(My) Theoretical Perspective

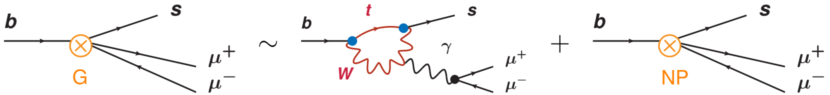
Wolfgang Altmannshofer
waltmann@ucsc.edu

UC SANTA CRUZ

Beyond the Flavor Anomalies IV

Casa Convalescencia, Barcelona, Spain
April 19 - 21, 2023

Rare B Decays as a Probe of New Physics



$$G \sim \frac{1}{16\pi^2} \frac{g^4}{m_W^2} \frac{m_t^2}{m_W^2} V_{tb} V_{ts}^* + \frac{C_{NP}}{\Lambda_{NP}^2}$$

measure precisely

calculate precisely the SM contribution

get information on NP coupling and scale

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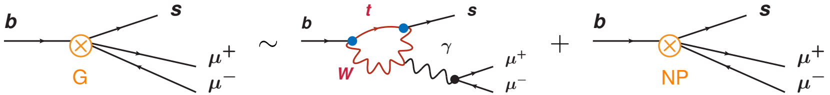


$$G \sim \frac{1}{16\pi^2} \frac{g^4}{m_W^2} \frac{m_t^2}{m_W^2} V_{tb} V_{ts}^* + \frac{C_{\text{NP}}}{\Lambda_{\text{NP}}^2}$$

measure precisely

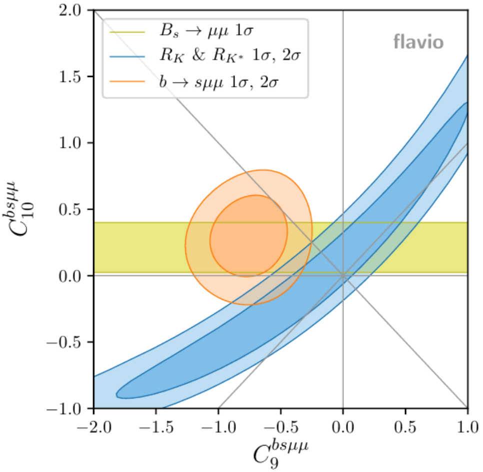
calculate precisely the SM contribution

get information on NP coupling and scale

$b \to s\ell\ell$ decays probe high new physics scales

$$C_{\text{NP}} \sim 1 \quad \Leftrightarrow \quad \Lambda_{\text{NP}} \sim 35\ \text{TeV}$$

$b \to s\ell\ell$ Status, Winter/Spring 2023



Greljo, Salko, Smolkovic, Stangl 2212.10497

(+ many others, see previous talk)

$$C_9^{bs\mu\mu}(\bar{s}\gamma_\alpha P_L b)(\bar{\mu}\gamma^\alpha \mu)$$

$$C_{10}^{bs\mu\mu}(\bar{s}\gamma_\alpha P_L b)(\bar{\mu}\gamma^\alpha \gamma_5 \mu)$$

- LFU ratios in agreement with SM
- $B_s \to \mu^+\mu^-$ branching ratio in agreement with SM
- $b \to s\mu\mu$ observables prefer non-standard C_9
- Tensions in the global fit

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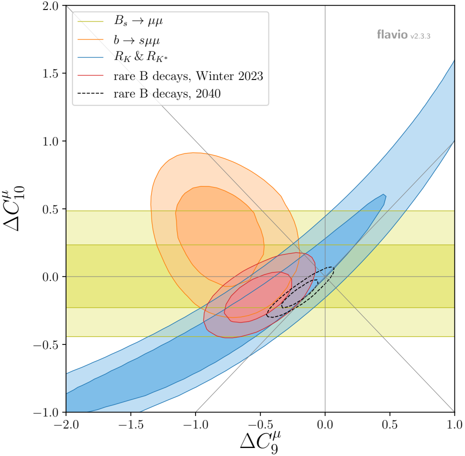


WA, Gadam, Profumo in preparation

$$\Delta C_9^\mu (\bar{s}\gamma_\alpha P_L b)(\bar{\mu}\gamma^\alpha \mu)$$

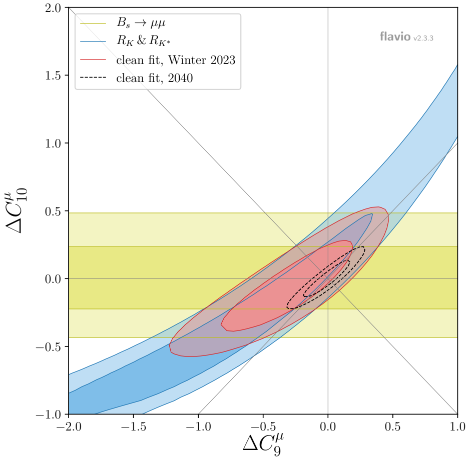
$$\Delta C_{10}^\mu (\bar{s}\gamma_\alpha P_L b)(\bar{\mu}\gamma^\alpha \gamma_5 \mu)$$

- LFU ratios in agreement with SM
- $B_s \to \mu^+\mu^-$ branching ratio in agreement with SM
- $b \to s\mu\mu$ observables prefer non-standard C_9
- Tensions in the global fit (actually not too terrible...)

$$\Delta C_9^\mu \simeq -0.53 \pm 0.18$$

$$\Delta C_{10}^\mu \simeq -0.16 \pm 0.13$$

Approach 1: Ignore $b \to s\mu\mu$



WA, Gadam, Profumo in preparation

$$\Delta C_9^{\mu} (\bar{s}\gamma_\alpha P_L b)(\bar{\mu}\gamma^\alpha \mu)$$

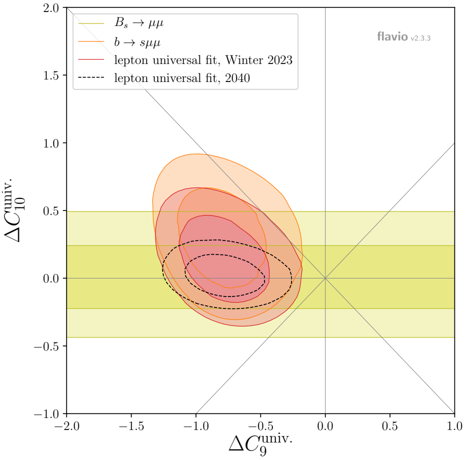
$$\Delta C_{10}^{\mu} (\bar{s}\gamma_\alpha P_L b)(\bar{\mu}\gamma^\alpha \gamma_5 \mu)$$

- LFU ratios in agreement with SM
- $B_s \to \mu^+\mu^-$ branching ratio in agreement with SM
- $b \to s\mu\mu$ observables “fixed” by hadronic physics
- Constraints on muon specific New Physics

$$\Delta C_9^{\mu} \simeq -0.28 \pm 0.33$$

$$\Delta C_{10}^{\mu} \simeq -0.07 \pm 0.22$$

Approach 2: Assume NP is Lepton Universal



WA, Gadam, Profumo in preparation

$$\Delta C_9^{\text{univ.}} (\bar{s}\gamma_\alpha P_L b)(\bar{\ell}\gamma^\alpha \ell)$$

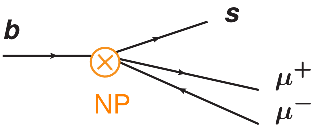
$$\Delta C_{10}^{\text{univ.}} (\bar{s}\gamma_\alpha P_L b)(\bar{\ell}\gamma^\alpha \gamma_5 \ell)$$

- LFU ratios don't give constraints
- $B_s \to \mu^+\mu^-$ branching ratio in agreement with SM
- $b \to s\mu\mu$ observables prefer non-standard C_9
- 2.8σ preference for new physics in C_9

$$\Delta C_9^{\text{univ.}} \simeq -0.80 \pm 0.22$$

$$\Delta C_{10}^{\text{univ.}} \simeq +0.12 \pm 0.20$$

New Physics or Underestimated Uncertainties?



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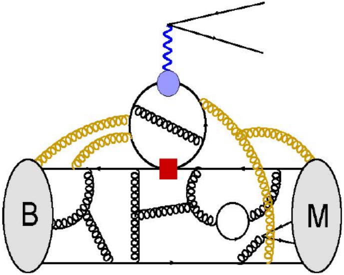

Main Sources of Theory Uncertainty

	$B_s \to \mu\mu$ rate	$b \to s\mu\mu$ rates	angular observables	LFU ratios

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CKM input	✓	✓	✗	✗

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(local) form factors	✓	✓	✓	✗

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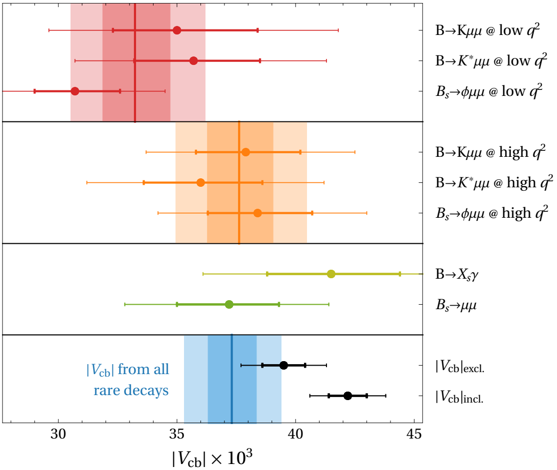
CKM input	✓	✓	✗	✗
(local) form factors	✓	✓	✓	✗
“charm loops”	✗	✓	✓	✗

The Role of V_{cb}



WA, Lewis 2112.03437

- Predictions for $b \to s\mu\mu$ rates depend sensitively on $|V_{cb}|$.
- Since many years there are tensions between inclusive and exclusive determinations of V_{cb}.
- The rare B decay rates could be partially explained by a (very) low $|V_{cb}|$.
- Why does almost everyone use the inclusive V_{cb} value?

$B \to K$ Form Factors

- $B \to K$ form factors are determined with very high precision from lattice calculations

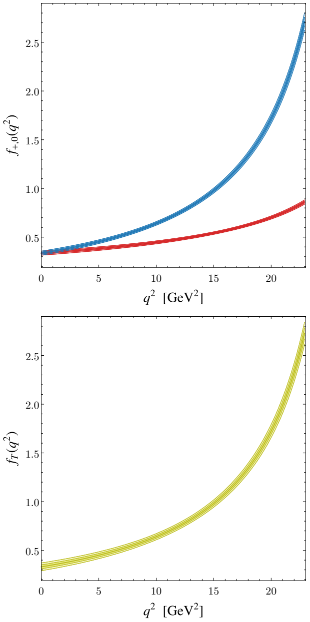
  Fermilab/MILC 1509.06235
  HPQCD 2207.12468

  (see talk by Parrott in the afternoon)

- combination by Becirevic, Piazza, Sumensari 2301.06990 has percent level accuracy!

- I get a bit nervous seeing such a high precision. Are the results robust?

[On the right I am ploting the form factors from Becirevic et al. 2301.06990]



$B \to K^*$ Form Factors

- LCSR + lattice combinations by

  Bharucha, Straub, Zwicky
  1503.05534
  Gubernari, Kokulu, van Dyk
  1811.00983

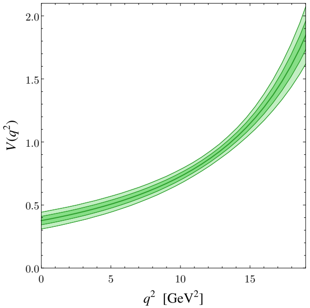
  (see talk by Gubernari in the afternoon)

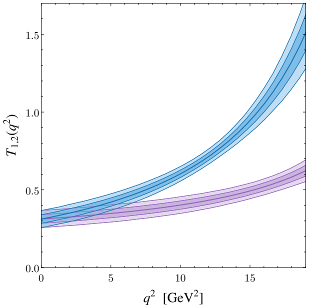
- Uncertainties around 5% - 10%

- How reliable are the uncertainties?
  What even is a $B \to K^*$ form factor?
  Better to do $B \to K\pi$?

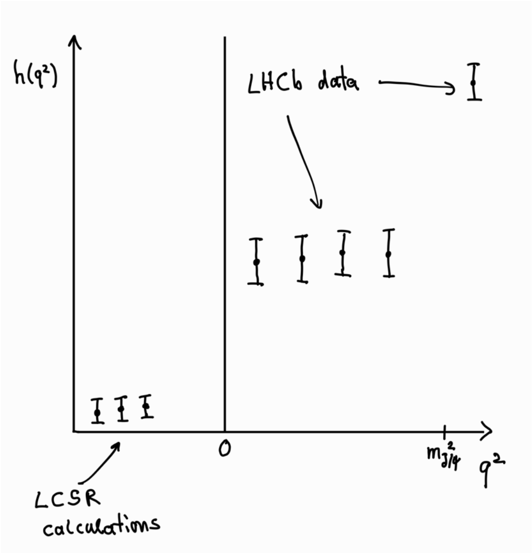
  (see talk by Virto/Reboud in the afternoon)

[On the right I am ploting
form factors from BSZ]





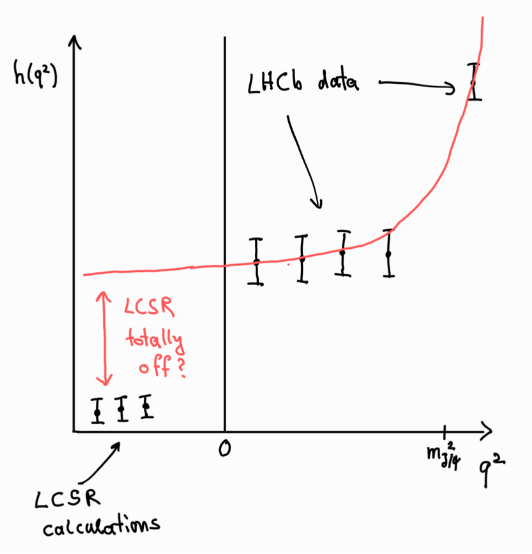
“Charm Loops”



[Note: This is a sketch of my own very naive understanding]

Paramterize them and fit them to data and/or LCSR calculations

"Charm Loops"



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Paramterize them and fit them to data and/or LCSR calculations

How reliable are the LCSR calculations?

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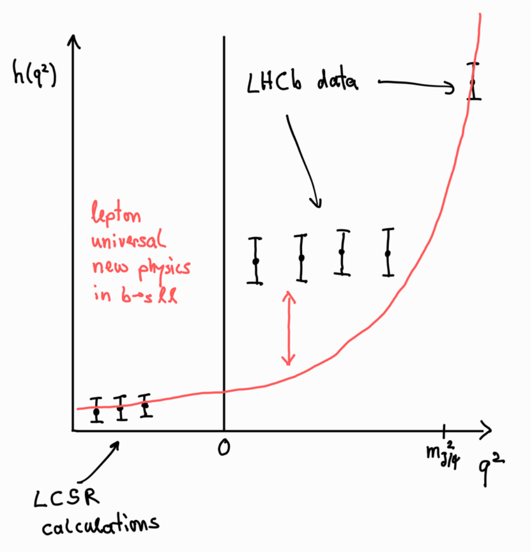

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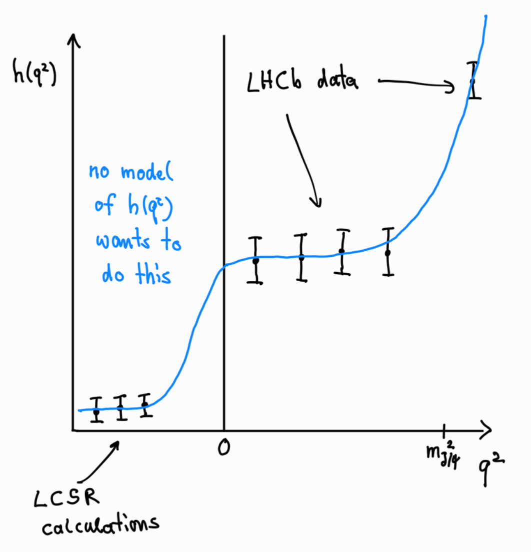


[Note: This is a sketch of my own very naive understanding]

Paramterize them and fit them to data and/or LCSR calculations

How reliable are the LCSR calculations?

How flexible are the parameterizations of the non-local effects?

New Physics Model Building

theory input / bias

'motivated' models — address other open questions: hierarchy problem, SM flavor puzzle,...
ensure the model is renormalizable, UV complete, ...

simplified models — introduce new particles in the simplest way possible
(e.g. a single lepto-quark or a single Z' boson)

effective field theory (SMEFT / LEFT) — parameterize new physics model independently
(need to make minimal assuptions, e.g. new physics is heavy)

experimental input

(inspired by Marco Nardecchia)

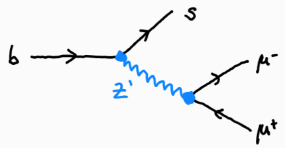
My Perspective on New Physics (I)

- Looking back to 2013: explanations of the "P_5' anomaly" want $\Delta C_9 \sim -1$ (could be lepton universal or muon specific)
- $\Delta C_9 = -\Delta C_{10}$ was also OK, but the data then (as now) is perfectly compatible with SM-like C_{10}

  $\rightarrow$ new physics only in C_9 seems the more minimal option
- Simplified model approach:

  Introduce a Z' with vector coupling to muons $g^V_{\mu\mu}$ and flavor changing coupling to left-handed quarks g^L_{bs}

My Perspective on New Physics (II)

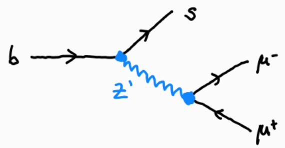


P_5' wants

$$\frac{g_{sb}^L g_{\mu\mu}^V}{m_{Z'}^2} \sim \frac{|\Delta C_9|}{(35\text{ TeV})^2}$$

.

My Perspective on New Physics (II)



P_5' wants

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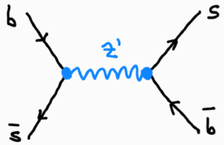
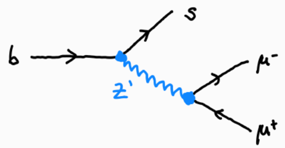


Constraint from B_s mixing

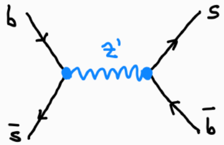
$$\frac{(g^L_{sb})^2}{m^2_{Z'}} \lesssim \frac{1}{(250 \text{ TeV})^2}$$

My Perspective on New Physics (II)



P'_5 wants

$$\frac{g^L_{sb} g^V_{\mu\mu}}{m^2_{Z'}} \sim \frac{|\Delta C_9|}{(35\text{ TeV})^2}$$



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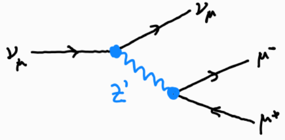
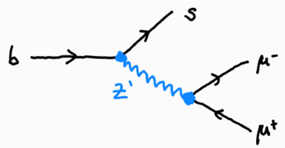


Fairly weak constraints on the muon coupling from neutrino tridents

$$\frac{(g^V_{\mu\mu})^2}{m^2_{Z'}} \lesssim \frac{1}{(300\text{ GeV})^2}$$

.

My Perspective on New Physics (II)



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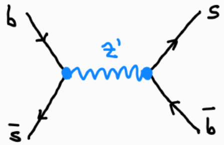

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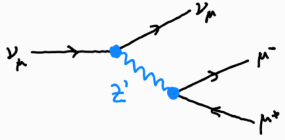
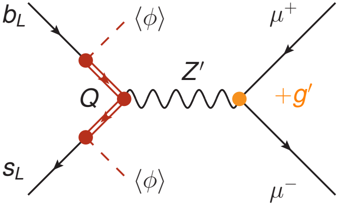


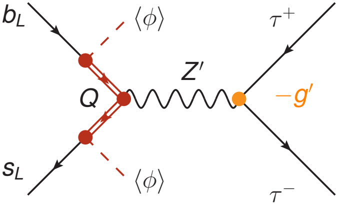
Fairly weak constraints on the muon coupling from neutrino tridents

$$\frac{(g^V_{\mu\mu})^2}{m^2_{Z'}} \lesssim \frac{1}{(300\text{ GeV})^2}$$

$\rightarrow$ Want a Z' with O(1) vectorial couplings to muons and small flavor changing couplings to quarks.

From a model building perspective, the most straight forward thing is to gauge muon number minus tau number, $L_\mu - L_\tau$.





Genuine prediction:
Violation of lepton flavor universality in $b \to s\ell\ell$ at the $\sim 20\%$ level.

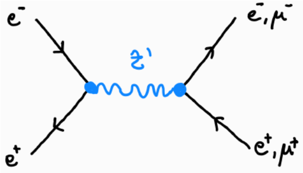
WA, Gori, Pospelov, Yavin 1403.1269; WA, Yavin 1508.07009

$$\frac{\mathrm{BR}(b \to s\mu\mu)}{\mathrm{BR}(b \to see)} \simeq 0.8 \ , \qquad \frac{\mathrm{BR}(b \to s\tau\tau)}{\mathrm{BR}(b \to see)} \simeq 1.2$$

My Perspective on New Physics (IV)

- Now we know that $\mu - e$ universality holds to a good approximation.
  $\rightarrow$ Gauge $L_e + L_\mu - 2L_\tau$?

- Possible issue: the Z' has also O(1) couplings to electrons
  $\rightarrow$ Strong constraints from LEP



$$\frac{(g^V_{\mu\mu})^2}{m^2_{Z'}} \simeq \frac{(g^V_{ee})^2}{m^2_{Z'}} \lesssim \frac{1}{(3.5\ \text{TeV})^2}$$

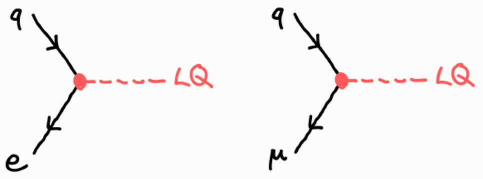
- One finds an upper bound on $|\Delta C_9| \lesssim 0.7$
  (WA, Straub 1411.3161; also Greljo, Salko, Smolkovic, Stangl 2212.10497)

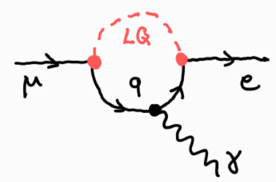
$\rightarrow$ Z' seems uncomfortably close to the bounds from LEP and B_s mixing

My Perspective on New Physics (V)

- What about leptoquarks? (much weaker constraints from B_s mixing)

- But single leptoquarks don't like to be lepton universal.
  One tends to run into trouble with lepton flavor violation.

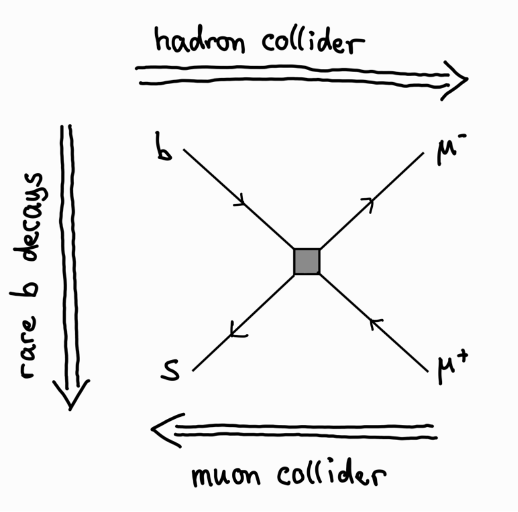




- Most natural scenario seems to be multiple leptoquarks that are related by $SU(2)$ or $SU(3)$ flavor symmetries.

[for more leptoquarks see talk by Stefanek after the break]

Collider Probes of $b \to s\mu\mu$

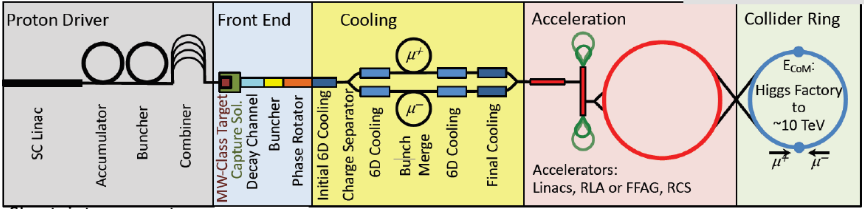


[see also talk by Wilsch after the break]

A Muon Collider?

Muon collider design is driven by finite muon lifetime

MAP collaboration



Short, intense proton bunches to produce hadronic showers

Muon are captured, bunched and then cooled by ionisation cooling in matter

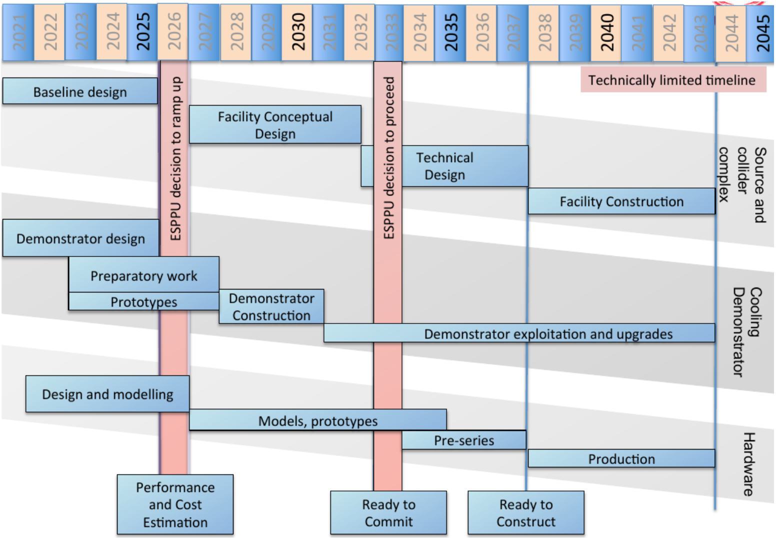
Collision

Acceleration to collision energy

Protons produce pions
Pions decay to muons

talk by D. Schulte @ Muon Collider Agora, Feb 16 2022

A Muon Collider!



talk by D. Schulte @ Muon Collider Agora, Feb 16 2022

Non-Standard $\mu^+\mu^- \to bs$ at a Muon Collider

$$\frac{d\sigma(\mu^+\mu^- \to b\bar{s})}{d\cos\theta} = \frac{3}{16}\sigma(\mu^+\mu^- \to bs)\left(1 + \cos^2\theta + \frac{8}{3}A_{\rm FB}\cos\theta\right)$$

$$\frac{d\sigma(\mu^+\mu^- \to \bar{b}s)}{d\cos\theta} = \frac{3}{16}\sigma(\mu^+\mu^- \to bs)\left(1 + \cos^2\theta - \frac{8}{3}A_{\rm FB}\cos\theta\right)$$

Total cross section increases with the center of mass energy

$$\sigma(\mu^+\mu^- \to bs) = \frac{G_F^2\alpha^2}{8\pi^3}|V_{tb}V_{ts}^*|^2\, s\, \left(|C_9|^2 + |C_{10}|^2\right)$$

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$$\sigma(\mu^+\mu^- \to bs) = \frac{G_F^2\alpha^2}{8\pi^3}|V_{tb}V_{ts}^*|^2\, s\, \Big(|C_9|^2 + |C_{10}|^2\Big)$$

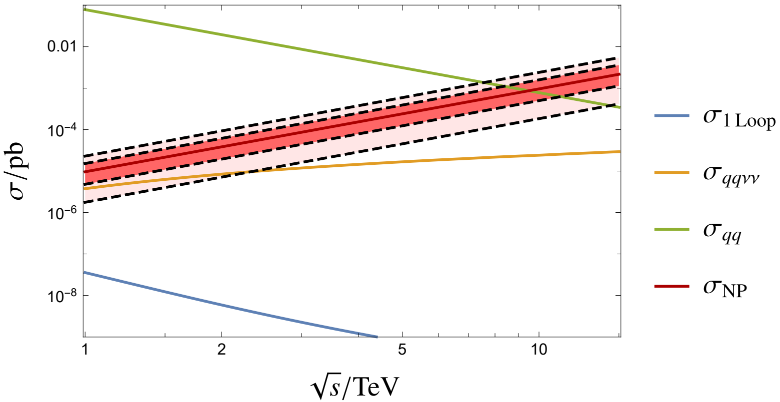
Forward backward asymmetry is sensitive to the chirality strcuture

$$A_{\rm FB} = \frac{-3{\rm Re}(C_9 C_{10}^*)}{2(|C_9|^2 + |C_{10}|^2)}$$

Need charge tagging to measure the forward backward asymmetry

Backgrounds

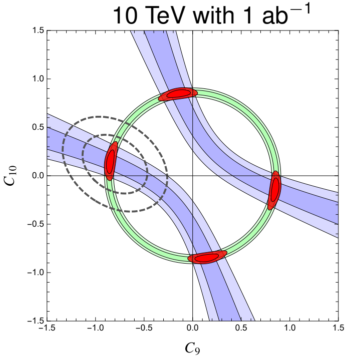
WA, Gadam, Profumo 2203.07495 and in preparation

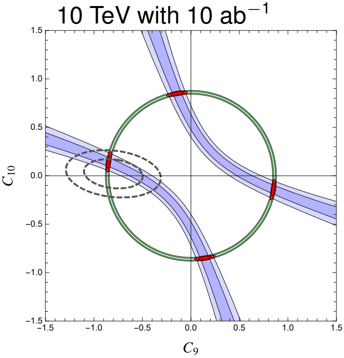


- Main background falls with $\sqrt{s}$; new physics signal increases.
- Signal/Background ~ 1 for $\sqrt{s} \sim 10$ TeV.

Sensitivity Projections

WA, Gadam, Profumo 2203.07495 and in preparation





- Branching ratio (green) and A_{FB} (blue) are complementary.
- If there is new physics in $b \to s\ell\ell$, a 10 TeV muon collider would clearly see it, and one does not need to worry about long distance QCD.
- If there is no new physics, rare decays and a 10 TeV muon collider give roughly the same constraints.

(see also Huang et al. 2103.01617; Asadi et al. 2104.05720; Azatov et al. 2205.13552)

Summary

- R_K and R_{K^*} are gone, but the $b \to s\ell\ell$ branching ratios are still low and angular distributions are off.

- If there is new physics in rare $b \to s\ell\ell$, it has to (approximately) preserve $e - \mu$ universality.

$\rightarrow$ Interesting implications for model building.

- Ultimate test of the $b \to s\ell\ell$ anomalies could come from a 10 TeV muon collider.
  (but hopefully we can sort this out earlier ...)