Z' MODELS AT A MUON COLLIDER

Mass reach and model discrimination

arXiv:2402.18460 (EPJC 84, 568 (2024))

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HELMHOLTZ

DESY.

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- Describe these models in terms of **effective Lagrangian** with different **axial** and **vector** couplings to SM fermions:

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

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

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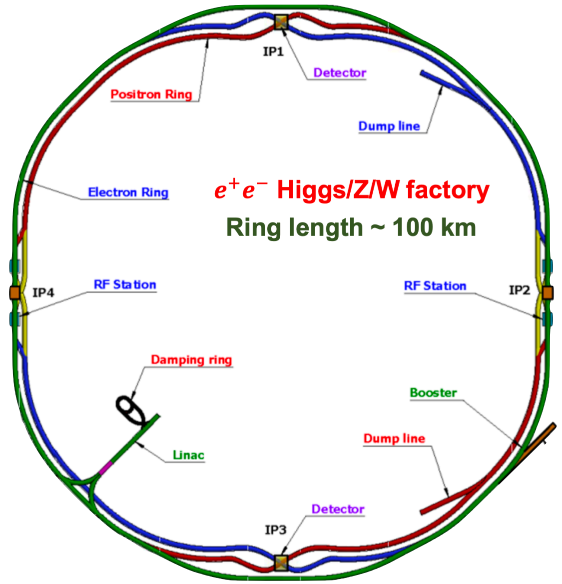
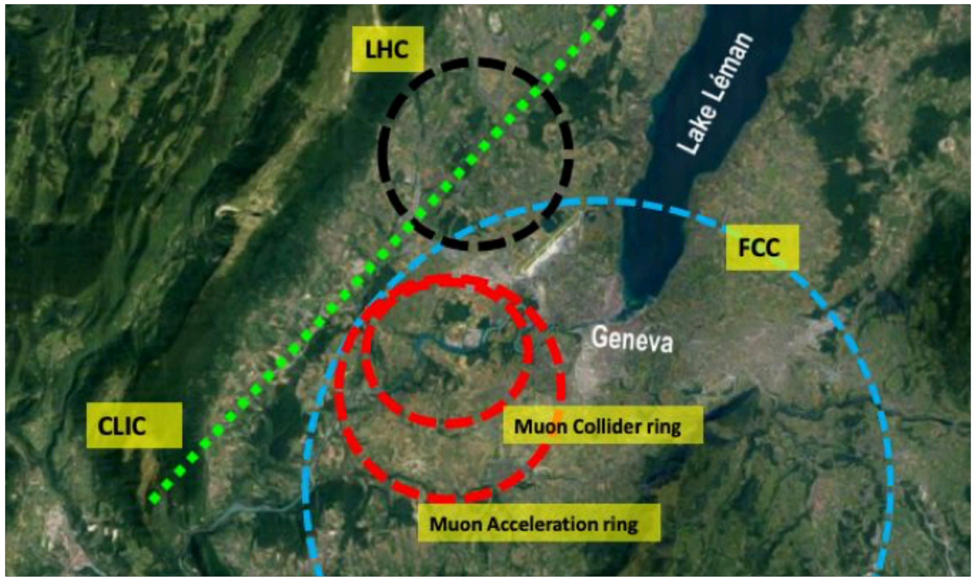
Model	$g_{Z'}$	$2v_l$	$2a_l$
SSM	$\frac{e}{s_W c_W}$	$2s_W^2 - \frac{1}{2}$	$-\frac{1}{2}$
E_6	$\frac{e}{c_W}$	$\frac{2\cos\beta}{\sqrt{6}}$	$\frac{\cos\beta}{\sqrt{6}} + \frac{\sqrt{10}\sin\beta}{6}$
LR	$\frac{e}{c_W}$	$\frac{1}{\alpha} - \frac{\alpha}{2}$	$\frac{\alpha}{2}$
ALR	$\frac{e}{s_W c_W \sqrt{1-2s_W^2}}$	$\frac{5}{2} s_W^2 - 1$	$-\frac{1}{2} s_W^2$
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

Future Colliders

How to study such scenarios?



- Possible near future machines:
  - ➡ **CEPC, FCC-ee, CLIC, ILC,…**
  - ➡ Improvement of discovery reach from **Higgs & electroweak precision measurements**



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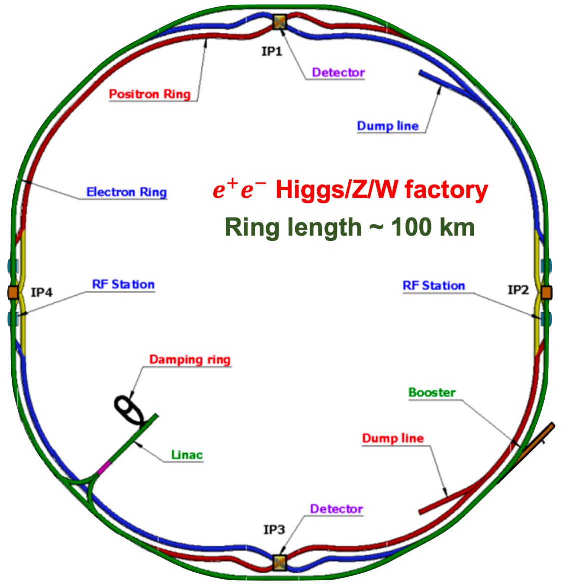
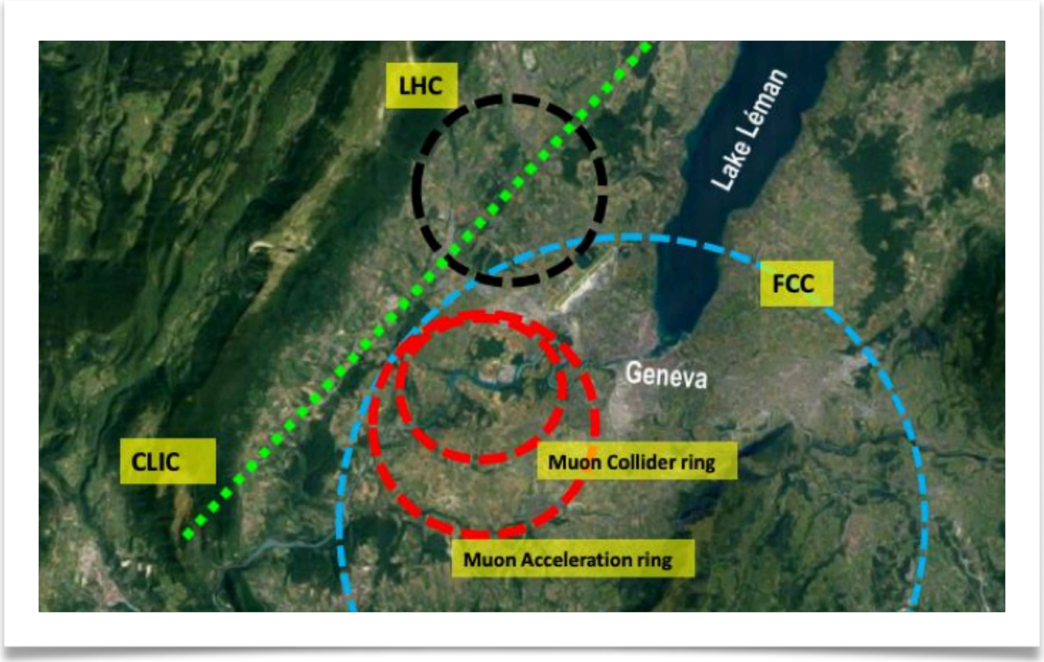
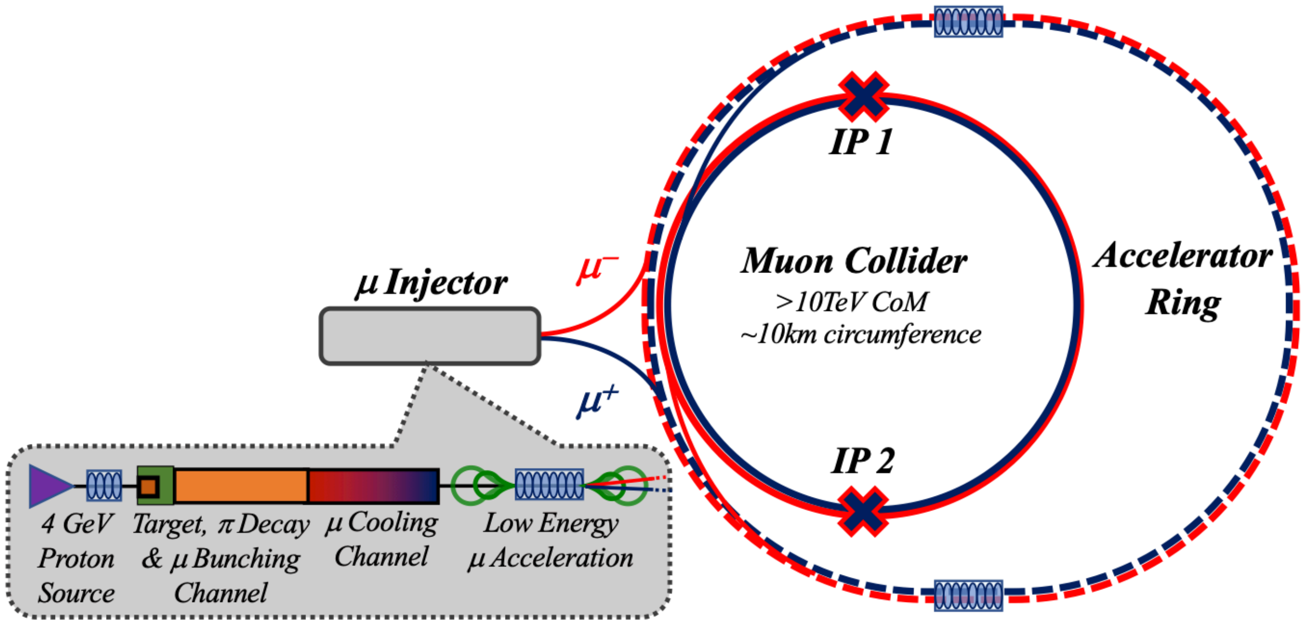
- Possible near future machines:
  - ➡ **CEPC, FCC-ee, CLIC, ILC,...**
  - ➡ Improvement of discovery reach from **Higgs & electroweak precision measurements**
- Further into the future: **high energy machine** with more direct access to SM extensions
  - ➡ Study prospects for future **muon collider**





Muon Collider



Challenging, but not impossible!

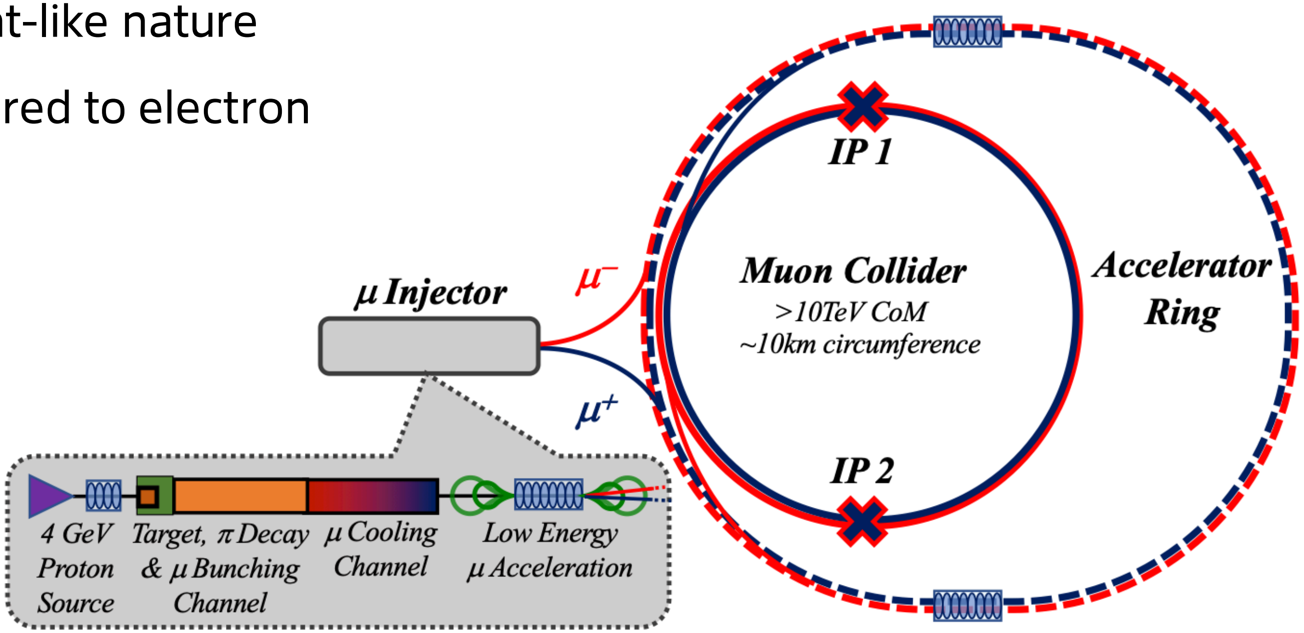
[arXiv:2303.08533]

Muon Collider

✦ **Pros:**

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

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



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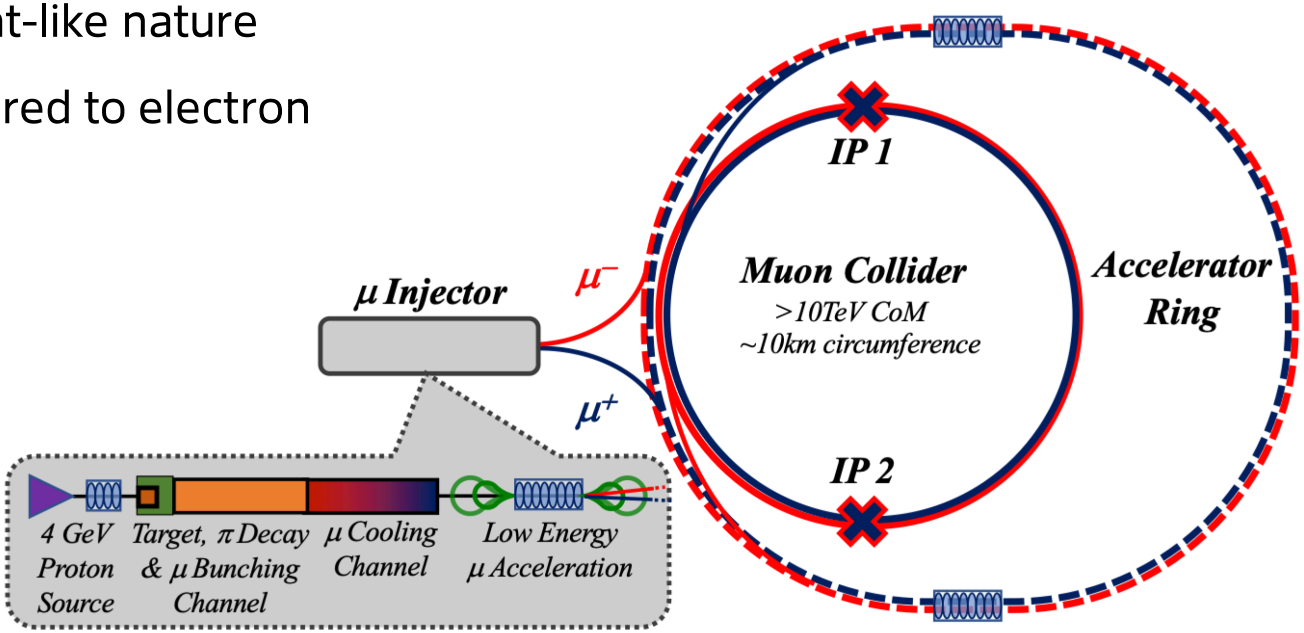

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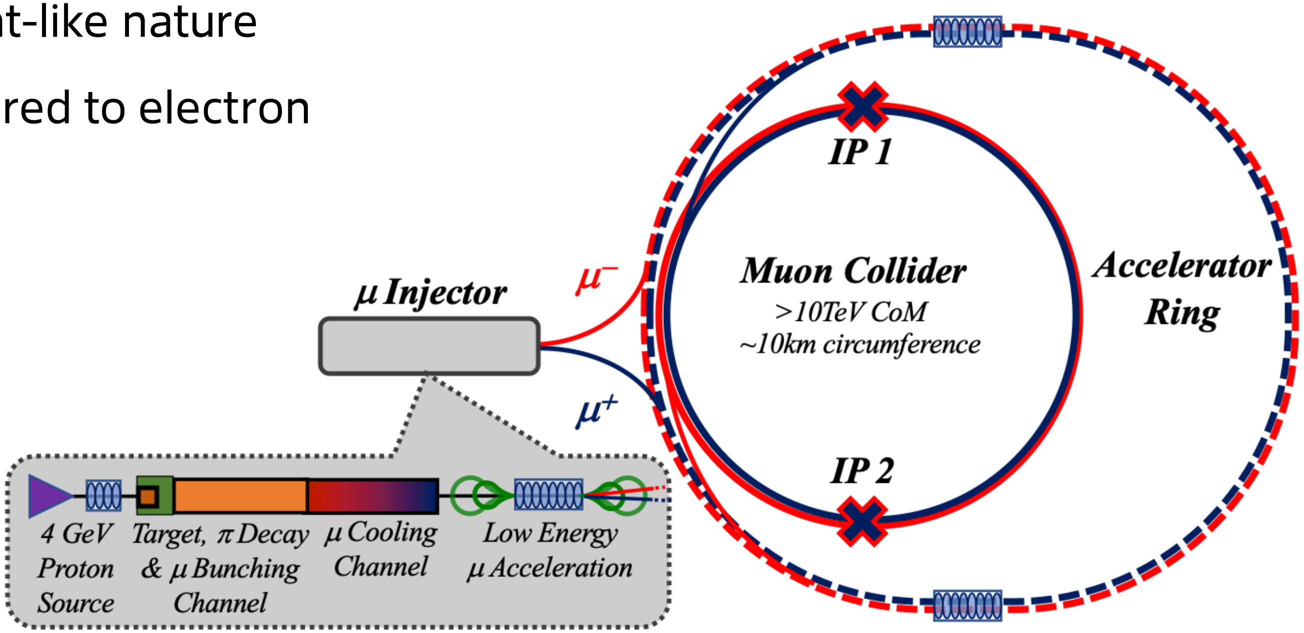

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$E_{CM} = \{3, 10\}\,\text{TeV}, \qquad L_{int} = 10\,\text{ab}^{-1}(E/10\text{ TeV})^2$

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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**".*

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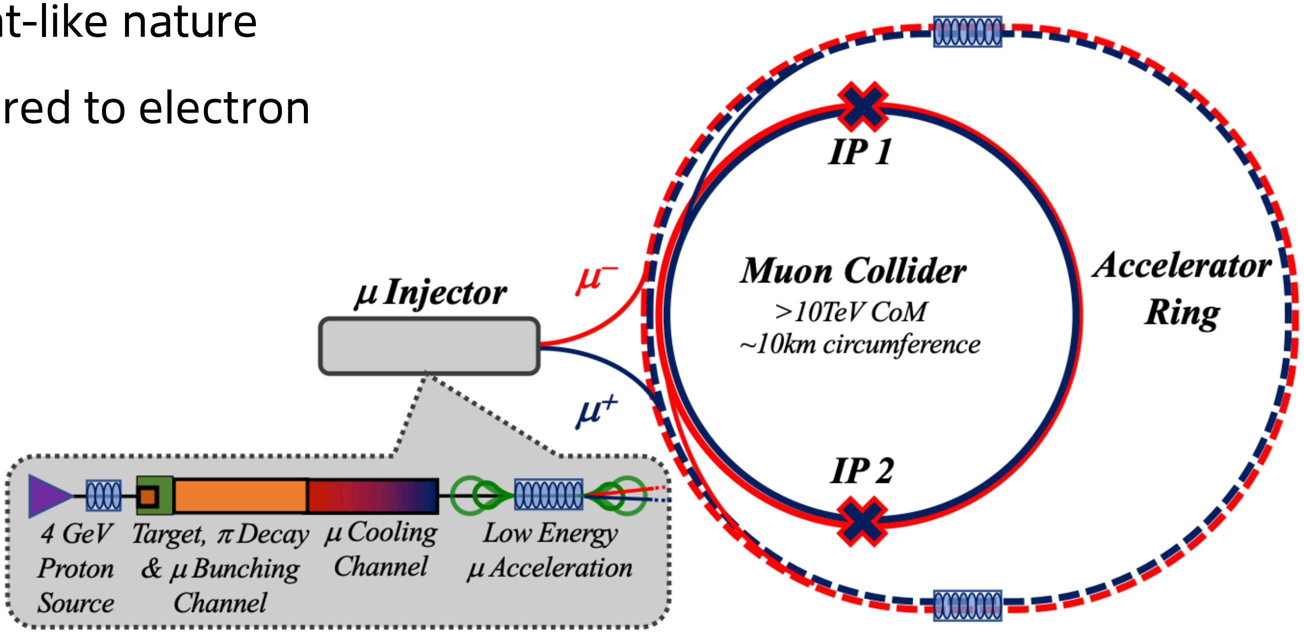

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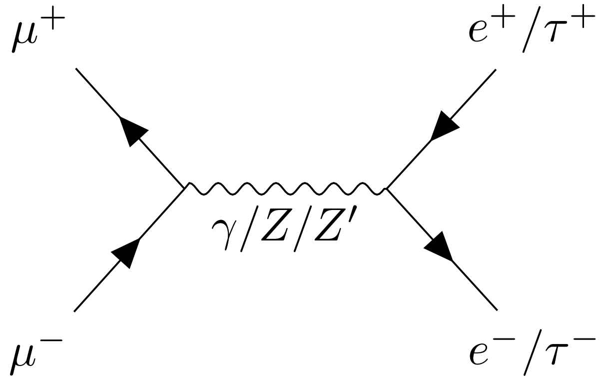
Setup

What do we study?

- Study **s-channel** lepton production at a muon collider



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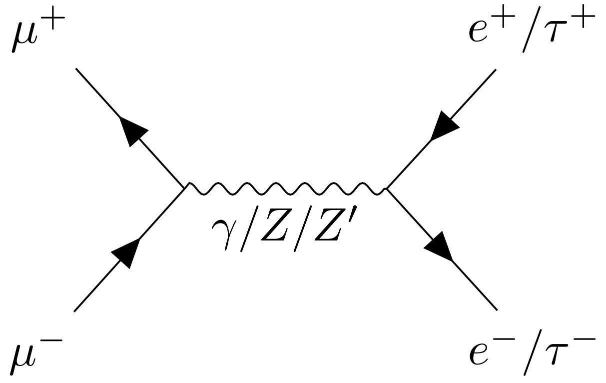
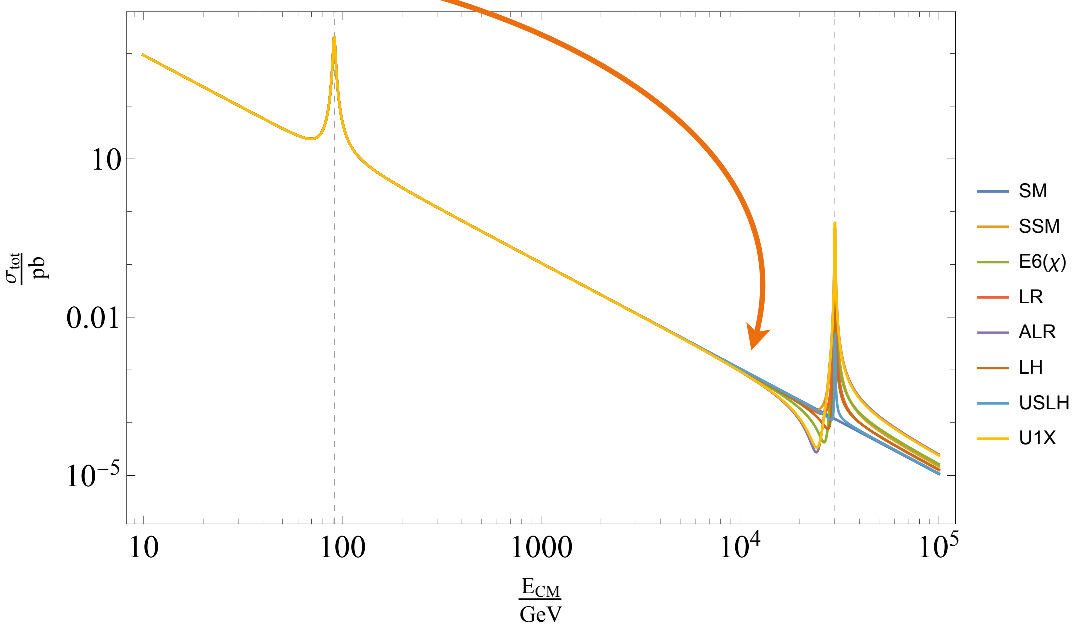
- Born approximation gives reliable results

$\Rightarrow$ **Particularly simple analysis**





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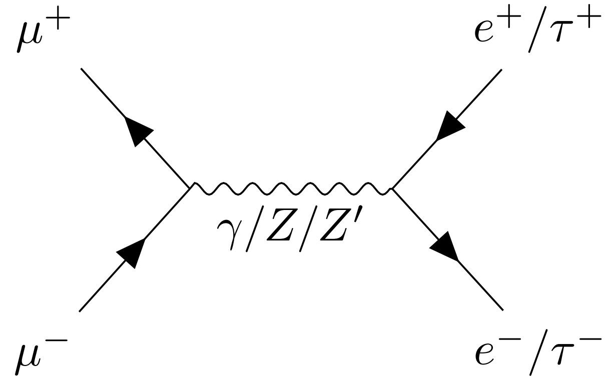

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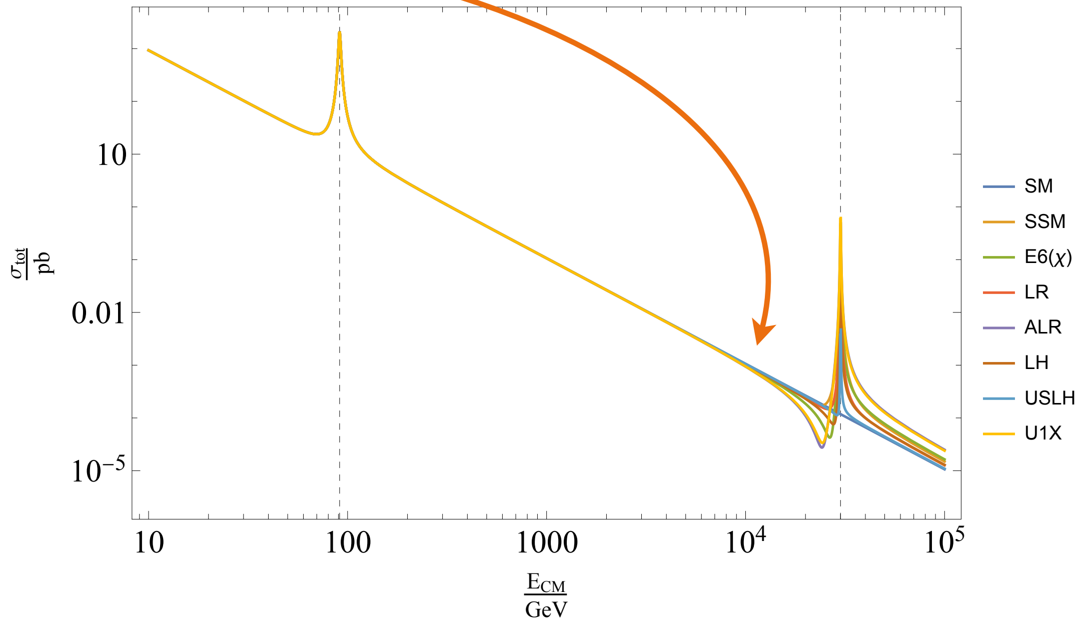


- Discuss statistical significance in terms of χ^2 w.r.t. reference observables $\hat{O}_i$ and uncertainties $\Delta\hat{O}_i$:

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

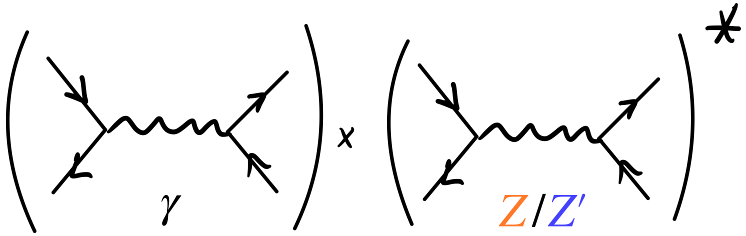
- Determine boundaries of regions where

$\chi^2(a_l', v_l', M_{Z'}) < \chi^2_{crit}(n_{ob})$ at 95% confidence level

Asymmetries

How do they work?

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



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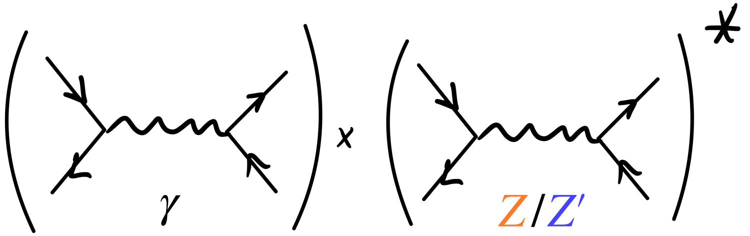

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- **Forward-backward asymmetry:**

$$A_{FB}^{f} = \frac{\sigma_F^f(0 \leq \theta < \frac{\pi}{2}) - \sigma_B^f(\frac{\pi}{2} \leq \theta < \pi)}{\sigma_{tot}^f}$$

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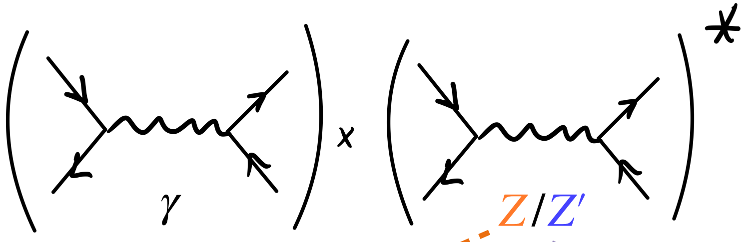

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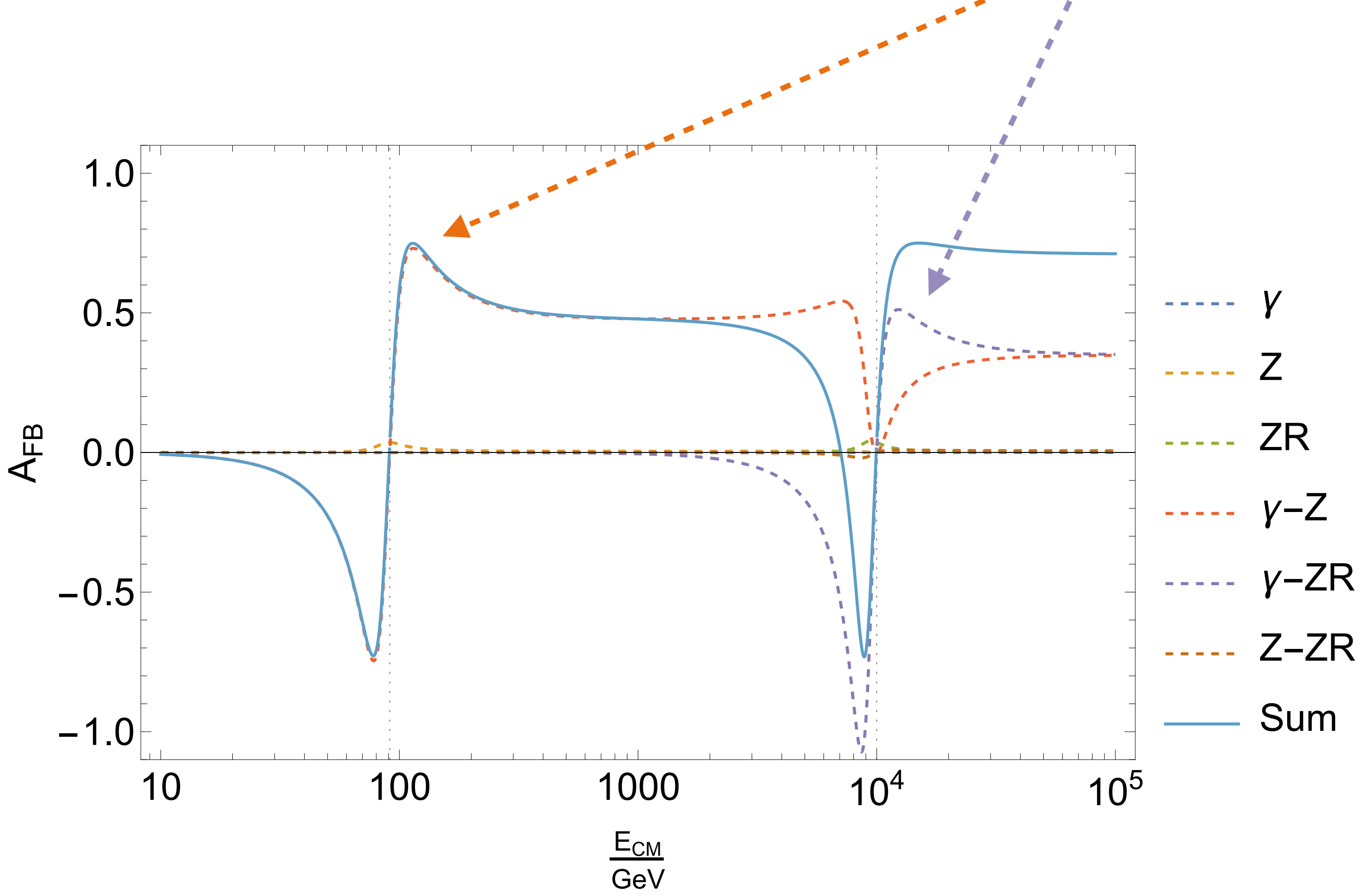
- γ-Z and γ-Z′ interference are the main drivers of forward backward asymmetry



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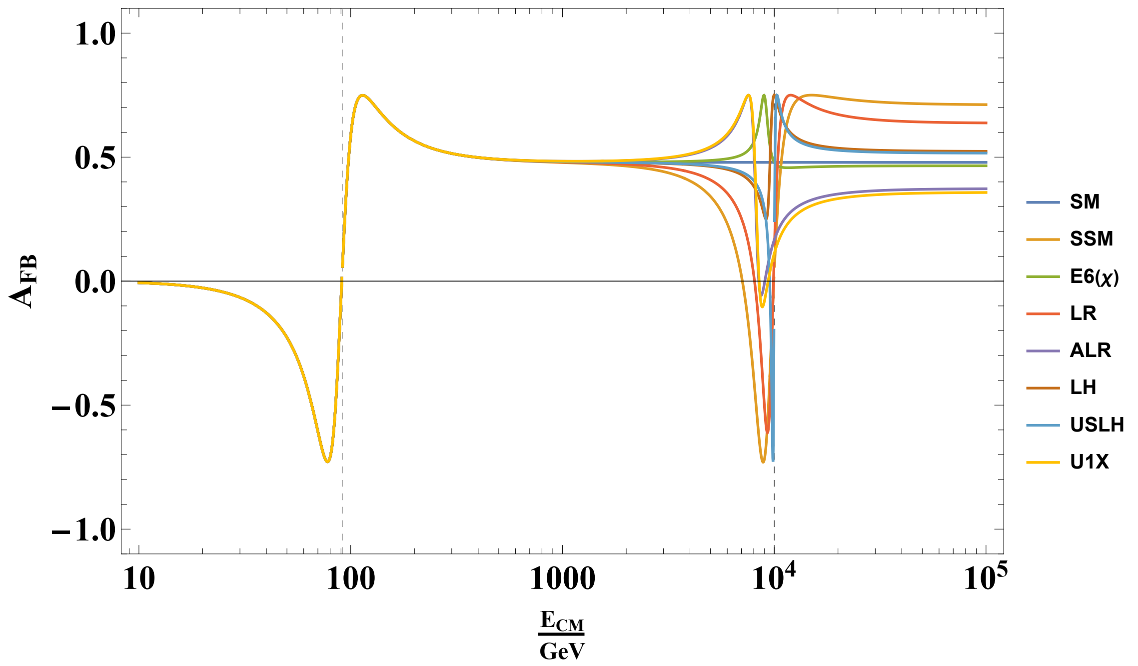

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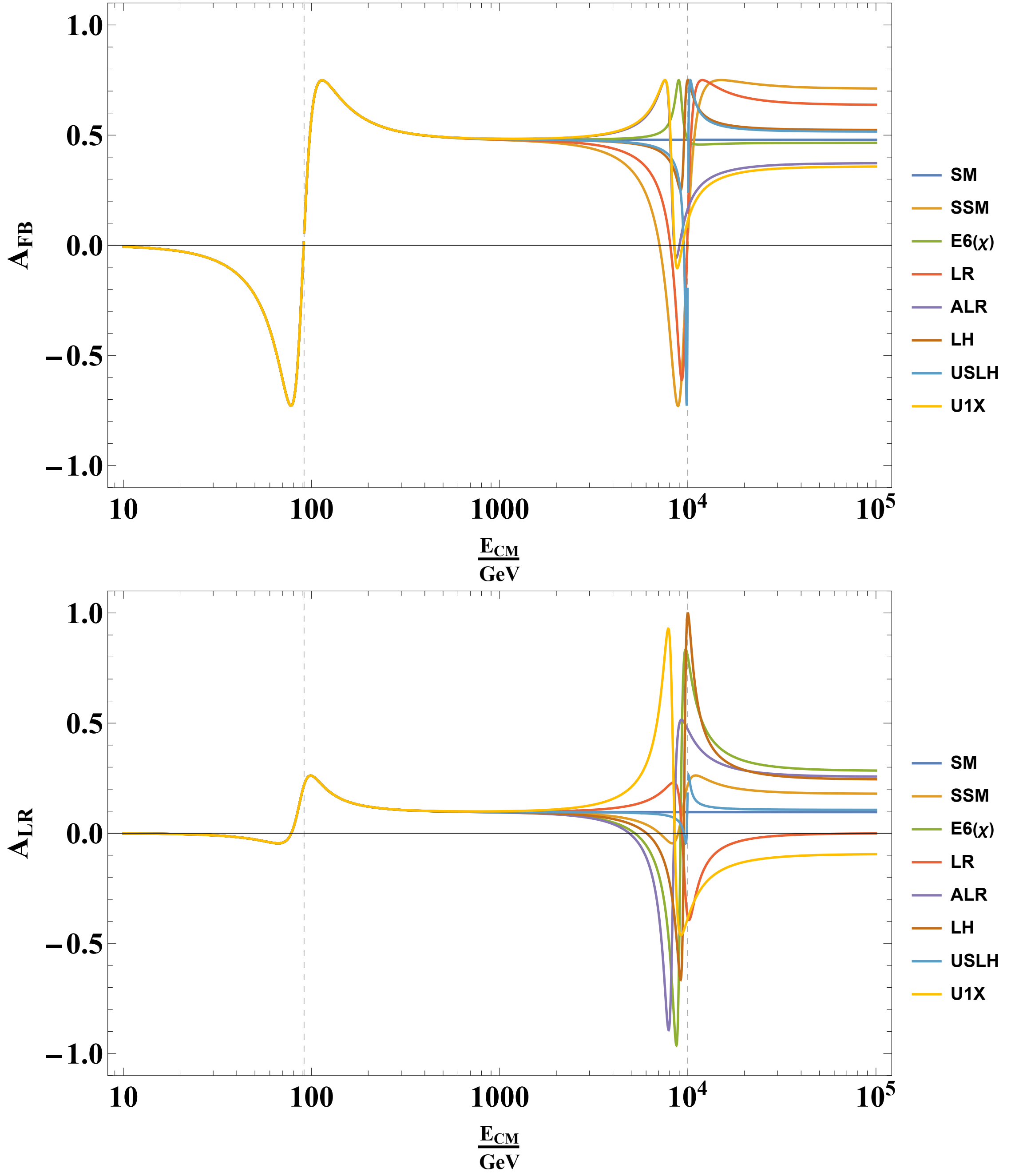

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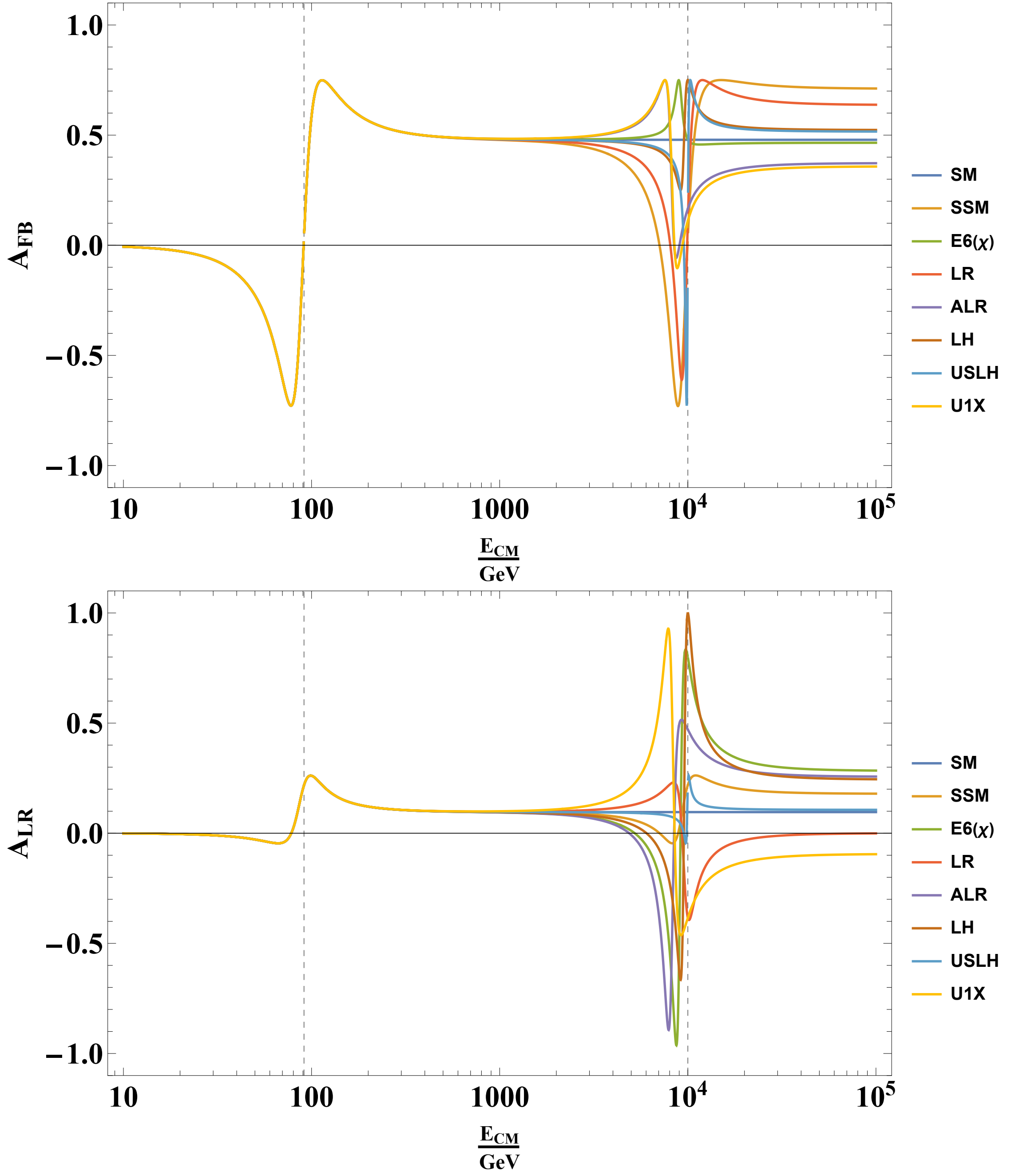

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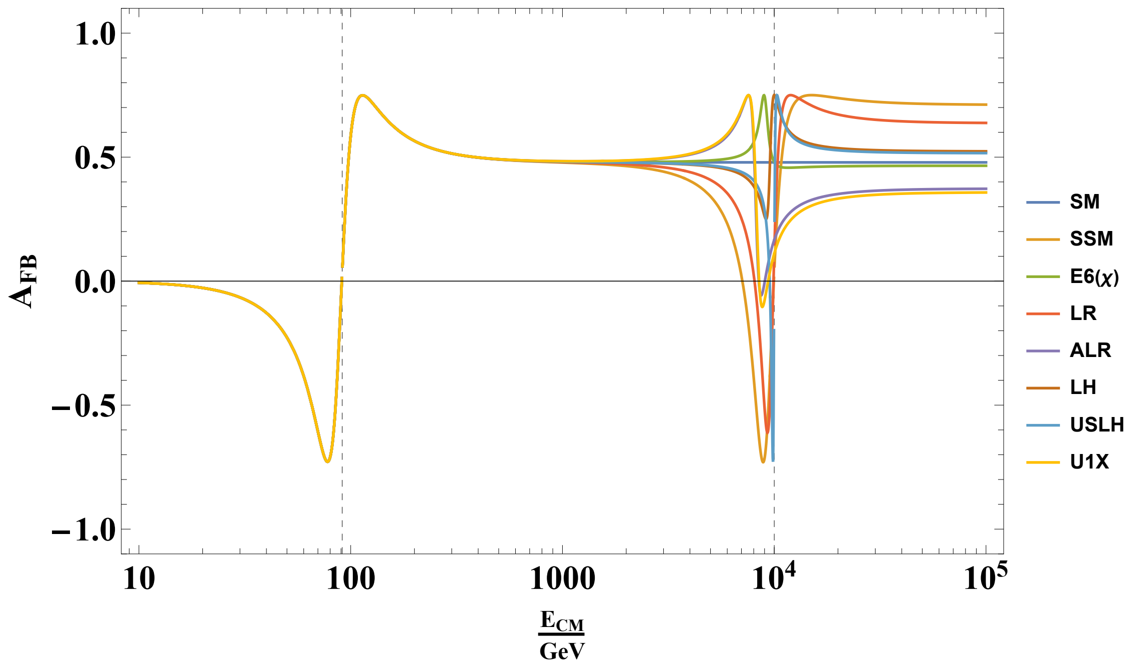
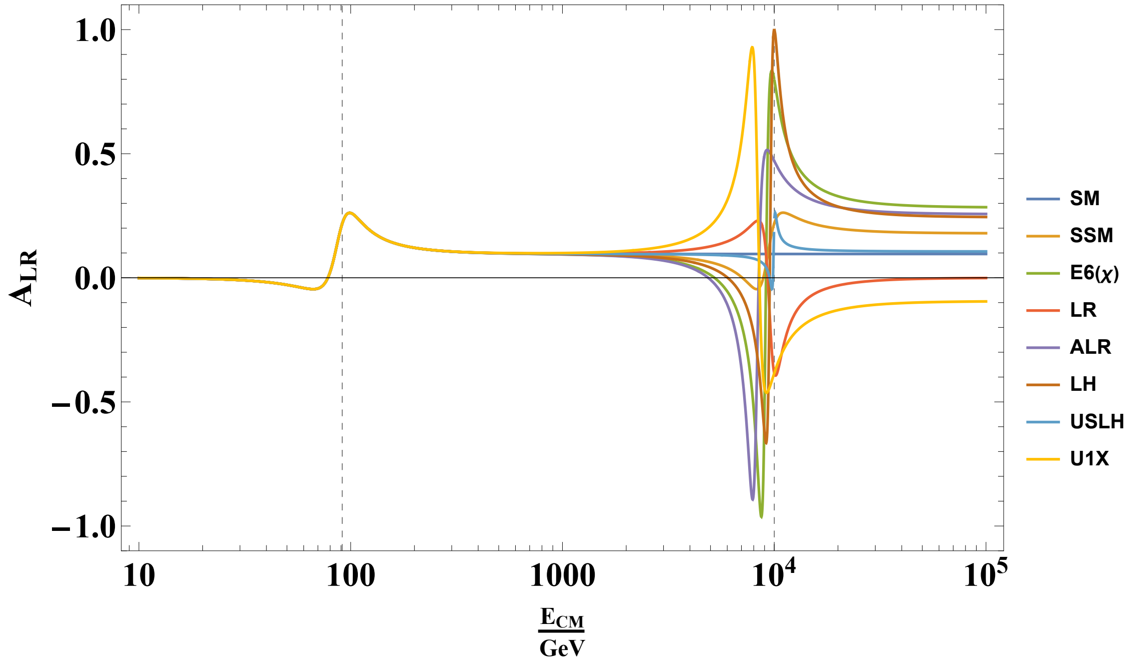
- Signal strengths can be significant even far off-peak
  $\Rightarrow$ **yields a high reach/discrimination power**





Results

Mass reach

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

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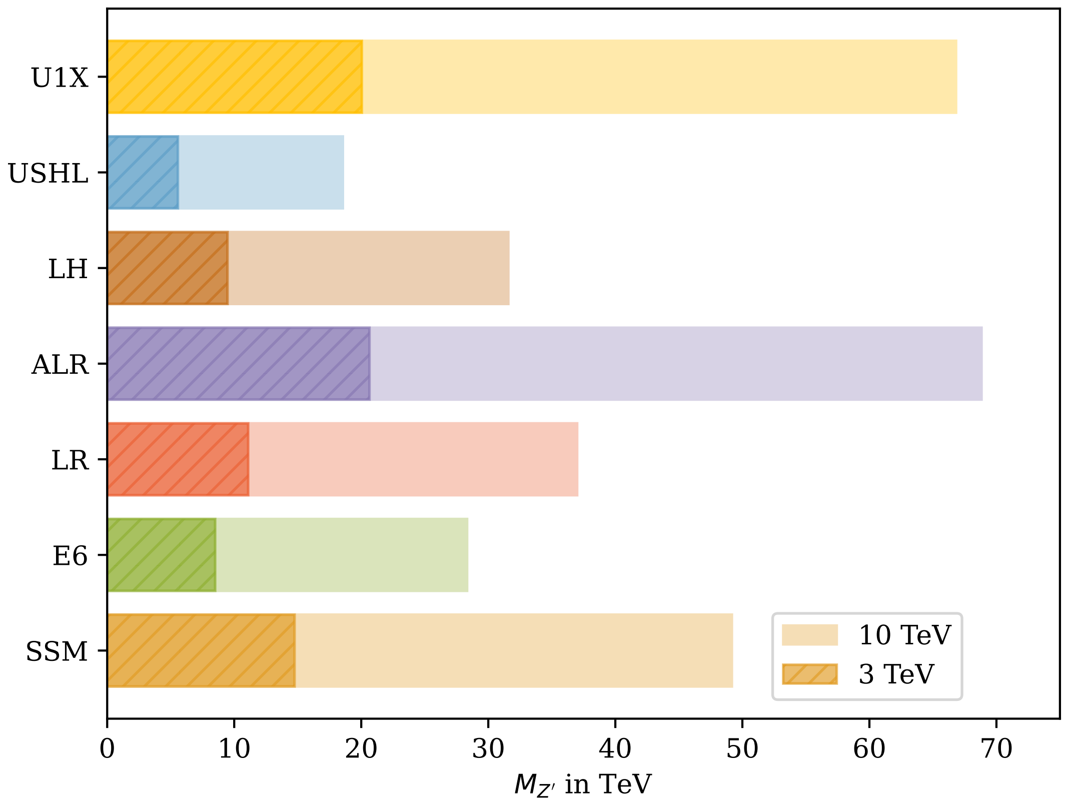
- **We find limits up to** $M_{Z'} \sim 70$ TeV
  (Note: current LHC limits up to ~ 5 TeV)
- Reach depends on magnitude of couplings
- Highest reach for ALR, due to large axial and vector couplings to leptons



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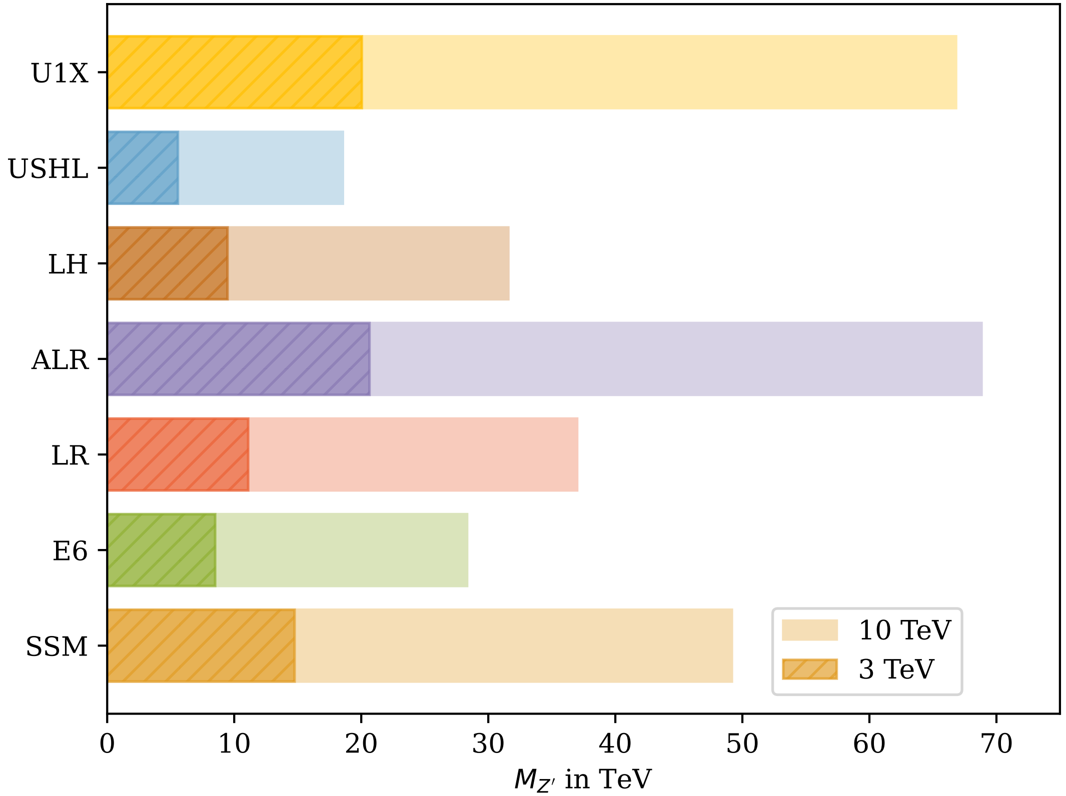
- Reach depends on magnitude of couplings
- Highest reach for ALR, due to large axial and vector couplings to leptons
- Extension to hadronic observables could push reach by up to $\sim 50\,\%$, depending on the model
  (see LEP-discussion [arXiv:hep-ph/9607306])



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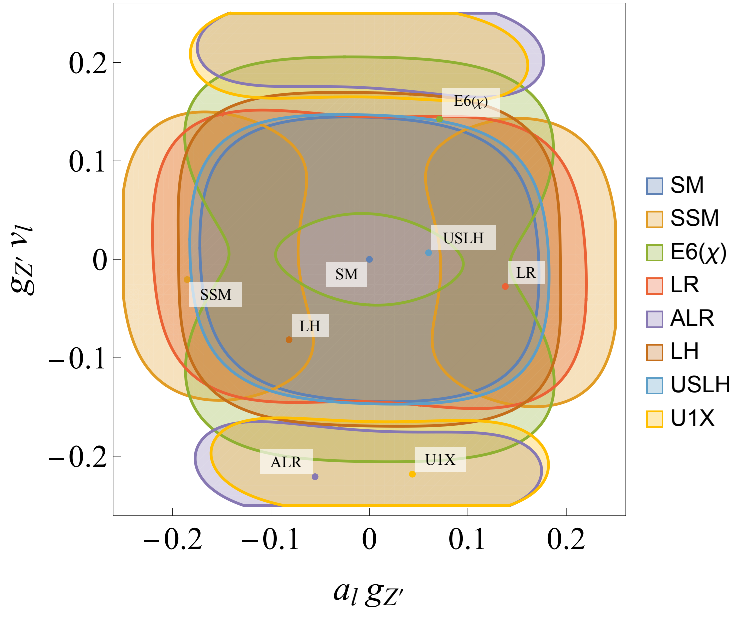
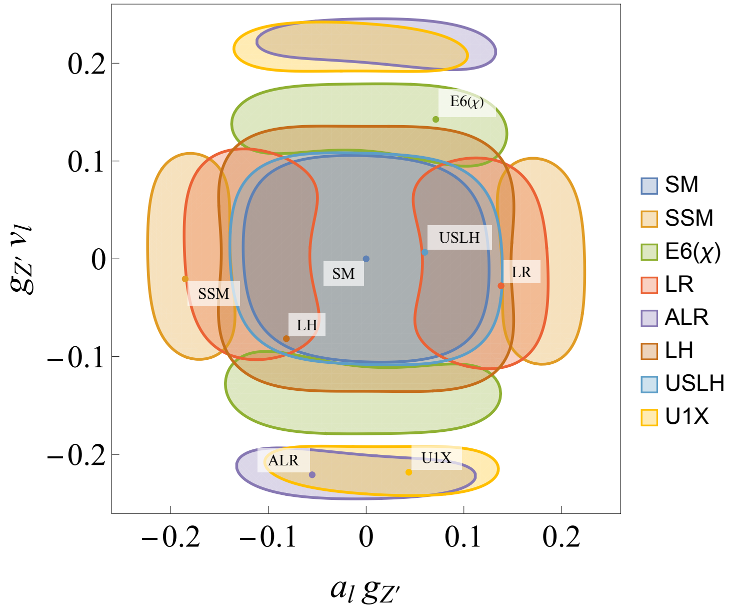
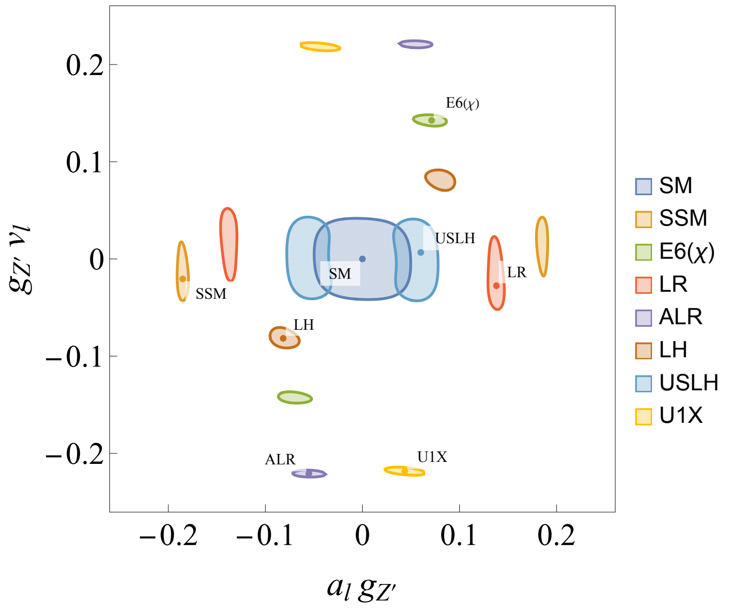
- **Resolution power** for $L_{int} = 10\,\mathrm{ab}^{-1}$, $E_{CM} = 10$ TeV, $P_{eff} = 0\,\%$ for three different Z′ masses



$M_{Z'} = 40$ TeV



$M_{Z'} = 30$ TeV



$M_{Z'} = 15$ TeV

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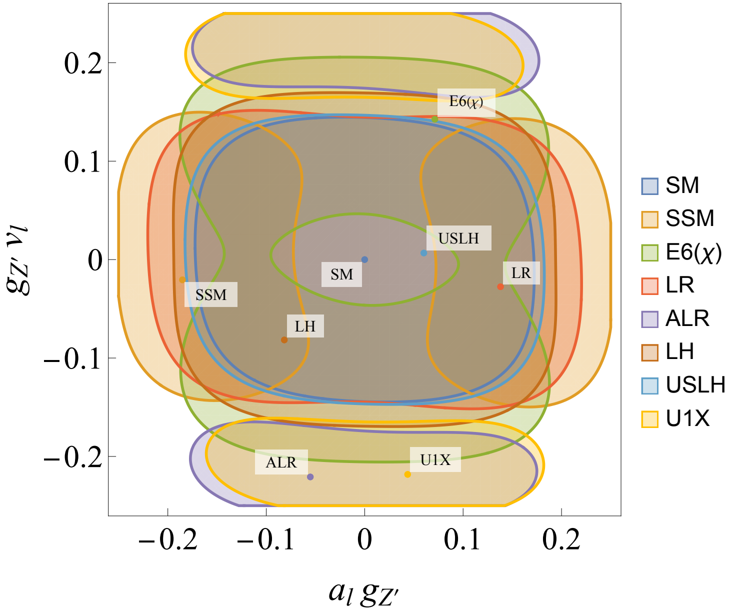

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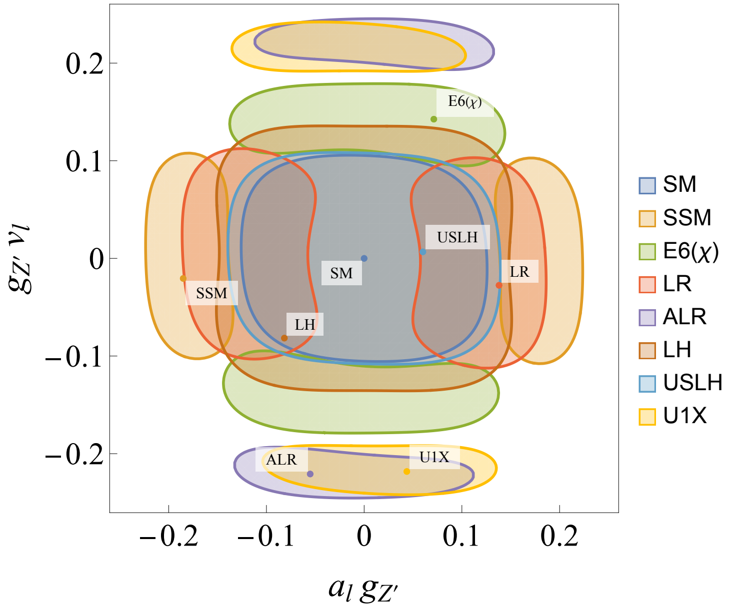

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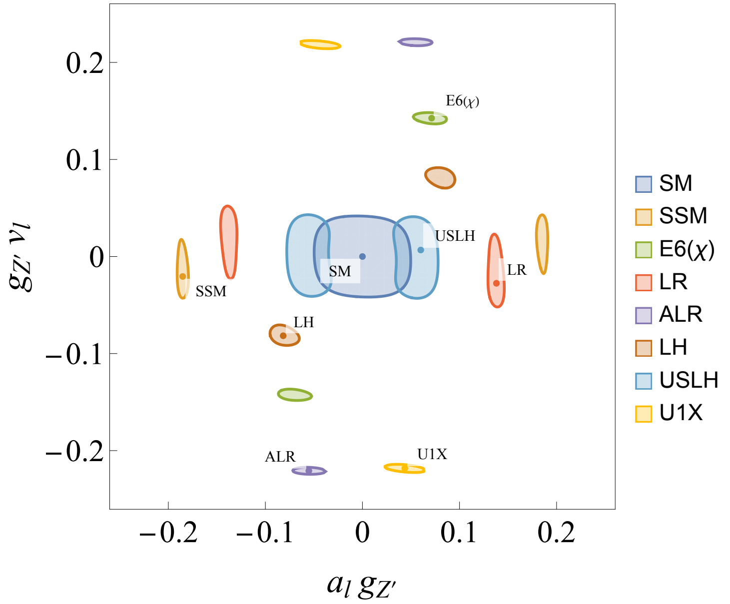

$M_{Z'} = 15\,\text{TeV}$

- **Significant resolution even without polarization**

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Polarization

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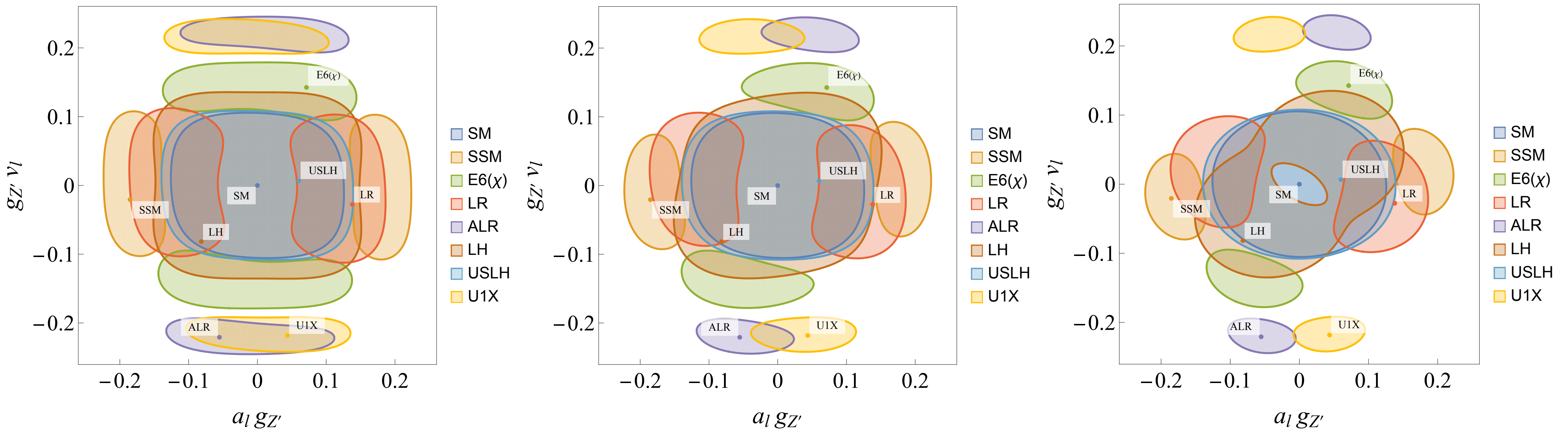

$P_{eff} = 0\,\%$, $\Delta_{sys}(A_{Pol}) = 5\,\%$ $\quad$ $P_{eff} = 30\,\%$, $\Delta_{sys}(A_{Pol}) = 5\,\%$ $\quad$ $P_{eff} = 0\,\%$, $\Delta_{sys}(A_{Pol}) = 1\,\%$

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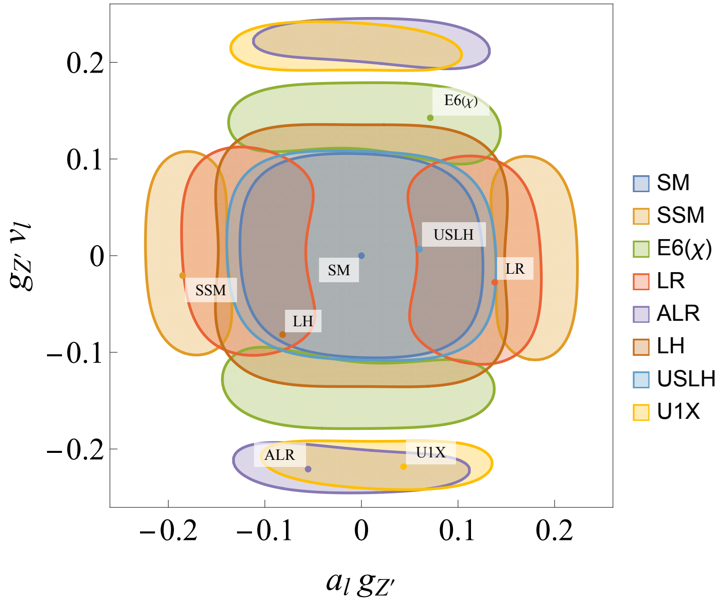

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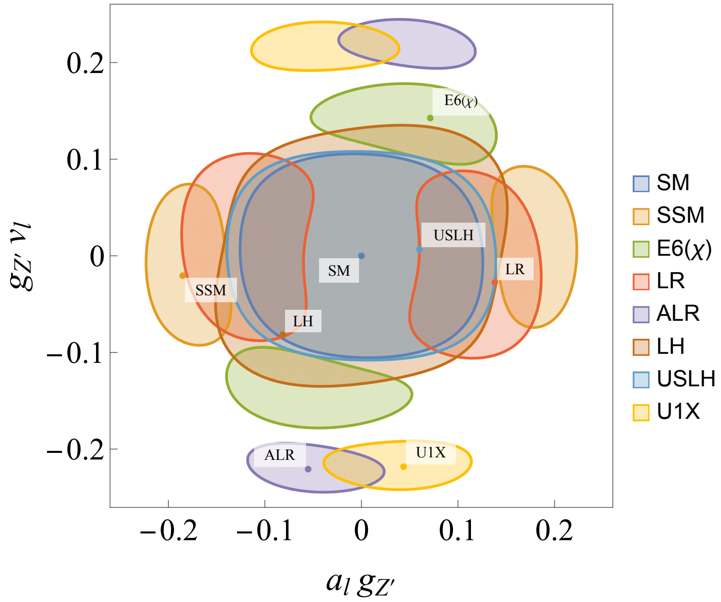

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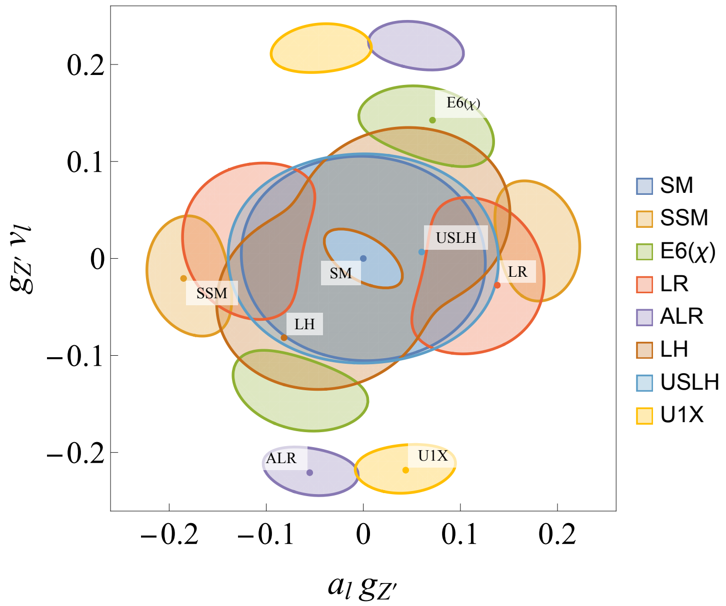

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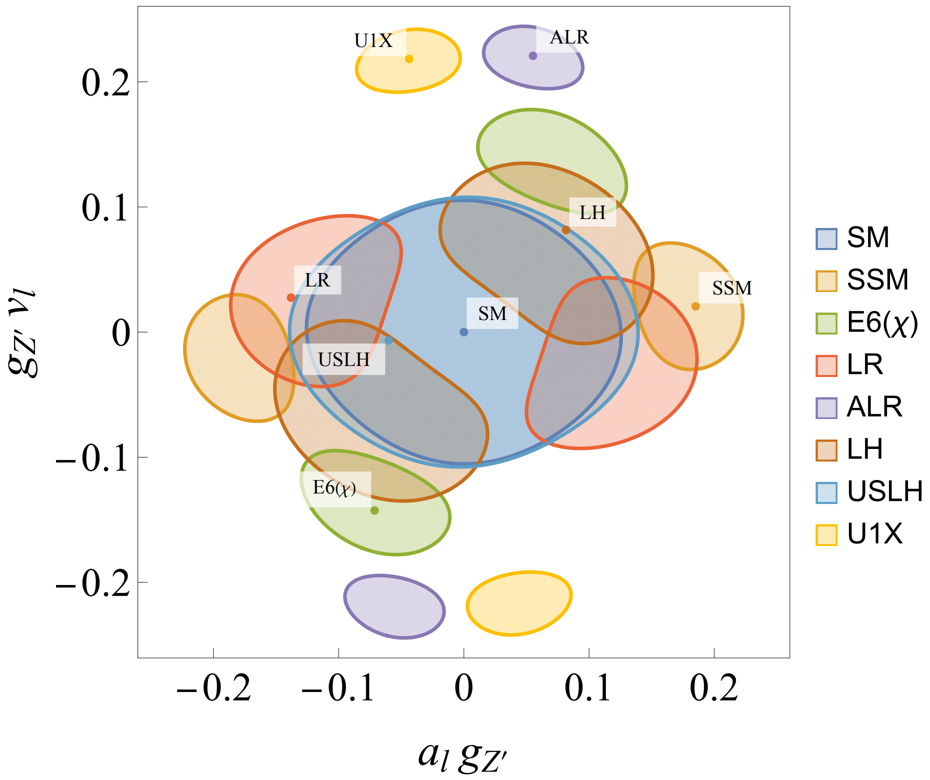
- Similar yields for either using polarized beams or low error on polarization measurement

Conclusion

What could we find at a muon collider?

- Variety of well-motivated **Z′ models** in the literature



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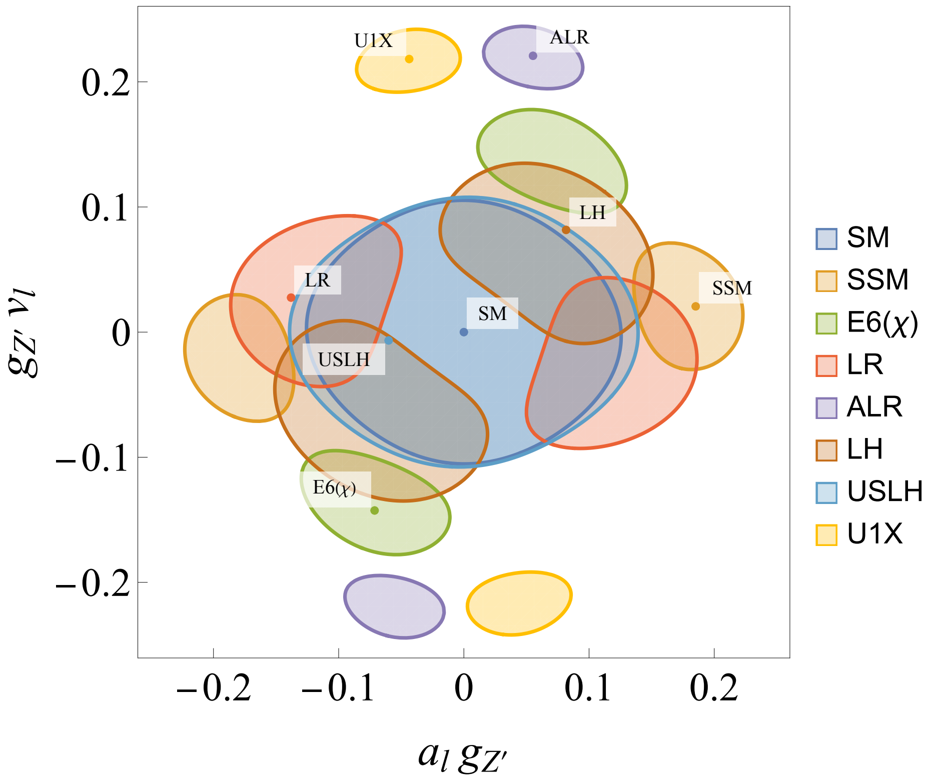
- **Muon collider** as a powerful tool for finding and resolving them



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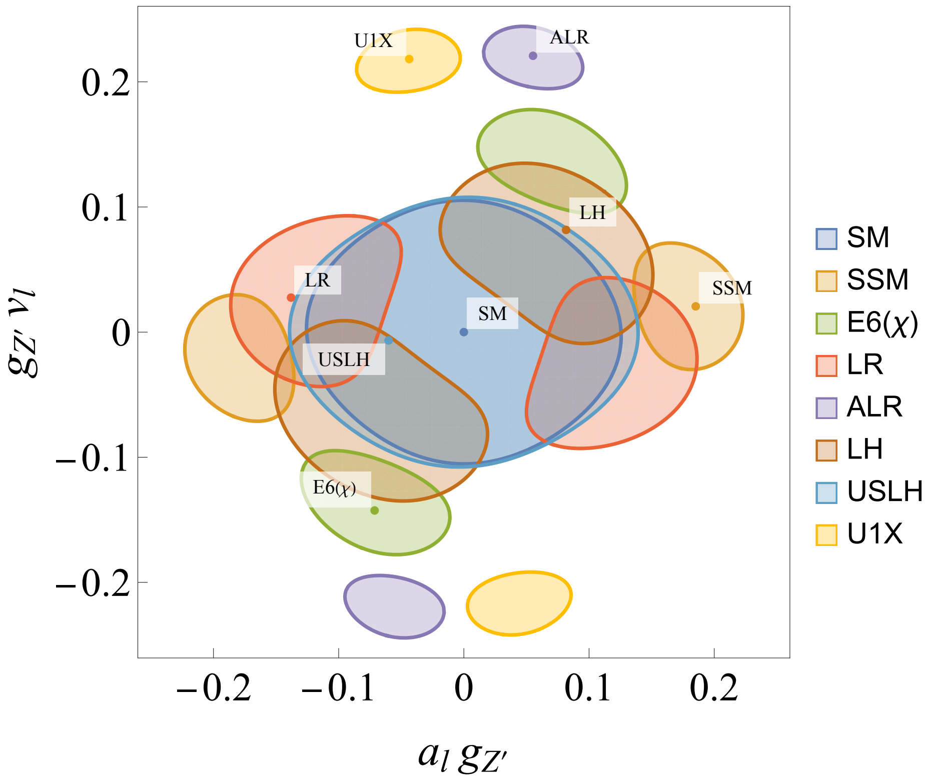

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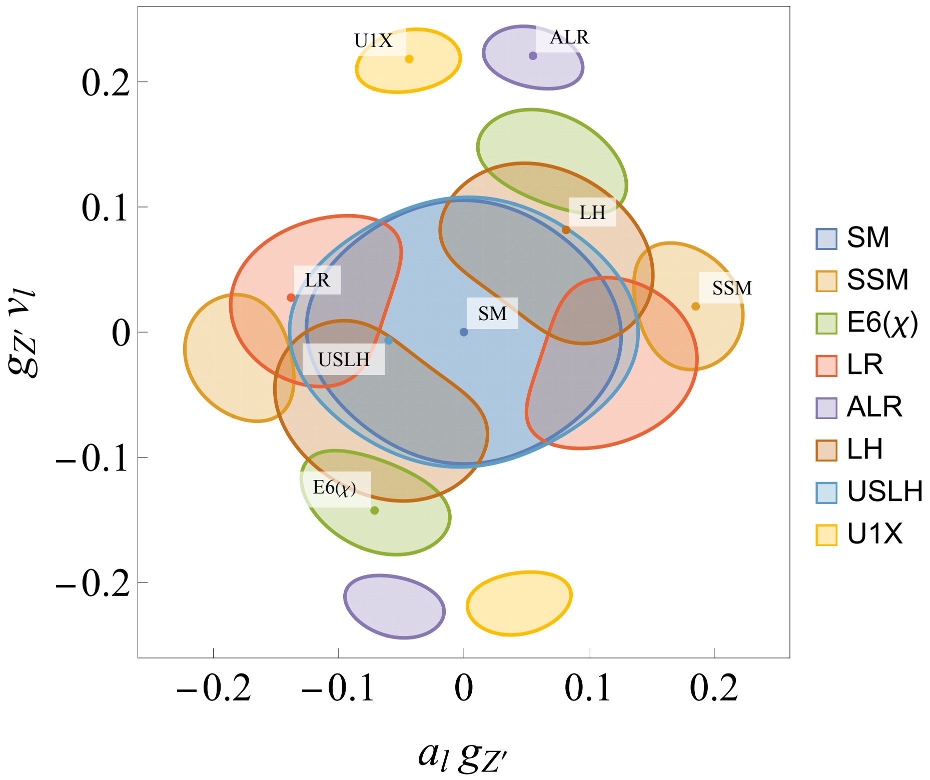

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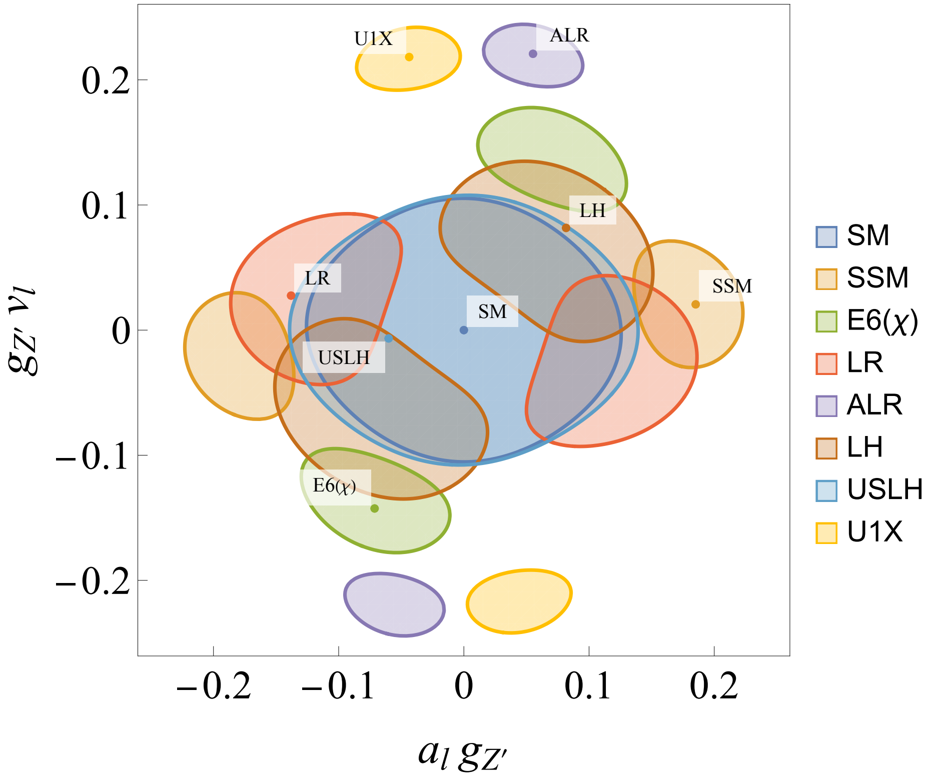

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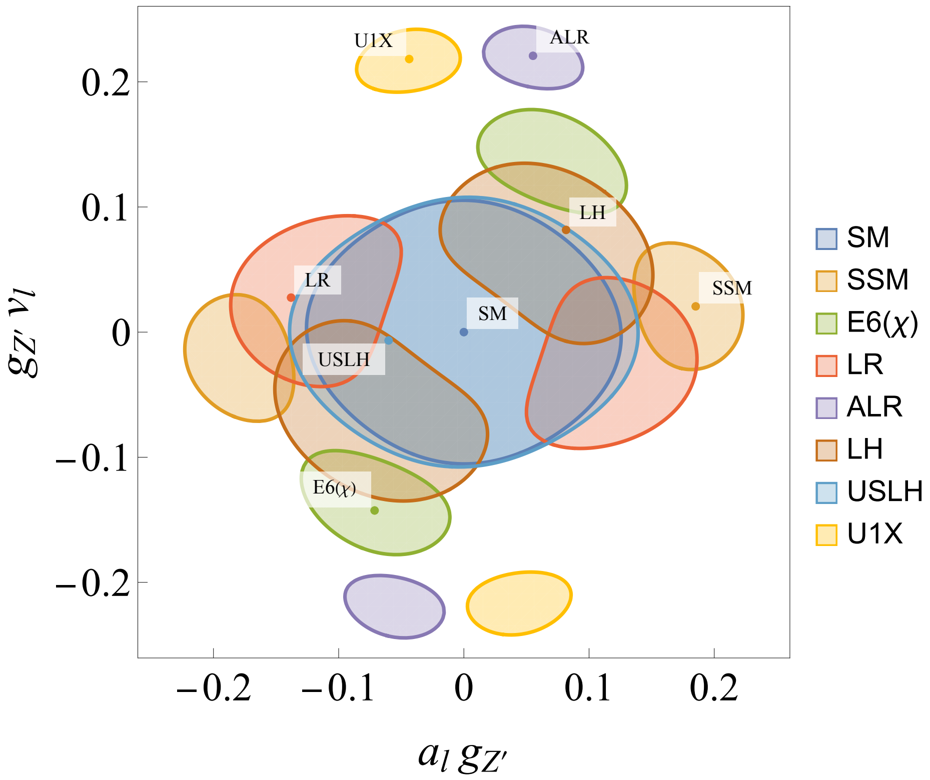

Thank you!

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