

R value measurement from 2.00 to 4.95 GeV and
study of $e^+e^- \rightarrow 3(\pi^+\pi^-)$ near nucleon-pair threshold

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Outline

- Introduction
- R value measurement from 2.00 to 4.95 GeV
 - ▶ Motivation
 - ▶ Analysis Strategy
 - ▶ Signal simulation
 - ▶ Systematic uncertainty
 - ▶ Summary
- Study of $e^+e^- \rightarrow 3(\pi^+\pi^-)$ near nucleon-pair threshold
 - ▶ Motivation
 - ▶ Event selection
 - ▶ Signal extraction
 - ▶ Summary and next to do
- Summary and Prospect

Standard Model

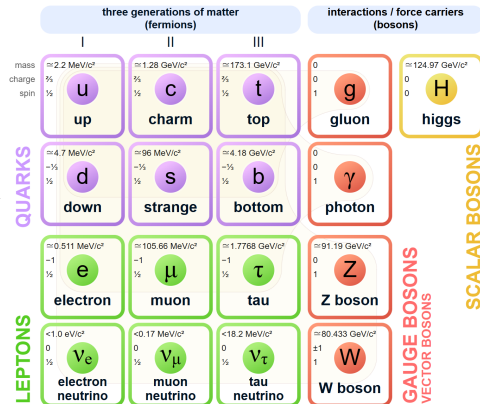
✓ describes the **fundamental particles** that make up the visible world of matter and **how they interact with each other.**

✗ but it still does not explain issues

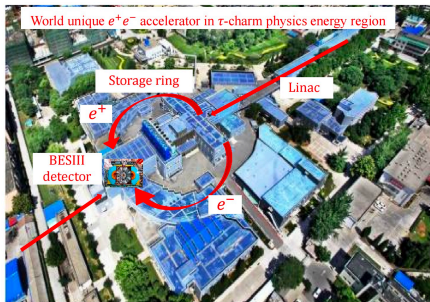
- Existence of dark matter and dark energy
- Mass of the neutrinos



Experiments: test of SM, search for new physics beyond SM



BEPCII and BESIII



Double rings

$$E_{\text{cm}} = 1.84 - 4.95 \text{ GeV}$$

Peak luminosity @ $E_{\text{cm}} = 3.773 \text{ GeV}$:

$$1.1 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$$

Circumference: 237.53 m

Crossing angle: $2 \times 11 \text{ mrad}$

Electromagnetic Calorimeter

CsI(Tl): $L=28 \text{ cm}$

Barrel $\sigma_E=2.5\%$

Endcap $\sigma_E=5.0\%$

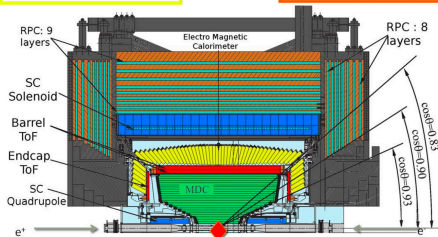
Muon Counter

RPC

Barrel: 9 layers

Endcap: 8 layers

$\sigma_{\text{spatial}}: 1.48 \text{ cm}$



Main Drift Chamber

Small cell, 43 layer

$\sigma_{xy}=130 \mu\text{m}$

$dE/dx \sim 6\%$

$\sigma_p/p = 0.5\%$ at 1 GeV

Time Of Flight

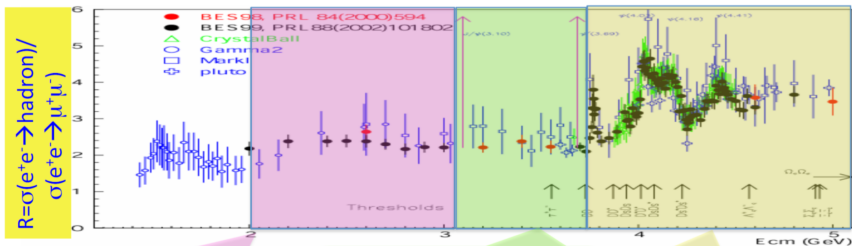
Plastic scintillator

$\sigma_T(\text{barrel}): 68 \text{ ps}$

$\sigma_T(\text{endcap}): 110 \text{ ps}$

(update to 60 ps with MRPC)

Physics at τ -charm energy region



- Hadron form factors
- $\Upsilon(2175)$ resonance
- Multiquark states with s quark, Zs
- MLLA/LPHD and QCD sum rule predictions

- Light hadron spectroscopy
- Gluonic and exotic states
- Process of LFV and CPV
- Rare and forbidden decays
- Physics with τ lepton

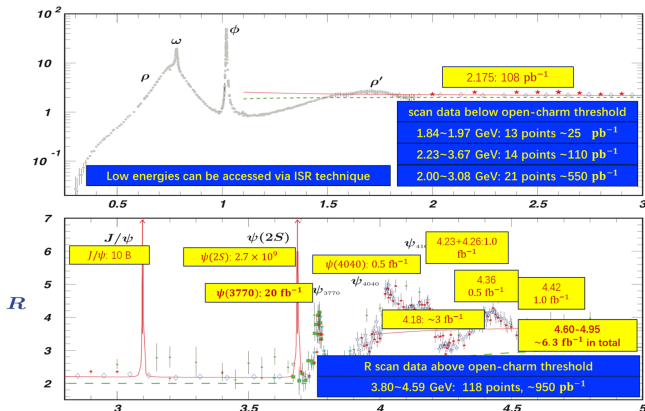
- XYZ particles
- D mesons
- f_D and f_{D_s}
- D_0 - $\bar{D}_0$ mixing
- Charm baryons

BESIII Data Set

The advantages in BESIII:

- ✓ Large datasets at tau-charm region
- ✓ Both energy scan and ISR methods can be used

- $> 40 \text{ pb}^{-1}$ data collected
- Large Charmonium events
 - $1 \times 10^{10} J/\psi$
 - $2.7 \times 10^9 \psi'$
 - $20 \text{ fb}^{-1} \psi(3773)$
- Unique scan data
 - τ lepton threshold
 - Chic1 threshold
 - Λ_c pair threshold
 - R scan
 - XYZ scan



► Ideal environment to measure **inclusive/exclusive** hadronic cross section!

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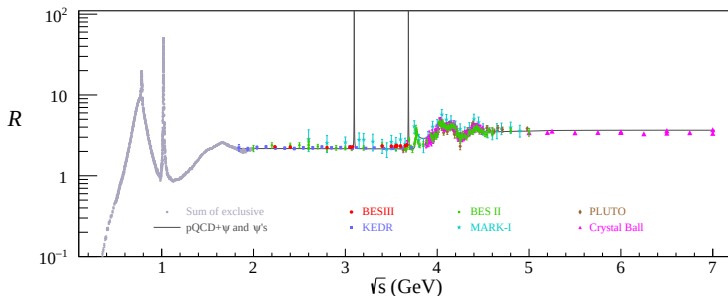
The definition of R value

The R value is defined by

$$R = \frac{\sigma(e^+e^- \rightarrow \text{hadrons})}{\sigma(e^+e^- \rightarrow \mu^+\mu^-)}$$

Precise R value (inclusive hadronic cross sections) will contribute to:

- Determination of QED running coupling constant at Z pole, *i.e.*, $\alpha(M_Z^2)$
- Calculation of anomalous magnetic moment of the muon, $a_\mu = (g-2)/2$
- Search for the higher excitation states or exotic states with $J^{PC} = 1^{--}$
- Precise R value in open-charm region could be used to constraint the mass of charm quark



Running of QED coupling constant: $\Delta\alpha(s)$

The contributions to $\Delta\alpha(s)$ can be distinguished to three pieces:

$$\Delta\alpha(s) = 1 - \alpha(0)/\alpha(s) = \Delta\alpha_{\text{lepton}}(s) + \Delta\alpha_{\text{had}}^{(5)}(s) + \Delta\alpha_{\text{top}}(s)$$

- The $\Delta\alpha_{\text{had}}^{(5)}(s)$ should be calculated by using R value:

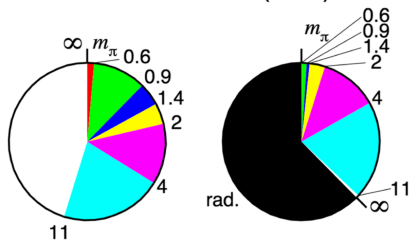
$$\Delta\alpha_{\text{had}}^{(5)}(s) = -\frac{\alpha s}{3\pi} \text{Re} \int_{m_\pi^2}^{\infty} ds' \frac{R(s')}{s'(s' - s - i\epsilon)}$$

Fractional contribution to $\Delta\alpha_{\text{had}}^{(5)}(M_Z^2)$:

Phys. Rev. D 97, 114025 (2018)

value

(error)²



Eur. Phys. J. C 80, 241 (2020)

Source	Contribution($\times 10^{-4}$)
$\Delta\alpha_{\text{lepton}}(M_Z^2)$	314.979 ± 0.002
$\Delta\alpha_{\text{had}}^{(5)}(M_Z^2)$	276.0 ± 1.0
$\Delta\alpha_{\text{top}}(M_Z^2)$	-0.7180 ± 0.0054

The $\Delta\alpha_{\text{had}}^{(5)}(s)$ is sensitive with R value!

Muon anomalous magnetic moment

- An important input in the SM prediction via experiment results
- Dominant uncertainty of SM value: hadronic vacuum polarization (HVP)

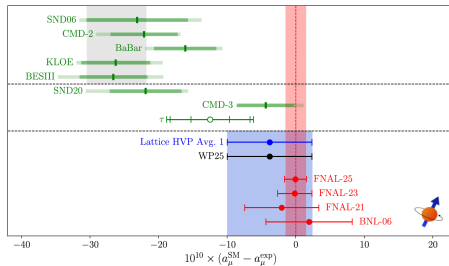
$$a_{\mu}^{\text{LO-HVP}} = \left(\frac{\alpha m_{\mu}}{3\pi} \right)^2 \int_{m_{\pi}^2}^{\infty} ds \frac{R(s)K(s)}{s^2}$$

- Precision of hadronic process cross section measurement should be improved.

Phys. Rept. 1143, 1-158(2025)

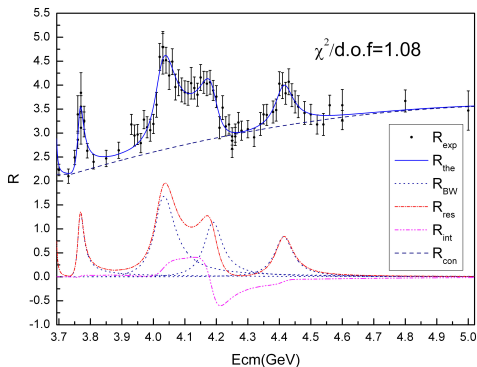
Phys. Rep. 887, 1 (2020)

Source	Contribution($\times 10^{-11}$)
QED	116584718.931 ± 0.104
a_{μ}^{Weak}	153.6 ± 1.0
$a_{\mu}^{\text{LO-HVP}}$	6931 ± 40
$a_{\mu}^{\text{NLO-HVP}}$	-98.3 ± 0.7
$a_{\mu}^{\text{NNLO-HVP}}$	12.4 ± 0.1
a_{μ}^{HLbL}	92 ± 18
SM	116591810 ± 43



High mass charmonia

- No enough experimental information to understand broad resonances at 4040, 4160 and 4415 MeV.
- More resonances not seen in BESII, such as $\psi(4660)$.



- Precise R value measurement at BESIII: large luminosity and many energy points!
- Only inclusive method can be applied in high energy region.

Overview of inclusive R value

Data sample: 2.00 – 4.95 GeV, 190 energy points accumulated from 2013 to 2024, total luminosity 8239.7 pb⁻¹.

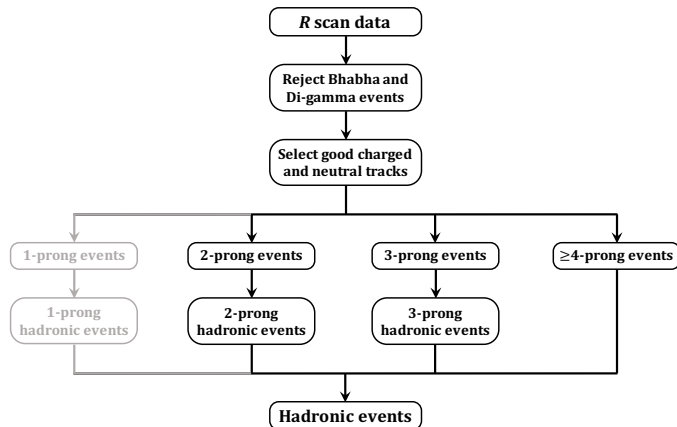
Experimentally, the R value is determined by

$$R = \frac{N_{\text{had}}^{\text{obs}} - N_{\text{bkg}}}{\sigma_{\mu\mu}^0 \mathcal{L}_{\text{int.}} \epsilon_{\text{trig}} (1 + \delta) \epsilon_{\text{had}}}$$

- $N_{\text{had}}^{\text{obs}}$: number of observed hadronic events.
- N_{bkg} : number of residual background events.
- $\sigma_{\mu\mu}^0(s) = 86.85 \text{ nb/s}$: leading order QED cross section for $e^+e^- \rightarrow \mu^+\mu^-$.
- $\mathcal{L}_{\text{int.}}$: integrated luminosity measured by analyzing Bhabha events.
- ϵ_{trig} : trigger efficiency, $\sim 100\%$.
- $(1 + \delta)$: ISR correction factor.
- ϵ_{had} : detection efficiency of hadronic events, from simulation.

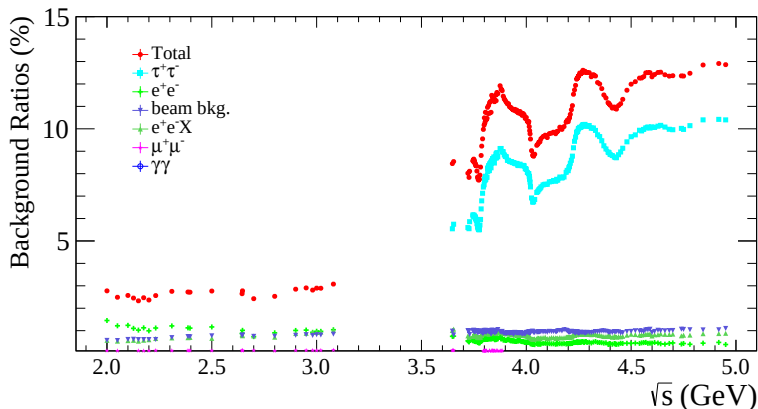
Event selection

Similar **energy-dependent** selection criteria, used in [PRL 128, 062004 (2022)], are applied in this work:



- A series of selection criteria to suppress QED background processes.

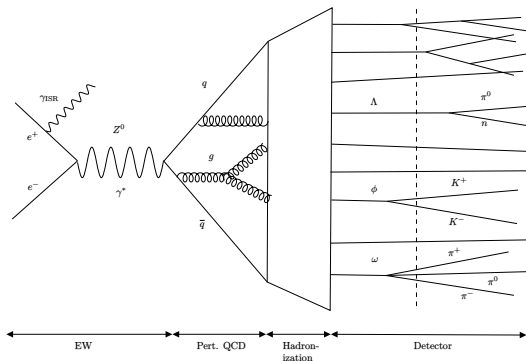
Numbers of residual background events



- ▶ Bhabha, Di-gamma, and Di-muon events are produced by **BABAYAGANLO**.
- ▶ Di-tau events are simulated by **KKMC** with relatively high precision.
- ▶ Two-photon events are generated by **DIAG36**, **EKHARA**, and **GALUGA 2.0**.
- ▶ Beam-associated background is estimated by a **sideband-like** method.
- ▶ Di-tau events are dominant and range from 6% to 10%.

Inclusive simulation model: LUARLW

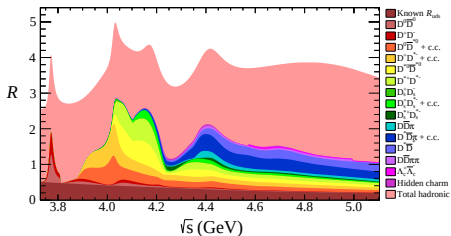
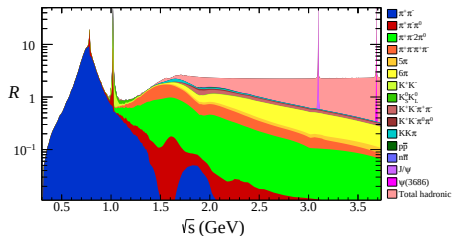
Hadronization procedure in electron-positron annihilation:



Main features of LUARLW:

- ▶ A self-consistent inclusive generator developed based on **JETSET**.
- ▶ **Initial-state radiation (ISR)** process is implemented from $2m_\pi$ to given $\sqrt{s}$.
- ▶ Kinematic quantities of initial hadrons are sampled by the **Lund** area law.
- ▶ Phenomenological parameters are tuned based on comparisons between data and MC.

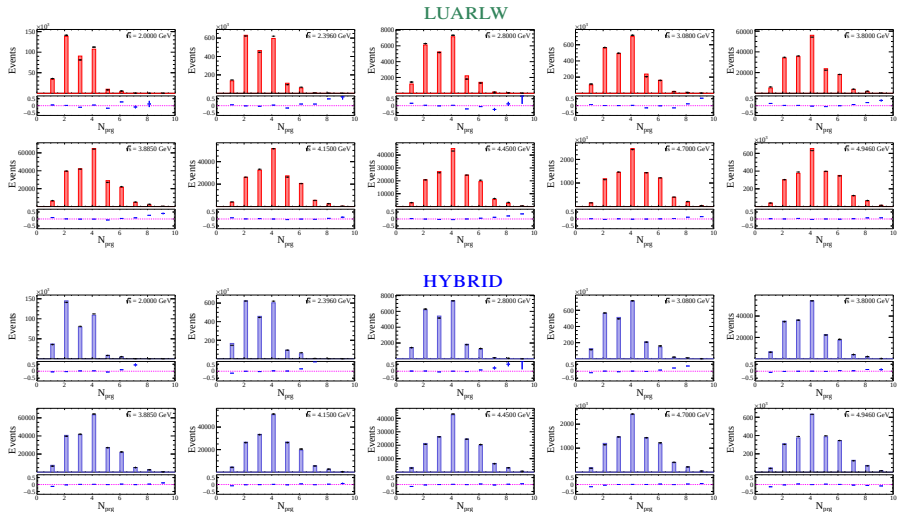
Exclusive point of view: HYBRID



The main features of the HYBRID model:

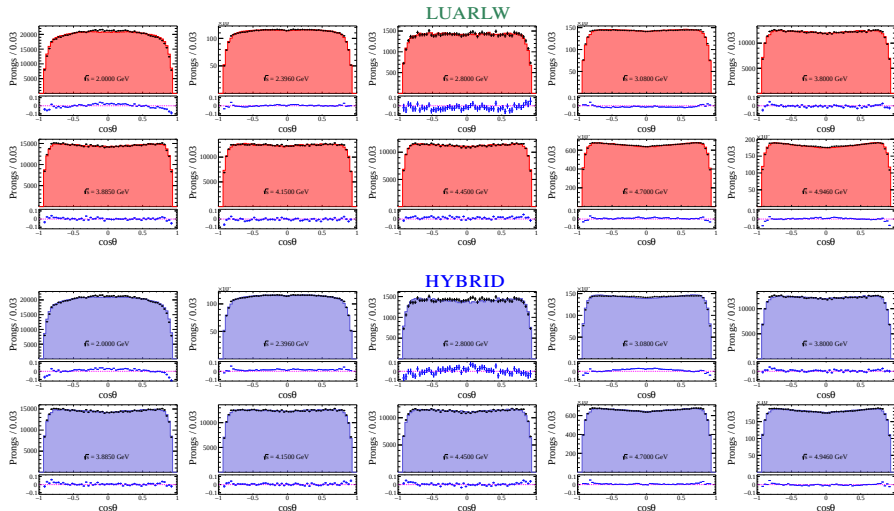
- Combination of **THREE** well-established MC models: **PHOKHARA**, **CONEXC**, and **LUARLW**.
- As much as currently known **experimental knowledges** are implemented, especially the almost complete **open** and **hidden-charm** processes have been measured at BESIII.
- The fractions of known exclusive processes range from **80%** at $\sqrt{s} = 2.00$ GeV to **40%** at $\sqrt{s} = 4.95$ GeV.
- Different **ISR** and **VP** schemes are used for a conservative cross check.

Reproduction of data: N_{prg}



Both the two models give good description of the N_{prg} distributions in data.

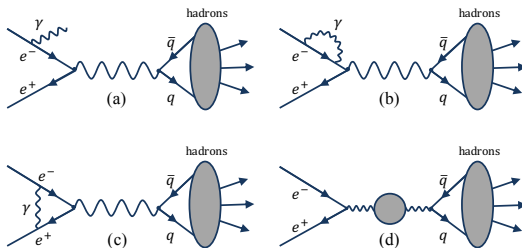
Reproduction of data: $\cos \theta$



Both the two models give reasonable $\cos \theta$ distributions in data.

ISR correction factors

In LUARLW, the **Feynman Diagram** scheme is used to simulate ISR correction and calculate $(1 + \delta)$. Following ISR procedures are considered:



The total hadronic cross section measured by experiment is the total effect of all these diagrams:

$$\sigma_{\text{had}}^{\text{tot}}(s) = \delta_{\text{vert}} \frac{\sigma_{\text{had}}^0(s)}{|1 - \Pi(s)|^2} + \int_0^{x_m} F_{\text{FD}}(x, s) \frac{\sigma_{\text{had}}^0(s')}{|1 - \Pi(s')|^2} dx.$$

Thus

$$(1 + \delta)(s) \equiv \sigma_{\text{had}}^{\text{tot}}(s) / \sigma_{\text{had}}^0(s)$$

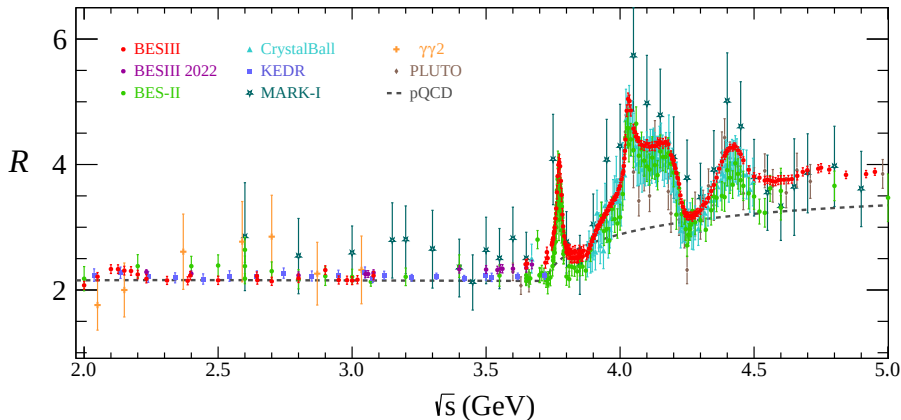
Systematic uncertainty

$\sqrt{s}$ (GeV)	Event selection	Beam background	QED background	Luminosity	Signal model	ISR factor	Trigger efficiency	Total
2.0000	0.44	0.20	0.10	0.37	1.53	0.54	0.10	1.74
2.1750	0.41	0.20	0.11	0.35	0.47	0.50	0.10	0.91
2.3864	0.38	0.29	0.17	0.34	0.95	0.56	0.10	1.27
2.5000	0.41	0.43	0.10	0.39	1.29	0.63	0.10	1.61
2.7000	0.50	0.02	0.15	0.40	0.41	0.68	0.10	1.04
3.0200	0.44	0.23	0.27	0.39	0.71	0.60	0.10	1.16
3.6474	0.21	1.26	0.34	0.40	1.85	0.96	0.10	2.50
3.8400	0.21	0.48	0.35	0.71	1.69	1.34	0.10	2.36
4.0180	0.17	0.76	0.28	0.36	0.82	0.50	0.10	1.33
4.1800	0.18	0.85	0.28	0.35	1.48	0.60	0.10	1.87
4.3800	0.22	0.66	0.32	0.36	1.00	0.59	0.10	1.44
4.5600	0.35	0.38	0.37	0.40	1.80	0.62	0.10	2.05
4.7397	0.18	0.85	0.35	0.35	1.51	0.50	0.10	1.88
4.9509	0.38	0.47	0.39	0.41	1.37	0.62	0.10	1.72

- Evaluated at all 190 energy points but are only presented for selected energies.
- The uncertainties associated with the hadronic event selection are estimated by applying alternative selection criteria.
- Total systematic uncertainties are less than 3.0% at almost all of the energy points.

Measured R values from 2.00 to 4.95 GeV

Comparing our R values from 2.00 to 4.95 GeV with other's results:



- At almost all of energy points, the total uncertainties of the R values are less than 3.0%.
- Consistent with the BESIII result in 2022 from 2.23 to 3.67 GeV.
- Energy points are much denser than other experiments, especially in the open-charm region.

Summary and Outlook

► Summary

- Both LUARLW and HYBRID models can reasonably reproduce the inclusive hadronic events from $\sqrt{s} = 2.00$ to 4.95 GeV.
- The corresponding R values are obtained with precision better than 3.0%.

► Next to do

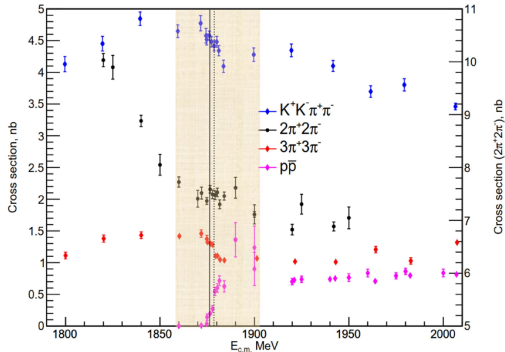
- Finish the draft review and submit.

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Structure around 1.9 GeV

- The “dip” structure around 1.9 GeV was first observed by the DM2 experiment in the 6π channel.
- Up to now, this structure has been observed in many channels.



- Among them, the 6π process has the largest significance.

Explanation of the structure

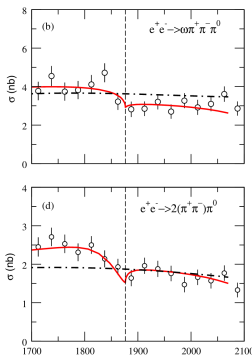
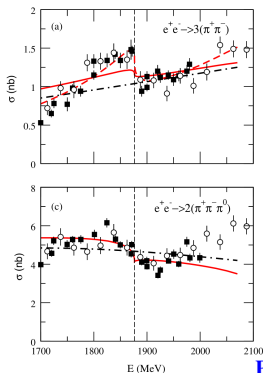
► $N\bar{N}$ strong interaction

No structure in $2(\pi^+\pi^-)$ contradicts this possibility.

► Existence of the resonance $\rho(1900)$

Large uncertainties in the $\rho(1900)$ parameters.

► Presence of an under-threshold $p\bar{p}$ resonance



Phys. Rev. D **92**, 054032 (2015)

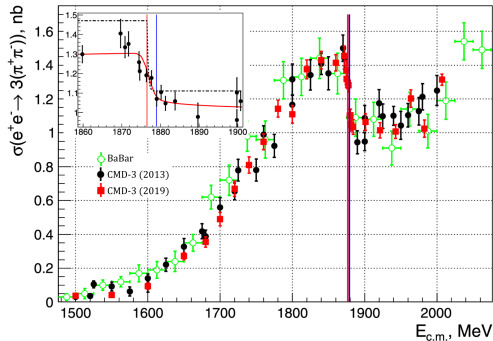
Phys. Rev. D **98**, 113011 (2018)

Final state	Data	M (MeV)	Γ (MeV)
$3(\pi^+\pi^-)$	CMD3'13	1878.3 ± 5.3	24.7 ± 8.7
$3(\pi^+\pi^-)$	BABAR'06	1884 ± 29	72 ± 29
$2(\pi^+\pi^-\pi^0)$	BABAR'06	1896 ± 60	53 ± 58
$2(\pi^+\pi^-\pi^0)$	DM2'86	1878 ± 40	126 ± 92
$3(\pi^+\pi^-)$	DM2'86	1888 ± 18	44 ± 37
$\phi\pi^0$	BABAR'08	1906.7 ± 8.8	38 ± 52
$\eta\pi^+\pi^-$	SND'18	1812 ± 31	162 ± 70
$\eta\pi^+\pi^-$	BABAR'07	1831 ± 48	146 ± 167
$\eta\pi^+\pi^-$	BABAR'18	1879 ± 63	159 ± 137
$K^+K^-3\pi$	BABAR'07	1902 ± 26	11 ± 20
$K^+K^-\pi^+\pi^-$	BABAR'12	1906 ± 15	28 ± 99
$K^+K^-\pi^+\pi^-$	CMD3'16	1805 ± 52	115 ± 14
$K^+K^-\pi^0\pi^0$	BABAR'12	1800 ± 16	107 ± 35
$p\bar{p}$	CMD3'16	1888.8 ± 2.4	12 ± 10
$p\bar{p}$	BABAR'13	1885.8 ± 8.6	12 ± 16
$n\bar{n}$	SND'14	1890.6 ± 5.2	29 ± 35
$p\bar{p}, n\bar{n}$	3 expts.	1888.3 ± 2.8	10.0 ± 4.1

$3(\pi^+\pi^-)$ in experiment

- Many experiments have measured the 6π process: DM2, CMD-3 and BaBar.
- About 100 events per energy point with large uncertainty.

Phys. Lett. B 794 (2019) 64-68



BESIII data gives higher statistics, more precise results are needed.

Data sets for $3(\pi^+\pi^-)$ measurement

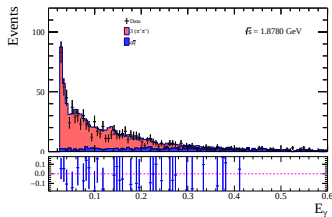
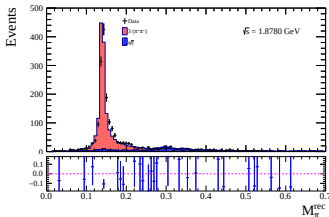
- *R*-scan data collected in 2024:
 - ▶ 13 energy points from 1.84 to 1.97 GeV
 - ▶ 1 MeV/step near the $p\bar{p}$ threshold
 - ▶ BOSS version: 713
- Signal MC:
 - $e^+e^- \rightarrow \pi^+\pi^+\pi^+\pi^-\pi^-\pi^-$
 - Conexc PHSP (200k events)
- $e^+e^- \rightarrow q\bar{q}$: Hybrid (600k events)
- Minor QED background

$\sqrt{s}$ (GeV)	$\mathcal{L}_{\text{int.}}$ (pb $^{-1}$)
1.8441	1.5012
1.8741	2.0026
1.8760	2.0142
1.8780	2.0189
1.8791	1.4854
1.8801	2.0328
1.8809	1.3409
1.8822	2.0210
1.8860	2.0327
1.8902	2.0312
1.9038	2.0222
1.9437	2.0368
1.9735	2.2291

Event selection

A **recoil method** is applied:

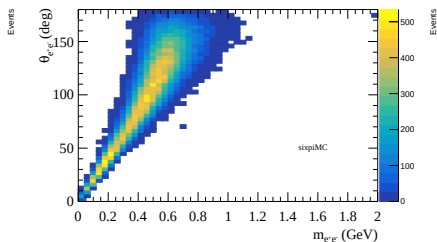
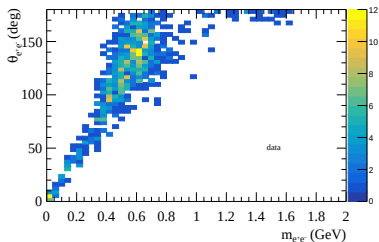
- $V_r < 1 \text{ cm}, |V_z| < 10 \text{ cm}, |\cos\theta| < 0.93$
- $N_{\text{chagre}} \geq 5, N_+ \text{ and } N_- \geq 2$
- Successful vertex fit under pion hypothesis with five tracks
- $E_\gamma < 0.25 \text{ GeV}$
- Select events with M_π^{rec} closest to the pion mass.
- $0 < M_\pi^{\text{rec}} < 0.25 \text{ GeV}$



Background analysis

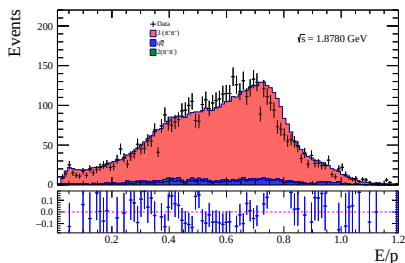
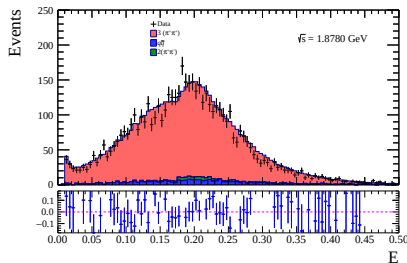
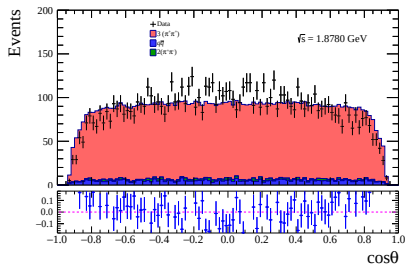
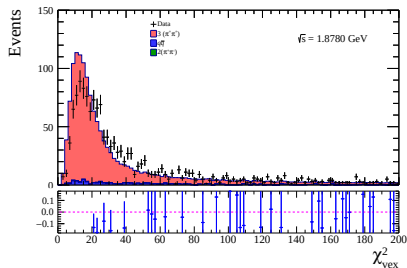
Dominant backgrounds:

- ▶ $e^+e^- \rightarrow q\bar{q}$, Based on the **hybrid** generator.
- ▶ $e^+e^- \rightarrow 2(\pi^+\pi^-)\gamma^{\text{ISR}}$: gamma-conversion process.



- ▶ The gamma-conversion process($\gamma + X \rightarrow e^+e^- + X'$) is identified if the $M_{e^+e^-}$ is less than $0.1\text{GeV}/c^2$ and their open angle is less than 15°

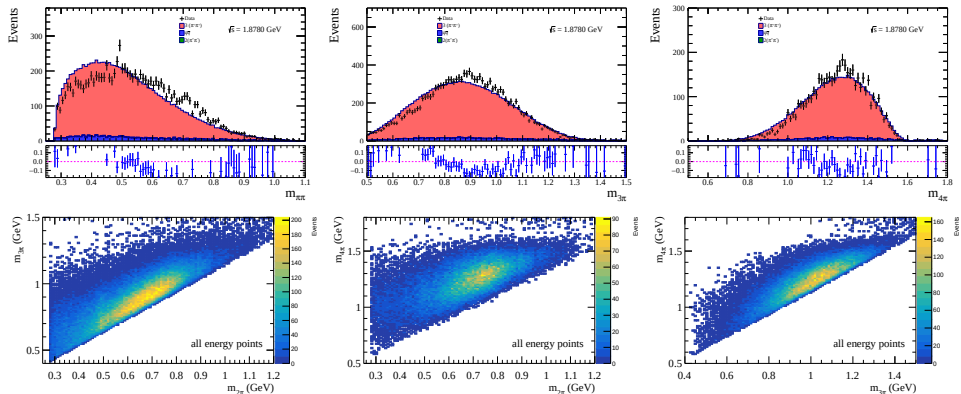
Comparisons between data and MC



- There is no peaking background, the signal purity is 90 – 95%.

Multi-pi spectrum

The mass spectrum structure of multi-pion is not clear.

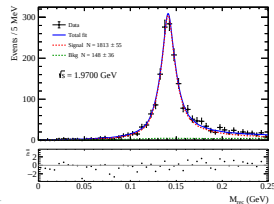
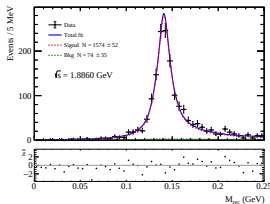
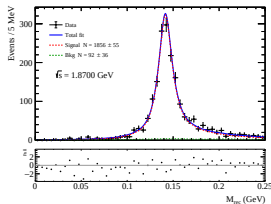
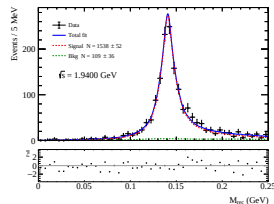
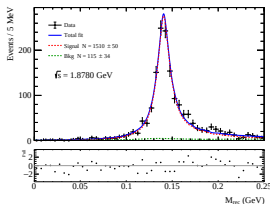
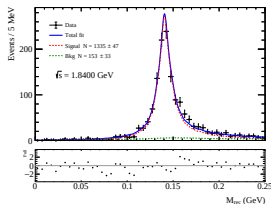


► A PWA is required to ensure the accuracy of the efficiency.

M_{rec} fit at each energy point

An unbinned maximum likelihood fit used to extract signal yield:

- Signal: 6π MC shape convolved with a Gaussian.
- Background: hadron MC shape / Chebyshev polynomial.



Summary and next to do

► Summary

- The event selection using the recoil method are determined.
- The background has been preliminarily studied, and a high signal purity is achieved.

► Next to do

- A more detailed background study should be performed.
- PWA is required to ensure the accuracy of the MC efficiency.
- The systematic uncertainty will be studied.

Summary and Prospect

► Inclusive R value from 2.00 to 4.95 GeV

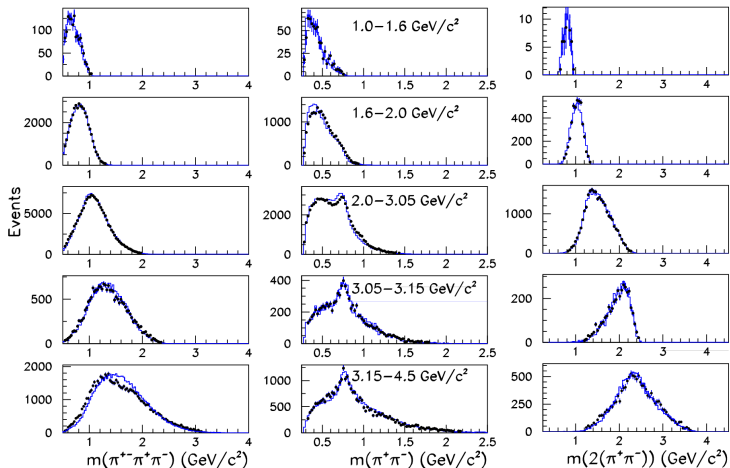
- ✓ R values obtained from 2.00 to 4.95 GeV at 190 energy points, precision better than 3.0%.
- ✓ Push the review forward.

► Study of $e^+e^- \rightarrow 3(\pi^+\pi^-)$

- ✓ The event selection is determined, and signal events are preliminarily extracted.
 - Further background analysis and MC tuning are ongoing.
 - The systematic uncertainty will be studied.

Backup

Comparison with BaBar



Selection criteria

Track Level

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

Event Level

At least 2 good charged hadronic tracks

- **Number of good charged hadronic tracks = 2:**
 - $|\Delta\theta| = |\theta_1 + \theta_2 - 180^\circ| > 10^\circ$ or $|\Delta\phi| = ||\phi_1 - \phi_2| - 180^\circ| > 15^\circ$
 - At least 2 isolated photons
- **Number of good charged hadronic tracks = 3:**
 - The two highest momentum tracks are required not back-to-back: $|\Delta\theta| = |\theta_1 + \theta_2 - 180^\circ| < 10^\circ$ or $|\Delta\phi| = ||\phi_1 - \phi_2| - 180^\circ| < 15^\circ$
 - (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

Inclusive detection efficiency: ϵ_{had}

The detection efficiency of the process $e^+e^- \rightarrow \text{hadrons}$ with different N_{prg} requirements:

