$B_d \rightarrow D\pi$ time dependent analysis

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on behalf of the $B \rightarrow D\pi$ group

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Padova, B2OC Time Dependent Workshop, 09/07/2015

Outline

Introduction

The $B_d \to D\pi$ TD analysis group

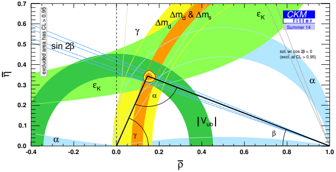
Dortmund

- Ulrich Eitschberger, Alex Birnkraut, Julian Wishahi.
- Selection, Flavour Tagging.

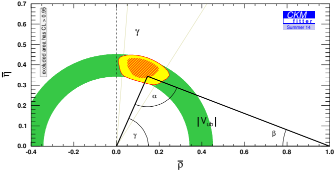
Lausanne

- Conor Fitzpatrick, Mirco Dorigo, Vincenzo Battista.
- Fit, Flavour tagging.

- γ is the least known among the CKM angles.
- Global fit:
  - $\left(67.08^{+0.97}_{-2.17}\right)^\circ$
- Direct measurements:
  - $\left(73.2^{+6.3}_{-7.0}\right)^\circ$
- Better precision is required to constraint New Physics.
- The γ measurement is driven by DK decays (better sensitivity), but the very high statistics in $D\pi$ decays can be exploited as well.
- We expect $\approx 490k\ B_d \rightarrow D\pi$ events in 3 fb^{-1}.



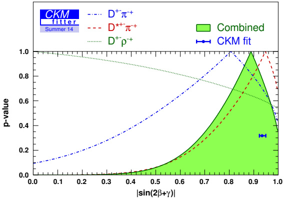
Global CKM fit



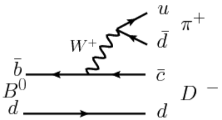
CKM fit with trees (only $\gamma(DK)$ used)

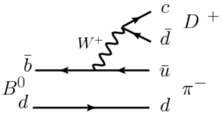
$B_d \to D\pi$ decays

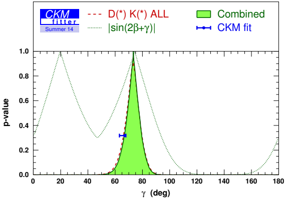
- Non *flavour-specific* decays: $B^0 \to D^{\pm}\pi^{\mp}$, $\bar{B}^0 \to D^{\pm}\pi^{\mp}$ (four decay modes).
- Theoretically clean way to measure the CKM angle γ.
- Some inputs required:
  - CKM angle β (experimentally well known).
  - Ratio $r = \left|\frac{A[\bar{B}^0 \to D^- \pi^+]}{A[B^0 \to D^- \pi^+]}\right|$ (estimated $\approx 2\%$).



World average of $\sin(2\beta + \gamma)$







World average of γ (using 2β as an external input)

Selection

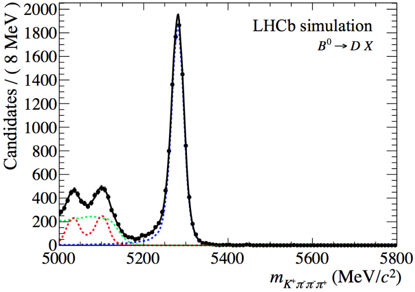
$B_d \to D\pi$ selection (1)

- A cut and mass vetoes based selection has been implemented (now under optimization):
  - Reco 14, Stripping 20 and 20r1, both magnet polarities combined.
  - Stripping line: /BhadronCompleteEvent/Phys/B02DPiD2HHHBeauty2CharmLine
- Rectangular cut efficiencies:

Cut	Signal efficiency (MC)
B0_DIRA_OWNPV> 0.9999	0.9860
B0_IPCHI2_OWNPV< 16	0.9912
obsDminusTime> 0	0.9766
Dminus_FDCHI2_ORIVX> 1	0.9634
Dminus_IPCHI2_TOPPV> 1	0.9634
$1845 <$obsMassDminus< 1895	0.9755
piplus_isMuon$! = 1$	0.9882
piplus_PIDK< 2	0.9523
piminus_IPCHI2_OWNPV> 9	0.9853
piminus0_IPCHI2_OWNPV> 9	0.9848
Kplus_IPCHI2_OWNPV> 9	0.9833
piminus_PIDK< 5	0.9599
piminus0_PIDK< 5	0.900
Kplus_PIDK> 0	0.9667
Total	0.7087

$B_d \to D\pi$ selection (2)

- The following mis-ID background contaminate the sample:
  - $B_s \to D_s(\to KK\pi)\pi$
  - $\Lambda_b \to \Lambda_c(\to K\pi p)\pi$
- Cuts on $PID_{K/p} - PID_\pi$ and $KK\pi/Kp\pi$ invariant masses are applied.
- Resulting, total signal efficiency: 65.86%.
- Events for m_{B_d} in [5200, 5500] MeV:
  - $\approx$ 490.000 signal candidates.
  - $\approx$ 31.000 background candidates.
- Low mass background ($B_d \to D^*\pi$, $B_d \to D\rho$) present as well.
- Combinatorial suppressed, $B_d \to DK$ negligible.
- Further improvements and studies are ongoing.



Time-dependent decay rates

Quantum mechanics of $B^0 \to D^{\pm}\pi^{\mp}$ decays

- Initial flavour B^0 or $\bar{B}^0$, no CPV in mixing, final state f ($D^+\pi^-$ *or* $D^-\pi^+$):

$$\frac{d\Gamma(B^0 \to f)}{dt}(t) = \frac{1}{4\tau}e^{-t/\tau}\Big[\cosh\left(\frac{\Delta\Gamma_d t}{2}\right) - D_f \sinh\left(\frac{\Delta\Gamma_d t}{2}\right) + C_f \cos\left(\Delta m_d t\right) - S_f \sin\left(\Delta m_d t\right)\Big],$$

$$\frac{d\Gamma(\bar{B}^0 \to f)}{dt}(t) = \frac{1}{4\tau}e^{-t/\tau}\Big[\cosh\left(\frac{\Delta\Gamma_d t}{2}\right) - D_f \sinh\left(\frac{\Delta\Gamma_d t}{2}\right) - C_f \cos\left(\Delta m_d t\right) + S_f \sin\left(\Delta m_d t\right)\Big],$$

- CP coefficients (for $\bar{f}$, just put $S_{\bar{f}}$ and $D_{\bar{f}}$ in the decay rate equation):

$$S_f = \frac{2r\sin[\Delta - (\gamma + 2\beta)]}{1 + r^2}, \qquad S_{\bar{f}} = \frac{2r\sin[\Delta + (\gamma + 2\beta)]}{1 + r^2},$$

$$D_f = \frac{2r\cos[\Delta - (\gamma + 2\beta)]}{1 + r^2}, \qquad D_{\bar{f}} = \frac{2r\cos[\Delta + (\gamma + 2\beta)]}{1 + r^2},$$

$$C = \frac{1 - r^2}{1 + r^2},$$

- *Flavour Tagging* and *asymmetries* (production, detection and FT efficiency) can be implemented with the DecRateCoeff class.

Effective CP coefficients from DecRateCoeff

- Given $c_f = S_f, D_f$ or C, the effective coefficient c_{eff} is given by:

$$c_{eff}(q_t = 0) = (1 + q_f a_{det})\{(1 + a_{prod})[1 - \epsilon_{tag}(1 + a_{tageff})]U(\eta)\alpha(+1, q_f) + (1 - a_{prod})[1 - \epsilon_{tag}(1 - a_{tageff})]U(\eta)\alpha(-1, q_f)\};$$

$$c_{eff}(q_t = +1) = (1 + q_f a_{det})\{(1 + a_{prod})\epsilon_{tag}(1 + a_{tageff})P(\eta)(1 - \omega(\eta))\alpha(+1, q_f) + (1 - a_{prod})\epsilon_{tag}(1 - a_{tageff})P(\eta)\bar{\omega}(\eta)\alpha(-1, q_f)\};$$

$$c_{eff}(q_t = -1) = (1 + q_f a_{det})\{(1 + a_{prod})\epsilon_{tag}(1 + a_{tageff})P(\eta)\omega(\eta)\alpha(+1, q_f) + (1 - a_{prod})\epsilon_{tag}(1 - a_{tageff})P(\eta)(1 - \bar{\omega}(\eta))\alpha(-1, q_f)\}.$$

- CP even coefficient (D_f):

$$\alpha(q_i, +1) = c_f, \qquad \alpha(q_i, -1) = c_{\bar{f}}.$$

- CP odd coefficients (C_f, S_f):

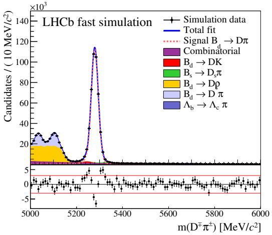
$$\alpha(q_i, +1) = q_i c_f, \qquad \alpha(q_i, -1) = -q_i c_{\bar{f}}.$$

Toy studies

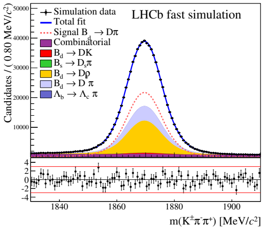
Introduction

- Need to check fit stability, biases, sensitivity...
- Strategy:
  - fit to B_d and D mass distributions;
  - fit to the *sWeighted* proper time distribution.
- Full simulation takes into account:
  - Time resolution (per-event error or average model)
  - Acceptance (or *time-dependent efficiency*)
  - Flavour tagging:
    - mistag calibrations $(p_0, p_1, \langle\eta\rangle)$ for B^0 and $\bar{B}^0$
    - mistag distributions
    - tagging efficiency (with asymmetry)
  - One or more *exclusive* taggers can be handled and combined by DecRateCoeff.

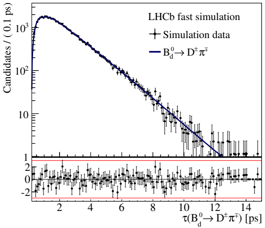
Fit to a toy sample



B_d mass



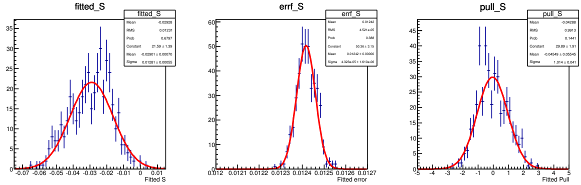
D mass



B_d proper time

Pull distributions-signal only (1)

- No background (cFit to signal only)
- Acceptance, mean resolution, asymmetries, FT included.
- Gaussian-like, unbiased pull distributions with $\sigma \approx 1$.



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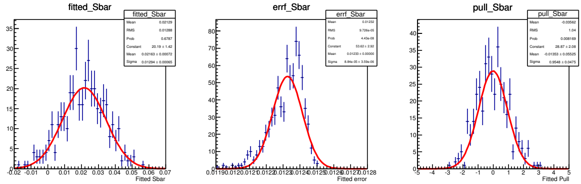
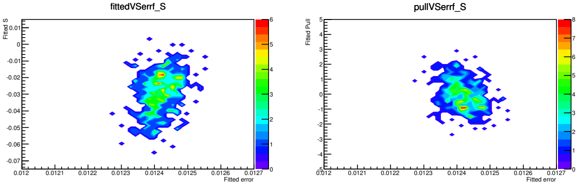


$\bar{S}$

Pull distributions-signal only (2)

- No background (cFit to signal only)
- Acceptance, mean resolution, asymmetries, FT included.
- No "hidden" structures in the pull distributions



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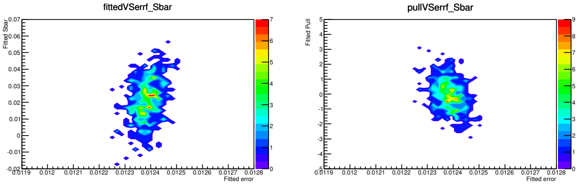
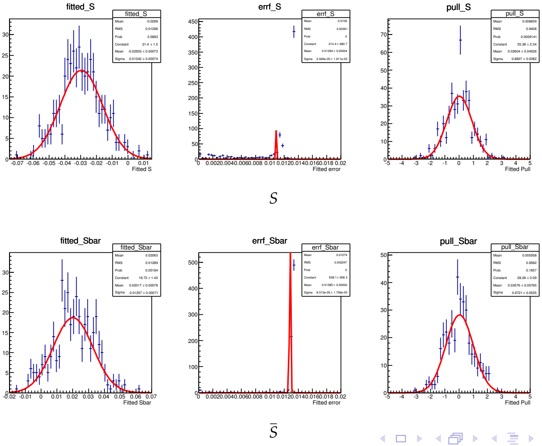


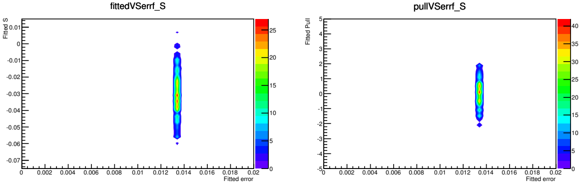
$\bar{S}$

- sFit to *sWeighted* proper time distribution
- Acceptance, mean resolution, asymmetries, FT included.
- Gaussian-like, unbiased pull distributions.
- Many toys have uncertainty underestimated: scale factor $s_W = \Sigma_i W_i / \Sigma_i W_i^2$ in the log-likelihood required.



Pull distributions-signal+background (2)

- sFit to *sWeighted* proper time distribution
- Acceptance, mean resolution, asymmetries, FT included.
- No "hidden" structures in the pull distributions



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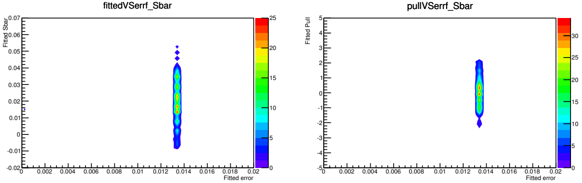


$\bar{S}$

Summary

- First estimation of sensitivity on S_f, $S_{\bar{f}}$:

Parameter	Mode	Mean value	Mean error
S_f	No Bkg	-0.02901 ± 0.00070	0.01242 ± 0.00001 ($\approx 43\%$)
$S_{\bar{f}}$	No Bkg	0.02163 ± 0.00072	0.01233 ± 0.00001 ($\approx 57\%$)
S_f	sFit	-0.02953 ± 0.00073	0.01094 ± 0.00004 ($\approx 37\%$)
$S_{\bar{f}}$	sFit	0.02017 ± 0.00078	0.01285 ± 0.00002 ($\approx 63\%$)

- We look forward to adopt the GammaCombo package to translate these numbers into a sensitivity on γ.

Job parallelization

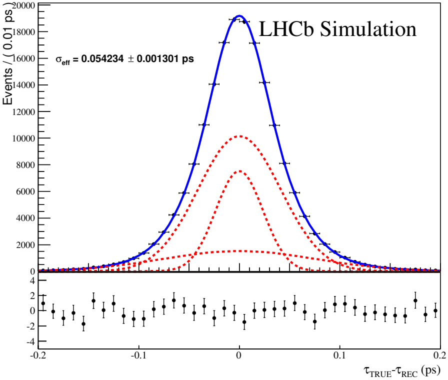
- Toy generation and fitting can be (quite) time consuming:
  - Time fit (full model with average resolution): $\approx$ 1 hour per toy.
- Simple (bash) scripts to parallelize jobs on CERN LSF batch system have been written:
  - Standard "bsub" command.
  - One or more toy per job.
  - Can select queue (1nh, 8nh, 1nd etc...), number of cores per job, reserved memory space.
- Output (root files, log files) is automatically dumped on EOS.

```
[vibattis@lxplus0088 ~]$ bqueues -u vibattis
QUEUE_NAME      PRIO STATUS          MAX JL/U JL/P JL/H NJOBS  PEND   RUN  SUSP
test             99  Open:Active       -    1    -    -     1     0     1     0
8nm              46  Open:Active       -  200    -    -    18     0    18     0
1nh              42  Open:Active       - 10000    -    -    83    47    36     0
8nh              24  Open:Active       -    -    -    -  7823  5274  2549     0
1nd              23  Open:Active       -    -    -    - 36396 34364  2032     0
2nd              22  Open:Active       -    -    -    - 23702 19260  4442     0
1nw              21  Open:Active    5000    -    -    - 11618  6620  4998     0
2nw              21  Open:Active    4500    -    -    - 14974 11463  3511     0
```

Monte Carlo (Reco 14, Stripping 21)

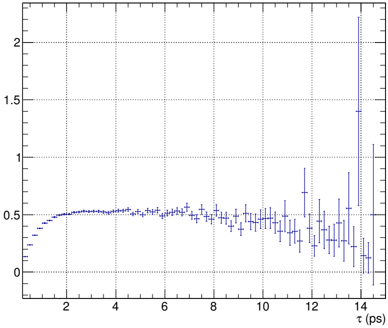
Time resolution

- Definition: $\tau_{TRUE} - \tau_{RECO}$.
- First estimate of time resolution on Stripping 21 Monte Carlo.
- Final selection not yet applied (still under development).
- Model: triple-Gaussian distribution.
- Cut on $\tau_{ERR} < 100$ fs to suppress tails.
- Effective resolution: $\sigma_{eff} = \sqrt{f_1\sigma_1^2 + f_2\sigma_2^2 + (1 - f_1 - f_2)\sigma_3^2}$



Acceptance

- Simplest approach; ratio between the following histograms:
  - τ_{TRUE} distribution from (official LHCb) MC;
  - Toy sample without acceptance.
- Can be parametrized by a cubic spline PDF (RooCubicSplineFun class already implemented in B2DXFitters package).



Conclusions

Conclusions

- Analysis ongoing; we look forward for the final selection and the data sample.
- Our experience with the B2DXFitters package:
  - Awesome environment, lot of useful tools.
  - DecRateCoeff class allows to build very complicated PDFs in few lines of code.
  - Excellent timing performances.
- However:
  - The effective CP coefficients comes out from a "black box"; we're happy to learn as much as possible about that in this workshop.
  - Flavour tagging implementation is not completely crystal clear:
    - ntuples require a "pre-calibration" before they can be used.

Thank you

Backup

Motivations for $B^0 \to D^{\pm}\pi^{\mp}$

- Angle β well known from the *golden mode* $B^0 \to J/\psi K_S$: $\beta = \left(21.89^{+0.74}_{-0.77}\right)^{\circ}$.
- From β, the angles α and/or γ can be determined.
- Angle α affected by uncertainties:
  - $\sin 2\alpha$ from time-dependent $B^0 \to \pi^+\pi^-$: non-negligible penguin-pollution.
  - $\sin 2\alpha$ from $B^0 \to \pi^0\pi^0$: extremely challenging in a hadron collider.
- On the other hand, γ can be extracted (together with Δ) from $B^0 \to D^{\pm}\pi^{\mp}$ decays, where *tree level* amplitudes occur.
- Strong phase Δ:
  - It comes out from (CP conserving) intermediate strong interactions (*rescattering*).
  - First order (*tree level*): color-allowed spectator diagrams ($\Delta = 0$).
  - Higher orders: non-factorizable contributions ($\Delta \neq 0$ but small).
- Reference: I. Dunietz, *Clean CKM information from $B_d \to D^{*\mp}\pi^{\pm}$*, Phys. Lett. **B247** (1998) 179–182.

Estimate of the r ratio

- The $B^0 \to D^{\pm}\pi^{\mp}$ and $B^0 \to D_s^{\pm}\pi^{\mp}$ are related by SU(3) symmetry.
- Up to SU(3) breaking effects, the following equality holds:

$$r = \tan\theta_c \frac{f_D}{f_{D_s}} \sqrt{\frac{\mathcal{B}(B^0 \to D_s^+\pi^-)}{\mathcal{B}(B^0 \to D^-\pi^+)}}.$$

- Using inputs from branching ratio measurements and lattice QCD calculations, an estimation is:

$$r = 0.021 \pm 0.004 \pm 0.006,$$

  where the last uncertainty accounts for SU(3) breaking effects.
- Reference: Belle Collaboration, *Measurement of CP violation in $B^0 \to D^{*-}\pi^+$ and $B^0 \to D^-\pi^+$ decays*, Phys. Rev. **D73**, 092003 (2006).

Quantum mechanics of $B^0 \to D^\pm \pi^\mp$ decays (1)

- The time evolution of $|\psi(t)\rangle$, initially built as $|\psi(0)\rangle = a(0)\,|B^0\rangle + b(0)\,|\bar{B}^0\rangle$, can be described by a 2×2 complex Hamiltonian H:

$$H = M - \frac{i}{2}\Gamma,$$

where the two Hermitian matrices M and Γ are the *mass* and the *decay* matrix respectively.

- If CPT invariance holds, the *eigenstates* $|B_L\rangle$ (*low mass*) and $|B_H\rangle$ (*high mass*) of H can be written as:

$$|B_L\rangle = p\,|B^0\rangle + q\,|\bar{B}^0\rangle, \qquad |B_H\rangle = p\,|B^0\rangle - q\,|\bar{B}^0\rangle, \qquad |p|^2 + |q|^2 = 1.$$

- For B^0 ($\bar{B}^0$) mesons, $\left|\frac{p}{q}\right| = 1$ is a good approximation (no CP violation *in mixing*).
- The following quantities can be also defined:

$$\Delta m_d = m_H - m_L \qquad \Delta\Gamma_d = \Gamma_L - \Gamma_H, \qquad \tau = \left(\frac{\Gamma_L + \Gamma_H}{2}\right)^{-1}.$$

- Current measurements: $\Delta m_d = 0.510 \pm 0.003\ \text{ps}^{-1}$, $\tau = 1.519 \pm 0.005$ ps , $\Delta\Gamma_d$ compatible with zero.

- Amplitudes:

$$A_f = \langle f|T|B^0\rangle, \qquad \bar{A}_f = \langle f|T|\bar{B}^0\rangle,$$

$$\lambda_f = \frac{q}{p}\frac{\bar{A}_f}{A_f} = re^{i(\Delta-2\beta-\gamma)}, \qquad \bar{\lambda}_{\bar{f}} = \frac{p}{q}\frac{A_{\bar{f}}}{\bar{A}_{\bar{f}}} = re^{i(\Delta+2\beta+\gamma)},$$

- CP coefficients:

$$C_f = \frac{1-|\lambda_f|^2}{1+|\lambda_f|^2}, \qquad S_f = \frac{2Im(\lambda_f)}{1+|\lambda_f|^2}, \qquad D_f = \frac{2Re(\lambda_f)}{1+|\lambda_f|^2},$$

$$C_{\bar{f}} = \frac{1-|\bar{\lambda}_{\bar{f}}|^2}{1+|\bar{\lambda}_{\bar{f}}|^2}, \qquad S_{\bar{f}} = \frac{2Im(\bar{\lambda}_{\bar{f}})}{1+|\bar{\lambda}_{\bar{f}}|^2}, \qquad D_{\bar{f}} = \frac{2Re(\bar{\lambda}_{\bar{f}})}{1+|\bar{\lambda}_{\bar{f}}|^2}.$$

- In the B^0 meson system, $|q/p| = 1$.
- CPT invariance: $|\bar{A}_f| = |A_{\bar{f}}|$, $|\bar{A}_{\bar{f}}| = |A_f|$, thus $|\lambda_f| = |\bar{\lambda}_{\bar{f}}| = r$.

Flavout tagging calibration

- Calibration curves:

$$\omega(\eta) = p_0 + \frac{\Delta p_0}{2} + (p_1 + \frac{\Delta p_1}{2})(\eta - \langle\eta\rangle),$$
$$\omega(\eta) = p_0 - \frac{\Delta p_0}{2} + (p_1 - \frac{\Delta p_1}{2})(\eta - \langle\eta\rangle).$$

- Calibration channels:
  - OS standard combination: $B_s^0 \to D_s^- \pi^+$, $B^0 \to D^* \mu\nu$, $B^0 \to J/\psi K^*$, $B^+ \to D^0 \pi^+$, $B^+ \to J/\psi K^+$.
  - SSπ: $B^0 \to J/\psi K^*$.

$p_0 - \langle\eta\rangle$	$0.0062 \pm 0.0019 \pm 0.0040$
$\Delta p_0/2$	0.0070 ± 0.0006
p_1	$0.982 \pm 0.007 \pm 0.034$
$\Delta p_1/2$	0.033 ± 0.006

OS calibration.

				stat.		type 1 syst.		type 2 syst. for $B^0 \to J/\psi K_s$
p_0	=	0.4232	±	0.0029	±	0.0020	±	0.0019
p_1	=	1.011	±	0.064	±	0.009	±	0.030
Δp_0	=	-0.0026	±	0.0043	±	0.0024	±	0.0013
Δp_1	=	-0.171	±	0.096	±	0.029	±	0.027

SSπ calibration.