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Study of Quarkonium Energy Correlator (QEC) at BESIII

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Outline

- ➔ Motivation
- ➔ Analysis method
- ➔ Data and MC samples
- ➔ Event selection
- ➔ J/ψ QEC analysis
- ➔ $\psi(2S)$ QEC analysis
- ➔ 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

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

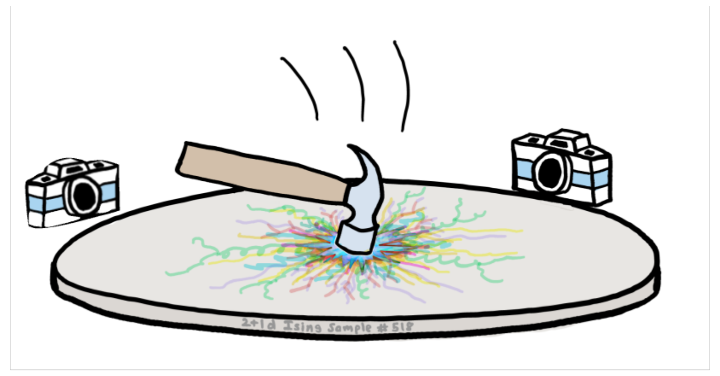
- Encoded in $\langle \mathcal{O}_1 \rangle, \langle \mathcal{O}_8 \rangle$
- Remains largely unkown: amount of energy released? Energy distribution?

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 arised from theorists

PRL 133, 191901 (2024)

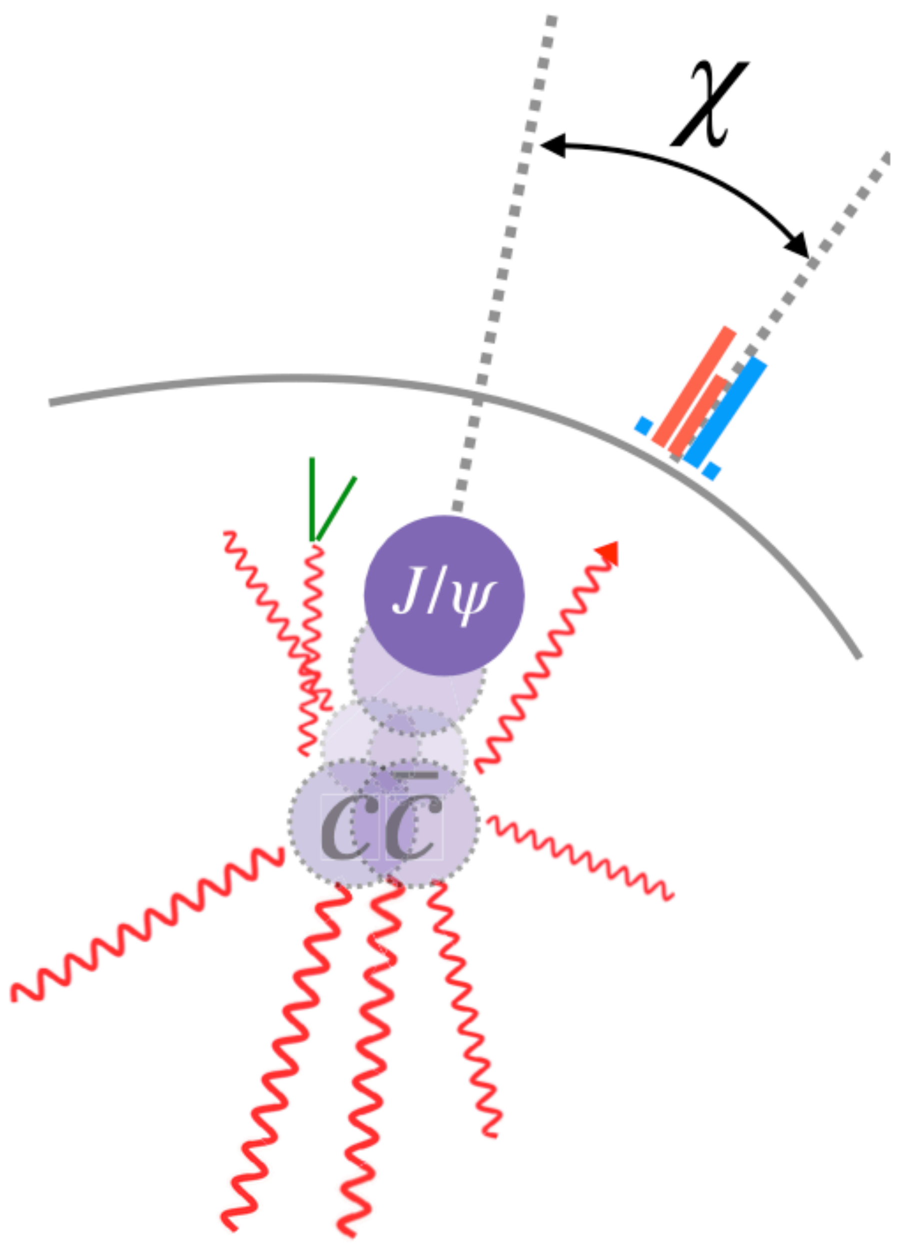
Quarkonium Energy Correlator

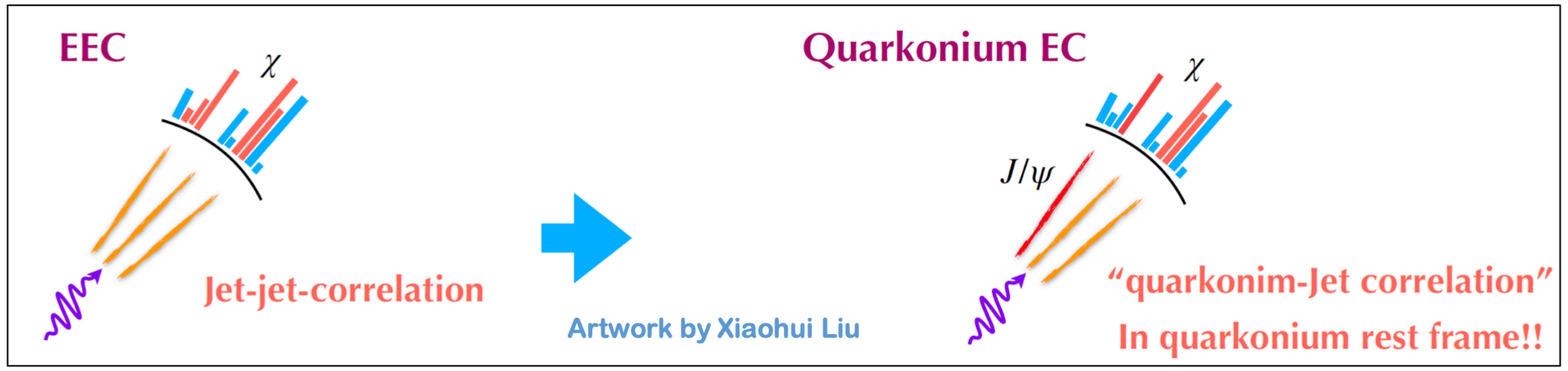
PRL 133, 191901 (2024)

➔ **QEC Definition:**

$$\Sigma(\cos\chi) = \int d\sigma \sum_i \frac{E_i}{M}\delta(\cos\chi - \cos\theta_i)$$

- $d\sigma$: 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: the mass of the J/ψ



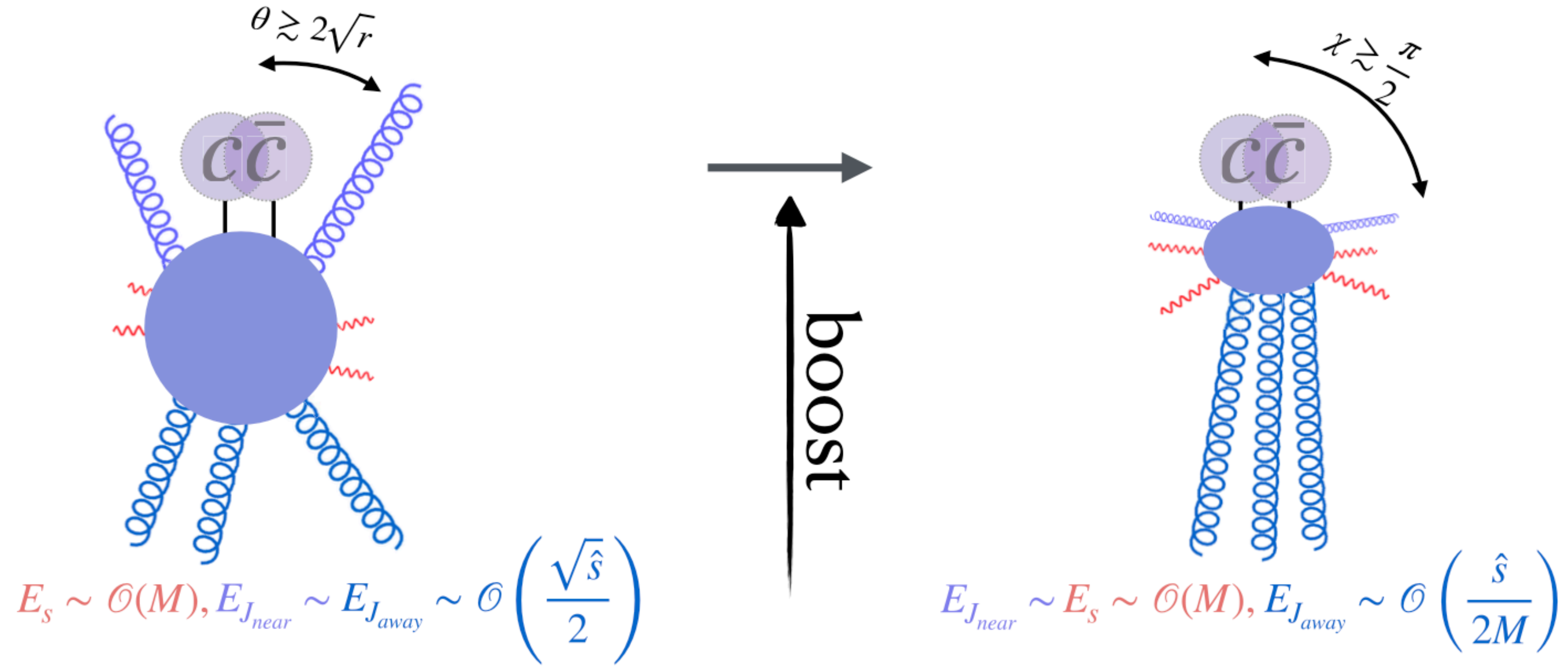


➔ **Advantage of QEC observable**

- 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)

$$\Sigma(\cos\chi) = \sum_{ch} \Sigma^{ch}_{P.T.}(\cos\chi) + \Sigma^{ch}_{N.P.}(\cos\chi),$$

➔ **Hard radiation contribution $\Sigma_{P.T.}$**

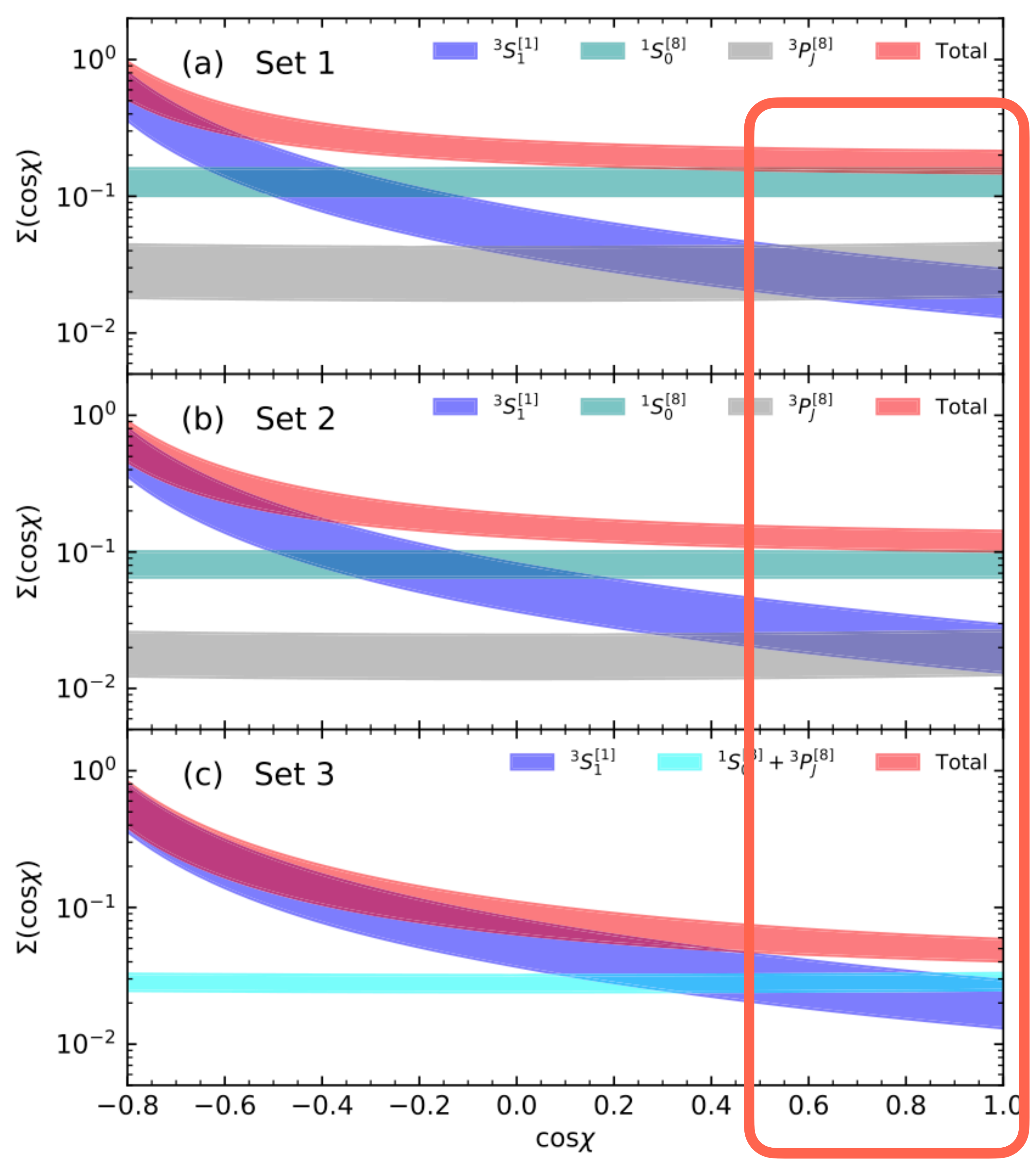
- Color-singlet (CS) mechanism: $e^+e^- \to \gamma^* \to c\bar{c}[^3S_1^{[1]}] + g + g$
- Calculate using pertubative theory
- Dominate when $\chi \gtrsim (\pi/2)$

➔ **Nonperturbative soft radiation contribution $\Sigma_{N.P}$**

- Color-octet (CO) mechanism: $e^+e^- \to \gamma^* \to c\bar{c}[^1S_0^{[8]}, ^3P_J^{[8]}] + g$
- Physics necessary for comprehending the hadronization mechanism
- Dominate when $\chi \lesssim (\pi/2)$

➔ **Advantages at BESIII**

- Lower energy → Nonperturbative contribution more significant than perturbative contribution
- Clean detection environment → better suppress feed-down background



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

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

Analysis method

Analysis method

- ➔ Reconstruct prompt J/ψ by $J/\psi \to \mu^+\mu^-$ and prompt $\psi(2S)$ by $\psi(2S) \to \pi^+\pi^- J/\psi, J/\psi \to \mu^+\mu^-/e^+e^-$
  - ❖ Only muon channel has been used for preliminary study so far
- ➔ Require additional charged tracks accompanying charmonia
- ➔ Remove the contributions from feed-down effects
  - ❖ Non-prompt J/ψ — ISR return return back to J/ψ and $\psi(2S)$, prompt $\psi(2S)$, χ_{cJ}
  - ❖ Non-prompt $\psi(2S)$ — ISR return back to $\psi(2S)$
- ➔ The main event selection basically follows BAM-557

Data and MC samples

Data and MC samples

- As a preliminary study, only data at $\sqrt{s} = 4.946\,\mathrm{GeV}$ is used
  - Integrated luminosity $160.37 \pm 0.07 \pm 0.85\,\mathrm{pb}^{-1}$
  - Boss version: 7.0.7
- Inclusive and exclusive signal MC samples (200 thousand events for each)
  - $J/\psi X$ — ConExc
    - $\pi^+\pi^- J/\psi$, $\pi^0\pi^0 J/\psi$, $K^+K^- J/\psi$, $K^0_S K^0_S J/\psi$, $K^0_L K^0_L J/\psi$, $\eta J/\psi$, $\eta' J/\psi$ (PHSP); $J/\psi \to \mu^+\mu^-$ (PHOTOS VLL)
    - Relative ratios refer to cross section measurement
  - $\gamma_{\mathrm{ISR}} J/\psi$ — KKMC
    - $\gamma_{\mathrm{ISR}} J/\psi$; $J/\psi \to \mu^+\mu^-$ (PHOTOS VLL)
  - $\psi(2S)X$ — ConExc
    - $\pi^+\pi^-\psi(2S)$, $\pi^0\pi^0\psi(2S)$ (PHSP); $\psi(2S) \to \pi^+\pi^- J/\psi$, $\pi^0\pi^0 J/\psi$ (JPIPI), $\eta J/\psi$ (HELAMP); $J/\psi \to \mu^+\mu^-$ (PHOTOS VLL)
    - Relative ratio between $\pi^+\pi^-\psi(2S)$ and $\pi^0\pi^0\psi(2S)$ follows 2 : 1 relation
    - $\psi(2S)$ decay BFs follow PDG values
  - $\gamma_{\mathrm{ISR}}\psi(2S)$ — KKMC
    - $\gamma_{\mathrm{ISR}}\psi(2S)$; $\psi(2S) \to J/\psi X$; $J/\psi \to \mu^+\mu^-$ (PHOTOS VLL)
  - $\chi_{cJ} X$ — KKMC
    - $\gamma_{\mathrm{ISR}}\psi(2S)$; $\psi(2S) \to \gamma\chi_{cJ}$ (P2GC1 or P2GC2); $\chi_{cJ} \to \gamma J/\psi$ (AV2GV); $J/\psi \to \mu^+\mu^-$ (PHOTOS VLL)

Event selection

Track and Shower selection

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

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

Event selection

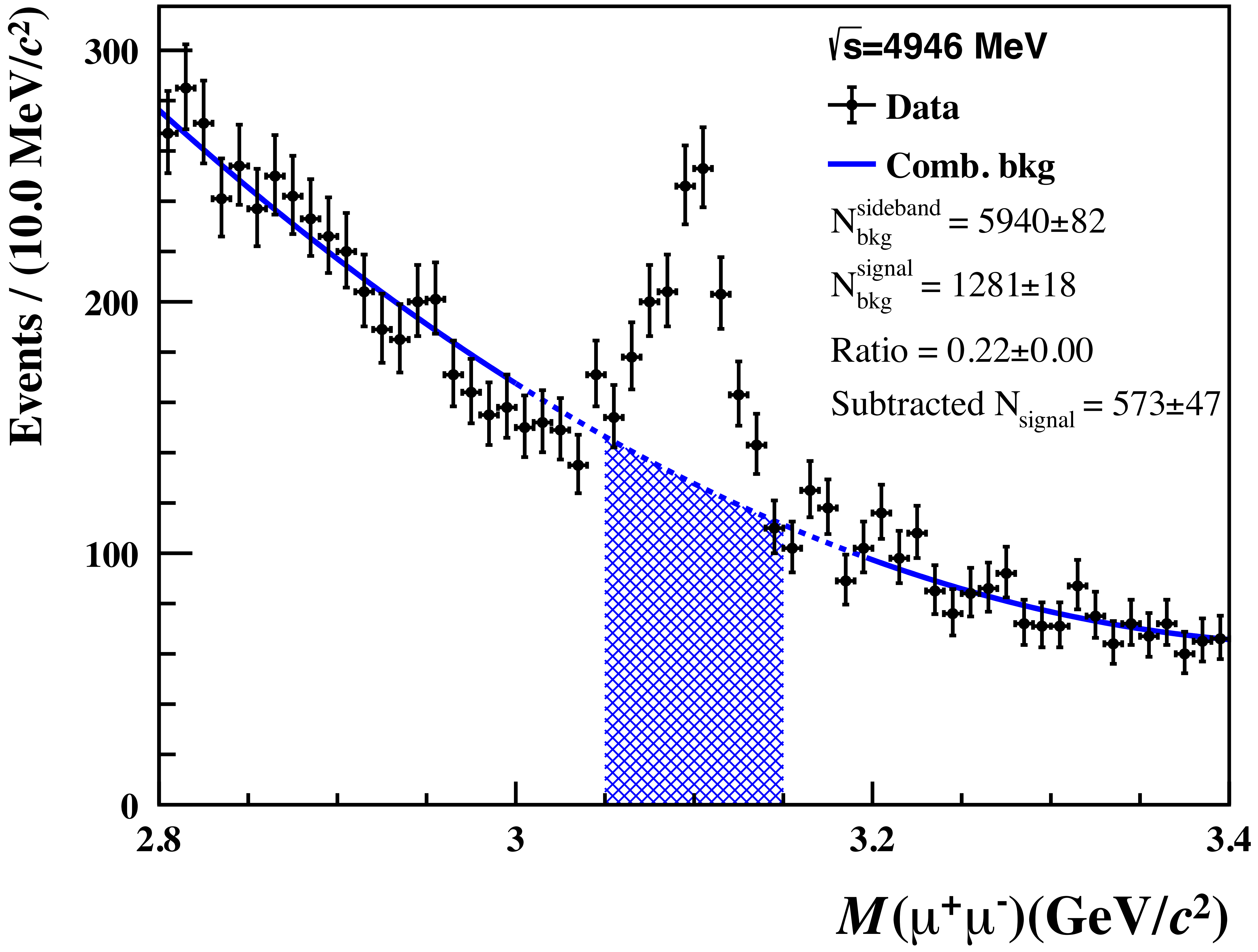
- $e^+e^- \to J/\psi X, J/\psi \to \mu^+\mu^-$
  - More than one positive or more than one negative reconstructed charged tracks
  - For muon identification, require EMC deposited energy $E^{\mu}_{\mathrm{EMC}} < 0.6\,\mathrm{GeV}$
- $e^+e^- \to \gamma_{\mathrm{ISR}} J/\psi, J/\psi \to \mu^+\mu^-$
  - Exactly one positive and one negative reconstructed charged tracks and less than two photons
- $e^+e^- \to \gamma_{\mathrm{ISR}} \psi(2S), \psi(2S) \to \pi^+\pi^- J/\psi, J/\psi \to \mu^+\mu^-$
  - Exactly two positive and two negative reconstructed charged tracks and less than two photons
  - At least one pair of selected charged tracks satisfy J/ψ selection
  - 1C kinematic fit to J/ψ mass to choose the only muon pair with minimal χ^2, $\chi^2 < 50$
- $e^+e^- \to \psi(2S) X, \psi(2S) \to \pi^+\pi^- J/\psi, J/\psi \to \mu^+\mu^-$
  - More than two positive or more than two negative reconstructed charged tracks
  - Same J/ψ kinematic fit requirement
  - All other charged track pairs are considered as $\pi^+\pi^-$ without PID
- $e^+e^- \to \chi_{cJ} X, \chi_{cJ} \to \gamma J/\psi, J/\psi \to \mu^+\mu^-$
  - Exactly one positive and one negative reconstructed charged tracks and at least two photons
  - More than one positive or more than one negative reconstructed charged tracks and at least one photon

    } One of the configurations
  - Same J/ψ kinematic fit requirement

Event selection — $e^+e^- \to J/\psi X$

- ➔ Di-muon invariant mass spectrum
- ➔ Sideband region: [2.8,3.0] ∪ [3.2,3.4] GeV/c²
- ➔ Signal region: [3.05,3.15] GeV/c²

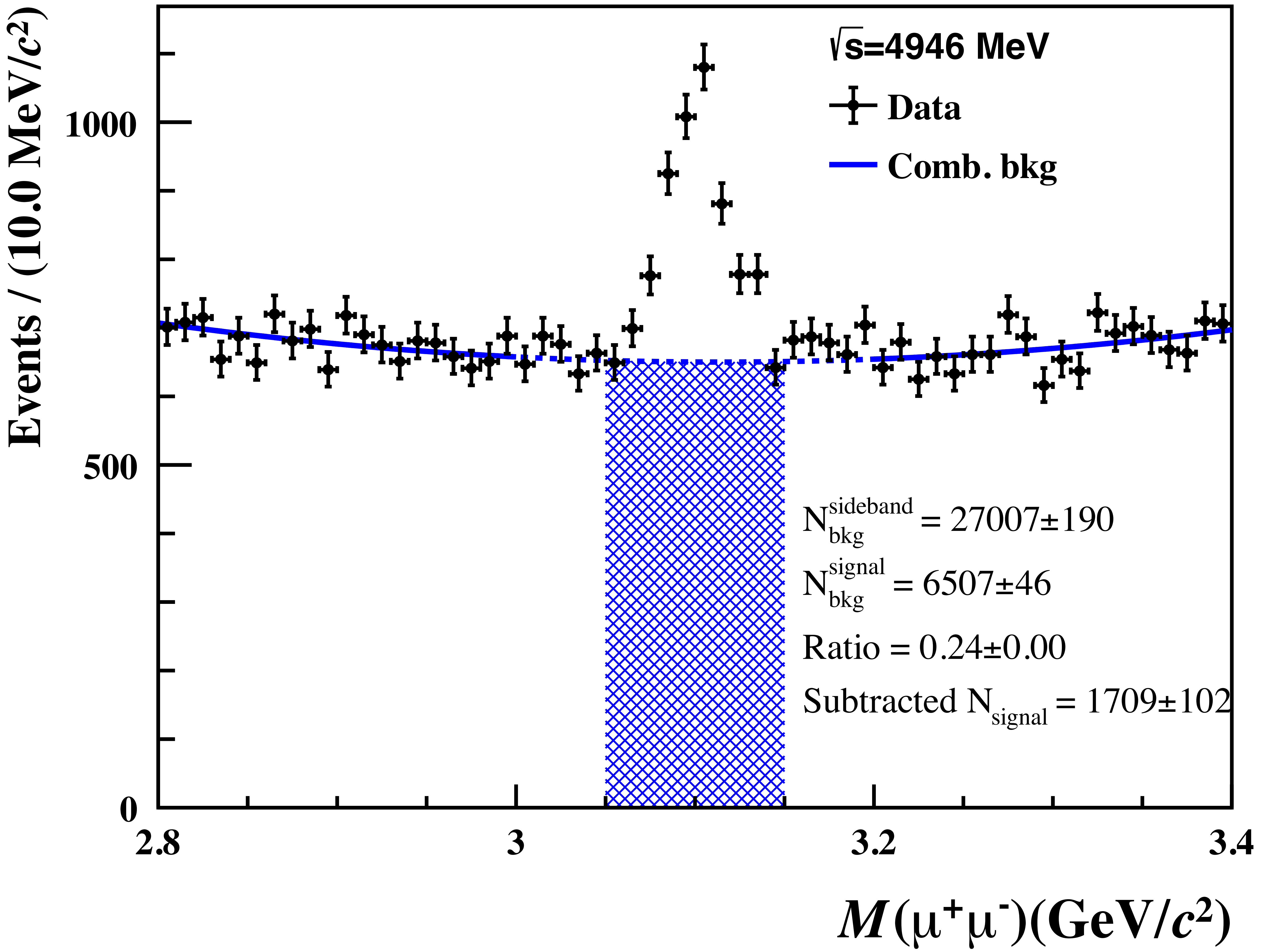
- ➔ Fit sideband region by a quadratic function
  - ❖ Estimated background yields in the sideband region: 5940 ± 82
- ➔ Extrapolate to signal region
  - ❖ Estimated background yields in the signal region: 1281 ± 18
- ➔ Signal yields in the signal region after subtracting background: 573 ± 47



Event selection — $e^+e^- \to \gamma_{ISR} J/\psi$

- ➔ Di-muon invariant mass spectrum
- ➔ Sideband region: [2.8,3.0] ∪ [3.2,3.4] GeV/c²
- ➔ Signal region: [3.05,3.15] GeV/c²

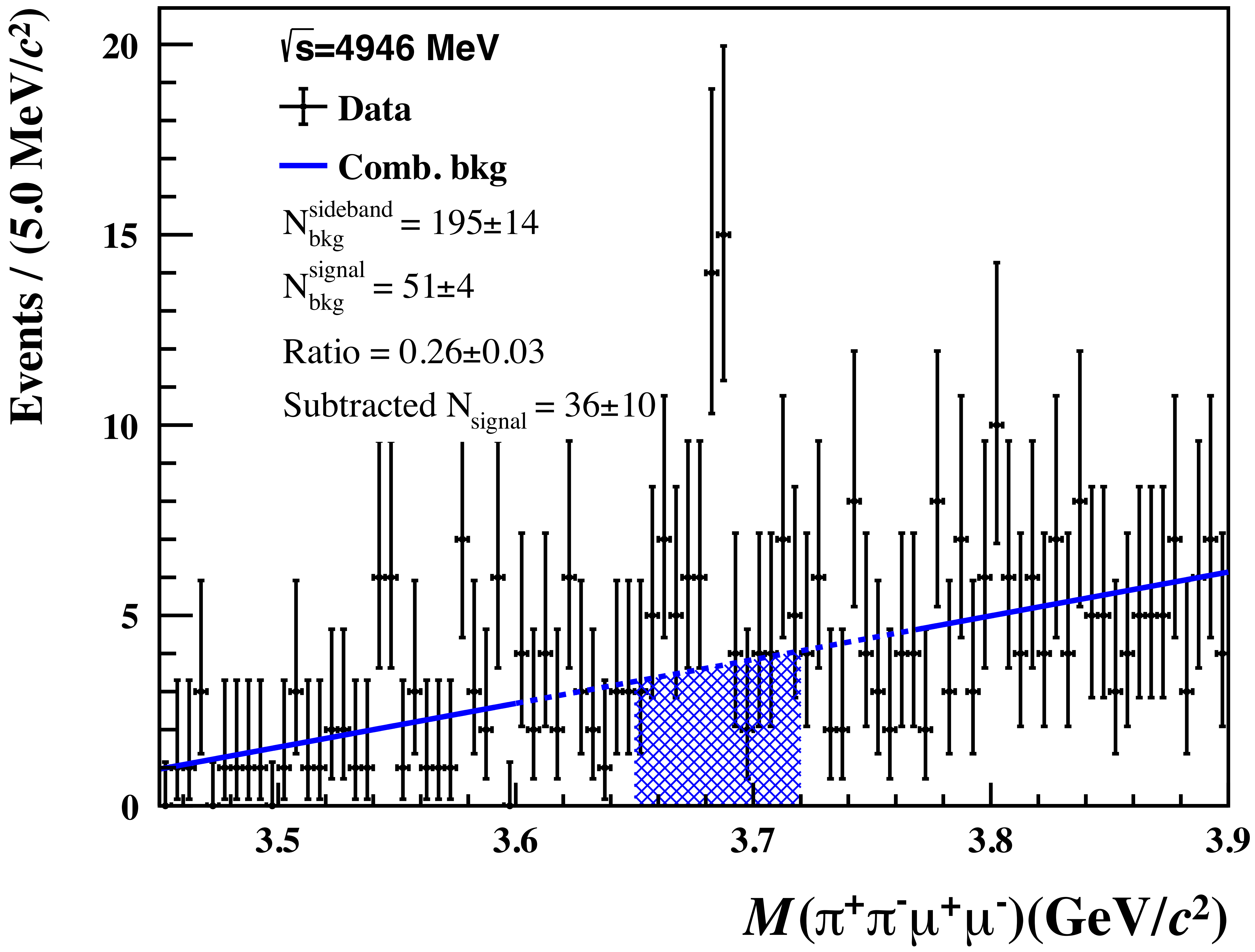
- ➔ Fit sideband region by a quadratic function
  - ❖ Estimated background yields in the sideband region: 27007 ± 190
- ➔ Extrapolate to signal region
  - ❖ Estimated background yields in the signal region: 6507 ± 46
- ➔ Signal yields in the signal region after subtracting background: 1709 ± 102



Event selection — $e^+e^- \to \psi(2S)X$

- ➔ $\pi^+\pi^-\mu^+\mu^-$ invariant mass spectrum
- ➔ Sideband region: [3.45,3.60] ∪ [3.77,3.90] GeV/c^2
- ➔ Signal region: [3.65,3.72] GeV/c^2

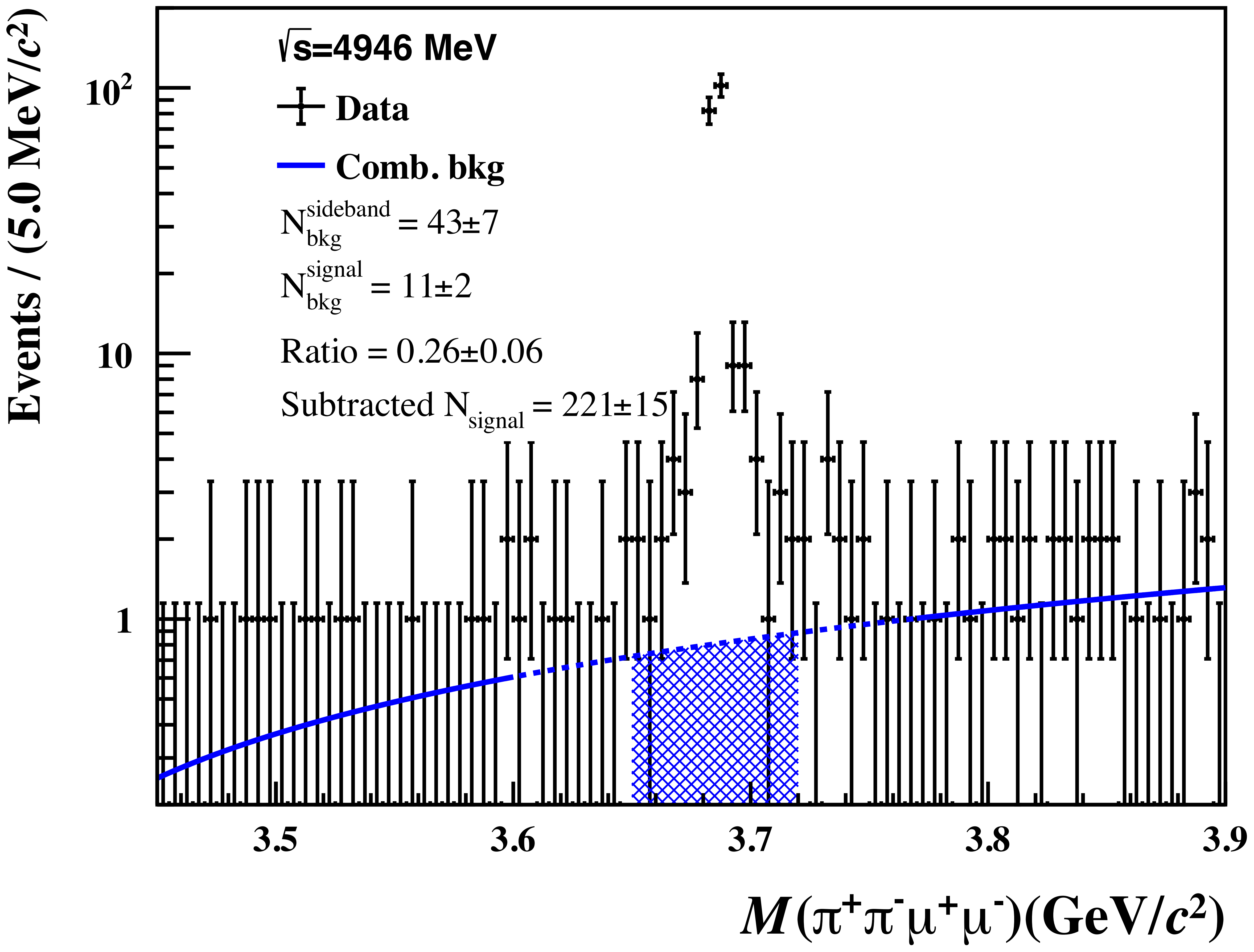
- ➔ Fit sideband region by a linear function
  - ❖ Estimated background yields in the sideband region: 195 ± 14
- ➔ Extrapolate to signal region
  - ❖ Estimated background yields in the signal region: 51 ± 4
- ➔ Signal yields in the signal region after subtracting background: 36 ± 10



Event selection — $e^+e^- \to \gamma_{\rm ISR}\psi(2S)$

- ➔ $\pi^+\pi^-\mu^+\mu^-$ invariant mass spectrum
- ➔ Sideband region: [3.45,3.60] ∪ [3.77,3.90] GeV/c²
- ➔ Signal region: [3.65,3.72] GeV/c²

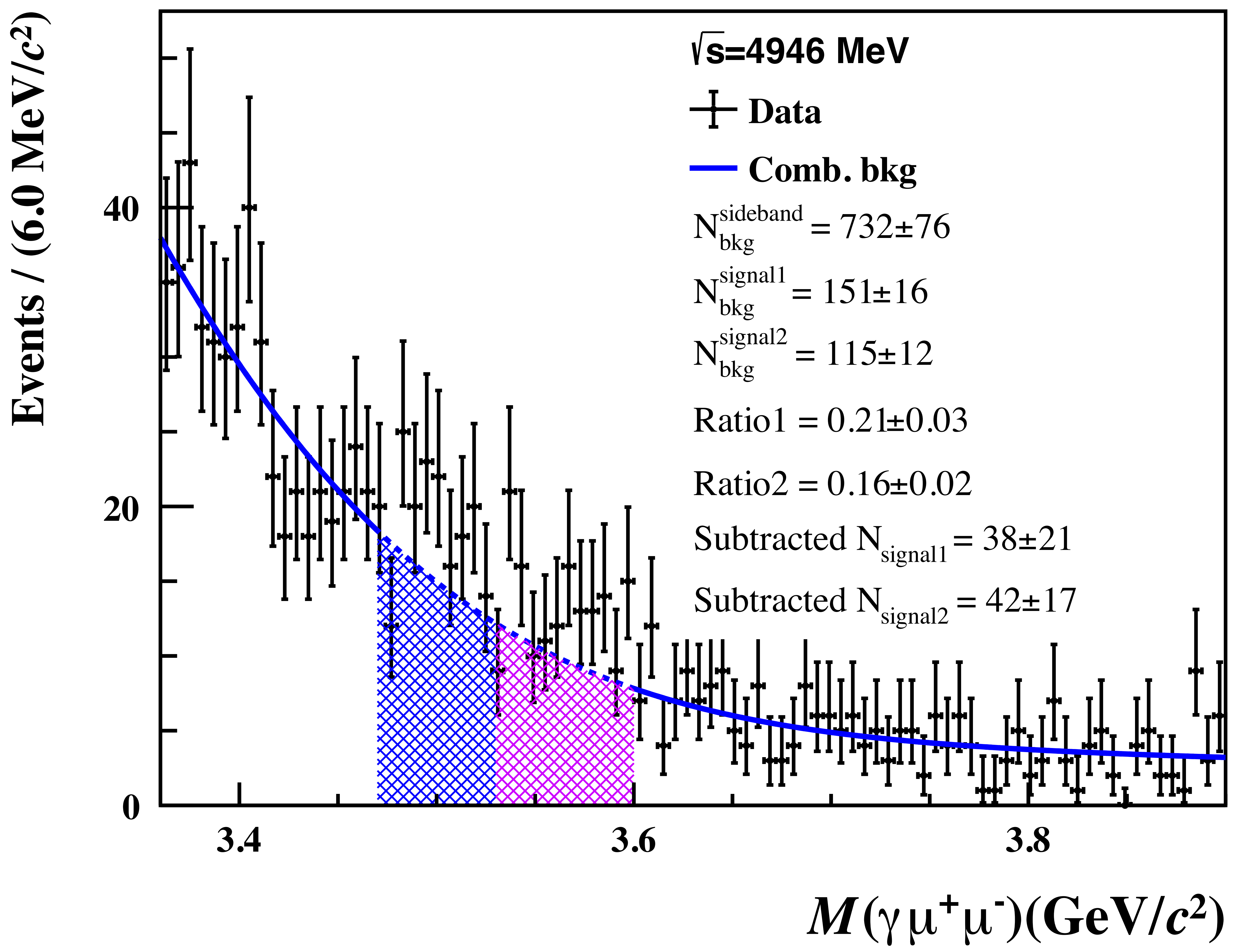
- ➔ Fit sideband region by a linear function
  - ❖ Estimated background yields in the sideband region: 43 ± 7
- ➔ Extrapolate to signal region
  - ❖ Estimated background yields in the signal region: 11 ± 2
- ➔ Signal yields in the signal region after subtracting background: 221 ± 15



Event selection — $e^+e^- \to \chi_{cJ}X$ ($J = 1,2$)

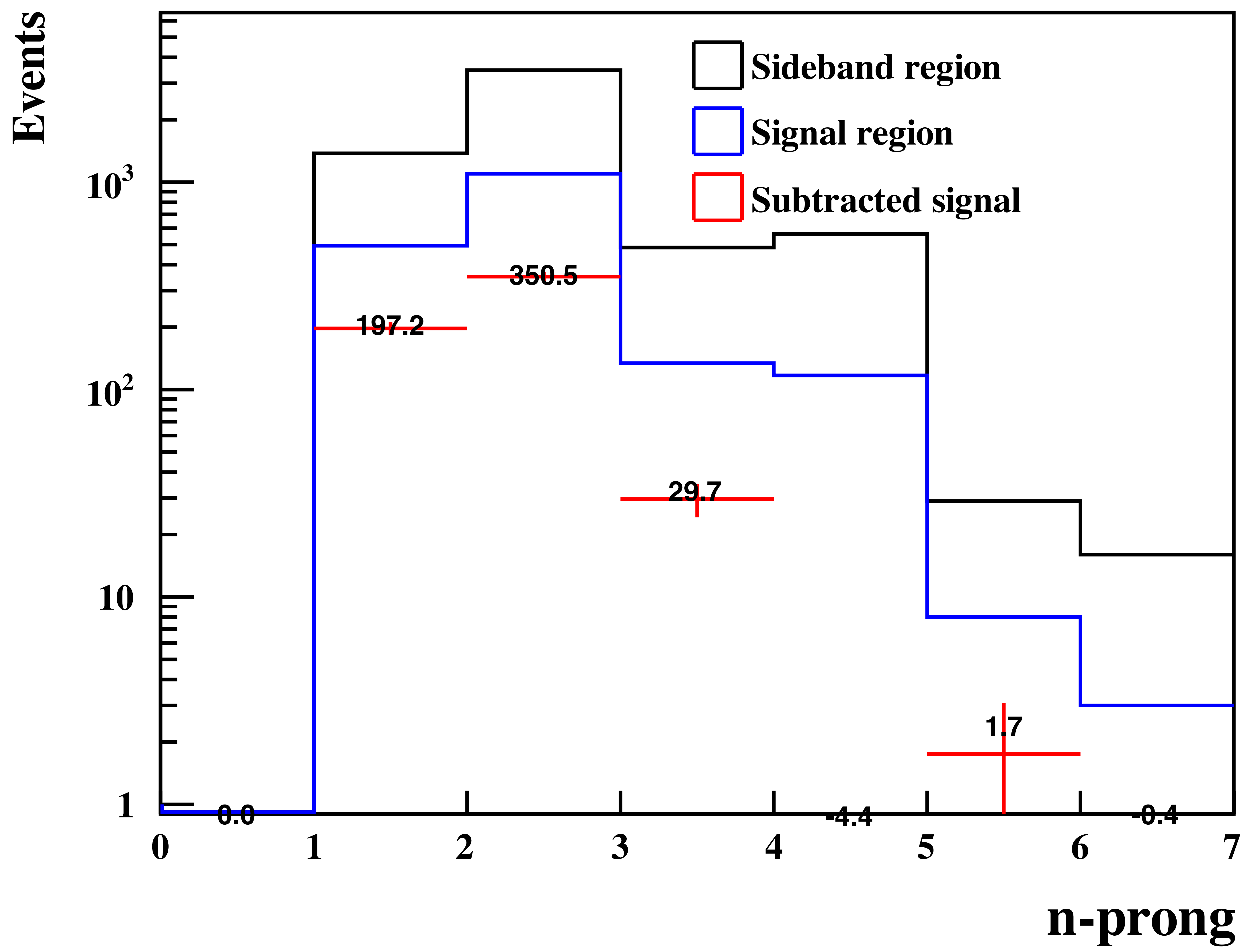
- ➔ $\gamma\mu^+\mu^-$ invariant mass spectrum
- ➔ Sideband region: [3.36,3.47] ∪ [3.60,3.90] GeV/c²
- ➔ χ_{c1} signal region: [3.65,3.72] GeV/c²
- ➔ χ_{c2} signal region: [3.53,3.60] GeV/c²

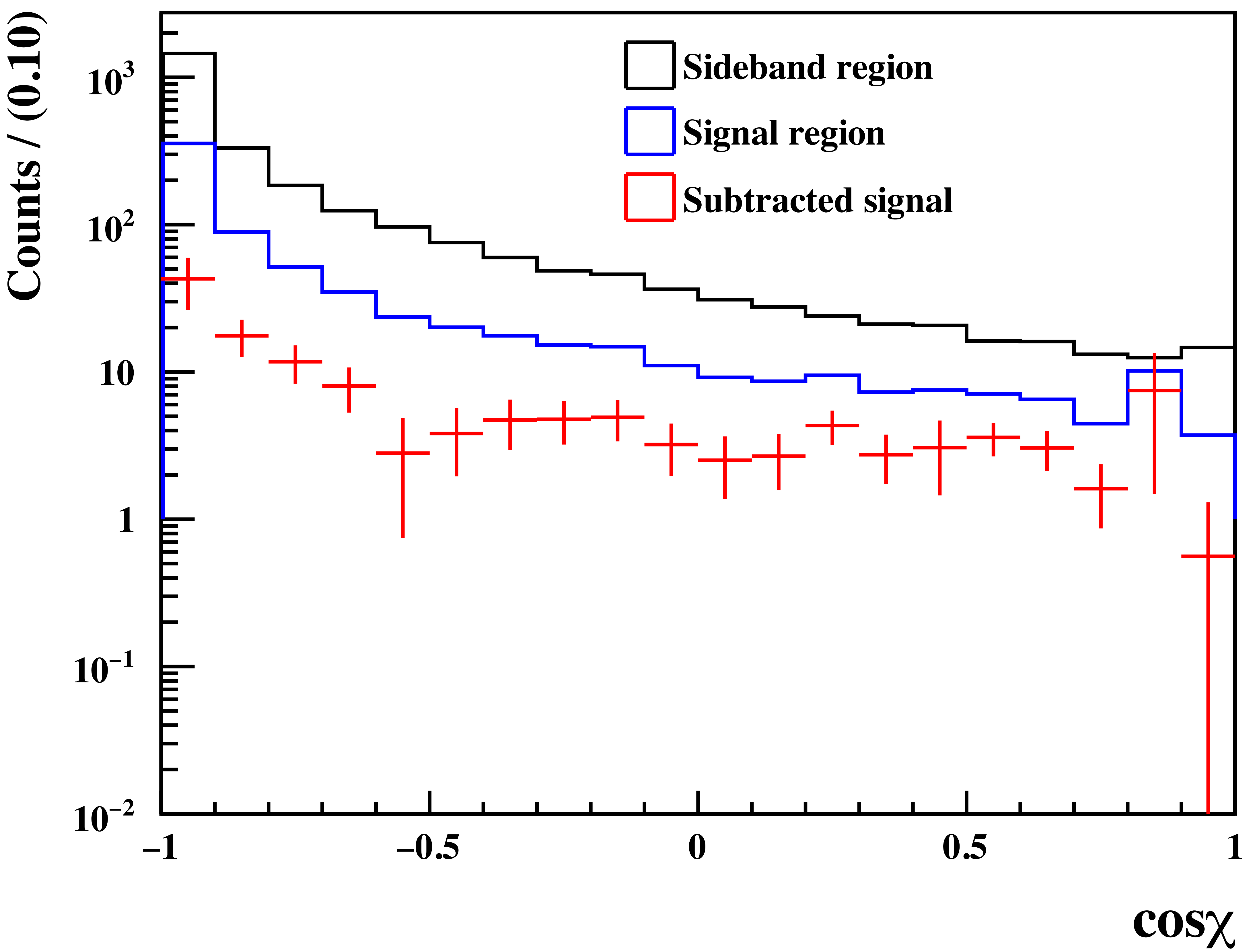
- ➔ Fit sideband region by an exponential function
  - ❖ Estimated background yields in the sideband region: 732 ± 76
- ➔ Extrapolate to signal region
  - ❖ Estimated background yields in the χ_{c1} signal region: 151 ± 16
  - ❖ Estimated background yields in the χ_{c2} signal region: 115 ± 12
- ➔ Signal yields in the signal region after subtracting background: 38 ± 21 (χ_{c1}), 42 ± 17 (χ_{c2})



J/ψ QEC analysis

J/ψ QEC — sideband subtraction





- Number of charged tracks acconpanying J/ψ
- Assuming sideband scale factor is independent on n-prong

- Pion assumption on all other good charged tracks
- Boost to J/ψ rest frame
- Angular distribution weighted by pion energy
- Assuming sideband scale factor is independent on $\cos\chi$

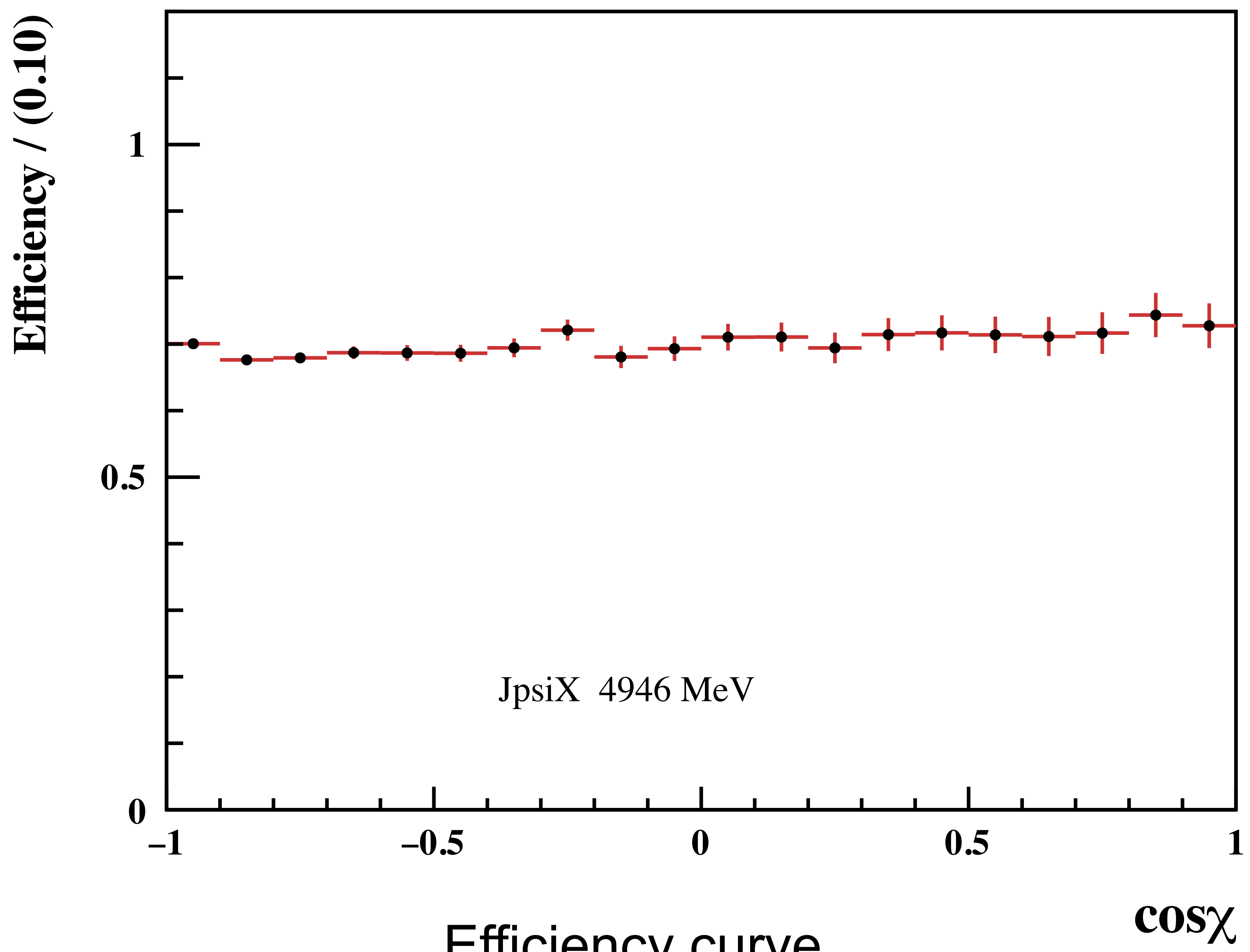
J/ψ background analysis

Contamination rates and efficiencies are studied by MC simulation

- ➔ $N^{\rm bkg}_{J/\psi {\rm ISR}} = \mathcal{R}^{\rm bkg}_{J/\psi {\rm ISR}} \times N^{\rm obs}_{J/\psi {\rm ISR}} = 8.4 \pm 0.6$
  - ❖ $N^{\rm obs}_{J/\psi {\rm ISR}} = 1709 \pm 102$, $\mathcal{R}^{\rm bkg}_{J/\psi {\rm ISR}} = (4.94 \pm 0.19) \times 10^{-3}$
- ➔ $N^{\rm bkg}_{\psi(2S){\rm ISR}} = \dfrac{N^{\rm obs}_{\psi(2S){\rm ISR}} \times \tilde{\mathcal{B}}_{\psi(2S)\to J/\psi X} \times \mathcal{R}^{\rm bkg}_{\psi(2S){\rm ISR}}}{\epsilon_{\psi(2S){\rm ISR}} \times \mathcal{B}_{\psi(2S)\to\pi^+\pi^- J/\psi}} = 351.9 \pm 23.9$
  - ❖ $N^{\rm obs}_{\psi(2S){\rm ISR}} = 221 \pm 15$, $\tilde{\mathcal{B}}_{\psi(2S)\to J/\psi X} = \mathcal{B}_{\psi(2S)\to J/\psi X} - \mathcal{B}_{\psi(2S)\to\gamma\chi_{c1}} \times \mathcal{B}_{\chi_{c1}\to\gamma J/\psi} - \mathcal{B}_{\psi(2S)\to\gamma\chi_{c2}} \times \mathcal{B}_{\chi_{c2}\to\gamma J/\psi} = 56.2\,\%$, $\mathcal{R}^{\rm bkg}_{\psi(2S){\rm ISR}} = (45.3 \pm 0.2)\,\%$, $\epsilon_{\psi(2S){\rm ISR}} = (46.1 \pm 0.1)\,\%$, $\mathcal{B}_{\psi(2S)\to\pi^+\pi^- J/\psi} = 34.68\,\%$
- ➔ $N^{\rm bkg}_{\psi(2S)X} = \dfrac{(N^{\rm obs}_{\psi(2S)X} - \mathcal{R}'^{\rm bkg}_{\psi(2S){\rm ISR}} \times N^{\rm obs}_{\psi(2S){\rm ISR}}) \times \tilde{\mathcal{B}}_{\psi(2S)\to J/\psi X} \times \mathcal{R}^{\rm bkg}_{\psi(2S)X}}{\bar{\epsilon}_{\psi(2S)X} \times \mathcal{B}_{\psi(2S)\to\pi^+\pi^- J/\psi}} = 88.6 \pm 26.6$
  - ❖ $N^{\rm obs}_{\psi(2S)X} = 36 \pm 10$, $N^{\rm obs}_{\psi(2S){\rm ISR}} = 221 \pm 15$, $\tilde{\mathcal{B}}_{\psi(2S)\to J/\psi X} = 56.2\,\%$, $\mathcal{R}'^{\rm bkg}_{\psi(2S){\rm ISR}} = (1.22 \pm 0.04)\,\%$, $\mathcal{R}^{\rm bkg}_{\psi(2S)X} = (67.5 \pm 0.2)\,\%$, $\bar{\epsilon}_{\psi(2S)X} = (41.1 \pm 0.2)\,\%$, $\mathcal{B}_{\psi(2S)\to\pi^+\pi^- J/\psi} = 34.68\,\%$
- ➔ $N^{\rm bkg}_{\chi_{c1}X} = \dfrac{N^{\rm obs}_{\chi_{c1}X} \times \mathcal{R}^{\rm bkg}_{\chi_{c1}X}}{\epsilon_{\chi_{c1}X}} = (1.8 \pm 1.0)$, $N^{\rm bkg}_{\chi_{c2}X} = \dfrac{N^{\rm obs}_{\chi_{c2}X} \times \mathcal{R}^{\rm bkg}_{\chi_{c2}X}}{\epsilon_{\chi_{c2}X}} = (2.0 \pm 0.8)$
  - ❖ $N^{\rm obs}_{\chi_{c1}X} = 38 \pm 21$, $\mathcal{R}^{\rm bkg}_{\chi_{c1}X} = (2.2 \pm 0.0)\,\%$, $\epsilon_{\chi_{c1}X} = (46.7 \pm 0.2)\,\%$
  - ❖ $N^{\rm obs}_{\chi_{c2}X} = 42 \pm 17$, $\mathcal{R}^{\rm bkg}_{\chi_{c2}X} = (2.0 \pm 0.0)\,\%$, $\epsilon_{\chi_{c2}X} = (41.1 \pm 0.1)\,\%$
- ➔ $N^{\rm sig}_{J/\psi X} = N^{\rm obs}_{J/\psi X} - N^{\rm bkg}_{J/\psi {\rm ISR}} - N^{\rm bkg}_{\psi(2S){\rm ISR}} - N^{\rm bkg}_{J/\psi X} - N^{\rm bkg}_{\chi_{c1}{\rm ISR}} - N^{\rm bkg}_{\chi_{c2}{\rm ISR}} = 126 \pm 58$
  - ❖ $N^{\rm obs}_{J/\psi X} = 573 \pm 47$

J/ψ QEC

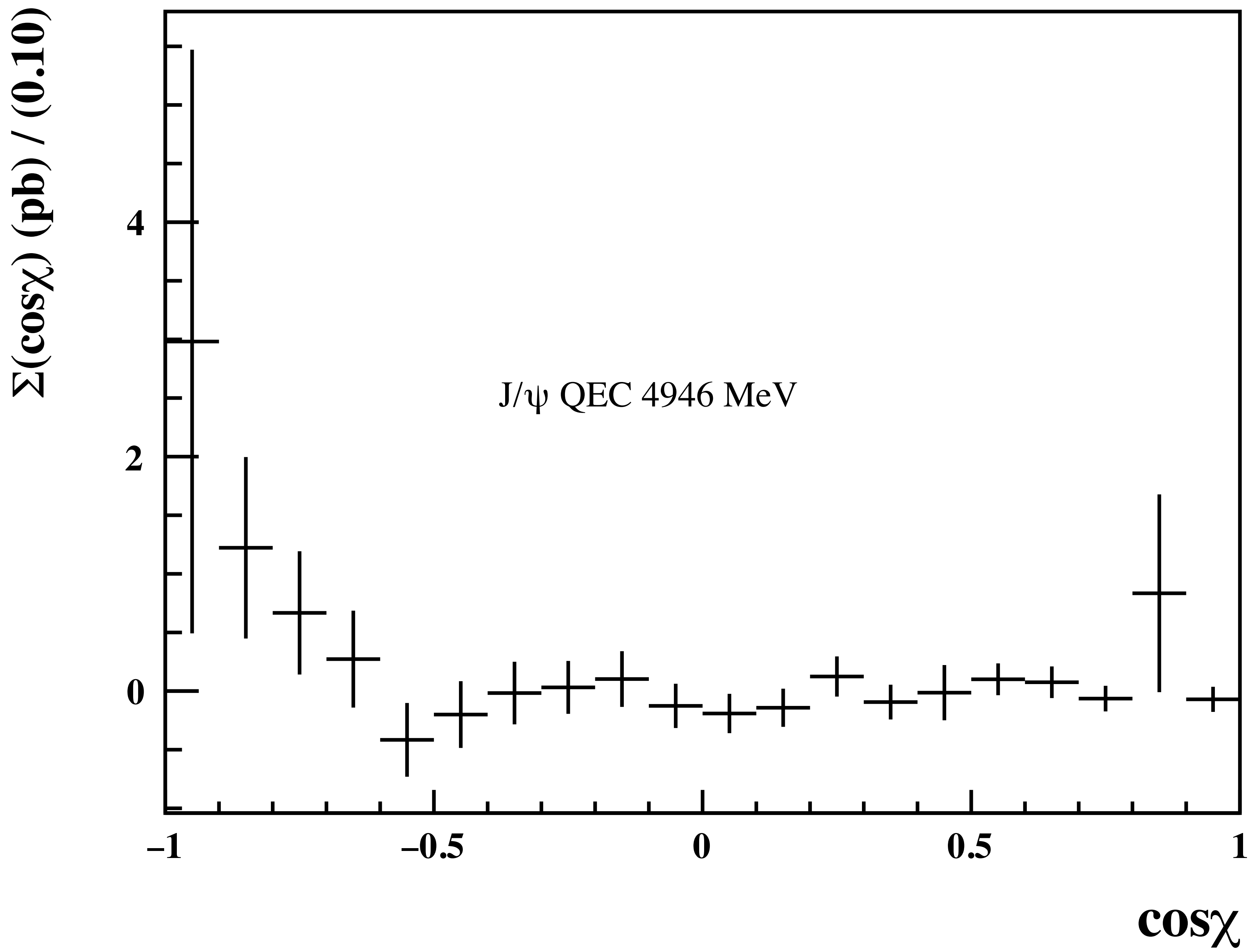
$$\Sigma_{\text{QEC}}(\cos\chi) = \int d(\sigma_{J/\psi X})\Sigma_i \frac{E_i}{M_{J/\psi}}\delta(\cos\theta_i - \cos\chi)$$
$$= \frac{1}{\mathscr{L}}\int d(\mathscr{L}\sigma_{J/\psi X})\Sigma_i \frac{E_i}{M_{J/\psi}}\delta(\cos\theta_i - \cos\chi)$$
$$= \frac{1}{\mathscr{L}}\int \frac{d(N_{J/\psi X})}{\mathscr{B}_{J/\psi\to\mu^+\mu^-}}\Sigma_i \frac{E_i}{M_{J/\psi}}\delta(\cos\theta_i - \cos\chi)\frac{1}{\epsilon_i}$$



Efficiency curve

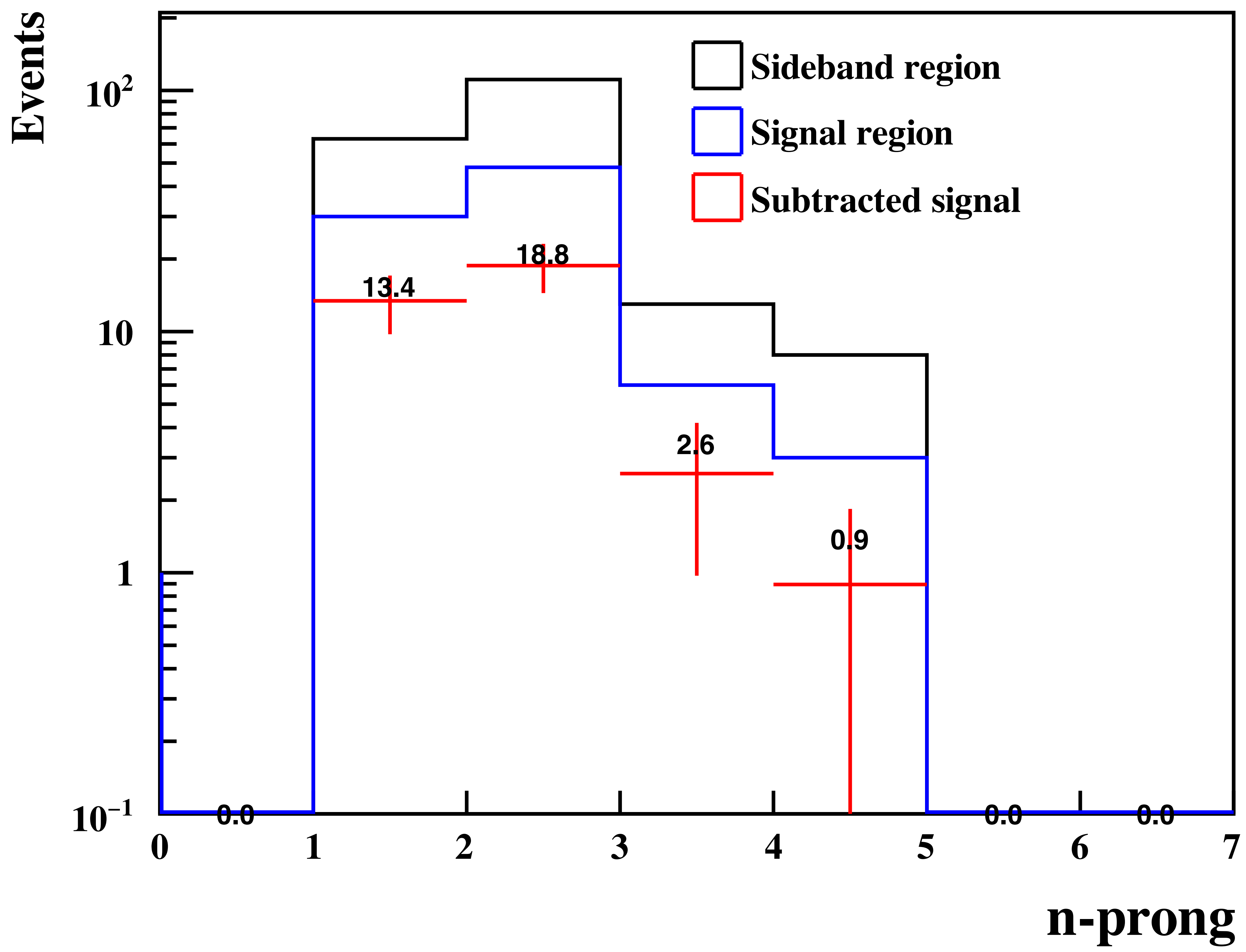
Final J/ψ QEC distribution @ 4946 MeV

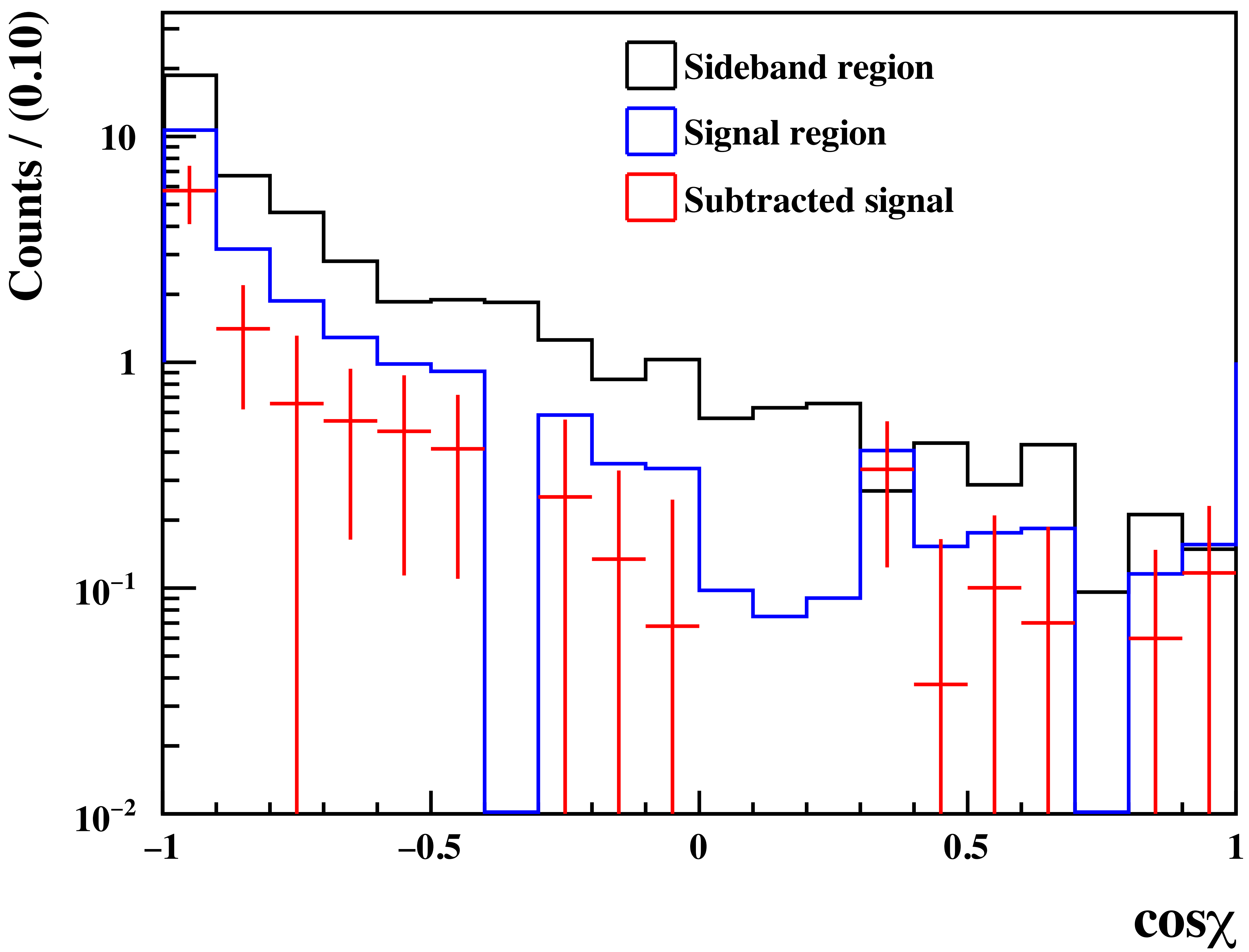
- Background subtracted
- Consider experimental efficiency



$\psi(2S)$ QEC analysis

$\psi(2S)$ QEC — sideband subtraction





- Number of charged tracks acconpanying $\psi(2S)$
- Assuming sideband scale factor is independent on n-prong

- Pion assumption on all other good charged tracks
- Boost to $\psi(2S)$ rest frame
- Angular distribution weighted by pion energy
- Assuming sideband scale factor is independent on $\cos\chi$

$\psi(2S)$ background analysis

Contamination rates and efficiencies are studied by MC simulation

➔ $N^{\rm bkg}_{\psi(2S){\rm ISR}} = \mathscr{R}^{\rm bkg}_{\psi(2S){\rm ISR}} \times N^{\rm obs}_{\psi(2S){\rm ISR}} = 2.7 \pm 0.2$

- $N^{\rm obs}_{\psi(2S){\rm ISR}} = 221 \pm 15$, $\mathscr{R}^{\rm bkg}_{\psi(2S){\rm ISR}} = (1.22 \pm 0.04)\ \%$

➔ $N^{\rm sig}_{\psi(2S)X} = N^{\rm obs}_{\psi(2S)X} - N^{\rm bkg}_{\psi(2S){\rm ISR}} = 33 \pm 10$

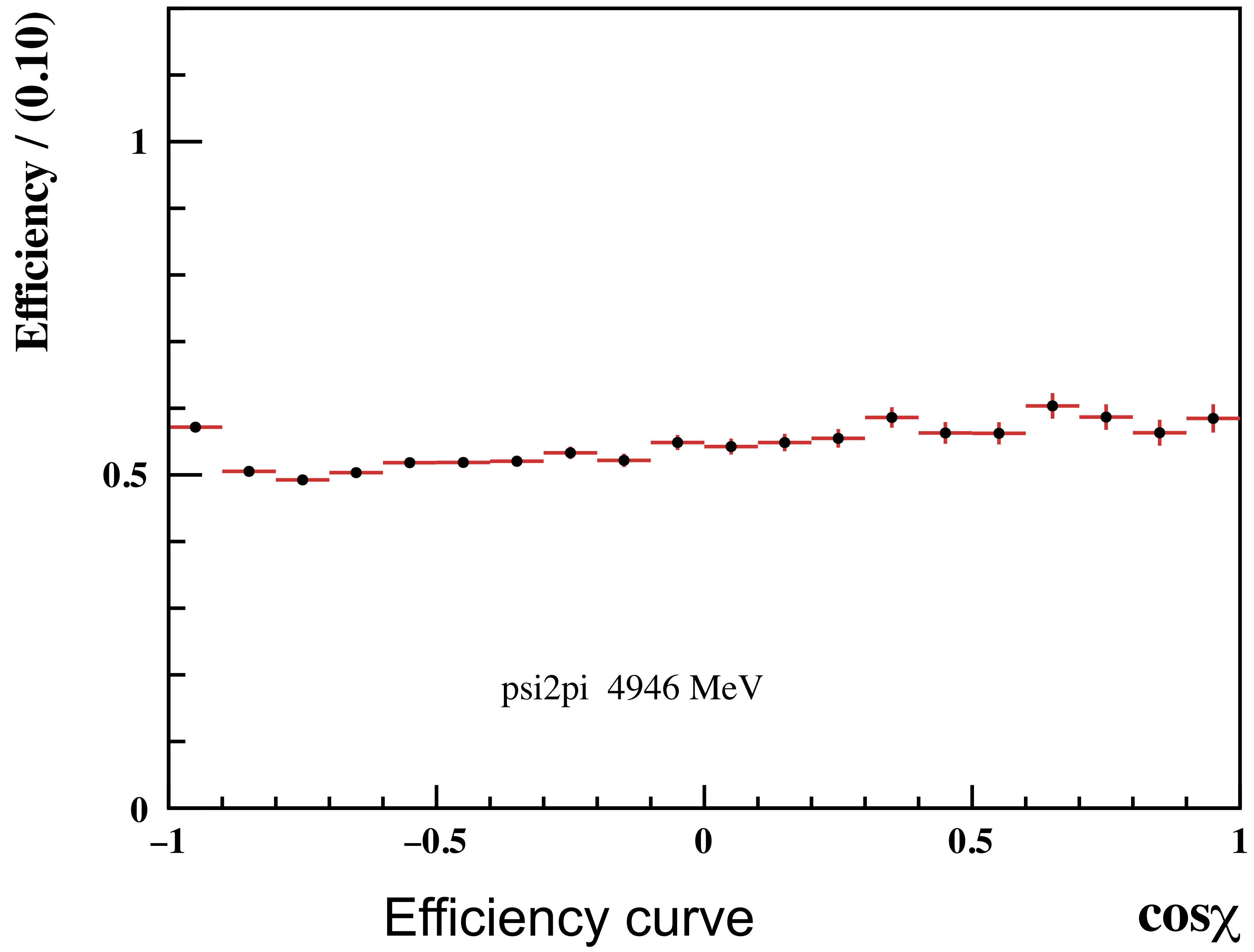
- $N^{\rm obs}_{\psi(2S)X} = 36 \pm 10$

$\psi(2S)$ QEC

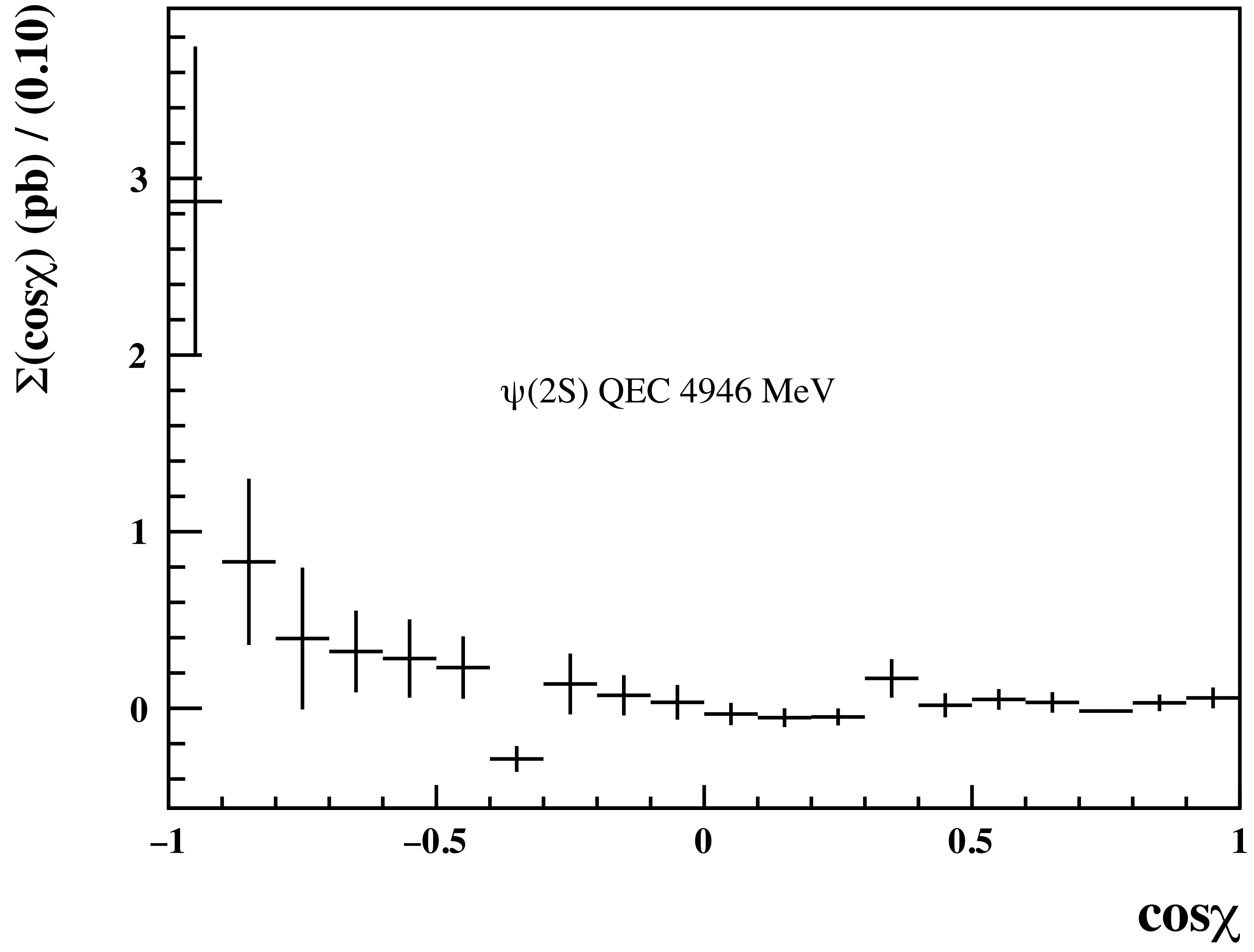
$$\rightarrow \Sigma_{\mathrm{QEC}}(\cos\chi) = \int \mathrm{d}(\sigma_{\psi(2S)X})\Sigma_i \frac{E_i}{M_{\psi(2S)}}\delta(\cos\theta_i - \cos\chi)$$
$$= \frac{1}{\mathscr{L}}\int \mathrm{d}(\mathscr{L}\sigma_{\psi(2S)X})\Sigma_i \frac{E_i}{M_{\psi(2S)}}\delta(\cos\theta_i - \cos\chi)$$
$$= \frac{1}{\mathscr{L}}\int \frac{\mathrm{d}(N_{\psi(2S)X})}{\cdot\,\mathscr{B}_{\psi(2S)\to\pi^+\pi^-J/\psi}\cdot\mathscr{B}_{J/\psi\to\mu^+\mu^-}}\Sigma_i \frac{E_i}{M_{\psi(2S)}}\delta(\cos\theta_i - \cos\chi)\cdot\frac{1}{\epsilon_i}$$

Final $\psi(2S)$ QEC distribution @ 4946 MeV

- Background subtracted
- Consider experimental efficiency



Efficiency curve

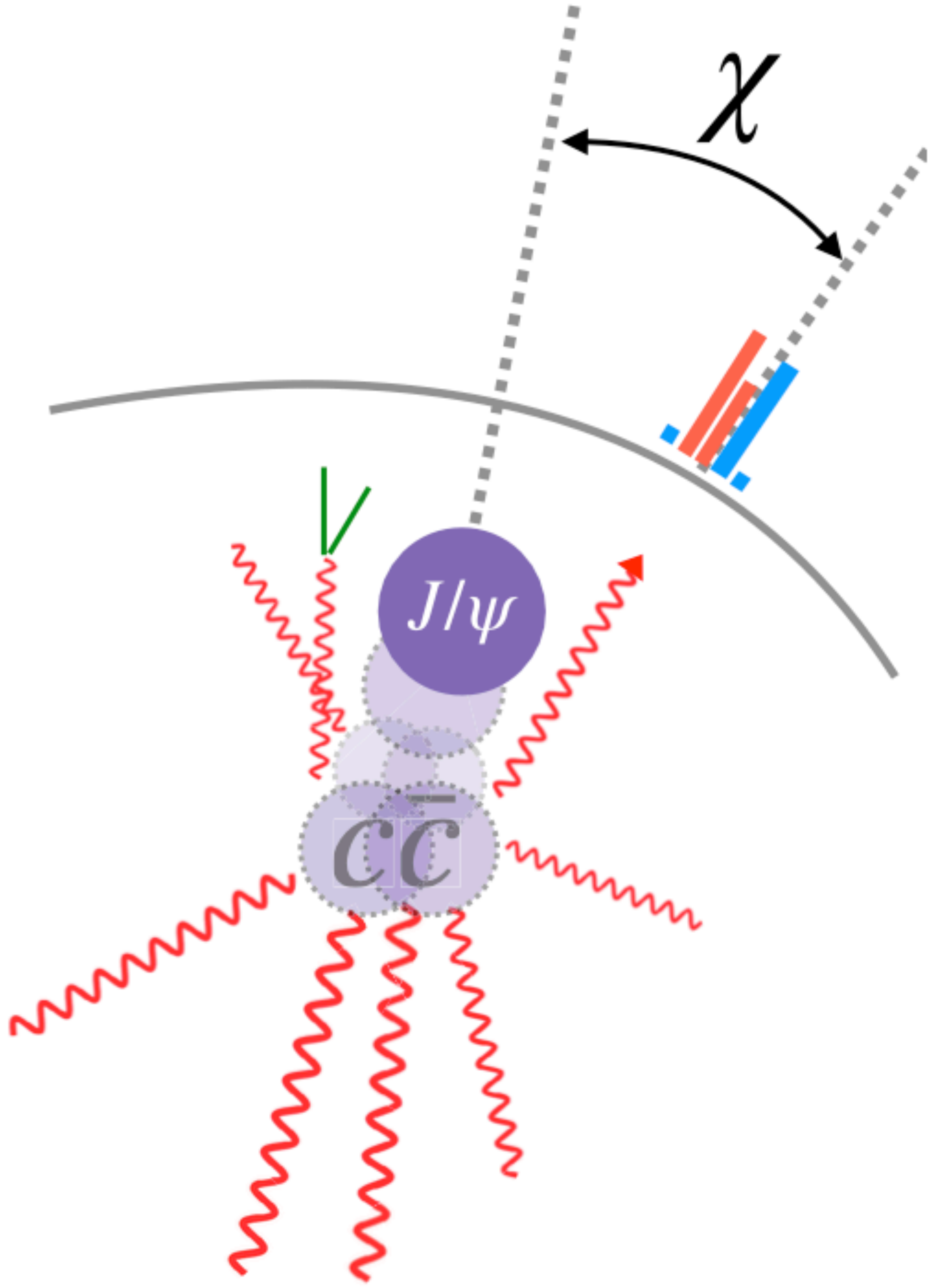


Summary

Summary

- ➔ Energy-energy correlator sheds light on hadronization
- ➔ A new observable — **Q**uarkonium **E**nergy **C**orrelator (**QEC**)
- ➔ We perform the first study on J/ψ and $\psi(2S)$ QEC at BESIII using 4946 data
- ➔ Next to do:
  - ❖ Improve analysis strategy, e.g. Mis-ID correction, $\cos\chi$-denpendent scale factor, contamination rate and efficiency
  - ❖ Ultilize more data at high energy points
  - ❖ …

Thanks for your attention!



Backup

$J/\psi - \psi(2S)$ QEC ratio