Inclusive π^0/K_S^0 production at $\sqrt{s}=$ 4.843, 4.918 and 4.951 GeV

Linqin Huang[1], Weiping Wang[2,3], Yateng Zhang[4],

Yue Pan[5], Wenbiao Yan[6] and Yuxiang Zhao[1]

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

Mar.12th, 2025

00 Outline

- Introduction
- Data sets
- Hadronic event selection
- $e^+e^- \to \pi^0 + X$
- $e^+e^- \to K_S^0 + X$
- Summary

01 Introduction

◆ Confinement

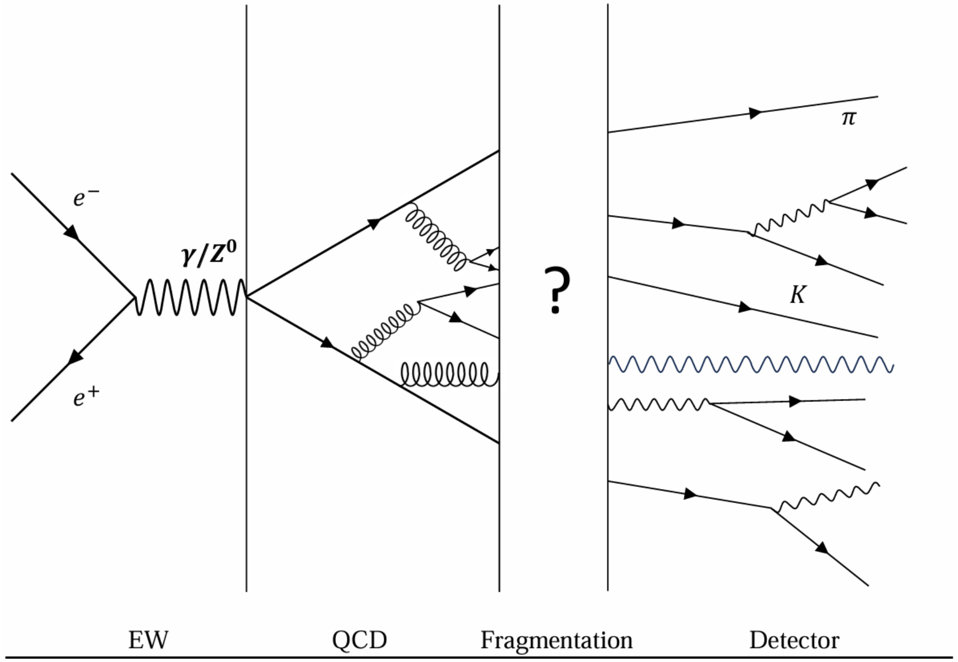
✓ No existing isolated quarks or gluons.

◆ Fragmentation functions (FFs)

✓ **Describe how quarks or gluons transform into hadrons.**

$$D_i^h(z, Q^2),$$

- i: quark, anti-quark or gluon
- h: hadrons like $\pi^0, K_S^0, \pi^\pm$ etc..
- z: energy fraction of hadron. ($z = 2E_h/\sqrt{s}$ in e^+e^-)
- Q^2 : four momentum transfer in the reaction

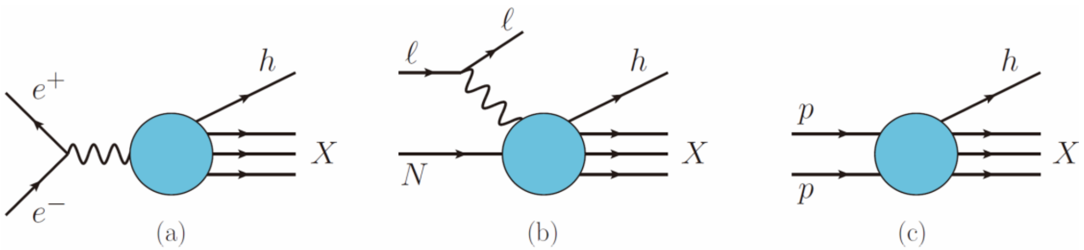


✓ **Probability of finding color-neutral h, need experimental data as input.**

✓ **Essential manifestations of QCD and confinement.**

01 Introduction

◆ FFs in SIA, SIDIS and pp scattering



$$\sigma^{e^+e^-\to h+X} = \sum_q \sigma(e^+e^- \to q\bar{q}) \otimes FF$$

$$\sigma^{lN\to lh+X} = \sum_q PDF \otimes \sigma(eq \to e'q') \otimes FF$$

$$\sigma^{pp\to h+X} = \sum_q PDF \otimes PDF \otimes \sigma(q_1 q_2 \to q_1' q_2') \otimes FF$$

- e^+e^- experiments, no parton distribution function (PDF) needed, is the cleanest laboratory for the fragmentation function studies.

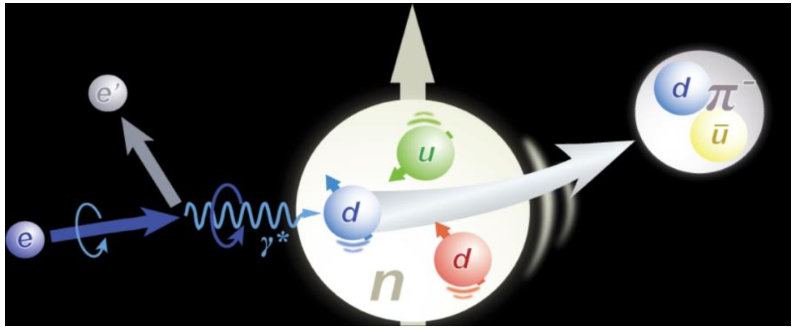
◆ Fragmentation functions (FFS) as Important input for the study of the nucleon structure

- ☐ Experimental observable: polarized structure functions:

$$g_1^h(x, Q^2, z) = \frac{1}{2}\sum_q e_q^2 [\boxed{\Delta q(x, Q^2)}\,\boxed{D_q^h(z, Q^2)} + \Delta\bar{q}(x, Q^2) D_{\bar{q}}^h(z, Q^2)]$$

Parton distributions (PDFs)

FFs



- Understanding how partons build up intrinsic properties of the nucleon

01 Introduction

◆ Fragmentation function in e^+e^-annihilation

✓ **Measure the normalized differential cross-section of the inclusive production of final state hadron "h"**

$$\frac{1}{\sigma_{tot}(e^+e^- \to \mathrm{hadrons})}\frac{d\sigma(e^+e^- \to h + X)}{dp_h}$$

- h is a particular type of hadron like $\pi^0, \pi^\pm, K^\pm \cdots$
- p_h is momentum of hadron
- At leading order: $\sim \sum e_q^2 D_q^h(z, Q^2)$, Q^2 is the energy of virtual photon in e^+e^-annihilation

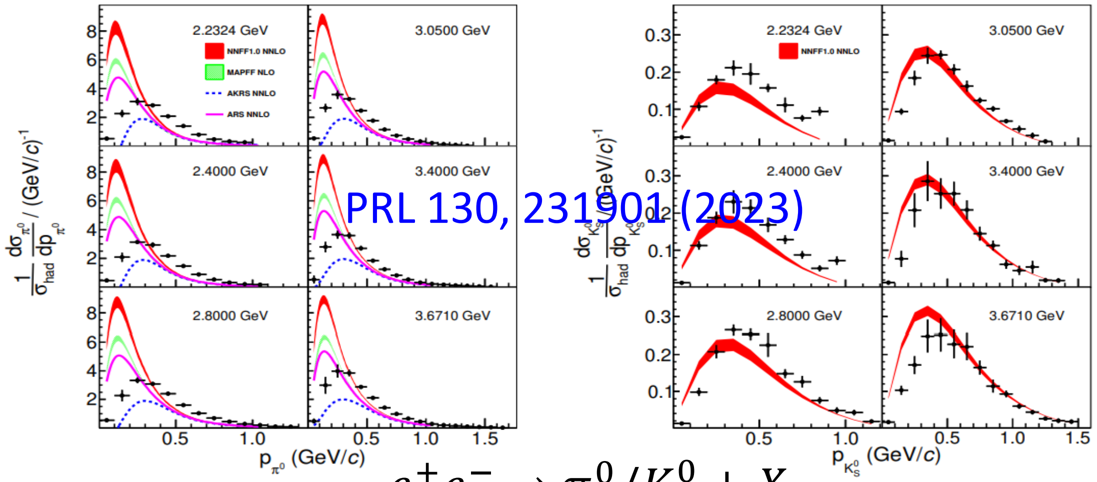
✓ **In practice, the normalized differential cross-section for the inclusive production is measured by:**

$$\frac{1}{\sigma_{had}}\frac{d\sigma}{dp} = f_{correct}\frac{N}{N_{\mathrm{had}}}\frac{1}{\Delta p}$$

N_{had}: Number of total hadronic events
$f_{correct}$ containing efficiency and ISR corrections

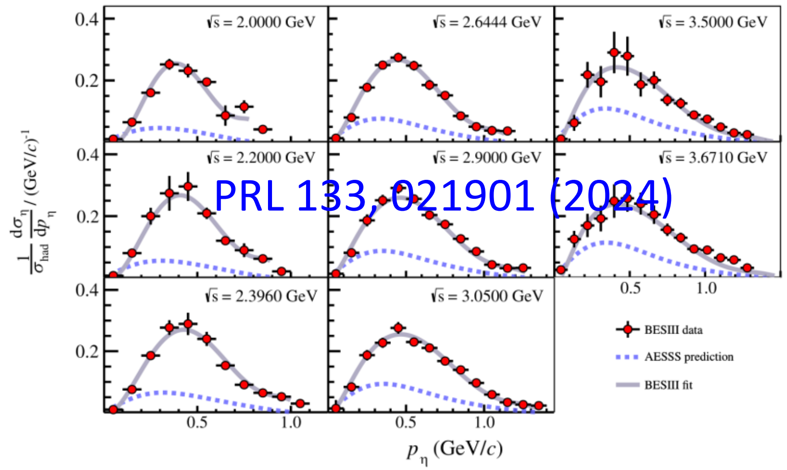
01 Introduction

◆ Inclusive $\pi^0/K_S^0/\eta\ /\pi^{\pm}/K^{\pm}$@ BESIII @ 2.00~3.67 GeV



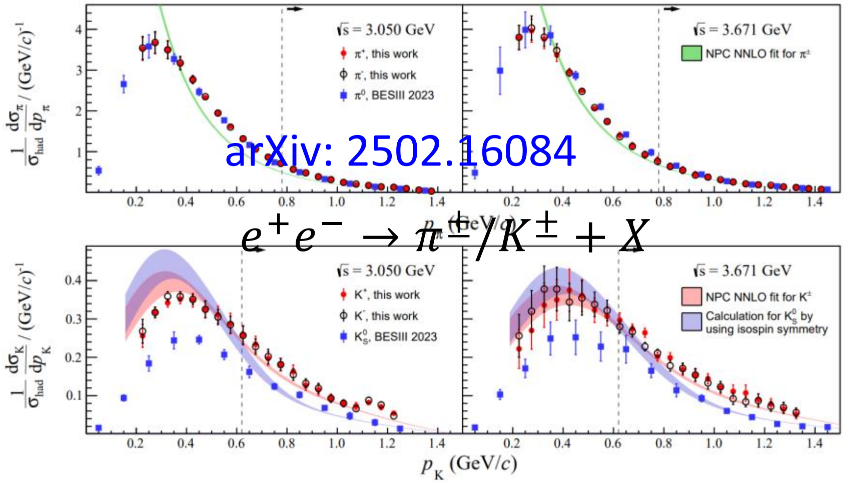
PRL 130, 231901 (2023)

$e^+e^- \to \pi^0/K_S^0 + X$



PRL 133, 021901 (2024)

$e^+e^- \to \eta + X$



arXiv: 2502.16084

$e^+e^- \to \pi^{\pm}/K^{\pm} + X$

- Move to ~5 GeV for these analysis

02 Data Sets

◆ Data sample

Sample	$\sqrt{s}$ (GeV)	Lum. (pb^{-1})	BOSS	Run.No
4840	4.843	525.16	707	65647-65864
4914	4.918	207.82		65867-65935
4946	4.951	159.28		65938-66224

◆ MC Simulation

Same as R-value analysis

- $e^+e^- \to q\bar{q}$: **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**

03

Hadronic Event Selection

Hadronic event selection: Same as R-value analysis

Track Level

- **Veto Bhabha and Di-gamma events**
  - $N_{\text{shower}} \geq 2$
  - $E_1 \geq E_2 \geq 0.65 E_{\text{beam}}$
  - $|\Delta\theta| = |\theta_1 + \theta_2 - 180°| < 10°$
- **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 , $|\cos\theta| < 0.93$
  - $p_{\text{track}} < 0.94 p_{\text{beam}}$, 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 $p > 0.65 p_{\text{beam}}$
  - 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 $E/p > 0.8$) ≤ 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

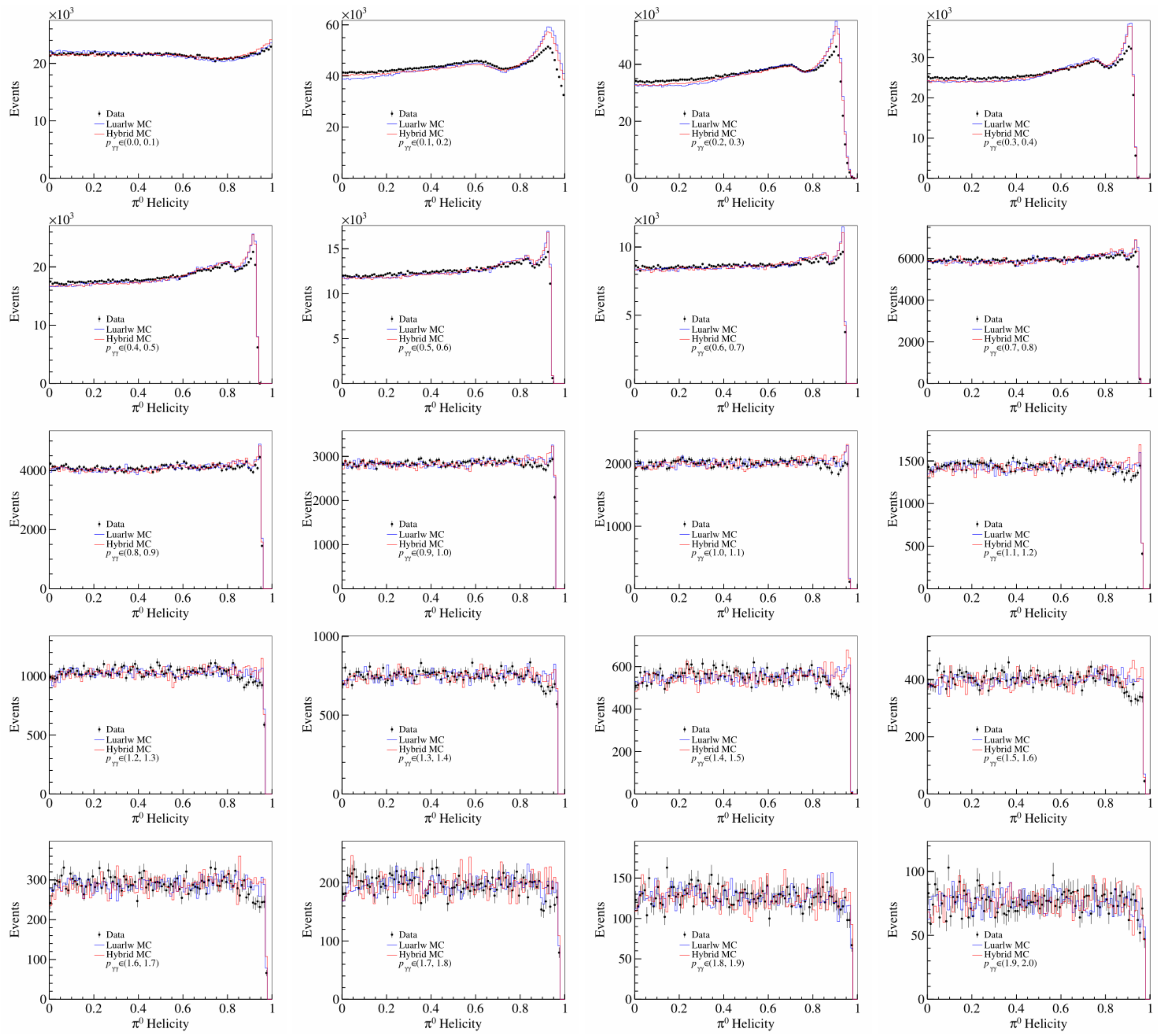
04

$$e^+e^- \rightarrow \pi^0 + X$$

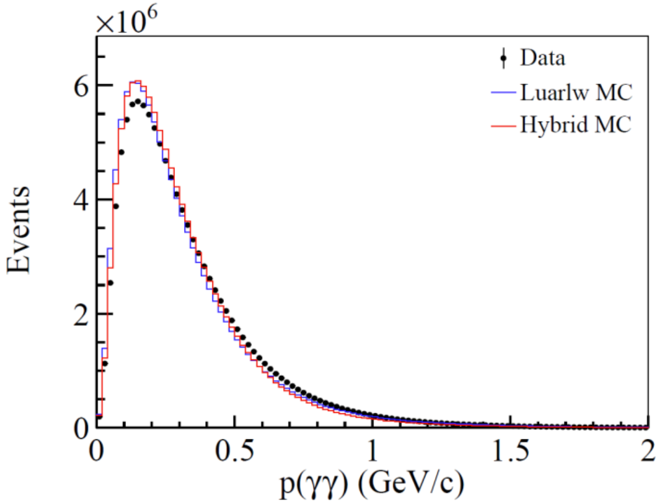
04 $e^+e^- \to \pi^0 + X$

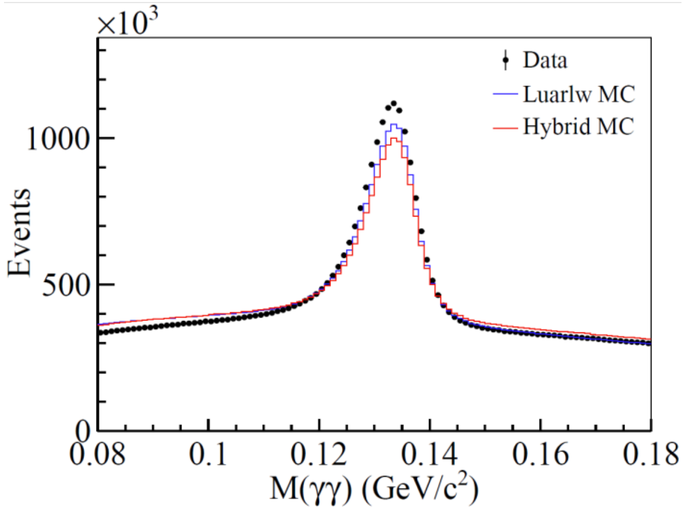
Hadronic event selection

- **Good photon**
  - •Ebarrel >25 MeV; Eendcap >50 MeV ;
  - •0≤TDC≤14
  - •Nγ ≥2, θ(γ,charge) > 10°;
- **Loop 2 photons to form π^0 candidate**
- **π^0 Helicity: $|E_{\gamma 1} - E_{\gamma 2}|/p_{\pi^0}$<0.8**
- **π^0 yields VS momentum**

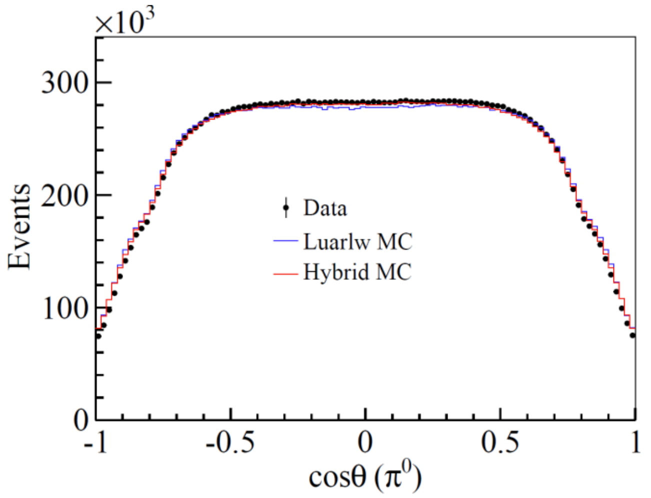


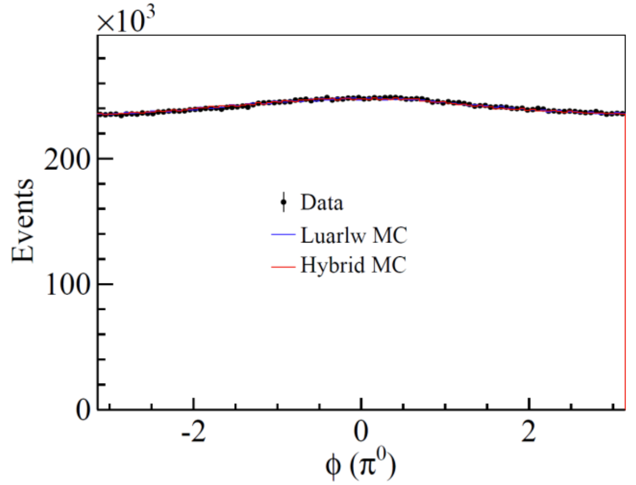
$e^+e^- \to \pi^0 + X$ Comparing Data to Inclusive MC

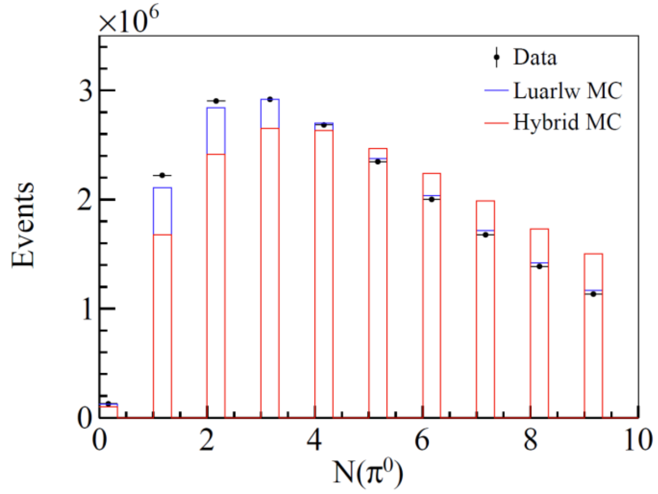




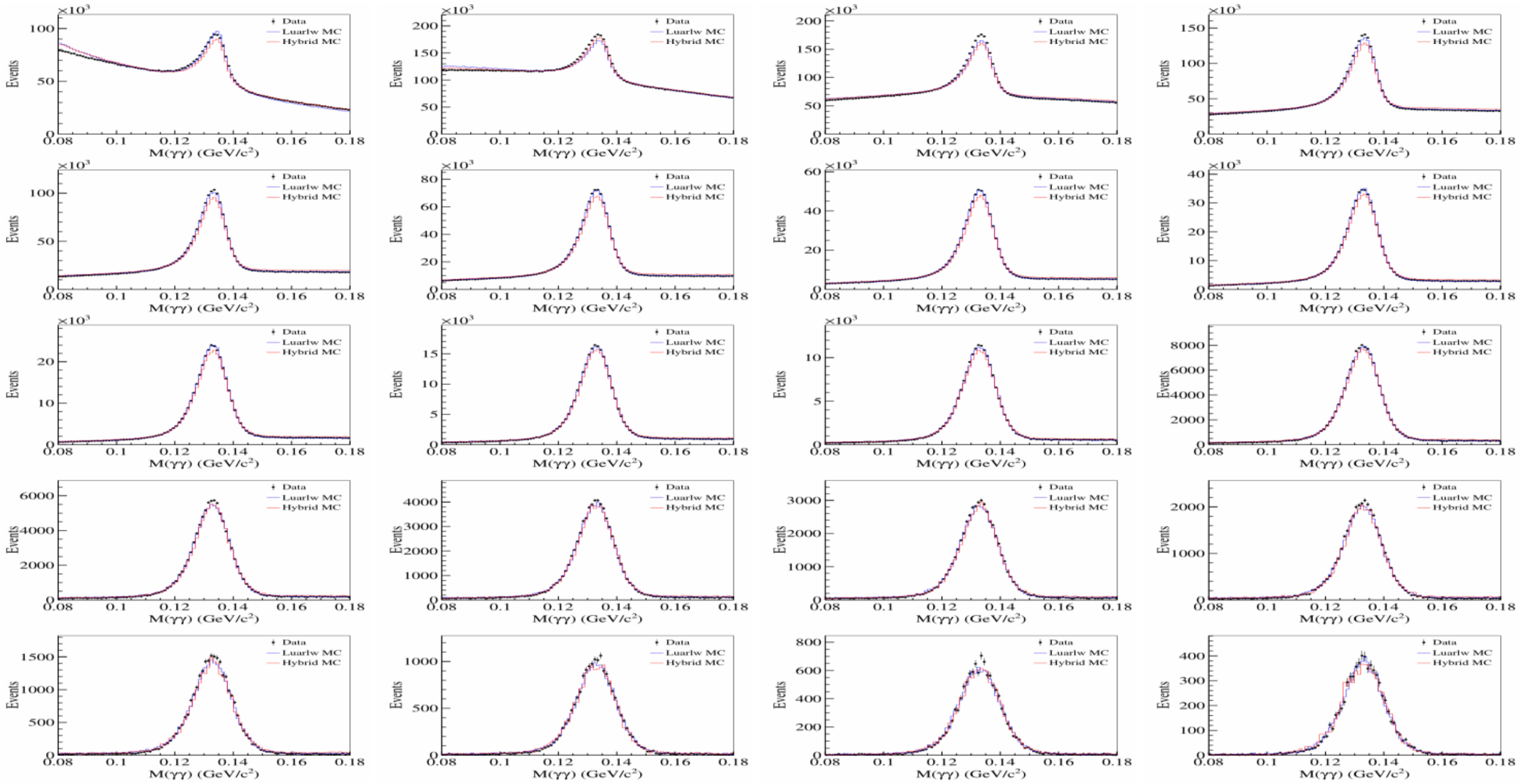
- Points with error bars: experimental data
- Blue histograms: Luarlw MC
- Red histograms: Hybrid MC
- Luarlw/Hybrid model can reproduce the experimental data







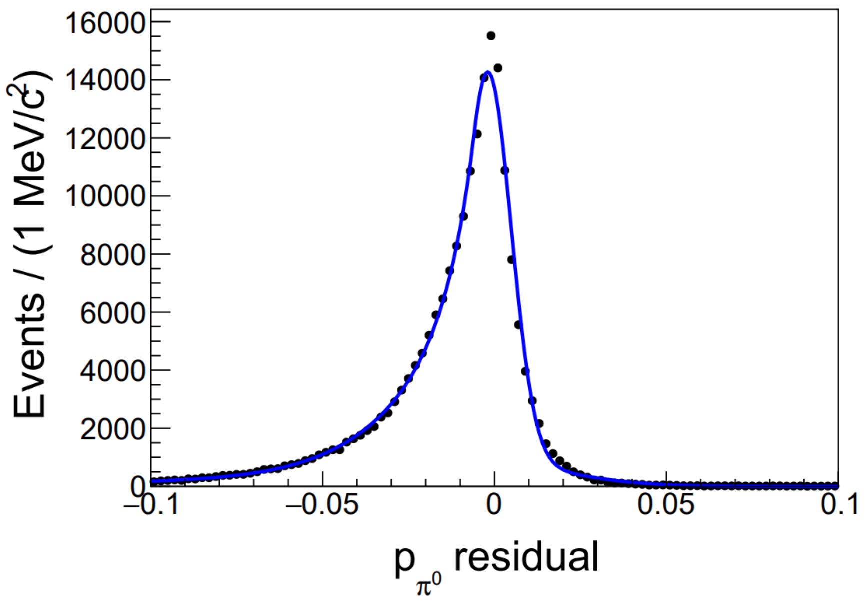
04 $e^+e^- \to \pi^0 + X$ Comparing Data to Inclusive MC



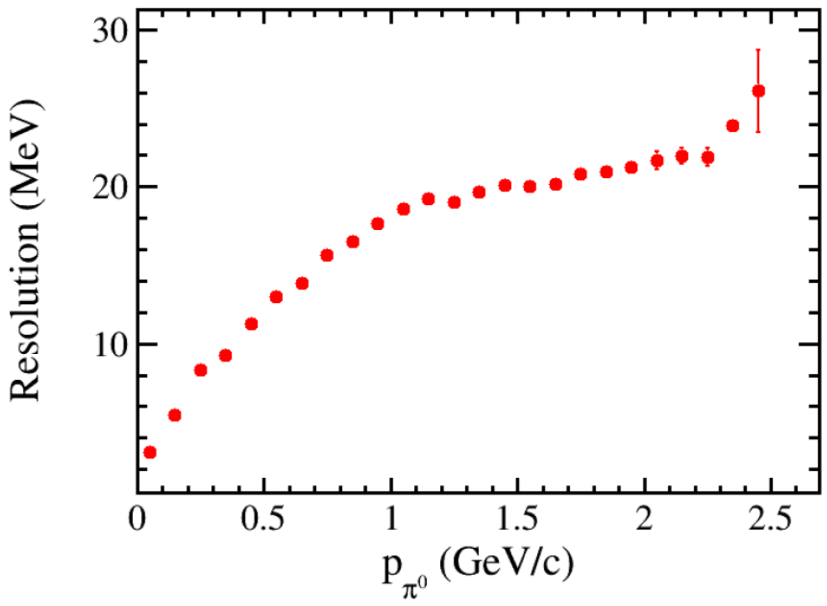
- π^0 mass in different momentum regions
- Points with error bars: experimental data
- Blue histograms: Luarlw MC
- Red histograms: Hybrid MC

04

$e^+e^- \to \pi^0 + X$



Fitting with Crystal Ball

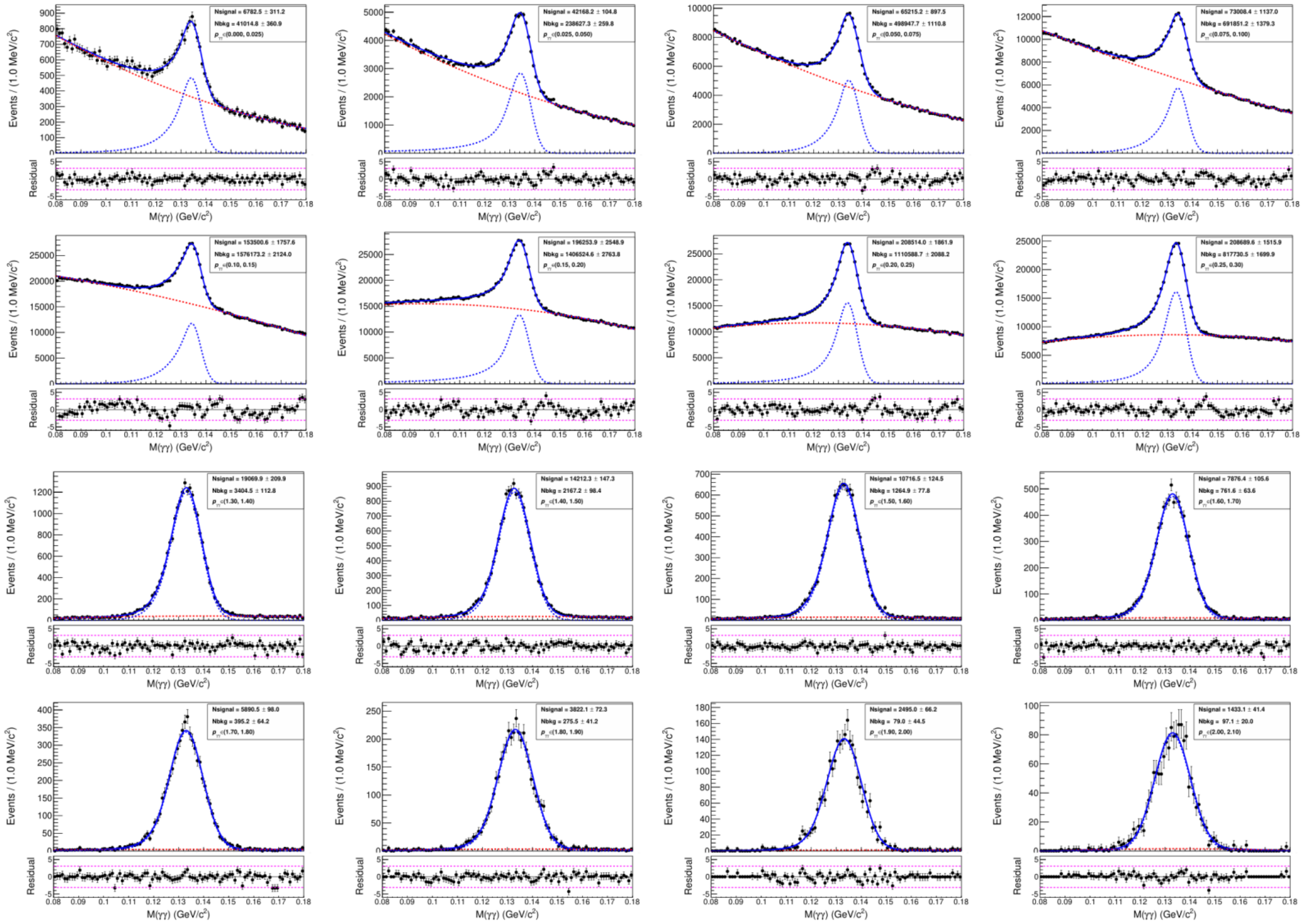


Resolution of π^0

Binning scheme:

- 25 MeV for p<0.1 GeV
- 50 MeV for p<0.5 GeV
- 100 MeV for p>0.5 GeV

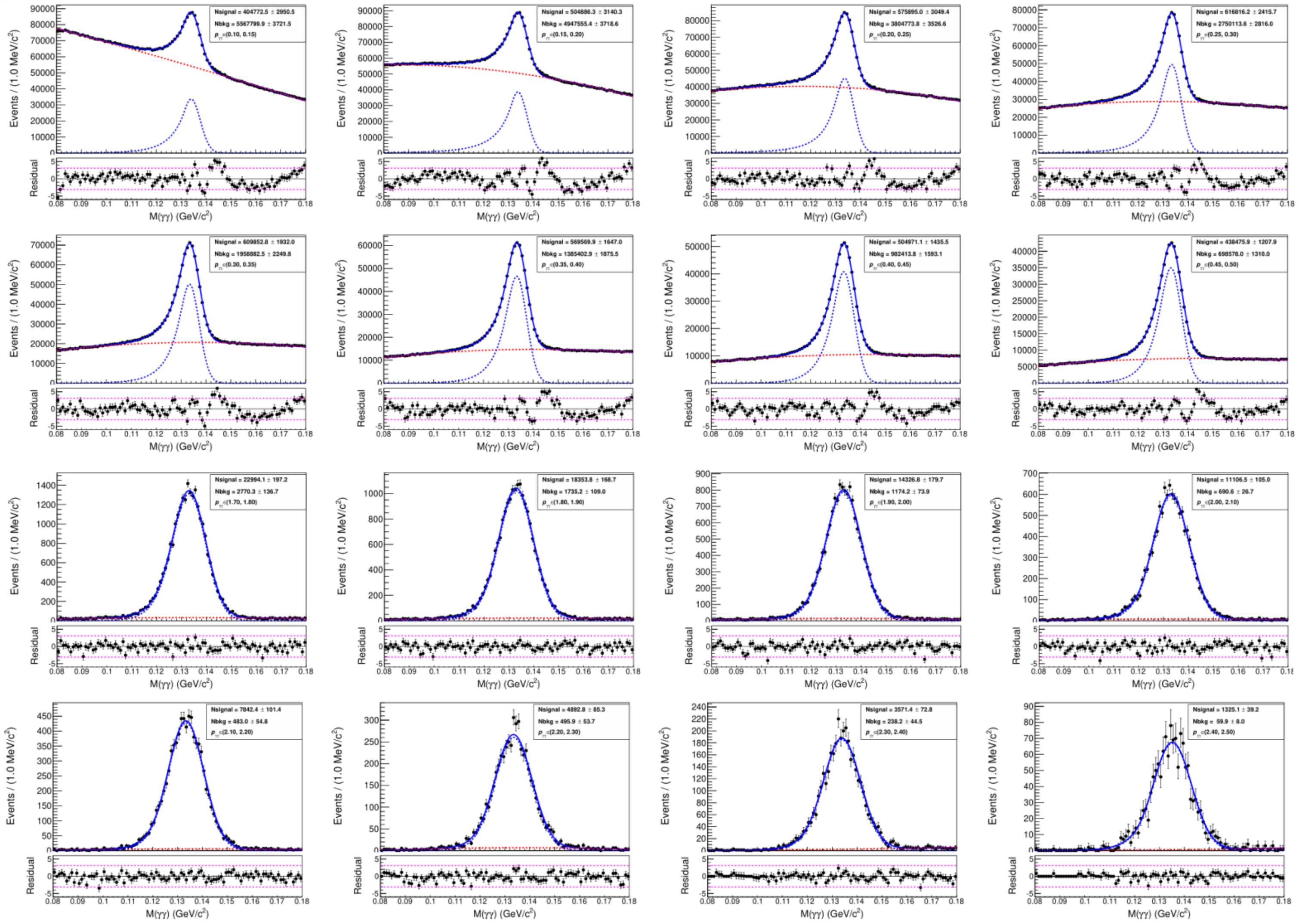
$e^+e^- \to \pi^0 + X$



- Un-binned maximum likelihood fit to data
  - Signal: CB⊗Gaussian
  - Background: Chebyshev polynomials

04

$e^+e^- \to \pi^0 + X$



- Un-binned maximum likelihood fit to MC
  - Signal: CB⊗Gaussian
  - Background: Chebyshev polynomials

04

$e^+e^- \to \pi^0 + X$

◆ Normalized differential cross section with efficiency and ISR corrections

$$\frac{1}{\sigma_{\text{had}}}\frac{d\sigma_{\pi^0}}{dp_{\pi^0}} = f_{correct}\frac{N_{\pi^0}}{N_{\text{had}}}\frac{1}{\Delta p_{\pi^0}}$$

- $f_{correct} = \frac{\bar{N}_{\pi^0}^{\text{tru}}(\text{off})}{\bar{N}_{\text{had}}^{\text{tru}}(\text{off})} \bigg/ \frac{\bar{N}_{\pi^0}^{\text{obs}}(\text{on})}{\bar{N}_{\text{had}}^{\text{obs}}(\text{on})}$

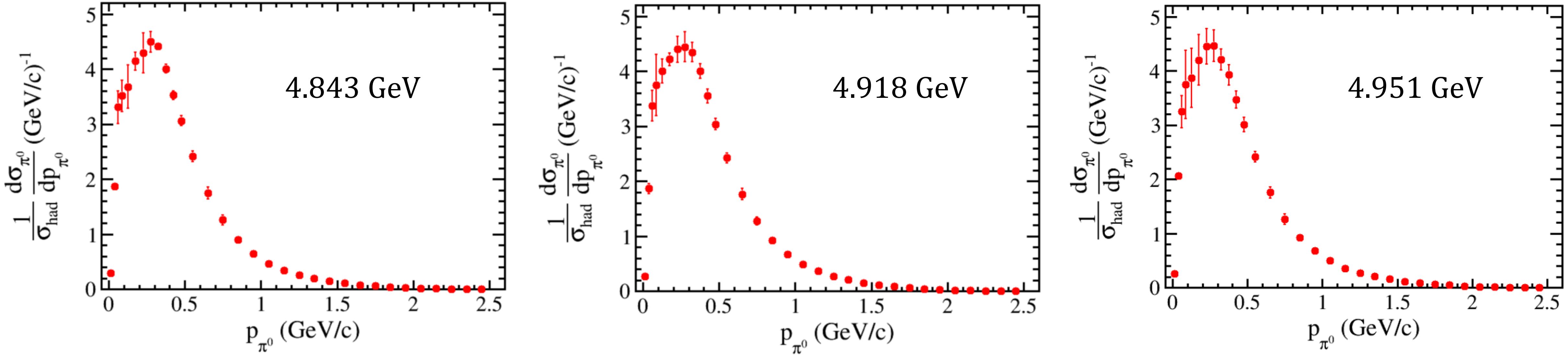
✓ $\bar{N}$: events extracted from signal MC

✓ On: with ISR returned events included

✓ Off: without contributions from ISR returned events

$e^+e^- \to \pi^0 + X$

Differential cross section



$$\frac{1}{\sigma_{\mathrm{had}}}\frac{d\sigma_{\pi^0}}{dp_{\pi^0}} = f_{correct}\frac{N_{\pi^0}}{N_{\mathrm{had}}}\frac{1}{\Delta p_{\pi^0}}$$

Systematic uncertainty study

- MC model (dominant, 5-10%)
  - ✓ The difference between Luarlw MC and Hybrid MC (with Luarlw as nominal MC model)
- π^0 Helicity:
  - ✓ π^0 Helicity<0.8 → π^0 Helicity<0.78 (0.82)
- π^0 Reconstruction:
  - ✓ 1% for single photon, 2% for π^0
- π^0 Fitting strategies (1-2%)
  - ✓ Signal shape: CB → MC shape
  - ✓ Background shape: 2-order Chebyshev → 3-order Chebyshev

04 $e^+e^- \to \pi^0 + X$

Systematic uncertainty study

◆ Hadronic Event Selection

✓ The Alternative cuts applied to estimated uncertainties from hadronic event selection (on going)

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	$0.45 \sim 0.55$ 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	$0.75 \sim 0.85$	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	$80 \sim 120$ MeV	eeene
	isolated photon angle	20°	$15^\circ \sim 25^\circ$	isoang
	isolated photon energy	100 MeV	$75 \sim 125$ MeV	isoene
	PID ratio value	0.25	$0.1 \sim 0.4$	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

05

$$e^+e^- \to K_S^0 + X$$

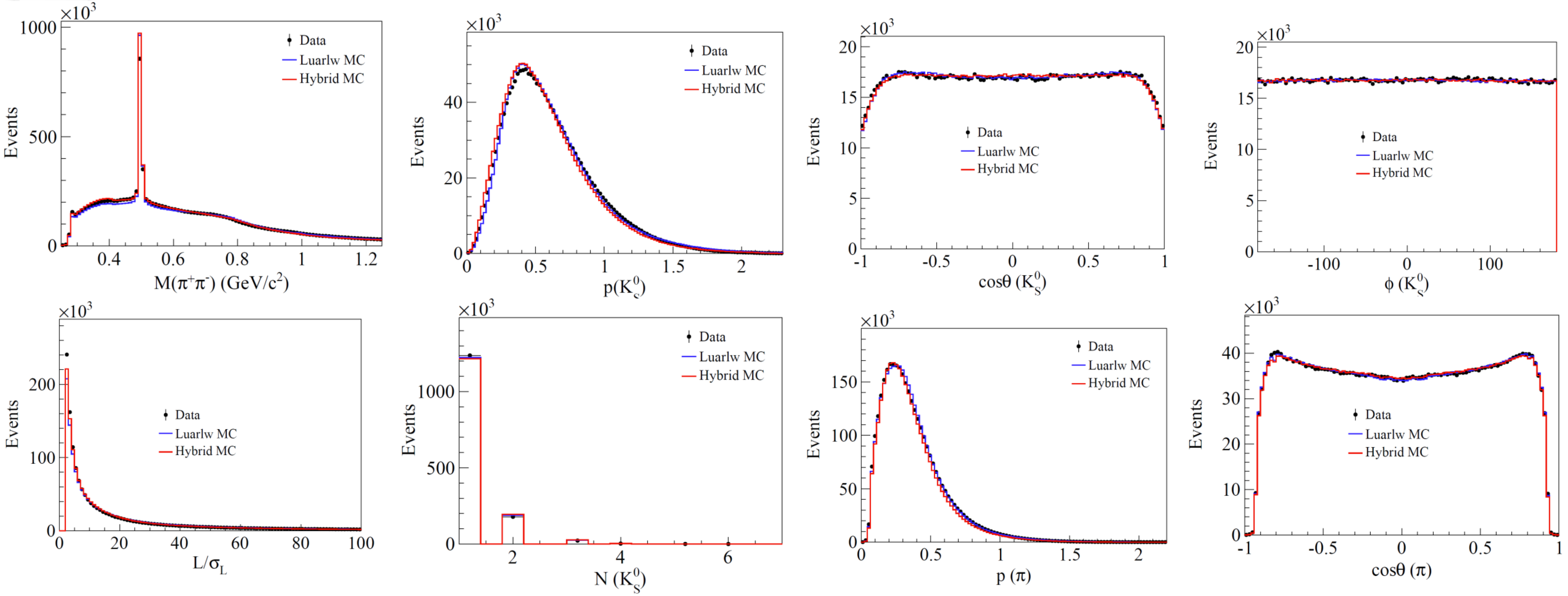
$e^+e^- \to K_S^0 + X$ -Event Selection

Hadronic Event Selection

- Charged Tracks:
  - |Vr|<10 cm && |Vz|<30 cm && |cosθ|<0.93
- PID:
  - π: $\mathrm{Prob}(\pi) > \mathrm{Prob}(K)$ && $\mathrm{Prob}(\pi) > \mathrm{Prob}(p)$
  - N(π^+)≥1 && N(π^-)≥1
- Second Vertex fit
  - Loop all ($\pi^+\pi^-$) pairs
  - Decay length over error: L/σ_L>2
- 0.47<|M($\pi^+\pi^-$)|<0.53 GeV

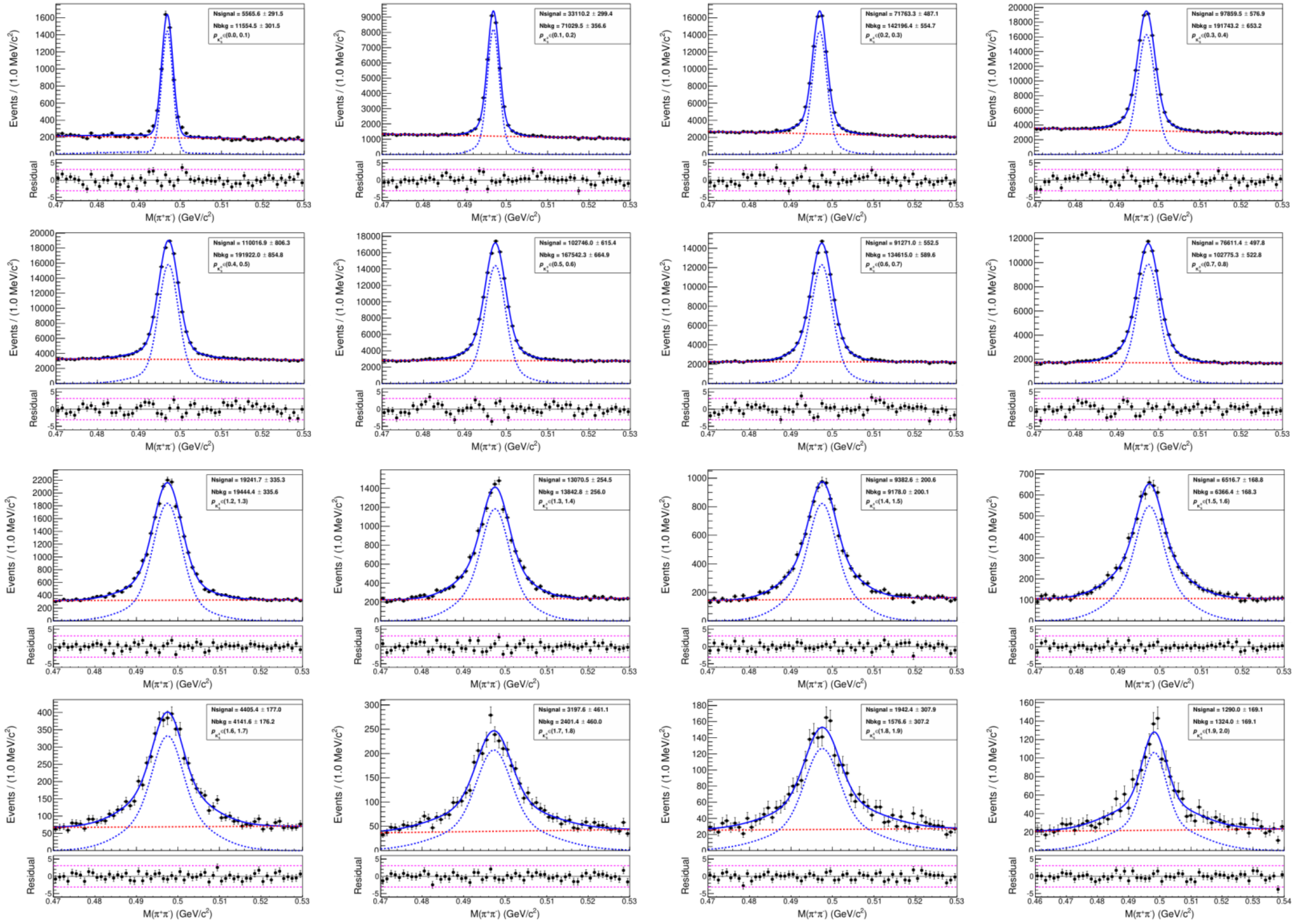
K_S^0 Selection

$e^+e^- \to K_S^0 + X$ Comparing Data to Inclusive MC



- Points with error bars: experimental data
- Blue histograms: Luarlw MC, Red histograms: Hybrid MC
- Luarlw/Hybrid model can reproduce the experimental data

05 $e^+e^- \to K_S^0 + X$

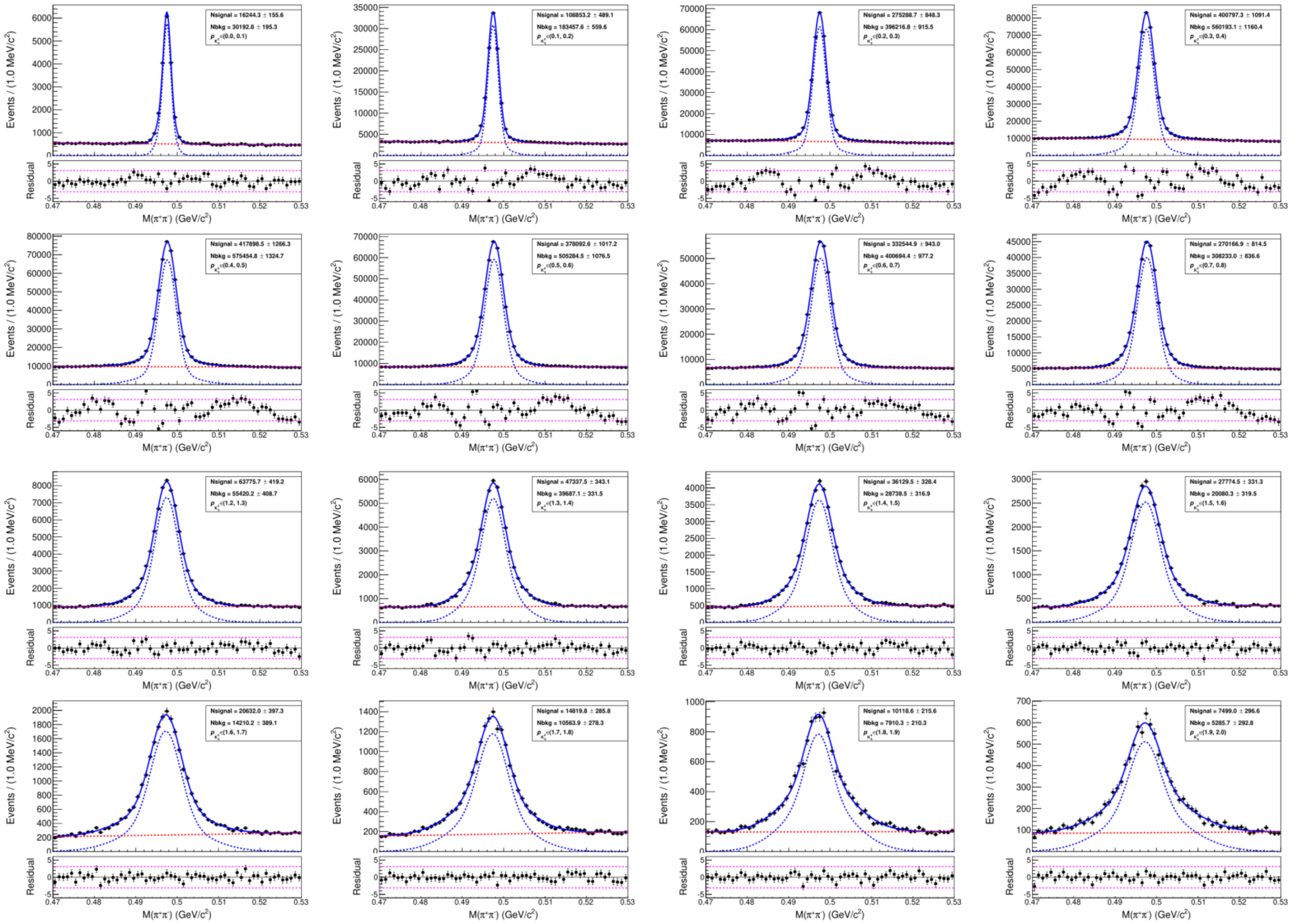


- Un-binned maximum likelihood fit to data
  - Signal: Double Gaussian
  - Background: Chebyshev polynomials

Binning scheme: 100 MeV

05

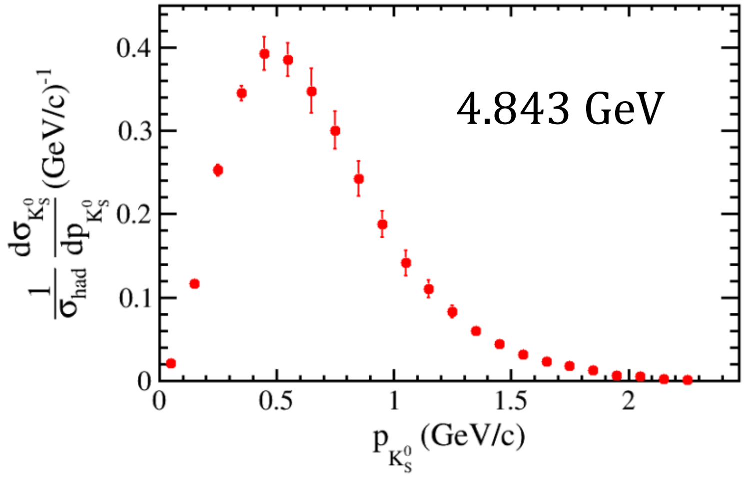
$e^+e^- \to K_S^0 + X$

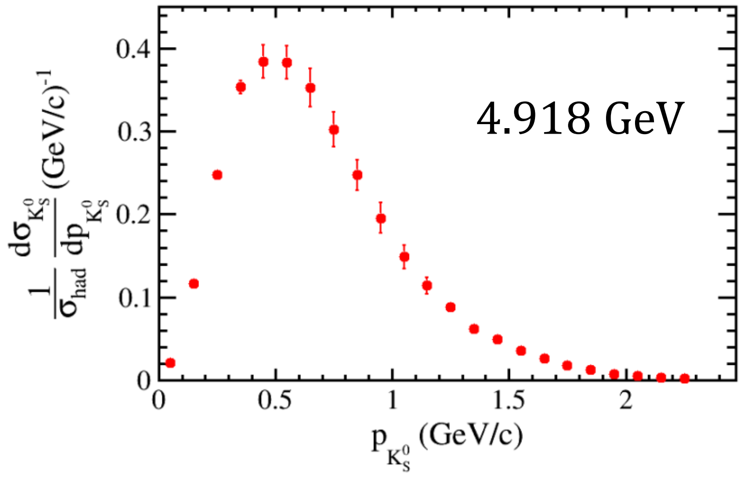


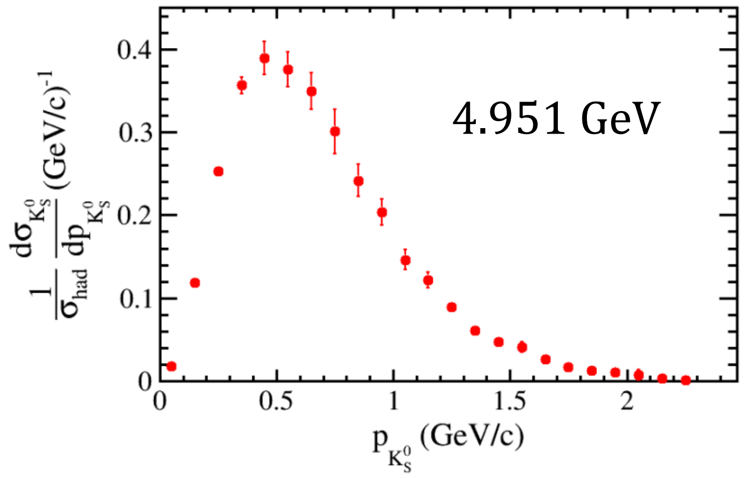
- Un-binned maximum likelihood fit to MC
  - Signal: Double Gaussian
  - Background: Chebyshev polynomials

05 $e^+e^- \to K_S^0 + X$

Normalized differential cross section with efficiency and ISR corrections







$$\frac{1}{\sigma_{\mathrm{had}}}\frac{d\sigma_{K_S^0}}{dp_{K_S^0}} = f_{correct}\frac{N_{K_S^0}}{N_{\mathrm{had}}}\frac{1}{\Delta p_{K_S^0}}$$

$e^+e^- \rightarrow K_S^0 + X$

Systematic uncertainty study

- MC model (dominant, 5-10%)
  - ✓ The difference between Luarlw MC and Hybrid MC (with Luarlw as nominal MC model)
- PID
  - ✓ 1% per pion
- K_S^0 reconstruction:
  - ✓ 1% (https://docbes3.ihep.ac.cn/cgi-bin/DocDB/ShowDocument?docid=520)
- K_S^0 fitting strategies (1-2%)
  - ✓ Signal shape: double gauss → single gauss
  - ✓ Background shape: 1-order Chebyshev → 2-order Chebyshev
- Hadronic event selection

06 Summary and next to do

- Summary
  - ✓ The processes of $e^+e^- \to \pi^0/K_S^0$ + X have been measured at c.m. energies 4.843, 4.918 and 4.951 GeV.
  - ✓ Dominant systematic uncertainty has been studied.
  - ✓ Offer important experimental information for unpolarized fragmentation function study around 5 GeV.
- Next to do
  - ✓ Remaining systematic uncertainty studies and preparing memo.

Backup