Measurement of $e^+e^- \to \pi^+\pi^- J/\psi$ in the vicinity of the $X(3872)$ mass

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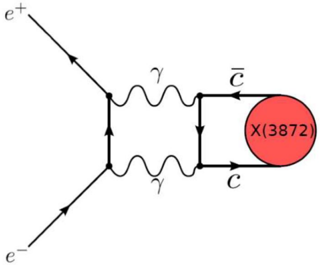
Section 1

Introduction

Introduction

- Proposal to take data:
  - $200\,\mathrm{pb}^{-1}$ at $X(3872)$ mass
  - $200\,\mathrm{pb}^{-1} \sim 5\,\mathrm{MeV}$ below $X(3872)$ mass
- 1^{++} state, need two photons!



Data taking in June 2017:

- Run 52108 - 52206 at $\sqrt{s} = 3.86741\,\mathrm{GeV}$: $(108.87 \pm 0.04)\,\mathrm{pb}^{-1}$
- Run 52207 - 52297 at $\sqrt{s} = 3.87131\,\mathrm{GeV}$: $(110.31 \pm 0.04)\,\mathrm{pb}^{-1}$

Introduction

Parameters of the $X(3872)$

- $m = (3871.69 \pm 0.17)\,\text{MeV}$
- $\Gamma_{tot} < 1.2\,\text{MeV}$ (90 % C.L.)
- $\mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-) > 2.6\,\%$ (90 % C.L.)
- $\Gamma_{ee} \times \mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-) < 0.13\,\text{eV}$ (90 % C.L.)

Goal of this analysis

- Measure cross section of $e^+e^- \to \pi^+\pi^- J/\psi$
  - via $J/\psi \to \ell^+\ell^-$
- Set improved limits on $\Gamma_{ee}(X(3872)) \times \mathcal{B}(X(3872) \to \pi^+\pi^- J/\psi)$ and maybe $\Gamma_{tot}(X(3872))$

Data Sets

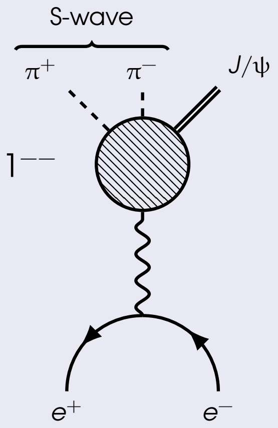
- 2017 $X(3872)$ data:
  - $\sqrt{s} = 3.86741\,\text{GeV}$: $(108.87 \pm 0.04 \pm 1.26)\,\text{pb}^{-1}$
  - $\sqrt{s} = 3.87131\,\text{GeV}$: $(110.31 \pm 0.04 \pm 0.78)\,\text{pb}^{-1}$
- 2013 XYZ scan data:
  - $\sqrt{s} = 3.80765\,\text{GeV}$: $(50.54 \pm 0.03 \pm 0.51)\,\text{pb}^{-1}$
  - $\sqrt{s} = 3.89624\,\text{GeV}$: $(52.61 \pm 0.03 \pm 0.52)\,\text{pb}^{-1}$

Section 2

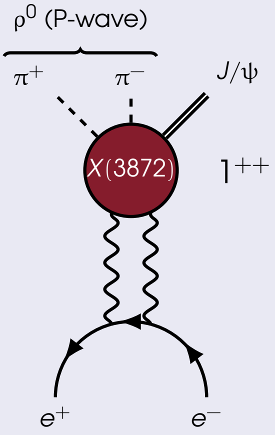
Signal MC

$e^+e^- \to \pi^+\pi^- J/\psi$

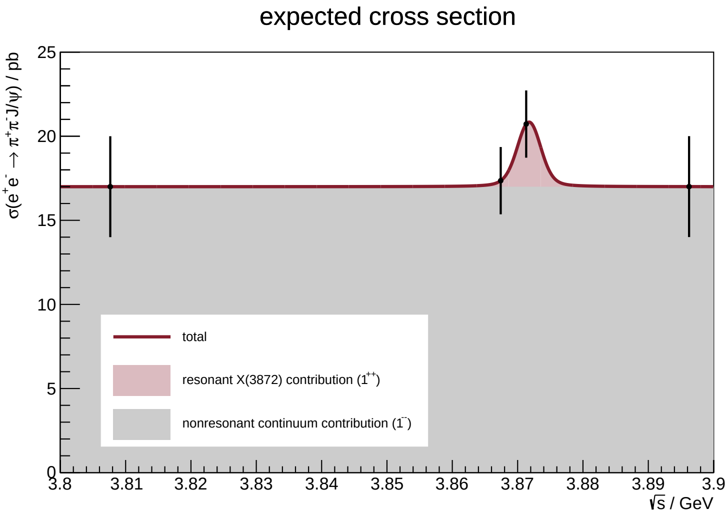
Nonresonant Continuum



Resonant $X(3872)$ Formation



Cross Section (Assuming Signal)



Signal MC

Signal MC

- KKMC + EvtGen, including ISR + FSR, flat lineshape
- for each energy point:
  - 5×10^5 with $J/\psi \to e^+e^-$
  - 5×10^5 with $J/\psi \to \mu^+\mu^-$
- model $X(3872) \to \rho^0(\to \pi^+\pi^-)J/\psi(\to \ell^+\ell^-)$

Continuum MC Models (1)

Generator Settings

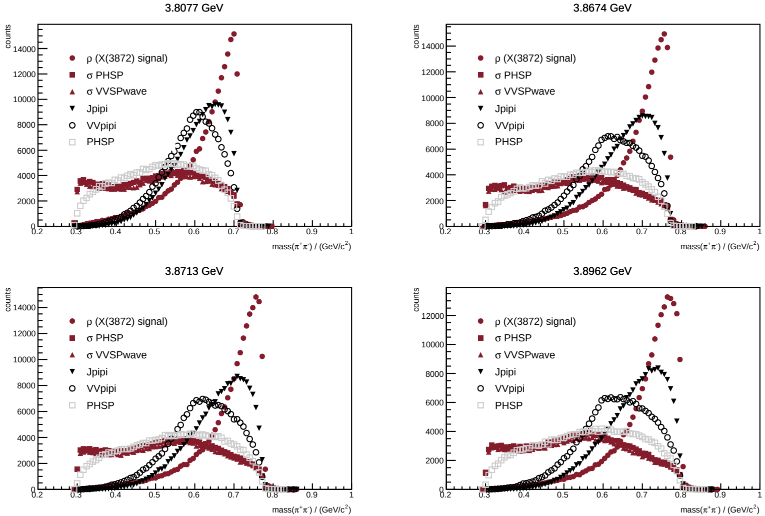
- KKMC + EvtGen, including ISR + FSR, flat lineshape
- for each energy point:
  - 5×10^5 with $J/\psi \to e^+e^-$
  - 5×10^5 with $J/\psi \to \mu^+\mu^-$

EvtGen Models

- $e^+e^- \to \pi^+\pi^- J/\psi(\to \ell^+\ell^-)$ VVpipi
- $e^+e^- \to \pi^+\pi^- J/\psi(\to \ell^+\ell^-)$ Jpipi
- $e^+e^- \to \sigma(\to \pi^+\pi^-) J/\psi(\to \ell^+\ell^-)$ PHSP
- $e^+e^- \to \sigma(\to \pi^+\pi^-) J/\psi(\to \ell^+\ell^-)$ VVS_PWAVE
- $e^+e^- \to \pi^+\pi^- J/\psi(\to \ell^+\ell^-)$ PHSP

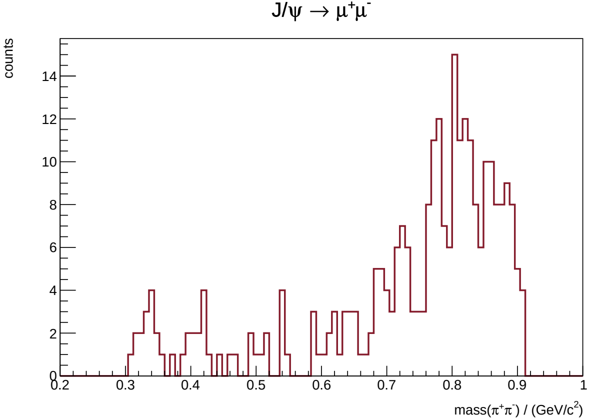
Continuum MC Models(2)

Comparisson



Continuum MC Models(3)
Cross Check

$482\,\text{pb}^{-1}$ of data at $\sqrt{s} = 4007.6\,\text{MeV}$ favors VVpipi and Jpipi models. We use the VVpipi model.



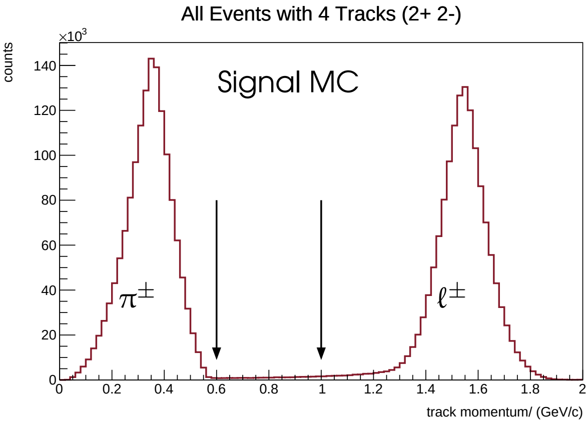
Section 3

Preselection

Event Selection

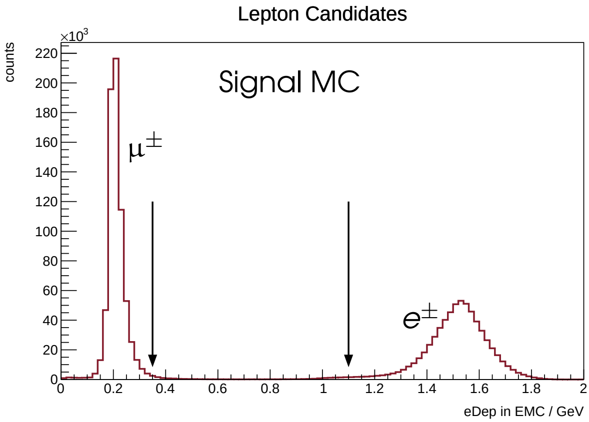
- boss version 7.0.3
- 4 good charged tracks, net charge $= 0$:
  - $|z_{POCA}| < 10\,\text{cm}$
  - $r_{POCA} < 1\,\text{cm}$
  - $|\cos\theta| < 0.93$

Particle ID (1): $\pi^\pm$ or $\ell^\pm$?



- $\pi^\pm$ momenta are required to be $< 0.6\,\text{GeV}$
- $\ell^\pm$ momenta are required to be $> 1.0\,\text{GeV}$

Particle ID (2): $\mu^\pm$ or $e^\pm$?



- $\mu^\pm$ candidates should deposit $< 0.35\,\text{GeV}$ in EMC
- $e^\pm$ candidates should deposit $> 1.1\,\text{GeV}$ in EMC

Section 4

Background Study

Background MC

for each energy point:

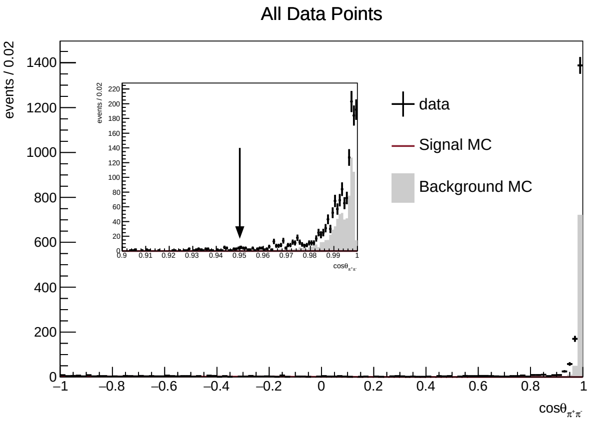
- 10^7 events $e^+e^- \to \gamma e^+e^-$ with Babayaga 3.5 ($\cong 3\times$ luminosity)
- 10^6 events $e^+e^- \to \gamma\mu^+\mu^-$ with Phokhara ($\cong 180\times$ luminosity)
- 10^7 events $e^+e^- \to e^+e^-e^+e^-$ with BesTwogam ($\cong 5\times$ luminosity)
- 10^7 events $e^+e^- \to e^+e^-\mu^+\mu^-$ with BesTwogam ($\cong 12\times$ luminosity)
- 10^6 events $e^+e^- \to e^+e^-q^+q^-$ with BesTwogam ($\cong 6\times$ luminosity)
- 10^6 events $e^+e^- \to 2\pi^+2\pi^-$ with ConExc ($\cong 45\times$ luminosity)
- 10^6 events $e^+e^- \to K_S^0K^\pm\pi^\mp$ with ConExc ($\cong 180\times$ luminosity)
- 5×10^5 events $e^+e^- \to \pi^+\pi^-K^+K^-$ with ConExc ($\cong 23\times$ luminosity)
- 10^6 events $e^+e^- \to \gamma_{ISR}\psi'$ with EvtGen ($\cong 150\times$ luminosity)

red: ≈ 2.6 expected events under J/ψ peak, (e^+e^- mode), violet: ≈ 1.4 (e^+e^-), blue: ≈ 2.6 ($\mu^+\mu^-$), green: ≈ 0.0 (both modes), black: $0.1 \lesssim N_{exp} \lesssim 0.5$ (both modes)

Gamma Conversion Background Rejection (1)

$J/\psi \to e^+e^-$

Cosine of opening angle between both $\pi^\pm$ candidates

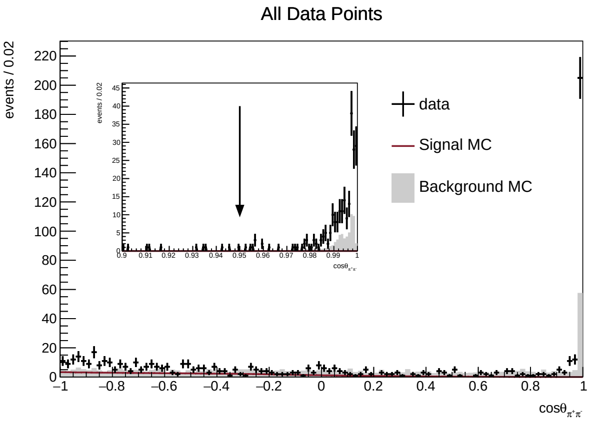


Require $\cos\theta_{\pi\pi} < 0.95$

Gamma Conversion Background Rejection (2)

$J/\psi \to \mu^+\mu^-$

Cosine of opening angle between both $\pi^\pm$ candidates

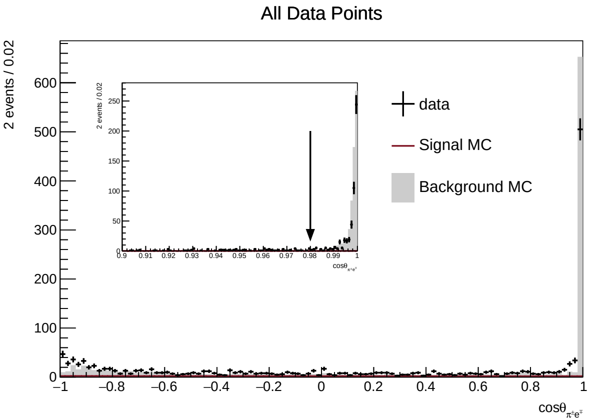


Require $\cos\theta_{\pi\pi} < 0.95$

Gamma Conversion Background Rejection (3)

$J/\psi \to e^+e^-$

Cosine of opening angle between $\pi^\pm$ and $e^\mp$ candidates

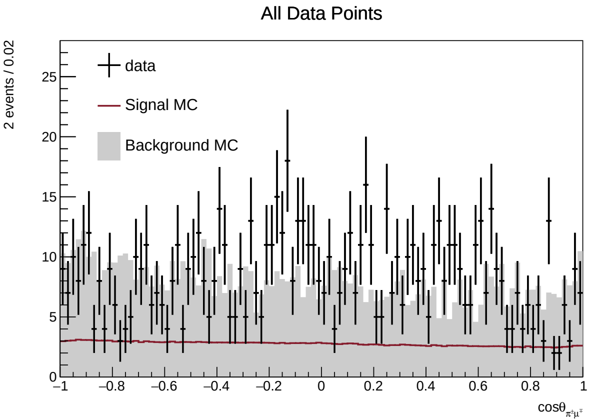


Require $\cos\theta_{\pi^\pm e^\mp} < 0.98$

Gamma Conversion Background Rejection (4)

$J/\psi \to \mu^+\mu^-$

Cosine of opening angle between $\pi^\pm$ and $\mu^\mp$ candidates



No Cut

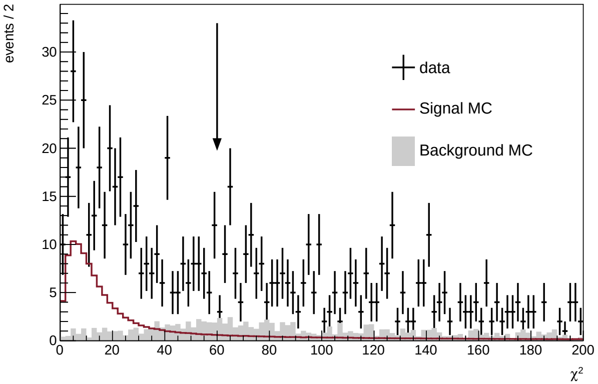
Kinematic Fit

- Perform a kinematic fit (total four momentum + vertex): include beam energy spread (2017 data)

χ^2 Distribution (1)

$J/\psi \to e^+e^-$

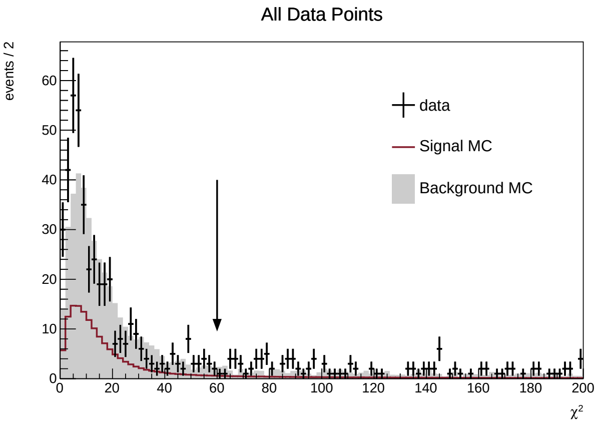
All Data Points



Require $\chi^2 < 60$

χ^2 Distribution (2)

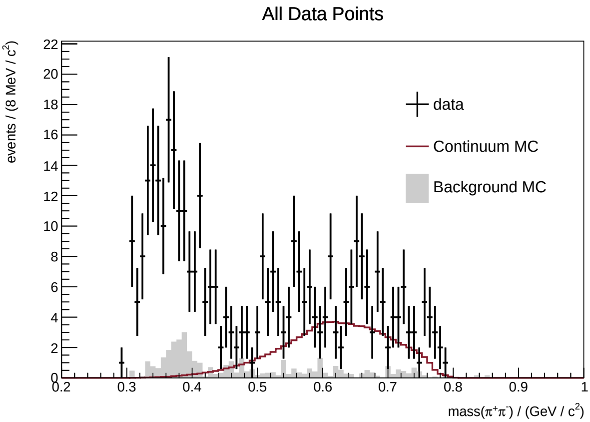
$J/\psi \to \mu^+\mu^-$



Require $\chi^2 < 60$

$mass(\pi^+\pi^-)$ Distribution (1)

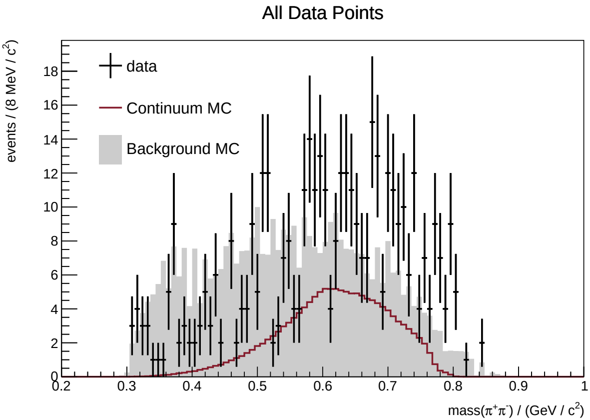
$J/\psi \to e^+e^-$



No Cut (would introduce a large systematic uncertainty)

$mass(\pi^+\pi^-)$ Distribution (2)

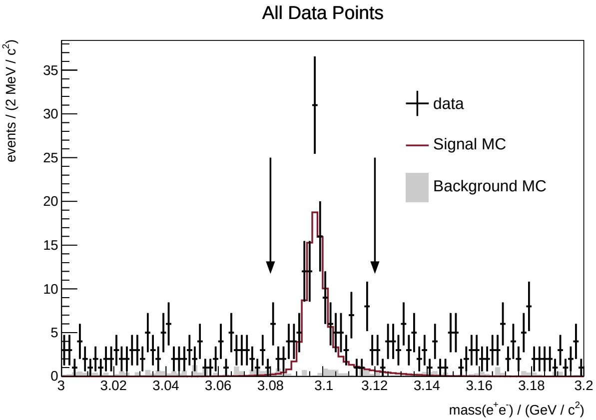
$J/\psi \to \mu^+\mu^-$



No cut

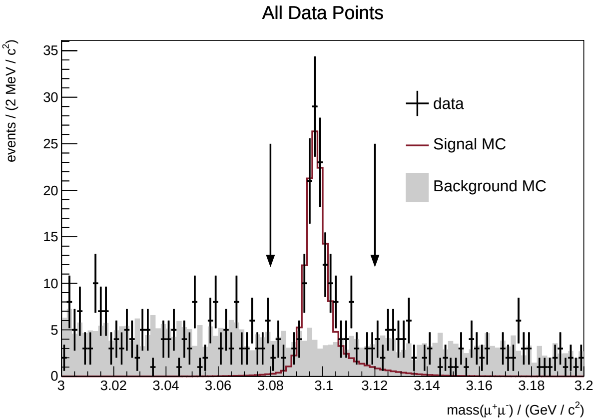
$mass(e^+e^-)$ distribution (1)

$J/\psi \to e^+e^-$



$mass(\mu^+\mu^-)$ distribution (2)

$J/\psi \rightarrow \mu^+\mu^-$



Conclusion of Background Study

- Almost perfect description of bakground by MC
- Background seems to be flat

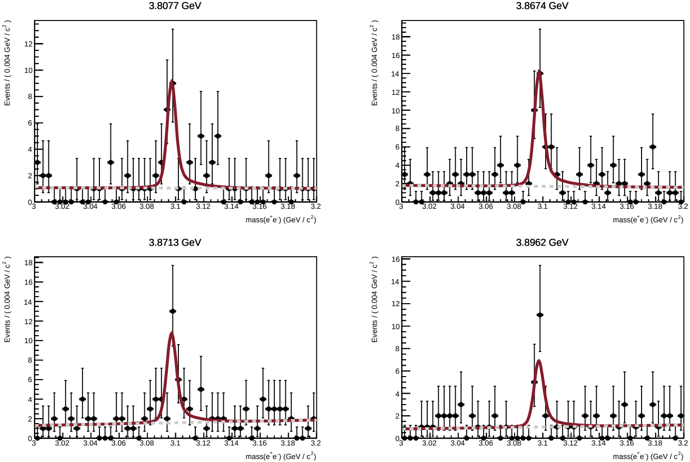
Section 5

Cross Section

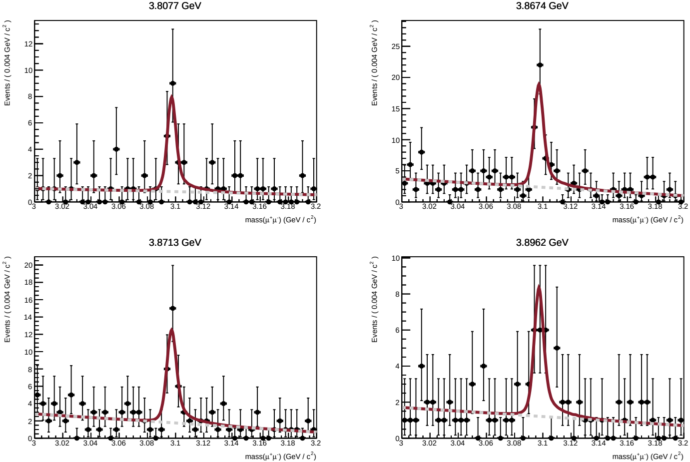
Fit to the $\ell^+\ell^-$ Spectrum: Get N_{obs}

- N_{obs} obtained by a maximum likelihood fit to the $mass(\ell^+\ell^-)$ spectrum
- Signal shape: MC lineshape
- Background shape: linear function

Fit to the $mass(e^+e^-)$ Spectrum: Get N_{obs}

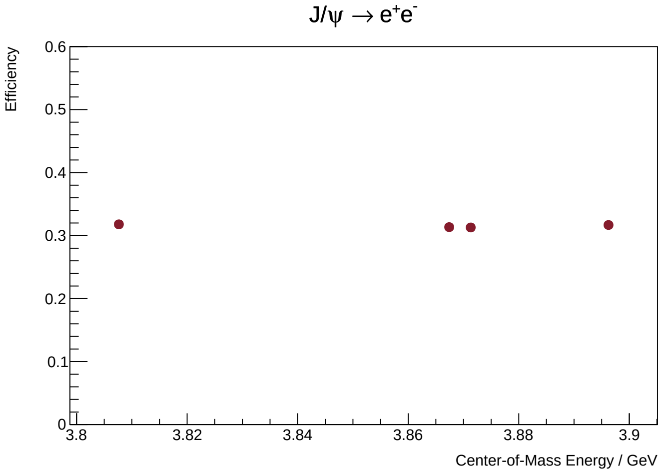


Fit to the $mass(\mu^+\mu^-)$ Spectrum: Get N_{obs}



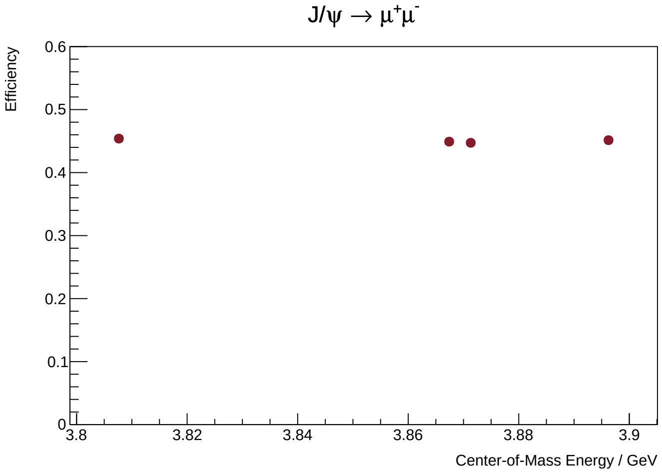
Efficiency (1)

$J/\psi \rightarrow e^+e^-$



Efficiency (2)

$J/\psi \rightarrow \mu^+\mu^-$

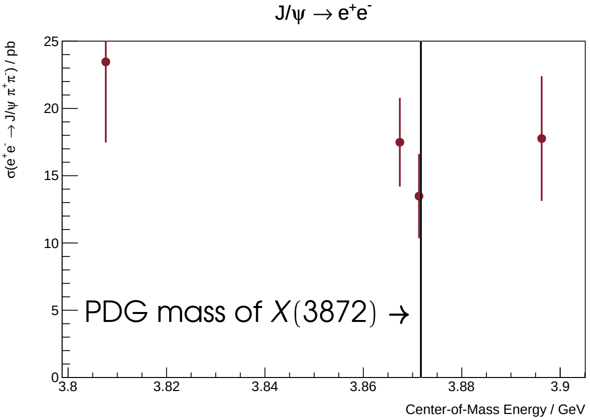


Cross Section (1)

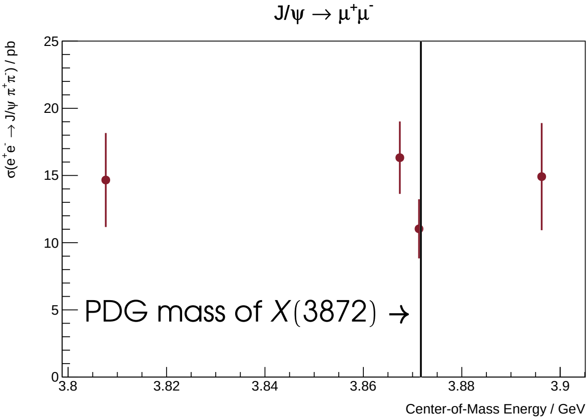
$$\sigma(e^+e^- \to \pi^+\pi^- J/\psi) = \frac{N_{obs}}{\int \mathcal{L}dt \cdot \varepsilon \cdot (1+\delta) \cdot \mathcal{B}(J/\psi \to \ell^+\ell^-)}$$

- N_{obs} obtained from fit to $\ell^+\ell^-$ spectrum
- $\int \mathcal{L}dt$ determined from Bhabha events
- ε see previous slide
- $\mathcal{B}(J/\psi \to e^+e^-) = 5.971\,\%$ taken from PDG
- $\mathcal{B}(J/\psi \to \mu^+\mu^-) = 5.961\,\%$ taken from PDG
- $1+\delta = 0.895$ obtained from KKMC (flat lineshape)

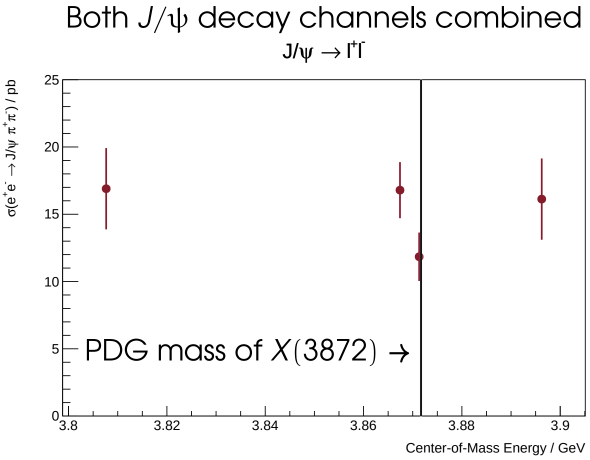
Cross Section (2)



Cross Section (3)



Cross Section (4)



Systematic Uncertainties (1)

systematic uncertainties independent from $\sqrt{s}$

- Tracking Efficiency: 4 % (tracks)
- J/ψ branching fraction (from PDG): 0.6 % for both J/ψ modes

kinematic fit

- $0.5\times$ efficiency difference between kinematic fit with and without correction of the helix parameters

Systematic Uncertainties (2)

fit to the $mass(\ell^+\ell^-)$ spectrum

- Change the background parameterization to 2nd order polynomial
- take deviation as systematic uncertainty

decay model in the continuum MC

- Decay modeled as $e^+e^- \to \pi^+\pi^- J/\psi(\to \ell^+\ell^-)$ in VVpipi
- Change this to $e^+e^- \to \sigma(\to \pi^+\pi^-)J/\psi(\to \ell^+\ell^-)$ in PHSP
- take the difference in efficiency as systematic uncertainty

Systematic Uncertainties (3)

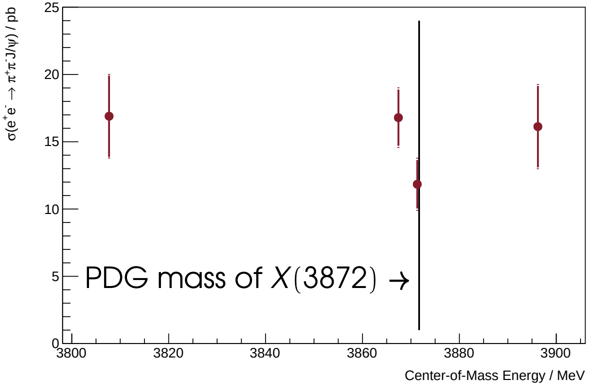
$\sqrt{s}$	3.80765	3.86741	3.87131	3.89624
$\int \mathcal{L} dt$	1.0 %	1.2 %	0.7 %	1.0 %
tracking	4.0 %	4.0 %	4.0 %	4.0 %
$\mathcal{B}(J/\psi \to e^+e^-)$	0.6 %	0.6 %	0.6 %	0.6 %
$\mathcal{B}(J/\psi \to \mu^+\mu^-)$	0.6 %	0.6 %	0.6 %	0.6 %
kinematic fit (e^+e^-)	0.88 %	0.84 %	0.88 %	0.86 %
kinematic fit ($\mu^+\mu^-$)	0.69 %	0.70 %	0.73 %	0.68 %
fit (e^+e^-)	4.9 %	3.9 %	5.1 %	10.4 %
fit ($\mu^+\mu^-$)	0.66 %	2.0 %	8.1 %	1.4 %
decay model (e^+e^-)	2.2 %	2.7 %	2.2 %	2.4 %
decay model ($\mu^+\mu^-$)	3.6 %	4.0 %	3.7 %	4.0 %
Sum (e^+e^-)	6.8 %	6.4 %	7.0 %	11 %
Sum ($\mu^+\mu^-$)	5.6 %	6.2 %	9.8 %	5.9 %

Cross Section Result (1)

	$\sigma(e^+e^- \to \pi^+\pi^- J/\psi)$/pb		
$\sqrt{s}$	e^+e^- mode	$\mu^+\mu^-$ mode	both modes combined
3.80765	$23.5 \pm 6.0 \pm 1.6$	$14.7 \pm 3.5 \pm 0.8$	$16.9 \pm 3.0 \pm 0.7$
3.86741	$17.5 \pm 3.3 \pm 1.1$	$16.3 \pm 2.7 \pm 1.0$	$16.8 \pm 2.1 \pm 0.7$
3.87131	$13.5 \pm 3.1 \pm 0.9$	$11.0 \pm 2.2 \pm 1.1$	$11.8 \pm 1.8 \pm 0.7$
3.89624	$17.8 \pm 4.6 \pm 2.0$	$14.9 \pm 4.0 \pm 0.9$	$16.1 \pm 3.0 \pm 0.8$

Cross Section Result (2)

Tiny horizontal lines indicate effect of systematic uncertainties



Section 6

Upper Limit

Lineshape

- Model of flat continuum and relativistic Breit-Wigner:

$$\sigma_{e^+e^-\to\pi^+\pi^-J/\psi}(\sqrt{s}) = \sigma_{cont} + 12\pi \frac{\Gamma_{tot}\Gamma_{ee} \times \mathcal{B}(X(3872) \to \pi^+\pi^- J/\psi)}{\left(s - m_0^2\right)^2 + m_0^2\Gamma_{tot}^2}$$

- $\Gamma_{ee} \times \mathcal{B}(X(3872) \to \pi^+\pi^- J/\psi)$ treated as one parameter
- in total 3 parameters
- This parameterization is convolved with a Gaussian modelling the beam spread (1.4 MeV for off-resonance point, 1.7 MeV for on-resonance, determined by BEMS)

Bayesian Formalism (1)

Common approach: "... *integrate the likelihood until* 90 %"
In Bayesian formalism, this is possible because:

- Likelihood function $L(x|\theta)$ is interpreted as conditional pdf $f(x|\theta)$ of data x, given the parameter θ
- Using Bayes' Theorem, this is converted into the pdf $f(\theta|x)$ of the parameter θ, given the data x:

$$f(\theta|x) = \frac{f(x|\theta)\pi(\theta)}{\int f(x|\theta)\pi(\theta)\,d\theta} \propto f(x|\theta)\pi(\theta)$$

- Prior pdf $\pi(\theta)$ is very often taken to be constant within the physical region, zero otherwise. Other choices possible.
- Construction of credible interval (confidence interval for frequentists) by integration of pdf $f(\theta|x)$ is natural.

Bayesian Formalism (2)

Treatment of nuisance parameters (parameters in likelihood function, but not of interest):

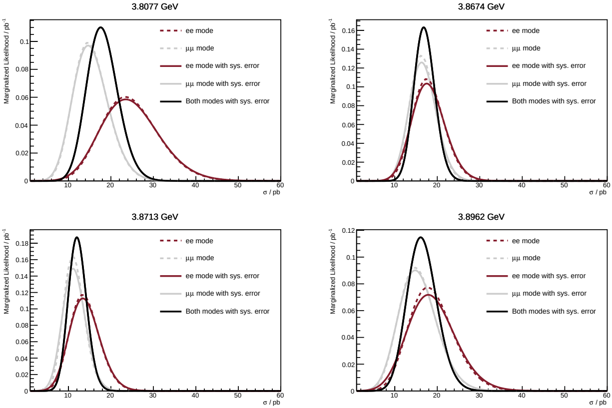
- Marginlaization (integration) of likelihood over nuisance parameters θ_n ($\tilde{\theta}$: parameter of interest, not normalized):

$$f(\tilde{\theta}|x) = \int f((\tilde{\theta}, \theta_n)|x)\, d\theta_n$$

- This is not the same as profiling the likelihood (frequentist method)

Likelihood Function (1)

Marginalized likelihood functions of cross section at each energy point.
Convolution with Gaussian to incorporate systematic uncertainties.



Likelihood Function (2)

Global likelihood function is product of the likelihood functions of the previous page evaluated at the cross section given by the lineshape parameterization:

$$L = \prod_{i=1}^{4} L_i(\sigma = \sigma_{\sqrt{s}=\sqrt{s_i}}(\Gamma_{ee} \times \mathcal{B}, \Gamma_{tot}, \sigma_{cont}))$$

σ_{cont} is a nuisance parameter and needs to be marginalized over.

Systematic Uncertainties (1)

Systematic uncertainties of lineshape parameters are:

- $X(3872)$ mass, uncertainty taken from PDG ($m_0 = (3871.69 \pm 0.17)\,\mathrm{MeV}/c^2$)
- $\sqrt{s}$ taken from the BEMS measurement (2017 data) or using official values (2013 data)
- Spread of $\sqrt{s}$ calculated from BEMS result

$\sqrt{s}$ / MeV	$\delta\sqrt{s}$ / MeV
3807.7 ± 0.6	
3867.410 ± 0.031	1.406 ± 0.025
3871.31 ± 0.06	1.73 ± 0.06
3896.2 ± 0.8	

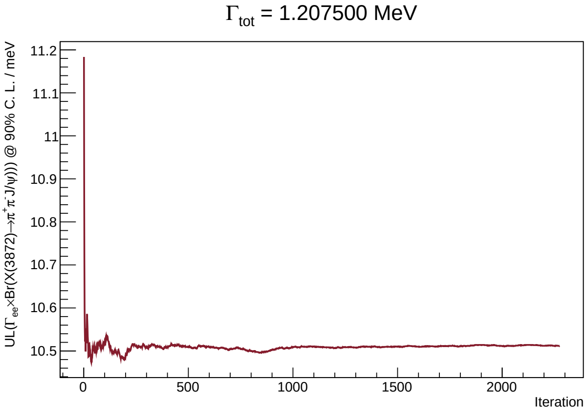
Systematic Uncertainties (2)

Systematic uncertainties of lineshape parameters are accounted for by the following procedure:

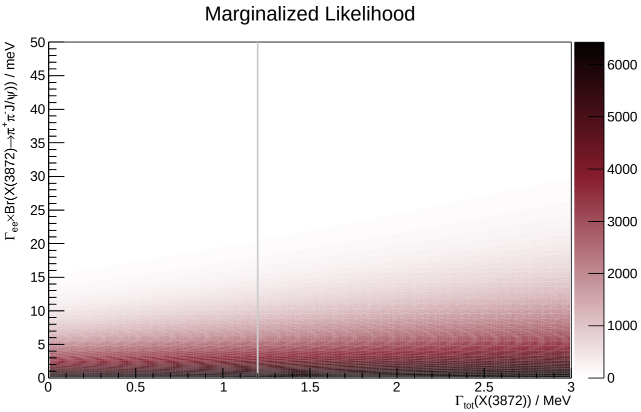
- Lineshape parameters are randomly sampled from Gaussians with mean and variance according to its central value and uncertainty.
- Likelihood function is calculated.
- These steps are repeated several times
- The average of the likelihood functions of each iteration is the likelihood function including systematic uncertainties.

Systematic Uncertainties (3)

Upper limit on $\Gamma_{ee} \times \mathcal{B}$ for a fixed total width depending on number of iterations: Converging at $\approx$ 1000 iterations.

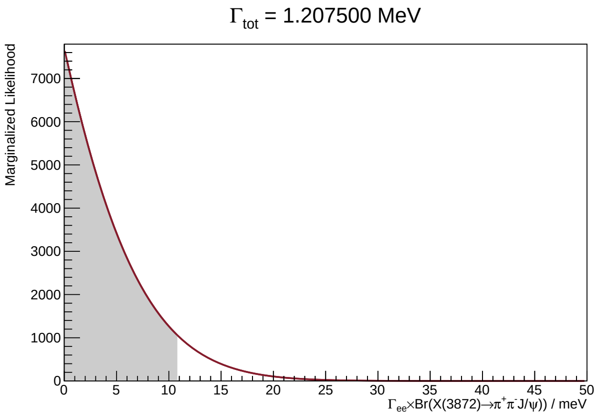


Full Likelihood Function

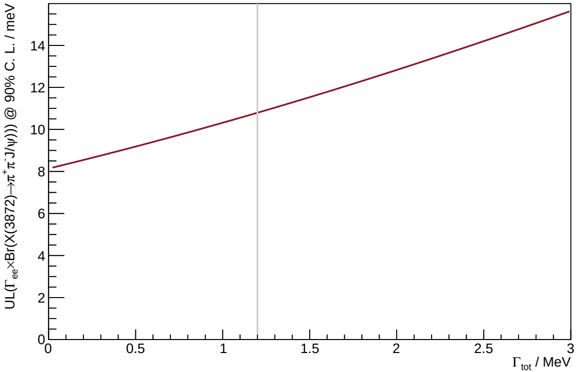


Grey line: current upper limit on Γ_{tot}

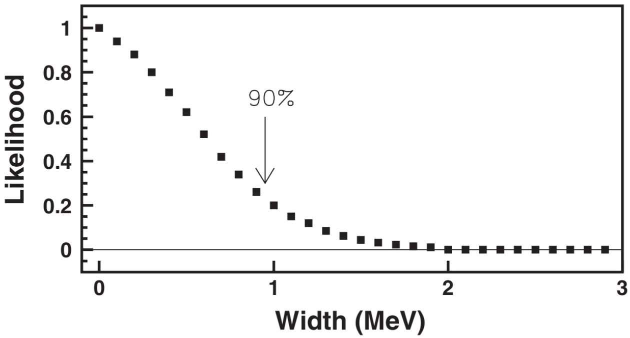
Total Width Dependent Upper Limit



Total Width Dependent Upper Limit

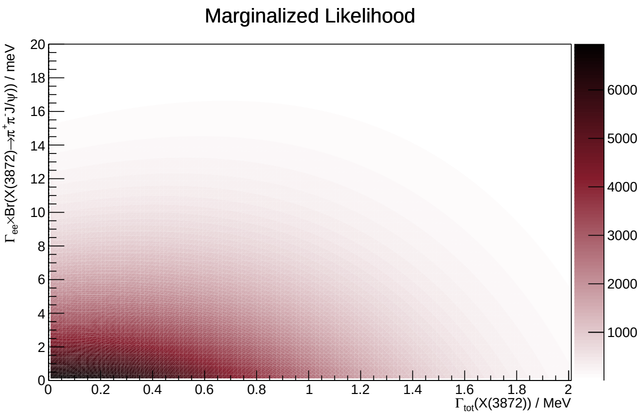


Full Likelihood Function with Prior for Total Width

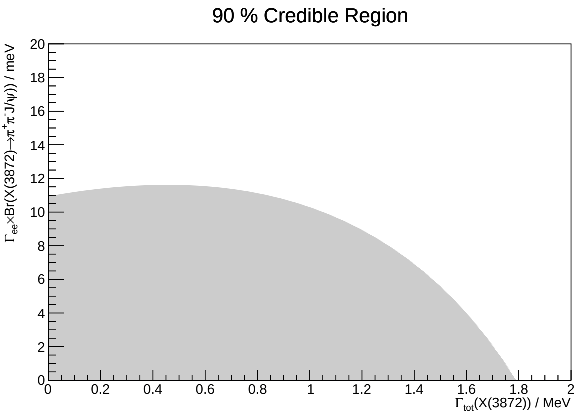


Likelihood function of Γ_{tot} from the original Belle paper (Phys. Rev. D **84**, 052004). We approximate the shape by a zero-mean Gaussian. The variance is set in such a way, that the upper limit coincides with 1.2 MeV. This function is then used as the prior for Γ_{tot}.

Full Likelihood Function with Prior for Total Width

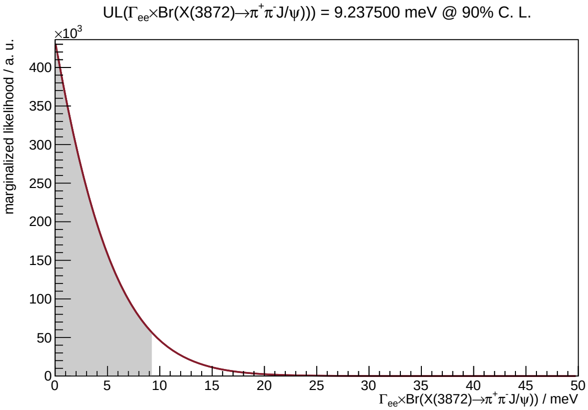


2D Credible Region



Upper Limit Independent from Total Width

Marginalization over Γ_{tot}: Likelihood only depends on $\Gamma_{ee} \times \mathcal{B}$.



Conclusion

- Analysis of $e^+e^- \to J/\psi\pi^+\pi^-$ at 4 different $\sqrt{s}$ close to the $X(3872)$ mass
- No significant enhancement at the $X(3872)$ mass
- Measurement is consistent with constant cross section
- An upper limit on $\Gamma_{ee} \times \mathcal{B}(X(3872) \to \pi^+\pi^-)$ has been determined in a Γ_{tot} dependent and independent way:
  - $\Gamma_{ee} \times \mathcal{B} < 11\,\text{meV}$ at the 90 % confidence level for $\Gamma_{tot} = 1.2\,\text{MeV}$
  - $\Gamma_{ee} \times \mathcal{B} < 9\,\text{meV}$ at the 90 % confidence level (factor 14 improvement compared to previous measurement)
- 2D credible region for $(\Gamma_{ee} \times \mathcal{B}) \times \Gamma_{tot}$ has been determined as well

Thank You!