Overview of rare B-decays

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(on behalf of the LHCb collaboration
including results from ATLAS, Belle and CMS)

FPCP
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Rare decays

EW penguins
\[ B^{0/+} \rightarrow K^{(*)0/+}\mu^+\mu^- \]
\[ B^0_s \rightarrow \phi\mu^+\mu^- \]
\[ B^+ \rightarrow K^+\mu^+\mu^- \]
\[ B^+ \rightarrow \pi^+\mu^+\mu^- \]
\[ \Lambda_b \rightarrow \Lambda^0\mu^+\mu^- \]

Radiative decays
\[ B^0 \rightarrow K^*\gamma \]
\[ B^0_s \rightarrow \phi\gamma \]
\[ B^+ \rightarrow K^+\pi^+\pi^-\gamma \]

Baryons rare decay
\[ \Lambda^0_b \rightarrow pK^-\mu^+\mu^- \]
\[ \Lambda^0_b \rightarrow \rho\pi^-\mu^+\mu^- \]

Test of LFU
\[ R(K) \]
\[ R(K^*) \]

Very rare decays
\[ B^0_{(s)} \rightarrow \mu^+\mu^- \]
\[ B^0_{(s)} \rightarrow \tau^+\tau^- \]
\[ B^0_{(s)} \rightarrow \mu^+\mu^+\mu^- \]

Rare charm decays
\[ D^0 \rightarrow \mu^+\mu^- \]
\[ D^0 \rightarrow \pi^+\pi^-\mu^+\mu^- \]
\[ D^0 \rightarrow K^+\pi^-\mu^+\mu^- \]

LFV
\[ B^0_{(s)} \rightarrow e^+\mu^- \]
\[ D^0 \rightarrow e^+\mu^- \]
\[ \tau \rightarrow \mu^+\mu^- \]

Strange decays
\[ K^0_s \rightarrow \mu^+\mu^- \]
\[ \Sigma^+ \rightarrow \rho\mu^+\mu^- \]

Huge physics program (including also non B hadrons decay)
Only some analyses covered today
Why rare decays?

- Proceed via FCNC transitions
- Suppressed in the SM, occur only at loop level or beyond
- New Physics can significantly contribute

New physics can contribute by:
- Enhancing or suppressing decay rates
- Introducing new CPV sources
- Modifying the angular distribution of the final-state particles

Probes NP models at energy scales higher than direct searches
How to describe rare FCNC?

Rare hadron decays cover a wide energy range:

\[0.2 \text{GeV} \ldots 4 \text{GeV} \ldots 80 \text{GeV} \ldots \sim 100 \text{ TeV} \, ?\]

- \(\Lambda_{QCD}\) (non-perturbative regime)
- \(\Lambda_b\) (b mass)
- \(\Lambda_{EW}\) (W mass)
- \(\Lambda_{NP}\) (new physics scale)

Rare decays are described by an effective Hamiltonian described by an operator product expansion:

\[
H_{eff} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i \left[ C_i(\mu) O_i(\mu) + C'_i(\mu) O'_i(\mu) \right]
\]

- \(C_i\) (Wilson coefficient): perturbative, short distance physics, sensitive to \(E > \Lambda_{EW}\)
- \(O_i\) (operators): non-perturbative QCD, long distance physics

\(i=1, 2\) Tree
\(i=3-6, 8\) Gluon penguin
\(i=7\) Photon penguin
\(i=9, 10\) Electroweak penguin
\(i=S\) Higgs (scalar) penguin
\(i=P\) Pseudoscalar penguin

\(C_i\) being the left-handed part
\(O_i\) being the right-handed part (suppressed in the SM)
Looking for New Physics

New Physics can:
- affect SM operator contributions (Wilson coefficients)
- enter through new operators (right-handed $O'_i$, $O_{S,P}$)

Different $q^2$ regions probe different processes\[1\]

Photon pole (not in $B\to Pll$)

\[1\] $q^2$: invariant mass squared of the dimuon system
Looking for New Physics

New Physics can:
- affect SM operator contributions (Wilson coefficients)
- enter through new operators (right-handed O’S)

<table>
<thead>
<tr>
<th>Operator $O_i$</th>
<th>$B_{s,d} \rightarrow X_{s,d} \mu^+\mu^-$</th>
<th>$B_{s,d} \rightarrow \mu^+\mu^-$</th>
<th>$B_{s,d} \rightarrow X_{s,d} \gamma$</th>
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<tbody>
<tr>
<td>$O_7$</td>
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</table>

Eg. $d\Gamma/dq$

$C_7$
$C_9$
$C_{10}$
Fully leptonic decays
Very rare decay, FCNC and helicity suppressed
Very sensitive to possible (pseudo)scalar new physics contributions
- Only $C_{10}$ contributes in the Standard Model
- NP sensitivity in $C_S$ and $C_P$ is larger than in $C_{10}$ (no helicity suppression)

Precisely predicted in the SM ([Bobeth et al, Phys. Rev. Lett. 112, 101801]):

$$B_{SM}(B^0_s \rightarrow \mu^+\mu^-) = (3.65 \pm 0.23) \times 10^{-9}$$

$$B_{SM}(B^0 \rightarrow \mu^+\mu^-) = (1.06 \pm 0.09) \times 10^{-10}$$

Ratio of BF powerful test of NP:
- No divergences from the SM with MFV

Theoretical uncertainty dominated by:
- CKM matrix element (experimental inputs needed)
- $B$ decays constant (improvement expected from lattice calculations)
LHCb + CMS measurement with full Run 1 dataset:

\[ \mathcal{B}(B^0_s \rightarrow \mu^+ \mu^-) = (2.8^{+0.7}_{-0.6}) \times 10^{-9} \]

\[ \mathcal{B}(B^0 \rightarrow \mu^+ \mu^-) = (3.0^{+1.6}_{-1.4}) \times 10^{-10} \]

- First observation of \( B_s \rightarrow \mu \mu \) decay (6.2 \( \sigma \) significance)
- First evidence of \( B^0 \rightarrow \mu \mu \) decay (3.0 \( \sigma \) significance)

\[ R = \frac{\mathcal{B}(B^0 \rightarrow \mu^+ \mu^-)}{\mathcal{B}(B^0_s \rightarrow \mu^+ \mu^-)} = 0.14^{+0.08}_{-0.06} \]

2.3 \( \sigma \) compatibility with the SM prediction
ATLAS measurement:

\[ \mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-) = (0.9^{+1.1}_{-0.8}) \times 10^{-9} \]

\[ \mathcal{B}(B^0 \rightarrow \mu^+ \mu^-) < 4.2 \times 10^{-10} @ 95\% \text{ CL} \]

\(B_s^0\) signal significance: 1.4\(\sigma\)

2D likelihood is compatible with SM at 2\(\sigma\)
New LHCb analysis (3fb\(^{-1}\) of Run1 + 1.4fb\(^{-1}\) of Run2)

Improvements:
- new signal isolation
- PID: better di-hadron background rejection
- new BDT: 50% better bkg rejection

\[
\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-) = (3.0 \pm 0.6 \text{ (stat)} ^{+0.3}_{-0.2} \text{ (syst)}) \times 10^{-9}
\]

\[
\mathcal{B}(B^0 \rightarrow \mu^+ \mu^-) \leq 3.4 \times 10^{-10} \quad @ 95\% \text{ CL}
\]

First observation by a single experiment 7.8 \sigma

**B_s \rightarrow \mu^+\mu^- : lifetime**

- **Effective lifetime: complementary probe of new physics**

- In the SM, only the heavy mass eigenstate decays to $\mu^+\mu^-$

  $$ A_{\Delta \Gamma} = \frac{\Gamma(B_s^0 \rightarrow \mu^+\mu^-) - \Gamma(B_s^+ \rightarrow \mu^+\mu^-)}{\Gamma(B_s^0 \rightarrow \mu^+\mu^-) + \Gamma(B_s^+ \rightarrow \mu^+\mu^-)} = +1 $$

- $\tau_{\mu\mu} = 1.610 \pm 0.012$ ps

- Assuming extreme NP scenario of $\tau_{\mu\mu} = \tau_L$ for a 5 $\sigma$ observation the precision needed is 0.038 ps

- **LHCb measurement:**

  $$ \tau(B_s^0 \rightarrow \mu^+\mu^-) = 2.04 \pm 0.44 \pm 0.05 \text{ ps} $$

$\mathbf{B}(s) \rightarrow \tau^+\tau^-$

- Same considerations as for the $B_s \rightarrow \mu\mu$, in terms of SM predictions and NP, but less helicity suppression.
- MFV models which accomodate LFU anomalies predict enhancement of $BR(B(s) \rightarrow \tau\tau)$ up to a few percent.
- With $B \rightarrow \mu\mu$ can be used to test LFU.
  \[
  \mathcal{B}(B^0 \rightarrow \tau^+\tau^-)_{SM} = (2.22 \pm 0.19) \times 10^{-8} \\
  \mathcal{B}(B^0_s \rightarrow \tau^+\tau^-)_{SM} = (7.73 \pm 0.49) \times 10^{-7}
  \]
- LHCb analysis: 3fb$^{-1}$
- Very challenging experimentally (two $\nu$ in the final state).
- $B^0_s$ and $B^0$ cannot be separated.
- $B^0 \rightarrow D^+(K^-\pi^+\pi^+)D^-_s(K^+K^-\pi^-)$ as control channel.
  \[
  \mathcal{B}(B^0_s \rightarrow \tau^+\tau^-) < 6.8 \times 10^{-3} \text{ at 95\% CL} \\
  \mathcal{B}(B^0 \rightarrow \tau^+\tau^-) < 2.1 \times 10^{-3} \text{ at 95\% CL}
  \]
\( K_S \rightarrow \mu^+\mu^- \)

New Result

**SM prediction:** \( B(K^0_S \rightarrow \mu\mu) = (5.0 \pm 1.5) \times 10^{-12} \)

[Isidori et al JHEP 01 (2004) 009]

- Dominated by the long distance effects
- Can be enhanced by NP, e.g. new light scalars (up to \( 10^{-10} \))
- Previous LHCb limit: \( BF(K^0_S \rightarrow \mu\mu) < 9 \times 10^{-9} \) @ 90% CL

**LHCb analysis, 3fb\(^{-1}\):**

- Two trigger categories
- Normalisation channel: \( K^0_S \rightarrow \pi^+\pi^- \) (also main background)
- ML fit to extract the signal yield

\[
B(K^0_S \rightarrow \mu^+\mu^-) < 1.0 \times 10^{-9} \text{ @ 95\% CL}
\]
b → s(d) l⁺l⁻ transitions
How to search for new physics in EW penguin decays?

Measurement of differential branching fractions. e.g.: $B^0 \rightarrow K^{(*)0}\mu^+\mu^-$, $B^+ \rightarrow K^{(*)+}\mu^+\mu^-$, $\Lambda_b \rightarrow \Lambda\mu^+\mu^-$, $B_s \rightarrow \phi\mu^+\mu^-$, $B^+ \rightarrow \pi^+\mu^+\mu^-$ decays

- SM predictions limited by hadronic uncertainties on form factor

Angular analyses. e.g.: $B^+ \rightarrow K^{(*)+}\mu^+\mu^-$, $B_s \rightarrow \phi\mu^+\mu^-$ and $B \rightarrow K^{*0}e^+e^-$

- Existence of variables with small theory uncertainties

Test of lepton universality. e.g.: $R(K)=B^+ \rightarrow K^+\mu^+\mu^-/B^+ \rightarrow K^+e^+e^-$, $R(K*)=B \rightarrow K^*\mu^+\mu^-/B \rightarrow K^*e^+e^-$,

- Cancellation of hadronic uncertainties in theory predictions

I won’t talk about this today
Dedicated talk by Samuel Coquereau
Measurements of various $b \to s$ transitions systematically below the SM

Pointing towards anomaly in C9

[LHCb, JHEP 06 (2014) 133]
[LHCb, JHEP 11 (2016) 047]
[LHCb, JHEP 04 (2017) 142]

[Bouchard et al, JHEP 07 (2011) 067] [Horgan et al, PRL 112 (2014) 212003]
Measurements of various $b \to s$ transitions systematically below the SM

Pointing towards anomaly in C9

**$B^0 \to K^*0 \mu\mu$**

- $F_L$, $A_{FB}$ and $d\mathcal{B}/dq^2$
- Good agreement with the SM predictions
- Same trend of LHCb measurement

**First measurement of the S-wave fraction in the $K^+\pi^-$ system**

**S-wave fraction compatible with theory predictions**

$$BF(B^0 \to K^*(892)^0\mu^+\mu^-), \text{ for } 1.1 < q^2 < 6.0 \text{ GeV}^2/c^4 :$$

$$d\mathcal{B}/dq^2 = (0.342^{+0.017}_{-0.017}(\text{stat}) \pm 0.009(\text{syst}) \pm 0.023(\text{norm})) \times 10^{-7} c^4/\text{GeV}^2$$

**B → K*μ+μ- angular analysis**

- Final state fully described by $q^2 = m^2(μμ)$ and three angles $Ω = (θ_l, θ_K, φ)$
- Measurement of CP-averaged angular terms and CP asymmetries, described by eight observables
- $S_i, F_L, A_{FB}$, sensitive to Wilson coefficients $C_7, C_9, C_{10}$

\[
\frac{1}{d(\Gamma + \bar{\Gamma})/dq^2} \frac{d^4(\Gamma + \bar{\Gamma})}{dq^2 dΩ} = \frac{9}{32\pi} \left[ \frac{3}{4} (1 - F_L) \sin^2 θ_K + F_L \cos^2 θ_K \right. \\
\left. + \frac{1}{4} (1 - F_L) \sin^2 θ_K \cos 2θ_l - F_L \cos^2 θ_K \cos 2θ_l + S_3 \sin^2 θ_K \sin^2 θ_l \cos 2φ \\
+ S_4 \sin 2θ_K \sin 2θ_l \cos φ + S_5 \sin 2θ_K \sin θ_l \cos φ \\
+ \frac{4}{3} A_{FB} \sin^2 θ_K \cos θ_l + S_7 \sin 2θ_K \sin θ_l \sin φ \\
+ S_8 \sin 2θ_K \sin 2θ_l \sin φ + S_9 \sin^2 θ_K \sin^2 θ_l \sin 2φ \right]
\]

- Fraction of longitudinal polarisation of the $K^*$
- Forward-backward asymmetry of the dilepton system
B → K*μ+μ- angular analysis

Final state fully described by $q^2 = m^2(\mu\mu)$ and three angles $\Omega = (\theta_l, \theta_K, \phi)$

Measurement of CP-averaged angular terms and CP asymmetries, described by eight observables $S_i, F_L, A_{FB}$, sensitive to Wilson coefficients $C_7(\prime), C_9(\prime), C_{10}(\prime)$

These observables are dependent on $B \rightarrow K^*$ form factors

Additional set of variables can be built from ratio of observables, less dependent on factor uncertainties:

$$eg: \quad P_5' = \frac{S_5}{\sqrt{F_L(1 - F_L)}}$$

[Descotes-Genon, JHEP 05 (2013) 137]
B → K* μ⁺μ⁻ angular analysis (LHCb)

Unbinned maximum likelihood fit to invariant mass and the three decay angles (cosθ₁, cosθₖ and φ)

Fit in each q² bin

P'₅ LHCb local deviation from SM:
- 2.8σ in 4 < q² < 6 GeV²/c⁴
- 3.0σ in 6 < q² < 8 GeV²/c⁴

χ² fit performed to the CP-averaged angular observables Fₖ, A_{FB} and S₃-S₉

Global 3.4σ from the SM predictions
B → K* µ⁺µ⁻ angular analysis (ATLAS and CMS)

**ATLAS:**

![ATLAS results](image)

- Extraction of F_L, S_i and P_{i'} in six bins of q^2
- Compatible with LHCb and Belle results
- Compatibility with the SM within 3σ

**CMS:**

![CMS results](image)

- P_1 and P_{5'} angular determined in bins of q^2
- Consistent with LHCb measurement and SM predictions
B → K* l⁺l⁻ angular analysis (Belle)

- Measurement of $P'_4$ and $P'_5$
- LFU test, measurement of $Q^i = P_{\mu^i} - P_{e^i}$
- Results compatible with the SM predictions

2.6σ in $P'_5$ for the muon channels (1.3σ for the electrons)

[arXiv:1612.05014v1]
Putting all together

LHCb/Belle and ATLAS show deviations from the SM in $4<q^2_{\mu\mu}<8$ GeV

CMS shows better agreement

Good agreement with SM for $B \rightarrow K^* e^+ e^-$: hint of LFU?
Global fits

- Contributions from NP constrained through global fits to the Wilson coefficients
- Use of $b\rightarrow sll$ (angular, LFU and diff BF), $B\rightarrow\mu\mu$ and $b\rightarrow s\gamma$ data, ~100 observables

![Graphs showing global fit results]

- BSM contribution seems to be needed to accommodate the data
- Preference for NP in $C9$ at ~3-5 $\sigma$ level
- Is it really NP or is due to charm loops contributions?
Interpretation of global fits

Anomalies due to new physics
e.g.: Vector-like contribution could come from new tree level contribution from a $Z'$ with a mass of a few TeV

$$C_9 + C_9^{\text{NP}}$$

Vector-like contribution could point to a problem with our understanding of QCD. Are we correctly estimating charm loop contributions?

$$C_9^{\text{eff}} = C_9 + \sum_j \eta_j e^{i\delta_j} A_j(q^2)$$

Inclusive analysis to measure the resonance effects in $C_9$

- LHCb measurement of the phase difference between short- and long-distance contributions
Phase difference in $B^+ \to K^+\mu^+\mu^-$ decays

- Fit of to full dimuon mass distribution
  - Sum of relativistic Breit–Wigner amplitudes to describe resonances
  - short-distance contribution in terms of an effective field theory description
  - $B^+ \to J/\psi(\to \mu^+\mu^-)K^+$ as normalisation channel
- Magnitudes and relative phases between the resonances and the short-distance contribution allowed to vary in the fit
- Model includes: resonances ($\rho, \omega, \phi, J/\psi, \psi(2S)$), charmonium states: ($\psi(3770), \psi(4040), \psi(4160), \psi(4415)$)

[Figure 1: Reconstructed $K^+\mu^+\mu^-$ mass of the selected $B^+$ candidates. The fit to the data is described in the text.]
BF of the short-distance component:

$$\frac{d\Gamma}{dq^2} = \frac{G_F^2\alpha^2|V_{tb}V_{ts}^*|^2}{128\pi^5}|k|\beta \left\{ \frac{2}{3}|k|^2\beta^2 |C_{10}|f_+(q^2)|^2 + \frac{4m^2_\mu(m_B^2 - m_K^2)^2}{q^2m_B^2} |C_{10}|f_0(q^2)|^2 \right\}$$

$$+ |k|^2 \left[ 1 - \frac{1}{3}\beta^2 \right] \left| C_9 f_+(q^2) + 2C_7 \frac{m_b + m_s}{m_B + m_K} f_T(q^2) \right|^2 \right\}$$

BF of the short-distance component:

$$\mathcal{B}(B^+ \to K^+ \mu^+ \mu^-) = (4.37 \pm 0.15 \pm 0.23) \times 10^{-7}$$

In very good agreement with the old result

[JHEP 06 (2014) 133]

Measurement of the Wilson coefficient:

- $|C_{10}| < |C_{10}^{SM}|$ and $|C_9 | > |C_9^{SM}|$ if both free
- $|C_9 | < |C_9^{SM}|$ if $C_{10}$ constrained to the SM

Exclusion of $C_9 = 0$ hypothesis $> 5 \sigma$

Compatible with previous measurement

Working on measurement in $B^0 \to K^{*0}\mu^+\mu^-$
Other rare decay results
Very rare charm

<table>
<thead>
<tr>
<th>LFV, LNV, BNV</th>
<th>FCNC</th>
<th>VMD</th>
<th>Radiative</th>
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</thead>
<tbody>
<tr>
<td>0</td>
<td>10^{-15}</td>
<td>10^{-14}</td>
<td>10^{-13}</td>
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<tr>
<td>(D_{(s)}^+ \to h^- l^+ l^+)</td>
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- Dominated by long distance contributions
- Possible to access short distance contribution away from resonances in some channels (\(D\to X_u l^+ l^-\))
- SM predictions typically \(<10^{-9}\) for non resonant decays
- NP could enhance BF up to \(O(10^{-6})\)

(Burdman et al. PHYSICAL REVIEW D 66, 014009 2002)
Most precise results from LHCb analyses (No competitors for fully charged final states thanks to the large statistics)

Expect improvements with the new Run 2 LHCb trigger

Observation of $D^0 \rightarrow K\pi^+\mu^+\mu^+$ in the $\rho$-$\omega$ region in $\mu^-\mu^+$ mass [LHCb, arXiv:1510.08367]

Search for $D^0 \rightarrow \pi^+\pi^-\mu^+\mu^+$ [LHCb, PLB 728 (2014) 234]

Search for $D^0 \rightarrow \mu^-\mu^+$ [LHCb, PLB 725 (2013) 15]

Search for $D^+(s) \rightarrow \pi^+\mu^-\mu^+$ [LHCb, PLB 724 (2013) 203]

Search for $D^0 \rightarrow e^+\mu^+$ [LHCb, PLB 754 (2016) 167]
Conclusion

Rare decays are an excellent place where to look for new physics:
- precise predictions and clean experimental observables
- allow to probe higher energies than direct searches

Large number of analyses performed with LHC Run1 statistics

First Run2 analyses ready (many more to come)

No significant NP evidence from a single measurement, but many B meson anomalies pointing towards the same direction

Many new results expected soon to clarify these intriguing results!
Thanks for the attention!
**Baryons decays: \( \Lambda_b^0 \rightarrow p\pi^-\mu^+\mu^- \)**

- BF \( O(10^{-8}) \) in the SM, could be enhanced by NP
- Combined measurement of + improvement in lattice QCD calculation: measurement of \( IV_{tdl}/IV_{tsl} \) and test of MFV

- LHCb analysis with 3 fb\(^{-1}\)
- Normalized to \( \Lambda_b \rightarrow p\pi J/\psi \)
- First observation of \( b \rightarrow d \) in baryon system

\[
\mathcal{B}(\Lambda_b^0 \rightarrow p\pi^-\mu^+\mu^-) = (6.9 \pm 1.9 \pm 1.1^{+1.3}_{-1.0}) \times 10^{-8}
\]

5.5 \( \sigma \) significance

(More results in the baryon sector, see talk from Eluned Smith)
Additional weak phases could arise because of NP

First evidence for CP violation found in $\Lambda_b \to p\pi\pi\pi$ at 3.3σ

LHCb measurement, 3 fb$^{-1}$

$$\Delta \mathcal{A}_{CP} \equiv \mathcal{A}_{CP}(\Lambda_b^0 \to pK^-\mu^+\mu^-) - \mathcal{A}_{CP}(\Lambda_b^0 \to pK^-J/\psi)$$

$$= \mathcal{A}_{raw}(\Lambda_b^0 \to pK^-\mu^+\mu^-) - \mathcal{A}_{raw}(\Lambda_b^0 \to pK^-J/\psi)$$

$$\Delta \mathcal{A}_{CP} = (-3.5 \pm 5.0 \text{ (stat)} \pm 0.2 \text{ (syst)}) \times 10^{-2}$$
Measurement of the triple product asymmetry
Independent of reconstruction and production asymmetry

\[ a_{\text{T-odd}}^{CP} \sim \cos(\delta^1_e - \delta^1_o) \sin(\phi^1_e - \phi^1_o) \]

\[ a_{\text{T-odd}}^{CP} = (1.2 \pm 5.0 \, \text{(stat)} \pm 0.7 \, \text{(syst)}) \times 10^{-2} \]

The asymmetry is enhanced if there is a small strong phase difference.

Search for parity violation:

\[ a_{P}^{\text{T-odd}} = (-4.8 \pm 5.0 \, \text{(stat)} \pm 0.7 \, \text{(syst)}) \times 10^{-2} \]

All results are compatible with CP and parity conservation.