Study of prompt J/ψ production in e^+e^- annihilation at center-of-mass energies from 3.810 GeV to 4.600 GeV

Olga BAKINA

On behalf of BESIII-JINR group

Joint Institute for Nuclear Research
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Motivation I

- There are two main theoretical approaches to calculate the heavy quarkonium production at different hard-scattering scales: CSM and NRQCD with COM.

  For nonperturbative calculations it is necessary to obtain matrix elements which are extracted from experimental data.

- B-factories prompt J/ψ production at $\sqrt{s} = 10.6$ GeV:
  - $\sigma(e^+e^- \to J/\psi + X) = 2.5 \pm 0.21 \pm 0.21$ pb (BaBar)
  - $\sigma(e^+e^- \to J/\psi + X) = 1.47 \pm 0.10 \pm 0.13$ pb (Belle)
  - $\sigma(e^+e^- \to J/\psi + X) = 1.9 \pm 0.2$ pb (CLEO)

  These results are not entirely consistent with each other.

- Theoretical prediction for energy region 4.6 ~ 5.6 GeV:
  - The CO LDMEs are nonzero assuming prompt J/ψ production larger than 10 pb.

  Ref.: arXiv:1409.2293v2 [hep-ph] 4 Aug 2016

- We are able to measure prompt J/ψ production at the lowest point $\sqrt{s} = 4.6$ GeV of this energy region using the XYZ data of the BESIII experiment.

Motivation II

There is a series of exclusive cross-section measurements performed by the BESIII experiment in considered energy region:

- $e^+e^- \rightarrow J/\psi\pi^+\pi^-$ (arXiv:1611.01317v1 [hep-ex] 4 Nov 2016)
- $e^+e^- \rightarrow J/\psi\pi^0\pi^0$ (arXiv:1506.06018v2 [hep-ex] 1 Aug 2015)
- $e^+e^- \rightarrow J/\psi\eta,\pi^0$ (arXiv:1503.06644v1 [hep-ex] 23 Mar 2015)
- $e^+e^- \rightarrow J/\psi\eta'$ (arXiv:1605.03256v1 [hep-ex] 11 May 2016)
- $e^+e^- \rightarrow J/\psi K^+K^-,K^0K^0$ (arXiv:1802.01216v1 [hep-ex] 4 Feb 2018)
- ...

Are there any other significant nontrivial contributions?

The XYZ data (2012-2014)

ID	$\sqrt{s}, MeV$	Run number	$\mathcal{L}_{int}, pb^{-1}$
3810	$3807.65 \pm 0.10 \pm 0.58$	$33490 - 33556$	$50.54 \pm 0.03 \pm 0.49$
3900	$3896.24 \pm 0.11 \pm 0.72$	$33572 - 33657$	$52.61 \pm 0.03 \pm 0.51$
4009	$4007.62 \pm 0.05 \pm 0.66$	$23463 - 24141$	$481.96 \pm 0.01 \pm 4.68$
4090	$4085.45 \pm 0.14 \pm 0.66$	$33659 - 33719$	$52.63 \pm 0.03 \pm 0.51$
4190	$4188.59 \pm 0.15 \pm 0.68$	$30372 - 30437$	$43.09 \pm 0.03 \pm 0.42$
4210	$4207.73 \pm 0.14 \pm 0.61$	$31983 - 32045$	$54.55 \pm 0.03 \pm 0.53$
4220	$4217.13 \pm 0.14 \pm 0.67$	$32046 - 32140$	$54.13 \pm 0.03 \pm 0.53$
4230	$4226.26 \pm 0.04 \pm 0.65$	$30438 - 30491$	$44.40 \pm 0.03 \pm 0.43$
4230	$4226.26 \pm 0.04 \pm 0.65$	$32239 - 33484$	$1047.34 \pm 0.14 \pm 10.16$
4245	$4241.66 \pm 0.12 \pm 0.73$	$32141 - 32226$	$55.59 \pm 0.04 \pm 0.54$
4260	$4257.97 \pm 0.04 \pm 0.66$	$29677 - 30367, 31561 - 31981$	$825.67 \pm 0.13 \pm 8.01$
4310	$4307.89 \pm 0.17 \pm 0.63$	$30492 - 30557$	$44.90 \pm 0.03 \pm 0.44$
4360	$4358.26 \pm 0.05 \pm 0.62$	$30616 - 31279$	$539.84 \pm 0.10 \pm 5.24$
4390	$4387.40 \pm 0.17 \pm 0.65$	$31281 - 31325$	$55.18 \pm 0.04 \pm 0.54$
4420	$4415.58 \pm 0.04 \pm 0.72$	$31327 - 31390$	$44.67 \pm 0.03 \pm 0.43$
4420	$4415.58 \pm 0.04 \pm 0.72$	$36773 - 38140$	$1028.89 \pm 0.13 \pm 9.98$
4470	$4467.06 \pm 0.11 \pm 0.73$	$36245 - 36393$	$109.94 \pm 0.04 \pm 1.07$
4530	$4527.14 \pm 0.11 \pm 0.72$	$36398 - 36588$	$109.98 \pm 0.04 \pm 1.07$
4575	$4574.50 \pm 0.18 \pm 0.70$	$36603 - 36699$	$47.67 \pm 0.03 \pm 0.46$
4600	$4599.53 \pm 0.07 \pm 0.74$	$35227 - 36213$	$566.93 \pm 0.11 \pm 5.50$

- The XYZ data (2012-2014) and corresponding MC sets are reconstructed and simulated under BOSS 6.6.4.p01;

- The “4009” data (2011) and corresponding MC samples are reconstructed and simulated under BOSS 6.6.4

Energy measurement: M. Ablikim et al. "Measurement of the center-of-mass energies at BESIII via the di-muon process", arXiv:1510.08654 [hep-ex] 29 Oct 2015

Luminosity measurement: M. Ablikim et al. "Precision measurement of the integrated luminosity of the data taken by BESIII at center of mass energies between 3.810 GeV and 4.600 GeV", arXiv:1503.03408 [hep-ex] 11 Mar 2015

Measurement procedure

$$\sigma_{e^+e^-\to J/\psi_{prompt}X} = \frac{1}{\mathcal{L}} \times \left(Y_{J/\psi X} - Y_{\psi'_{ISR}\to J/\psi X} - Y_{\psi'\to J/\psi X} - Y_{\chi_c\to\gamma J/\psi}\right)$$

- Signal: e+e- $\longrightarrow$ $J/\psi_{prompt}X$,

here J/ψ_{prompt} is originated from sources other than classical charmonium decays or ISR.

- Major background sources: $\{\psi', \chi_{c1,2}\} \longrightarrow J/\psi X$
- Initial-state radiation (ISR) return to:
  - **Resonances:** $e^+e^- \longrightarrow \gamma J/\psi$, $e^+e^- \longrightarrow \gamma\psi'$

    (exclude by cuts)
  - **Continuum:** $e^+e^- \longrightarrow \gamma J/\psi X$

    (take into account by applying QED calculation)

Observed number of $e^+e^- \to J/\psi X$ events estimation for $Y_{J/\psi X}$ yield measurement

$$\sigma_{e^+e^- \to J/\psi_{prompt} X} = \frac{1}{\mathcal{L}} \times \left(Y_{J/\psi X} - Y_{\psi'_{ISR} \to J/\psi X} - Y_{\psi' \to J/\psi X} - Y_{\chi_c \to \gamma J/\psi}\right)$$

$$Y_{J/\psi X} = \frac{N^{obs}_{J/\psi X} - \mathcal{R}^{bg}_{J/\psi_{ISR}} \times N^{obs}_{J/\psi_{ISR}}}{\bar{\epsilon}_{J/\psi X} \times \mathcal{B}_{J/\psi \to \mu^+ \mu^-}}$$

Selection criteria for $e^+e^- \to J/\psi X \to \mu^+\mu^- X$

Each selected event must contain one of the following track configuration:

- exactly one positive and one negative reconstructed charged tracks and at least two photons (suppression of ~98% e+e- → $(\gamma_{ISR})J/\psi$ events)
- exactly two positive and two negative reconstructed charged tracks and at least two photons (suppression of ~50% e+e- → $(\gamma_{ISR})\psi'$ events)
- exactly two positive and two negative reconstructed charged tracks, less than two photons while the charged tracks do not form the ψ' signal via the $J/\psi\pi^+\pi^-$ final state
- other configurations with more than one positive or more than one negative reconstructed charged tracks
-

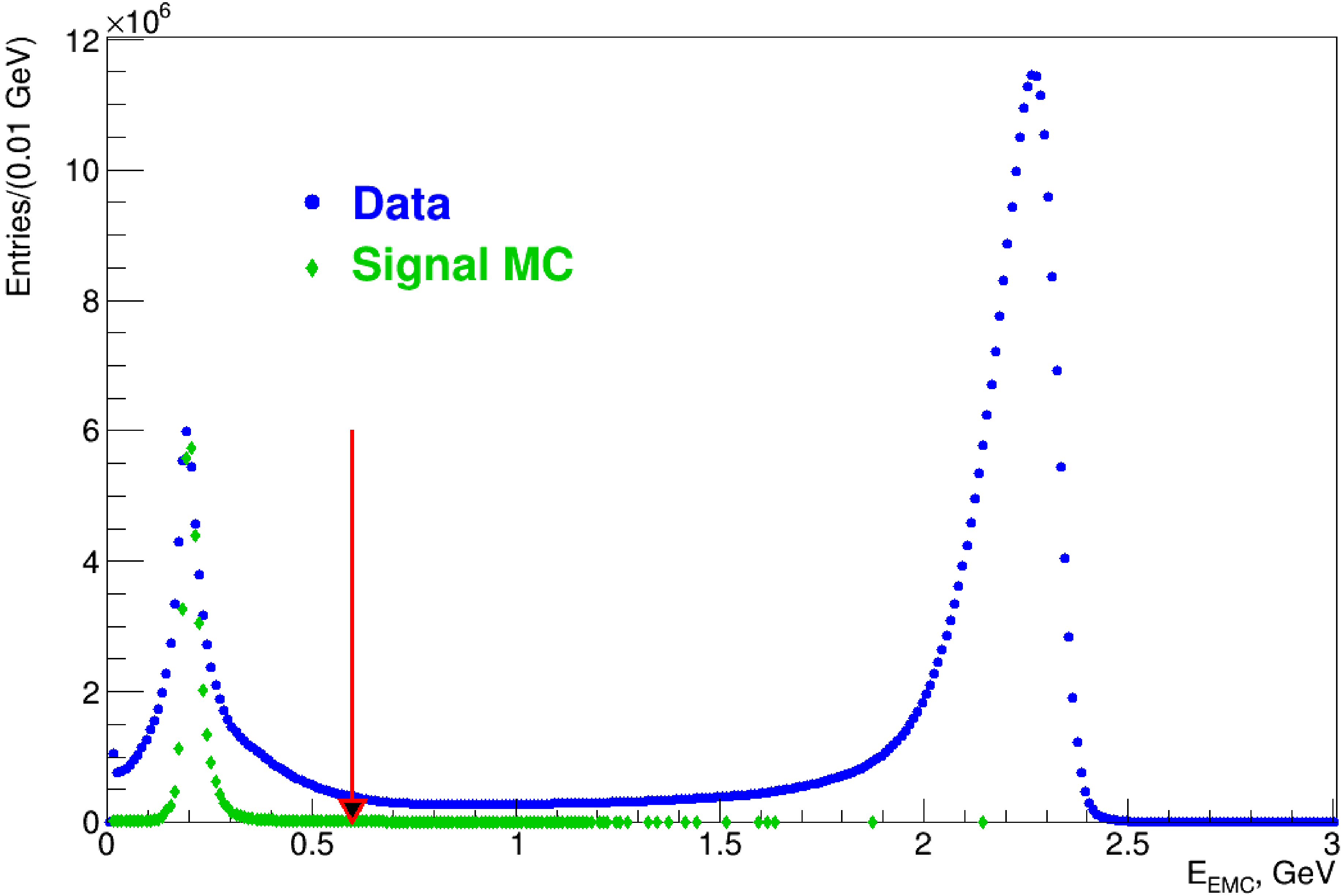
Charged tracks criteria:

- $\cos(\Theta) < 0.93$ (for each charged track);
- $r < 1$ cm, $|z| < 10$ cm (for each charged track);
- $E_{emc} < 0.6$ GeV (muons from J/ψ decay identification);
- 2.8 GeV $< M_{\mu^+\mu^-} <$ 3.4 GeV (mass window for J/ψ);

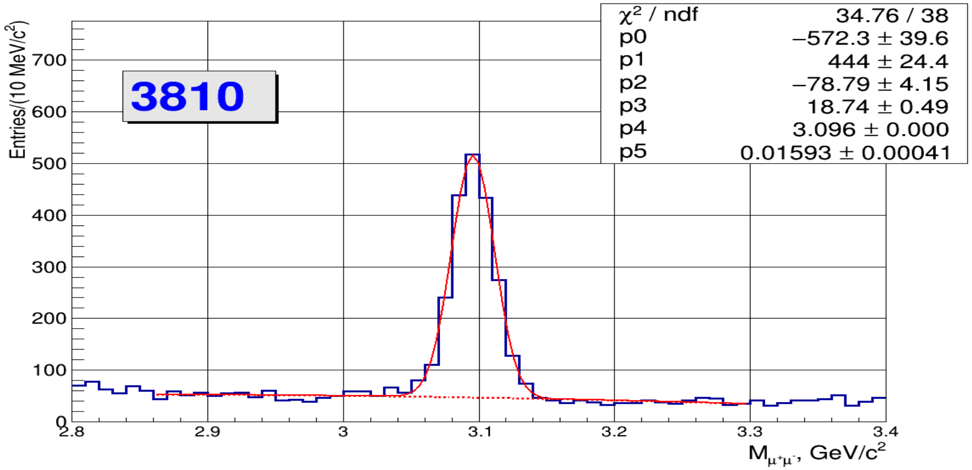
Photons criteria:

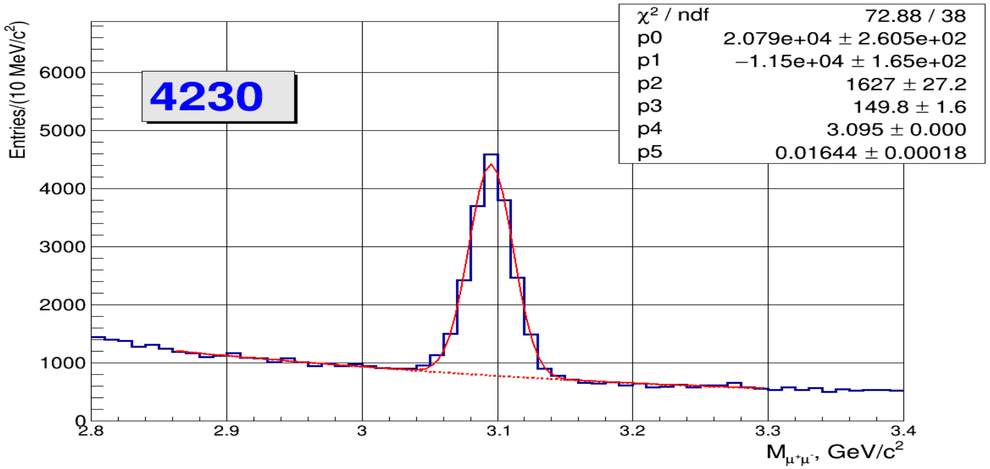
- EMC: $0 \leq t \leq 14$ ns;
- E > 25 MeV (barrel), E > 50 MeV (end-cups);
- The angle between the neutral track and the nearest charged track > 20°;

The energy deposited in the EMC for all charged tracks

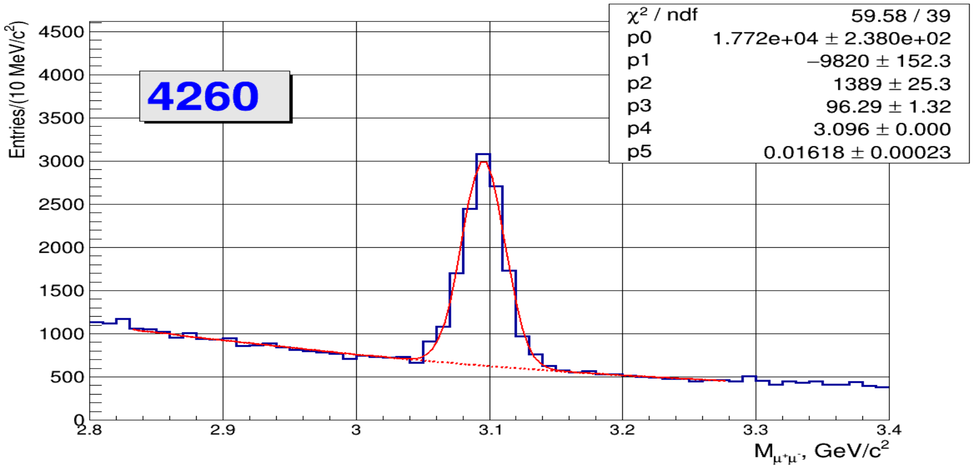


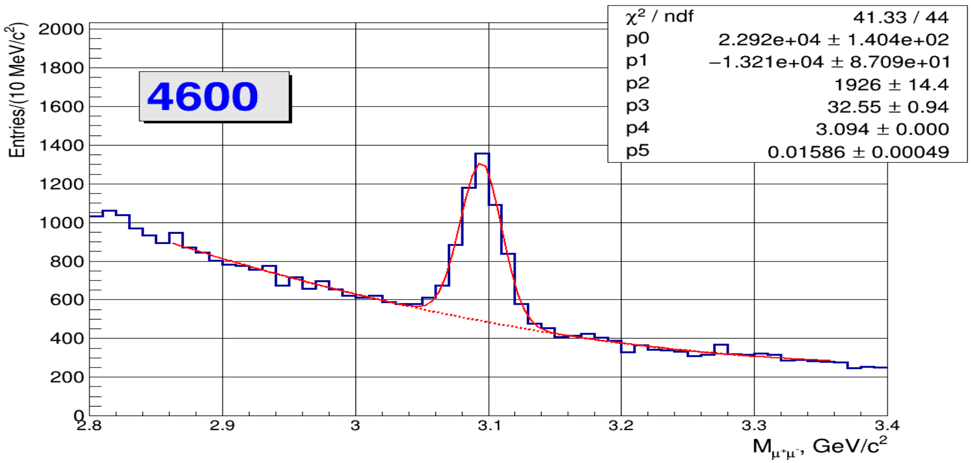
Observed number of J/ψX events





Fit a normalized gaussian function (signal) and a quadratic polynomial (background) to the data





Observed number of $e^+e^- \to (\gamma_{ISR})J/\psi$ events estimation for calculation number of background events (accroding to KKMC R^{bg} is ~2%)

$$\sigma_{e^+e^-\to J/\psi_{prompt}X} = \frac{1}{\mathcal{L}} \times \left(Y_{J/\psi X} - Y_{\psi'_{ISR}\to J/\psi X} - Y_{\psi'\to J/\psi X} - Y_{\chi_c\to\gamma J/\psi}\right)$$

$$Y_{J/\psi X} = \frac{N^{obs}_{J/\psi X} - \mathcal{R}^{bg}_{J/\psi_{ISR}} \times N^{obs}_{J/\psi_{ISR}}}{\bar{\epsilon}_{J/\psi X} \times \mathcal{B}_{J/\psi\to\mu^+\mu^-}}$$

Selection criteria for ISR return to J/ψ resonance
$(e^+e^- \to (\gamma_{ISR})J/\psi \to (\gamma_{ISR})\mu^+\mu^-)$

Each selected event must contain the following track configuration:

- exactly one positive and one negative reconstructed charged tracks and less than two photons

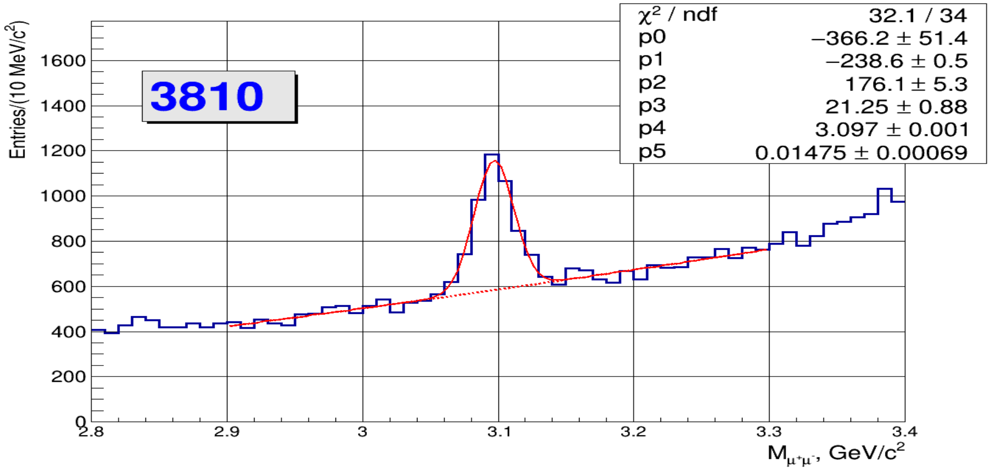
Charged tracks criteria:

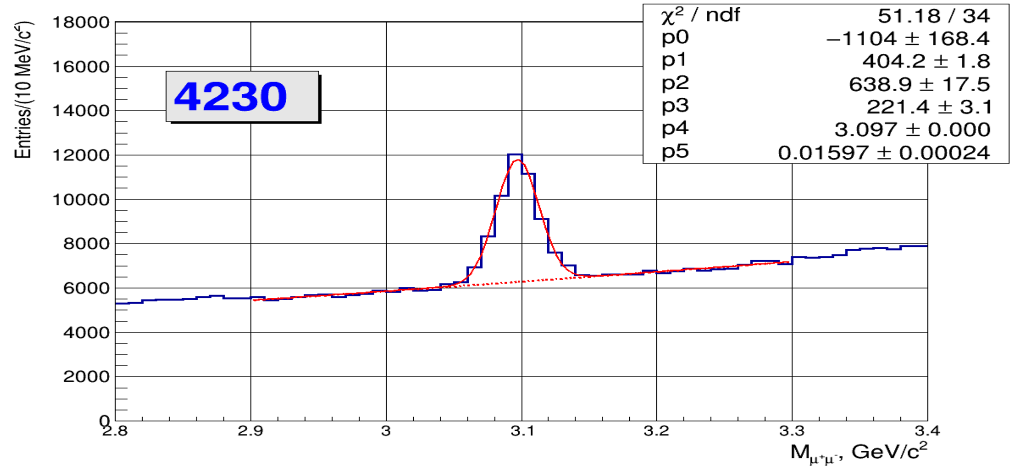
- $\cos(\Theta) < 0.93$ (for each charged track);
- $r < 1$ cm, $|z| < 10$ cm (for each charged track);
- $E_{emc} < 0.6$ GeV (muons from J/ψ decay identification);
- $2.8 \text{ GeV} < M_{\mu^+\mu^-} < 3.4$ GeV (mass window for J/ψ);

Photons criteria:

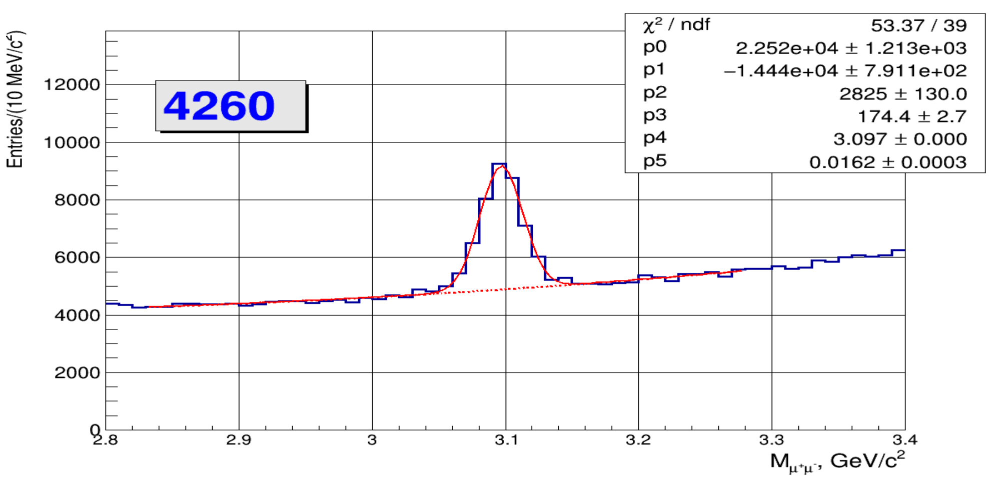
- EMC: $0 \le t \le 14$ ns;
- $E > 25$ MeV (barrel), $E > 50$ MeV (end-cups);
- The angle between the neutral track and the nearest charged track $> 20^\circ$;

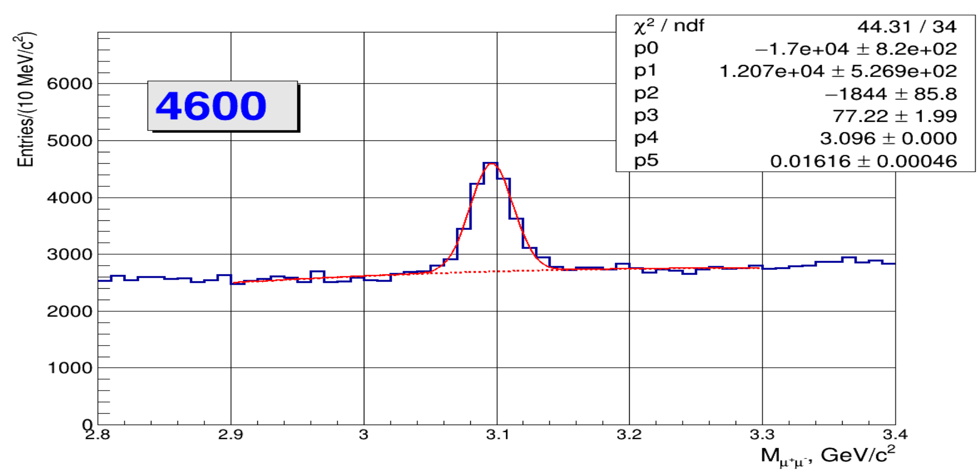
Observed number of (γ_{ISR})J/ψ events





Fit a normalized gaussian function (signal) and a quadratic polynomial (background) to the data





Observed number of $e^+e^- \to \psi'X$ with $\psi' \to J/\psi X$ events estimation for $Y_{\psi' \to J/\psi X}$ yield measurement

$$\sigma_{e^+e^- \to J/\psi_{prompt} X} = \frac{1}{\mathcal{L}} \times \left(Y_{J/\psi X} - Y_{\psi'_{ISR} \to J/\psi X} - Y_{\psi' \to J/\psi X} - Y_{\chi_c \to \gamma J/\psi} \right)$$

$$Y_{\psi' \to J/\psi X} = \frac{N^{obs}_{\psi' X} \times \tilde{\mathcal{B}}_{\psi' \to J/\psi X}}{\bar{\epsilon}_{\psi' X} \times \mathcal{B}_{\psi' \to J/\psi \pi^+\pi^-} \times \mathcal{B}_{J/\psi \to \mu^+\mu^-}}$$

$$\tilde{\mathcal{B}}_{\psi' \to J/\psi X} = \mathcal{B}_{\psi' \to J/\psi X} - \mathcal{B}_{\psi' \to \gamma\chi_{c1}} \times \mathcal{B}_{\chi_{c1} \to \gamma J/\psi} - \mathcal{B}_{\psi' \to \gamma\chi_{c2}} \times \mathcal{B}_{\chi_{c2} \to \gamma J/\psi}$$

Selection criteria for $e^+e^- \to \psi'X \to J/\psi\pi^+\pi^-X$

Each selected event must contain one of the following track configuration:

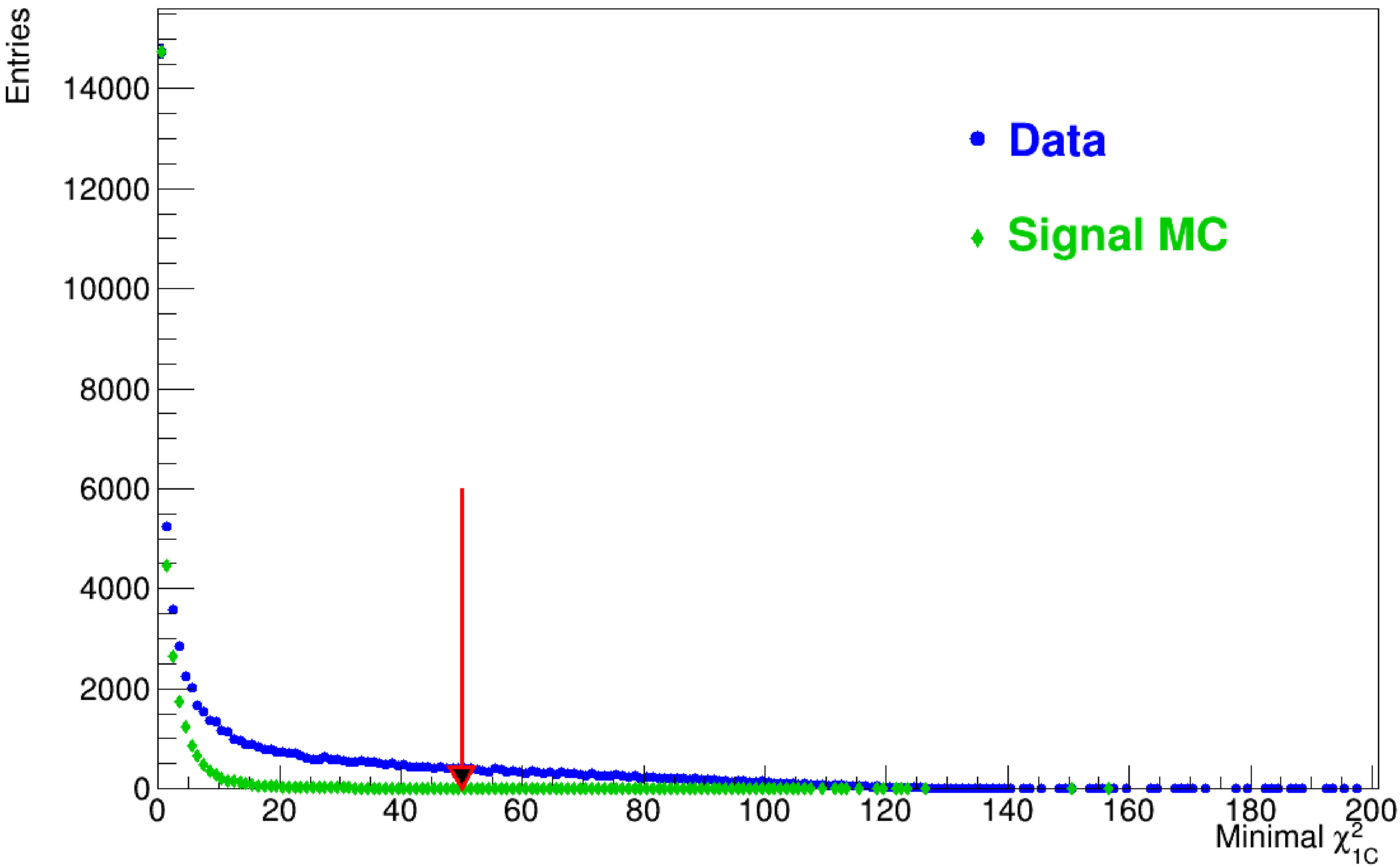
- exactly two positive and two negative reconstructed charged tracks and at least two photons (suppression of ~50% e+e- $\to (\gamma_{ISR})\psi'$ events)
- more than two positive or more than two negative reconstructed charged tracks

Additionally, 1C kinematic fit to the J/ψ mass:

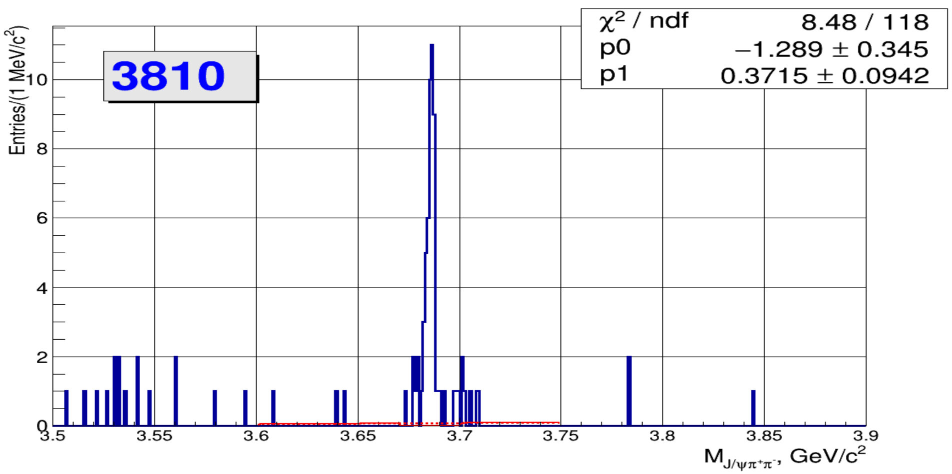
- 3.0 GeV < $M_{\mu^+\mu^-}$ < 3.2 GeV;
- $\mu^+\mu^-$ combination with minimal χ^2;
- $\chi^2_{min} < 50$;

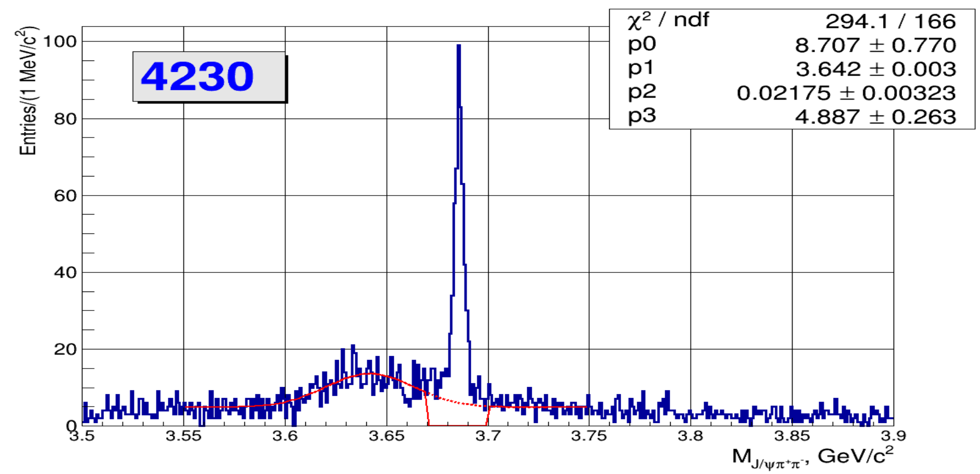
All other charged track pairs are considered as $\pi^+\pi^-$ without any particle identification.

χ^2_{min} for 1C kinematic fit to the J/ψ mass

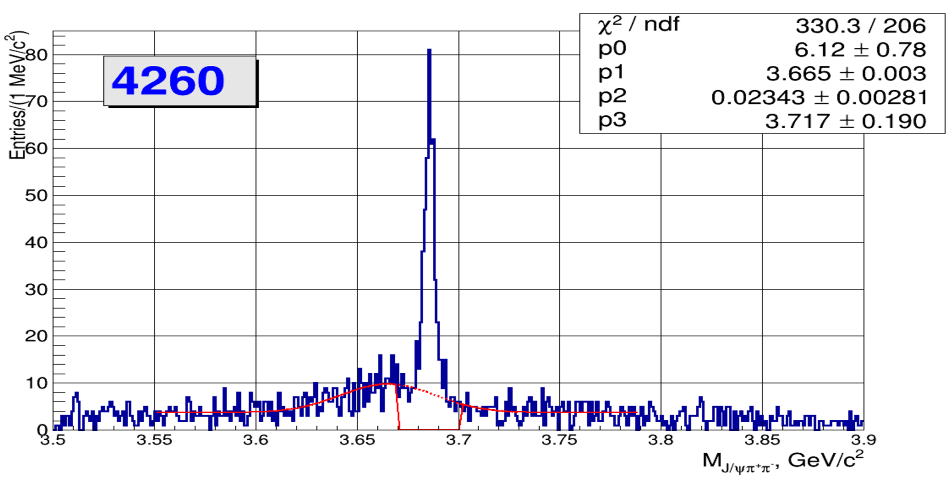


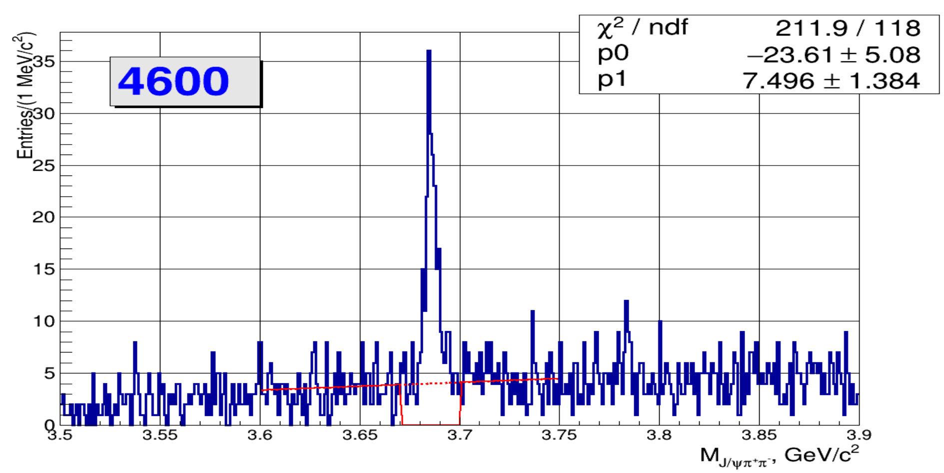
Observed number of ψ'X events





Background is fitted by a gaussian function and a constant
(by a line for other points)





Observed number of $e^+e^- \to (\gamma_{ISR})\psi'$ with $\psi' \to J/\psi X$ events estimation for $Y_{\psi' ISR \to J/\psi X}$ yield measurement

$$\sigma_{e^+e^- \to J/\psi_{prompt} X} = \frac{1}{\mathcal{L}} \times \left(Y_{J/\psi X} - Y_{\psi'_{ISR} \to J/\psi X} - Y_{\psi' \to J/\psi X} - Y_{\chi_c \to \gamma J/\psi}\right)$$

$$Y_{\psi'_{ISR} \to J/\psi X} = \frac{N^{obs}_{\psi'_{ISR}} \times (1 - \epsilon_{\psi'_{ISR}}) \times \tilde{\mathcal{B}}_{\psi' \to J/\psi X}}{\epsilon_{\psi'_{ISR}} \times \mathcal{B}_{\psi' \to J/\psi \pi^+\pi^-} \times \mathcal{B}_{J/\psi \to \mu^+\mu^-}}$$

$$\tilde{\mathcal{B}}_{\psi' \to J/\psi X} = \mathcal{B}_{\psi' \to J/\psi X} - \mathcal{B}_{\psi' \to \gamma\chi_{c1}} \times \mathcal{B}_{\chi_{c1} \to \gamma J/\psi} - \mathcal{B}_{\psi' \to \gamma\chi_{c2}} \times \mathcal{B}_{\chi_{c2} \to \gamma J/\psi}$$

Selection criteria for ISR return to ψ' resonance
$(e^+e^- \to (\gamma_{ISR})\psi' \to (\gamma_{ISR})J/\psi\pi^+\pi^-)$

Each event must contain the following track configuration:

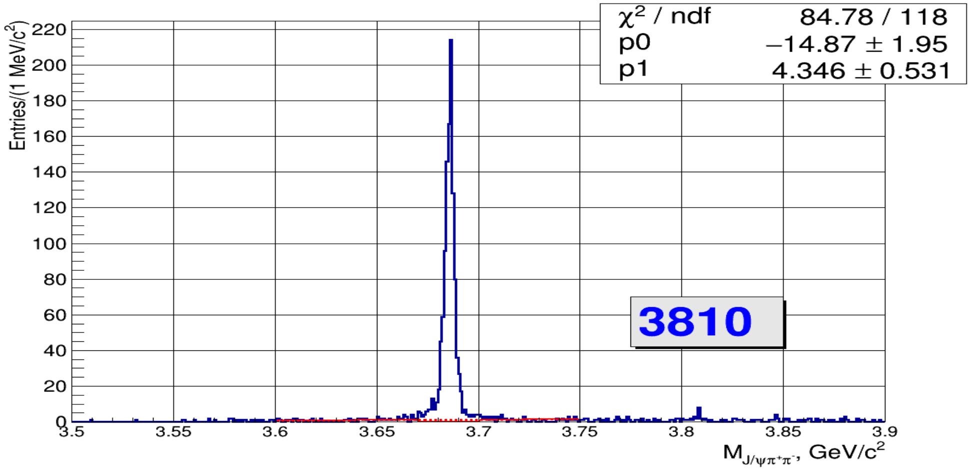
- exactly two positive and two negative reconstructed charged tracks and less than two photons

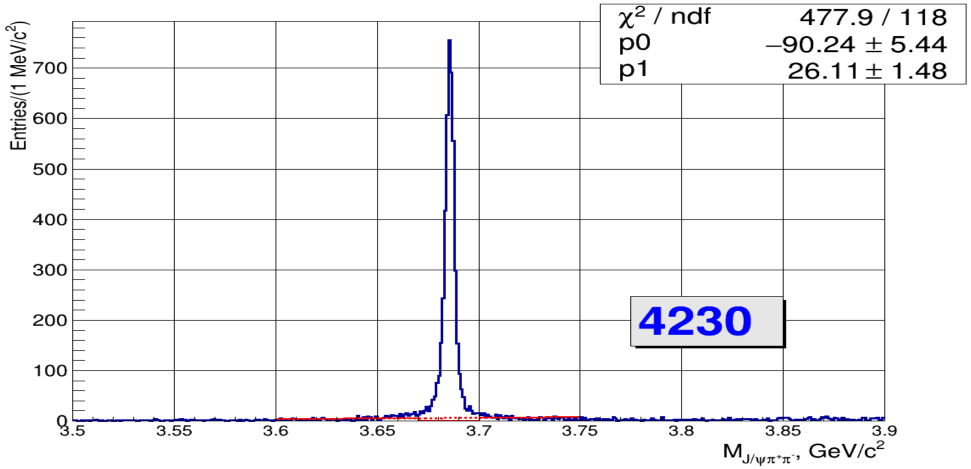
Additionally, 1C kinematic fit to the J/ψ mass:

- 3.0 GeV < $M_{\mu^+\mu^-}$ < 3.2 GeV;
- $\mu^+\mu^-$ combination with minimal χ^2;
- $\chi^2_{min} < 50$;

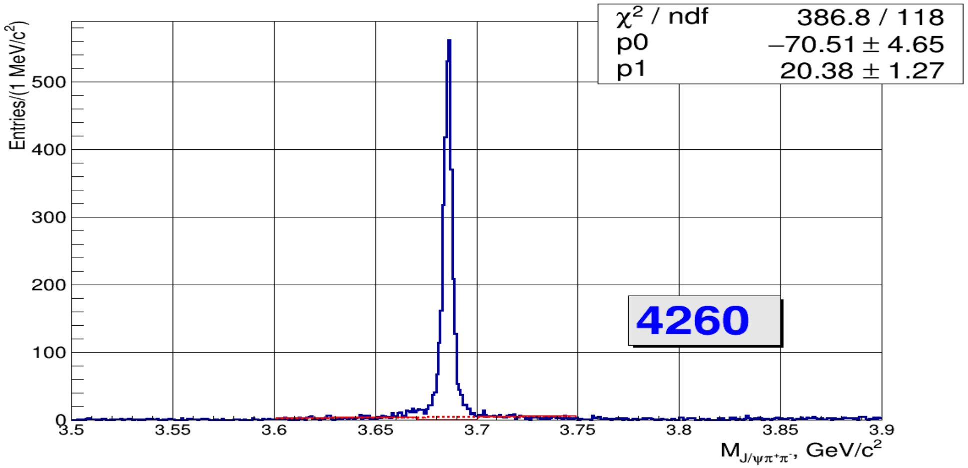
All other charged track pairs are considered as $\pi^+\pi^-$ without any particle identification.

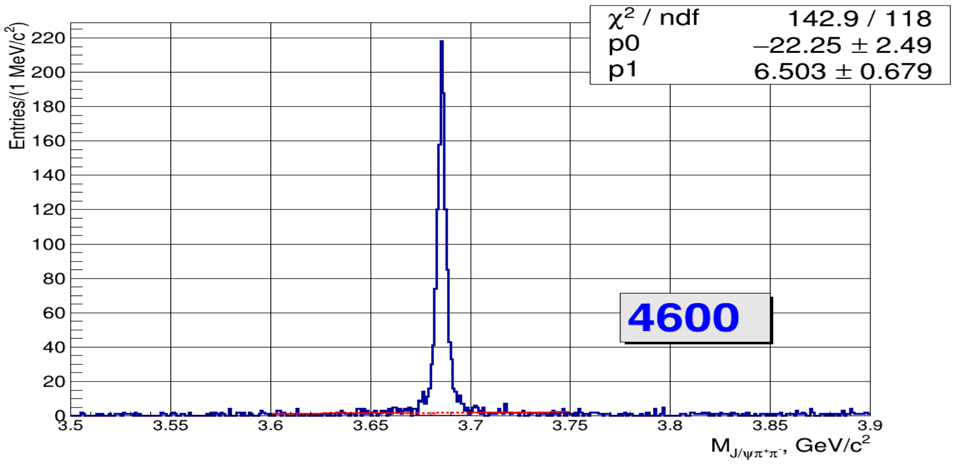
Observed number of $(\gamma_{ISR})\psi'$ events





Background is fitted by a line





Observed number of $e^+e^- \to \chi_c X$ with $\chi_c \to \gamma J/\psi$ events estimation for $Y_{\chi c \to \gamma J/\psi}$ yield measurement

$$\sigma_{e^+e^- \to J/\psi_{prompt} X} = \frac{1}{\mathcal{L}} \times \left(Y_{J/\psi X} - Y_{\psi'_{ISR} \to J/\psi X} - Y_{\psi' \to J/\psi X} - Y_{\chi_c \to \gamma J/\psi} \right)$$

$$Y_{\chi_c \to \gamma J/\psi} = \frac{N^{obs}_{\chi_c X}}{\epsilon_{\chi_c X} \times \mathcal{B}_{J/\psi \to \mu^+ \mu^-}}$$

Selection criteria for $e^+e^- \to \chi_{c1,2}X \to \gamma J/\psi X$

Each selected event must contain one of the following track configuration (according to J/ψ selection criteria described above):

- exactly one positive and one negative reconstructed charged tracks and at least two photons
- exactly two positive and two negative reconstructed charged tracks and at least two photons
- exactly two positive and two negative reconstructed charged tracks, exactly one photon while the charged tracks do not form the ψ' signal via the $J/\psi\pi+\pi-$ final state
- other configurations with more than one positive or more than one negative reconstructed charged tracks and at least one photon

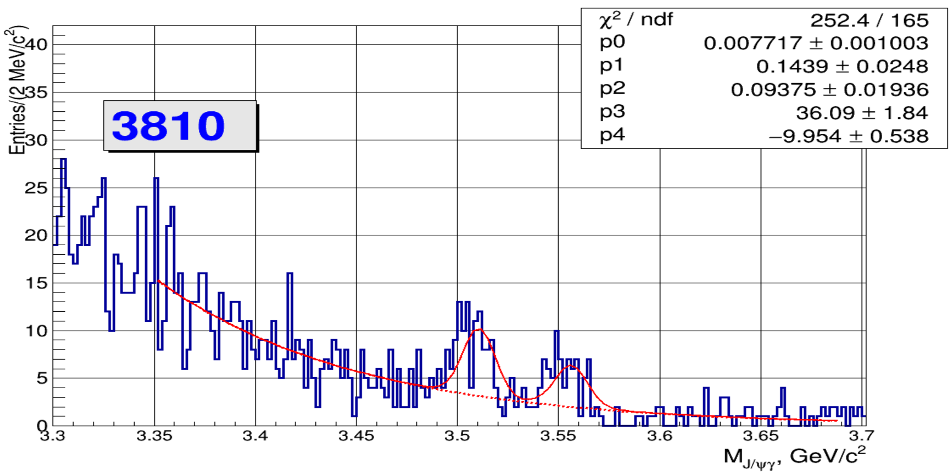
Additionally, 1C kinematic fit to the J/ψ mass:

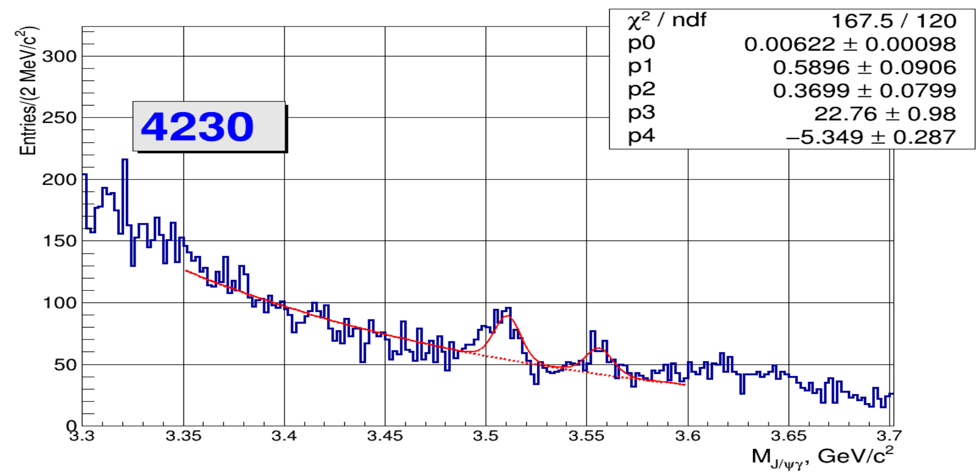
- 3.0 GeV < $M_{\mu^+\mu^-}$ < 3.2 GeV;
- $\mu^+\mu^-$ combination with minimal χ^2;
- $\chi^2_{min} < 50$;

At least two photons for 2-track events and at least one photon for other events:

- EMC: $0 \leq t \leq 14$ ns;
- E > 25 MeV (barrel), E > 50 MeV (end-cups);
- The angle between the neutral track and the nearest charged track > 20˚;

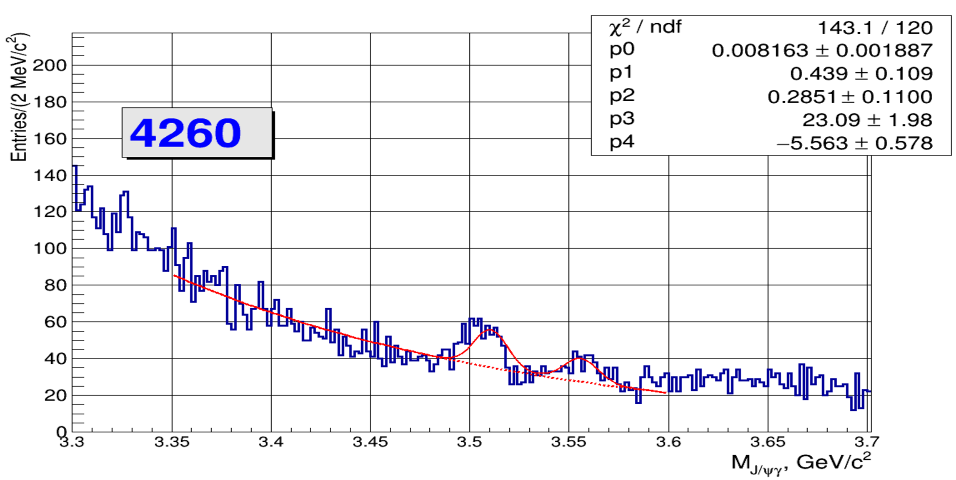
Observed number of $\chi_{c1,2}X$ events

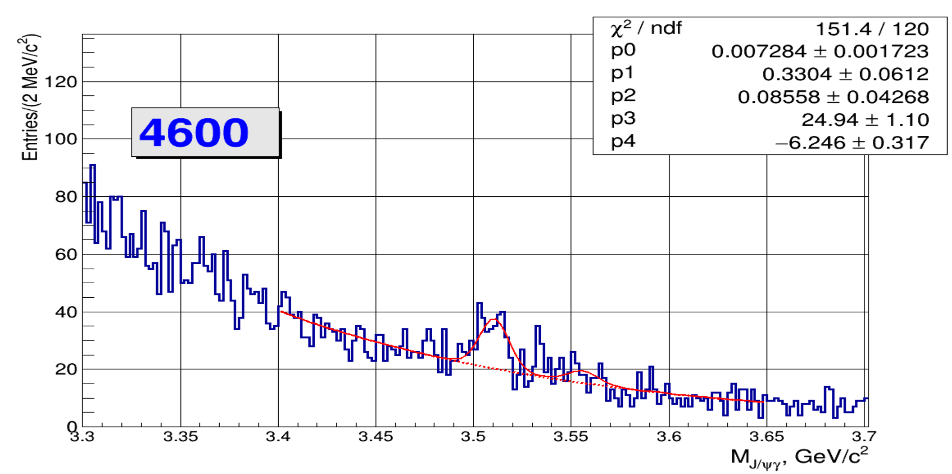




Fit two Breit-Wigner convoluted with a gaussian functions (signal) and an exponential function (background) to the data

Masses and widths of $\chi_{c1,2}$ are fixed parameters.





Observed number of events

ID	$N^{obs}_{e^+e^-\to J/\psi X}$	$N^{bg}_{e^+e^-\to(\gamma_{ISR})J/\psi}$	$N^{obs}_{e^+e^-\to\psi' X}$	$N^{obs}_{e^+e^-\to(\gamma_{ISR})\psi'}$	$N^{obs}_{e^+e^-\to\chi_{c1} X}$	$N^{obs}_{e^+e^-\to\chi_{c2} X}$
3810	1874 ± 49	38 ± 2	56 ± 8	1107 ± 34	71 ± 12	46 ± 9
3900	1109 ± 40	30 ± 1	29 ± 5	651 ± 26	49 ± 10	17 ± 7
4009	7033 ± 113	343 ± 6	228 ± 16	3779 ± 63	297 ± 27	120 ± 19
4090	599 ± 32	27 ± 2	14 ± 4	319 ± 18	34 ± 9	16 ± 7
4190	503 ± 30	19 ± 1	14 ± 5	196 ± 14	17 ± 7	6 ± 6
4210	659 ± 34	23 ± 1	23 ± 6	224 ± 15	3 ± 7	16 ± 8
4220	722 ± 34	21 ± 1	34 ± 7	208 ± 15	6 ± 7	1 ± 7
4230	627 ± 32	19 ± 1	23 ± 6	179 ± 14	32 ± 8	9 ± 6
4230	14983 ± 157	455 ± 6	561 ± 36	4473 ± 69	291 ± 36	179 ± 33
4245	727 ± 35	21 ± 1	16 ± 5	244 ± 16	21 ± 8	8 ± 7
4260	9629 ± 132	421 ± 7	406 ± 34	3208 ± 58	216 ± 31	138 ± 28
4310	493 ± 32	19 ± 1	26 ± 6	135 ± 12	15 ± 7	11 ± 6
4360	5341 ± 101	180 ± 4	507 ± 27	1751 ± 43	178 ± 26	114 ± 21
4390	480 ± 31	17 ± 1	50 ± 9	167 ± 13	29 ± 8	15 ± 6
4420	405 ± 28	15 ± 1	32 ± 7	135 ± 12	15 ± 7	21 ± 7
4420	9147 ± 137	342 ± 5	904 ± 35	3117 ± 57	313 ± 34	190 ± 28
4470	775 ± 44	35 ± 2	48 ± 9	339 ± 19	38 ± 10	24 ± 9
4530	674 ± 42	36 ± 2	39 ± 8	261 ± 16	42 ± 11	9 ± 8
4575	341 ± 28	11 ± 1	19 ± 6	124 ± 11	24 ± 7	4 ± 5
4600	3255 ± 94	144 ± 4	194 ± 19	1214 ± 36	163 ± 27	42 ± 19

Efficiency

- To estimate efficiency we need to produce inclusive Monte Carlo samples of unknown composition.
- We assumed that efficiency mainly depends on topology of events (track multiplicity).
- Thus we decided to produce appropriate Monte Carlo samples as a mixture of major exclusive channels with typical topologies.
- Weights for the mixture we obtain from track multiplicity of the real data .

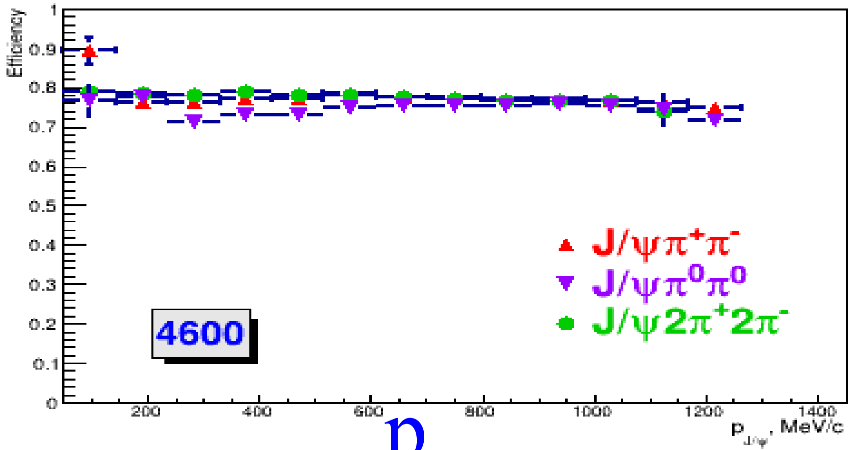
Monte Carlo

- **J/ψ: mix of the major exclusive channels weighted with multiplicity**
  - **MC samples (PHSP, each energy point):** $J/\psi\pi^+\pi^-$, $J/\psi\pi^0\pi^0$, $J/\psi 2\pi^+ 2\pi^-$, where $J/\psi \to \mu^+\mu^-$
- **ψ': mix of the major exclusive channels weighted with multiplicity**
  - **MC samples (PHSP, each energy point):** $\psi'\pi^+\pi^-$, $\psi'\pi^0\pi^0$, where

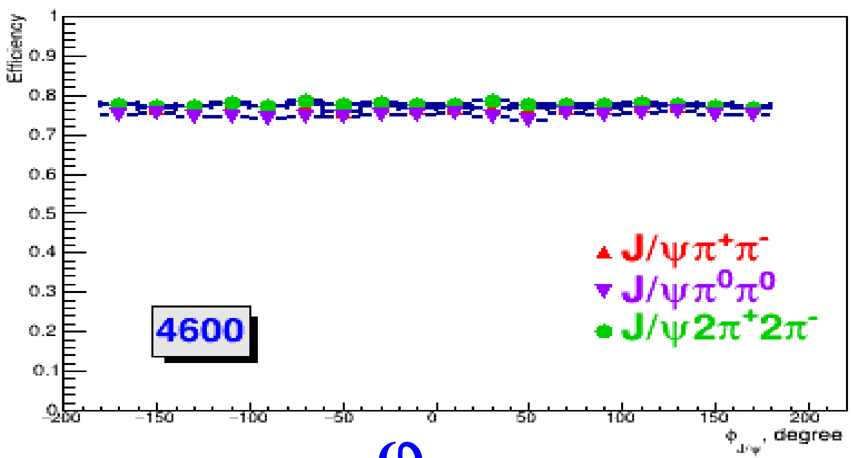
    $\psi' \to J/\psi\pi^+\pi^-$ and $J/\psi \to \mu^+\mu^-$
- **ψ'_{ISR}: one exclusive channel**
  - **MC samples (KKMC, each energy point):** $(\gamma_{ISR})\psi'$, where

    $\psi' \to J/\psi\pi^+\pi^-$ and $J/\psi \to \mu^+\mu^-$
- **$\chi_{c1,2}$: one exclusive three-particle channel**
  - **MC samples (PHSP, each energy point):** $\chi_{c1,2}2\gamma$,

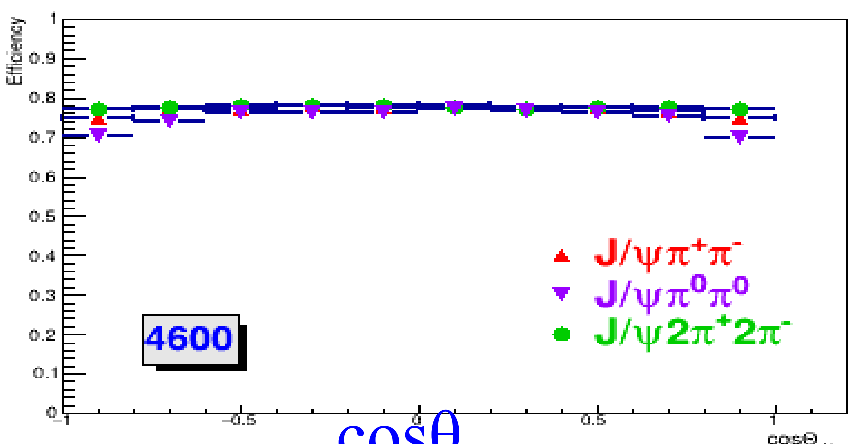
    where $\chi_{c1,2} \to J/\psi\gamma$ and $J/\psi \to \mu^+\mu^-$



$p_{J/\psi}$



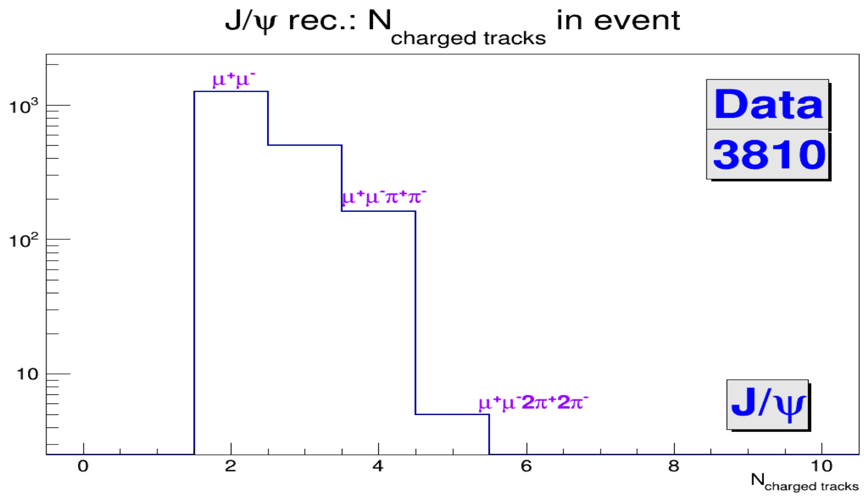
$\varphi_{J/\psi}$

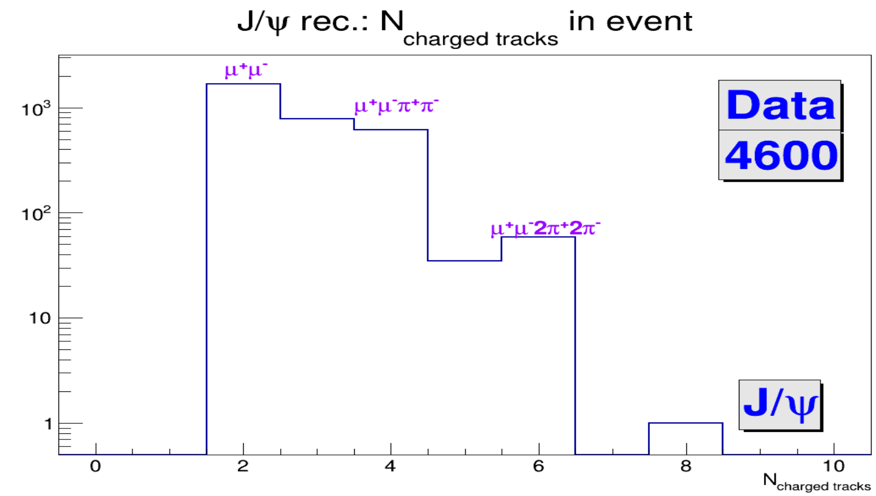


$\cos\theta_{J/\psi}$

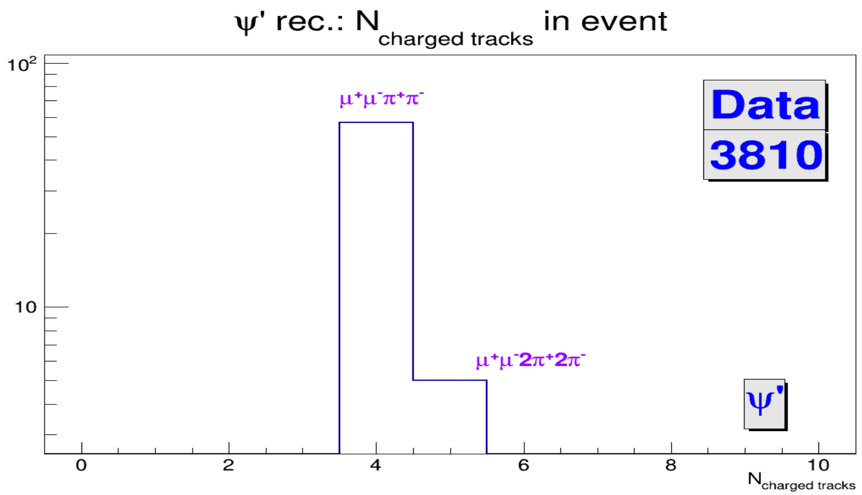
Momentum and angular dependence of J/ψ efficiency

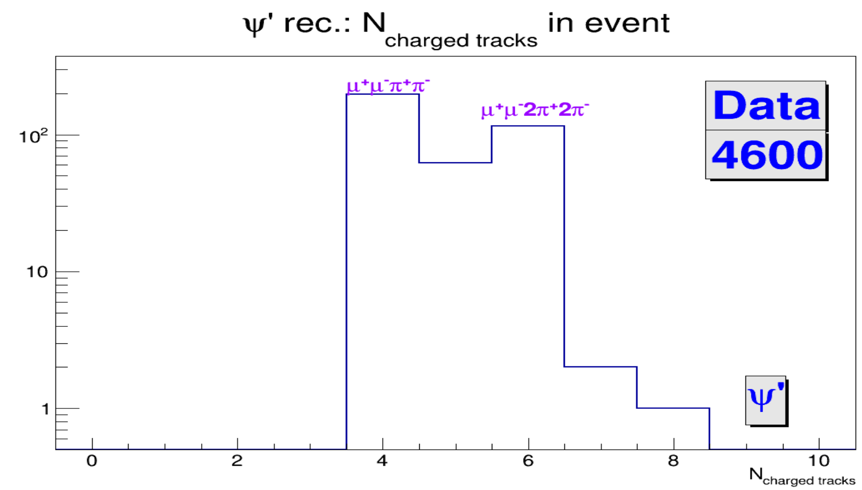
Multiplicity of charged tracks for selected J/ψ and ψ'





Logarithmic scale



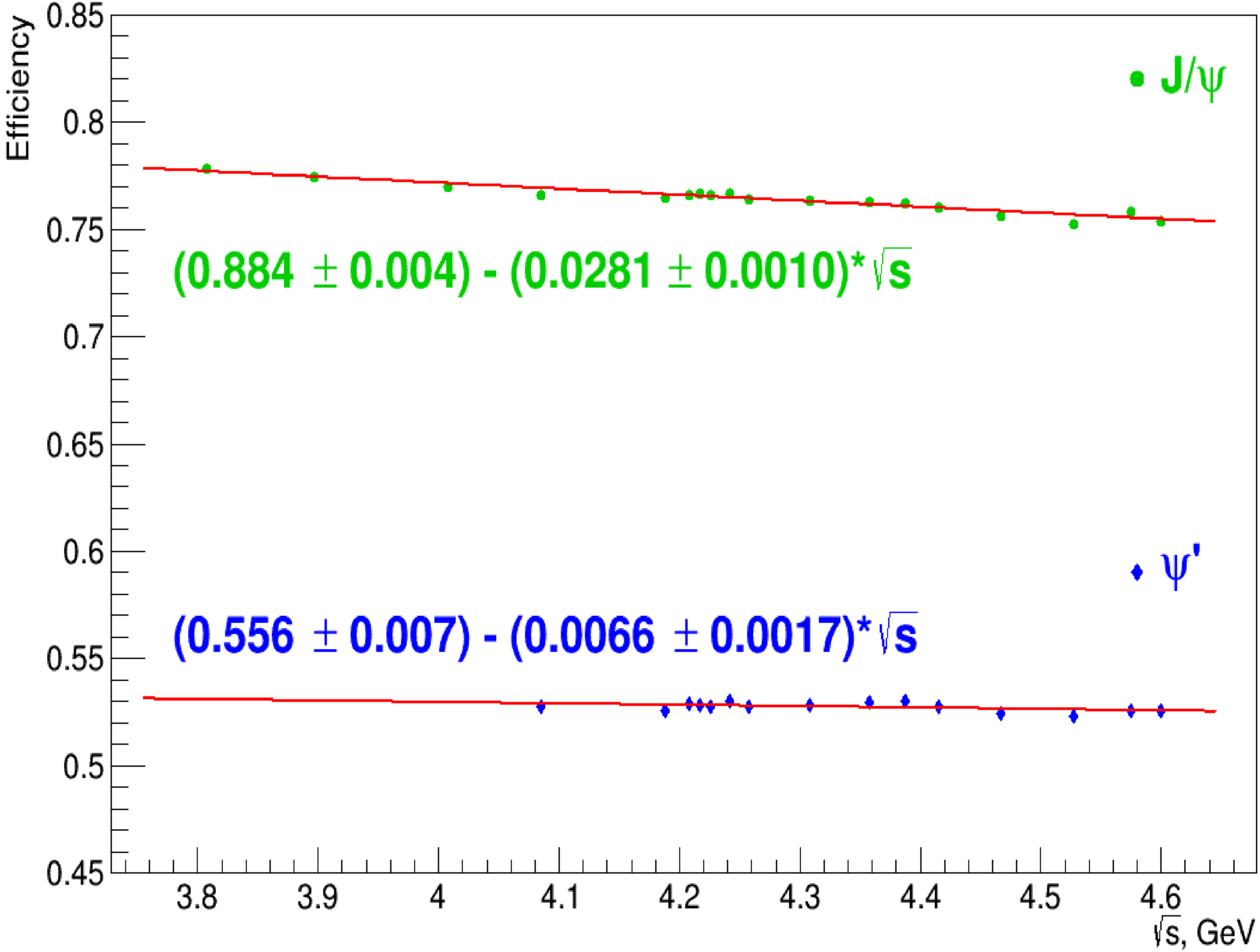


Efficiency of J/ψ reconstruction

ID	$\epsilon_{J/\psi\pi^0\pi^0}$, %	N_{2track}	$\epsilon_{J/\psi\pi^+\pi^-}$, %	N_{4track}	$\epsilon_{J/\psi 2\pi^+ 2\pi^-}$, %	N_{6track}	$\bar{\epsilon}_{e^+e^-\to J/\psi X}$, %
3810	77.79 ± 0.11	1266	78.22 ± 0.11	160	78.13 ± 0.11	0	77.84 ± 0.10
3900	77.36 ± 0.11	735	78.17 ± 0.11	102	79.23 ± 0.10	0	77.45 ± 0.10
4009	76.82 ± 0.11	4469	77.98 ± 0.11	805	76.45 ± 0.11	9	77.00 ± 0.09
4090	76.41 ± 0.11	411	77.86 ± 0.11	60	76.73 ± 0.11	3	76.60 ± 0.10
4190	76.10 ± 0.11	295	77.76 ± 0.11	75	77.54 ± 0.11	7	76.45 ± 0.09
4210	76.02 ± 0.11	363	77.85 ± 0.11	152	77.79 ± 0.11	5	76.57 ± 0.08
4220	76.06 ± 0.11	366	77.81 ± 0.11	178	77.62 ± 0.11	11	76.65 ± 0.08
4230	76.03 ± 0.11	7662	77.64 ± 0.11	3983	77.62 ± 0.11	174	76.60 ± 0.08
4245	75.95 ± 0.11	356	77.83 ± 0.11	211	77.86 ± 0.11	2	76.65 ± 0.08
4260	75.81 ± 0.11	4941	77.60 ± 0.11	2246	77.75 ± 0.11	128	76.40 ± 0.08
4310	75.67 ± 0.11	250	77.60 ± 0.11	133	77.65 ± 0.11	8	76.36 ± 0.08
4360	75.52 ± 0.11	2502	77.49 ± 0.11	1153	78.06 ± 0.11	257	76.27 ± 0.08
4390	75.45 ± 0.11	254	77.50 ± 0.11	129	78.05 ± 0.11	20	76.23 ± 0.08
4420	75.24 ± 0.11	4425	77.35 ± 0.11	1978	77.88 ± 0.11	416	76.01 ± 0.08
4470	75.06 ± 0.11	408	77.11 ± 0.11	145	77.77 ± 0.11	7	75.62 ± 0.09
4530	74.87 ± 0.11	419	76.95 ± 0.11	79	77.67 ± 0.11	14	75.27 ± 0.09
4575	74.85 ± 0.11	131	77.02 ± 0.11	83	77.71 ± 0.11	14	75.82 ± 0.08
4600	74.76 ± 0.11	1704	76.92 ± 0.11	576	77.66 ± 0.11	55	75.36 ± 0.09

Efficiency of ψ' reconstruction

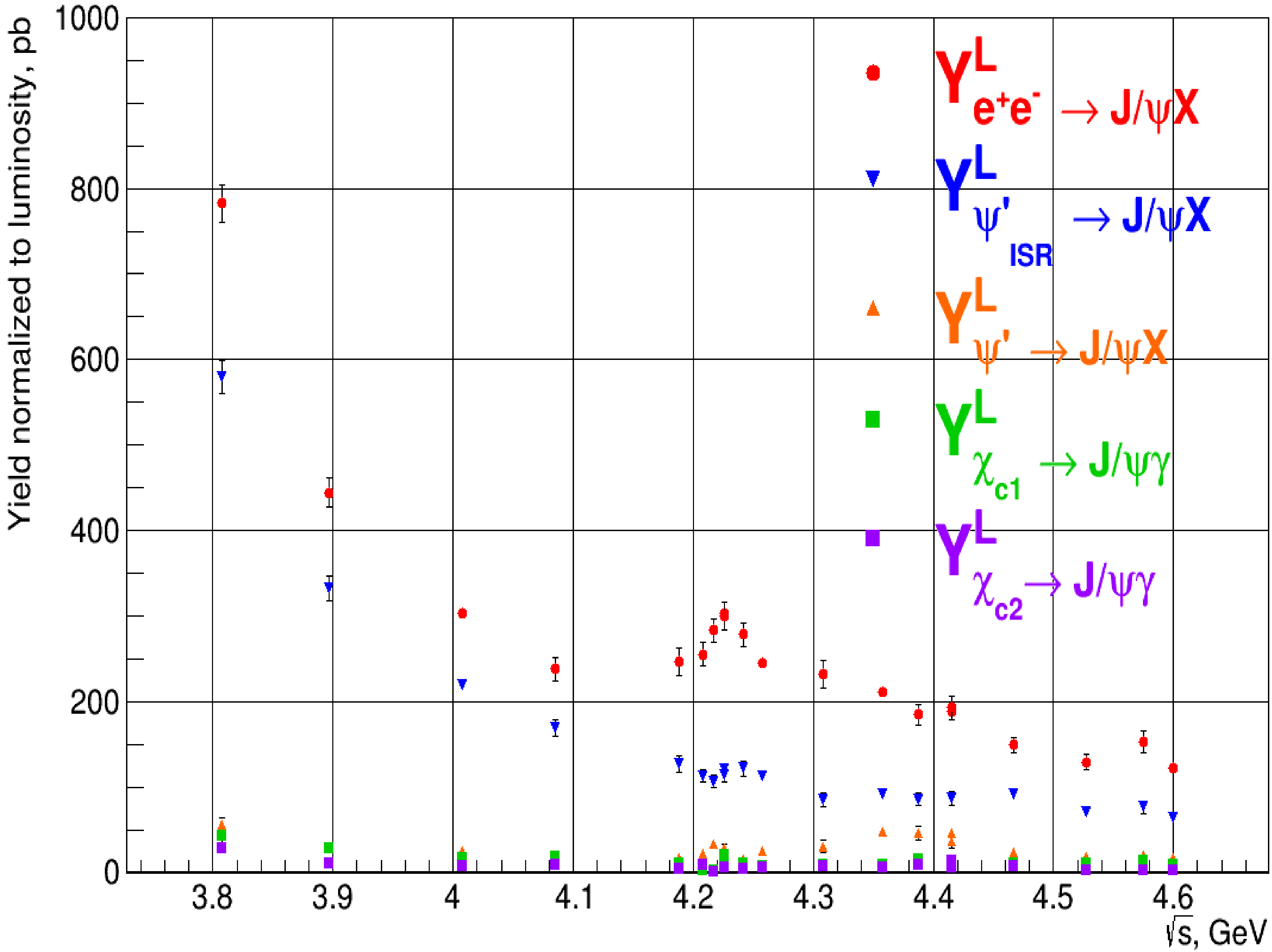
ID	$\epsilon_{\psi'\pi^0\pi^0}$, %	N_{4track}	$\epsilon_{\psi'\pi^+\pi^-}$, %	N_{6track}	$\bar{\epsilon}_{e^+e^-\to\psi' X}$, %
4090	52.73 ± 0.13	14	48.96 ± 0.13	0	52.73 ± 0.13
4190	53.01 ± 0.13	15	51.11 ± 0.13	5	52.54 ± 0.10
4210	53.27 ± 0.13	19	51.67 ± 0.13	6	52.88 ± 0.10
4220	53.49 ± 0.13	23	51.61 ± 0.13	13	52.81 ± 0.09
4230	53.25 ± 0.13	475	51.50 ± 0.13	195	52.74 ± 0.10
4245	53.23 ± 0.13	13	51.94 ± 0.13	3	53.04 ± 0.11
4260	53.19 ± 0.13	384	51.64 ± 0.13	154	52.75 ± 0.10
4310	53.19 ± 0.13	25	51.92 ± 0.13	11	52.80 ± 0.10
4360	53.42 ± 0.13	281	52.47 ± 0.13	278	52.95 ± 0.09
4390	53.33 ± 0.13	37	52.54 ± 0.13	24	53.02 ± 0.09
4420	53.00 ± 0.13	565	52.48 ± 0.13	467	52.76 ± 0.09
4470	52.61 ± 0.13	40	52.04 ± 0.13	16	52.44 ± 0.10
4530	52.48 ± 0.13	28	52.16 ± 0.13	25	52.33 ± 0.09
4575	52.65 ± 0.13	19	52.33 ± 0.13	11	52.53 ± 0.09
4600	52.60 ± 0.13	211	52.54 ± 0.13	120	52.58 ± 0.09


Efficiency
J/ψ
(0.884 ± 0.004) - (0.0281 ± 0.0010)* √s
ψ'
(0.556 ± 0.007) - (0.0066 ± 0.0017)* √s
√s, GeV

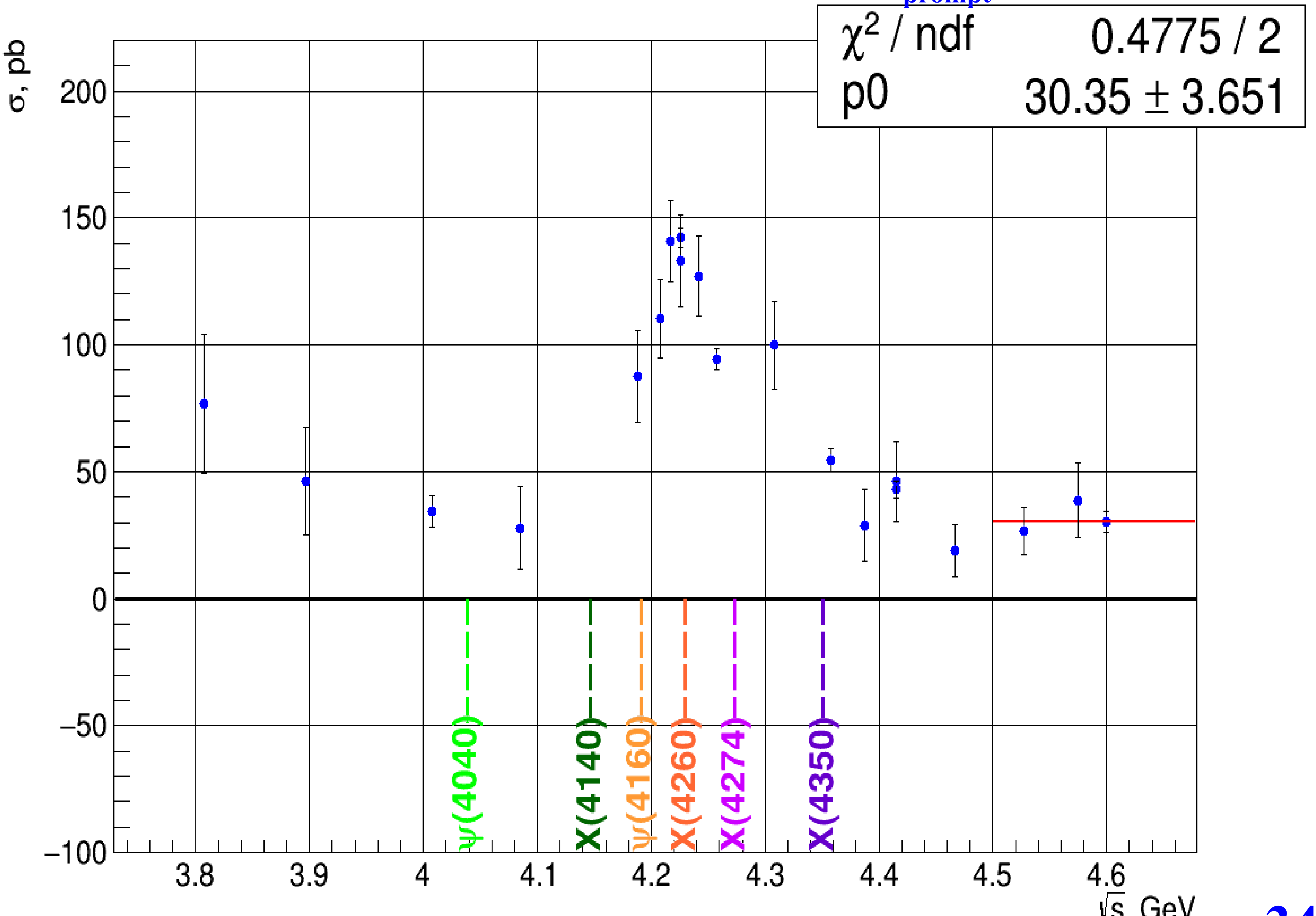
MC-based estimated efficiency

ID	$\bar{\epsilon}_{e^+e^-\to J/\psi X}$, %	$\bar{\epsilon}_{e^+e^-\to \psi' X}$, %	$\epsilon_{e^+e^-\to (\gamma_{ISR})\psi'}$, %	$\epsilon_{e^+e^-\to \chi_{c1} X}$, %	$\epsilon_{e^+e^-\to \chi_{c2} X}$, %
3810	77.84 ± 0.10	53.09 ± 0.95	50.71 ± 0.13	55.84 ± 0.13	53.05 ± 0.13
3900	77.45 ± 0.10	53.03 ± 0.96	50.35 ± 0.13	56.18 ± 0.13	53.58 ± 0.13
4009	77.00 ± 0.09	52.96 ± 0.98	49.37 ± 0.13	59.30 ± 0.13	54.50 ± 0.13
4090	76.60 ± 0.10	52.73 ± 0.13	49.39 ± 0.13	60.12 ± 0.13	55.94 ± 0.13
4190	76.45 ± 0.09	52.54 ± 0.10	49.28 ± 0.13	60.15 ± 0.13	57.13 ± 0.13
4210	76.57 ± 0.08	52.88 ± 0.10	49.67 ± 0.13	60.01 ± 0.13	57.36 ± 0.13
4220	76.65 ± 0.08	52.81 ± 0.09	49.63 ± 0.13	59.99 ± 0.13	57.34 ± 0.13
4230	76.60 ± 0.08	52.74 ± 0.10	48.98 ± 0.13	59.98 ± 0.13	57.69 ± 0.13
4230	76.60 ± 0.08	52.74 ± 0.10	48.98 ± 0.13	59.98 ± 0.13	57.69 ± 0.13
4245	76.65 ± 0.08	53.04 ± 0.11	49.66 ± 0.13	59.79 ± 0.13	57.49 ± 0.13
4260	76.40 ± 0.08	52.75 ± 0.10	48.36 ± 0.13	59.68 ± 0.13	57.49 ± 0.13
4310	76.36 ± 0.08	52.80 ± 0.10	48.96 ± 0.13	59.09 ± 0.13	57.39 ± 0.13
4360	76.27 ± 0.08	52.95 ± 0.09	49.03 ± 0.13	58.68 ± 0.13	56.96 ± 0.13
4390	76.23 ± 0.08	53.02 ± 0.09	49.16 ± 0.13	58.48 ± 0.13	56.94 ± 0.13
4420	76.01 ± 0.08	52.76 ± 0.09	48.84 ± 0.13	58.37 ± 0.13	56.82 ± 0.13
4420	76.01 ± 0.08	52.76 ± 0.09	48.84 ± 0.13	58.37 ± 0.13	56.82 ± 0.13
4470	75.62 ± 0.09	52.44 ± 0.10	47.94 ± 0.13	58.35 ± 0.13	56.12 ± 0.13
4530	75.27 ± 0.09	52.33 ± 0.09	47.64 ± 0.13	58.22 ± 0.13	55.83 ± 0.13
4575	75.82 ± 0.08	52.53 ± 0.09	48.11 ± 0.13	57.81 ± 0.13	55.66 ± 0.13
4600	75.36 ± 0.09	52.58 ± 0.09	47.84 ± 0.13	57.88 ± 0.13	55.70 ± 0.13

Yield of J/ψ from different sources normalized to corresponding luminosity



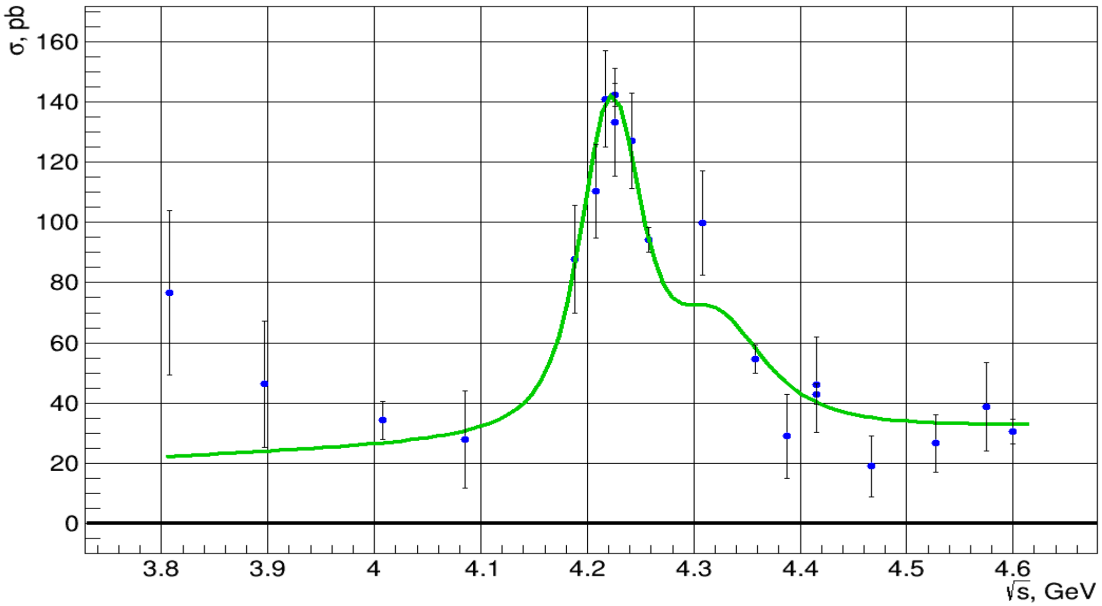
Observed cross-section of e+e- → J/ψ_{prompt} + X



Deconvolution to Born cross-section

$$\sigma^{obs} = (1+\delta) * \sigma_{fit}^{Born} = \int \sigma_{fit}^{Born}(s(1-x))F(x,s)dx$$

The cross-section line shape for iteration process is obtained by fitting two Breit-Wigner convoluted with a gaussian functions for resonances and const*$\sqrt{(\sqrt{s} - M_{J/\psi})}$ for continuum to the measured cross-section

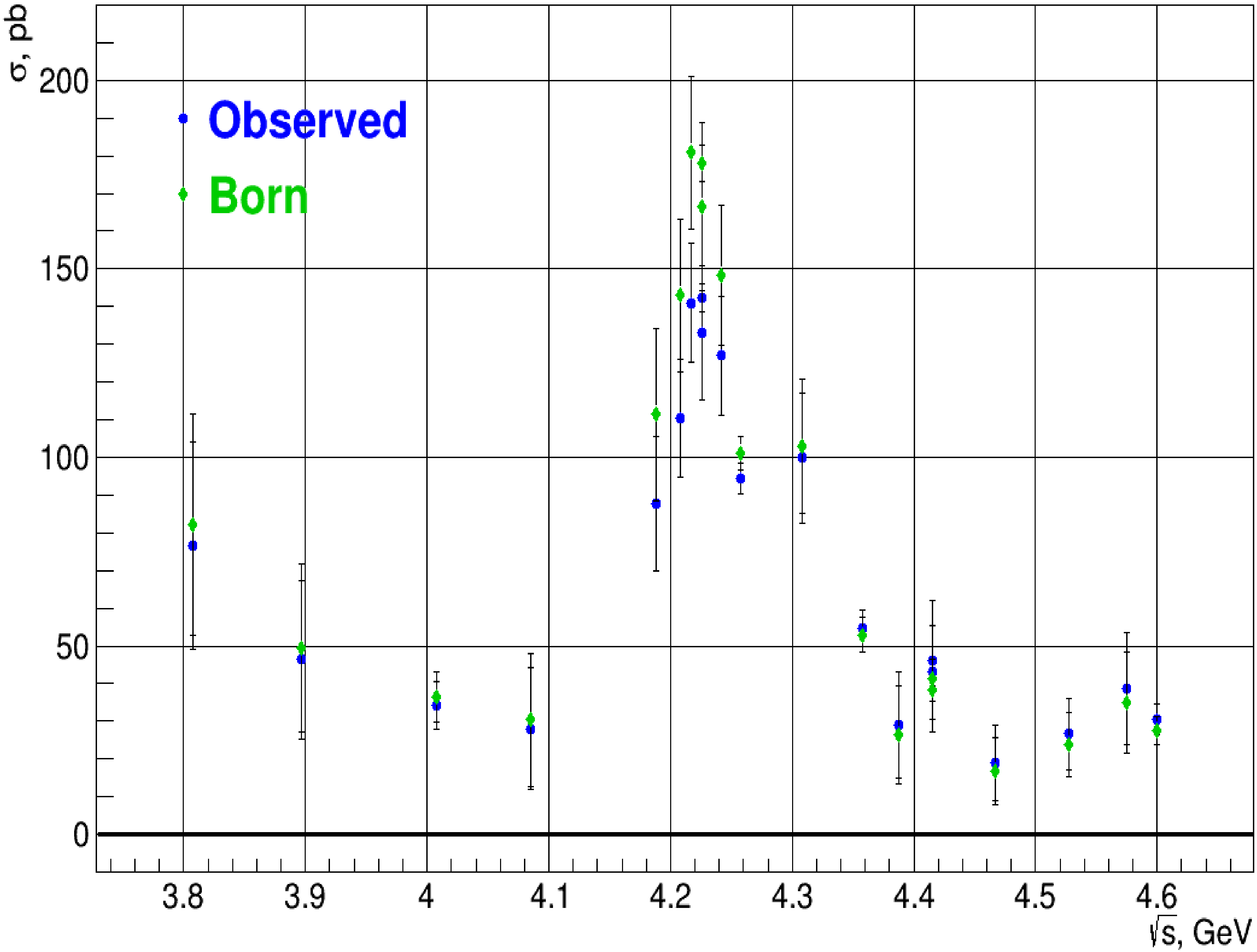


Masses and **widths** of the resonances are fixed parameters, and its values are taken from **BESIII e+e- → J/ψπ+π- paper** (arXiv:1611.01317v1 [hep-ex] 4 Nov 2016)**:**

M_1 = 4222.0 ± 3.1 MeV/c², Γ_1 = 44.1 ± 4.3 MeV

M_2 = 4320.0 ± 10.4 MeV/c², Γ_2 = 101.4 ± 25.3 MeV

Observed and Born cross-section of e+e- $\rightarrow J/\psi_{prompt} + X$



Observed and Born cross-section (statistical errors only)

ID	E_{cms}, MeV	$\mathcal{L}_{int}, pb^{-1}$	σ^{obs}	$(1+\delta)$	σ^{Born}
3810	3.80765	50.54	76.62 ± 27.37	0.933	82.10 ± 29.33
3900	3.89624	52.61	46.36 ± 20.99	0.937	49.46 ± 22.39
4009	4.00762	481.96	34.21 ± 6.21	0.936	36.56 ± 6.64
4090	4.08545	52.63	27.95 ± 16.17	0.921	30.36 ± 17.56
4190	4.18859	43.09	87.71 ± 17.90	0.788	111.32 ± 22.71
4210	4.20773	54.55	110.32 ± 15.58	0.771	143.00 ± 20.20
4220	4.21713	54.13	141.01 ± 15.91	0.780	180.80 ± 20.39
4230	4.22626	44.40	133.17 ± 17.87	0.800	166.56 ± 22.36
4230	4.22626	1047.34	142.33 ± 3.78	0.800	178.02 ± 4.73
4245	4.24166	55.59	127.06 ± 15.81	0.857	148.28 ± 18.45
4260	4.25797	825.67	94.29 ± 4.06	0.933	101.10 ± 4.35
4310	4.30789	44.90	99.85 ± 17.25	0.969	103.08 ± 17.80
4360	4.35826	539.84	54.59 ± 4.72	1.031	52.95 ± 4.58
4390	4.3874	55.18	28.92 ± 14.08	1.090	26.53 ± 12.92
4420	4.41558	44.67	46.22 ± 15.84	1.122	41.21 ± 14.12
4420	4.41558	1028.89	42.99 ± 3.38	1.122	38.32 ± 3.01
4470	4.46706	109.94	18.96 ± 10.15	1.132	16.75 ± 8.96
4530	4.52714	109.98	26.63 ± 9.45	1.120	23.78 ± 8.44
4575	4.5745	47.67	38.75 ± 14.79	1.107	34.99 ± 13.36
4600	4.59953	566.93	30.41 ± 4.11	1.101	27.62 ± 3.73

Study of systematics : Tracking

- Due to the discrepancy between MC and data is 1% for charged track reconstructed efficiency and 1% for photon reconstructed efficiency we performed the following variations of reconstructed efficiencies to obtain systematic errors of tracking:

$\varepsilon_{J/\psi}$: **2%** variation

$\varepsilon_{\psi'} = \varepsilon_{J/\psi} * \varepsilon_{\pi\pi} = \varepsilon_{J/\psi} * (\varepsilon_{\pi})^2$: **2%** variation

$\varepsilon_{\chi c1,2} = \varepsilon_{J/\psi} * \varepsilon_{\gamma}$: **1%** variation

- Errors of charged tracking were summed linearly, errors of photon tracking were also summed linearly, then resulting contributions were summed quadratically.

Study of systematics : Tracking

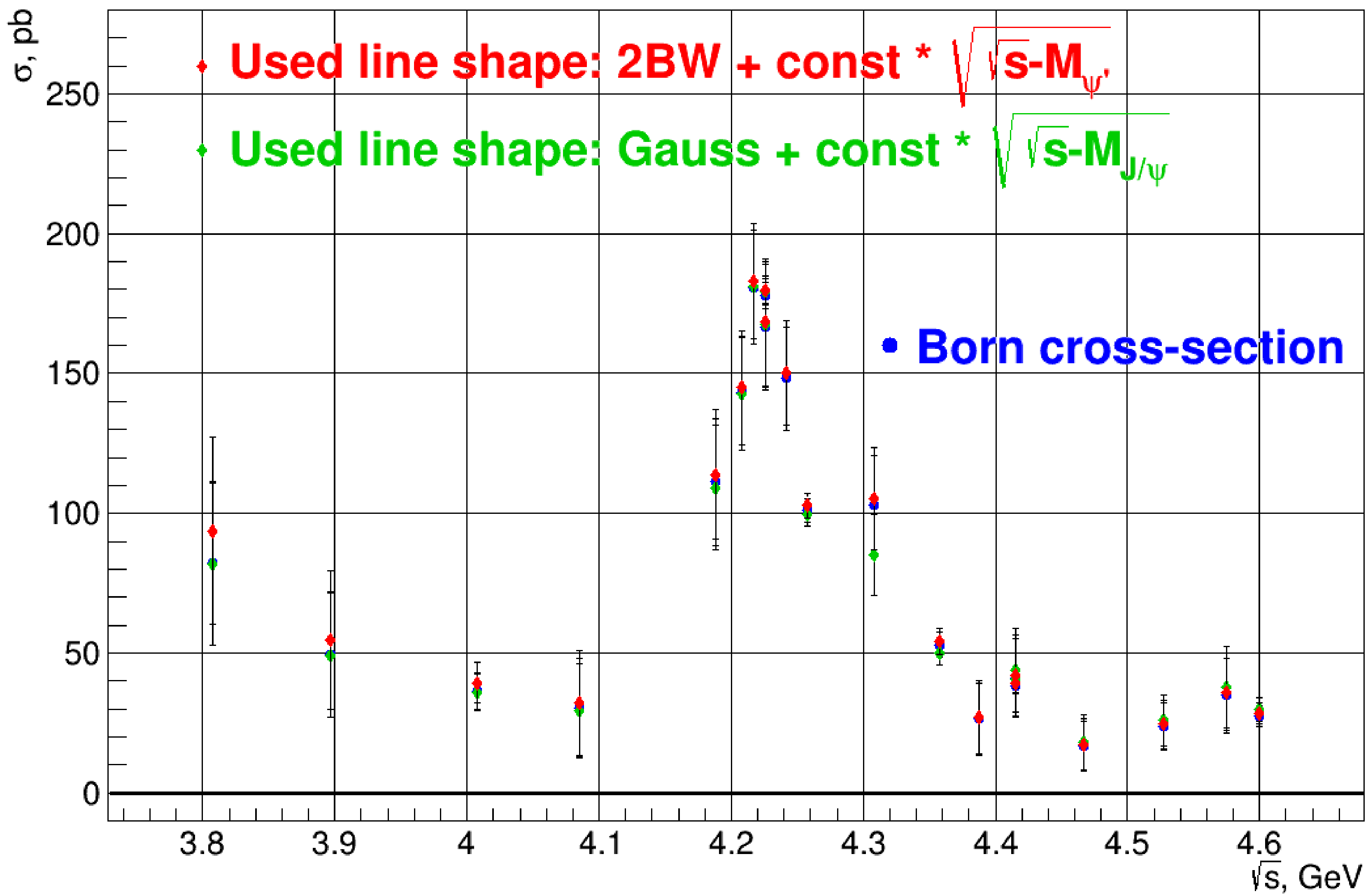
ID	$\mathcal{L}_{int}, pb^{-1}$	σ^{obs}	$\Delta_{\sigma(\epsilon_{J/\psi})}, pb$	$\Delta_{\sigma(\epsilon_{\psi' ISR})}, pb$	$\Delta_{\sigma(\epsilon_{\psi'})}, pb$	$\Delta_{\sigma(\epsilon_{\chi_{c1}})}, pb$	$\Delta_{\sigma(\epsilon_{\chi_{c2}})}, pb$
3810	50.54	76.62 ± 27.37	10.39	23.51	1.13	0.42	0.28
3900	52.61	46.36 ± 20.99	5.81	13.38	0.56	0.28	0.10
4009	481.96	34.21 ± 6.21	3.59	8.65	0.49	0.17	0.08
4090	52.63	27.95 ± 16.17	2.74	6.68	0.28	0.18	0.09
4190	43.09	87.71 ± 17.90	0.72	5.02	0.33	0.11	0.04
4210	54.55	110.32 ± 15.58	0.03	4.50	0.43	0.02	0.09
4220	54.13	141.01 ± 15.91	0.72	4.23	0.65	0.03	0.01
4230	44.40	133.17 ± 17.87	0.47	4.48	0.53	0.20	0.06
4230	1047.34	142.33 ± 3.78	0.52	4.75	0.55	0.08	0.05
4245	55.59	127.06 ± 15.81	0.15	4.82	0.30	0.11	0.04
4260	825.67	94.29 ± 4.06	0.23	4.38	0.51	0.07	0.05
4310	44.90	99.85 ± 17.25	0.36	3.34	0.60	0.09	0.07
4360	539.84	54.59 ± 4.72	0.67	3.60	0.97	0.09	0.06
4390	55.18	28.92 ± 14.08	1.07	3.36	0.93	0.15	0.08
4420	44.67	46.22 ± 15.84	0.73	3.38	0.73	0.09	0.14
4420	1028.89	42.99 ± 3.38	0.79	3.38	0.91	0.09	0.05
4470	109.94	18.96 ± 10.15	1.30	3.50	0.45	0.10	0.07
4530	109.98	26.63 ± 9.45	0.76	2.71	0.37	0.11	0.02
4575	47.67	38.75 ± 14.79	0.64	2.94	0.42	0.14	0.03
4600	566.93	30.41 ± 4.11	0.56	2.44	0.35	0.08	0.02

Study of systematics : E_{emc} cut, $N_{J/\psi}$ fit

- To decrease statistical fluctuations we combined the data into 3 groups (3810-4090, 4190-4310, 4360-4600) and we obtained relative systematic errors of the following sources:
  - E_{emc} cut: the value was varied as 0.5 GeV
  - $N_{J/\psi}$: fit a cubic polynomial to the data for background

- Using relative systematic errors we obtained absolute systematic errors for each energy point in corresponding group

Study of systematics: Deconvolution to Born cross-section procedure



Study of systematics : E_{emc} cut, $N_{J/\psi}$ fit

ID	$\mathcal{L}_{int}, pb^{-1}$	σ^{obs}	$\Delta_{\sigma(E_{emc})}, pb$	$\Delta_{\sigma(N_{J/\psi})}, pb$	$\Delta_{\sigma(ISRcor.)}, pb$
3810	50.54	76.62 ± 27.37	4.20	3.05	11.55
3900	52.61	46.36 ± 20.99	2.54	1.84	5.11
4009	481.96	34.21 ± 6.21	1.87	1.36	2.81
4090	52.63	27.95 ± 16.17	1.53	1.11	1.88
4190	43.09	87.71 ± 17.90	0.61	0.11	2.55
4210	54.55	110.32 ± 15.58	0.77	0.14	1.94
4220	54.13	141.01 ± 15.91	0.99	0.18	2.06
4230	44.40	133.17 ± 17.87	0.93	0.17	1.80
4230	1047.34	142.33 ± 3.78	1.00	0.19	1.93
4245	55.59	127.06 ± 15.81	0.89	0.17	1.98
4260	825.67	94.29 ± 4.06	0.66	0.12	1.60
4310	44.90	99.85 ± 17.25	0.70	0.13	17.92
4360	539.84	54.59 ± 4.72	0.09	1.51	3.01
4390	55.18	28.92 ± 14.08	0.05	0.80	0.61
4420	44.67	46.22 ± 15.84	0.07	1.28	2.56
4420	1028.89	42.99 ± 3.38	0.07	1.19	2.38
4470	109.94	18.96 ± 10.15	0.03	0.53	1.51
4530	109.98	26.63 ± 9.45	0.04	0.74	2.14
4575	47.67	38.75 ± 14.79	0.06	1.07	2.94
4600	566.93	30.41 ± 4.11	0.05	0.84	2.22

Study of systematics : Luminosity, BF

- **Luminosity:** total errors of luminosity measurement were took into account to obtain systematic error for each energy point

Ref.: M. Ablikim et al. "Precision measurement of the integrated luminosity of the data taken by BESIII at center of mass energies between 3.810 GeV and 4.600 GeV", arXiv:1503.03408 [hep-ex] 11 Mar 2015

- **Branching fractions:** errors of branching fractions of all charmonia decays used in the analysis were took into account to obtain systematic error for each energy point

Ref.: Tanabashi et al. (Particle Data Group), Phys. Rev. D 98, 030001 (2018)

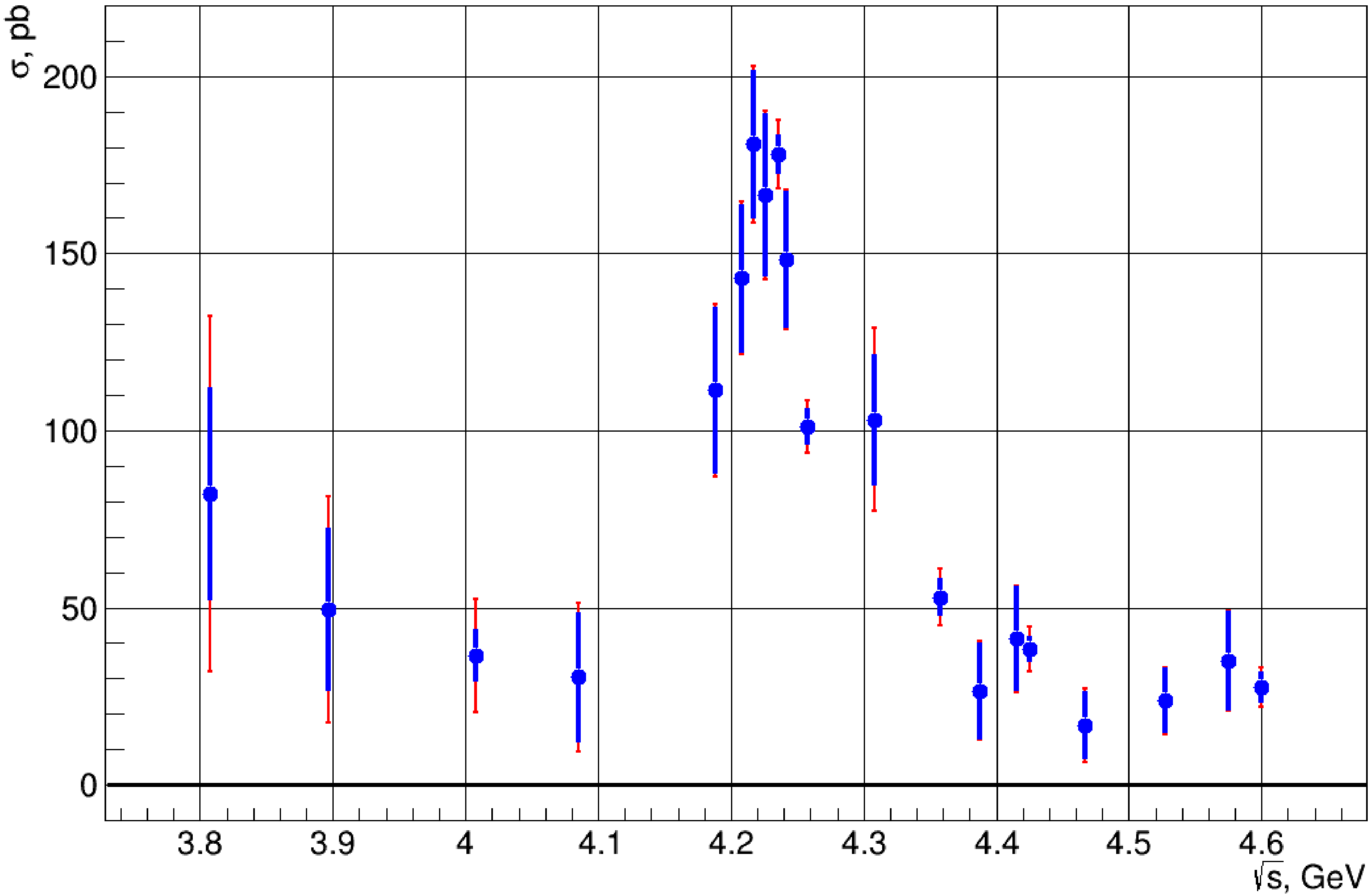
Study of systematics : Luminosity, BF

ID	$\mathcal{L}_{int}, pb^{-1}$	σ^{obs}	$\Delta_{\sigma(\mathcal{L}_{int})}, pb$	$\Delta_{\sigma(\mathcal{B}_{J/\psi\to\mu^+\mu^-})}, pb$	$\Delta_{\sigma(\mathcal{B}_{\psi'\to J/\psi\pi^+\pi^-})}, pb$	$\Delta_{\sigma(\tilde{\mathcal{B}}_{\psi'\to J/\psi X})}, pb$
3810	50.54	76.62 ± 27.37	0.74	0.42	5.50	6.97
3900	52.61	46.36 ± 20.99	0.45	0.26	3.11	3.94
4009	481.96	34.21 ± 6.21	0.33	0.19	2.10	2.66
4090	52.63	27.95 ± 16.17	0.27	0.15	1.58	2.01
4190	43.09	87.71 ± 17.90	0.85	0.49	1.25	1.58
4210	54.55	110.32 ± 15.58	1.07	0.61	1.16	1.47
4220	54.13	141.01 ± 15.91	1.37	0.78	1.20	1.52
4230	44.40	133.17 ± 17.87	1.29	0.74	1.22	1.54
4230	1047.34	142.33 ± 3.78	1.38	0.79	1.29	1.63
4245	55.59	127.06 ± 15.81	1.24	0.70	1.18	1.49
4260	825.67	94.29 ± 4.06	0.91	0.52	1.20	1.52
4310	44.90	99.85 ± 17.25	0.97	0.55	1.00	1.26
4360	539.84	54.59 ± 4.72	0.53	0.30	1.21	1.53
4390	55.18	28.92 ± 14.08	0.28	0.16	1.14	1.45
4420	44.67	46.22 ± 15.84	0.45	0.26	1.06	1.35
4420	1028.89	42.99 ± 3.38	0.42	0.24	1.14	1.44
4470	109.94	18.96 ± 10.15	0.18	0.10	0.99	1.25
4530	109.98	26.63 ± 9.45	0.26	0.15	0.77	0.98
4575	47.67	38.75 ± 14.79	0.38	0.21	0.84	1.06
4600	566.93	30.41 ± 4.11	0.30	0.17	0.70	0.89

Observed and Born cross-section

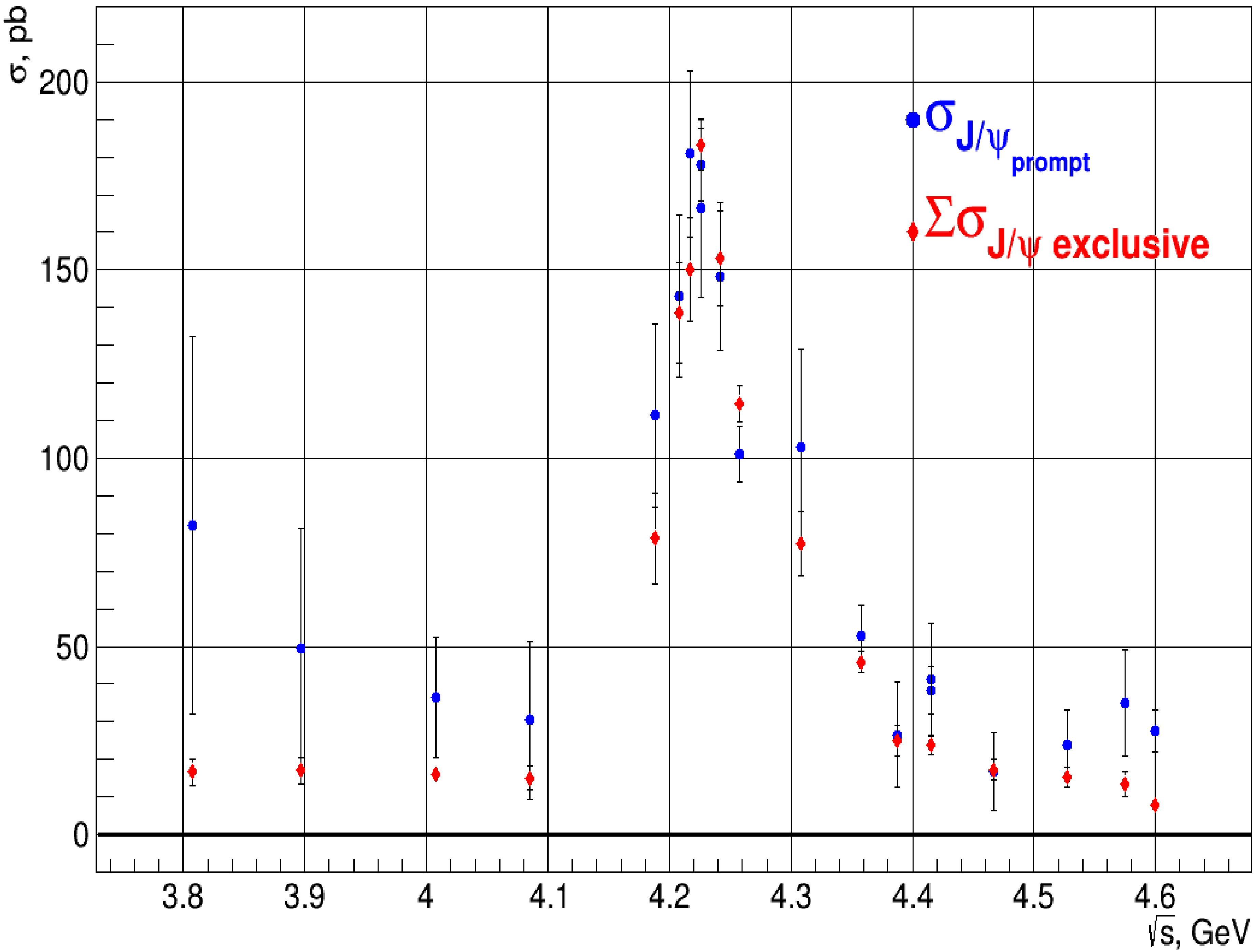
ID	E_{cms}, MeV	$\mathcal{L}_{int}, pb^{-1}$	σ^{obs}	$(1+\delta)$	σ^{Born}
3810	3.80765	50.54	$76.62 \pm 27.37 \pm 36.53$	0.933	$82.10 \pm 29.33 \pm 40.81$
3900	3.89624	52.61	$46.36 \pm 20.99 \pm 20.63$	0.937	$49.46 \pm 22.39 \pm 22.59$
4009	4.00762	481.96	$34.21 \pm 6.21 \pm 13.37$	0.936	$36.56 \pm 6.64 \pm 14.56$
4090	4.08545	52.63	$27.95 \pm 16.17 \pm 10.22$	0.921	$30.36 \pm 17.56 \pm 11.26$
4190	4.18859	43.09	$87.71 \pm 17.90 \pm 6.50$	0.788	$111.32 \pm 22.71 \pm 8.63$
4210	4.20773	54.55	$110.32 \pm 15.58 \pm 5.49$	0.771	$143.00 \pm 20.20 \pm 7.38$
4220	4.21713	54.13	$141.01 \pm 15.91 \pm 6.22$	0.780	$180.80 \pm 20.39 \pm 8.24$
4230	4.22626	44.40	$133.17 \pm 17.87 \pm 6.09$	0.800	$166.56 \pm 22.36 \pm 7.83$
4230	4.22626	1047.34	$142.33 \pm 3.78 \pm 6.46$	0.800	$178.02 \pm 4.73 \pm 8.31$
4245	4.24166	55.59	$127.06 \pm 15.81 \pm 5.85$	0.857	$148.28 \pm 18.45 \pm 7.10$
4260	4.25797	825.67	$94.29 \pm 4.06 \pm 5.61$	0.933	$101.10 \pm 4.35 \pm 6.22$
4310	4.30789	44.90	$99.85 \pm 17.25 \pm 4.78$	0.969	$103.08 \pm 17.80 \pm 18.59$
4360	4.35826	539.84	$54.59 \pm 4.72 \pm 5.83$	1.031	$52.95 \pm 4.58 \pm 6.41$
4390	4.3874	55.18	$28.92 \pm 14.08 \pm 5.74$	1.090	$26.53 \pm 12.92 \pm 5.30$
4420	4.41558	44.67	$46.22 \pm 15.84 \pm 5.32$	1.122	$41.21 \pm 14.12 \pm 5.39$
4420	4.41558	1028.89	$42.99 \pm 3.38 \pm 5.55$	1.122	$38.32 \pm 3.01 \pm 5.49$
4470	4.46706	109.94	$18.96 \pm 10.15 \pm 5.53$	1.132	$16.75 \pm 8.96 \pm 5.11$
4530	4.52714	109.98	$26.63 \pm 9.45 \pm 4.11$	1.120	$23.78 \pm 8.44 \pm 4.25$
4575	4.5745	47.67	$38.75 \pm 14.79 \pm 4.38$	1.107	$34.99 \pm 13.36 \pm 4.93$
4600	4.59953	566.93	$30.41 \pm 4.11 \pm 3.65$	1.101	$27.62 \pm 3.73 \pm 3.99$

Born cross-section with statistical and total errors



Cross-section of exclusive processes with J/ψ

ID	$\pi^+\pi^- J/\psi$	$\pi^0\pi^0 J/\psi$	$K^+K^- J/\psi$	$K^0K^0 J/\psi$	$\eta J/\psi$	$\eta' J/\psi$
3810	$16.7 \pm 3.3 \pm 1$	–	–	–	–	–
3900	$17.1 \pm 3.4 \pm 1$	–	–	–	–	–
4009	$16 \pm 1.1 \pm 1$	–	–	–	–	–
4090	$15 \pm 3.1 \pm 0.9$	–	–	–	–	–
4190	$15.5 \pm 3.8 \pm 0.9$	$9 \pm 3.3 \pm 0.6$	–	–	$50.8 \pm 10.2 \pm 2.1$	–
4210	$53.4 \pm 5.4 \pm 3.1$	$22.7 \pm 4.6 \pm 1.5$	–	–	$57.8 \pm 9.6 \pm 3.2$	–
4220	$60.3 \pm 5.7 \pm 3.5$	$27.4 \pm 4.9 \pm 1.8$	–	–	$57.7 \pm 9.7 \pm 3$	–
4230	$85.1 \pm 1.5 \pm 4.9$	$35.4 \pm 1.3 \pm 2.2$	$5.27 \pm 0.63 \pm 0.75$	$1.6 \pm 0.5 \pm 0.3$	$47 \pm 2 \pm 2.2$	$3.7 \pm 0.7 \pm 0.3$
4245	$84.4 \pm 6.3 \pm 4.9$	$40.3 \pm 5.8 \pm 2.7$	–	–	$24.8 \pm 6.5 \pm 2$	–
4260	$59.5 \pm 1.4 \pm 3.4$	$28.3 \pm 1.3 \pm 1.8$	$3.08 \pm 0.47 \pm 0.4$	$1.2 \pm 0.4 \pm 0.2$	$15.7 \pm 1.4 \pm 0.9$	$3.9 \pm 0.8 \pm 0.3$
4310	$52 \pm 5.7 \pm 3$	$24.1 \pm 4.9 \pm 1.6$	–	–	–	–
4360	$25.4 \pm 1.2 \pm 1.5$	$13.8 \pm 1.1 \pm 0.9$	–	–	$5.6 \pm 1.2 \pm 0.6$	–
4390	$20 \pm 3.2 \pm 1.2$	$4.7 \pm 1.9 \pm 0.3$	–	–	–	–
4420	$12.1 \pm 0.6 \pm 0.7$	$2.7 \pm 1.9 \pm 0.2$	$0.97 \pm 0.22 \pm 0.14$	–	$7.5 \pm 0.9 \pm 0.6$	–
4470	$13.3 \pm 2.1 \pm 0.8$	–	$3.8 \pm 1.3 \pm 0.5$	–	–	–
4530	$10.6 \pm 1.9 \pm 0.6$	–	$4.3 \pm 1.4 \pm 0.7$	–	–	–
4575	$13.4 \pm 3.2 \pm 0.8$	–	–	–	–	–
4600	$6.4 \pm 0.7 \pm 0.4$	–	$1.42 \pm 0.33 \pm 0.2$	–	–	–


σ, pb
200
150
100
50
0
3.8
3.9
4
4.1
4.2
4.3
4.4
4.5
4.6
√s, GeV
$\sigma_{J/\psi_{prompt}}$
$\Sigma\sigma_{J/\psi\ exclusive}$

Conclusion

- Analysis procedure has been elaborated
- The first estimation of $e^+e^- \to J/\psi_{prompt}X$ is obtained
- The result is rather consistent with total exclusive cross-section
- The result for the prompt J/ψ production in the range above 4.5 GeV is

$$\sigma = 27.5 \pm 3.3 \pm 4.4 \text{ pb}$$

- This value is one of the main result of the performed studies and could be used for tests of J/ψ production models (NRQCD).
- Memo is almost ready