$B_{(d,s)} \to K_S hh$ decays in LHCb

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LHC France 2013, 2-6 April 2013, Annecy, France

Outline

- **$b \to q\bar{q}s$ and current measurements**
- **Selection of events**
- **Fit model**
- **Systematic uncertainties**
- **Results**
- **Current status and future plans**

$b\to q\bar{q}s$ decays

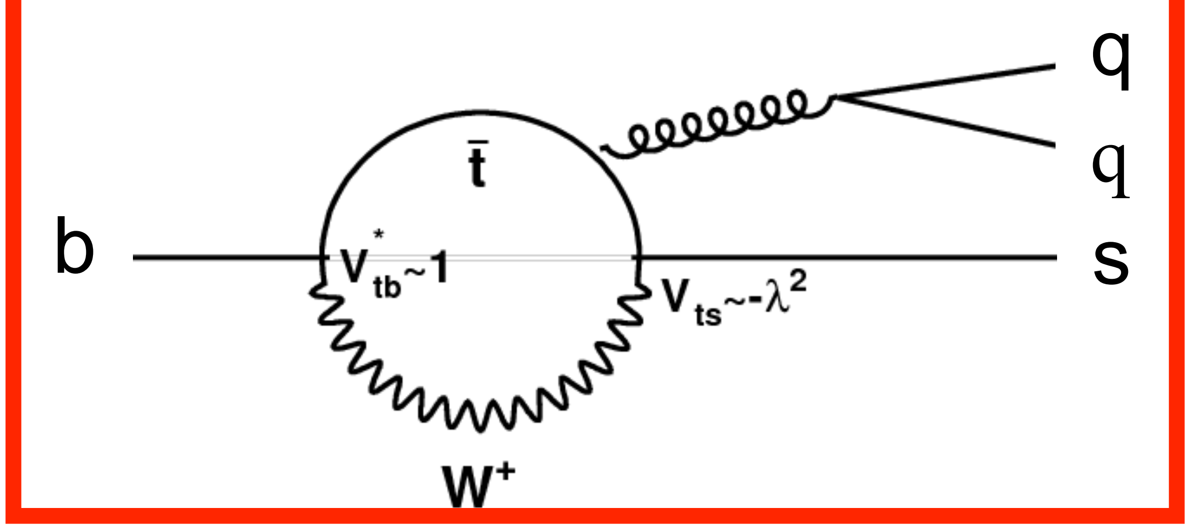
$$A_{CP}(\Delta t) = S_f \sin(\Delta m t) + C_f \cos(\Delta m t)$$

Mixing induced CP asymmetries in $b\to c\bar{c}s$, $S_f \sim \sin 2\beta$, expected to be almost equal to $b\to q\bar{q}s$, according to the SM.

$$S_{c\bar{c}s} = S_{q\bar{q}s} + \Delta S_{SM} = -\eta_{CP}\sin 2\beta$$

$b\to c\bar{c}s$ tree level golden mode $B^0\to J/\psi K_S$

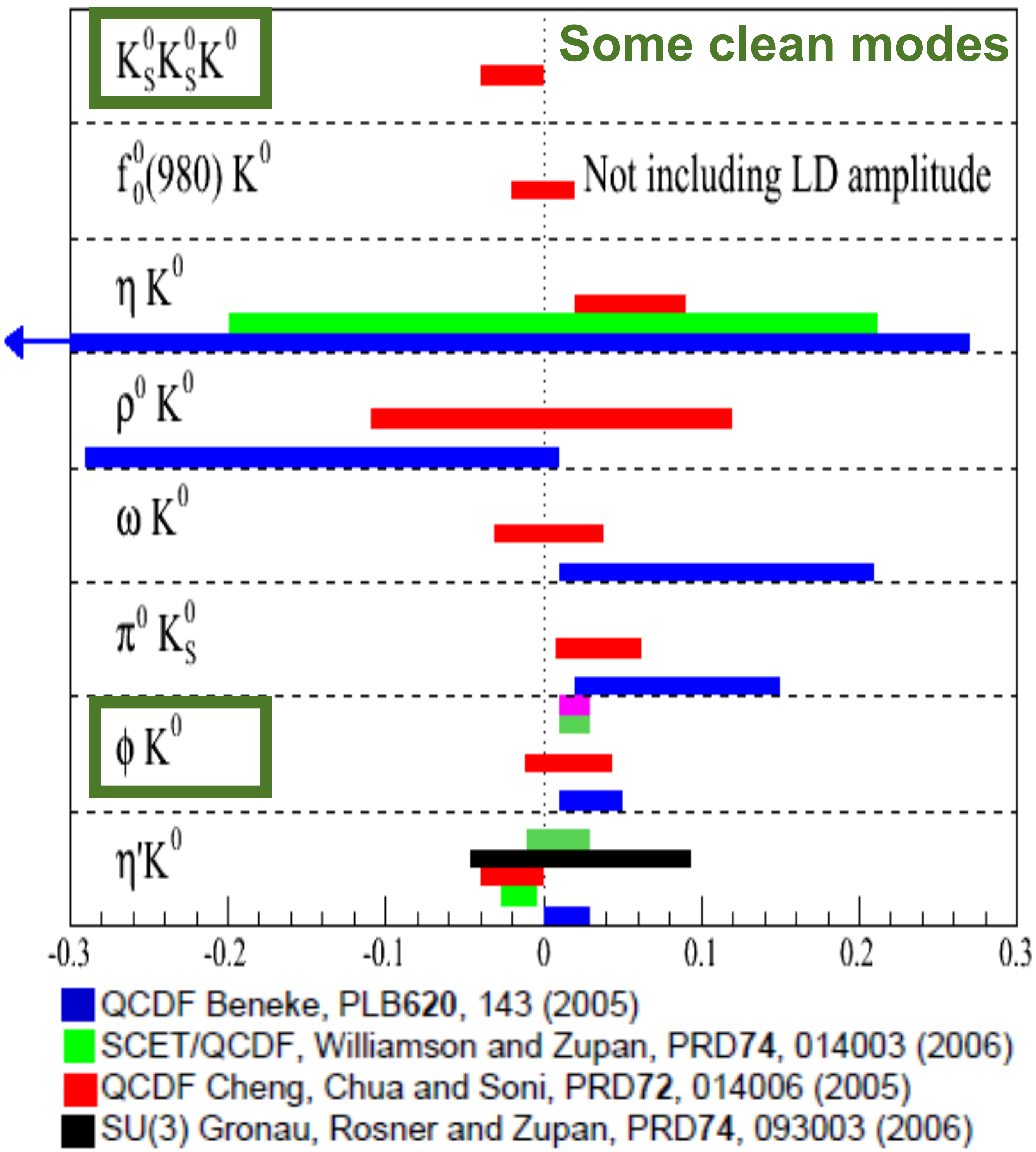
$b\to q\bar{q}s$ penguin dominated

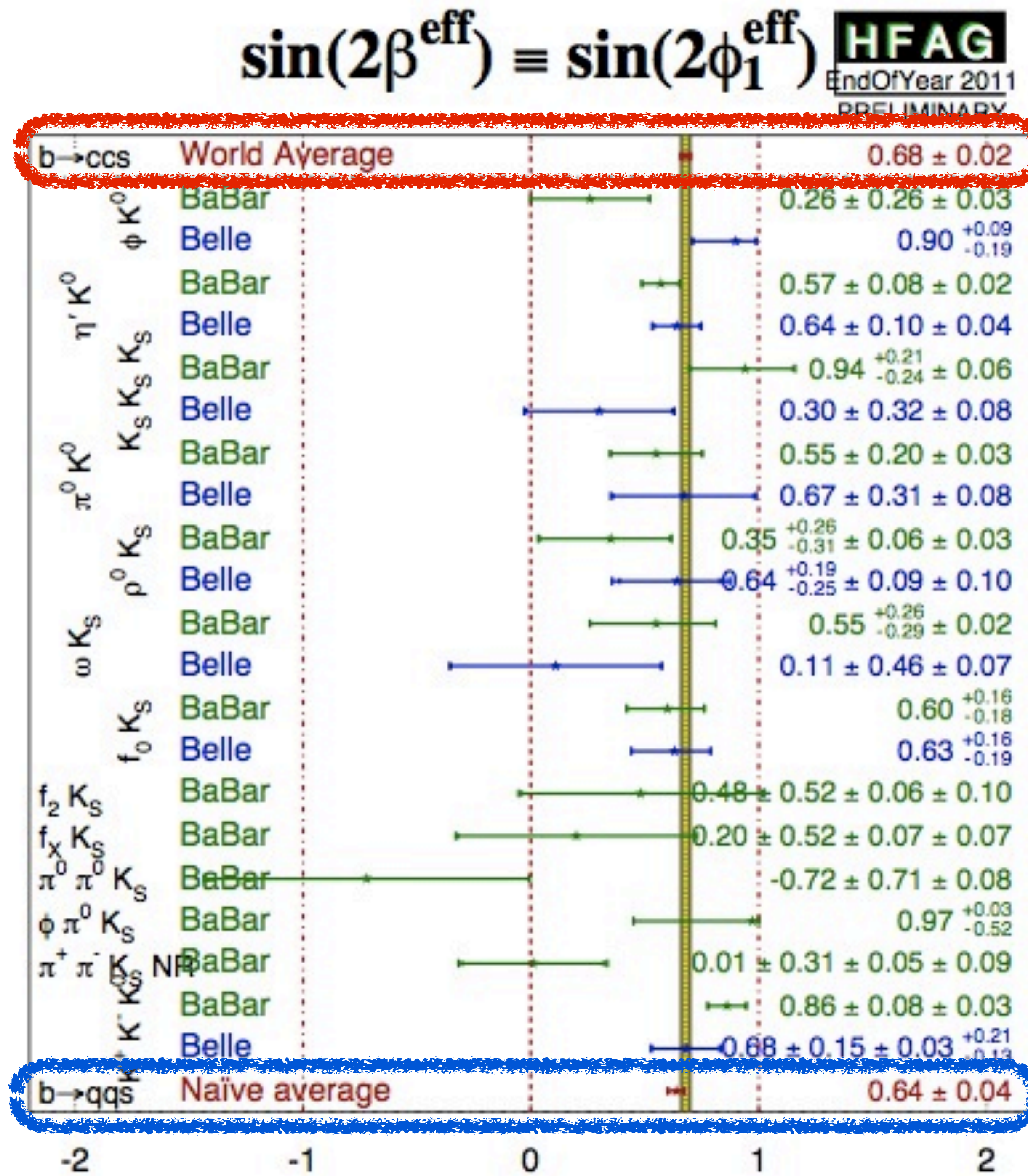


NP contribution from new particles in the loop. New phases might affect the measurement of CKM angle β

b→qq̄s decays

Theoretical prediction for ΔS_{SM}





$\sin 2\beta(b\to c\bar{c}s)=0.68\pm0.02$

$\sin 2\beta(b\to q\bar{q}s)=0.64\pm0.04$

$b \to q\bar{q}s$ @ LHCb

- $B_{(d,s)} \to K_S\pi^+\pi^-$, $K_SK^+K^-$, $K_SK^\pm\pi^\mp$ **3-body ($b \to q\bar{q}s$) decays.**
  ⇒ The resonant structure has information on sin2β.

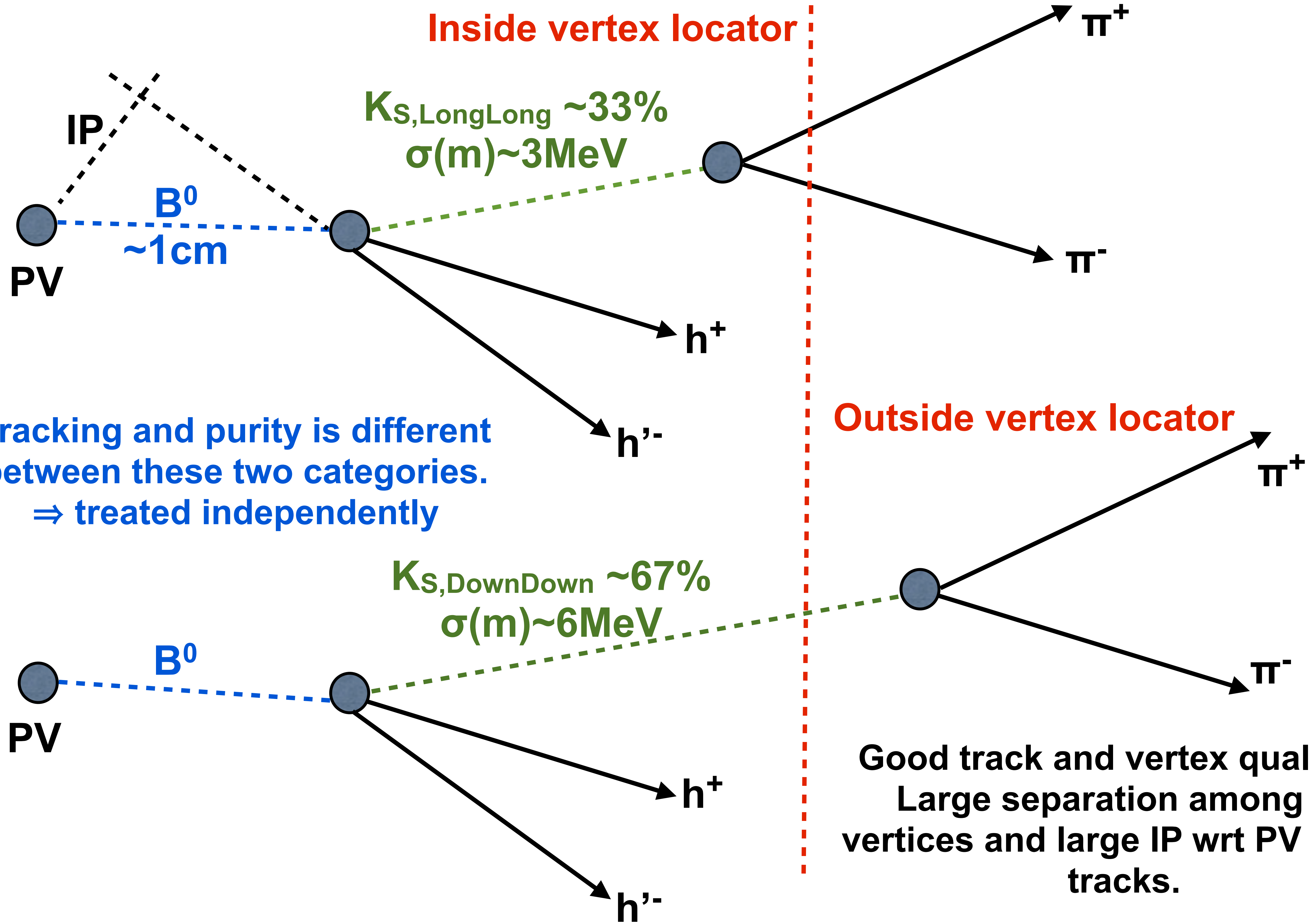
- **Rare decays (BF~10^{-6})⇒ long way to phase extraction.**

  First step, is to establish the branching fraction of these modes, using 1/fb of 2011 data (LHCb-CONF-2012-023).
  Simplest: time integrated and flavor-tag averaged

  - **LHC produce copious amounts of $B_{(u,d,s)}$ mesons. LHCb is well suited to look for rare decays**
  - **B_d decays studied in B-factories**
  - **B_s decays not studied so far (Tree level dominated, theoretically cleaner, in some of them information on $\gamma+\beta_s$, PLB645(2007)201-203)**

Decay mode	Branching fraction (10^{-6}) BaBar	Branching fraction (10^{-6}) Belle	Branching fraction (10^{-6}) World average
$B^0 \to K^0\pi^+\pi^-$	50.2 ± 2.3	47.5 ± 4.4	49.6 ± 2.0
$B^0 \to K^0K^\pm\pi^\mp$	6.4 ± 1.2	< 18	6.4 ± 1.2
$B^0 \to K^0K^+K^-$	23.8 ± 2.6	28.3 ± 5.2	24.7 ± 2.3

Event reconstruction

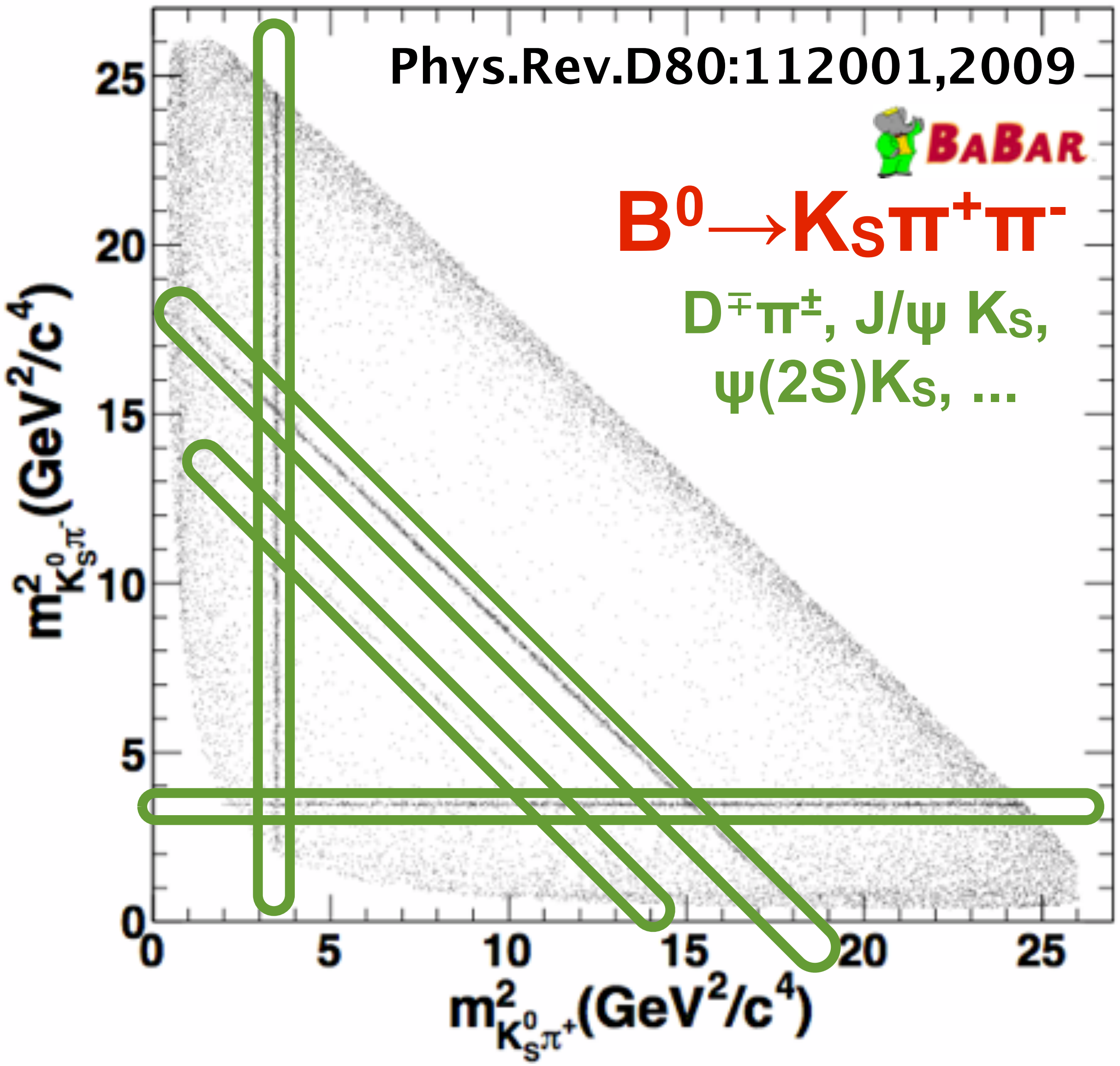


Tracking and purity is different between these two categories.
⇒ treated independently

Good track and vertex qualities. Large separation among all vertices and large IP wrt PV for all tracks.

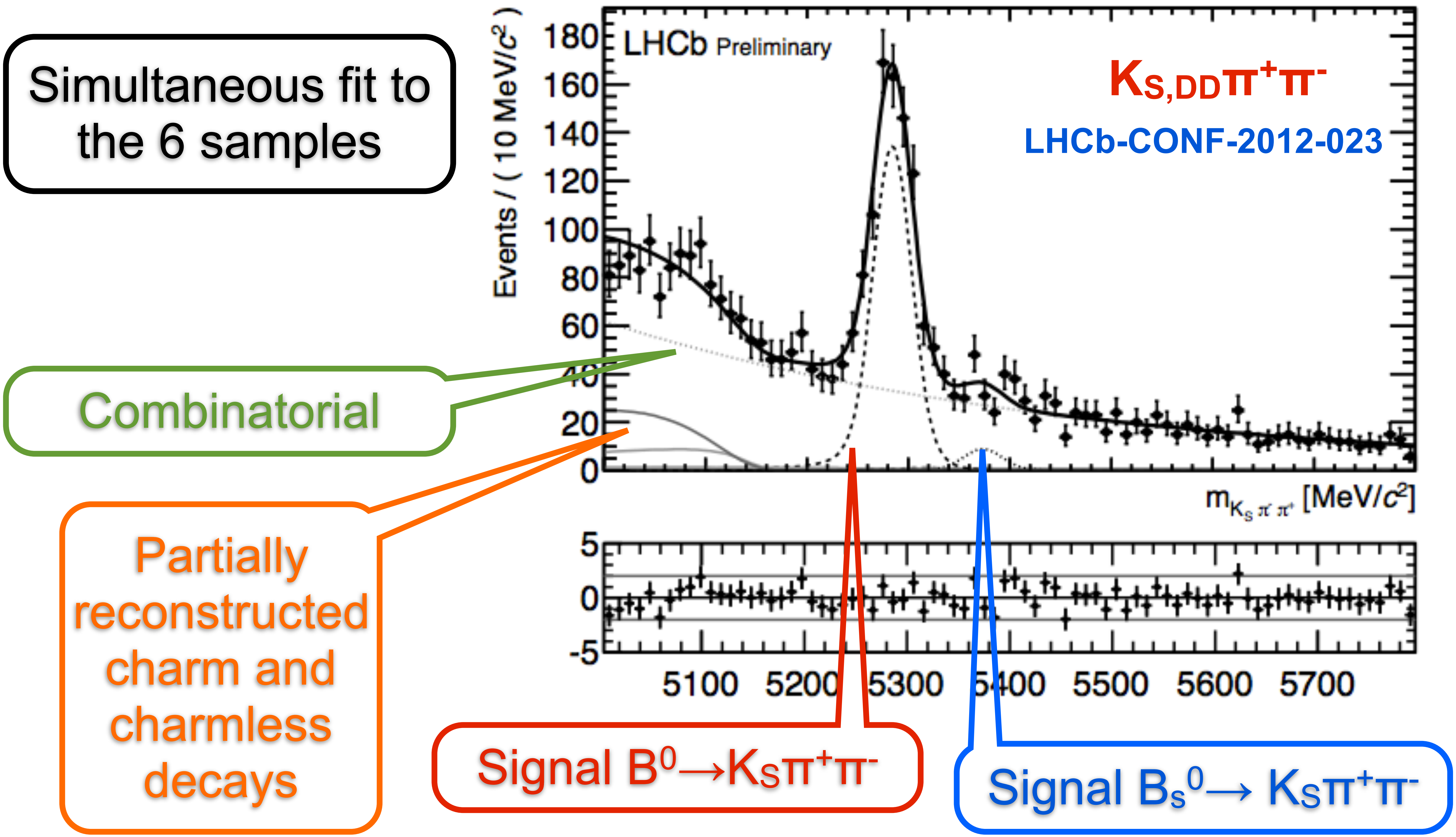
Vetoes, BDT and PID criteria

- Background rejection using a multivariate discriminant, BDT. Flight distances, impact parameters, B transverse momenta and direction angle
- Veto of fully reconstructed 2-body decays with charm. $\Delta M \sim \pm 30$MeV rejected.
- PID requirement using mostly Cherenkov detectors information. ~85-90% efficiency with ~5-10% misID



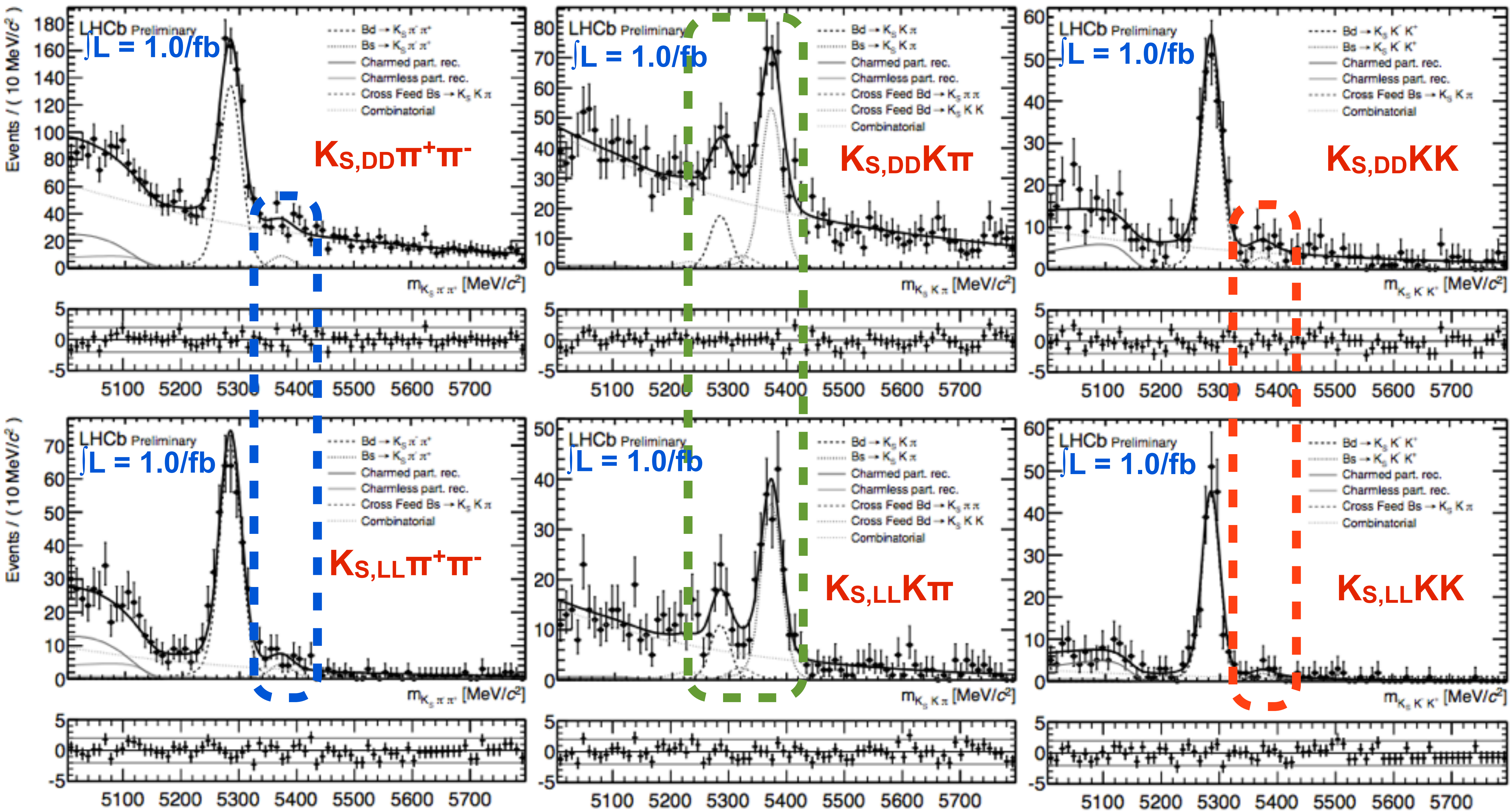
Fit model

Simultaneous fit to the 6 samples



Fit projections

LHCb-CONF-2012-023



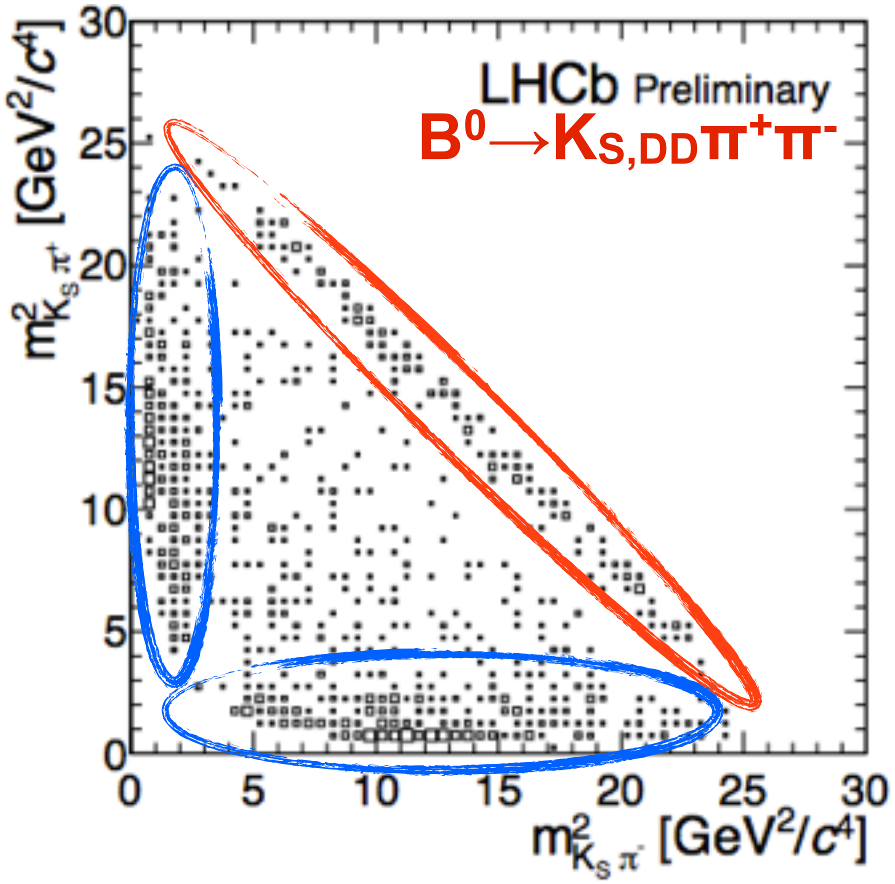
$B_s \to K_S\pi^+\pi^-$, 4.3σ (stat)

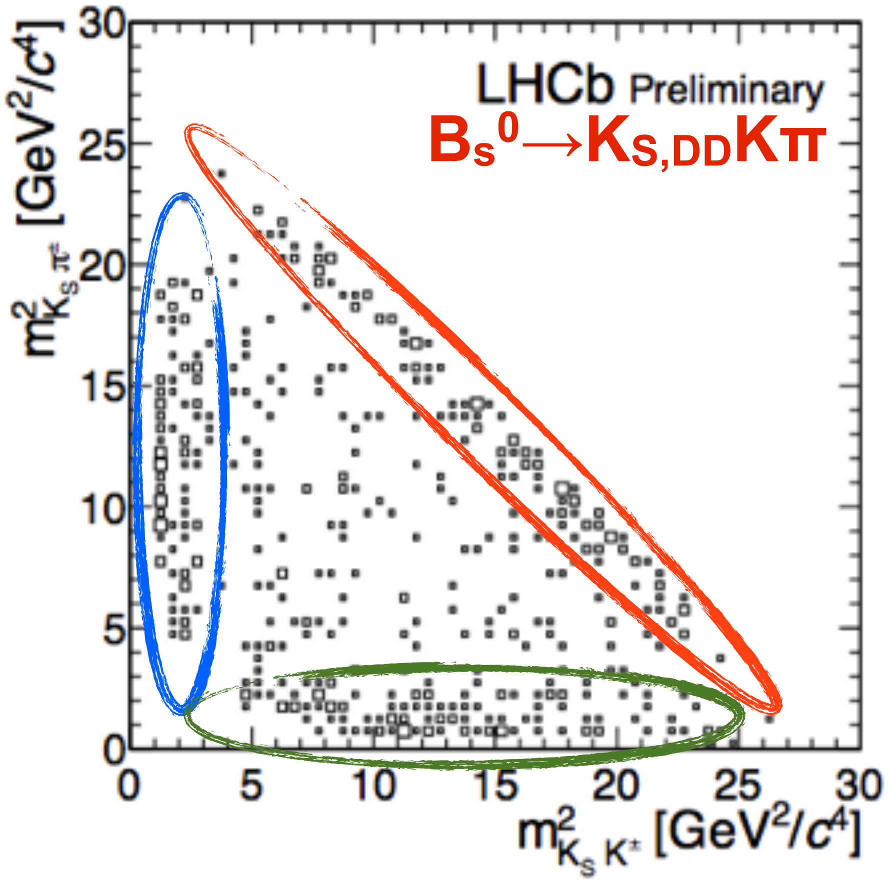
$B_d \to K_S K^+\pi^-$, 7.6σ (confirmation)
$B_s \to K_S K^+\pi^-$ clearly present (first obs.)

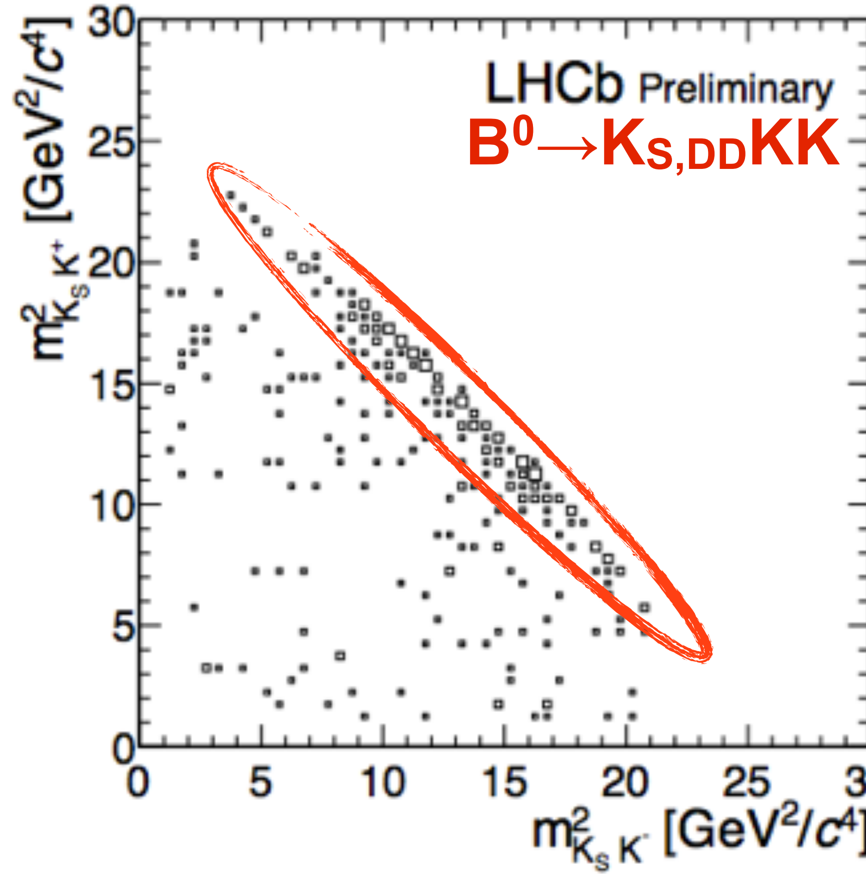
$B_s \to K_S K^+K^-$, 3.3σ (stat)

Dalitz plot distributions

B signal mass window, no bkg subtracted nor efficiency corrected distributions







$B^0 \to \rho(770) K_S$
$B^0 \to f_0(980) K_S$

$B^0 \to K^*(892)^\pm \pi^\mp$
$B^0 \to (K\pi)_0^{*\pm} \pi^\mp$

$B_s^0 \to K^*(892)^0 K_S$ (?)

$B_s^0 \to K^*(892)^\pm K^\mp$ (?)
$B_s^0 \to (K\pi)_0^\pm K^\mp$ (?)

Structures in low $K_S K$ masses

$B^0 \to \varphi(1020) K_S$
$B^0 \to f_0(980) K_S$

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Branching fractions ratio

BF relative to $B^0 \to K_S \pi^+ \pi^-$

$$\frac{\mathcal{B}\left(B^0_{d,s} \to K^0_S h^{\pm} h'^{\mp}\right)}{\mathcal{B}\left(B^0 \to K^0_S \pi^+ \pi^-\right)} = \frac{\epsilon^{\text{sel.}}_{B^0 \to K^0_S \pi^+\pi^-}}{\epsilon^{\text{sel.}}_{B^0_{d,s} \to K^0_S h^{\pm} h'^{\mp}}} \frac{\epsilon^{\text{PID}}_{B^0 \to K^0_S \pi^+\pi^-}}{\epsilon^{\text{PID}}_{B^0_{d,s} \to K^0_S h^{\pm} h'^{\mp}}} \frac{N_{B^0_{d,s} \to K^0_S h^{\pm} h'^{\mp}}}{N_{B^0 \to K^0_S \pi^+\pi^-}} \frac{f_d}{f_{d,s}}$$

ε^{PID} computed from dedicated $D^{*+} \to D^0(K^- \pi^+)\pi^+$ control samples, corrected by the kinematic of the decay

ε^{sel} encloses reconstruction, offline selection and trigger efficiencies. Binned over the DP

Large inefficiency expected in the DP borders. Rotation to squared DP. Very large MC samples needed to compute this effect

Phys.Rev. D72 (2005) 052002

Mode	Down-Down	Long-Long
$B^0 \to K^0_S \pi^+\pi^-$	689 ± 35	355 ± 21
$B^0 \to K^0_S K^{\pm}\pi^{\mp}$	85 ± 19	50 ± 11
$B^0 \to K^0_S K^+ K^-$	230 ± 17	189 ± 14
$B^0_s \to K^0_S \pi^+\pi^-$	47 ± 18	24 ± 8
$B^0_s \to K^0_S K^{\pm}\pi^{\mp}$	265 ± 23	170 ± 16
$B^0_s \to K^0_S K^+ K^-$	13 ± 7	9 ± 4

$f_d/f_s = 0.267 \pm 0.021$

LHCb Phys. Rev. D 85, 032008 (2012)

Systematic uncertainties

$K_{S,DD}$

Relative BF	Selection	Trigger	PID	Fit	f_s/f_d	Total
$\mathcal{B}(B^0 \to K^0_S K^\pm \pi^\mp)/\mathcal{B}(B^0 \to K^0_S \pi^+\pi^-)$	5%	3.4%	2.0%	11%	—	13%
$\mathcal{B}(B^0 \to K^0_S K^+ K^-)/\mathcal{B}(B^0 \to K^0_S \pi^+\pi^-)$	6%	2.5%	3.3%	3%	—	8%
$\mathcal{B}(B^0_s \to K^0_S \pi^+\pi^-)/\mathcal{B}(B^0 \to K^0_S \pi^+\pi^-)$	14%	1.8%	1.1%	9%	9%	19%
$\mathcal{B}(B^0_s \to K^0_S K^\pm \pi^\mp)/\mathcal{B}(B^0 \to K^0_S \pi^+\pi^-)$	7%	1.4%	2.5%	3%	9%	12%
$\mathcal{B}(B^0_s \to K^0_S K^+ K^-)/\mathcal{B}(B^0 \to K^0_S \pi^+\pi^-)$	11%	3.0%	3.7%	22%	9%	27%

$K_{S,LL}$

Relative BF	Selection	Trigger	PID	Fit	f_s/f_d	Total
$\mathcal{B}(B^0 \to K^0_S K^\pm \pi^\mp)/\mathcal{B}(B^0 \to K^0_S \pi^+\pi^-)$	19%	1.1%	3.0%	10%	—	22%
$\mathcal{B}(B^0 \to K^0_S K^+ K^-)/\mathcal{B}(B^0 \to K^0_S \pi^+\pi^-)$	9%	0.5%	4.5%	4%	—	10%
$\mathcal{B}(B^0_s \to K^0_S \pi^+\pi^-)/\mathcal{B}(B^0 \to K^0_S \pi^+\pi^-)$	12%	1.2%	1.1%	13%	9%	20%
$\mathcal{B}(B^0_s \to K^0_S K^\pm \pi^\mp)/\mathcal{B}(B^0 \to K^0_S \pi^+\pi^-)$	7%	1.7%	1.6%	3%	9%	12%
$\mathcal{B}(B^0_s \to K^0_S K^+ K^-)/\mathcal{B}(B^0 \to K^0_S \pi^+\pi^-)$	18%	1.3%	4.6%	12%	9%	24%

Selection efficiency often limited by statistic uncertainty of the simulated samples. Efficiency of ~10^{-4}. Very large MC productions needed

Fit uncertainty from fit model and fixed parameters in the fit. Use of pseudo-experiments to evaluate this contribution. Variation of signal and background models

Results

$$\mathcal{B}(B^0 \to K^0\pi^+\pi^-) = (4.96 \pm 0.20) \times 10^{-5}$$ **PDG World average**

$$\frac{\mathcal{B}(B^0 \to K^0_S K^\pm\pi^\mp)}{\mathcal{B}(B^0 \to K^0_S\pi^+\pi^-)} = 0.117 \pm 0.018\ (\text{stat.}) \pm 0.018\ (\text{syst.}),$$
$$\frac{\mathcal{B}(B^0 \to K^0_S K^+K^-)}{\mathcal{B}(B^0 \to K^0_S\pi^+\pi^-)} = 0.53 \pm 0.04\ (\text{stat.}) \pm 0.04\ (\text{syst.}),$$
$$\frac{\mathcal{B}(B^0_s \to K^0_S\pi^+\pi^-)}{\mathcal{B}(B^0 \to K^0_S\pi^+\pi^-)} = 0.24 \pm 0.06\ (\text{stat.}) \pm 0.04\ (\text{syst.}),$$
$$\frac{\mathcal{B}(B^0_s \to K^0_S K^\pm\pi^\mp)}{\mathcal{B}(B^0 \to K^0_S\pi^+\pi^-)} = 1.96 \pm 0.15\ (\text{stat.}) \pm 0.20\ (\text{syst.}),$$
$$\frac{\mathcal{B}(B^0_s \to K^0_S K^+K^-)}{\mathcal{B}(B^0 \to K^0_S\pi^+\pi^-)} = 0.084 \pm 0.031\ (\text{stat.}) \pm 0.019\ (\text{syst.}),$$

$$\mathcal{B}(B^0 \to K^0 K^\pm\pi^\mp) = (5.8 \pm 0.9 \pm 0.9 \pm 0.2) \times 10^{-6},$$
$$\mathcal{B}(B^0 \to K^0 K^+K^-) = (2.63 \pm 0.20 \pm 0.20 \pm 0.11) \times 10^{-5},$$
$$\mathcal{B}(B^0_s \to K^0\pi^+\pi^-) = (1.19 \pm 0.30 \pm 0.20 \pm 0.05) \times 10^{-5},$$
$$\mathcal{B}(B^0_s \to K^0 K^\pm\pi^\mp) = (9.7 \pm 0.7 \pm 1.0 \pm 0.4) \times 10^{-5},$$
$$\mathcal{B}(B^0_s \to K^0 K^+K^-) = (4.2 \pm 1.5 \pm 0.9 \pm 0.2) \times 10^{-6},$$

Ratio of branching fractions

- **Branching fraction measurements compatible with previous measurements**
- **Systematic and statistical uncertainties of the same order**
- **$B_d \to K_S K^+\pi^-$ confirmation at 7.6σ and $B_s \to K_S K^+\pi^-$ first observation**
- **Evidence for $B_s \to K_S K^+K^-$ and $B_s \to K_S\pi^+\pi^-$**

LHCb-CONF-2012-023

Current status

- **Analysis over same data sample (2011, 1/fb) has been improved. Targets to a paper before summer. <u>Clermont-Ferrand, LPNHE</u> and Warwick.**
- **Some of the improvements:**
  - **Selection and BDT optimization**
  - **Fit model and partially reconstructed background description**
  - **Global selection + PID sWeight for efficiency extraction.**
  - **Reduction of systematic uncertainties**

Future plans

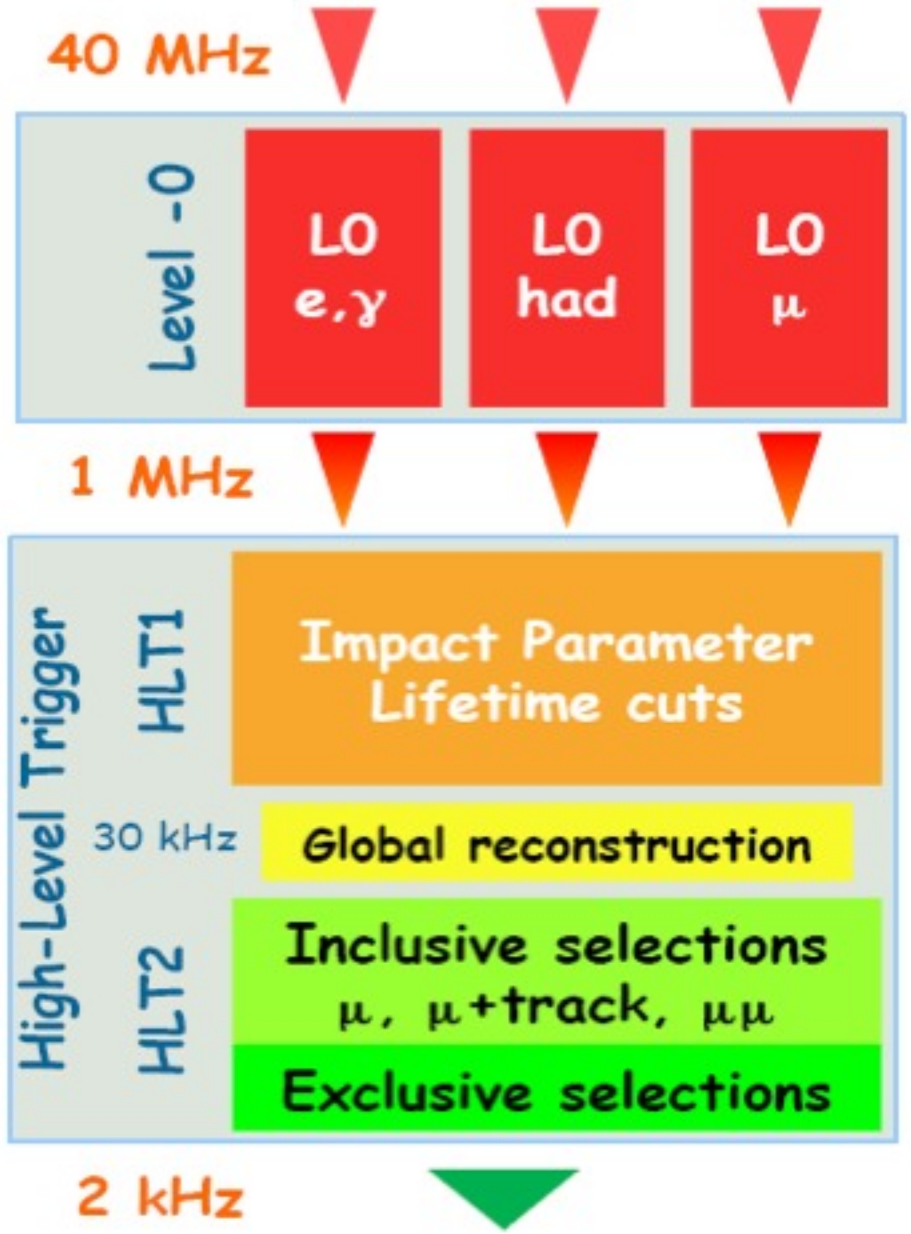
- Short term
  - Paper with branching fractions
- Medium term (2013)
  - Simplest amplitude analysis for well established decay modes: time integrated, untagged (no CPV analysis)
  - Already large amounts of information from the resonant content
  - Needs a robust Dalitz plot model
- Long term (next few years)
  - CPV in flavor specific decays
  - Untagged time dependent model
- Very long term (>2018)
  - Tagged and time dependent analysis
  - Simpler amplitude analyses for the suppressed modes

Conclusions

- We have presented the current status for $B_{(d,s)} \to K_S hh$ decays at LHCb (details at LHCb-CONF-2012-023)
- First observation of the $B_s \to K_S K \pi$ decay and confirmation for $B_d \to K_S K \pi$ decay mode.
- Evidence for the existence of $B_s \to K_S \pi\pi$ and $B_s \to K_S KK$ decay modes
- Branching fraction measurements compatible with previous measurements
- There is a clear strategy, of many steps, to proceed towards CPV measurements in these decays

BACKUP SLIDES

Trigger criteria



Bandwidth and rate limited. High transverse energy (>3.5GeV), main efficiency loss for >2-body decays in hadron triggers

Significant displacement from PV and track quality. >90% efficient

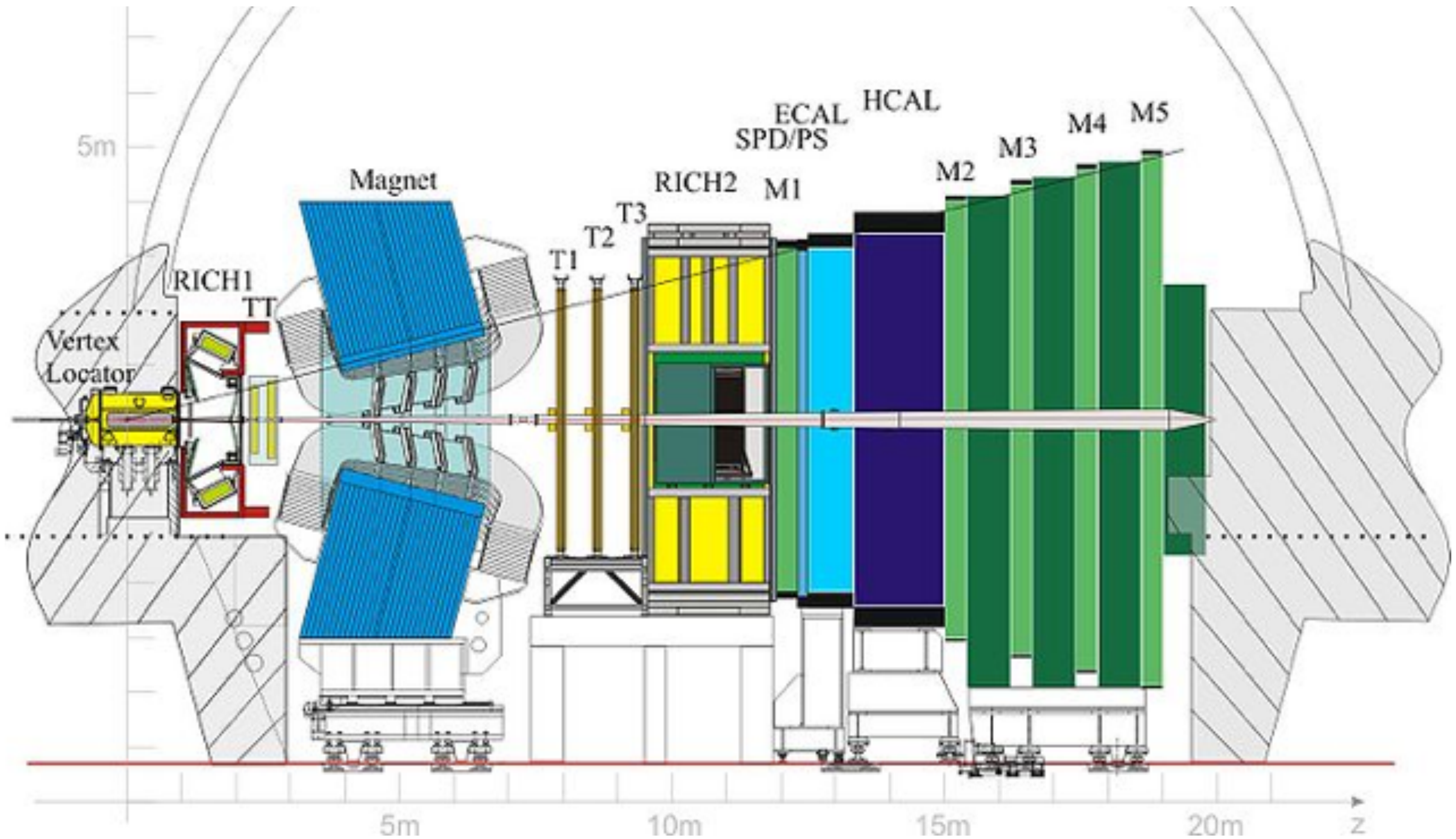
Reconstruction of B (secondary) vertices using 2, 3 and 4 tracks. Standard vertex quality and impact parameter requirement. Exploits decay topology. >90% efficient

Low hadron triggers efficiency is partially compensated by selecting trigger independent of signal, fired typically by another B decay (~50%)

LHCb experiment

- Physics goals
  - Precise CPV measurements in B and D systems
  - Rare decays
  - Spectroscopy
  - QCD/EW physics

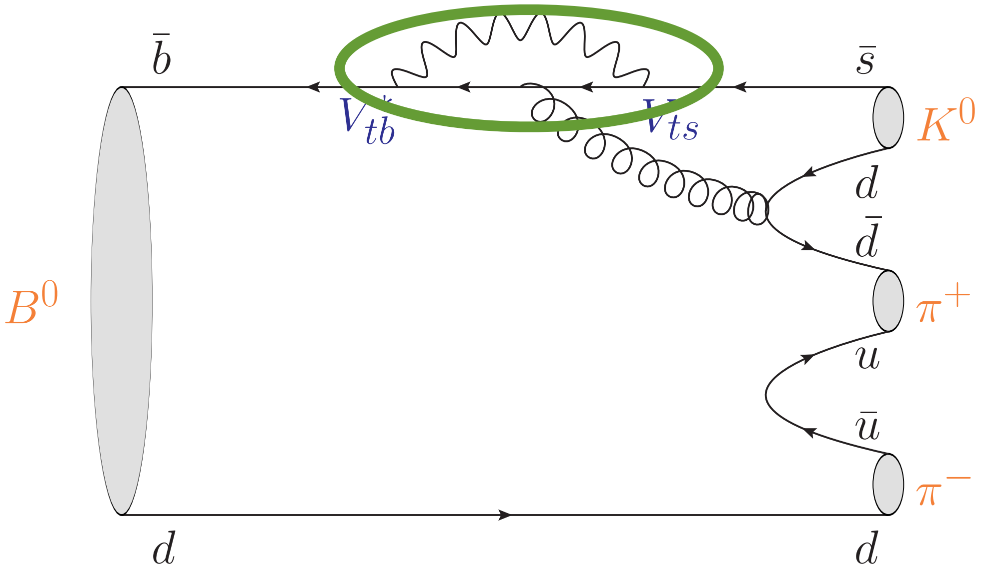
- Single-arm forward spectrometer, covers $2<\eta<5$ pseudo-rapidity range, captures ~40% of heavy quark cross-section
- High precision vertexing, tracking and PID systems
- High trigger efficiency



2010: $\int L$ = 36/pb
2011: $\int L$ = 1.0/fb
2012: $\int L$ = 2.0/fb

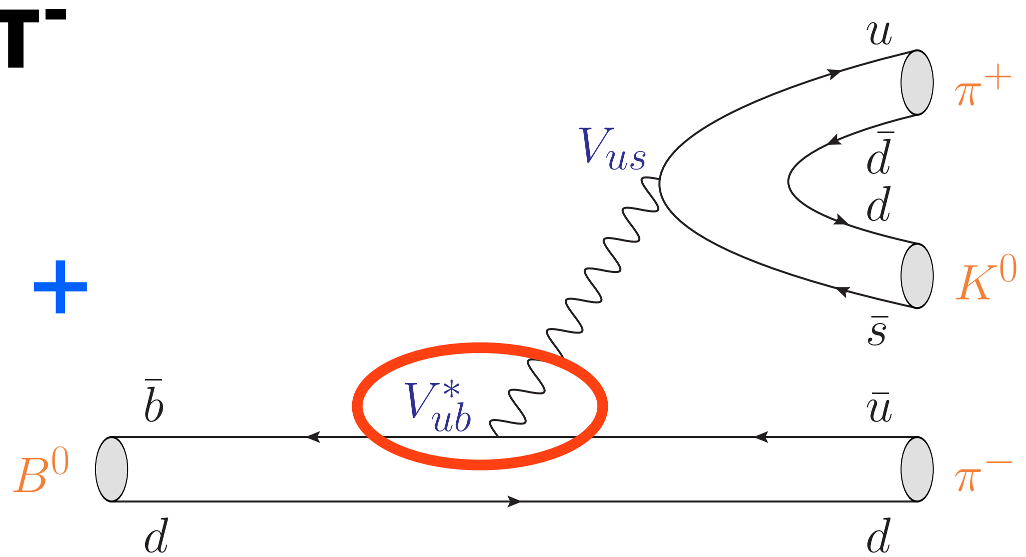
For this presentation only 2011 data was used LHCb-CONF-2012-023

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



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

\+ mixing diagrams +



Decay dominated by penguin diagrams. NP from particles in the loop can introduce additional phases in the extraction of β, ie. effect in mixing induced CP asymmetries.
From SM $b \rightarrow q\bar{q}s \sim b \rightarrow c\bar{c}s$, well known from $B^0 \rightarrow J/\psi K_S$

DCS tree level diagram, with a relative weak phase equal to γ angle. Strong relative phases and relative for each Q2B contribution might be different due to hadronic factors in the resonant content

$B_s \rightarrow K\pi\pi$ are dominated by tree diagrams (negligible penguin contribution) yielding a theoretically cleaner γ extraction, and sensibility to $\gamma+\beta_s$

Phys.Rev. D74 (2006) 051301, Phys.Rev.D75:014002,2007

Measurement of all relative phases require a full time dependent Dalitz analysis of the decay and strong phases measurements

Pre selection criteria

Important to avoid large variation of selection efficiency over the Dalitz plot.
Loose requirements in the momentum of the daughter tracks

Variable	Selection requirement
K^0_S daughter track momentum	$> 2\,\mathrm{GeV}/c$
Long-Long K^0_S flight distance	$> 30\,\mathrm{mm}$
Down-Down K^0_S daughter minimum impact parameter χ^2 wrt PVs	> 4
Long-Long K^0_S daughter minimum impact parameter χ^2 wrt PVs	> 9
Long-Long K^0_S daughter track fit χ^2/ndof	< 4
Down-Down Mass difference wrt nominal K^0_S mass	$< 30\,\mathrm{MeV}/c^2$
Long-Long Mass difference wrt nominal K^0_S mass	$< 20\,\mathrm{MeV}/c^2$
χ^2 of K^0_S vertex fit	< 12
Down-Down χ^2 separation of K^0_S vertex and the PV	> 50
Long-Long χ^2 separation of K^0_S vertex and the PV	> 80
Down-Down K^0_S momentum	$> 6\,\mathrm{GeV}/c$

$K_S \to \pi^+\pi^-$ divided into two categories: decaying inside (long-long, ~33%) and outside (down-down, ~67%) the vertex locator

Variable	Selection requirement
Sum of the daughters' transverse momenta	$> 3000\,\mathrm{MeV}/c$
p_T of at least 2 B daughters	$> 800\,\mathrm{MeV}/c$
Mass of the B candidate	$4779 < m_{K^0_S h^\pm h'^\mp} < 5866\,\mathrm{MeV}/c^2$
IP wrt PV of highest p_T B daughter	$> 0.05\,\mathrm{mm}$
Maximum DOCA χ^2 of any 2 daughters	< 5
Transverse momentum of the B candidate	$> 1500\,\mathrm{MeV}/c$
χ^2 of B vertex fit	< 12
Cosine of B pointing angle	> 0.9999
Minimum B IP χ^2 wrt PVs	< 4
Minimum vertex distance wrt PVs	$> 1\,\mathrm{mm}$
χ^2 separation of B vertex and associated PV	> 50

B candidate selection

Fit model

- **Simultaneous unbinned extended maximum likelihood fit**
  - **6 samples, 3 final states ($K_S\pi\pi$, $K_SK\pi$, K_SKK) times 2 for each K_S category**
  - **Signal: Crystal Ball functions, with common means and widths. Radiative tail parameter is shared in all samples and extracted from simulated events.**
  - **Misidentified events: Modeled as signal and yield constrained to the signal yield using misID efficiency.**
  - **Partially reconstructed decays: Threshold function convoluted with mass resolution function. From simulated events. Yield constrained fro BFs.**
  - **Combinatorial: Exponential function, with separate slopes for each K_S category**

Vetoes, BDT and PID criteria

- Background rejection using a multivariate discriminant, BDT. Flight distances, impact parameters and B transverse momenta and direction angle
- Vetoed the ±30MeV mass window, ~3 times the resolution, under the relevant particle hypothesis. Fully reconstructed $B \to$2-body decays.
  - $D^0 \to (K\pi, \pi\pi, KK)$, $D^+ \to (K_S K, K_S\pi)$, $D_s^+ \to (K_S K, K_S\pi)$, $\Lambda_c \to pK_S$
  - $J/\psi \to (\pi\pi, \mu\mu, KK)$, $\chi_{c0} \to (\pi\pi, \mu\mu, KK)$
- PID applied on top of the selection
  - Tracks decaying in flight are removed
  - Logarithm of the likelihood ratio of different particle hypothesis, ΔLL, mostly based in Cherenkov detector information
  - For pions $\Delta LL(K-\pi)<0$ and $\Delta LL(p-\pi)<10$
  - For kaons $\Delta LL(K-\pi)>5$ and $\Delta LL(p-K)<10$
  - Efficiency of ~85-90% and mis-ID ~5-10% for single tracks