Measurement of the branching fraction of $J/\psi \to \phi\eta$

Nefedov Yury, Bakina Olga, Boyko Igor, Wang Ping

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Motivation I

Improved estimation of the mixing angle between strong and electromagnetic amplitudes in $J/\psi \to \phi\eta$ decay

Formulas of cross section for lineshape fit of $J/\psi \to \phi\eta$

$$\sigma_{\rm born}(s) = |\mathcal{A}_{cont.} + \mathcal{A}_{\gamma} + \mathcal{A}_{3g}|^2$$

$$= \frac{\sigma_0}{s^2}\left|1 + \frac{3/\alpha\,\sqrt{s\,\Gamma_e\Gamma_\mu}}{(s-M^2)+i\,\sqrt{s}\,\Gamma}\cdot(1+Ae^{i\,\varphi})\right|^2 \times \left[\frac{|P|}{\sqrt{s}}\right]^3$$

where σ_0 can be expressed through the $Br(J/\psi \to \phi\eta)$:

$$\sigma_0 = \frac{4\pi\alpha^2 s}{3}\cdot\frac{Br(J/\psi\to\phi\eta)}{Br(J/\psi\to\mu\mu)}\cdot\frac{1}{|1+Ae^{i\,\varphi}|^2}\left[\frac{\sqrt{s}}{|P|}\right]^3$$

✓ The value of the $Br(J/\psi \to \phi\eta)$ is obtained directly from the fit

Motivation I

Fit result:

$Br = (10.5 \pm 0.5) \times 10^{-4}$

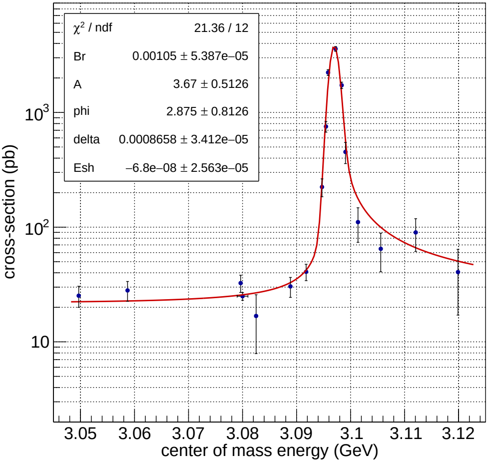
$\varphi = 2.88 \pm 0.81$

PDG weighted average:

$(7.5 \pm 0.8) \times 10^{-4}$

BES-2 measurement:

$(8.99 \pm 0.18 \pm 0.89) \times 10^{-4}$



Motivation I

Include PDG val. in fit

$$\chi^2(new) = \chi^2(old) + \frac{|Br(fit) - Br(PDG)|^2}{\sigma^2(PDG)}$$

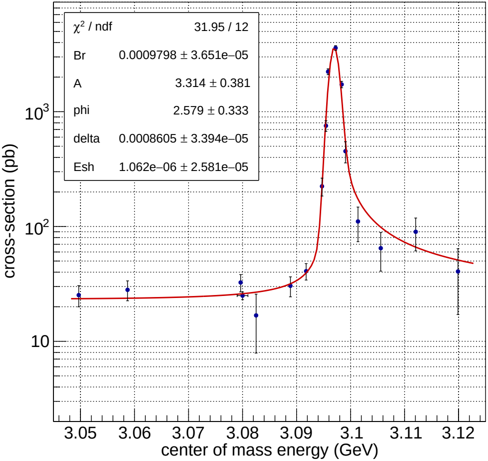
$$Br(PDG) = (7.5 \pm 0.8) \times 10^{-4}$$

Fit result:

$Br = (9.8 \pm 0.4) \times 10^{-4}$

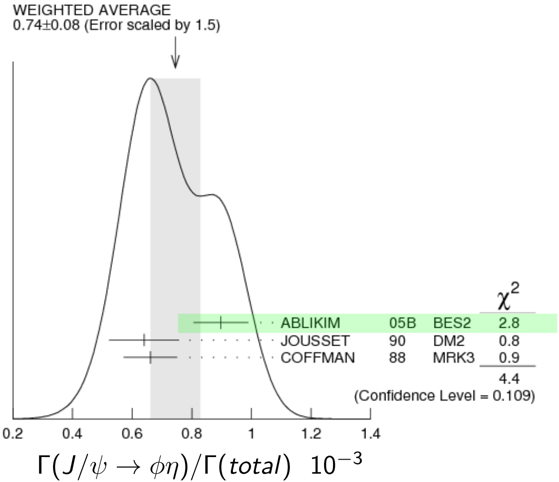
$\varphi = 2.58 \pm 0.33$

✓ **Error on φ is reduced by factor 2.5**



Motivation II

The existing measurements of $Br(J/\psi \to \phi\eta)$ are ambiguous (PDG-2019)



Data & Monte-Carlo samples

Measurements are performed in the decay chain:
$\psi(3686) \to \pi^+\pi^- J/\psi, \quad J/\psi \to \phi\eta, \quad \phi \to K^+K^-, \quad \eta \to \gamma\gamma.$

- We used DST for $\psi(3686)$ 2009 and 2012.
- We used a continuum sample at 3.65 GeV to estimate the background from non resonant production.
- We used $\psi(3686)$ inclusive Monte Carlo simulated data for 2009 and 2012 (official samples).
- We generated signal MC data with BesEvenGen.
- We used two versions of the BOSS software
  - **6.6.4p1** for 2009: data, MC and continuum sample
  - **6.6.4p3** for 2012: data and MC

Event Selection I: $\psi(3686) \to \pi^+\pi^- J/\psi$

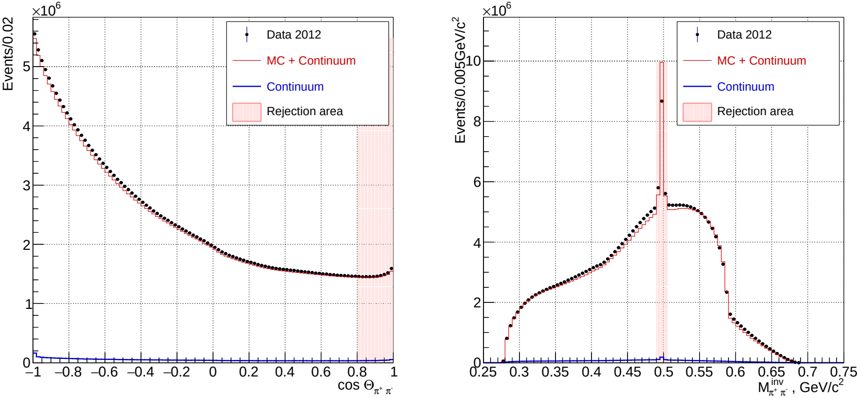
At least two opposite charged soft pions:

- $|R_{xy}| \leq 1$ cm; $|R_z| \leq 10$ cm
- $cos(\Theta) \leq 0.80$
- PID: $Prob(\pi) > max(Prob(K), Prob(proton), 0.001)$
- $P_\pi < 0.45$ GeV$/c$

We consider a good pair of $\pi^+\pi^-$ if:

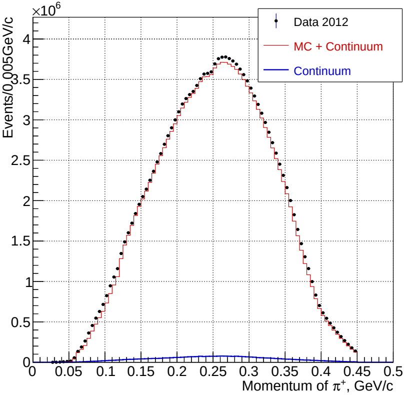
- $\cos(\Theta_{\pi^+\pi^-}) < 0.80$ *(to suppress pions flying in one direction)*
- $|M^{inv}_{\pi^+\pi^-} - M(K^0_S)| > 0.008$ GeV$/c^2$ *(to suppress pions from K^0_s)*
- $3.0 \leqslant M^{rec}_{\pi^+\pi^-} \leqslant 3.2$ GeV$/c^2$
  where the recoil mass is: $M^{rec}_{\pi^+\pi^-} = \sqrt{(P_{ecm} - p_{\pi^+} - p_{\pi^-})^2}$

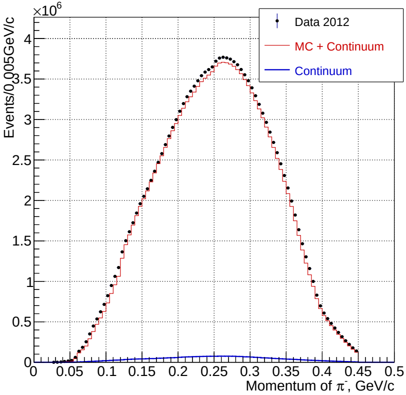
Selection $\pi^+\pi^-$: data vs MC



- Good agreement between data and inclusive MC
- The 2009 distributions are almost identical

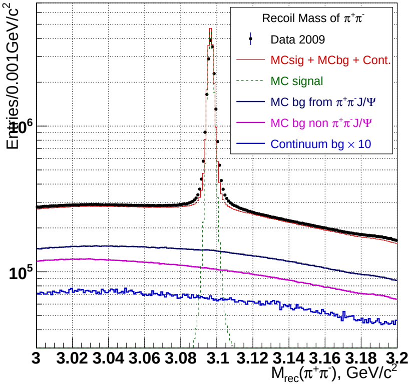
Selection $\pi^+\pi^-$: data vs MC

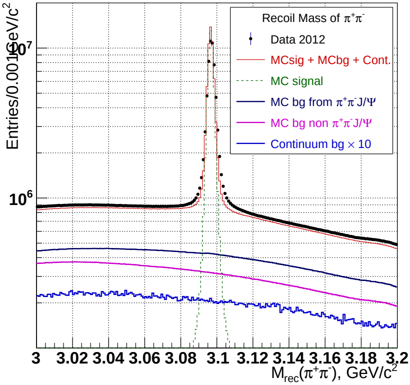




- Good agreement between data and inclusive MC
- The 2009 distributions are almost identical

Recoil mass of $\pi^+\pi^-$: data vs MC





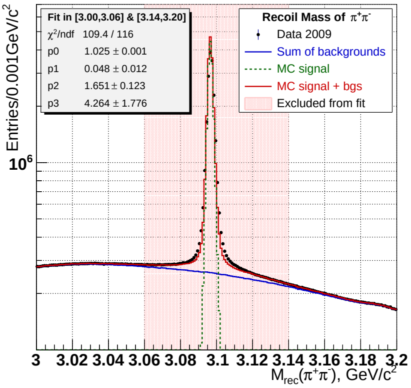
- These distributions were used to estimate the number of J/ψ in our selection

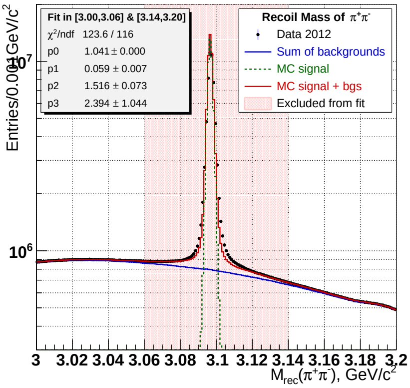
Estimation of the number of J/ψ

Side-Band Method

- Fit data in the region far from the J/ψ peak:
  $$M^{rec}_{\pi^+\pi^-} \in [3.00; 3.06] \cup [3.14; 3.20] \text{ GeV}/c^2$$
- The fitting function is:
  $$MC(Bkg) \times P_3(M^{rec}_{\pi^+\pi^-} - 3.1) + Cont + MC(Sig),$$
  - $MC(Bkg)$ is the sum of the background distributions
  - $P_3(x)$ is the third order polynomial
  - $Cont$ is the non-resonance production
  - $MC(Sig)$ is the signal distribution
- The number of J/ψ is calculated as the number of data minus the fitted background

The side-band fit of $M^{rec}_{\pi^+\pi^-}$





$M^{rec}_{\pi^+\pi^-}$ (GeV/c^2)	$N(J/\psi)$ in 2009	$N(J/\psi)$ in 2012
[3.055, 3.145]	17839834 ± 8108	55383311 ± 14357
[3.092, 3.102]	15738304 ± 4603	48669687 ± 8111

Systematic uncertainties in the side-band fit

Variation of polynomial order (P-degree) and fit range

	P-degree	fit range (GeV/c^2)	χ^2/ndf	$N_{J/\psi}$	δ(%)
2009	3	[3.00,3.06] ∪ [3.14,3.20]	109/116	17839834	—
	2	[3.00,3.06] ∪ [3.14,3.20]	115/117	17834768	0.03
	4	[3.00,3.06] ∪ [3.14,3.20]	107/115	17805529	0.19
	3	[3.00,3.05] ∪ [3.15,3.20]	91/96	17850882	0.06
	3	[3.00,3.07] ∪ [3.13,3.20]	140/136	17818151	0.12
2012	3	[3.00,3.06] ∪ [3.14,3.20]	124/116	55383311	—
	2	[3.00,3.06] ∪ [3.14,3.20]	129/117	55373982	0.02
	4	[3.00,3.06] ∪ [3.14,3.20]	122/115	55340269	0.08
	3	[3.00,3.05] ∪ [3.15,3.20]	104/96	55415283	0.06
	3	[3.00,3.07] ∪ [3.13,3.20]	177/136	55330721	0.09

- numbers are given for «wide interval» $M^{rec}_{\pi^+\pi^-} \in [3.055, 3.145]\mathrm{GeV}/c^2$
- for a narrower interval the error is much smaller

Second method for estimation of the number of J/ψ

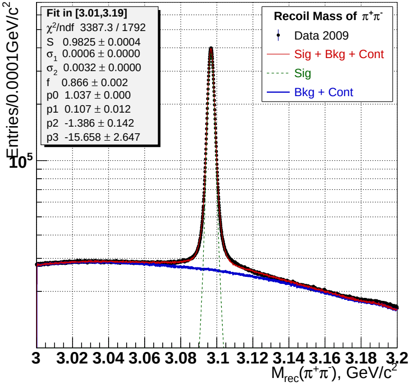
Fit method

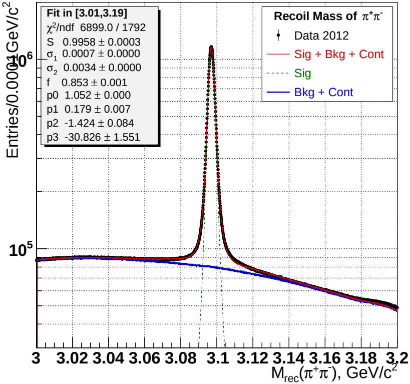
- Fit data in the entire range of $M^{rec}_{\pi^+\pi^-}$
- The fitting function is:

$$MC(Bkg) \times P_3(M^{rec}_{\pi^+\pi^-} - 3.1) + Cont + Sig(M^{rec}_{\pi^+\pi^-})$$
$$Sig(m) = S \times MC(Sig) \otimes (f \cdot \mathcal{G}(m, \sigma_1) + (1-f) \cdot \mathcal{G}(m, \sigma_2))$$

  - $MC(Sig)$ is the signal distribution convolving with the sum of two Gaussian functions $\mathcal{G}(m, \sigma)$
  - σ_1, σ_2, f and S are the parameters of the fit
- The number of J/ψ is calculated as the integral of $Sig(M^{rec}_{\pi^+\pi^-})$ in the corresponding window

The fit of $M^{rec}_{\pi^+\pi^-}$ in the entire range





$M^{rec}_{\pi^+\pi^-}$ (GeV/c^2)	$N(J/\psi)$ in 2009	$\delta(\%)$	$N(J/\psi)$ in 2012	$\delta(\%)$
[3.055, 3.145]	17603315 ± 4161	1.3	54740554 ± 6751	1.2
[3.092, 3.102]	15703865 ± 3929	0.22	48560298 ± 6357	0.22

- δ is the difference from side-band method

Number of $\psi(3686) \to \pi^+\pi^- J/\psi$ events

Summary: $Br \equiv Br(\psi' \to \pi^+\pi^- J/\psi)$

	$M^{rec}_{\pi^+\pi^-}$ (GeV/c^2)	N(J/ψ)	δ_{sys}(%)	ε(%)	Br (%)
2009	[3.055, 3.145]	17839834	1.3	47.80 ± 0.28	34.9 ± 0.5
	[3.092, 3.102]	15738304	0.22	42.65 ± 0.26	34.5 ± 0.3
2012	[3.055, 3.145]	55383311	1.2	45.99 ± 0.28	35.3 ± 0.5
	[3.092, 3.102]	48669687	0.22	40.80 ± 0.24	35.0 ± 0.3

- Numbers will be used in the rest of this presentation
- Selection efficiency ε was obtained from inclusive MC with corrections on pion tracking efficiency

Notes on branching ratio $Br(\psi' \to \pi^+\pi^- J/\psi)$

- ✓ The systematic errors are dominant
- ✓ Good agreement of branching obtained in wide and narrow intervals: errors are fully correlated and therefore $\sigma_\Delta = \sqrt{|\sigma_1^2 - \sigma_2^2|} = 0.4\%$
- ✓ Good agreement between 2009 and 2012
- ✓ Good agreement with previous BES-3 result based on the same 2009 data: $B(\psi' \to \pi^+\pi^- J/\psi) = (34.98 \pm 0.02 \pm 0.45)\%$

Event Selection: $J/\psi \to \phi\eta$ ($\phi \to K^+K^-$; $\eta \to \gamma\gamma$)

Charged tracks

- We choose $\pi^+\pi^-$ with $M^{rec}_{\pi^+\pi^-}$ closest to the mass of J/ψ
- $M^{rec}_{\pi^+\pi^-} \in [3.092, 3.102]$ GeV$/c^2$
- In addition to the selected pions there must be two opposite charged kaons:
  - $|R_{xy}| \leq 1$ cm; $|R_z| \leq 10$ cm
  - $cos(\Theta) \leq 0.80$
  - PID: $Prob(K) > max(Prob(\pi), Prob(proton), 0.001)$

At least two photons:

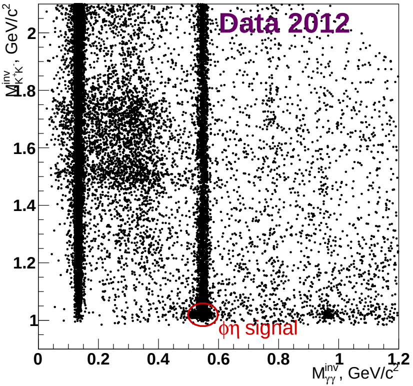
- $E_\gamma > 25$ MeV (barrel EMC) or $E_\gamma > 50$ MeV (end-cap EMC)
- $\alpha_\gamma > 10^\circ$ for the angle relative to the nearest charged track

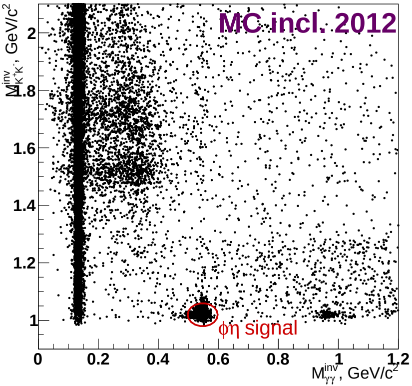
Event Selection: $\psi' \to \pi^+\pi^- J/\psi, \quad J/\psi \to \phi\eta$

5C kinematic constraints

- the 4-momentum of the system $\pi^+\pi^- K^+ K^- 2\gamma$ should be P_{ecm}
- the invariant mass $M^{inv}(K^+ K^- 2\gamma)$ should be $M_{J/\psi}$
- we choose two photons with minimal χ^2_{5C}
- the event is discarded if $\chi^2_{5C} > 80$
- the event is discarded if there is a third photon such that:
$$\chi^2_{5C}(\pi^+\pi^- K^+ K^- 3\gamma) < \chi^2_{5C}(\pi^+\pi^- K^+ K^- 2\gamma)$$

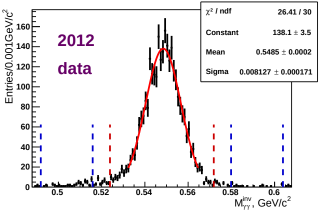
Invariant masses $M^{inv}_{K^+K^-}$ vs $M^{inv}_{\gamma\gamma}$; Data and MC

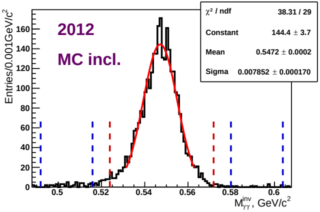


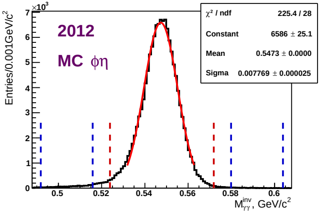


- Inclusive MC does not contain $K^+K^-\eta$ events above M_ϕ
- We generated MC data with final state $K^+K^-\eta$ (background MC) using BesEvenGen

Invariant mass of $\eta \to \gamma\gamma$



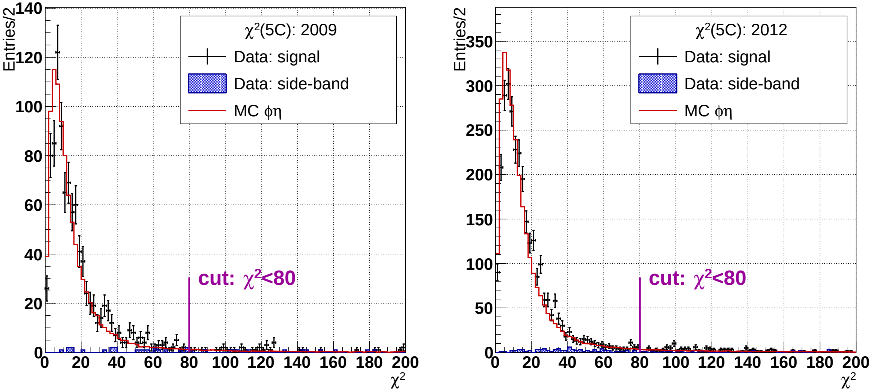




✓ Here we show only events with $2M_K \leqslant M^{inv}_{K^+K^-} \leqslant 1.1$ GeV$/c^2$

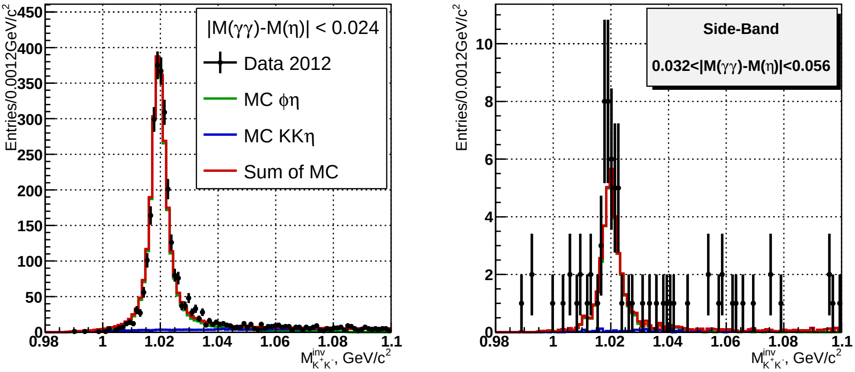
- The distributions fit with Gauss: $\sigma(\eta) \sim 8$ MeV
- The dashed lines show the selection window and side bands

$\chi^2(5C)$ for signal and side-band events



- Good agreement between data and signal MC

Invariant mass of $\phi \to K^+K^-$



- The data appears to be shifted to the right relative of the MC curve
- This is consistent with interference of $KK(\phi) - KK(non\ resonant)$
- The effect was ignored in all previous measurements
- BESIII precision is so high that we must take into account the interference effect

Fit of $M^{inv}_{K^+K^-}$

Resonant part

- the relativistic Breit-Wigner corrected for the phase space:

$$\mathcal{BW}_\phi(m) = \frac{\kappa f^2(m)}{(m^2 - M_\phi^2)^2 + m^2\,\Gamma^2(m)},$$

where energy dependant width $\Gamma(m)$ is

$$\Gamma(m) = \Gamma_\phi \left(\frac{p_K(m)}{p_K(M_\phi)}\right)^3 \frac{M_\phi}{m} \frac{B(p_K(m))}{B(p_K(M_\phi))},$$

$f(m)$ is correction factor and $B(p)$ is Blatt-Weisskopf penetration form factor:

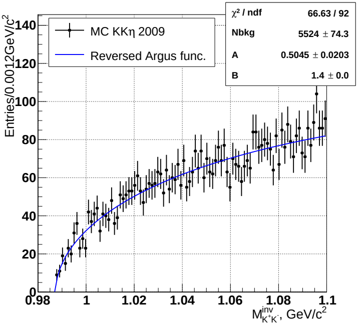
$$f(m) = \frac{p_\phi(m)}{p_\phi(M_\phi)} \frac{p_K(m)}{p_K(M_\phi)} \frac{B(p_\phi(m))}{B(p_\phi(M_\phi))} \frac{B(p_K(m))}{B(p_K(M_\phi))}, \quad B(p) = \frac{1}{\sqrt{1 + (rp)^2}}.$$

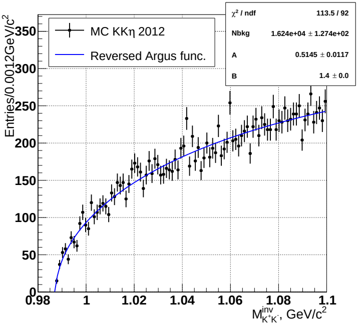
Fit of $M^{inv}_{K^+K^-}$

Background:

- reversed Argus function:

$$\mathcal{AR}(m) = m \cdot \exp(A \cdot \log(v) - B \cdot v), \qquad v = 1 - \left(1 - \frac{m-L}{U}\right)^2$$



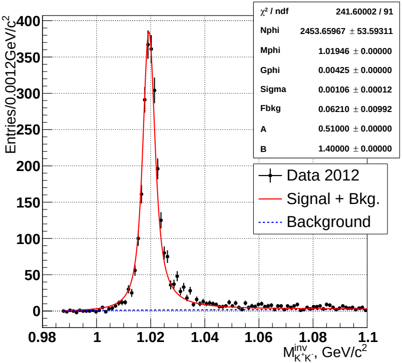


- Fit of MC $K^+K^-\eta$ background with Argus function

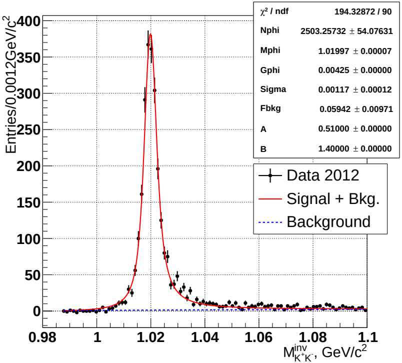
Fit of $M^{inv}_{K^+K^-}$ data by incoherent sum

- The incoherent sum of the Breit-Wigner convoluted with Gauss and Argus function:

$$\mathcal{BW}_\phi(m) \otimes \mathcal{G}(m) + \mathcal{AR}(m)$$



M_ϕ is fixed at the PDG value



M_ϕ is a free parameter

In general the data are described poorly: ~ 0.5MeV shift relative to the PDG M_ϕ

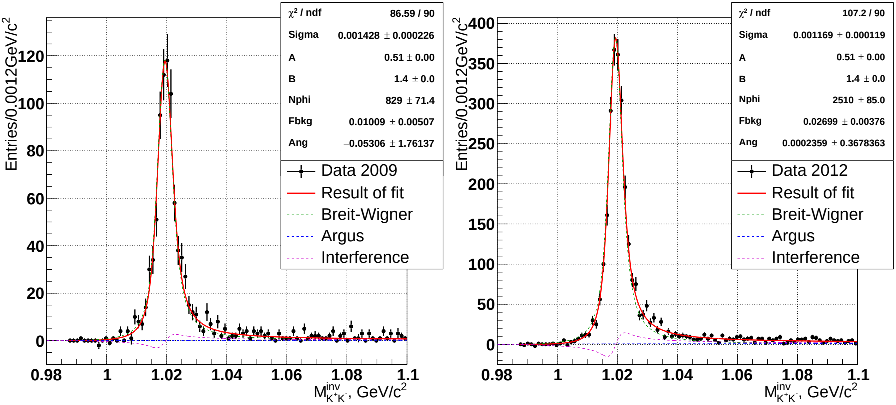
Fit of $M^{inv}_{K^+K^-}$ data, the interference

- The interference between $\phi\eta$ and $K^+K^-\eta$ final states:

$$\left|\mathcal{A}_{BW}(m) \times N_R \exp(i\,\vartheta) + \sqrt{\mathcal{AR}(m)}\right|^2 \otimes \mathcal{G}(m)$$

  - $\mathcal{A}_{BW}(m)$ is the Breit-Wigner amplitude
  - N_R is the magnitude of the ϕ resonance
  - ϑ is the mixing angle
  - $\mathcal{AR}(m)$ is the Argus function

Fit of $M^{inv}_{K^+K^-}$ data, the interference

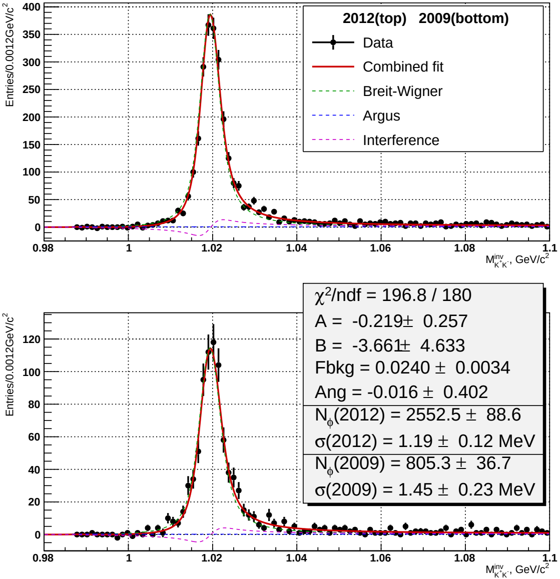


- $\chi^2/ndf = 0.96$ for 2009 and 1.2 for 2012
- If M_ϕ is a free fit parameter then the fitted value is consistent with the PDG value within the fit error
- Both results are compatible to the zero mixing angle

Combined fit of $M^{inv}_{K^+K^-}$ data

- Both data periods are fitted at the same time
- Background parameters (A, B, $\mathtt{Fbkg}$) and mixing angle are common

- Taking into account the interference changes the N_ϕ by $3 \div 4\%$, which is $\sim (1. \div 1.5) \times \sigma(stat)$
- This effect was ignored in all past measurements



Branching fraction of $J/\psi \to \phi\eta$

Summary

	$N(K^+K^-\gamma\gamma)$	$\varepsilon(\%)$	$N(J/\psi)$	$Br(J/\psi \to \phi\eta)$
2009	805.3 ± 36.7	32.79 ± 0.17	15738304	$(8.1 \pm 0.4)\times10^{-4}$
2012	2552.5 ± 88.6	31.90 ± 0.10	48669687	$(8.5 \pm 0.3)\times10^{-4}$

- Selection efficiency ε was obtained from signal MC with corrections on kaon tracking efficiency
- We used the following branchings from PDG 2018:
  $Br(\eta \to \gamma\gamma) = (39.41 \pm 0.20)\%$
  $Br(\phi \to K^+K^-) = (49.2 \pm 0.5)\%$
- The errors are statistical only

PDG 2018: $Br(J/\psi \to \phi\eta) = (7.5 \pm 0.8) \times 10^{-4}$

Systematic uncertainties

- **Number of J/ψ:**
  - we estimated $\delta_{sys}(N_{J/\psi}) = 0.22\%$ for interval $M^{rec}_{\pi^+\pi^-} \in [3.092, 3.102]$
- **Branching fractions (PDG):**
  - $\delta Br(\phi \to K^+K^-) \oplus \delta Br(\eta \to \gamma\gamma) = 1.1\%$
- **Track reconstruction efficiency:**
  - the standard value $2 \times 1\%$ looks too big for this analisis, so we performed additional study to estimate difference in reconstruction efficiencies of kaons in data and MC (see the next slide)
- **Photon reconstruction efficiency:**
  - $2 \times 1\%$
    here we are also trying to do additional study to reduce this error
    The analysis is not yet complete
- **Varing selection critiria:**
  this part is not complete yet
  - varying χ^2 cut
  - varying side-band criteria

Difference of tracking efficiency: Data vs MC

- We used process: $\psi' \to \pi^+\pi^- J/\psi, \quad J/\psi \to \pi^+\pi^- K^+K^-$ to measure the track efficiencies of pions and kaons
- For kaons:
  - $\pi^+\pi^-$ pair was selected as described in «Event Selection I» $M^{rec}_{\pi^+\pi^-} \in [3.095, 3.099]$ GeV$/c^2$
  - "tag" a J/ψ decay by $\pi^+\pi^- K^{(\pm)}$ with a missing mass about M_K
  - we checked whether $K^{(\mp)}$ was reconstructed or not
- For pions:
  - "tag" a J/ψ event by $\pi^+\pi^- K^+K^-$ with invariant mass: $M^{inv} \in [3.087, 3.105]$ GeV$/c^2$
  - we search for additional $\pi^{(\pm)}$ and the missing mass is about M_π
  - we checked whether $\pi^{(\mp)}$ was reconstructed or not

definition of track reconstruction efficiency ϵ

$$\epsilon = \frac{N_6}{N_6 + N_5}$$

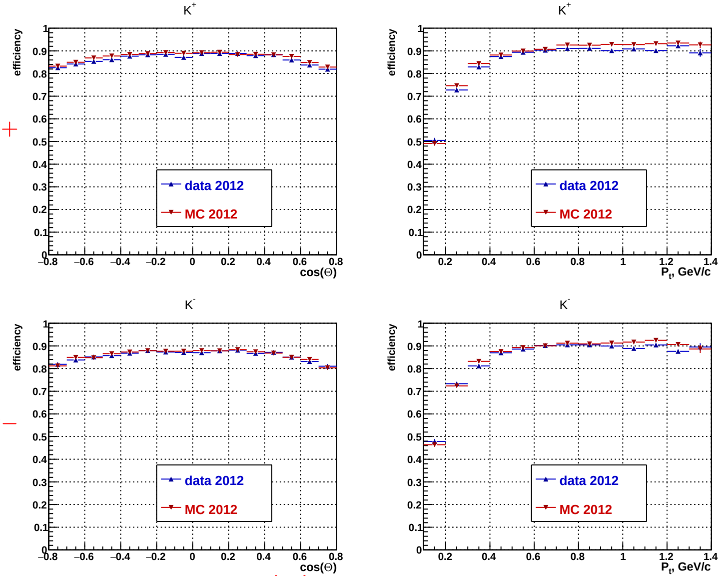
N_6 — all six tracks reconstructed

N_5 — one track (π or K) is missing

Kaons: reconstruction track efficiency in 2012

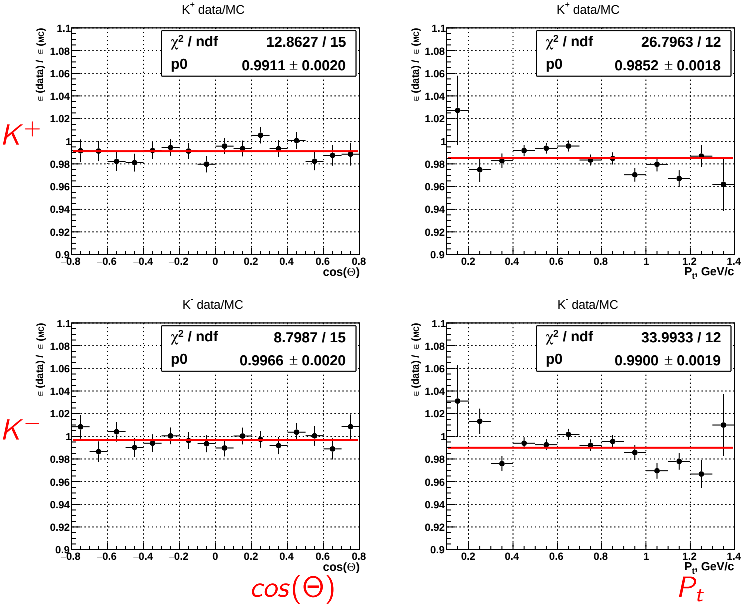
K^+

K^-



$cos(\Theta)$ P_t

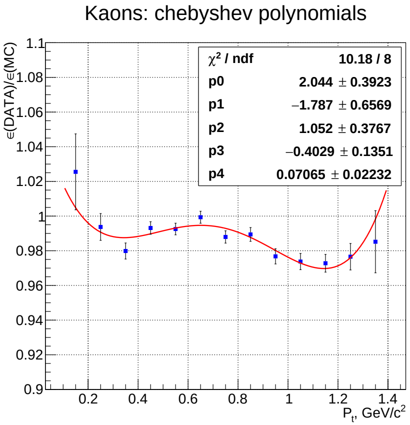
Kaons: $\epsilon_{DATA}/\epsilon_{MC}$ in 2012

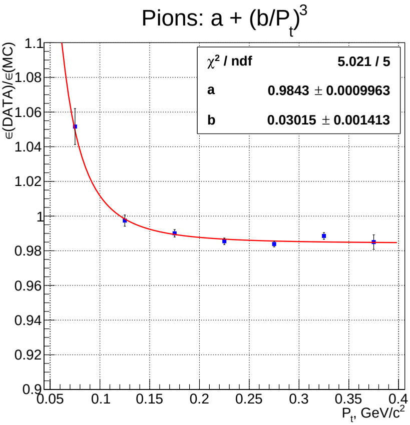


Efficiency corrections

- To improve consistency between data and MC we used re-weighting for $\pi^+\pi^-$ and K^+K^- in MC
- Kolmogorov–Smirnov test showed that ratios of efficiencies for K^+ and K^- have the same distribution (the same fact for π^+ and π^-)
- There is no dependence on the polar angle of kaons and pions
- Efficiency corrections were obtained as a function on transverse momentum P_t

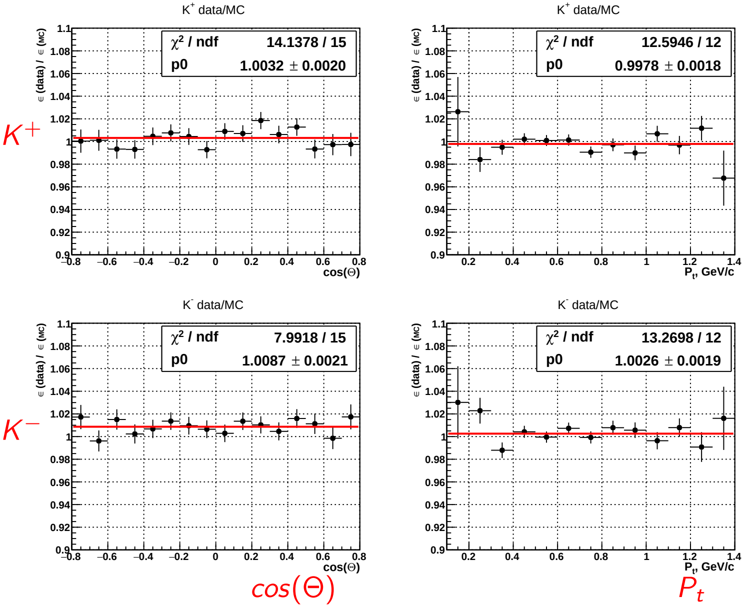
Efficiency corrections in 2012





✓ These corrections have been already applied for calculations of selection efficiencies for $\psi(3686) \to \pi^+\pi^- J/\psi$ and $J/\psi \to \phi\eta$ shown above

Kaons: $\epsilon_{DATA}/\epsilon_{MC}$ in 2012 after corrections



Conclusion

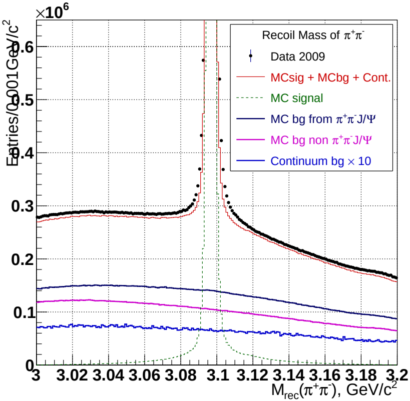
- We measured the branching fraction of $J/\psi \to \phi\eta$:
  $(8.1 \pm 0.4)\times10^{-4}$ for data 2009
  $(8.5 \pm 0.3)\times10^{-4}$ for data 2012
- We continue the work for estimation of systematic uncertainties
- Memo in the process of preparation

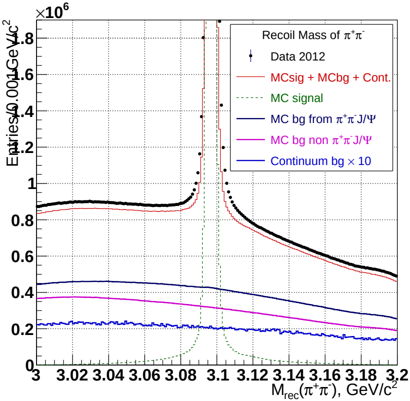
prospective result

- We got 0.24×10^{-4} cumulative statistical error
- We expect $\sim 0.2 \times 10^{-4}$ systematic error
- Total error will be $\sim 0.31 \times 10^{-4}$ (current PDG average is 0.8×10^{-4})

Backup slides

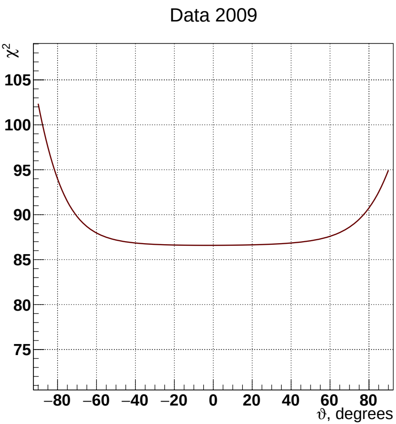
Recoil mass of $\pi^+\pi^-$: data vs MC

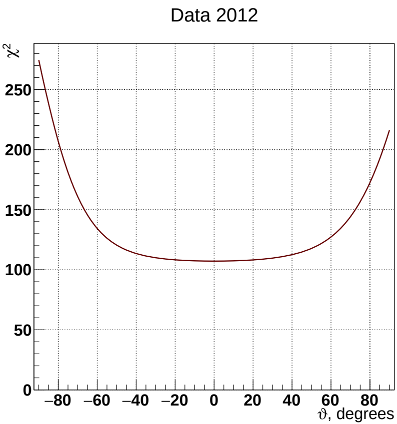




- The pictures are in linear scale and zoomed to show the tails of MC signal distribution J/ψ in our selection

Scan for mixing angle

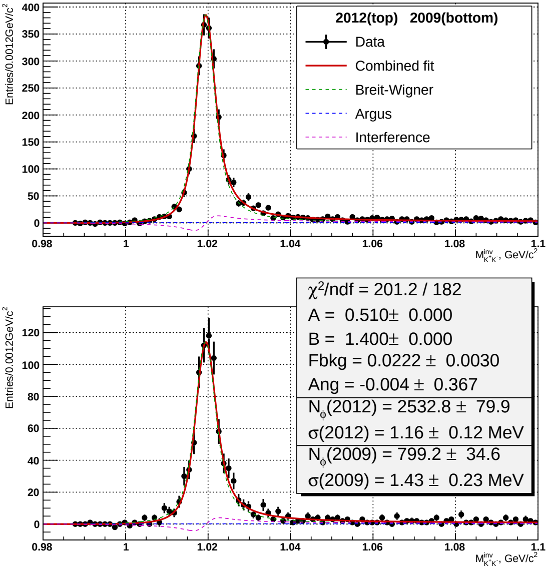




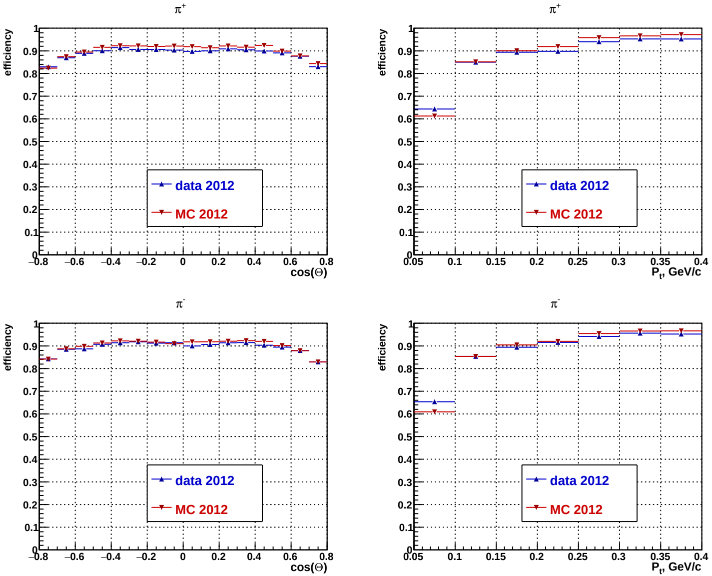
- the angle is fixed at a specific value, a fit was performed and the χ^2 of the fit is displayed
- zero angle is preferred for both data periods

Combined fit of $M^{inv}_{K^+K^-}$ data

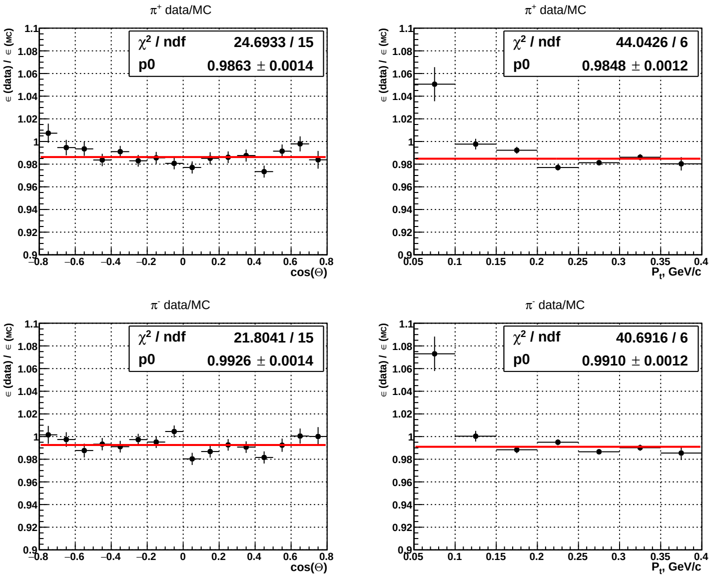
- parameters A and B are fixed
- almost the same quality of the fit: $\chi^2/ndf = 1.1$
- errors of N_ϕ reduced by $\sim 10\%$



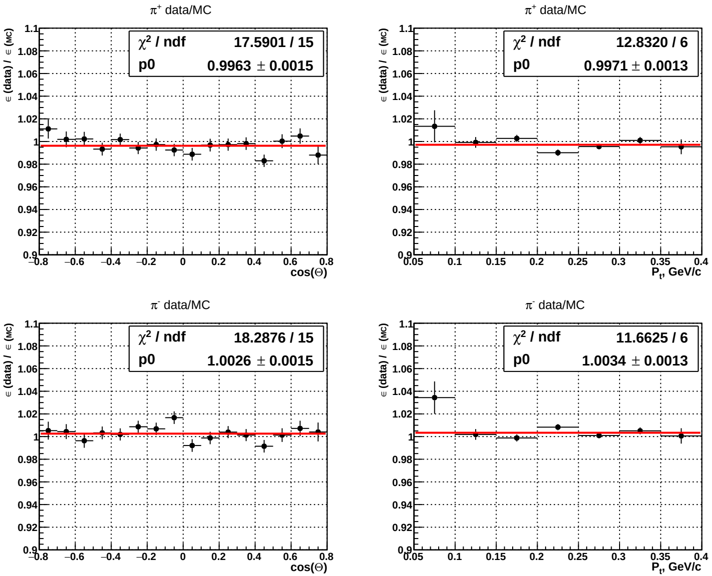
Pions: reconstruction track efficiency in 2012



Pions: $\epsilon_{DATA}/\epsilon_{MC}$ in 2012

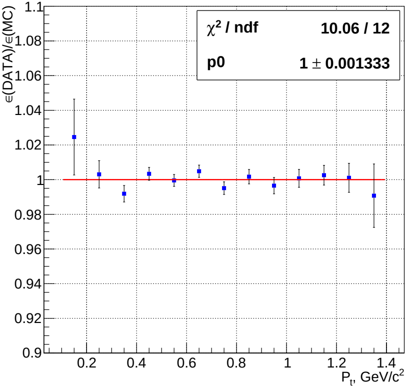


Pions: $\epsilon_{DATA}/\epsilon_{MC}$ in 2012 after corrections



Check after efficiency corrections in 2012

Kaons: chebyshev polynomials



Pions