Dipion mass spectrum in X(3872) decay

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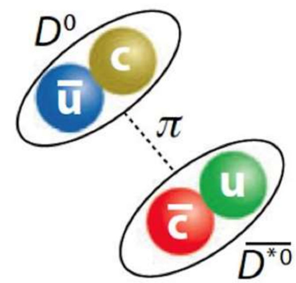
Theoretical input from: Adam Szczepaniak *and* Mikhail Mikhasenko

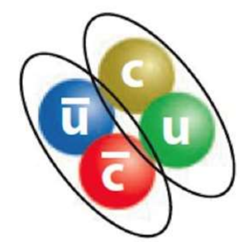
Update to the talk given by Baaska at BandQ on Mar 5, 2020: https://indico.cern.ch/event/879097/

Motivation

- X(3872) might be a loosely bound $D^0\overline{D}^{*0}$ molecular state or tightly bound tetraquark.
- In this analysis, I am trying to separate **interfering $\boldsymbol{\rho^0 \to \pi^+\pi^-}$ and $\boldsymbol{\omega \to \pi^+\pi^-}$ contributions** to $\boldsymbol{B^+ \to K^+X(3872)}$, $\boldsymbol{X(3872) \to \pi^+\pi^- J/\psi}$. Their relative strength is important for X(3872) interpretations.
  - $\boldsymbol{X(3872) \to J/\psi\ \rho^0\ , \rho^0 \to\ \pi^+\ \pi^-}$
    - Isospin violating decay of X(3872), isospin conserving decay of $\boldsymbol{\rho^0}$
    - From the shape of m($\boldsymbol{\pi^+\pi^-}$), dominant component in $\boldsymbol{X(3872) \to \pi^+\pi^- J/\psi}$
  - $\boldsymbol{X(3872) \to\ J/\psi\ \omega\ ,\ \omega\ \to \pi^+\ \pi^-\ \pi^0}$
    - Isospin conserving decays of X(3872), isospin conserving decay of $\boldsymbol{\omega}$
    - Only low-mass tail of $\boldsymbol{\omega}$ peak contributes to X(3872) decays.
    - BR($\boldsymbol{\omega\ \to \pi^+\ \pi^-\ \pi^0}$) = 89.3%
    - Observed by Belle [arXiv:hep-ex/0505037 (2005)] and BaBar [PRD 82, 011101 (2010)].
      - From Babar $\mathrm{r} =$ $\boldsymbol{BR(X(3872) \to J/\psi\ \omega)}$ **/ BR**$\boldsymbol{(X(3872) \to \pi^+\pi^-\ J/\psi)}$ **=** $\boldsymbol{0.8 \pm 0.3}$
    - Unpublished LHCb results [Guido Andreassi, INFN, Rome, CERN-THESIS-2014-243].
  - $\boldsymbol{X(3872) \to\ J/\psi\ \omega, \omega\ \to \pi^+\ \pi^-}$
    - Isospin conserving decay of X(3872), isospin violating decay of $\boldsymbol{\omega}$
    - BR($\boldsymbol{\omega\ \to \pi^+\ \pi^-}$) = 1.5%.
    - Naively expect
      - $\boldsymbol{R_\omega \equiv \Gamma(X(3872) \to J/\psi\ \omega, \omega\ \ \to \pi^+\ \pi^-)\ /\ \Gamma(X(3872) \to \pi^+\pi^-\ J/\psi\ ) = r\ \cdot BR(\omega\ \ \to \pi^+\ \pi^-)}$ **=** $\boldsymbol{0.012 \pm 0.005}$
      - Small but its effect can be much bigger via $\boldsymbol{\rho^0}$ - $\boldsymbol{\omega}$ interference
    - CDF [PRL 96, 102002 (2006)] and Belle [PRD 84, 052004 (2011)] tried to establish this contribution, but had insufficient statistics (see next slides)



D^0–$\overline{D}^{*0}$ "molecule"

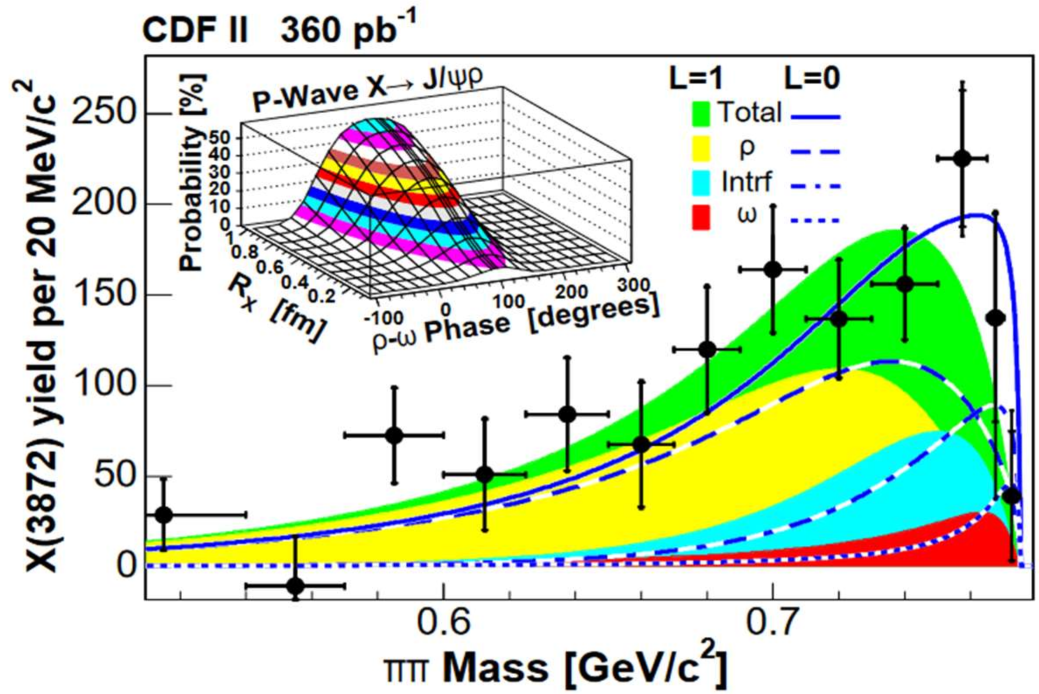


Diquark–diantiquark

CDF II analysis

PRL 96, 102002 (2006)

- CDF II studied m($\pi^+\pi^-$) with low statistics data set.
- Analyzed 1260 ± 130 X(3872) candidates from prompt production i.e. with high background to subtract
- They considered rho-omega interference via Breit-Wigner (BW) sum
- Omega contribution insignificant
- $\boldsymbol{R_\omega}$ < 10% (no systematic errors)



$$\boldsymbol{dN/\mathrm{dm}_{\pi\pi} \propto |M|^2}$$

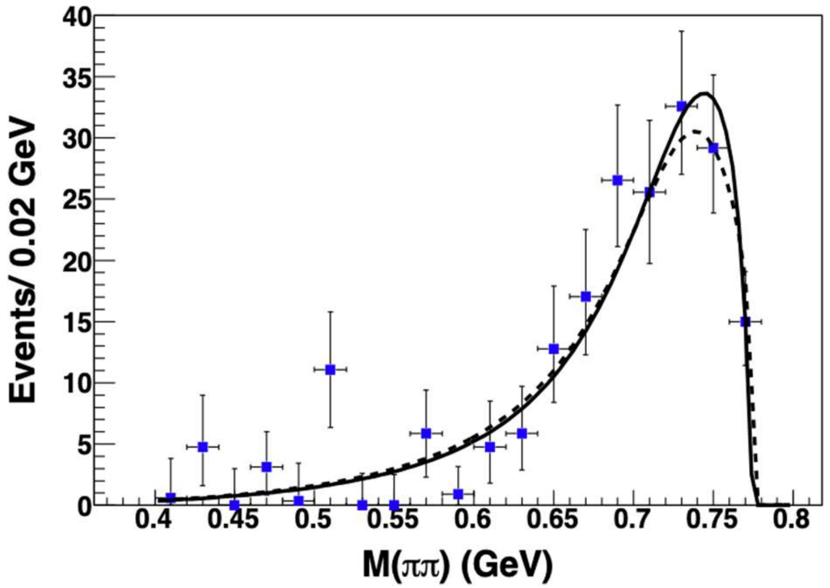
$$\boldsymbol{M = BW_\rho + e^{i\phi} A_\omega BW_\omega}$$

(they fixed the phase to $\phi = 95^\circ$)

Belle analysis

PRD 84, 052004 (2011)

- Analyzed 159 ± 15 X(3872) candidates from B decays (low background)
- Also use BW sum approach
- Omega contribution is insignificant (~1.3sigma)
- $\boldsymbol{R_\omega \sim 0.004 \pm 0.003}$ (no systematic errors)
- They don't discuss how mass resolution was taken into account in the fit – it matters in the ω region



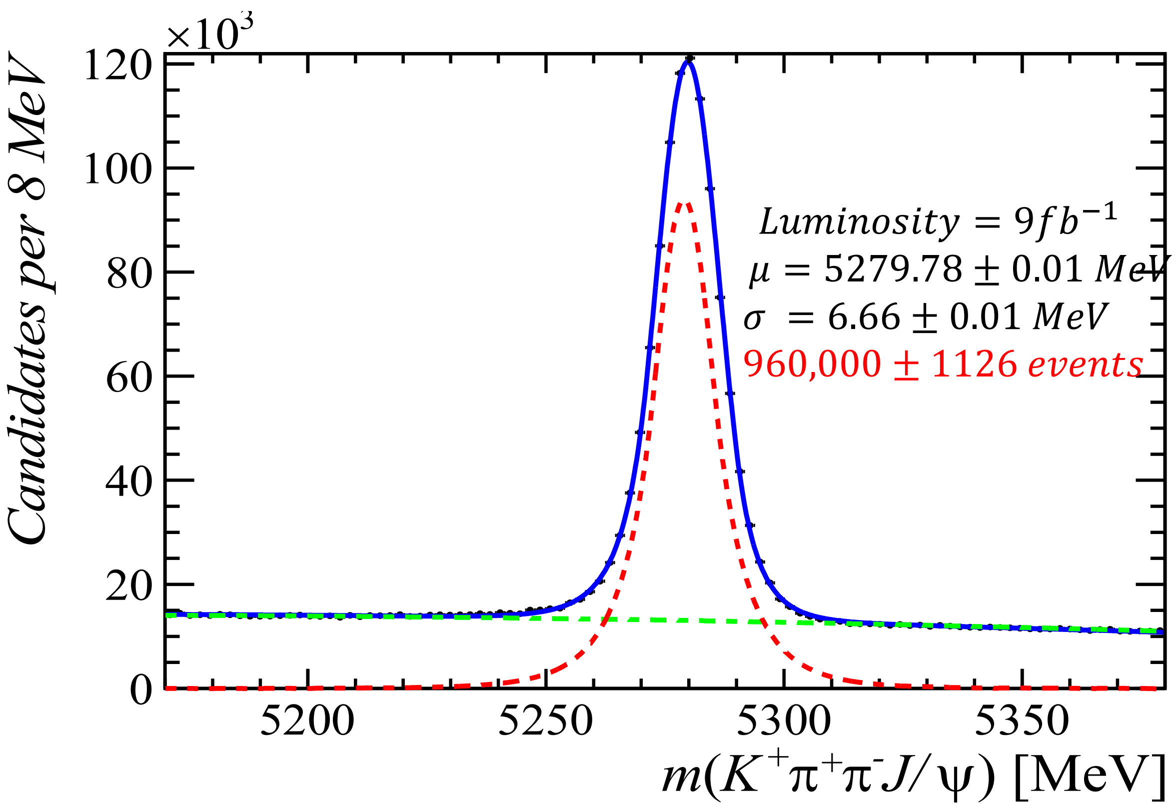
$$\boldsymbol{dN/\mathrm{dm}_{\pi\pi} \propto |M|^2}$$

$$\boldsymbol{M = BW_\rho + e^{i\phi} A_\omega BW_\omega}$$

(they also fixed the phase to $\phi = 95$ deg)

$B^+ \to K^+\pi^+\pi^- J/\psi$ mass fit

With J/psi mass and vertex constraints

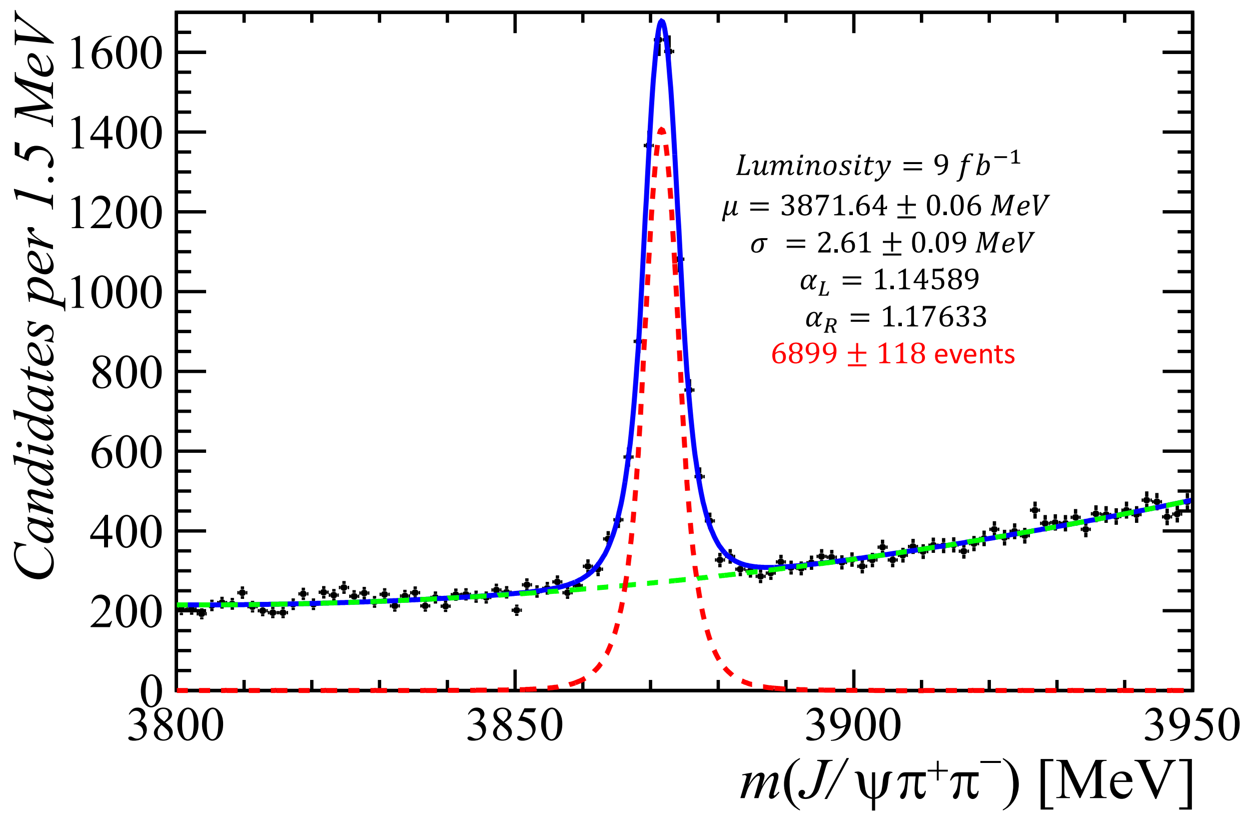


DSCB function was used for fit the signal peak and second order polynomial for the background signal.

Dominated by $\boldsymbol{B^+ \to J/\psi\, K(\dots)^+, K(\dots)^+ \to K^+\pi^+\pi^-}$

X(3872)

After 2σ B mass cut, with B mass constraint



43 times larger data set than analyzed by Belle!

$\pi^+ \pi^-$ mass spectrum

We performed 2D fit to $[m_{J/\psi\pi}\ , m_{\pi\pi}]$ in the narrow $m_{\pi\pi}$ bins to get $\frac{dN_X}{dm_{\pi\pi}}$ distribution.

Essentially, fit to $m_{J/\psi\pi\pi}$ in $m_{\pi\pi}$ bins, but must keep $m_{\pi\pi}$ dependence because of the phase-space factor.

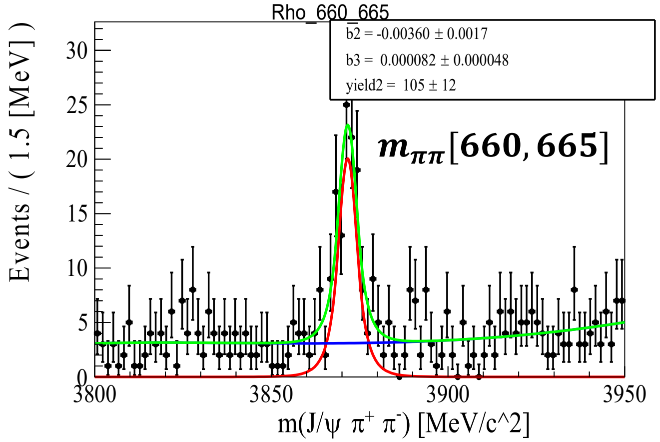
Phase-space factor (J/ψ momentum in X(3872) rest frame)

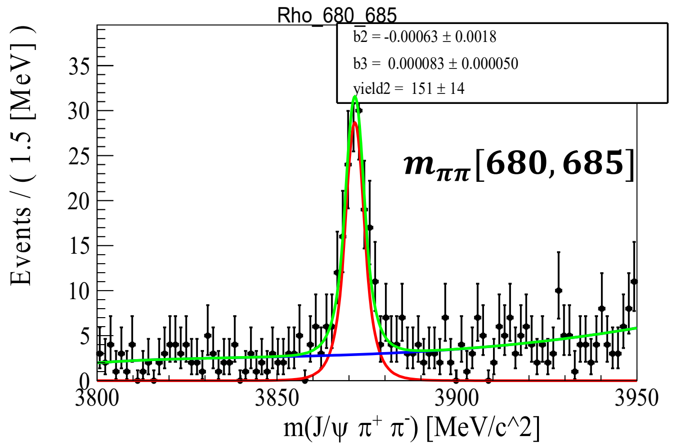
X(3872) shape parameters are fixed by the total fit of $m(J/\psi\,\pi^+\pi^-)$

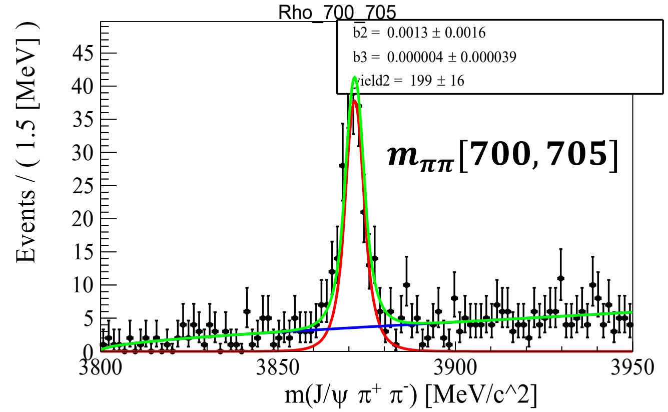
$$PDF(m_{J/\psi\pi\pi}, m_{\pi\pi}) = P_{J/\psi}(m_{J/\psi\pi\pi}, m_{\pi\pi})\,[N_X\, DSCB(m_{J/\psi\pi\pi}) + \\ +b_0 + b_1(m_{J/\psi\pi\pi} - m_{X(3872)}) + b_2(m_{J/\psi\pi\pi} - m_{X(3872)})^2]$$

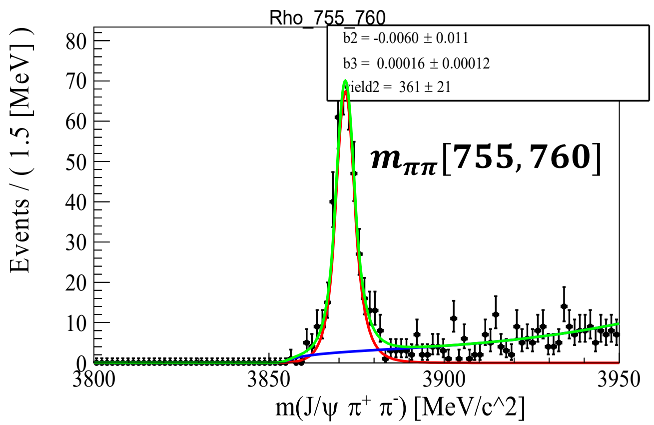
$$P_{J/\psi} = \frac{\sqrt{(m_{J/\psi\pi\pi} - m_{J/\psi} - m_{\pi\pi})(m_{J/\psi\pi\pi} - m_{J/\psi} + m_{\pi\pi})(m_{J/\psi\pi\pi} + m_{J/\psi} - m_{\pi\pi})(m_{J/\psi\pi\pi} + m_{J/\psi} + m_{\pi\pi})}}{2m_{J/\psi\pi\pi}}$$

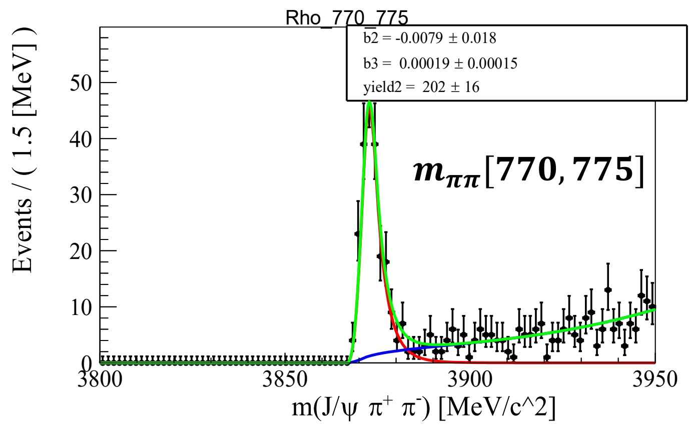
$\pi^+ \pi^-$ mass spectrum (some examples of X(3872) fit)

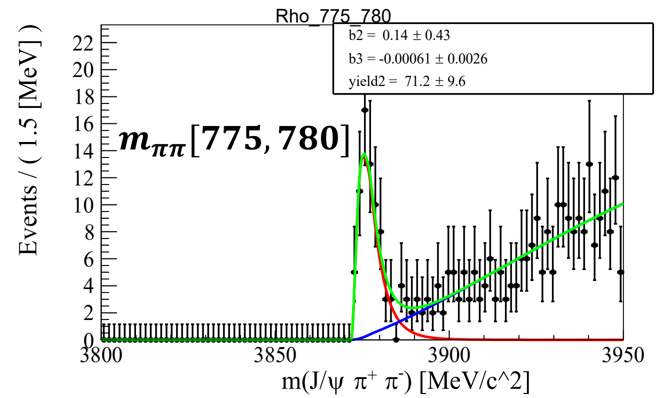






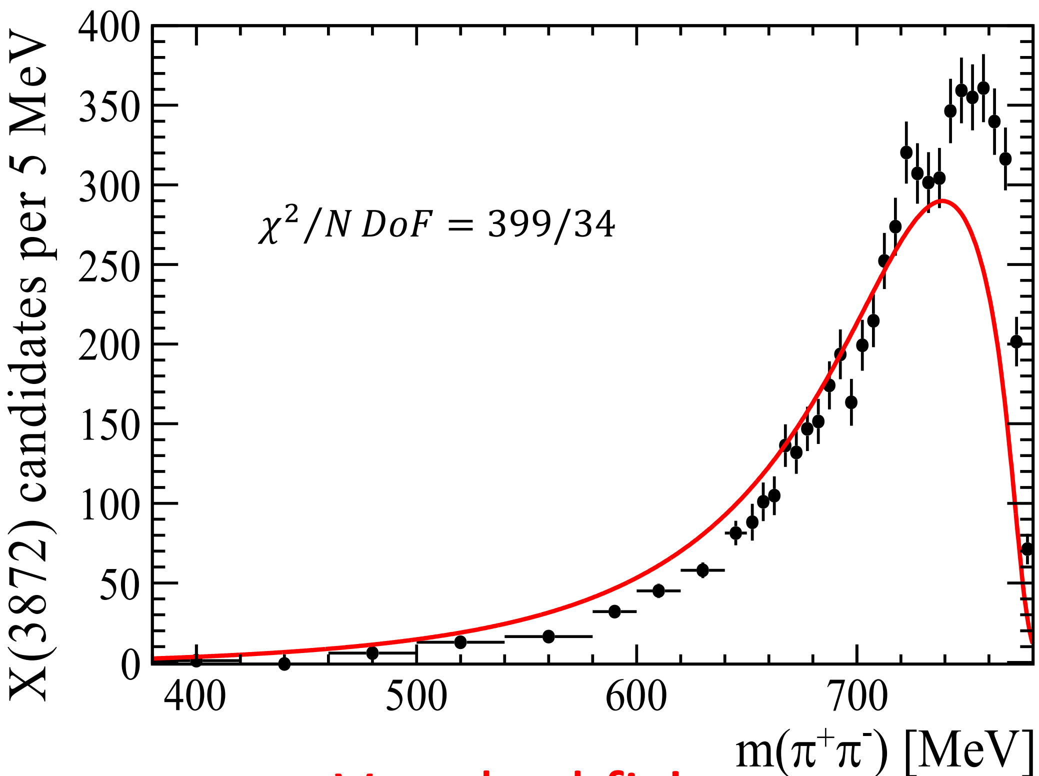






Fit of $\boldsymbol{\rho^0}$ alone to $\boldsymbol{\pi^+ \pi^-}$ mass spectrum

The PDF is corrected for the modest efficiency change with the mass and smeared with the detector resolution (see my previous presentation!)



Very bad fit!

$$PDF(m_{\pi\pi}) = \frac{dN}{dm_{\pi\pi}} = S\,p\,q\,|M|^2$$

$$M = BW_\rho(m_{\pi\pi}|m_\rho,\Gamma_\rho) = \frac{m_\rho \Gamma_\rho B_1(q,q_\rho)}{m_\rho^2 - m_{\pi\pi}^2 - i m_\rho \Gamma_\rho(m_{\pi\pi})}$$

S is an overall scaling factor.

p is the momentum of J/ψ meson in X(3872) rest frame .

q is the momentum of pion in ρ^0 rest frame.

mass dependent width is

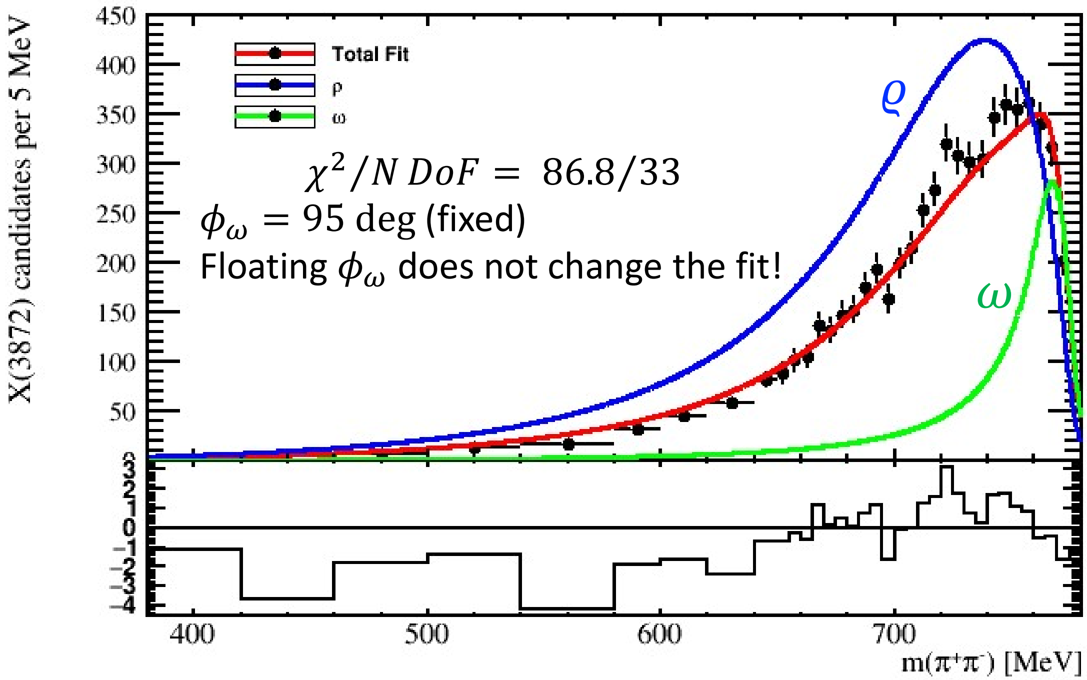
$$\Gamma(m_{\pi\pi}) = \Gamma_\rho \frac{q}{q_\rho} \frac{m_\rho}{m_{\pi\pi}} B_1(q,q_\rho)^2$$

Momentum-barrier (including Blatt-Weiskopf factor)

$$B_1(q,q_\rho) = \frac{q}{q_\rho}\sqrt{\frac{1+R^2 q_\rho^2}{1+R^2 q^2}}$$

R is a hadron size (we use R=0.3 fm)

Fit of $\boldsymbol{\rho^0} + \boldsymbol{\omega}$ (BW sum)



$$M = BW_\rho(m_{\pi\pi}|m_\rho, \Gamma_\rho) + \\ + e^{i\phi_\omega} A_\omega BW_\omega(m_{\pi\pi}|m_\omega, \Gamma_\omega)$$

Significance of ω contribution (from $\Delta\chi^2$) is very large ~ 17σ!

I – integral of PDF with no efficiency and no mass smearing:

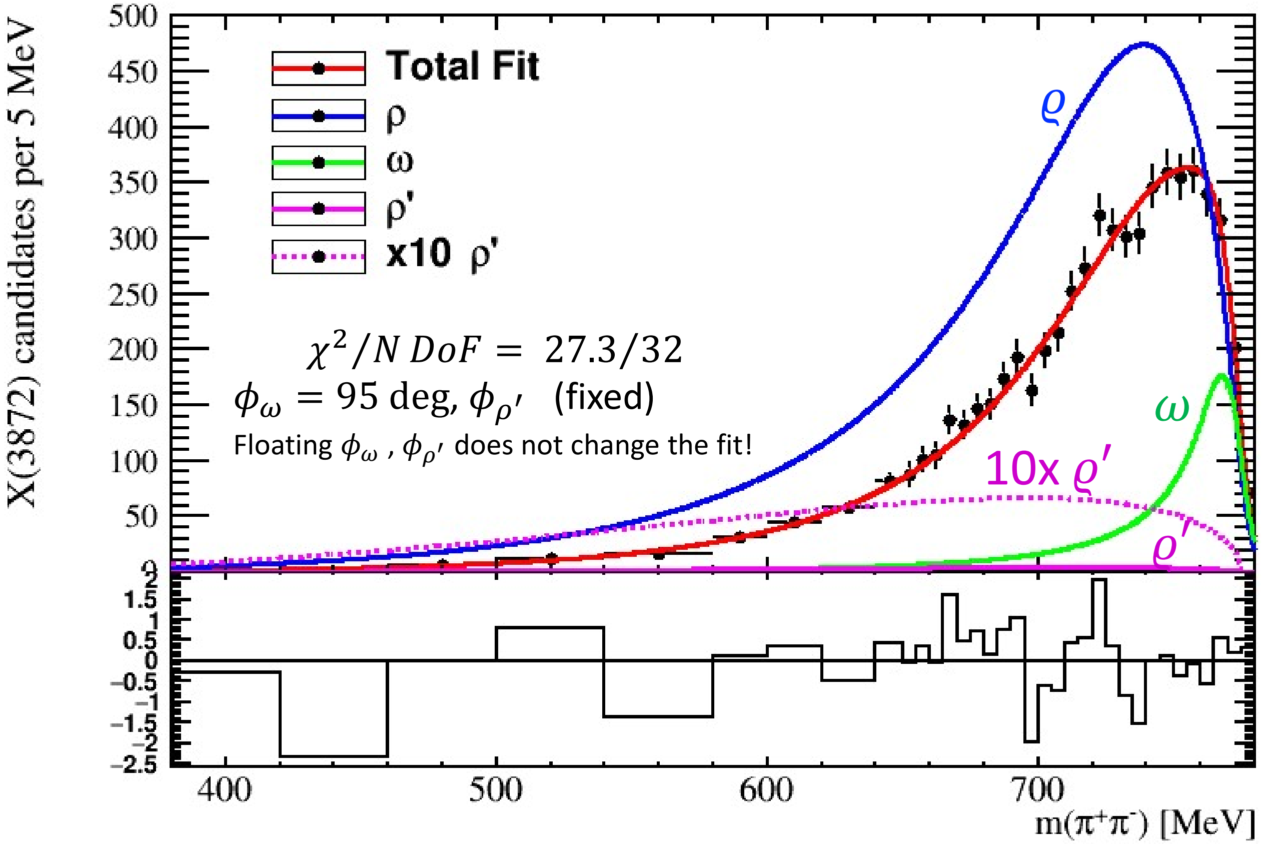
$$R_\varrho \equiv \frac{I_\varrho}{I_{tot}} = 1.367 \pm 0.005$$

$$R_\omega \equiv \frac{I_\omega}{I_{tot}} = 0.27 \pm 0.01 \quad R_{\omega/\rho} = 0.191 \pm 0.009$$

Fit is better but still bad (p-value = 1 x 10^{-6})

Fit of $\boldsymbol{\rho} + \boldsymbol{\omega} + \boldsymbol{\rho}'(\mathbf{1450})$ (BW sum)

new



$\rho(1450)$ [r] $I^G(J^{PC}) = 1^+(1^{--})$

Mass $m = 1465 \pm 25$ MeV [l]
Full width $\Gamma = 400 \pm 60$ MeV [l]

Significance of ϱ' contribution (from $\Delta\chi^2$) is very large ~ 7.7σ!

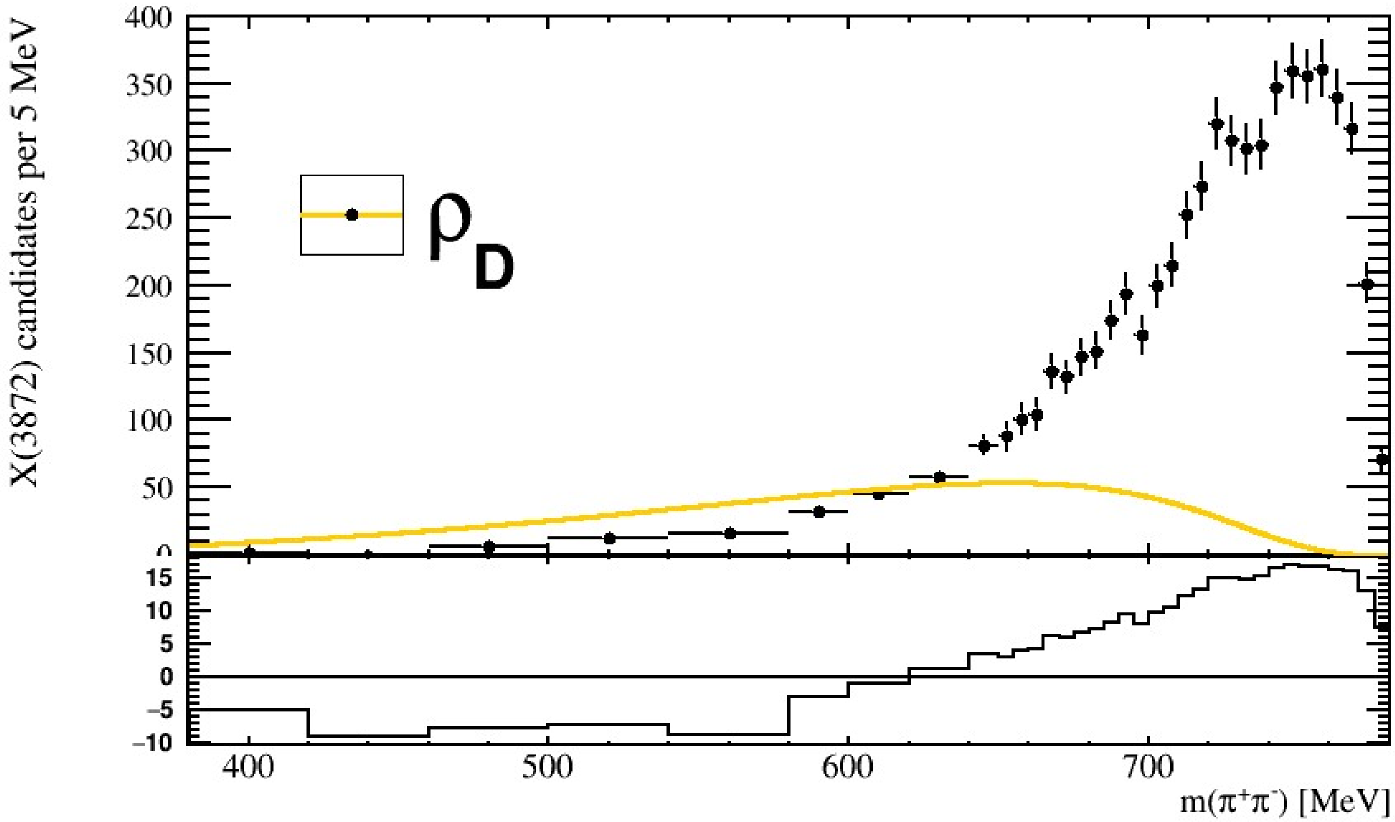
$R_\varrho = 1.65 \pm 0.03$

$R_\omega = 0.18 \pm 0.02$ $R_{\omega/\rho} = 0.11 \pm 0.01$

$R_{\rho'} = 0.031 \pm 0.010$ $R_{\rho'/\rho} = 0.019 \pm 0.005$

Fit is very good!
(p-value = 70%)

D$-$wave $\boldsymbol{\rho}$?   (BW sum)



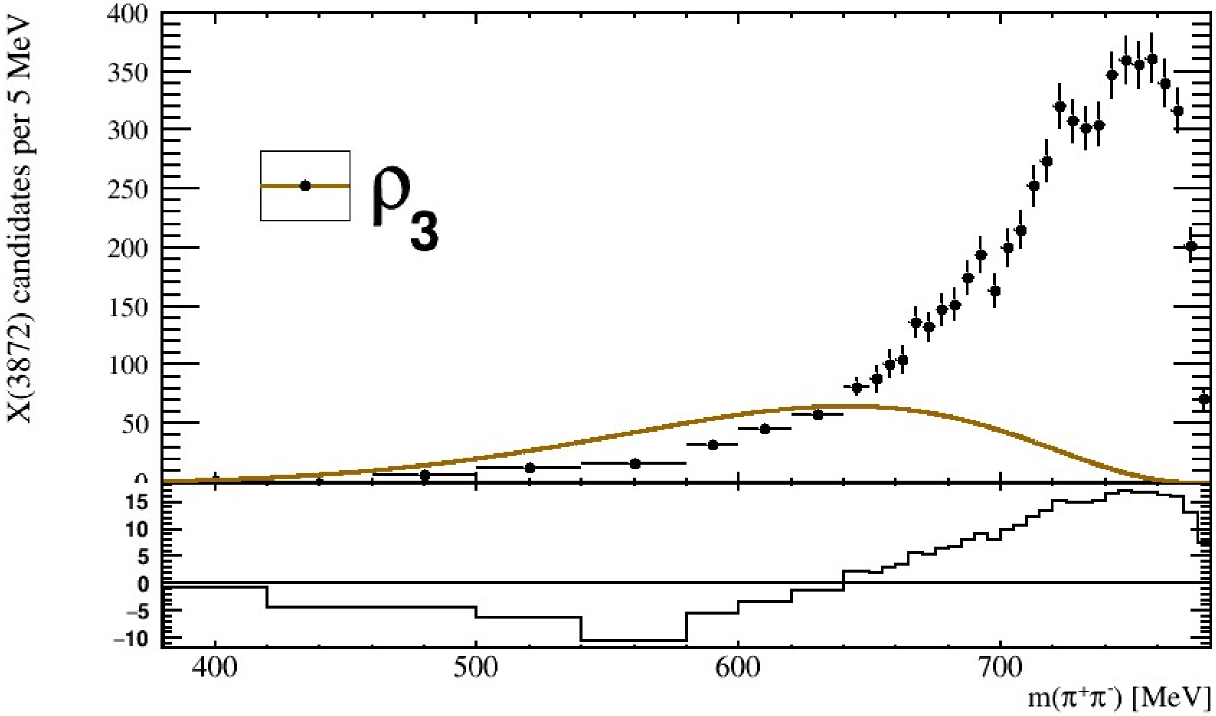
It has been suggested to investigate adding $\rho(770)$ produced in D-wave decay of X(3872) – shape shown on the left.

The previous analysis of angular correlations in X(3872) decays showed that S-wave dominates. D-wave contribution to the rate < 4% at 95% CL [LHCb, PRD92, 01102 (2015)].

When added incoherently to the fits to the $m(\pi^+\pi^-)$ distribution (at any stage), fits always prefer to make this contribution negligible.

Other J^{PC} of $\pi^+\pi^-$? (BW sum)

new



It has been suggested to investigate other quantum numbers of $\pi^+\pi^-$ than 1^{--}.

Only odd J are allowed in X(3872) decays!

$\rho_3(1690)$ $I^G(J^{PC}) = 1^+(3^{--})$

Mass $m = 1688.8 \pm 2.1$ MeV [I]
Full width $\Gamma = 161 \pm 10$ MeV [I] $(S = 1.5)$

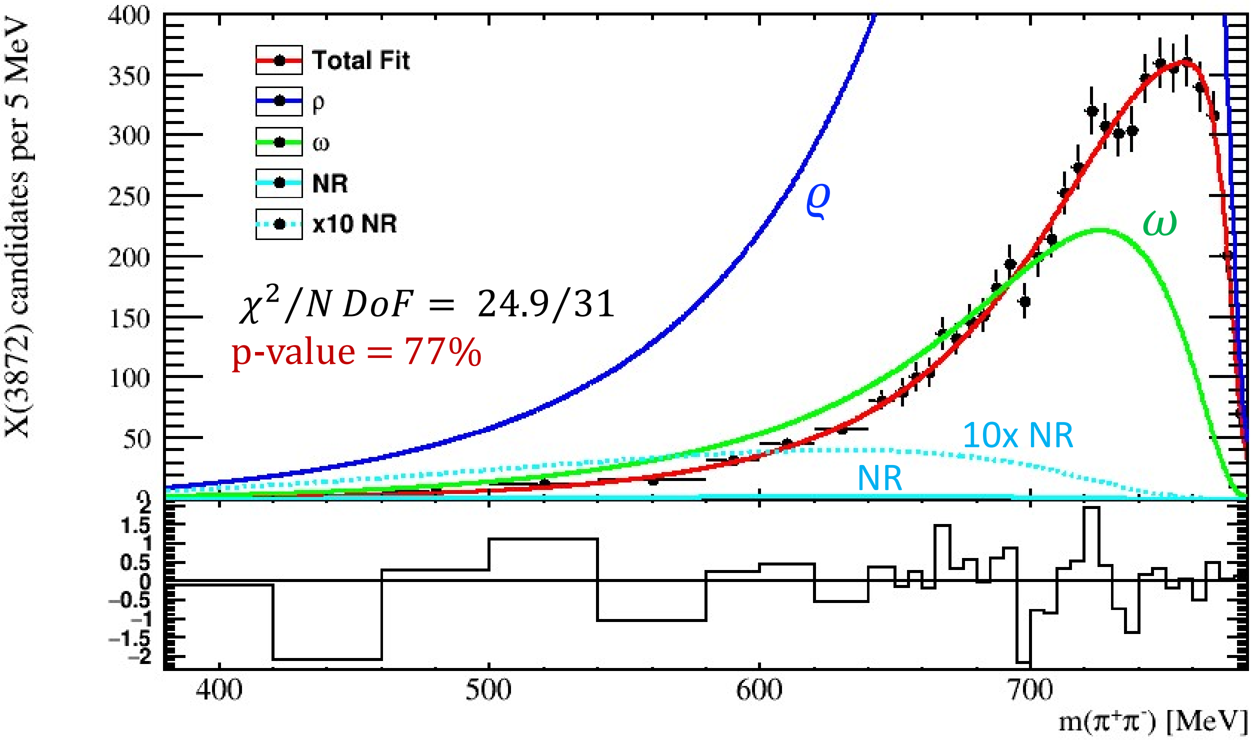
Would be produced in D-wave decays of X(3872).

When added incoherently to the fits to the $m(\pi^+\pi^-)$ distribution (at any stage), fits always prefer to make this contribution negligible.

Fit of $\boldsymbol{\rho^0} + \boldsymbol{\omega} + \boldsymbol{NR}$ (1-channel K-matrix)

Using sum of Breit-Wigners for strongly overlapping resonances of the same quantum numbers is known to have bad theoretical properties (violates unitarity). Try K-matrix approach instead (1-channel i.e. $\pi\pi$).

$$M = \frac{\frac{m_\rho \Gamma_\rho}{m_\rho^2 - m_{\pi\pi}^2} B_1(q,q_\rho) + \frac{A_\omega m_\omega \Gamma_\omega}{m_\omega^2 - m_{\pi\pi}^2} B_1(q,q_\omega) + A_{NR} B_1(q,q_\rho)}{1 - i\left(\frac{m_\rho \Gamma_\rho}{m_\rho^2 - m_{\pi\pi}^2} + \frac{m_\omega \Gamma_\omega}{m_\omega^2 - m_{\pi\pi}^2} + C_{NR}\right)}$$



Good quality fits require ρ, ω and small, but significant non-resonant component

$R_\rho = 4.1 \pm 1.0$

$R_\omega = 0.86 \pm 0.62$ $\quad R_{\omega/\rho} = 0.21 \pm 0.08$

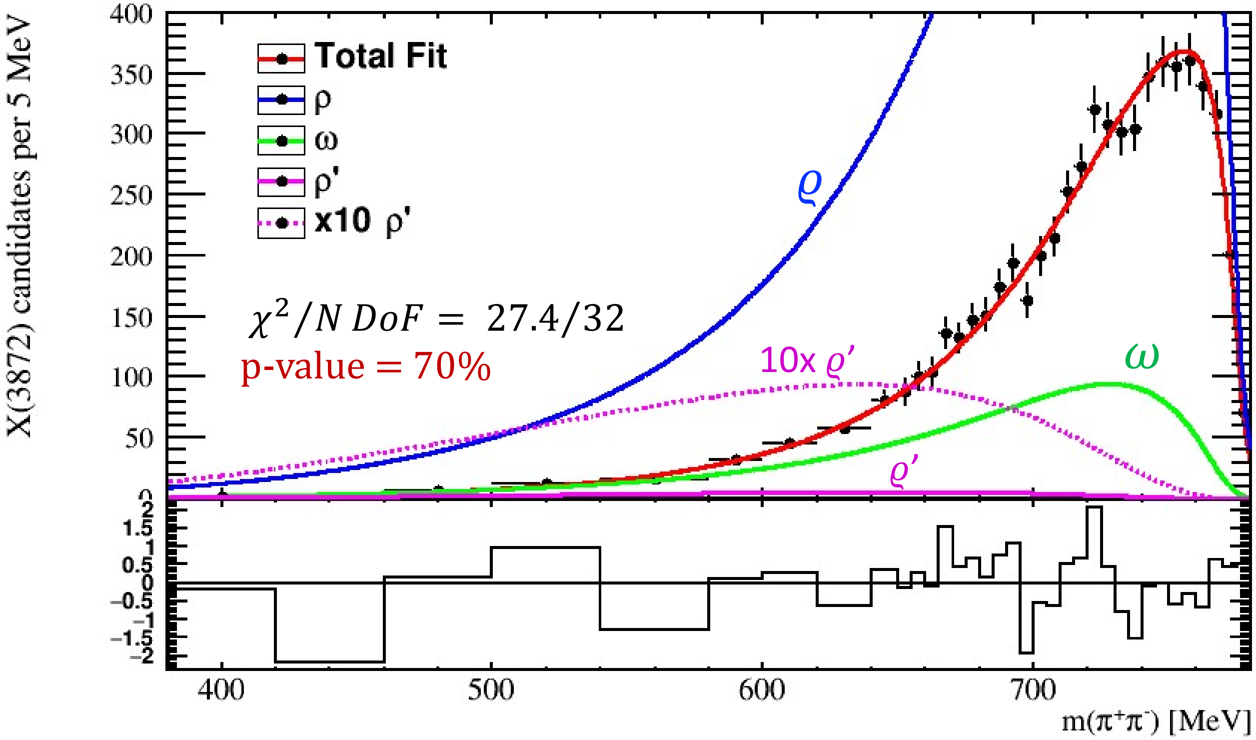
$R_{NR} = 0.019 \pm 0.019$ $\quad R_{NR/\rho} = 0.005 \pm 0.006$

Large negative interference of $\rho - \omega$. Their total magnitudes poorly constrained. Their ratio better determined.

Fit of $\boldsymbol{\rho} + \boldsymbol{\omega} + \boldsymbol{\rho}'$(1450) (1-channel K-matrix)

new

$$M = \frac{\frac{m_\rho \Gamma_\rho}{m_\rho^2 - m_{\pi\pi}^2} B_1(q, q_\rho) + \frac{A_\omega m_\omega \Gamma_\omega}{m_\omega^2 - m_{\pi\pi}^2} B_1(q, q_\omega) + \frac{m_{\rho'} \Gamma_{\rho'}}{m_{\rho'}^2 - m_{\pi\pi}^2} B_1(q, q_{\rho'})}{1 - i\left(\frac{m_\rho \Gamma_\rho}{m_\rho^2 - m_{\pi\pi}^2} + \frac{m_\omega \Gamma_\omega}{m_\omega^2 - m_{\pi\pi}^2} + \frac{m_{\rho'} \Gamma_{\rho'}}{m_{\rho'}^2 - m_{\pi\pi}^2}\right)}$$



Instead of non-resonant component can also obtain good quality fits by adding ρ'

$R_\varrho = 3.13 \pm 0.25$

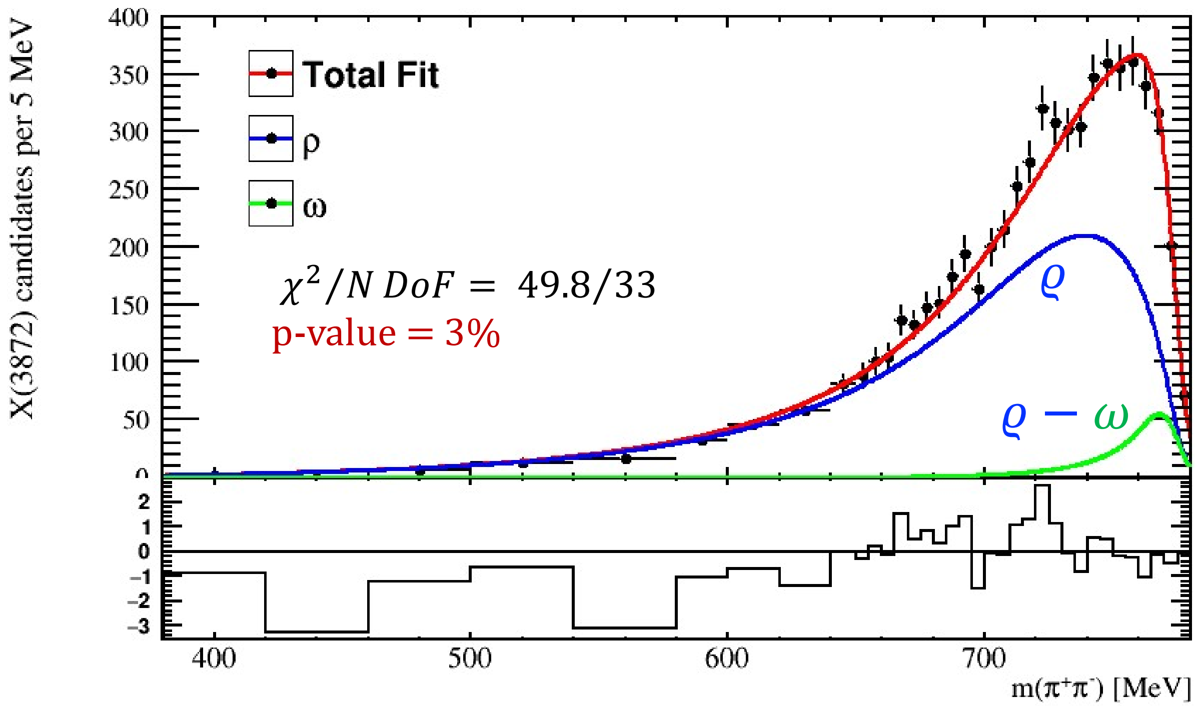
$R_\omega = 0.38 \pm 0.11 \quad R_{\omega/\rho} = 0.12 \pm 0.03$

$R_{\rho'} = 0.043 \pm 0.011 \quad R_{\rho'/\rho} = 0.014 \pm 0.004$

In spite of different shapes, obtain similar rate fractions as with the BW sum approach

Fit of $\boldsymbol{\rho} + (\boldsymbol{\rho} - \boldsymbol{\omega})$ interference

$$M = BW_\rho\left(m_{\pi\pi}\middle|m_\rho, \Gamma_\rho\right)\left[1 + A_\omega \frac{{m_{\pi\pi}}^2}{m_\omega^2 - m_{\pi\pi}^2 - i m_\omega \Gamma_{\omega(m_{\pi\pi})}}\right]$$



Suggested by Mikhail Mikhasenko, following the paper on EM pion form-factors H. Leutwyler arXiv-ph/0212324 (2002). Often used as effective parameterization in other works.

$R_\varrho = 0.718 \pm 0.013$

$R_{\varrho-\omega} = 0.041 \pm 0.004 \quad R_{\varrho-\omega/\rho} = 0.057 \pm 0.007$

Positive $\boldsymbol{\rho} - \boldsymbol{\omega}$ interference in this approach.

Fit quality much better than other two-component models, but not perfect.

Misha: consistent with two channels, $\pi\pi$ and $\pi\pi\pi$, coupled in unitary way

Fit of $\boldsymbol{\rho} + \boldsymbol{\omega} + \boldsymbol{\pi\pi} + \boldsymbol{\pi\pi\pi}$ (4-channel K-matrix)

Derived by Adam Szczepaniak ("singles" K-matrix generalization)

new

$$t11 := \frac{\left(-\frac{G2\, g31^2\, g42^2}{(m3-s)\,(m4-s)} + \frac{g41^2}{m4-s} + \frac{g31^2}{m3-s}\right)}{1 - \frac{g42^2\, G2}{m4-s} - \frac{g31^2\, G1}{m3-s} - \frac{g41^2\, G1}{m4-s} + \frac{g42^2\, g31^2\, G1\, G2}{(m3-s)\,(m4-s)}} :$$

$$t41 := \frac{g41}{1 - \frac{g42^2\, G2}{m4-s} - \frac{g31^2\, G1}{m3-s} - \frac{g41^2\, G1}{m4-s} + \frac{g42^2\, g31^2\, G1\, G2}{(m3-s)\,(m4-s)}} :$$

$$t31 := \frac{g31 \cdot \left(1 - \frac{g42^2 \cdot G2}{m4-s}\right)}{1 - \frac{g42^2\, G2}{m4-s} - \frac{g31^2\, G1}{m3-s} - \frac{g41^2\, G1}{m4-s} + \frac{g42^2\, g31^2\, G1\, G2}{(m3-s)\,(m4-s)}} :$$

$$t21 := \frac{\frac{g42 \cdot g41}{m4-s}}{1 - \frac{g42^2\, G2}{m4-s} - \frac{g31^2\, G1}{m3-s} - \frac{g41^2\, G1}{m4-s} + \frac{g42^2\, g31^2\, G1\, G2}{(m3-s)\,(m4-s)}} :$$

Adam: coupled continuum states, $\pi\pi$ (1) and $\pi\pi\pi$ (2), and "bare" one-particle states, $\boldsymbol{\rho}$ (3) coupling to $\pi\pi$ and $\boldsymbol{\omega}$ (4) coupling to $\pi\pi$ and $\pi\pi\pi$, in addition to $\boldsymbol{\rho}$- $\boldsymbol{\omega}$ mixing.

$$Pvec1 := 1 + G1 \cdot t11$$

$$Pvec2 := G2 \cdot t21$$

$$Pvec3 := \frac{t31}{m3-s}$$

$$Pvec4 := \frac{t41}{m4-s}$$

$$G1 = i\sqrt{1 - 4\frac{m_\pi{}^2}{s}}$$

$$G2 = i\sqrt{1 - 9\frac{m_\pi{}^2}{s}}$$

$$s = m_{\pi\pi}{}^2$$

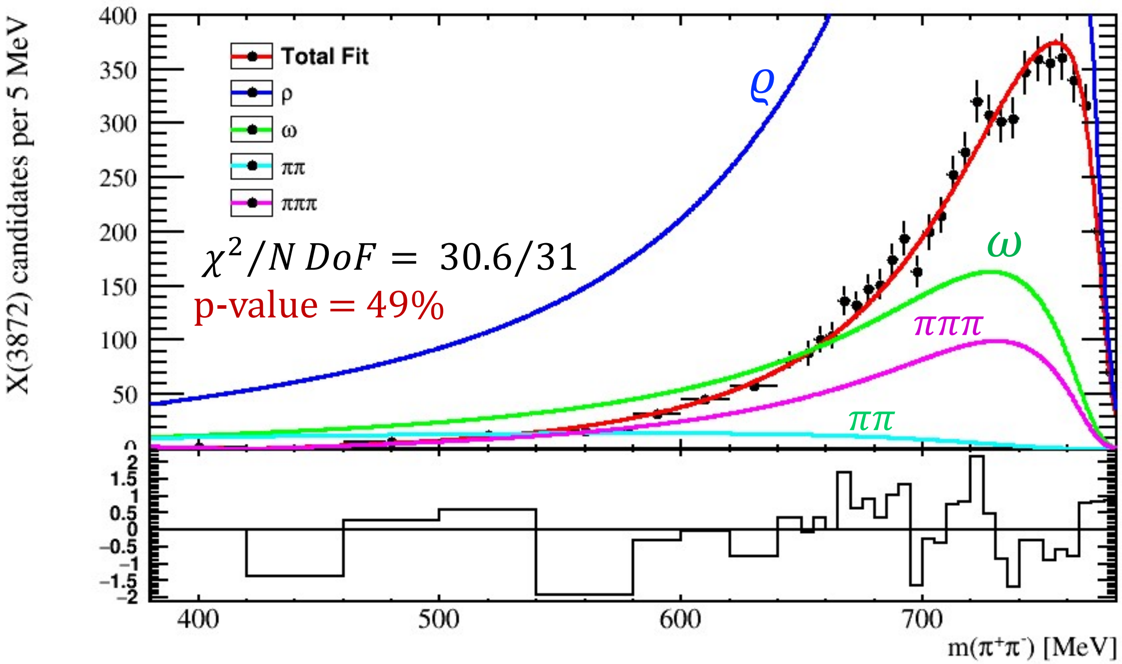
$$\mathrm{mj} = m_j{}^2$$

$$gjk = \sqrt{m_j \Gamma_j BR(j \to k)}$$

$$M = A_\rho\, Pvec3 + A_\omega\, Pvec4 + A_{\pi\pi}\, Pvec1 + A_{\pi\pi\pi} Pvec2$$

Fit of $\boldsymbol{\rho} + \boldsymbol{\omega} + \boldsymbol{\pi\pi} + \boldsymbol{\pi\pi\pi}$ (4-channel K-matrix)

Very preliminary!



Good quality fit!

$R_{\varrho} = 3.48 \pm 0.31$

$R_{\omega} = 0.77 \pm 0.27$ $R_{\omega/\rho} = 0.22 \pm 0.06$

$R_{\pi\pi\pi} = 0.39 \pm 0.09$ $R_{\pi\pi\pi/\rho} = 0.11 \pm 0.02$

$R_{\pi\pi} = 0.18 \pm 0.04$ $R_{\pi\pi/\rho} = 0.052 \pm 0.015$

Results for $\boldsymbol{\rho}$ and $\boldsymbol{\omega}$ similar to 1-channel K-matrix results.

Better motivated theoretically.

Summary

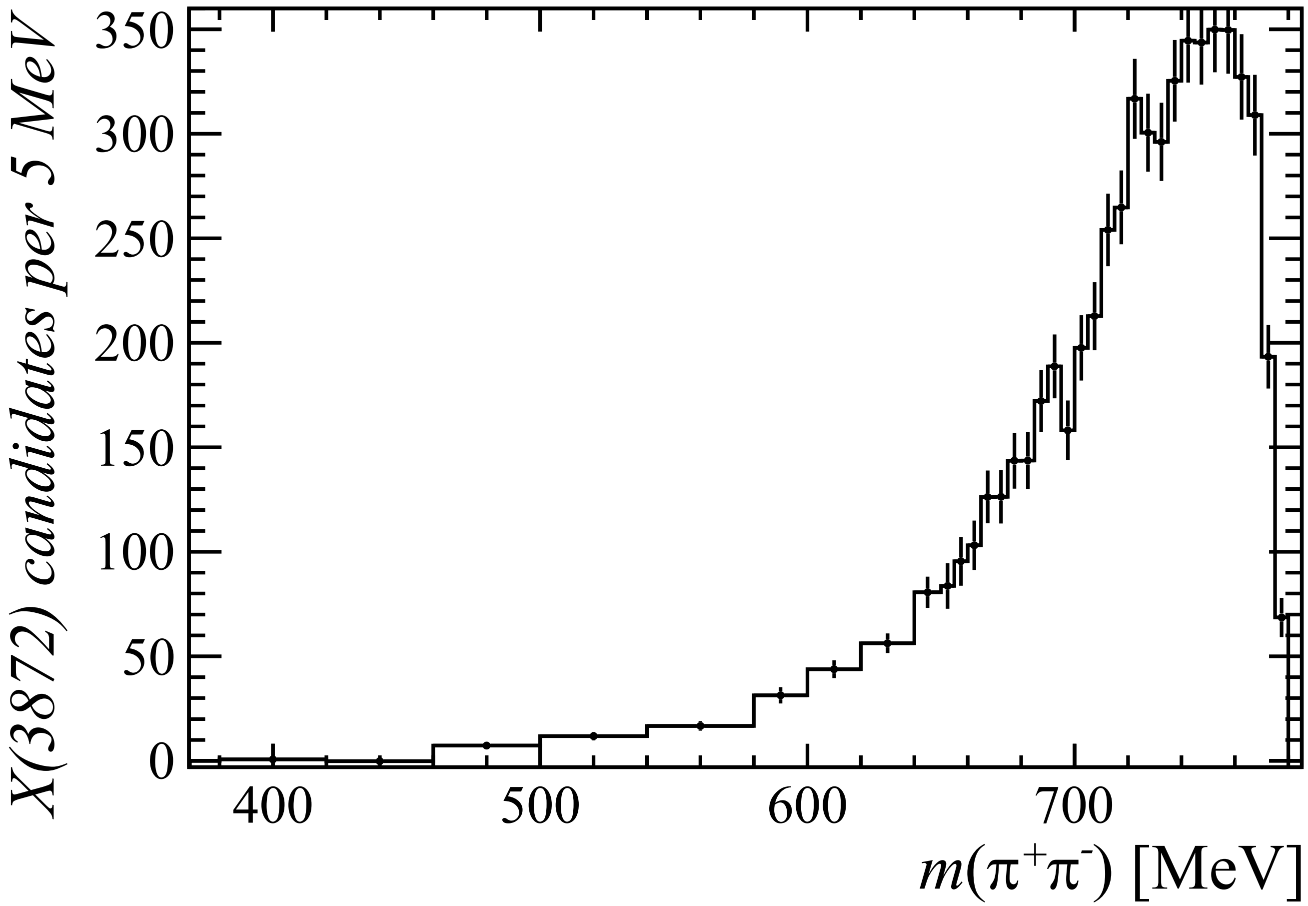
- We have performed analysis of $m(\pi^+\pi^-)$ distribution in $X(3872) \to \pi^+\pi^- J/\psi$ decays, reconstructed from $B^+ \to K^+X(3872)$ decays, with signal statistics 43 times larger than previously used in this type of analysis
- The decay is dominated by $\rho^0 \to \pi^+\pi^-$, but ω is very significant ($> 17\sigma$), which is established for the first time
- Additional component(s) are required for a good quality fit, but they are model dependent: tail of $\rho(1450)$, non-resonant or $\pi\pi\pi$ coupled-channel.
- Good quality fits suggest large negative interference between ρ^0 and ω is at play. They point to even larger rate of isospin violating $X(3872) \to \rho^0 J/\psi$ decays then previously believed, which strengthens molecular interpretation of X(3872), which naturally predicts isospin violating decays. However, quantitative rate results are model dependent.
- More results to come

BACKUP SLIDES

Selection

- $\boldsymbol{B^+ \to K^+\pi^+\pi^- J/\psi}$
- **Data** : Using a full statistics. Run1+Run2 (2011,2012,2015,2016,2017,2018).
- Stripping line: **StrippingB2XMuMu_Line**
- **Loose selection including PID cuts:**
  - PIDK > -5 for kaons < 5 for pions
  - PIDK for pions smaller than for the kaon candidate

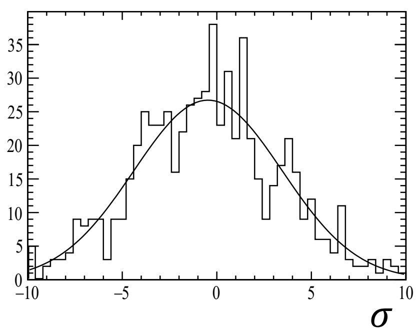
$\pi^+ \pi^-$ mass spectrum



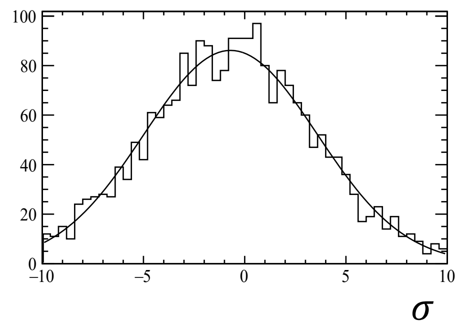
Mass resolution and Smearing

signal MC samples were generated. About 100K reconstructed events in this study. Using MC truth information, we get $m_{\pi\pi}^{true}$. For different bins of $m_{\pi\pi}^{true}$ distribution, we plotted $m_{\pi\pi}^{true}$ - $m_{\pi\pi}^{reco}$ and fitted with simple Gaussian function.

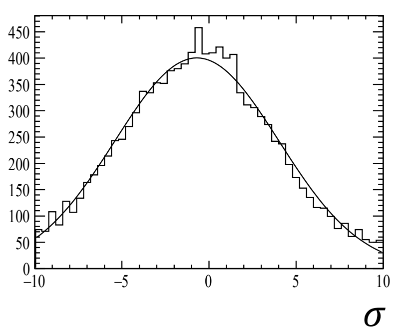
Rho_480_530_True



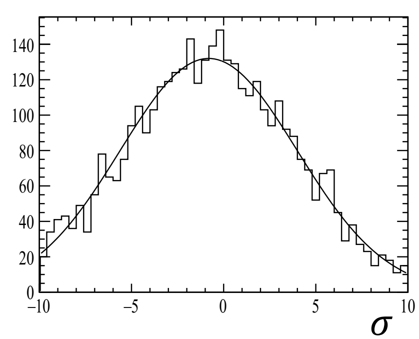
Rho_580_630_True

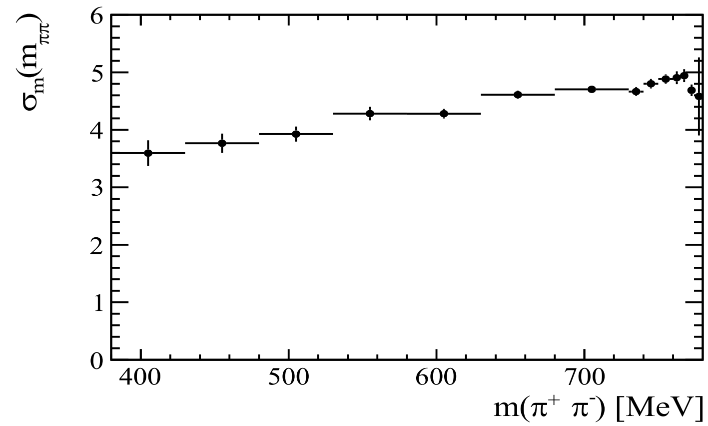


Rho_680_730_True



Rho_740_750_True





Use this as a look up table for $\sigma_m(m_{\pi\pi})$

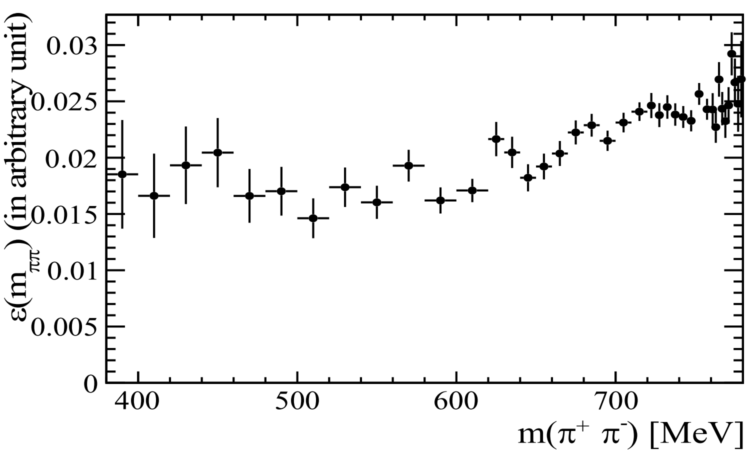
$$PDF'(m_{\pi\pi}) = \int_{-3\sigma}^{+3\sigma} PDF(m_{\pi\pi}^{true})G(m_{\pi\pi}|m_{\pi\pi}^{true}, \sigma_m(m_{\pi\pi}))\ d\, m_{\pi\pi}^{true}$$

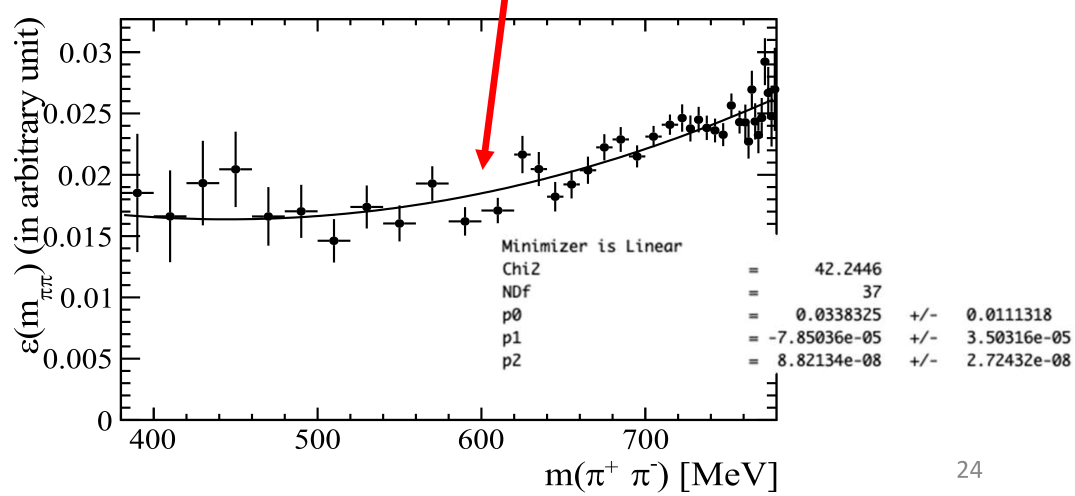
Efficiency

To obtain relative variation of efficiency with $m_{\pi\pi}$:

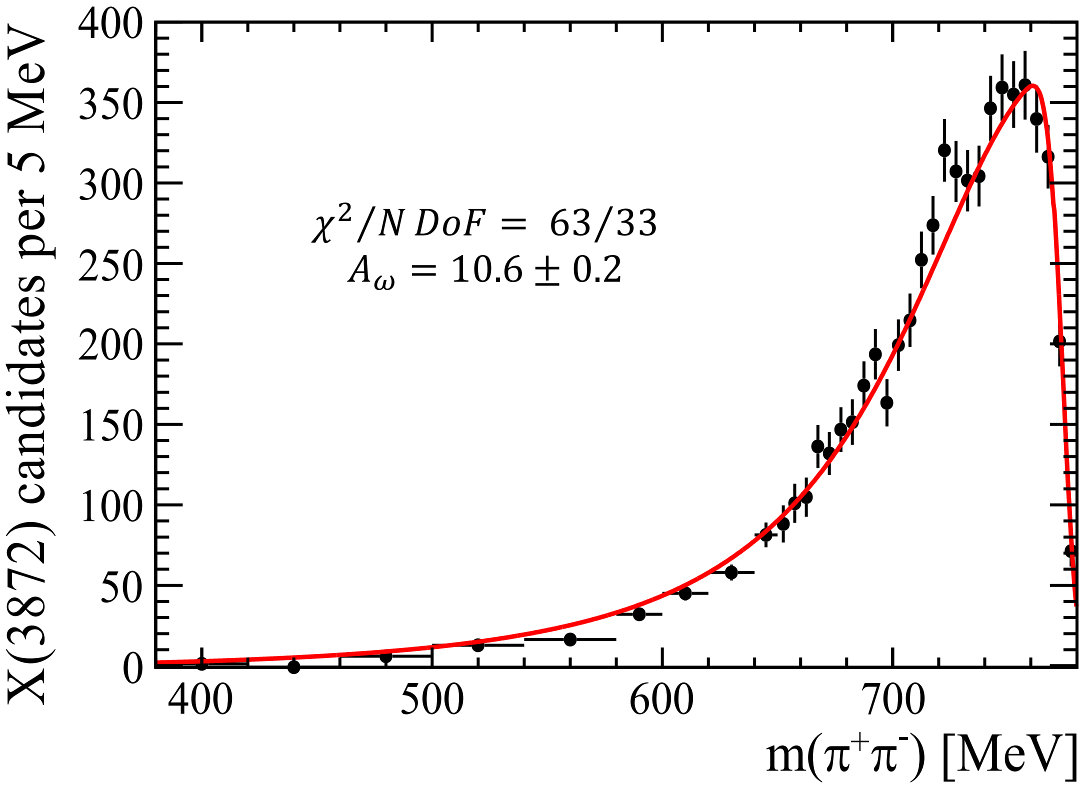
- Obtain generator level histogram of $m_{\pi\pi}^{\mathrm{true}}$
- Smear $m_{\pi\pi}^{true}$ with $\sigma_m(m_{\pi\pi})$ to obtain generator level distribution in "reconstructed" mass $\left(\frac{dN}{dm_{\pi\pi}}\right)_{gen}$
- Plot reconstructed $m_{\pi\pi}$ distribution in the signal MC $\left(\frac{dN}{dm_{\pi\pi}}\right)_{gen}$
- $\varepsilon(m_{\pi\pi}) = \left(\frac{dN}{dm_{\pi\pi}}\right)_{reco} \Big/ \left(\frac{dN}{dm_{\pi\pi}}\right)_{gen}$

$PDF'(m_{\pi\pi}) = \varepsilon(m_{\pi\pi})\, PDF(m_{\pi\pi})$

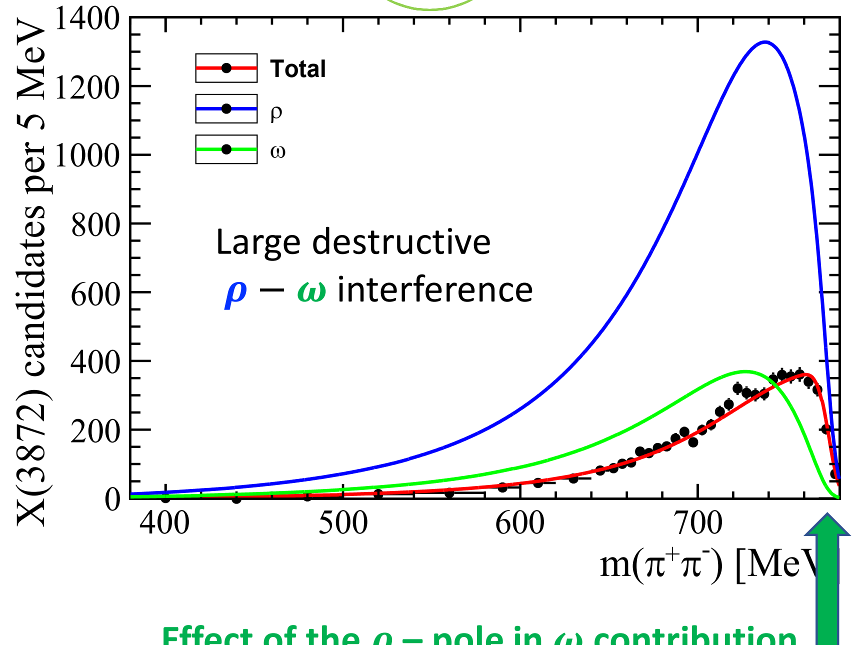




Fit of $\boldsymbol{\rho^0} + \boldsymbol{\omega}$ (K-matrix)



$$M = \frac{\frac{m_\rho \Gamma_\rho}{m_\rho^2 - m_{\pi\pi}^2} B_1(q, q_\rho) + \frac{A_\omega m_\omega \Gamma_\omega}{m_\omega^2 - m_{\pi\pi}^2} B_1(q, q_\omega)}{1 - i\left(\frac{m_\rho \Gamma_\rho}{m_\rho^2 - m_{\pi\pi}^2} + \frac{m_\omega \Gamma_\omega}{m_\omega^2 - m_{\pi\pi}^2}\right)}$$



K-matrix shape of $\boldsymbol{\omega}$ is much different than naïve BW:

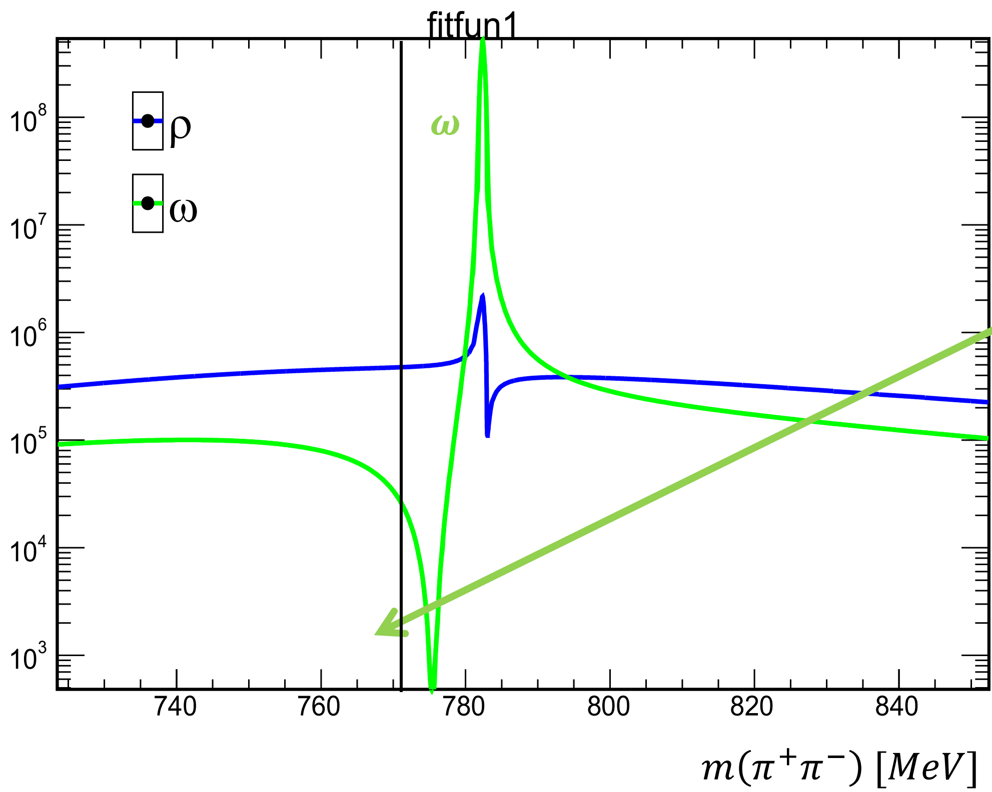
Effect of the $\boldsymbol{\rho}$ – pole in $\boldsymbol{\omega}$ contribution.
Even with no ρ in the numerator, ρ is present in the denominator and makes a dent in the ω tail at m_ρ. ω does peak at m_ω but this is beyond the X(3872) phase-space limit.

Fit with K-matrix is much better than with BW sum
but still not satisfactory (p-value = 0.1%)

For illustration how K-matrix works

Change m_X from 3872 MeV to 4000 MeV

PDF
no eff
no smear

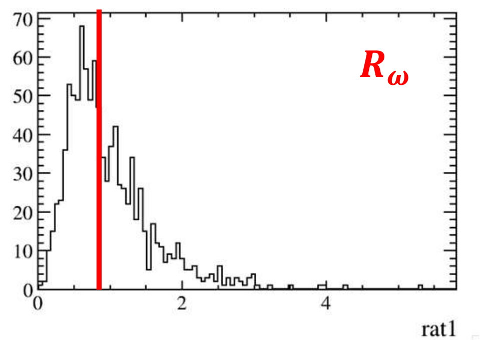


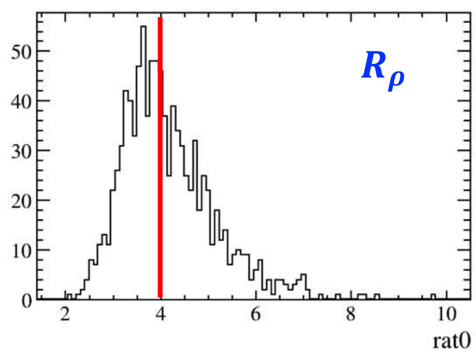
$$M = \frac{\frac{A_\omega m_\omega \Gamma_\omega}{m_\omega^2 - m_{\pi\pi}^2} B_1(q, q_\omega)}{1 - i\left(\frac{m_\rho \Gamma_\rho}{m_\rho^2 - m_{\pi\pi}^2} + \frac{m_\omega \Gamma_\omega}{m_\omega^2 - m_{\pi\pi}^2}\right)}$$

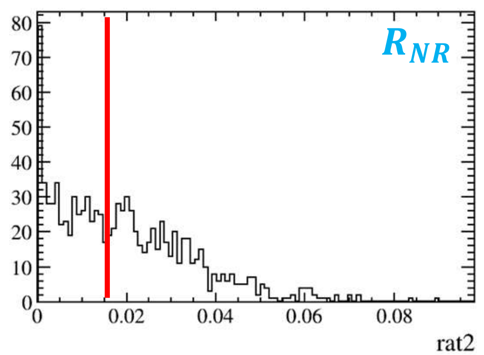
Errors on rate ratios

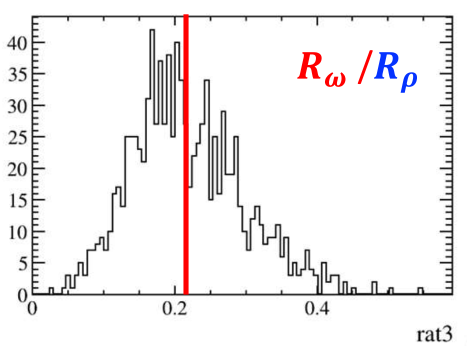
Errors on R obtained via statistical simulations:

- The fit parameters varied around the fit results according to multivariate Gaussian distribution according to the fit covariance matrix.
- The distributions of R are not Gaussian (next below) – will need to decide how to handle this (on the previous slide we used RMS – very naïve).
- In the future, we also want to get away from Gaussian approximation by using the likelihood on the data.



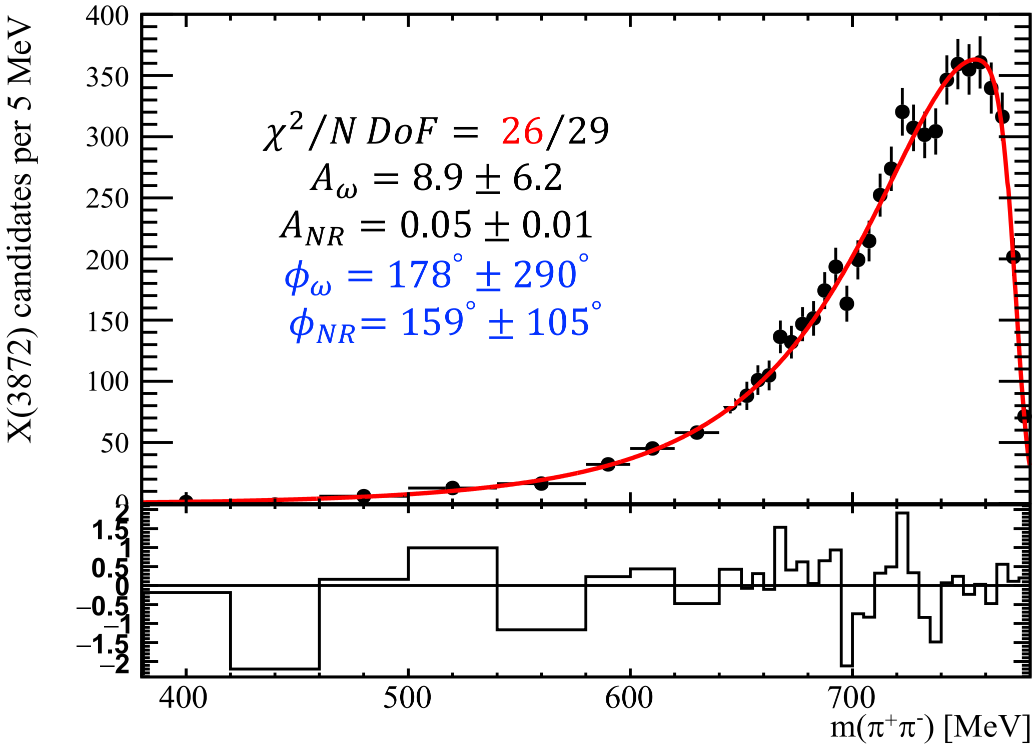




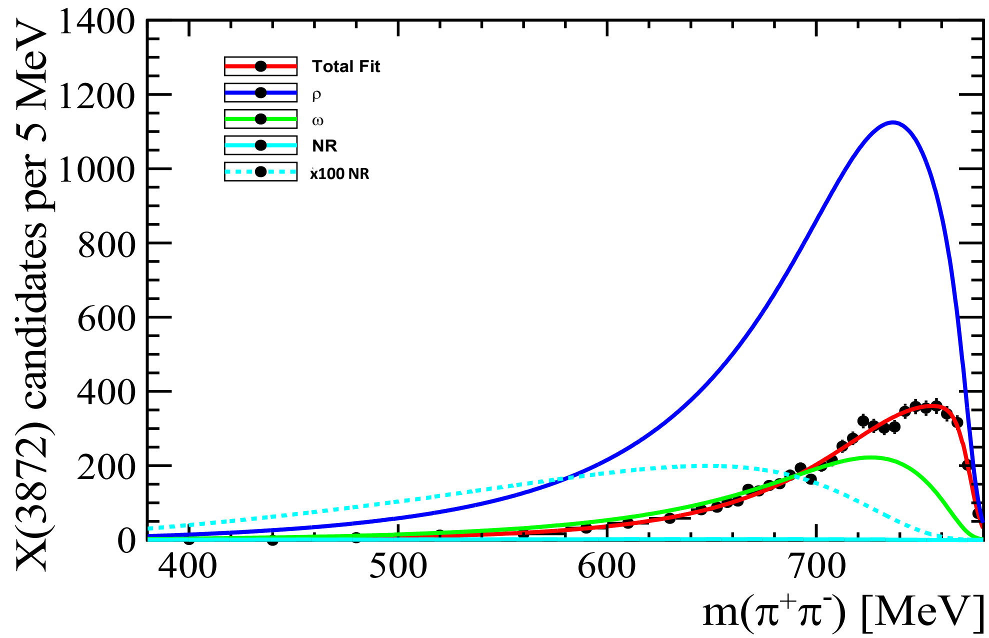


Fit of $\rho^0 + \omega + NR$ (K-matrix) with complex phases

In proper K-matrix there should be no complex phases in the numerator!



$$M = \frac{\frac{m_\rho \Gamma_\rho}{m_\rho^2 - m_{\pi\pi}^2} B_1(q,q_\rho) + \frac{e^{i\phi_\omega} A_\omega m_\omega \Gamma_\omega}{m_\omega^2 - m_{\pi\pi}^2} B_1(q,q_\omega) + e^{i\phi_{NR}} A_{NR} B_1(q,q_\rho)}{1 - i\left(\frac{m_\rho \Gamma_\rho}{m_\rho^2 - m_{\pi\pi}^2} + \frac{m_\omega \Gamma_\omega}{m_\omega^2 - m_{\pi\pi}^2} + C_{NR}\right)}$$



Fit quality does not change when complex phases are allowed – the data speaks to validity of the K-matrix approach.

	m_ρ	m_ω	Γ_ρ (MeV)	Γ_ω (MeV)	χ^2/NDF	ϕ_ω	ϕ_{NR}	A_ω (formula dependent)	A_{NR}	I_ρ/I_{tot}	I_ω/I_{tot}	I_{NR}/I_{tot}	I_ω/I_ρ
ρ alone (BW or K-matrix)	775.49	-	146.2	-	398.9/34	-	-	-	-	1	-	-	-
$\rho+\omega$ (BW sum)	775.49	782.65	146.2	8.49	86.8/33	1.7	-	48.6 ± 1.1	-	1.44	0.27	-	0.19
$\rho+\omega$ (BW sum)	775.49	782.65	146.2	8.49	86.8/32	2.1 ± 2.2	-	8.7 ± 35.7	-	1.43	0.27	-	0.19
$\rho+\omega$ (K-matrix)	775.49	782.65	146.2	8.49	63.4/33	-	-	10.6 ± 0.2	-	4.66	1.39	-	0.29
$\rho+\omega+$NR (K-matrix)	775.49	782.65	146.2	8.49	25.7/31	-	-	8.9 ± 1.6	0.043 ± 0.025	4.00±0.97	0.85±0.61	0.02±0.02	0.21±0.08
$\rho+\omega+$NR (K-matrix with phases)	775.49	782.65	146.2	8.49	25.7/29	3.1 ± 1.6	3.1 ± 5.4	8.9 ± 1.6	0.043 ± 0.026	4.00	0.84	0.02	0.21
$\rho+\omega+$NR (K-matrix)	757.4 ± 24.3	782.65	146.2	8.49	24.6/30	-	-	3.6 ± 3.6	0.084 ± 0.029	1.53	0.03	0.02	0.02
$\rho+\omega+$NR (K-matrix)	775.49	778.6 ± 4.3	146.2	8.49	24.6/30	-	-	9.1 ± 2.0	0.058 ± 0.017	5.22	1.31	0.04	0.25
$\rho+\omega+$NR (K-matrix)	775.49	782.65	165.8 ± 20.7	8.49	24.2/30	-	-	10.0 ± 2.0	0.073 ± 0.048	4.46	0.93	0.04	0.21
$\rho+\omega+$NR (K-matrix)	775.49	782.65	146.2	24 ± 23	24.2/30	-	-	2.4 ± 3.0	0.076 ± 0.059	3.63	0.56	0.05	0.15

- We fix rho and omega masses and widths to the PDG values in the default fit.
- When allowed to float obtain values consistent with the PDG, but with large errors. Also fit qualities don't improve much at all.
- The fitted omega mass has relatively small error – astonishing that we can determine this mass, even though the pole is beyond the phase-space.
- **This all speaks to validity of K-matrix approach!**

Use BDT selection to probe selection cuts dependence

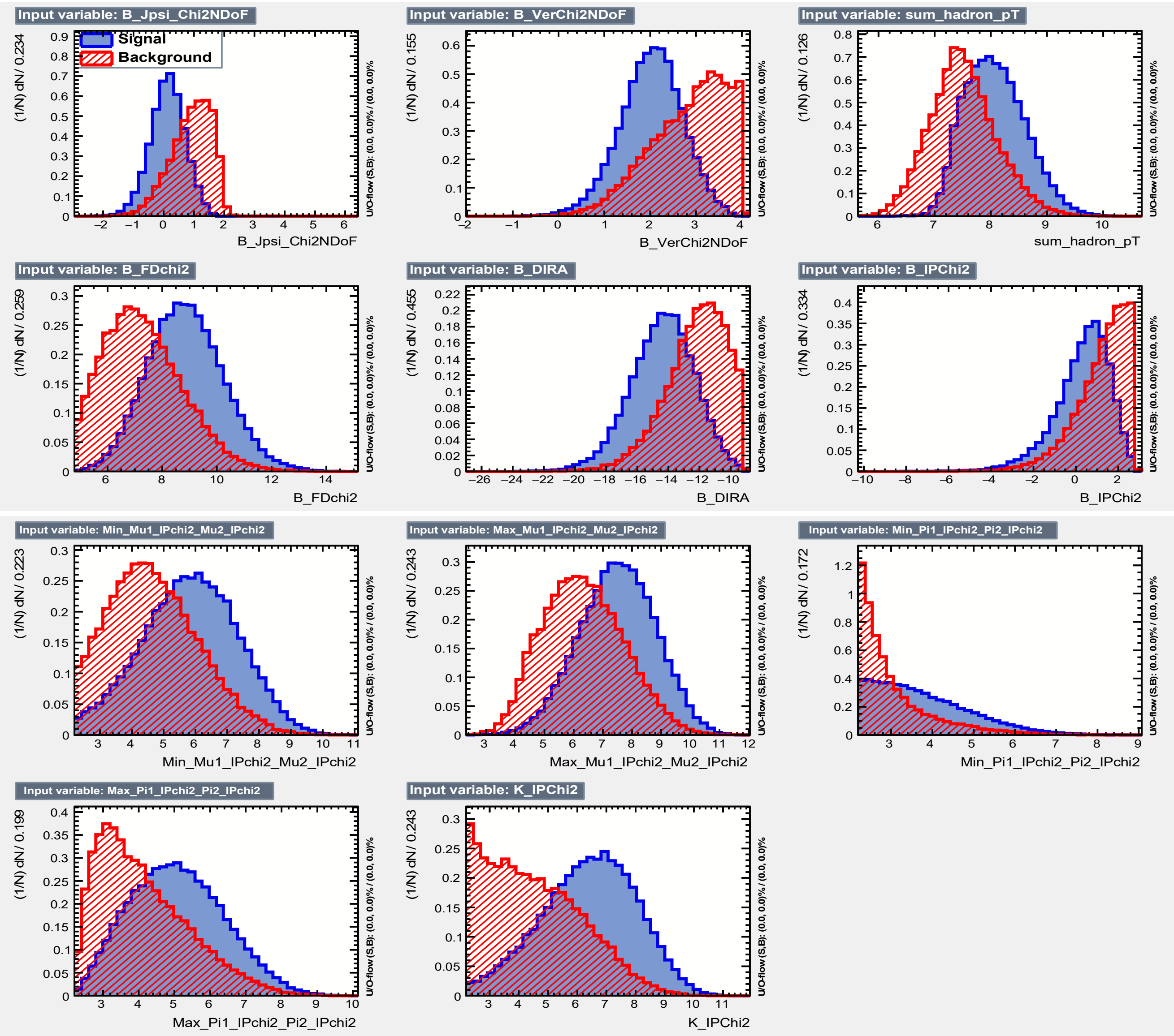
Training Variables :

- Log(B_Jpsi_Chi2NDoF)
- Log(B_ENDVERTEX_CHI2)
- Log(B_FDchi2)
- Log(1-B_DIRA)
- Log(B_IPchi2)
- Log(min(Mu1_IPchi2 _ownpv,Mu2_IPchi2 _ownpv))
- Log(max(Mu1_IPchi2 _ownpv,Mu2_IPchi2 _ownpv))
- Log(min(Pi1_IPchi2 _ownpv,Pi2_IPchi2 _ownpv))
- Log(max(Pi1_IPchi2 _ownpv,Pi2_IPchi2 _ownpv))
- Log(K_IPchi2_ownpv)

Train not on MC but real data:

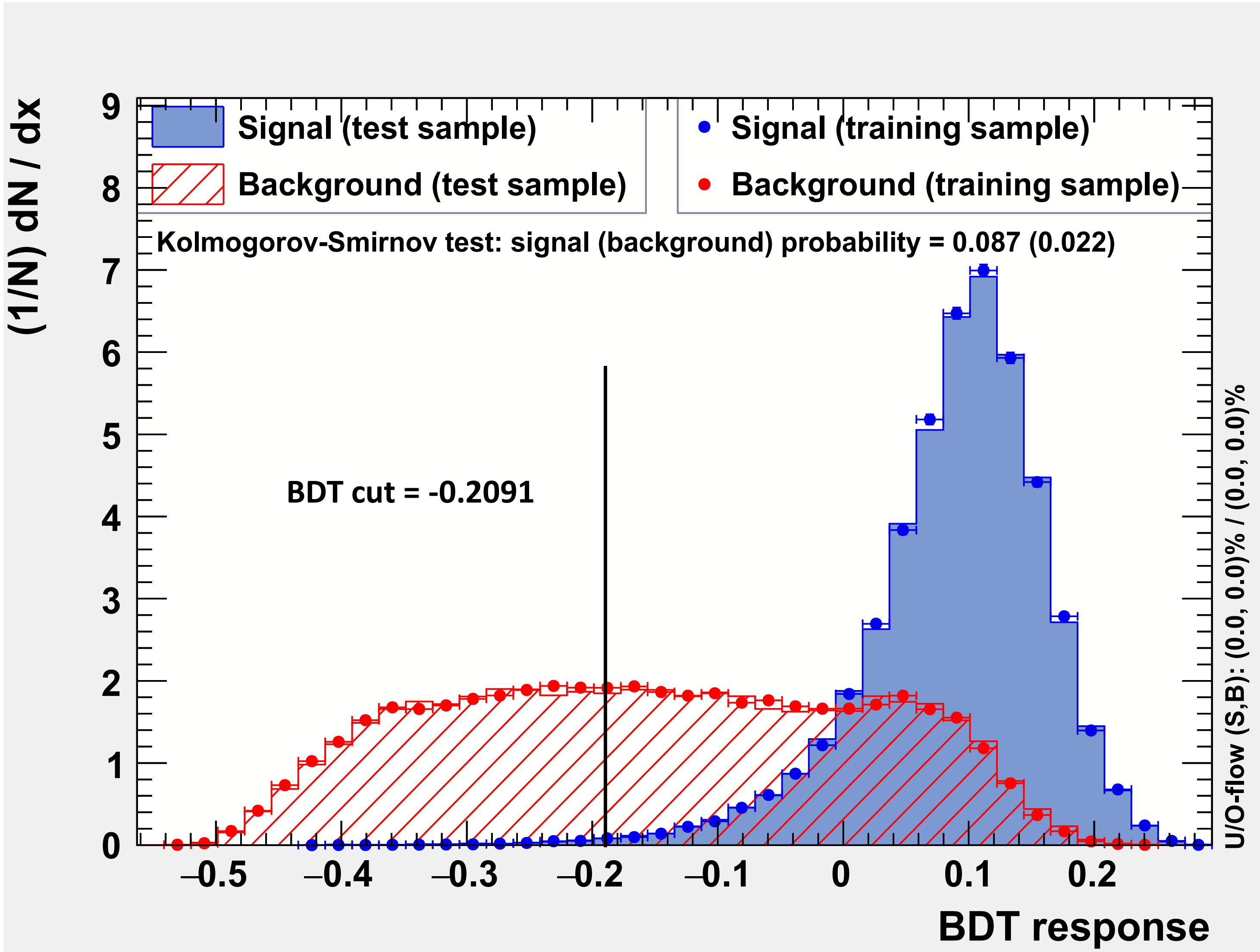
- Signal sample = $B^+ \to K^+\psi(2S), \psi(2S) \to \pi^+\pi^- J/\psi$
- Background sample = X sideband data from B sidebands

BDT output

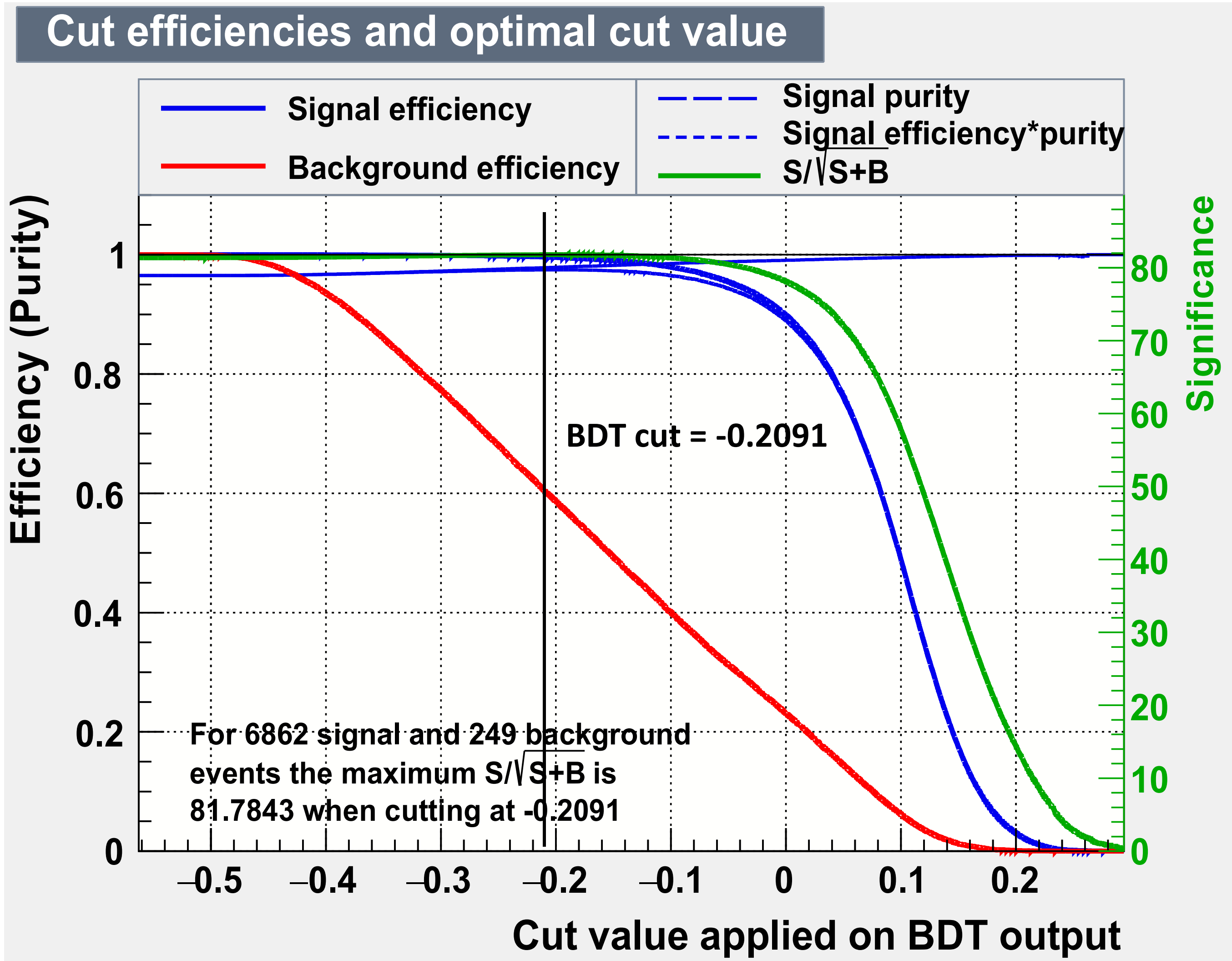


Input variable: B_Jpsi_Chi2NDoF
Signal
Background
B_Jpsi_Chi2NDoF
Input variable: B_VerChi2NDoF
B_VerChi2NDoF
Input variable: sum_hadron_pT
sum_hadron_pT
Input variable: B_FDchi2
B_FDchi2
Input variable: B_DIRA
B_DIRA
Input variable: B_IPChi2
B_IPChi2
Input variable: Min_Mu1_IPchi2_Mu2_IPchi2
Min_Mu1_IPchi2_Mu2_IPchi2
Input variable: Max_Mu1_IPchi2_Mu2_IPchi2
Max_Mu1_IPchi2_Mu2_IPchi2
Input variable: Min_Pi1_IPchi2_Pi2_IPchi2
Min_Pi1_IPchi2_Pi2_IPchi2
Input variable: Max_Pi1_IPchi2_Pi2_IPchi2
Max_Pi1_IPchi2_Pi2_IPchi2
Input variable: K_IPChi2
K_IPChi2

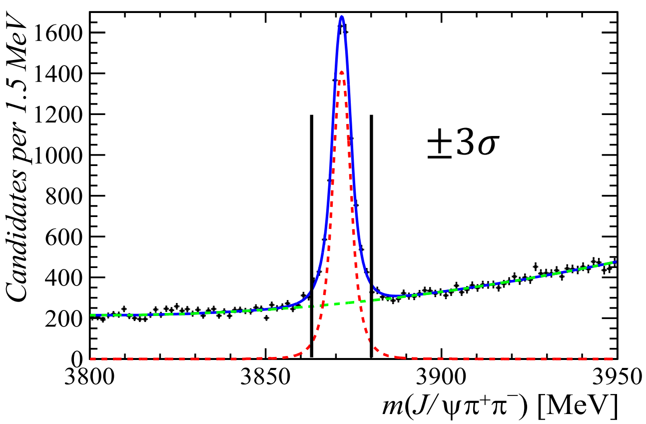
BDT output


Signal (test sample)
Background (test sample)
Signal (training sample)
Background (training sample)
Kolmogorov-Smirnov test: signal (background) probability = 0.087 (0.022)
BDT cut = -0.2091
(1/N) dN / dx
BDT response
U/O-flow (S,B): (0.0, 0.0)% / (0.0, 0.0)%
9
8
7
6
5
4
3
2
1
0
–0.5
–0.4
–0.3
–0.2
–0.1
0
0.1
0.2

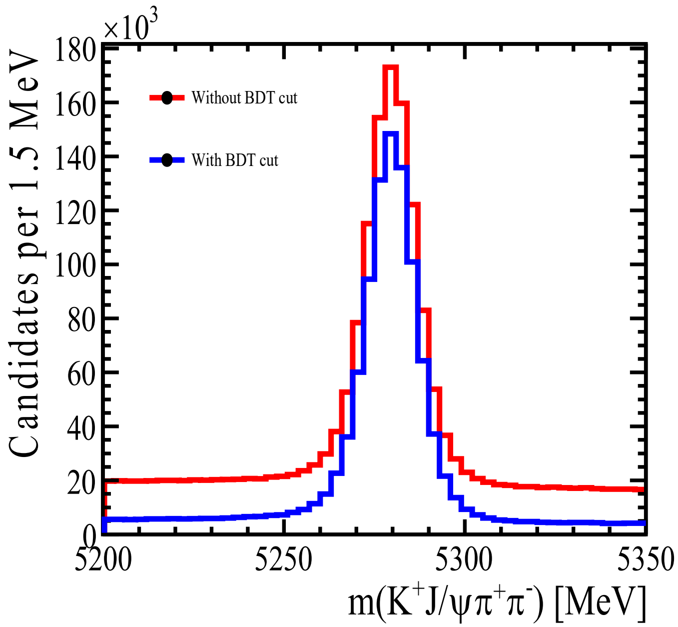
Optimization



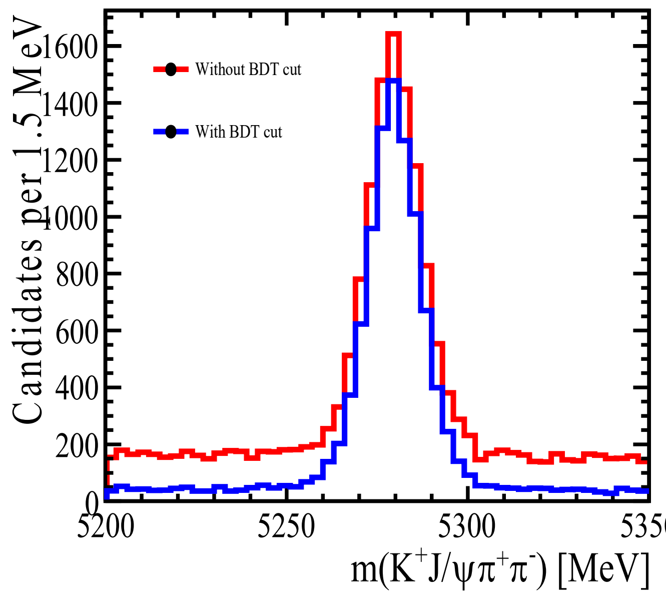
Bkg suppression



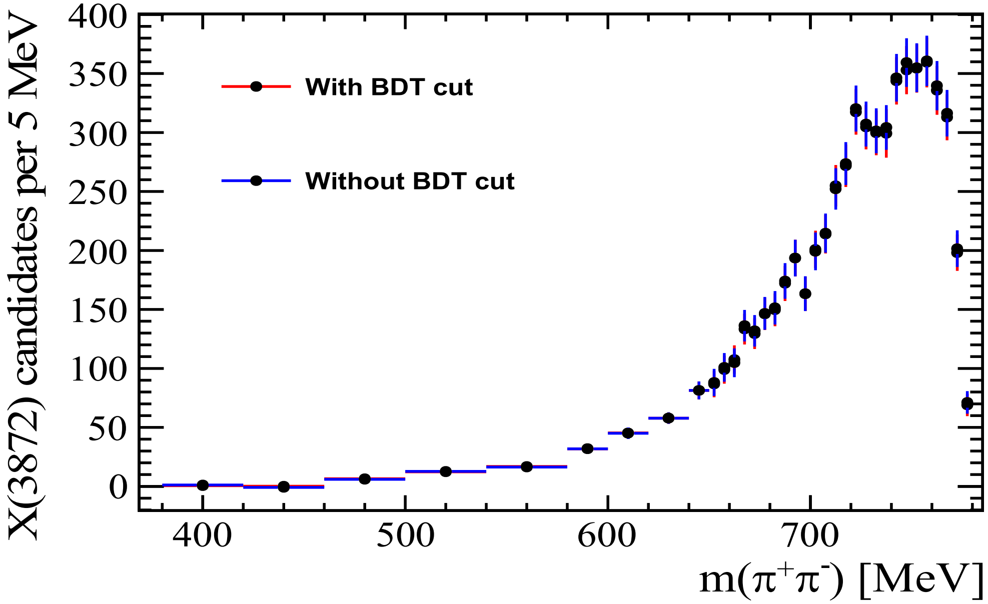
Without X(3872) mass cut



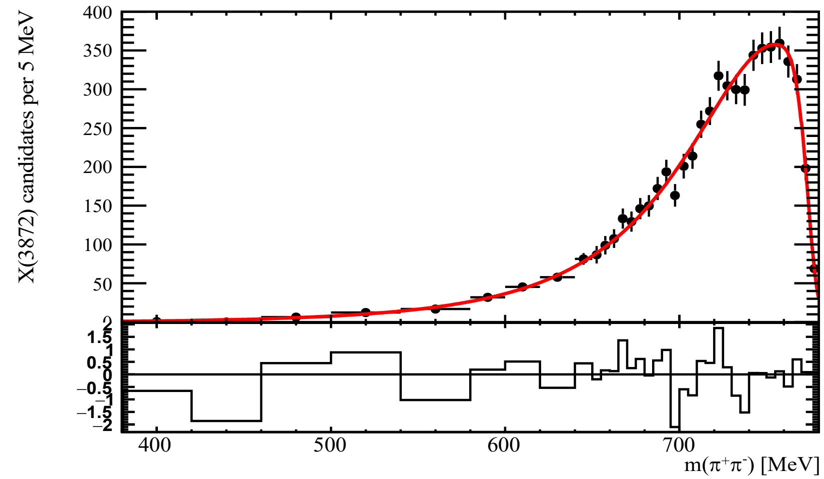
With X(3872) mass cut



$\pi^+\pi^-$ mass spectrum



$$M = \frac{\frac{m_\rho \Gamma_\rho}{m_\rho^2 - m_{\pi\pi}^2} B_1(q,q_\rho) + \frac{A_\omega m_\omega \Gamma_\omega}{m_\omega^2 - m_{\pi\pi}^2} B_1(q,q_\omega) + A_{NR} B_1(q,q_\rho)}{1 - i\left(\frac{m_\rho \Gamma_\rho}{m_\rho^2 - m_{\pi\pi}^2} + \frac{m_\omega \Gamma_\omega}{m_\omega^2 - m_{\pi\pi}^2} + C_{NR}\right)}$$



	mass of ρ	mass of ω	Γ_ρ	Γ_ω	$\chi^2/ndof$	ϕ_ω	ϕ_{NR}	A_ω	A_{NR}	I_ρ/I_{tot}	I_ω/I_{tot}	I_{NR}/I_{tot}	I_ω/I_ρ
$\rho + \omega$ + NR (K-matrix)	775.49	782.65	146.2	8.49	23.5/31	-	-	8.8 ± 1.6	0.044 ± 0.024	3.93	0.81	0.02	0.20

Non-B bkg reduced substantially, with hardly any loss to signal efficiency.
The fit results hardly change. **Selection cut systematics is negligible!**