Rare decays

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Introduction

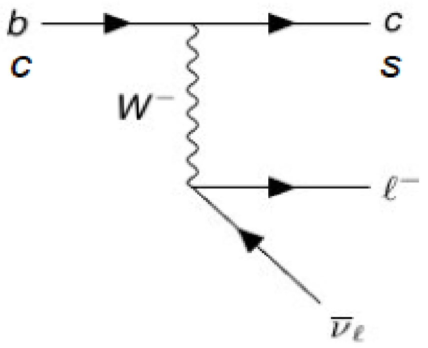
- Main Goals of Flavour Physics
- CKM paradigm
- What are rare decays?
- Why look for rare decays?

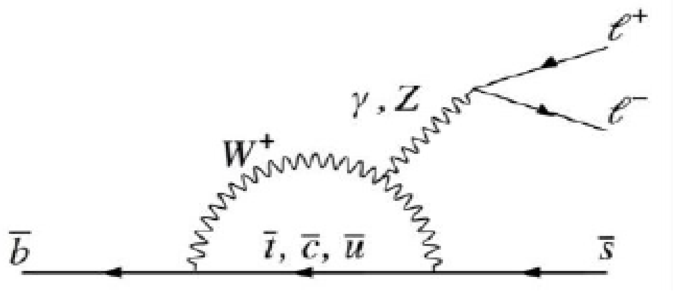
Typical Rare decays

- Semileptonic b-> c transition
- Semileptonic b-> s transitions
- Radiative b-> s gamma
- B(d,s) -> mu-mu, B(d,s) -> l nu decays
- B -> K nu nu, K -> pi nu nu
- Semileptonic Tau-decays (also muon-decays)
- LFV decays (B(d,s) -> ll’ decays), $e^+ + e^-$ -> ll’

An example

Charged currents versus neutral currents





- One charged lepton in the final state
- Tree level
- Theoretically clean
- Abundance of data
- Experimentally challenging due to missing neutrino

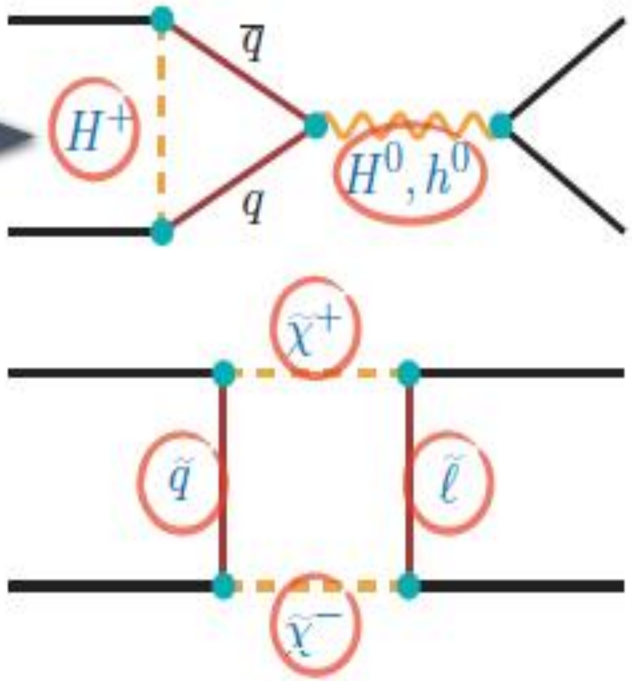
- Dilepton final states
- Forbidden at tree level in SM
- Sensitive to NP
- Highly suppressed, statistically limited in experiments
- Mainly on e-μ asymmetry

Another example

PROBE FOR NEW PHYSICS?

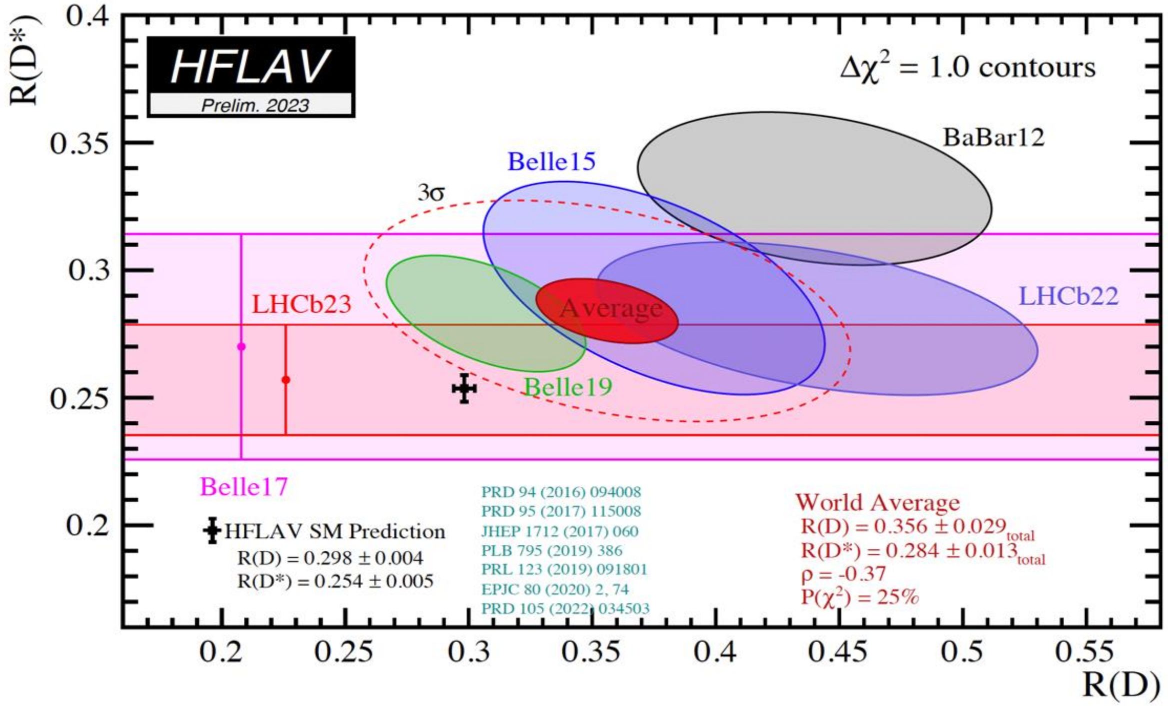
- **Through direct searches:**
  - Produce "real" new particles at high energy and discovery via their decays or interactions with the detectors.
- **Through indirect searches:**
  - "Virtual" new particles participating in the **RARE PROCESSES** and detecting any deviations from the SM predictions.

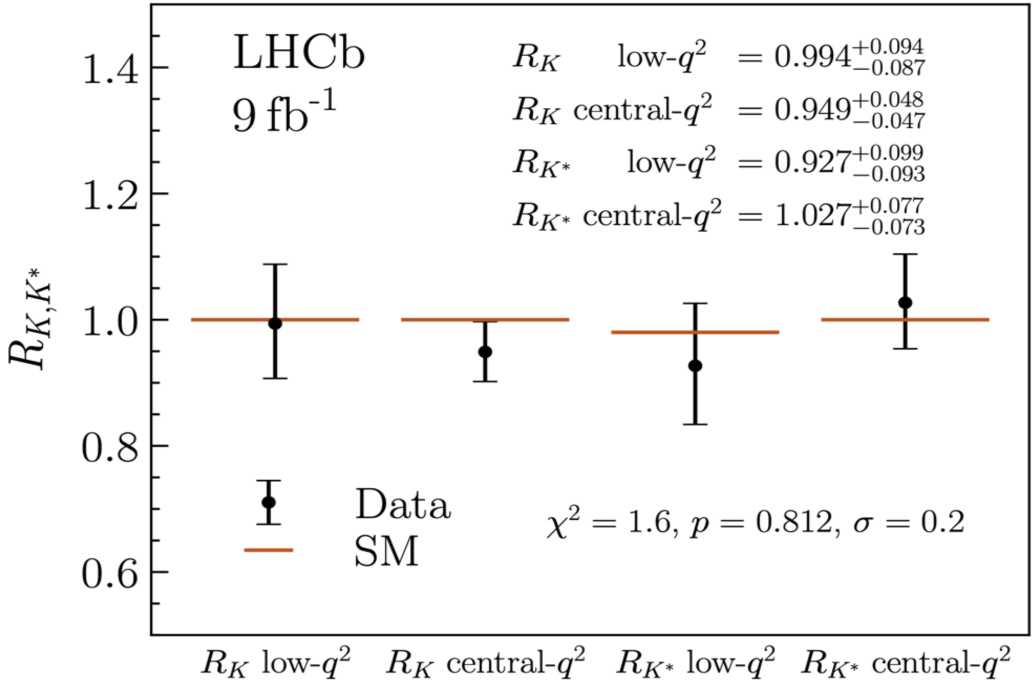
If new particles cannot be observed in the direct searches, here is the place we shall dig in!



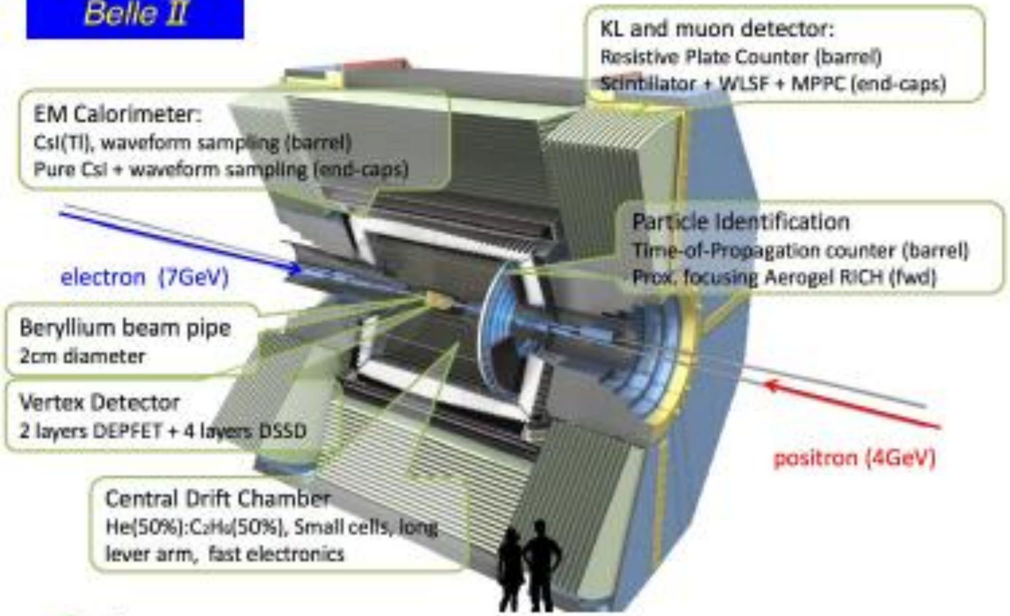
Direct and indirect searches are both necessary and complement each other!

Current B anomalies

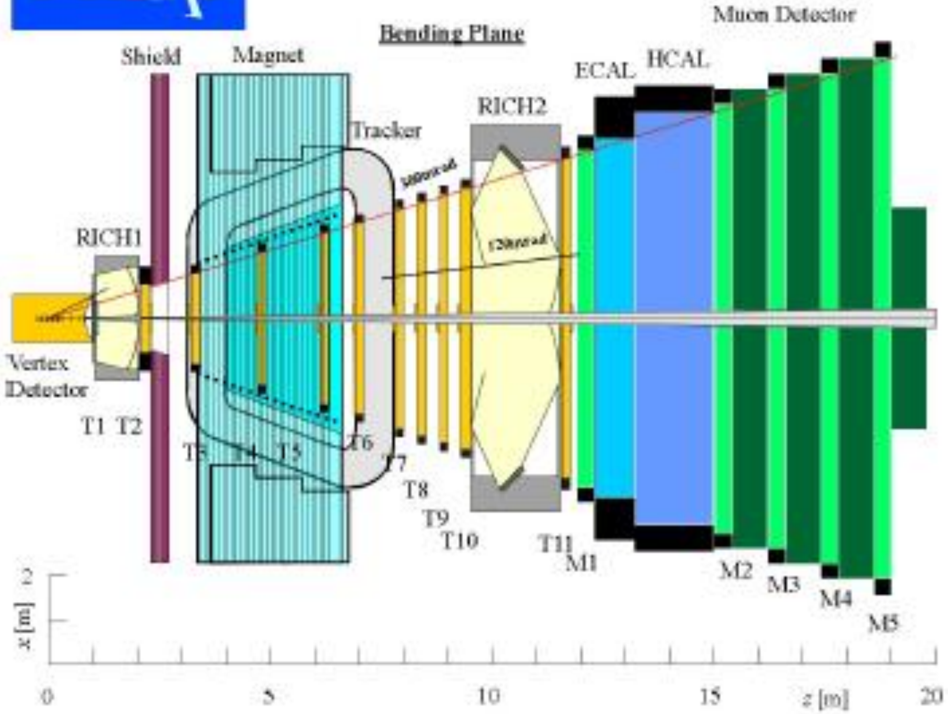




Belle II Detector



- ✓ clean event environment
- ✓ high trigger efficiency
- ✓ high-efficiency detection of neutrals
- ✓ many high-statistics control samples
- ✓ time-dependent analysis
- ◉ smaller cross-section than hadron



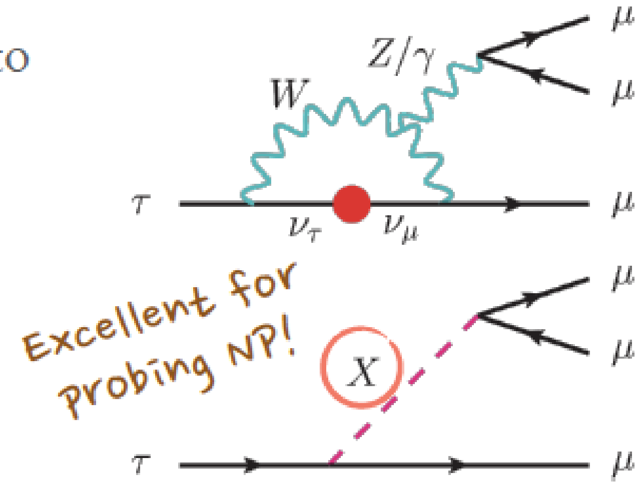
- ✓ large production cross-section
- ✓ large boost: excellent time res
- ◉ dedicated trigger required
- ◉ hard to do neutrals and neutrinos

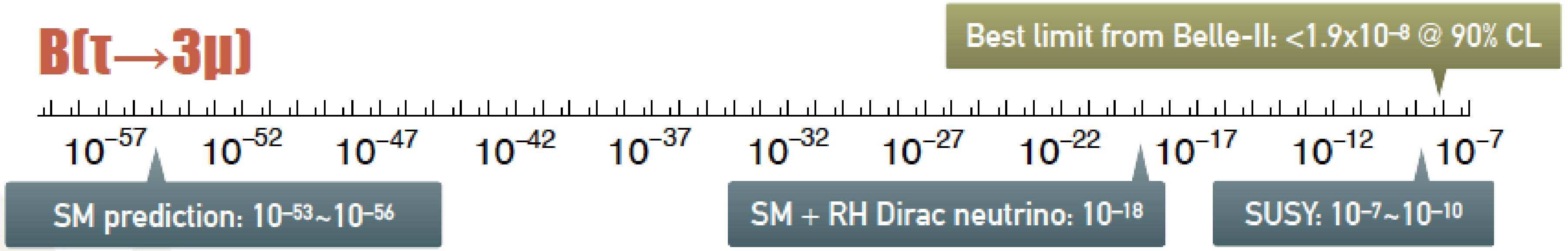
Experimental challenges for LFU tests

- Hadronic part: most of uncertainties cancel in the ratio at 1st order
- Missing neutrinos for (semi-)leptonic processes:
  - e^+e^- machines: inferred using beam condition & mising info
  - Hadron machines: more difficult, using info such as decay vertices, isolation info, kinematics of visible part, etc
- Electron: generally more difficult in experiments such as LHCb
- Muon: difficuties in μ/π separation for low-P tracks @ BESIII
- Tau lepton: short lifetime, decaying into final states with $\geq 1\nu$
  - e^+e^- machines: $\tau \to e\bar{\nu}\nu, \mu\bar{\nu}\nu, \pi(\pi^0)\nu$
  - Hadron machines: $\tau \to \mu\bar{\nu}\nu, \pi\pi\pi(\pi^0)\nu$

SEARCH FOR $\tau \rightarrow 3\mu$: INTRODUCTION

- A **charged lepton flavor violating (CLFV)** decay of τ to 3 muons, no missing neutrinos.
- Allowed by neutrino oscillations in SM, but with extraordinarily small branching fractions beyond experimental accessibility!
- The rate can be **strongly enhanced with New Physics scenarios**; experimentally the three-muon final state is accessible and clean.

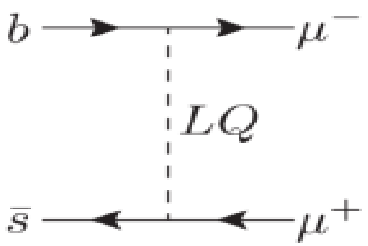


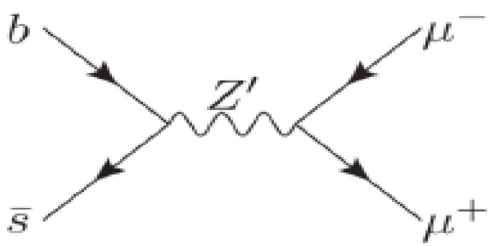


Favourite Models@ Market

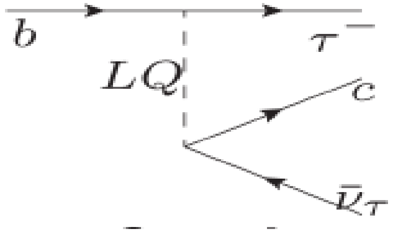
Hundreds of specific models reduce to the same important TeV-scale features ⇒ take a bottom up approach

Neutral current





Charged current:



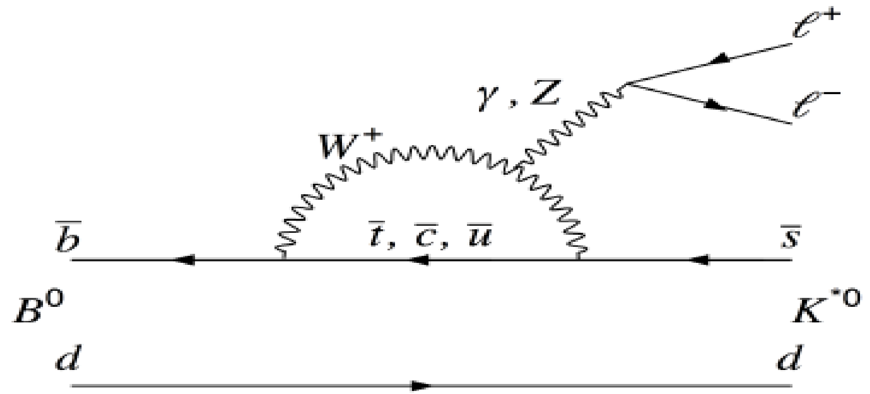
Vector/scalar option for leptoquark (LQ)

Typical semileptonic decays

$b \to s l^+ l^-$ in Standard Model

$$BR(B \to K\mu^+\mu^-) = BR(B \to Ke^+e^-)$$

BR$\sim \mathcal{O}(10^{-7})$: loop+EW+CKM



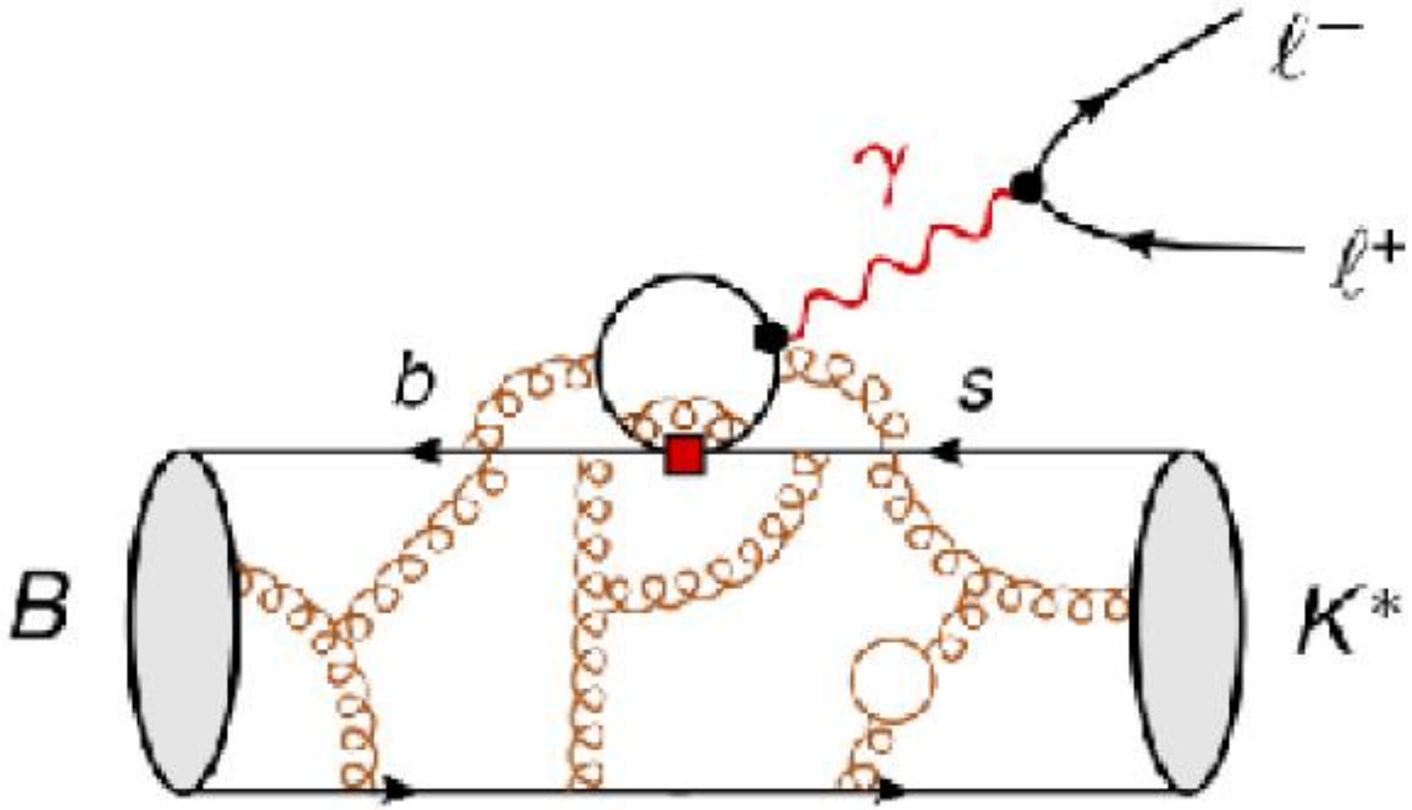
Predicting $B \to M\ell^+\ell^-$

$$\mathcal{A} = \texttt{local} + \texttt{non-local}$$

`local`: interpolate lattice at high q^2 and LCSR at low q^2. $q^2 = m_{ll}^2$.

`non-local`: no lattice. Most use QCD factorisation: perturbative charm loop+ad-hoc

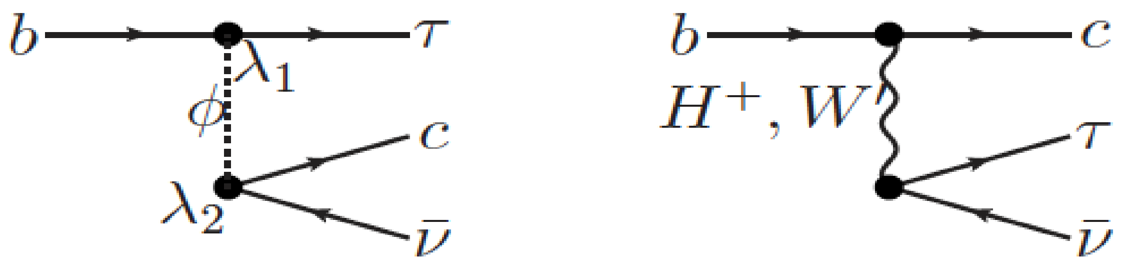
`EOS` approach: interpolate $q^2 < 0$ LCOPE and measurements of BRs/angular dists at $q^2 = M_{J/\psi}^2$.



ℓ^-
γ
ℓ^+
b
s
B
K^*

EFT

$R_{D^{(*)}}$: BSM Explanations



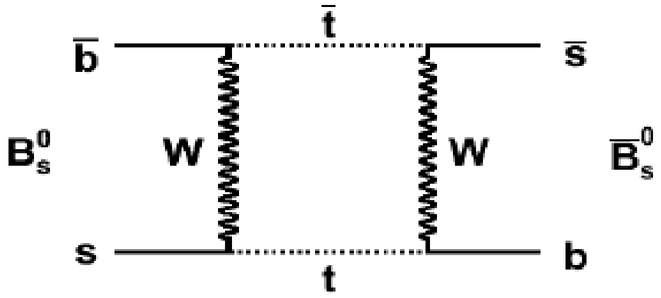
$$\mathcal{L}_{WET} = -\frac{2\lambda_1\lambda_2}{M^2} (\bar{c}\gamma^\mu P_L \nu) (\bar{\tau}\gamma_\mu P_L b) + H.c.$$

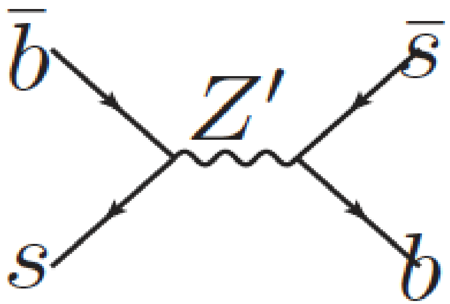
Fit to data tells us

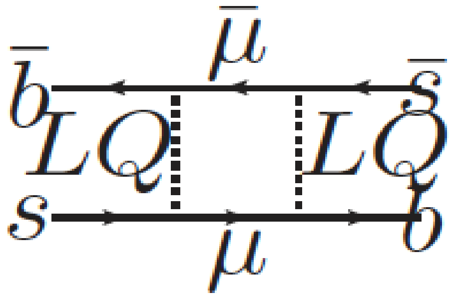
$$M = 3.4 \text{ TeV} \times \sqrt{\lambda_1\lambda_2}$$

$B_s - \bar{B}_s$ **Mixing**

Measurement agrees with SM.





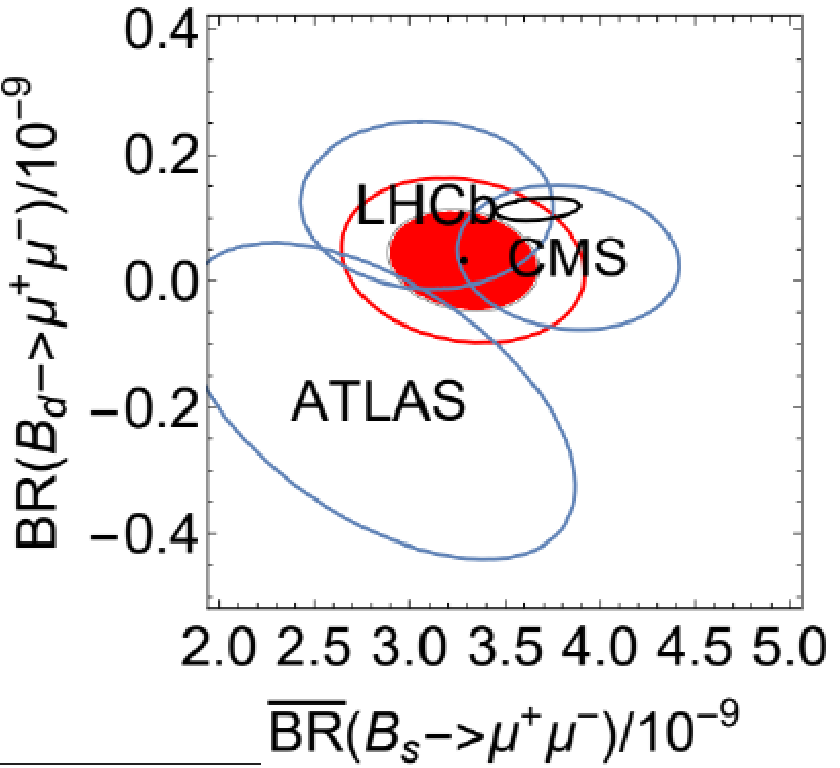


$$g_{sb} = \frac{g_X}{2} \sin 2\theta_{sb} \lesssim \frac{M_{Z'}}{194 \text{ TeV}}$$ but uncertain from QCD sum rules and lattice[6].

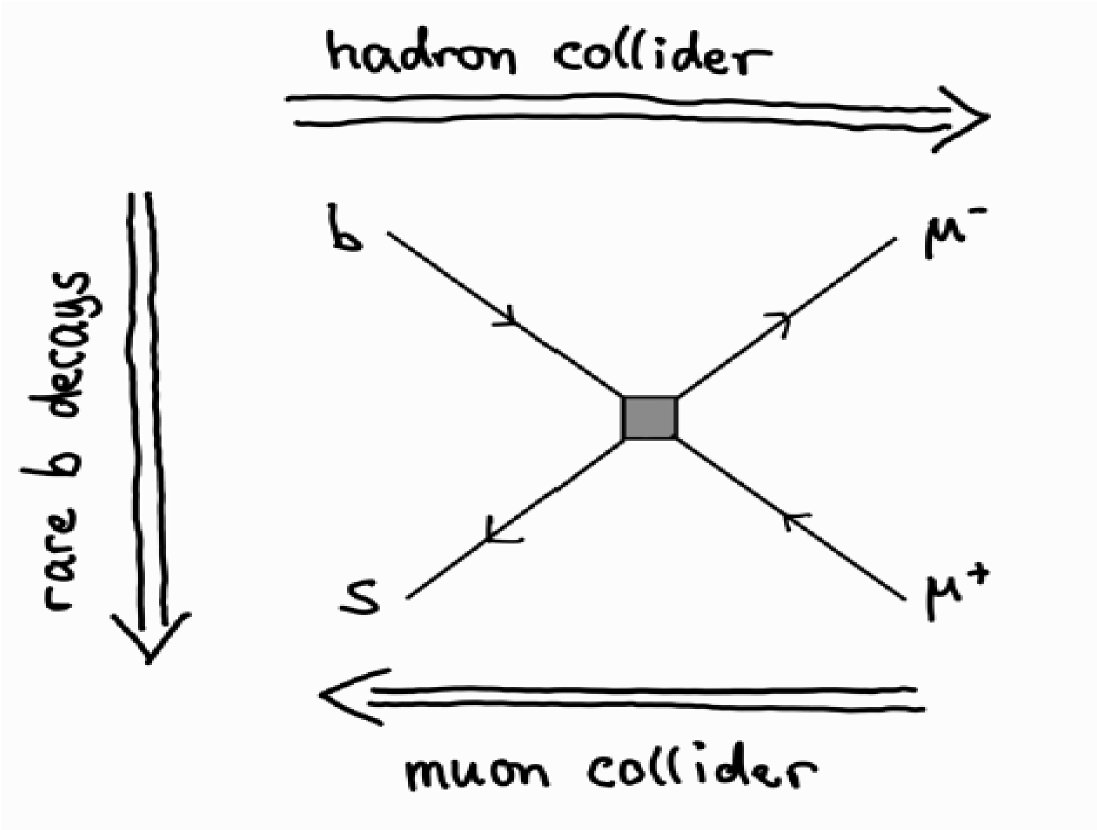
[6] King, Lenz, Rauh, arXiv:1904.00940

$BR(B_s \to \mu^+\mu^-)$:[4]: SM: 1.6σ

$B_s = (\bar{b}s)$, $B_d = (\bar{b}d)$



[4]SM: Feldmann, Gubernari, Huber, Seitz, 2211.04209; Combination: BCA, Davighi, 2211.11766



W Altmannshofer

LFV

- In the SM, charged lepton flavor violation is suppressed by the tiny neutrino mass splittings

$$\text{e.g.}\quad \mathrm{BR}(\mu \to 3e) \sim \mathrm{BR}(\mu \to e\nu_e\nu_\mu)\left|\frac{g^2}{16\pi^2}\frac{\Delta m_\nu^2}{m_W^2}\right|^2 \sim 10^{-50}$$

- Any observation in the foreseeable future would be an unambiguous sign of new physics.

- Can search for lepton flavor violation in many different ways:

1) At low energies in lepton or hadron decays: $\mu \to e\gamma$, $B_s \to \tau\mu$, ...
2) At high energies in decays of heavy resonances: $Z \to \mu e$, $h \to \tau\mu$, ...
3) At high energies in non-resonant production: $e^+e^- \to \tau\mu$, ...

- Generic scaling of a new physics effect with the flavor changing coupling g_{NP} and the new physics scale Λ_{NP}

$$\frac{\text{BR}(\mu \to 3e)}{\text{BR}(\mu \to e\nu_\mu\bar{\nu}_e)} \sim g_{\text{NP}}^2 \left(\frac{v}{\Lambda_{\text{NP}}}\right)^4 \lesssim 10^{-12}$$

$$\frac{\text{BR}(\tau \to 3\mu)}{\text{BR}(\tau \to \mu\nu_\mu\bar{\nu}_\tau)} \sim g_{\text{NP}}^2 \left(\frac{v}{\Lambda_{\text{NP}}}\right)^4 \lesssim 10^{-8}$$

- For O(1) couplings, this corresponds to new physics scales of

$$\Lambda_{\text{NP}} \gtrsim 100 \text{ TeV} \quad \text{for muons}$$

$$\Lambda_{\text{NP}} \gtrsim 10 \text{ TeV} \quad \text{for taus}$$

More LFV

- The scaling of LFV cross sections with the center of mass energy depends on the type of operator:

$$\frac{\sigma(e^+e^- \to \tau\mu)}{\sigma(e^+e^- \to \tau^+\tau^-)} \sim g_{\text{NP}}^2 \left(\frac{v^4}{\Lambda_{\text{NP}}^4}\right),\ g_{\text{NP}}^2 \left(\frac{sv^2}{\Lambda_{\text{NP}}^4}\right),\ g_{\text{NP}}^2 \left(\frac{s^2}{\Lambda_{\text{NP}}^4}\right)$$

- For some operators one will have enhanced sensitivity at high energies. (Assuming one does not resolve the higher dimensional operators.)

- How sensitive is one to $\tau\mu$ production at future e^+e^- colliders?

- In WA, Munbodh, Oh 2305.03869 we show that high-energy runs of FCC-ee/CEPC have sensitivity that is comparable and complementary to other probes.

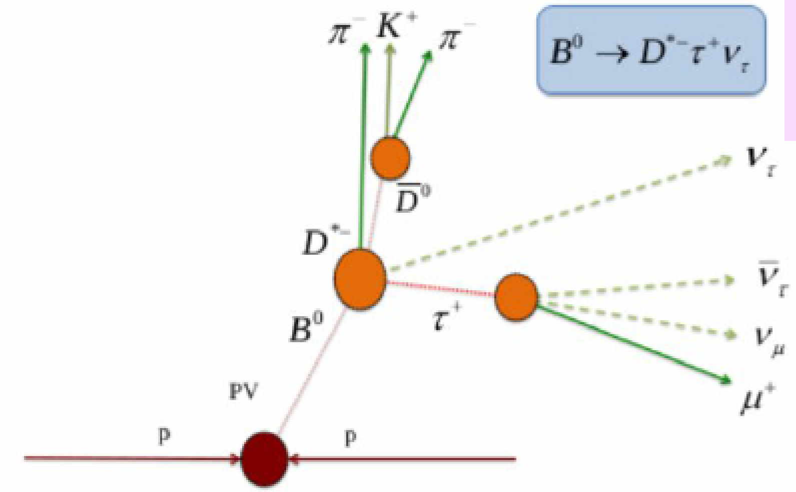
OUTLOOK

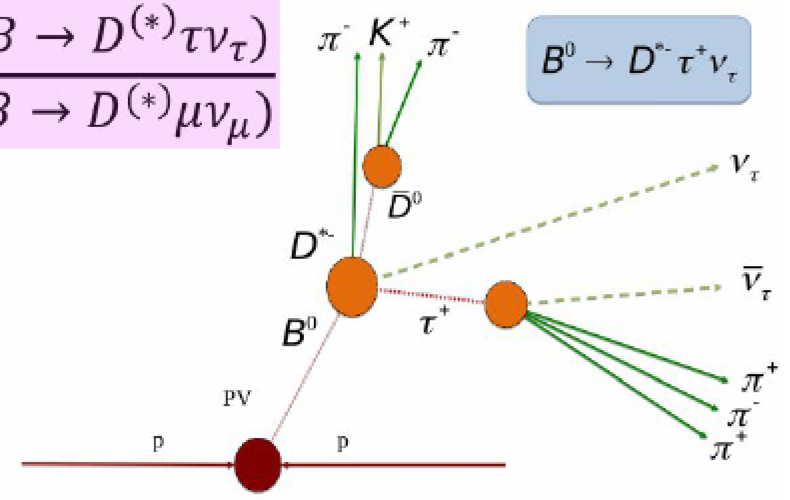
- CKM picture established
- No trace of new Physics
- Belle II / LHCb will continue to search
- Excellent time ahead!

Thanks!

R(D$^{(*)}$) measurements @ LHCb

$$R(D^{(*)}) = \frac{\mathcal{B}(B \to D^{(*)}\tau\nu_\tau)}{\mathcal{B}(B \to D^{(*)}\mu\nu_\mu)}$$





Muonic $\tau \to \mu\bar{\nu}\nu$:

- Large statistics
- Study of τ and μ modes in one dataset
- Can measure R(D) and R(D*) simultaneously

Hadronic $\tau \to \pi\pi\pi(\pi^0)\bar{\nu}$:

- Relatively high purity
- External BR measurement for normalization
- Decay vertex of τ well measured to suppress dominant backgrounds
- 3π dynamics important for the separation of B-> D*DX backgrounds