Single one point and inclusive hadron pair energy correlator studies at BESIII

Ling Ge[1], Jian Zu[2], Linqin Huang[2], WeipingWang[3,4], Yateng Zhang[5],

Yuxiang Zhao[2], Yue Pan[1] , Xiaorong Zhou[6], and Wenbiao Yan[6]

[1]Southeast University
[2]Institute of Modern Physics, CAS
[3]Johannes Gutenberg-Universität, Mainz
[4]Helmholtz Institute, Mainz
[5]ZhengZhou University
[6]University of Science and Technology of China

Tau-QCD Group meeting
Sep.10th, 2025

Outline

- Introduction of Energy-energy correlator (EEC)
- Common Data Analysis
- Analysis of single one point energy correlator (SEC)
- Analysis of Inclusive hadron pair energy-energy correlator
- Summary

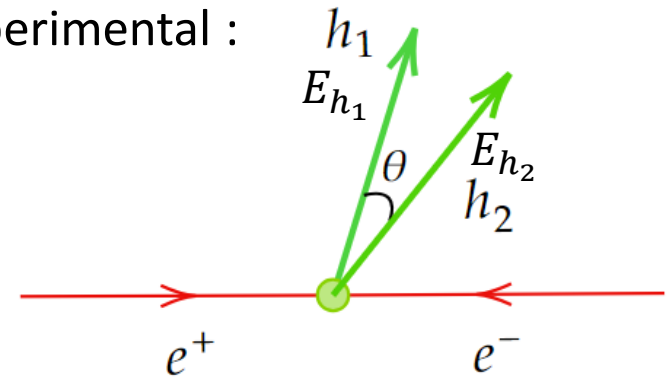
1 Introduction

- Different measurements of the energy correlator have different definition depending on the application itself. A General definition of two point **energy-energy correlator (EEC):**

$$\mathrm{EEC}(\theta) = \sum_{i,j}^{n} d\sigma \frac{E_i E_j}{E^2} \delta(\theta - \theta_{ij})$$

θ_{ij}: opening angle between charged particles

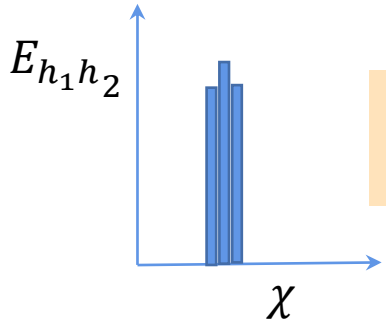
- Experimental :



(h_1, h_2): charged hadron pair

Runs over all charged particle pairs
h_1, h_2 is counted twice, $(h_1, h_2), (h_2, h_1)$

$$\frac{1}{\sqrt{s} \cdot \sqrt{s}} \frac{\sum_i^{N_{h_{12}}} E_{h_1} E_{h_2}}{N_{had}} \frac{1}{\Delta\chi}$$



Energy-weighted two-particle angular correlation

Energy weighted differential cross section

- $\chi = (1 - \cos\theta)/2$
- $N_{h_{12}}$: Number of observed charged hadron pairs

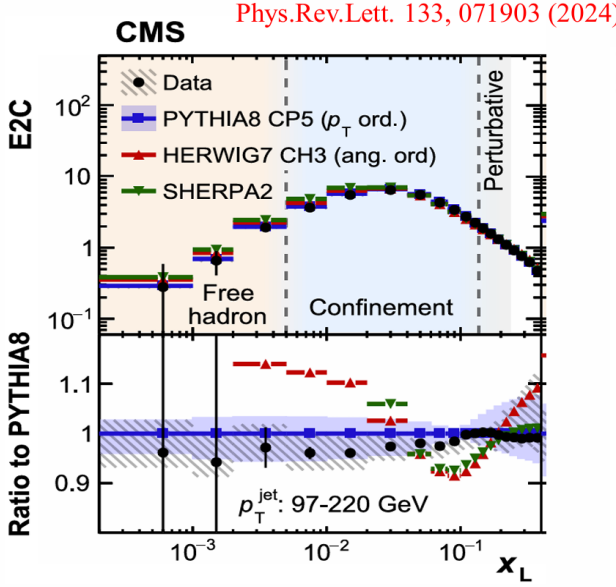
1 Introduction

✓ EEC is very useful in precision tests of QCD

✓ Research related to EEC is currently very popular and developing rapidly.

- Determines the most precise $\alpha_s(m_Z)$ with EEC

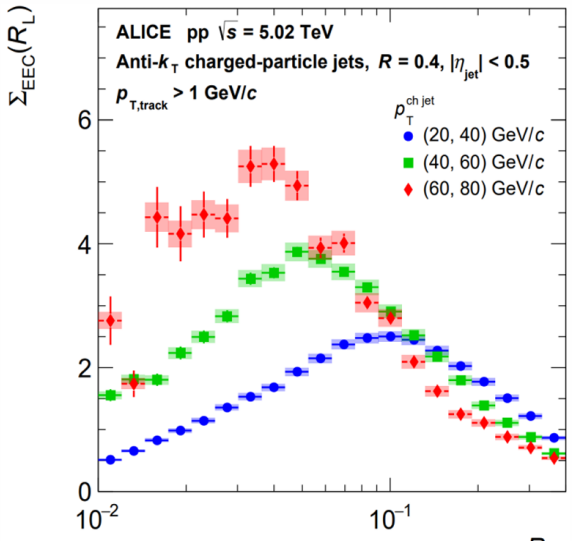
Phys.Rev.Lett. 133, 071903 (2024)



X_L: the angular distance between the two particles of the E2C pair

- Exposing the parton-hadron transition

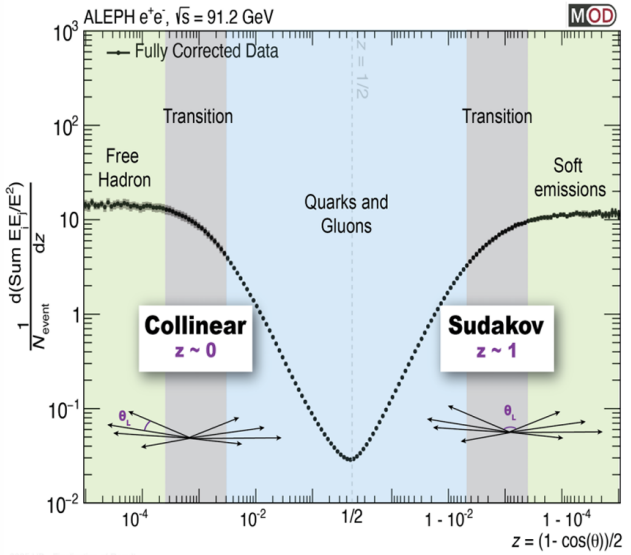
arXiv: 2409.12687



R_L: Angular distance of charged particle pair

- Improve precision and finer angular resolution of E2C measurements at very small and large angles

arXiv: 2505.11828



z: $(1 - cos\theta)/2$

✓ Provide experimental information for EEC at lower energy with BESIII data.

1 Introduction-how about the simplest one particle?

◆ Definition of **single one point energy correlator (SEC)**

$$\mathrm{SEC} = \frac{1}{\sqrt{s}} \frac{\sum_i^N E_h}{N_{had}} \frac{1}{\Delta\chi}$$

$\chi = (1-\cos\theta)/2$

(θ: polar angle)

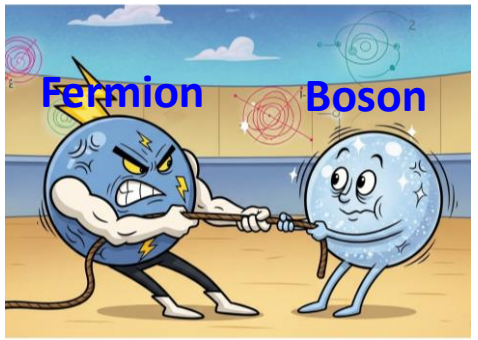
The angular distribution is sensitive to fundamental parameter in quantum field theory

◆ The SEC measurements can be interpreted as the energy flux one point function:

Diego M. Hofman and Juan Maldacena JHEP05(2008)012

$$\mathrm{SEC} = \langle \varepsilon(\chi) \rangle_{\mathrm{charge}} = N_0 \left(1 + a_2 \left(\sin^2\theta - \frac{1}{3}\right)\right)$$

Crossing at 0 suggest the transition from fermion D.O.F. to Bosonic D.O.F



Can we observe the crossing?

- Theoretical understanding of a2

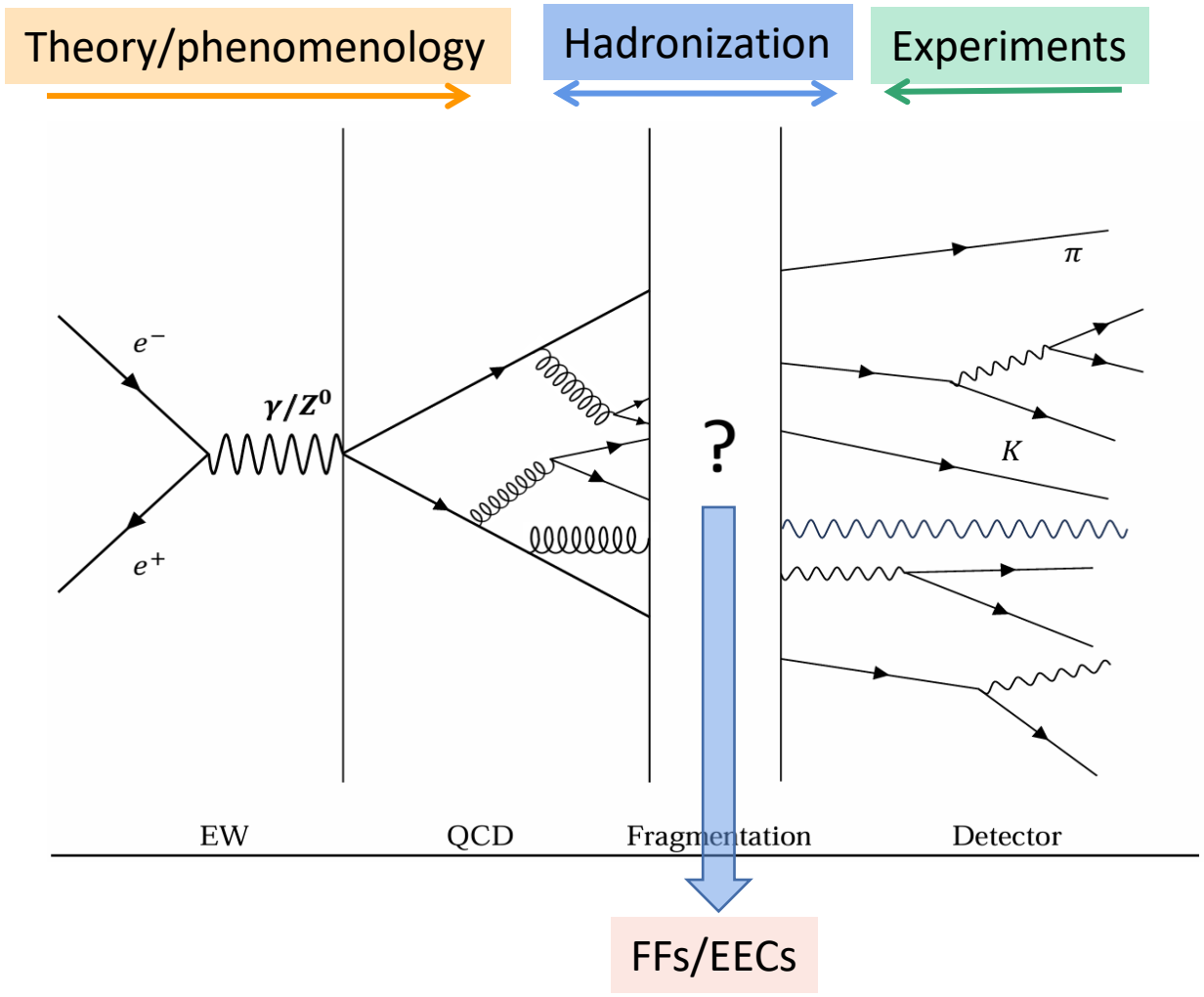
✓ free fermion $a_2 = -\frac{3}{2}$

✓ free boson $a_2 = 3$

✓ Conformal collider bound: $-\frac{3}{2} \le a_2 \le 3$

No experiment has observed this phenomena before!

1 Introduction



EECs: Another handle to understand **asymptotic freedom and confinement**

2 Common Data Analysis

◆Data sample

$\sqrt{s}$ (GeV)	Lum.(pb^{-1})	BOSS	$\sqrt{s}$ (GeV)	Lum.(pb^{-1})	BOSS
2.0000	10.07	665p01	2.6444	33.72	665p01
2.2000	13.70		2.9000	105.3	
2.3960	66.87		3.5104	183.6	703

◆MC Simulation

Same as R-value analysis: BAM-330

- $e^+e^- \to q\bar{q}$: **LUARLW/HYBRID**
- $e^+e^- \to e^+e^-$
- $e^+e^- \to \gamma\gamma$
- $e^+e^- \to \mu^+\mu^-$

} **Babayaga 3.5**

- $e^+e^- \to \tau^+\tau^-$: **KKMC**
- $e^+e^- \to e^+e^- + X$ (X: leptons and hadrons) : **DIAG36, EKHARA, GALUGA 2.0**

2 Common Data Analysis

◆ Hadronic Event Selections are same as R-value analysis published in PRL 128, 062004 (2022)

Track Level

- **Veto Bhabha and Di-gamma events**
  - $N_{\text{shower}} \geq 2$
  - $E_1 \geq E_2 \geq 0.65E_{\text{beam}}$
  - $|\Delta\theta| = |\theta_1 + \theta_2 - 180°| < 10°$
- **Isolated photon**
  - Energy deposition should be larger than 0.1 GeV
  - Angle from the nearest charged track should be larger than 20°
  - $0 < T_{\text{EMC}} < 700$ ns
- **Good charged hadronic tracks**
  - $|V_r| < 0.5$ cm , $|V_z| < 5.0$ cm , $|\cos\theta| < 0.93$
  - $p_{\text{track}} < 0.94p_{\text{beam}}$, where $p_{\text{beam}} \approx E_{\text{beam}}$
  - $\chi_{\text{prob.}} = \left(\mathrm{d}E/\mathrm{d}x_{\text{measure}} - \mathrm{d}E/\mathrm{d}x_{\text{proton}}\right) / \sigma_{\text{proton}} > 10$
  - Remove charged tracks when $E/p > 0.8$ and $p > 0.65p_{\text{beam}}$
  - Veto γ-conversions when $M(e^+ e^-) < 0.1$ GeV and $\theta_{ee} < 15°$

Event Level

At least 2 good charged hadronic tracks

- **Number of good charged hadronic tracks = 2:**
  - $|\Delta\theta| = |\theta_1 + \theta_2 - 180°| > 10°$ or $|\Delta\phi| = ||\phi_1 - \phi_2| - 180°| > 15°$
  - At least 2 isolated photons
- **Number of good charged hadronic tracks = 3:**
  - The two highest momentum tracks are required not back-to-back: $|\Delta\theta| = |\theta_1 + \theta_2 - 180°| < 10°$ or $|\Delta\phi| = ||\phi_1 - \phi_2| - 180°| < 15°$
  - (number of track with $E/p > 0.8) \leq 1$
  - (number of track with PID ratio > 0.25) ≤ 1, where the PID ratio is defined as $r_{\text{PID}} = \frac{\text{Prob.}(e)}{\text{Prob.}(p)+\text{Prob.(K)}+\text{Prob.}(\pi)+\text{Prob.}(e)}$
- **Number of good charged hadronic tracks ≥ 4:**
  No additional requirements

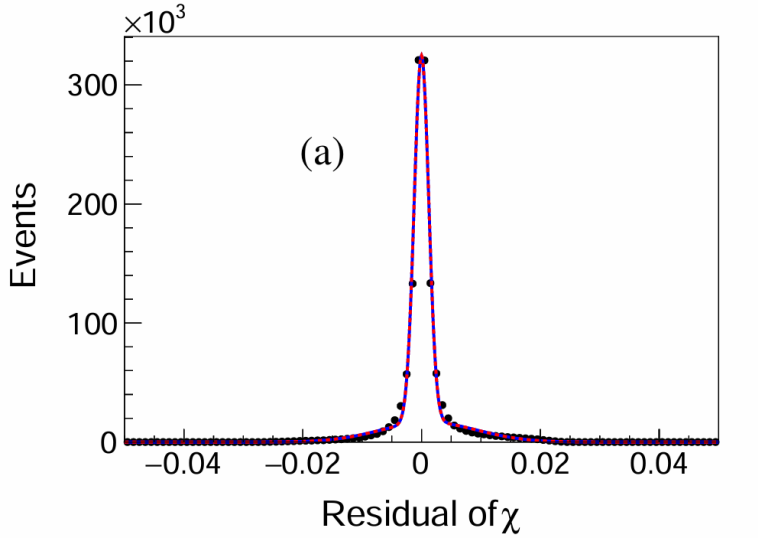
◆ PID selection criteria Combined dE/dx and TOF

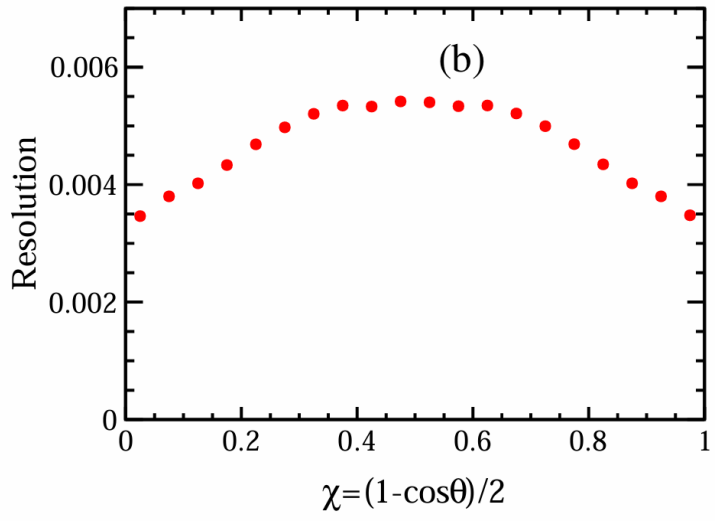
- $\pi: Prob(\pi) > \&Prob(K)\&Prob(\pi) > Prob(p)$
- $K: Prob(K) > \&Prob(\pi)\&Prob(K) > Prob(p)$
- $p: Prob(p) > \&Prob(\pi)\&Prob(p) > Prob(K)$

2 Common Data Analysis

◆ Binning Scheme

✓ Resolution of χ





χ_{left}	χ_{right}	χ_{center}	χ_{width}
0.0188	0.0362	0.0261	0.0174
0.0362	0.0698	0.0503	0.0336
0.0698	0.1346	0.0970	0.0648
0.1346	0.1869	0.1586	0.0523
0.1869	0.2594	0.2202	0.0726
0.2594	0.3602	0.3057	0.1007
0.3602	0.5000	0.4244	0.1398
0.5000	0.6398	0.5756	0.1398
0.6398	0.7406	0.6943	0.1007
0.7406	0.8131	0.7798	0.0726
0.8131	0.8654	0.8414	0.0523
0.8654	0.9302	0.9030	0.0648
0.9302	0.9638	0.9497	0.0336
0.9638	0.9812	0.9739	0.0174

✓ Studied by signal MC
✓ Fit the residual with a double Gaussian function
✓ Bin size is 5 times larger than the resolution

2 Common Data Analysis

◆Background Study

✓ QED background

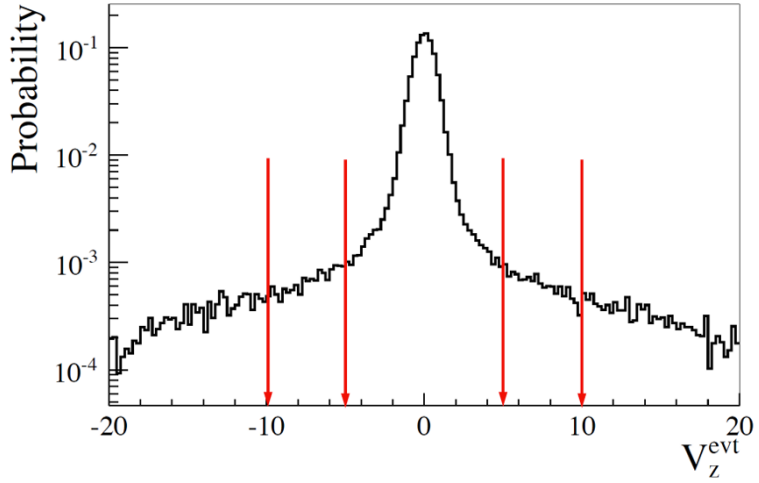
- Bhabha process: $e^+e^- \to e^+e^-$.
- Di-gamma process: $e^+e^- \to \gamma\gamma$.
- Di-muon process: $e^+e^- \to \mu^+\mu^-$.
- Di-tau process: $e^+e^- \to \tau^+\tau^-$.
- Two-photon processes: $e^+e^- \to e^+e^- + X$ $(X = e^+e^-, \mu^+\mu^-, \pi^+\pi^-, K^+K^-, \eta, \eta')$.

$$\sum E_{\rm bkg}^{\rm QED} = \frac{\sigma_{\rm bkg}\mathcal{L}_{\rm int}\sum E_{\rm MC}^{\rm sur}}{N_{\rm MC}^{\rm gen}}$$

✓ Beam associated background

$$V_z^{\rm evt} = \frac{\sum_1^{N_{\rm crude}} V_z(i)}{N_{\rm crude}}$$

- The events with $|V_z^{evt}| \in (5, 10)$ cm are regarded as the beam-associated background



Outline

- Introduction of EEC
- Common Data Analysis
- **Analysis of single one point energy correlator (SEC)**
- Analysis of inclusive hadron pair energy-energy correlator
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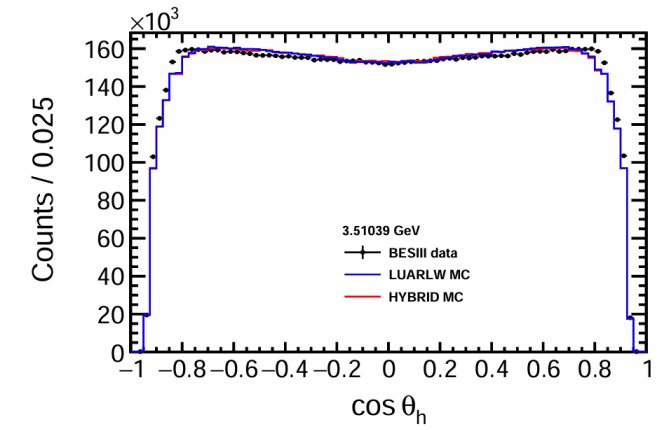
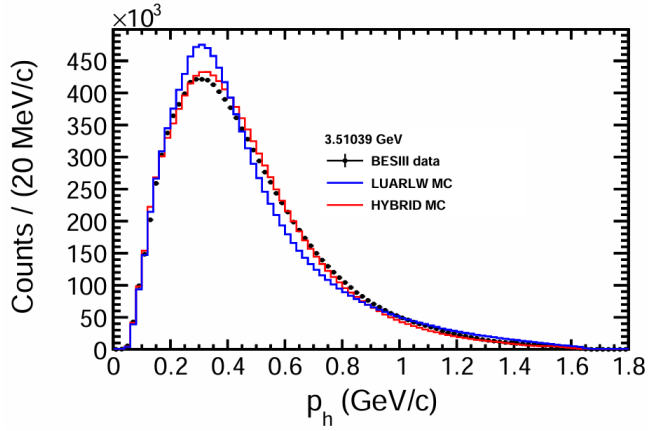
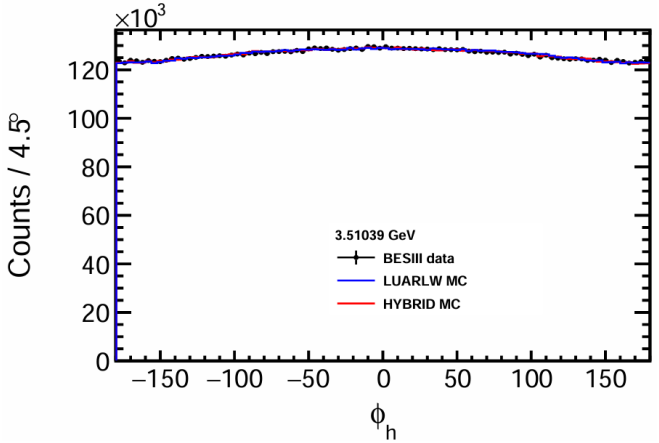
3 Analysis of SEC

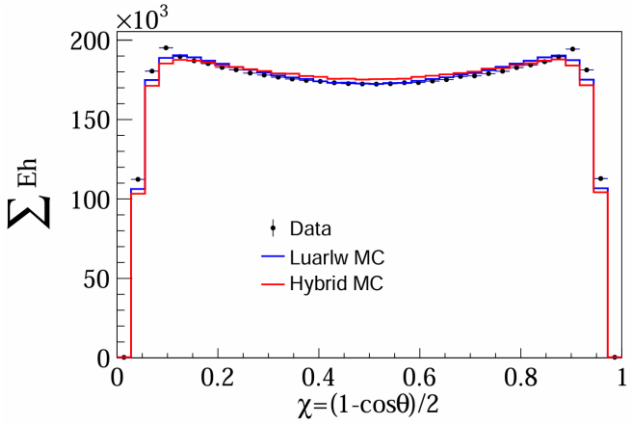
$$SEC = f_{corr}\frac{1}{\sqrt{s}}\frac{\sum_i^{N_{h^\pm}} E_{h_i^\pm}}{N_{had}}\frac{1}{\Delta\chi}$$

- Comparison between data and MC at 3.5104 GeV









✓ Blue: Luarlw MC
✓ Red: Hybrid MC

✓ Reasonably good agreement between data and MC

3 Analysis of SEC

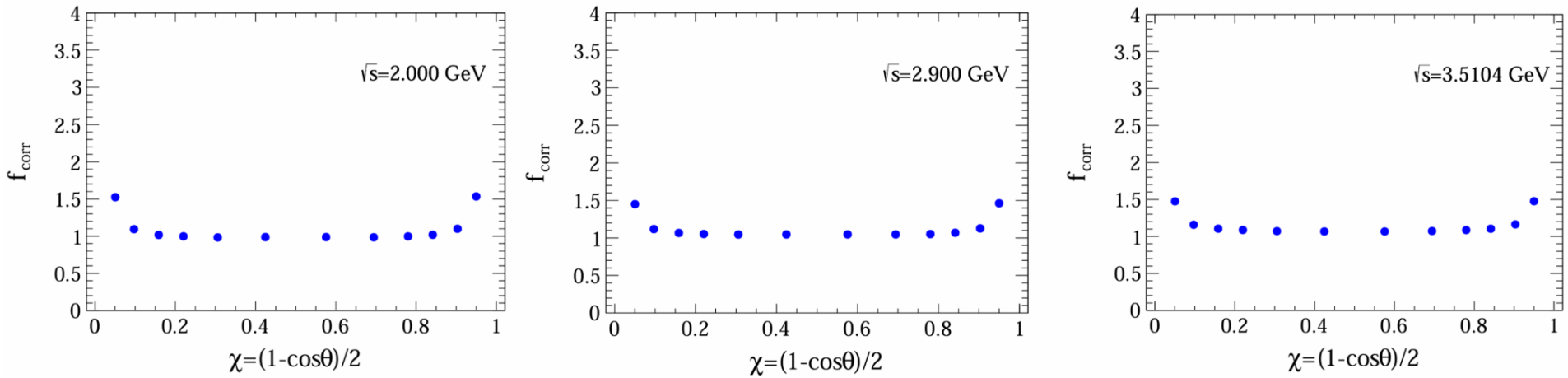
$$SEC = f_{corr}\frac{1}{\sqrt{s}}\frac{\sum_i^{N_{h^\pm}} E_{h_i^\pm}}{N_{had}}\frac{1}{\Delta\chi}$$

Corrections with efficiency and ISR effects

- $f_\epsilon = \dfrac{\sum_i \bar{E}_{h_i}^{\mathrm{obs}}(\mathrm{on})}{\bar{N}_{\mathrm{had}}^{\mathrm{obs}}(\mathrm{on})} \Big/ \dfrac{\sum_i \bar{E}_{h_i}^{\mathrm{tru}}(\mathrm{on})}{\bar{N}_{\mathrm{had}}^{\mathrm{tru}}(\mathrm{on})}$
- $f_{ISR} = \dfrac{\sum_i \bar{E}_{h_i}^{\mathrm{tru}}(\mathrm{on})}{\bar{N}_{\mathrm{had}}^{\mathrm{tru}}(\mathrm{on})} \Big/ \dfrac{\sum_i \bar{E}_{h_i}^{\mathrm{tru}}(\mathrm{off})}{\bar{N}_{\mathrm{had}}^{\mathrm{tru}}(\mathrm{off})}$

$$f_{correct} = 1/(f_\epsilon \times f_{ISR})$$

- ✓ $\bar{E}$: energy extracted from signal MC
- ✓ On: with ISR returned events included
- ✓ Off: without contributions from ISR returned events



3 Analysis of SEC

◆ Statistical Results

✓ Normalized energy-energy correlator with efficiency and ISR corrected

$$SEC = f_{corr}\frac{1}{\sqrt{s}}\frac{\sum_i^{N_{h^\pm}} E_{h_i^\pm}}{N_{had}}\frac{1}{\Delta\chi}$$

✓ Statistical uncertainties

Number of observed events → (Error propagation) → Energy sum

- For a certain bin:

Eur. Phys. J. C 77 (2017) 12, 872

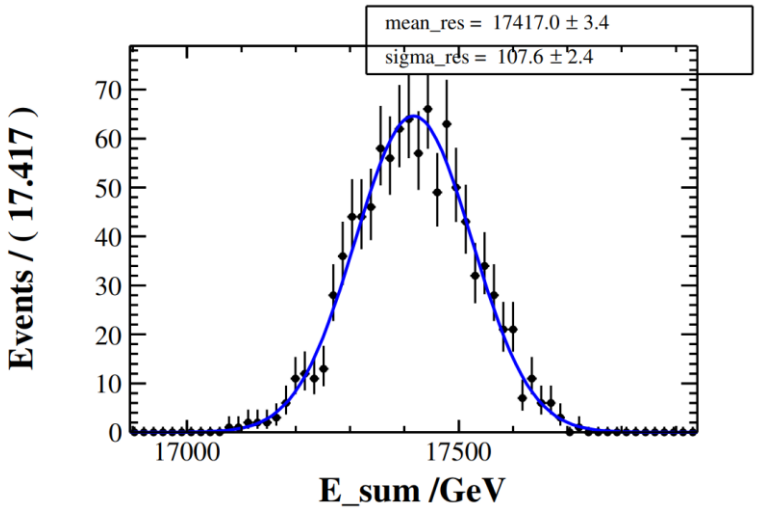
Weighting each event with Poisson-distribution ($\lambda = 1$)

↓

Generate 1000 group replicas

- The statistical uncertainty on each bin is then defined as the standard deviation :

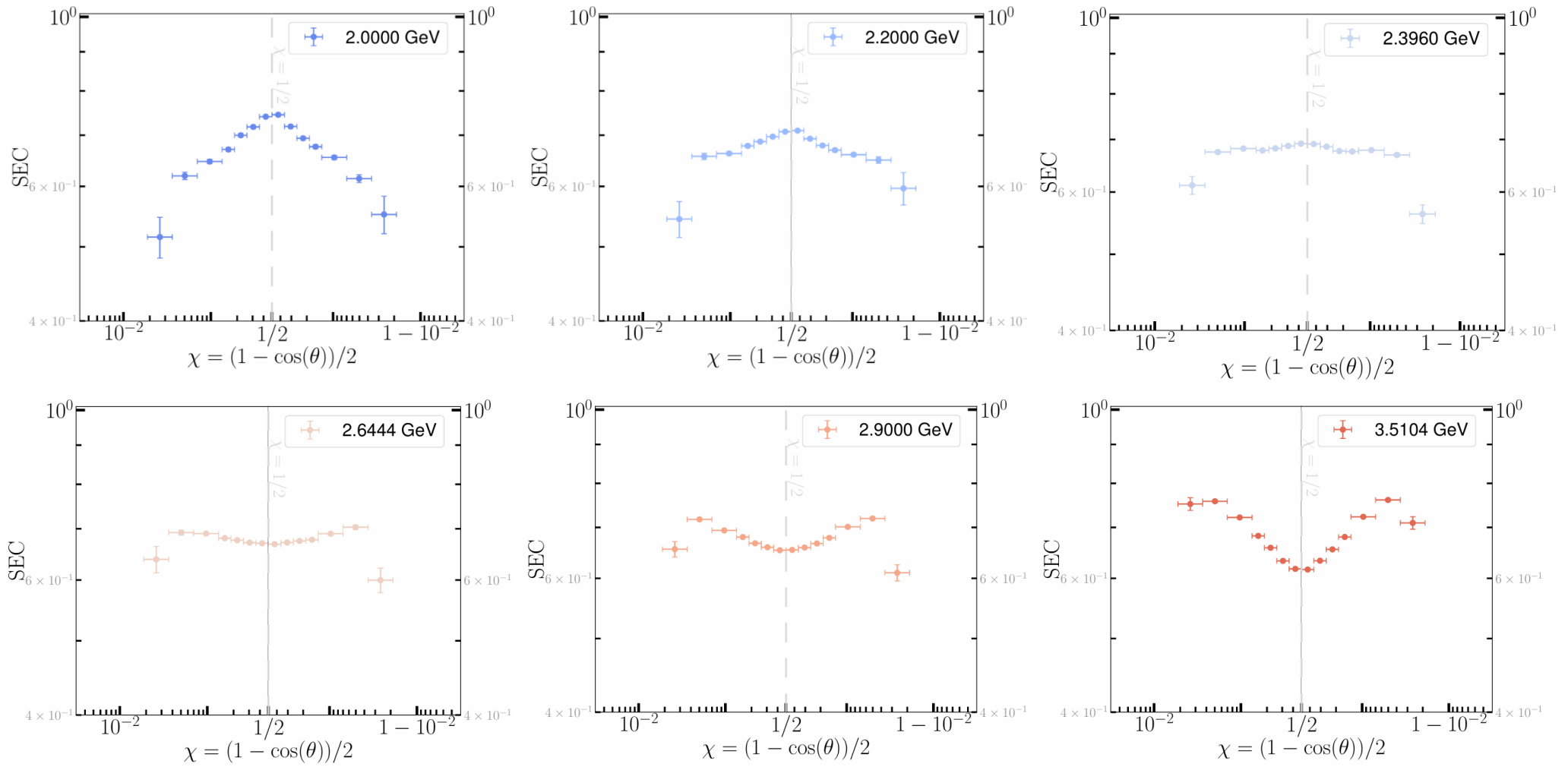
$$\sigma = \sqrt{\frac{\sum_{i=1}^{N}(x_i - \bar{x})^2}{N}}$$



3 Analysis of SEC

$$SEC = f_{corr}\frac{1}{\sqrt{s}}\frac{\sum_i^{N_{h^\pm}} E_{h_i^\pm}}{N_{had}}\frac{1}{\Delta\chi}$$

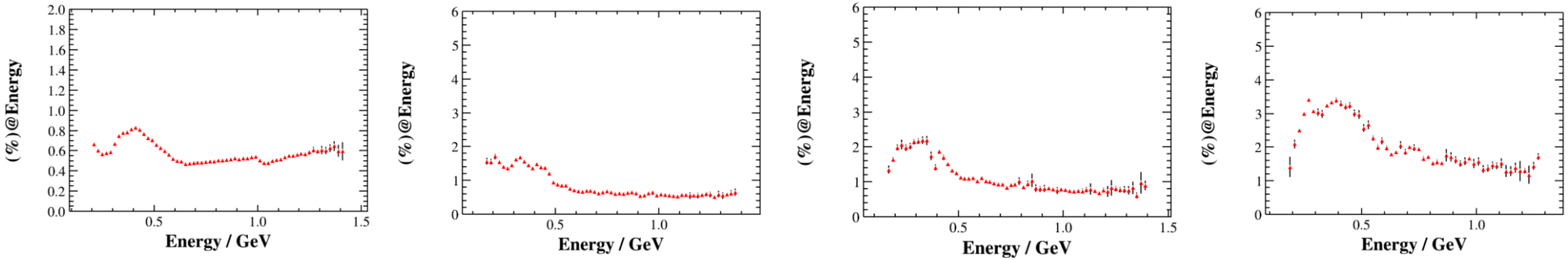
Statistical Results



3 Analysis of SEC-Systematic Uncertainty

- MC model (dominant)
  - ✓ The difference between Luarlw MC and Hybrid MC (2~14%)
- Energy resolution (negligible)
  - ✓ Studied by signal MC in different (cosθ vs E) bins
  - ✓ Fit the residual with a double Gaussian function

Uncertainty in different cosθ and E coverage



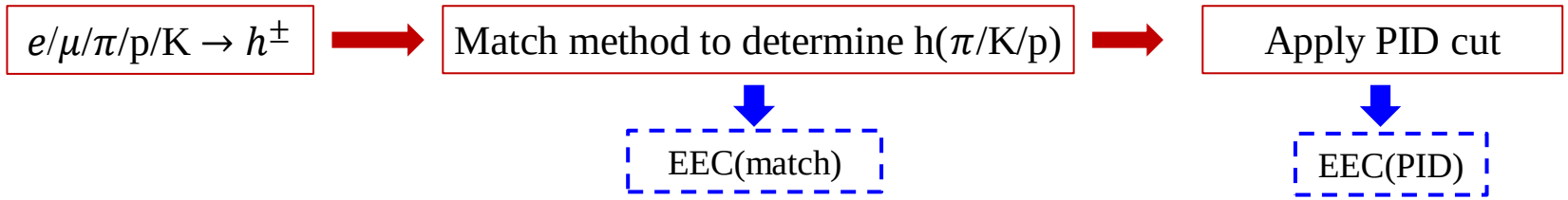
	$\|\cos\theta\|$~(0~0.8)	$\|\cos\theta\|$~(0.8~0.85)	$\|\cos\theta\|$~(0.85~0.9)	$\|\cos\theta\|$~(0.9~0.95)
E<0.5 GeV	0.7%	1.5%	2.0%	3.0%
E>0.5 GeV	0.5%	0.7%	1.0%	1.5%

3 Analysis of SEC-Systematic Uncertainty

- Hadronic event selection (~1%)

Category	Source	Nominal	Alternative	Abbreviation
Veto Bhabha and $\gamma\gamma$	E_{ratio}	$0.65E_{\text{beam}}$	$0.6 \sim 0.7E_{\text{beam}}$	Eratio
	$\Delta\theta$	10°	$5^\circ \sim 15^\circ$	dthveto
Selection of good tracks	V_r	0.5 cm	0.45 ~ 0.55 cm	Vr
	χ_{Prob}	10	15	Chip
	p_{track}	$0.94p_{\text{beam}}$	$0.92 \sim 0.96p_{\text{beam}}$	ptrack
	E/p ratio	0.8	0.75 ~ 0.85	Epratio
	Bhabha momentum limit	$0.65p_{\text{beam}}$	$0.6 \sim 0.7p_{\text{beam}}$	BBplmt
	gamma conversion angle	15°	$10^\circ \sim 20^\circ$	eeang
	gamma conversion mass	100 MeV	80 ~ 120 MeV	eeene
	isolated photon angle	20°	$15^\circ \sim 25^\circ$	isoang
	isolated photon energy	100 MeV	75 ~ 125 MeV	isoene
	PID ratio value	0.25	0.1 ~ 0.4	pidratio
2 prongs events	$\Delta\theta$	10°	$5^\circ \sim 15^\circ$	2prgdth
	$\Delta\phi$	15°	$10^\circ \sim 20^\circ$	2prgdphi
3 prongs events	$\Delta\theta$	10°	$5^\circ \sim 15^\circ$	3prgdth
	$\Delta\phi$	15°	$10^\circ \sim 20^\circ$	3prgdphi

- Mis-identification from $e/\mu/\pi$/p/K (~2%)
  - ✓ Estimated by signal MC:

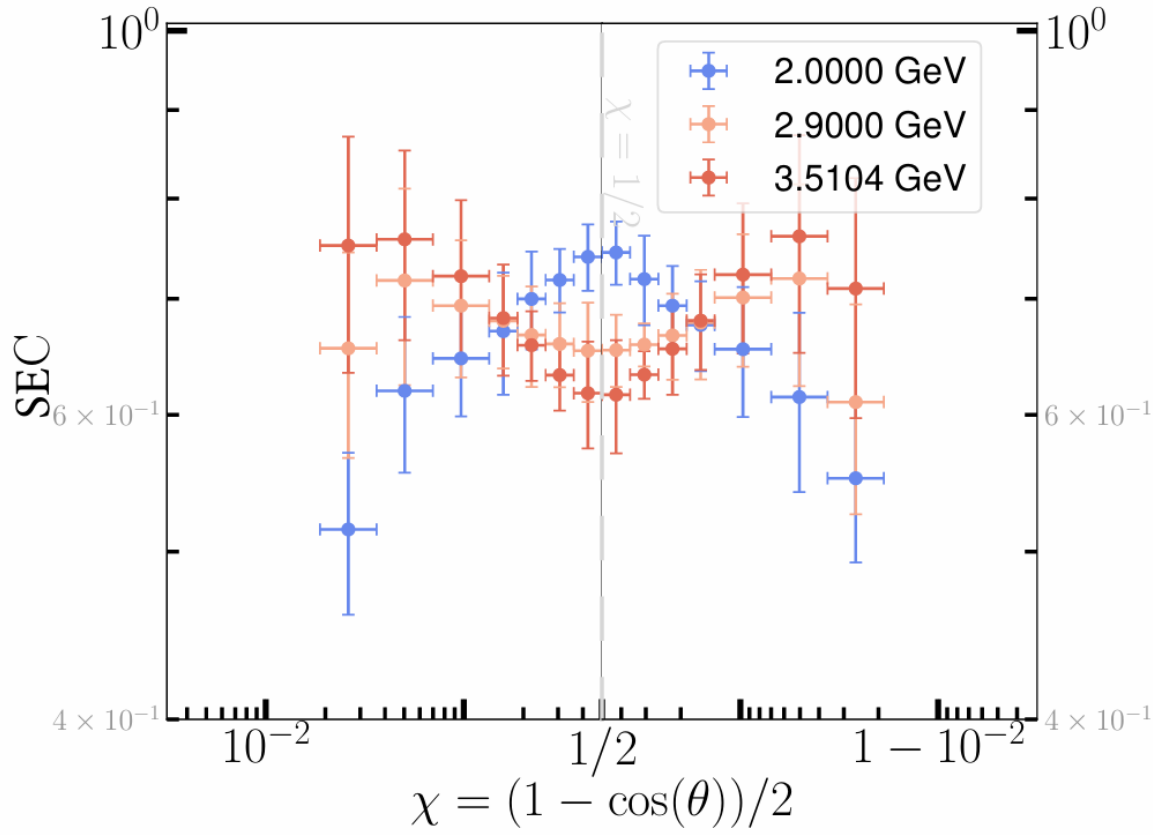


  - ✓ The difference between EEC (match) and EEC (PID) is taken as the systematic uncertainty

3 Analysis of SEC

Final Results

$$SEC = f_{corr}\frac{1}{\sqrt{s}}\frac{\sum_i^{N_{h^\pm}} E_{h_i^\pm}}{N_{had}}\frac{1}{\Delta\chi}$$

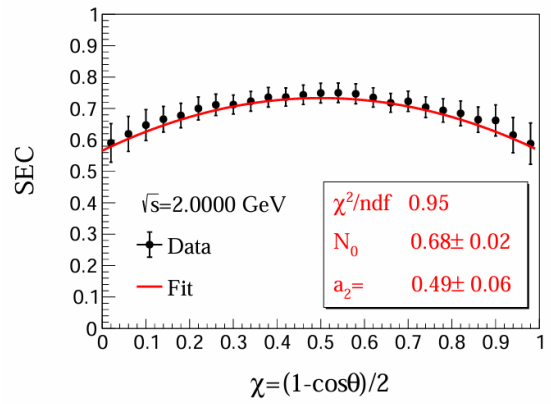


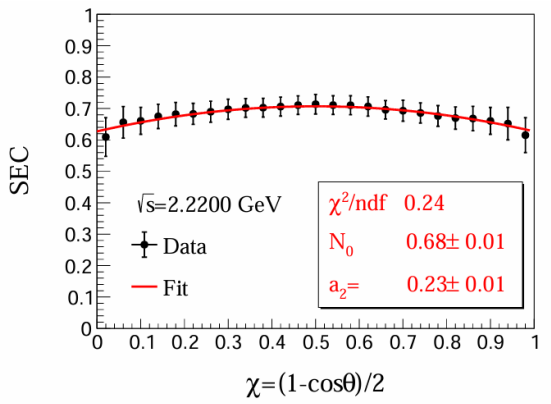
3 Analysis of SEC

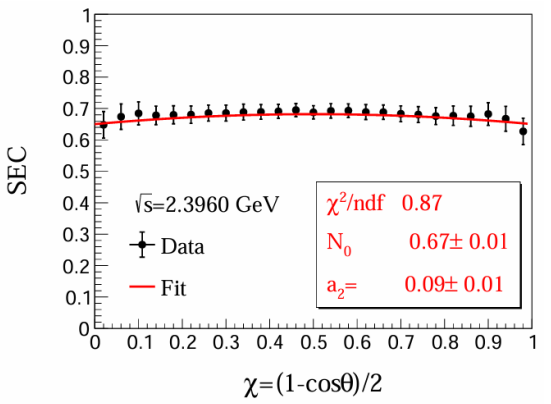
◆ SEC fit with a2

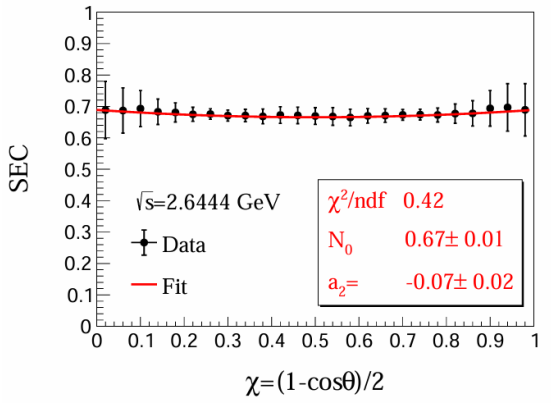
A uniform χ bin width was adopted for the SEC measurement to facilitate a more robust fit to the

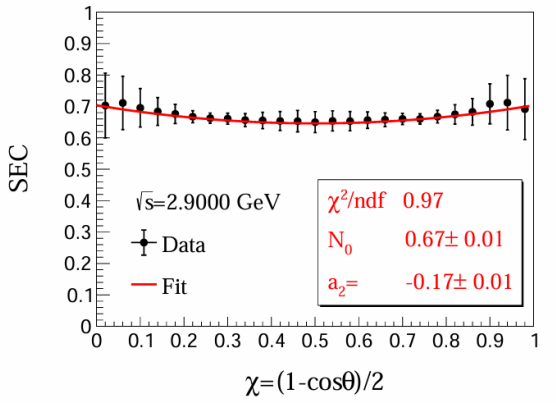
$$\mathrm{SEC} = \langle \varepsilon(\chi) \rangle_{\mathrm{charge}} = N_0 \left(1 + a_2 \left(\sin^2\theta - \frac{1}{3}\right)\right), \qquad \mathrm{SEC} = N_0 \left(1 + a_2 \left(\sin^2\theta - \frac{1}{3}\right)\right) = N_0 \left(1 + a_2 \left(2\chi - 2\chi^2 - \frac{1}{3}\right)\right).$$

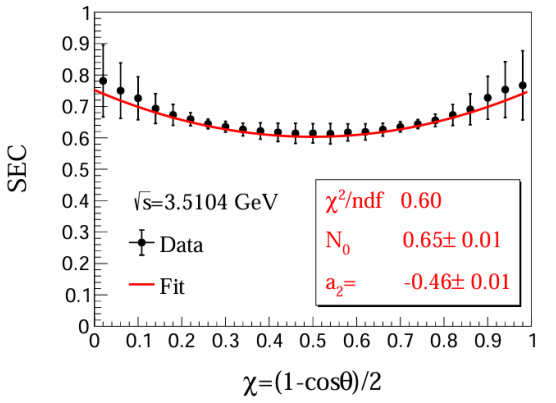








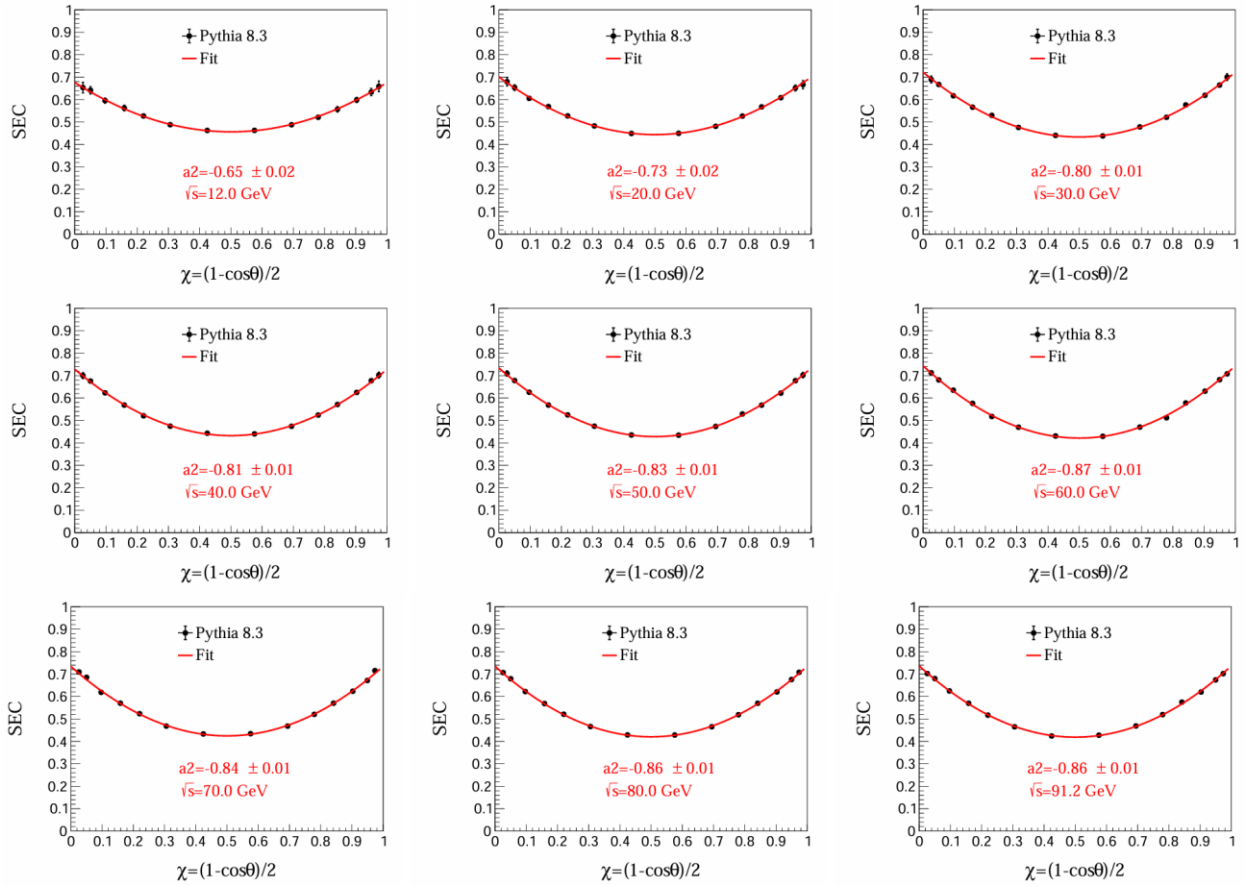




3 Analysis of SEC

◆ SEC fit with a2

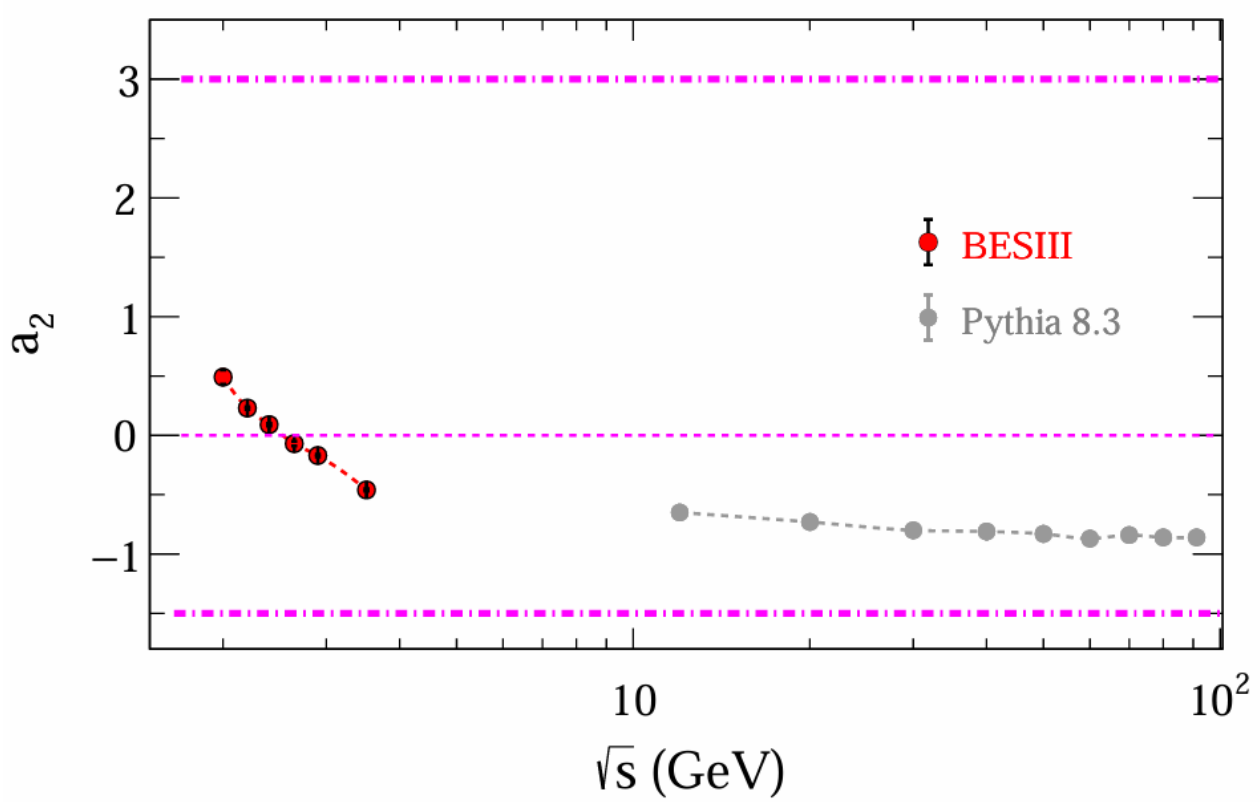
How the a_2 evolves in the higher energy regime?



- ✓ Similar analysis with the Pythia MC truth
- ✓ @ $12.0 < \sqrt{s} < 91.2$ GeV

3 Analysis of SEC

Extracted a2



Crossing 0 around 3 GeV!

Outline

- Introduction of EEC
- Common Data Analysis
- Analysis of single one point energy correlator (SEC)
- **Analysis of inclusive hadron pair energy-energy correlator (EEC)**
- Summary

4 Analysis of inclusive hadron pair EEC

- Same analysis strategy as the SEC measurements

$$SEC = f_{corr}\frac{1}{\sqrt{s}}\frac{\sum_i^{N_{h^\pm}} E_{h_i^\pm}}{N_{had}}\frac{1}{\Delta\chi} \Rightarrow EEC = f_{corr}\frac{1}{\sqrt{s}\cdot\sqrt{s}}\frac{\sum_i^{N_{h_{12}}} E_{h_1}E_{h_2}}{N_{had}}\frac{1}{\Delta\chi}$$

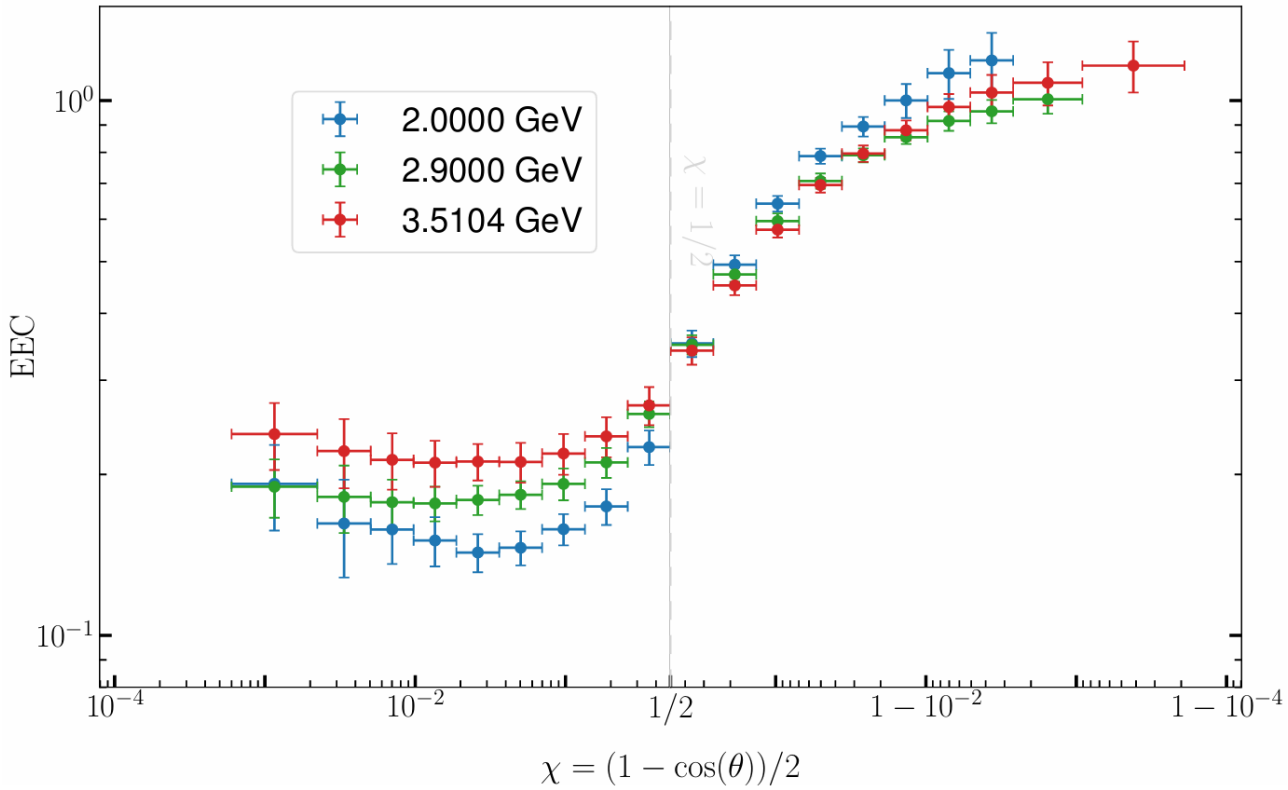
- ✓ MC simulations
- ✓ Background estimations
- ✓ Binning scheme
- ✓ Efficiency and ISR corrections
- ✓ Systematic uncertainties

Bin-by-bin analysed with the same method used in SEC

4 Analysis of inclusive hadron pair EEC

◆ Final results

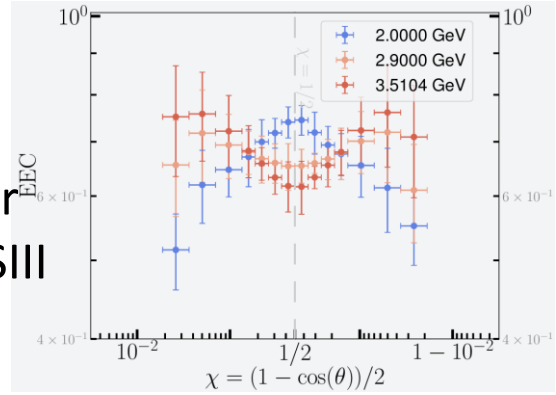
$$EEC = f_{corr}\frac{1}{\sqrt{s}\cdot\sqrt{s}}\frac{\sum_i^{N_{h_{12}}} E_{h_1}E_{h_2}}{N_{had}}\frac{1}{\Delta\chi}$$

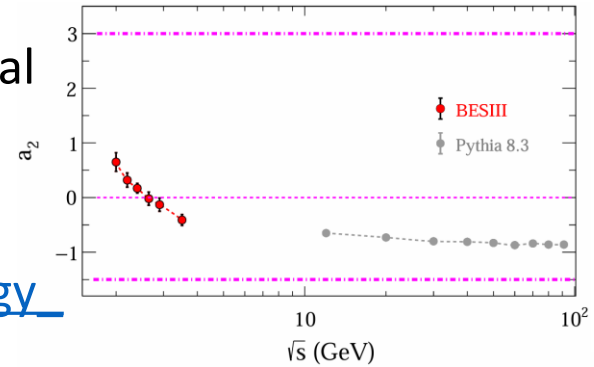


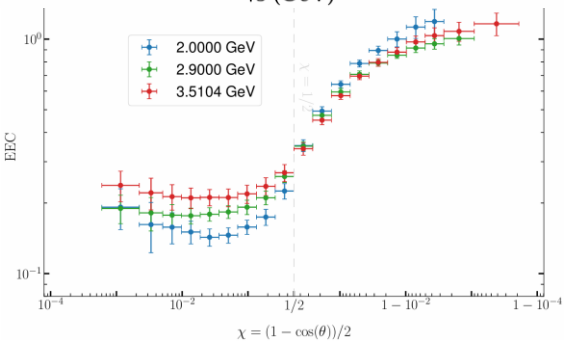
Summary

- Summary
  - ✓ The single one point energy correlator (SEC) and inclusive hadron pair EEC have been studied at c.m. energies from 2.00 to 3.51 GeV at BESIII for the first time.
  - ✓ EEC is another handle to study hadronization in addition to fragmentation functions. It is very powerful to study the fundamental parameters of QCD, such as α_s, a_2.
  - ✓ **Analysis memo is ready for review**: https://docbes3.ihep.ac.cn/DocDB/0017/001735/001/Energy_energy_correlator_studies_at_BESIII__SEC__h_h_EEC_0908.pdf
- Inclusive tagged pion EEC and Azimuthal-dependent EEC will be ready soon.

Thanks for your attention!







Back up