



CP violation in $B \rightarrow hhh$ @ LHCb

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on behalf of the LHCb Collaboration

5th International Workshop on the CKM Unitary Triangle
September 9-13 2008
Roma, Italy

outline

- ▶ motivation
- ▶ LHCb
 - ▶ trigger
 - ▶ selection strategy
 - ▶ yields, S/B
- ▶ CKM γ measurements
- ▶ CPV: Dalitz anisotropy

motivation

- ▶ **hhh** corresponds to the following decays
BR - $O(10^{-5} - 10^{-6})$
 - $B_{+-} \rightarrow \pi^{+-} \pi^{+-} \pi^{+-}$
 - $B_{+-} \rightarrow K^{+-} \pi^{+-} \pi^{+-}$
 - $B_{+-} \rightarrow K^{+-} K^{+-} \pi^{+-}$
 - $B_{+-} \rightarrow K^{+-} K^{+-} K^{+-}$
 - $B_{+-} \rightarrow \rho^{+-} \rho^{+-} \pi^{+-}$
 - $B_{+-} \rightarrow \rho^{+-} \rho^{+-} K^{+-}$

- ▶ contain **CKM V_{ub}** transitions
 - ▶ presence of CP Violation (**CPV**)
 - ▶ possibility of γ measurement
- ▶ **rare decays** $B^+ \rightarrow K^- \pi^+ \pi^+$, $B^+ \rightarrow K^+ K^+ \pi^-$
 - ▶ could be enhanced by new physics
- ▶ **3 body** amplitude analysis: measure resonant states magnitudes and **phases**
 - ▶ access to additional CPV information

LHCb

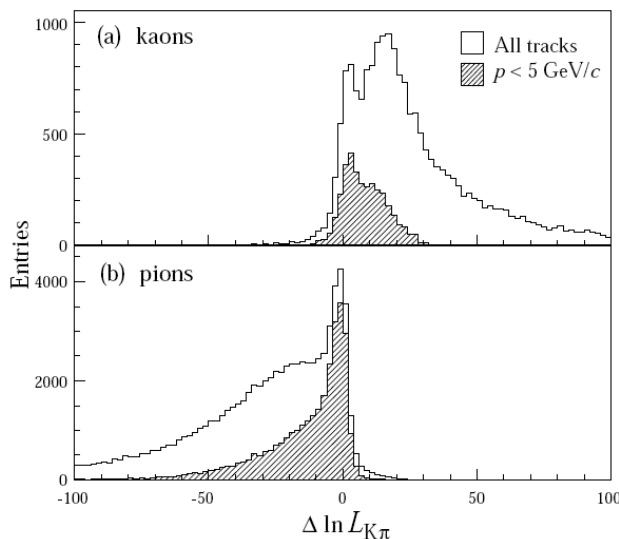
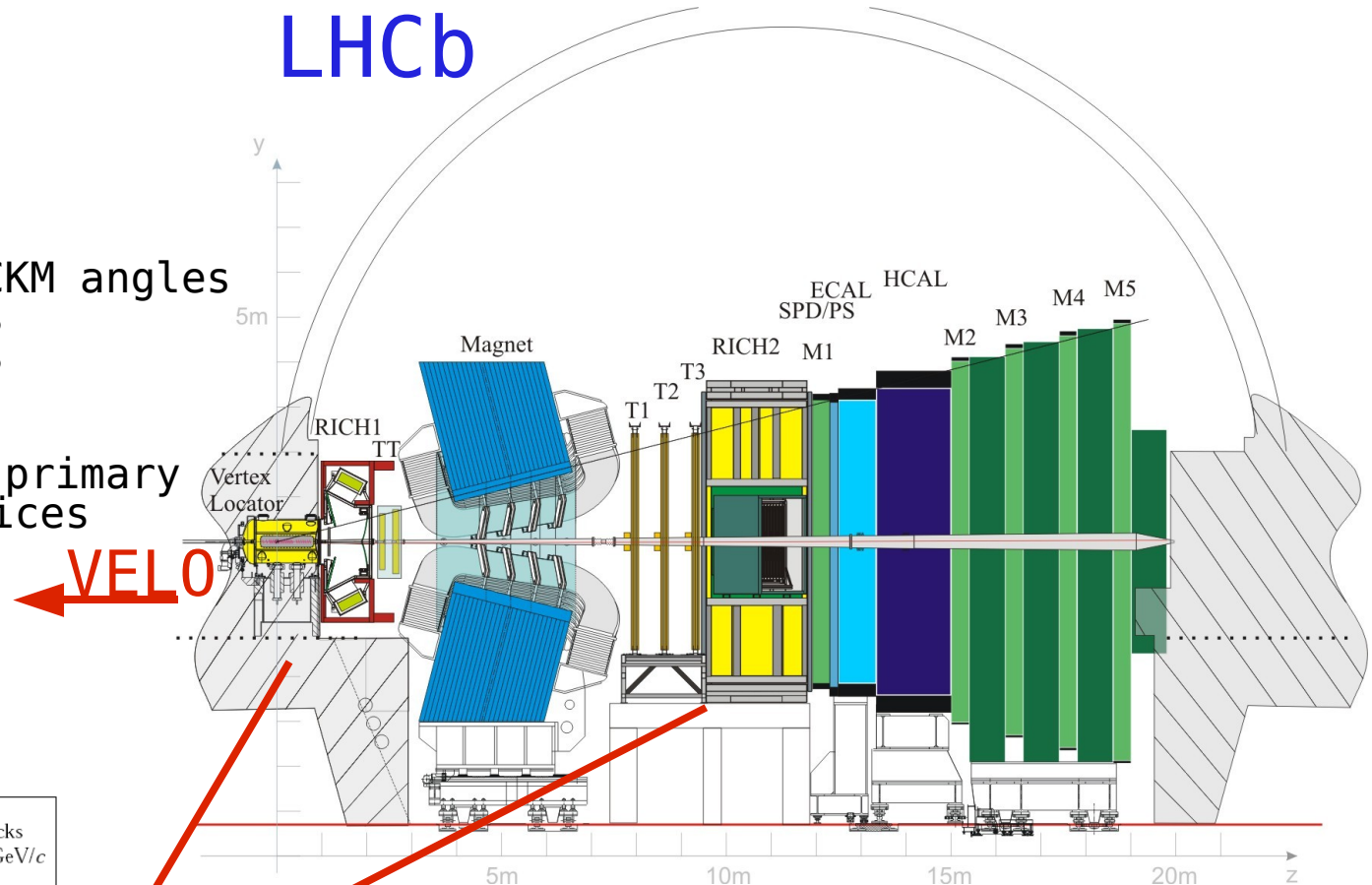
1 nominal year = 2fb^{-1}
 $\sim 10^{12}$ bb pairs produced

goals

- ▶ precise measure of CKM angles
- ▶ Bs mixing parameters
- ▶ NP in loop processes

characteristics

- ▶ good resolution for primary and secondary vertices
- ▶ PV res $\sim 50 \mu\text{m}$
- ▶ SV res $\sim 200 \mu\text{m}$ in beam direction



RICH: K, π identification

- ▶ good separation between pion and kaon
- ▶ B mass resolution $\sim 15 \text{ MeV}$ (2 body decays)
- ▶ trigger dedicated to select b events

trigger

$b\bar{b}$ production @ 14 TeV

- ▶ intense boost in beam direction, average B momentum $p \sim 80$ GeV
- ▶ signature: high transverse momentum (p_t) tracks

L0 (hardware trigger) : 40 MHz \rightarrow 1 MHz

- ▶ searches for high E_t (p_t) calo clusters (muon segments)

HLT1 (software trigger) : 1 MHz \rightarrow 30 kHz

- ▶ confirm seeds by finding matching long tracks

HLT2 (software trigger) : 30 kHz \rightarrow 2 kHz

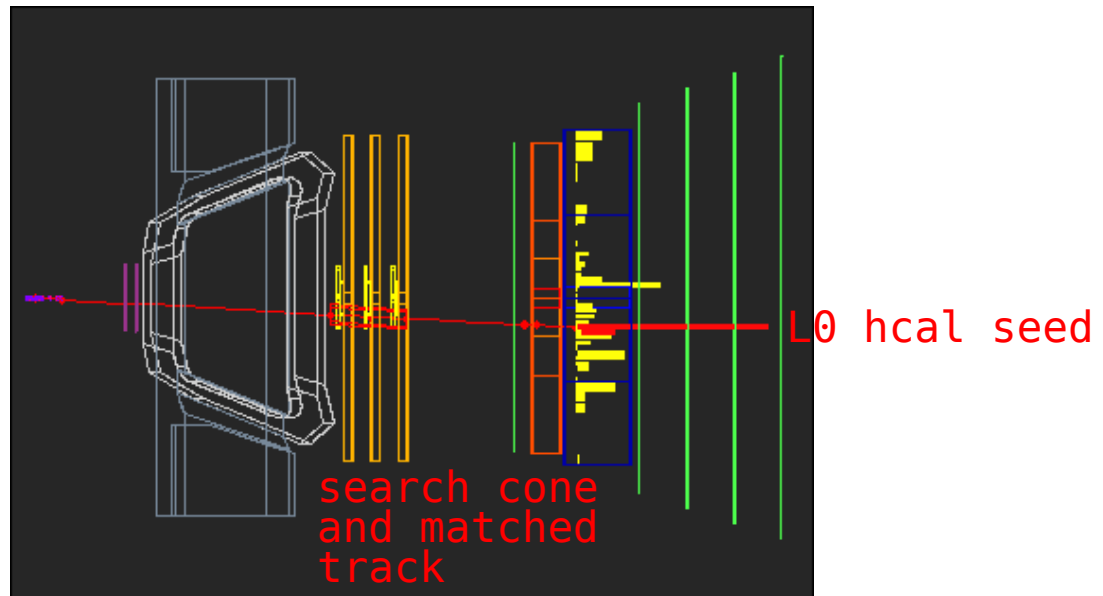
- ▶ at lower rate, tries to make specific B candidates with broad cuts

hhh efficiencies

L0 \sim 45%

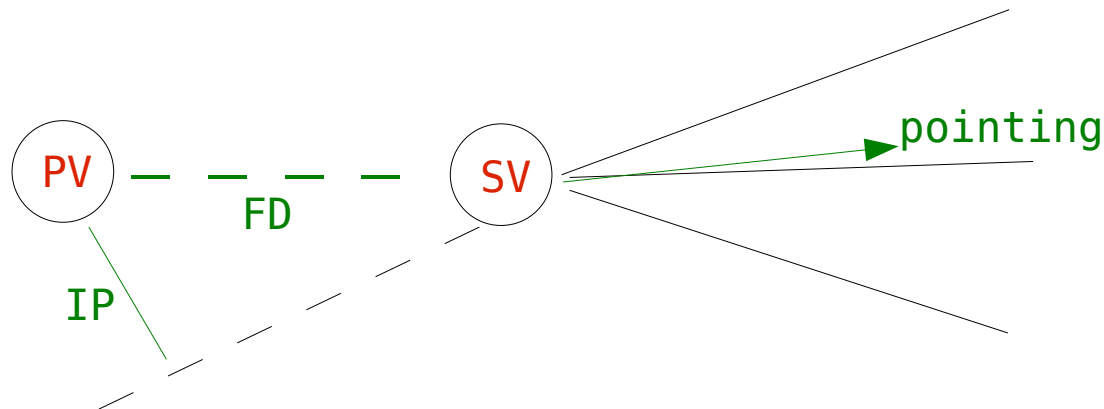
HLT1 \sim 80%

HLT2 $>$ 90%



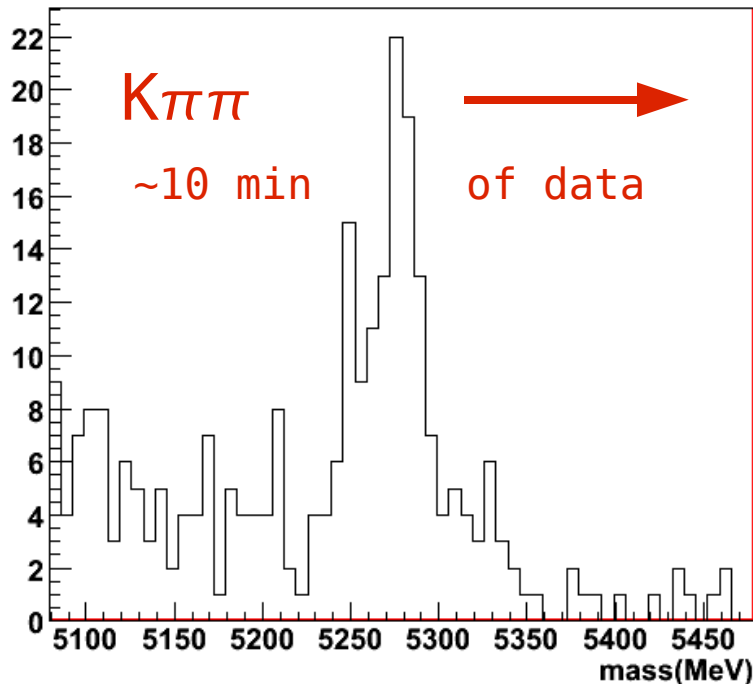
hhh selection strategy

- ▶ primary vertex (PV) charged track multiplicity ~ 70
 - ▶ 1st task : minimize combinatorics background
- ▶ identification cuts to id kaons, pions and protons
 - ▶ RICH detector
- ▶ looks for 3 charged particles with high p_t
- ▶ use IP to select tracks not originated from PV
- ▶ fit a good χ^2 vertex (SV)
- ▶ which has some flight distance (FD) from PV
 - ▶ good resolution provided by VELO
- ▶ sum of 3 daughter momentum must be colinear to FD - pointing
- ▶ invariant mass inside a reasonable window Δm



yields, S/B

	eff (%)	Yield (10^3)	S/B	BR (10^{-5})
$\pi \pi \pi$	1.1	141.7	1.4	1.62 ± 0.15
$K \pi \pi$	1.1	494.4	3.1	5.6 ± 0.7
$K K \pi$	1	38.8	0.3	0.50 ± 0.07
$K K K$	1	236.4	21.5	3.01 ± 0.22
$p p \sim \pi$	0.9	22.5	0.2	0.31 ± 0.02
$p p \sim K$	0.8	39.2	1.5	0.59 ± 0.05



events used to calculate S/B on bb inclusive sample

- ▶ B mass resolution = 19 MeV
- ▶ eff includes reconstruction, selection cuts and L0 (hardware trigger) effects
- ▶ results for 100% efficient HLT (software trigger)
 - ▶ expect HLT eff ~ 70% for hhh

comparing with B factories

- ▶ $K\pi\pi$: BaBar (Belle) published their analysis for ~ 2100 (4300) signal events taken from 226 (386) M BB pairs
hep-ex/0507004 (hep-ex/0512066)
- ▶ statistics: 2 order of magnitude above in 1st nominal year
 - ▶ many possibilities!
 - ▶ example: new physics search on rare $B^+ \rightarrow K^- \pi^+ \pi^+$, $K^+ K^+ \pi^-$
 - ▶ SM BR : 0 (10^{-14}), 0 (10^{-11})
 - ▶ enhanced by Minimal Supersymmetric SM : 0 (10^{-9}), 0 (10^{-6})
 - ▶ current limits: $< 9.5 \times 10^{-7}$, $< 1.6 \times 10^{-7}$, 90% CL
Babar: hep-ex/08080900
- ▶ other examples: CPV in baryon sector, baryonic number violation, ...

CKM γ measurements

- ▶ There are studies showing the possibility of extracting γ at LHCb using the decay $B^+ \rightarrow K^+ \pi^+ \pi^-$
 - ▶ G. Gilles, CERN-THESIS-2007-050
- ▶ On this talk I'm going to focus in an approach which combines $B^+ \rightarrow K^+ \pi^+ \pi^-$ and $B^0 \rightarrow K_S \pi^+ \pi^-$ based on the possibility of **untagged** analysis on neutral B
 - ▶ I. Bediaga, G. Guerrer, J. Miranda, Phys. Rev. D **76**, 073011 (2007)

LHCb : $B^0 \rightarrow K_S \pi^+ \pi^-$

▶ similar selection strategy to hhh

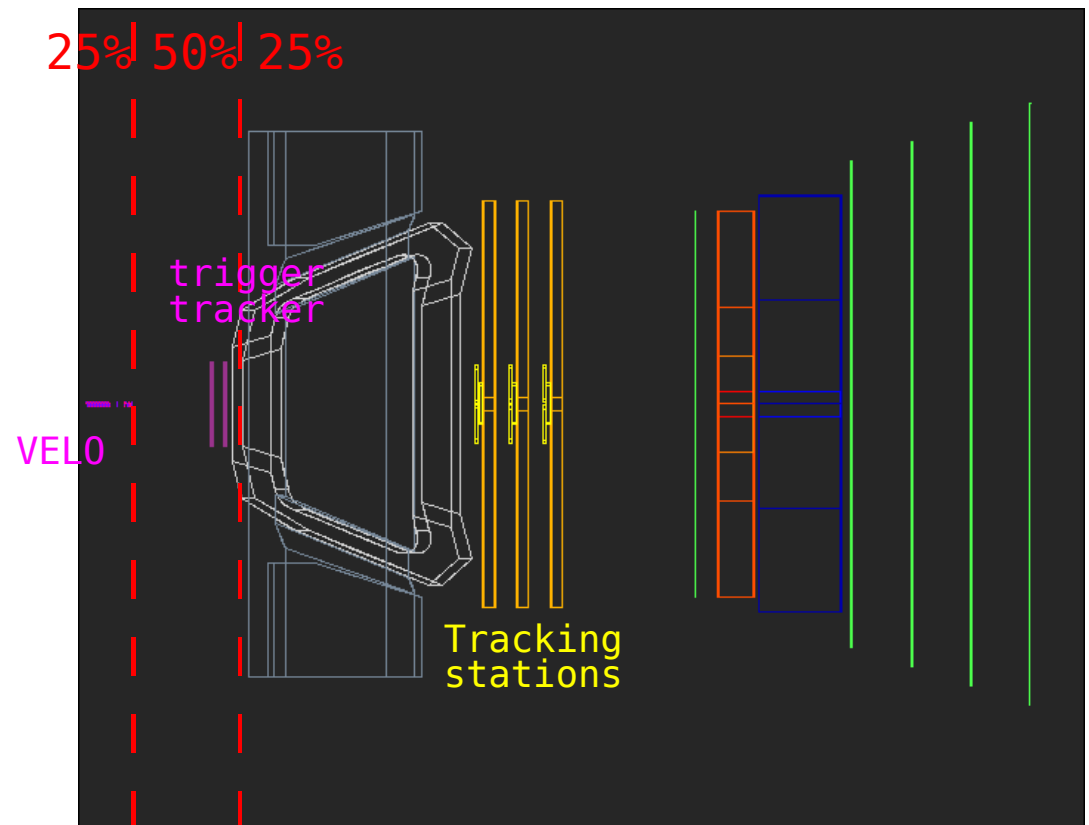
▶ $eff = 0.5\%$ (1.1% in B^+)

▶ 25% K_S decays after trigger tracker straight lines at T stations, no p → event lost

▶ 50% decay after VELO but before trigger tracker, having worse defined tracks

▶ $BR = 2.24 \times 10^{-5}$
(5.6×10^{-5} in B^+)

▶ $Yield = 90k / 2fb^{-1}$
(494k in B^+)



Dalitz plot analysis

- ▶ decay amplitude is a complex function of the Dalitz plot variables (s_{12}, s_{23}) parametrized as a coherent sum of resonant and non-resonant contributions

$$A(s_{12}, s_{23}) = \sum_k (a_k e^{i\delta_k} M_k) + a_{NR} e^{i\delta_{NR}} M_{NR}$$

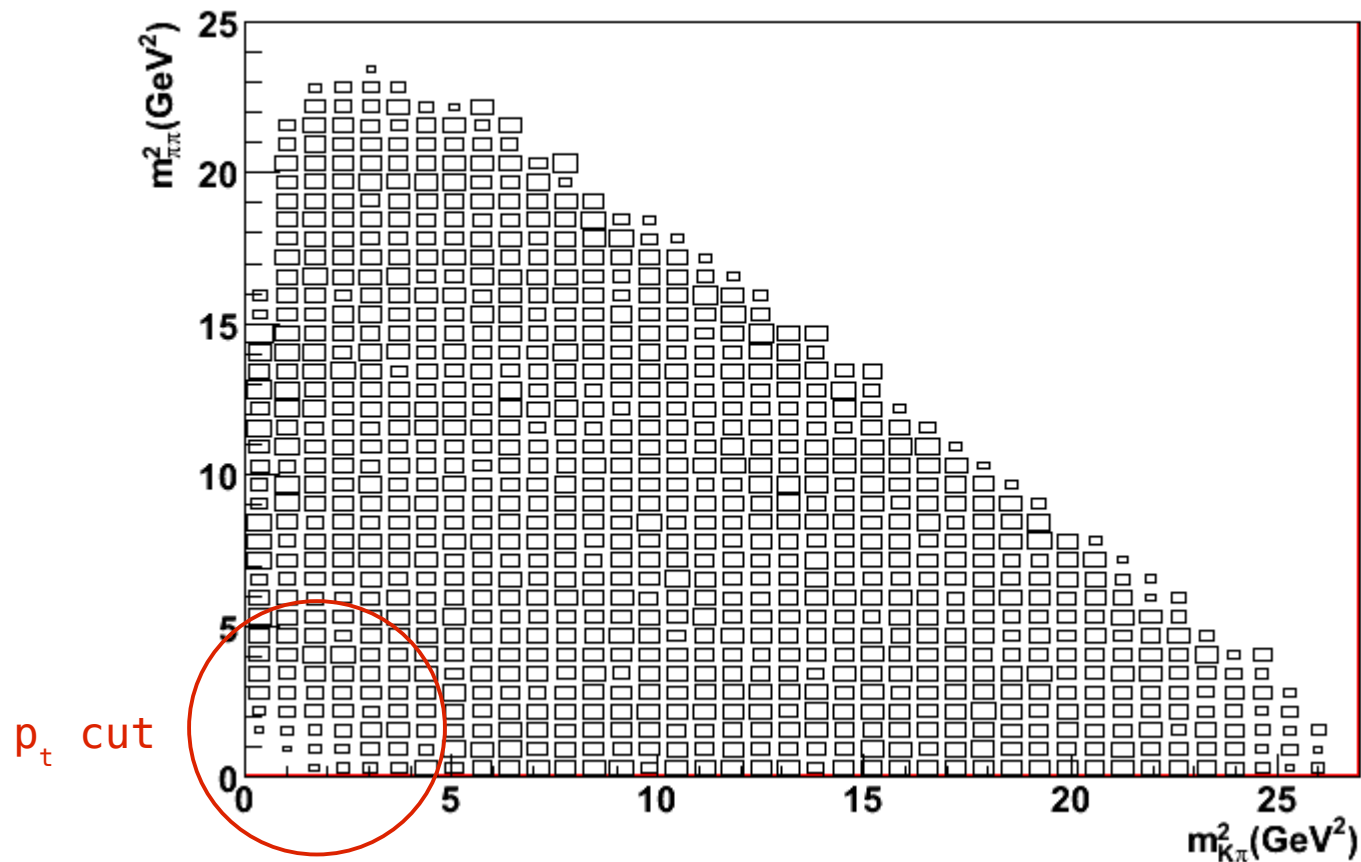
- ▶ a : magnitude, δ : strong + weak phase
- ▶ Dalitz plot fit to $|A(s_{12}, s_{23})|^2$ returns a 's and δ 's
- ▶ usual CPV
$$A_{CP}(k) = (a_k^+ - a_k^-) / (a_k^+ + a_k^-)$$
 - ▶ inspired by 2 body idea of difference in num of events
 - ▶ model dependent
 - ▶ ignores information on δ !!!

ex: BaBar K π π analysis, Phys. Rev. D **72**, 072003 (2005)

Belle K π π analysis, Phys. Rev. Lett. **96**, 251803 (2006)

LHCb Dalitz plot acceptance: $K\pi\pi$

- ▶ no significant difference between regions
- ▶ low at **corners** due to p_t cuts
 - ▶ kept small as possible to reduce combinatorics

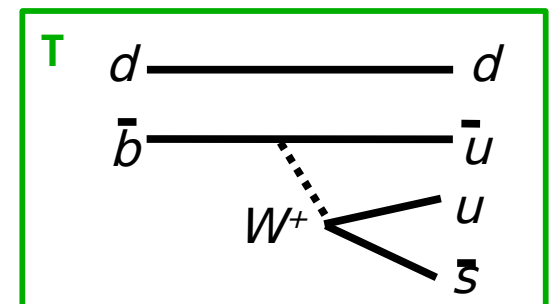
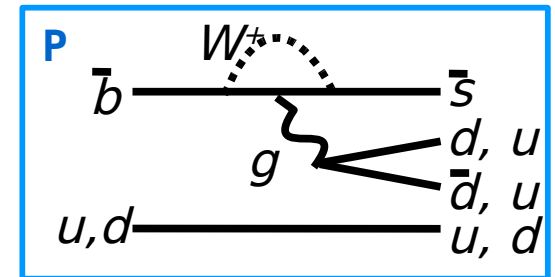


γ : $B^+ \rightarrow K^+ \pi^+ \pi^-$ and $B^0 \rightarrow K_S^0 \pi^+ \pi^-$

dominant contributions for K^* resonance

$B^+ \rightarrow K^{*0} \pi^+$: $V_{bt} V_{ts}^*$ **P**

$B^0 \rightarrow K^{*+} \pi^-$: $V_{bt} V_{ts}^*$ **P** + $V_{bu} V_{us}^*$ **T**

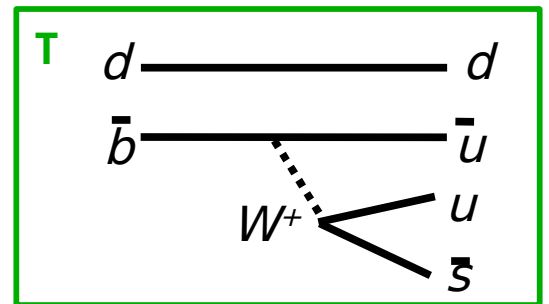
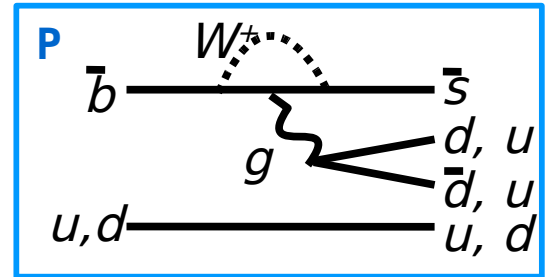


γ : $B^+ \rightarrow K^+ \pi^+ \pi^-$ and $B^0 \rightarrow K_S^0 \pi^+ \pi^-$

dominant contributions for K^* resonance

$B^+ \rightarrow K^{*0} \pi^+$: $V_{bt} V^{*ts}$ **P**

$B^0 \rightarrow K^{*+} \pi^-$: $V_{bt} V^{*ts}$ **P** + $V_{bu} V^{*us}$ **T**



1st step: amplitude analysis of charged B

- ▶ extracts $B^+ : V_{bt} V^{*ts} \propto a e^{i\delta}$
 $B^- : V^{*bt} V_{ts} \propto a e^{i\delta}$
 which should be equal in absence of weak phase
- ▶ parameters are extracted relative to $B^+ \rightarrow \chi c^0 K^+$ which should have same contribution in neutral decay, allowing comparison of parameters

$$\gamma : B^+ \rightarrow K^+ \pi^+ \pi^- \quad \text{and} \quad B^0 \rightarrow K_S \pi^+ \pi^-$$

dominant contributions for K^* resonance

$$B^+ \rightarrow K^{*0} \pi^+ : V_{bt} V^{*ts} \mathbf{P}$$



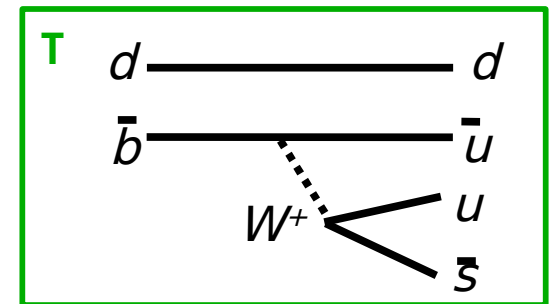
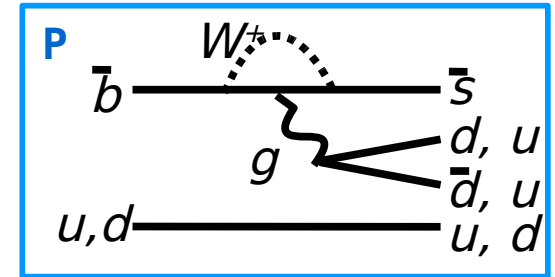
$$B^0 \rightarrow K^{*+} \pi^- : V_{bt} V^{*ts} \mathbf{P} + V_{bu} V^{*us} \mathbf{T}$$

2nd step: amplitude analysis of neutral B

▶ inputs \mathbf{P} from B^+

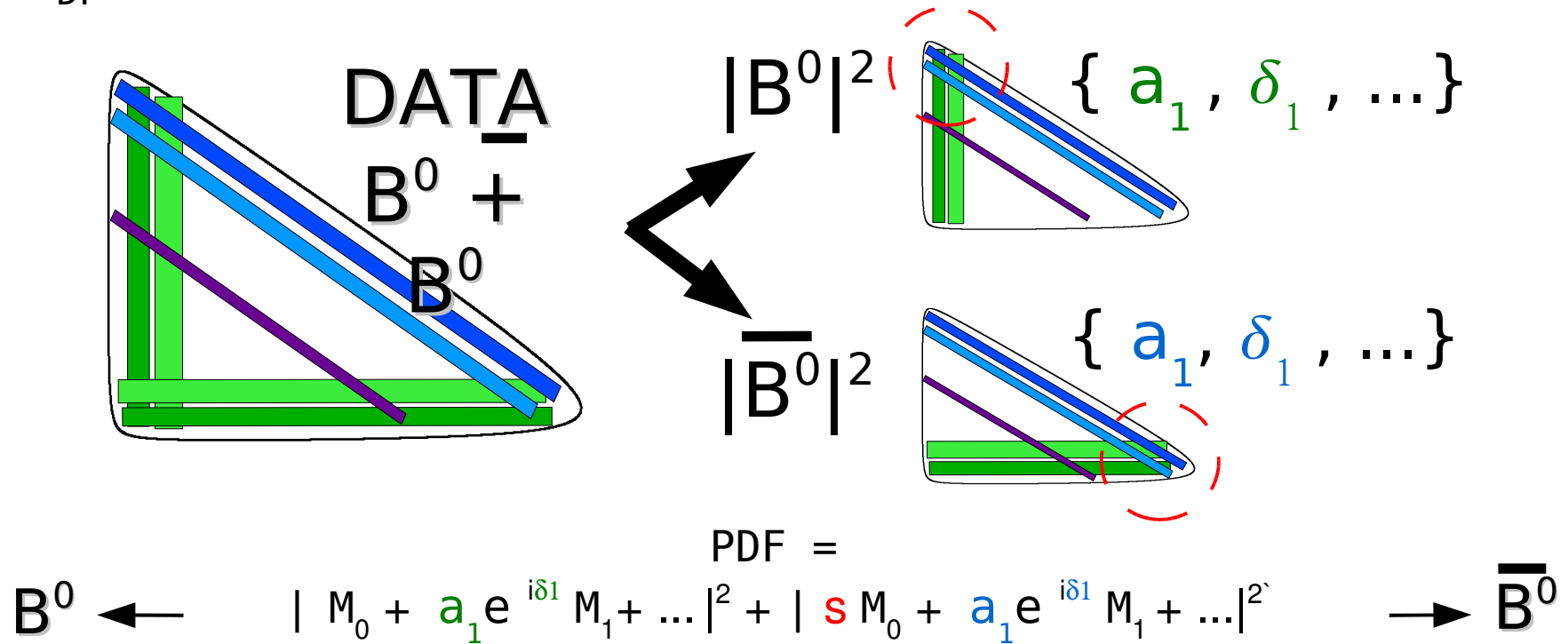
▶ extracts $B^0 : V_{bu} V^{*us} \propto a e^{i\delta}$
 $\bar{B}^0 : V^{*bu} V_{us} \propto \bar{a} e^{i\bar{\delta}}$

$$\gamma = (\delta - \bar{\delta}) / 2$$



amplitude analysis of neutral B

▶ reconstructing $K_S \pi^+ \pi^-$ without tagging for B^0 or anti- B^0 leads to a joint DP. In a single fit procedure it's possible to extract parameters from B^0 and anti- B^0 . The intuition behind is the non-overlap of interference regions – the identity of each DP



- ▶ s : free parameter for scale, allows to measure number of events of both samples
- ▶ unambiguous extraction of a 's and δ 's

γ measurement: $K\pi\pi$

- ▶ the ability of measuring γ is related to its own value and the ratio $r = T / P$ in $B^0 \rightarrow K^* \pi$
- ▶ we can measure r
- ▶ conflicting theoretical predictions
Beneke, Neubert Nucl. Phys **B675**, 333(2003)
Buras et al, Phys. Rev.Lett **92** 101804 (2004)

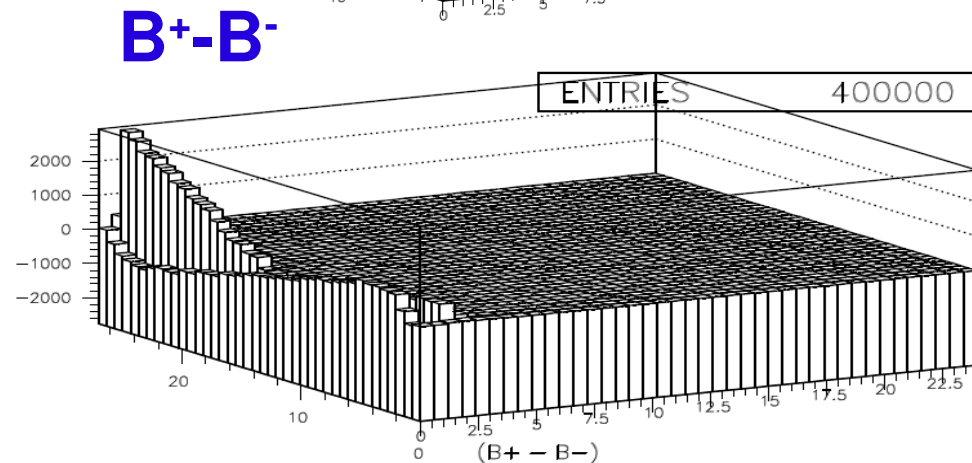
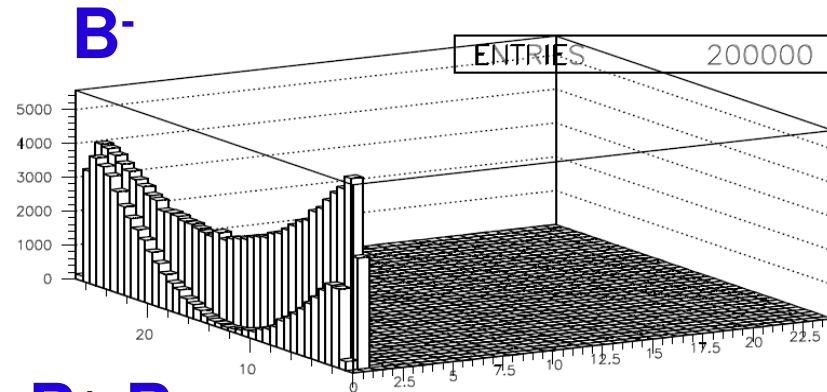
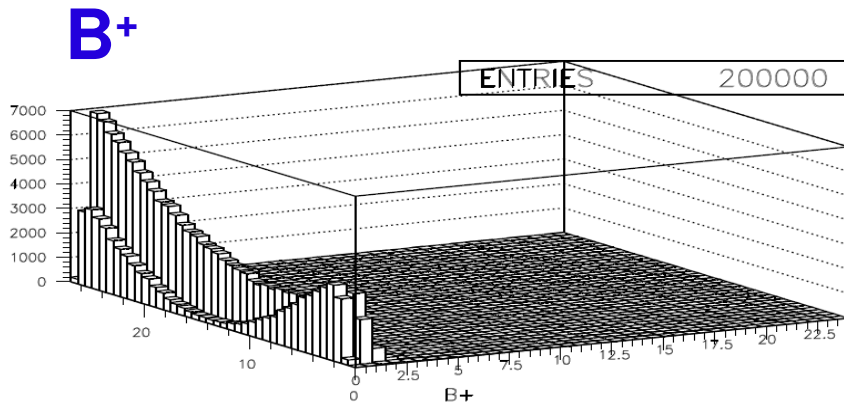
Monte Carlo test

- ▶ 100 samples of 100k B^0 events
- ▶ no background nor acceptance included
- ▶ inputs inspired by BaBar
- ▶ input $\gamma = 69^\circ$, $r = 0.45$
- ▶ extracts $\gamma = 69^\circ \pm 5^\circ$

phase role in CPV

- ▶ example: pure phase effect

mode	DP+:	200K	DP-:	200K
	a+	$\delta+$	a-	$\delta-$
$\rho(770)K$	0.874	0.00	0.874	2.44
$f_0(980)K$	1.02	2.29	1.02	2.29



- ▶ $A_{CP}(\rho) = 0$
- ▶ but evident CPV
- ▶ need a new quantity to measure asymmetries which takes phase into account

Dalitz anisotropy

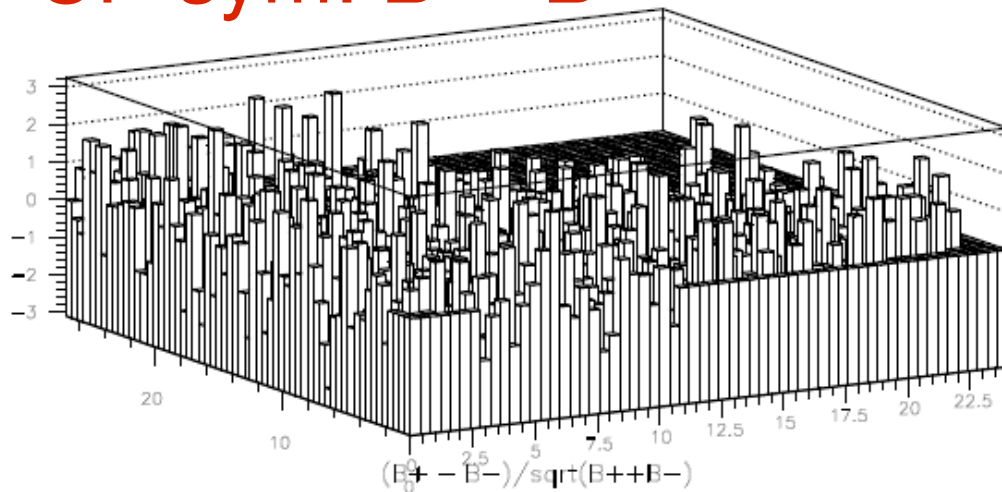
└─▶ Ti-Pei Li and Yu-qian Ma, Astr.Jour. 272:317-324(1983)

- ▶ inspired by astrophysics statistical methods, we use the significance calculated in each bin (i) of the Dalitz plot

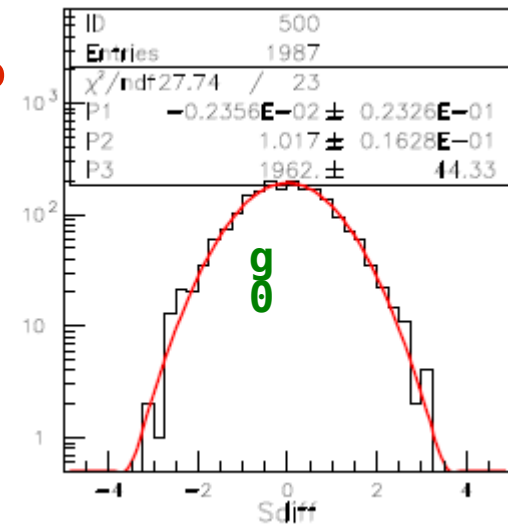
$$S_{CP}(i) = \frac{N^+(i) - N^-(i)}{\sqrt{N^+(i) + N^-(i)}}$$

- ▶ it returns a gaussian g_0 , centered at 0 and width=1 in case of CP symmetry

CP sym: $B^+ - B^-$



S_{CP}

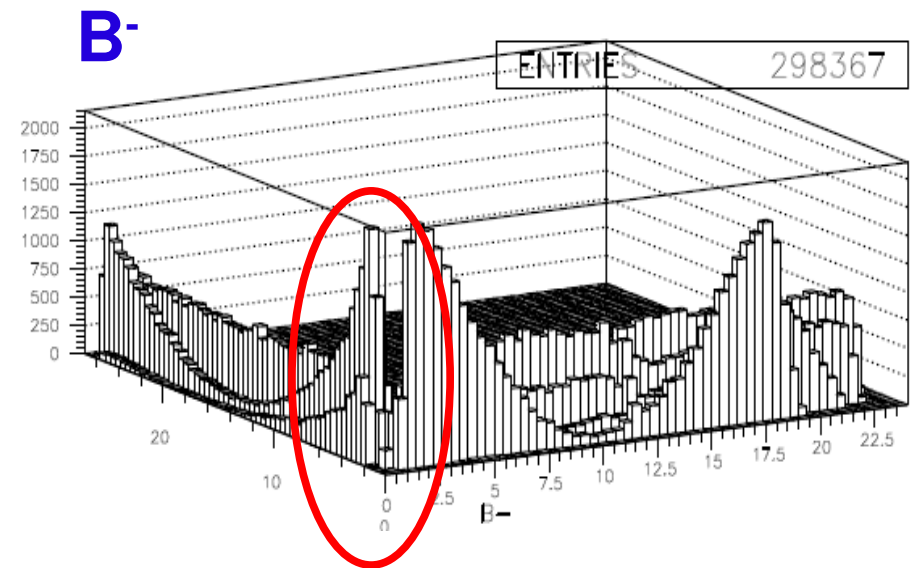
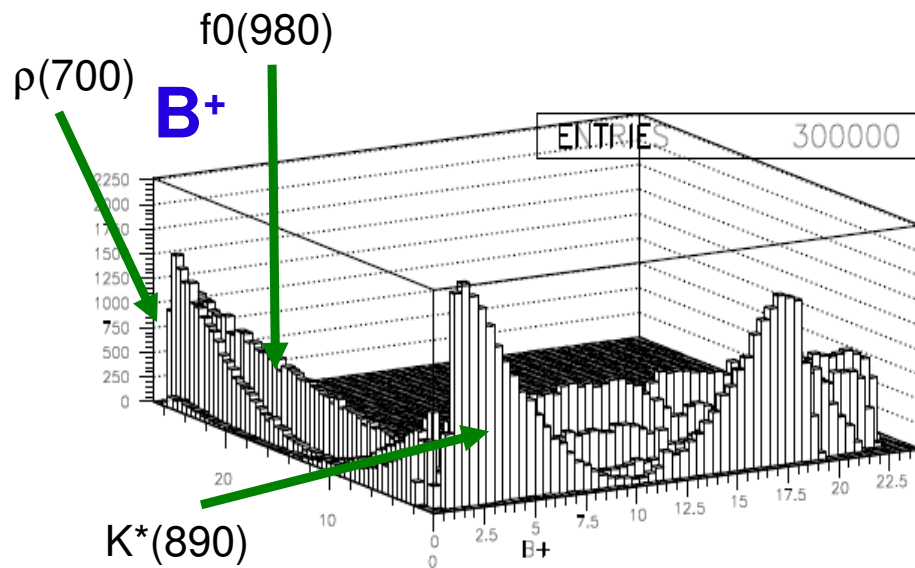


- ▶ possible to isolate CPV effects from statistical fluctuations by visual inspection

Dalitz anisotropy: $K\pi\pi$ example

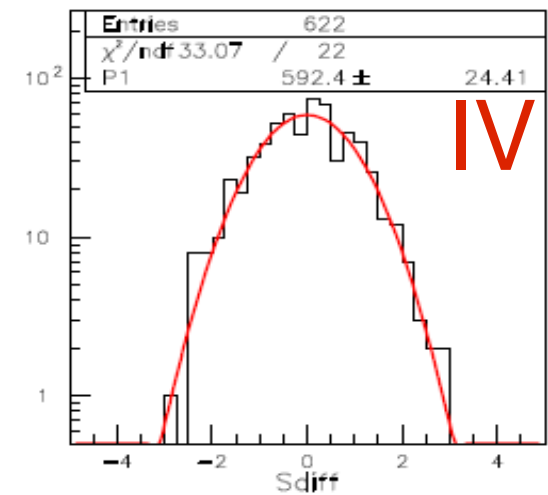
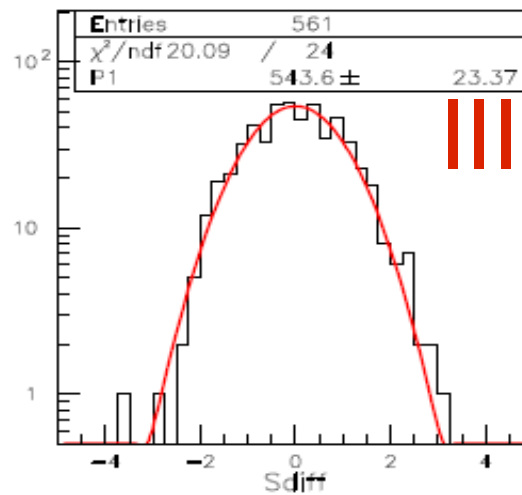
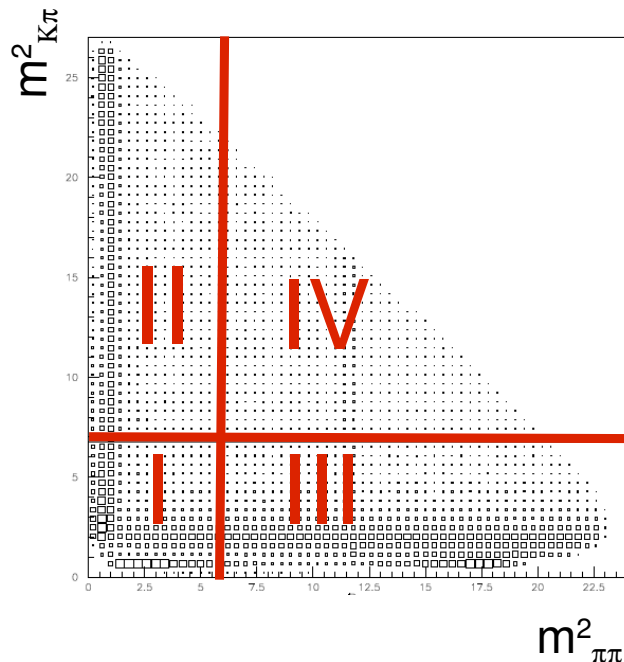
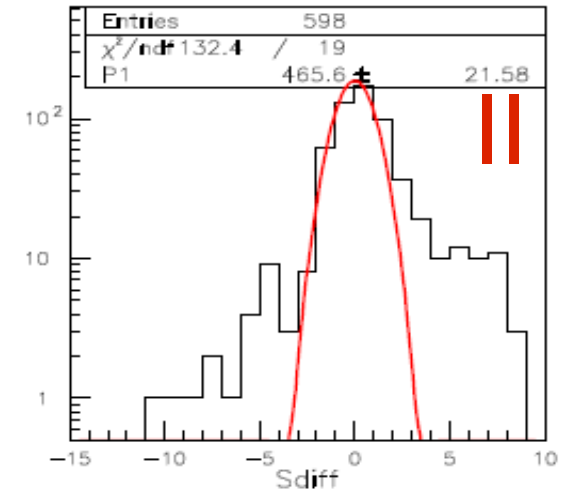
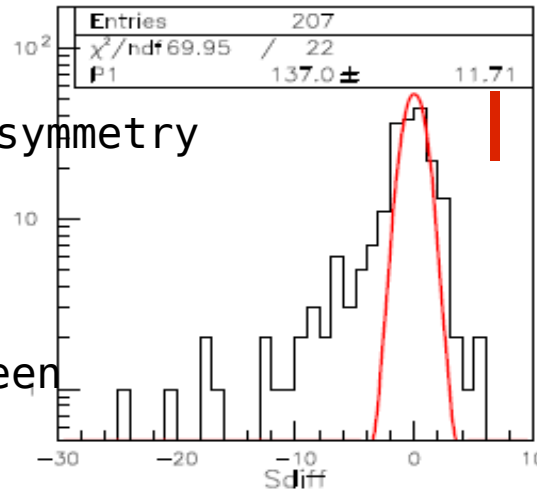
► fast MC sample inspired by BaBar parameters and 1 nominal year of LHCb statistics (~300k)

mode	B+		B-	
	a+	δ_+	a-	δ_-
$K^*(890)\pi$	1.00	0.00	1.00	0.00
$K(1430)\pi$	2.08	0.1	2.08	0.1
$\rho(770)K$	0.874	-0.55	0.874	0.49
$f_0(980)K$	1.02	2.29	1.02	2.29
χK	0.3	-2.52	0.3	-2.52
NR	0.6	-1.85	0.6	-1.85



Dalitz anisotropy: $K\pi\pi$ example

- ▶ divide DP in 4 regions
region I and II \rightarrow CPV
region III and IV \rightarrow CP symmetry
- ▶ any contrib out g_0 is signature of CPV
- ▶ reg I and II show clear 5-sigma difference between B^+ and B^-



conclusion

LHCb

- ▶ large statistics, ~2 orders of magnitude more than B factories → many possibilities and a rich environment for physics, stay tuned for exciting results!

γ measurement

- ▶ possibility of measuring γ in $K\pi\pi$ channels
- ▶ idealized fast MC study points to 5° error in 1 nominal year of LHCb data (2fb^{-1})

amplitude analysis of B neutral

- ▶ possibility of extracting parameters from B^0 and anti- B^0 in an **untagged** joint sample

Dalitz anisotropy

- ▶ **model independent, fast approach** to spot regions of CPV before full amplitude analysis
- ▶ sensible to phase difference
- ▶ it can be used to **steer amplitude analysis**
 - ▶ pick a 3 body channel X
 - ▶ check if different regions have CPV as expected in SM
 - ▶ move to long term detailed analysis
- ▶ work ongoing to define a quantitative measurement

extra

hhh selection cuts

- ▶ PID cuts + $\Delta m = 200$ MeV
- ▶ similar distributions, only pt is slightly different

tracks	pt (MeV)	> 200
	Σ pt (MeV)	> 3800
	IPS	> 4
	Σ track chi2ndof i	< 12
B	vertex chi2	< 15
	cosp	> 0.99994
	IPS	< 3
	FS	> 20
	Σ ip i (SV) (mm)	< 0.15
	vi_ip1 (mm)	> 0.5

▶ IPS – impact parameter significance

▶ FS – flight distance significance

▶ cosp – pointing cut, dot product of tracks momentum sum and SV-PV

▶ ip (SV) – ip with regards to B vertex

▶ vi_ip1 is a vertex isolation cut which allows 1 extra track inside sphere of radius 0.5 mm centered at SV