Curious Link of Exclusive & Inclusive CPV in Charmless 3-body B^+ Decays

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National Taiwan University

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I. The Striking Plot, and a Curiosity — LHCb 1408.5373 (PRD)

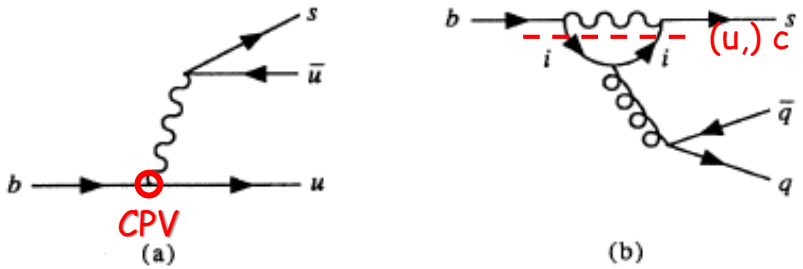
II. FSI: elastic vs inelastic

III. FSI: soft vs hard
- CPT and inelastic hadron scattering
- a Critique

IV. Unitarity/CPT at Quark Level: a 30-yr "Sum Rule" — Gérard and WSH, PRL'89 PRD'91

V. Conclusion

I. The Striking Plot, and a Curiosity



Bander, Silverman, Soni, PRL'79

LHCb 1408.5373 (PRD)

PHYSICAL REVIEW D 90, 112004 (2014)

Measurements of *CP* violation in the three-body phase space of charmless $B^\pm$ decays

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

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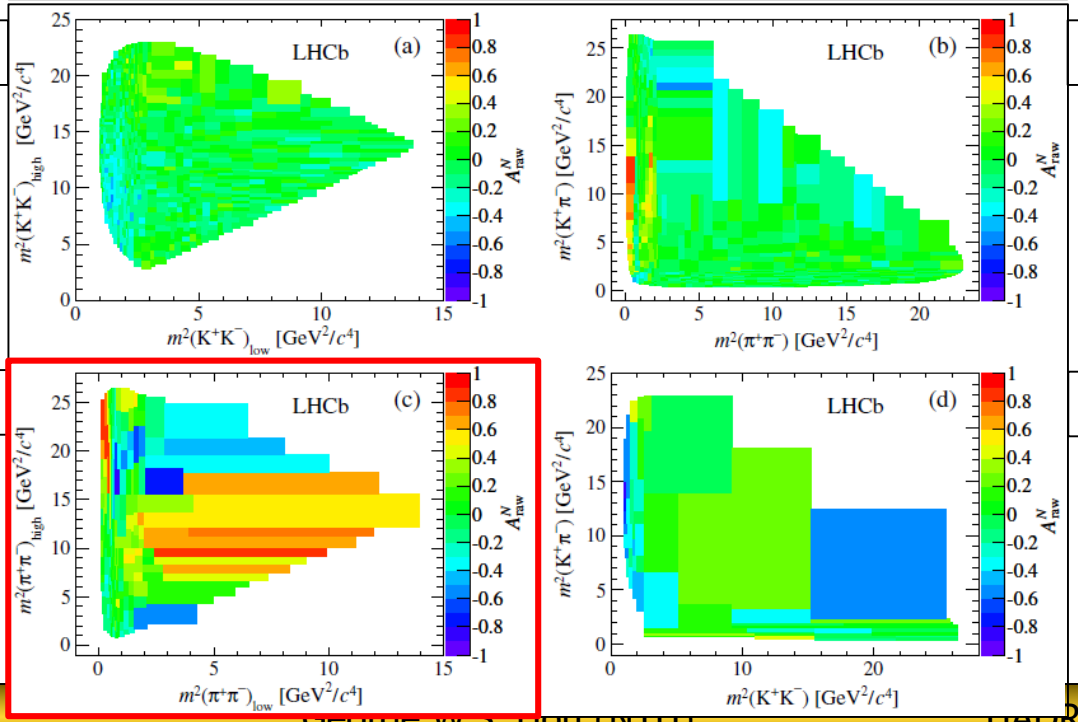
The charmless three-body decay modes $B^\pm \to K^\pm\pi^+\pi^-$, $B^\pm \to K^\pm K^+K^-$, $B^\pm \to \pi^\pm K^+K^-$ and $B^\pm \to \pi^\pm\pi^+\pi^-$ are reconstructed using data, corresponding to an integrated luminosity of 3.0 fb^{-1}, collected by the LHCb detector. The inclusive *CP* asymmetries of these modes are measured to be

$$A_{CP}(B^\pm \to K^\pm\pi^+\pi^-) = +0.025 \pm 0.004 \pm 0.004 \pm 0.007,$$
$$A_{CP}(B^\pm \to K^\pm K^+K^-) = -0.036 \pm 0.004 \pm 0.002 \pm 0.007,$$
$$A_{CP}(B^\pm \to \pi^\pm\pi^+\pi^-) = +0.058 \pm 0.008 \pm 0.009 \pm 0.007,$$
$$A_{CP}(B^\pm \to \pi^\pm K^+K^-) = -0.123 \pm 0.017 \pm 0.012 \pm 0.007,$$

where the first uncertainty is statistical, the second systematic, and the third is due to the *CP* asymmetry of the $B^\pm \to J/\psi K^\pm$ reference mode. The distributions of these asymmetries are also studied as functions of position in the Dalitz plot and suggest contributions from rescattering and resonance interference

KKK

Kππ



πππ

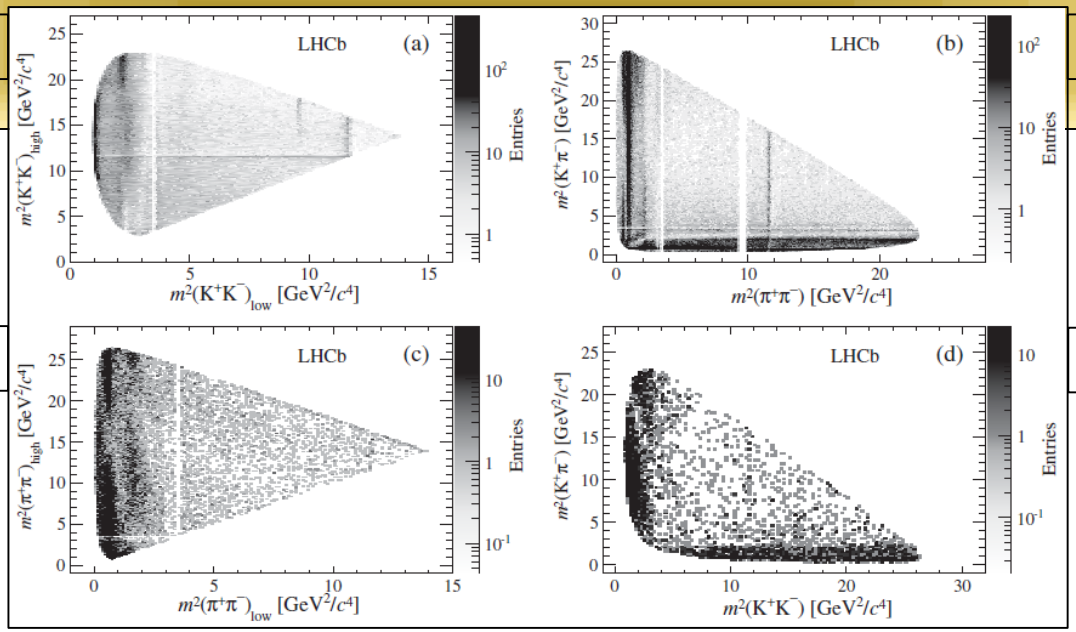
πKK

- strikingly large CPV
- strong variations in DP

KKK 181k

Kππ 109k

LHCb 1408.5373 (PRD)

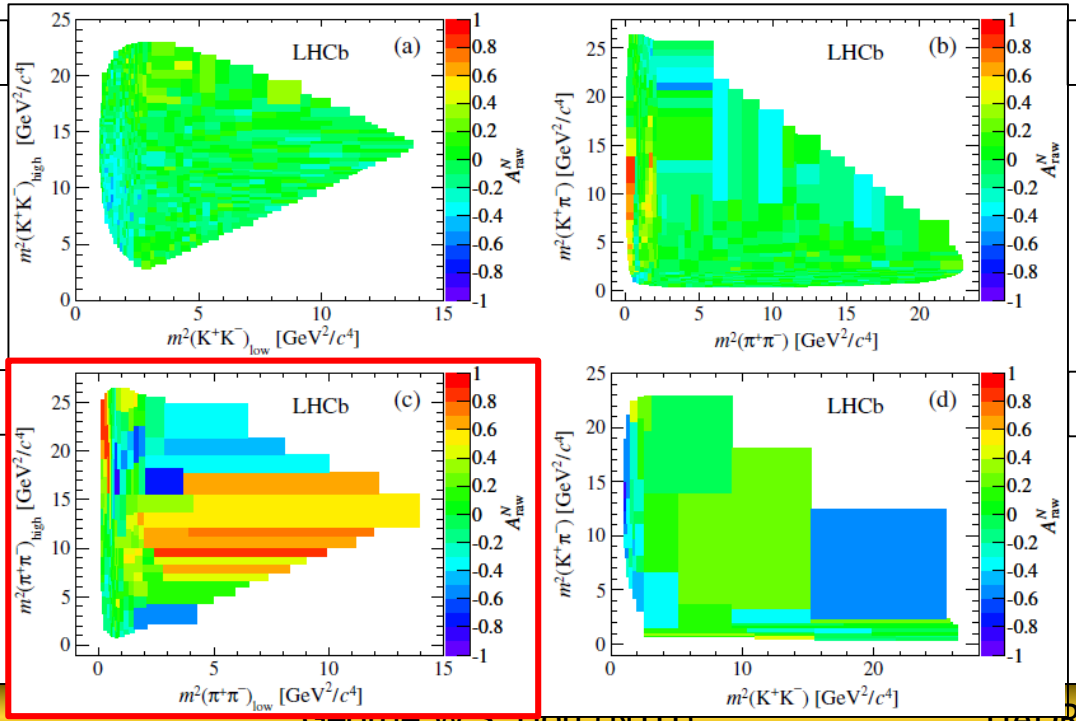


πππ 25k

πKK 6k

KKK

Kππ



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bins w/ same # evts

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BR (10^{-5})		
5.1	$A_{CP}(B^\pm \to K^\pm\pi^+\pi^-) = +0.025 \pm 0.004 \pm 0.004 \pm 0.007,$	$+\ 2.7 \pm 0.8\%$ (PDG)
3.4	$A_{CP}(B^\pm \to K^\pm K^+K^-) = -0.036 \pm 0.004 \pm 0.002 \pm 0.007,$	$-\ 3.3 \pm 0.8\%$
1.5	$A_{CP}(B^\pm \to \pi^\pm\pi^+\pi^-) = +0.058 \pm 0.008 \pm 0.009 \pm 0.007,$	$+\ 5.7 \pm 1.3\%$
0.5	$A_{CP}(B^\pm \to \pi^\pm K^+K^-) = -0.123 \pm 0.017 \pm 0.012 \pm 0.007,$	$-12.2 \pm 2.1\%$

where the first uncertainty is statistical, the second systematic, and the third is due to the *CP* asymmetry of the $B^\pm \to J/\psi K^\pm$ reference mode. The distributions of these asymmetries are also studied as functions of position in the Dalitz plot and suggest contributions from rescattering and resonance interference

a Curiosity

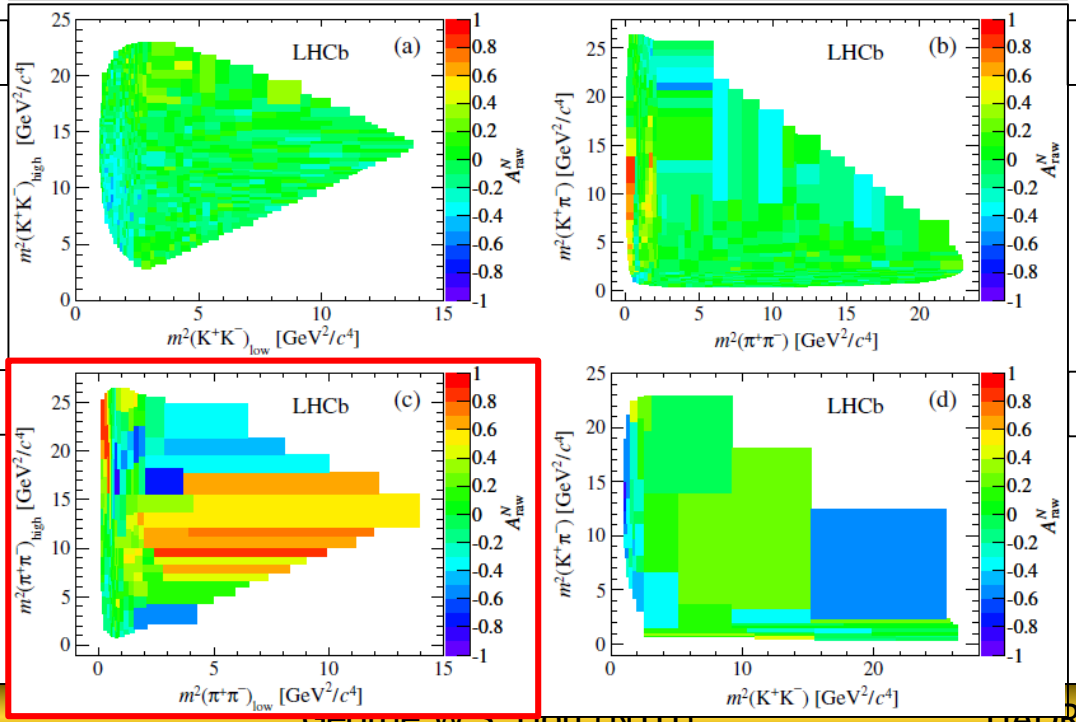
0.3% (b → s)

1.1% (b → d)

sub-percent

KKK

Kππ



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109k	3.4	$A_{CP}(B^\pm \to K^\pm K^+K^-) = -0.036 \pm 0.004 \pm 0.002 \pm 0.007$,	$-3.3 \pm 0.8\%$
25k	1.5	$A_{CP}(B^\pm \to \pi^\pm\pi^+\pi^-) = +0.058 \pm 0.008 \pm 0.009 \pm 0.007$,	$+5.7 \pm 1.3\%$
6k	0.5	$A_{CP}(B^\pm \to \pi^\pm K^+K^-) = -0.123 \pm 0.017 \pm 0.012 \pm 0.007$,	$-12.2 \pm 2.1\%$

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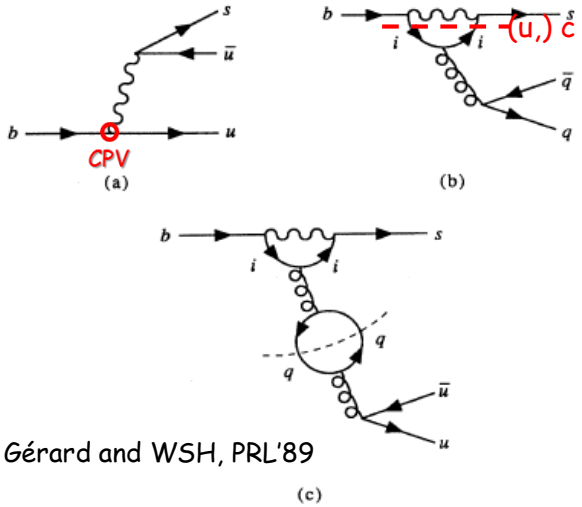


Gérard and WSH, PRL'89

TABLE I. (Semi-)inclusive branching ratio B and asymmetries for $b \to s$ and $b \to d$ processes for $\rho = -0.5$, $\eta = 0.15$, and $m_t = M_W$. a_0 is with Figs. 1(a) and 1(b) only, while a is the result with Fig. 1(c) taken into account. The entry "0.0" stands for a very small positive number.

	B (%)	a_0 (%)	a (%)
$b \to su\bar{u}$	0.46	1.2	0.0
$b \to sd\bar{d} + ss\bar{s}$	0.54	0.5	0.5
Total $b \to s$ (no charm)	1.19	0.7	0.2
$b \to du\bar{u}$	0.71	−0.7	−0.0
$b \to dd\bar{d} + ds\bar{s}$	0.07	−4.2	−4.2
Total $b \to d$ (no charm)	0.80	−1.0	−0.4

~ 0.12, 0.35

Gérard and WSH, PRD'91

II. FSI: elastic vs inelastic

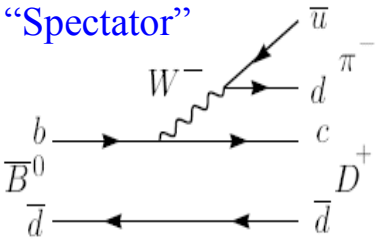
Experiment-driven take on Final State Interactions

Observation of the Color-Suppressed Decay $\overline{B}^0 \to D^0\pi^0$

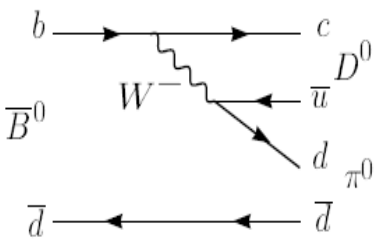
Belle, PRL'02

Mode	Signal Yield	Σ	$B\overline{B}$ bg	$D^{*0}h^0$	$q\overline{q}$ bg	$\epsilon(\%)$	$\mathcal{B}$ $(\times 10^{-4})$	UL $(\times 10^{-4})$	Th $(\times 10^{-4})$
$D^0\pi^0$	$126.2\ ^{+16.1\ +7.2}_{-15.5\ -5.2}$	9.3	26.7	1.3	145.6	1.79	$3.1 \pm 0.4 \pm 0.5$	–	0.7
$D^{*0}\pi^0$	$26.4\ ^{+7.7\ +1.6}_{-7.1\ -2.2}$	4.1	5.9	–	10.4	0.42	$2.7\ ^{+0.8\ +0.5}_{-0.7\ -0.6}$	–	1.0
$D^0\eta^*$	$22.1\ ^{+7.0\ +2.0}_{-6.3\ -1.8}$	4.2	3.4	0.7	19.1	0.67	$1.4\ ^{+0.5}_{-0.4} \pm 0.3$	–	0.5
$D^{*0}\eta$	$7.8\ ^{+3.6}_{-3.0} \pm 0.7$	3.3	1.4	–	1.5	0.17	$2.0\ ^{+0.9}_{-0.8} \pm 0.4$	4.6	0.6
$D^0\omega$	$32.5\ ^{+9.4\ +4.0}_{-8.6\ -3.1}$	4.4	$5.3(2.3)^\dagger$	1.4	58.5	0.80	$1.8 \pm 0.5\ ^{+0.4}_{-0.3}$	–	0.7
$D^{*0}\omega$	$16.1\ ^{+6.8}_{-6.0} \pm 2.4$	3.0	$5.3(1.5)^\dagger$	–	13.8	0.23	$3.1\ ^{+1.3}_{-1.1} \pm 0.8$	7.9	1.7

"Spectator"



Color-suppressed



PHYSICAL REVIEW D, VOLUME 65, 096007

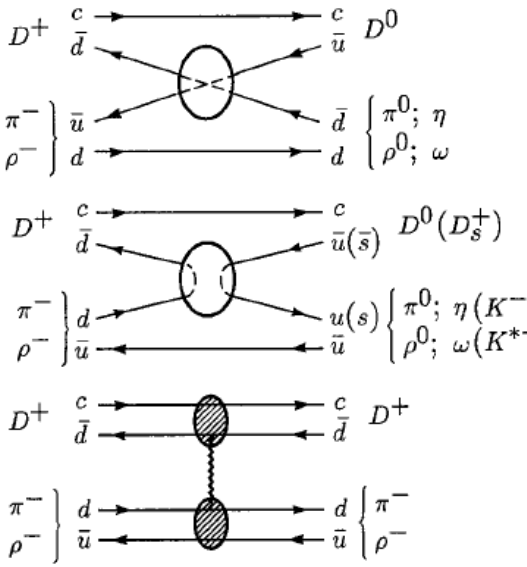
Final state rescattering and color-suppressed $\bar{B}^0 \to D^{(*)0}h^0$ decays

Chun-Khiang Chua* and Wei-Shu Hou
Physics Department, National Taiwan University, Taipei, Taiwan 10764, Republic of China

Kwei-Chou Yang
Physics Department, Chung Yuan Christian University, Chung-Li, Taiwan 32023, Republic of China

(Received 11 December 2001; published 7 May 2002)

The color-suppressed $\bar{B}^0 \to D^{(*)0}\pi^0$, $D^{(*)0}\eta$, $D^0\omega$ decay modes have just been observed for the first time. The rates are all larger than expected, hinting at the presence of final state interactions. Considering the $\bar{B}^0 \to D^{(*)0}\pi^0$ mode alone, an elastic $D^{(*)}\pi \to D^{(*)}\pi$ rescattering phase difference $\delta \equiv \delta_{1/2} - \delta_{3/2} \sim 30°$ would suffice, but the $\bar{B}^0 \to D^{(*)0}\eta$, $D^0\omega$ modes compel one to extend the elastic formalism to SU(3) symmetry. We



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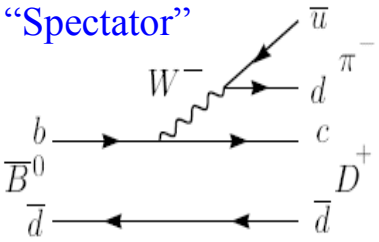

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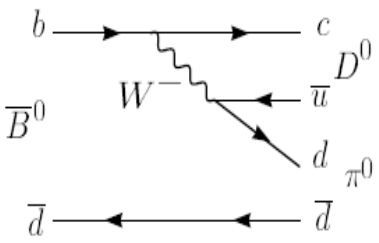
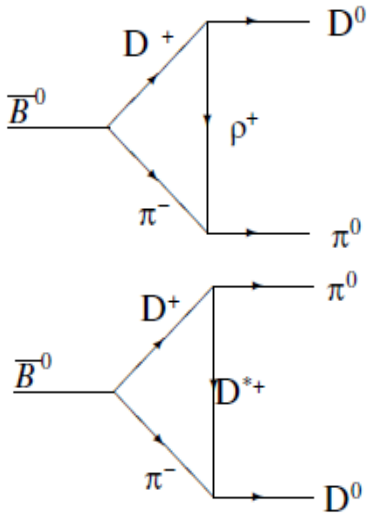


PHYSICAL REVIEW D 71, 014030 (2005)

Final state interactions in hadronic *B* decays

Hai-Yang Cheng,[1] Chun-Khiang Chua,[1] and Amarjit Soni[2]
[1]*Institute of Physics, Academia Sinica, Taipei, Taiwan 115, Republic of China*
[2]*Physics Department, Brookhaven National Laboratory, Upton, New York 11973, USA*
(Received 5 October 2004; published 26 January 2005)

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



- Meson loops: how does it work when far off-shell?
- Went on to Inelastic, for sake of "charmless" (e.g. Kπ)
  → diagramatics is cherry-picking and arbitrary.

I'm not at all adverse to Final State Interactions

CLEO Era

- "Prospects for direct CP violation in exclusive and inclusive charmless B decays"
  He, WSH, Yang, PRL'98
- "Electroweak Penguins, FSI Phases, and CP Violation in B → Kπ Decays"
  Deshpande, He, WSH, Pakvasa, PRL'99
- "Possibility of Large Final State Interaction Phases in Light of B → Kπ, ππ Decays"
  WSH, Yang, PRL'00

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- "Indication for Large Rescatterings in Charmless Rare B Decays"
  Chua, WSH, Yang, MPLA'03

➔ 2004: DCPV in B Observed!

Belle*
BaBar

III. FSI: soft vs hard

- CPT and inelastic hadron scattering
- Some Critique

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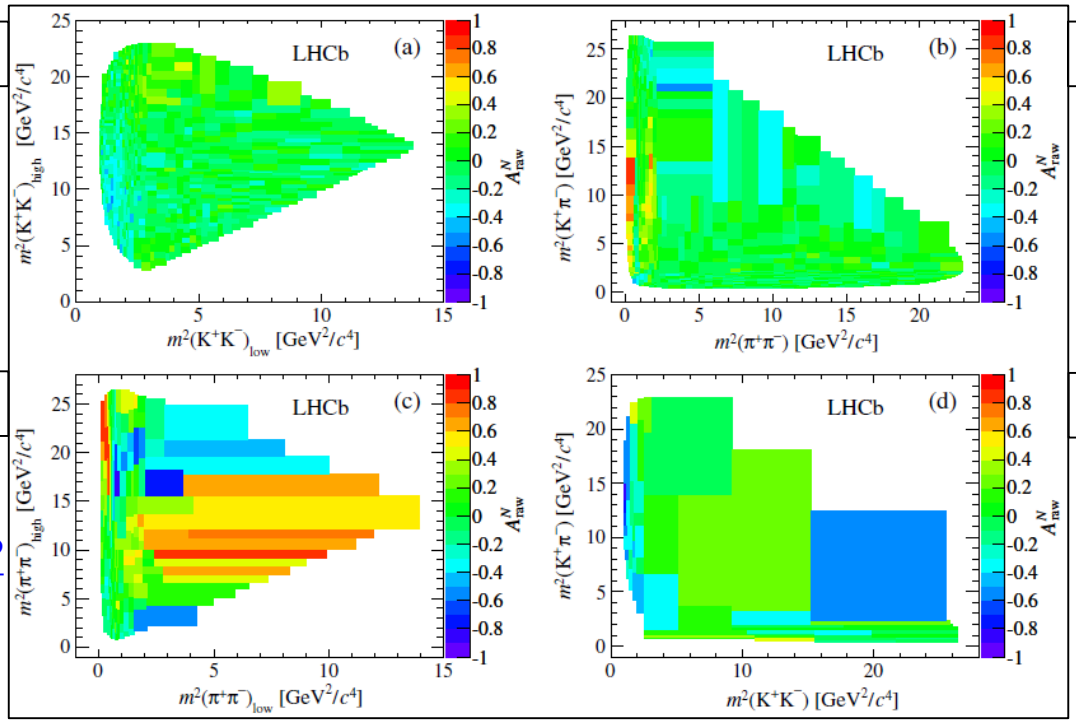
Kππ



πππ

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- strikingly large CPV
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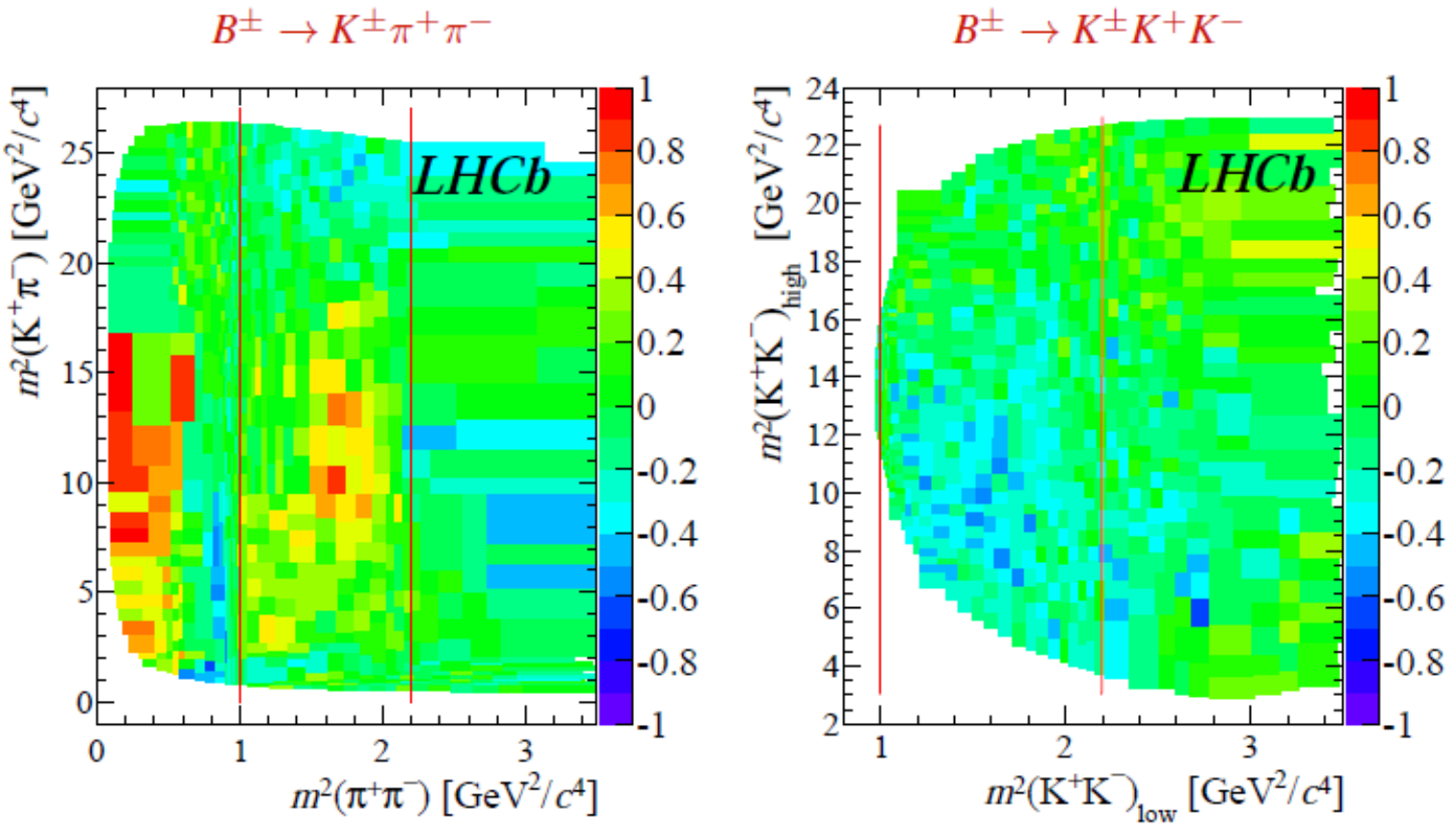
(1, 2.2) GeV^2

"All the inelasticity of the $\pi\pi$ interaction goes into the KK channel"?

Not Quite.

$B^\pm \to K^\pm h^+ h^-$ charge asymmetries: a zoom at low $\pi^+\pi^-/K^+K^-$ mass



$\pi^+\pi^- \leftrightarrows K^+K^-$ rescattering? *CPT* symmetry imposes a constraint on particle/antiparticle partial widths: $\sum \Gamma_i(B \to f_i) = \sum \Gamma_i(\bar{B} \to \bar{f}_i)$.

Strong phase difference would come from $\pi\pi \leftrightarrows KK$ rescattering.

Alberto dos Reis @ Hadron 2015

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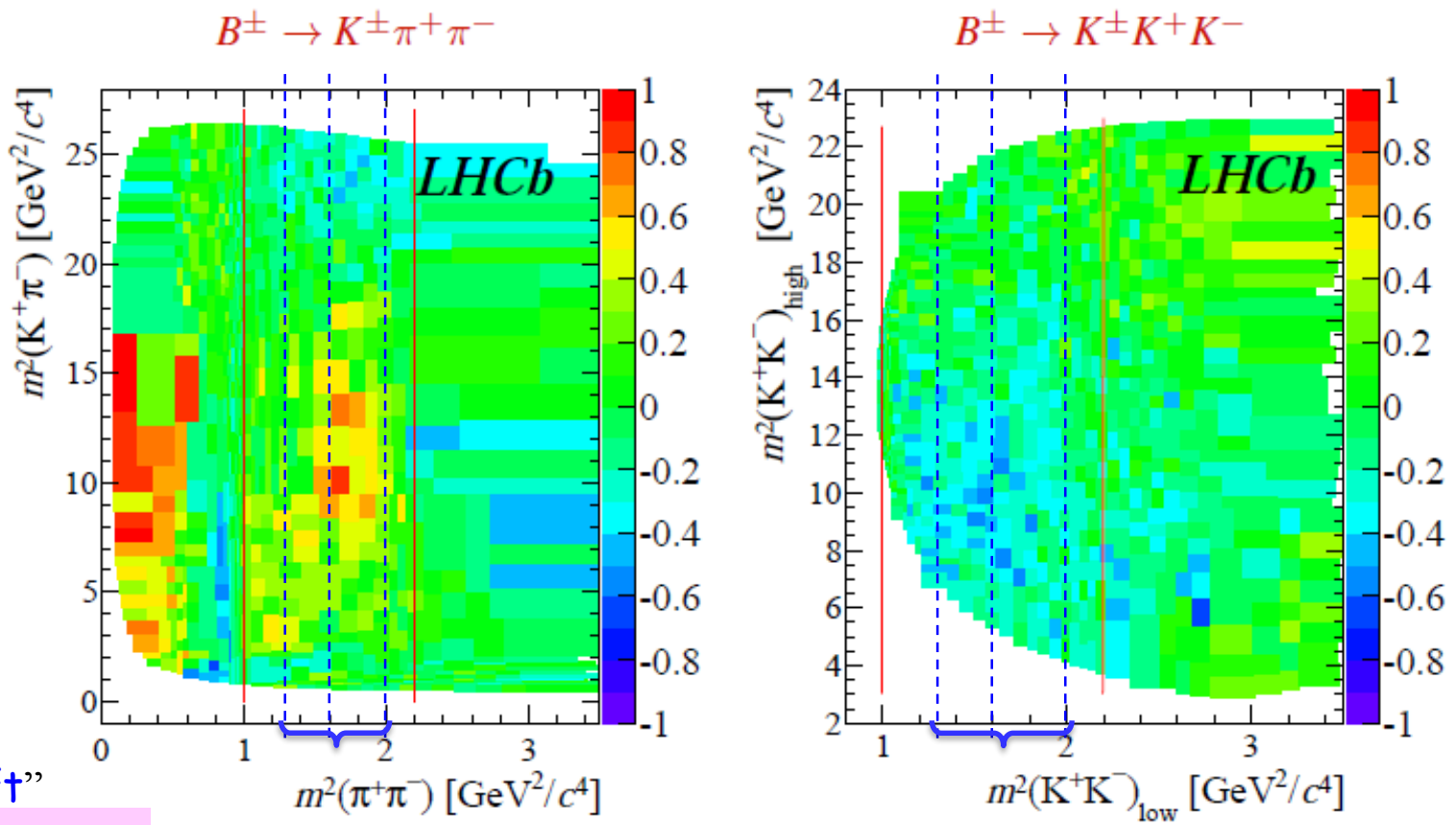

"soft"

KKnπ thresholds
n = 0, 1, 2, 3

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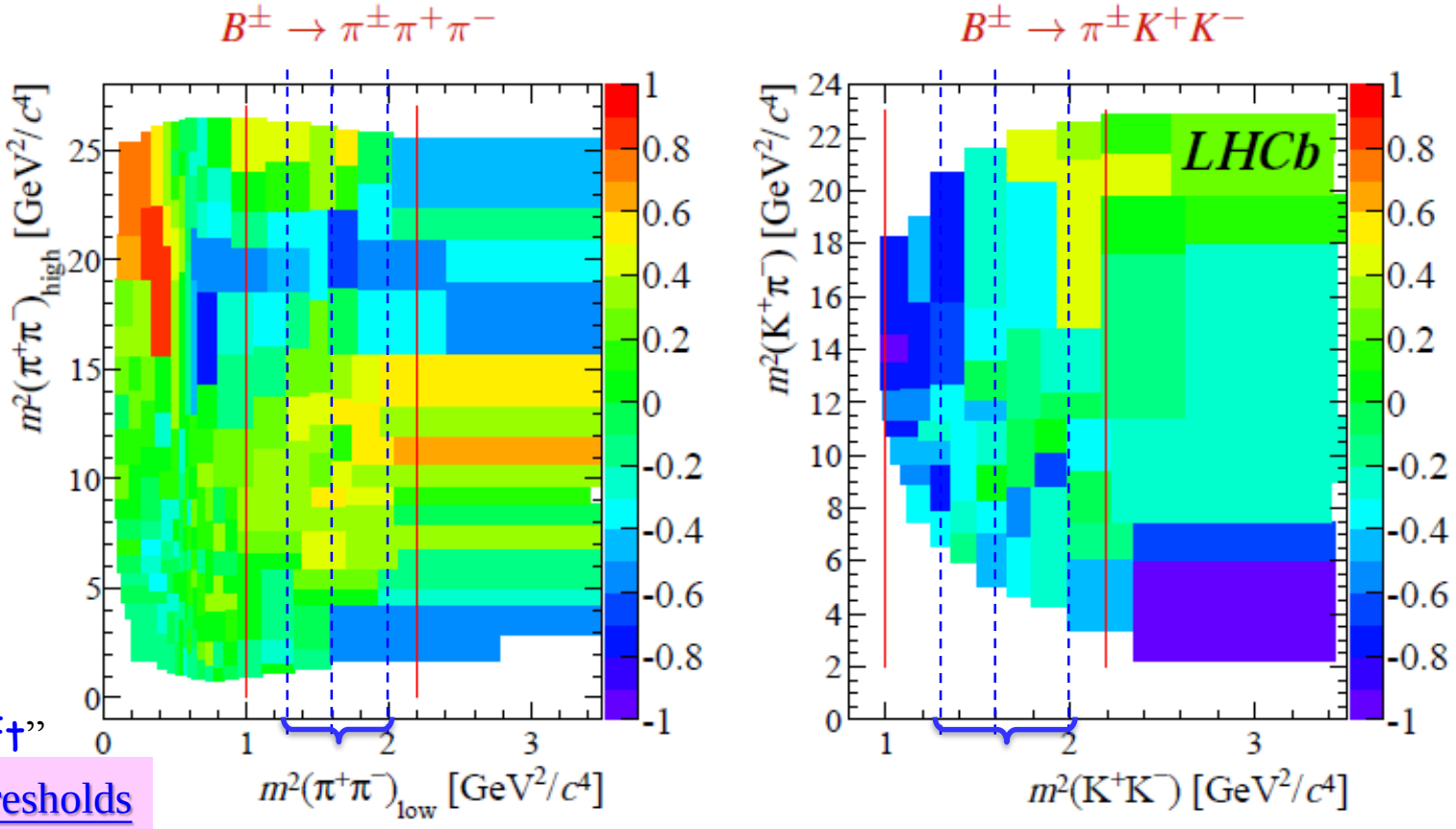

"soft"

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Similar effect in $B^\pm \to \pi^\pm h^+ h^-$ (more evident in $B^\pm \to \pi^\pm K^+ K^-$).

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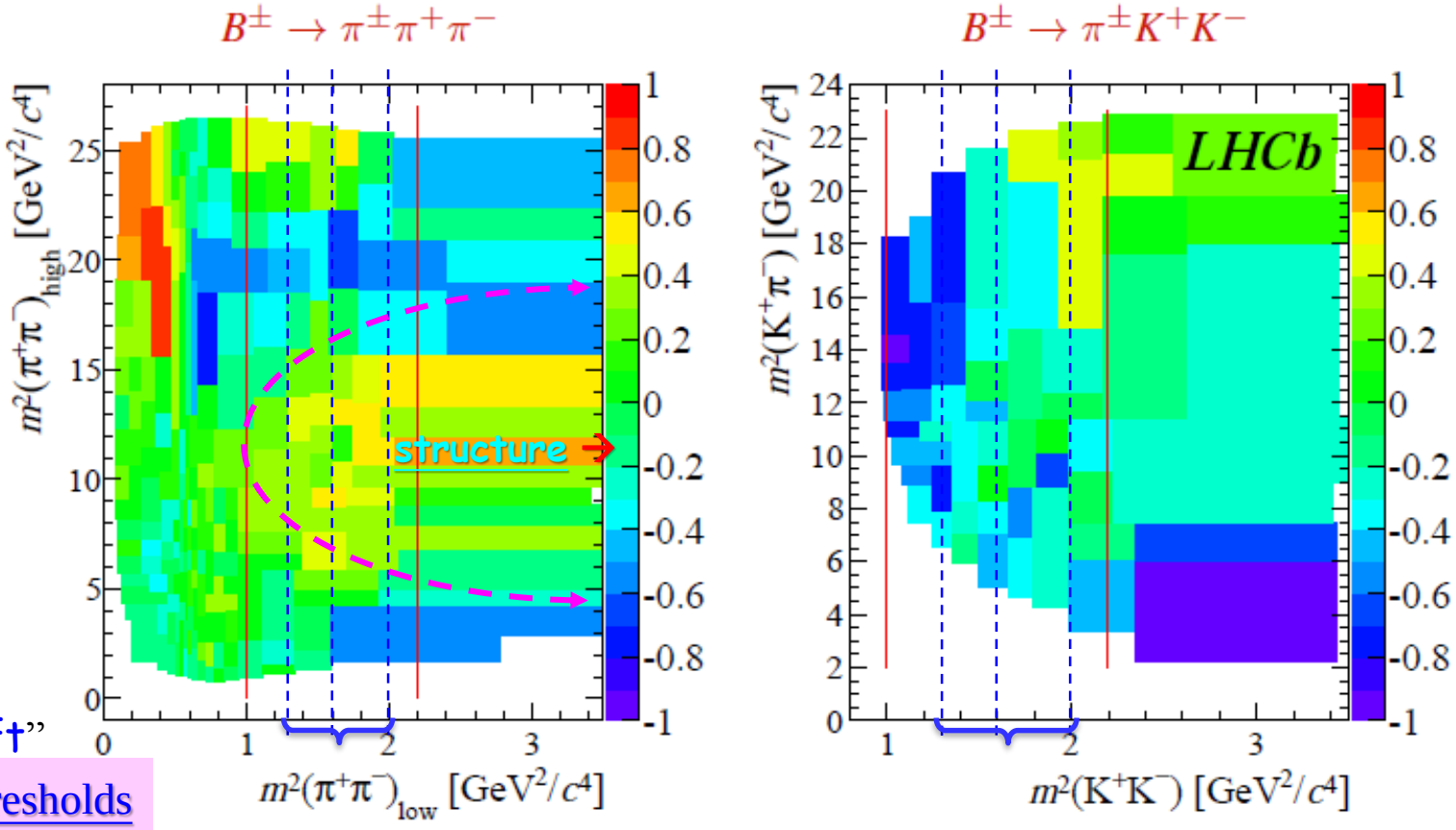

structure →

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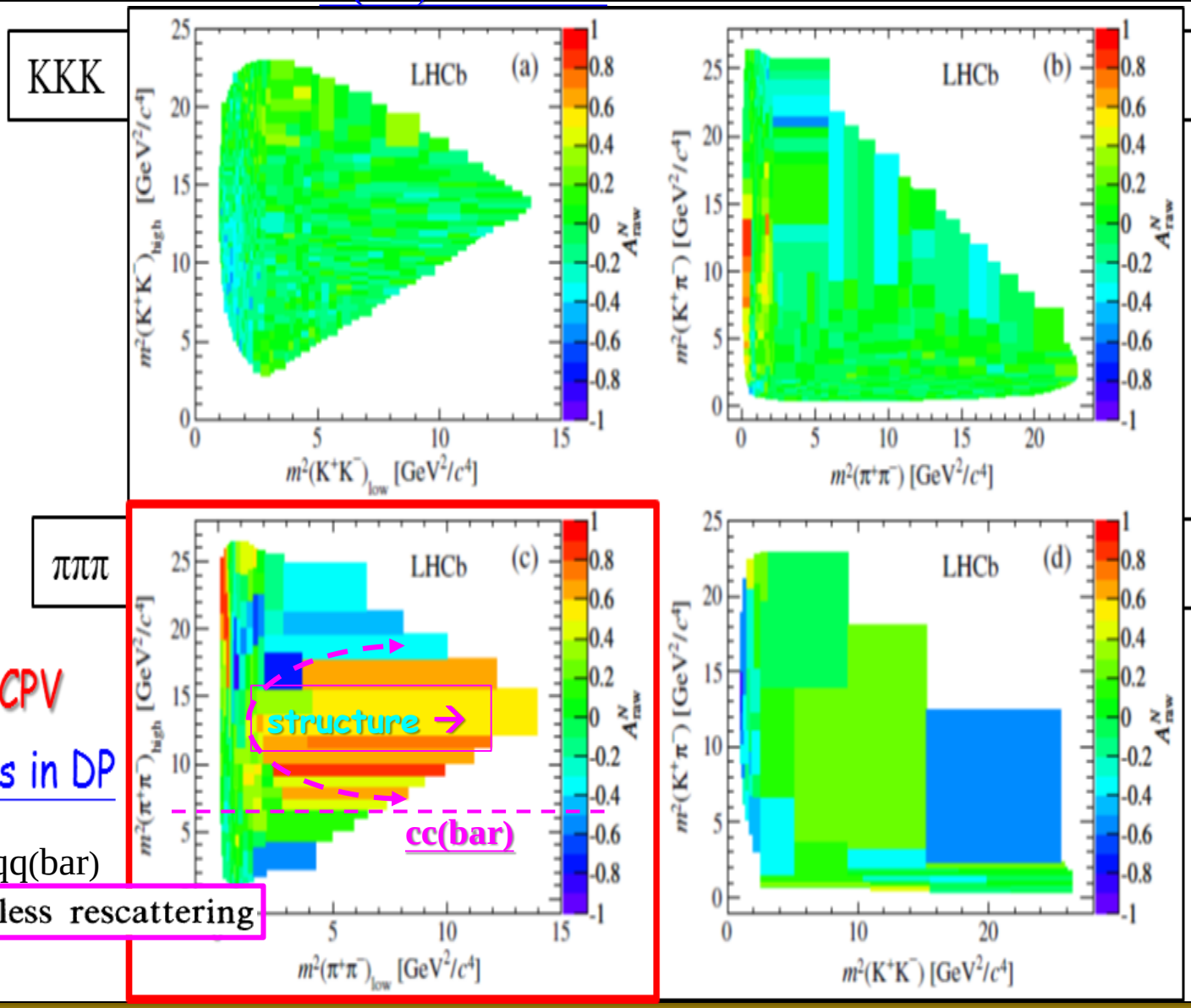
"soft": $K+n\pi \to K+n\pi$ rescattering

hard : $(D\bar{D}+X) \to$ charmless rescattering

cc(bar) = annihilate

LHCb 1408.5373 (PRD)



- strikingly large CPV
- strong variations in DP

hard: cc(bar) to qq(bar)

$(D\bar{D}+X) \to$ charmless rescattering

IV. Unitarity/CPT at Quark Level

a 30-yr "Sum Rule"

Gérard and WSH, PRL'89
PRD'91

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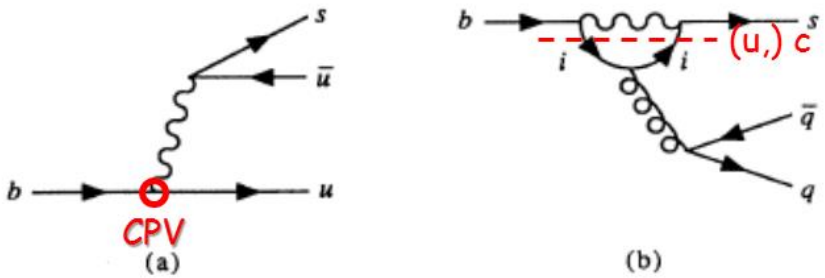
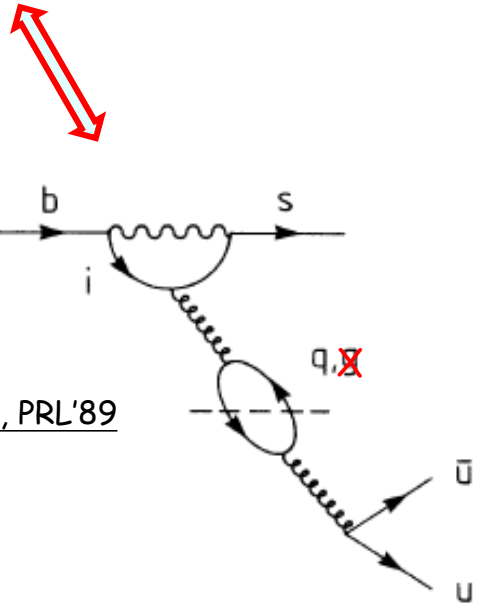
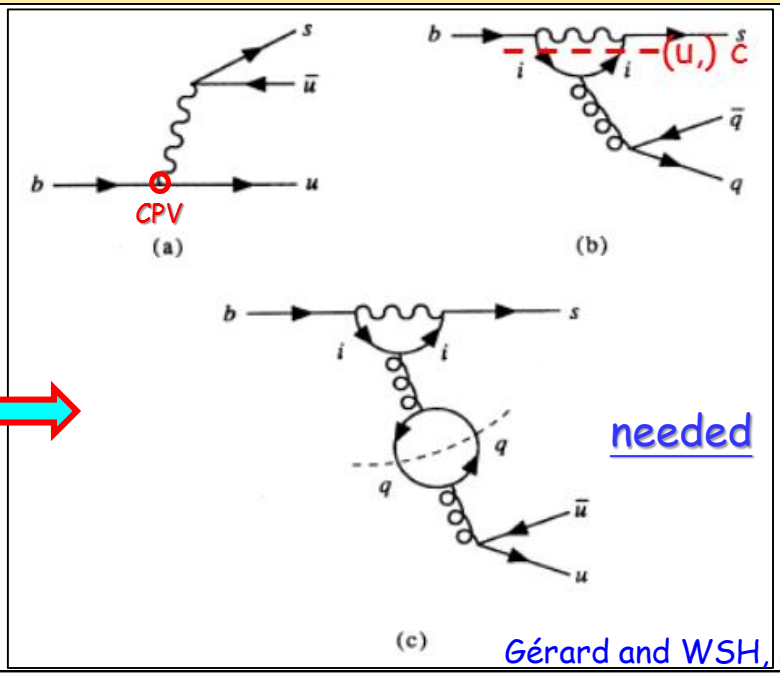
Bander, Silverman, Soni, PRL'79





Gérard and WSH, PRL'89



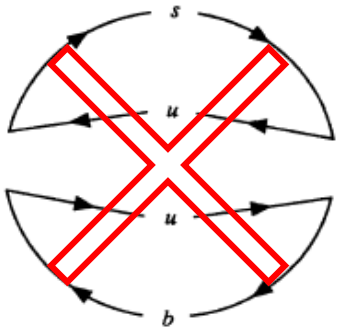
Gérard and WSH, PRD'91

TABLE I. (Semi-)inclusive branching ratio B and asymmetries for $b \to s$ and $b \to d$ processes for $\rho = -0.5$, $\eta = 0.15$, and $m_t = M_W$. a_0 is with Figs. 1(a) and 1(b) only, while a is the result with Fig. 1(c) taken into account. The entry "0.0" stands for a very small positive number. ~0.12, 0.35

	B (%)	a_0 (%)	a (%)
$b \to su\bar{u}$	0.46	1.2	0.0
$b \to sd\bar{d} + ss\bar{s}$	0.54	0.5	0.5
Total $b \to s$ (no charm)	1.19	0.7	0.2
$b \to du\bar{u}$	0.71	−0.7	−0.0
$b \to dd\bar{d} + ds\bar{s}$	0.07	−4.2	−4.2
Total $b \to d$ (no charm)	0.80	−1.0	−0.4

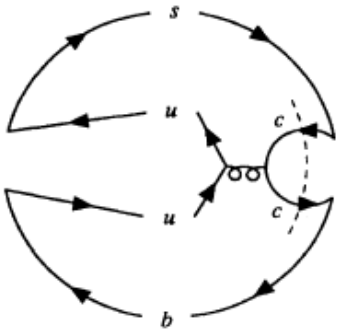
Unitarity/CPT at Quark Level

inclusive b → s/d CPV should vanish for 2mc > mb

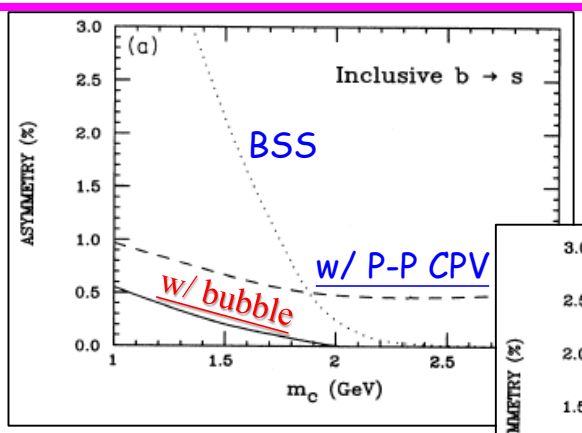


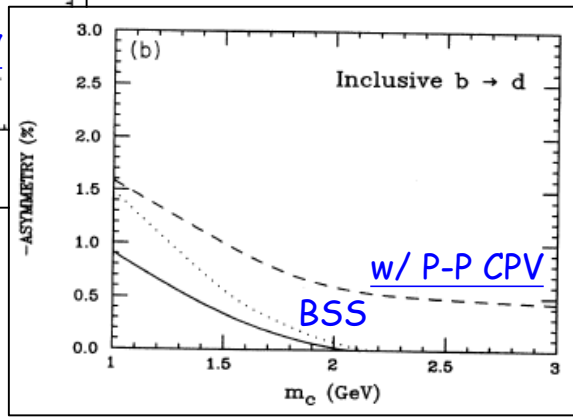
(a)

BSS



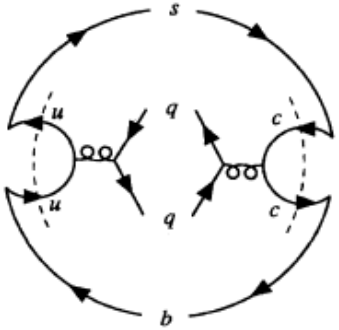
(b)



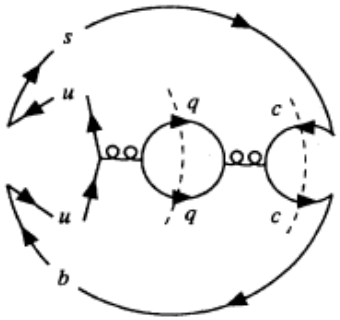


Gérard and WSH, PRD'91

Purposed Pure-P DCPV ⇒ CPT/Unitarity



(c)



(d)

FIG. 3. Amplitude squared term-by-term analysis for BSS mechanism: (a) tree-tree interference ($b \to su\bar{u}$); (b) tree-penguin interference ($b \to su\bar{u}$); (c) penguin-penguin interference ($b \to sq\bar{q}$); and (d) tree–double-penguin interference.

TABLE I. (Semi-)inclusive branching ratio B and asymmetries for $b \to s$ and $b \to d$ processes for $\rho = -0.5$, $\eta = 0.15$, and $m_t = M_W$. a_0 is with Figs. 1(a) and 1(b) only, while a is the result with Fig. 1(c) taken into account. The entry "0.0" stands for a very small positive number. ~0.12, 0.35

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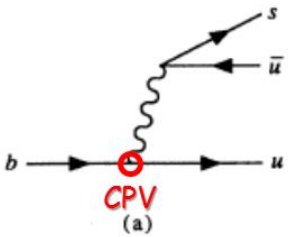
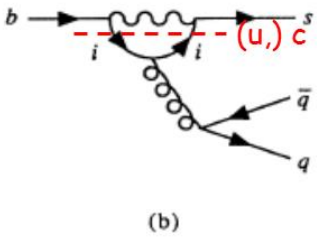
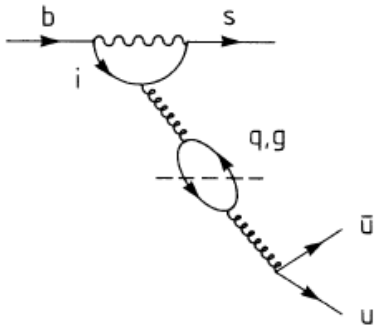
a 30-yr "Sum Rule"

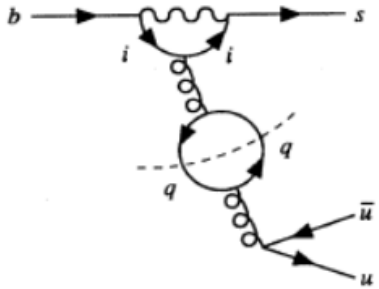
inclusive b → s/d CPV sub-%: $2m_c$ threshold-suppress





[b → sgg absent]





Gérard and WSH, PRL'89

Gérard and WSH, PRD'91

TABLE I. Inclusive branching ratios (BR) and asymmetries for $b \to s$ and $b \to d$ processes for $\rho = -0.6$, $\eta = 0.25$, and $m_t = 60$ GeV. a_0 is with Fig. 1 only, while a is the result with Fig. 2 taken into account.

	BR (%)	a_0 (%)	a (%)
$b \to su\bar{u}$	0.53	1.8	−1.7
$b \to sd\bar{d} + ss\bar{s} + sgg$	1.44	0.8	0.8
Total $b \to s$ (no charm)	2.12	1.0	0.1
$b \to du\bar{u}$	1.23	−0.8	0.7
$b \to dd\bar{d} + ds\bar{s} + dgg$	0.19	−6.0	−6.0
Total $b \to d$ (no charm)	1.45	−1.5	−0.2

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	B (%)	a_0 (%)	a (%)
$b \to su\bar{u}$	0.46	1.2	0.0
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Total $b \to s$ (no charm)	1.19	0.7	0.2
$b \to du\bar{u}$	0.71	−0.7	−0.0
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Total $b \to d$ (no charm)	0.80	−1.0	−0.4

Pure Penguin DCPV picked up by LHCb measurement

LHCb 1408.5373 (PRD)

PHYSICAL REVIEW D 90, 112004 (2014)

Measurements of *CP* violation in the three-body phase space of charmless $B^\pm$ decays

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

(Received 25 August 2014; published 11 December 2014)

The charmless three-body decay modes $B^\pm \to K^\pm\pi^+\pi^-$, $B^\pm \to K^\pm K^+K^-$, $B^\pm \to \pi^\pm K^+K^-$ and $B^\pm \to \pi^\pm\pi^+\pi^-$ are reconstructed using data, corresponding to an integrated luminosity of 3.0 fb^{-1}, collected by the LHCb detector. The inclusive *CP* asymmetries of these modes are measured to be

$$A_{CP}(B^\pm \to K^\pm\pi^+\pi^-) = +0.025 \pm 0.004 \pm 0.004 \pm 0.007, \quad +2.7 \pm 0.8\%$$
$$A_{CP}(B^\pm \to K^\pm K^+K^-) = -0.036 \pm 0.004 \pm 0.002 \pm 0.007, \quad -3.3 \pm 0.8\%$$
$$A_{CP}(B^\pm \to \pi^\pm\pi^+\pi^-) = +0.058 \pm 0.008 \pm 0.009 \pm 0.007, \quad +5.7 \pm 1.3\%$$
$$A_{CP}(B^\pm \to \pi^\pm K^+K^-) = -0.123 \pm 0.017 \pm 0.012 \pm 0.007, \quad -12.2 \pm 2.1\%$$

(PDG)

where the first uncertainty is statistical, the second systematic, and the third is due to the *CP* asymmetry of the $B^\pm \to J/\psi K^\pm$ reference mode. The distributions of these asymmetries are also studied as functions of position in the Dalitz plot and suggest contributions from rescattering and resonance interference

s ud(bar) u(bar)d
s us(bar) u(bar)s

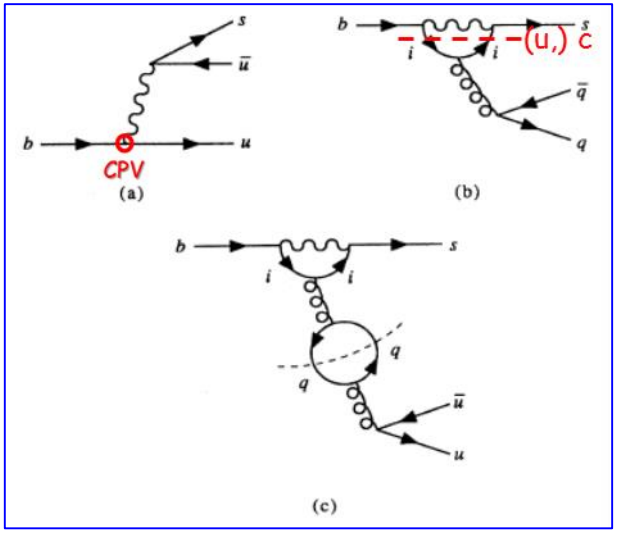
d ud(bar) u(bar)d
d us(bar) u(bar)s

a Curiosity

0.3% (b → s)

1.1% (b → d)

sub-percent



Gérard and WSH, PRD'91

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Total $b \to d$ (no charm)	0.80	−1.0	−0.4

~ 0.12, 0.35

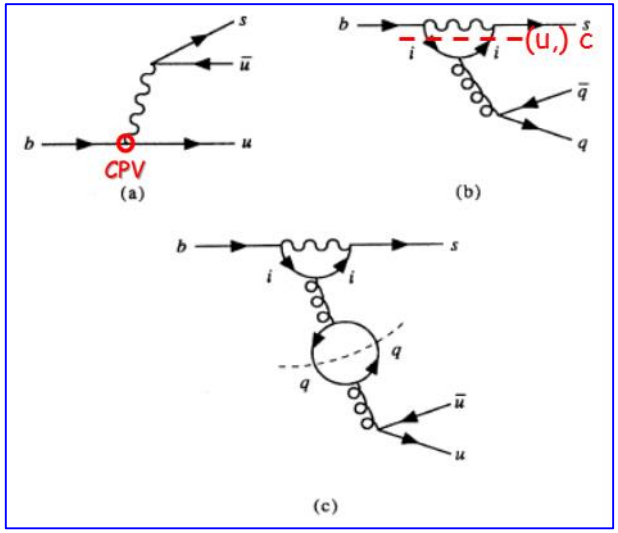
Improving the Inclusive DCPV Theory

- Interested theorists can try (a bit muddied/complicated).

Greub and Linniger, PLB'00, PRD'01 WSH, NPB'88

- Need to consider b → sg, known to be ~ 0.5% (b → sqq(bar) ~ 1%).
  - But "on-shell" gluon does not give much absorptive parts, how to incorporate?
  - In what part of "$h'^+h^-h^+$" Dalitz Plot does b → sg interfere with b → sqq(bar)?

- Near cancellation guaranteed by the strength of absorptive part of Penguin. Interesting to see experimental development and further affirmation.



Gérard and WSH, PRD'91

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~ 0.12, 0.35

V. Conclusion

- From "CP violation in inclusive and exclusive charmless B decays"

sistently, we found the surprising result that $O(\alpha_s^2)$ contributions are as important as $O(\alpha_s)$ effects for individual semi-inclusive modes such as $b \to su\bar{u}$. These unexpected results were uncovered because we chose to study the rates and asymmetries of semi-inclusive charmless B decays, and we therefore had to pay better attention to general conditions such as unitarity and CPT.

The upshot of our results is that the *total* inclusive charmless $b \to s$ and $b \to d$ decay asymmetries are rather suppressed. Nature seems to prefer hiding away the effects of CP violation, by one form of cancellation or another. In our case it is indeed a subtle one. The situa-

Gérard and WSH, PRD'91

- LHCb'14 Observation of $B^+ \to h'^+h^-h^+$ 3-body DCPV
  - Large CPV, strongly varying across Darlitz Plot
  - Inclusive CPV for $B^+ \to K^+h^-h^+$ and $B^+ \to \pi^+h^-h^+$ @ sub%

➔ LHCb has affirmed 30-yr DCPV "Sum Rule" and affirmed quark-hadron duality in charmless 3-body B^+ decay CPV