Measurement of R ratios at BESIII

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Outline

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  - Signal and backgrounds
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- **Exclusive measurements**
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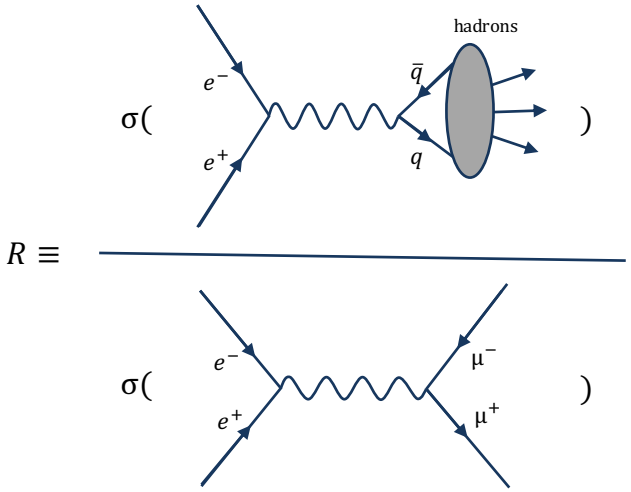
  - $e^+e^- \to \omega\eta/\pi^0$
  - $e^+e^- \to K^+K^-\pi^0\pi^0$
- **Summary**

The definition of R ratio

R is defined as the ratio of the production rate of hadron and muon pairs:

$$R \equiv \frac{\sigma^0(e^+e^- \to \text{hadrons})}{\sigma^0(e^+e^- \to \mu^+\mu^-)} \equiv \frac{\sigma^0_{\text{had}}}{\sigma^0_{\mu\mu}}$$

That is:



According to the QED theory:

$$\sigma^0_{\mu\mu}(s) = \frac{4\pi\alpha^2}{3s}\frac{\beta_\mu(3-\beta_\mu^2)}{2}$$

Why R ratios?

R ratios can contribute to:

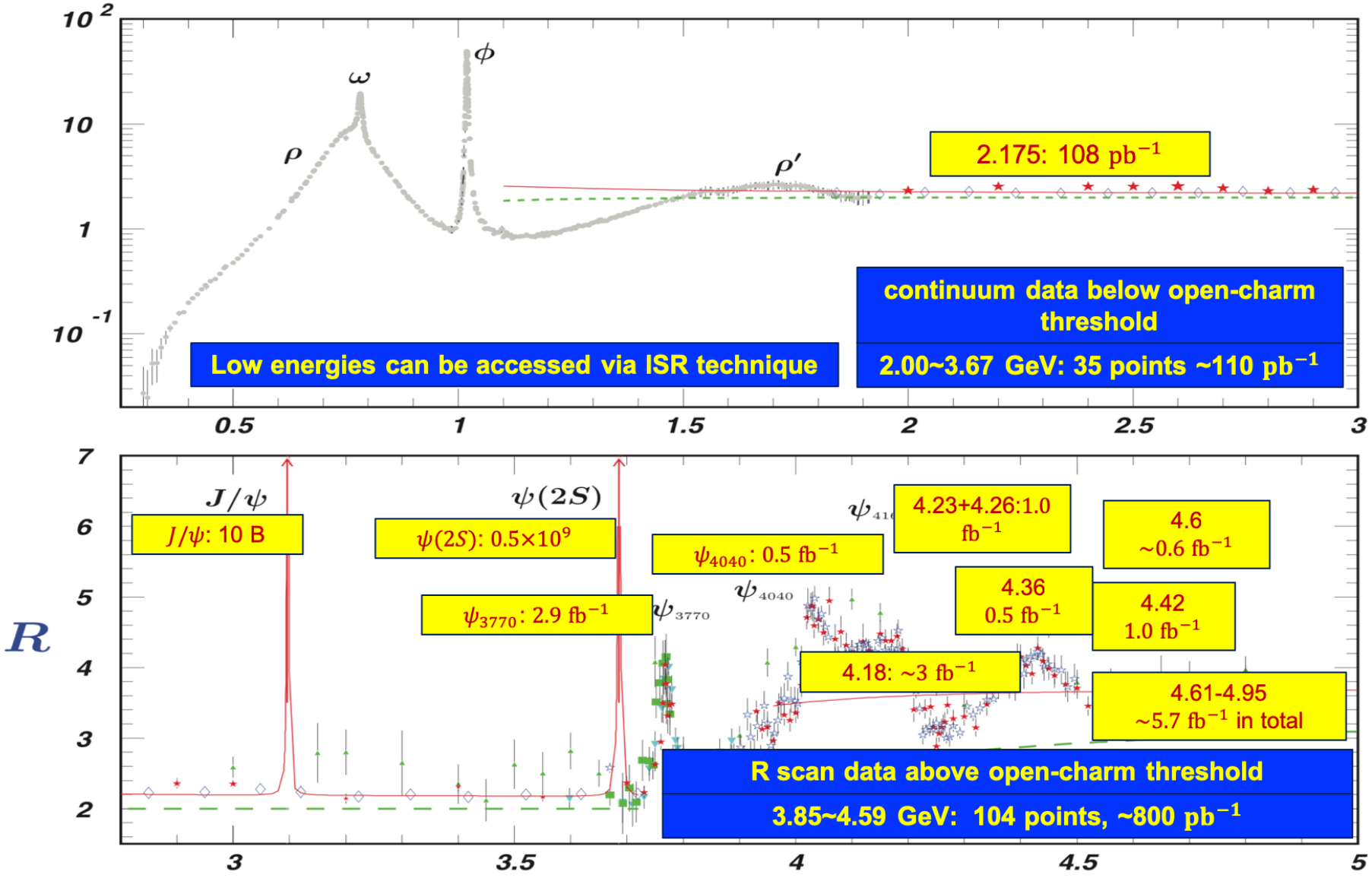
- Calculation of anomalous magnetic moment of Muon: $a_\mu = (g_\mu - 2)/2$.

Source	Contribution($\times 10^{11}$)
a_μ^{QED}	116584718.92 ± 0.03
a_μ^{Weak}	153.6 ± 1.0
a_μ^{had} [LO]	6939 ± 40
a_μ^{had} [NLO]	-98.7 ± 0.9
a_μ^{had} [NNLO]	12.4 ± 0.1
$a_\mu^{\text{had, l-l}}$	105 ± 26
a_μ^{SM}	116591830 ± 48
a_μ^{exp}	116592091 ± 63
Δa_μ	261 ± 79

- Determination of running coupling constant of QED theory at M_Z: $\Delta\alpha(M_Z^2)$.

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

Prog. Theor. Exp. Phys. 2020, 083C01 (2020); PRD 98, 030001 (2018); PRD 97, 114025 (2018)


10^2
10
1
10^{-1}
ρ
ω
ϕ
ρ'
2.175: 108 pb^{-1}
continuum data below open-charm threshold
2.00~3.67 GeV: 35 points ~110 pb^{-1}
Low energies can be accessed via ISR technique
0.5
1
1.5
2
2.5
3
R
7
6
5
4
3
2
J/ψ
J/ψ: 10 B
$\psi(2S)$
$\psi(2S)$: 0.5×10^9
ψ_{3770}: 2.9 fb^{-1}
ψ_{3770}
ψ_{4040}: 0.5 fb^{-1}
ψ_{4040}
4.23+4.26:1.0 fb^{-1}
4.6 ~0.6 fb^{-1}
4.36 0.5 fb^{-1}
4.42 1.0 fb^{-1}
4.18: ~3 fb^{-1}
4.61-4.95 ~5.7 fb^{-1} in total
R scan data above open-charm threshold
3.85~4.59 GeV: 104 points, ~800 pb^{-1}
3
3.5
4
4.5
5

Determination of R ratio in experiment

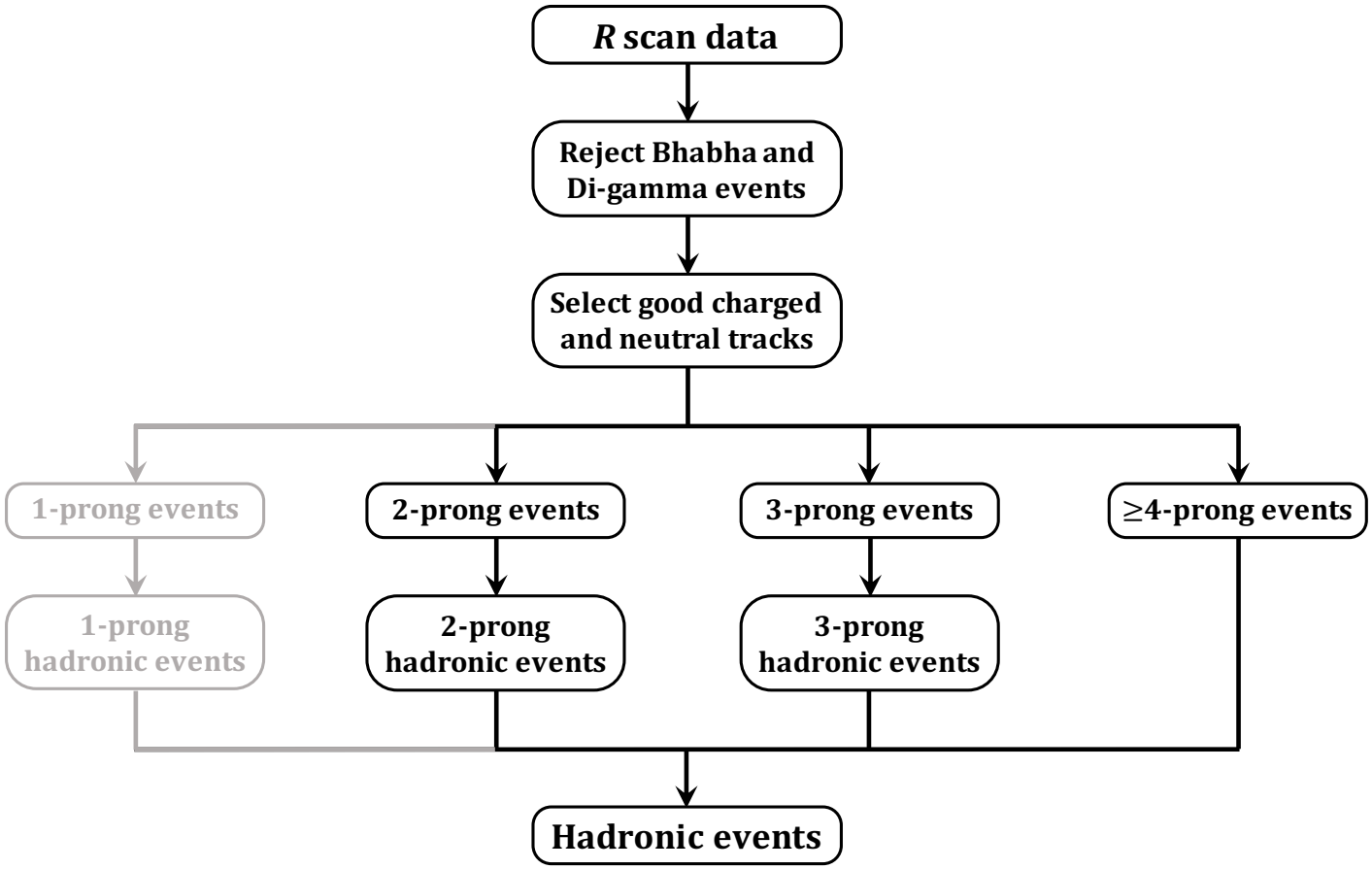
Experimentally, R ratio is determined by

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

- $N_{\text{had}}^{\text{obs}}$: Numbers of observed hadronic events.
- N_{bkg}: Number of the residual background events.
- $\mathcal{L}_{\text{int.}}$: Integrated luminosity.
- $\varepsilon_{\text{trig}}$: Trigger efficiency.
- ε_{had}: Detection efficiency of the hadronic events.
- $(1+\delta)$: ISR correction factor.
- $\sigma_{\mu\mu}^{0}(s) = 86.85\ \text{nb}/s$: Leading order QED cross section for $e^+e^- \to \mu^+\mu^-$.

Signal and background estimation

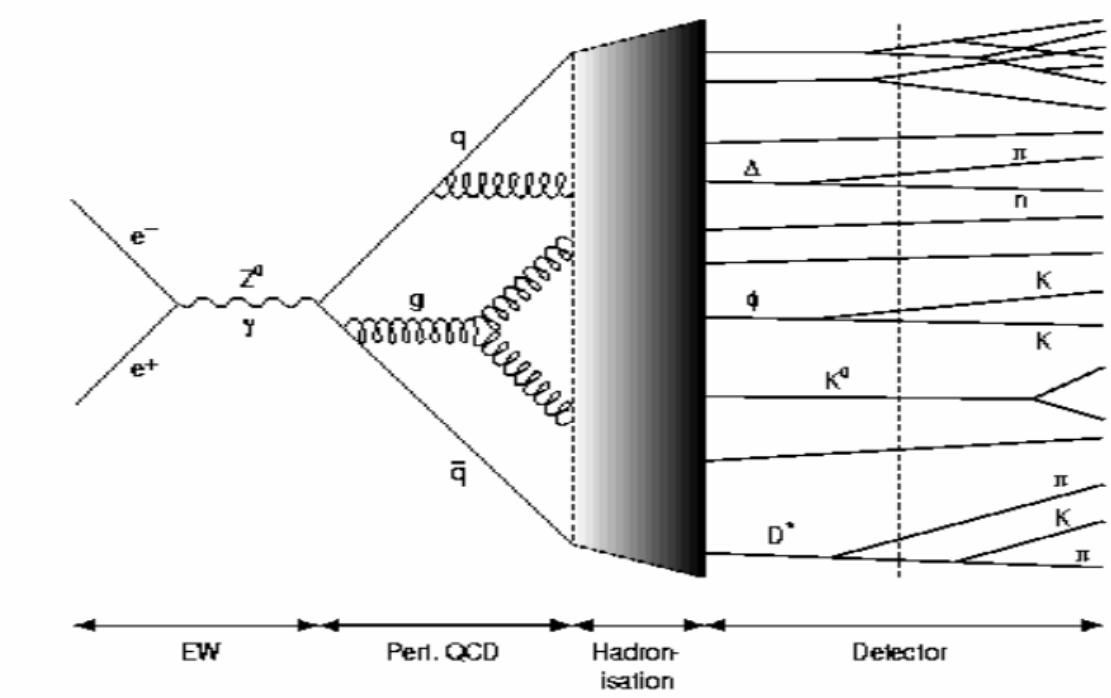
Selection of inclusive hadronic events from data:



- Residual QED-related backgrounds are estimated by using dedicated MC generators.
- Beam-associated backgrounds are studied by separate-beam data.

Signal simulation: LUARLW model

Hadronization procedure in LUARLW model:

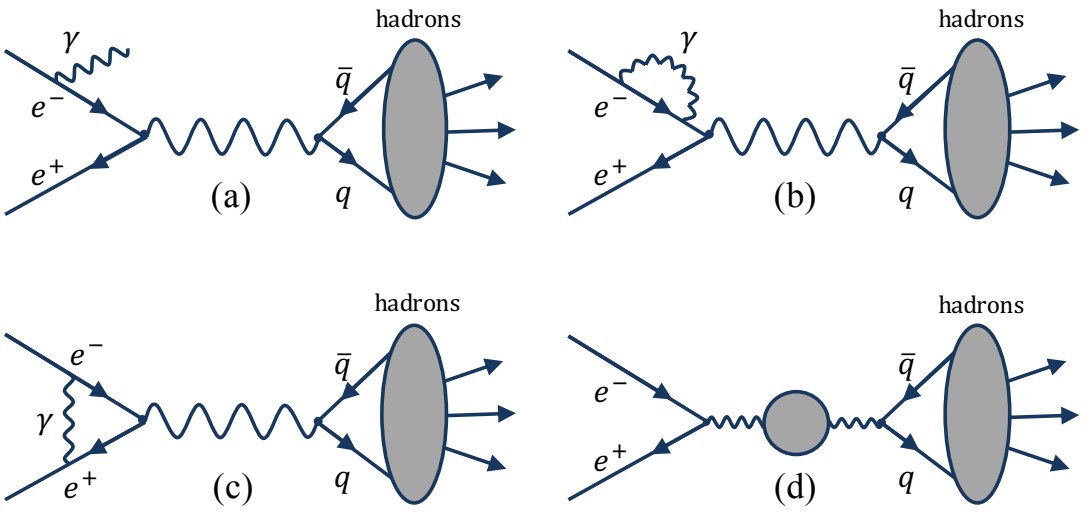


Features of LUARLW model:

- Development of JETSET for low energy experiments.
- Simulate production and decay of both continuum and resonance states.
- Kinematics of initial hadrons are determined by Lund Area Law **[arXiv:hep-ph/9910285]**.
- Phenomenological parameters should be tuned according to experiment data.
- Integrated the Initial-state radiation (ISR) and Vacuum Polarization (VP) corrections.

ISR in LUARLW: Feynman Diagram

In LUARLW, the Feynman Diagram (FD) scheme is used to simulate ISR correction and calculate $(1+\delta)$. Feynman diagrams related to ISR procedure are:



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

$$\sigma^{\rm tot}_{\rm had}(s) = \beta \int_0^{x_m} {\rm d}x \frac{x^\beta}{x}\left(1 - x + \frac{x^2}{2}\right) \frac{\sigma^0_{\rm had}(s')}{|1-\Pi(s')|^2} + \delta_{\rm vert} \frac{\sigma^0_{\rm had}(s)}{|1-\Pi(s)|^2},$$

and

$$1+\delta \equiv \sigma^{\rm tot}_{\rm had}/\sigma^0_{\rm had}$$

According to definition of R, its uncertainty is expressed as

$$\left(\frac{\Delta R}{R}\right)^2_{\text{sys}} = \left(\frac{\Delta \tilde{N}}{\tilde{N}}\right)^2 + \left(\frac{\Delta \mathcal{L}_{\text{int.}}}{\mathcal{L}_{\text{int.}}}\right)^2 + \left(\frac{\Delta \varepsilon_{\text{had}}}{\varepsilon_{\text{had}}}\right)^2 + \left[\frac{\Delta(1+\delta)}{(1+\delta)}\right]^2 + \left(\frac{\Delta \varepsilon_{\text{trig}}}{\varepsilon_{\text{trig}}}\right)^2,$$

where

$$\tilde{N} = N^{\text{obs}}_{\text{had}} - N_{\text{bkg}}$$

In practice, its uncertainties are addressed in different aspects:

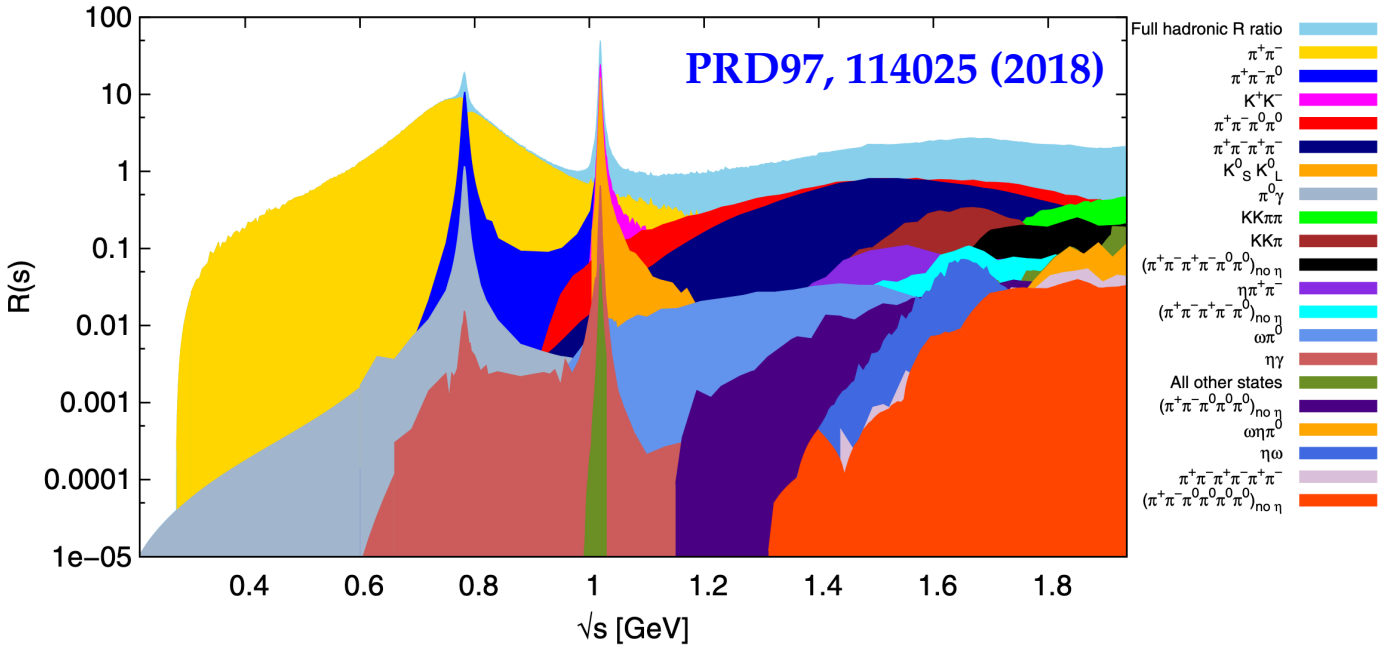
- Event selection: all implemented selection criteria are slightly changed.
- Background estimation: different methods and background simulation models are used.
- Integrated luminosity: uncertainty is evaluated in **CPC 41, 063001 (2017)**.
- Signal simulation: Hybrid model is development and used as a cross check.
- ISR correction factor: considered in calculation precision, different σ^0_{had}.
- Trigger efficiency: $\varepsilon_{\text{trig}}$ approaches 100% with an uncertainty less than 0.1%.

Hybrid model

The Hybrid model is developed as an alternative simulation model of hadronic events.

Hybrid model is consisted of THREE components:

- ConExc: simulates 51 exclusive processes with known cross section line-shapes.
- Phokhara: describes 10 well known processes such as $e^+e^- \to 2\pi, 3\pi, 4\pi$ etc..
- LUARLW: responsible for remain unknown processes with tuned parameters.

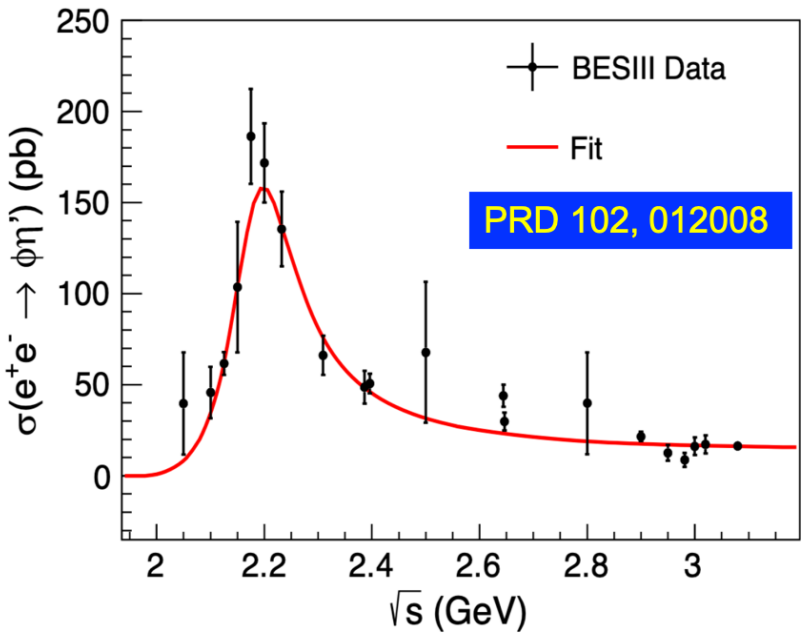


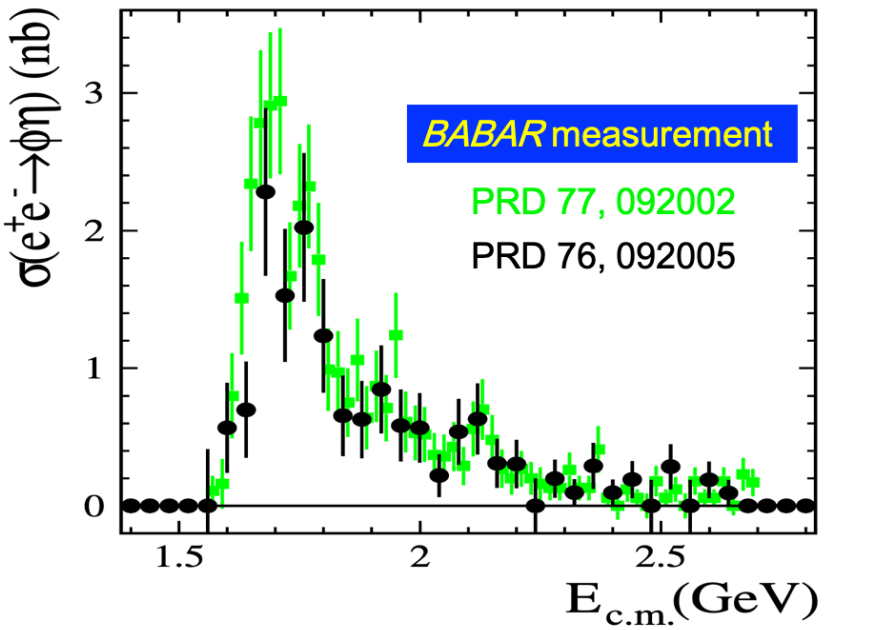
- As much as known experimental knowledge is implemented in ConExc.
- Residual double-countings among the three components are negligible.

Latest exclusive measurements at BESIII

Exclusive measurement: $e^+e^- \to \phi\eta/\eta'$

BESIII measured the $e^+e^- \to \phi\eta/\eta'$ processes at $\sqrt{s} = 2.00 \sim 3.08$ GeV:





If the resonance structure observed in these two processes are $\phi(2170)$:

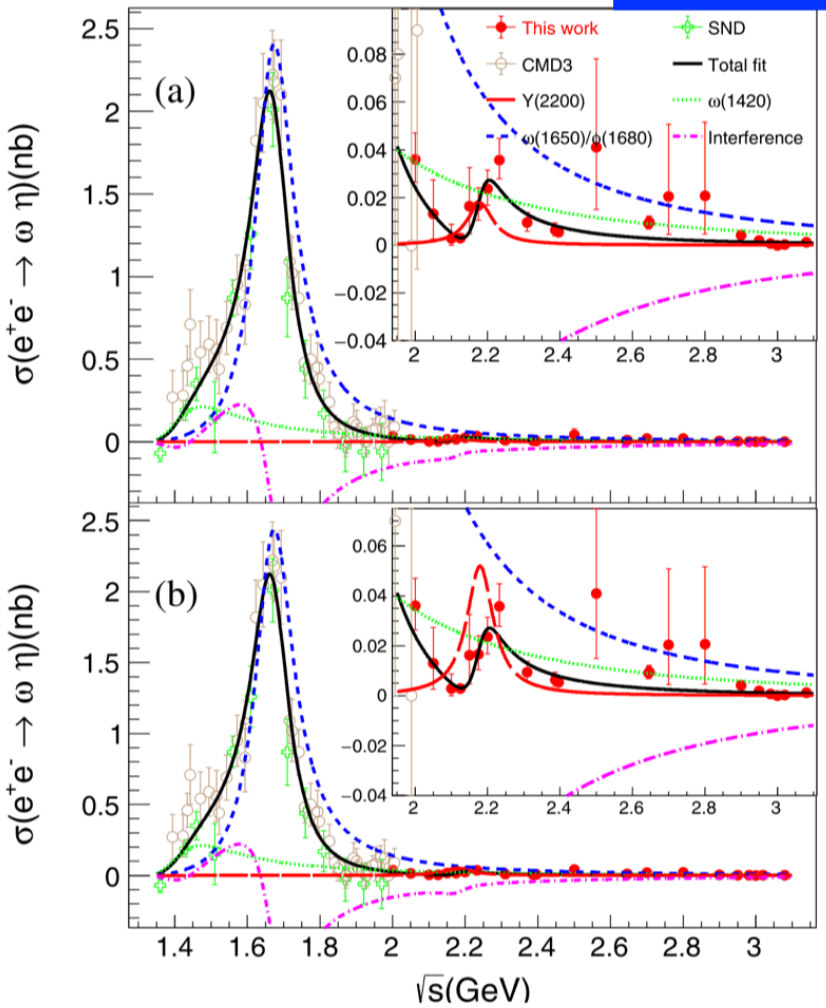
$$\frac{Br[\phi(2170) \to \phi\eta] \cdot \Gamma_{ee}^{\phi(2170)}}{Br[\phi(2170) \to \phi\eta'] \cdot \Gamma_{ee}^{\phi(2170)}} = 0.23 \pm 0.10 \pm 0.18$$

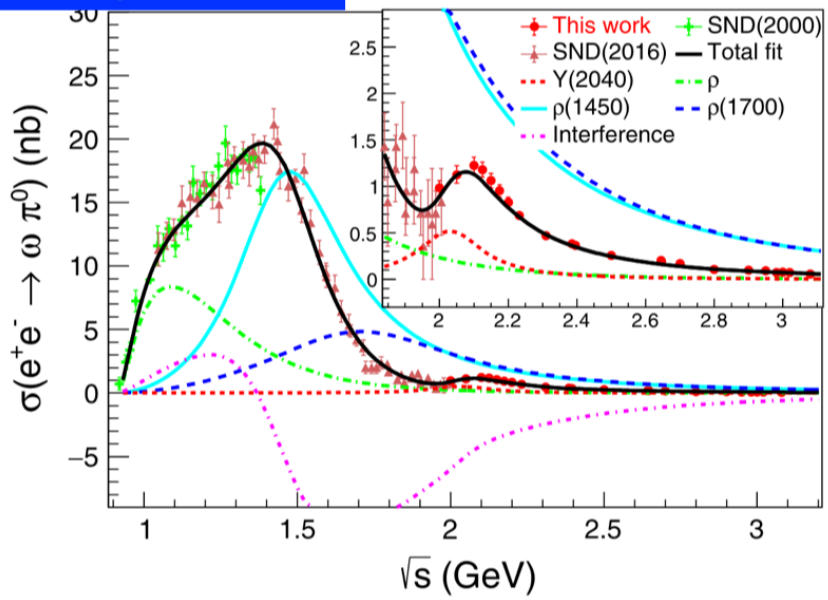
which disagrees the predictions of several models.

Exclusive measurement: $e^+e^- \to \omega\eta/\pi^0$

BESIII measured the $e^+e^- \to \omega\eta/\pi^0$ processes at $\sqrt{s} = 2.00 \sim 3.08$ GeV:

PLB 813, (2021) 136059

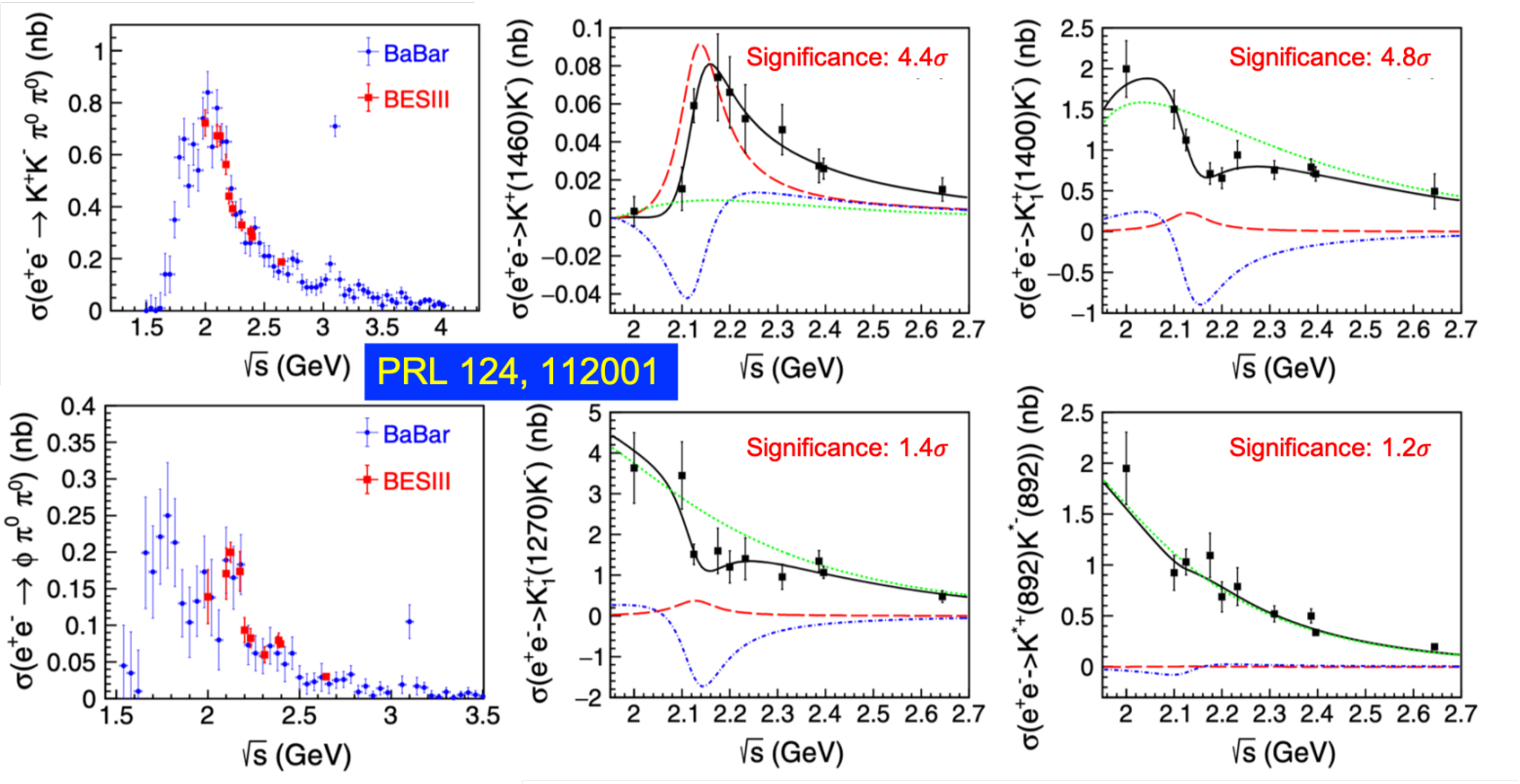




- ✓ Observed resonance in $e^+e^- \to \omega\eta$ fits the properties of $\phi(2170)$
- ✓ Structure in $e^+e^- \to \omega\pi^0$ is either $\rho(2150)$ or $\rho(2000)$

Exclusive measurement: $e^+e^- \to K^+K^-\pi^0\pi^0$

BESIII measured the $e^+e^- \to K^+K^-\pi^0\pi^0$ processes at $\sqrt{s} = 2.000 \sim 2.644$ GeV:



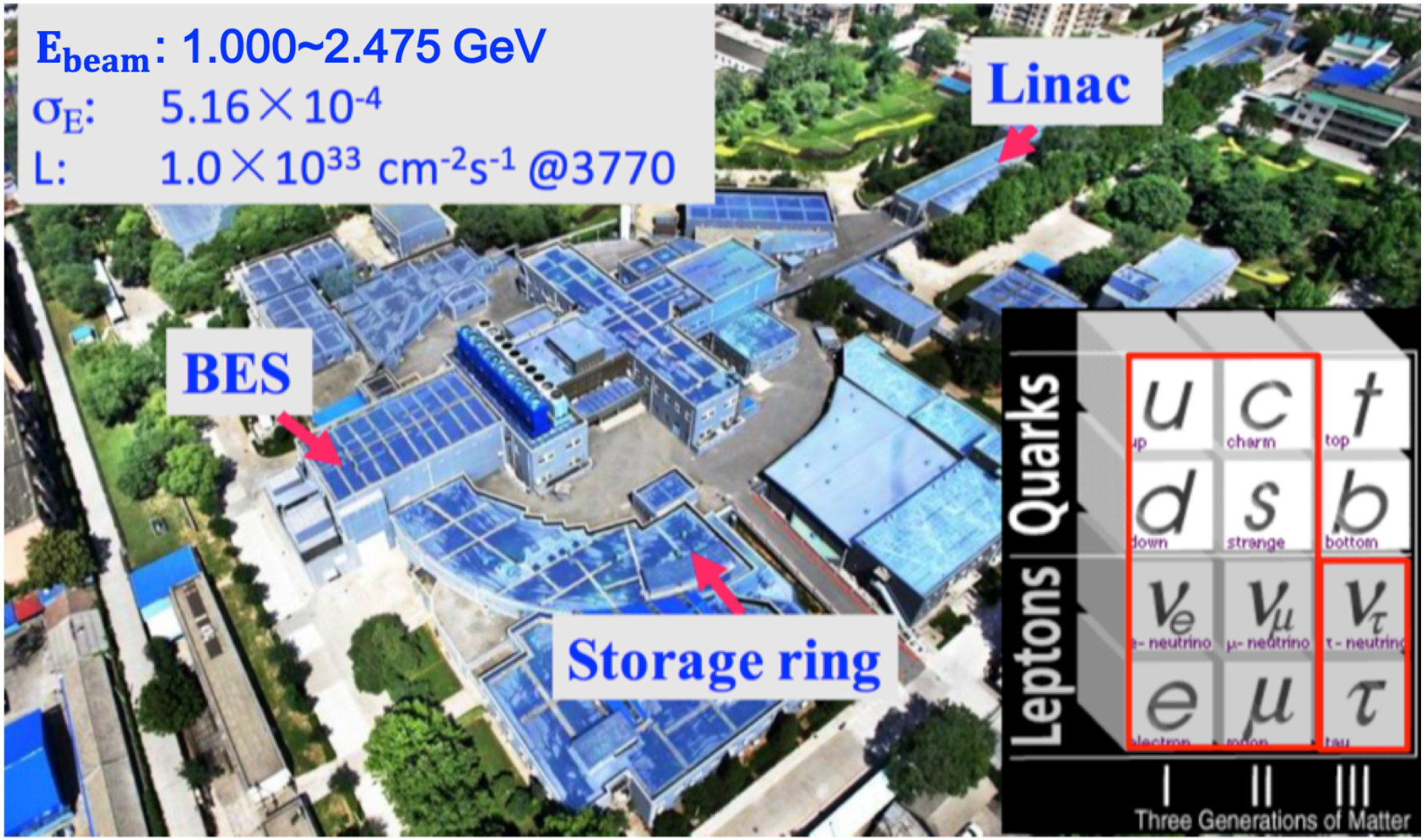
- ✓ The PWA study for the $K^+K^-\pi^0\pi^0$ final states, with the cross sections of subprocesses $e^+e^- \to K^+(1460)K^-, K_1^+(1400)K^-, K_1^+(1270)K^-$ and $K^*(892)K^*(892)$ extracted.
- ✓ Assuming the structure observed in these subprocesses is $\phi(2170)$, above estimated significances in these processes can help to distinguish corresponding theoretic models.

Summary

- After numerous tuning and checking on signal simulation models, significant progress of R measurement is made at BESIII.
- The current nominal and alternative signal simulation models can both describe data well and result in consistent R ratios.
- Latest exclusive measurements provide valuable input to the vector meson spectroscopy.

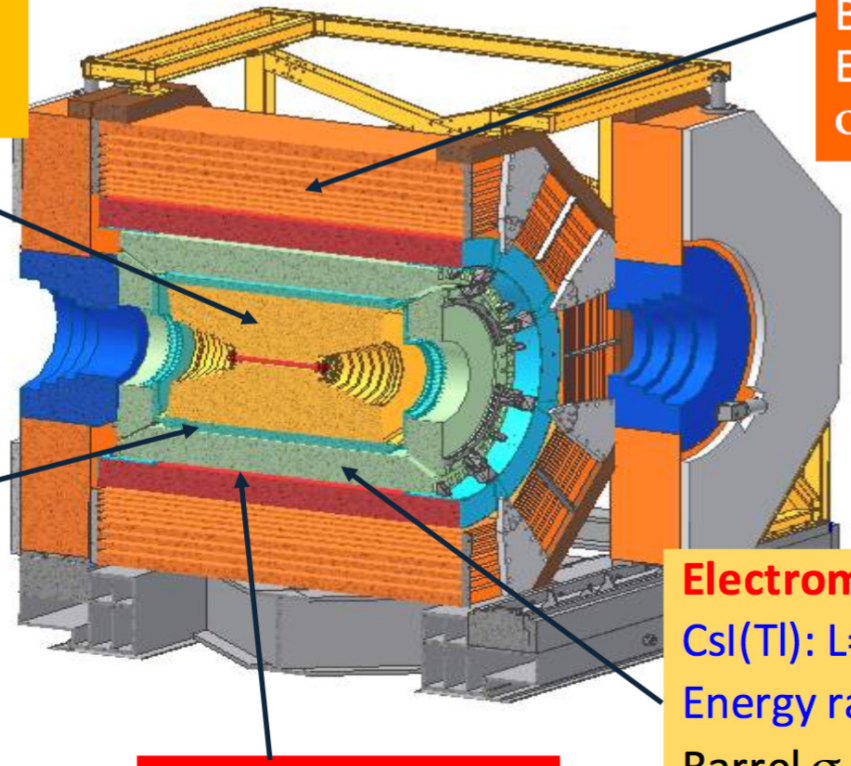
Thanks for your attention!

Backups


E_{beam}: 1.000~2.475 GeV
σ_E: 5.16×10^{-4}
L: 1.0×10^{33} $cm^{-2}s^{-1}$ @3770
Linac
BES
Storage ring
Quarks
Leptons
u
c
t
up
charm
top
d
s
b
down
strange
bottom
ν_e
ν_μ
ν_τ
e- neutrino
μ- neutrino
τ- neutrino
e
μ
τ
electron
muon
tau
I
II
III
Three Generations of Matter

Main Drift Chamber
Small cell, 43 layer
σ_{xy}=130 μm, dE/dx~6%
σ_p/p = 0.5% at 1 GeV

Muon Counter
Resistive plate chamber
Barrel: 9 layers
Endcaps: 8 layers
$\sigma_{spatial}$: 1.48 cm



Time Of Flight
Plastic scintillator
σ_T(barrel): 80 ps
σ_T(endcap): 110 ps
65 ps with MRPC ETOF

SC Magnet 1.0T

Electromagnetic Calorimeter
CsI(Tl): L=28 cm (15X_0)
Energy range: 0.02-2GeV
Barrel σ_E 2.5%, σ_l 6mm
Endcap σ_E 5.0%, σ_l 9mm

ISR in Hybrid: Structure Function

In Hybrid generator, the Structure Function (SF) scheme is implemented:

$$\sigma_{\rm had}^{\rm tot}(s) = \int_0^{x_m} {\rm d}x F_{\rm SF}(x,s) \frac{\sigma_{\rm had}^0(s')}{|1-\Pi(s')|^2},$$

where

$$F_{\rm SF}(x,s) = \beta x^{\beta-1}\Delta - \beta(1-\frac{1}{2}x) - \frac{1}{8}\beta^2\left[4(2-x)\ln x + \frac{1+3(1-x)^2}{x}\ln(1-x) + 6 - x\right],$$

$$\begin{aligned}\Delta &= 1 + \frac{\alpha}{\pi}\left(\frac{3}{2}L + \frac{\pi^2}{3} - 2\right) + \left(\frac{\alpha}{\pi}\right)^2\left\{\left[\frac{9}{8} - 2\zeta(2)\right]L^2 + \left[-\frac{45}{16} + \frac{11}{2}\zeta(2) + 3\zeta(3)\right]L\right. \\ &\quad \left. -\frac{6}{5}\left[\zeta(2)\right]^2 - \frac{9}{2}\zeta(3) - 6\zeta(2)\ln 2 + \frac{3}{8}\zeta(2) + \frac{57}{12}\right\}.\end{aligned}$$

- Exactly same input hadronic cross section $\sigma_{\rm had}^0$ as that of LUARLW generator.
- Fred Jegerlehner group calculated $\Pi(s)$ is used, which is different from LUARLW.
- This ISR correction scheme is integrated in Hybrid model.