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Study of J/ψ Energy Correlator

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Outline

- ➔ Motivation
- ➔ Analysis method
- ➔ Data and MC samples
- ➔ Event selection
- ➔ QEC analysis
- ➔ Systematic uncertainties
- ➔ Summary

Motivation

Heavy quarkonium as a probe to study hadronization

➔ Foundamental questions to strong interaction:
How does colorful quarks and gluons transform into colorless hadrons — **Hadronization**?

➔ **Heavy quarkonium** — an ideal system for studying the hadronization mechanism, how $c\bar{c} \to J/\psi$?

➔ Classic method — NRQCD factorization

$$(2\pi)^3 2P_H^0 \frac{d\sigma_H}{d^3P_H} = \sum_n d\hat{\sigma}_n(P_H)\langle \mathcal{O}_n^H \rangle$$

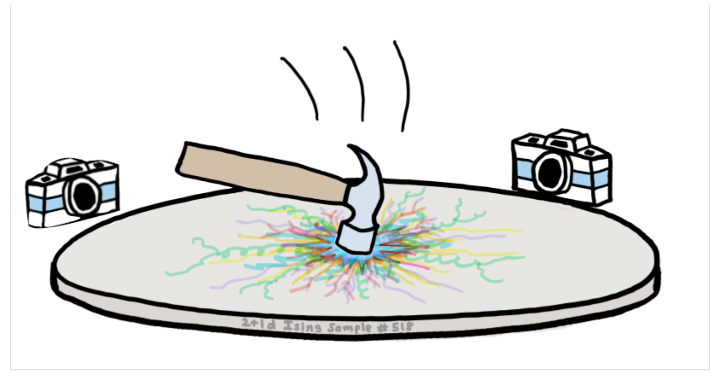
- Encoded in $\langle \mathcal{O}_1 \rangle, \langle \mathcal{O}_8 \rangle$
- Remains largely unkown: amount of energy released? Energy distribution?

Production of a heavy quark pair
Expansion in α_s

Hadronization — Long Distance Matrix Elements (LDME)
Expansion in v

➔ New insight — **Energy-Energy Correlator (EEC)**

$$\frac{d\Sigma}{d\cos\chi} = \sum_{i,j} \int \frac{E_i E_j}{Q^2} \sigma(\vec{n}_i \cdot \vec{n}_j - \cos\chi) d\sigma$$



Caron-Huot, Kologlu, Kravchuk, Meltzer, Simmons-Duffin, 2022

- ❖ Energy-weighted two-particle angular correlation
- ❖ Physics application: CMS α_s extraction from EEC ratio, Signature of jet from EEC by reanalyzing LEP data

See Huaxing Zhu's reports in Collaboration Meeting

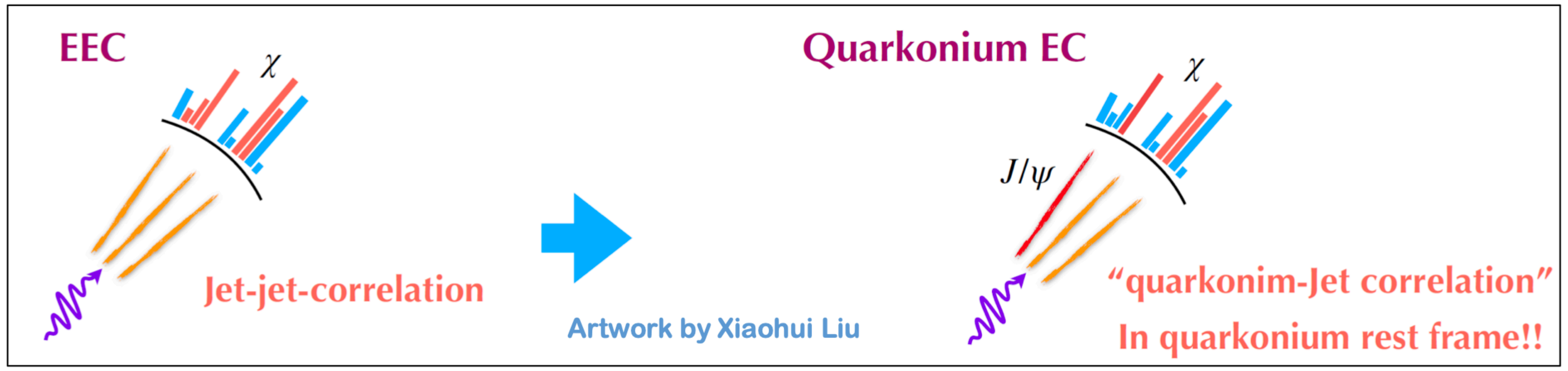
➔ **Quarkonium Energy Correlator (QEC)** — a novel observable   PRL 133, 191901 (2024)

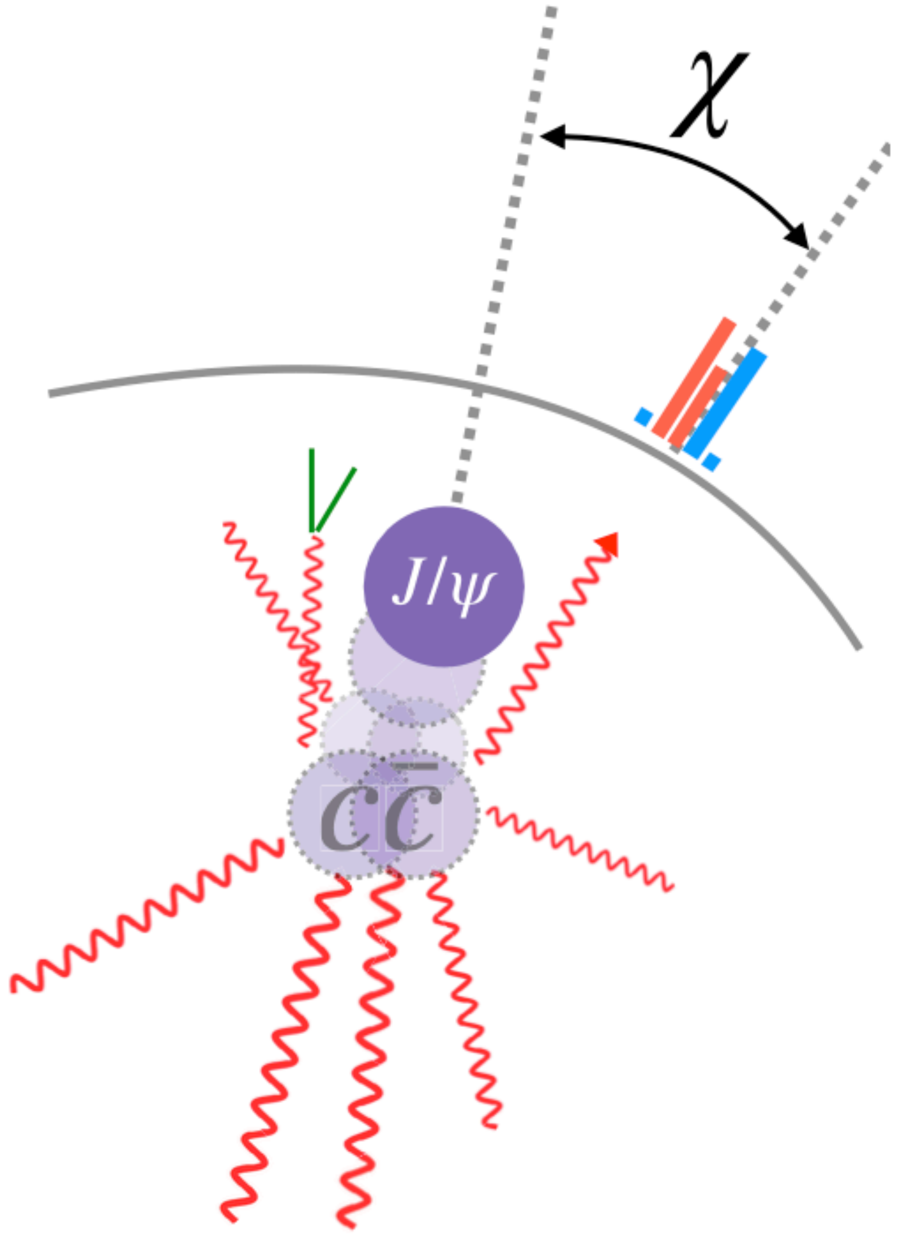
Quarkonium Energy Correlator

PRL 133, 191901 (2024)

➔ QEC Definition: $\Sigma(\cos\chi) = \int d\sigma \sum_i \frac{E_i}{M_{J/\psi}} \delta(\cos\chi - \cos\theta_i)$

- $d\sigma$: the differential cross section for generating J/ψ
- χ: the angular of detector relative to the flying direction to J/ψ
- E_i: the total energy carried by particles propagating at the angle θ_i
- $M_{J/\psi}$: the mass of the J/ψ



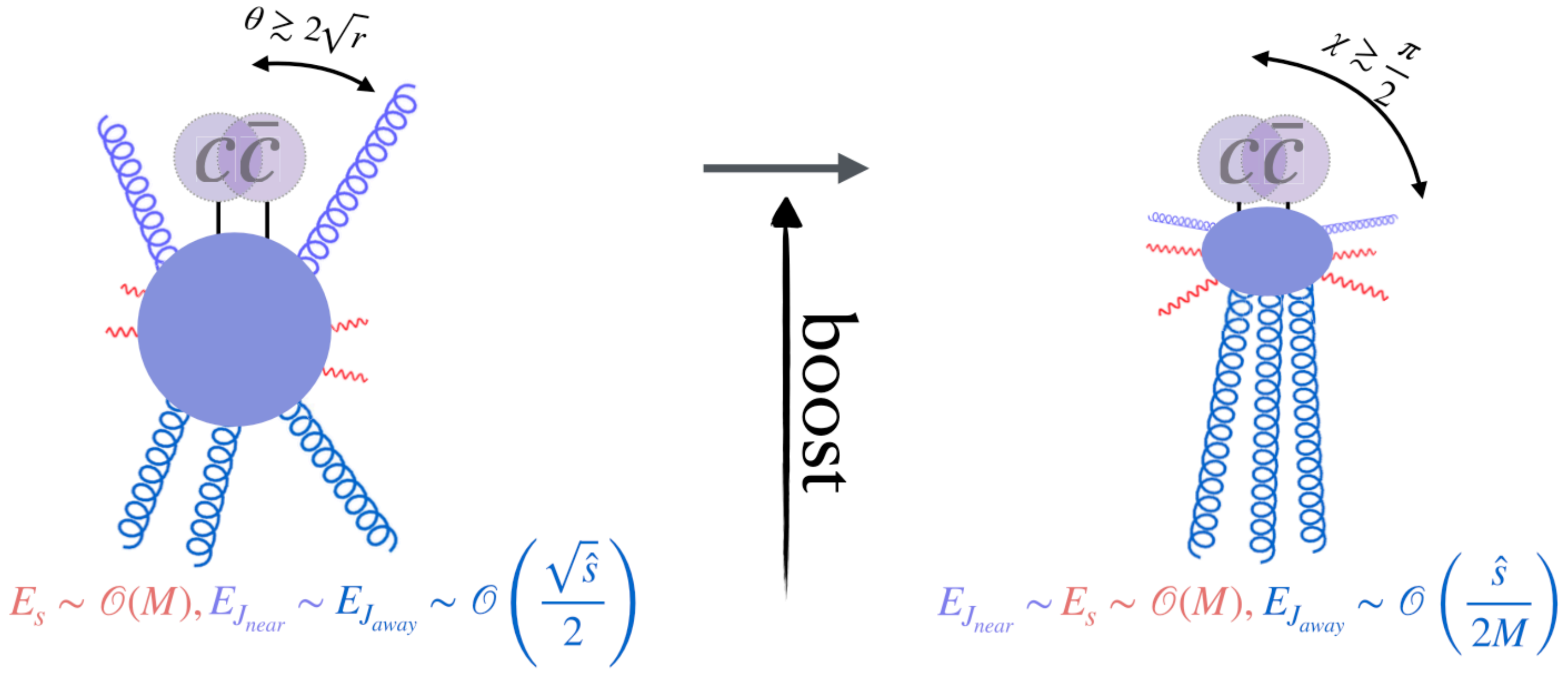


➔ Advantage of QEC observable

- Clear physical meaning: average energy at the angle χ emitted during the hadronization
- Infrared-safe property (theorist's point of view): Quarkonium-hadron correlator weighted by the energy of light hadrons
- Distinguishing capability between different production mechanisms (Color-singlet (CS) or Color-octet (CO) mechanisms in the NRQCD)

➔ Magic trick — boost into J/ψ rest frame

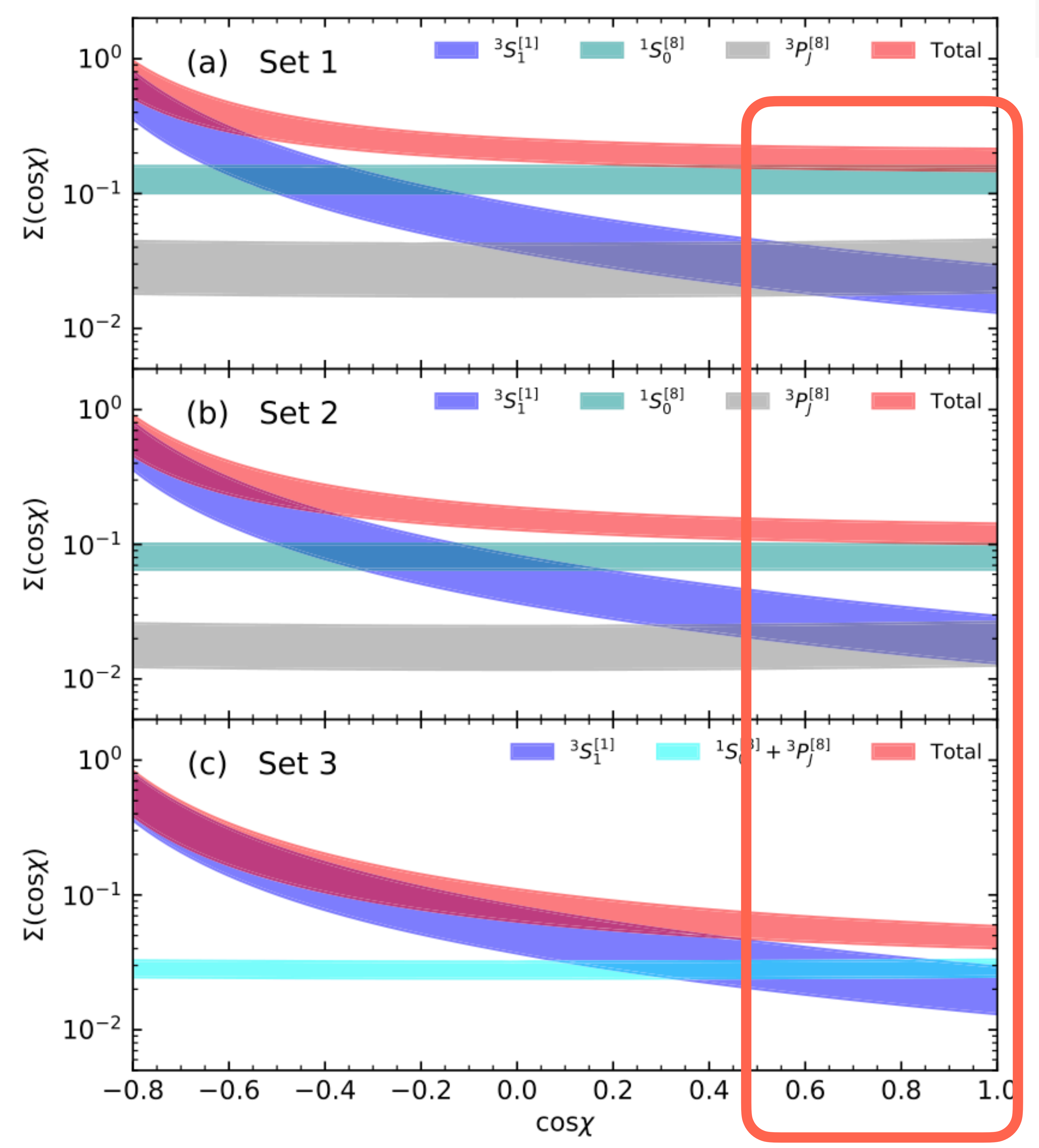
- Dead-cone effects: collinear radiation suppression
- Hard radiation depopulated at $\cos\chi \sim 1$



QEC in e^+e^- scenario: $e^+e^- \to \gamma^* \to J/\psi + X$

PRL 133, 191901 (2024)

- ➔ $\Sigma(\cos\chi) = \Sigma^{CS}_{P.T.}(\cos\chi) + \Sigma^{CO}_{P.T.}(\cos\chi) + \Sigma^{CS}_{N.T.}(\cos\chi) + \Sigma^{CO}_{N.T.}(\cos\chi)$
  - CS: $e^+e^- \to \gamma^* \to c\bar{c}[^3S_1^{[1]}] + g + g$
  - CO: $e^+e^- \to \gamma^* \to c\bar{c}[^1S_0^{[8]}, ^3P_J^{[8]}] + g$
  - P.T.: **hard radiation contribution** calculated by perturbative theory
  - N.P.: **soft radiation contribution** calculated by NRQCD
  - $\Sigma^{CO}_{P.T.}$ and $\Sigma^{CS}_{N.P.}$ are neglected at the leading order
- ➔ **Hard radiation contribution $\Sigma^{CS}_{P.T.}$ dominates where $\chi \gtrsim (\pi/2)$**
- ➔ **Soft radiation contribution $\Sigma^{CO}_{N.P}$ dominate when $\chi \lesssim (\pi/2)$**
  - Physics necessary for comprehending the hadronization mechanism



Theoretical predictions for J/ψ energy correlator in e^+e^- collision at Belle energy

Sizable hadronization effect!
``See`` the hadronization energy distribution

- ➔ **Advantages at BESIII**
  - Lower energy → Nonperturbative contribution more significant than perturbative contribution
  - Clean detection environment → better suppress feed-down background

Analysis method

Analysis method — QEC

➔ To measure the J/ψ energy correlator experimentally, a simple transformation to theoretical expression

$$\Sigma(\cos\chi) = \frac{1}{\mathcal{L}}\int d(\mathcal{L}\sigma_{J/\psi X})\sum_i \frac{E_i}{M_{J/\psi}}\delta(\cos\chi - \cos\theta_i),$$

$$= \frac{1}{\mathcal{L}}\int \frac{dN^{\text{sig}}_{J/\psi X}}{\mathcal{B}_{J/\psi\to\mu^+\mu^-}}\sum_i \frac{E_i}{M_{J/\psi}}\delta(\cos\chi - \cos\theta_i)\frac{1}{\varepsilon_i},$$

➔ Reconstruct J/ψ using di-muon channel

❖ Bhabha contamination in di-electron channel

➔ The summation goes over charged hadrons, $\pi^\pm/K^\pm$

❖ Ignore proton ⇒ BESIII energy is not sufficient to generate $p\bar{p}J/\psi$

❖ Ignore e/μ ⇒ Produced through electro-week interaction

$\mathscr{L}$: integrated luminosity

N^{sig}: the number of reconstructed signal

$\mathscr{B}_{J/\psi\to\mu^+\mu^-}$: the BF of $J/\psi \to \mu^+\mu^-$

ε: effieincy curve

Analysis method — feed-down background

- ➔ Real signal: prompt J/ψ from continuum process
- ➔ Fake signal: non-prompt J/ψ produced via either ISR process or deexcitation of highly exicted charmonium state ⇒ **Feed-down background**
- ➔ Basically following BAM-557, feed-down background is categorized into following parts

❖ J/ψISR

$$N^{\rm bkg}_{J/\psi{\rm ISR}} = N^{\rm obs}_{J/\psi{\rm ISR}} \times \mathcal{R}^{\rm bkg}_{J/\psi{\rm ISR}}$$

❖ $\psi(2S)$ISR

$$N^{\rm bkg}_{\psi(2S){\rm ISR}} = \frac{N^{\rm obs}_{\psi(2S){\rm ISR}}}{\varepsilon_{\psi(2S){\rm ISR}} \times \mathcal{B}_{\psi(2S)\to\pi^+\pi^- J/\psi}} \times \tilde{\mathcal{B}}_{\psi(2S)\to J/\psi X} \times \mathcal{R}^{\rm bkg}_{\psi(2S){\rm ISR}}$$

❖ $\psi(2S)X$

$$N^{\rm bkg}_{\psi(2S)X} = \frac{N^{\rm obs}_{\psi(2S)X} - \mathcal{R}'^{\rm bkg}_{\psi(2S){\rm ISR}} \times N^{\rm obs}_{\psi(2S){\rm ISR}}}{\varepsilon_{\psi(2S)X} \times \mathcal{B}_{\psi(\epsilon S)\to\pi^+\pi^- \mathcal{J}/\psi}} \times \tilde{\mathcal{B}}_{\psi(2S)\to J/\psi X} \times \mathcal{R}^{\rm bkg}_{\psi(2S)X}$$

❖ $\chi_{cJ}\,(J=1,2)$

$$N^{\rm sig}_{\chi_{cJ}} = \frac{N^{\rm obs}_{\chi_{cJ}} \times \mathcal{R}^{\rm bkg}_{\chi_{cJ}}}{\varepsilon_{\chi_{cJ}}}$$

$N^{\rm obs}$: reconstructed event number
$\mathscr{B}$: BF
ε: effieincy
$\mathscr{R}$: contamination rate

- ➔ Actual signal number $N^{\rm sig}_{J/\psi X} = N^{\rm obs}_{J/\psi X} - N^{\rm bkg}_{J/\psi{\rm ISR}} - N^{\rm bkg}_{\psi(2S){\rm ISR}} - N^{\rm bkg}_{\psi(2S)X} - N^{\rm bkg}_{\chi_{c1}X} - N^{\rm bkg}_{\chi_{c2}X}$

Data and MC samples

Data and MC samples

- ➔ Data sample at high energy $\sqrt{s} = 4.600 \sim 4.951\,\mathrm{GeV}$ is used
  - ❖ Integrated luminosity around $6.44\,\mathrm{pb}^{-1}$
  - ❖ Boss version: 7.0.6 for 4600-4700, 7.0.7 for 4740-4946

- ➔ Five MC samples
  - ❖ $J/\psi X$: several exclusive channels with cross sections from BESIII measurements
    - $e^+e^- \to \pi^+\pi^- J/\psi,\ \pi^0\pi^0 J/\psi,\ K^+K^- J/\psi,\ K_S^0K_S^0 J/\psi,\ K_L^0K_L^0 J/\psi,\ \eta J/\psi,\ \eta' J/\psi;\ J/\psi \to \mu^+\mu^-$
  - ❖ J/ψISR: J/ψ produced via ISR process
  - ❖ $\psi(2S)X$: several exclusive channels with cross sections from BESIII measurements
    - $e^+e^- \to \pi^+\pi^-\psi(2S),\ \pi^0\pi^0\psi(2S),\ \eta\psi(2S);\ \psi(2S) \to \pi^+\pi^- J/\psi$
  - ❖ $\psi(2S)$ISR: $\psi(2S)$ produced via ISR process
  - ❖ $\chi_{cJ}\,(J=1{,}2)$: χ_{cJ} produced via $\psi(2S) \to \gamma\chi_{cJ}, \chi_{cJ} \to \gamma J/\psi$

Phys. Rev. D 106 (2022) 072001
arXiv:2505.13222
Phys. Rev. Lett. 131 (2023) 211902
Phys. Rev. D 107 (2023) 092005
Phys. Rev. D 109 (2024) 092012
BAM-00726

Phys. Rev. D 104 (2021) 052012
BAM-00908
BAM-00867
JHEP 10 (2021) 177
Phys. Rev. D 109 (2024) 112004

Event selection

Track and Shower selection

- Good charged tracks
  - $|V_r| < 1\,\mathrm{cm}$, $|V_z| < 10\,\mathrm{cm}$, $|\cos\theta| < 0.93$

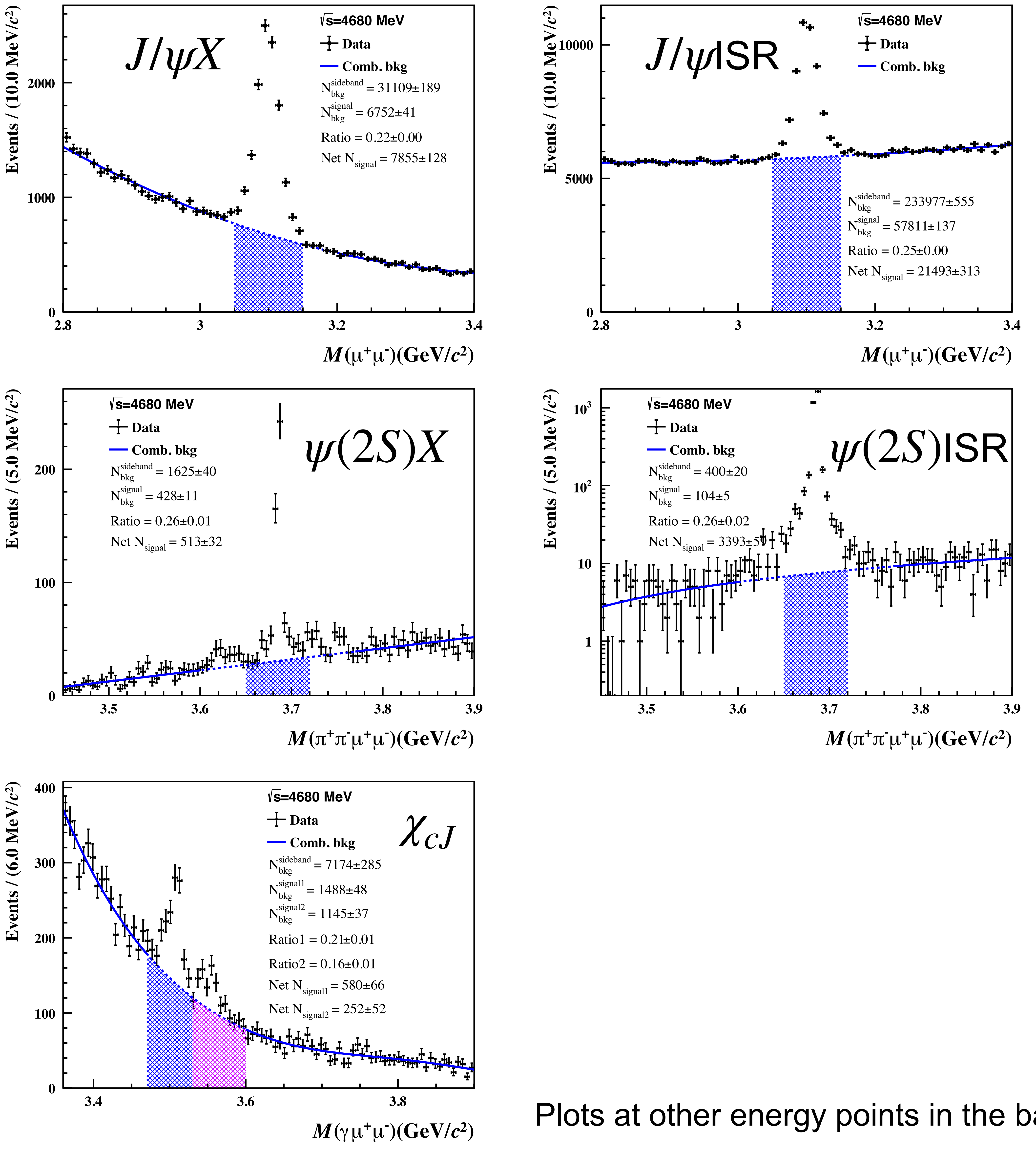
- PID
  - π: $\mathscr{L}(\pi) > 0, \mathscr{L}(\pi) > \mathscr{L}(K)$
  - K: $\mathscr{L}(K) > 0, \mathscr{L}(K) > \mathscr{L}(\pi)$
  - μ: $0.1 < E_{\mathrm{EMC}} < 0.4\,\mathrm{GeV}$

- Good photons
  - Barrel ($|\cos\theta| < 0.8$): $E > 25\,\mathrm{MeV}$
  - Endcap ($0.86 < |\cos\theta| < 0.92$): $E > 50\,\mathrm{MeV}$
  - $0 < T_{\mathrm{TDC}} < 14(\times 50\,\mathrm{ns})$
  - Isolation angle $\theta > 20^\circ$

Event selection

- ➔ $J/\psi X$
  - ❖ $N_{\mathrm{charged}} > 2, N_+ \geq 1, N_- \geq 1,\ 2.8 < M_{\mu^+\mu^-} < 3.4\,\mathrm{GeV}/c^2$
- ➔ J/ψISR
  - ❖ $N_+ = 1, N_- = 1, N_\gamma < 2,\ 2.8 < M_{\mu^+\mu^-} < 3.4\,\mathrm{GeV}/c^2$
- ➔ $\psi(2S)X$
  - ❖ $N_{\mathrm{charged}} > 4, N_+ \geq 2, N_- \geq 2, 3.05 < M_{\mu^+\mu^-} < 3.15\,\mathrm{GeV}/c^2$
  - ❖ 1C kinematic fit to J/ψ mass to choose the only muon pair with minimal χ^2, $\chi^2 < 50$
  - ❖ No PID requirement on pions decay from $\psi(2S)$
- ➔ $\psi(2S)$ISR
  - ❖ $N_+ = 2, N_- = 2, N_\gamma < 2, 3.05 < M_{\mu^+\mu^-} < 3.15\,\mathrm{GeV}/c^2$
  - ❖ 1C kinematic fit to J/ψ mass to choose the only muon pair with minimal χ^2, $\chi^2 < 50$
  - ❖ No PID requirement on pions decay from $\psi(2S)$
- ➔ χ_{cJ}
  - ❖ $N_+ = 1, N_- = 1, N_\gamma \geq 2$ or $N_{\mathrm{charged}} > 2, N_+ \geq 1, N_- \geq 1, N_\gamma \geq 1; 3.05 < M_{\mu^+\mu^-} < 3.15\,\mathrm{GeV}/c^2$
  - ❖ 1C kinematic fit to J/ψ mass to choose the only muon pair with minimal χ^2, $\chi^2 < 50$

Data fitting



Plots at other energy points in the backup

Signal/Sideband region definitions

- $\mu^+\mu^-$ invariant mass spectrum

Sideband region: [2.8,3.0] ∪ [3.2,3.4] GeV/c²
Signal region: [3.05,3.15] GeV/c²

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

Sideband region: [3.45,3.60] ∪ [3.77,3.90] GeV/c²
Signal region: [3.65,3.72] GeV/c²

- $\gamma\mu^+\mu^-$ invariant mass spectrum

Sideband region: [3.36,3.47] ∪ [3.60,3.90] GeV/c²
χ_{c1} signal region: [3.65,3.72] GeV/c²
χ_{c2} signal region: [3.53,3.60] GeV/c²

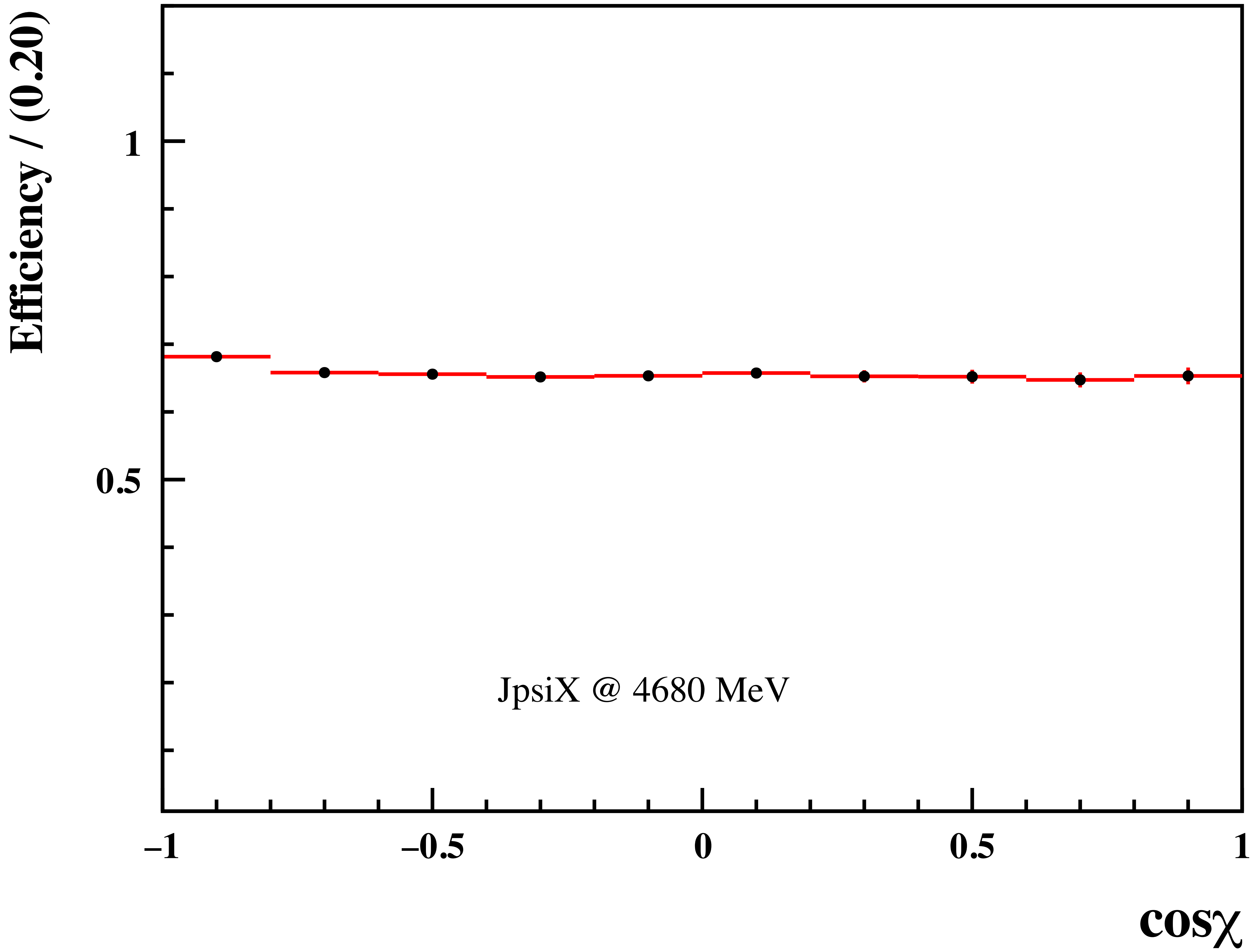
Fit functions

- $J/\psi X$: Quadratic function
- J/ψISR: Quadratic function
- $\psi(2S)X$: Linear function
- $\psi(2S)$ISR: Linear function
- χ_{cJ}: Exponential + Gaussian

Sideband subtraction

- Fit sideband region ⇒ Estimate background yields in the sideband region
- Extrapolate to signal region ⇒ Estimate background yields in the signal region
- Count total event number in signal region
- Signal yields = Total event number - estimated background yields

Efficiency

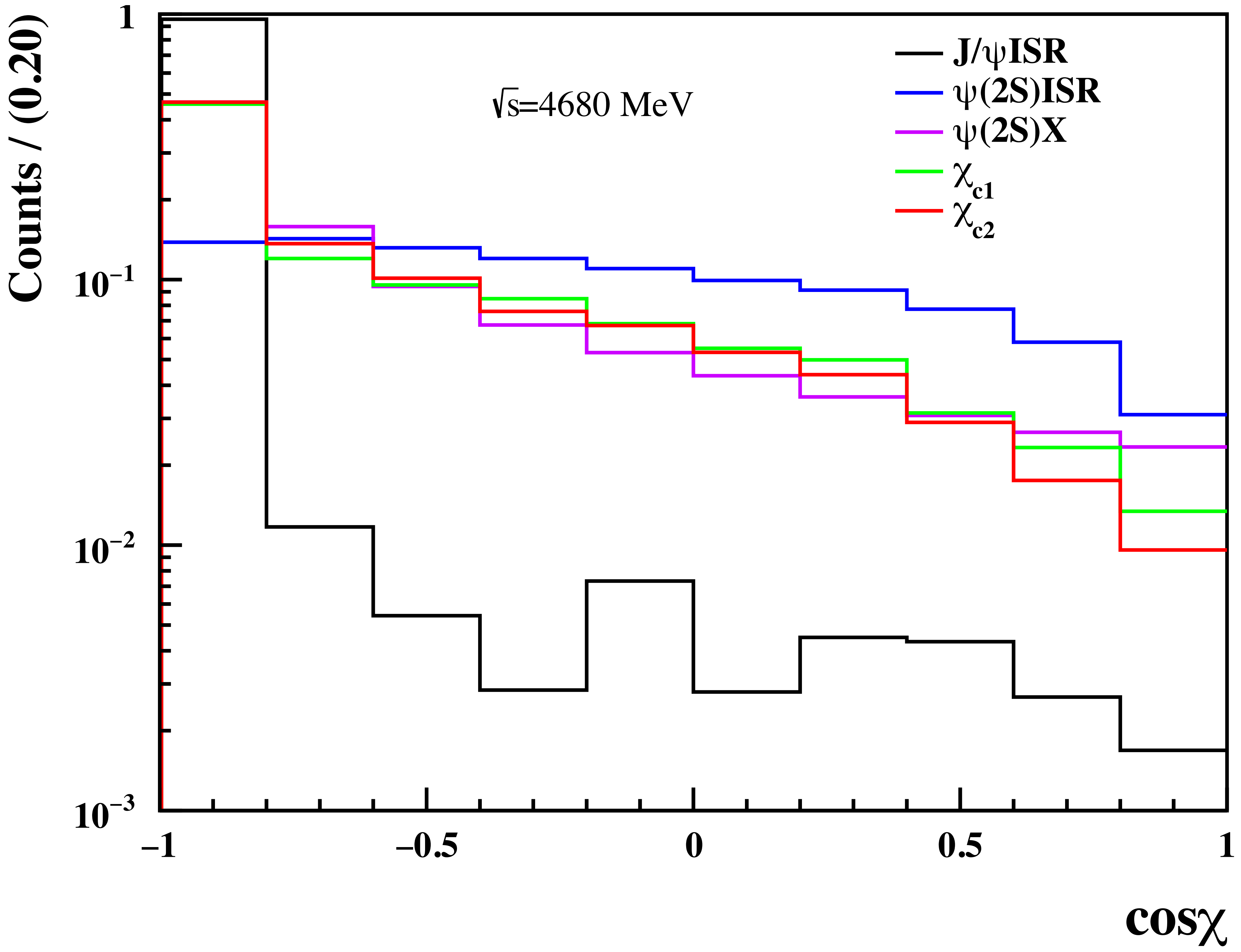


$J/\psi X$ efficiency curve as a function of $\cos\chi$
Estimated by using $J/\psi X$ MC samples
Flat distribution

Energy point	$\varepsilon_{\psi(2S)\mathrm{ISR}}$	$\varepsilon_{\psi(2S)X}$	$\varepsilon_{\chi_{c1}X}$	$\varepsilon_{\chi_{c2}X}$
4600	48.69 ± 0.14	47.15 ± 0.10	48.15 ± 0.11	42.50 ± 0.11
4612	47.41 ± 0.20	32.83 ± 0.13	48.44 ± 0.16	42.19 ± 0.16
4626	46.72 ± 0.14	42.16 ± 0.10	48.18 ± 0.11	42.38 ± 0.11
4640	46.99 ± 0.14	49.62 ± 0.10	48.25 ± 0.11	42.25 ± 0.11
4660	46.83 ± 0.14	46.88 ± 0.10	47.81 ± 0.11	42.14 ± 0.11
4680	46.99 ± 0.08	43.24 ± 0.06	47.76 ± 0.06	41.89 ± 0.06
4700	46.90 ± 0.14	41.52 ± 0.10	47.89 ± 0.11	42.10 ± 0.11
4740	47.29 ± 0.20	51.96 ± 0.14	47.52 ± 0.16	41.70 ± 0.16
4750	47.07 ± 0.14	40.05 ± 0.10	47.70 ± 0.11	41.87 ± 0.11
4780	47.10 ± 0.14	44.22 ± 0.10	47.59 ± 0.11	41.58 ± 0.11
4840	46.73 ± 0.14	41.55 ± 0.10	47.29 ± 0.11	41.59 ± 0.11
4914	46.42 ± 0.20	44.85 ± 0.14	46.61 ± 0.16	41.19 ± 0.16
4946	46.18 ± 0.20	51.36 ± 0.14	46.62 ± 0.16	41.37 ± 0.16

Average efficiency (%) for each background samples
Estimated by MC simulation

Background contamination



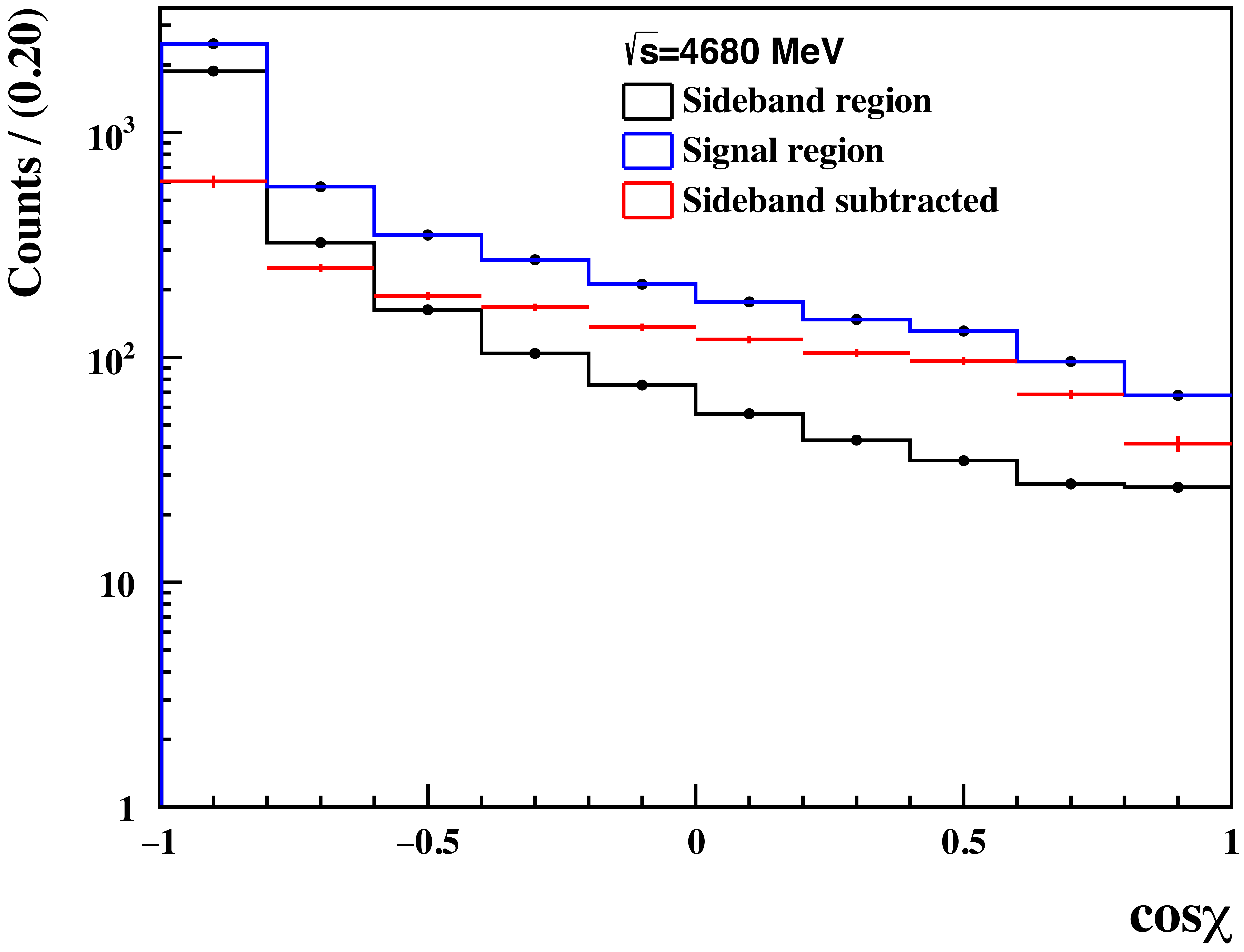
Energy point	$\mathcal{R}^{\rm bkg}_{J/\psi\rm ISR}$	$\mathcal{R}^{\rm bkg}_{\psi(2S)\rm ISR}$	$\mathcal{R}'^{\rm bkg}_{\psi(2S)\rm ISR}$	$\mathcal{R}^{\rm bkg}_{\psi(2S)X}$	$\mathcal{R}^{\rm bkg}_{\chi_{c1}X}$	$\mathcal{R}^{\rm bkg}_{\chi_{c2}X}$
4600	0.48 ± 0.02	45.99 ± 0.11	1.21 ± 0.05	67.33 ± 0.07	2.20 ± 0.03	2.07 ± 0.03
4612	0.47 ± 0.03	45.62 ± 0.16	1.49 ± 0.07	61.91 ± 0.11	2.16 ± 0.05	1.96 ± 0.04
4626	0.48 ± 0.02	45.31 ± 0.11	1.50 ± 0.05	65.84 ± 0.07	2.19 ± 0.03	2.05 ± 0.03
4640	0.50 ± 0.02	45.55 ± 0.11	1.45 ± 0.05	69.17 ± 0.07	2.19 ± 0.03	2.04 ± 0.03
4660	0.48 ± 0.02	45.31 ± 0.11	1.42 ± 0.05	67.92 ± 0.07	2.21 ± 0.03	2.06 ± 0.03
4680	0.47 ± 0.01	45.31 ± 0.06	1.36 ± 0.03	66.42 ± 0.04	2.18 ± 0.02	2.03 ± 0.02
4700	0.47 ± 0.02	45.23 ± 0.11	1.46 ± 0.05	65.73 ± 0.08	2.18 ± 0.03	2.11 ± 0.03
4740	0.47 ± 0.03	45.35 ± 0.16	1.27 ± 0.07	70.28 ± 0.10	2.23 ± 0.05	2.08 ± 0.05
4750	0.48 ± 0.02	45.11 ± 0.11	1.17 ± 0.05	65.02 ± 0.08	2.14 ± 0.03	2.13 ± 0.03
4780	0.48 ± 0.02	45.12 ± 0.11	1.20 ± 0.05	67.15 ± 0.07	2.22 ± 0.03	2.05 ± 0.03
4840	0.47 ± 0.02	44.97 ± 0.11	1.23 ± 0.05	66.01 ± 0.07	2.12 ± 0.03	2.03 ± 0.03
4914	0.48 ± 0.03	44.75 ± 0.16	1.34 ± 0.07	67.76 ± 0.10	2.24 ± 0.05	1.96 ± 0.04
4946	0.46 ± 0.03	44.75 ± 0.16	1.22 ± 0.07	70.47 ± 0.10	2.13 ± 0.05	2.06 ± 0.04

Normalized background QEC distribution in as a function of $\cos\chi$
Estimated by using background MC samples

Average contamination rate (%) for each background samples
Estimated by MC simulation

QEC analysis

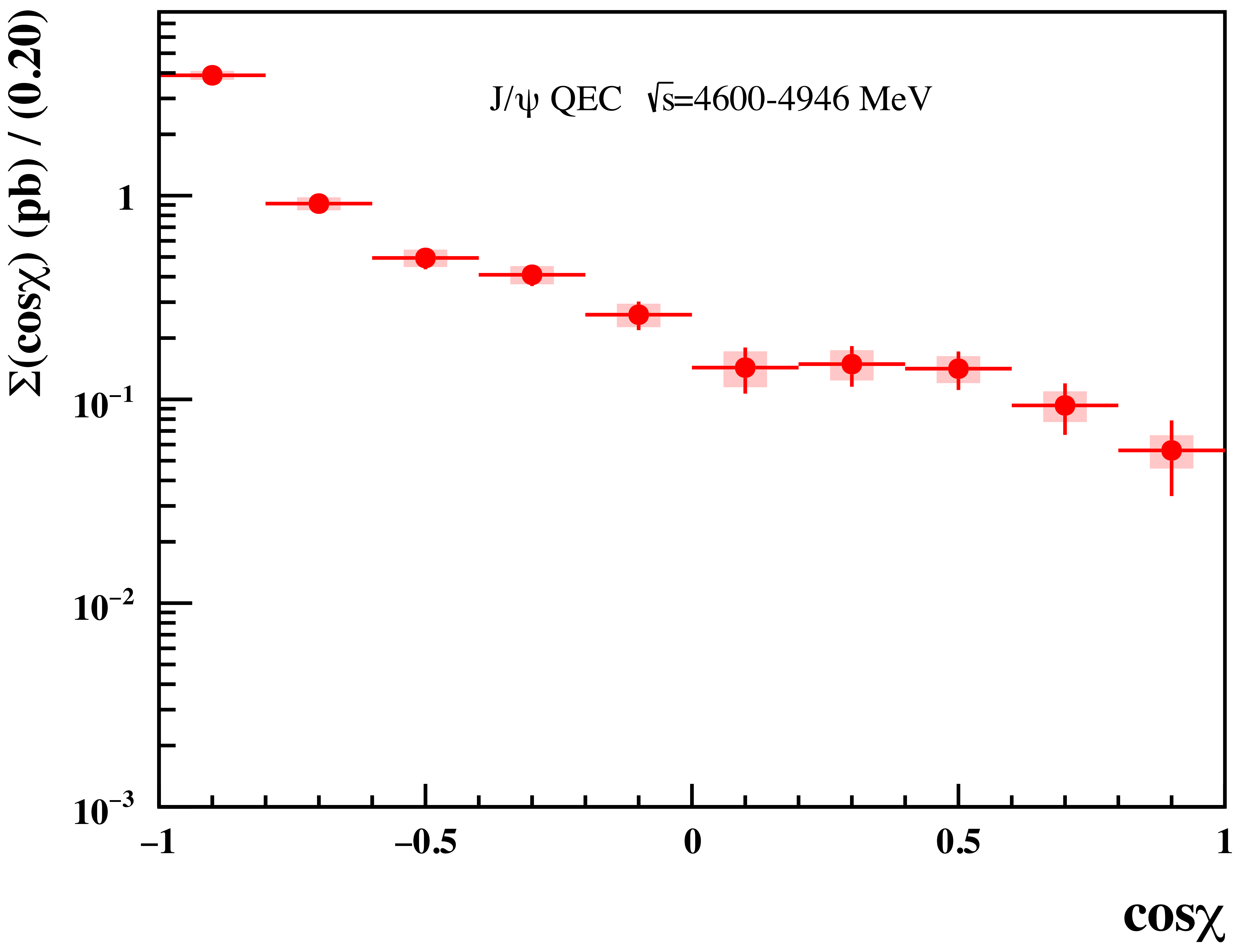
$J/\psi X$ energy weighted angular distribution



$$\Sigma(\cos\chi) = \frac{1}{\mathcal{L}}\int d(\mathcal{L}\sigma_{J/\psi X})\sum_i \frac{E_i}{M_{J/\psi}}\delta(\cos\chi - \cos\theta_i),$$

- ➔ $J/\psi X$ sample on data
- ➔ E/M weighted $\cos\chi$ distribution
- ➔ **Blue**: in the $M_{\mu^+\mu^-}$ signal region
- ➔ **Black**: in the $M_{\mu^+\mu^-}$ sideband region after scale
- ➔ **Red**: **Blue** - **Black**
- ➔ Distributions at other energy points in backup

J/ψ energy correlator results



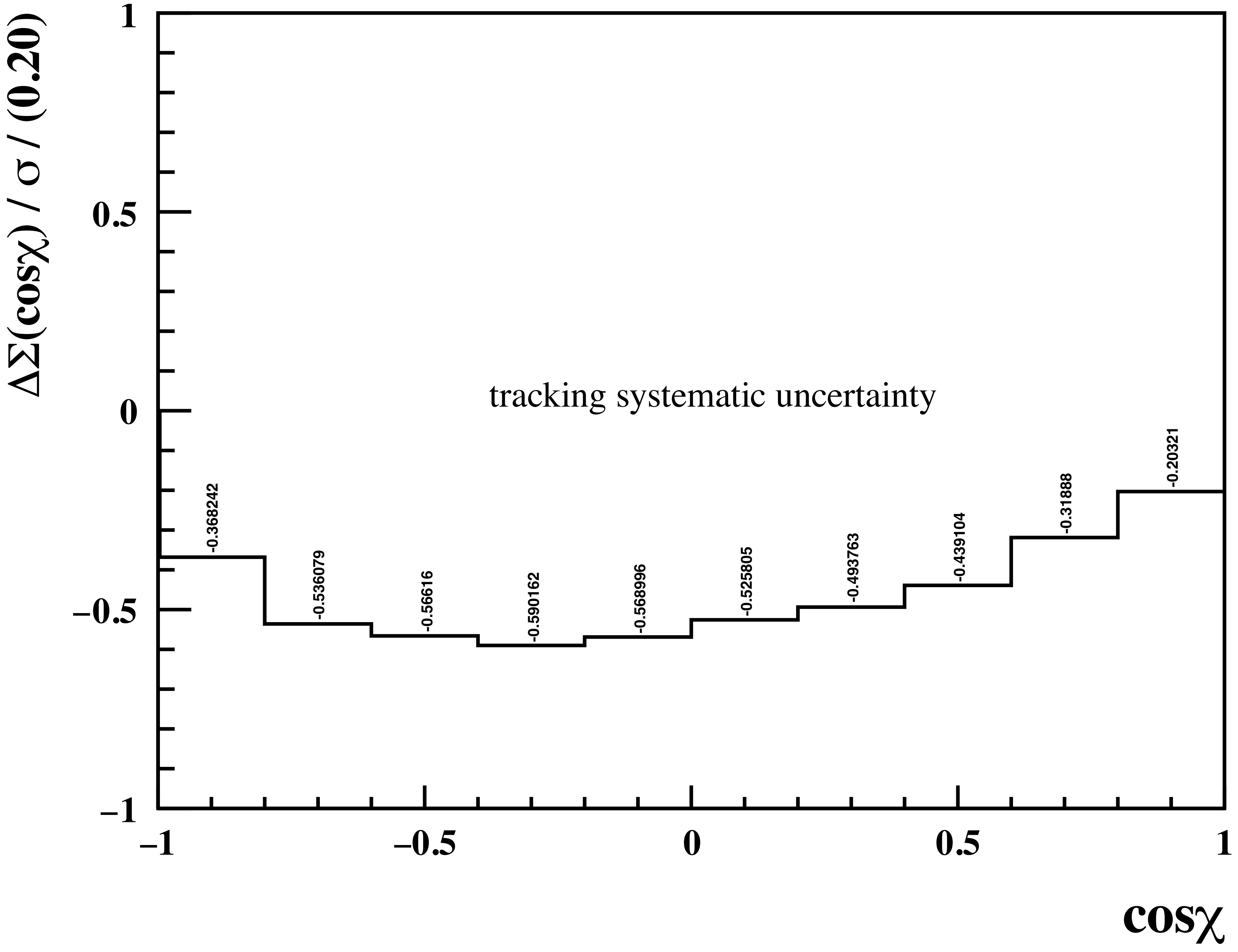
$$\Sigma(\cos\chi) = \frac{1}{\mathcal{L}}\int d(\mathcal{L}\sigma_{J/\psi X})\sum_i \frac{E_i}{M_{J/\psi}}\delta(\cos\chi - \cos\theta_i),$$

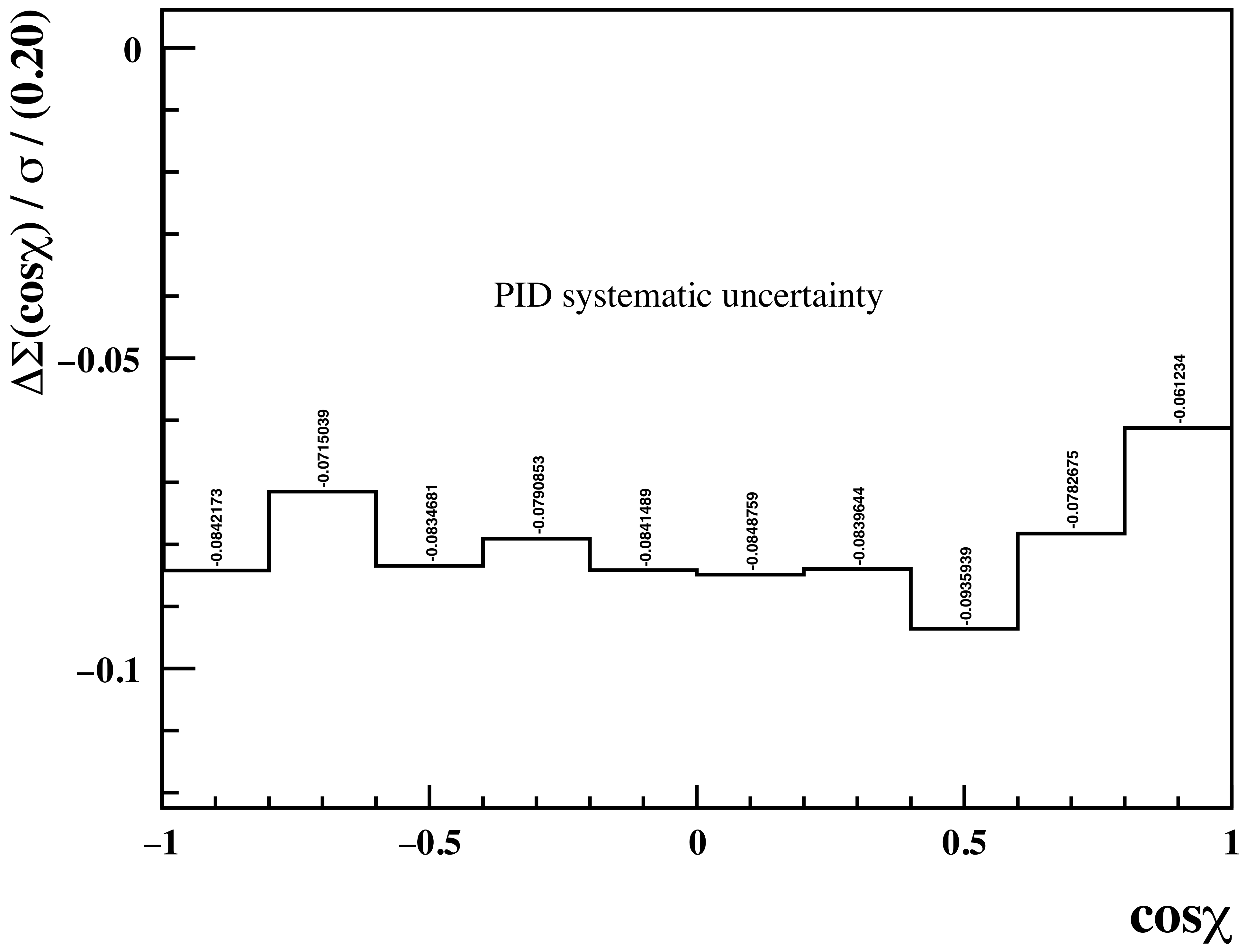
$$= \frac{1}{\mathcal{L}}\int \frac{dN^{\mathrm{sig}}_{J/\psi X}}{\mathcal{B}_{J/\psi\to\mu^+\mu^-}}\sum_i \frac{E_i}{M_{J/\psi}}\delta(\cos\chi - \cos\theta_i)\frac{1}{\varepsilon_i},$$

- ➔ Feed-down background subtracted
- ➔ Reconstruction efficiency corrected
- ➔ Luminosity and BF normalized
- ➔ Combining results from all energy points according to their uncertainties in each bin
- ➔ Error bars: statistical uncertainties
- ➔ Boxes: systematic uncertainties
- ➔ Result at single energy point in backup

Systematic uncertainties

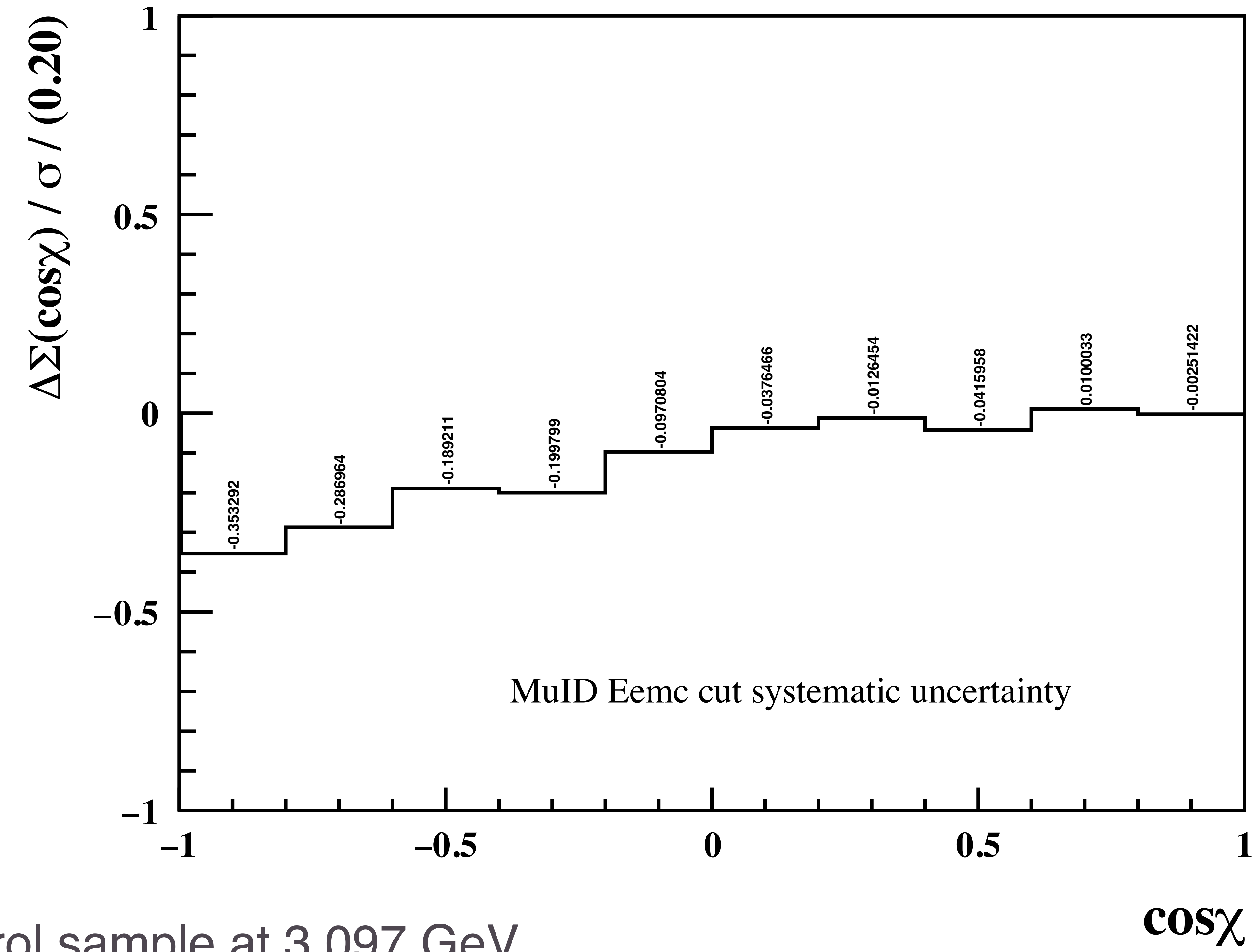
Tracking & PID

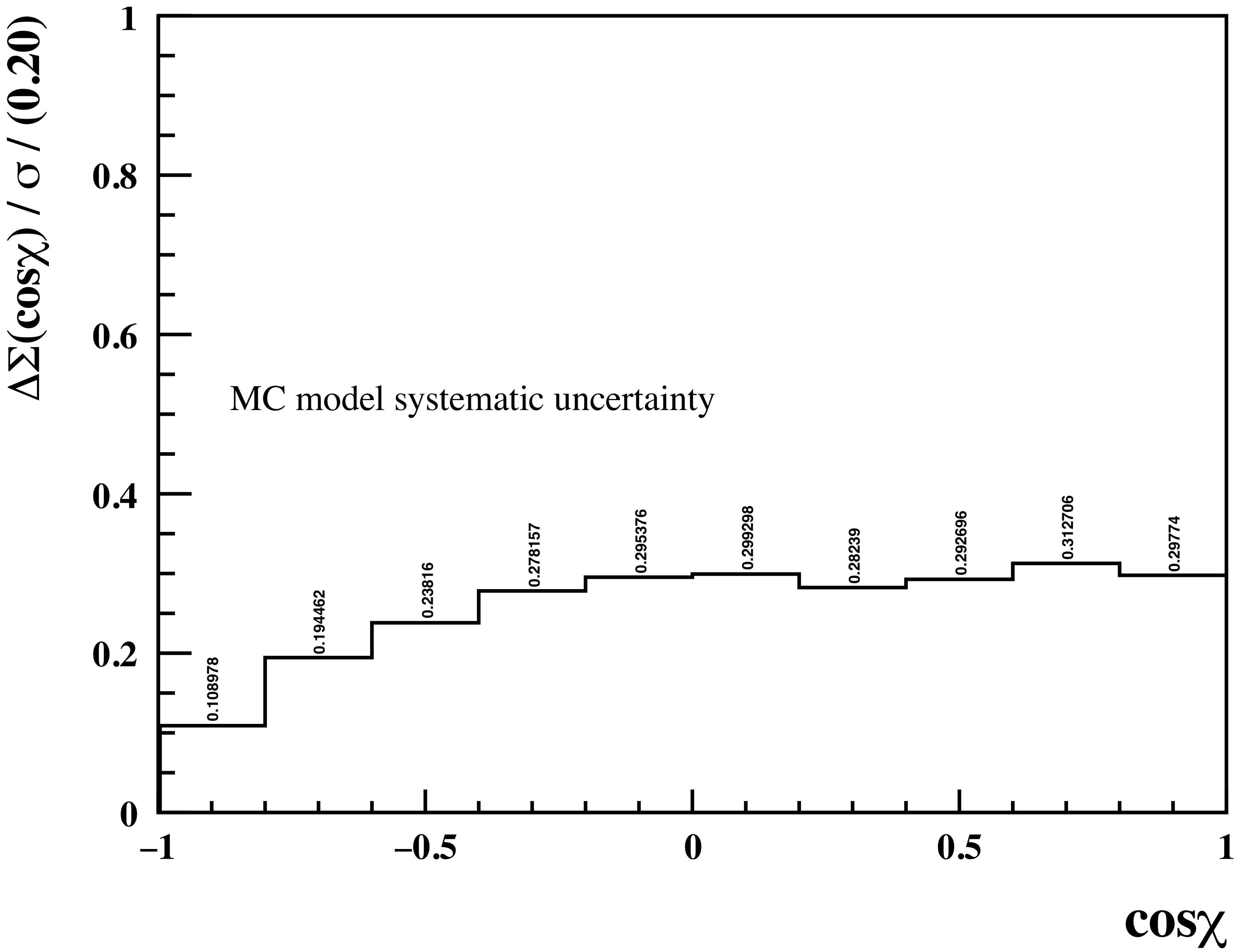




- ➔ Reference: DocDB-1283, Study of $K^{\pm}/\pi^{\pm}$ tracking and PID efficiencies for 8.0 fb^{-1} $\psi(3770)$ data
- ➔ Tracking: 1% for each muon track, refer to DocDB-1283 to study $\pi^{\pm}/K^{\pm}$ pt-dependent tracking efficiency
- ➔ PID: refer to DocDB-1283 to study $\pi^{\pm}/K^{\pm} \to \pi^{\pm}/K^{\pm}$ p-dependent correct-ID and mis-ID probability
- ➔ Estimate the relative difference between alternative QEC result and nominal result bin-by-bin

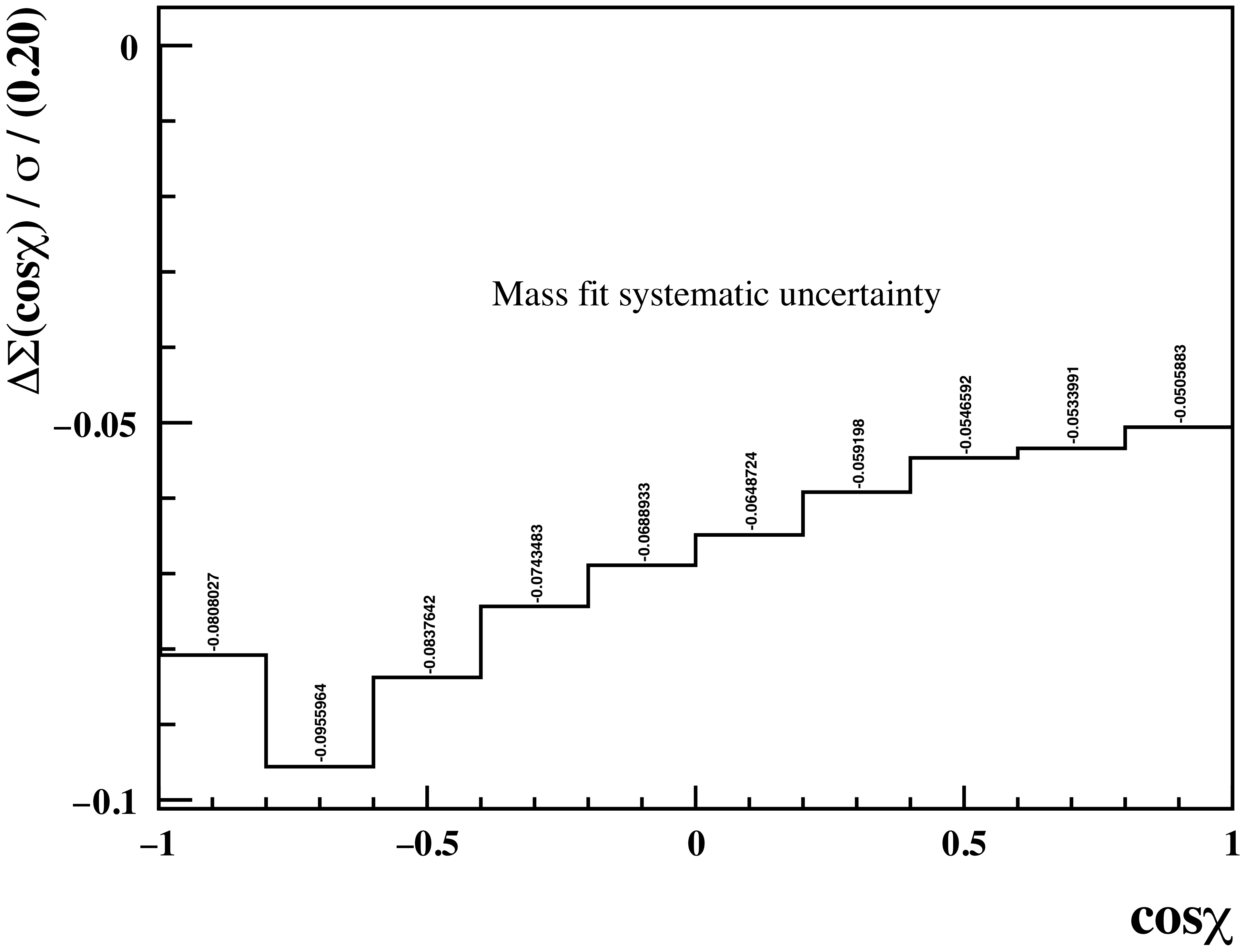
Muon E_{EMC} cut & MC model





- ➔ Muon E_{EMC} cut
  - ❖ $J/\psi \to \mu^+\mu^-$ control sample at 3.097 GeV
    - Selection criteria in the backup
  - ❖ Reweight MC samples accroding to polar angle-dependent data-MC difference
- ➔ MC model
  - ❖ Vary the cross sections of $\pi^+\pi^- J/\psi$, $K^+K^- J/\psi$, $K^0_S K^0_S J/\psi$, $\eta J/\psi$, $\eta' J/\psi$ by $\pm 1\sigma$
  - ❖ Vary the cross sections of $\pi^+\pi^-\psi(2S)$, $\pi^0\pi^0\psi(2S)$, $\eta\psi(2S)$ by $\pm 1\sigma$
  - ❖ Take quadratic sums of the largest variances from each process as systematic uncertainty

Fit

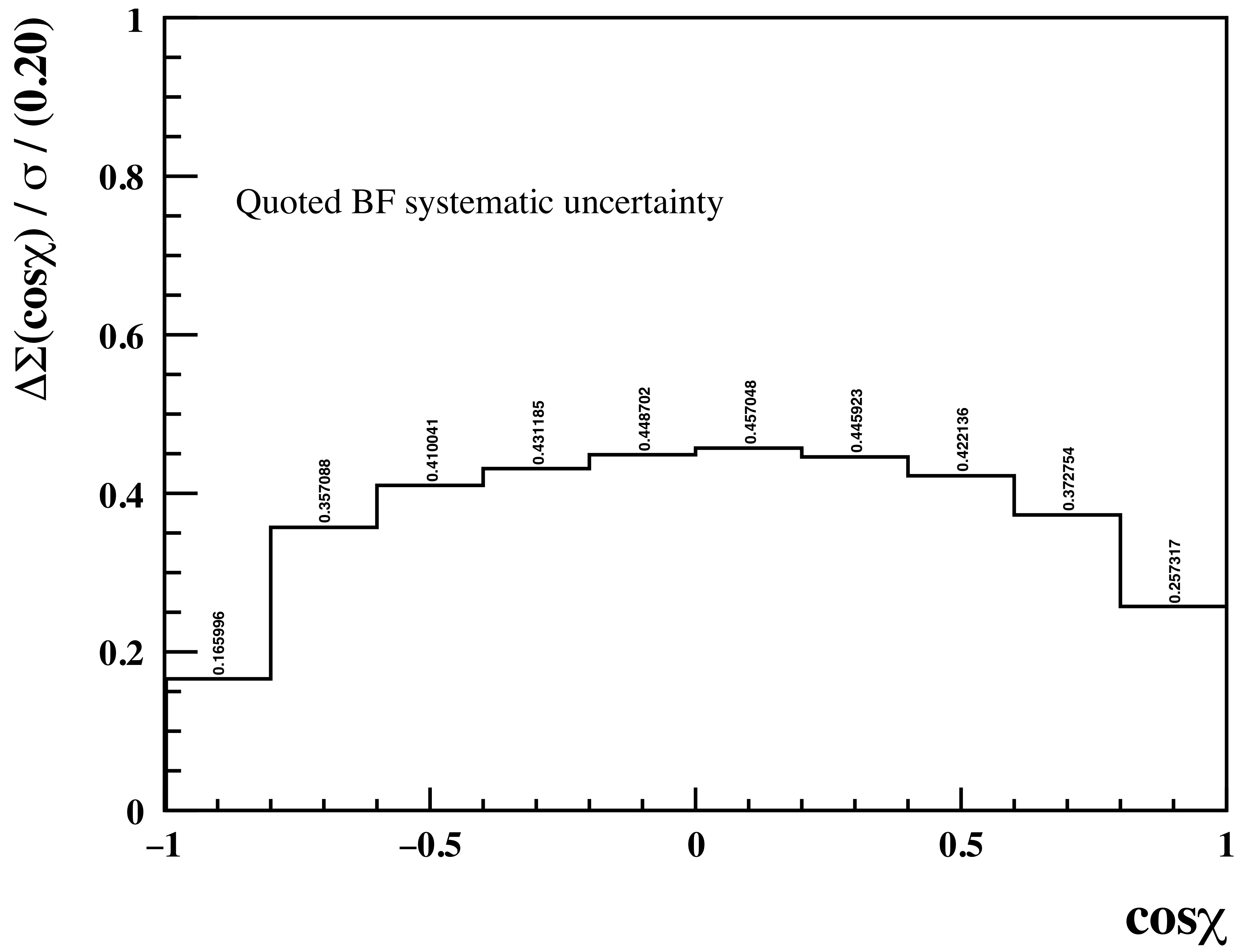


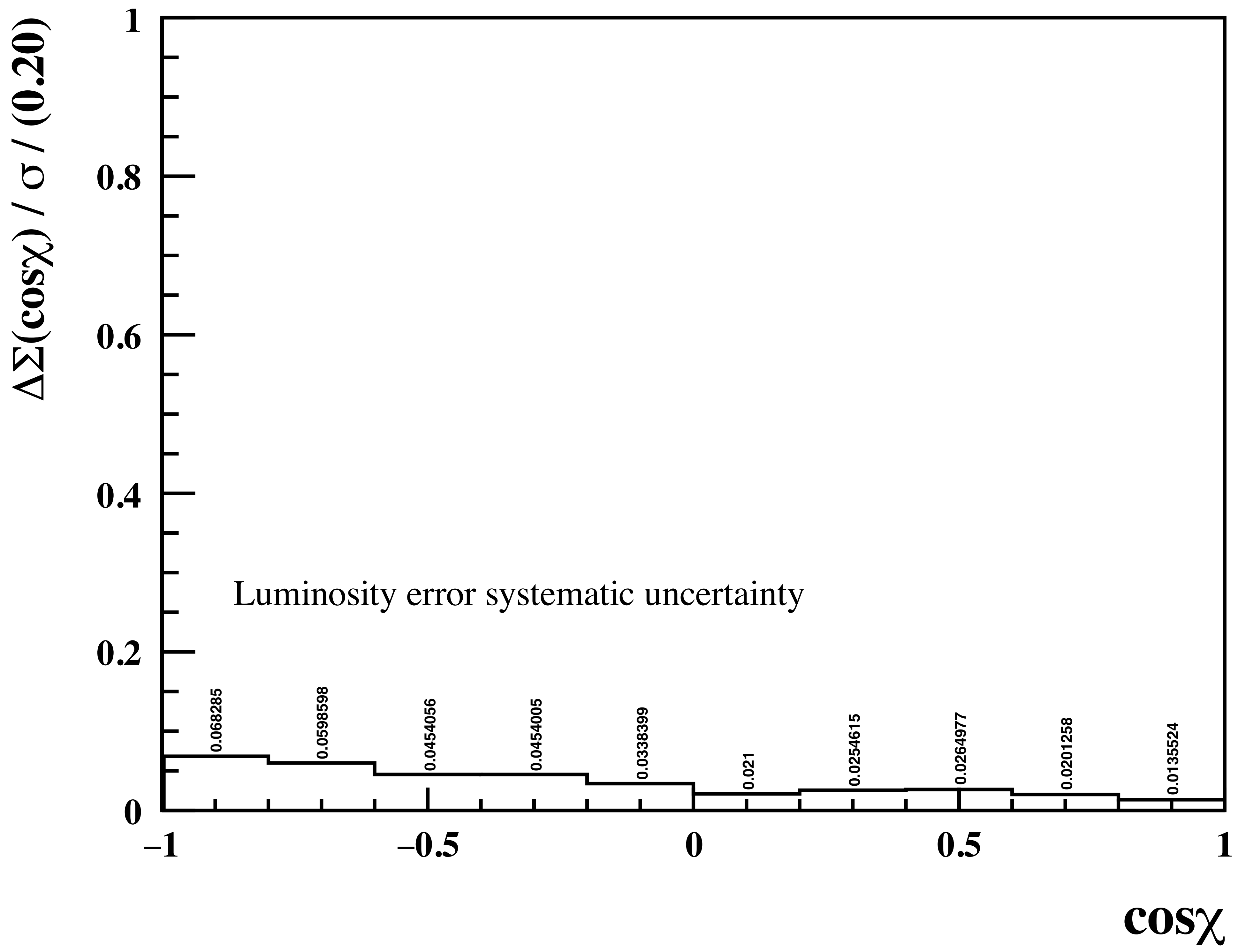
- $J/\psi X$: 2-nd order polynomial → 3-rd order polynomial
- J/ψISR: 2-nd order polynomial → 3-rd order polynomial
- $\psi(2S)X$: linear function → 2-nd order polynomial
- $\psi(2S)$ISR: linear function → 2-nd order polynomial
- χ_{cJ}: Exponential + Gaussian → 3-rd order polynomial + Gaussian

➔ Use the alternative fitting model to replace the nominal

➔ The resultant difference between the nominal QEC result and the alternative QEC result is taken as the systematic uncertainty

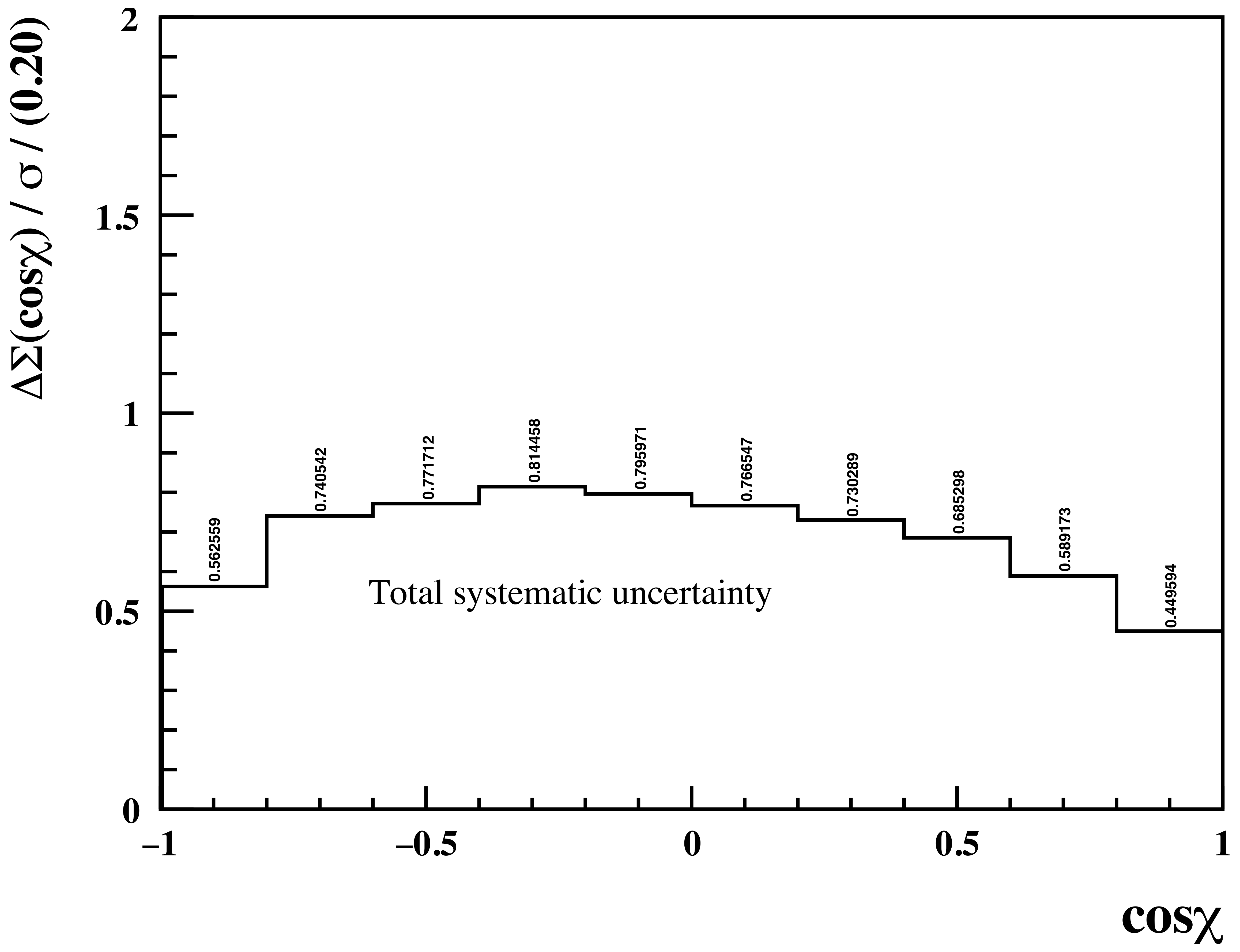
Quoted BF & Luminosity





- ➔ Quoted BF
  - ❖ Vary the BFs of $J/\psi \to \mu^+\mu^-$, $\psi(2S) \to J/\psi X$, $\psi(2S) \to \pi^+\pi^- J/\psi$, $\psi(2S) \to \gamma\chi_{c1}$, $\psi(2S) \to \gamma\chi_{c2}$, $\chi_{c1} \to \gamma J/\psi$, $\chi_{c2} \to \gamma J/\psi$ by $\pm 1\sigma$
  - ❖ The quadratic sums of the largest variations from each process are assigned as systematic uncertainty
- ➔ Luminosity
  - ❖ Vary the luminosity at each energy point by $\pm 1\sigma$
  - ❖ The largest variation is assigned as systematic uncertainty

Total systematic uncertainty

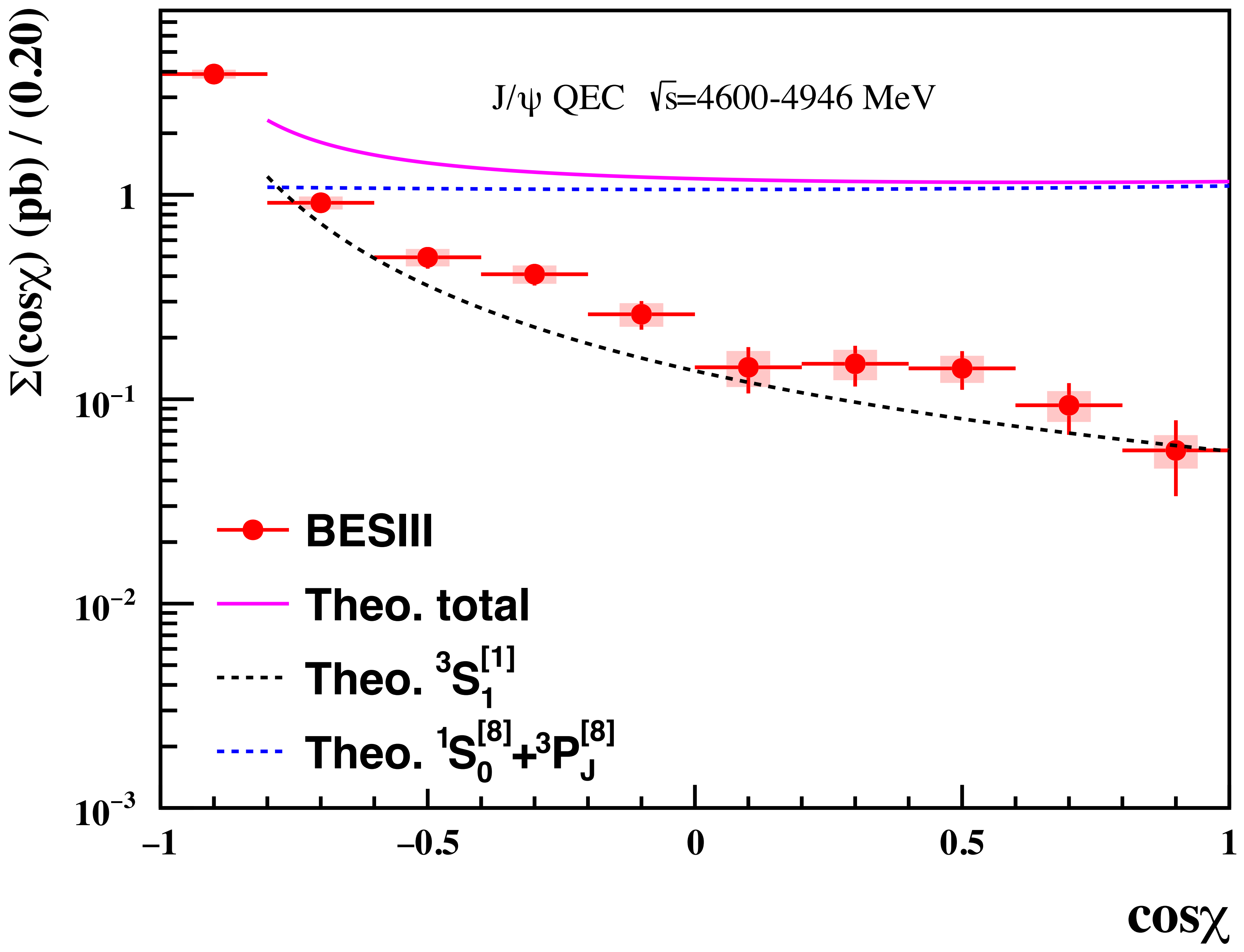


The total systematic uncertainty is the quadratic sum of the systematic uncertainty from each source

Summary

Summary

- ➔ J/ψ energy correlator is firstly studied using 4.600~4.946 GeV 6.44 fb^{-1} data at BESIII
- ➔ Comparing our results with theoretical calculations, our measurement can help to test the NRQCD calculation and understand hadronization mechanism and strong interaction
- ➔ Memo is ready for your review:
  - ❖ https://docbes3.ihep.ac.cn/DocDB/0017/001708/001/JpsiQEC_memo_v1.0.pdf



PRL 133, 191901 (2024)
$\sqrt{s}$=5 GeV e^+e^-

Thanks for your attention!

Backup

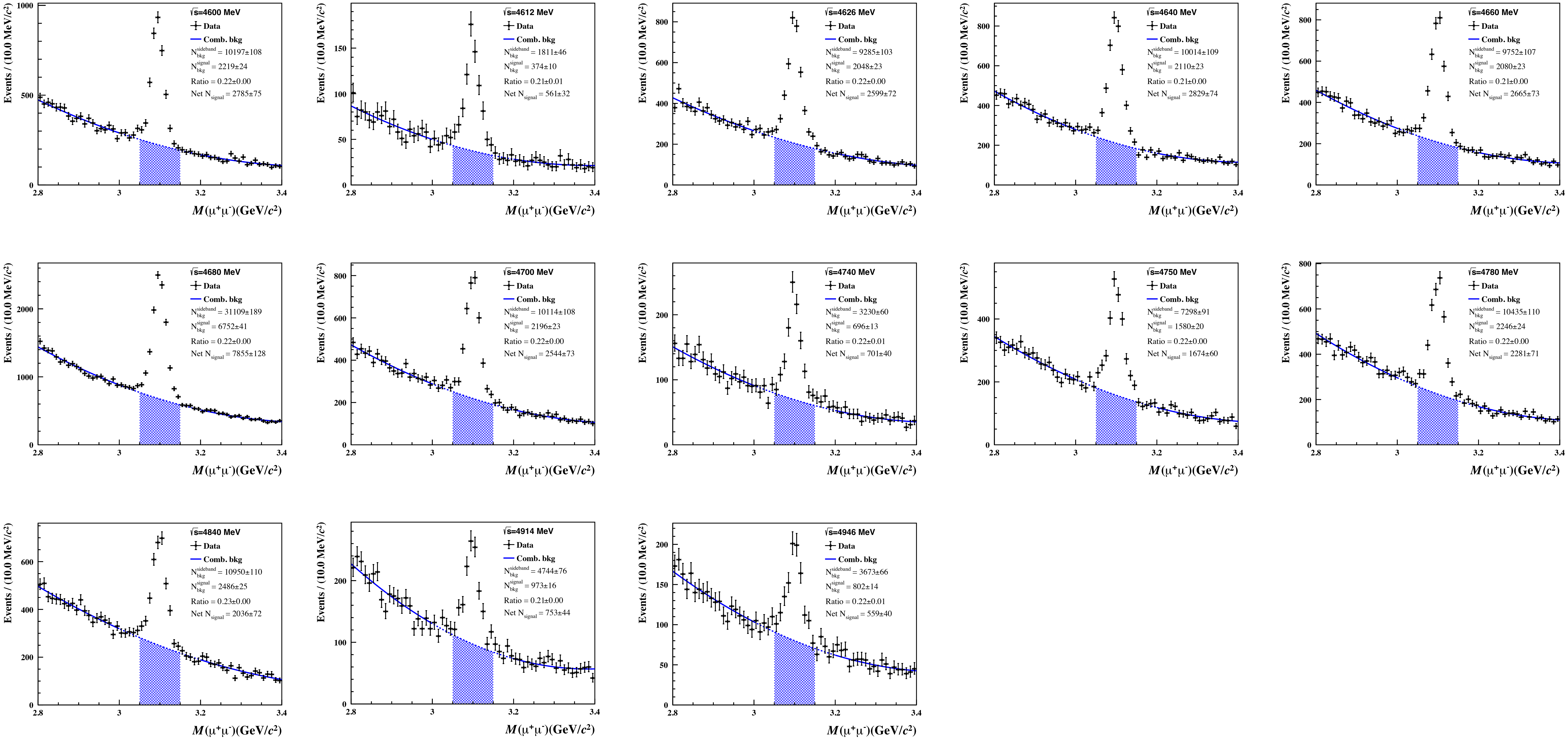
Data sample and input BFs

Sample	$\sqrt{s}$ (MeV)	$\mathcal{L}^i_{\rm int}$ (pb^{-1})	BOSS version
4600	$4599.53 \pm 0.07 \pm 0.74$	$586.9 \pm 0.1 \pm 3.9$	7.0.6
4612	$4611.86 \pm 0.12 \pm 0.30$	$103.65 \pm 0.05 \pm 0.55$	
4626	$4628.00 \pm 0.06 \pm 0.32$	$521.53 \pm 0.11 \pm 2.76$	
4640	$4640.91 \pm 0.06 \pm 0.38$	$551.65 \pm 0.12 \pm 2.92$	
4660	$4661.24 \pm 0.06 \pm 0.29$	$529.43 \pm 0.12 \pm 2.81$	
4680	$4681.92 \pm 0.08 \pm 0.29$	$1667.39 \pm 0.21 \pm 8.84$	
4700	$4698.82 \pm 0.10 \pm 0.36$	$535.54 \pm 0.12 \pm 2.84$	
4740	$4739.70 \pm 0.20 \pm 0.30$	$163.87 \pm 0.07 \pm 0.87$	7.0.7
4750	$4750.05 \pm 0.12 \pm 0.29$	$366.55 \pm 0.10 \pm 1.94$	
4780	$4780.54 \pm 0.12 \pm 0.30$	$511.47 \pm 0.12 \pm 2.71$	
4840	$4843.07 \pm 0.20 \pm 0.31$	$525.16 \pm 0.12 \pm 2.78$	
4914	$4918.02 \pm 0.34 \pm 0.35$	$208.11 \pm 0.08 \pm 1.10$	
4946	$4950.93 \pm 0.36 \pm 0.44$	$160.37 \pm 0.07 \pm 0.85$	

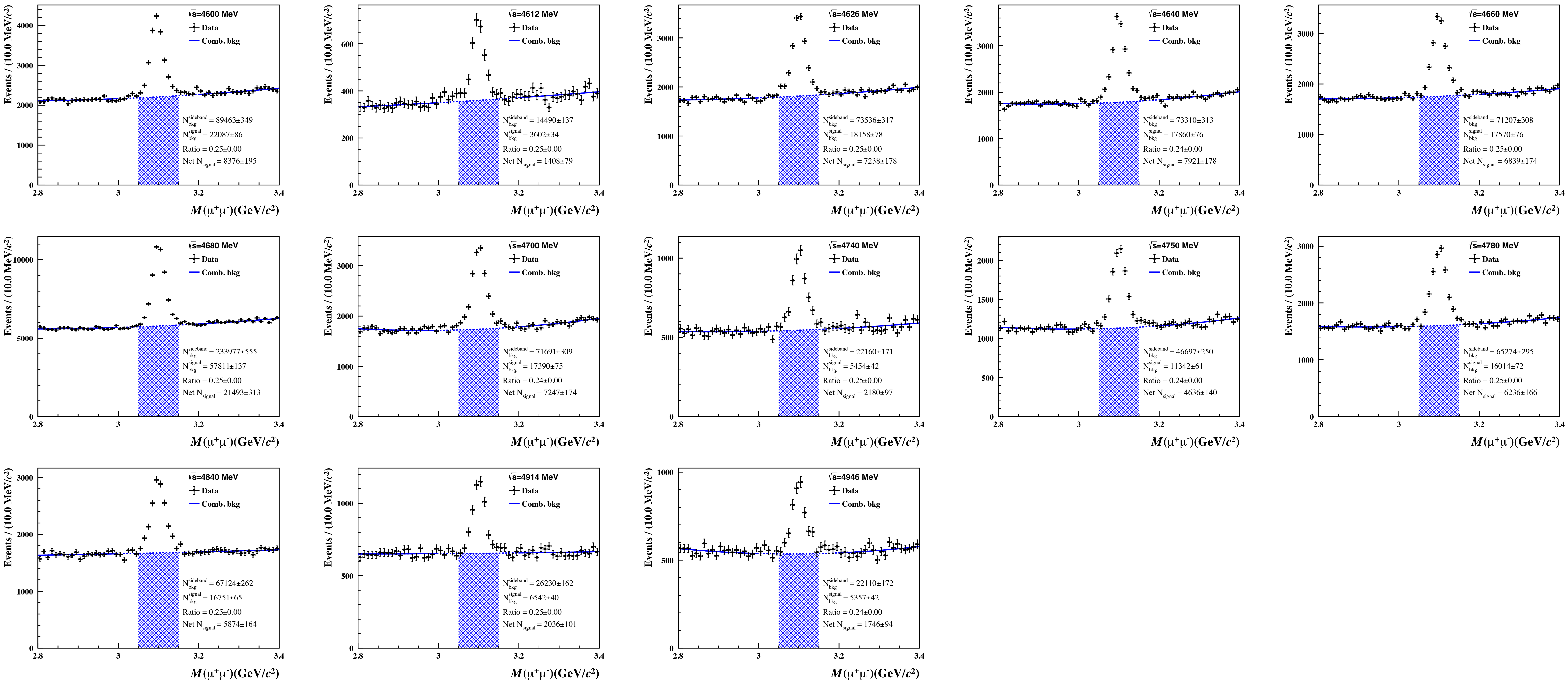
Decay mode	Branching fraction (%)
$J/\psi \to \mu^+\mu^-$	5.961 ± 0.033
$\psi(2S) \to J/\psi X$	61.4 ± 0.6
$\psi(2S) \to \pi^+\pi^- J/\psi$	34.68 ± 0.30
$\psi(2S) \to \gamma\chi_{c1}$	9.75 ± 0.24
$\psi(2S) \to \gamma\chi_{c2}$	9.52 ± 0.20
$\chi_{c1} \to \gamma J/\psi$	34.3 ± 1.0
$\chi_{c2} \to \gamma J/\psi$	19.0 ± 0.5

Table 1: Branching fractions of charmonia decays used in this analysis.

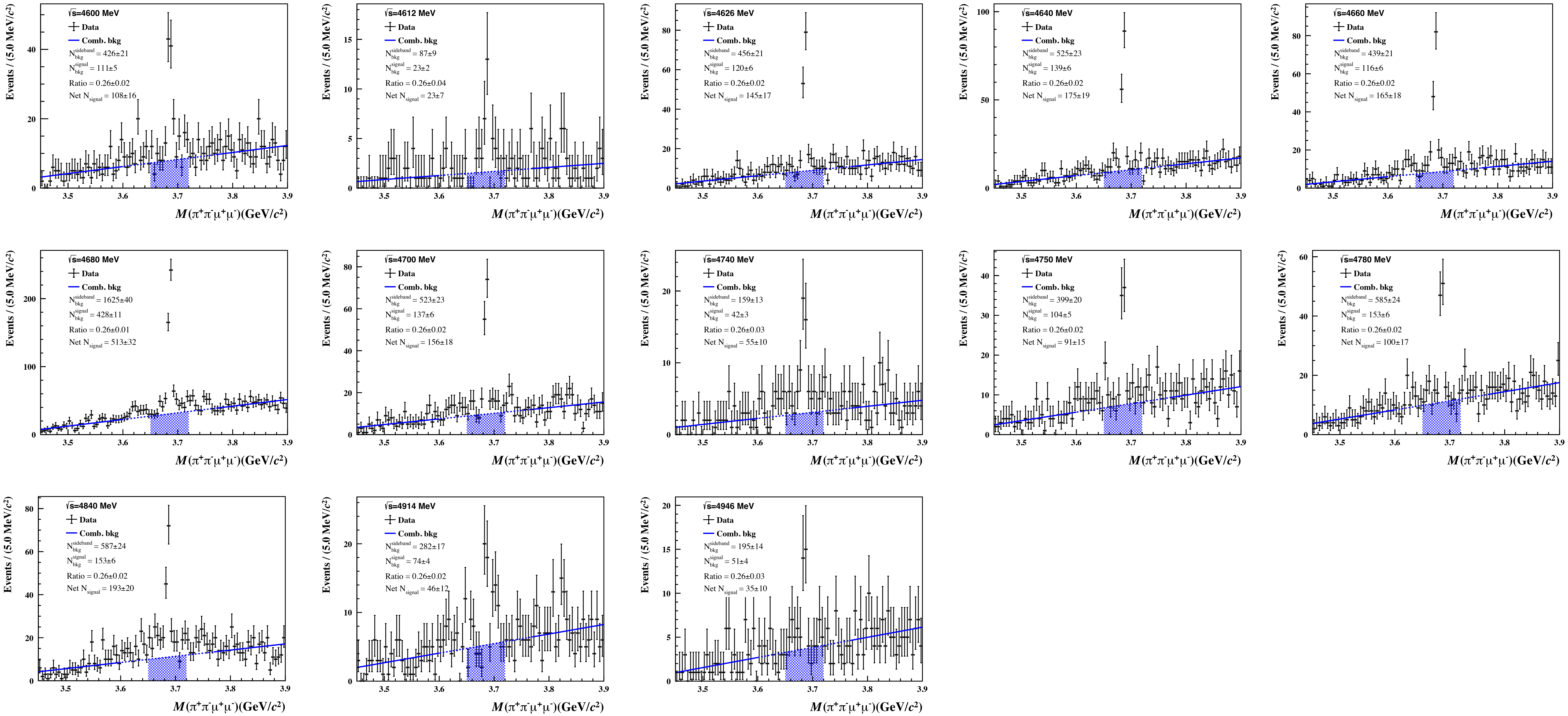
$J/\psi X$


Events / (10.0 MeV/c²)
M(μ⁺μ⁻)(GeV/c²)
Data
Comb. bkg
√s=4600 MeV
N^sideband_bkg = 10197±108
N^signal_bkg = 2219±24
Ratio = 0.22±0.00
Net N_signal = 2785±75
√s=4612 MeV
N^sideband_bkg = 1811±46
N^signal_bkg = 374±10
Ratio = 0.21±0.01
Net N_signal = 561±32
√s=4626 MeV
N^sideband_bkg = 9285±103
N^signal_bkg = 2048±23
Ratio = 0.22±0.00
Net N_signal = 2599±72
√s=4640 MeV
N^sideband_bkg = 10014±109
N^signal_bkg = 2110±23
Ratio = 0.21±0.00
Net N_signal = 2829±74
√s=4660 MeV
N^sideband_bkg = 9752±107
N^signal_bkg = 2080±23
Ratio = 0.21±0.00
Net N_signal = 2665±73
√s=4680 MeV
N^sideband_bkg = 31109±189
N^signal_bkg = 6752±41
Ratio = 0.22±0.00
Net N_signal = 7855±128
√s=4700 MeV
N^sideband_bkg = 10114±108
N^signal_bkg = 2196±23
Ratio = 0.22±0.00
Net N_signal = 2544±73
√s=4740 MeV
N^sideband_bkg = 3230±60
N^signal_bkg = 696±13
Ratio = 0.22±0.01
Net N_signal = 701±40
√s=4750 MeV
N^sideband_bkg = 7298±91
N^signal_bkg = 1580±20
Ratio = 0.22±0.00
Net N_signal = 1674±60
√s=4780 MeV
N^sideband_bkg = 10435±110
N^signal_bkg = 2246±24
Ratio = 0.22±0.00
Net N_signal = 2281±71
√s=4840 MeV
N^sideband_bkg = 10950±110
N^signal_bkg = 2486±25
Ratio = 0.23±0.00
Net N_signal = 2036±72
√s=4914 MeV
N^sideband_bkg = 4744±76
N^signal_bkg = 973±16
Ratio = 0.21±0.00
Net N_signal = 753±44
√s=4946 MeV
N^sideband_bkg = 3673±66
N^signal_bkg = 802±14
Ratio = 0.22±0.01
Net N_signal = 559±40

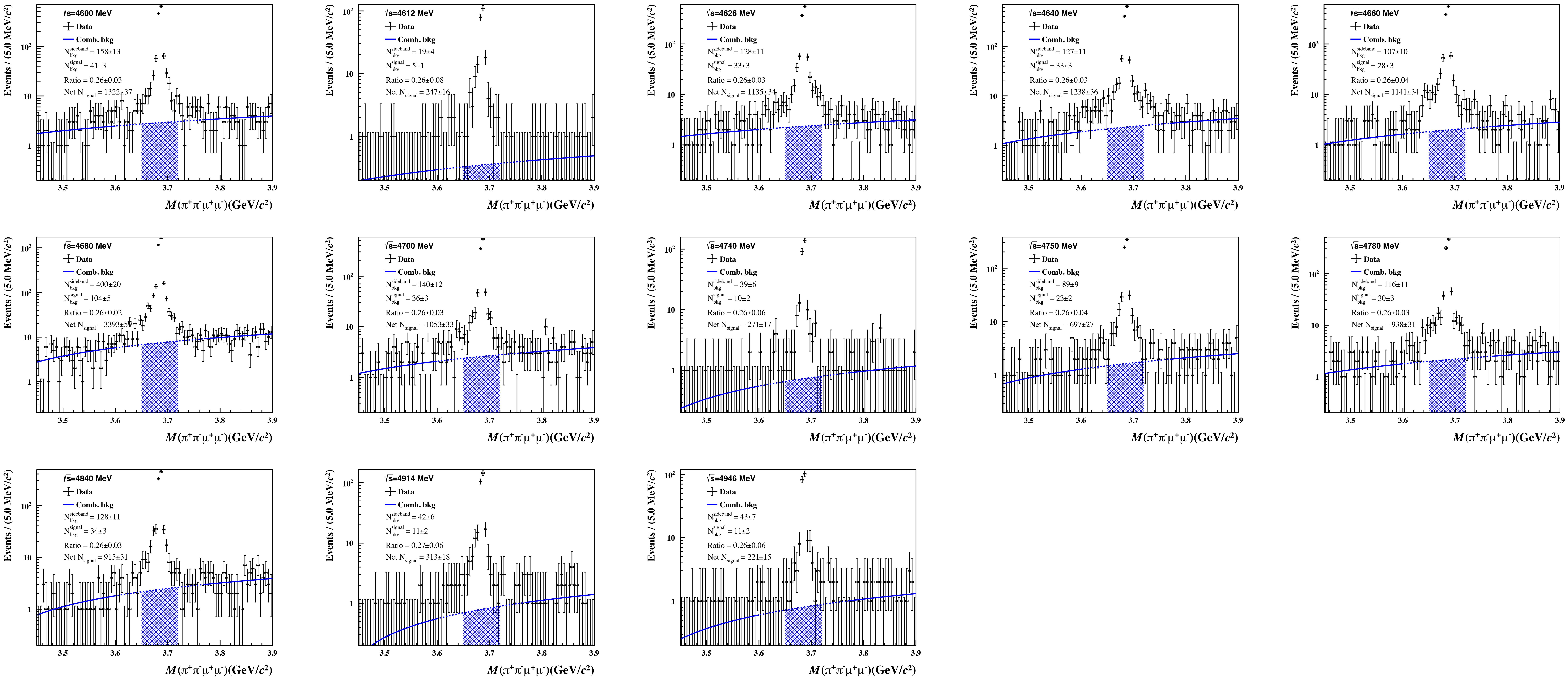
J/ψISR


√s=4600 MeV
Data
Comb. bkg
N_bkg^sideband = 89463±349
N_bkg^signal = 22087±86
Ratio = 0.25±0.00
Net N_signal = 8376±195
√s=4612 MeV
N_bkg^sideband = 14490±137
N_bkg^signal = 3602±34
Ratio = 0.25±0.00
Net N_signal = 1408±79
√s=4626 MeV
N_bkg^sideband = 73536±317
N_bkg^signal = 18158±78
Ratio = 0.25±0.00
Net N_signal = 7238±178
√s=4640 MeV
N_bkg^sideband = 73310±313
N_bkg^signal = 17860±76
Ratio = 0.24±0.00
Net N_signal = 7921±178
√s=4660 MeV
N_bkg^sideband = 71207±308
N_bkg^signal = 17570±76
Ratio = 0.25±0.00
Net N_signal = 6839±174
√s=4680 MeV
N_bkg^sideband = 233977±555
N_bkg^signal = 57811±137
Ratio = 0.25±0.00
Net N_signal = 21493±313
√s=4700 MeV
N_bkg^sideband = 71691±309
N_bkg^signal = 17390±75
Ratio = 0.24±0.00
Net N_signal = 7247±174
√s=4740 MeV
N_bkg^sideband = 22160±171
N_bkg^signal = 5454±42
Ratio = 0.25±0.00
Net N_signal = 2180±97
√s=4750 MeV
N_bkg^sideband = 46697±250
N_bkg^signal = 11342±61
Ratio = 0.24±0.00
Net N_signal = 4636±140
√s=4780 MeV
N_bkg^sideband = 65274±295
N_bkg^signal = 16014±72
Ratio = 0.25±0.00
Net N_signal = 6236±166
√s=4840 MeV
N_bkg^sideband = 67124±262
N_bkg^signal = 16751±65
Ratio = 0.25±0.00
Net N_signal = 5874±164
√s=4914 MeV
N_bkg^sideband = 26230±162
N_bkg^signal = 6542±40
Ratio = 0.25±0.00
Net N_signal = 2036±101
√s=4946 MeV
N_bkg^sideband = 22110±172
N_bkg^signal = 5357±42
Ratio = 0.24±0.00
Net N_signal = 1746±94
Events / (10.0 MeV/c²)
M(μ⁺μ⁻)(GeV/c²)

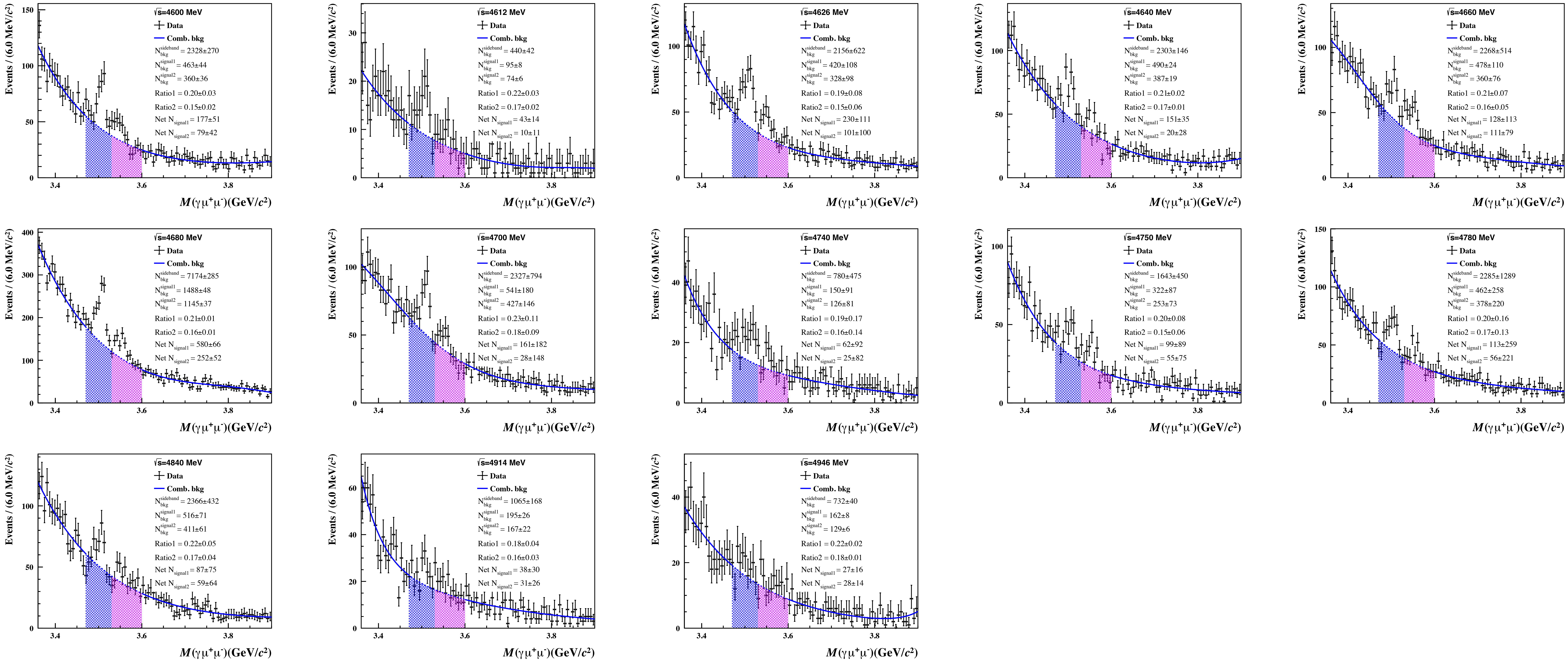
$\psi(2S)X$


√s=4600 MeV
Data
Comb. bkg
N_bkg^sideband = 426±21
N_bkg^signal = 111±5
Ratio = 0.26±0.02
Net N_signal = 108±16
√s=4612 MeV
N_bkg^sideband = 87±9
N_bkg^signal = 23±2
Ratio = 0.26±0.04
Net N_signal = 23±7
√s=4626 MeV
N_bkg^sideband = 456±21
N_bkg^signal = 120±6
Ratio = 0.26±0.02
Net N_signal = 145±17
√s=4640 MeV
N_bkg^sideband = 525±23
N_bkg^signal = 139±6
Ratio = 0.26±0.02
Net N_signal = 175±19
√s=4660 MeV
N_bkg^sideband = 439±21
N_bkg^signal = 116±6
Ratio = 0.26±0.02
Net N_signal = 165±18
√s=4680 MeV
N_bkg^sideband = 1625±40
N_bkg^signal = 428±11
Ratio = 0.26±0.01
Net N_signal = 513±32
√s=4700 MeV
N_bkg^sideband = 523±23
N_bkg^signal = 137±6
Ratio = 0.26±0.02
Net N_signal = 156±18
√s=4740 MeV
N_bkg^sideband = 159±13
N_bkg^signal = 42±3
Ratio = 0.26±0.03
Net N_signal = 55±10
√s=4750 MeV
N_bkg^sideband = 399±20
N_bkg^signal = 104±5
Ratio = 0.26±0.02
Net N_signal = 91±15
√s=4780 MeV
N_bkg^sideband = 585±24
N_bkg^signal = 153±6
Ratio = 0.26±0.02
Net N_signal = 100±17
√s=4840 MeV
N_bkg^sideband = 587±24
N_bkg^signal = 153±6
Ratio = 0.26±0.02
Net N_signal = 193±20
√s=4914 MeV
N_bkg^sideband = 282±17
N_bkg^signal = 74±4
Ratio = 0.26±0.02
Net N_signal = 46±12
√s=4946 MeV
N_bkg^sideband = 195±14
N_bkg^signal = 51±4
Ratio = 0.26±0.03
Net N_signal = 35±10
Events / (5.0 MeV/c²)
M(π⁺π⁻μ⁺μ⁻)(GeV/c²)

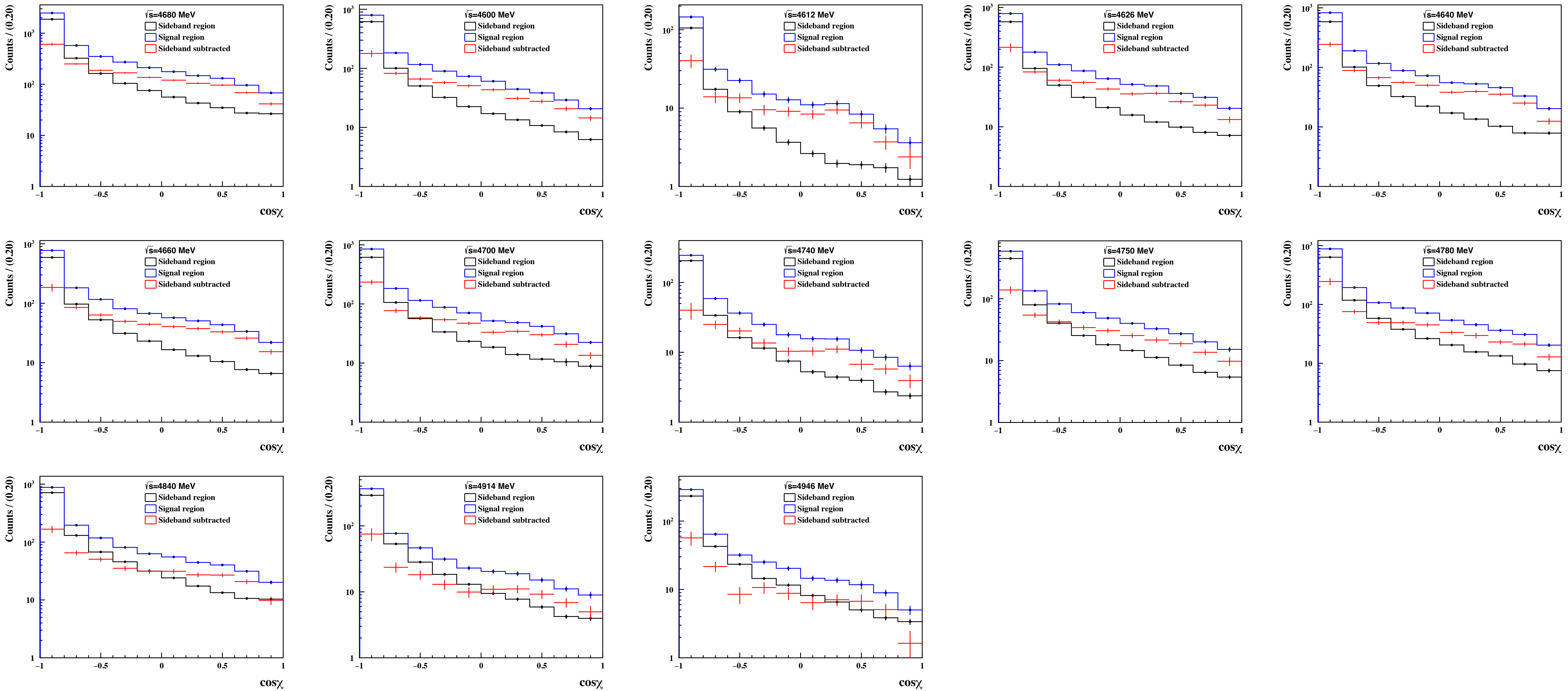
$\psi(2S)$ISR


√s=4600 MeV
Data
Comb. bkg
$N_{bkg}^{sideband}$ = 158±13
N_{bkg}^{signal} = 41±3
Ratio = 0.26±0.03
Net N_{signal} = 1322±37
√s=4612 MeV
$N_{bkg}^{sideband}$ = 19±4
N_{bkg}^{signal} = 5±1
Ratio = 0.26±0.08
Net N_{signal} = 247±16
√s=4626 MeV
$N_{bkg}^{sideband}$ = 128±11
N_{bkg}^{signal} = 33±3
Ratio = 0.26±0.03
Net N_{signal} = 1135±34
√s=4640 MeV
$N_{bkg}^{sideband}$ = 127±11
N_{bkg}^{signal} = 33±3
Ratio = 0.26±0.03
Net N_{signal} = 1238±36
√s=4660 MeV
$N_{bkg}^{sideband}$ = 107±10
N_{bkg}^{signal} = 28±3
Ratio = 0.26±0.04
Net N_{signal} = 1141±34
√s=4680 MeV
$N_{bkg}^{sideband}$ = 400±20
N_{bkg}^{signal} = 104±5
Ratio = 0.26±0.02
Net N_{signal} = 3393±59
√s=4700 MeV
$N_{bkg}^{sideband}$ = 140±12
N_{bkg}^{signal} = 36±3
Ratio = 0.26±0.03
Net N_{signal} = 1053±33
√s=4740 MeV
$N_{bkg}^{sideband}$ = 39±6
N_{bkg}^{signal} = 10±2
Ratio = 0.26±0.06
Net N_{signal} = 271±17
√s=4750 MeV
$N_{bkg}^{sideband}$ = 89±9
N_{bkg}^{signal} = 23±2
Ratio = 0.26±0.04
Net N_{signal} = 697±27
√s=4780 MeV
$N_{bkg}^{sideband}$ = 116±11
N_{bkg}^{signal} = 30±3
Ratio = 0.26±0.03
Net N_{signal} = 938±31
√s=4840 MeV
$N_{bkg}^{sideband}$ = 128±11
N_{bkg}^{signal} = 34±3
Ratio = 0.26±0.03
Net N_{signal} = 915±31
√s=4914 MeV
$N_{bkg}^{sideband}$ = 42±6
N_{bkg}^{signal} = 11±2
Ratio = 0.27±0.06
Net N_{signal} = 313±18
√s=4946 MeV
$N_{bkg}^{sideband}$ = 43±7
N_{bkg}^{signal} = 11±2
Ratio = 0.26±0.06
Net N_{signal} = 221±15
Events / (5.0 MeV/c^2)
$M(\pi^+\pi^-\mu^+\mu^-)$(GeV/c^2)

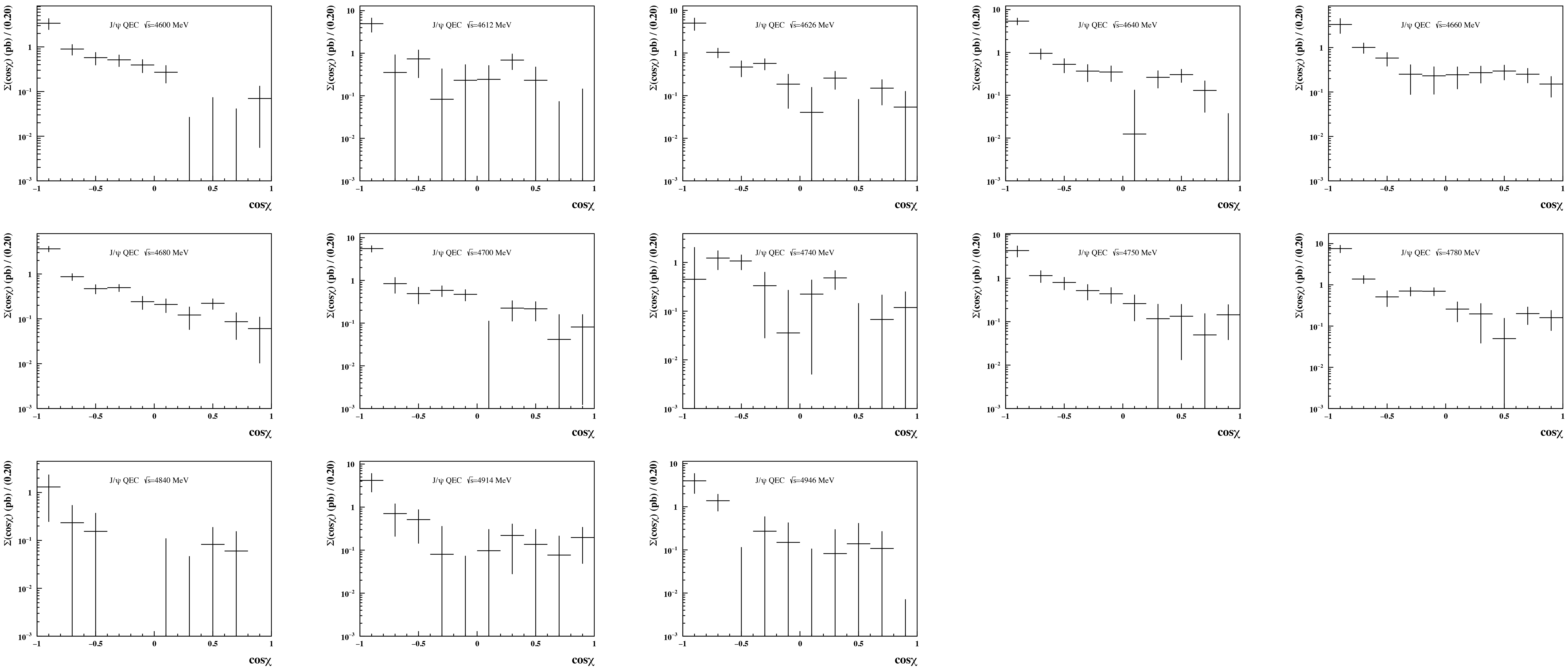
χ_{cJ}


√s=4600 MeV
Data
Comb. bkg
$N_{bkg}^{sideband}$ = 2328±270
$N_{bkg}^{signal1}$ = 463±44
$N_{bkg}^{signal2}$ = 360±36
Ratio1 = 0.20±0.03
Ratio2 = 0.15±0.02
Net $N_{signal1}$ = 177±51
Net $N_{signal2}$ = 79±42
√s=4612 MeV
$N_{bkg}^{sideband}$ = 440±42
$N_{bkg}^{signal1}$ = 95±8
$N_{bkg}^{signal2}$ = 74±6
Ratio1 = 0.22±0.03
Ratio2 = 0.17±0.02
Net $N_{signal1}$ = 43±14
Net $N_{signal2}$ = 10±11
√s=4626 MeV
$N_{bkg}^{sideband}$ = 2156±622
$N_{bkg}^{signal1}$ = 420±108
$N_{bkg}^{signal2}$ = 328±98
Ratio1 = 0.19±0.08
Ratio2 = 0.15±0.06
Net $N_{signal1}$ = 230±111
Net $N_{signal2}$ = 101±100
√s=4640 MeV
$N_{bkg}^{sideband}$ = 2303±146
$N_{bkg}^{signal1}$ = 490±24
$N_{bkg}^{signal2}$ = 387±19
Ratio1 = 0.21±0.02
Ratio2 = 0.17±0.01
Net $N_{signal1}$ = 151±35
Net $N_{signal2}$ = 20±28
√s=4660 MeV
$N_{bkg}^{sideband}$ = 2268±514
$N_{bkg}^{signal1}$ = 478±110
$N_{bkg}^{signal2}$ = 360±76
Ratio1 = 0.21±0.07
Ratio2 = 0.16±0.05
Net $N_{signal1}$ = 128±113
Net $N_{signal2}$ = 111±79
√s=4680 MeV
$N_{bkg}^{sideband}$ = 7174±285
$N_{bkg}^{signal1}$ = 1488±48
$N_{bkg}^{signal2}$ = 1145±37
Ratio1 = 0.21±0.01
Ratio2 = 0.16±0.01
Net $N_{signal1}$ = 580±66
Net $N_{signal2}$ = 252±52
√s=4700 MeV
$N_{bkg}^{sideband}$ = 2327±794
$N_{bkg}^{signal1}$ = 541±180
$N_{bkg}^{signal2}$ = 427±146
Ratio1 = 0.23±0.11
Ratio2 = 0.18±0.09
Net $N_{signal1}$ = 161±182
Net $N_{signal2}$ = 28±148
√s=4740 MeV
$N_{bkg}^{sideband}$ = 780±475
$N_{bkg}^{signal1}$ = 150±91
$N_{bkg}^{signal2}$ = 126±81
Ratio1 = 0.19±0.17
Ratio2 = 0.16±0.14
Net $N_{signal1}$ = 62±92
Net $N_{signal2}$ = 25±82
√s=4750 MeV
$N_{bkg}^{sideband}$ = 1643±450
$N_{bkg}^{signal1}$ = 322±87
$N_{bkg}^{signal2}$ = 253±73
Ratio1 = 0.20±0.08
Ratio2 = 0.15±0.06
Net $N_{signal1}$ = 99±89
Net $N_{signal2}$ = 55±75
√s=4780 MeV
$N_{bkg}^{sideband}$ = 2285±1289
$N_{bkg}^{signal1}$ = 462±258
$N_{bkg}^{signal2}$ = 378±220
Ratio1 = 0.20±0.16
Ratio2 = 0.17±0.13
Net $N_{signal1}$ = 113±259
Net $N_{signal2}$ = 56±221
√s=4840 MeV
$N_{bkg}^{sideband}$ = 2366±432
$N_{bkg}^{signal1}$ = 516±71
$N_{bkg}^{signal2}$ = 411±61
Ratio1 = 0.22±0.05
Ratio2 = 0.17±0.04
Net $N_{signal1}$ = 87±75
Net $N_{signal2}$ = 59±64
√s=4914 MeV
$N_{bkg}^{sideband}$ = 1065±168
$N_{bkg}^{signal1}$ = 195±26
$N_{bkg}^{signal2}$ = 167±22
Ratio1 = 0.18±0.04
Ratio2 = 0.16±0.03
Net $N_{signal1}$ = 38±30
Net $N_{signal2}$ = 31±26
√s=4946 MeV
$N_{bkg}^{sideband}$ = 732±40
$N_{bkg}^{signal1}$ = 162±8
$N_{bkg}^{signal2}$ = 129±6
Ratio1 = 0.22±0.02
Ratio2 = 0.18±0.01
Net $N_{signal1}$ = 27±16
Net $N_{signal2}$ = 28±14
Events / (6.0 MeV/c^2)
$M(\gamma\mu^+\mu^-)$(GeV/c^2)

$J/\psi X$ energy weighted angular distribution

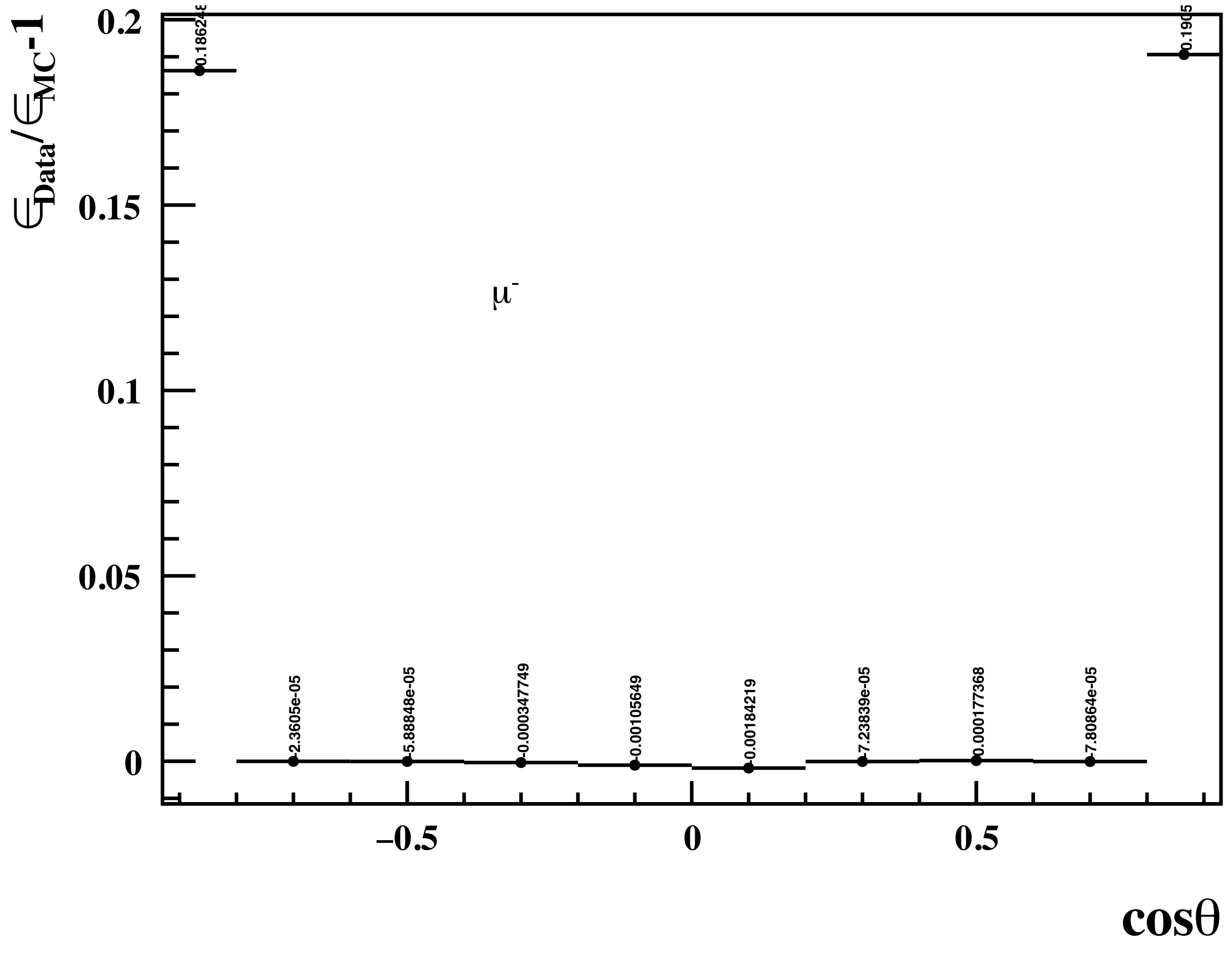


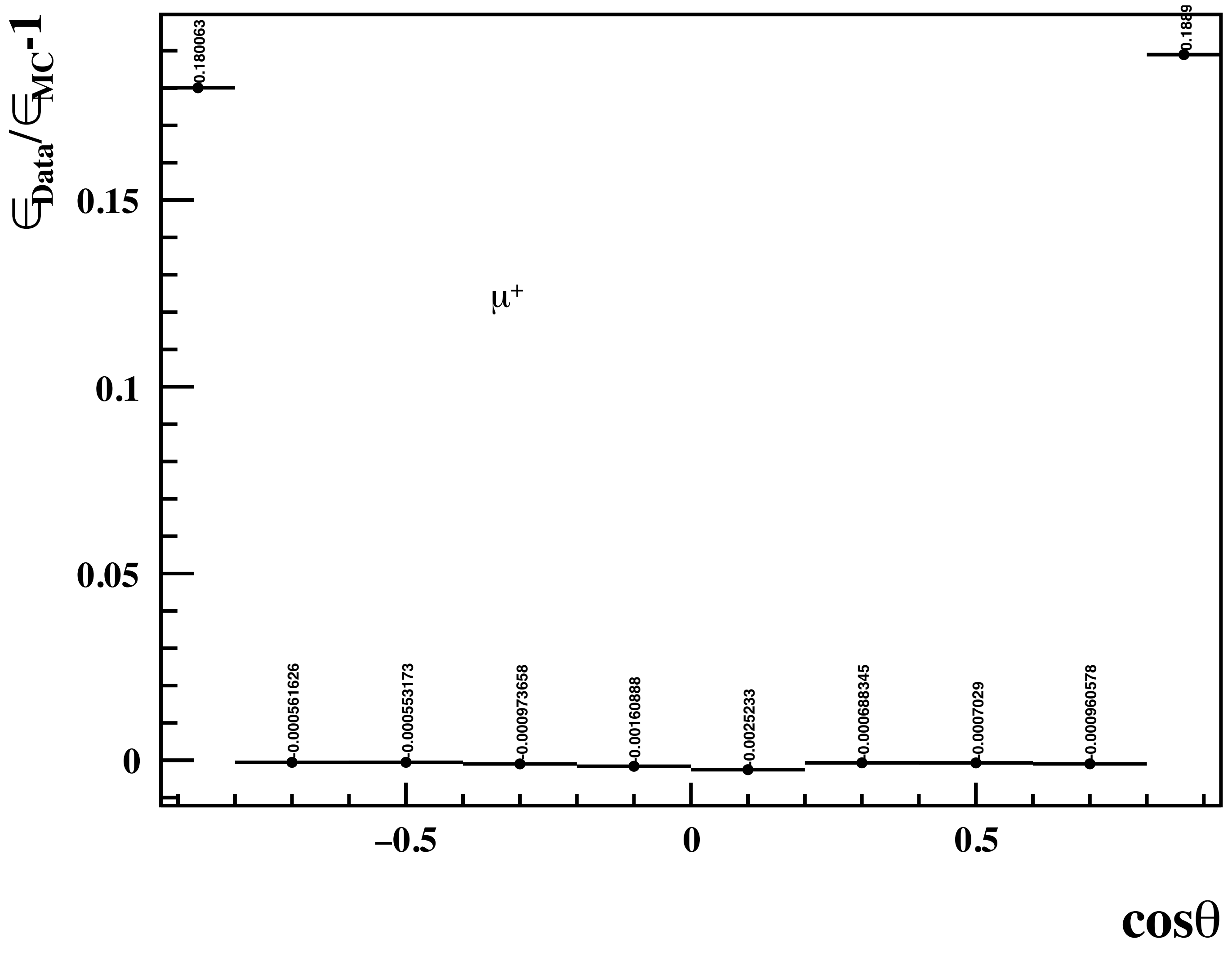
QEC results at single energy point



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

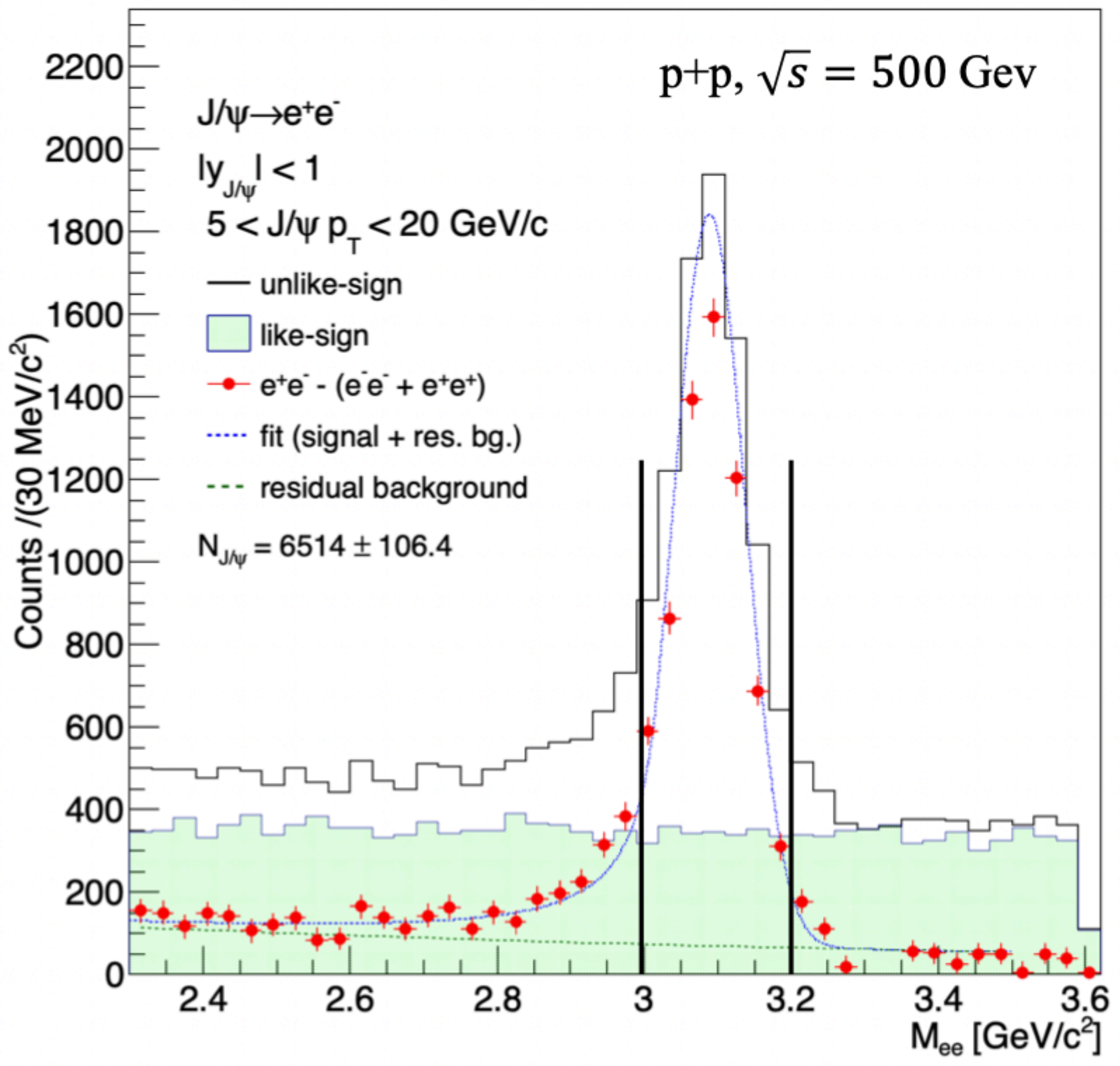
- ➔ Event selection
  - ❖ The number of good charged tracks equal to 2, and the total charge sum equal to 0
  - ❖ For tag muon, $\mathscr{L}_\mu > 0.001, \mathscr{L}_\mu > \mathscr{L}_e, \mathscr{L}_\mu > \mathscr{L}_K$
  - ❖ For tag muon, the ratio of EMC deposited energy E and MDC momentum P should satisfy $E/p < 0.3$
  - ❖ For tag muon, the depth in MUC should be larger than 40 cm
  - ❖ No good neutral shower is reconstructed
  - ❖ The opening angle between two charged tracks should satisfy $\theta_{\mu^+\mu^-} > 177°$
- ➔ Purity: >99.9% in the MC simulation
- ➔ Data-MC difference $\varepsilon_{\text{Data}}/\varepsilon_{\text{MC}} - 1$





STAR results

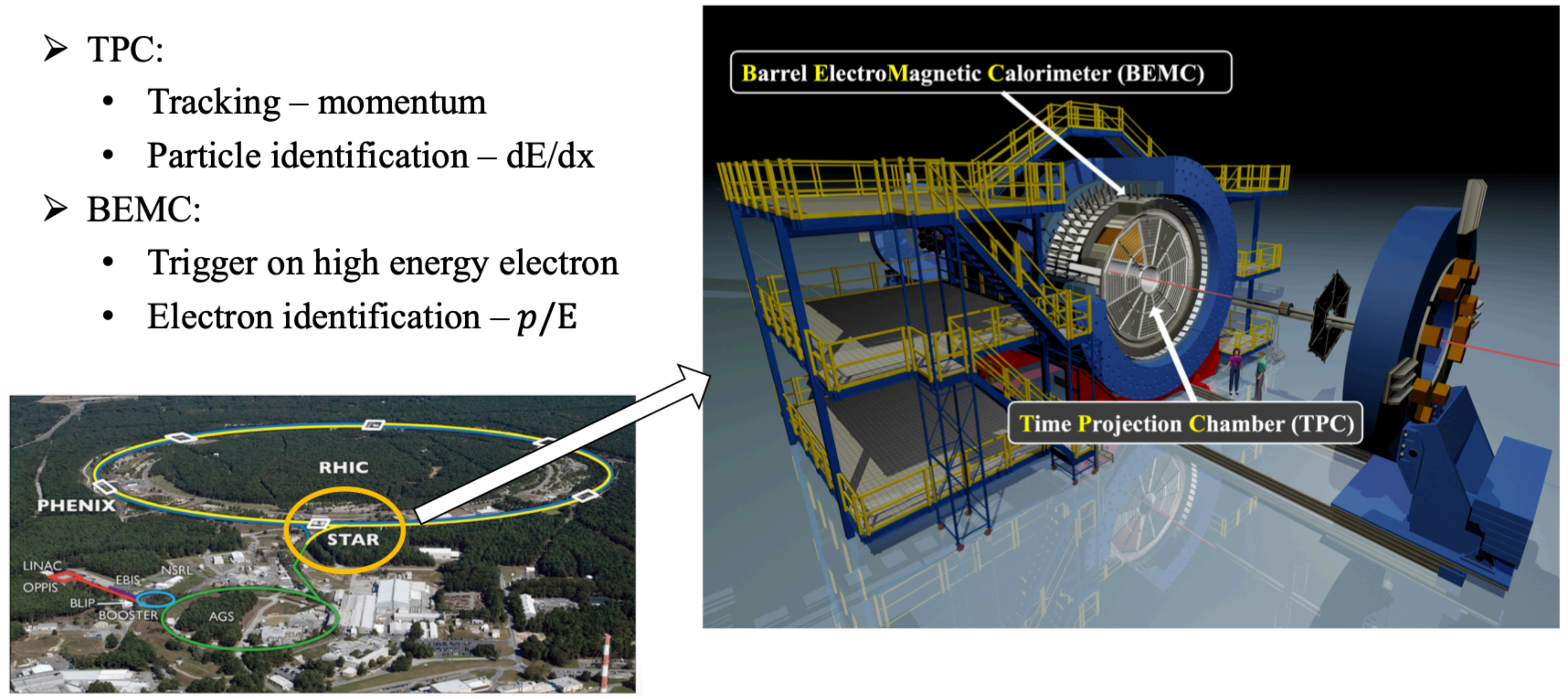
Dandan Shen'talk at Hot Quarks 2025



- Decay channel : $J/\psi \to e^+e^-$, |y|<1 with p+p $\sqrt{s} = 500$ GeV
- J/ψ p_T range: 5-20 GeV/c
- Mass range: [3.0, 3.2] GeV/c²

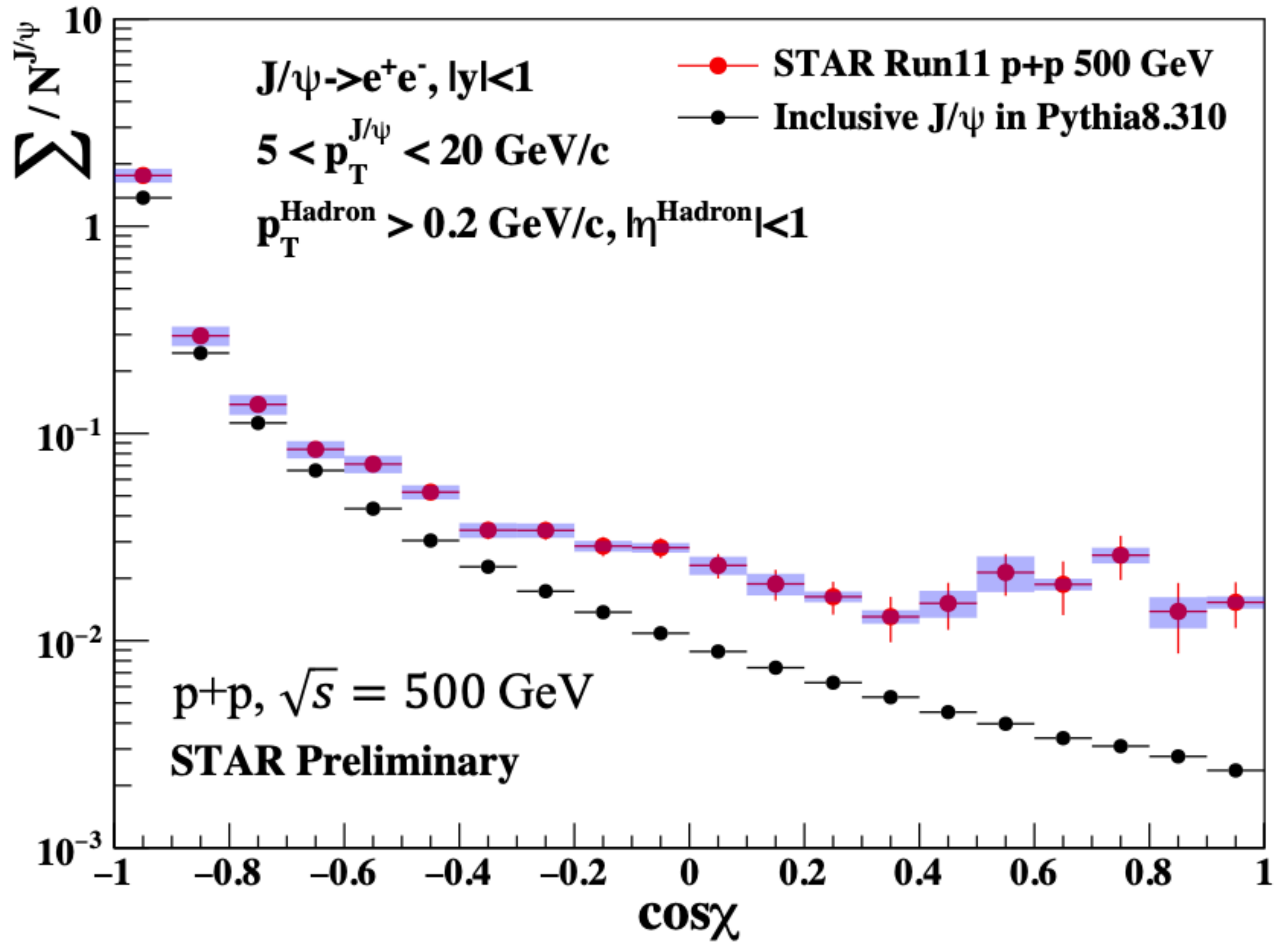
The Solenoid Tracker At RHIC (STAR)

- TPC:
  - Tracking – momentum
  - Particle identification – dE/dx
- BEMC:
  - Trigger on high energy electron
  - Electron identification – p/E



	2011	2017	2022
$\sqrt{s}$(GeV)	500	510	508
L_{int} (pb^{-1})	25	350	400
Pseudo-rapidity range	$|\eta| < 1$	$|\eta| < 1$	$|\eta| < 1$ $2.5 < \eta < 4$

This work



- No significant $\cos\chi$ dependence in large $\cos\chi$ range
- Significantly different J/ψ energy correlator between PYTHIA8 and data at $\cos\chi > 0$ (~7σ difference)
- Studies on extracting J/ψ hadronization process's energy emission is on going