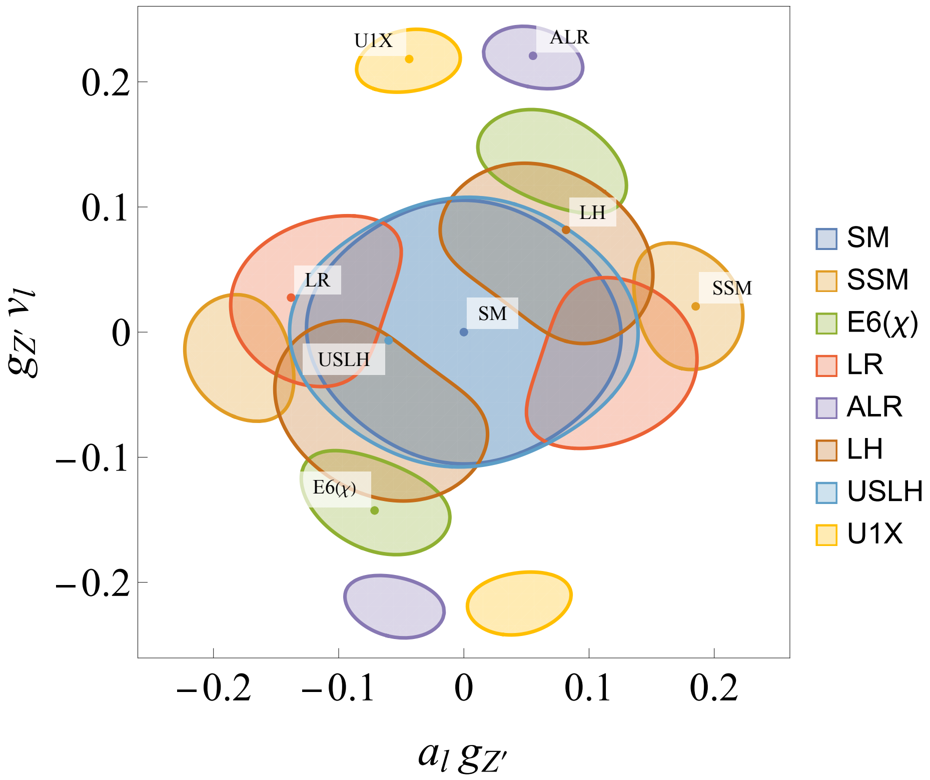
$P_{eff} = 0\,\%$, $\Delta_{sys}(A_{Pol}) = 1\,\%$

- Similar yields for either using polarized beams or low error on polarization measurement

Conclusion

What could we find at a muon collider?

- Large variety of well-motivated **Z′ models** in the literature
- **Muon collider** as a powerful tool for finding and resolving them
- **Significant reach** of muon colliders to find Z′ bosons of up to ~ 70 TeV
- **Strong resolving power** between Z′ models for masses up to ~ 30 TeV
- Accurate **polarization measurement or polarized beams** can yield significant increase in model discrimination



Thank you!

Contact

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Muon Collider

*"At this stage, building upon significant prior work, **no insurmountable technological issues were identified**. Therefore a development path can address the major challenges and deliver a **3 TeV muon collider by 2045**".*

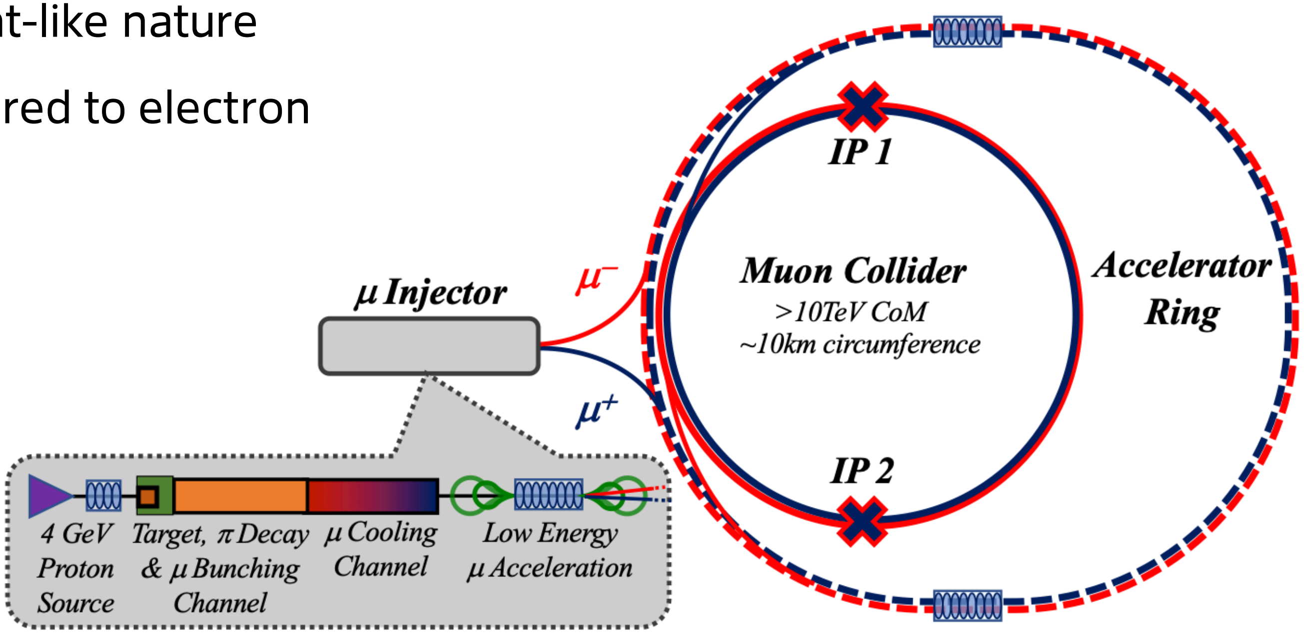
✦ **Pros:**

- Clean collision environment due to their point-like nature
- Bremsstrahlung significantly reduced compared to electron colliders due to their high mass

  ⇒ Energy loss per turn: $\frac{\Delta E_\mu}{\Delta E_e} \simeq 10^{-10}$

✦ **Cons:**

- Short lifetime of muons ($\tau_0 = 2.2\,\mu s$, $\tau(7\,\text{TeV}) \simeq 150\,\text{ms}$)
- Beam induced background
- High neutrino flux



Options we discuss:

$E_{CM} = \{3,10\}\,\text{TeV}, \quad L_{int} = 10\,\text{ab}^{-1}(E/10\,\text{TeV})^2$

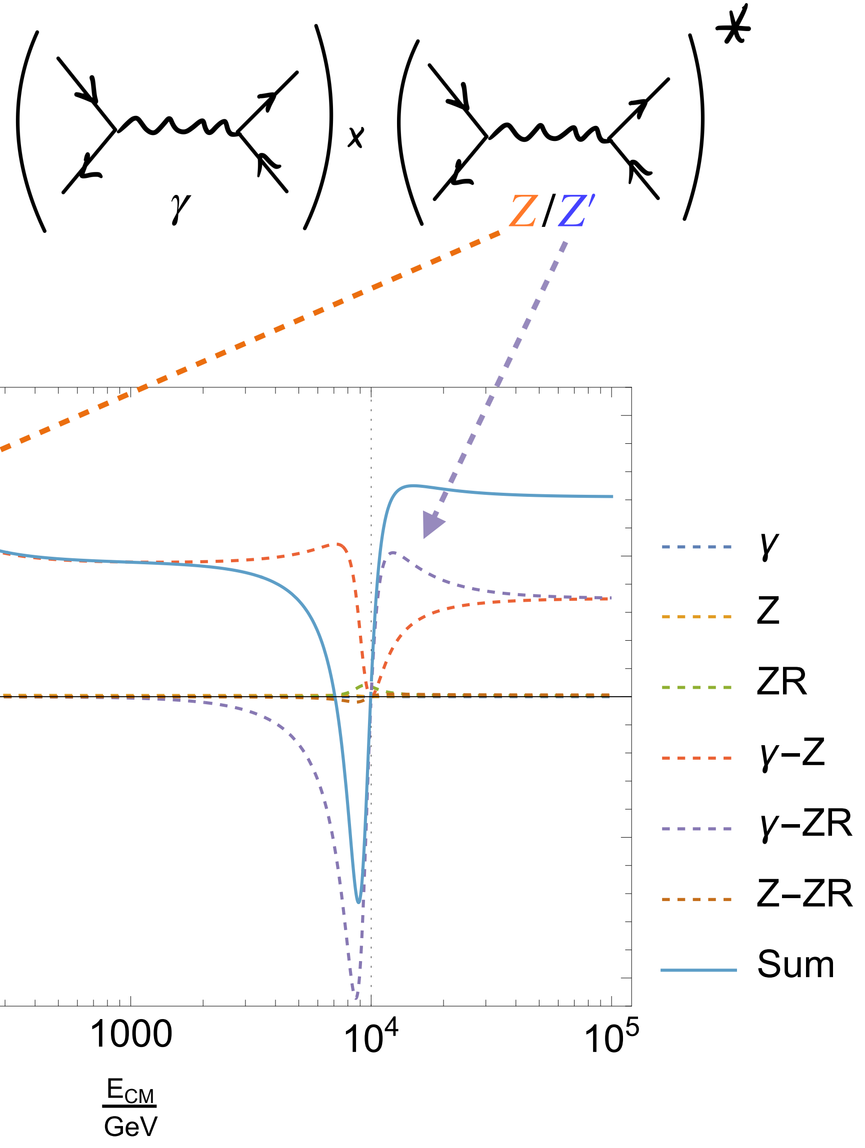
Challenging, but not impossible!

[arXiv:2303.08533]

Asymmetries

How do they work?

$$|\mathscr{A}(\mu^+\mu^- \to f\bar{f})|^2 \supset$$



- Can study amplitude **interference effects** in angular distributions or **asymmetries**
- **Forward-backward asymmetry:**

$$A^f_{FB} = \frac{\sigma^f_F(0 \leq \theta < \frac{\pi}{2}) - \sigma^f_B(\frac{\pi}{2} \leq \theta < \pi)}{\sigma^f_{tot}}$$

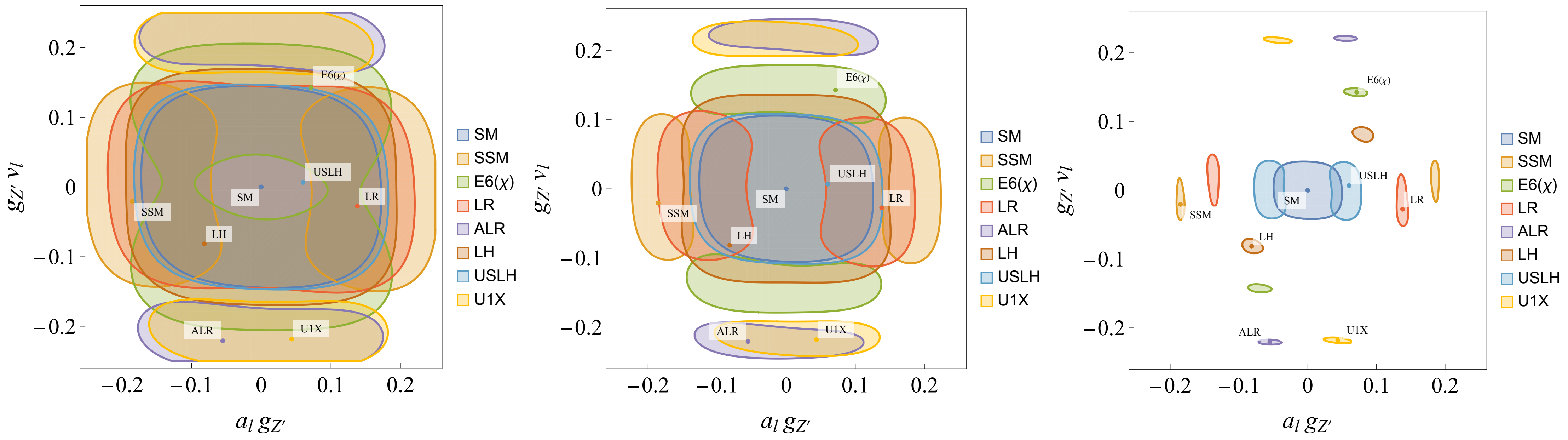
- γ-Z and γ-Z′ interference are the main drivers of forward backward asymmetry

Results

Model discrimination

- Use $\chi^2_{M_{Z'}}(a_l, v_l)$ for fixed mass and vary couplings w.r.t. reference models: $$\chi^2_{M_{Z'}}(a_l, v_l) = \sum_{i=1}^{n_{ob}} \left[\frac{\hat{O}_i - O_{i,M_{Z'}}(a_l, v_l)}{\Delta \hat{O}_i} \right]^2$$

- **Resolution power** for $L_{int} = 10\,\text{ab}^{-1}$, $E_{CM} = 10$ TeV, $P_{eff} = 0\,\%$ for three different Z′ masses



$M_{Z'} = 40$ TeV $\quad$ $M_{Z'} = 30$ TeV $\quad$ $M_{Z'} = 15$ TeV

- **Significant resolution even without polarization**