

Probing New Physics at a Muon Collider

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Aditya Gadam

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$$\begin{aligned} O_9^\ell &= (\bar{s}\gamma^\alpha P_L b)(\bar{\ell}\gamma_\alpha \ell) , \\ O_{10}^\ell &= (\bar{s}\gamma^\alpha P_L b)(\bar{\ell}\gamma_\alpha \gamma_5 \ell) , \\ O_S^\ell &= (\bar{s}P_R b)(\bar{\ell}\ell) , \\ O_P^\ell &= (\bar{s}P_R b)(\bar{\ell}\gamma_5 \ell) . \end{aligned}$$

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- Motivates *model independent* study of $b \rightarrow s \mu \mu$ operators: 4 fermion contact operators of dimension 6
- EFT with $\mathcal{O}(1)$ couplings: $\Lambda_{NP} \sim 35 \text{ TeV}$

Global Fits

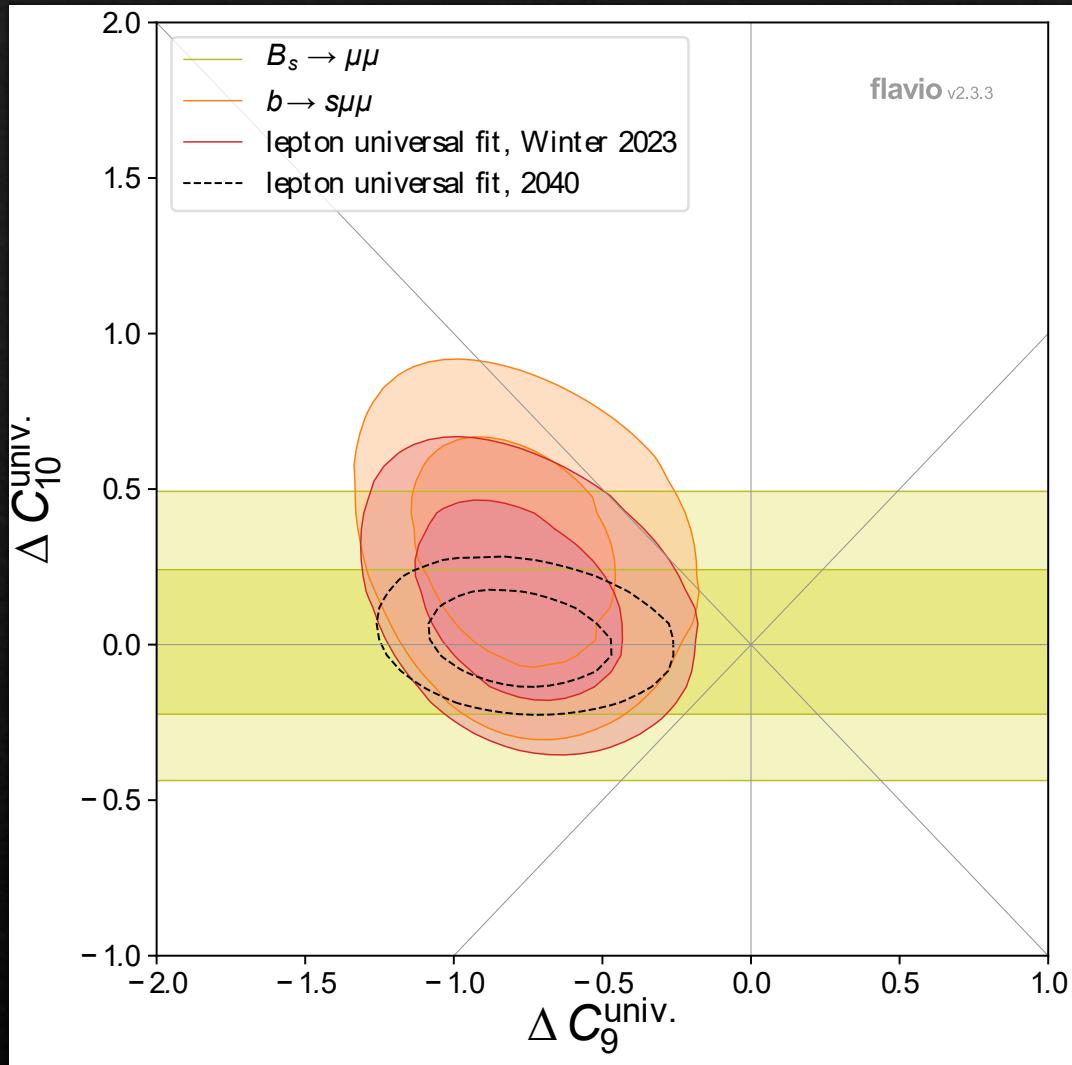
- LFU scenario motivated by the SM compatible* $R_K, R_{K^*}, \text{Br}(B_s \rightarrow \mu^+ \mu^-)$

*Status changed after LHCb update in Dec 2022

$$R_{K^{(*)}} \equiv \frac{\text{Br}(B \rightarrow K^{(*)} \mu^+ \mu^-)}{\text{Br}(B \rightarrow K^{(*)} e^+ e^-)}$$

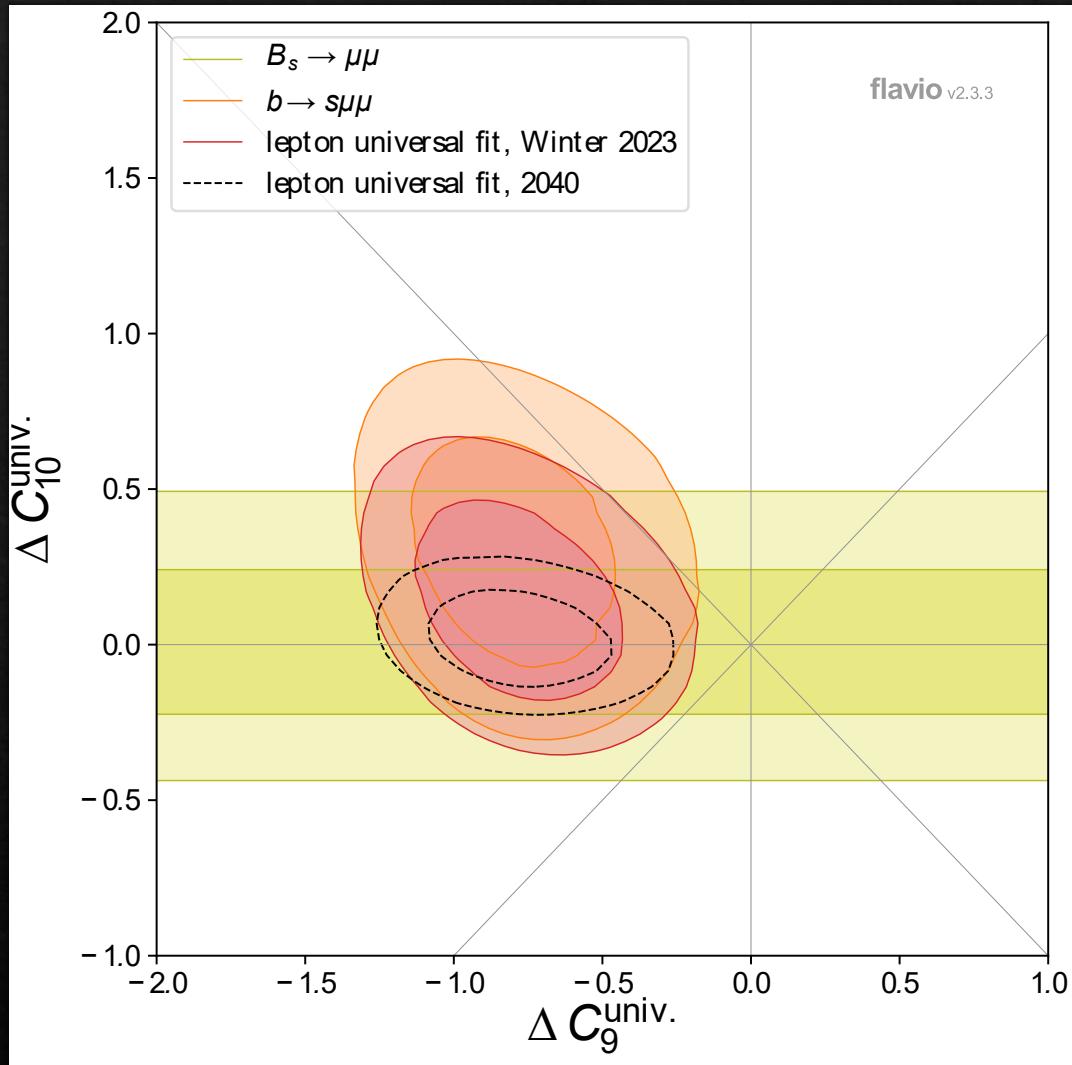
Global Fits

- Assuming a LFU scenario motivated by the tests $R_K, R_{K^*}, \text{Br}(B_s \rightarrow \mu^+ \mu^-)$, that are SM compatible
- Multivariate Gaussian fitting for best fit values:
 $\Delta C_9^{\text{univ.}} = -0.81 \pm 0.22$, $\Delta C_{10}^{\text{univ.}} = +0.12 \pm 0.20$,



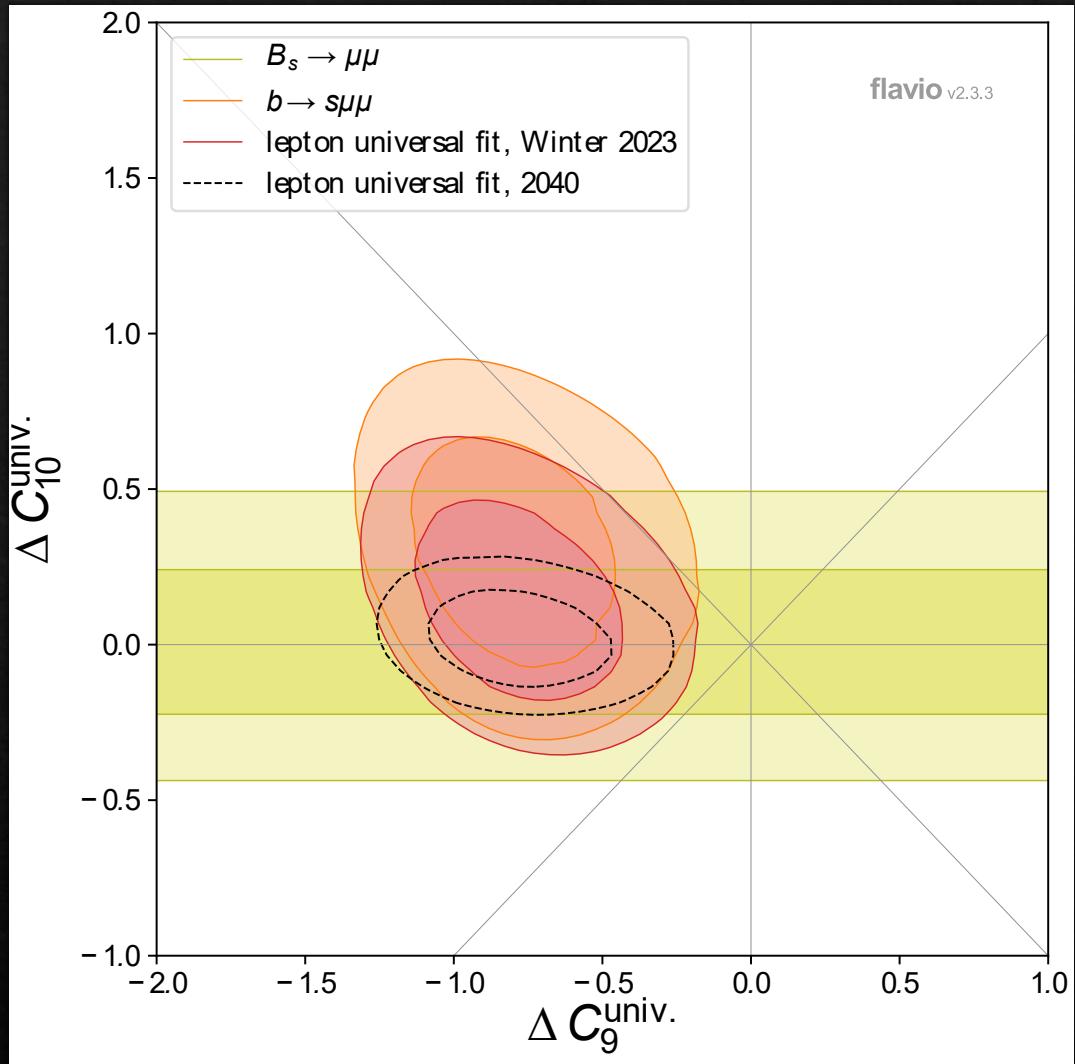
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- The $b \rightarrow s\mu\mu$ fit is sensitive to hadronic uncertainties
- Requires theoretically clean $b \rightarrow s\mu\mu$ tests: Muon Collider



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- ❖ Various competing backgrounds must still be considered

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- ❖ RG flow the coefficients to produce accurate benchmark values
- ❖ Test scenarios for no NP, as well as NP described by the global best fit

The Background

- ❖ **Irreducible one-loop** $\mu^+ \mu^- \rightarrow bs$

$$\sigma_{\text{bg}}^{\text{loop}} \propto \frac{G_F^2 m_t^4 \alpha^2}{128\pi^3} |V_{tb} V_{ts}^*|^2 \frac{1}{s} \quad (\texttt{FormCalc})$$

The Background

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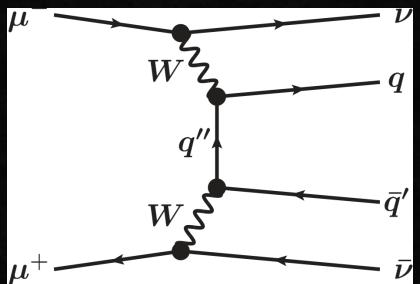
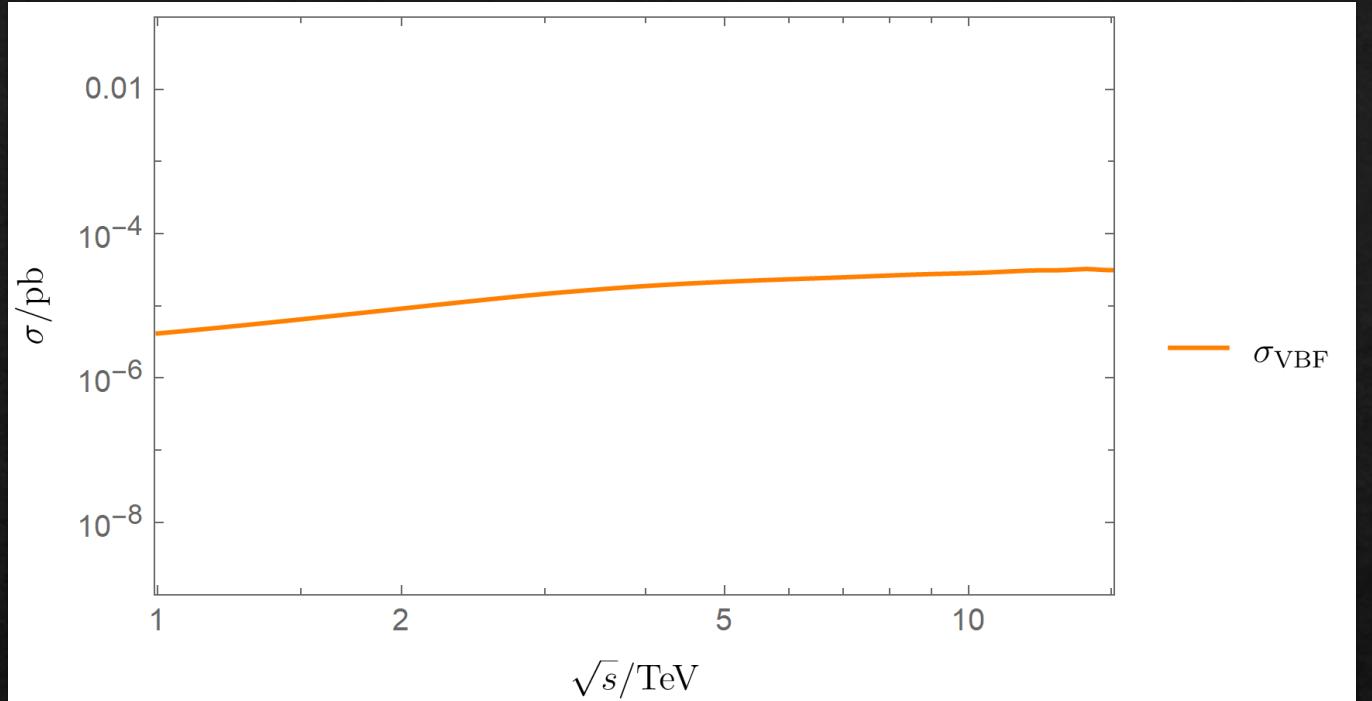
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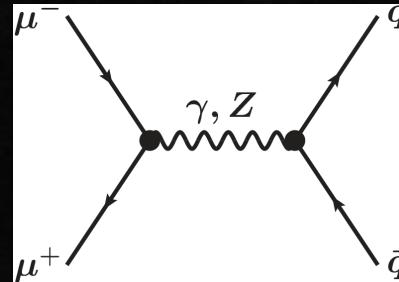
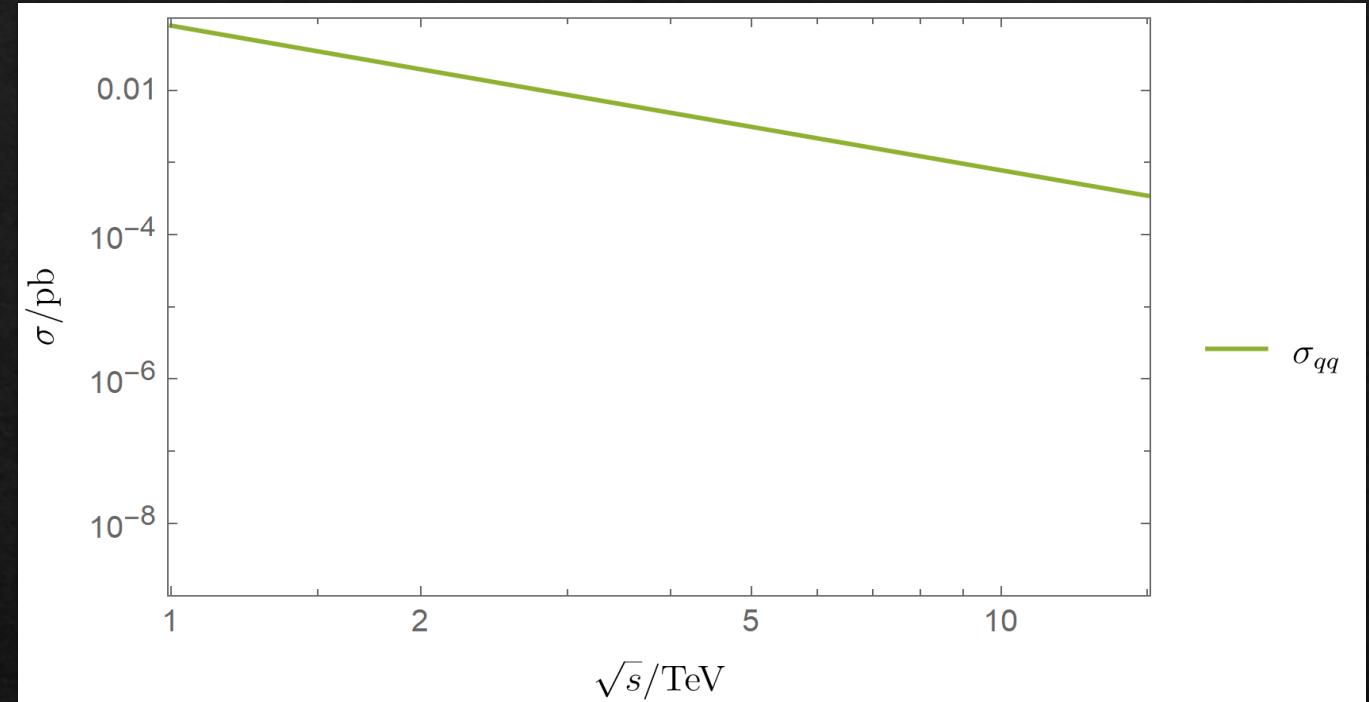
- ❖ **Missing energy** $\mu^+ \mu^- \rightarrow qq' \nu\nu$

Monte Carlo: `MadGraph`

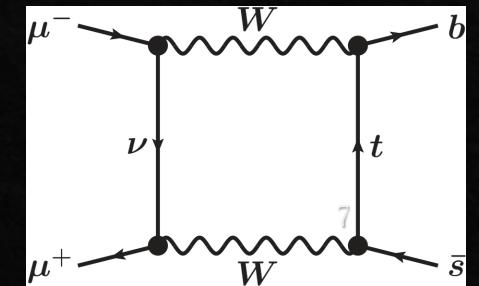
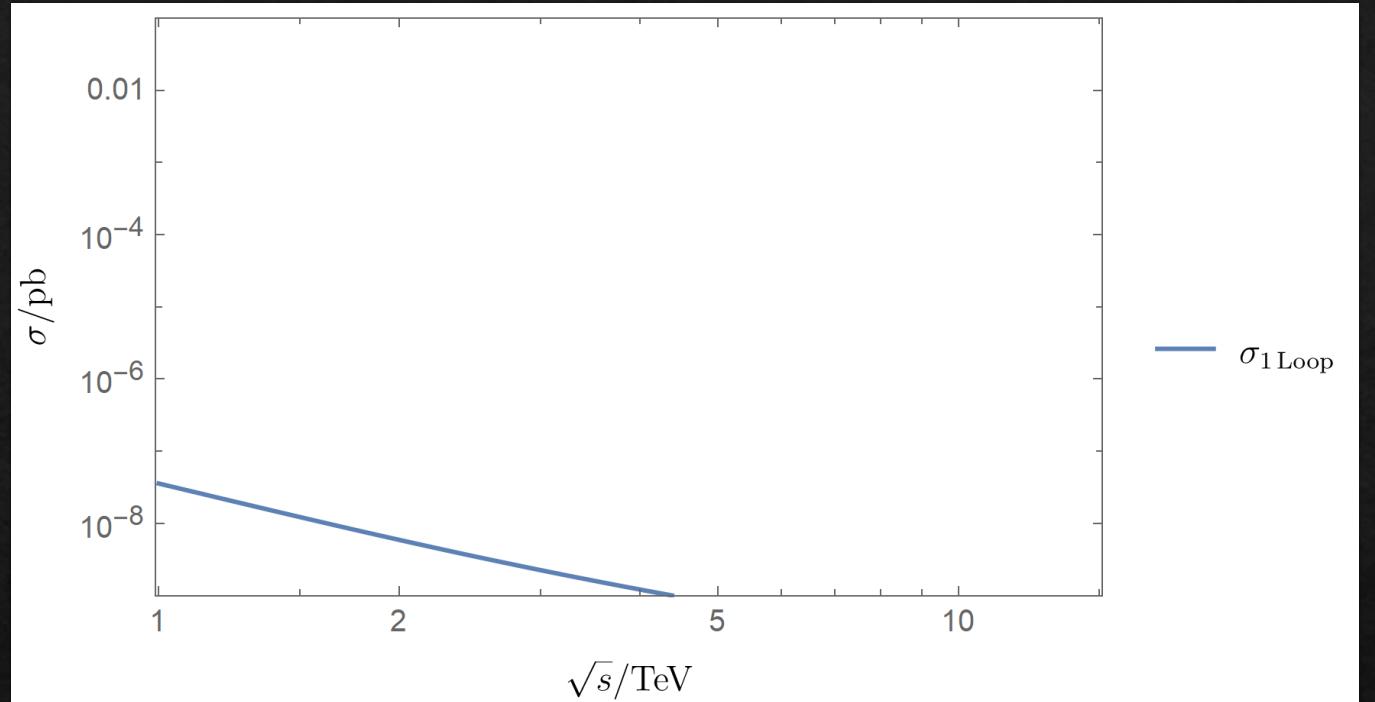
The Verdict on Sensitivity



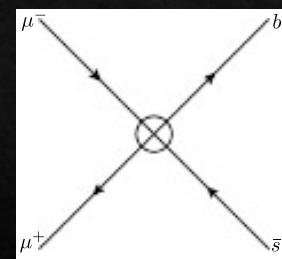
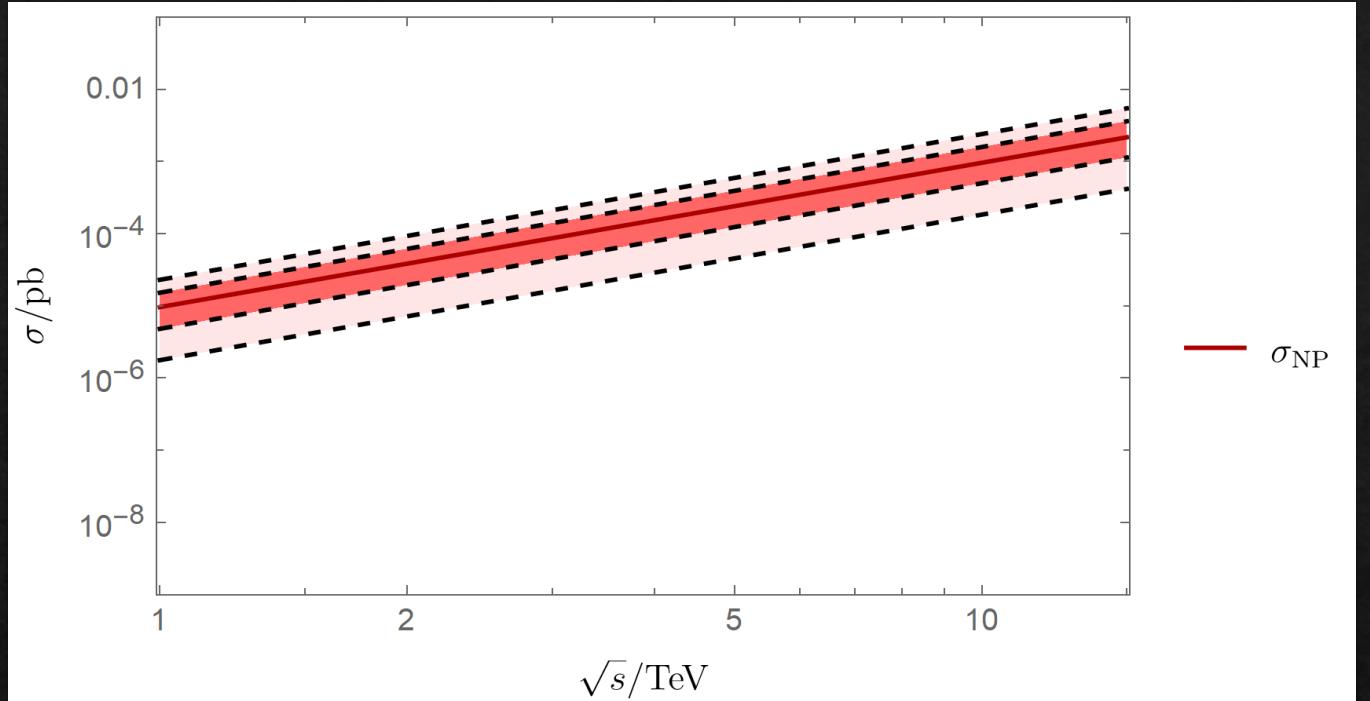
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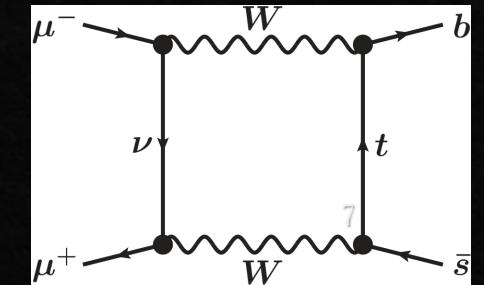
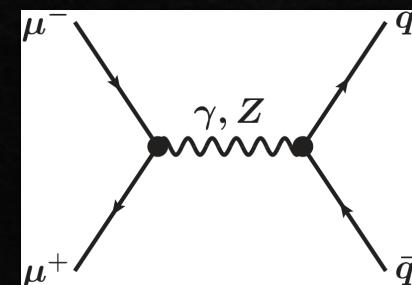
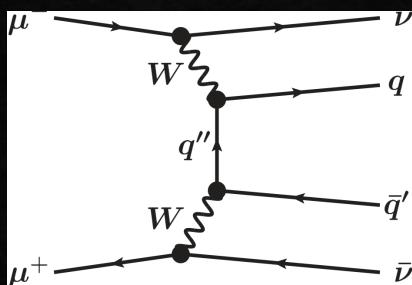
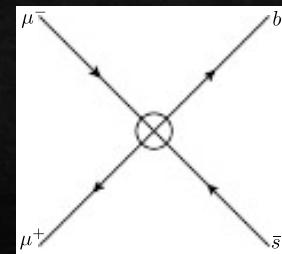
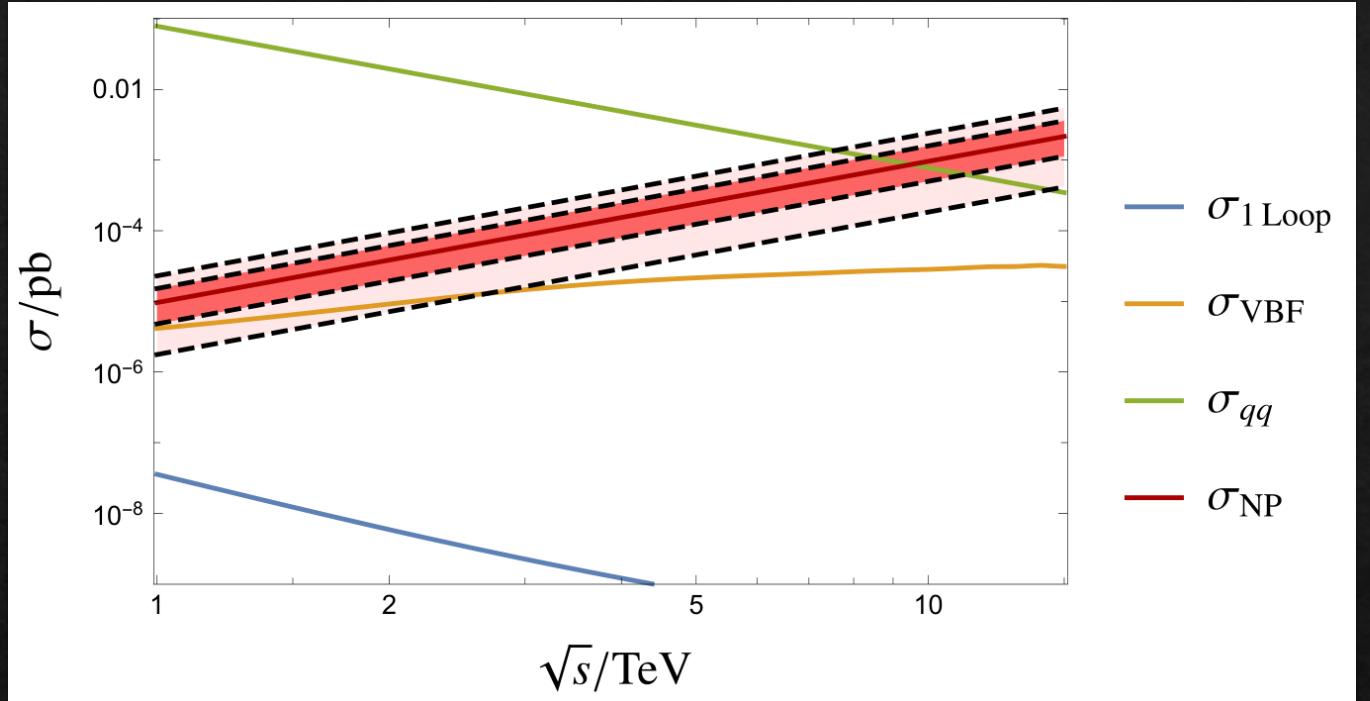
The Verdict on Sensitivity



- Evaluated at global best fit values
- Perturbative unitarity is safe: EFT has a natural cutoff

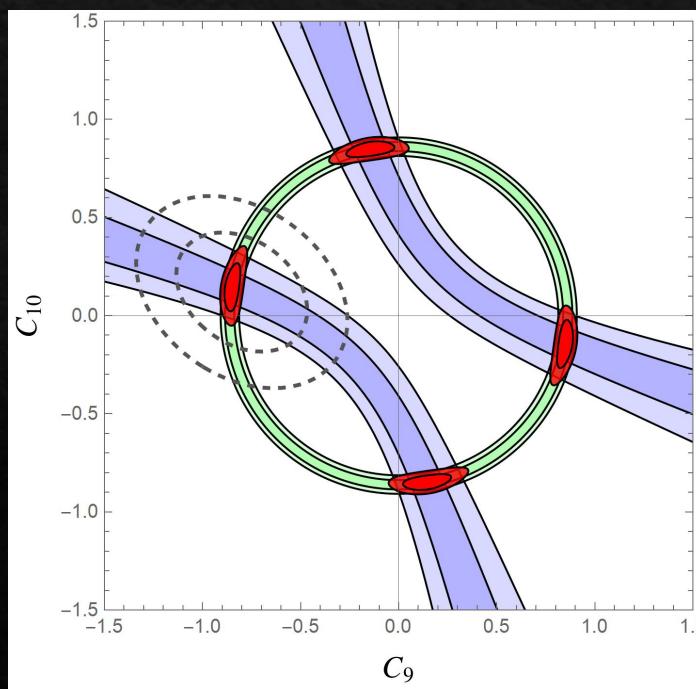
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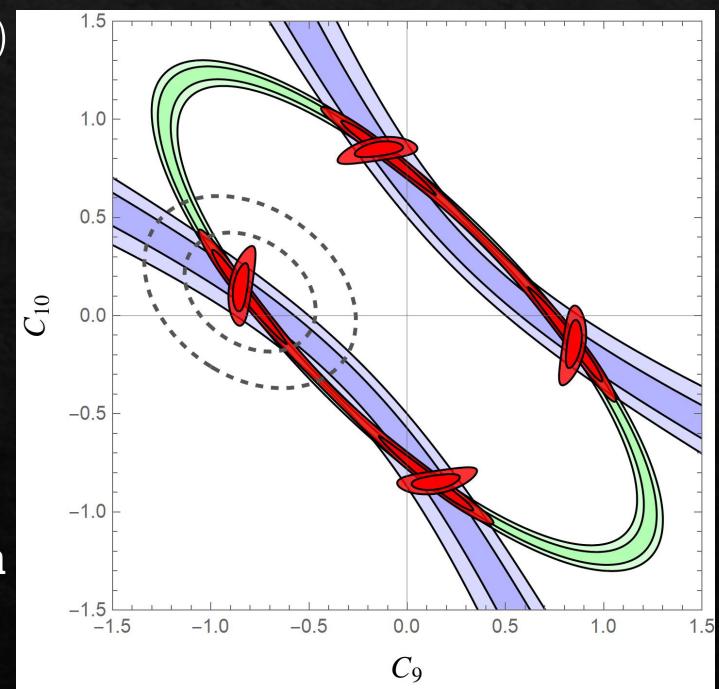


Muon Collider: 10 TeV, 1 ab^{-1}

Unpolarized



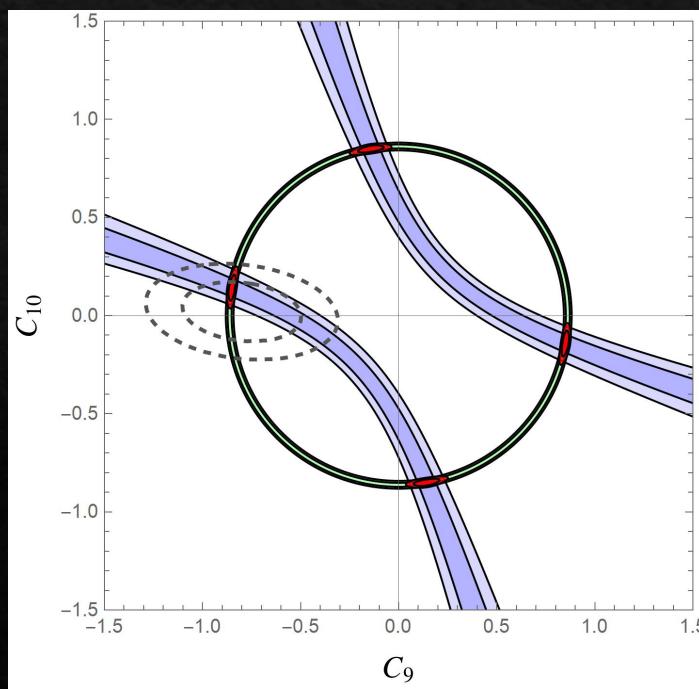
Polarized



- Assuming $\mathcal{A}_{\text{NP}} \sim \mathcal{A}_{\text{SM}}$ and $\mathcal{O}(1)$ couplings: $\Lambda_{\text{NP}} \sim 35 \text{ TeV}$
- Red: Joint Exclusion
- Purple: Forward Backward Asymmetry Exclusion (charge tagged)
- Green: Event Number Exclusion
- Dotted: B Decay Global Fit

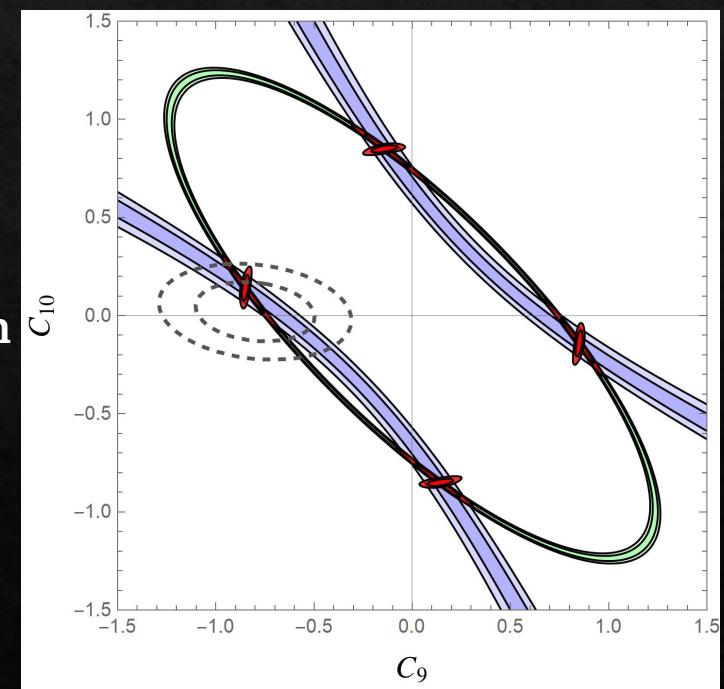
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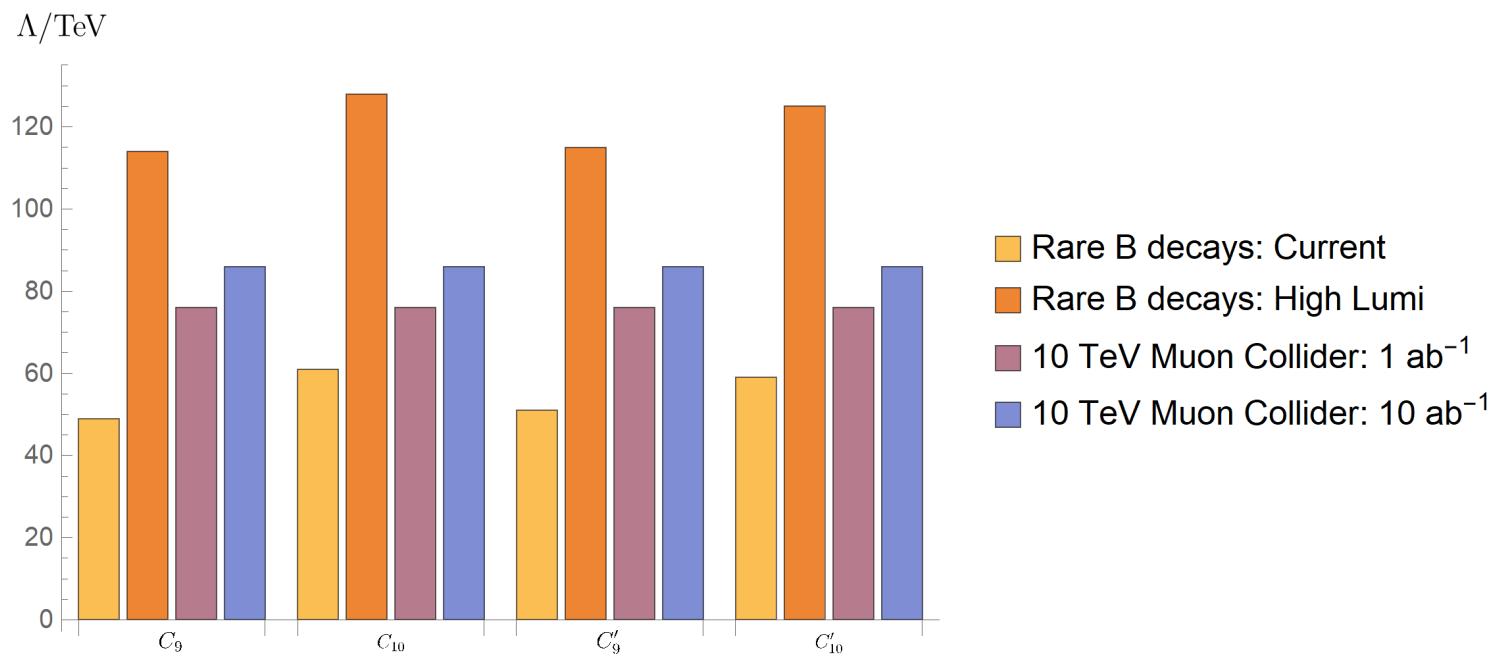
- Red: Joint Exclusion
- Purple: Forward Backward Asymmetry Exclusion
- Green: Event Number Exclusion
- Dotted: Projections of B Decay Global Fit
- Assuming unchanged central values through the HL-LHC era

Polarized



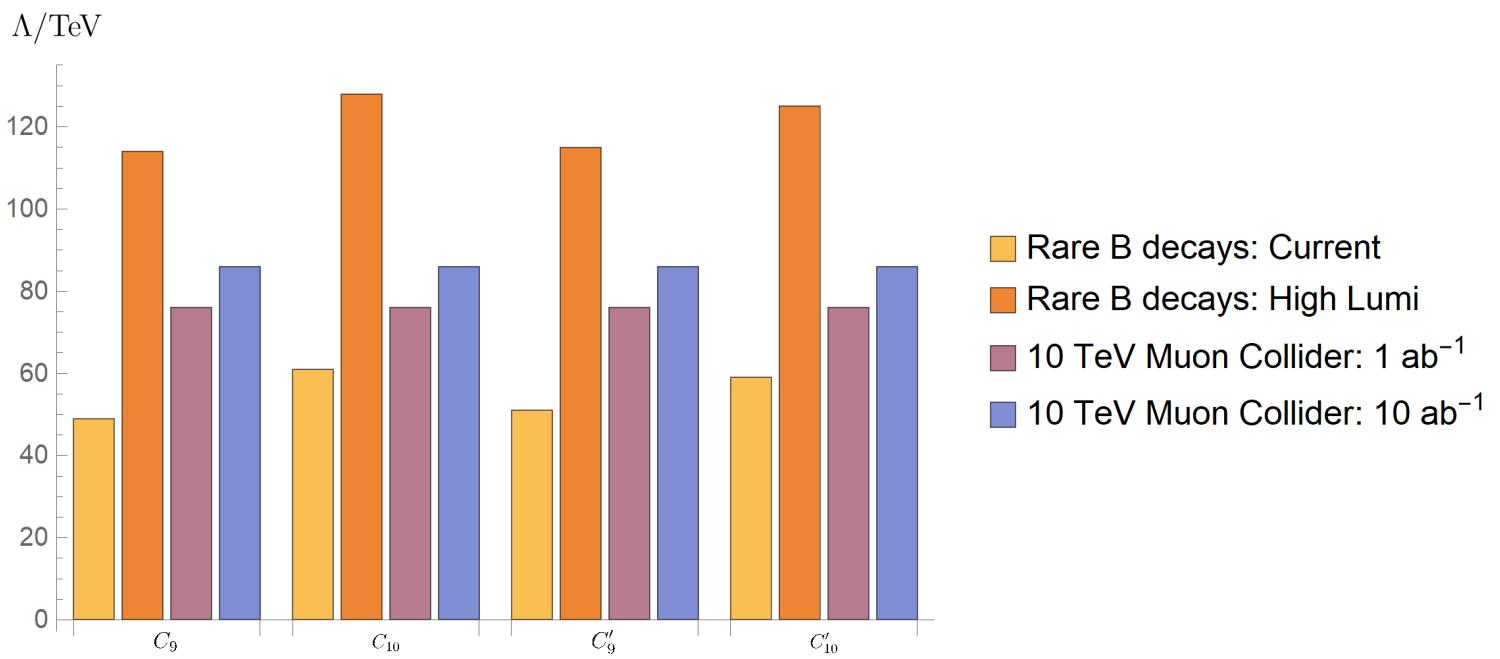
No NP Scenario

- Allows us to probe much higher scales than the generic expectation of 35 TeV



No NP Scenario

- ❖ Allows us to probe much higher scales than the generic expectation of 35 TeV
- ❖ Provides strong exclusions on heavy new physics associated with the B sector



Conclusion

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- ❖ Polarized beams provide complementary data
- ❖ Adding muon collider data to global fits of B decays significantly improves precision, even at $1/\text{ab}$!

“

Thank you for your attention!

”

THE END

Questions?

References

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Backup Slides

Event Numbers

- Considering events from both final states
- Error accounts for theoretical signal, background, and considers systematic uncertainty at the 2% level independently
- Precision: 22%, 7% and 3% respectively

$$N_{\text{tot}} = N_{\text{bg}} + \mathcal{L} \times \epsilon_b (1 - \epsilon_s) \sigma(\mu^+ \mu^- \rightarrow bs)$$

$$N_{\text{bg}} = \mathcal{L} \times \sum_{q=u,d,s,c,b} 2\epsilon_q (1 - \epsilon_q) \sigma(\mu^+ \mu^- \rightarrow q\bar{q})$$

Unpolarized

	6 TeV, 4 ab ⁻¹	10 TeV, 1 ab ⁻¹	10 TeV, 10 ab ⁻¹
N_{tot}	10050 ± 220	$1,740 \pm 50$	$17,400 \pm 220$
N_{bg}	8670 ± 220	780 ± 42	$7,800 \pm 200$
N_{sig}	1380 ± 310	960 ± 68	$9,600 \pm 300$

Polarized

	6 TeV, 4 ab ⁻¹	10 TeV, 1 ab ⁻¹	10 TeV, 10 ab ⁻¹
N_{tot}	7890 ± 180	$1,490 \pm 50$	$14,580 \pm 190$
N_{bg}	6610 ± 180	600 ± 40	$5,947 \pm 160$
N_{sig}	1280 ± 250	890 ± 60	8905 ± 250

Forward Backward Asymmetry

$$N_{\text{sig, obs}}^{\text{F}, b\bar{s}} = \epsilon_{\pm} N_{\text{sig}}^{\text{F}, b\bar{s}} + (1 - \epsilon_{\pm}) N_{\text{sig}}^{\text{F}, s\bar{b}}$$

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$$A_{\text{FB}}^{\text{obs}} = (2\epsilon_{\pm} - 1) \left(\frac{N_{\text{sig}}}{N_{\text{tot}}} A_{\text{FB}} + \frac{N_{\text{bg}}}{N_{\text{tot}}} A_{\text{FB}}^{\text{bg}} \right)$$

$$\delta A_{\text{FB}}^{\text{obs}} = \frac{2}{N_{\text{tot}}^2} \sqrt{(N_{\text{obs}}^{\text{F}})^2 (\delta N_{\text{obs}}^{\text{B}})^2 + (N_{\text{obs}}^{\text{B}})^2 (\delta N_{\text{obs}}^{\text{F}})^2}$$

- We consider a charge tagging rate of 70%
- Ignore small corrections from mis-tagging flavor and charge
- Evaluate the observed asymmetry from the truth level asymmetries

	6 TeV, 4 ab ⁻¹	10 TeV, 1 ab ⁻¹	10 TeV, 10 ab ⁻¹
Unpolarized	(22.7 ± 1.7)%	(16.4 ± 2.9)%	(16.4 ± 1.6)%
Polarized	(xx.x ± x.x)%	(xx.x ± x.x)%	(xx.x ± x.x)%

Final Results

- ❖ We may also observe the incredible increase in precision relative to the global fits

$$1\text{ab}^{-1} : \Delta C_9^{\text{univ.}} = -0.81 \pm 0.03 , \quad \Delta C_{10}^{\text{univ.}} = 0.12 \pm 0.08$$

$$10\text{ab}^{-1} \Delta C_9^{\text{univ.}} = -0.81 \pm 0.01 , \quad \Delta C_{10}^{\text{univ.}} = 0.12 \pm 0.04$$

vs

$$\Delta C_9^{\text{univ.}} = -0.81 \pm 0.22 , \quad \Delta C_{10}^{\text{univ.}} = +0.12 \pm 0.20 ,$$

RGE Running

$$\begin{aligned}
\Delta C_9^\mu(m_b) &\simeq \Delta C_9^\mu(\sqrt{s}) \left[1 - \frac{n_\ell \alpha}{3\pi} \log\left(\frac{s}{m_b^2}\right) - \frac{\alpha}{16\pi s_W^2} \left(\frac{1}{c_W^2} + 2 + \frac{m_t^2}{2m_W^2} \right) \log\left(\frac{s}{m_Z^2}\right) \right] \\
&+ \Delta C_{10}^\mu(\sqrt{s}) \left[\frac{\alpha}{2\pi} \log\left(\frac{s}{m_b^2}\right) + \frac{\alpha}{16\pi s_W^2} \left(\frac{1}{c_W^2} + 2 \right) (1 - 4s_W^2) \log\left(\frac{s}{m_Z^2}\right) \right], \\
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&+ \Delta C_9^\mu(\sqrt{s}) \left[\frac{\alpha}{2\pi} \log\left(\frac{s}{m_b^2}\right) + \frac{\alpha}{16\pi s_W^2} \left(\frac{1}{c_W^2} + 2 \right) (1 - 4s_W^2) \log\left(\frac{s}{m_Z^2}\right) \right]
\end{aligned}$$