Theoretical study of heavy flavor physics

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Outline

- Introduction/Overview
- Theory of non-leptonic B decays
- Polarizations
- Factorization assisted topological diagram approach for hadronic B/D decays
- Summary

Flavor physics is important

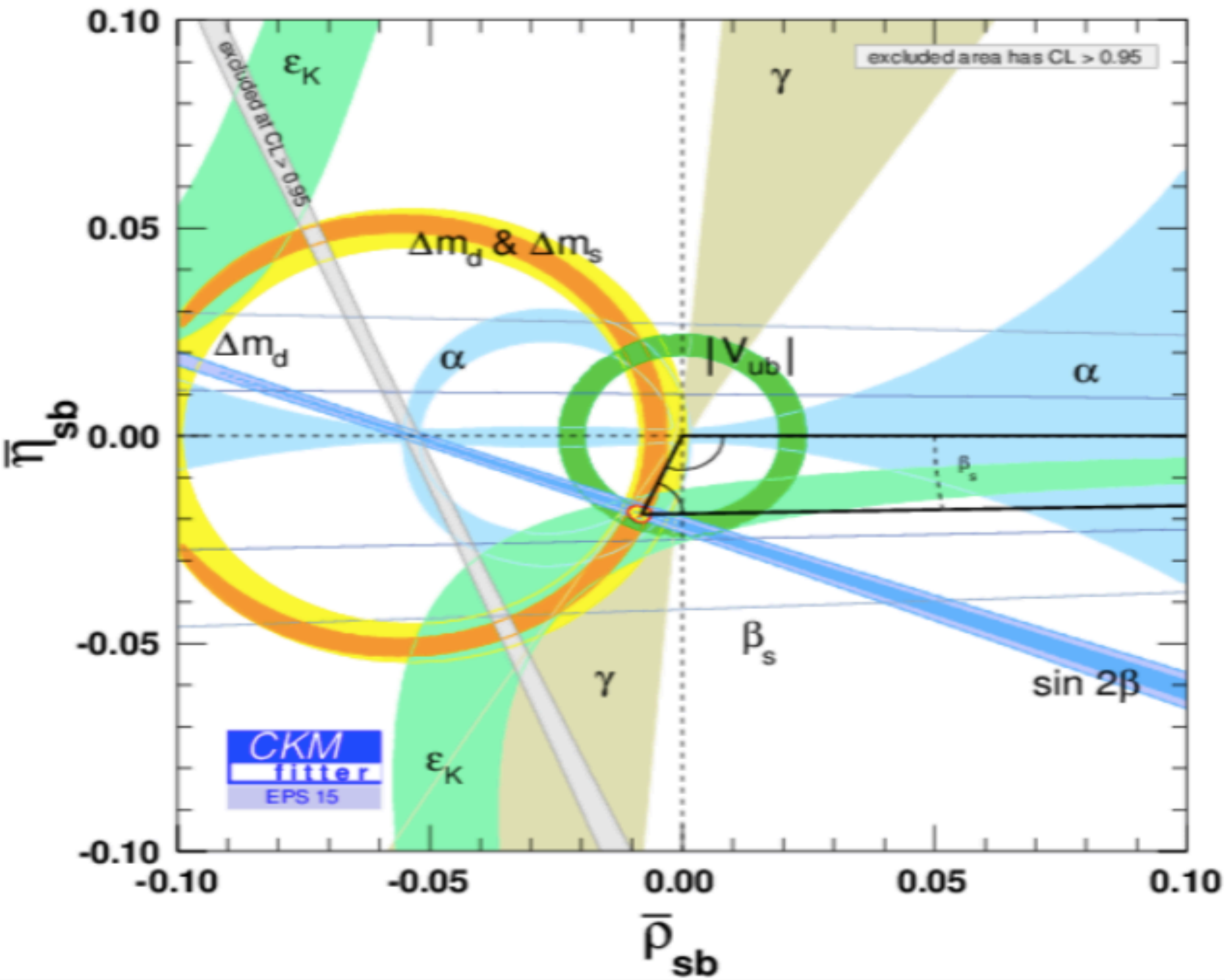
Progress in flavour physics may help understand open questions in cosmology - SM CPV insufficient to explain matter/antimatter asymmetry

Flavour physics is a proven tool of discovery:

- BR($K^0_L \to \mu\mu$) & GIM → prediction of charm
- CP violation → need for a third generation
- B mixing → mass of top is very heavy

Lesson from history: precise measurements of processes suppressed in existing theories have high sensitivity to new physics (NP) contributions. An excellent way to look for the NP expected at the TeV scale!

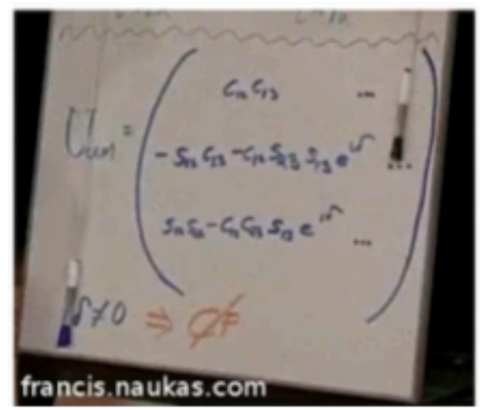
CKM triangle measurement



The CKM (Cabibbo·Kobayashi·Maskawa) matrix

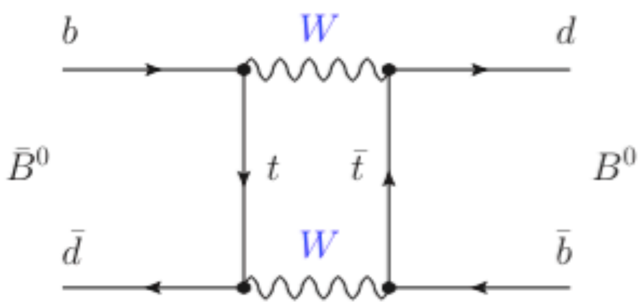
Another possible parametrisations (Chau and Keung parametrisation, adopted by PDG):

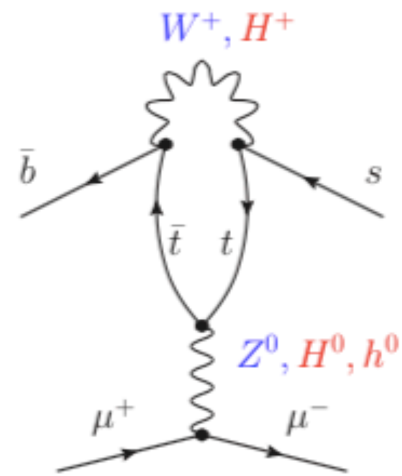
$$U = \begin{pmatrix} c_{12}\, c_{13} & s_{12}\, c_{13} & s_{13}\, e^{-i\delta} \\ -s_{12}\, c_{23} - c_{12}\, s_{23}\, s_{13}\, e^{i\delta} & c_{12}\, c_{23} - s_{12}\, s_{23}\, s_{13}\, e^{i\delta} & s_{23}\, c_{13} \\ s_{12}\, s_{23} - c_{12}\, c_{23}\, s_{13}\, e^{i\delta} & -c_{12}\, s_{23} - s_{12}\, c_{23}\, s_{13}\, e^{i\delta} & c_{23}\, c_{13} \end{pmatrix}$$



New physics probes

Search for deviations from SM predictions from virtual contributions of new heavy particles in loop processes





- Measure CP violating phases and study rare decays of heavy quarks
- Compare to very precise predictions of the SM
  - Uncertainties from QCD is main problem
- Most interesting processes those where SM contribution is suppressed (e.g FCNC)
  - Effects of New Physics (NP) are large
- Discovery potential for NP extends to mass scales >> centre-of-mass energy of collision

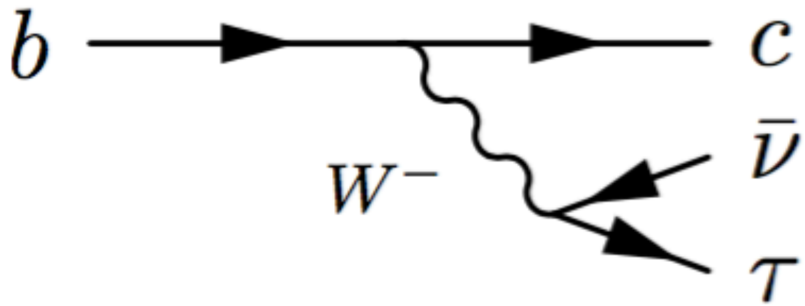
$\bar{B} \to D^{(*)}\tau\bar{\nu}$ Br ~ 0.7+1.3 % in the SM

Not rare, but two or more missing neutrinos

Data available since 2007 (Belle, BABAR, LHCb)

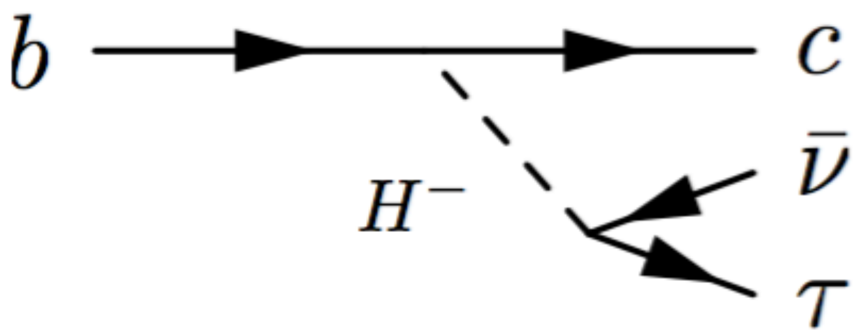
Theoretical motivation

W.S. Hou and B. Grzadkowski (1992)



SM: gauge coupling

lepton universality



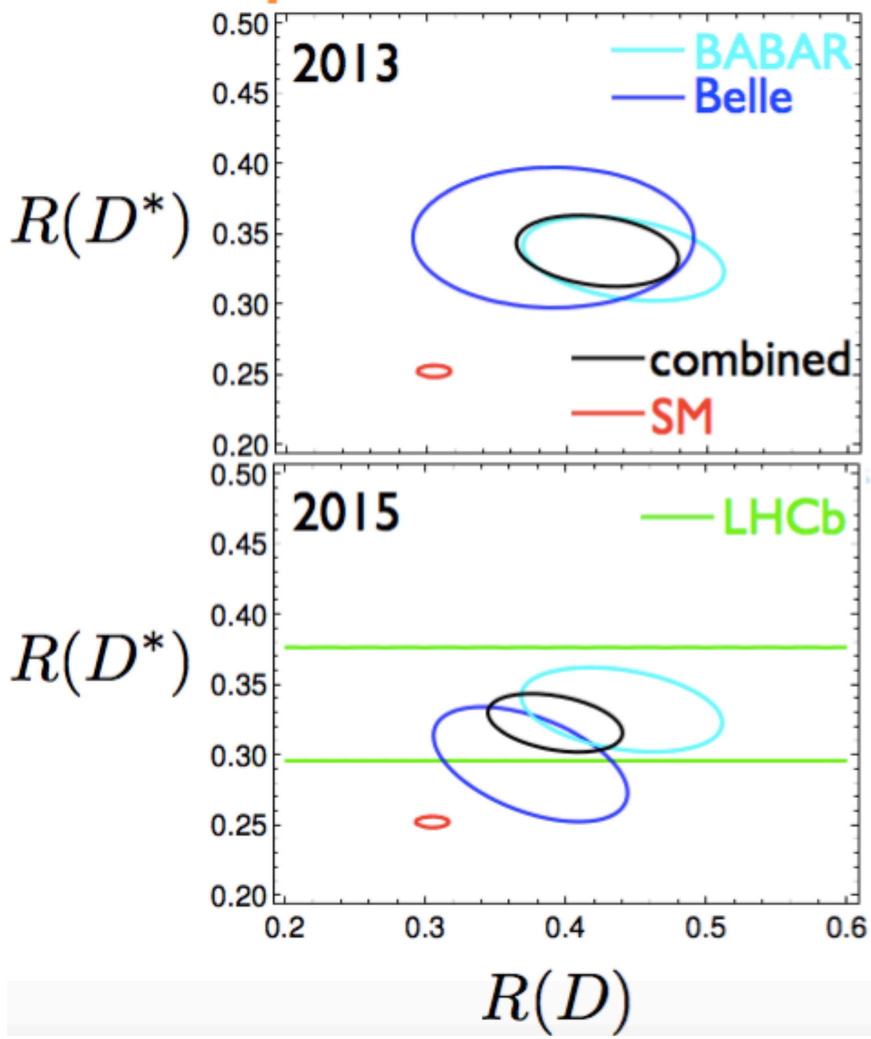
Type-II 2HDM (SUSY)

Yukawa coupling

$\propto m_b m_\tau \tan^2\beta$

$$R(X) = \frac{\Gamma(B \to X\tau\bar{\nu})}{\Gamma(B \to X(e/\mu)\bar{\nu})}$$

Experiments



$$R(D) = 0.421 \pm 0.058$$
$$R(D^*) = 0.337 \pm 0.025$$

~3.5σ

Y. Sakaki, MT, A. Tayduganov, R. Watanabe

$$R(D) = 0.391 \pm 0.041 \pm 0.028$$
$$R(D^*) = 0.322 \pm 0.018 \pm 0.012$$

~3.9σ HFAG

Standard model predictions

Theoretical uncertainty: form factors

data from $\bar{B} \to D^{(*)}\ell\bar{\nu}$ $(\ell = e, \mu)$

+ HQET or pQCD

+ lattice QCD

$R(D) = 0.296 \pm 0.016$ (Fajfer, Kamenik, Nisandzic)

0.302 ± 0.015 (Sakaki, MT, Tayduganov, Watanabe)

0.299 ± 0.011 (Bailey et al.)

$0.337^{+0.038}_{-0.037}$ (Fan, Xiao, Wang, Li)

$0.391 \pm 0.041 \pm 0.028$ (Exp. HFAG)

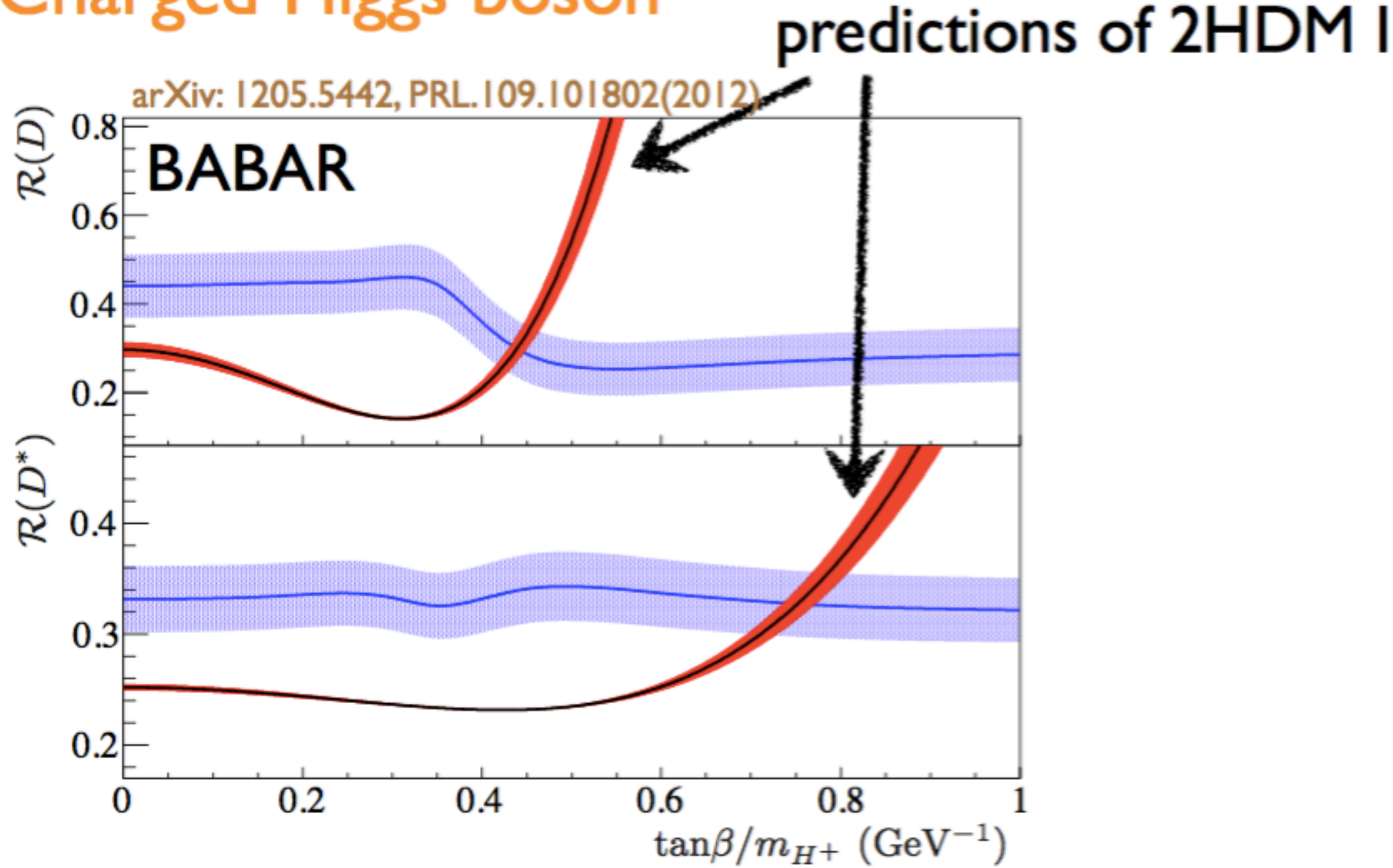
$R(D^*) = 0.252 \pm 0.003$ (Fajfer, Kamenik, Nisandzic)

0.252 ± 0.004 (Sakaki, MT, Tayduganov, Watanabe)

$0.269^{+0.021}_{-0.020}$ (Fan, Xiao, Wang, Li)

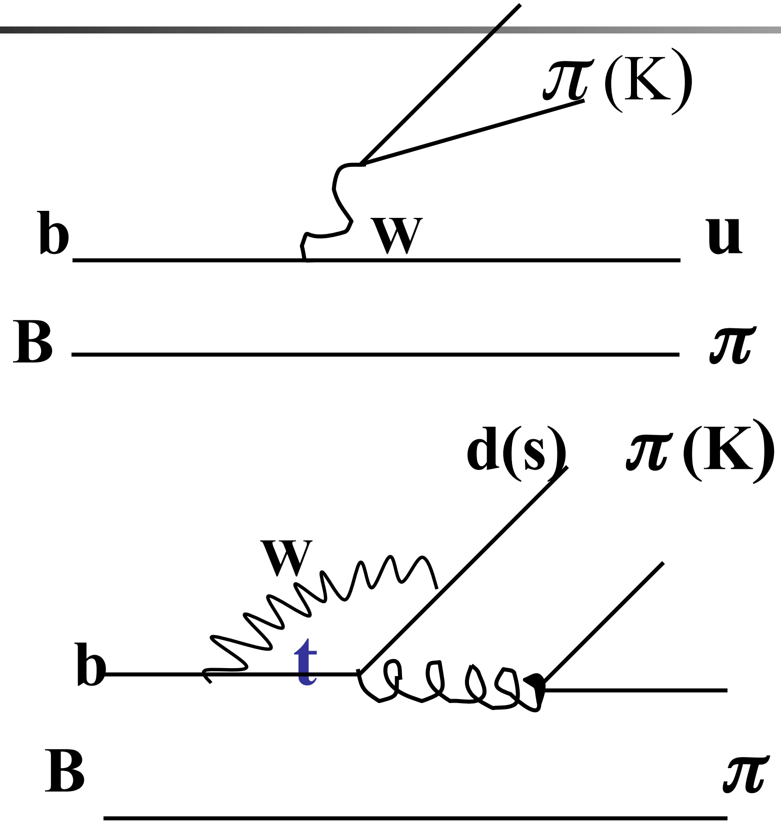
$0.322 \pm 0.018 \pm 0.012$ (Exp. HFAG)

Charged Higgs boson



Charged Higgs *excluded* at 99.8% CL

Rich physics in hadronic B decays



The standard model describes interactions amongst quarks and leptons

In experiments, we can only observe hadrons

How can we test the standard model without solving QCD?

Perturbative calculations

- In principle, all hadronic physics should be calculated by QCD
- In fact, you can always use QCD to calculate any process,

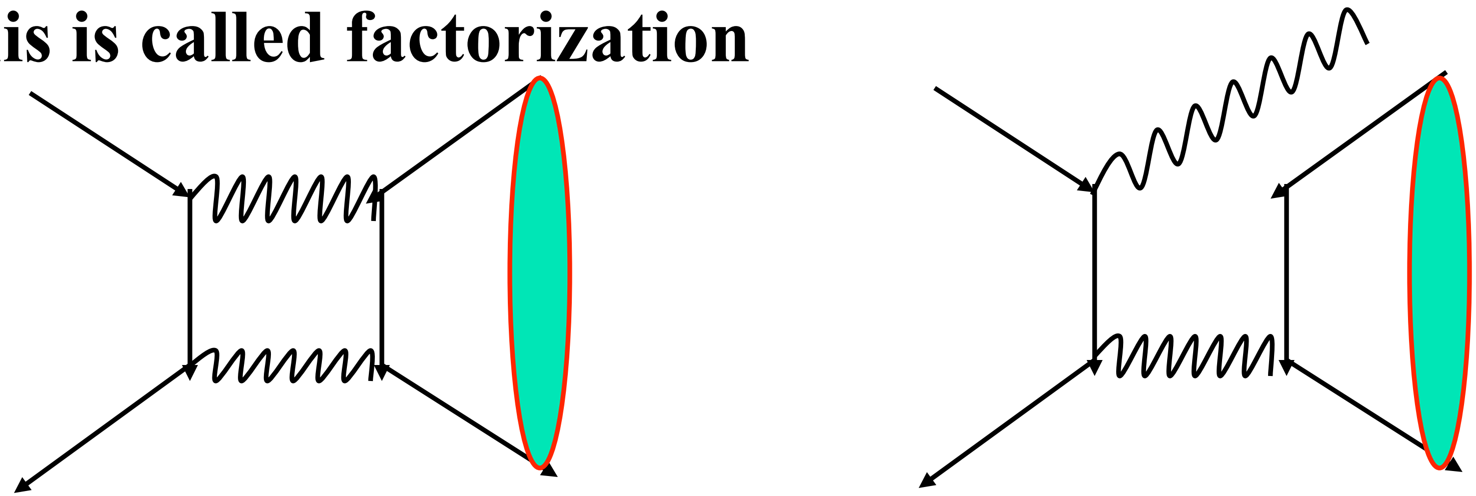
provided you can renormalize the infinities and do all order calculations.

Divergences

- Perturbation calculation means order by order
- Involving loop diagrams
- Therefore divergences unavoidable
- Ultraviolet divergences → renormalization
- Infrared divergences ? **Infrared divergence in virtual corrections should be canceled by real emission**
- In exclusive QCD processes → factorization

It is very difficult for **exclusive processes**

- infrared finite seems not possible, no free gluon can be emitted
- Infrared divergence should be absorbed into meson wave function (distribution amplitude)
- This is called factorization



Factorization can only be proved in power expansion by operator product expansion. To achieve that, we need a hard scale Q

- In the certain order of 1/Q expansion, the hard dynamics characterized by Q and the soft dynamic factorize
- The former into hard kernals H and the latter into distribution amplitude ϕ
- Factorization theorem holds up to all oders in α_s, but to cerntain power in 1/Q
- H is process-dependent, but calculable
- ϕ are universal (process-independent) ⇨ predictive power of factorization theorem
- In B decays the hard scale Q is just the b quark mass

Hadronic matrix elements calculations

- QCD-methods based on factorization work well for many processes

  Perturbative QCD approach based on k_T factorization
  [Keum, Li, Sanda, 00'; Lu, Ukai, Yang, 00']

  - collinear QCD Factorization approach
    [Beneke, Buchalla, Neubert, Sachrajda, 99']
  - Soft-Collinear Effective Theory
    [Bauer, Pirjol, Stewart, 01']

  - Unavailable for $1/m_b$ power corrections

- Topological diagrammatic approach

  [Chau, Cheng, et al, 91'; Chiang, Rosner, et al, 04']

- Work well for most of charmless B decays, except for pi K puzzle etc.

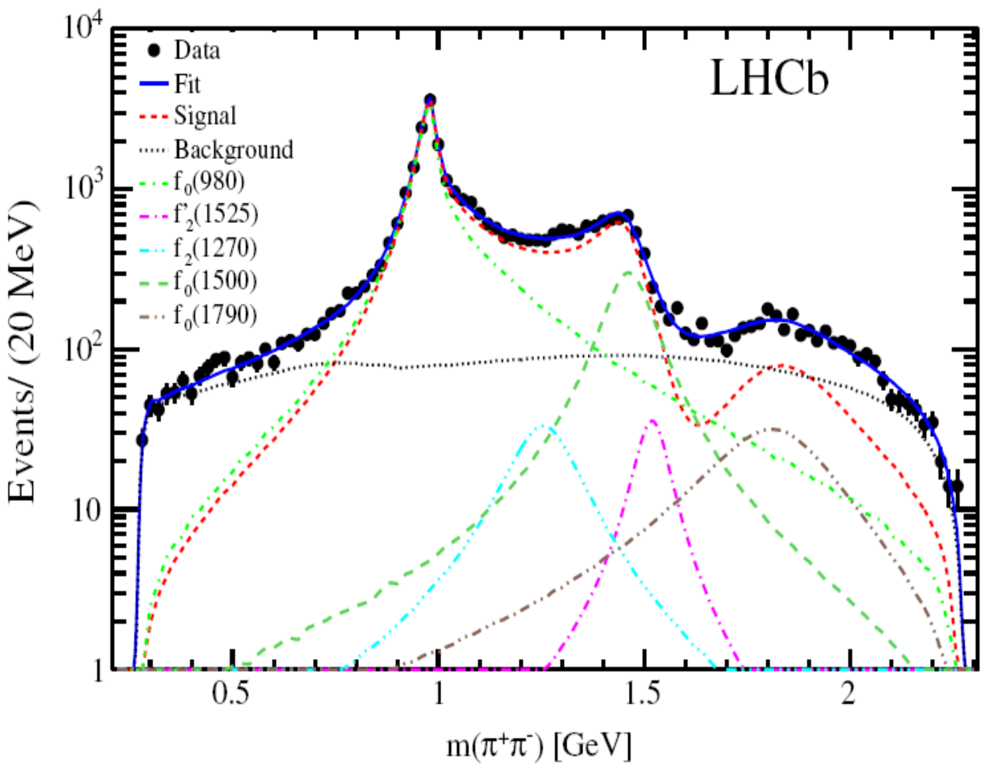
Recently many CP measurements for 3-body B decays

PHYSICAL REVIEW D **89,** 092006 (2014)

Measurement of resonant and *CP* components in $\bar{B}_s^0 \to J/\psi\pi^+\pi^-$ decays

R. Aaij *et al.*[*]
(LHCb Collaboration)

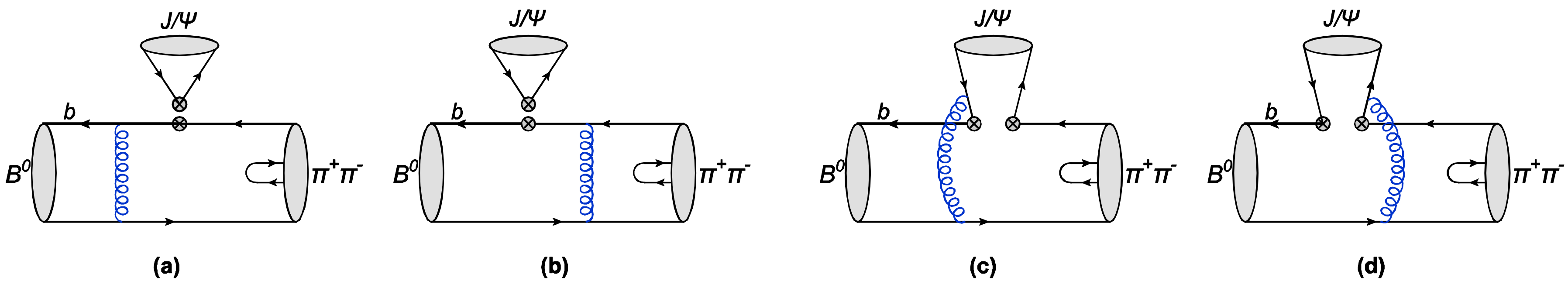
(Received 25 February 2014; published 14 May 2014)



Component	Solution I	Solution II
$f_0(980)$	$70.3 \pm 1.5^{+0.4}_{-5.1}$	$92.4 \pm 2.0^{+0.8}_{-16.0}$
$f_0(1500)$	$10.1 \pm 0.8^{+1.1}_{-0.3}$	$9.1 \pm 0.9 \pm 0.3$
$f_0(1790)$	$2.4 \pm 0.4^{+5.0}_{-0.2}$	$0.9 \pm 0.3^{+2.5}_{-0.1}$

$$\frac{\mathcal{B}\left(\overline{B}_s^0 \to J/\psi\pi^+\pi^-\right)}{\mathcal{B}\left(\overline{B}_s^0 \to J/\psi\phi\right)} = (19.79 \pm 0.47 \pm 0.52)\%.$$

W.F Wang, H.n. Li, Wei Wang, CDL, PRD91 (2015) 9, 094024



In perturbative QCD approach

$$B^0_{(s)} \to J/\Psi\pi^+\pi^-$$

S-wave resonant states ……….

CP Violation in *B* → *π π (K)* *(real prediction before exp.)*

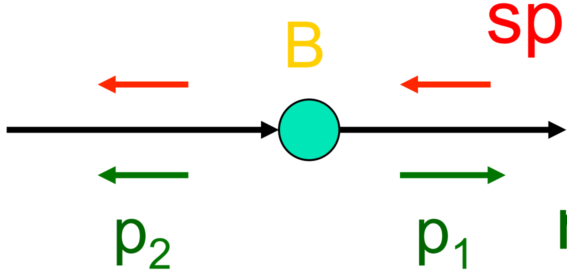
			(2001)	*(2004)*
CP(%)	FA	BBNS	PQCD	Exp
π^+K^-	+9±3	+5±9	–17±5	–9.7±1.2
$\pi^+\pi^-$	–5±3	–6±12	+30±10	+38±7

Annihilation type diagram play a very important role in direct CP violation of B decays by providing the necessary strong phase.

(Phys.Lett. B504 (2001) 6; Phys.Rev. D63 (2001) 074009)

For (V-A)(V-A), left-handed current

spin (this configuration is not allowed)



fermion flow

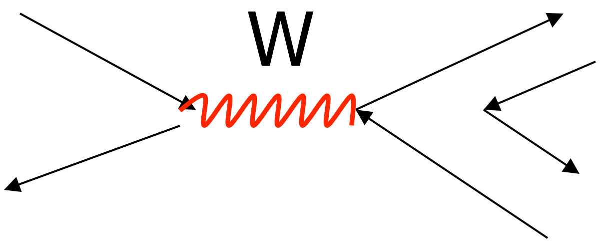
momentum

Like $B \rightarrow e\ \nu_e$

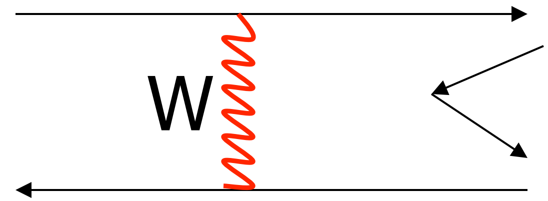
pseudo-scalar B requires spins in opposite directions, namely, helicity conservation

Annihilation suppression ~ $1/m_B$ ~ 10%

Annihilation-Type diagrams

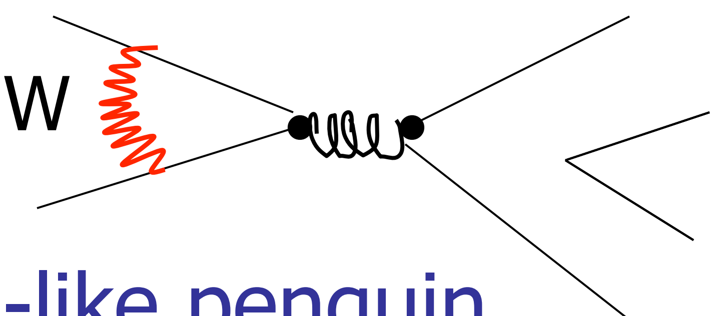


W annihilation

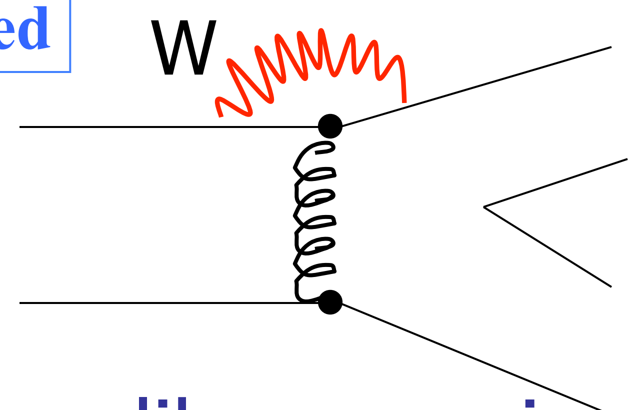


W exchange

Penguin type annihilation not suppressed



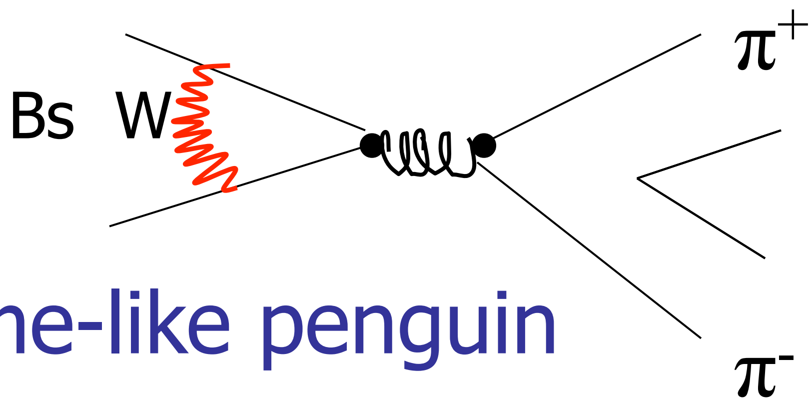
Time-like penguin



Space-like penguin

Pure annihilation type decay $B_s \to \pi^+\pi^-$

- **Very rare decay predicted in PRD76, 074018 (2008)**
- **BR=$(5.7 \pm 1.7)\times10^{-7}$**
- **No one expected to be measured**



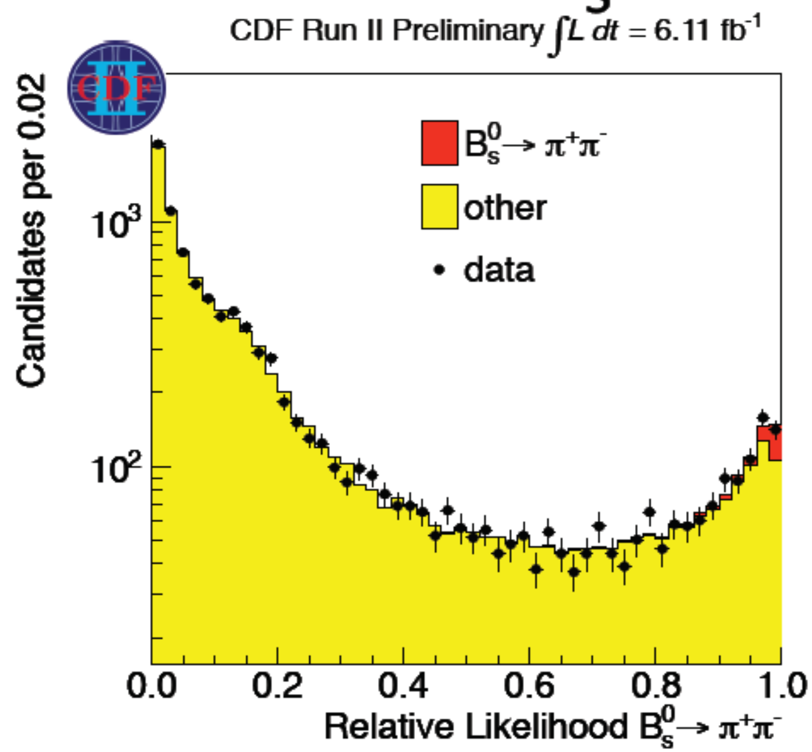
Time-like penguin

CDF Results

F.Ruffini, 1107.5760ex

ew for FPCP

First evidence: $B^0{}_s \to \pi^+\pi^-$



Later also measured by LHCb

$$\frac{f_s}{f_d} \times \frac{\mathcal{B}(B_s^0 \to \pi^+\pi^-)}{\mathcal{B}(B^0 \to K^+\pi^-)} = 0.008 \pm 0.002\ (stat.)\ \pm 0.001\ (syst.).$$

$$\mathcal{B}(B_s^0 \to \pi^+\pi^-) = (0.57 \pm 0.15\ (stat.) \pm 0.10\ (syst.)) \times 10^{-6}.$$

Agreement with pQCD: $0.57^{+0.18}_{-0.16}$ PRD 76, 074018(2008), and 0.42± 0.06 from Y Li et al., PRD 70, 034009 (2004)

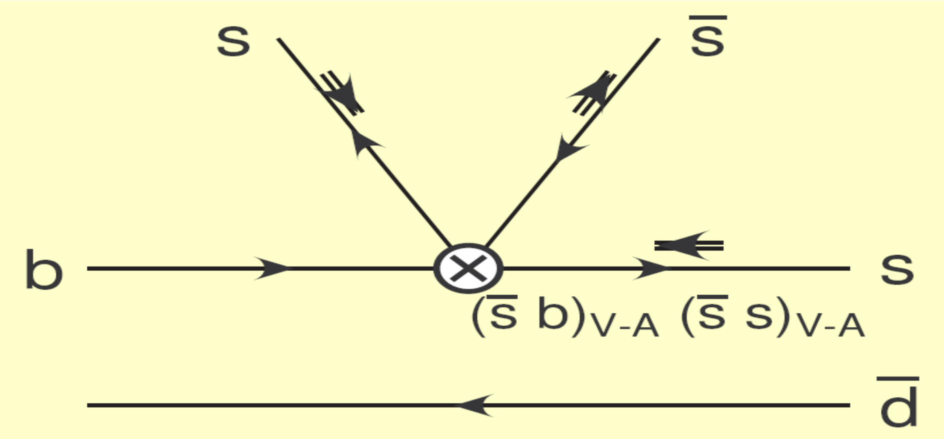
F. Ruffini 19

Counting Rules for B→VV Polarization

- The measured longitudinal fractions R_L for $B \rightarrow \rho\rho$ are close to 1.
- $R_L \sim 0.5$ in ϕK^* dramatically differs from the counting rules.
- Are the ϕK^* polarizations understandable?

Starting point: left-handed current in weak interaction

Helicity flip suppression of the transverse polarization amplitude



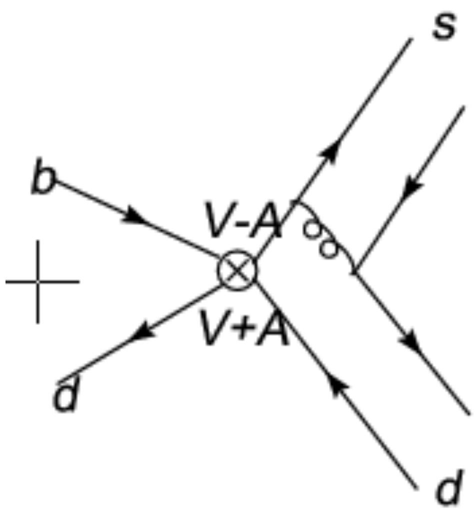
✠ $\overline{H}_{00} : \overline{H}_{--} : \overline{H}_{++} \sim \mathcal{O}(1) : \mathcal{O}(1/m_b) : \mathcal{O}(1/m_b^2)$

$00, --, ++$ stand for longitudinal, negative, positive helicity

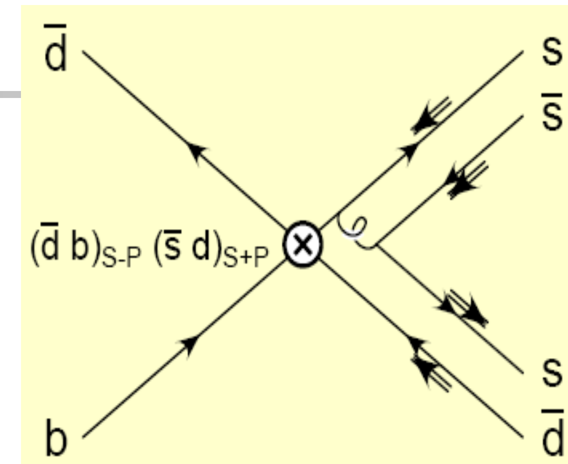
$\overline{H}_{--}/\overline{H}_{00} = \mathcal{O}(m_\phi/m_b)$: the helicity flip for $\bar{s}$ in the ϕ meson is required

$$R_L = \Gamma_L/\Gamma_{total} = \mathcal{O}(1), R_N \sim R_T = \mathcal{O}(m_V^2/m_B^2)$$

The annihilation diagram



Fierz Transformation



The (S+P)(S-P) current can break the counting rule,

The annihilation diagram contributes equally to the three polarization amplitudes

	Branching ratio(10^{-6})			Polarizations f_L		
	QCDF	PQCD	Expt	QCDF	PQCD	Expt
$B_s \to K^{*+}K^{*-}$	7.6	5.5		0.52	0.41	
$B_s \to K^{*0}\underline{K^{*0}}$	6.6	5.4	28.1±4.6±5.6	0.56	0.38	0.31±0.13
$B_s \to \rho^0\Phi$	0.18	0.23		0.88	0.86	
$B_s \to \omega\Phi$	0.18	0.17		0.95	0.69	
$B_s \to \Phi\Phi$	16.7	16.7	19±5	0.36	0.35	0.36±0.02
$B_s \to \underline{K^{*0}}\Phi$	0.37	0.39	1.1±0.29	0.43	0.50	0.51±0.17

Phys.Rev. D91 (2015) 054033

More obsevables

Modes	$Br(10^{-6})$	$f_L(\%)$	$f_\perp$ (%)	$\phi_\parallel$(rad)
$B^0 \to K^{*0}\phi$	$9.8^{+4.9}_{-3.8}$	$56.5^{+5.8}_{-5.9}$	$21.3^{+2.8}_{-2.9}$	$2.15^{+0.22}_{-0.19}$
Exp	9.8 ± 0.6	48 ± 3	24 ± 5	2.40 ± 0.13
$B^+ \to K^{*+}\phi$	$10.3^{+4.9}_{-3.8}$	$57.0^{+6.3}_{-5.9}$	$21.0^{+3.0}_{-3.0}$	$2.18^{+0.23}_{-0.19}$
Exp	10.0 ± 2.0	50 ± 5	20 ± 5	2.34 ± 0.18
$B_s \to \phi\phi$	$16.7^{+8.9}_{-7.1}$	$34.7^{+8.9}_{-7.1}$	$31.6^{+3.5}_{-4.4}$	$2.01^{+0.23}_{-0.23}$
Exp	19 ± 5	34.8 ± 4.6	$36.5 \pm 4.4 \pm 2.7$	$2.71^{+0.31}_{-0.36} \pm 0.22$
$B_s \to \bar{K}^{*0}\phi$	$0.39^{+0.20}_{-0.17}$	$50.0^{+8.1}_{-7.2}$	$24.2^{+3.6}_{-3.9}$	$1.95^{-0.21}_{-0.22}$
Exp^a	1.10 ± 0.29	$51 \pm 15 \pm 7$	$28 \pm 11 \pm 2$	$1.75 \pm 0.58 \pm 0.30$
$B_s \to K^{*0}\bar{K}^{*0}$	$5.4^{+3.0}_{-2.4}$	$38.3^{+12.1}_{-10.5}$	$30.0^{+5.3}_{-6.1}$	$2.12^{+0.21}_{-0.25}$
Exp	$28.1 \pm 4.6 \pm 5.6$	$31 \pm 12 \pm 4$	$38 \pm 11 \pm 4$	

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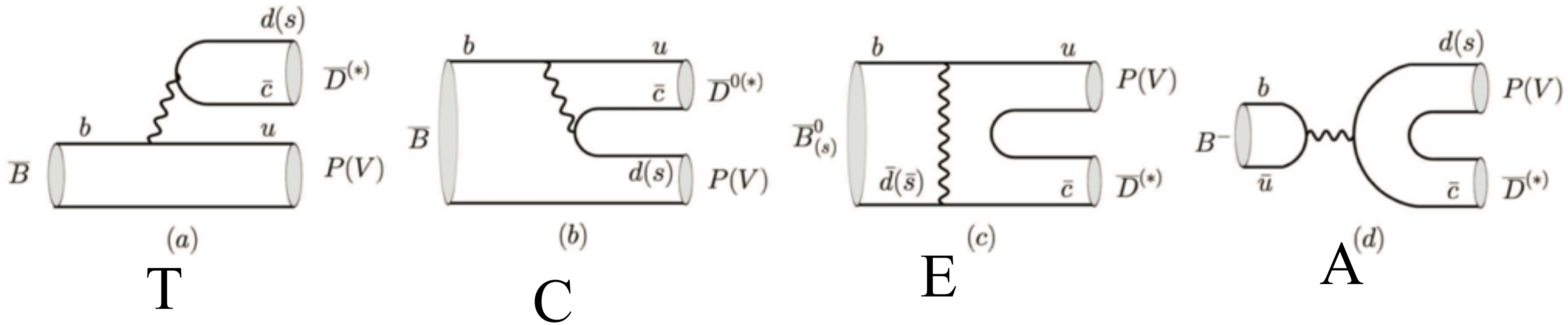
LHCb(new)	**10.5±2.2**	**20.1 ±7.0**	**21.5 ±4.8($f_\parallel$)**	

Hadronic decays with charm quark in the final states or initial state

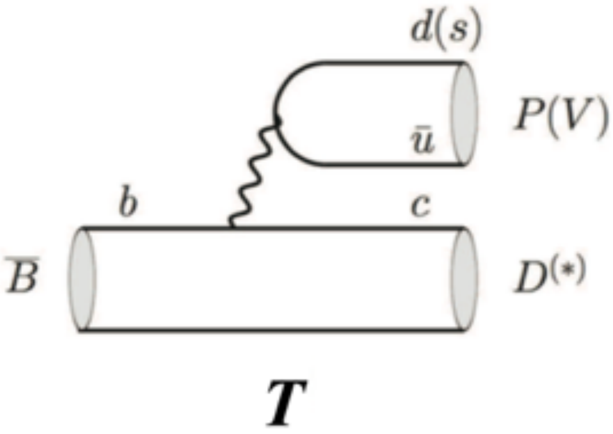
- **High precision measurements** of *B/D* decays already by BaBar, Belle, BESIII and LHCb, and to be pushed by **LHCb upgrade** and **Belle-II**.
- **High precision in theoretical calculation is urged**
- **Theoretically, it is not satisfied, since** there are mostly model calculations, some QCD sum rules calculation or rely on Lattice QCD: an ultimate tool but a formidable task now
- Charm quark mass is not large enough for heavy quark expansion

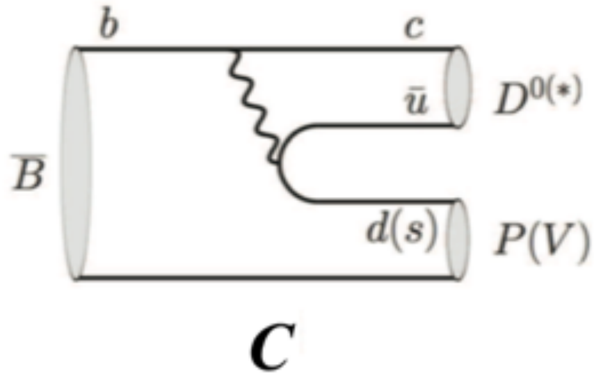
Topological diagrammatic approach

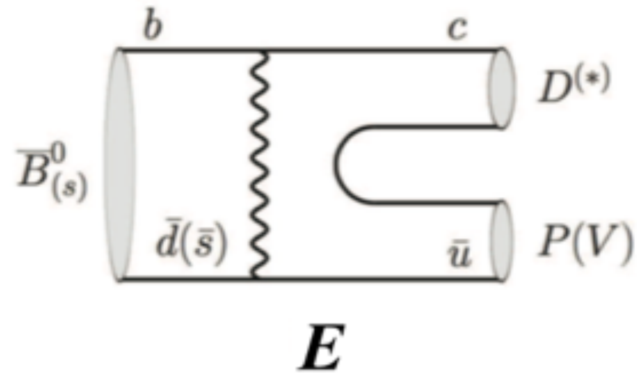
[Chiang, Senaha, 07']



- Distinct by weak interaction and flavor flows with all strong interaction encoded, including non-perturbative ones.   Model-independent
- Based on flavor SU(3) symmetry. Amplitudes with strong phases extracted from data. SU(3) breaking was lost.
- *DP*, *D*P* and *DV* fitted separately, 5 parameters for each category of decay modes. Less predictive.





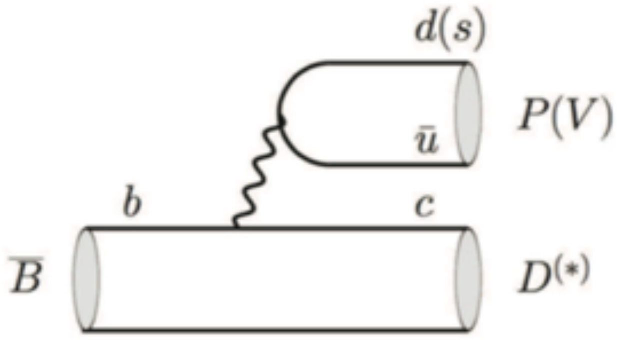


For the color favored diagram (T), it is proved factorization to all order of α_s expansion in soft -collinear effective theory,

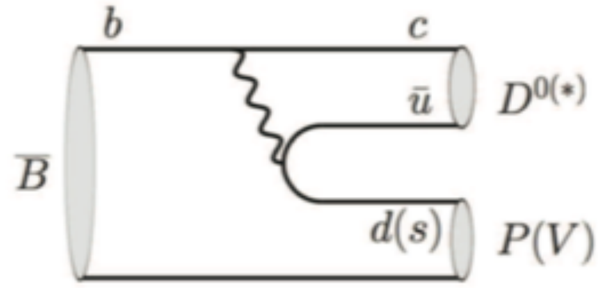
The decay amplitudes is just the decay constants and form factors times Wilson coeficients of four quark operators. The SU(3) breaking effect is automatically kept

No free parameter

$$T_c^{DP} = i\frac{G_F}{\sqrt{2}} V_{cb} V_{uq}^* a_1(\mu) f_P (m_B^2 - m_D^2) F_0^{B\to D}(m_P^2),$$



T



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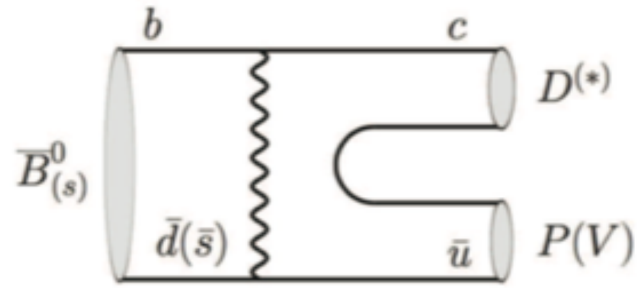


E

For other diagrams, we extract the amplitude and strong phase from experimental data by χ^2 fit

We factorize out the decay constants and form factor to keep the SU(3) breaking effect

$$C_c^{DP} = i\frac{G_F}{\sqrt{2}} V_{cb} V_{uq}^{*} f_D (m_B^2 - m_P^2) F_0^{B\to P}(m_D^2)\, \chi_c^C e^{i\phi_c^C},$$

$$E_c^{DP} = i\frac{G_F}{\sqrt{2}} V_{cb} V_{uq}^{*} m_B^2 f_B \frac{f_{D_{(s)}} f_P}{f_D f_\pi} \chi_c^E e^{i\phi_c^E},$$

Global Fit for all B→DP, D*P and DV decays (PRD92, 094016 (2015))

- 31 measured modes induced by $b \to c$ transitions

$$\chi_c^C = 0.48 \pm 0.01, \quad \phi_c^C = (56.6^{+3.2}_{-3.8})^\circ,$$

$$\chi_c^E = 0.024^{+0.002}_{-0.001}, \quad \phi_c^E = (123.9^{+3.3}_{-2.2})^\circ,$$

$$\chi^2/d.o.f. = 1.4$$

χ^2 is much smaller than previous topology diagram approach

Topological amplitudes

$$|T_c^{DP}| : |C_c^{DP}| : |E_c^{DP}| \sim 1 : 0.45 : 0.1$$

$B \rightarrow DP$

Meson	Mode	Amplitudes	$\mathcal{B}_{\rm exp}(\times 10^{-4})$	$\mathcal{B}_{\rm th}(\times 10^{-4})$
	Cabibbo-favored	$V_{cb}V_{ud}^*$		
$\overline{B}^0$	$D^+\pi^-$	$T+E$	26.8 ± 1.3	$24.7^{+0.2}_{-0.1} \pm 5.1 \pm 0.1$
	$D^0\pi^0$	$\frac{1}{\sqrt{2}}(E-C)$	2.6 ± 0.1	$2.5^{+0.1}_{-0.2} \pm 0.5 \pm 0.1$
	$D^0\eta$	$\frac{1}{\sqrt{2}}(C+E)\cos\phi$	2.4 ± 0.3	$1.9 \pm 0.1 \pm 0.4 \pm 0.1$
	$D^0\eta'$	$\frac{1}{\sqrt{2}}(C+E)\sin\phi$	1.38 ± 0.16	$1.3 \pm 0.1 \pm 0.2 \pm 0.1$
	$D_s^+K^-$	E	0.345 ± 0.032	$0.30^{+0.04}_{-0.02} \pm 0.00 \pm 0.03$
B^-	$D^0\pi^-$	$T+C$	48.1 ± 1.5	$49.0^{+1.4}_{-1.7} \pm 7.6 \pm 0.6$
$\overline{B}_s^0$	$D_s^+\pi^-$	T	30.4 ± 2.3	$30.2 \pm 0.0 \pm 6.0 \pm 0.1$
	D^0K^0	C		$5.9 \pm 0.3 \pm 1.2 \pm 0.3$
	Cabibbo-suppressed	$V_{cb}V_{us}^*$		
$\overline{B}^0$	D^+K^-	T	1.97 ± 0.21	$2.1 \pm 0.0 \pm 0.4 \pm 0.0$
	$D^0\overline{K}^0$	C	0.5 ± 0.1	$0.4 \pm 0.0 \pm 0.1 \pm 0.0$
B^-	D^0K^-	$T+C$	3.70 ± 0.17	$3.8 \pm 0.1 \pm 0.6 \pm 0.1$
$\overline{B}_s^0$	$D_s^+K^-$	$T+E$		$2.1 \pm 0.0 \pm 0.4 \pm 0.0$
	$D^0\eta$	$\frac{1}{\sqrt{2}}E\cos\phi - C\sin\phi$		$0.14 \pm 0.01 \pm 0.03 \pm 0.01$
	$D^0\eta'$	$\frac{1}{\sqrt{2}}E\sin\phi + C\cos\phi$		$0.21 \pm 0.01 \pm 0.04 \pm 0.01$
	$D^+\pi^-$	E		$0.011 \pm 0.001 \pm 0.000 \pm 0.001$
	$D^0\pi^0$	$\frac{1}{\sqrt{2}}E$	X	$0.005^{+0.001}_{-0.000} \pm 0.000 \pm 0.001$

B→D*P

Meson	Mode	Amplitudes	$\mathcal{B}_{\rm exp}(\times 10^{-4})$	$\mathcal{B}_{\rm th}(\times 10^{-4})$
	Cabibbo-favored	$V_{cb}V_{ud}^*$		
$\overline{B}^0$	$D^{*+}\pi^-$	$T+E$	27.6 ± 1.3	$24.9^{+0.2}_{-0.1} \pm 5.2 \pm 0.1$
	$D^{*0}\pi^0$	$\frac{1}{\sqrt{2}}(E-C)$	2.2 ± 0.6	$2.8 \pm 0.2 \pm 0.6 \pm 0.3$
	$D^{*0}\eta$	$\frac{1}{\sqrt{2}}(C+E)\cos\phi$	2.3 ± 0.6	$2.1 \pm 0.1 \pm 0.4 \pm 0.2$
	$D^{*0}\eta'$	$\frac{1}{\sqrt{2}}(C+E)\sin\phi$	1.40 ± 0.22	$1.4 \pm 0.1 \pm 0.2 \pm 0.1$
	$D_s^{*+}K^-$	E	0.219 ± 0.030	$0.22^{+0.03}_{-0.01} \pm 0.00 \pm 0.03$
B^-	$D^{*0}\pi^-$	$T+C$	51.8 ± 2.6	$50.7^{+1.5}_{-1.8} \pm 7.8 \pm 1.4$
$\overline{B}_s^0$	$D_s^{*+}\pi^-$	T	20 ± 5	$27.1 \pm 0.0 \pm 5.4 \pm 0.1$
	$D^{*0}K^0$	C		$6.6^{+0.3}_{-0.4} \pm 1.3 \pm 0.7$
	Cabibbo-suppressed	$V_{cb}V_{us}^*$		
$\overline{B}^0$	$D^{*+}K^-$	T	2.14 ± 0.16	$2.0 \pm 0.00 \pm 0.4 \pm 0.0$
	$D^{*0}\overline{K}^0$	C	0.36 ± 0.12	$0.45^{+0.02}_{-0.03} \pm 0.09 \pm 0.05$
B^-	$D^{*0}K^-$	$T+C$	4.20 ± 0.34	$3.8 \pm 0.1 \pm 0.6 \pm 0.1$
$\overline{B}_s^0$	$D_s^{*+}K^-$	$T+E$		$1.9 \pm 0.0 \pm 0.4 \pm 0.0$
	$D^{*0}\eta$	$\frac{1}{\sqrt{2}}E\cos\phi - C\sin\phi$		$0.15 \pm 0.01 \pm 0.03 \pm 0.02$
	$D^{*0}\eta'$	$\frac{1}{\sqrt{2}}E\sin\phi + C\cos\phi$		$0.23 \pm 0.01 \pm 0.04 \pm 0.02$
	$D^{*+}\pi^-$	E	< 0.061	$0.008 \pm 0.001 \pm 0.000 \pm 0.001$
	$D^{*0}\pi^0$	$\frac{1}{\sqrt{2}}E$		$0.004^{+0.004}_{-0.000} \pm 0.000 \pm 0.001$

B→DV

Meson	Mode	Amplitudes	$\mathcal{B}_{\rm exp}(\times 10^{-4})$	$\mathcal{B}_{\rm th}(\times 10^{-4})$
	Cabibbo-favored	$V_{cb}V_{ud}^*$		
$\overline{B}^0$	$D^+\rho^-$	$T+E$	78 ± 13	$65.3^{+0.5}_{-0.3} \pm 13.5 \pm 6.6$
	$D^0\rho^0$	$\frac{1}{\sqrt{2}}(E-C)$	3.2 ± 0.5	$2.6 \pm 0.2 \pm 0.6 \pm 0.1$
	$D^0\omega$	$\frac{1}{\sqrt{2}}(E+C)$	2.54 ± 0.16	$2.7 \pm 0.2 \pm 0.5 \pm 0.1$
	$D_s^+K^{*-}$	E	0.35 ± 0.10	$0.38^{+0.05}_{-0.02} \pm 0.00 \pm 0.06$
B^-	$D^0\rho^-$	$T+C$	134 ± 18	$105^{+2}_{-3} \pm 18 \pm 9$
$\overline{B}_s^0$	$D_s^+\rho^-$	T	70 ± 15	$78.6 \pm 0.0 \pm 15.7 \pm 7.9$
	D^0K^{*0}	C	3.5 ± 0.6	$4.9^{+0.2}_{-0.3} \pm 1.0 \pm 0.2$
	Cabibbo-suppressed	$V_{cb}V_{us}^*$		
$\overline{B}^0$	D^+K^{*-}	T	4.5 ± 0.7	$3.9 \pm 0.0 \pm 0.8 \pm 0.4$
	$D^0\overline{K}^{*0}$	C	0.42 ± 0.06	$0.37 \pm 0.02 \pm 0.07 \pm 0.02$
B^-	D^0K^{*-}	$T+C$	5.3 ± 0.4	$6.0^{+0.1}_{-0.2} \pm 1.0 \pm 0.5$
$\overline{B}_s^0$	$D_s^+K^{*-}$	$T+E$		$4.0^{+0.04}_{-0.03} \pm 0.8 \pm 0.4$
	$D^0\phi$	C	0.24 ± 0.07	$0.31^{+0.01}_{-0.02} \pm 0.06 \pm 0.02$
	$D^+\rho^-$	E		$0.019^{+0.002}_{-0.001} \pm 0.000 \pm 0.003$
	$D^0\rho^0$	$\frac{1}{\sqrt{2}}E$		$0.010 \pm 0.001 \pm 0.000 \pm 0.001$
	$D^0\omega$	$\frac{1}{\sqrt{2}}E$		$0.008 \pm 0.001 \pm 0.000 \pm 0.001$

Nonperturbative parameters χ^C, ϕ^C, χ^E, ϕ^E **are universal** for all the DP, D^*P and DV modes

Meson	Mode	Amplitudes	$\mathcal{B}_{\rm exp}(\times 10^{-5})$	$\mathcal{B}_{\rm FAT}(\times 10^{-5})$
$\overline{B}^0$		$V_{cb}V_{ud}^*$		
	$D_s^+K^-$	E	3.45 ± 0.32	$3.0^{+0.4}_{-0.2}\pm 0.0\pm 0.3$
	$D_s^{*+}K^-$	E $\propto \chi^E e^{i\phi^E}$	2.19 ± 0.30	$2.2^{+0.3}_{-0.1}\pm 0.0\pm 0.3$
	$D_s^+K^{*-}$	E	3.5 ± 1.0	$3.8^{+0.5}_{-0.2}\pm 0.0\pm 0.6$
$\overline{B}^0$		$V_{cb}V_{us}^*$		
	$D^0\overline{K}^0$	C	5.2 ± 0.7	$4.0\pm 0.0\pm 1.0\pm 0.0$
	$D^{*0}\overline{K}^0$	C $\propto \chi^C e^{i\phi^C}$	3.6 ± 1.2	$4.5^{+0.2}_{-0.3}\pm 0.9\pm 0.5$
	$D^0\overline{K}^{*0}$	C	4.2 ± 0.6	$3.7\pm 0.2\pm 0.7\pm 0.2$

Meson	Mode	Amplitudes	$\mathcal{B}_{\rm exp}(\times 10^{-3})$	$\mathcal{B}_{\rm FAT}(\times 10^{-3})$
$\overline{B}_s^0$		$V_{cb}V_{ud}^*$		
	$D_s^+\pi^-$	T factorization	3.04 ± 0.23	$3.02\pm 0.00\pm 0.6\pm 0.01$
	$D_s^{*+}\pi^-$	T	2.0 ± 0.5	$2.71\pm 0.00\pm 0.54\pm 0.01$
	$D_s^+\rho^-$	T	7.0 ± 1.5	$7.86\pm 0.00\pm 1.57\pm 0.79$

Global fit for hadronic D decays

(Phys.Rev. D86 (2012) 036012)

- 12 free parameters are extracted from 28 experimental data of D->PP branching ratios

$$\Lambda = 0.59 \ \text{GeV}, \quad \chi_{nf} = -0.84, \quad \chi_q^E = 0.09, \quad \chi_s^E = 0.19, \quad \chi_q^A = 0.10, \quad \chi_s^A = 0.16,$$
$$S_\pi = -0.66, \quad \phi = -0.55, \quad \phi_q^E = 4.90, \quad \phi_s^E = 4.05, \quad \phi_q^A = 3.73, \quad \phi_s^A = 3.36,$$

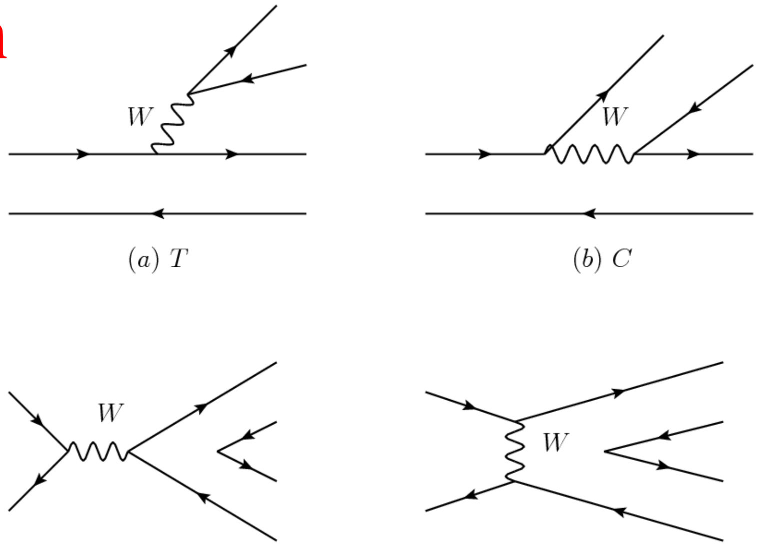
$$\chi^2/d.o.f = 8.1$$

- Λ describes the soft momentum in D meson
- The value of Glauber phase is consistent with the value extracted from B->πK data, resolving the puzzle for direct asymmetries in this mode

[H.n Li, S. Mishima, 0901.1272]

Topology diagrams for BRs

- According to weak interactions and flavor flows
- Include all strong interaction effects, involving final state interaction (FSI) effects
- Magnitude and phase are introduced to each topology
- This is a complete set
- Penguins are neglected for BRs due to suppression of CKM matrix elements



(a) T (b) C (c) A (d) E

$$a_1(\mu) = C_2(\mu) + \frac{C_1(\mu)}{N_c},$$
$$a_2(\mu) = \left(C_1(\mu) + \frac{C_2(\mu)}{N_c}\chi_{nf}\right) e^{i\phi},$$

Evolution scale

- Important flavor SU(3) breaking effects
- Non-negligible mass ratios $m_{K,\eta^{(\prime)}}/m_D$
- Suggested by the PQCD approach, the scale is set to the energy release depending on masses of final states

$$\mu = \sqrt{\Lambda m_D(1 - r_2^2)}, \quad r_2 = m_{P_2}^2/m_D^2$$

- Λ : the momentum of soft degrees of freedom, a free parameter to be determined

Singly Cabibbo-suppressed decays (10^{-3}), better agreement with data

Modes	Br(FSI)	Br(diagram)	Br(pole)	Br(exp)	Br(this work)
$D^0 \to \pi^+\pi^-$	1.59	2.24±0.10	2.2 ± 0.5	1.45±0.05	1.44
$D^0 \to K^+K^-$	4.56	1.92±0.08	3.0 ± 0.8	4.07±0.10	4.19
$D^0 \to K^0\overline{K}^0$	0.93	0	0.3 ± 0.1	0.320±0.038	0.35
$D^0 \to \pi^0\pi^0$	1.16	1.35±0.05	0.8 ± 0.2	0.81±0.05	0.55
$D^0 \to \pi^0\eta$	0.58	0.75±0.02	1.1 ± 0.3	0.68±0.07	0.94
$D^0 \to \pi^0\eta'$	1.7	0.74±0.02	0.6 ± 0.2	0.91±0.13	0.64
$D^0 \to \eta\eta$	1.0	1.44±0.08	1.3 ± 0.4	1.67±0.18	1.48
$D^0 \to \eta\eta'$	2.2	1.19±0.07	1.1 ± 0.1	1.05±0.26	1.52
$D^+ \to \pi^+\pi^0$	1.7	0.88±0.10	1.0 ± 0.5	1.18±0.07	0.88
$D^+ \to K^+\overline{K}^0$	8.6	5.46±0.53	8.4 ± 1.6	6.12±0.22	5.97
$D^+ \to \pi^+\eta$	3.6	1.48±0.26	1.6 ± 1.0	3.54±0.21	3.37
$D^+ \to \pi^+\eta'$	7.9	3.70±0.37	5.5 ± 0.8	4.68±0.29	4.54
$D_S^+ \to \pi^0 K^+$	1.6	0.86±0.09	0.5 ± 0.2	0.62±0.23	0.65
$D_S^+ \to \pi^+ K^0$	4.3	2.73±0.26	2.8 ± 0.6	2.52±0.27	2.21
$D_S^+ \to K^+\eta$	2.7	0.78±0.09	0.8 ± 0.5	1.76±0.36	1.00
$D_S^+ \to K^+\eta'$	5.2	1.07±0.17	1.4 ± 0.4	1.8±0.5	1.92

Branching ratios for Cabibbo-favored decays of $D \to PV(\%)$

Modes	diagrams	Br(FSI)	Br(diagrammatic)	Br(pole)	Br(FAT)	Br(exp)
$D^0 \to \pi^+ K^{*-}$	T_V, E_P	4.69	5.91 ± 0.70	3.1 ± 1.0	7.12	$5.44^{+0.70}_{-0.53}$
$D^0 \to \pi^0 \overline{K}^{*0}$	C_P, E_P	3.49	2.82 ± 0.34	2.9 ± 1.0	3.51	3.44 ± 0.35
$D^0 \to \overline{K}^0 \rho^0$	C_V, E_V	0.88	1.54 ± 1.15	1.7 ± 0.7	1.28	$1.26^{+0.14}_{-0.16}$
$D^0 \to \overline{K}^0 \omega$	C_V, E_V	2.16	2.26 ± 1.38	2.5 ± 0.7	2.23	2.22 ± 0.12
$D^0 \to \overline{K}^0 \phi$	E_P	0.90	0.868 ± 0.139	0.8 ± 0.2	0.818	0.834 ± 0.074
$D^0 \to K^- \rho^+$	T_P, E_V	11.19	10.8 ± 2.2	8.8 ± 2.2	9.80	10.8 ± 0.7
$D^0 \to \eta \overline{K}^{*0}$	C_P, E_P, E_V	0.51	0.96 ± 0.32	0.7 ± 0.2	1.00	0.96 ± 0.30
$D^0 \to \eta' \overline{K}^{*0}$	C_P, E_P, E_V	0.005	0.012 ± 0.003	0.016 ± 0.005	0.015	< 0.11
$D^+ \to \pi^+ \overline{K}^{*0}$	C_P	0.64	1.83 ± 0.49	1.4 ± 1.3	1.81	1.51 ± 0.16
$D^+ \to \overline{K}^0 \rho^+$	T_P, C_V	11.77	9.2 ± 6.7	15.1 ± 3.8	6.0	9.6 ± 2.0
$D_s^+ \to \pi^+ \rho^0$	A_P, A_V	0.080		0.4 ± 0.4	0.026	0.02 ± 0.012
$D_s^+ \to \pi^+ \omega$	A_P, A_V	0.0		0	0.25	0.25 ± 0.07
$D_s^+ \to \pi^+ \phi$	T_V	2.89	4.38 ± 0.35	4.3 ± 0.6	3.1	4.5 ± 0.4
$D_s^+ \to \pi^0 \rho^+$	A_P, A_V	0.080		0.4 ± 0.4	0.026	
$D_s^+ \to K^+ \overline{K}^{*0}$	C_P, A_V	3.86		4.2 ± 1.7	4.12	3.95 ± 0.2
$D_s^+ \to \overline{K}^0 K^{*+}$	C_V, A_P	3.37		1.0 ± 0.6	4.4	5.4 ± 1.2
$D_s^+ \to \eta \rho^+$	T_P, A_P, A_V	9.49		8.3 ± 1.3	6.5	8.9 ± 0.8
$D_s^+ \to \eta' \rho^+$	T_P, A_P, A_V	2.61		3.0 ± 0.5	2.3	12.5 ± 2.2

Phys.Rev. D89 (2014) 5, 054006

Penguin parameterization

- Use the long-distance hadronic parameters fixed by the data of branching ratios
- Try to formulate penguin contribution without introducing additional free parameters
- The tree operators are all (V-A)(V-A)
- For penguins, the hadronic matrix elements with (V-A)(V-A) operators are the same as tree level operators

Predictions of Direct CP asymmetries

Modes	a_{CP}(FSI)	a_{CP}(diagram)	a_{CP}^{tree}	$a_{CP}^{tot}(\times 10^{-3})$
$D^0 \to \pi^+\pi^-$	0.02 ± 0.01	0.86	0	0.74
$D^0 \to K^+K^-$	0.13 ± 0.8	-0.48	0	-0.54
$D^0 \to \pi^0\pi^0$	-0.54 ± 0.31	0.85	0	0.26
$D^0 \to K^0\overline{K}^0$	-0.28 ± 0.16	0	0.69	0.90
$D^0 \to \pi^0\eta$	1.43 ± 0.83	-0.16	-0.29	-0.61
$D^0 \to \pi^0\eta'$	-0.98 ± 0.47	-0.01	0.43	1.67
$D^0 \to \eta\eta$	0.50 ± 0.29	-0.71	0.29	0.18
$D^0 \to \eta\eta'$	0.28 ± 0.16	0.25	-0.30	0.97
$D^+ \to \pi^+\pi^0$		0	0	-0.23
$D^+ \to K^+\overline{K}^0$	-0.51 ± 0.30	-0.38	-0.08	-0.93
$D^+ \to \pi^+\eta$		-0.65	-0.46	0.63
$D^+ \to \pi^+\eta'$		0.41	0.30	1.28
$D_S^+ \to \pi^0K^+$		0.88	0.17	0.76
$D_S^+ \to \pi^+K^0$		0.52	-0.01	0.87
$D_S^+ \to K^+\eta$		-0.19	0.75	0.76
$D_S^+ \to K^+\eta'$		-0.41	-0.48	1.83

LHCb-PAPER-2013-003

LHCb-CONF-2013-003

LHCb combination

Semileptonic: $\Delta A_{CP} = (+0.49 \pm 0.30(stat.) \pm 0.14(syst.))\ \%$

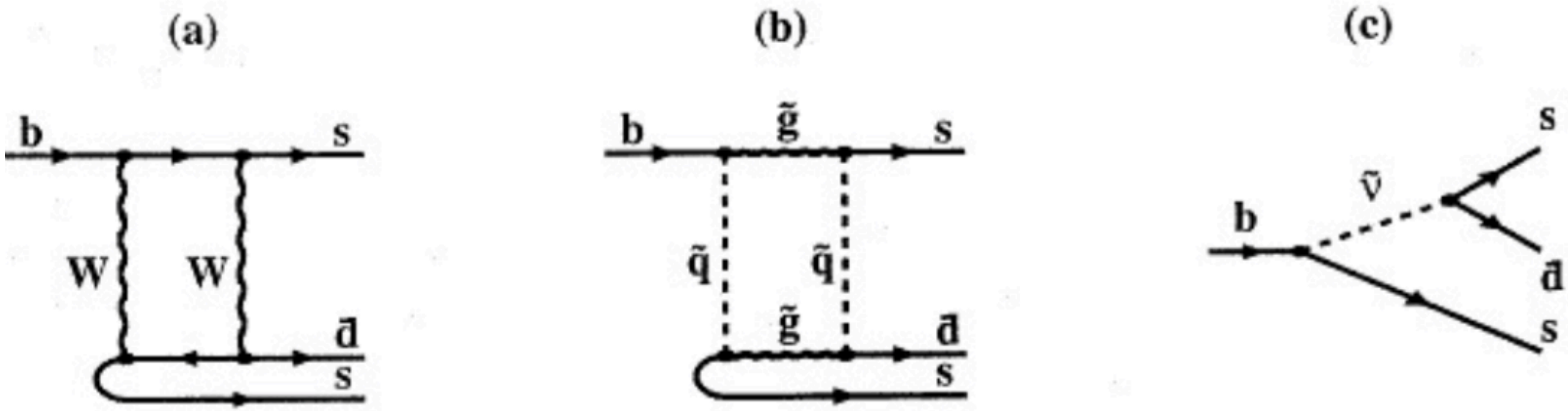
Prompt: (preliminary) $\Delta A_{CP} = (-0.34 \pm 0.15(stat.) \pm 0.10(syst.))\ \%$

- The two measurement are compatible at the 3 % level
  - $\chi 2 = 4.85$
- Naive average (neglecting indirect CP violation)

$$\Delta A_{CP,LHCb} = (-0.15 \pm 0.16)\ \%$$

Search for new physics in hadronic B decays-1example

K. Huitu, C.D. Lü, P. Singer D.X. Zhang, **Phys. Rev. Lett. 81, 4313 (1998), hep-ph/9809566.**



$b \to ss\bar{d}$ transition (a) SM, (b) MSSM, (c) MSSM with R-parity violating coupling

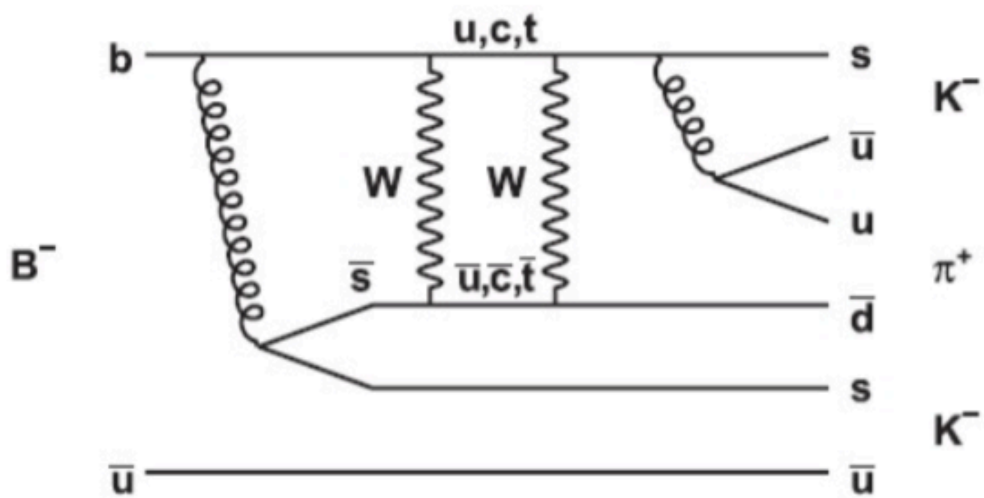
SM BRs: ~ 10^{-14},

New physics can reach 10^{-6}

Experimental search starting from OPAL @ LEP, phys. Lett. B 476 (2000) 233, later searched also by Belle/Babar

BABAR collaboration, Phys. Rev. D 78 (2008) 091102 [arXiv:0808.0900]

A search for the decay $B^- \to K^- K^- \pi^+$, Using a sample of $(467 \pm 5) \times 10^6$ $B\overline{B}$ pairs collected with the BABAR detector.



Result : No evidence for these decays was found and a upper limit was set as

$$\mathcal{B}(B^- \to K^- K^- \pi^+) < 1.6 \times 10^{-7}$$

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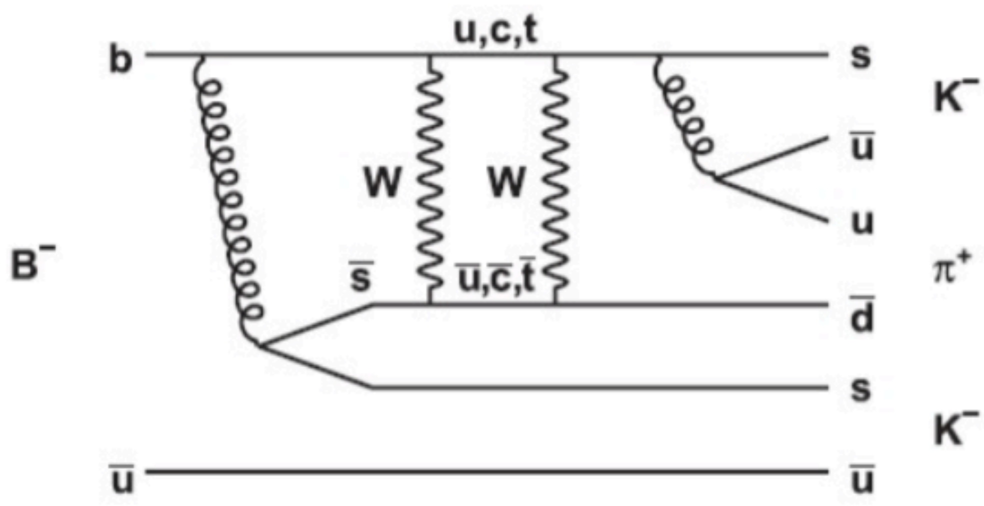

Similar channel $B^- \to \pi^- \pi^- K^+$

Result : No evidence for these decays was found and a upper limit was set as

LHCb?

$$\mathcal{B}(B^- \to K^- K^- \pi^+) < 1.6 \times 10^{-7}$$

Summary

- High-energy QCD processes must involve both perturbative and nonperturbative dynamics.
- At leading power, the two dramatically different dynamics factorize.
- Theoretical study of non-leptonic D/B meson decays making great improvement with helping from rich experimental data
- **Flavor sector has only been tested at the 10% level and can be done much better**
- **We are still waiting for a clear New physics signal in the heavy flavor sector**

Thanks !