A JOURNEY TO FLAVOR TOWN

A THESIS DEFENSE/OFFENSE

ADITYA

ADVISOR (AND PERSON TO DIRECT COMMENTS AND QUESTIONS TO):

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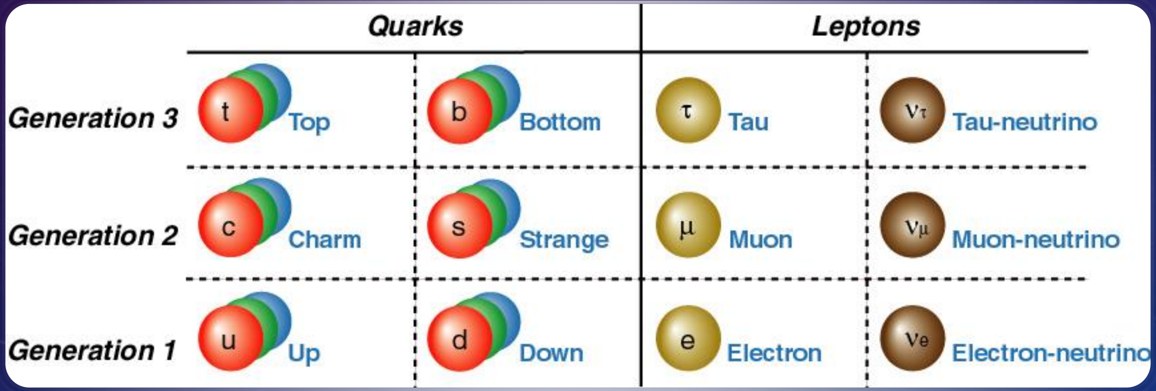
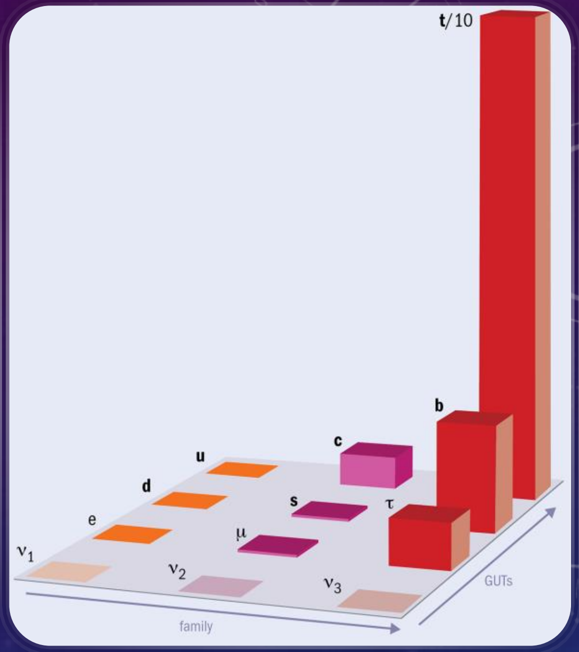


WHAT IS FLAVOR?

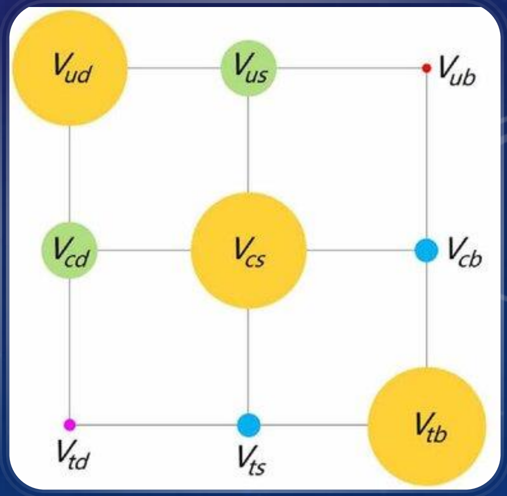
- The Standard Model (SM) is an excellent predictor of particle phenomena
- It encloses a description of several particles (irreps of various groups, notably the Poincare)
- Flavor physics revealed CP violation, provided hints of physics beyond the SM, and connects to the matter-antimatter asymmetry of the universe
- Flavor: distinction between species of elementary particles
- 6 flavors of quarks and leptons (different couplings, and Poincare and/or gauge invariants)
- Quarks: Up type and Down type; Leptons: Charged and Neutral (Different charge eigenstates)
- Strong and EM interactions are flavor diagonal
- Weak interactions *can* induce flavor changes

STANDARD MODEL FLAVOR PUZZLE

- All chiral fermions couple to a single Higgs field
- After electroweak symmetry breaking, generic Yukawa matrices would produce O(1) mixing between generations
- Diagonalized Yukawa matrix and CKM show a hierarchical peculiarity
- Mass hierarchies span an enormous 6 orders of magnitude
- Clear CKM hierarchies control decays, oscillations, mixing angles etc.
- The puzzle: WHY?
    - Why the hierarchical Yukawa structure? t'Hooft natural but not Dirac
    - Why the CKM hierarchy?
    - Why does the quark sector show minimal CP violation?
    - Why do neutrinos mix heavily but not quarks?



$$|V_{us}| \sim \lambda,\ |V_{cb}| \sim \lambda^2,\ |V_{ub}| \sim \lambda^3;\ \lambda \simeq 0.2$$



THE SUPERSYMMETRIC CLOCKWORK

AN ATTEMPT TO ANSWER

THE CLOCKWORK MECHANISM

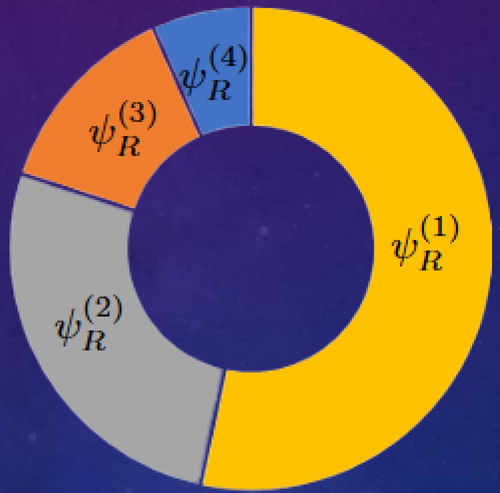
- The mechanism [Giudice et. al 1610.07962] can generate small (or large) scales from O(1) numbers
- As a quick introduction, let us consider a simple SM Clockwork, for the RH up quark $u_R \sim (3, 1, \frac{2}{3})$
  - Introduce N massless LH fermions $\{\psi_L^{(A)}\}$ and $N+1$ RH counterparts $\{\psi_R^{(A)}\}$
  - Global chiral symmetry present; Abelian factors $U(1)_L^{(A)}$ and $U(1)_R^{(A)}$
  - Break the symmetry: Spurions $m^{(A)} = m$ charged $(+1, -1)$ under $U(1)_L^{(A)} \times U(1)_R^{(A)}$ and $m_\chi^{(A)} = -m\chi$, charged $(+1, -1)$ under $U(1)_L^{(A)} \times U(1)_R^{(A+1)}$
  - One unbroken $U(1)$ factor $\implies$ One massless mode

$$\mathcal{L}_{breaking} = -m \sum_{A=1}^{N} \left(\overline{\psi}_L^{(A)} \psi_R^{(A)} - \chi \overline{\psi}_L^{(A)} \psi_R^{(A+1)} + \text{h.c.} \right)$$

CLOCKWORK: THE EXECUTION

The exponential suppression is made apparent by going to the mass eigen basis $\{\xi_R^{(A)}\}$

Observe the massless mode:



$$\xi_R^{(N+1)} = \mathcal{N} \sum_{A=1}^{N+1} \frac{\psi_R^{(A)}}{\chi^{A-1}}$$

$$\mathcal{N} \simeq 1$$

$$\text{Example: } \chi = 2, \quad N = 3$$

Massless mode has an exponentially suppressed overlap with the last pre-diagonalized gear.
Identify it with u_R and make everything else ***heavy*** $m \gg v$! Then,

$$\mathcal{L} \supset -\tilde{Y}^u \, \bar{q}_L \tilde{H} \, \psi_R^{(N+1)} \supset -\frac{1}{\chi^N} \tilde{Y}^u \, \bar{q}_L \tilde{H} \, u_R$$

CLOCKWORK AND THE SM

We consider the simplest setup:

- All quarks are identified with massless-modes after CW breaking
- Universal Clockwork breaking masses
- Universal gear ratios $\chi^{-1} = \lambda \sim 0.23$
- Gear numbers tune the scales [Alonso et. al 1807.09792]

$$Y_x^{ik} \simeq \tilde{Y}_x^{ik} \chi^{-N_q^i - N_x^k}, \qquad x \in \{u, d\}$$

$$N_q = \begin{pmatrix} 3 \\ 2 \\ 0 \end{pmatrix}, \quad N_u = \begin{pmatrix} 5 \\ 2 \\ 0 \end{pmatrix}, \quad N_d = \begin{pmatrix} 4 \\ 3 \\ 3 \end{pmatrix}$$

SUPERSYMMETRY

FIXING A *MASSIVE* PROBLEM

- The Higgs mass dependence on the UV cutoff and heaviest fields in the theory make the SM Higgs mass unlikely in its deviation from the Planck mass
- Supersymmetry is a well known, elegant, solution to the problem
- Superpartner contribution cancels the large mass corrections
- Clockwork theory can be extended with the SUSY principle!
- Our exploration regarded a simple SM flavor extension of the massless quarks and **heavy** gears:

$$W \supset \boldsymbol{\Phi}_{Q_i} \boldsymbol{m}_{Q_i} \boldsymbol{\Phi}_{Q_i^c} + \boldsymbol{\Phi}_{U_i} \boldsymbol{m}_{U_i} \boldsymbol{\Phi}_{U_i^c} + \boldsymbol{\Phi}_{D_i} \boldsymbol{m}_{D_i} \boldsymbol{\Phi}_{D_i^c} \\ + \tilde{Y}_u^{ij} H_u \boldsymbol{\Phi}_{Q_i} \boldsymbol{\Delta}_u^{ij} \boldsymbol{\Phi}_{U_j^c} + \tilde{Y}_d^{ij} H_d \boldsymbol{\Phi}_{Q_i} \boldsymbol{\Delta}_d^{ij} \boldsymbol{\Phi}_{D_j^c}$$

$\boldsymbol{\Phi}_{\psi_i}$: the chiral superfield corresponding to the subscripted fermion

$\boldsymbol{\Delta}_x^{ij}$: a projection operator selecting the massless gear fields corresponding to $(N_q^i + 1, N_x^j + 1)$

A BROKEN PRINCIPLE

SUSY has not been observed, to date. It must be broken at a scale higher than we can currently probe

- Gravity mediated soft SUSY breaking presents several new SUSY violating terms inducing squark and gear mixing
- We consider soft squark masses generated at the SUSY breaking scale $\mathcal{O}(\Lambda_{SUSY})$
- Gaugino masses are independent parameters

$$\begin{aligned}\mathcal{L}_{soft} \supset\ & \tilde{\mathbf{Q}}_i^\dagger \boldsymbol{\mu}_{Q_i}^2 \tilde{\mathbf{Q}}_i + \tilde{\mathbf{Q}}_i^{c\,\dagger} \boldsymbol{\mu}_{Q_i^c}^2 \tilde{\mathbf{Q}}_i^c + (M_Q^2)_{ij} \tilde{\mathbf{Q}}_i^\dagger \boldsymbol{\Delta}_Q^{ij} \tilde{\mathbf{Q}}_j \\ & + \tilde{\mathbf{U}}_i^\dagger \boldsymbol{\mu}_{U_i}^2 \tilde{\mathbf{U}}_i + \tilde{\mathbf{U}}_i^{c\,\dagger} \boldsymbol{\mu}_{U_i^c}^2 \tilde{\mathbf{U}}_i^c + (M_U^2)_{ij} \tilde{\mathbf{U}}_i^{c\,\dagger} \boldsymbol{\Delta}_U^{ij} \tilde{\mathbf{U}}_j^c \\ & + \tilde{\mathbf{D}}_i^\dagger \boldsymbol{\mu}_{D_i}^2 \tilde{\mathbf{D}}_i + \tilde{\mathbf{D}}_i^{c\,\dagger} \boldsymbol{\mu}_{D_i^c}^2 \tilde{\mathbf{D}}_i^c + (M_D^2)_{ij} \tilde{\mathbf{D}}_i^{c\,\dagger} \boldsymbol{\Delta}_D^{ij} \tilde{\mathbf{D}}_j^c \ ,\end{aligned}$$

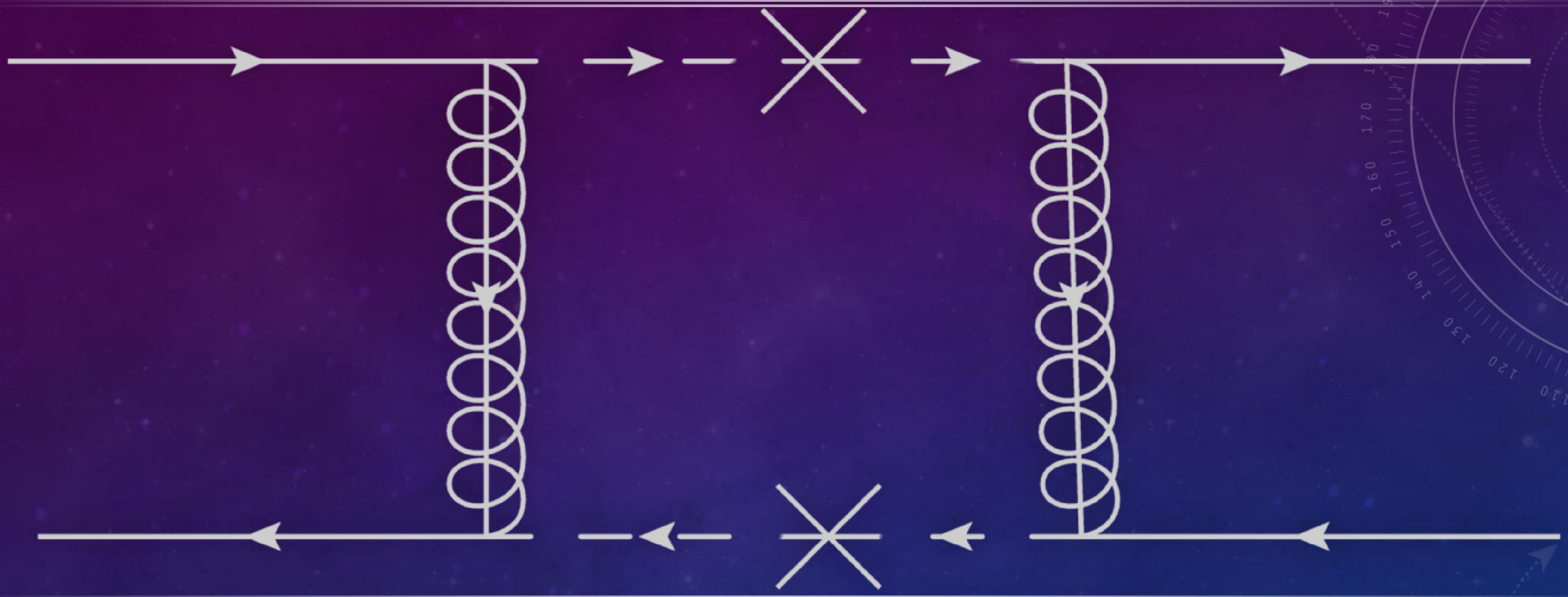
SQUARK MIXING

For a simplistic viability test, all soft breaking squark masses are set to m_S, and the gluino mass to m_g, with

$$\Lambda_{SUSY} \sim \max(m_S, m_g)$$

$$m_{\tilde{q}}^2 \simeq m_S^2 \begin{pmatrix} 1 & \chi^{-1} & \chi^{-3} \\ \chi^{-1} & 1 & \chi^{-2} \\ \chi^{-3} & \chi^{-2} & 1 \end{pmatrix},$$

$$m_{\tilde{u}}^2 \simeq m_S^2 \begin{pmatrix} 1 & \chi^{-1} & \chi^{-3} \\ \chi^{-1} & 1 & \chi^{-2} \\ \chi^{-3} & \chi^{-2} & 1 \end{pmatrix}, \quad m_{\tilde{d}}^2 \simeq m_S^2 \begin{pmatrix} 1 & \chi^{-1} & \chi^{-1} \\ \chi^{-1} & 1 & 1 \\ \chi^{-1} & 1 & 1 \end{pmatrix}$$



VALIDITY TESTING

DON'T GET IT MIXED UP

Tightest bounds on this theory are from Kaon mixing and decay processes: squark-gluino mediated box diagrams

Regimes of interest $\Delta m_K^{SUSY} < \delta(\Delta m_K^{SM}),\ |\epsilon_K^{SUSY}| < \delta\epsilon_K^{SM}$

$$\langle K^0|\, \overline{d}_L^\alpha \gamma_\mu s_L^\alpha \overline{d}_L^\beta \gamma^\mu s_L^\beta \,|\bar{K}^0\rangle = \frac{1}{3} B_1(\mu) m_K f_K^2,$$

$$\langle K^0|\, \overline{d}_R^\alpha s_L^\alpha \overline{d}_L^\beta s_R^\beta \,|\bar{K}^0\rangle = \frac{1}{4} B_4(\mu) m_K f_K^2 \frac{m_K^2}{(m_d(\mu)+m_s(\mu))^2},$$

$$\langle K^0|\, \overline{d}_R^\alpha s_L^\beta \overline{d}_L^\beta s_R^\alpha \,|\bar{K}^0\rangle = \frac{1}{12} B_5(\mu) m_K f_K^2 \frac{m_K^2}{(m_d(\mu)+m_s(\mu))^2}$$

$$C_i^{SUSY} \propto \alpha_s^2/\Lambda_{SUSY}^2$$

Bag parameters from lattice computations [Carrasco et. al 1505.06639]: $B_i(3\mathrm{GeV})$

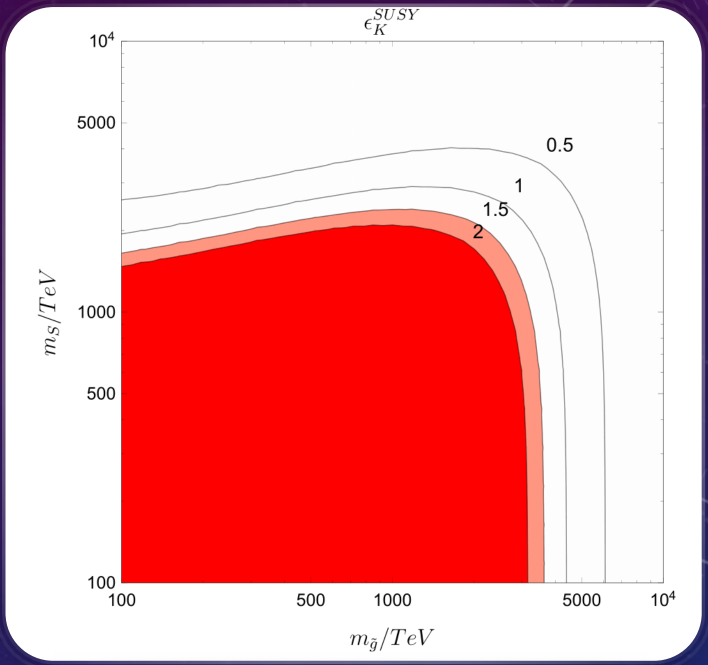
Use RGE matrices to flow Wilson coefficients $C_i^{SUSY}(\alpha_s; m_S, m_g)$ from $\Lambda_{SUSY} \to 3\ \mathrm{GeV}$, to evaluate $\vec{C}_{SUSY} \cdot \langle\vec{O}\rangle$

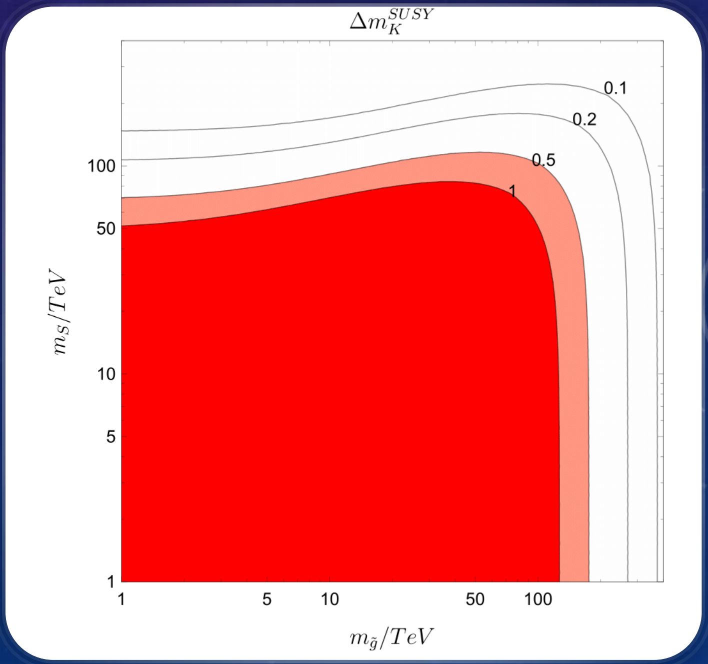
The complex result gives us $\Delta m_K^{SUSY} + i\epsilon_K^{SUSY}$

VALID PARAMETER SPACE

The ϵ_K plot indicates some contours labelling the ratio of the Clockwork SUSY contribution to ϵ_K to the theoretical uncertainty of the SM ϵ_K prediction in [Brod et. al, 1911.06822].

The Δm_K plot tracks the ratio of the corresponding New Physics contribution to Δm_K to the Standard Model experimental value found in the PDG review.





SUMMARY

- Clockwork is an answer to a part of the SM Flavor Puzzle: ***Hierarchies*** in quark masses, and the CKM
- Compatibility with SUSY can address another big discrepancy in scales: the Higgs mass and Planck scale
- The full theory is valid if $\Lambda_{SUSY} > 3 \text{ PeV}$
- The "simplest" model works, but must be fine tuned to ameliorate the Higgs sensitivity to the new UV of $\Lambda_{SUSY} > 3 \text{ PeV}$
- Further flavor mixing and fine-tuning can be incorporated and tweaked by having non-universal masses and gear ratios

2 B OR μ TO B – THAT IS THE QUESTION

AN ANALYSIS OF B DECAYS AT A MUON COLLIDER

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RARE B DECAYS

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

GLOBAL FITS

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

*Status changed after LHCb update in Dec 2022

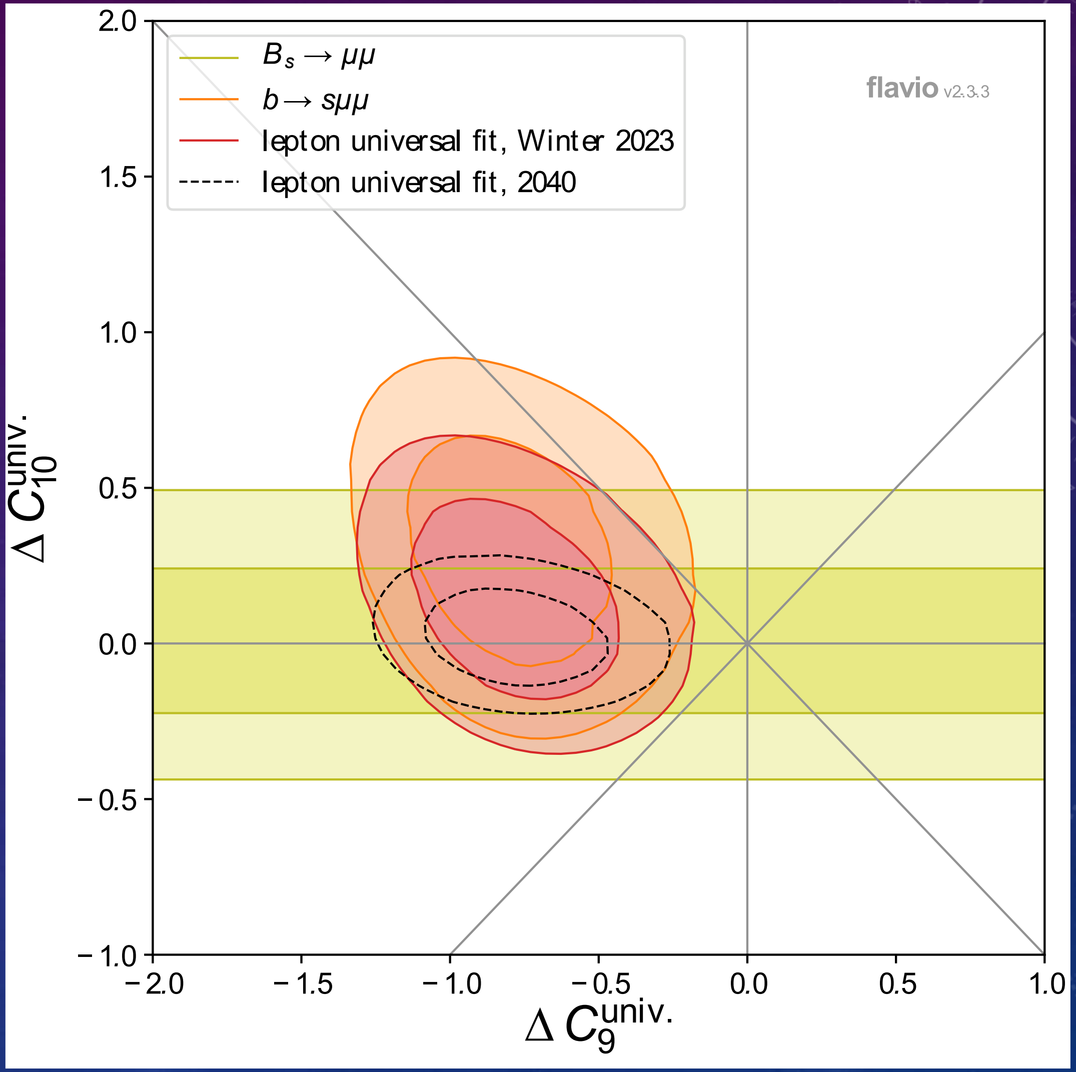
$$R_{K^{(*)}} \equiv \frac{\mathrm{Br}(B \to K^{(*)}\mu^+\mu^-)}{\mathrm{Br}(B \to K^{(*)}e^+e^-)}$$

GLOBAL FITS

- Assuming a LFU scenario motivated by the tests $R_K, R_{K^*}, \mathrm{Br}(B_s \to \mu^+\mu^-)$, that are SM compatible

- Multivariate Gaussian fitting for best fit values:

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



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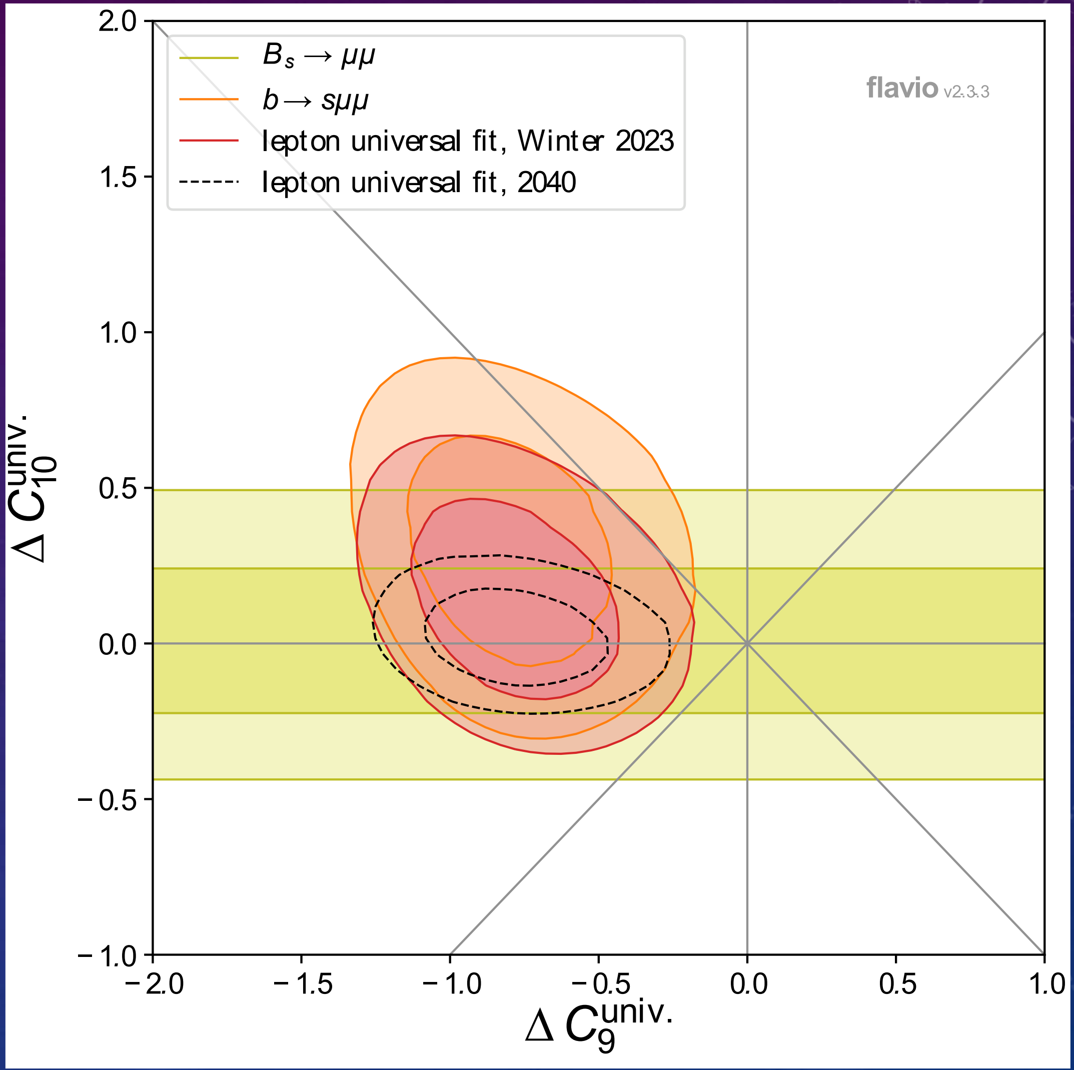

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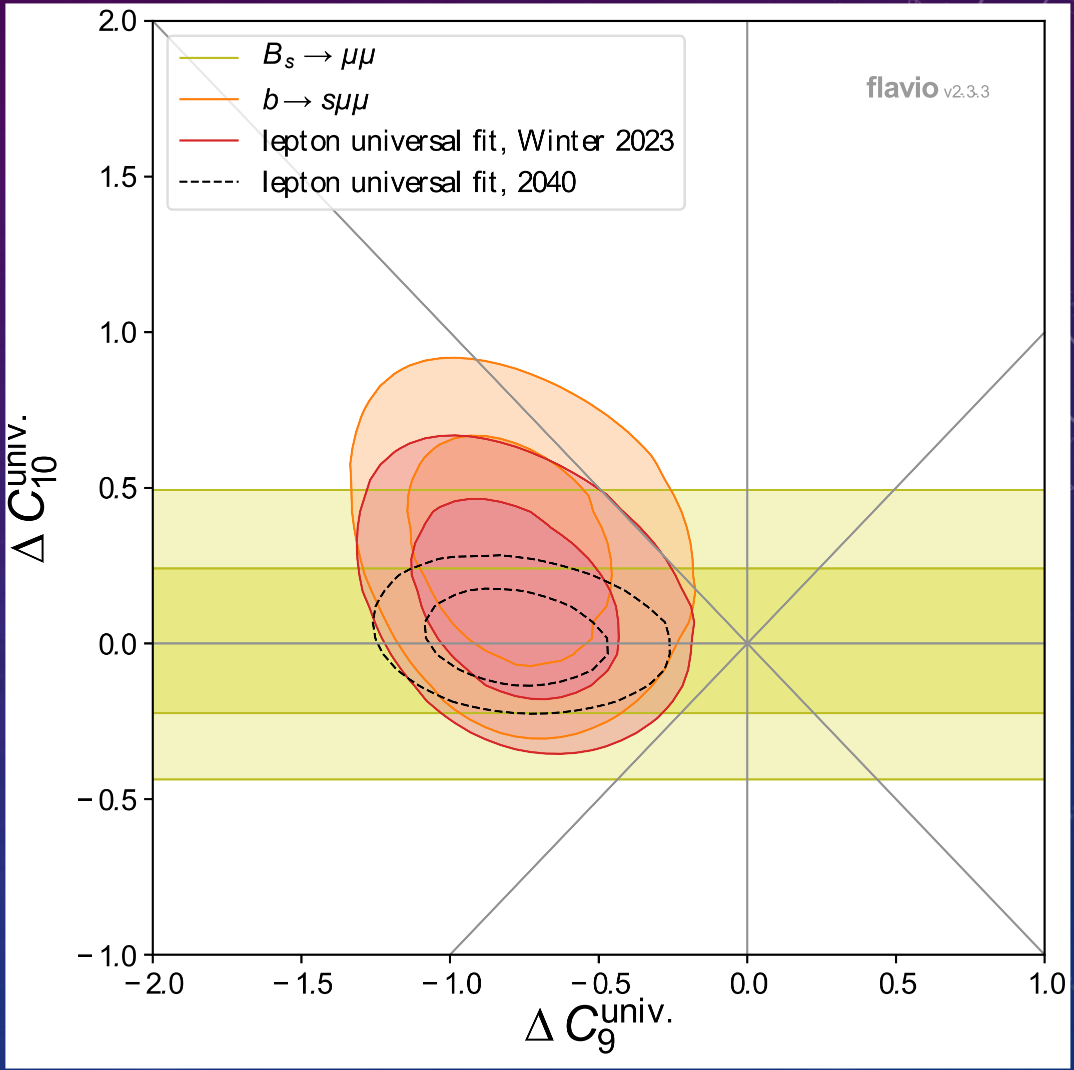
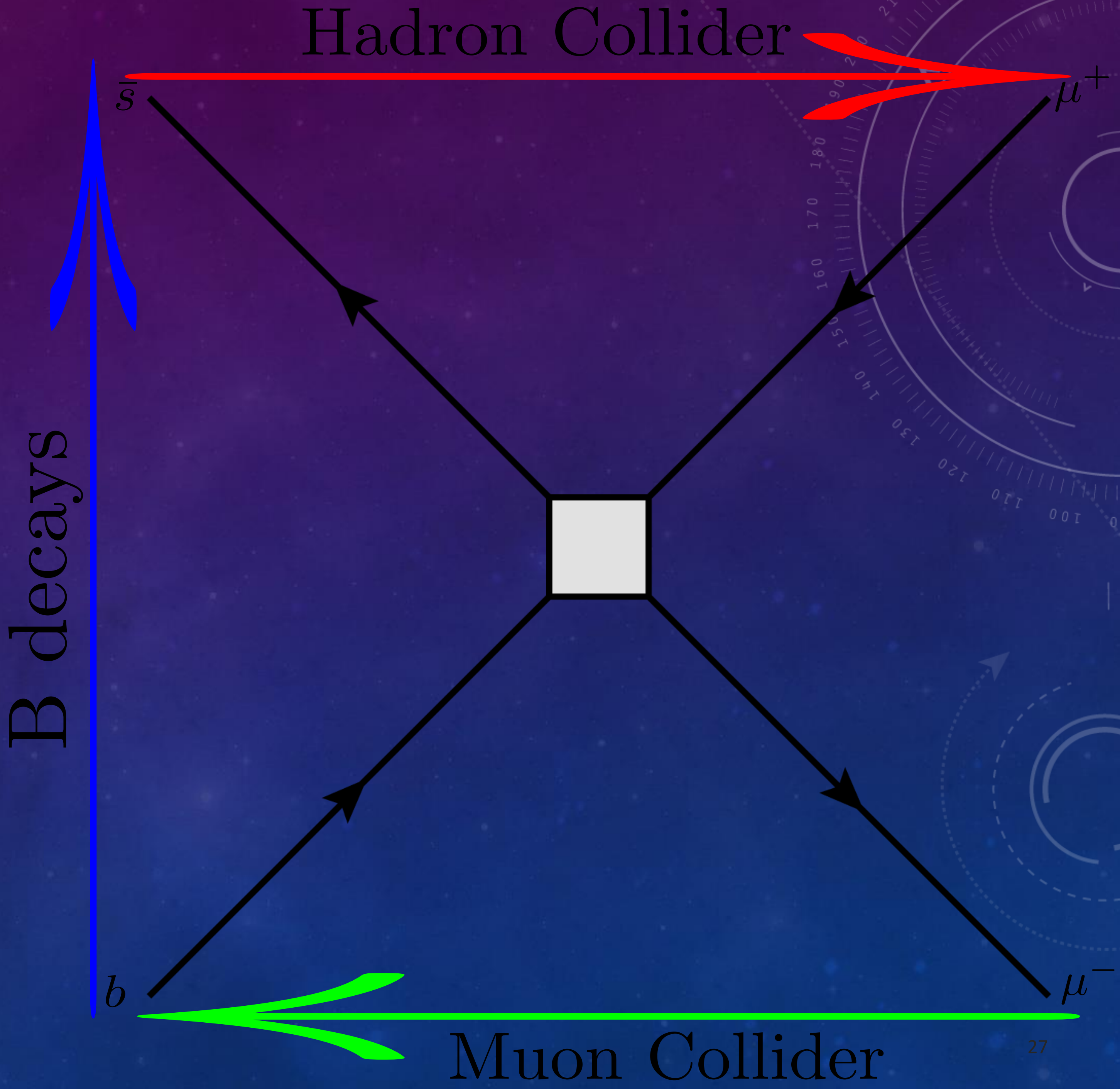
- **The $b \to s\mu\mu$ fit is sensitive to hadronic uncertainties**

- **Requires theoretically clean $b \to s\mu\mu$ tests: Muon Collider**



EXPLORING THE OPERATOR



AT A MUON COLLIDER

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- Excess/shortages in events and angular distributions constrain Wilson coefficients
- Various competing backgrounds must still be considered

THE ANALYSIS

- Compute differential cross section from polarized beams for $\mu^+\mu^- \to bs$

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- Evaluate observables corresponding to various scenarios in $\sqrt{s}$, $\mathcal{L}$
- 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** $\mu^+\mu^- \to bs$

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

THE BACKGROUND

- Irreducible one-loop $\mu^+\mu^- \to bs$

- Mis-tagged $\mu^+\mu^- \to qq$
  - Tree-level
  - Flavor tagging rates from LHCb

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

$$\sigma_{\rm bg}^{\rm jj} = \sum_{q \neq t} 2\epsilon_q (1-\epsilon_q)\ \sigma(\mu^+\mu^- \to q\bar{q})$$

THE BACKGROUND

- Irreducible one-loop $\mu^+\mu^- \to bs$
- Mis-tagged $\mu^+\mu^- \to qq$
  - Tree-level
  - Flavor tagging rates from LHCb
- VBF $\mu^+\mu^- \to qq' f f'$
  - Neutrino events dominate
  - Muon events can be vetoed by detection

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

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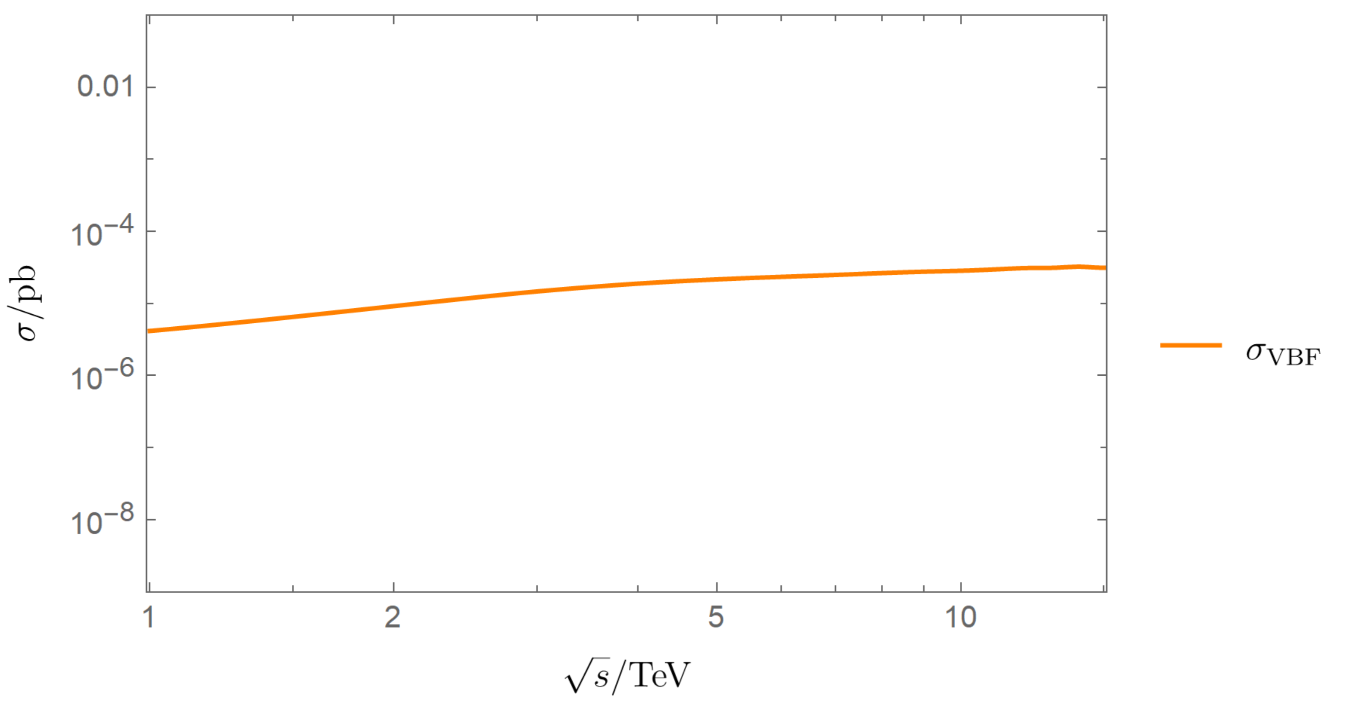
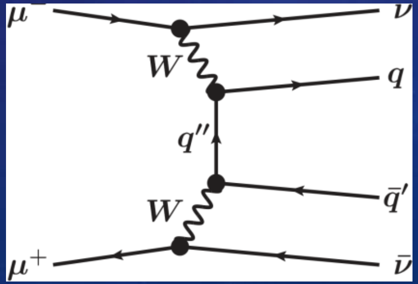
Monte Carlo: `MadGraph`

THE VERDICT ON SENSITIVITY





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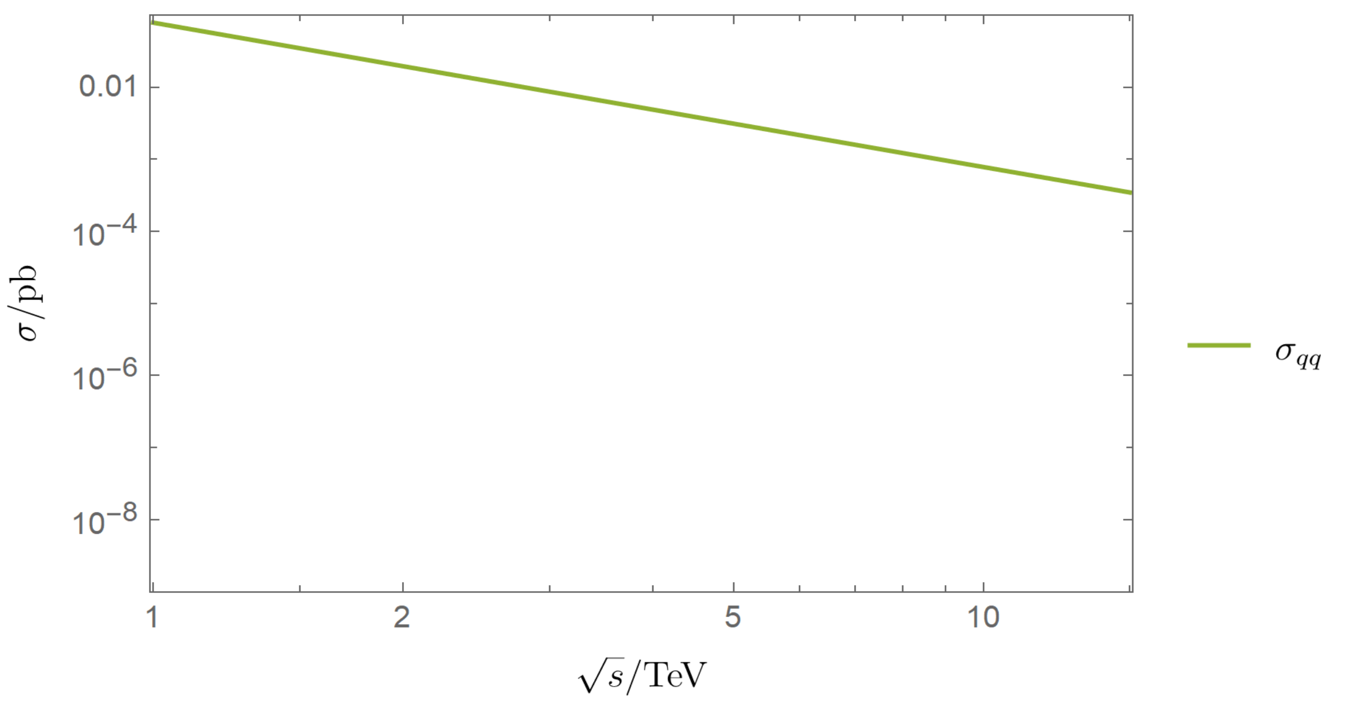

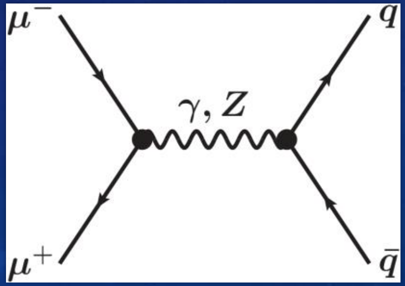

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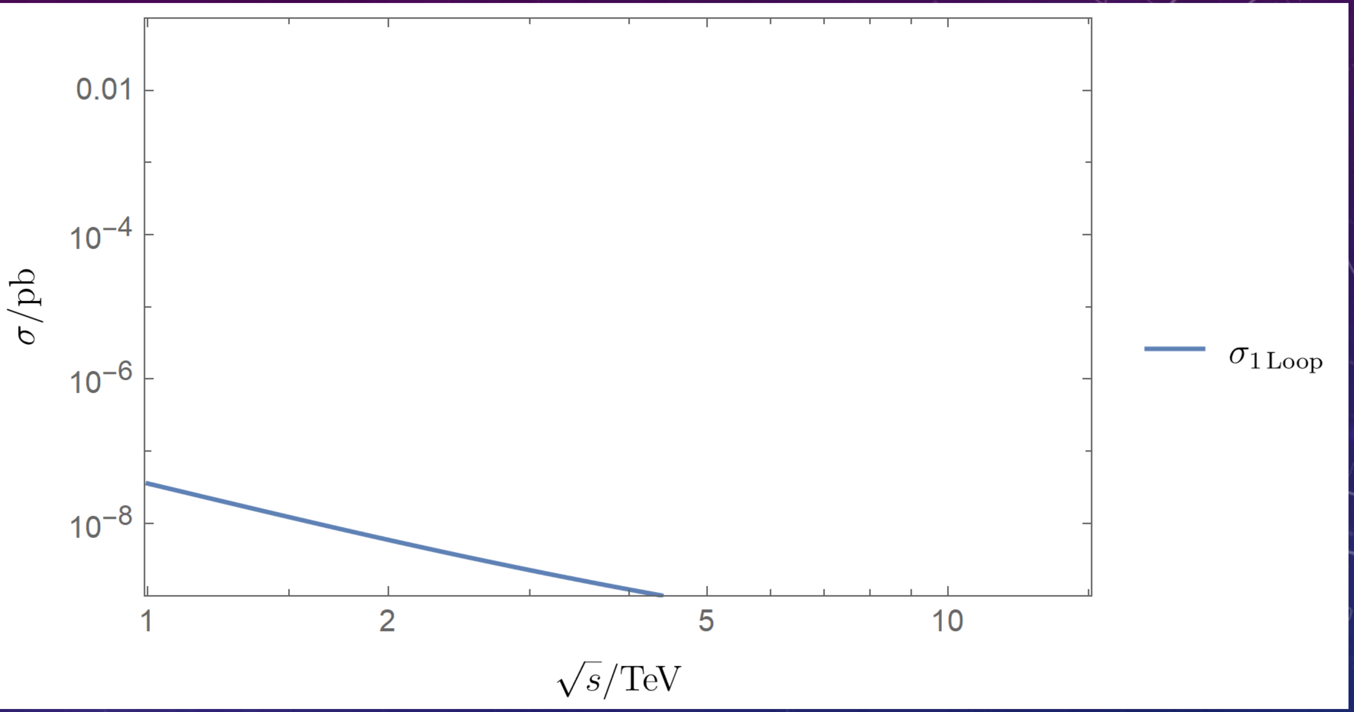

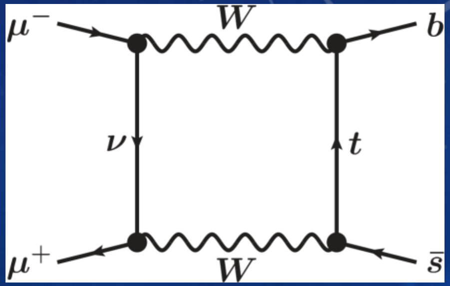

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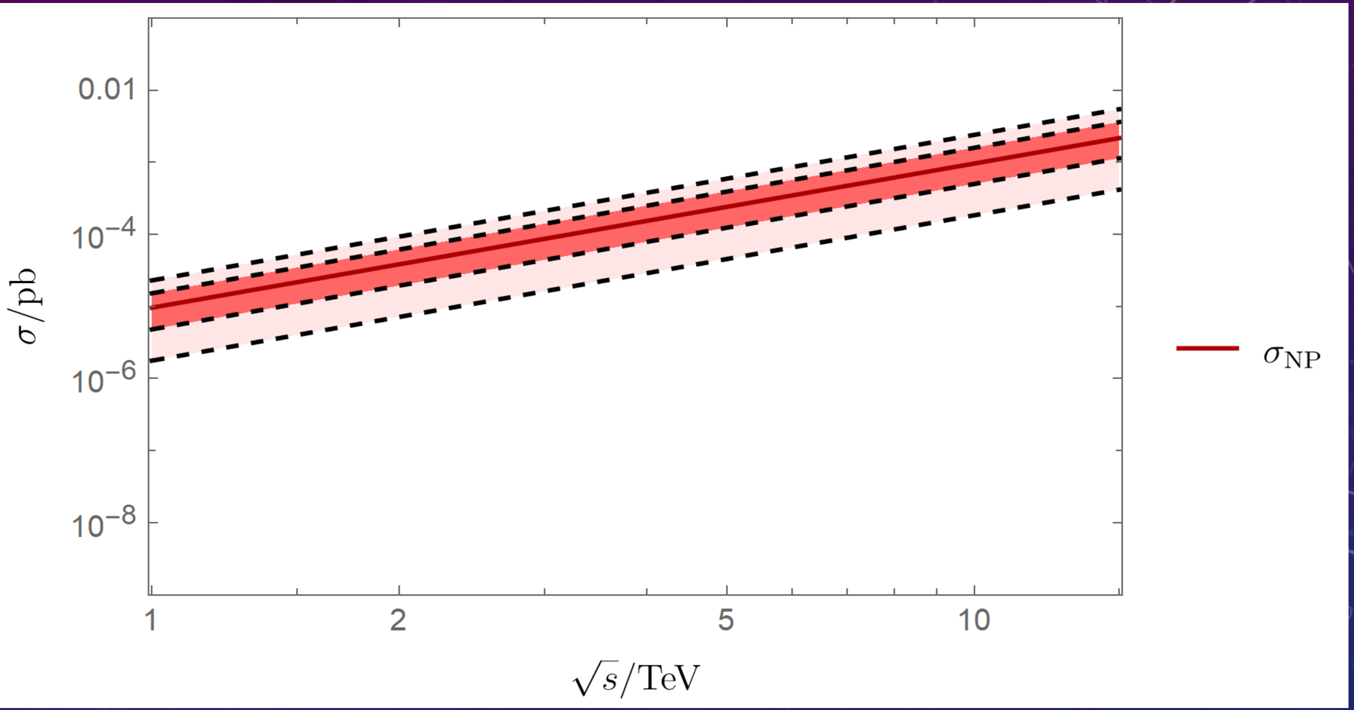

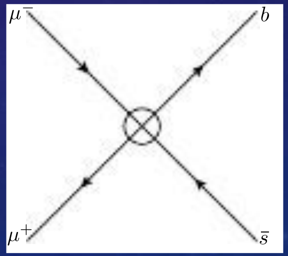

- Evaluated at global best fit values
- Perturbative unitarity is safe: EFT has a natural cutoff

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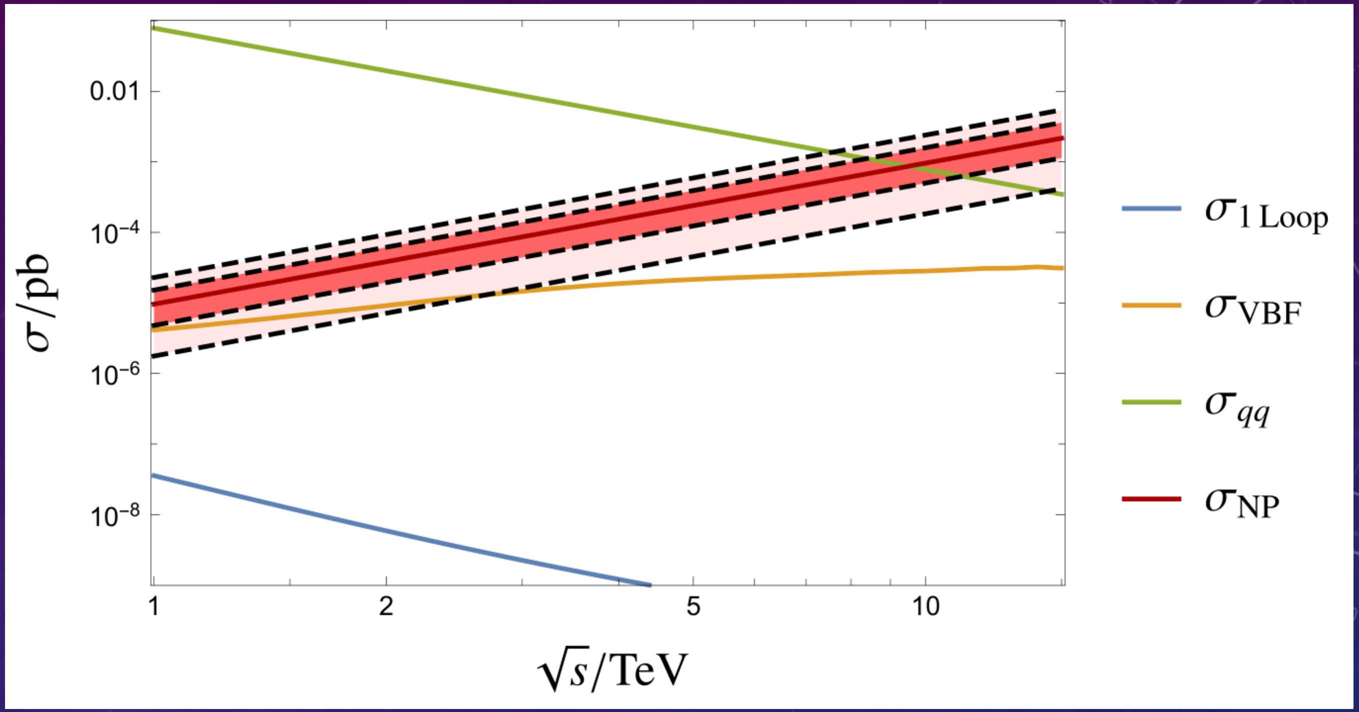
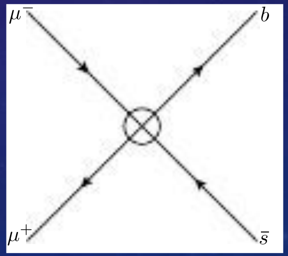
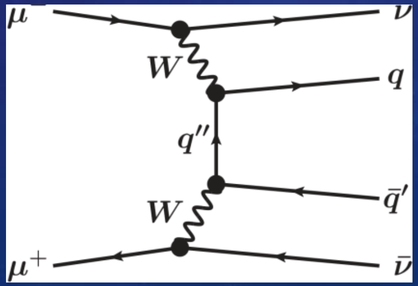
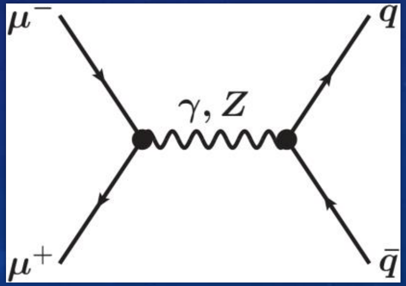
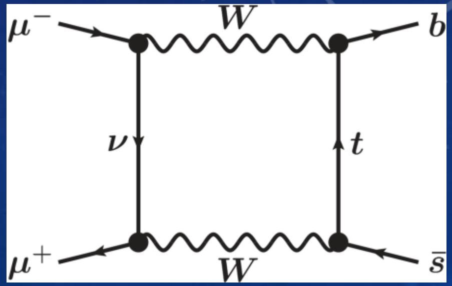




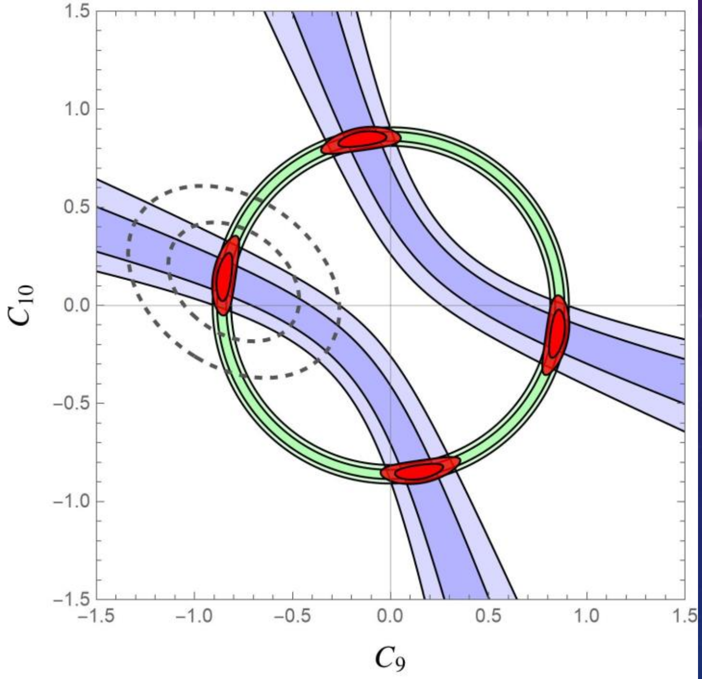






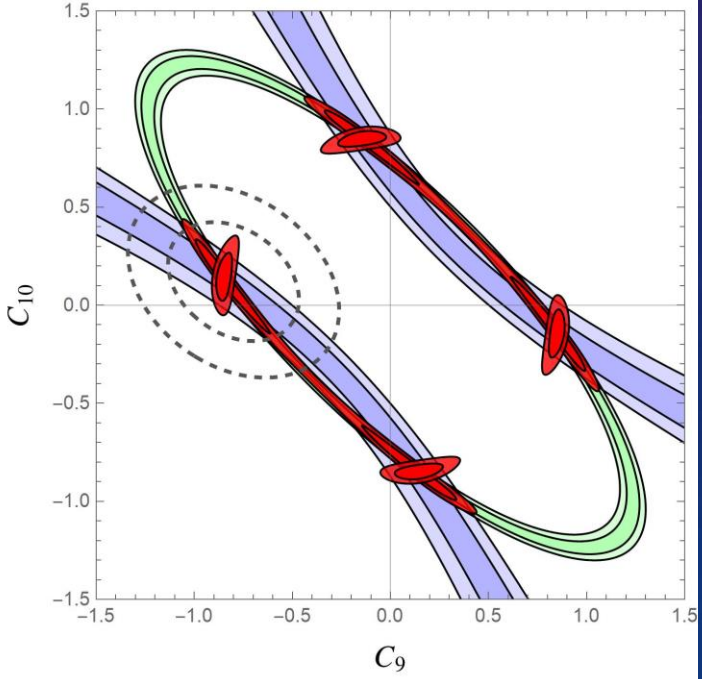
MUON COLLIDER: $10\ \mathrm{TeV},\ 1\ \mathrm{ab}^{-1}$

Unpolarized



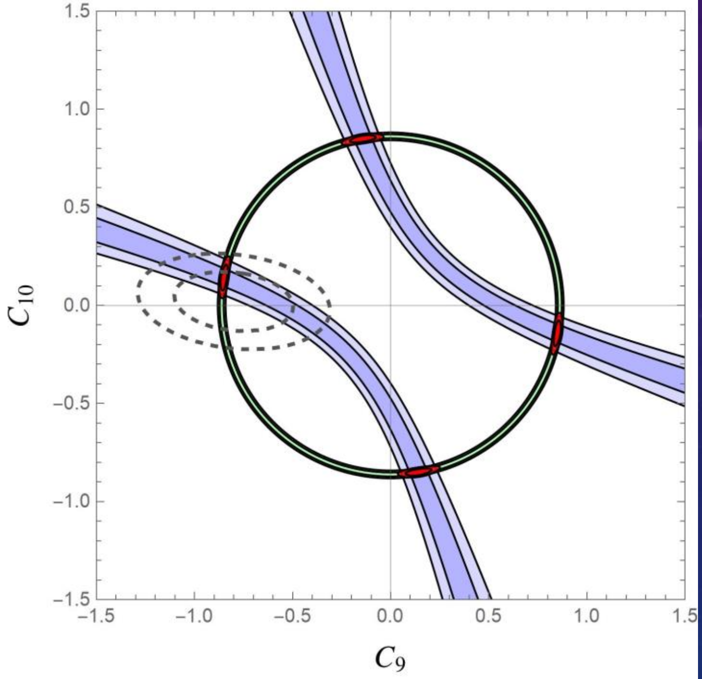
- **Assuming** $\mathcal{A}_{\mathrm{NP}} \sim \mathcal{A}_{\mathrm{SM}}$ **and** $\mathcal{O}(1)$ **couplings:** $\Lambda_{\mathrm{NP}} \sim 35\ \mathrm{TeV}$
- Red: Joint Exclusion
- Purple: Forward Backward Asymmetry Exclusion (charge tagged)
- Green: Event Number Exclusion
- Dotted: B Decay Global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

Polarized



MUON COLLIDER: $10\ \mathrm{TeV},\ 10\ \mathrm{ab}^{-1}$

Unpolarized



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- Green: Event Number Exclusion
- Dotted: Projections of B Decay Global Fit
- Assuming unchanged central values through the HL-LHC era

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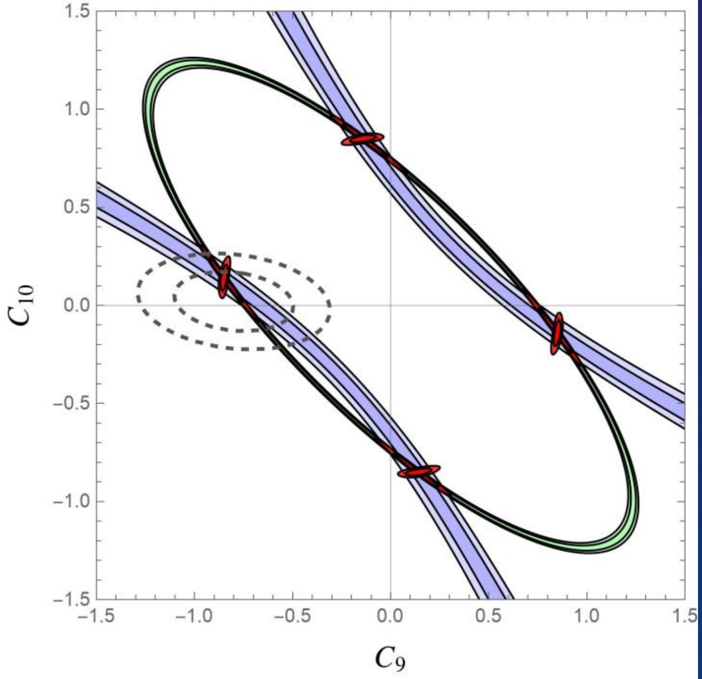

NO NP SCENARIO

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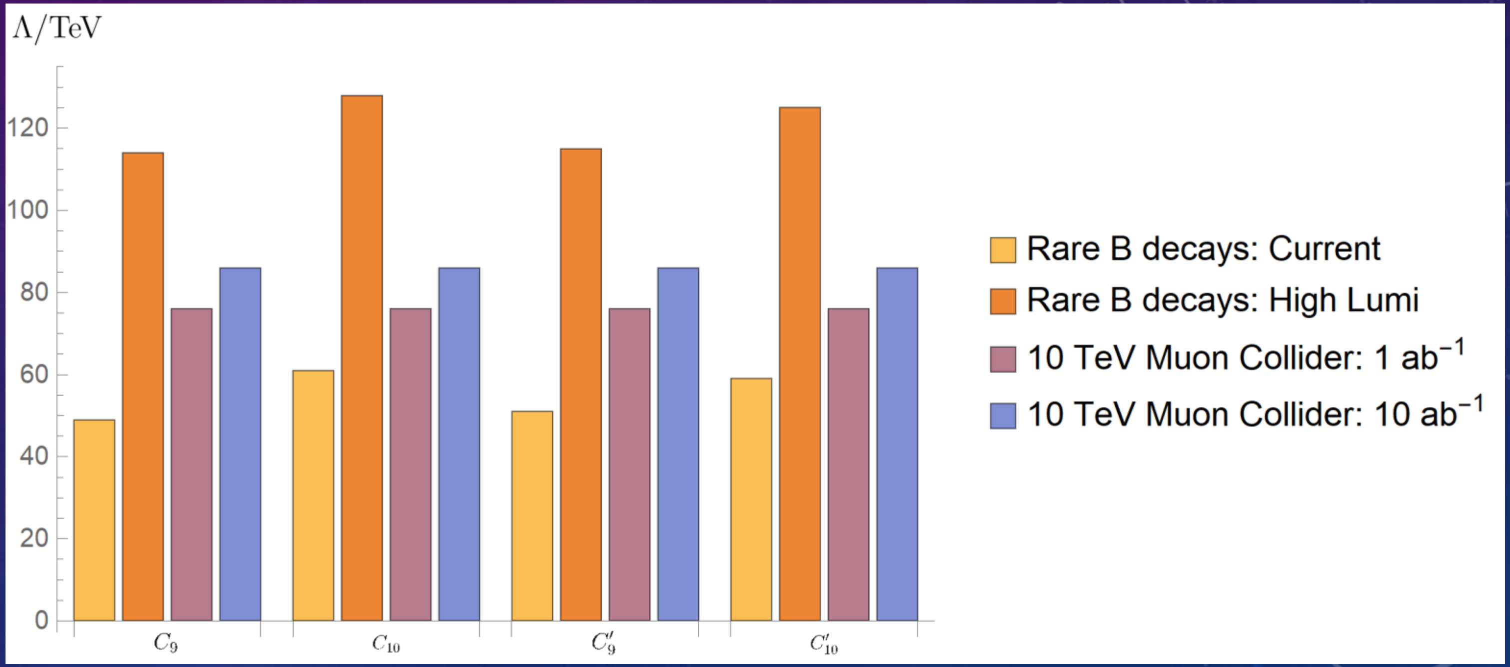

NO NP SCENARIO

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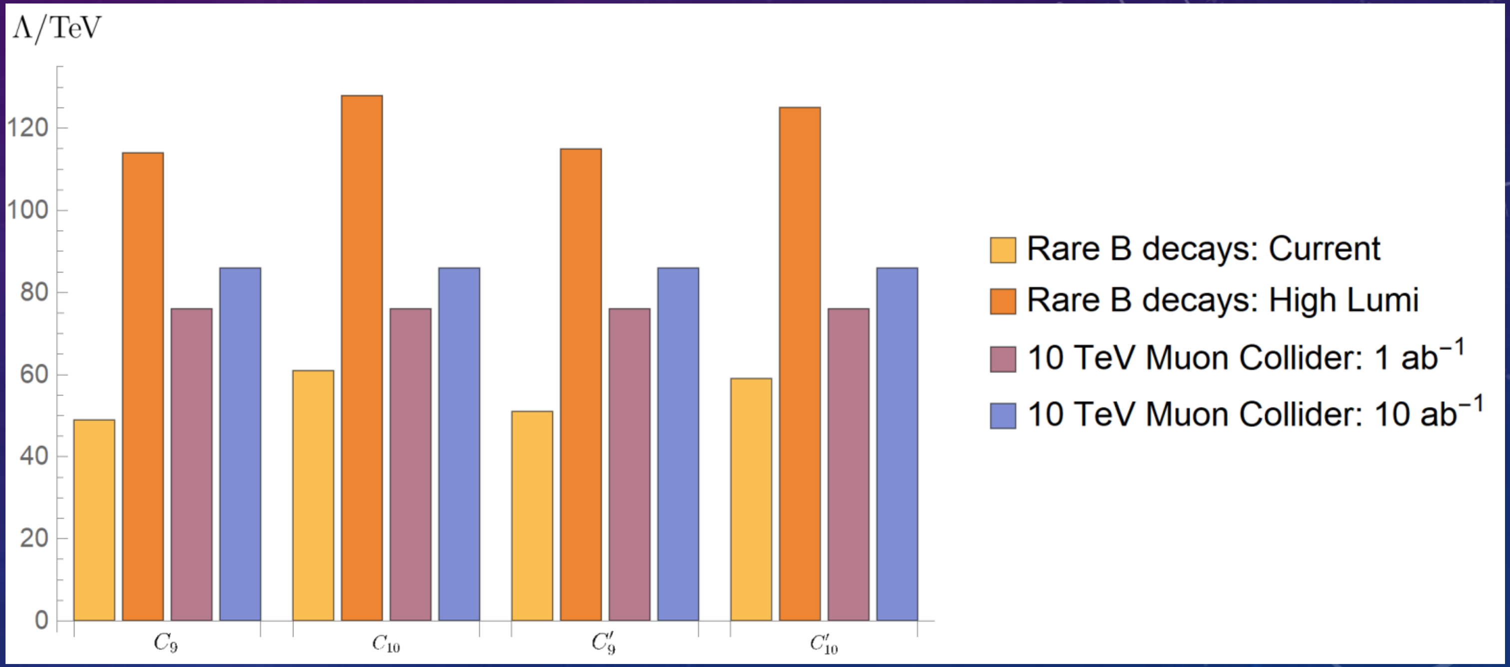
- Provides strong exclusions on heavy new physics associated with the B sector



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- Adding muon collider data to global fits of B decays significantly improves precision, even at 1/ab!

QUESTIONS?

HEAVY HANDED SIGNATURES IN LIGHT RESULTS

AN ANALYSIS OF $b \to s\nu\nu$ DECAYS

RARE B-DECAYS IN $b \to s\nu\nu$: MOTIVATION

Theoretical

- GIM and CKM suppression makes these decays of *b* quarks rare

Experimental

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  - Polarization can be measured - passes to fermionic children

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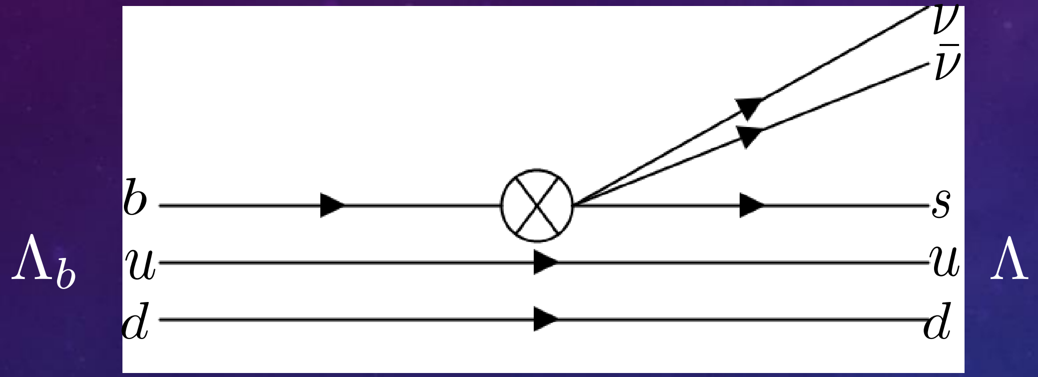
$\Lambda_b \to \Lambda \nu \bar{\nu}$



Conclusion: Soap from Friend!

bud to sud

Polarized: probes chiral NP structure	• Polarization measurements have been made[1] and will improve
Predicted[2] to be measured at future colliders	• No current bounds
Additional observable: A_{FB}	• Conditioned on $\cos\theta = \hat{p}_\Lambda \cdot \hat{s}_{\Lambda_b}$

[1]Buskulic et al.: 10.1016/0370-2693(95)01433-0
[2]Amhis, Kenzie, Reboud, Wiederhold: 2309.11353

THE FRAMEWORK: $\Lambda_b \to \Lambda \nu \bar{\nu}$

- Compute double differential decay rate of the Standard Model process
  - Polarized initial state (sample fraction) $\mathcal{P}_{\Lambda_b} = \frac{N^{\uparrow}_{\Lambda_b} - N^{\downarrow}_{\Lambda_b}}{N^{\uparrow}_{\Lambda_b} + N^{\downarrow}_{\Lambda_b}}$
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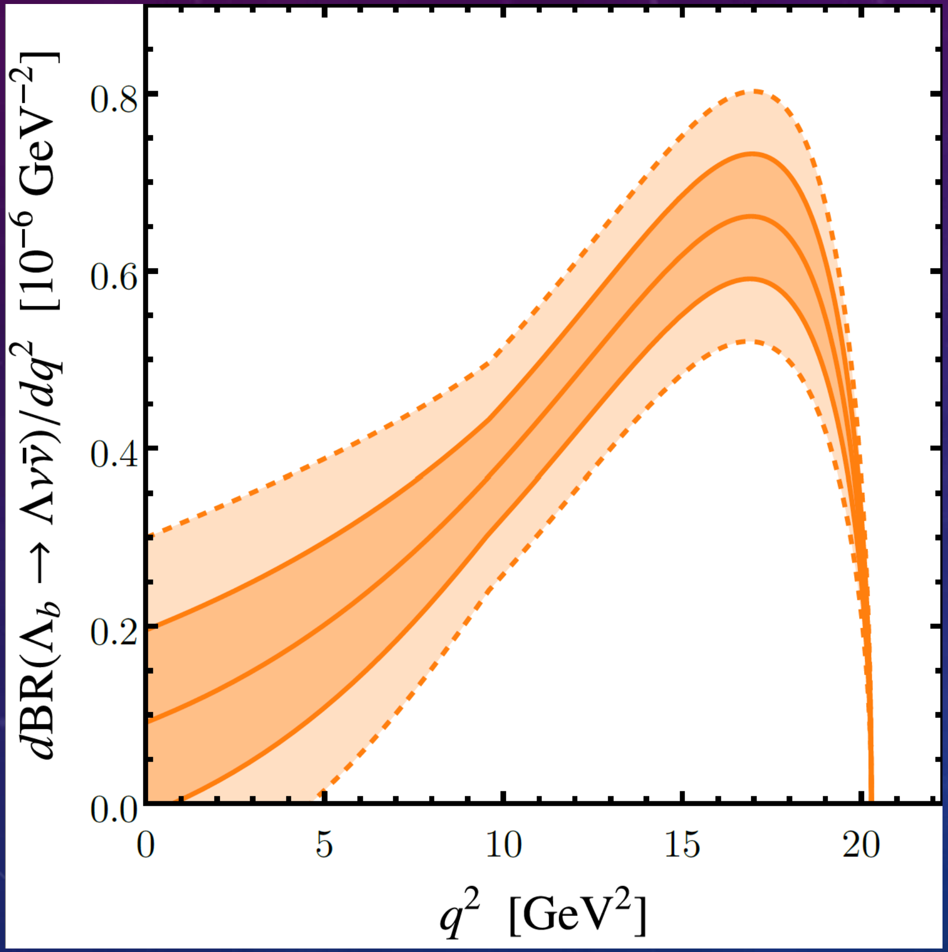
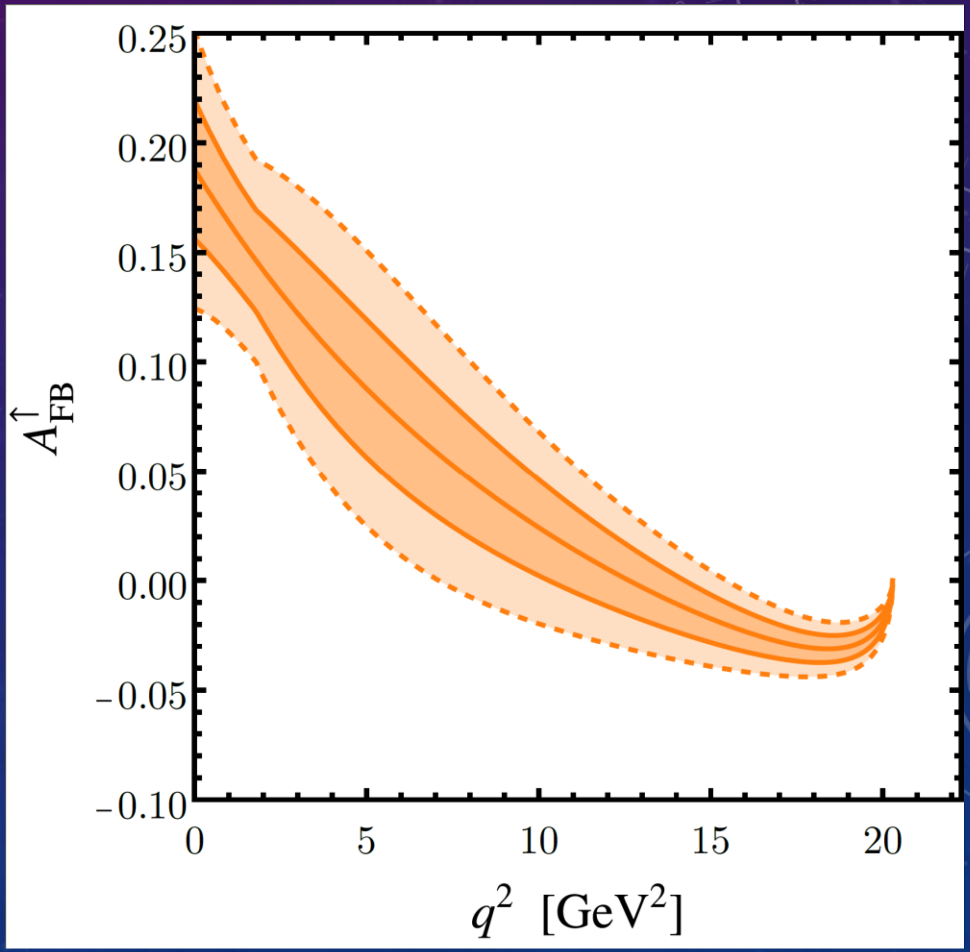
- Evaluate the bound on $C_{R,L}$

OBSERVABLES





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- Low vs High q^2: Form factor extrapolation uncertainty vs Phase space suppression and reduced statistics
- Consider covariances and disentangle uncertainties to boost precision

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Lab Frame

Λ_b Rest Frame

- Observed: Channel Decay Rate, $A_{\mathrm{F}B}$

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- Depends on di-neutrino mass
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- Only vector and axial elements used
  - Couples to neutrinos – scalar and tensor elements ignored

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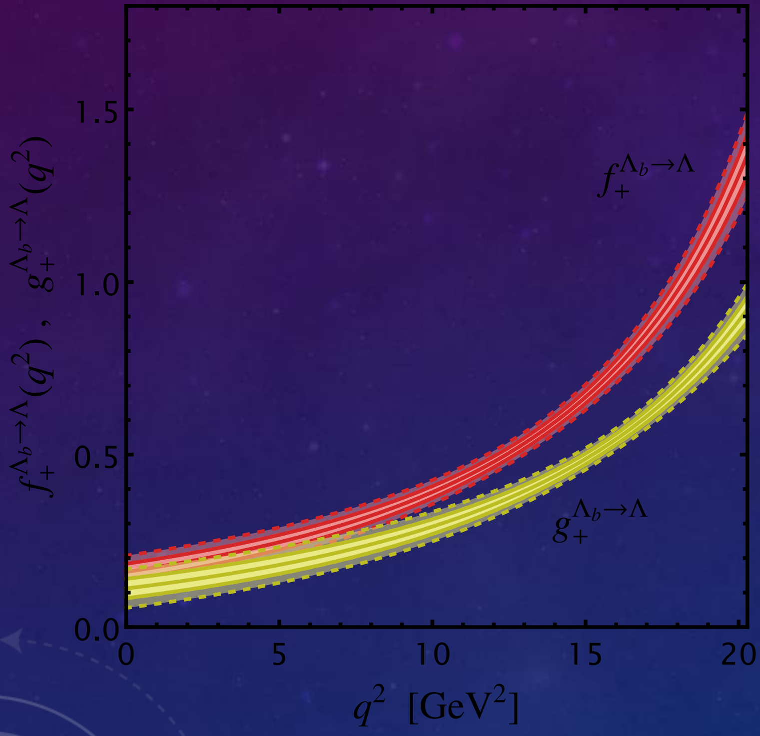
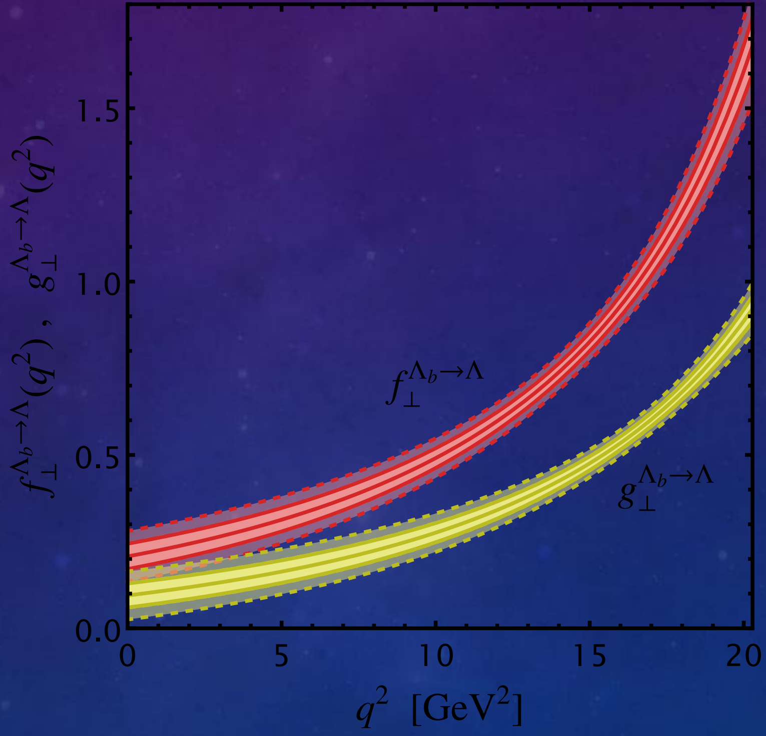
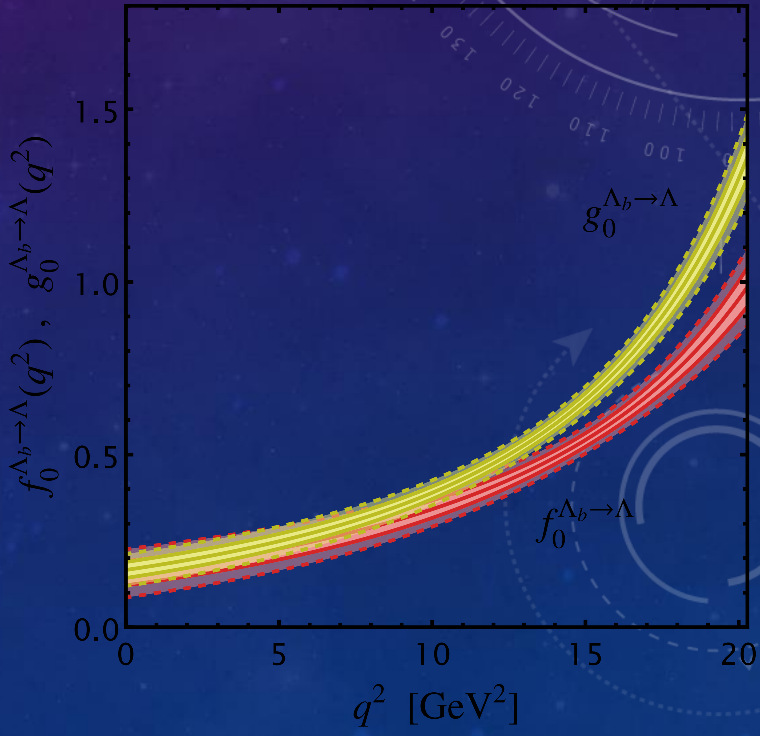
FORMING A PICTURE







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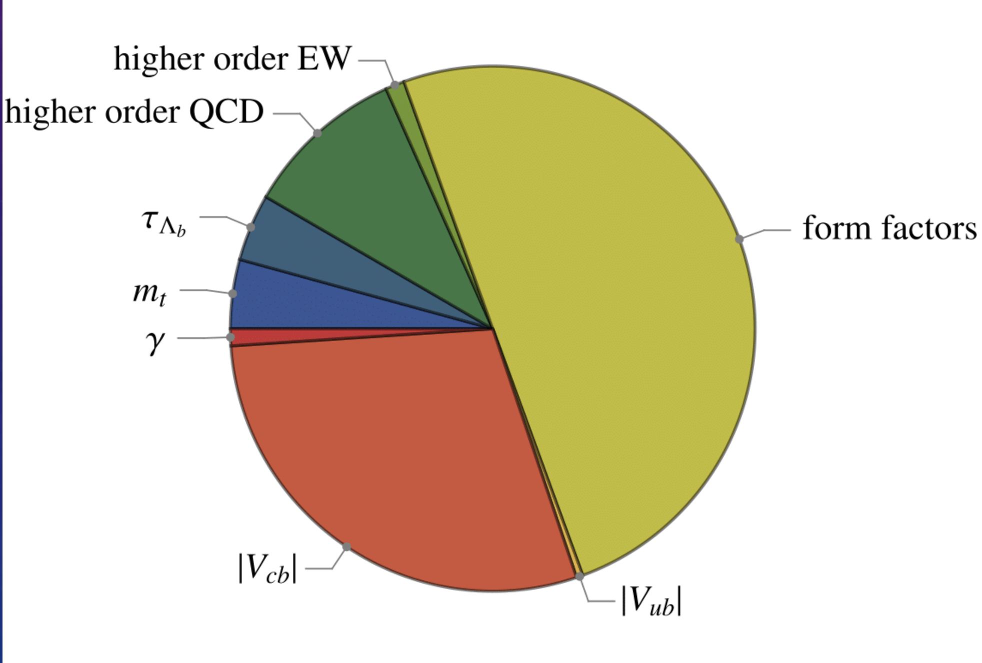
$$\mathrm{BR}(\Lambda_b \to \Lambda\nu\bar{\nu})_{\mathrm{SM}} = (7.71 \pm 1.06) \times 10^{-6}$$



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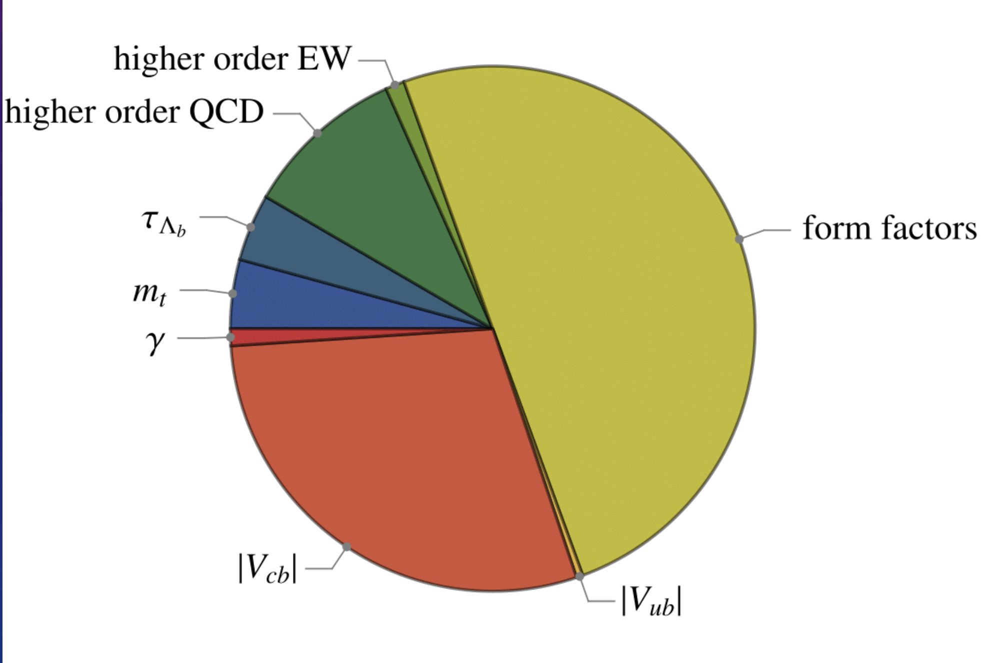
  - Second order expansion



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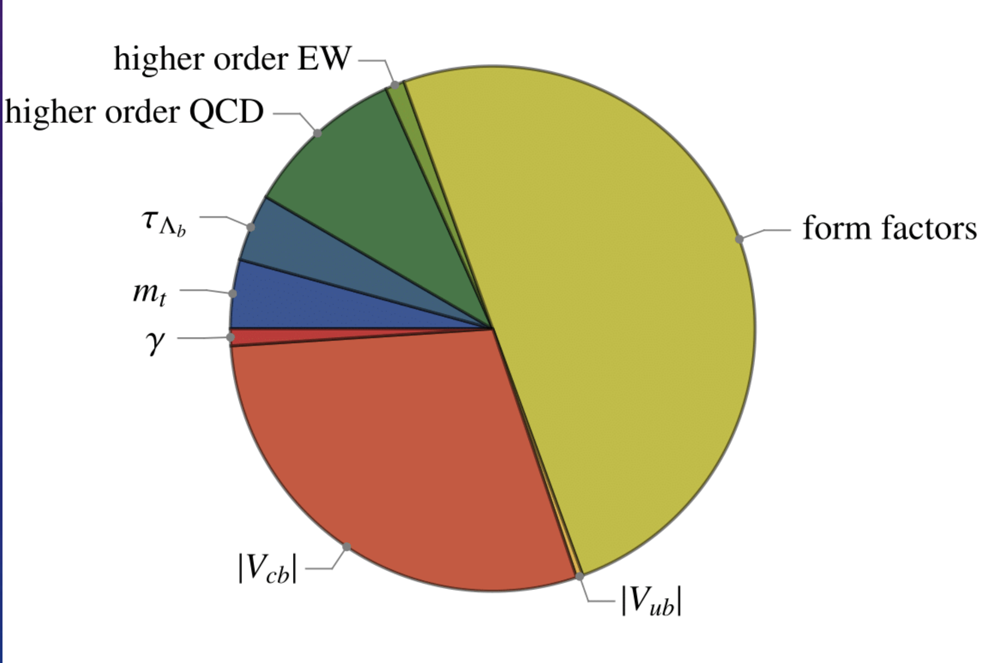

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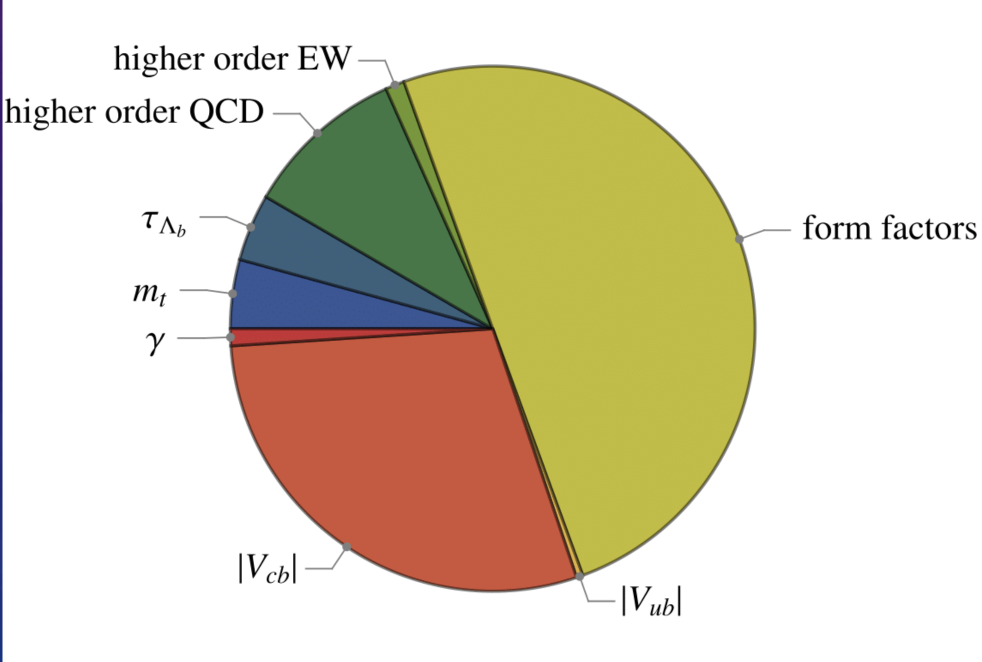

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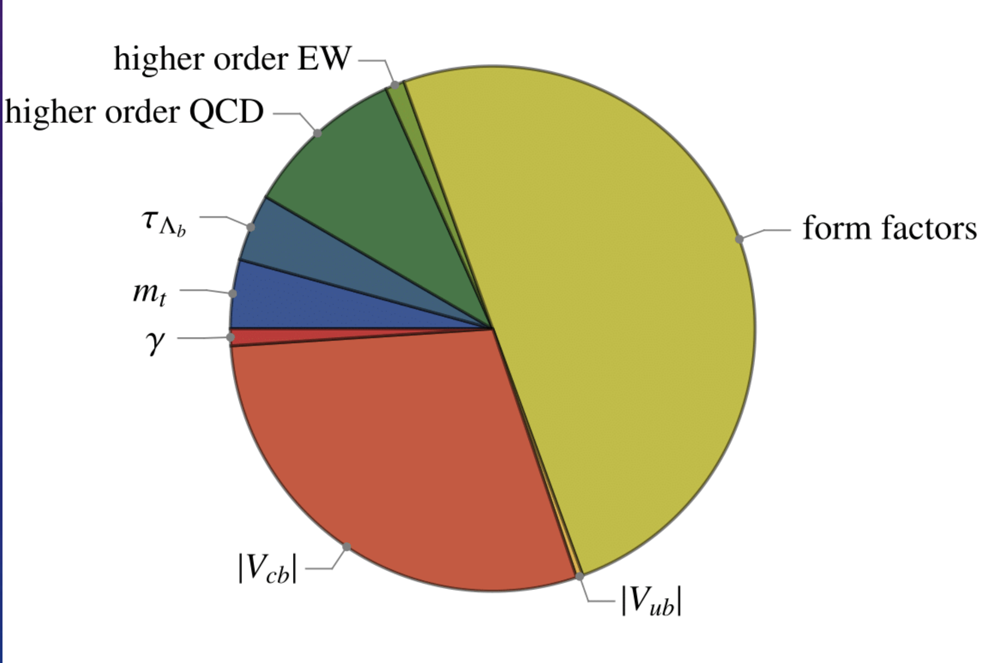
- Uncertainty in the lifetime propagates into the branching fraction



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NEW PHYSICS SENSITIVITY

- Interpretation:
  - Green: Branching Ratio Constraints
  - Purple: A_{FB} Constraints
  - Red: Joint Exclusion
  - $\mathcal{P}_{\Lambda_b} = -0.4$
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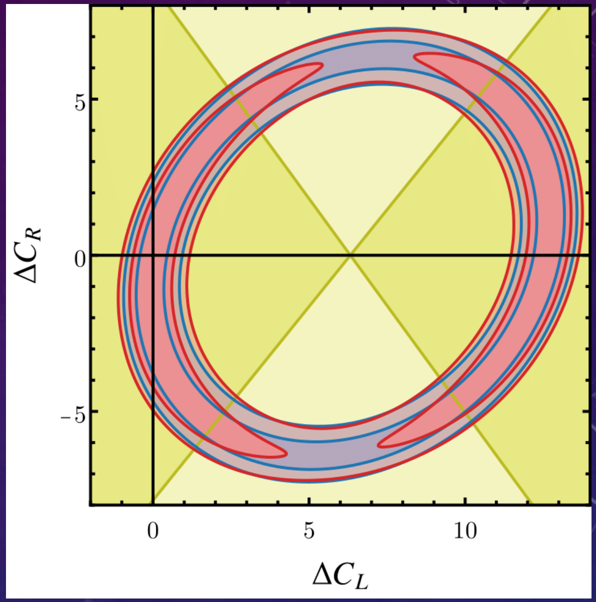

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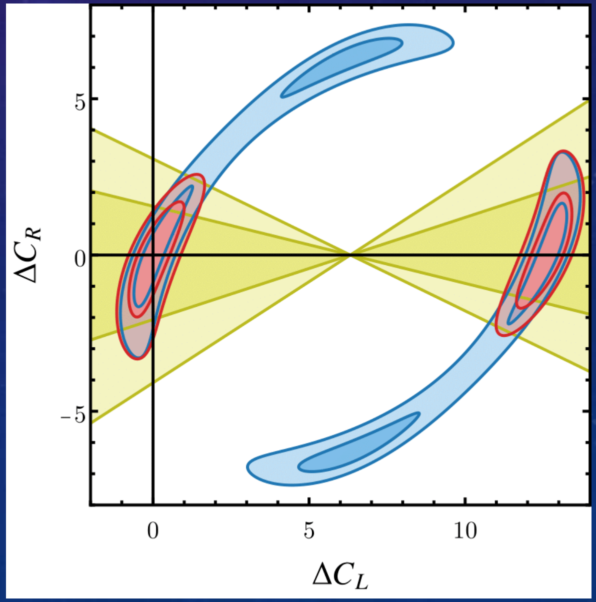

Zero-Crossing Binned

NEW PHYSICS SENSITIVITY

- Interpretation:
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-
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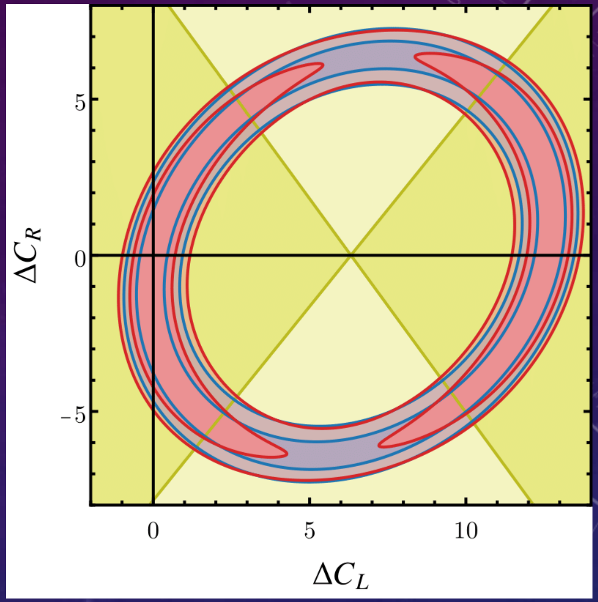

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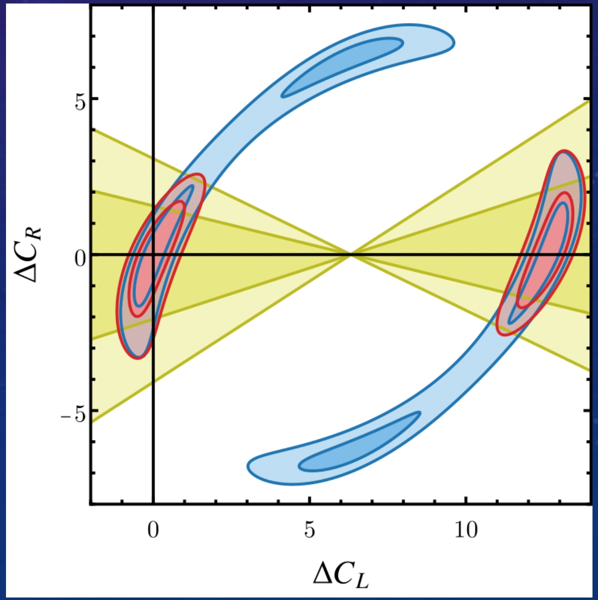

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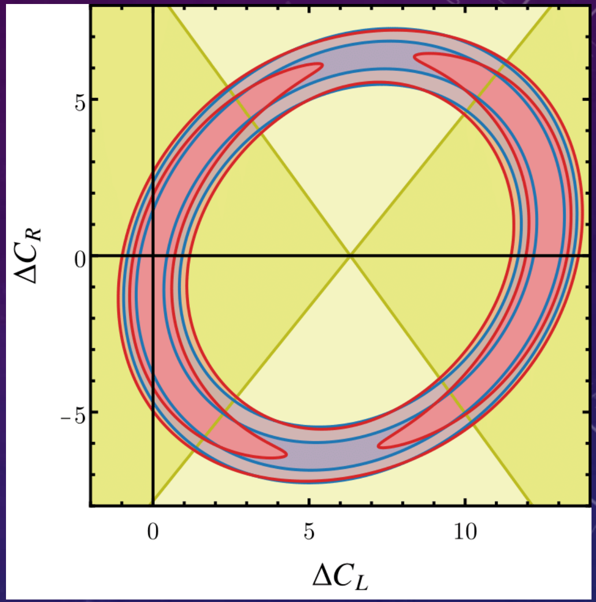

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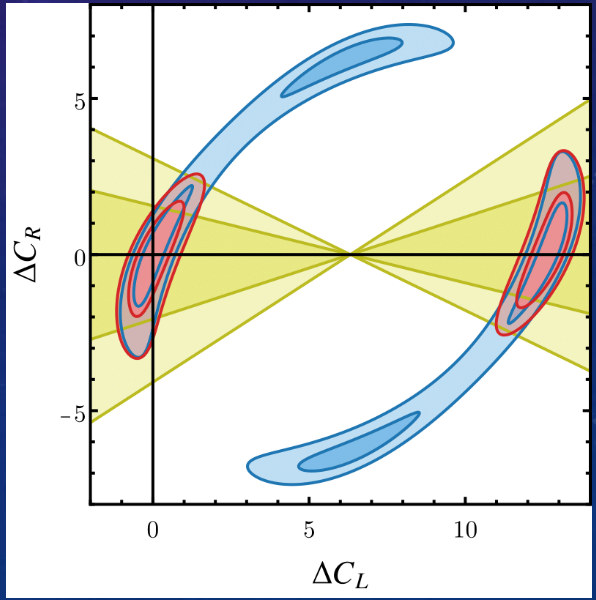

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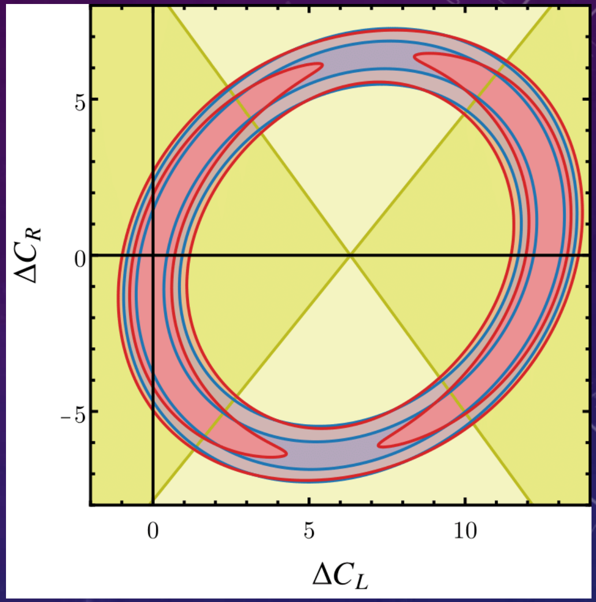

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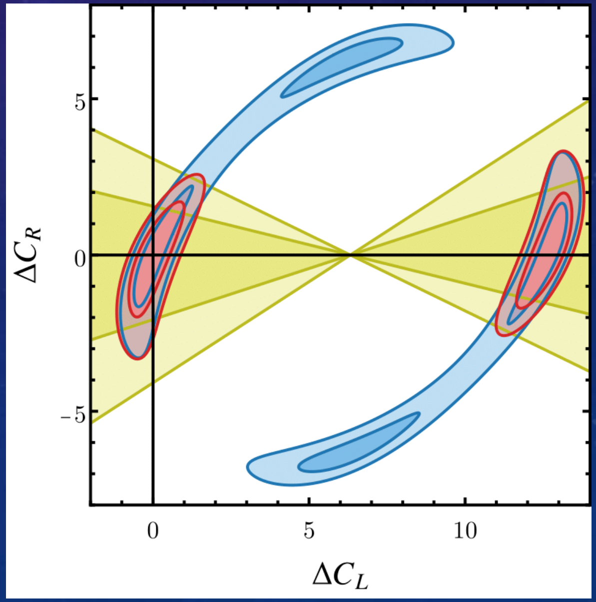

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CONCLUSION

OUTLOOK

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- Meson decays: current/future data
  - $B \to K^{(*)}\nu\nu,\ B_s \to \phi\nu\nu$

QUESTIONS?

ACKNOWLEDGEMENTS AND GRATITUDE



THANK YOU

TO THOSE THAT GUIDED MY RESEARCH

THANK YOU

TO THE BEST ADVISOR!

THANK YOU

My Partner, Kiley

My Family In Singapore

THANK YOU ALL!

BACKUP SLIDES: CLOCKWORK

THE 2 HIGGS CONSIDERATION

While considering a SUSY BSM theory, recall that we necessarily speak of multiple Higgs fields - H_u and H_d in this theory

Consider $\tan\beta = \langle H_u \rangle / \langle H_d \rangle$, where the region of validity is approximately $1 < \tan\beta < 65$, from constraints on the evolution of Yukawa couplings and LFV considerations

Large $\tan\beta$ = down type suppression. Let $n = \lfloor \log_\chi \tan\beta \rfloor$:

$$N_d = \begin{pmatrix} 4-n \\ 3-n \\ 3-n \end{pmatrix}$$

ASYMPTOTIC FREEDOM

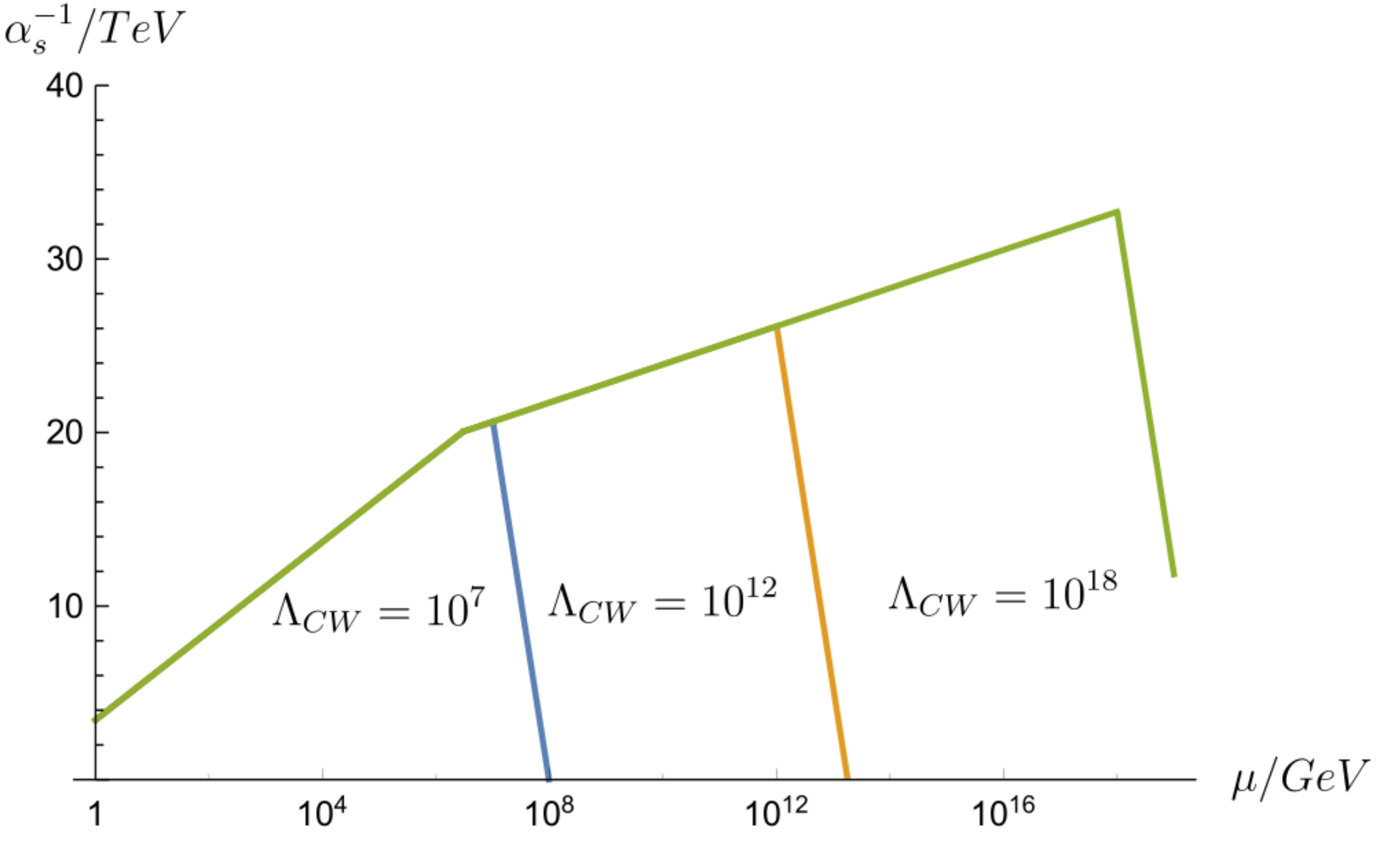
The asymptotic freedom of QCD is realized only in a theory with a few flavors of quarks. This is called into question above the Clockwork scale (where the first heavy gears become dynamic)

The number of gears makes it inevitable to develop a Landau Pole. This is not an issue as long as this occurs at an extremely high scale ($> M_P$), which is determined by the Clockwork scale, Λ_{CW}

$$\Lambda_{\mathrm{LP}} = \Lambda_{\mathrm{CW}} \exp\left[\frac{2\pi}{(24-3n)\alpha_s(\Lambda_{\mathrm{CW}})}\right] ,$$

From this, we obtain a lower bound on $\Lambda_{CW} > 10^{16}$! Visually,

ASYMPTOTIC FREEDOM



BACKUP SLIDES: MUON COLLIDER

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

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

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

Unpolarized

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

Polarized

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

FORWARD BACKWARD ASYMMETRY

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

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

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

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

- 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

	$6\,\text{TeV},\ 4\,\text{ab}^{-1}$	$10\,\text{TeV},\ 1\,\text{ab}^{-1}$	$10\,\text{TeV},\ 10\,\text{ab}^{-1}$
Unpolarized	$(22.7 \pm 1.7)\%$	$(16.4 \pm 2.9)\%$	$(16.4 \pm 1.6)\%$
Polarized	$(xx.x \pm x.x)\%$	$(xx.x \pm x.x)\%$	$(xx.x \pm x.x)\%$

FINAL RESULTS

$$1\text{ab}^{-1} : \Delta C_9^{\text{univ.}} = -0.81 \pm 0.03 \ , \quad \Delta C_{10}^{\text{univ.}} = 0.12 \pm 0.08$$
$$10\text{ab}^{-1} \Delta C_9^{\text{univ.}} = -0.81 \pm 0.01 \ , \quad \Delta C_{10}^{\text{univ.}} = 0.12 \pm 0.04$$

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

vs

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

RGE RUNNING

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

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

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