

Study of penguin's contribution in the measurement of the phase ϕ_s in $B_s^0 \rightarrow J/\psi\phi$ decays at LHCb

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Outline

- 1 Introduction
- 2 LHCb detector at LHC
- 3 Analysis of penguin's contribution in $B_s^0 \rightarrow J/\psi\phi$
- 4 Phenomenological interpretation
- 5 Conclusions and prospects

Standard Model

Three generations of matter (fermions)			
I	II	III	
mass – 2.3 MeV/c charge – $\frac{2}{3}$ spin – $\frac{1}{2}$ name – u up	1.28 GeV/c $\frac{2}{3}$ $\frac{1}{2}$ c charm	173.5 GeV/c $\frac{2}{3}$ $\frac{1}{2}$ t top	0 0 1 γ photon
4.8 MeV/c $-\frac{1}{2}$ $\frac{1}{2}$ d down	95.5 MeV/c $-\frac{1}{3}$ $\frac{1}{2}$ s strange	4.18 GeV/c $-\frac{1}{3}$ $\frac{1}{2}$ b bottom	0 0 1 g gluon
<2 eV/c 0 $\frac{1}{2}$ ν_e electron neutrino	<0.19 MeV/c 0 $\frac{1}{2}$ ν_μ muon neutrino	<18.2 MeV/c 0 $\frac{1}{2}$ ν_τ tau neutrino	91.2 GeV/c 0 1 Z^0 Z boson
0.511 MeV/c -1 $\frac{1}{2}$ e electron	105.7 MeV/c -1 $\frac{1}{2}$ μ muon	1,777 GeV/c -1 $\frac{1}{2}$ τ tau	80.4 GeV/c ± 1 1 W^\pm W boson
Gauge bosons			~125 GeV/c 0 0 H Higgs boson
Higgs boson (to be confirmed)			

Successes and limits

- Standard Model: describes particles and their interactions
- Validated by the experience so far
- **But** many questions remain unanswered:
 - mass hierarchy of elementary particles
 - predominance of matter on anti-matter...

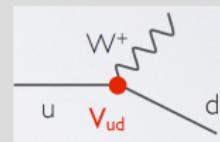
⇒ We search for New Physics beyond the Standard Model

CP Violation?

CKM Matrix

- CKM matrix accounts for CP violation and quark mixing

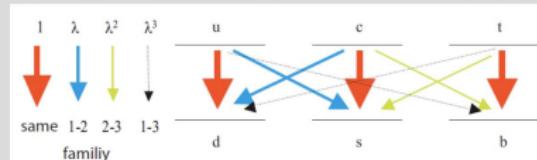
$$\begin{pmatrix} d \\ s \\ b \end{pmatrix}^{\text{saveur}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}^{\text{masse}}$$



- Wolfenstein parametrization of the CKM matrix:

$$V_{CKM} = \begin{pmatrix} 1 - \lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \lambda^2/2 & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

- $\lambda \sim 0.22$



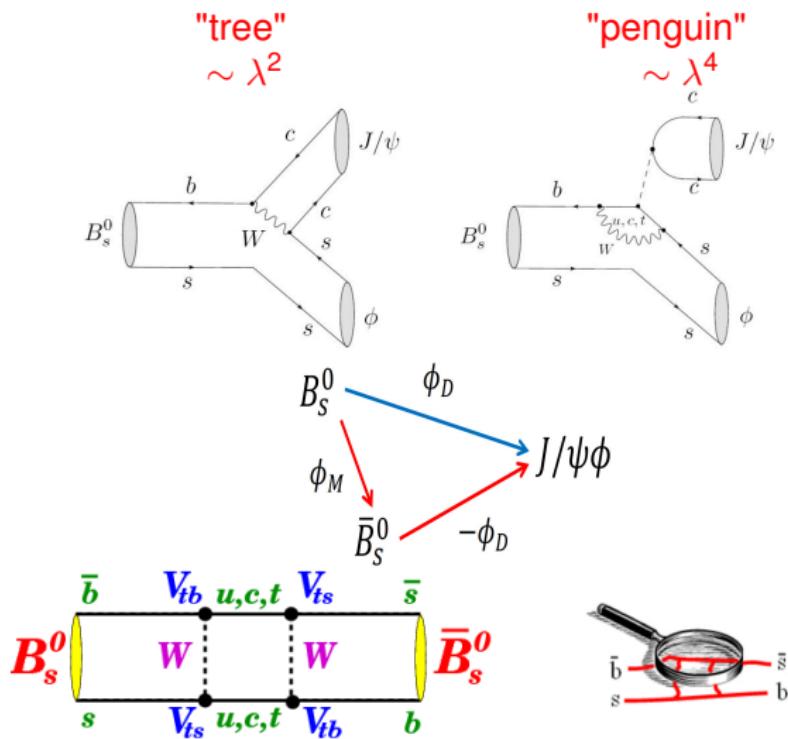
CP violating phase ϕ_s in $B_s^0 \rightarrow J/\psi\phi$ decay

Interference between B_s^0 decaying directly to $J/\psi\phi$
OR first oscillates to \bar{B}_s^0 and then decays to the same final state.

$$\phi_s = \phi_M - 2\phi_D = -2\beta_s + \Delta\phi_s^{\text{peng}} + \delta^{\text{NP}}$$

$$\beta_s = \arg\left(-\frac{V_{ts} V_{tb}^*}{V_{cs} V_{cb}^*}\right)$$

$$\lambda \sim 0.22$$



WHAT?

Study of penguin contributions in the measurement of the CP violating phase ϕ_s in $B_s^0 \rightarrow J/\psi \phi$ decays

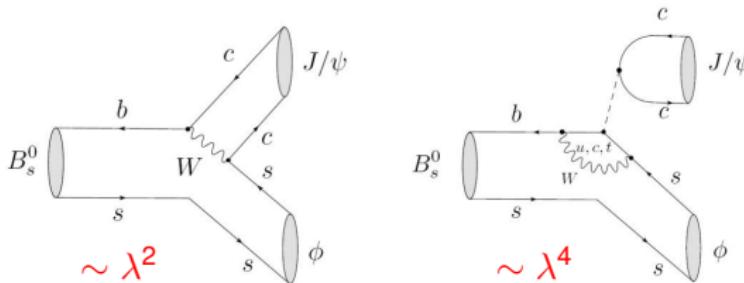
WHY?

- Indirect SM determination via global fits to experimental data, ignoring penguins: $\phi_s^{\text{SM no Peng}} = -2\beta_s = -0.0364 \pm 0.0016$
- $\phi_s^{\text{LHCb}}(1 \text{ fb}^{-1}) = 0.01 \pm 0.07(\text{stat}) \pm 0.01(\text{syst})$
- With LHCb upgrade, $\sigma_{\phi_s} \simeq 0.008 \Rightarrow$ mandatory to estimate penguin contribution to disentangle SM effects from possible NP!

HOW?

Estimate the penguin's contribution using
the control channel $B_s^0 \rightarrow J/\psi \bar{K}^{*0}$ [Faller,arXiv:0810.4248]

The $B_s^0 \rightarrow J/\psi \phi$ channel

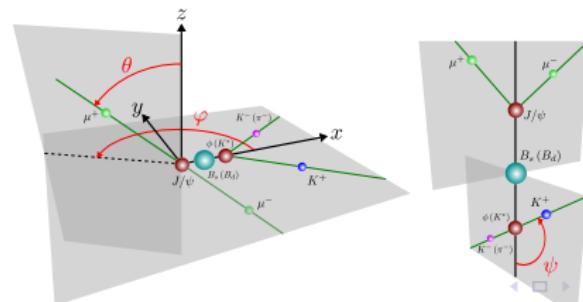


$b \rightarrow c\bar{c}s$

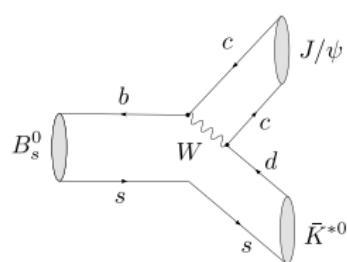
penguins suppressed by λ^2
relative to tree

a_i and θ_i : penguin's parameter for $B_s^0 \rightarrow J/\psi \phi$

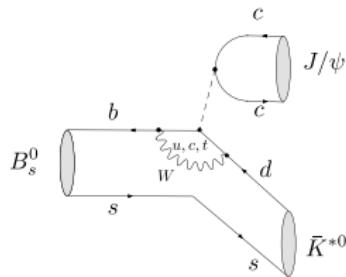
$a_i e^{i\theta_i} \simeq$ "Penguin/Tree ratio", polarization of final states: $i = 0, \perp, \parallel$
 $\lambda \sim 0.22$



The control channel $B_s^0 \rightarrow J/\psi \bar{K}^{*0}$



$\sim \lambda^2$



$\sim \lambda^2$

$$b \rightarrow c\bar{c}d$$

penguins are not suppressed relative to tree

a'_i and θ'_i : penguin parameters for $B_s^0 \rightarrow J/\psi \bar{K}^{*0}$
 $i = 0, \perp, \parallel, \lambda \sim 0.22$

Connecting $B_s^0 \rightarrow J/\psi \phi$ and $B_s^0 \rightarrow J/\psi \bar{K}^{*0}$

- Penguin parameters:
 - a_i and θ_i for $B_s^0 \rightarrow J/\psi \phi$
 - a'_i and θ'_i for $B_s^0 \rightarrow J/\psi \bar{K}^{*0}$
- Approximations of SU(3) flavour (quarks u, d, s are identical)

$$a_i = a'_i, \quad \theta_i = \theta'_i$$

$i = 0, \perp, \parallel$

Effect of penguin processes

- Shift on ϕ_s due to penguin diagrams

$$\tan(\Delta\phi_s^{i,\text{peng}}) = f(a_i, \theta_i)$$

$i = 0, \perp, \parallel$

What do we measure?

Observables

We have 2 observables for each polarization ($i = 0, \perp, \parallel$):

- The observable H_i

$$H_i = \frac{1 - 2a_i \cos \theta_i \cos \gamma + a_i^2}{1 + 2\epsilon a_i \cos \theta_i \cos \gamma + \epsilon^2 a_i^2} = \frac{1 - \lambda^2}{\lambda^2} \left| \frac{\mathcal{A}_i}{\mathcal{A}'_i} \right|^2 \frac{f_{J/\psi K^*}^i \cdot BR(B_s^0 \rightarrow J/\psi \bar{K}^{*0})}{f_{J/\psi \phi}^i \cdot BR(B_s^0 \rightarrow J/\psi \phi)}$$

- Direct CP violation in $B_s^0 \rightarrow J/\psi \bar{K}^{*0}$

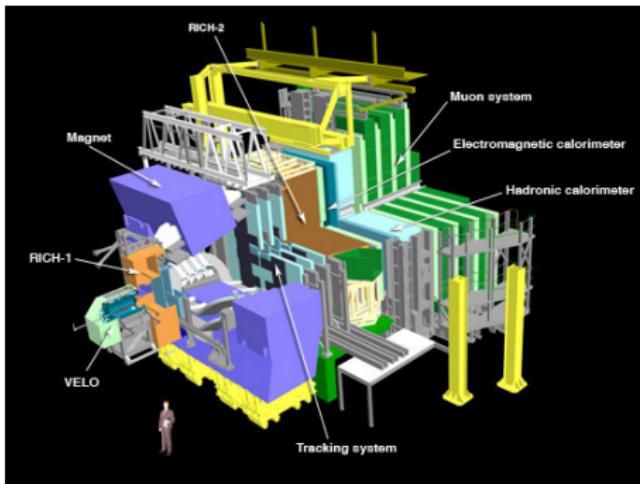
$$A_i^{CP} = \frac{2a_i \sin \theta_i \sin \gamma}{1 - 2a_i \cos \theta_i \cos \gamma + a_i^2} = \frac{\Gamma_{\bar{B}_s^0}^i - \Gamma_{B_s^0}^i}{\Gamma_{\bar{B}_s^0}^i + \Gamma_{B_s^0}^i}$$

H_i and A_i^{CP} form a non trivial system of two equations with two unknowns : a_i and $\theta_i \Rightarrow \Delta \phi_s^{i, \text{peng}}$

LHCb detector

- **LHC:** Large Hadron Collider

- 1 fb^{-1} , collected in 2011 at $\sqrt{s} = 7 \text{ TeV}$
- 2 fb^{-1} , collected in 2012 at $\sqrt{s} = 8 \text{ TeV}$

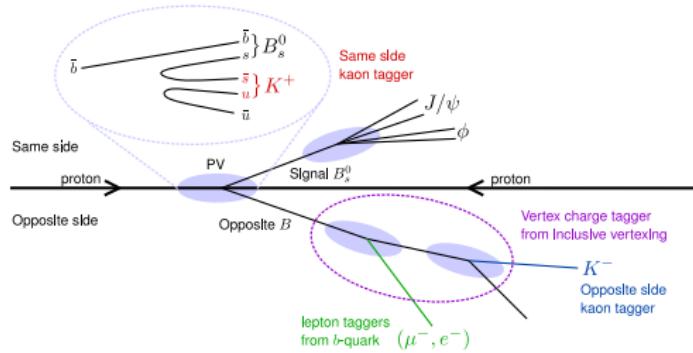


LHCb

- Physics program:
 - CP violation (beauty/charm)
 - Rare decays
- Forward geometry:
 - **VELO:**
Vertex reconstruction ($\sigma_{IP} \sim 14 \mu\text{m}$)
proper time measurement ($\sigma_t \sim 40 \text{ fs}$)
 - **Tracker & magnet**
track's reconstruction & momenta
($\delta p/p \sim 0.4\%$)
 - **2 RICH:** $K - \pi$ identification
 $2 \rightarrow 100 \text{ GeV}/c$
 - **Calorimeters:**
energy measurement, identify π^0, γ
 - **Muon systems:**
detect & reconstruct μ

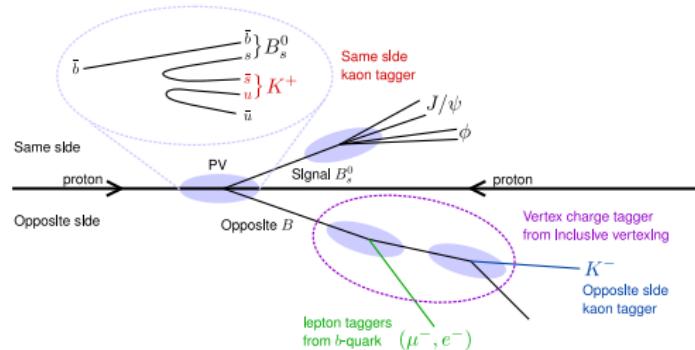
Opposite-side taggers (OST)

- $p\bar{p}$ collisions at LHC \Rightarrow production of b quarks, always created in pairs, $b\bar{b}$
- Uses the Opposite $B_s^0(\bar{B}_s^0)$ to determine the flavour of the Signal $B_s^0(\bar{B}_s^0)$
- μ, e from semi-leptonic modes, Kaon (K) from $b \rightarrow c \rightarrow s$, inclusive secondary vertex form B decay products



Same-side Kaon tagger (SSKT)

- Exploits the hadronization process of the $b(\bar{b})$ quark forming the Signal $B_s^0(\bar{B}_s^0)$
- b quark fragmentation $\Rightarrow s$ quark available to form a hadron which leads to a **charged kaon (K)**



Tagging algorithms

- Use mainly the **charge** of the taggers to identify each reconstructed event as either a B_s^0 ($q = +1$) or a \bar{B}_s^0 ($q = -1$) at production
- Calculate the probability that the tagging determination is wrong (**predicted mistag η**) using simulated events and then calibrate with real data.
- Determine tagging **efficiency (ϵ)** and **tagging power (ϵD^2)**, which represents the effective reduction of the signal sample size due to tagging

	Mistag	Efficiency	Tagging power
OST	39.2%	$(33.0 \pm 0.3)\%(\text{stat})$	$(36.8 \pm 0.2)\%(\text{stat})$
SSKT	35.0%	$(10.3 \pm 0.2)\%(\text{stat})$	$(0.9 \pm 0.2)\%(\text{stat})$
Total	35.9%	$(39.4 \pm 0.3)\%$	$(3.1 \pm 0.1 \pm 0.2)\%$

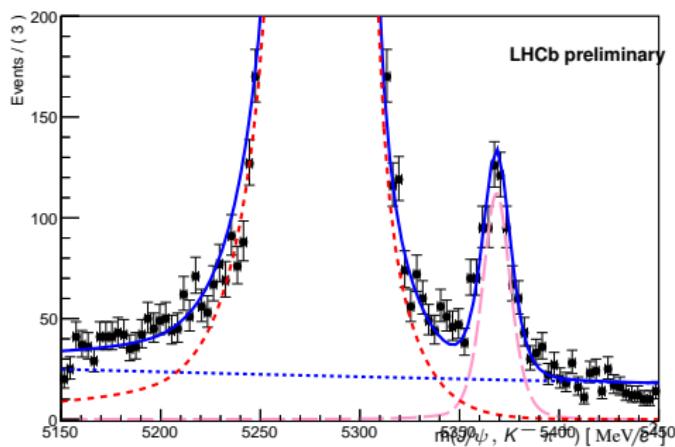
Analysis of penguin's contribution in $B_s^0 \rightarrow J/\psi \phi$

Analysis Methodology

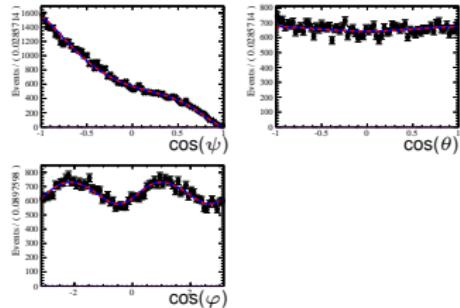
- The control channel $B_s^0 \rightarrow J/\psi \bar{K}^{*0}$ is a P2VV decay \Rightarrow angular analysis required to disentangle the polarization amplitudes
- Presence of P and S-wave in the $K\pi$ system
- Fit to mass, angles and split into $K^+\pi^-$ and $K^-\pi^+$ to extract:
 - polarization amplitudes and phases
 - polarization-dependent CP asymmetries
- Starting point [LHCb, PRD.86(2012)071102]: 0.37 fb^{-1} of $B_s^0 \rightarrow J/\psi \bar{K}^{*0}$ analyzed to extract BR and polarization fractions

Fit 2011+2012 real data (Preliminary!)

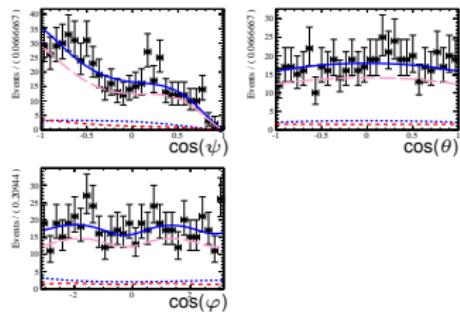
Full $m(J/\psi, K^-\pi^+)$ and angles fit



B^0 angles



B_s^0 angles



Same plots for $(J/\psi, K^+\pi^-)$

Results of Simultaneous fit to 2011+2012 data (preliminary!)

	3 fb^{-1} (preliminary)	0.37 fb^{-1} [LHCb, PRD.86(2012)071102]
$\frac{N_{B_s^0}}{N_{B^0}}$	$(0.88 \pm 0.03)\%$	$(0.85 \pm 0.09)\%$
$\frac{BR(B_s^0 \rightarrow J/\psi \bar{K}^{*0})}{BR(B^0 \rightarrow J/\psi \bar{K}^{*0})}$	$(4.74 \pm 0.16 \text{ (stat)}) \cdot 10^{-5}$	$(4.42 \pm 0.45 \text{ (stat)} \pm 0.80 \text{ (syst)}) \cdot 10^{-5}$
$f_0(B_s^0)$	$0.56 \pm 0.02 \text{ (stat)}$	$0.50 \pm 0.08 \text{ (stat)} \pm 0.02 \text{ (syst)}$
$f_{\parallel}(B_s^0)$	$0.18 \pm 0.03 \text{ (stat)}$	$0.19 \pm 0.09 \text{ (stat)} \pm 0.02 \text{ (syst)}$
$A_{\parallel}^{CP}(B_s^0)$	$xxx \pm 0.15 \text{ (stat)}$	—
$A_{\perp}^{CP}(B_s^0)$	$xxx \pm 0.11 \text{ (stat)}$	—
$A_0^{CP}(B_s^0)$	$xxx \pm 0.05 \text{ (stat)}$	—
$A^{CP}(B_d^0)$	$-0.002 \pm 0.003 \text{ (stat)}$	—

- Signal yields and polarization fractions consistent with previous results
- $$\frac{BR(B_s^0 \rightarrow J/\psi \bar{K}^{*0})}{BR(B^0 \rightarrow J/\psi \bar{K}^{*0})} = \frac{f_d}{f_s} \frac{N_{B_s^0}}{N_{B^0}} \times \text{corr}(B_s^0, B^0)$$
- $f_{\perp} = 1 - f_{\parallel} - f_0$

Direct CP violation

$$A^{CP} = A^{raw} + A^D(K^-\pi^+) - \kappa_s A^P(B_s^0) \quad [\text{LHCb, PRL.108(2012)201601}]$$

Observable	What we measure	Corrections
A^{CP}	A^{raw}	$A^D(K^-\pi^+), \kappa_s, A^P(B_s^0)$

- A^D is the detection asymmetry and A^P is the production asymmetry
- The dilution factor κ_s is due to the mixing in B_s^0 mesons:
 $|\kappa_s A^P(B_s^0)| \ll |A^D(K^-\pi^+)|, |A^{raw}|$

$$\begin{aligned} A_0^{CP} &= A_0^{raw} + A^D \quad (\text{longitudinal polarization}) \\ &\Rightarrow A_0^{CP} = xxx \pm 0.052(\text{exp}) \end{aligned}$$

Determination of the
observables H_i and A_i^{CP}

$\Rightarrow \Delta \phi_s^{i,\text{peng}} = f(H_i, A_i^{CP})$

$$H_0$$

$$H_0 = \frac{1-\lambda^2}{\lambda^2} \left| \frac{\mathcal{A}_0}{\mathcal{A}'_0} \right|^2 \frac{f_0^{J/\psi K^*} \cdot BR(B_s^0 \rightarrow J/\psi \bar{K}^{*0})}{f_0^{J/\psi \phi} \cdot BR(B_s^0 \rightarrow J/\psi \phi)}$$

Observable	What we measure	Corrections
H_0	$BR(B_s^0 \rightarrow J/\psi \phi), BR(B_s^0 \rightarrow J/\psi \bar{K}^{*0}), f_0^{J/\psi \phi}, f_0^{J/\psi K^*}$	$\frac{1-\lambda^2}{\lambda^2}, \left \frac{\mathcal{A}_0}{\mathcal{A}'_0} \right ^2$

- Branching fractions

- $BR(B_s^0 \rightarrow J/\psi \bar{K}^{*0}) = (4.74 \pm 0.16 \text{ (stat)} \pm 0.80 \text{ (syst)}) \times 10^{-5}$
- $BR(B_s^0 \rightarrow J/\psi \phi) = (1.05 \pm 0.11) \times 10^{-3}$ [LHCb-PAPER-2012-040]

- Polarization fractions

- $f_0^{J/\psi K^*} = 0.56 \pm 0.02$
- $f_0^{J/\psi \phi} = 0.52 \pm 0.01$ [LHCb-PAPER-2013-002]

- SU(3) breaking factor: $\left| \frac{\mathcal{A}'_0}{\mathcal{A}_0} \right| = 0.42 \pm 0.27$ [Faller et al., arXiv:0810.4248]

$$\Rightarrow H_0 = 1.36 \pm 0.57 \text{ (exp)} \pm 0.88 \text{ (theo)}$$

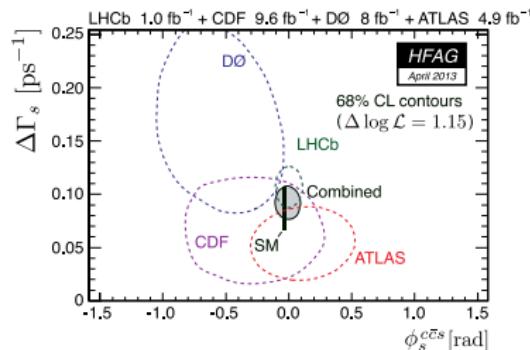
$\Delta\phi_s^{\text{peng}}$, blinded results

H_i and A_i^{CP} form a non trivial system of two equations with two unknowns : a_i and $\theta_i \Rightarrow \Delta\phi_s^{i,\text{peng}}$

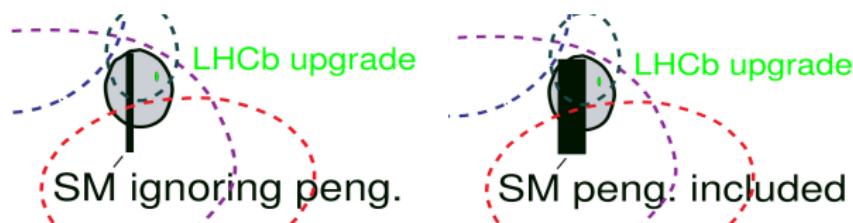
SOLUTION	Value	Experimental error	Theoretical error
$\Delta\phi_s^0$	xxx	0.02	0.06
$\Delta\phi_s^{\parallel}$	xxx	0.04	0.06
$\Delta\phi_s^{\perp}$	xxx	0.02	0.03

- Experimental uncertainties on $\Delta\phi_s^i$ in the order of 0.02–0.04
- Actual numbers depend a lot on theoretical inputs and central values

Effect of $\Delta\phi_s^{\text{peng}}$



Zoom in previous figure



Conclusions

- First look at angular analysis of $B_s^0 \rightarrow J/\psi \bar{K}^{*0}$ with 3 fb^{-1} to estimate penguin contribution in ϕ_s : BR, polarization amplitudes and direct CP asymmetry
- My contributions: fit, direct CP violation and phenomenological interpretation

Prospects

- Selection re-optimization using MVA ongoing
- Various analyses improvements/cross-checks ongoing (angular acceptance, sFit, helicity basis, fit in bins of $m_{K\pi}\dots$)
- Evaluate systematics
- Normalize $\text{BR}(B_s^0 \rightarrow J/\psi \bar{K}^{*0})$ to $\text{BR}(B_s^0 \rightarrow J/\psi \phi)$
- Control theoretical error in SU(3)

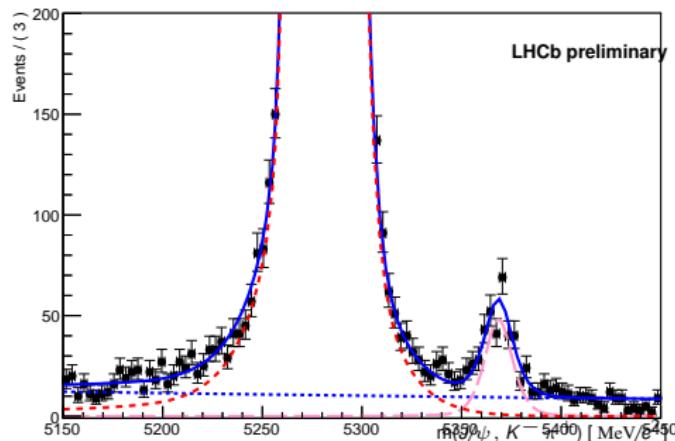
Backups

SU(3) factors

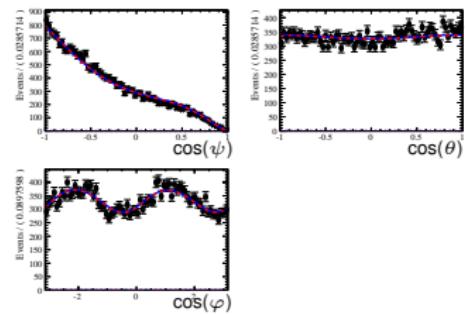
	[Fleischer,arXiv:0810.4248]	[Y.Xie,arXiv:1309.0313]
$ \frac{\mathcal{A}'_0}{\mathcal{A}_0} $	0.42 ± 0.27	0.86 ± 0.20
$ \frac{\mathcal{A}'_{ }}{\mathcal{A}_{ }} $	0.70 ± 0.29	0.85 ± 0.20
$ \frac{\mathcal{A}'_{\perp}}{\mathcal{A}_{\perp}} $	0.38 ± 0.16	0.87 ± 0.09

Fit 2011 real data

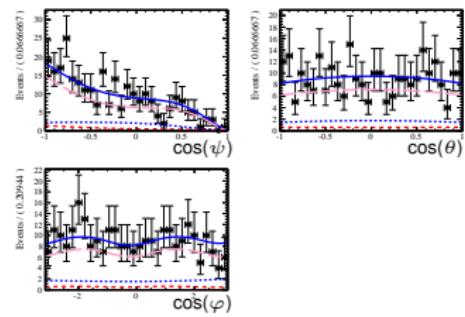
Full $m(J/\psi, K^-\pi^+)$ and angles fit



B^0 angles



B_s^0 angles



Same plots for $(J/\psi, K^+\pi^-)$

Fit model

$$\mathcal{P}_q(m_{J/\psi K\pi}, \Omega) = \mathcal{P}_q(m_{J/\psi K\pi}) \mathcal{P}_q(\Omega),$$

$\Omega = \psi, \theta, \varphi$ angles in transversity basis

$q = s, d$

Mass distribution

$$\begin{aligned}\mathcal{P}^{sig}(B_q) &= \\ f \times Apolonio(m_i, M_{B_q}, \sigma_1, a, b, n) + (1 - f) \times Apolonio(m_i, M_{B_q}, \sigma_2, a, b, n) \\ Apolonio(m, m_0, \sigma, a, b, n) &\simeq \exp \left(-b \sqrt{1 + \left(\frac{m-m_0}{\sigma} \right)^2} \right)\end{aligned}$$

$$\mathcal{P}^{bkg}(m_i) = e^{\kappa_{bkg} m_i}$$

Signal angular distribution

$$\mathcal{P}(\Omega) = \text{Acc}(\Omega) \times \text{Phys}(\Omega)$$

$$\text{Acc}(\Omega) = \text{Acc}_\psi(\psi) \text{Acc}_\theta(\theta) \text{Acc}_\varphi(\varphi)$$

Acceptances taken from MC

$\text{Acc}_\psi(\psi)$, $\text{Acc}_\theta(\theta)$: polynomial functions

$\text{Acc}_\varphi(\varphi)$: sinusoidal function

Background angular distribution

$$\mathcal{P}_{Bkg}(\Omega) = \text{Acc}_\psi(\psi) \times \text{Acc}_\theta(\theta) \times \left(1 + \sum_{n=1}^3 k_{pn} \varphi^n\right)$$

$\text{Acc}_\psi(\psi)$, $\text{Acc}_\theta(\theta)$ same as signal

$\text{Acc}_\varphi(\varphi)$ left free in the fit to the B_s^0 right-hand mass sideband

Update on BR($B_s^0 \rightarrow J/\psi \bar{K}^{*0}$)

$$\frac{BR(B_s^0 \rightarrow J/\psi \bar{K}^{*0})}{BR(B^0 \rightarrow J/\psi K^{*0})} = \frac{f_d}{f_s} \frac{\varepsilon_{B^0}^{\text{tot}}}{\varepsilon_{B_s^0}^{\text{tot}}} \frac{\lambda_{B^0}}{\lambda_{B_s^0}} \frac{f_{K^*}^{(d)}}{f_{K^*}^{(s)}} \frac{N_{B_s^0}}{N_{B^0}}$$

Parameter	Name	Value
Hadronization fractions	f_d/f_s	3.91 ± 0.31 [LHCb-PAPER-2012-037]
Efficiency ratio	$\varepsilon_{B^0}^{\text{tot}} / \varepsilon_{B_s^0}^{\text{tot}}$	0.97 ± 0.01 [LHCb-PAPER-2012-014]
Angular corrections	$\lambda_{B^0} / \lambda_{B_s^0}$	1.01 ± 0.04 [LHCb-PAPER-2012-014]
Ratio of K^* fractions	$f_{K^*}^{(s)} / f_{K^*}^{(d)}$	1.09 ± 0.08 [LHCb-PAPER-2012-014]
B signal yields	$N_{B_s^0} / N_{B^0}$	$(8.76 \pm 0.29) \times 10^{-3}$, fit to 3 fb^{-1} data

- Magenta numbers taken from the analysis with 0.37 fb^{-1} , update ongoing...
 - $\Rightarrow BR(B_s^0 \rightarrow J/\psi \bar{K}^{*0}) = (4.74 \pm 0.16 \text{ (stat)}) \times 10^{-5}$
 - compatible with previous result with 0.37 fb^{-1} :
 $BR(B_s^0 \rightarrow J/\psi \bar{K}^{*0}) = (4.42 \pm 0.45 \text{ (stat)} \pm 0.80 \text{ (syst)}) \times 10^{-5}$
- [LHCb-PAPER-2012-014]

Direct CP violation

$$A^{CP} = A^{raw} + A^D(K^-\pi^+) - \kappa_s A^P(B_s^0) \quad [\text{LHCb-PAPER-2013-018}]$$

- A^D is the detection asymmetry and A^P is the production asymmetry
- The dilution factor κ_s is due to the mixing in B_s^0 mesons:

$$\kappa_s = \frac{\int_0^\infty e^{-\Gamma_s t} \cos(\Delta m_s t) \varepsilon_s(t) dt}{\int_0^\infty e^{-\Gamma_s t} \cosh(\frac{\Delta \Gamma_s}{2} t) \varepsilon_s(t) dt}$$

κ_s is small ($\simeq -0.033 \pm 0.003$ in $B_s^0 \rightarrow K^-\pi^+$ [LHCb-2013-PAPER-018]) so $|\kappa_s A^P(B_s^0)| \ll |A^D(K^-\pi^+)|, |A^{raw}|$

Detection asymmetry

$$A_0^{CP} = A_0^{raw} + A^D$$

- $A^D = (-1.22 \pm 0.21)\%$ in $B_s^0 \rightarrow K^- \pi^+$ [LHCb-PAPER-2013-018]
- we did many cross-checks on B_s^0 and B^0 kinematics
- Re-use the detection asymmetry measured in $B_s^0 \rightarrow K^- \pi^+$ [LHCb-PAPER-2013-018] :
 - A^D measured in $D^{*+} \rightarrow D^0 \pi^+$ with $D^0 \rightarrow K^- \pi^+$
 - The kinematics of the D^{*+} sample reweighted to match those of $B_s^0 \rightarrow K^- \pi^+$ and $B^0 \rightarrow K^+ \pi^-$

$$\Rightarrow A_0^{CP} = 0.020 \pm 0.052(\text{exp})$$

$\Delta\phi_s^{\text{peng}}$, blinded results

H_i and A_i^{CP} form a non trivial system of two equations with two unknowns : a_i and $\theta_i \Rightarrow \Delta\phi_s^{i,\text{peng}}$

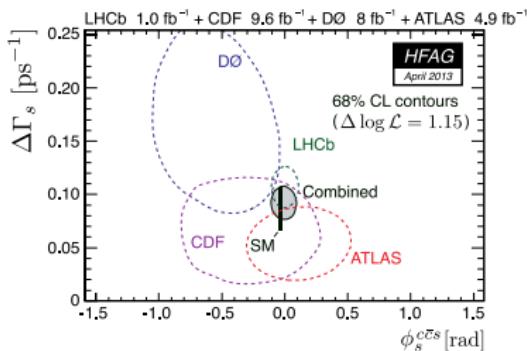
SOLUTION 1	value	experimental error	theoretical error
H_0	2.180	0.454	1.401
A_0^{CP}	0.020	0.052	0.000
a_0	0.786	0.189	0.583
θ_0	3.139	0.081	0.009
$\Delta\phi_s^0$	-0.023	0.019	0.059

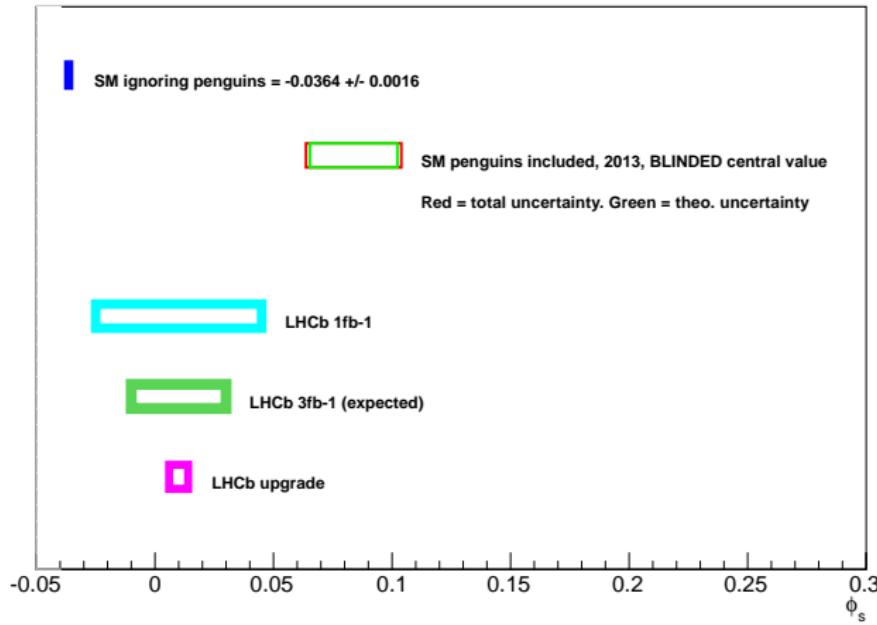
SOLUTION 2	value	experimental error	theoretical error
H_0	2.180	0.454	1.401
A_0^{CP}	0.020	0.052	0.000
a_0	1.663	0.209	0.645
θ_0	0.078	0.041	0.008
$\Delta\phi_s^0$	0.202	0.019	0.060

same for parallel and perpendicular polarizations

SOLUTION 1	value	experimental error	theoretical error
$\Delta\phi_s^0$	-0.023	0.019	0.059
$\Delta\phi_s^{\parallel}$	0.123	0.036	0.056
$\Delta\phi_s^{\perp}$	-0.018	0.021	0.030

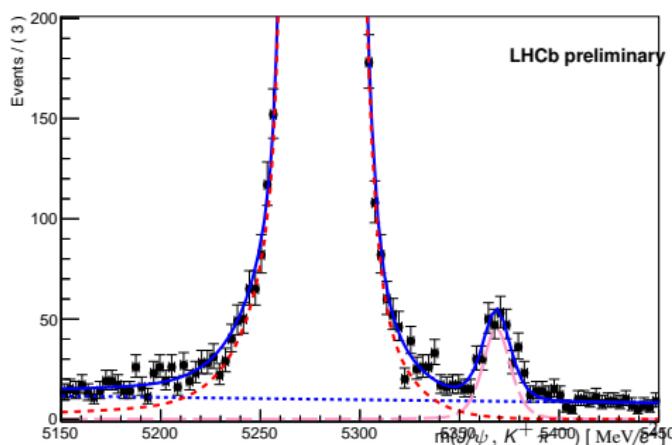
- Green numbers are blinded with same blinding string
- Experimental uncertainties on $\Delta\phi_s^i$ in the order of 0.02–0.04
- Actual numbers depend a lot on theoretical inputs and central values



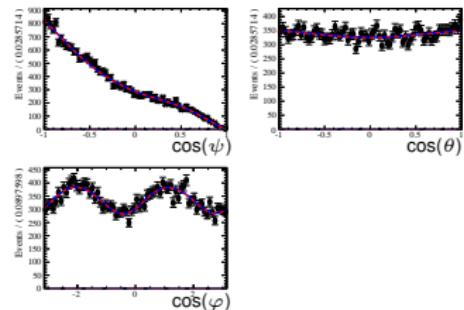


Fit 2011 real data

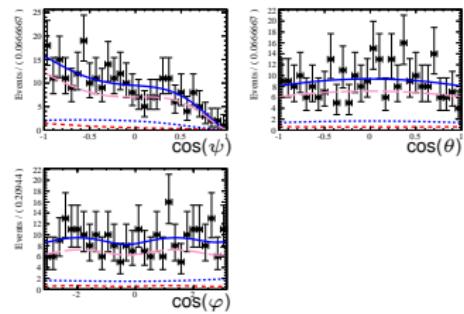
Full $m(J/\psi, K^+\pi^-)$ and angles fit



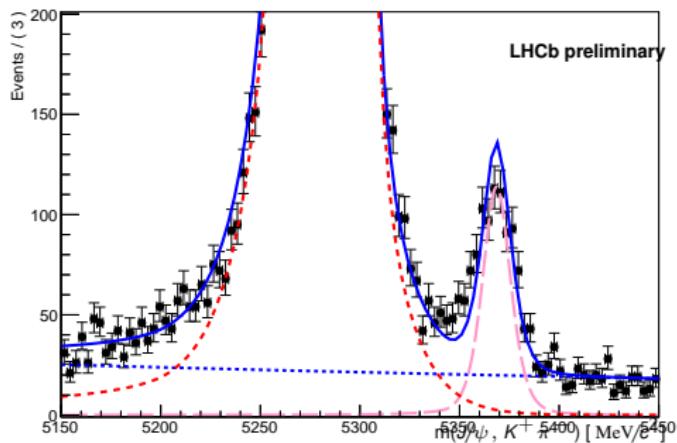
B^0 angles



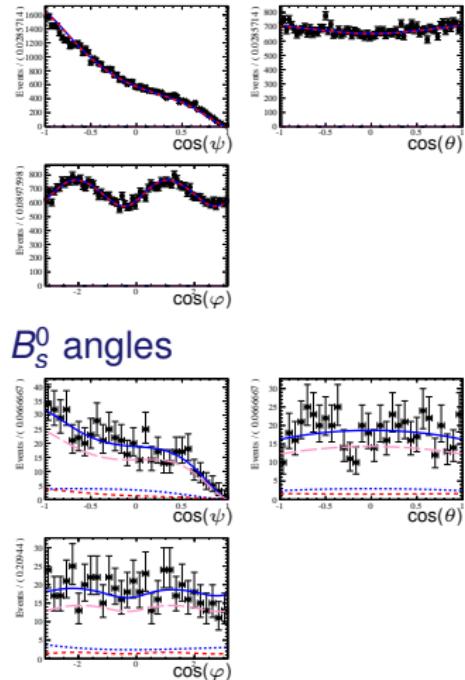
B_s^0 angles



Fit 2012 real data



B^0 angles



SOLUTION 1	value	experimental error	theoretical error
H_0	2.180	0.454	1.401
A_0^{CP}	0.030	0.052	0.000
a_0	1.663	0.209	0.645
θ_0	0.078	0.041	0.008
$\Delta\phi_s^0$	0.202	0.019	0.060
H_{\parallel}	0.952	0.253	0.395
A_{\parallel}^{CP}	-0.040	0.150	0.000
a_{\parallel}	0.811	0.376	0.586
θ_{\parallel}	0.027	0.106	0.008
$\Delta\phi_s^{\parallel}$	0.123	0.036	0.056
H_{\perp}	2.340	0.568	0.985
A_{\perp}^{CP}	0.084	0.110	0.000
a_{\perp}	0.907	0.227	0.391
θ_{\perp}	2.565	0.173	0.034
$\Delta\phi_s^{\perp}$	-0.018	0.021	0.030

Solving the 2-fold ambiguity in (a_i, θ_i)

➊ Measuring mixing induced CPV in $B^0 \rightarrow J/\psi \rho$ [Faller et al., arXiv:0810.4248]

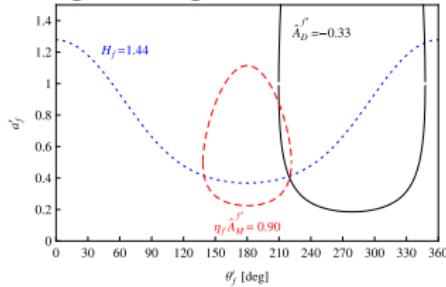


Figure 7: Illustration of the resolution of the twofold ambiguity in Fig. 6 through the mixing-induced CP violation in $B_d^0 \rightarrow J/\psi \rho^0$.

$$BR(B^0 \rightarrow J/\psi \rho) = (2.49 \pm 0.33 \pm 0.28) \times 10^{-5} \quad [\text{LHCb, PRD87, 052001 (2013)}]$$

➋ Hints of the physical solution can also been obtained from the expectations $a_i < 1$

Decay amplitude of $B_s^0 \rightarrow J/\psi \phi$ [Faller, arXiv:0810.4248]

$$A(B_s^0 \rightarrow J/\psi \phi) = (1 - \frac{\lambda^2}{2}) \mathcal{A} [1 + \epsilon \textcolor{red}{a}_i e^{i\theta_i} e^{i\gamma}]$$

$$\mathcal{A} = |V_{cb}|[T_c + P_c - P_t], \quad \epsilon = \frac{\lambda^2}{1 - \lambda^2}$$

- Penguin parameters are $\textcolor{red}{a}_i$ et θ_i ($f = 0, \perp, \parallel$)

$$\textcolor{red}{a}_i e^{i\theta_i} = (1 - \frac{\lambda^2}{2}) |V_{ub}/(\lambda V_{cb})| \left[\frac{P_u^f + P_t^f}{T_c^f + P_c^f - P_t^f} \right]$$

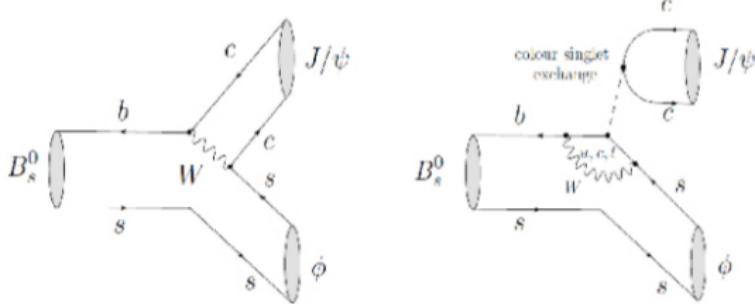
Effect of penguin processes

- Shift on ϕ_s due to penguin diagrams

$$\tan(\Delta\phi_s^{i,\text{peng}}) = \frac{2\epsilon \mathbf{a}_i \cos \theta_i \sin \gamma + \epsilon^2 \mathbf{a}_i^2 \sin 2\gamma}{1 + 2\epsilon \mathbf{a}_i \cos \theta_i \cos \gamma + \epsilon^2 \mathbf{a}_i^2 \cos 2\gamma}$$

$$\epsilon = \frac{\lambda^2}{1-\lambda^2}, \quad i = 0, \perp, \parallel$$

Decay amplitude



$$\begin{aligned}
 A(\bar{b} \rightarrow \bar{c}c\bar{s}) &= V_{cs}V_{cb}^*(A_T + P_c) + V_{us}V_{ub}^*P_u + V_{ts}V_{tb}^*P_t \\
 &= V_{cs}V_{cb}^*(A_T + P_c - P_t) + V_{us}V_{ub}^*(P_u - P_t)
 \end{aligned}$$

$$V_{ts}V_{tb}^* = -V_{us}V_{ub}^* - V_{cs}V_{cb}^*$$

$$\sim A\lambda^2(1 - \lambda^2/2)$$

$$\sim A\lambda^4(\rho + i\eta)$$

Mass fit with RooApollonios

- Function invented by Diego to describe the mass distribution, m .
See (23 May 2013)
- depends on 5 parameters: m_0, σ, a, b, n
- Define:

$$\xi = \frac{m - m_0}{\sigma}$$

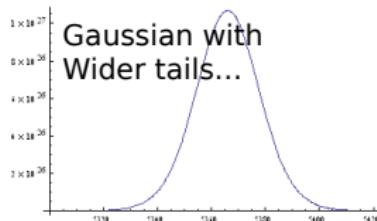
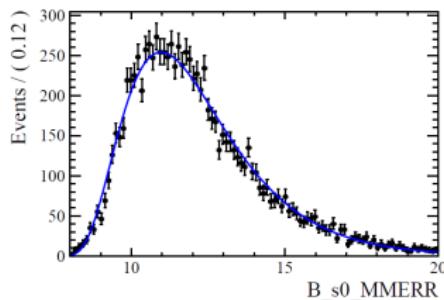
$$B = \frac{n\sqrt{1 + a^2}}{ab} - a$$

$$A = \exp\left(-b\sqrt{1 + a^2}\right) (B + a)^n$$

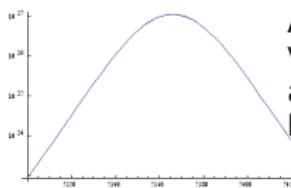
- If $\xi > -a$, $\text{Apollonios}(m, m_0, \sigma, a, b, n) = \exp\left(-b\sqrt{1 + \xi^2}\right)$
- Else, $\text{Apollonios}(m, m_0, \sigma, a, b, n) = A/(B - \xi)^n$

Mass resolution model

- The mass resolution has not a single value a Gaussian model is not enough
- We assume that the distribution of the mass resolution has the same functional form as that of the mass error (Amoroso/ LogGamma)
- In this case, the mass pdf, instead of a gaussian, should follow



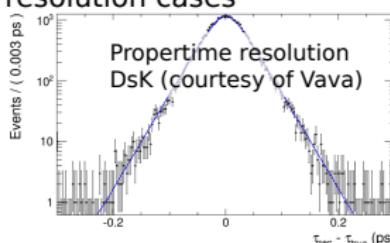
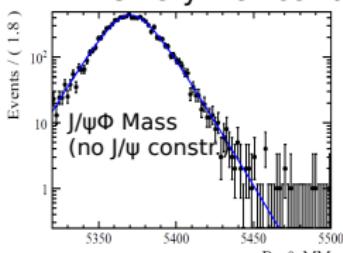
Log Scale
→



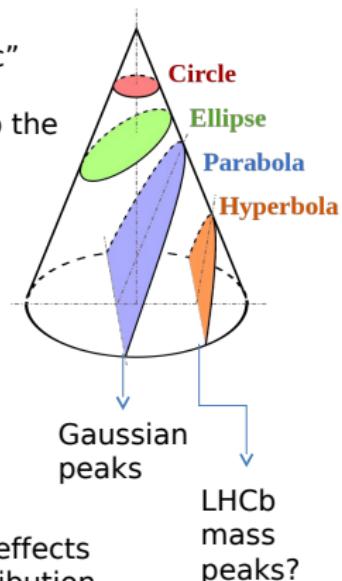
And this looks Very much like an hyperbola...

Introducing new function

- We define $\text{Pdf} = \exp^{\{\text{hyperbola}\}} =$
(hereafter Apollonios distribution)
 - i.e., basically we change the choice of “conic” function (Gaussian is $\exp^{\{\text{parabola}\}}$)
 - Converges to a gaussian of $\sigma = \theta/b$ close to the peak
 - Tails converge to exponential
- Fits very well certain resolution cases



Then we add a Crystalball like tail for radiative effects
Sadly, after J/ψ mass constrain, the mass distribution becomes a bit more complex...



Selection criteria for $B_s^0 \rightarrow J/\psi \bar{K}^{*0}$ candidates

Decay mode	Cut parameter	Final selection
all tracks	GLsb	>0.2
$J/\psi \rightarrow \mu^+ \mu^-$	$\chi_{\text{FD}}^2(J/\psi)$ $DOCA(J/\psi)$ $\chi_{\text{vtx}}^2(J/\psi)$ $\chi_{\text{IP}}^2(\mu)$	> 169 < 0.3 < 9 > 25
$\bar{K}^{*0} \rightarrow K^- \pi^+$	$\Delta \ln \mathcal{L}_{K\pi}(K)$ $\Delta \ln \mathcal{L}_{\pi K}(\pi)$ $p_T(K^+)$ $p_T(p^-)$ $M(K^- \pi^+)$ $\chi_{\text{IP}}^2/(K^+)$ $\chi_{\text{IP}}^2(p^-)$	< -6 < -6 > 500 MeV/c > 500 MeV/c $\in [826, 966] \text{ MeV}/c^2$ > 4 > 4
$B_s^0 \rightarrow J/\psi \bar{K}^{*0}$	$M(B_s^0)$ $\chi_{\text{IP}}^2(B_s^0)$	$\in [5200, 5450] \text{ MeV}/c^2$ < 25
$B^+ \rightarrow J/\psi K^+ \text{veto}$	$ M(J/\psi, K) - 5279 $	> 60 MeV/c ²

$$f_1(\Omega) = 2 \cos^2 \psi (1 - \sin^2 \theta \cos^2 \varphi)$$

$$f_2(\Omega) = \sin^2 \psi (1 - \sin^2 \theta \sin^2 \varphi)$$

$$f_3(\Omega) = \sin^2 \psi \sin^2 \theta$$

$$f_4(\Omega) = -\sin^2 \psi \sin 2\theta \sin \varphi$$

$$f_5(\Omega) = \frac{1}{\sqrt{2}} \sin 2\psi \sin^2 \theta \sin 2\varphi$$

$$f_6(\Omega) = \frac{1}{\sqrt{2}} \sin 2\psi \sin 2\theta \cos \varphi$$

$$f_7 = \frac{2}{3} [1 - \sin^2 \theta \cos^2 \varphi]$$

$$f_8 = \frac{\sqrt{6}}{3} \sin \psi \sin^2 \theta \sin(2\varphi)$$

$$f_9 = \frac{\sqrt{6}}{3} \sin \psi \sin(2\theta) \cos \varphi$$

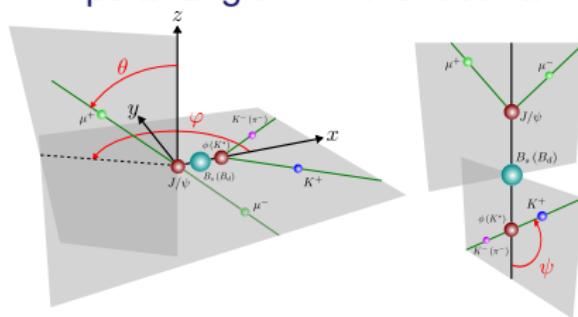
$$f_{10} = \frac{4\sqrt{3}}{3} (\cos \psi) [1 - \sin^2 \theta \cos^2 \varphi]$$

$$\begin{aligned}
\frac{d^3 \Gamma(K^- \pi^+)}{d\Omega} &\propto 2|A_0|^2 \cos^2 \psi (1 - \sin^2 \theta \cos^2 \varphi) + |A_{||}|^2 \sin^2 \psi (1 - \sin^2 \theta \sin^2 \varphi) + |A_{\perp}|^2 \sin^2 \psi \sin^2 \theta \\
&- |A_{||}| |A_{\perp}| \sin(\delta_{\perp} - \delta_{||}) \sin^2 \psi \sin(2\theta) \sin \varphi + \frac{1}{\sqrt{2}} |A_0| |A_{||}| \cos(\delta_{||} - \delta_0) \sin 2\psi \sin^2 \theta \sin 2\varphi \\
&+ \frac{1}{\sqrt{2}} |A_0| |A_{\perp}| \sin(\delta_{\perp} - \delta_0) \sin 2\psi \sin(2\theta) \cos \varphi + \frac{2}{3} |A_s|^2 (1 - \sin^2 \theta \cos^2 \varphi) \\
&+ \frac{\sqrt{6}}{3} |A_{||}| |A_s| \cos(\delta_{||} - \delta_s) \sin \psi \sin^2 \theta \sin(2\varphi) + \frac{\sqrt{6}}{3} |A_{\perp}| |A_s| \sin(\delta_s - \delta_{\perp}) \sin \psi \sin(2\theta) \cos \varphi \\
&+ \frac{4\sqrt{3}}{3} |A_0| |A_s| \cos(\delta_s - \delta_0) \cos \psi (1 - \sin^2 \theta \cos^2 \varphi)
\end{aligned}$$

$$\begin{aligned}
\frac{d^3 \bar{\Gamma}(K^+ \pi^-)}{d\Omega} &\propto 2|\bar{A}_0|^2 \cos^2 \psi (1 - \sin^2 \theta \cos^2 \varphi) + |\bar{A}_{||}|^2 \sin^2 \psi (1 - \sin^2 \theta \sin^2 \varphi) + |\bar{A}_{\perp}|^2 \sin^2 \psi \sin^2 \theta \\
&+ |\bar{A}_{||}| |\bar{A}_{\perp}| \sin(\delta_{\perp} - \delta_{||}) \sin^2 \psi \sin(2\theta) \sin \varphi + \frac{1}{\sqrt{2}} |\bar{A}_0| |\bar{A}_{||}| \cos(\delta_{||} - \delta_0) \sin 2\psi \sin^2 \theta \sin 2\varphi \\
&- \frac{1}{\sqrt{2}} |\bar{A}_0| |\bar{A}_{\perp}| \sin(\delta_{\perp} - \delta_0) \sin 2\psi \sin(2\theta) \cos \varphi + \frac{2}{3} |\bar{A}_s|^2 (1 - \sin^2 \theta \cos^2 \varphi) \\
&+ \frac{\sqrt{6}}{3} |\bar{A}_{||}| |\bar{A}_s| \cos(\delta_{||} - \delta_s) \sin \psi \sin^2 \theta \sin(2\varphi) - \frac{\sqrt{6}}{3} |\bar{A}_{\perp}| |\bar{A}_s| \sin(\delta_s - \delta_{\perp}) \sin \psi \sin(2\theta) \cos \varphi \\
&+ \frac{4\sqrt{3}}{3} |\bar{A}_0| |\bar{A}_s| \cos(\delta_s - \delta_0) \cos \psi (1 - \sin^2 \theta \cos^2 \varphi)
\end{aligned}$$

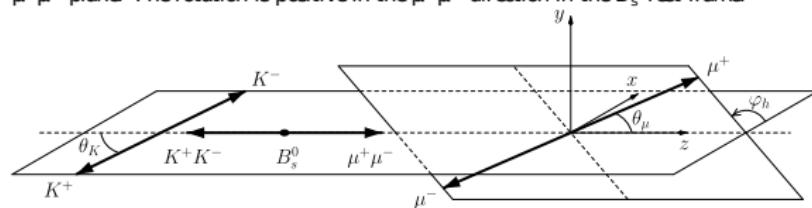
Definition of transversity angles

μ : polar angle θ , azimuthal angle φ in the rest frame of J/ψ
 K^+ : polar angle Ψ in the rest frame of ϕ



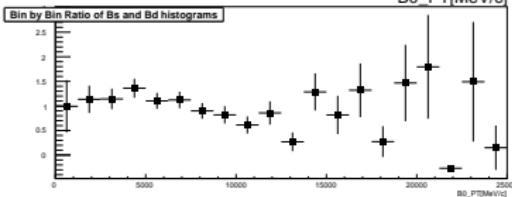
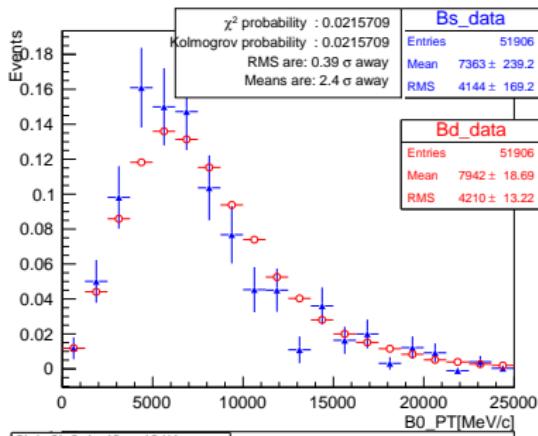
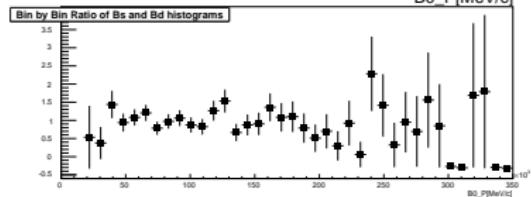
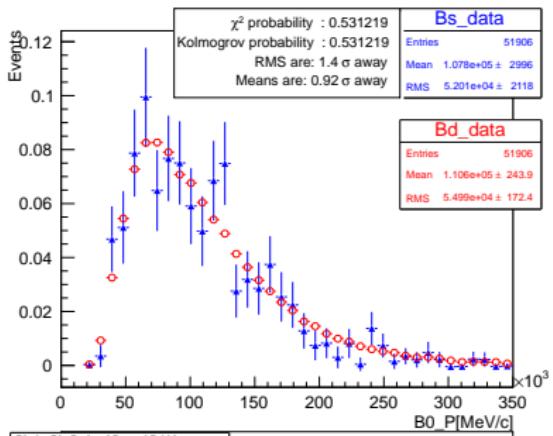
Definition of helicity angles

The helicity angles are denoted by $\Omega = (\theta_K, \theta_\mu, \phi_h)$ and their definition is shown in Fig. 7. The polar angle θ_K is the angle between the K^+ and the axis in the direction opposite to the B_s^0 in the K^+K^- center-of-mass system. Similarly, θ_μ is defined in the $\mu^+\mu^-$ centre-of-mass system with the direction of the μ^+ . The relative orientation of the K^+K^- and $\mu^+\mu^-$ systems is given by ϕ_h , the azimuthal angle between the two decay planes. This angle is defined by a rotation from the K^- side of the K^+K^- plane to the μ^+ side of the $\mu^+\mu^-$ plane. The rotation is positive in the $\mu^+\mu^-$ direction in the B_s^0 rest frame.

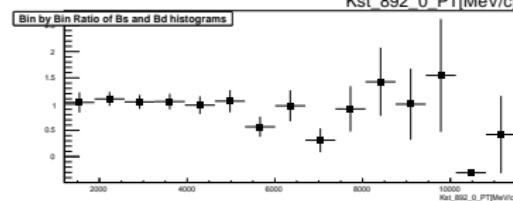
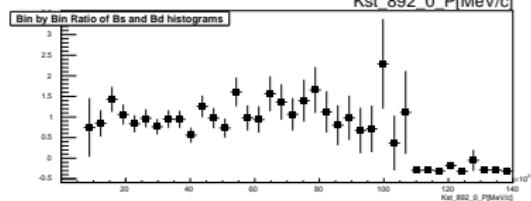
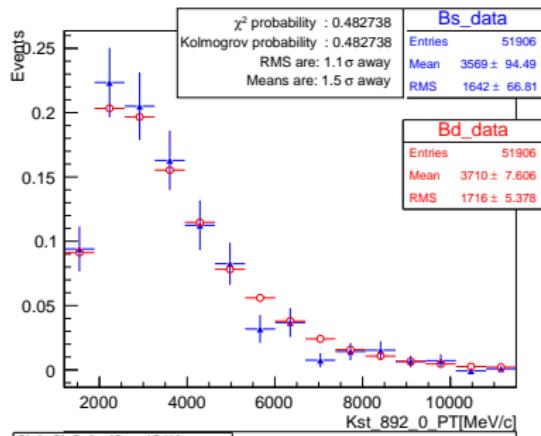
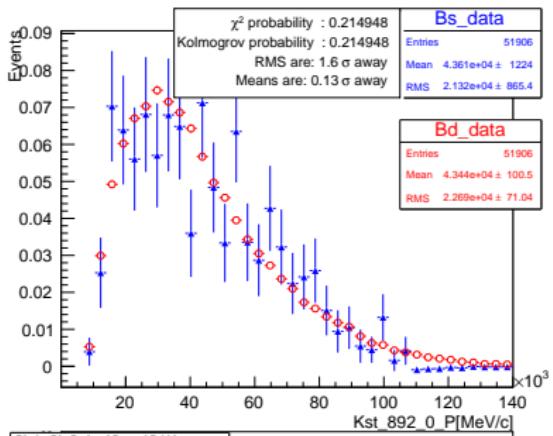


- We have checked (see my talk on 14/03) that:
- A^D doesn't change A^{CP} uncertainty
- A^D has no sizable effect on $\Delta\phi_s^{\text{peng}}$

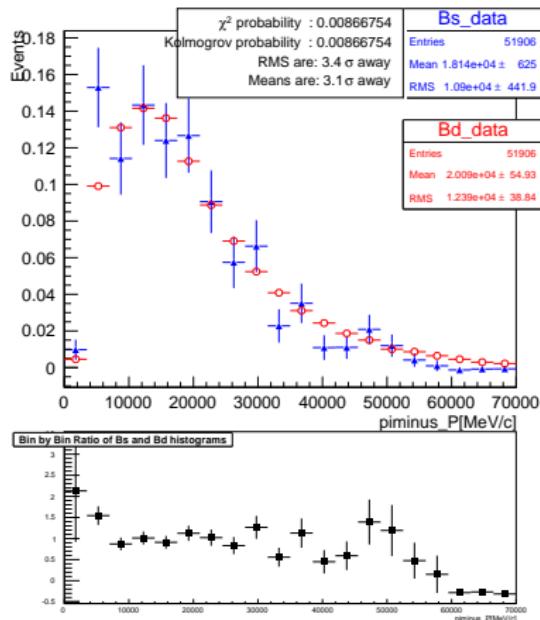
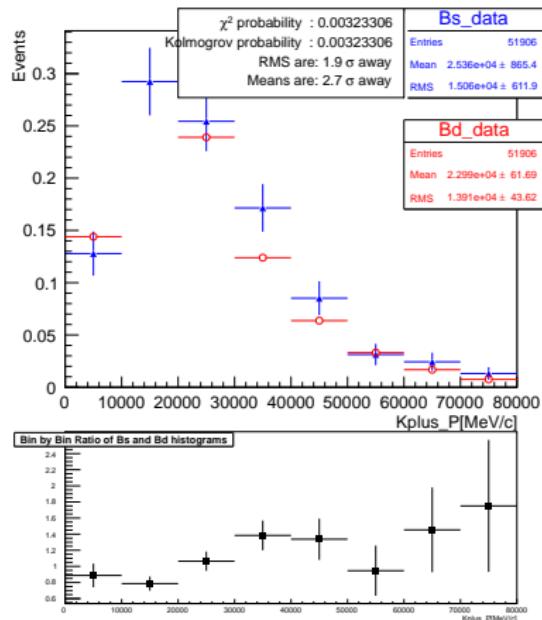
Kinematic variables of B_s^0 and B^0 in REAL DATA 2012



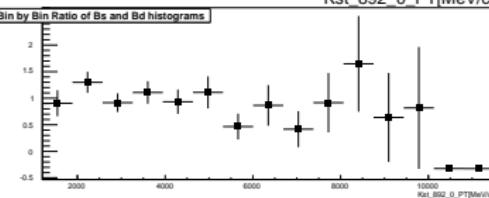
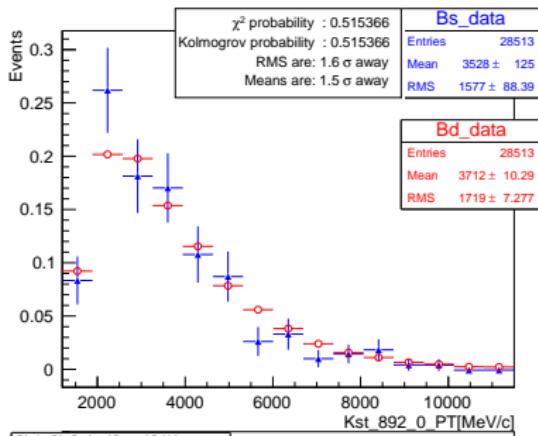
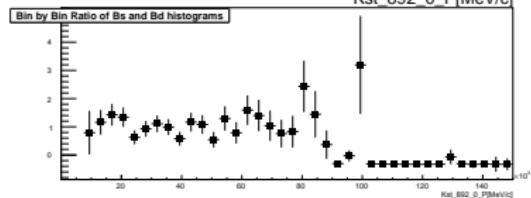
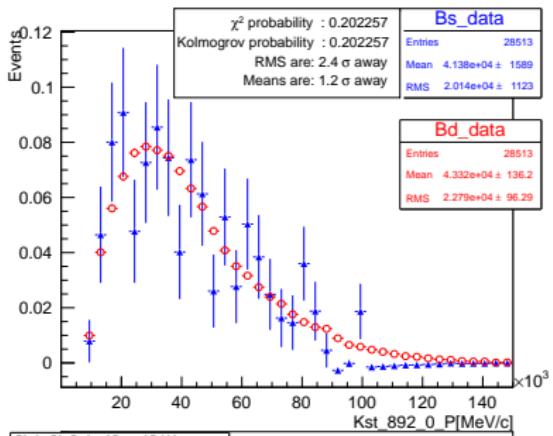
Kinematic variables of B_s^0 and B^0 in REAL DATA 2012



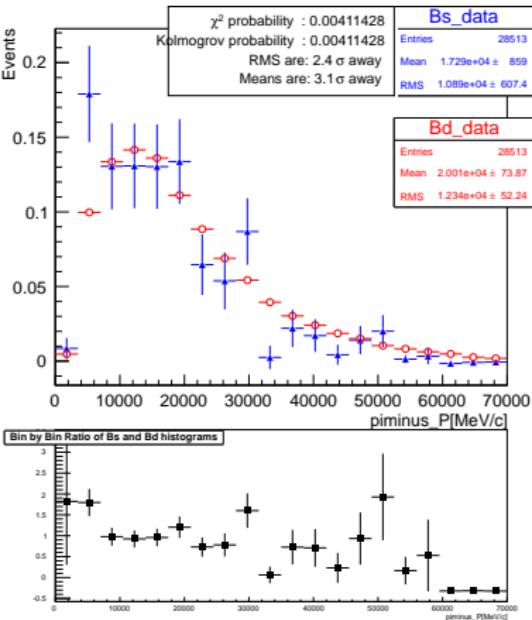
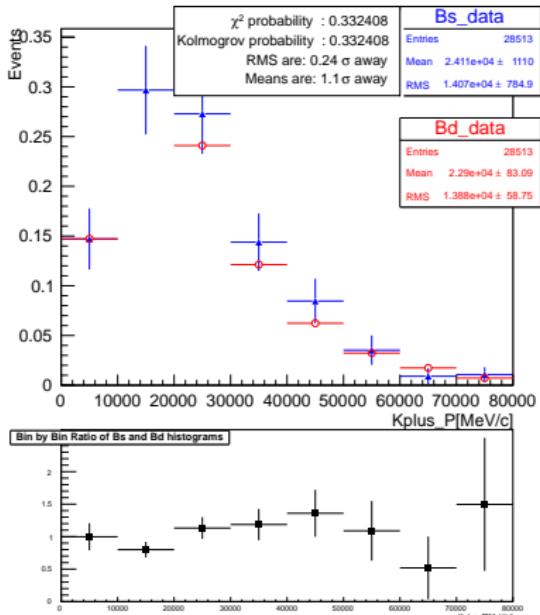
Kinematic variables of B_s^0 and B^0 in REAL DATA 2012



Kinematic variables of B_s^0 and B^0 in REAL DATA 2012, Magnet UP



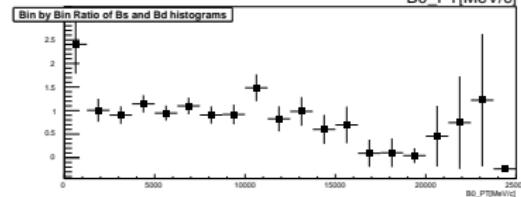
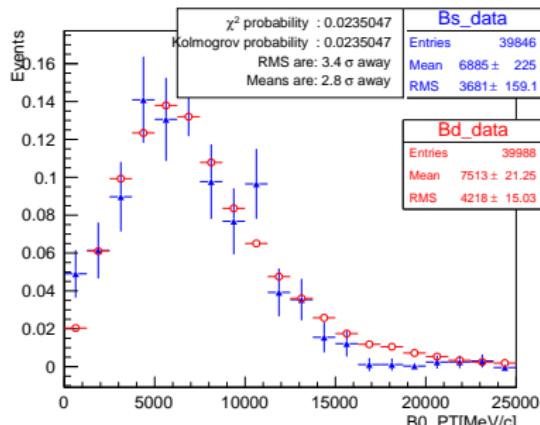
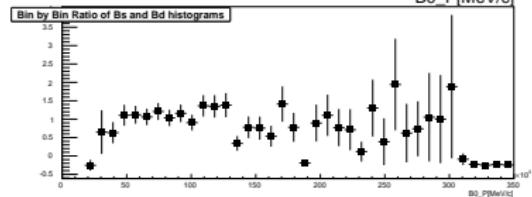
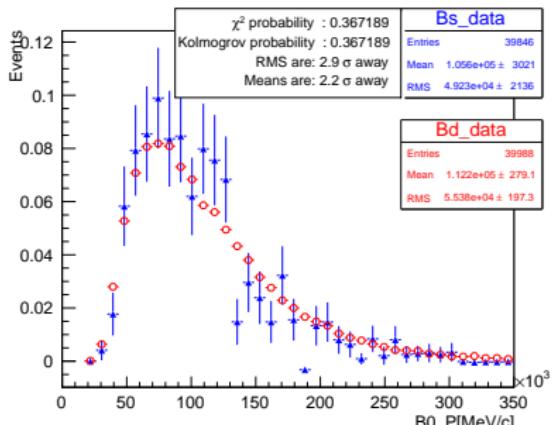
Kinematic variables of B_s^0 and B^0 in REAL DATA 2012, Magnet UP



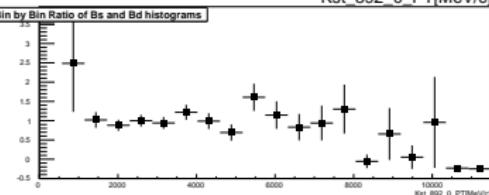
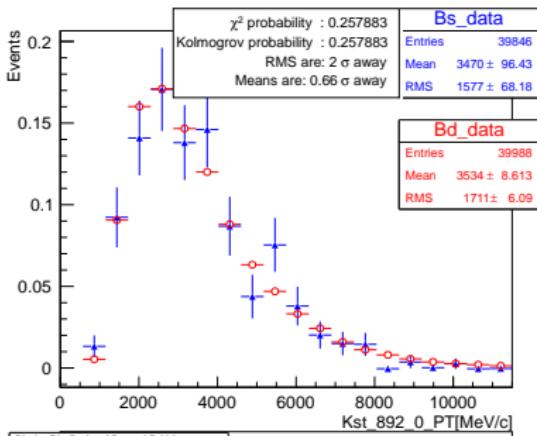
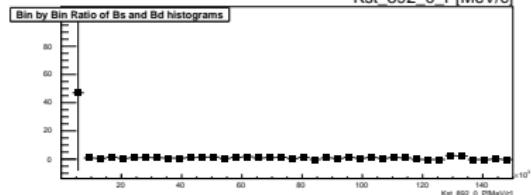
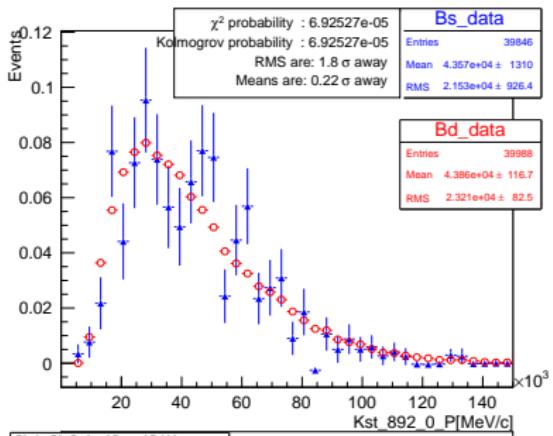
B_s^0 and B^0 decay chain have similar kinematic properties so B^0 can be used instead of B_s^0 to reweight the D^* sample

Same distributions for data 2012, magnet DOWN and for real data 2011, magnet DOWN, UP and DOWN+UP

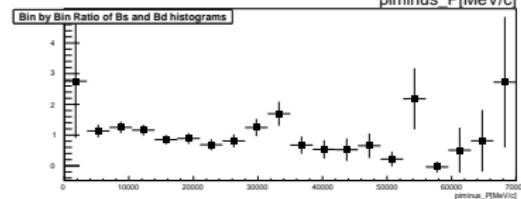
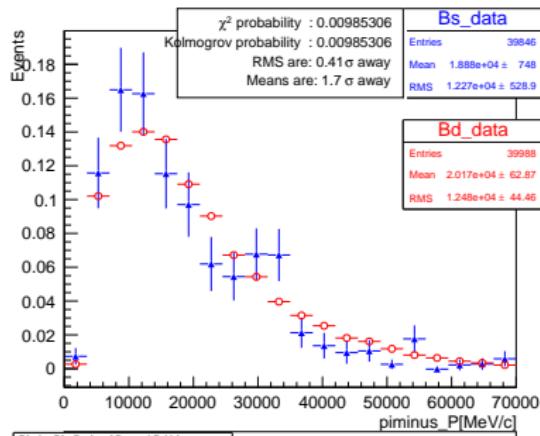
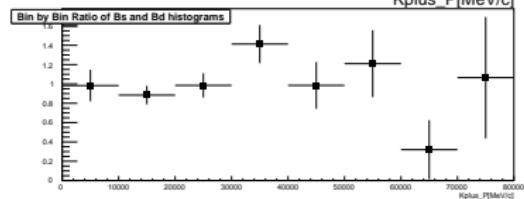
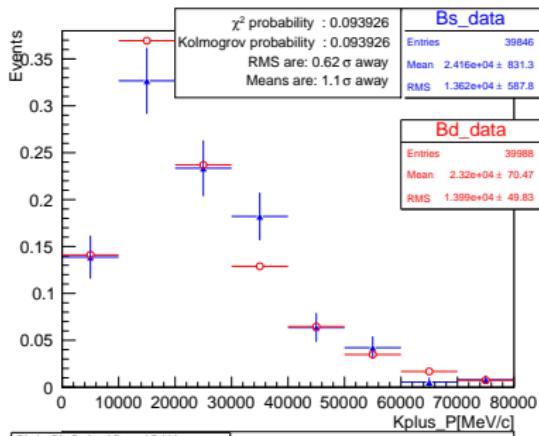
Kinematic variables of B_s^0 and B^0 in REAL DATA 2011



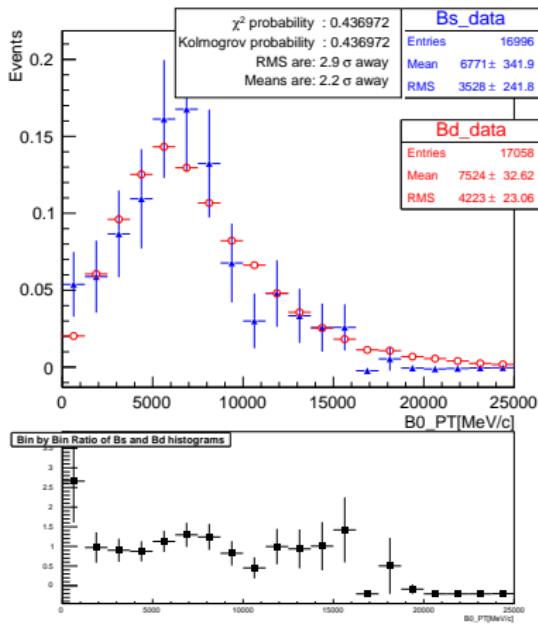
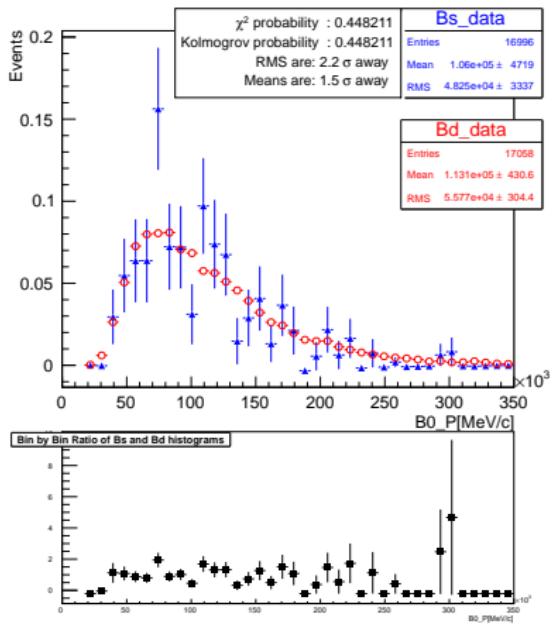
Kinematic variables of B_s^0 and B^0 in REAL DATA 2011



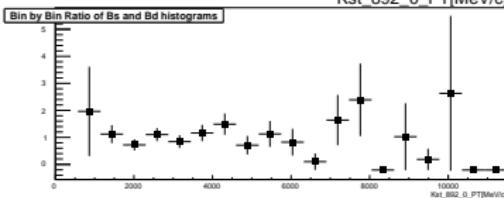
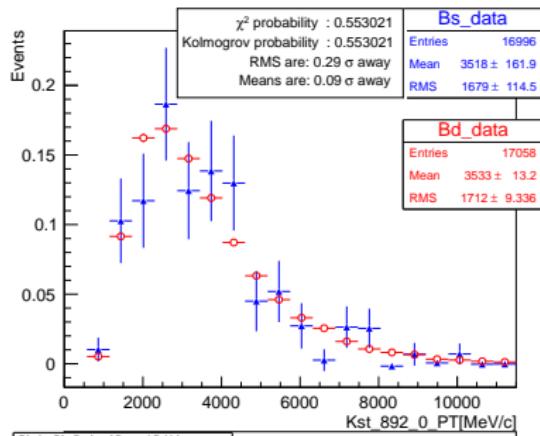
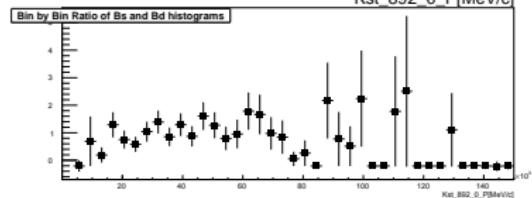
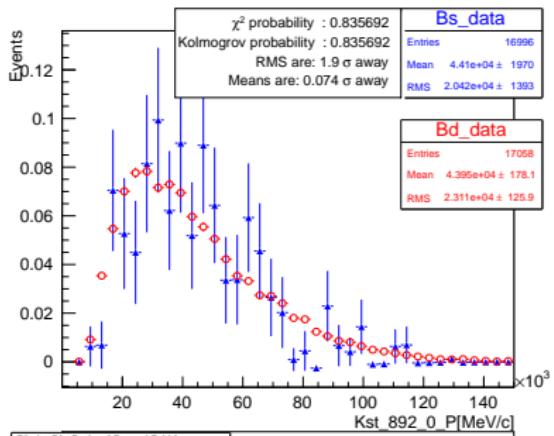
Kinematic variables of B_s^0 and B^0 in REAL DATA 2011



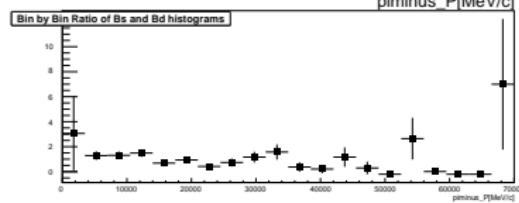
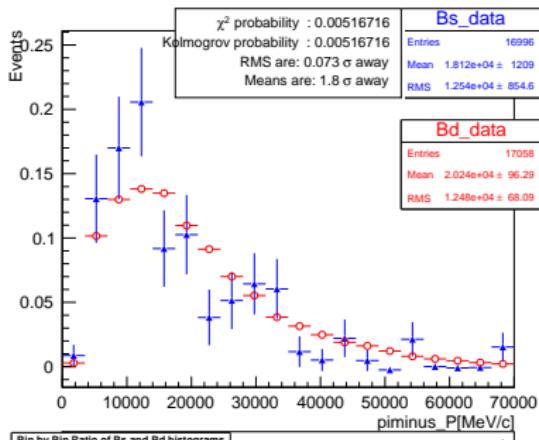
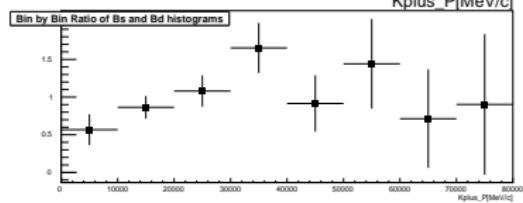
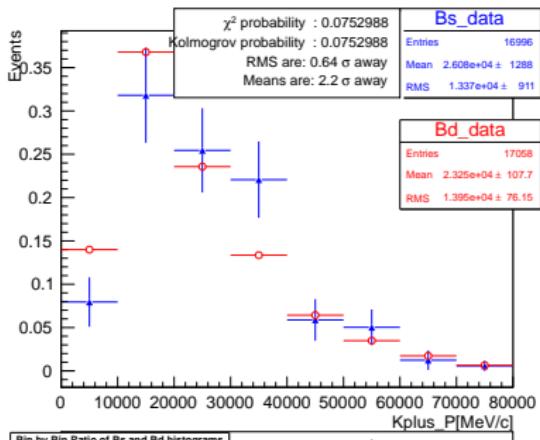
Kinematic variables of B_s^0 and B^0 in REAL DATA 2011, Magnet UP



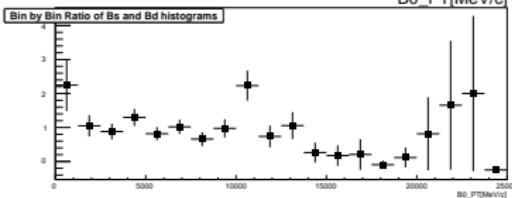
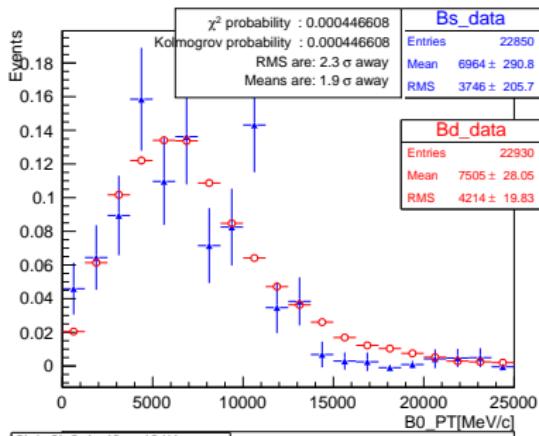
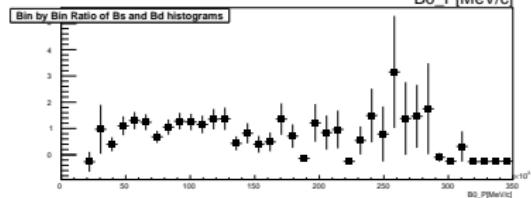
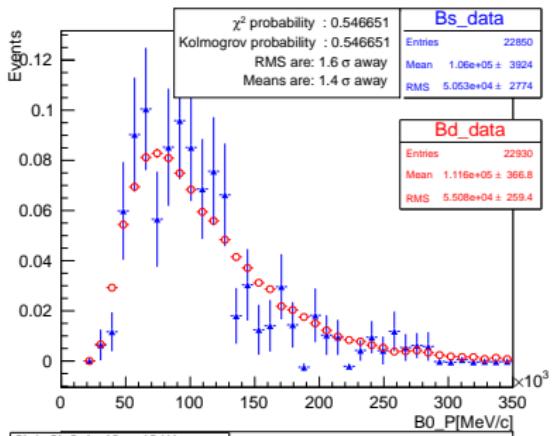
Kinematic variables of B_s^0 and B^0 in REAL DATA 2011, Magnet UP



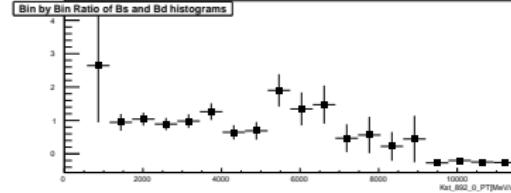
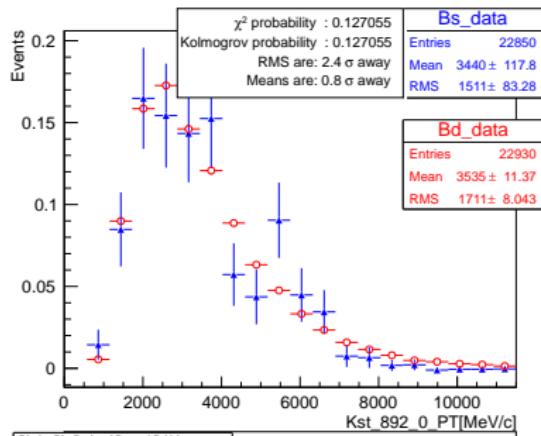
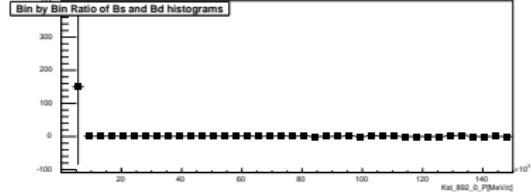
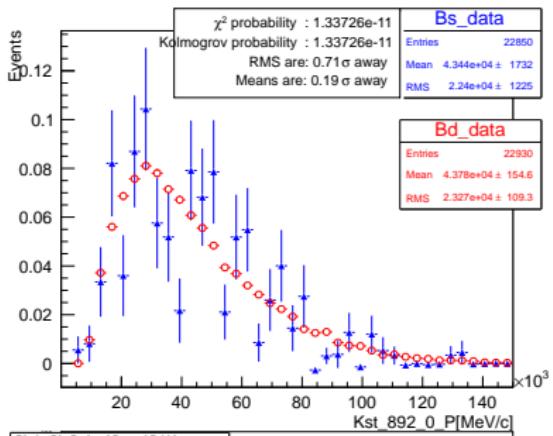
Kinematic variables of B_s^0 and B^0 in REAL DATA 2011, Magnet UP



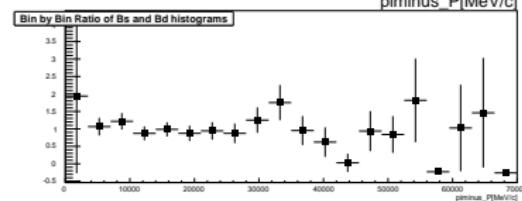
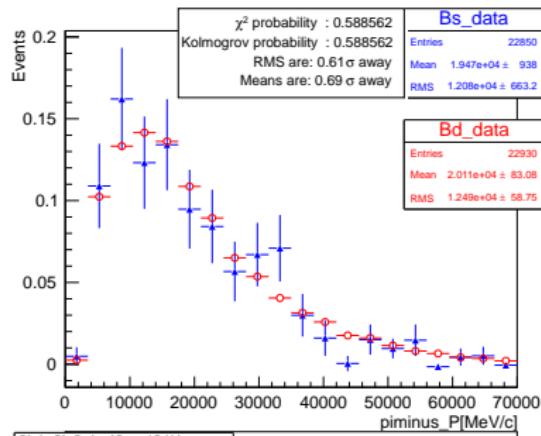
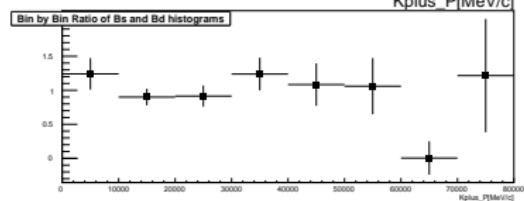
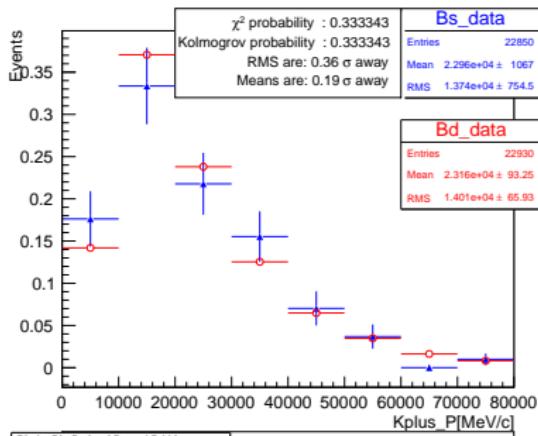
Kinematic variables of B_s^0 and B^0 in REAL DATA 2011, Magnet DOWN



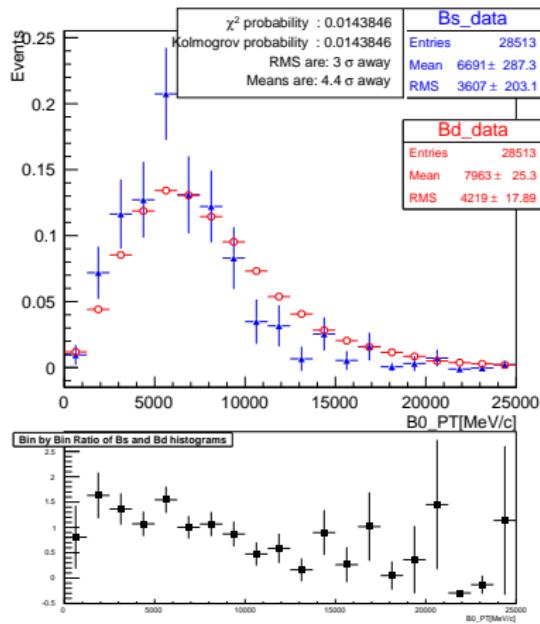
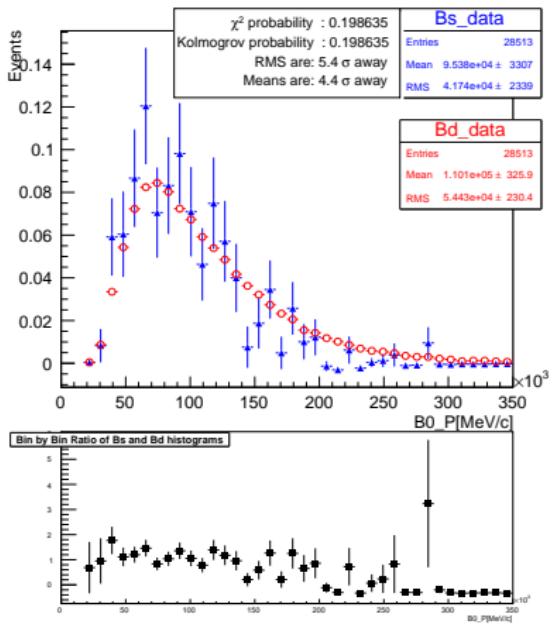
Kinematic variables of B_s^0 and B^0 in REAL DATA 2011, Magnet DOWN



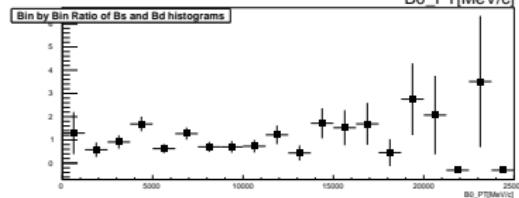
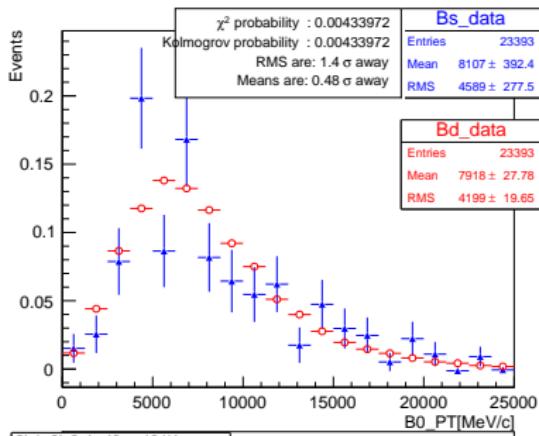
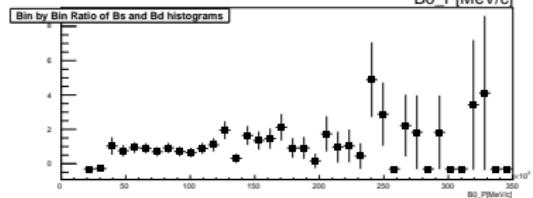
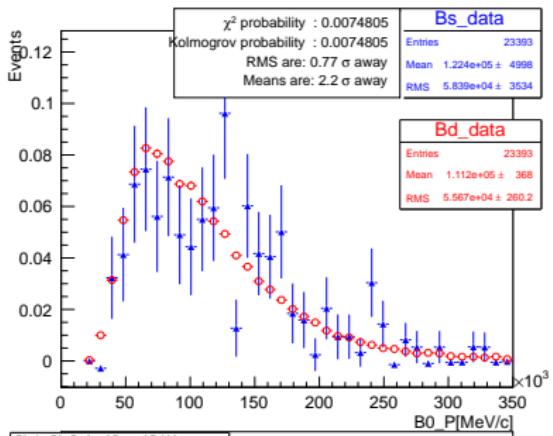
Kinematic variables of B_s^0 and B^0 in REAL DATA 2011, Magnet DOWN



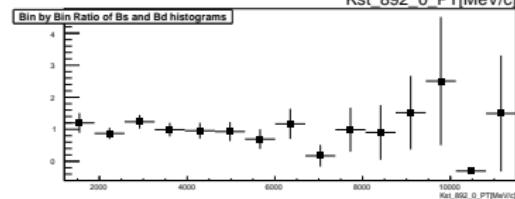
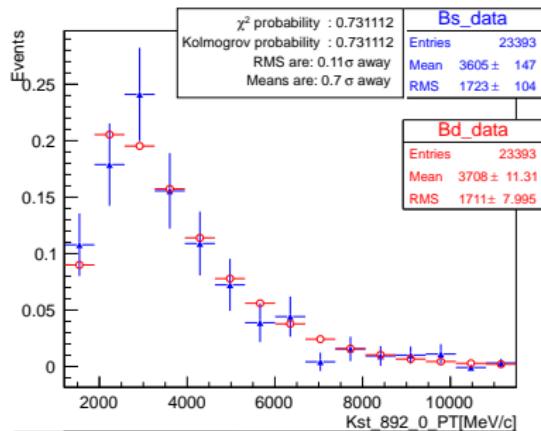
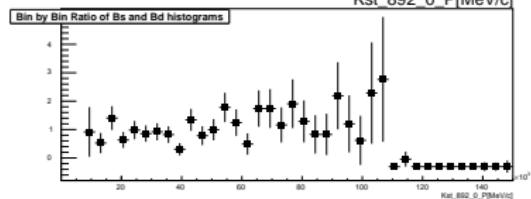
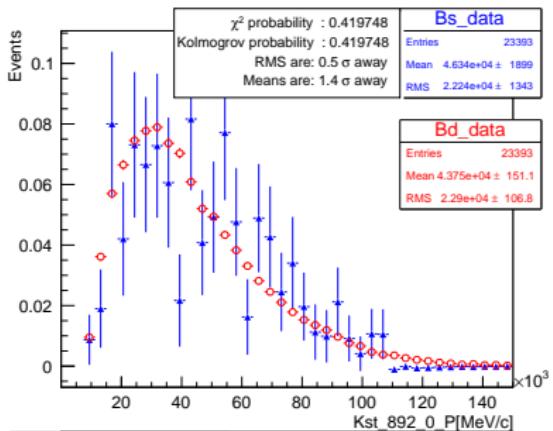
Kinematic variables of B_s^0 and B^0 in REAL DATA 2012, Magnet UP



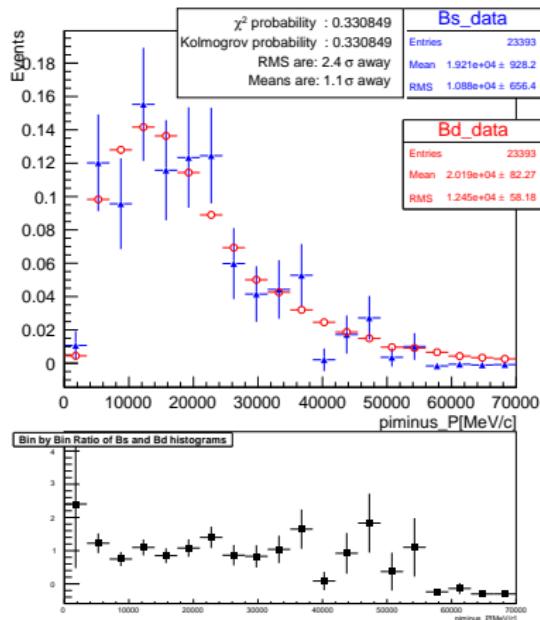
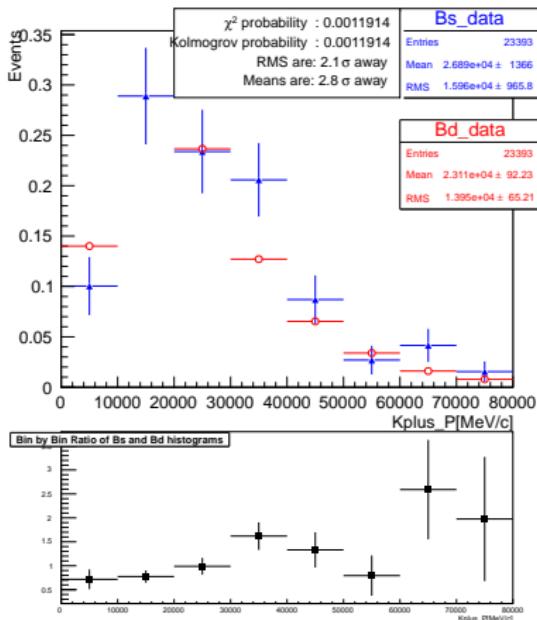
Kinematic variables of B_s^0 and B^0 in REAL DATA 2012, Magnet DOWN



Kinematic variables of B_s^0 and B^0 in REAL DATA 2012, Magnet DOWN



Kinematic variables of B_s^0 and B^0 in REAL DATA 2012, Magnet DOWN



Errors calculation

$$\begin{aligned}\frac{\partial \tan \Delta\phi_s}{\partial \theta} = & -\frac{2a\epsilon \sin \gamma \sin \theta}{1 + a^2 \cos(2\gamma)\epsilon^2 + 2a \cos \gamma \epsilon \cos \theta) \\ & + \frac{2a \cos \gamma \epsilon (a^2 \epsilon^2 \sin(2\gamma) + 2a \epsilon \sin \gamma \cos \theta) \sin \theta}{(1 + a^2 \cos(2\gamma)\epsilon^2 + 2a \cos \gamma \epsilon \cos \theta)^2}\end{aligned}$$

$$\begin{aligned}\frac{\partial \tan \Delta\phi_s}{\partial a} = & \frac{2a\epsilon^2 \sin(2\gamma) + 2\epsilon \sin \gamma \cos \theta}{1 + a^2 \cos(2\gamma)\epsilon^2 + 2a \cos \gamma \epsilon \cos \theta) \\ & - \frac{(2a \cos(2\gamma)\epsilon^2 + 2 \cos \gamma \epsilon \cos \theta)(a^2 \epsilon^2 \sin(2\gamma) + 2a \epsilon \sin \gamma \cos \theta)}{(1 + a^2 \cos(2\gamma)\epsilon^2 + 2a \cos \gamma \epsilon \cos \theta)^2}\end{aligned}$$

$$\sigma_{\tan \Delta\phi_s}^2 = \left(\frac{\partial \tan \Delta\phi_s}{\partial \theta}\right)^2 \sigma_\theta^2 + \left(\frac{\partial \tan \Delta\phi_s}{\partial a}\right)^2 \sigma_a^2 + 2 \left(\frac{\partial \tan \Delta\phi_s}{\partial \theta}\right) \left(\frac{\partial \tan \Delta\phi_s}{\partial a}\right) \sigma(a, \theta)$$