RARE DECAYS OF HEAVY QUARKS (THEORY)

Luca Silvestrini
INFN, Rome

- Introduction
- Rare B decays
- Rare D decays
- Conclusions

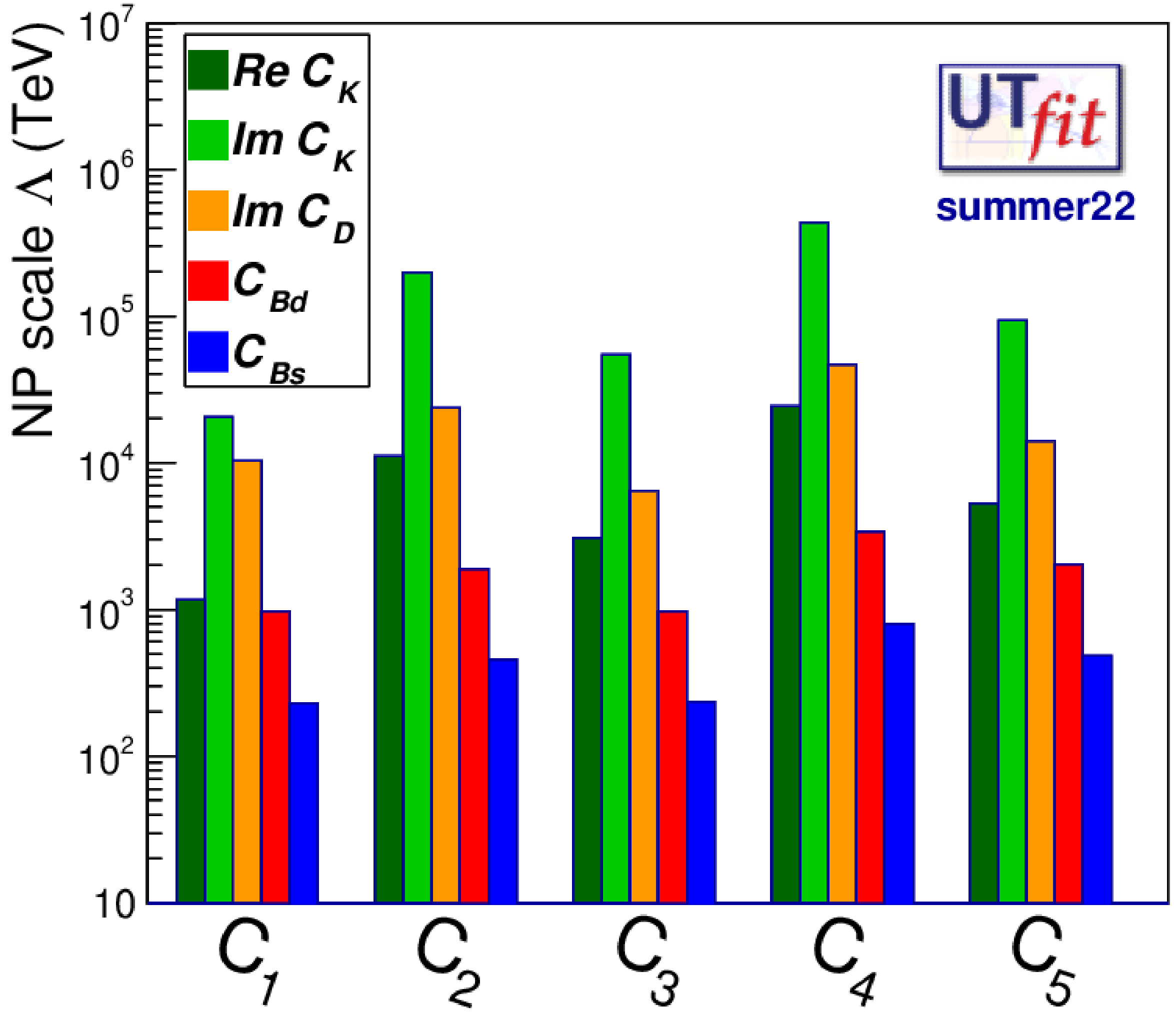
Introduction

- The LHC has so far confirmed the validity of the SM: the most general renormalizable theory w. gauge group $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$, 3 generations of quarks and leptons and one Higgs doublet
- No new particle has been detected, pushing lower bounds on NP in the multi-TeV range (with caveats)

Introduction

- The SM has several accidental symmetries, among which the absence of tree-level Flavour Changing Neutral Currents
- All flavour mixing & weak CPV in the SM occurs in charged currents, described by CKM parameters, e.g. λ, A, $\bar{\rho}$, $\bar{\eta}$
- FCNC couplings arise at loop level and are CKM- and GIM-suppressed: highly sensitive to virtual effects of heavy NP
- Flavour physics crucial for indirect NP searches, waiting for the energy frontier to be pushed further

Introduction



Introduction

- FCNC Z couplings and boxes for B decays have "hard GIM": m_q^2/M_W^2, so top-quark dominated and local
- FCNC gluon and photon couplings for B decays have "soft GIM": $\log(m_q^2/M_W^2)$, so infrared sensitive
- short-distance FCNC couplings for D decays suppressed by tiny CKM factors and GIM

Rare B Decays

- $B \to \tau\nu$
  - helicity suppressed tree-level decay
  - uncertainties from CKM element $|V_{ub}|$ and F_B
  - best SM prediction from UTA, which gives best knowledge of CKM factors and decay constants:

    $BR(B \to \tau\nu)^{TH} = (0.869 \pm 0.047)\ 10^{-4}$

    $BR(B \to \tau\nu)^{exp} = (1.06 \pm 0.19)\ 10^{-4}$
  - very sensitive to chirality-flipping NP, e.g. charged Higgs

Rare B Decays

- $B_{s,d} \to l^+l^-$
  - short distance contribution from Z-penguins and boxes, dominated by the top (C_{10}^A); negligible long distance, uncertainties from CKM elements and F_B
  - best SM prediction from UTA, which gives best knowledge of CKM factors and decay constants:

    $BR(B_s \to \mu^+\mu^-) = (3.47 \pm 0.14)\ 10^{-9}$

    $BR(B_d \to \mu^+\mu^-) = (9.48 \pm 0.36)\ 10^{-11}$
  - sensitive to NP in C_{10}^A and in (pseudo)scalar operators

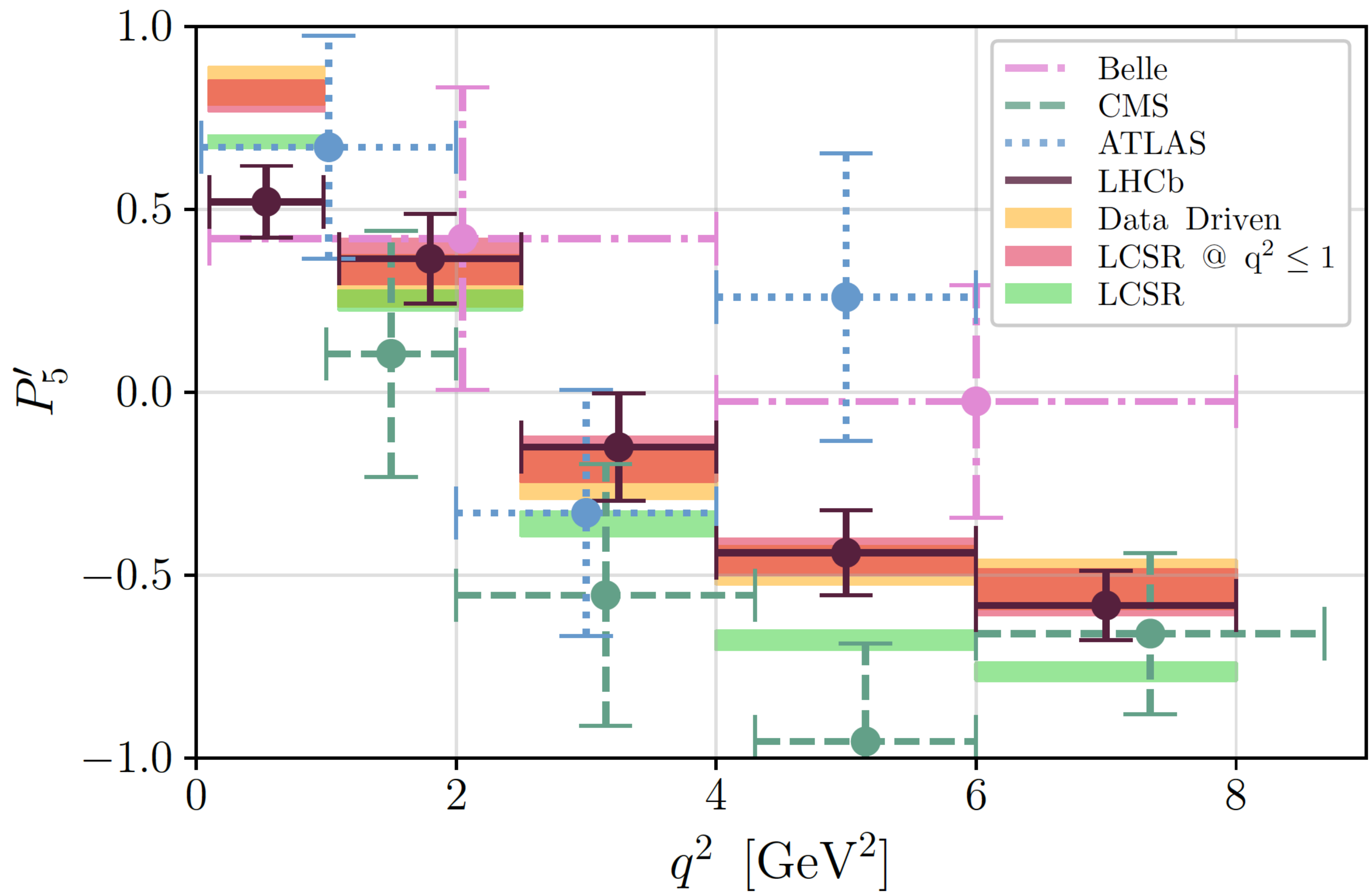
Rare B Decays

- $B \to K^{(*)}\nu\bar{\nu}$, $B \to \pi/\rho\nu\bar{\nu}$
  - also short-distance dominated, negligible long distance (however, tree-level contribution present for B^+ from charged lepton exchange)
  - with respect to $B_{s,d} \to l^+l^-$, additional uncertainty from form factors
  - no strong phase, so no direct CPV
  - interesting correlations with $b \to s,d\ l^+l^-$

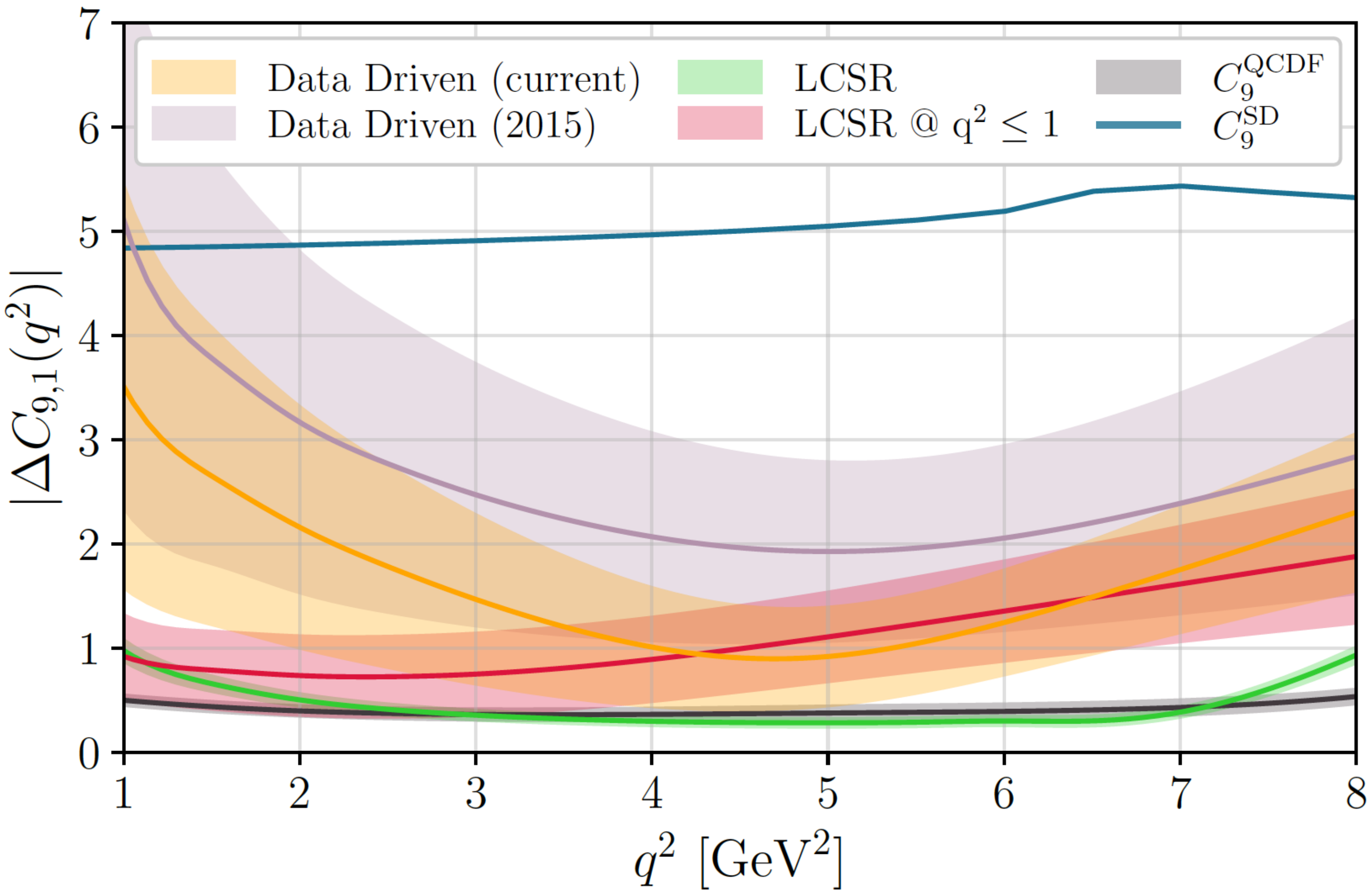
Rare B Decays

- $B \to K^{(*)}l^+l^-$, $B \to \pi/\rho l^+l^-$ and $B_s \to \phi l^+l^-$, $B_s \to K^{(*)}l^+l^-$
  - (much) more complicated due to photon contribution, which introduces some infrared sensitivity
  - in addition to form factors, need an estimate of "charming penguins", i.e. of rescattering from intermediate tetraquarks, $D_{(s)}^{(*)}$-$\overline{D}^{(*)}$ states, etc. (not a singularity in q^2, not related to J/ψ)
  - BR's and angular distributions not (yet) calculable

Charming Penguins in $B \to K^*l^+l^-$

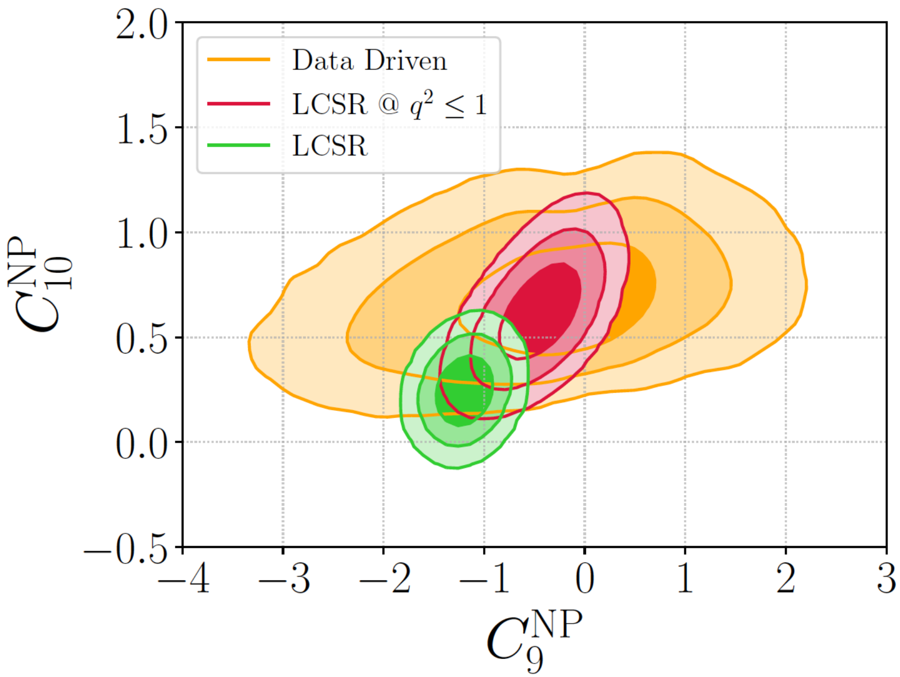


Charming Penguins in $B \to K^* l^+ l^-$



LUV in Rare B Decays

- Charming penguins & other hadronic effects cannot generate Lepton Universality Violation, so LUV would be a clear signal of NP
- However, the interpretation of LUV in terms of NP contributions is affected by hadronic uncertainties



Radiative B Decays

- Huge theoretical efforts to achieve full NNLO for inclusive $b \to s\gamma$ including the charm mass dependence
- Current SM predictions for $E_\gamma > 1.6$ GeV:
  - $BR(B \to X_s\gamma) = (3.40 \pm 0.17)\ 10^{-4}$
  - $BR(B \to X_{s+d}\gamma)/BR(B \to X_c l\nu) = (3.35 \pm 0.16)\ 10^{-3}$

Misiak, Rehman & Steinhauser, 2002.01548

- Error budget: 3% higher orders, 3% charm mass interpolation, 2.5% parametric & NP, improvable with more data

Radiative B Decays

- $A_{CP}(B \to X_{s+d}\gamma)$ null test of the SM, very sensitive to NP Hurth, Lunghi & Porod, hep-ph/0312260
- Exclusive radiative B decays more uncertain due to FFs and factorization
- Allow to access photon polarization through time-dependent CP asymmetries

Rare D decays as Null Tests of the Standard Model

- $D \to \mu^+\mu^-$
  - short distance contribution not observable (10^{-18})
  - long distance dominated by two-photon exchange: $BR(D \to \mu^+\mu^-) \sim 3\ 10^{-5}\ BR(D \to \gamma\gamma)$, could be around few times 10^{-13}

Burdman et al., hep-ph/0112235

- $D \to P\nu\bar{\nu}$
  - unobservably small, except for the possible LD τ contribution in charged D decays

Burdman et al., hep-ph/0112235

Rare D decays as Null Tests of the Standard Model

- $D \to P l^+ l^-$, $\Lambda_c \to p l^+ l^-$
  - given the smallness of SM short-distance contributions, one has $C_{10}^A \sim 0$ and therefore

    $A_{FB} = 0$

  - in the baryonic channel, one also has

    $F_L = 1/3$

    at the kinematic endpoints

Hiller et al. '21, '22

CONCLUSIONS

- Rare decays of heavy mesons are a powerful probe of NP
- Several very clean predictions available:
  - BR($B^+ \to \tau^+ \nu$), BR($B_{s,d} \to \mu^+ \mu^-$)
  - BR($B \to X_s \gamma$), BR($B \to X_s l^+ l^-$)
  - lepton universality
  - null tests in rare D decays
- Care must be taken in channels where long-distance contributions might be relevant