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S-Wave Contributions in Semi-Leptonic B decays

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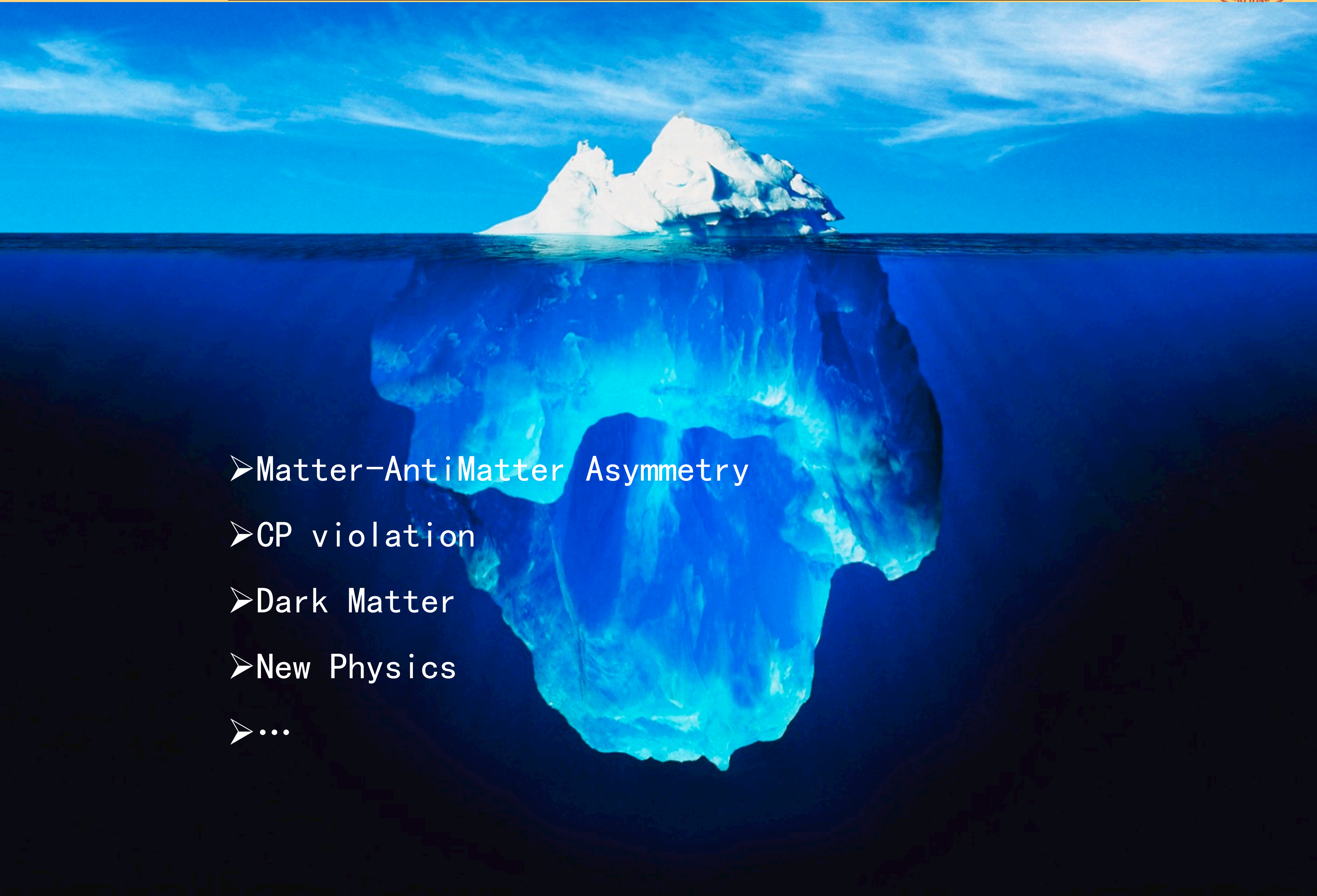
Outline

- Introduction
- Semi-Leptonic B decays into a vector

  B →ρlv; B->K*l+l-
- S-wave contributions
- Results based on χPT
- Summary and Outlook

SM is complete but…



- Matter-AntiMatter Asymmetry
- CP violation
- Dark Matter
- New Physics
- …

CP Violation

Mass Eigenstates $\neq$ Weak Eigenstates $\Rightarrow$ Quark Mixing

$$V_{CKM} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix}$$

CKM Matrix

Complex matrix described by 4 independent real parameters

Wolfenstein parametrization:

$$V_{CKM} \approx \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

phase

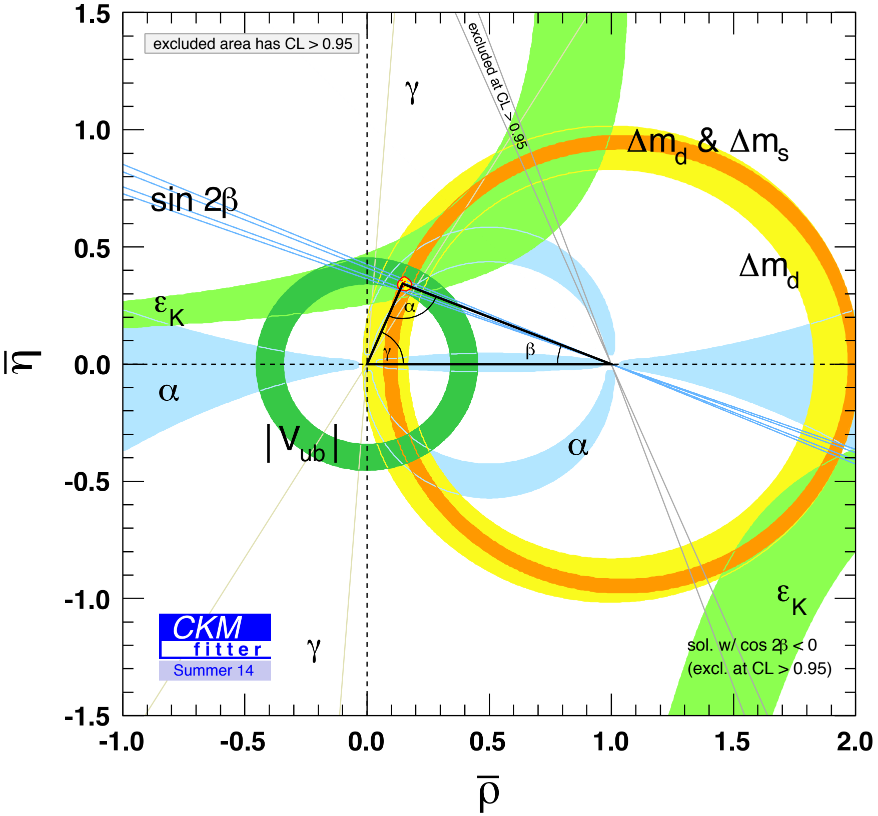
CP Violation:

$$J = \mathrm{Im}\left(V_{ik} V_{jk}^{*} V_{j\ell} V_{i\ell}^{*} \right) \neq 0$$

$$J \approx A^2 \lambda^6 \eta$$

$\eta = 0 \Rightarrow$ no CPV from SM

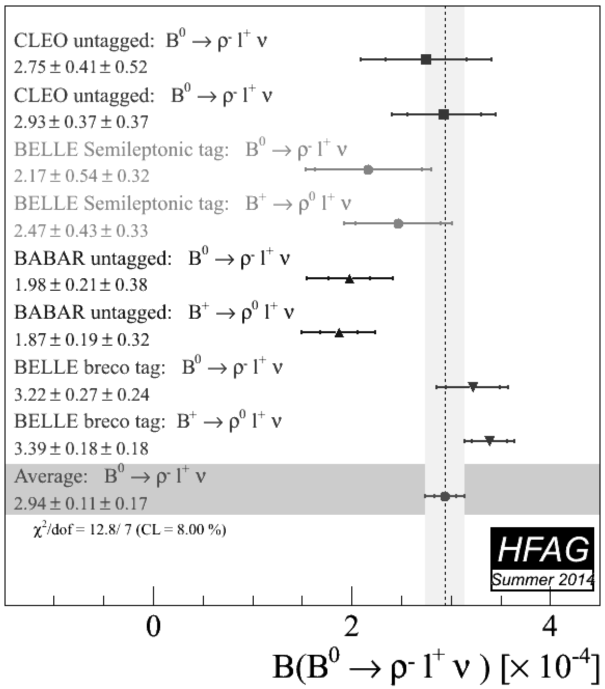
3σ deviation in $|V_{ub}|$



More channels:

$B_s \to Kl\nu$

$B \to \rho l\nu$



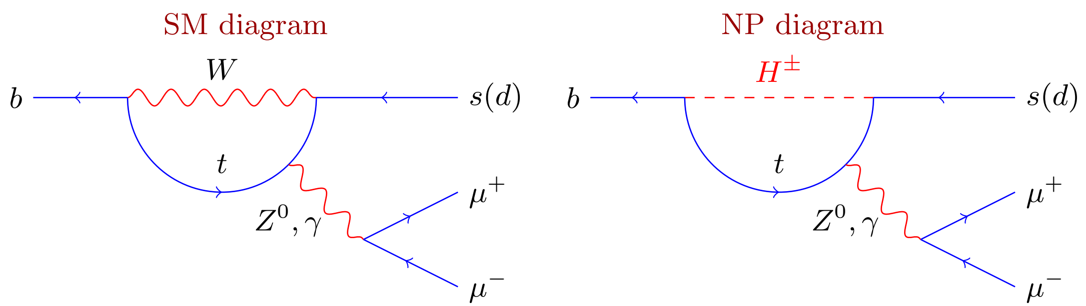
$$|V_{ub}| = (4.41 \pm 0.15\, {}^{+\,0.15}_{-\,0.17}) \times 10^{-3} \qquad \text{(inclusive)},$$

$$|V_{ub}| = (3.23 \pm 0.31) \times 10^{-3} \qquad \text{(exclusive)}.$$

$B \to \pi l\nu$

Indirect Search for NP

- Flavor Changing Neutral Currents (FCNC) is forbiddend at tree level in SM, but can proceed via the loop diagrams.
- New particles may change the amplitudes



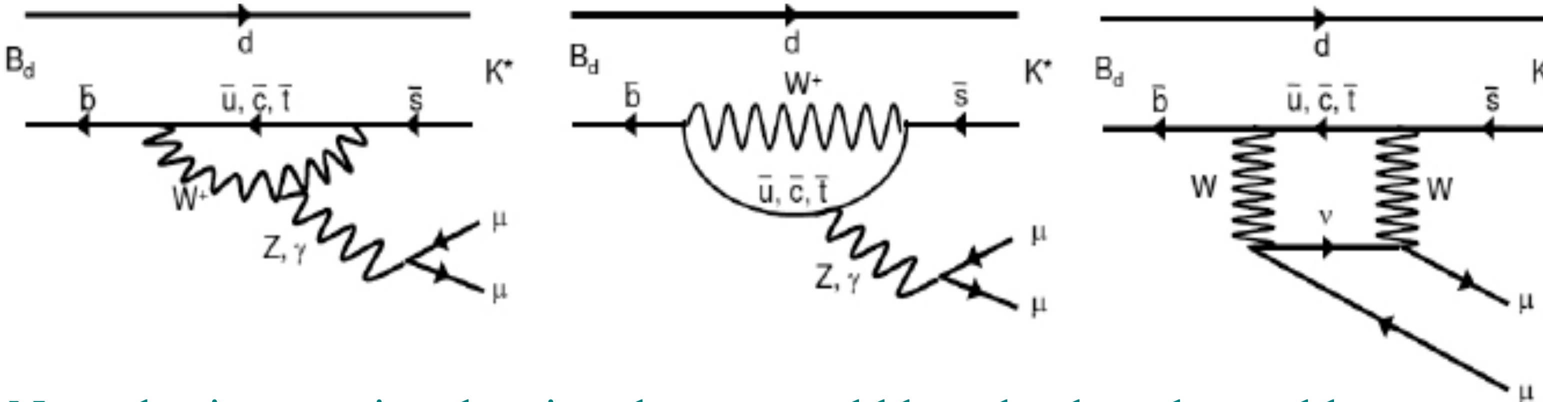
- Rare decays FCNC can probe NP virtual particles

  - **NP phases**
  - **Masses, Couplings**
  - **Helicity structure**

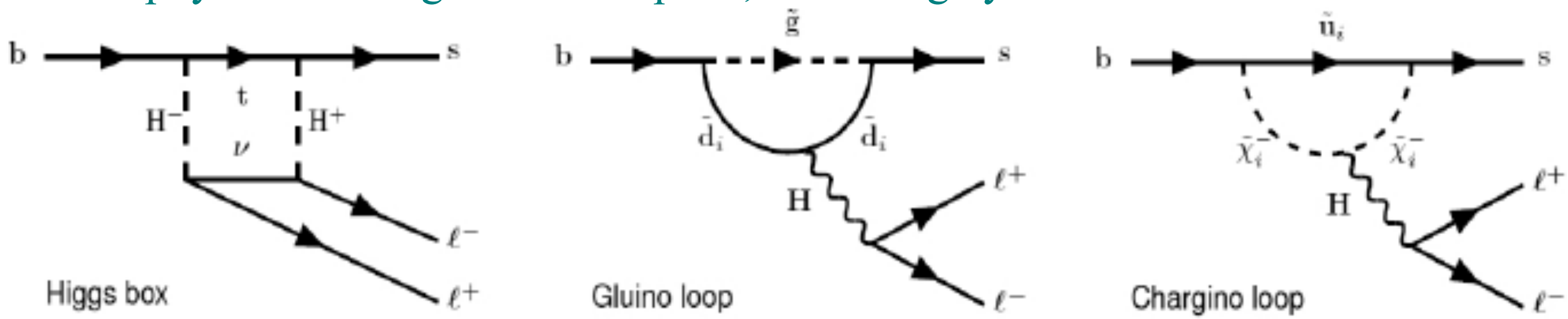
See Prof. W.S. Hou's talk

B→K*l+l-

- Within the SM, these processes proceed via loop diagrams like



- New physics entering the virtual parts, could largely alter observables

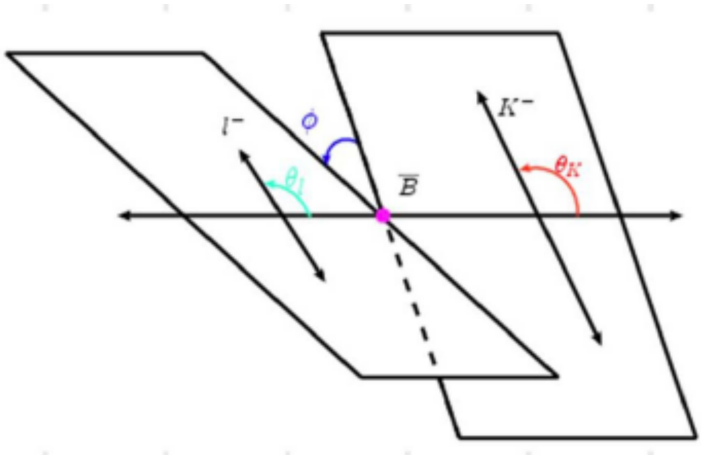


- Effective Hamiltonian: $\mathcal{H}_{eff} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_{i=1}^{10} (C_i^{SM} + \Delta C_i^{NP}) \mathcal{O}_i$

Wilson coeffs.
(short-dist. interactions)

Operators
(long-dist. interactions)

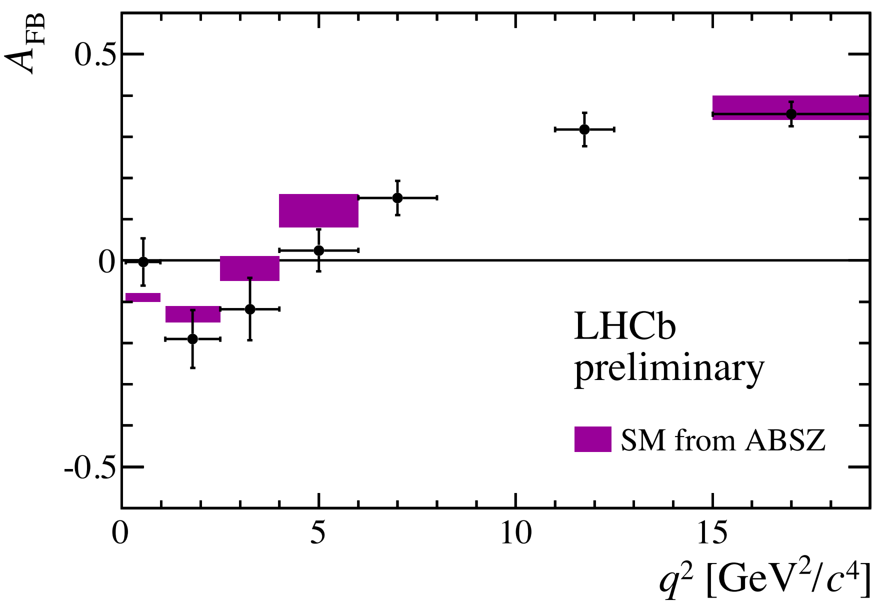
Forward-backward asymmetry



- θ_l: angle of emission between K^{*0} and μ^- in di-lepton rest frame
- θ_{K^*}: angle of emission between K^{*0} and K^- in di-meson rest frame.
- ϕ: angle between the two planes
- q^2: dilepton invariant mass square

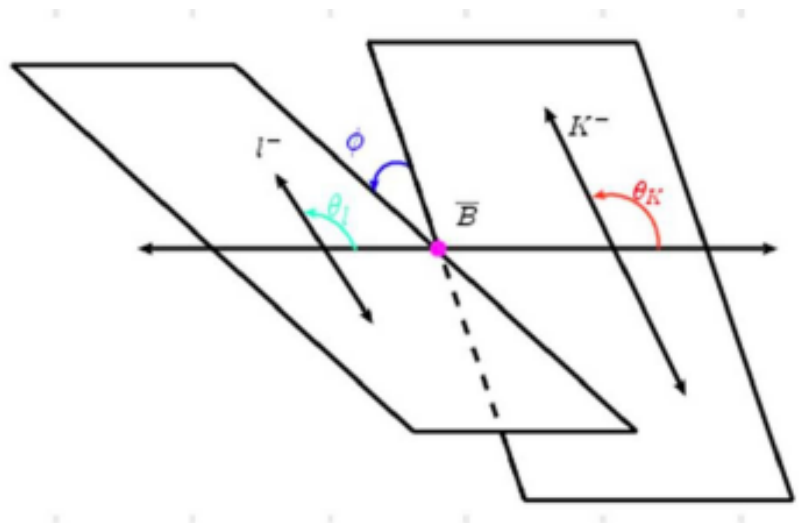
$$A_{\mathrm{FB}}(q^2) = \frac{P_{\mathrm{F}}(q^2) - P_{\mathrm{B}}(q^2)}{P_{\mathrm{F}}(q^2) + P_{\mathrm{B}}(q^2)}$$

A.Ali, et. al, hep-ph/9910221



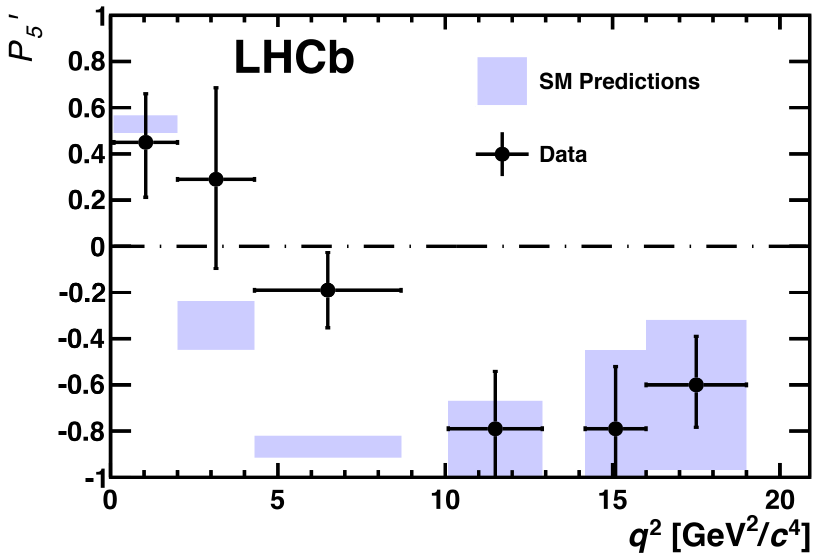
LHCb-CONF-2015-002 3fb^{-1}
ABSZ: 1503.05534

Angular distributions



$$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^3(\Gamma+\bar{\Gamma})}{\mathrm{d}\vec{\Omega}} = \frac{9}{32\pi}\Big[\tfrac{3}{4}(1-F_{\mathrm{L}})\sin^2\theta_K + F_{\mathrm{L}}\cos^2\theta_K + \tfrac{1}{4}(1-F_{\mathrm{L}})\sin^2\theta_K\cos 2\theta_\ell$$
$$- F_{\mathrm{L}}\cos^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi$$
$$+ S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi + S_5\sin 2\theta_K\sin\theta_\ell\cos\phi$$
$$+ \tfrac{4}{3}A_{\mathrm{FB}}\sin^2\theta_K\cos\theta_\ell + S_7\sin 2\theta_K\sin\theta_\ell\sin\phi$$
$$+ S_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi + S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\Big]$$

3.7σ deviations



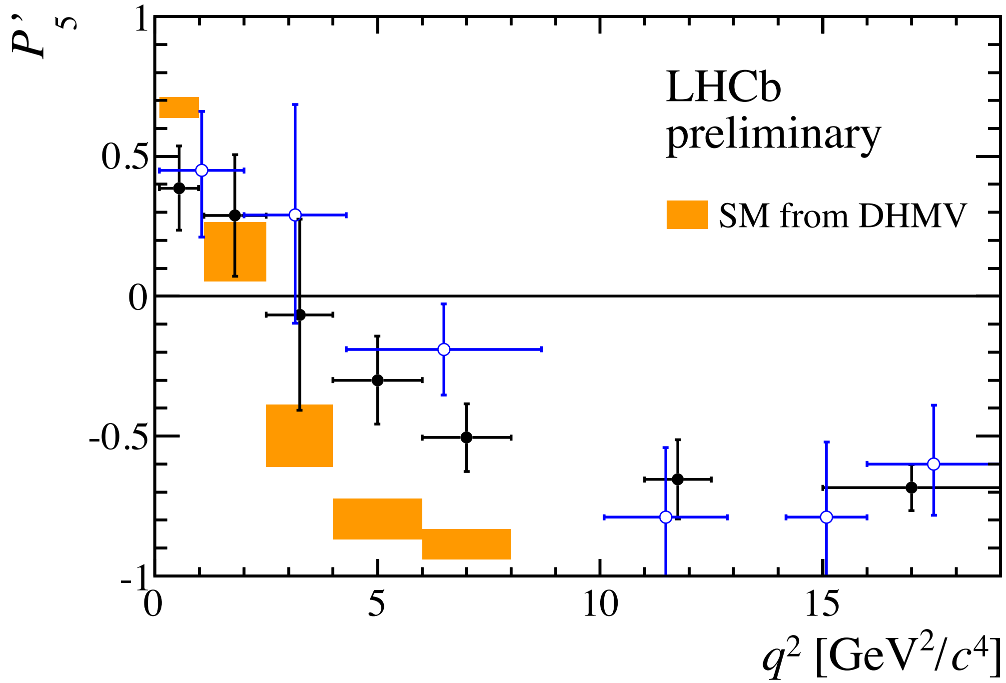
Form-factor independent observables $P_5' = \frac{S_5}{\sqrt{F_L(1-F_L)}}$

LHCb:1308.1707
SM: 1303.5794

We present a measurement of form-factor independent angular observables in the decay $B^0 \to K^*(892)^0\mu^+\mu^-$. The analysis is based on a data sample corresponding to an integrated luminosity of $1.0\,\text{fb}^{-1}$, collected by the LHCb experiment in pp collisions at a center-of-mass energy of 7 TeV. Four observables are measured in six bins of the dimuon invariant mass squared, q^2, in the range $0.1 < q^2 < 19.0\,\text{GeV}^2/c^4$. Agreement with Standard Model predictions is found for 23 of the 24 measurements. A local discrepancy, corresponding to 3.7 Gaussian standard deviations, is observed in one q^2 bin for one of the observables. Considering the 24 measurements as independent, the probability to observe such a discrepancy, or larger, in one is 0.5%.

3.7σ deviations

Form-factor independent observables $P_5' = \frac{S_5}{\sqrt{F_L(1-F_L)}}$



LHCb-CONF-2015-002
DHMV:1407.8526

See Rahul Sinha's talk

Neglecting the correlations between the observables, the measurements are largely in agreement with the Standard Model predictions. However, the observable P_5' exhibits a local tension with respect to the Standard Model prediction at a level of 3.7σ.

S-wave contributions

Due to limited life-time, vector mesons are reconstructed from two-pseudo-scalar mesons: K* (50 MeV): Kπ

$B \to K^* l^+ l^-$ is a four-body process.

Experimental cuts by LHCb:

LHCb-CONF-2015-002

$$m_{K^*} - \delta_m < m_{K\pi} < m_{K^*} + \delta_m \qquad \delta_m = 100\text{MeV}$$

$$\int_{(m_{K^*}-\delta_m)^2}^{(m_{K^*}+\delta_m)^2} dm_{K\pi}^2 |L_{K^*}(m_{K\pi}^2)|^2 = 0.56$$

L denotes the distribution function of Kπ system from K*

Narrow width limit (theoretical results):

$$\int dm_{K\pi}^2 |L_{K^*}(m_{K\pi}^2)|^2 = \mathcal{B}(K^{*+} \to K^0\pi^+) = \frac{2}{3}$$

S-wave contributions

Experimental cuts by LHCb:

$$m_{K*} - \delta_m < m_{K\pi} < m_{K*} + \delta_m \qquad \delta_m = 100\text{MeV}$$

We expect the S-wave: *Doring, Meissner, WW, 1307.0947*

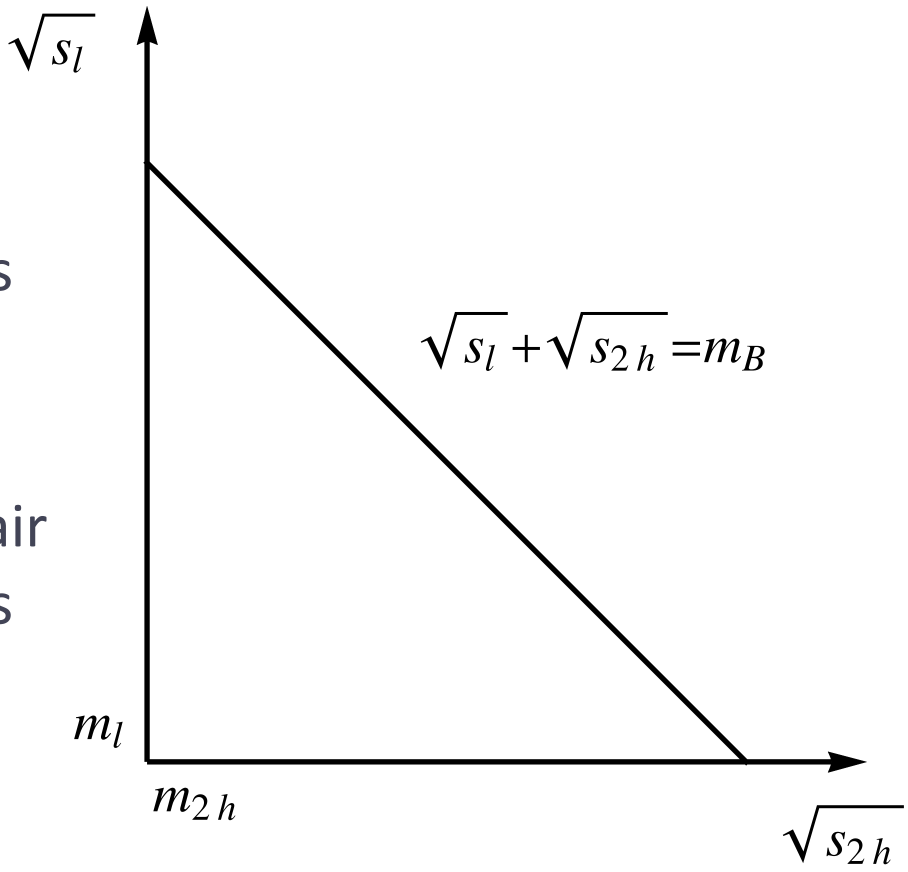
$$\int_{(m_{K*}-\delta_m)^2}^{(m_{K*}+\delta_m)^2} dm_{K\pi}^2 |L_S(m_{K\pi}^2)|^2 = 0.17$$

It is mandatory to include the S-wave.

Phase-space for B →$M_1M_2ll(\nu)$

s_l: lepton pair invariant mass square

s_{2h}: 2-hadron pair invariant mass square



Phase-space for B →$M_1M_2ll(\nu)$

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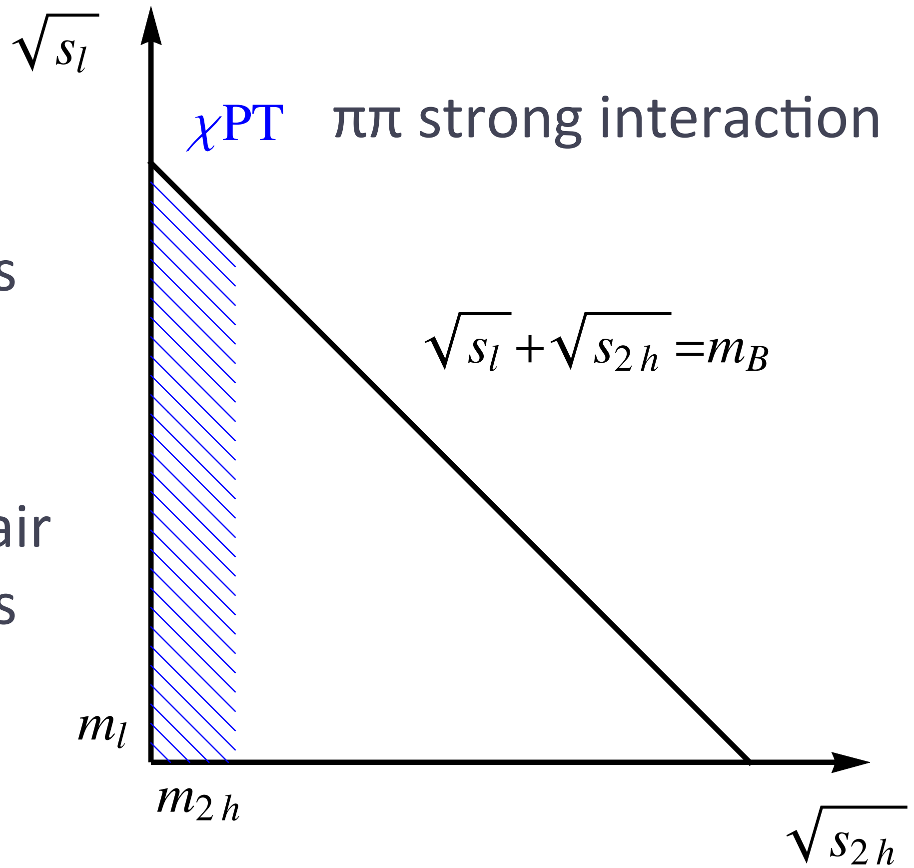

Phase-space for B →$M_1M_2ll(\nu)$

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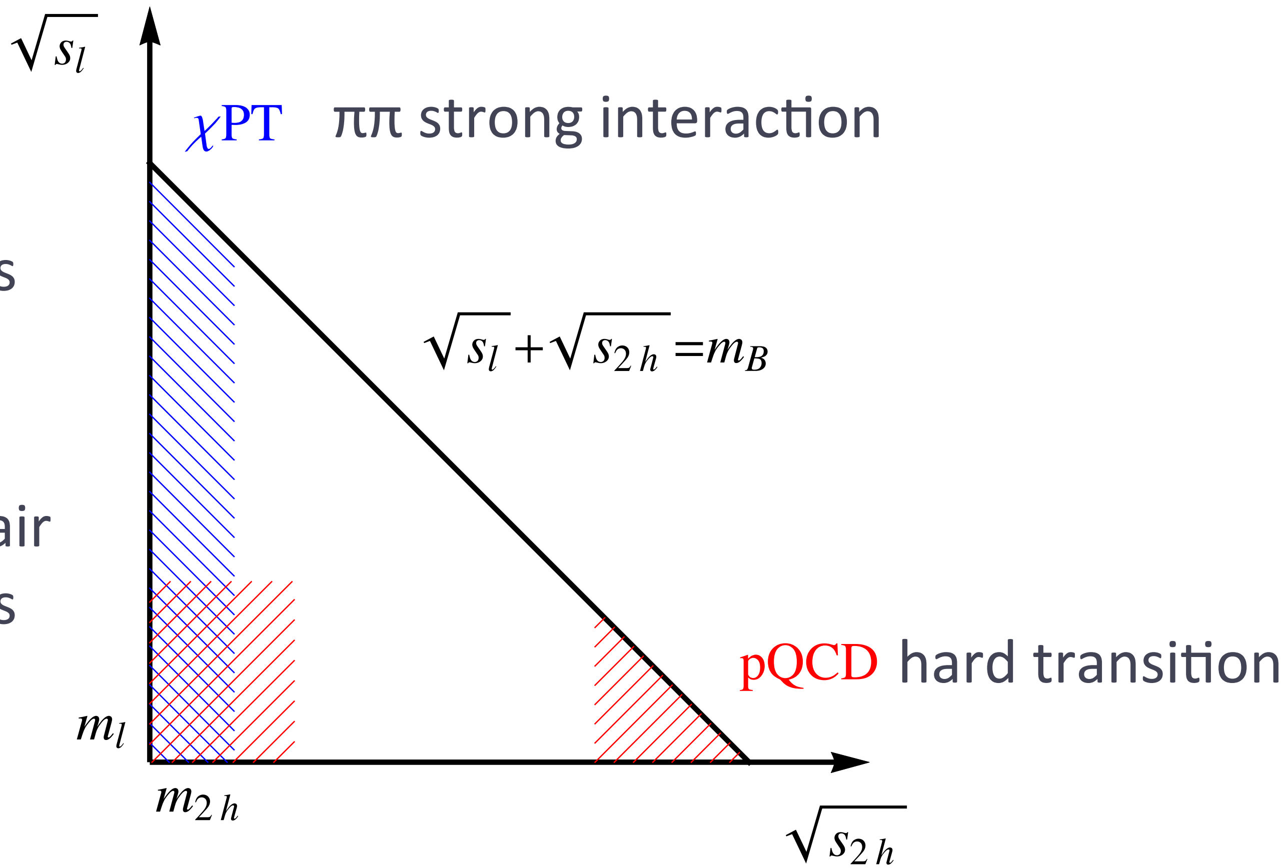
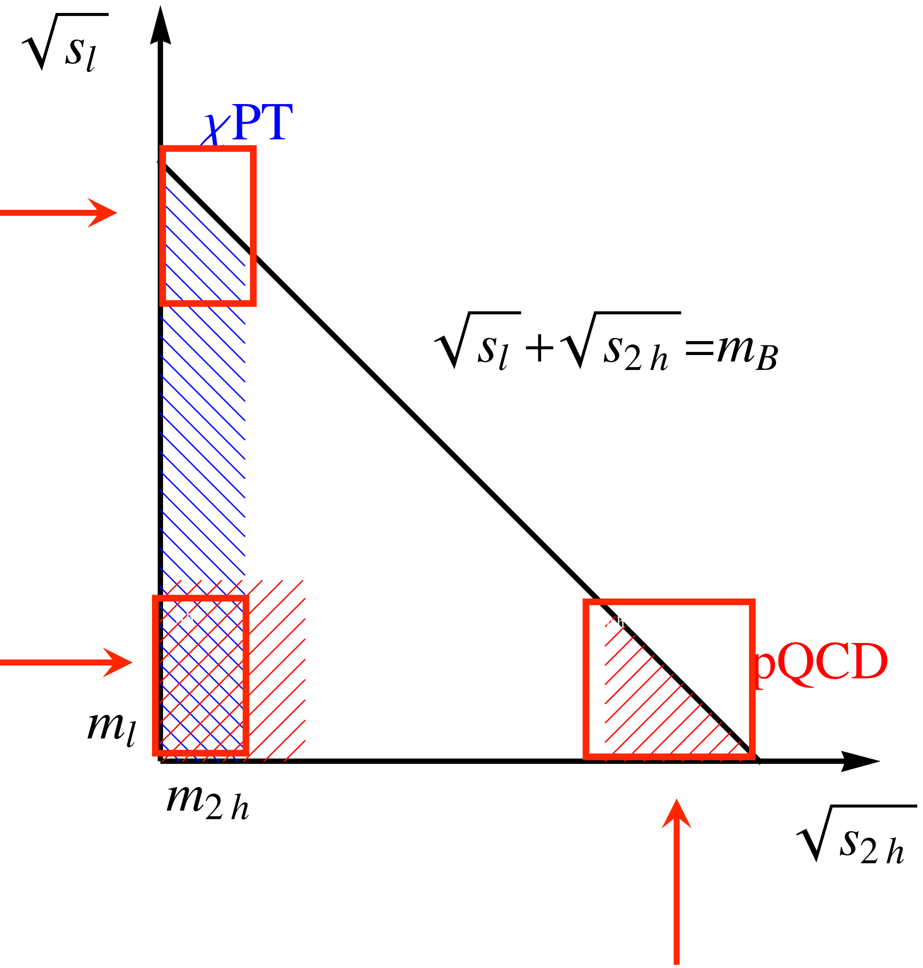


Phase-space for B →$M_1M_2ll(\nu)$

Heavy Meson χPT

χPT+pQCD



S-wave contributions

- To be more specific, consider the generalized transition form factors:

$$\begin{aligned}\langle (K\pi)_0(p_{K\pi})|\bar{s}\gamma_\mu\gamma_5 b|\overline{B}(p_B)\rangle &= -i\frac{1}{m_{K\pi}}\Big\{\Big[P_\mu - \frac{m_B^2-m_{K\pi}^2}{q^2}q_\mu\Big]\mathcal{F}_1^{B\to K\pi}(m_{K\pi}^2,q^2) \\ &\quad + \frac{m_B^2-m_{K\pi}^2}{q^2}q_\mu\mathcal{F}_0^{B\to K\pi}(m_{K\pi}^2,q^2)\Big\}, \\ \langle (K\pi)_0(p_{K\pi})|\bar{s}\sigma_{\mu\nu}q^\nu\gamma_5 b|\overline{B}(p_B)\rangle &= -\frac{\mathcal{F}_T^{B\to K\pi}(m_{K\pi}^2,q^2)}{m_{K\pi}(m_B+m_{K\pi})}[q^2P_\mu-(m_B^2-m_{K\pi}^2)q_\mu],\end{aligned}$$

Generalized Form factors in LCSR

$$\langle (K\pi)_0(p_{K\pi})|\bar{s}\gamma_\mu\gamma_5 b|\overline{B}(p_B)\rangle = -i\frac{1}{m_{K\pi}}\left\{\left[P_\mu - \frac{m_B^2-m_{K\pi}^2}{q^2}q_\mu\right]\mathcal{F}_1^{B\to K\pi}(m_{K\pi}^2,q^2) + \frac{m_B^2-m_{K\pi}^2}{q^2}q_\mu\mathcal{F}_0^{B\to K\pi}(m_{K\pi}^2,q^2)\right\},$$

$$\langle (K\pi)_0(p_{K\pi})|\bar{s}\sigma_{\mu\nu}q^\nu\gamma_5 b|\overline{B}(p_B)\rangle = -\frac{\mathcal{F}_T^{B\to K\pi}(m_{K\pi}^2,q^2)}{m_{K\pi}(m_B+m_{K\pi})}\left[q^2P_\mu-(m_B^2-m_{K\pi}^2)q_\mu\right],$$

Consider a generic correlation function

$$\Pi(p_{K\pi},q) = i\int d^4x\, e^{iq\cdot x}\langle (K\pi)_0(p_{K\pi})|\mathrm{T}\left\{j_{\Gamma_1}(x),j_{\Gamma_2}(0)\right\}|0\rangle$$

Hadron level:

$$\frac{\langle (K\pi)_0(p_{K\pi})|j_{\Gamma_1}|\overline{B}(p_{K\pi}+q)\rangle\langle\overline{B}(p_{K\pi}+q)|j_{\Gamma_2}|0\rangle}{m_B^2-(p_{K\pi}+q)^2} + \int_{s_0}^{\infty} ds\frac{\rho^h(s,q^2)}{s-(p_{K\pi}+q)^2},$$

Quark Hadron Duality

Quark level: Light cone OPE

$$\langle (K\pi)_0|\bar{s}(x)\gamma_\mu d(0)|0\rangle$$

$$\langle (K\pi)_0|\bar{s}(x)d(0)|0\rangle$$

$$\langle (K\pi)_0|\bar{s}(x)\sigma_{\mu\nu}d(0)|0\rangle$$

U.G. Meiβner, WW, arXiv:1312.3087

Chiral perturbation theory

χPT effective field theory based on the two assumptions

- π's are the Goldstone boson of $SU(3)_L \otimes SU(3)_R \to SU(3)_V$
- *(chiral) power counting* i.e. the theory has a small expansion parameter: $p^2/\Lambda^2_{\chi SB}$: $\Lambda_{\chi SB} \sim 4\pi F_\pi \sim 1.2$ GeV

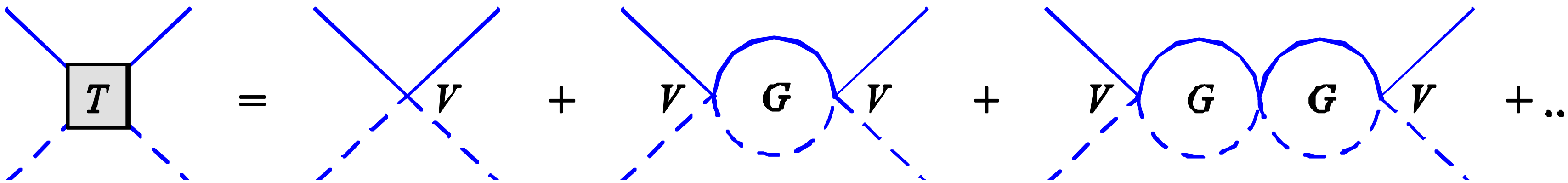
$$\mathcal{L}_{\Delta S=0} = \mathcal{L}^2_{\Delta S=0} + \mathcal{L}^4_{\Delta S=0} + \cdots = \frac{F_\pi{}^2}{4} \overbrace{\langle D_\mu U D^\mu U^\dagger + \chi U^\dagger + U \chi^\dagger \rangle}^{\pi\to l\nu,\ \pi\pi\to\pi\pi,\ K\to\pi..} + \overbrace{\sum_i L_i O_i}^{K\to\pi..} + \cdots$$

Fantastic chiral prediction $A_{\pi\pi} \sim (s - m_\pi^2)/F_\pi{}^2$ Weinberg, Colangelo *et al*

$$\mathcal{L}_{\Delta S=1} = \mathcal{L}^2_{\Delta S=1} + \mathcal{L}^4_{\Delta S=1} + \cdots = G_8 F^4 \underbrace{\langle \lambda_6 D_\mu U^\dagger D^\mu U \rangle}_{K\to 2\pi/3\pi} + \underbrace{G_8 F^2 \sum_i N_i W_i}_{K^+\to\pi^+\gamma\gamma,\, K\to\pi l^+ l^-} + \cdots$$

⚠ ChiPT limited to low energies

Unitarized Approach

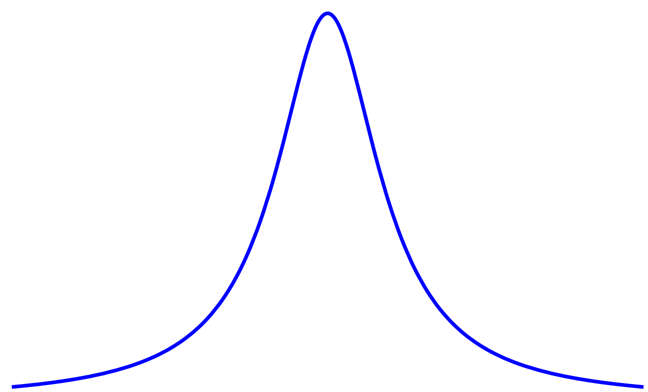


Summing all order contributions:

$$V + VGV + VGVGV + \ldots = \frac{V}{1 - GV}$$

1-GV=0

$s=s_0$

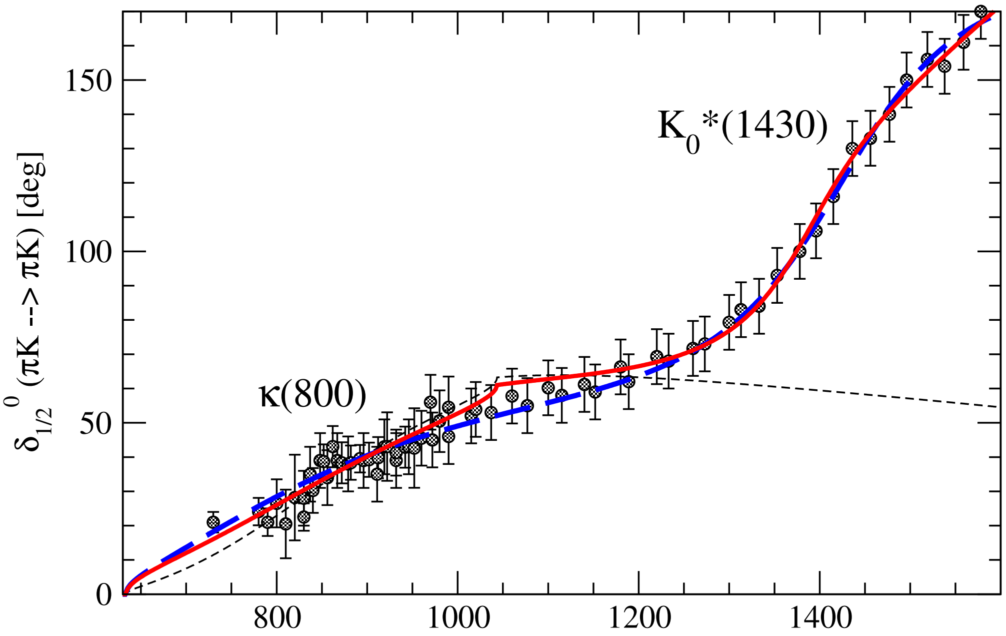


Above Threshold: pole corresponds to resonance

→ Hadron Molecule

Unitarized χPT and phase shift

M.Döring,U.-G.Meißner,WW,arXiv:1307.0947



Phase Shift

		z_0 [MeV]	$a_{-1}(K\eta)$ $[M_\pi]$	$a_{-1}(K\pi)$ $[M_\pi]$
$\kappa(800)$	this work (2-ch.)	$792-i\,279$		$-29-i\,57$
	this work (1-ch.)	$715-i\,283$		$-45-i\,62$
	Ref. [32] (χU)	$815-i\,226$		$-30-i\,57$
	Ref. [65] (Roy-S.)	$658-i\,279$		

Mass Pole

Scalar form factors in χPT

Scalar form factor: $\langle 0|\bar{s}d|K\pi\rangle = C_X B_0 F_{K\pi}(m_{K\pi}^2)$

QCD: $\mathcal{L} = \bar{q} i \not{D} q - m_q \bar{q} q$

$$\bar{q}q = -\frac{\partial \mathcal{L}}{\partial m_q}$$

Scalar form factors in χPT

Scalar form factor: $\langle 0|\bar{s}d|K\pi\rangle = C_X B_0 F_{K\pi}(m^2_{K\pi})$

Chiral Lagrangian: $\mathcal{L} = \frac{f^2}{4}\langle U^\dagger \chi_s + \chi_s^\dagger U\rangle$

$$\chi_s = 2B_0 \begin{pmatrix} 0 & 0 & m_{\bar{u}s} \\ 0 & 0 & m_{\bar{d}s} \\ m_{\bar{s}u} & m_{\bar{s}d} & 0 \end{pmatrix}$$

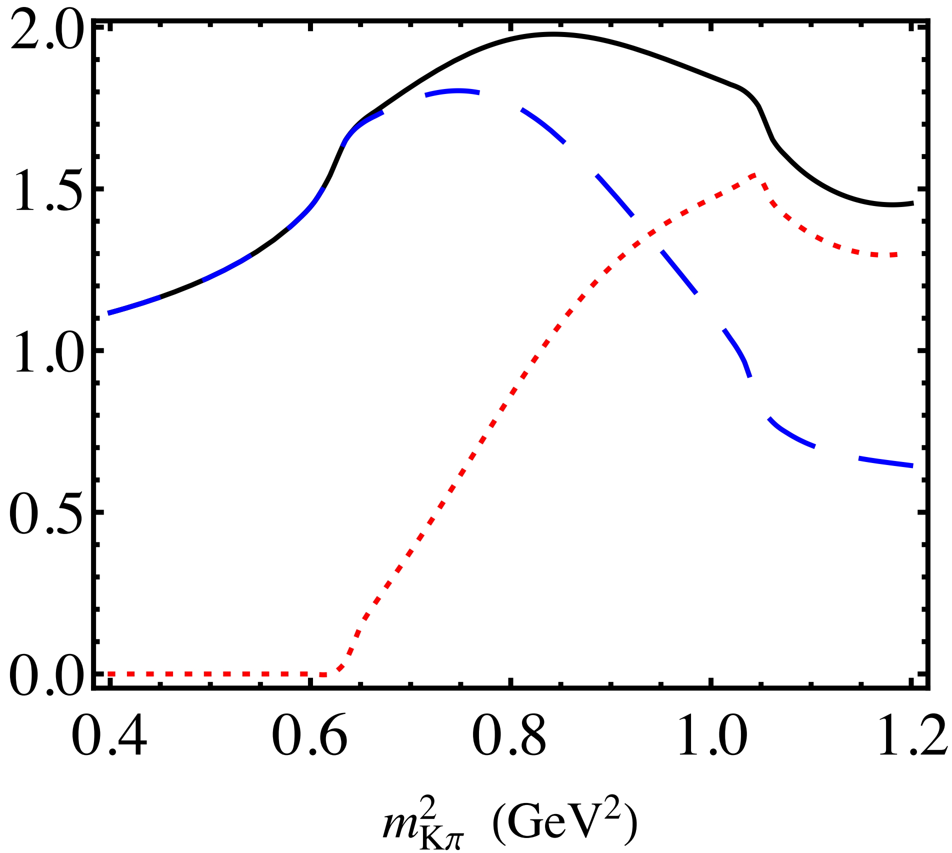
$$U = \exp\left(\frac{i\sqrt{2}}{f}\Phi\right)$$

$$\Phi = \begin{bmatrix} \frac{1}{\sqrt{2}}\pi^0 + \frac{1}{\sqrt{6}}\eta_8 & \pi^+ & K^+ \\ \pi^- & -\frac{1}{\sqrt{2}}\pi^0 + \frac{1}{\sqrt{6}}\eta_8 & K^0 \\ K^- & \bar{K}^0 & -\frac{2}{\sqrt{6}}\eta_8 \end{bmatrix}$$

Tree Level current: $\bar{s}u = -\partial\mathcal{L}/\partial m_{\bar{s}u}.$

$$\begin{aligned} \bar{q}q' = \bar{u}s + \bar{d}s + \bar{s}u + \bar{s}d \; &= \; \frac{B_0}{6}\Big[6\left(\pi^- K^+ + K^-\pi^+ + \pi^+ K^0 + \pi^-\bar{K}^0\right) \\ &- \sqrt{2}\left(K^- + K^+\right)\left(\sqrt{3}\eta_8 - 3\pi^0\right) \\ &- \sqrt{2}\left(K^0 + \bar{K}^0\right)\left(\sqrt{3}\eta_8 + 3\pi^0\right)\Big] \, . \end{aligned}$$

Scalar form factors in χPT

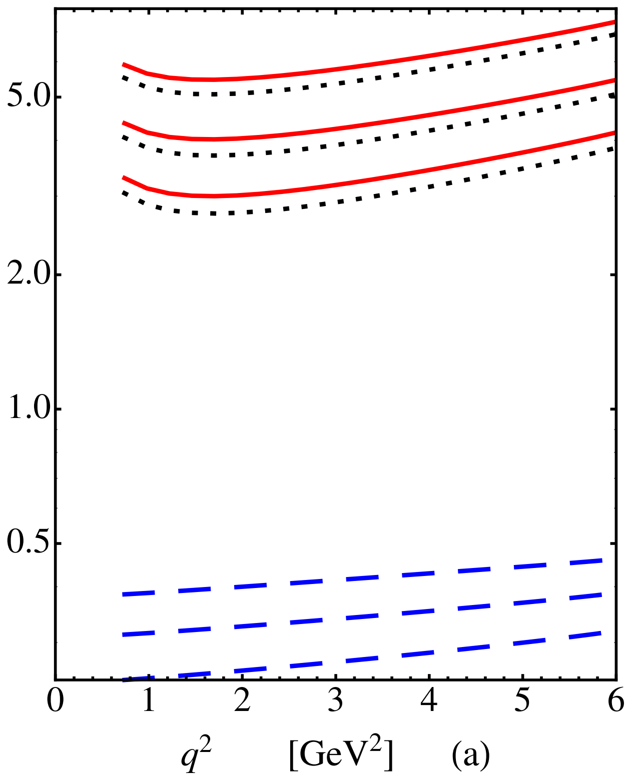


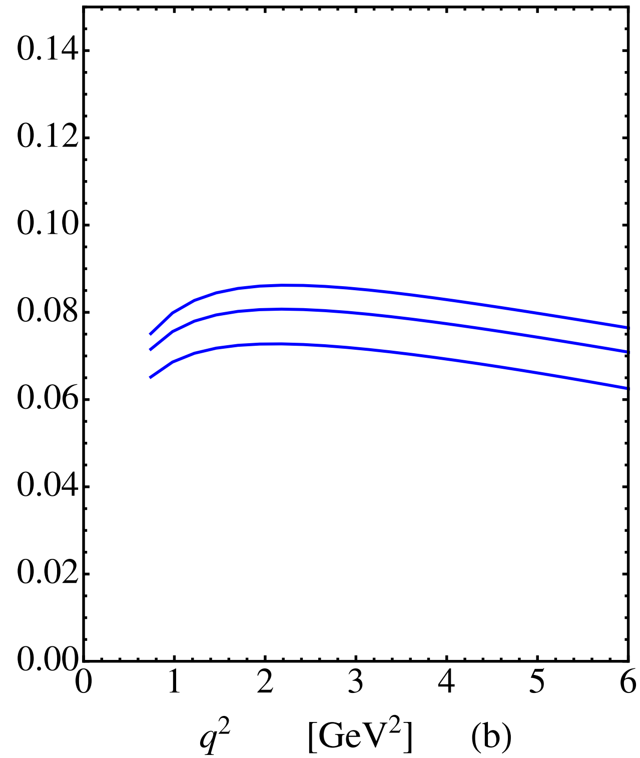
$$\langle 0|\bar{s}d|K\pi\rangle = C_X B_0 F_{K\pi}(m^2_{K\pi})$$

twice-subtracted Omnes solution matched onto χPT

Imaginary part
Real part
Magnitude

S-wave contributions in $B \rightarrow K\pi l^+ l^-$





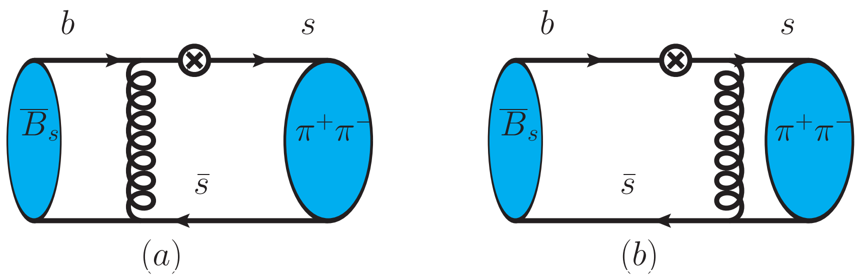
Decay widths:
Red: total
Black: P-wave
Blue:S-wave

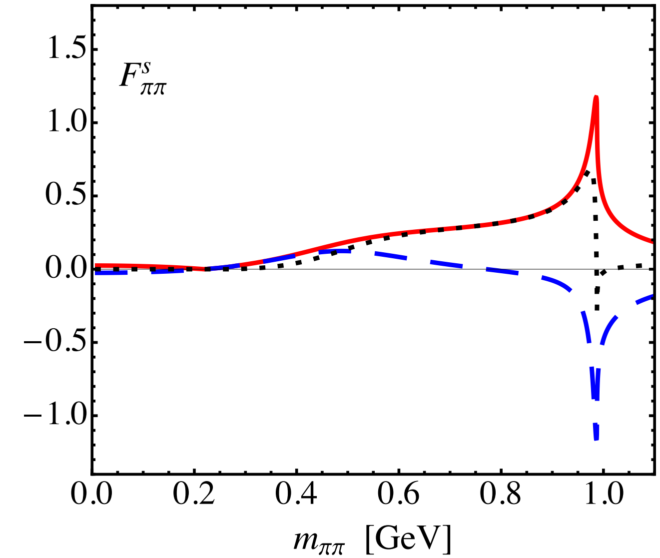
S-wave fraction

LHCb:F_S=0.04±0.04

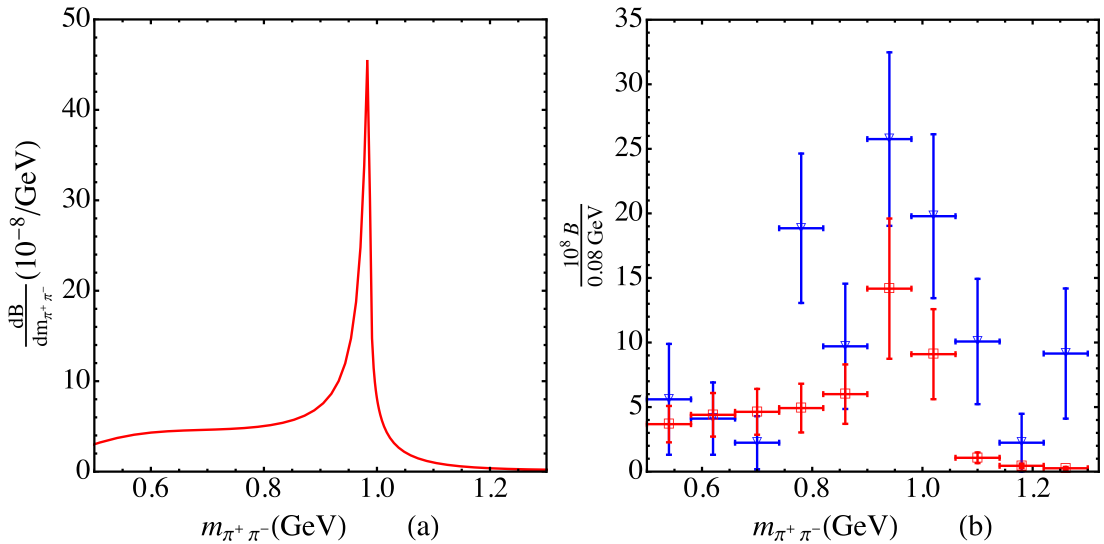
1304.6325

$B_s \to \pi^+\pi^-\mu^+\mu^-$





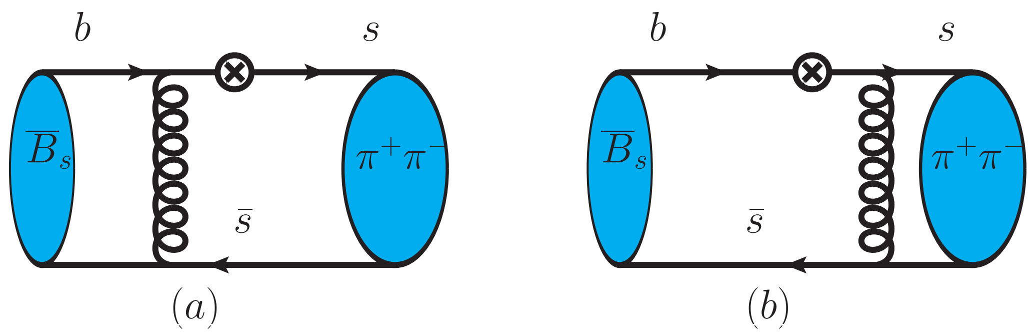
$$\sqrt{2}B_0\, F^s_{\pi\pi}(s) = \langle 0|\bar{s}s|\pi\pi\rangle_{\mathrm{I}=0}$$



LHCb:1412.6433

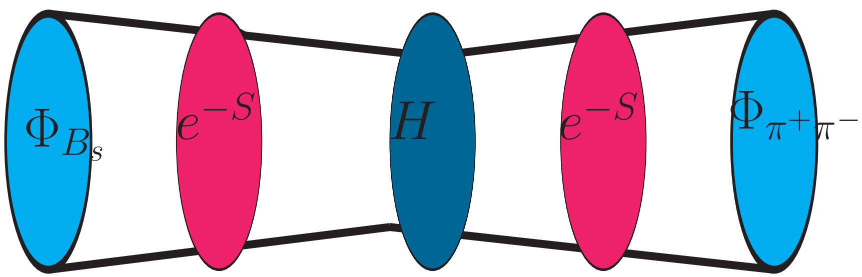
LCSR+χPT： WW,R.Zhu,1502.15104

$B_s \to \pi^+\pi^-\mu^+\mu^-$ in PQCD



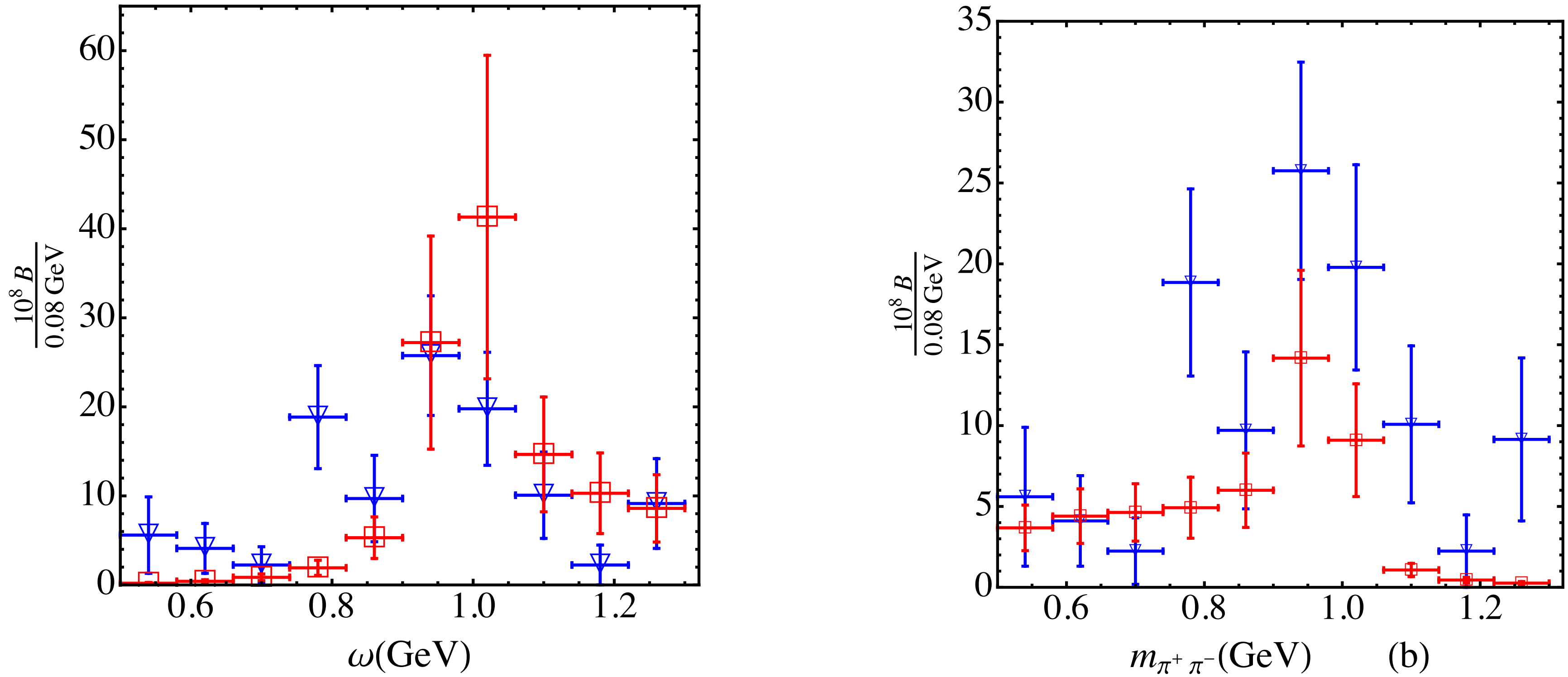
PQCD:

Y.Y.Keum, H.N.Li, A.I.Sanda
hep-ph/0004004
hep-ph/0004173



$$F \sim \int d^4k_1\, d^4k_2\, \mathrm{Tr}\, [\, C(t)\, \Phi_B(k_1)\, \Phi_1(k_2)\, H(k_1,k_2,t)\,]\, \exp\{-S(t)\}$$

$B_s \to \pi^+\pi^-\mu^+\mu^-$ in PQCD



LHCb:1412.6433

LCSR+χPT： WW,R.Zhu,1502.15104

PQCD: Wang, Li, Wang, Lu,1502.15104

Summary

- Heavy Flavor Physics
- $B \to \rho l \nu$ and $B \to K^* l^+ l^-$ are valuable
- S-wave contributions
- In large recoil &small invariant mass region:

  χPT & pQCD

PHYSICAL REVIEW D **71,** 014030 (2005)

Final state interactions in hadronic B decays

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There exist many experimental indications that final-state interactions (FSIs) may play a prominent role not only in charmful B decays but also in charmless B ones. We examine the final-state rescattering effects on the hadronic B decay rates and their impact on direct CP violation. The color-suppressed neutral modes such as $B^0 \to D^0\pi^0$, $\pi^0\pi^0$, $\rho^0\pi^0$, $K^0\pi^0$ can be substantially enhanced by long-distance rescattering effects. The direct CP-violating partial rate asymmetries in charmless B decays to $\pi\pi/\pi K$ and $\rho\pi$ are significantly affected by final-state rescattering, and their signs are generally different from that predicted by the short-distance (SD) approach. For example, direct CP asymmetry in $B^0 \to \rho^0\pi^0$ is increased to around 60% due to final-state rescattering effects whereas the short-distance picture gives about 1%. Evidence of direct CP violation in the decay $\overline{B}^0 \to K^-\pi^+$ is now established, while the combined *BABAR* and Belle measurements of $\overline{B}^0 \to \rho^\pm\pi^\mp$ imply a 3.6σ direct CP asymmetry in the $\rho^+\pi^-$ mode. Our predictions for CP violation agree with experiment in both magnitude and sign, whereas the QCD factorization predictions (especially for $\rho^+\pi^-$) seem to have some difficulty with the data. Direct CP violation in the decay $B^- \to \pi^-\pi^0$ is very small ($\lesssim 1\%$) in the standard model even after the inclusion of FSIs. Its measurement will provide a nice way to search for new physics as in the standard model QCD penguins cannot contribute (except by isospin violation). Current data on πK modes seem to violate the isospin sum-rule relation, suggesting the presence of electroweak penguin contributions. We have also investigated whether a large transverse polarization in $B \to \phi K^*$ can arise from the final-state rescattering of $D^{(*)}\bar{D}_s^{(*)}$ into ϕK^*. While the longitudinal polarization fraction can be reduced significantly from short-distance predictions due to such FSI effects, no sizable perpendicular polarization is found owing mainly to the large cancellations occurring in the processes $\overline{B} \to D_s^*\bar{D} \to \phi\overline{K}^*$ and $\overline{B} \to D_s\bar{D}^* \to \phi\overline{K}^*$, and this can be understood as a consequence of CP and SU(3) [CPS] symmetry. To fully account for the polarization anomaly (especially the perpendicular polarization) observed in $B \to \phi K^*$, FSI from other states or other mechanism, e.g., the penguin-induced annihilation, may have to be invoked. Our conclusion is that the small value of the longitudinal polarization in VV modes cannot be regarded as a clean signal for new physics.

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Final state interaction in $B \to KK$ decays

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We study the final state interaction effects in $B \to KK$ decays. We find that the t channel one-particle-exchange diagrams cannot enhance the branching ratios of $\overline{B}^0 \to K^0\overline{K}^0$ and $B^- \to K^0K^-$ very sizably. For the pure annihilation process $\overline{B}^0 \to K^+K^-$, the obtained branching ratio by the final state interaction is at $\mathcal{O}(10^{-8})$.

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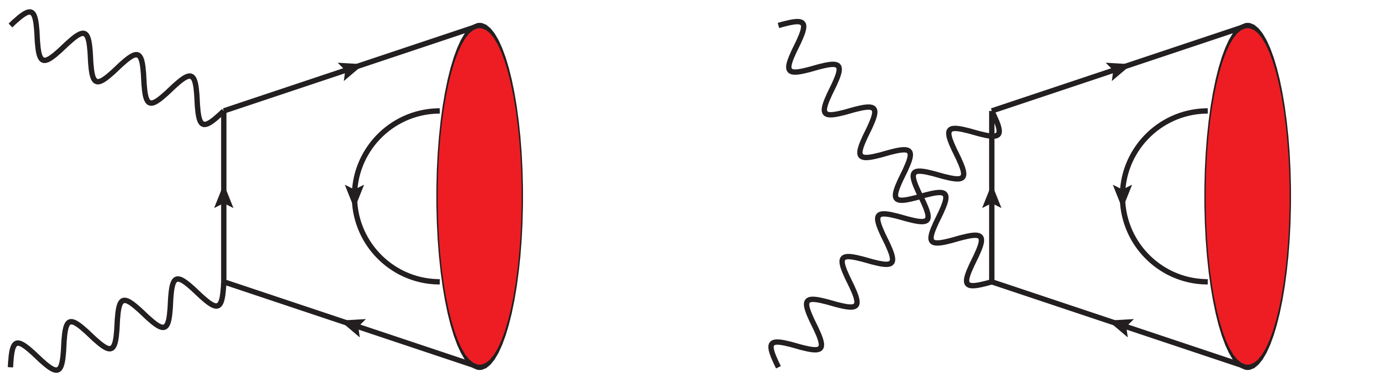
Thank you for your attention!

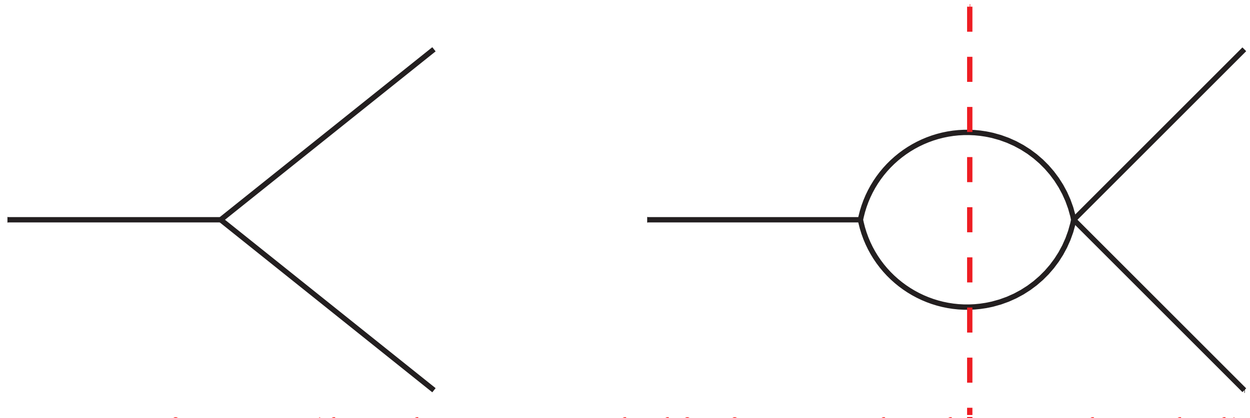
γγ*→ππ



$$T^{\mu\nu} = i \int d^4x\, e^{-iq\cdot x} \langle \pi(p)\pi(p')|\, T J^{\mu}_{\rm em}(x) J^{\nu}_{\rm em}(0)\, |0\rangle = -g_T^{\mu\nu} \sum_q \frac{e_q^2}{2} \int_0^1 dz\, \frac{2z-1}{z(1-z)}\, \Phi_q^{\pi\pi}(z,\zeta,W^2),$$

S-wave can be projected out!

Watson's theorem (1954)



In elastic region (below additional threshold):

$\mathrm{Im}[F] = F\,\sigma\,T^*$

Form factor and scattering amplitude carry the same phase!