Indirect Constraints on Third Generation Baryon Number Violation

Gael Finauri

IMPRS Colloquium

Max Planck – 23 May 2024

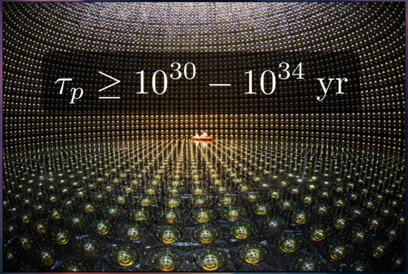
MAX-PLANCK-INSTITUT FÜR PHYSIK

based on M. Beneke, GF, A. A. Petrov 2404.09642

Matter-antimatter asymmetry of the Universe requires Baryon Number Violation (BNV)

Matter-antimatter asymmetry of the Universe requires Baryon Number Violation (BNV)

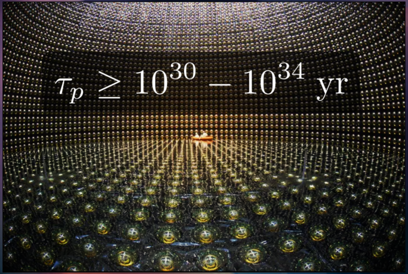
Proton lifetime τ_p is the strongest constraint on BNV:



Super-Kamiokande, Japan

Matter-antimatter asymmetry of the Universe requires Baryon Number Violation (BNV)

Proton lifetime τ_p is the strongest constraint on BNV:



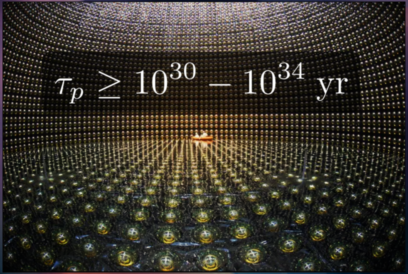
Super-Kamiokande, Japan

suggesting New Physics from very high scales

$$\Lambda_{\mathrm{BNV}} \sim 10^{15} - 10^{16}\ \mathrm{GeV}$$

Matter-antimatter asymmetry of the Universe requires Baryon Number Violation (BNV)

Proton lifetime τ_p is the strongest constraint on BNV:



Super-Kamiokande, Japan

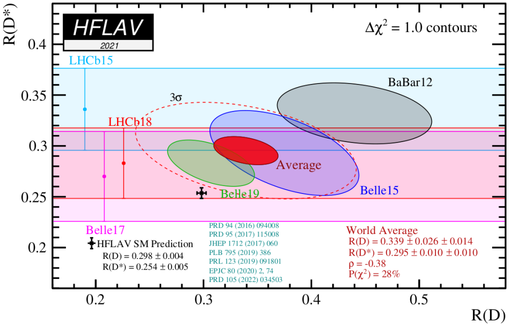
suggesting New Physics from very high scales

$$\Lambda_{\text{BNV}} \sim 10^{15} - 10^{16}\ \text{GeV}$$

But what if BNV needs third generation quarks?

Why?

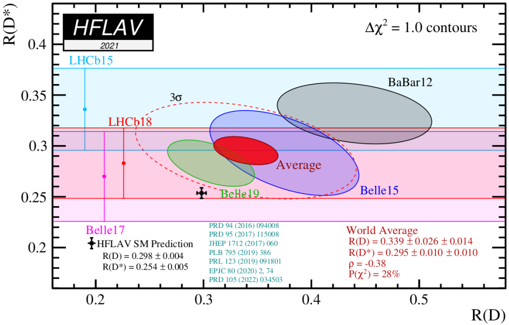
B-anomalies: set of observables in B decays showing discrepancies
SM predictions vs Experiments



Why?

B-anomalies: set of observables in B decays showing discrepancies SM predictions vs Experiments

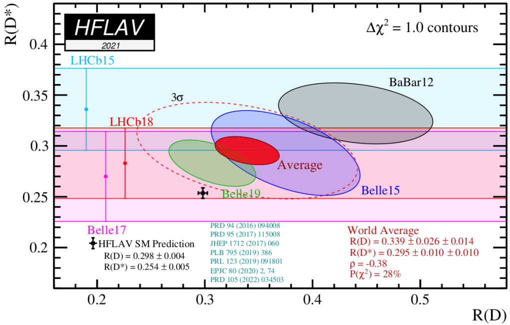
explained by New Physics at scales $\Lambda_{\text{fl}} \sim 1 - 10$ TeV



Why?

B-anomalies: set of observables in B decays showing discrepancies
SM predictions vs Experiments

explained by New Physics at scales
$\Lambda_{\text{fl}} \sim 1 - 10$ TeV

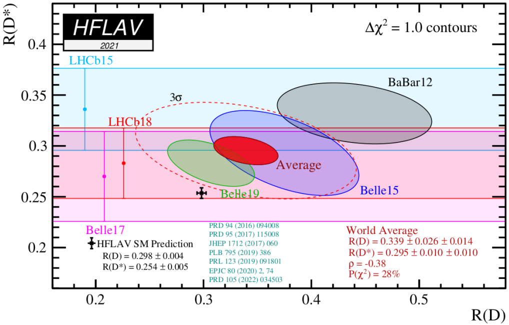


Natural questions:

- If BNV comes only from b quarks, can $\Lambda_{\text{BNV}} \sim \Lambda_{\text{fl}} \ll 10^{15}$ GeV be possible?

Why?

B-anomalies: set of observables in B decays showing discrepancies SM predictions vs Experiments



explained by New Physics at scales $\Lambda_{\text{fl}} \sim 1 - 10$ TeV

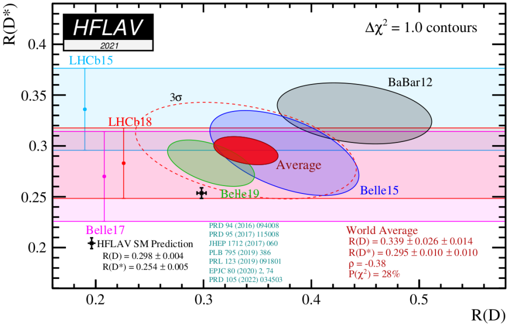
Natural questions:

- If BNV comes only from b quarks, can $\Lambda_{\text{BNV}} \sim \Lambda_{\text{fl}} \ll 10^{15}$ GeV be possible?
- Would it lead to observable BNV B decays?

Why?

B-anomalies: set of observables in B decays showing discrepancies SM predictions vs Experiments

explained by New Physics at scales $\Lambda_{\text{fl}} \sim 1 - 10$ TeV



Natural questions:

- If BNV comes only from b quarks, can $\Lambda_{\text{BNV}} \sim \Lambda_{\text{fl}} \ll 10^{15}$ GeV be possible?
- Would it lead to observable BNV B decays?

Answer: Don't know!

Proton would still decay through virtual b quarks, constraining Λ_{BNV}

Dominant Decay Channels

Assumption: BNV happens only if at least a b quark is involved.

Dominant Decay Channels

Assumption: BNV happens only if at least a b quark is involved.
Goal: as $\Gamma \propto 1/\Lambda_{\text{BNV}}^4$, find the smallest Λ_{BNV} allowed by proton decay

Dominant Decay Channels

Assumption: BNV happens only if at least a b quark is involved.

Goal: as $\Gamma \propto 1/\Lambda^4_{\text{BNV}}$, find the smallest Λ_{BNV} allowed by proton decay

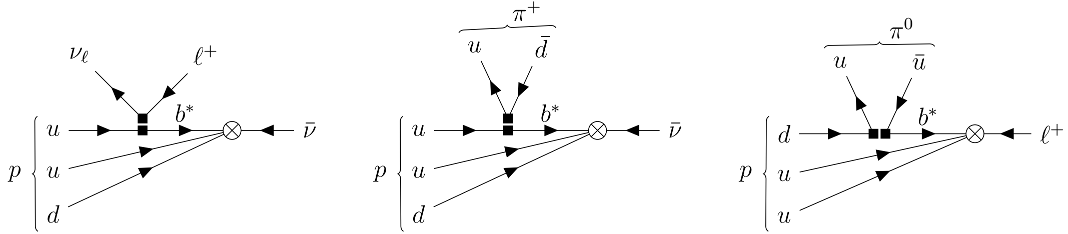
$\Rightarrow$ estimate the largest BNV B decay rate

Dominant Decay Channels

Assumption: BNV happens only if at least a b quark is involved.

Goal: as $\Gamma \propto 1/\Lambda^4_{\text{BNV}}$, find the smallest Λ_{BNV} allowed by proton decay

$\Rightarrow$ estimate the largest BNV B decay rate

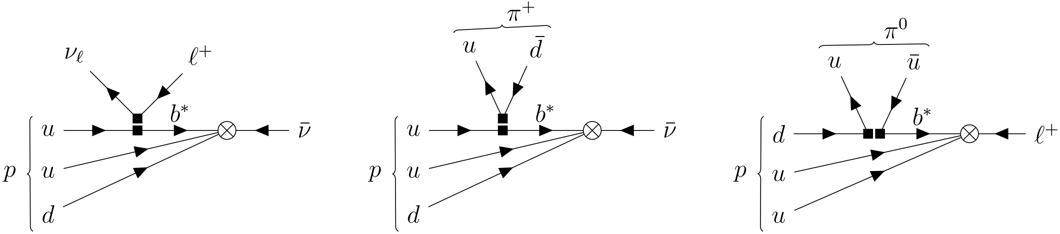


- $p \to \ell^+ \nu_\ell \bar{\nu}$
- $p \to \pi^+ \bar{\nu}$
- $p \to \pi^0 \ell^+$

mediated by weak interaction and four-fermion BNV operators ($\otimes$) from SMEFT:

Dominant Decay Channels

Assumption: BNV happens only if at least a b quark is involved.
Goal: as $\Gamma \propto 1/\Lambda_{\text{BNV}}^4$, find the smallest Λ_{BNV} allowed by proton decay
$\Rightarrow$ estimate the largest BNV B decay rate



- $p \to \ell^+ \nu_\ell \bar{\nu}$
- $p \to \pi^+ \bar{\nu}$
- $p \to \pi^0 \ell^+$

mediated by weak interaction and four-fermion BNV operators ($\otimes$) from SMEFT:

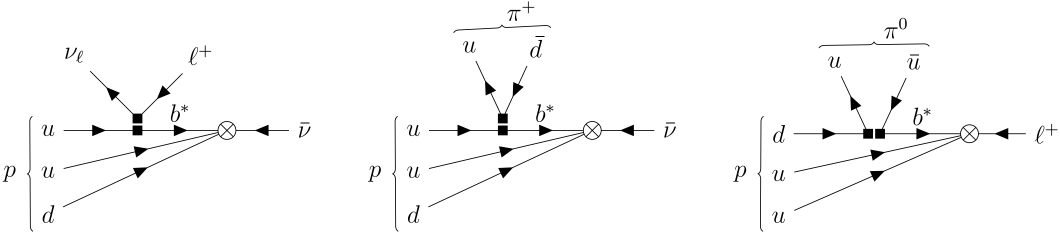
most suppressed $\Gamma(p \to f)$

Dominant Decay Channels

Assumption: BNV happens only if at least a b quark is involved.

Goal: as $\Gamma \propto 1/\Lambda_{\text{BNV}}^4$, find the smallest Λ_{BNV} allowed by proton decay

$\Rightarrow$ estimate the largest BNV B decay rate

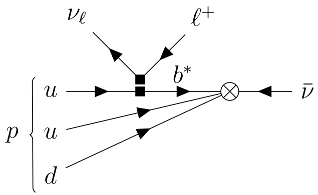


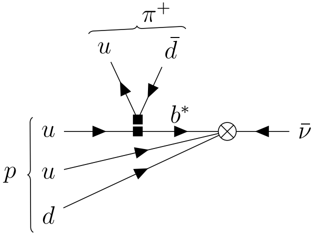
- $p \to \ell^+ \nu_\ell \bar{\nu}$
- $p \to \pi^+ \bar{\nu}$
- $p \to \pi^0 \ell^+$

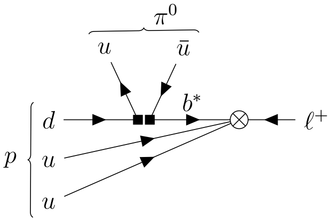
mediated by weak interaction and four-fermion BNV operators ($\otimes$) from SMEFT:

most suppressed $\Gamma(p \to f)$ ➡ smallest Λ_{BNV} from τ_p constraints

Assumption: BNV happens only if at least a b quark is involved.
Goal: as $\Gamma \propto 1/\Lambda_{\text{BNV}}^4$, find the smallest Λ_{BNV} allowed by proton decay
$\Rightarrow$ estimate the largest BNV B decay rate







- $p \to \ell^+ \nu_\ell \bar{\nu}$
- $p \to \pi^+ \bar{\nu}$
- $p \to \pi^0 \ell^+$

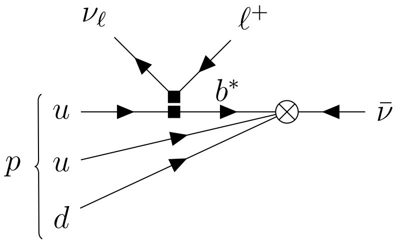
mediated by weak interaction and four-fermion BNV operators ($\otimes$) from SMEFT:

most suppressed $\Gamma(p \to f)$ ➡ smallest Λ_{BNV} from τ_p constraints ➡ highest $\Gamma(\bar{B} \to X\ell)$

Results for $p \to \ell^+ \nu_\ell \bar{\nu}$

Experimental bounds [Super-Kamiokande 2014]

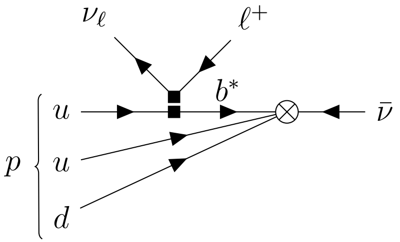
- $\Gamma(p \to e^+ \nu\nu) < 1.23 \cdot 10^{-64}$ GeV
- $\Gamma(p \to \mu^+ \nu\nu) < 0.95 \cdot 10^{-64}$ GeV



Results for $p \to \ell^+ \nu_\ell \bar{\nu}$

Experimental bounds [Super-Kamiokande 2014]

- $\Gamma(p \to e^+ \nu\nu) < 1.23 \cdot 10^{-64}$ GeV
- $\Gamma(p \to \mu^+ \nu\nu) < 0.95 \cdot 10^{-64}$ GeV



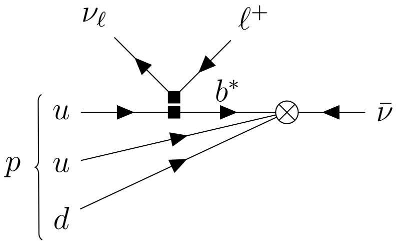
C_ν is the unknown dimensionless Wilson coefficient in the Weak Effective Theory (WET)

$$\Gamma(p \to \ell^+ \nu_\ell \bar{\nu}) = \frac{|C_\nu|^2}{\Lambda^4_{\text{BNV}}} \frac{|V_{ub}|^2 G_F^2 m_p^7}{7680\pi^3 m_b^2} 10^{-3}\text{GeV}^4 \times \begin{cases} 1.028\,, & \text{for } p \to e^+ \nu_e \bar{\nu} \\ 0.933\,, & \text{for } p \to \mu^+ \nu_\mu \bar{\nu} \end{cases}$$

Results for $p \to \ell^+ \nu_\ell \bar{\nu}$

Experimental bounds [Super-Kamiokande 2014]

- $\Gamma(p \to e^+ \nu\nu) < 1.23 \cdot 10^{-64}$ GeV
- $\Gamma(p \to \mu^+ \nu\nu) < 0.95 \cdot 10^{-64}$ GeV



C_ν is the unknown dimensionless Wilson coefficient in the Weak Effective Theory (WET)

$$\Gamma(p \to \ell^+ \nu_\ell \bar{\nu}) = \frac{|C_\nu|^2}{\Lambda^4_{\text{BNV}}} \frac{|V_{ub}|^2 G_F^2 m_p^7}{7680\pi^3 m_b^2} 10^{-3}\text{GeV}^4 \times \begin{cases} 1.028\,, & \text{for } p \to e^+ \nu_e \bar{\nu} \\ 0.933\,, & \text{for } p \to \mu^+ \nu_\mu \bar{\nu} \end{cases}$$

Using the experimental constraints

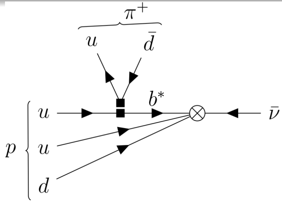
$$\left.\frac{\Lambda_{\text{BNV}}}{\sqrt{|C_\nu|}}\right|_{p \to e^+ \nu_e \bar{\nu}} > 6.59 \cdot 10^9 \text{ GeV} \qquad \left.\frac{\Lambda_{\text{BNV}}}{\sqrt{|C_\nu|}}\right|_{p \to \mu^+ \nu_\mu \bar{\nu}} > 6.86 \cdot 10^9 \text{ GeV}$$

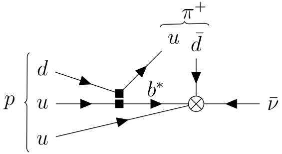
rather **high**! Already showing that $\Lambda_{\text{BNV}} \sim \Lambda_{\text{fl}}$ is ruled out!

Results for $p \to \pi^+ \bar{\nu}$

Experimental bounds [Super-Kamiokande 2014]
$\Gamma(p \to \pi^+ \nu) < 5.35 \cdot 10^{-65}$ GeV

Assume factorization, true up to $\mathcal{O}(1)$ corrections

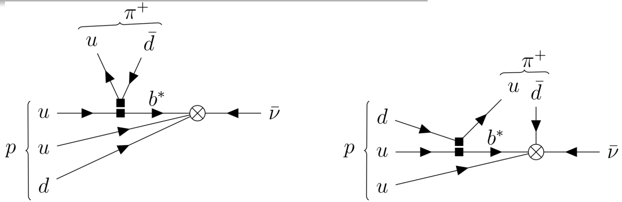




Results for $p \to \pi^+ \bar{\nu}$

Experimental bounds [Super-Kamiokande 2014]
$\Gamma(p \to \pi^+ \nu) < 5.35 \cdot 10^{-65}$ GeV

Assume factorization, true up to $\mathcal{O}(1)$ corrections

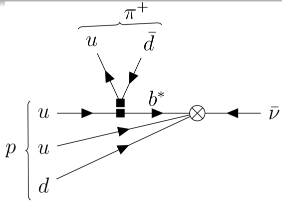


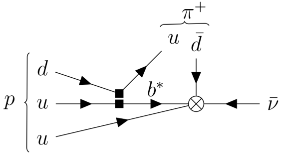
$$\Gamma(p \to \pi^+ \bar{\nu}) = \frac{|C_\nu|^2}{\Lambda_{\text{BNV}}^4} \frac{|V_{ud}|^2 |V_{ub}|^2 G_F^2 m_p^5 f_\pi^2}{1024 \pi m_b^2} (2.18 \cdot 10^{-5} \text{GeV}^4)$$

Results for $p \to \pi^+ \bar{\nu}$

Experimental bounds [Super-Kamiokande 2014]
$\Gamma(p \to \pi^+ \nu) < 5.35 \cdot 10^{-65}$ GeV

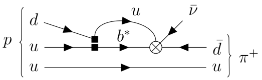
Assume factorization, true up to $\mathcal{O}(1)$ corrections

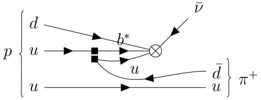


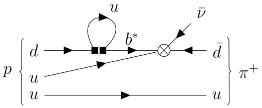


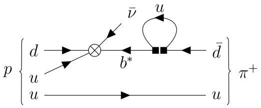
$$\Gamma(p \to \pi^+ \bar{\nu}) = \frac{|C_\nu|^2}{\Lambda^4_{\text{BNV}}} \frac{|V_{ud}|^2 |V_{ub}|^2 G_F^2 m_p^5 f_\pi^2}{1024 \pi m_b^2} (2.18 \cdot 10^{-5} \text{GeV}^4)$$

neglected suppressed contributions:







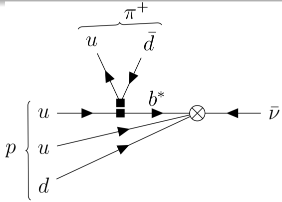


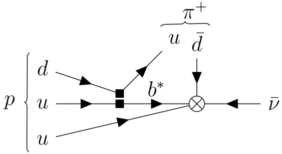
Results for $p \to \pi^+ \bar{\nu}$

Experimental bounds [Super-Kamiokande 2014]

$\Gamma(p \to \pi^+ \nu) < 5.35 \cdot 10^{-65}$ GeV

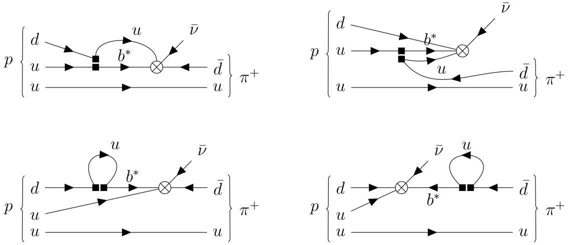
Assume factorization, true up to $\mathcal{O}(1)$ corrections





$$\Gamma(p \to \pi^+ \bar{\nu}) = \frac{|C_\nu|^2}{\Lambda^4_{\text{BNV}}} \frac{|V_{ud}|^2 |V_{ub}|^2 G_F^2 m_p^5 f_\pi^2}{1024 \pi m_b^2} (2.18 \cdot 10^{-5} \text{GeV}^4)$$

neglected suppressed contributions:



Using the experimental constraints

$$\left. \frac{\Lambda_{\text{BNV}}}{\sqrt{|C_\nu|}} \right|_{p \to \pi^+ \bar{\nu}} > 3.34 \cdot 10^9 \text{ GeV}$$

<u>less effective than leptonic decay</u>

Results for $p \to \pi^0 \ell^+$

Strongest experimental bounds [Super-Kamiokande 2020]

- $\Gamma(p \to \pi^0 e^+) < 0.87 \cdot 10^{-66}$ GeV
- $\Gamma(p \to \pi^0 \mu^+) < 1.30 \cdot 10^{-66}$ GeV

two independent operators contributing

⇒ 2D constraints!

Results for $p \to \pi^0 \ell^+$

Strongest experimental bounds [Super-Kamiokande 2020]

- $\Gamma(p \to \pi^0 e^+) < 0.87 \cdot 10^{-66}$ GeV
- $\Gamma(p \to \pi^0 \mu^+) < 1.30 \cdot 10^{-66}$ GeV

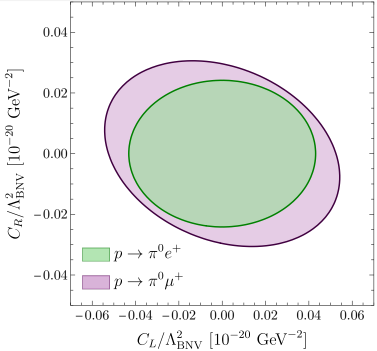
two independent operators contributing

➡ 2D constraints!

$$\Lambda_{\text{BNV}}\Big|_{p\to\pi^0 e^+} > 6.23 \cdot 10^{10}\ \text{GeV} \left(|C_R^e|^2 + 0.0014\,\text{Re}[C_L^{e\,*} C_R^e] + 0.304|C_L^e|^2\right)^{1/4},$$

$$\Lambda_{\text{BNV}}\Big|_{p\to\pi^0 \mu^+} > 5.63 \cdot 10^{10}\ \text{GeV} \left(|C_R^\mu|^2 + 0.283\,\text{Re}[C_L^{\mu\,*} C_R^\mu] + 0.308|C_L^\mu|^2\right)^{1/4},$$

Results for $p \to \pi^0 \ell^+$



Strongest experimental bounds [Super-Kamiokande 2020]

- $\Gamma(p \to \pi^0 e^+) < 0.87 \cdot 10^{-66}$ GeV
- $\Gamma(p \to \pi^0 \mu^+) < 1.30 \cdot 10^{-66}$ GeV

two independent operators contributing

⇨ 2D constraints!

$$\Lambda_{\text{BNV}}\Big|_{p\to\pi^0 e^+} > 6.23 \cdot 10^{10}\ \text{GeV} \left(|C_R^e|^2 + 0.0014\text{Re}[C_L^{e\,*} C_R^e] + 0.304|C_L^e|^2\right)^{1/4},$$

$$\Lambda_{\text{BNV}}\Big|_{p\to\pi^0 \mu^+} > 5.63 \cdot 10^{10}\ \text{GeV} \left(|C_R^\mu|^2 + 0.283\text{Re}[C_L^{\mu\,*} C_R^\mu] + 0.308|C_L^\mu|^2\right)^{1/4},$$

these coefficients are 10 times more constrained with respect to C_ν

Estimates for inclusive BNV B decays

We can estimate the branching ratio using $\Lambda_{\text{BNV}} > 6 \cdot 10^9$ GeV

$$\mathcal{B}(\bar{B} \to X\ell) \approx \frac{m_b^5}{2^{10} 3\pi^3 \Gamma_{\text{tot}}^B \Lambda_{\text{BNV}}^4}$$

Estimates for inclusive BNV B decays

We can estimate the branching ratio using $\Lambda_{\text{BNV}} > 6 \cdot 10^9$ GeV

$$\mathcal{B}(\bar{B} \to X\ell) \approx \frac{m_b^5}{2^{10} 3\pi^3 \Gamma_{\text{tot}}^B \Lambda_{\text{BNV}}^4} \approx (8|V_{cb}|G_F \Lambda_{\text{BNV}}^2)^{-2}$$

Estimates for inclusive BNV B decays

We can estimate the branching ratio using $\Lambda_{\text{BNV}} > 6 \cdot 10^9$ GeV

$$\mathcal{B}(\bar{B} \to X\ell) \approx \frac{m_b^5}{2^{10} 3\pi^3 \Gamma_{\text{tot}}^B \Lambda_{\text{BNV}}^4} \approx (8|V_{cb}|G_F \Lambda_{\text{BNV}}^2)^{-2} \lesssim \mathcal{O}(5 \cdot 10^{-29})$$

showing that direct observation is ruled out: $\bar{B} \not\to X\ell$

Estimates for inclusive BNV B decays

We can estimate the branching ratio using $\Lambda_{\text{BNV}} > 6 \cdot 10^9$ GeV

$$\mathcal{B}(\bar{B} \to X\ell) \approx \frac{m_b^5}{2^{10} 3 \pi^3 \Gamma_{\text{tot}}^B \Lambda_{\text{BNV}}^4} \approx (8|V_{cb}|G_F \Lambda_{\text{BNV}}^2)^{-2} \lesssim \mathcal{O}(5 \cdot 10^{-29})$$

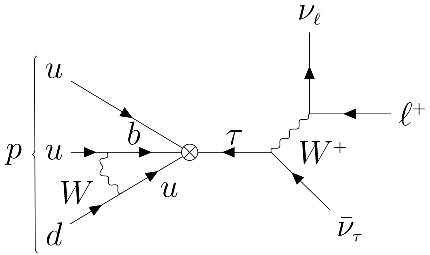
showing that direct observation is ruled out: $\bar{B} \not\to X\ell$

However...

what about operators with τ lepton? Not directly constrained by p decay!

BNV Operators with b and τ

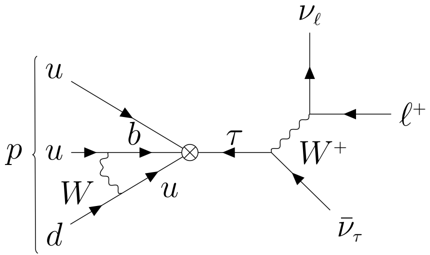
Both b and τ have to be virtual!
Efficiently constrained by loop induced effects



BNV Operators with b and τ

Both b and τ have to be virtual!
Efficiently constrained by loop induced effects
Estimate of this process $p \to \ell^+ \nu_\ell \bar{\nu}_\tau$ gives

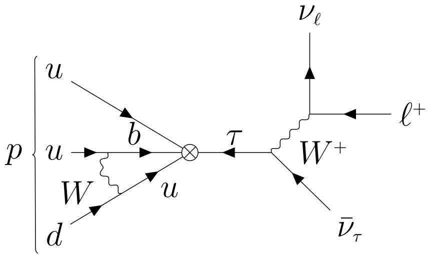
$$\Lambda_{\text{BNV}} \gtrsim (0.4 \div 1.8) \cdot 10^6 \text{ GeV}$$



BNV Operators with b and τ

Both b and τ have to be virtual!
Efficiently constrained by loop induced effects
Estimate of this process $p \to \ell^+ \nu_\ell \bar{\nu}_\tau$ gives

$$\Lambda_{\text{BNV}} \gtrsim (0.4 \div 1.8) \cdot 10^6 \text{ GeV}$$



$$\mathcal{B}(\bar{B} \to X\tau) \lesssim (10^{-13} \div 10^{-15})$$

closer to detectability, but experimental efficiency in reconstructing τ is much smaller...

Summary

Under the assumption that BNV occurs only if b quark is involved:

Summary

Under the assumption that BNV occurs only if b quark is involved:

- Scanned for the less constrained SMEFT operators

Summary

Under the assumption that BNV occurs only if b quark is involved:

- Scanned for the less constrained SMEFT operators
- Derived bounds for Λ_{BNV} from proton decay in three decay channels

Summary

Under the assumption that BNV occurs only if b quark is involved:

- Scanned for the less constrained SMEFT operators
- Derived bounds for Λ_{BNV} from proton decay in three decay channels
- Showed $\mathcal{B}(\bar{B} \to X\ell) \lesssim \mathcal{O}(5 \cdot 10^{-29}) \Rightarrow$ undetectable!

Summary

Under the assumption that BNV occurs only if b quark is involved:

- Scanned for the less constrained SMEFT operators
- Derived bounds for Λ_{BNV} from proton decay in three decay channels
- Showed $\mathcal{B}(\bar{B} \to X\ell) \lesssim \mathcal{O}(5 \cdot 10^{-29}) \Rightarrow$ undetectable!
- For τ less restrictive $\mathcal{B}(\bar{B} \to X\tau) \lesssim 10^{-13} \div 10^{-15}$

Summary

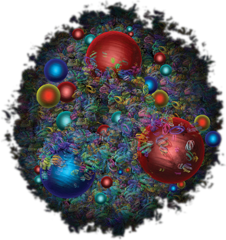
Under the assumption that BNV occurs only if b quark is involved:

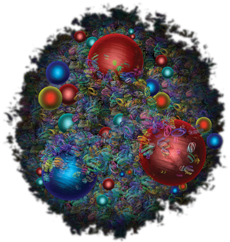
- Scanned for the less constrained SMEFT operators
- Derived bounds for Λ_{BNV} from proton decay in three decay channels
- Showed $\mathcal{B}(\bar{B} \to X\ell) \lesssim \mathcal{O}(5 \cdot 10^{-29}) \Rightarrow$ undetectable!
- For τ less restrictive $\mathcal{B}(\bar{B} \to X\tau) \lesssim 10^{-13} \div 10^{-15}$

Thank You!

Backup Slides

Theoretical predictions are affected by the **non-perturbative** nature of hadronic QCD





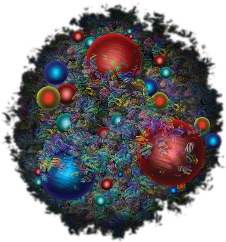
Theoretical predictions are affected by the **non-perturbative** nature of hadronic QCD

However nature provided an intrinsic perturbative scale $m_b \sim 5$ GeV

... in B Physics

Theoretical predictions are affected by the **non-perturbative** nature of hadronic QCD

However nature provided an intrinsic perturbative scale $m_b \sim 5$ GeV



$\Rightarrow$ B decays employing **Effective Field Theories** (HQET, SCET, ...) to separate perturbative physics from universal non-perturbative inputs