Status of R scan at BESIII

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(For the BESIII Collaboration)

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USTC, Hefei, China

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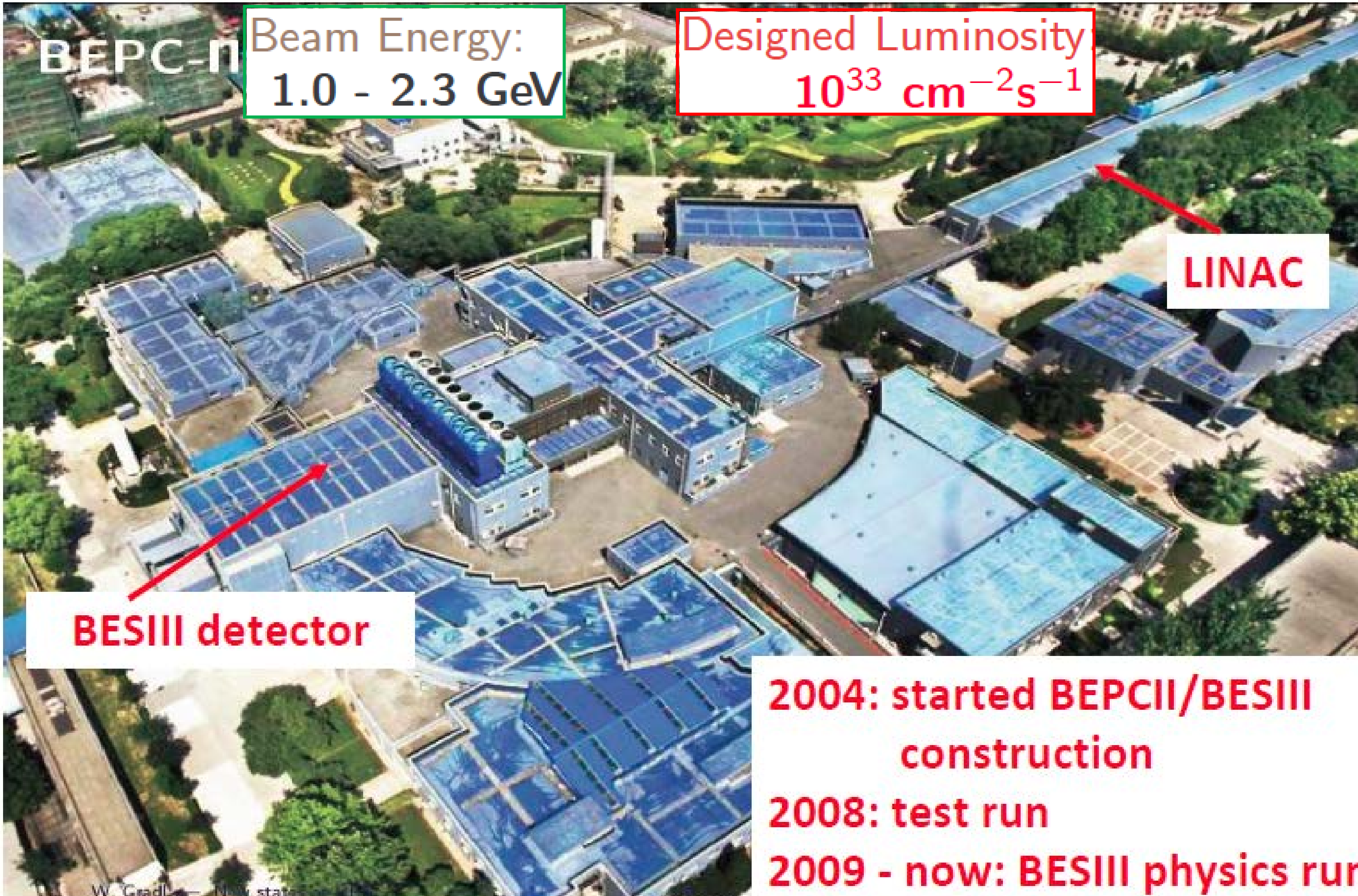
Outline

- Motivation
- Data samples of R-QCD scan
- Status of R value measurement
- Summary

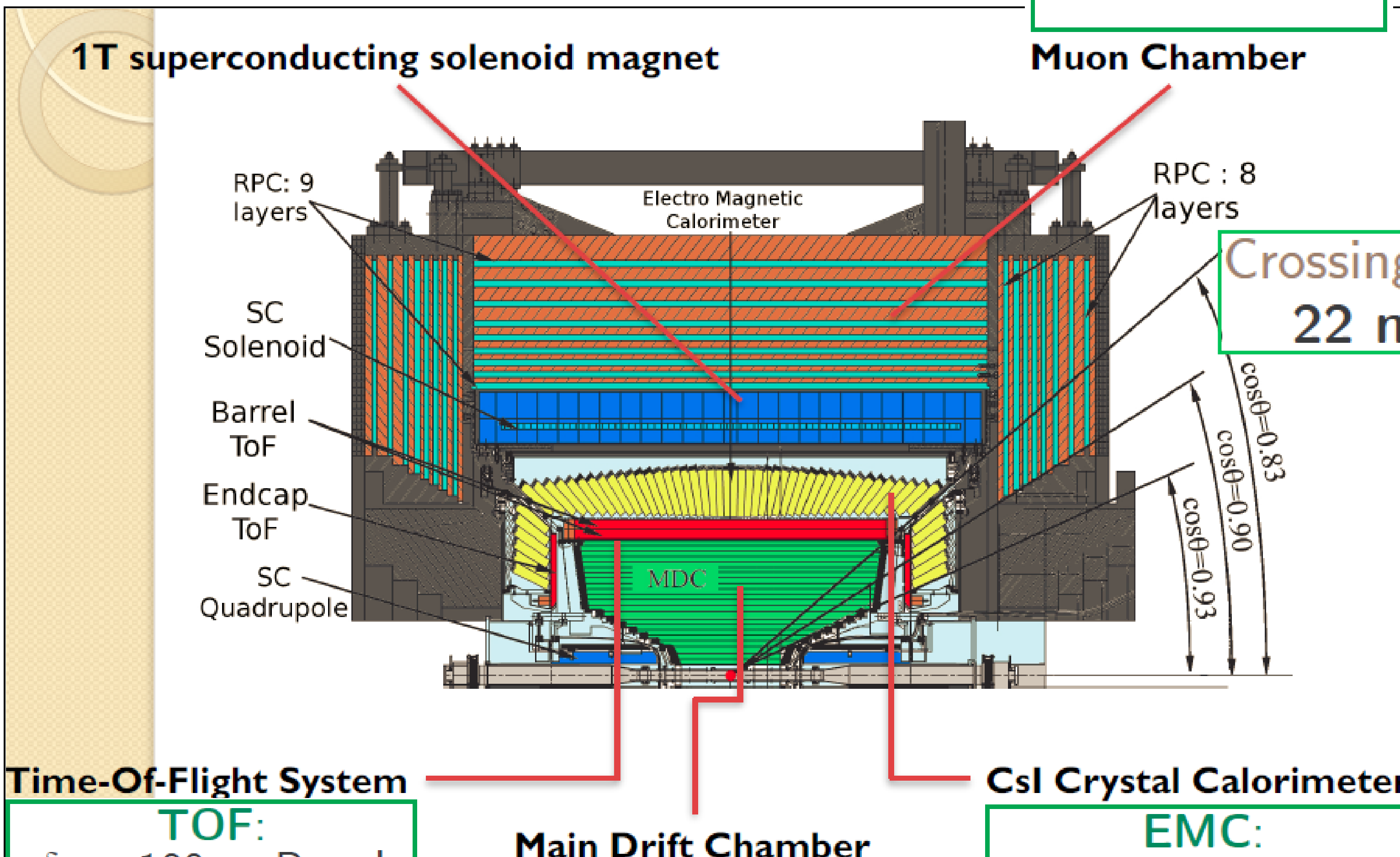
Beijing Electron-Positron Collider II (BEPCII)



Beijing Spectrometer III (BESIII)

MUC:

$\delta(xy) < 2$ cm



Crossing angle
22 mrad

TOF:

$\delta t = 100$ ps Barrel

$\delta t = 110$ ps Endcap

MDC:

$\frac{\delta p}{p} < 0.5\%$ @1 GeV

$\frac{\delta(dE/dx)}{dE/dx} < 6\%$

EMC:

$\frac{\delta E}{E} < 2.5\%$ @1 GeV

$\delta z = 0.6/\sqrt{E}$

Main projects of BESIII Physics

- BESIII physics
  - Charm
    - Light hadron spectrum ☞J/Ψ data
    - Charmonium ☞Ψ(2S) data
    - D physics ☞ Ψ(3770) line shape scan
    - Heavy charmonium
      - ☞Ψ(4040)
      - ☞Ψ(4190)
      - ☞Ψ(4415)
      - ☞X, Y, Z

      Line shape scan
  - Uncharm
    - τ
      - Mass
      - Decay channels
    - R&QCD
      - *R*(*s*) fine scan (*u*,*d*,*s*)
      - QED & QCD $\alpha(s)$, $(g\text{-}2)_\mu$
      - Inclusive distributions
      - Exclusive distributions
      - Correlation functions
      - Form factors
      - Fragmentation functions

      scan

Motivation

The main physical projects for R – QCD scan

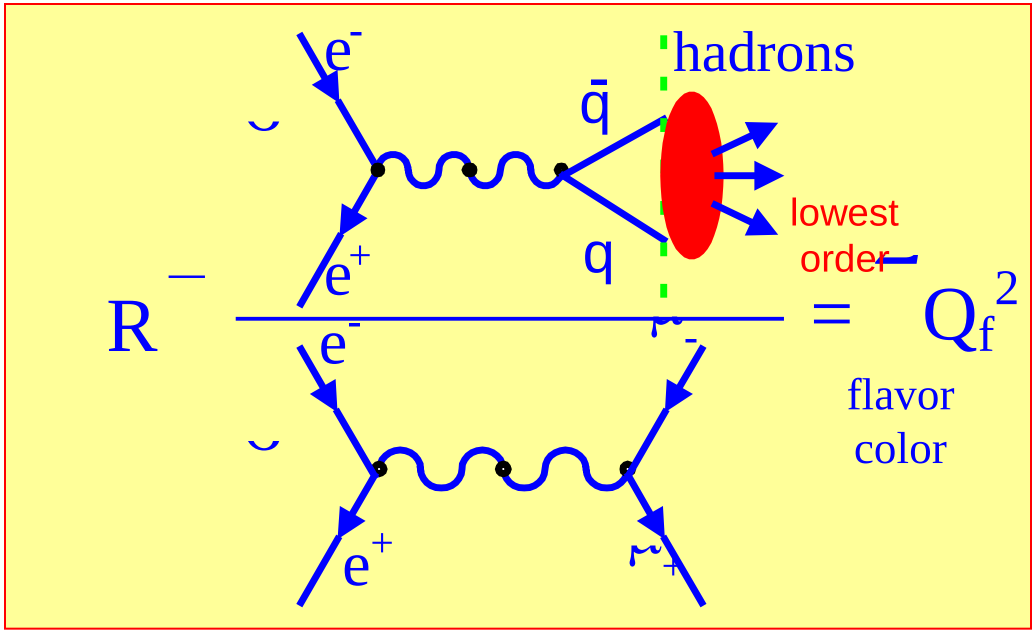
- R value between 2.0 – 4.6 GeV
- ψ-family line shape and resonant parameters
- Form factors of mesons and baryons

What is R Value

The Born cross section of e^+e^- annihilation into hadrons normalized by theoretical $\mu^+\mu^-$ cross section.

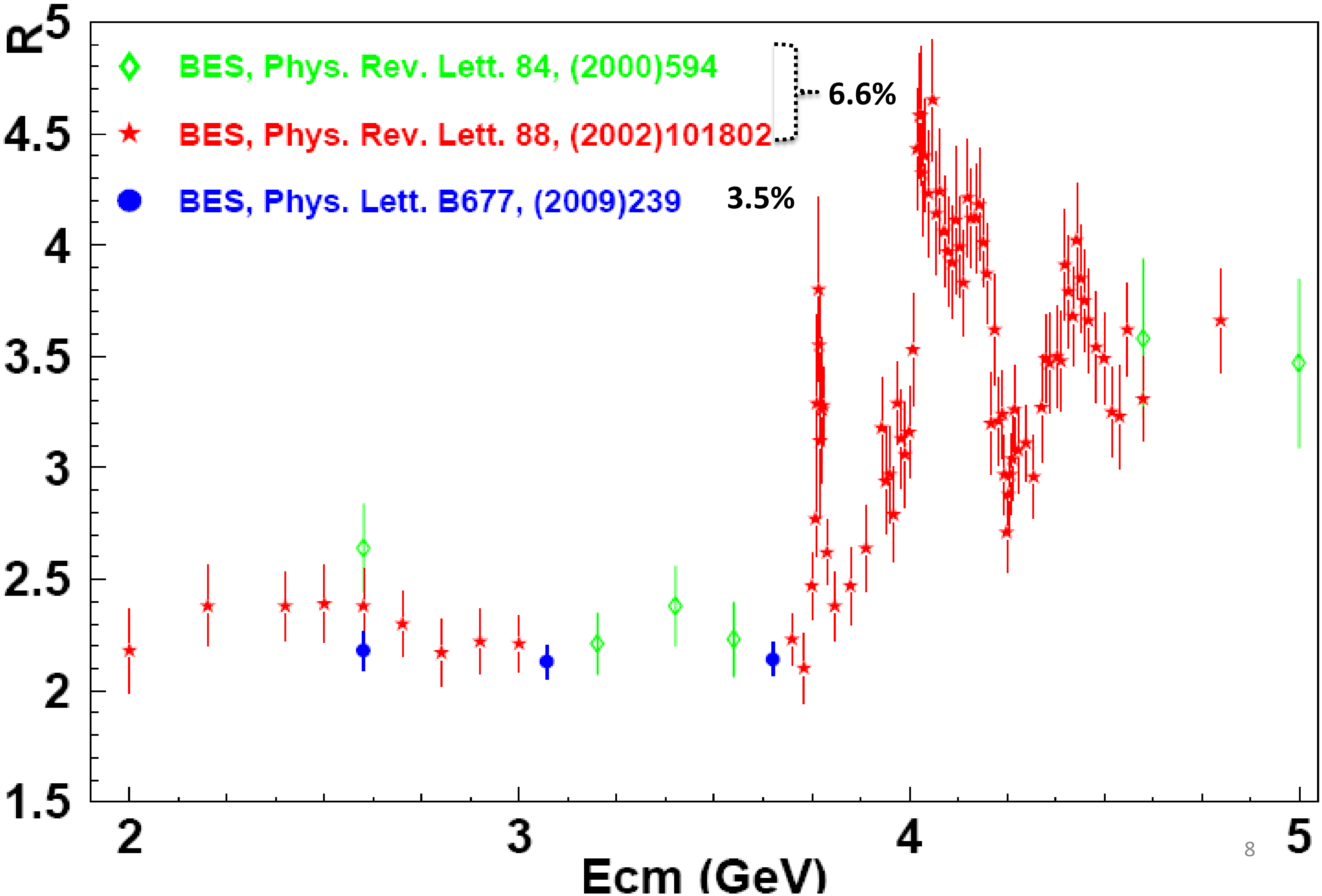
$$R = \frac{\sigma^0_{had}(e^+e^- \to \gamma^* \to \text{hadrons})}{\sigma^0_{\mu\mu}(e^+e^- \to \gamma^* \to \mu^+\mu^-)}$$

Feynman diagram of R value



Groups ever measured R value： BESII， VEPP， DAΦNE， DM2， DASP， PLUTO， Crystal-Ball， MARKI， MARKII， CLEO-c， AMY， JADE， TASSO， CUSB， MD-1， MARKJ， SLAC-LBL， MAC， γγ2……

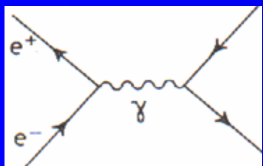
R value measurements at BESII



The significance of R value to the SM

R value is the direct evidence of number of color

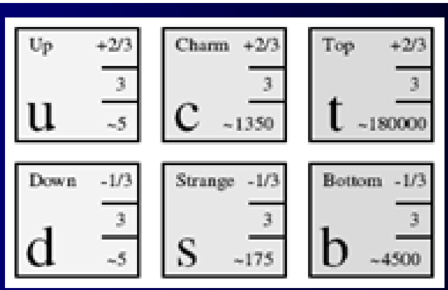
Quarks have, besides flavour, a new quantum number



μ^+, q

μ^-, q

COLOUR



$$\sigma\left(e^+e^- \to \mu^+\mu^-\right) = \frac{4\pi}{3}\frac{\alpha^2}{q^2}$$

$$\sigma\left(e^+e^- \to q\bar{q}\right) = \frac{4\pi}{3}\frac{\alpha^2}{q^2}e_q^2$$

e_q=1/3, 2/3

At a given energy:

$$\sigma\left(e^+e^- \to X\ hadrons\right) = \frac{4\pi}{3}\frac{\alpha^2}{q^2}\sum_{all\,q} e_q^2$$

at lowest order

sum of flavor

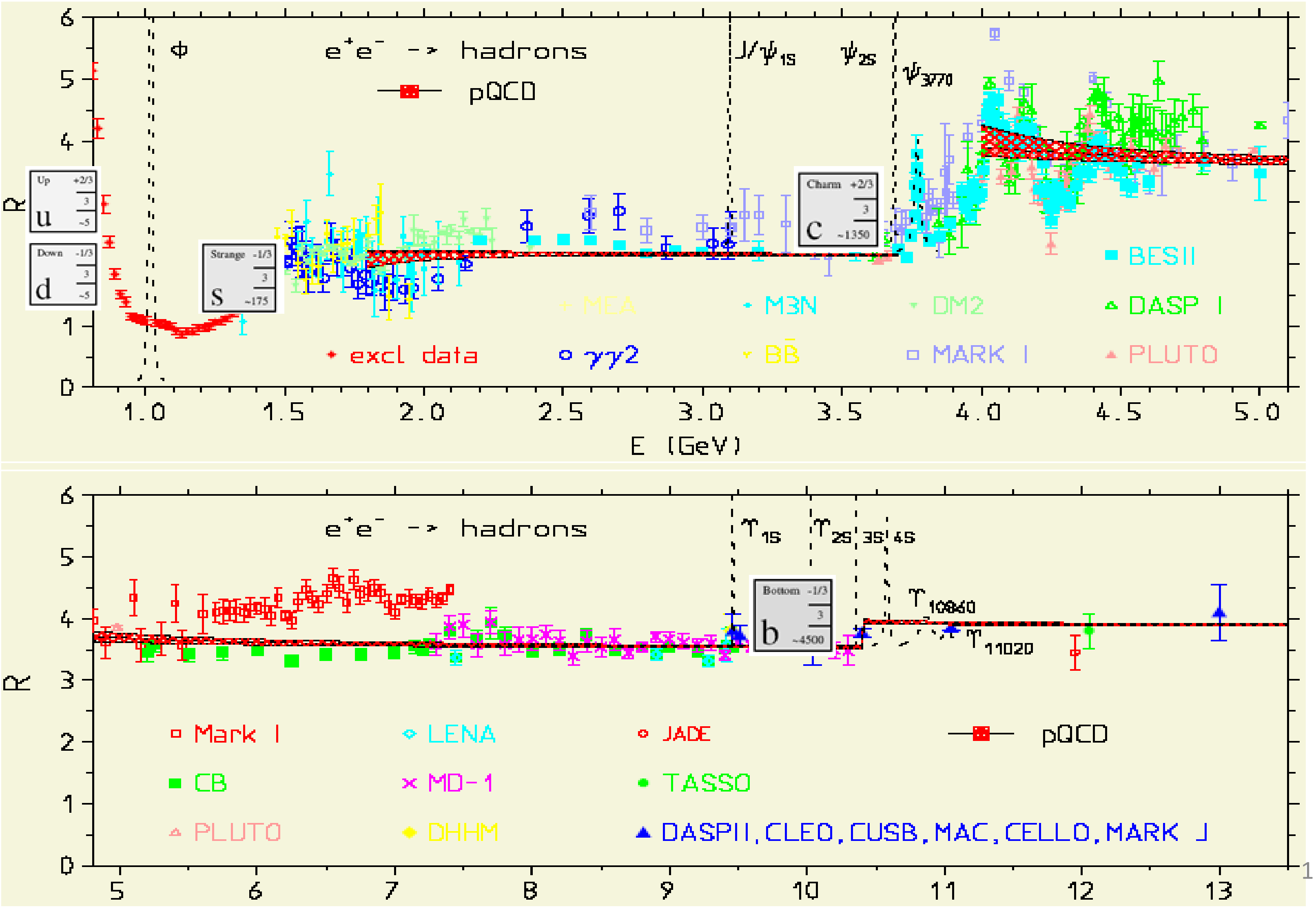
$$R_{had} = \frac{\sigma\left(e^+e^- \to X\right)}{\sigma\left(e^+e^- \to \mu^+\mu^-\right)} = \sum_{all\,q} e_q^2 = \begin{cases} 3\left[\left(\frac{2}{3}\right)^2 + \left(\frac{1}{3}\right)^2 + \left(\frac{1}{3}\right)^2\right] = 2 \\ 3\left[\left(\frac{2}{3}\right)^2_u + \left(\frac{1}{3}\right)^2_d + \left(\frac{1}{3}\right)^2_s + \left(\frac{2}{3}\right)^2_c + \left(\frac{1}{3}\right)^2_b\right] = \frac{11}{3} \end{cases}$$

below charm

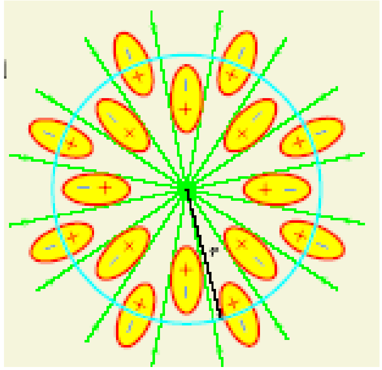
above bottom

R value measurements test QCD prediction

$$R = 3\sum_f Q_f^2[1 + (\frac{\alpha_s(s)}{\pi}) + 1.411(\frac{\alpha_s(s)}{\pi})^2 - 12.8(\frac{\alpha_s(s)}{\pi})^3 + ...]$$



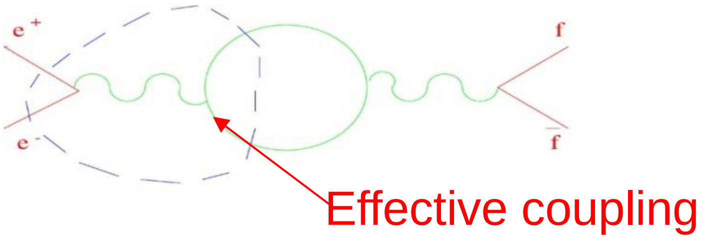
R value is the input parameter of α(s)



Electromagnetic coupling fine structure constant when momentum transfer approach zero：

$$\alpha^{-1}(0) \quad = \quad 137.03599911(46)$$

In high energy processes, vacuum is polarized. The effective coupling interaction is energy dependent, the so called EM running coupling constant：



$$\alpha(s) = \frac{\alpha(0)}{1 - \Delta\alpha(s)}$$

According to the contributions to vacuum polarization

$$\Delta\alpha(s) = \Delta\alpha_{e\mu\tau}(s) + \Delta\alpha_{top}(s) + \Delta\alpha^{(5)}_{had}(s)$$

① leptonic contribution：

$$\Delta\alpha_{e\mu\tau}(M_Z^2) = \sum_{l=e,\mu\tau} \frac{\alpha}{3\pi}[-\frac{8}{3} + \beta_l^2 - \frac{1}{2}\beta_l(3 - \beta_l^2)\ln(\frac{1-\beta_l}{1+\beta_l})] = 0.03142$$

R value is the input parameter of α(s)

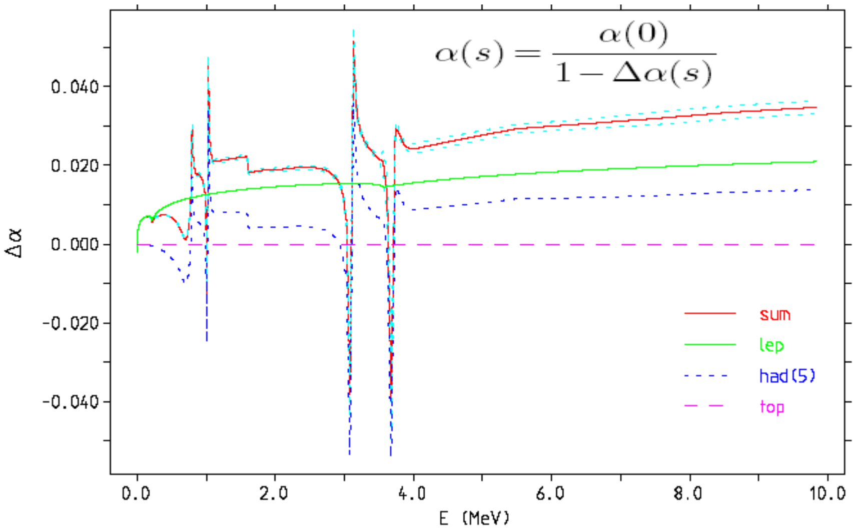
- top quark very heavy, contribution very small

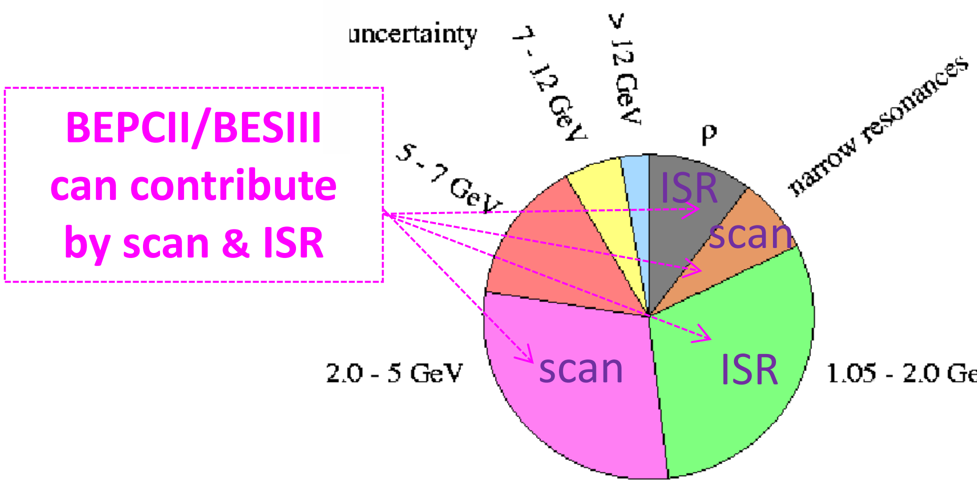
$$\Delta\alpha_{top}(M_Z^2) = -\frac{4\alpha}{45\pi}\frac{M_Z^2}{m_t^2} = -0.00007(1)$$

- quarks with flavors (u, d, s, c, b)

$$\Delta\alpha_{had}^{(5)}(M_Z^2) = \frac{\alpha M_Z^2}{3\pi}\int_{4m_\pi^2}^{\infty} ds \frac{R(s)}{s(s-M_Z^2-i\epsilon)}$$

$$= \frac{\alpha M_Z^2}{3\pi}\left[\int_{4m_\pi^2}^{(5GeV)^2} ds \frac{R_{exp}(s)}{s(s-M_Z^2-i\epsilon)} + \int_{(5GeV)^2}^{\infty} ds \frac{R_{QCD}(s)}{s(s-M_Z^2-i\epsilon)}\right]$$





Improve the precision of R value can decrease the uncertainty of Δα(s) effectively.

R value is the input parameter of $(g\text{-}2)_\mu$

The Dirac equation of a charged fermion in electromagnetic field (A,B)

$$i\hbar\frac{\partial}{\partial t}\varphi = [\frac{1}{2m}(\vec{P}+\frac{e}{c}\vec{A})^2 + \frac{e\hbar}{2mc}\vec{\sigma}\cdot\vec{B} - e\phi]\varphi$$

point-like fermion has magnetic moment

$$\vec{\mu} = -\frac{e\hbar}{2mc}\vec{\sigma} = -\frac{e}{mc}\vec{S}$$

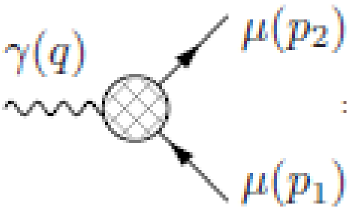
define Bohr magneton:

$$\mu_B = \frac{e\hbar}{2mc}$$

the magnetic moment of bare fermion:

$$\mu = g\mu_B S \qquad g = 2$$

Considering the radiative correction of the vertex

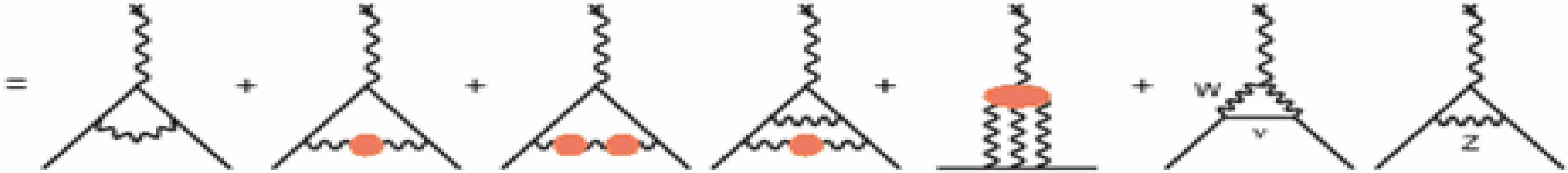


$\Rightarrow g \neq 2 \Rightarrow$ anomalous magnetic moment: $a_\mu = (g_\mu-2)/2$

R value is the input parameter of $(g\text{-}2)_\mu$

The Standard Model (SM) prediction for muon (g-2):

$$a_\mu^{SM} = a_\mu^{QED} + a_\mu^{had,LO} + a_\mu^{had,HO} + a_\mu^{had,LBL} + a_\mu^{weak}$$



= (QED)	$(11\,658\,470.35 \pm 0.28)10^{-10}$	(5-loop!)
+ (had,LO)	$(684.7$ to $709.0 \pm 6)10^{-10}$	(Big spread, largest error)
+ (had,HO)	$(-10.0 \pm 0.6)10^{-10}$	
+ (had,LBL)	$(8.0 \pm 4.0)10^{-10}$	(sign change since 1998)
+ (weak)	$(15.4 \pm 0.2)10^{-10}$	(2-loop)

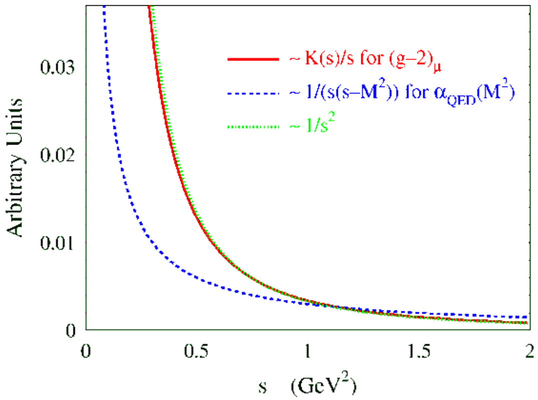
$a_\mu^{had,LO}$ from data via dispersion integral

$$a_\mu^{had,LO} = \frac{1}{4\pi^3}\int_{4m_\pi^2}^{\infty} \sigma_{had}^0(s)K(s)ds$$

Recent data included CMD-2, SND, BES 2-5 GeV, ALEPH τ.
NEW: CMD-2 prelim update

σ_{had}^0 bare cross-section for $e^+e^- \rightarrow$ hadrons, i.e. taking out radiative corrections.

QED kernel $K(s) \sim m_\mu^2/3s$, gives strong weight to low energy data.



R value is the input parameter of $(g-2)_\mu$

Discrepancy between SM and experiments:

$a_\mu^{EXP} = 116592089\ (63) \times 10^{-11}$

E821 – Final Report: PRD73 (2006) 072
with latest value of $\lambda = \mu_\mu / \mu_p$ (Codata '06)

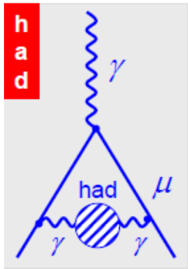
	$a_\mu^{SM} \times 10^{11}$	$(\Delta a_\mu = a_\mu^{EXP} - a_\mu^{SM}) \times 10^{11}$	σ
[1]	116 591 773 (53)	316 (82)	3.8
[2]	116 591 782 (59)	307 (86)	3.6
[3]	116 591 834 (49)	255 (80)	3.2
[4]	116 591 773 (48)	316 (79)	4.0
[5]	116 591 929 (52)	160 (82)	2.0

with $a_\mu^{HHO}(lbl) = 105\ (26) \times 10^{-11}$

[1] HMNT06, PLB649 (2007) 173.
[2] F. Jegerlehner and A. Nyffeler, arXiv:0902.3360.
[3] Davier et al, arXiv:0908.4300 August 2009 (includes BaBar)
[4] Hagiwara, Liao, Martin, Nomura, Teubner, Oct '09 (preliminary)
[5] Davier et al, arXiv:0906.5443v2 August 2009 (τ data).

R value is the input parameter of $(g\text{-}2)_\mu$

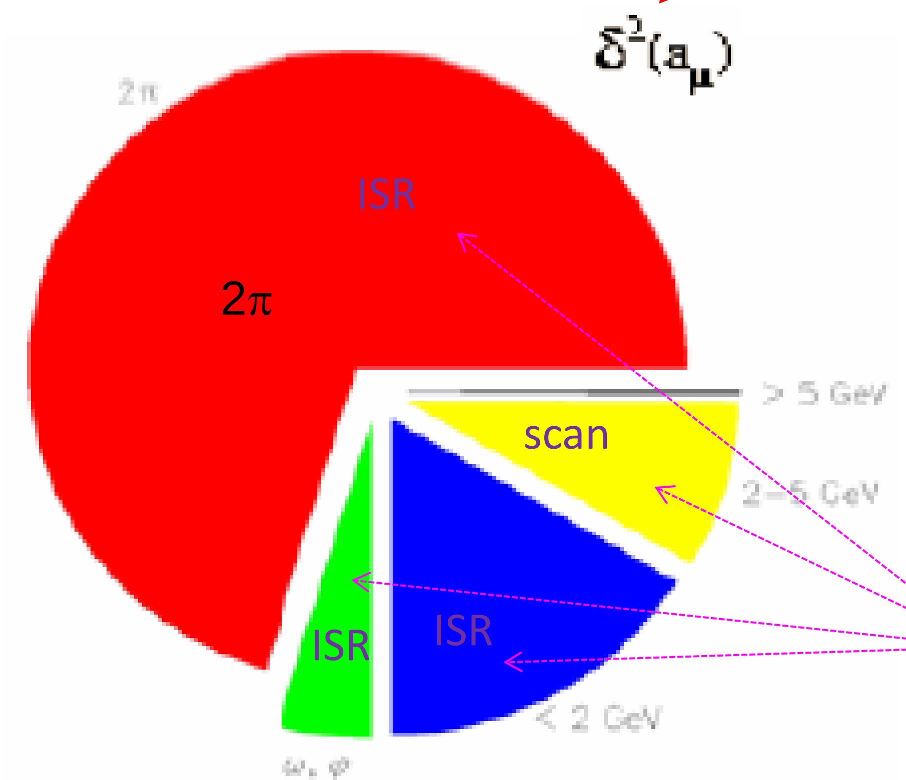
The contribution of the hadronic cross section to (g-2):



$$\alpha_\mu^{had} = \left(\frac{\alpha m_\mu}{3\pi}\right)^2 \int_{4m_\pi^2}^{\infty} ds' \frac{\hat{K}(s')}{s'^2} R(s')$$

$$= \left(\frac{\alpha m_\mu}{3\pi}\right)^2 \left[\int_{4m_\pi^2}^{(5GeV)^2} ds' \frac{\hat{K}(s')}{s'^2} R_{exp}(s') + \int_{(5GeV)^2}^{\infty} ds' \frac{\hat{K}(s')}{s'^2} R_{QCD}(s')\right]$$

Experiment error



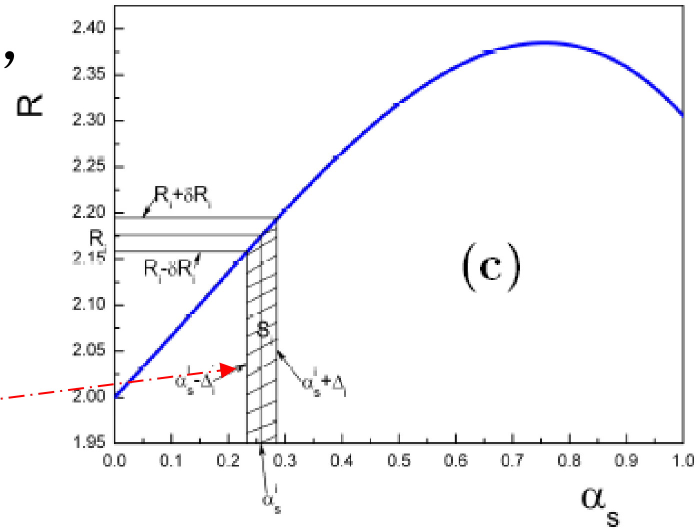
BEPCII/BESIII can contribute by scan & ISR

Measurement of α_s at by R values

Solve equation $R_{QCD}(\alpha_s(s_i)) = R_{exp}(s_i) \pm \Delta R_{exp}(s_i)$

Obtain coupling constant at every energies, and then evolve them to 5 GeV with

$$Q^2 \frac{\partial \alpha_s(Q^2)}{\partial Q^2} = \beta(\alpha_s(Q^2))$$



Weighted average

$$\overline{\alpha_s}(5GeV) = \sum_i \frac{\alpha_s(s_i)}{S_i} \Big/ \sum_i \frac{1}{S_i}$$

$$S_i = \int_{\alpha_s(s_i)-\Delta_i'}^{\alpha_s(s_i)+\Delta_i} R(\alpha_s) d\alpha_s$$

errors $\overline{\Delta}_{down} = \sqrt{1/\sum_i \Delta_i'^{-2}}$ $\overline{\Delta}_{up} = \sqrt{1/\sum_i \Delta_i^{-2}}$

$\sqrt{s}$(GeV)	$\alpha_s^{(3)}(s)$	$\alpha_s^{(4)}(25\ \mathrm{GeV}^2)$	$\bar{\alpha}_s^{(4)}(25\ \mathrm{GeV}^2)$	$\alpha_s^{(5)}(M_Z^2)$
2.60	$0.266^{+0.030+0.125}_{-0.030-0.116}$	$0.212^{+0.018+0.068}_{-0.019-0.086}$		
3.07	$0.192^{+0.029+0.103}_{-0.029-0.101}$	$0.169^{+0.022+0.074}_{-0.023-0.086}$	$0.209^{+0.044}_{-0.050}$	$0.117^{+0.012}_{-0.017}$
3.65	$0.207^{+0.015+0.104}_{-0.015-0.104}$	$0.189^{+0.012+0.082}_{-0.013-0.091}$		

PDG2006 $\alpha_s(M_Z^2) = 0.1170 \pm 0.0012$

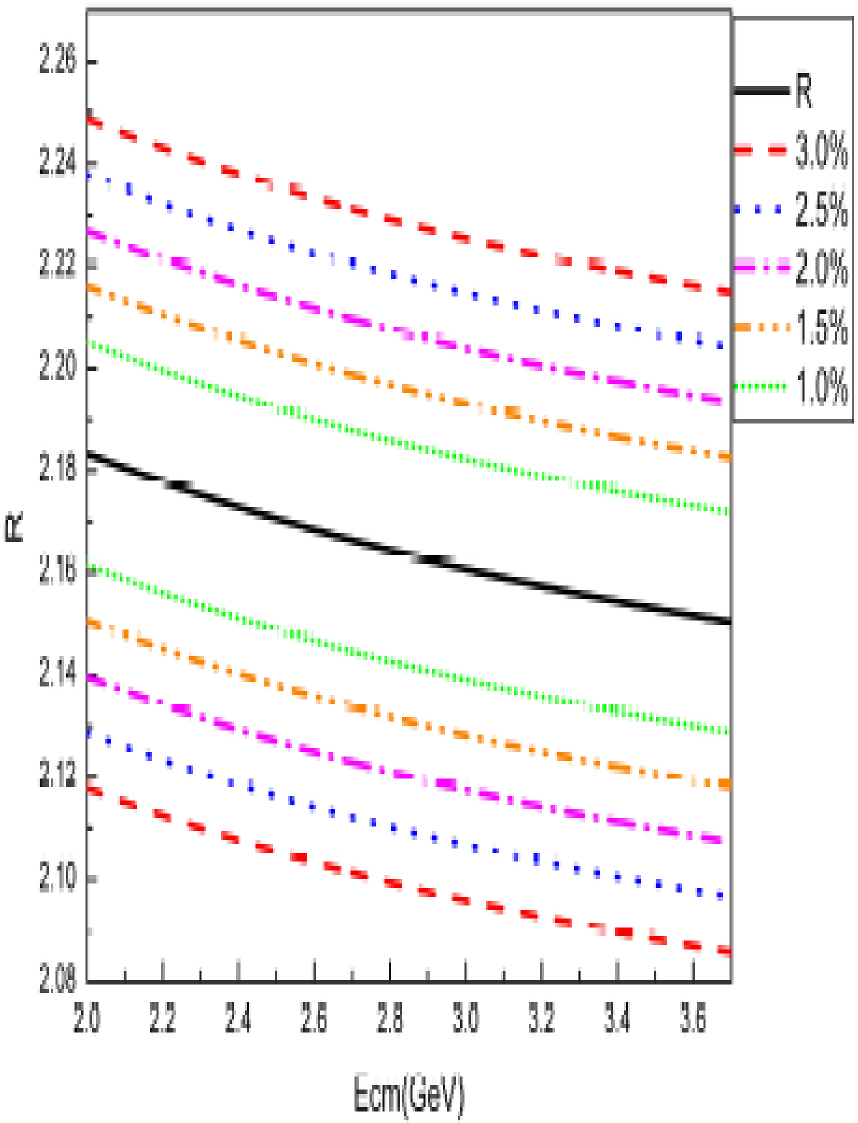
R value error → error of α_s

α_s error \ R error / E_{cm} /GeV	3.0%		2.5%		2.0%		1.5%		1.0%	
	Up(%)	Dw(%)	Up(%)	Dw(%)	Up(%)	Dw(%)	Up(%)	Dw(%)	Up(%)	Dw(%)
2.00	37.7	35.4	31.1	29.6	24.7	23.7	18.4	17.8	12.2	11.9
2.10	38.1	35.9	31.4	29.9	25.0	24.0	18.6	18.1	12.3	12.1
2.20	38.4	36.3	31.8	30.3	25.3	24.3	18.8	18.3	12.5	12.2
2.30	38.8	36.8	32.0	30.7	25.5	24.6	19.0	18.5	12.6	12.4
2.40	39.2	37.2	32.4	31.0	25.8	24.9	19.2	18.7	12.8	12.5
2.50	39.6	37.6	32.8	31.4	26.0	25.2	19.4	18.9	12.9	12.6
2.60	40.0	38.1	33.0	31.8	26.3	25.4	19.6	19.1	13.0	12.7
2.70	40.2	38.5	33.3	32.1	26.5	25.8	19.8	19.3	13.1	12.9
2.80	40.6	38.9	33.6	32.4	26.7	26.0	20.0	19.5	13.2	13.0
2.90	41.0	39.3	33.9	32.7	27.0	26.2	20.2	19.7	13.3	13.2
3.00	41.4	39.7	34.3	33.1	27.3	26.5	20.4	19.9	13.5	13.3
3.10	41.6	40.1	34.4	33.4	27.4	26.7	20.4	20.1	13.5	13.4
3.20	42.0	40.4	34.8	33.7	27.7	27.0	20.7	20.2	13.7	13.5
3.30	42.3	40.8	35.0	34.0	27.8	27.2	20.8	20.4	13.8	13.7
3.40	42.6	41.1	35.3	34.2	28.1	27.4	21.0	20.6	14.0	13.7
3.50	42.9	41.5	35.6	34.6	28.3	27.6	21.1	20.8	14.1	13.8
3.60	43.1	41.8	35.8	34.8	28.3	27.9	21.3	20.9	14.1	14.0
3.70	43.4	42.1	36.0	35.1	28.7	28.1	21.4	21.0	14.2	14.1

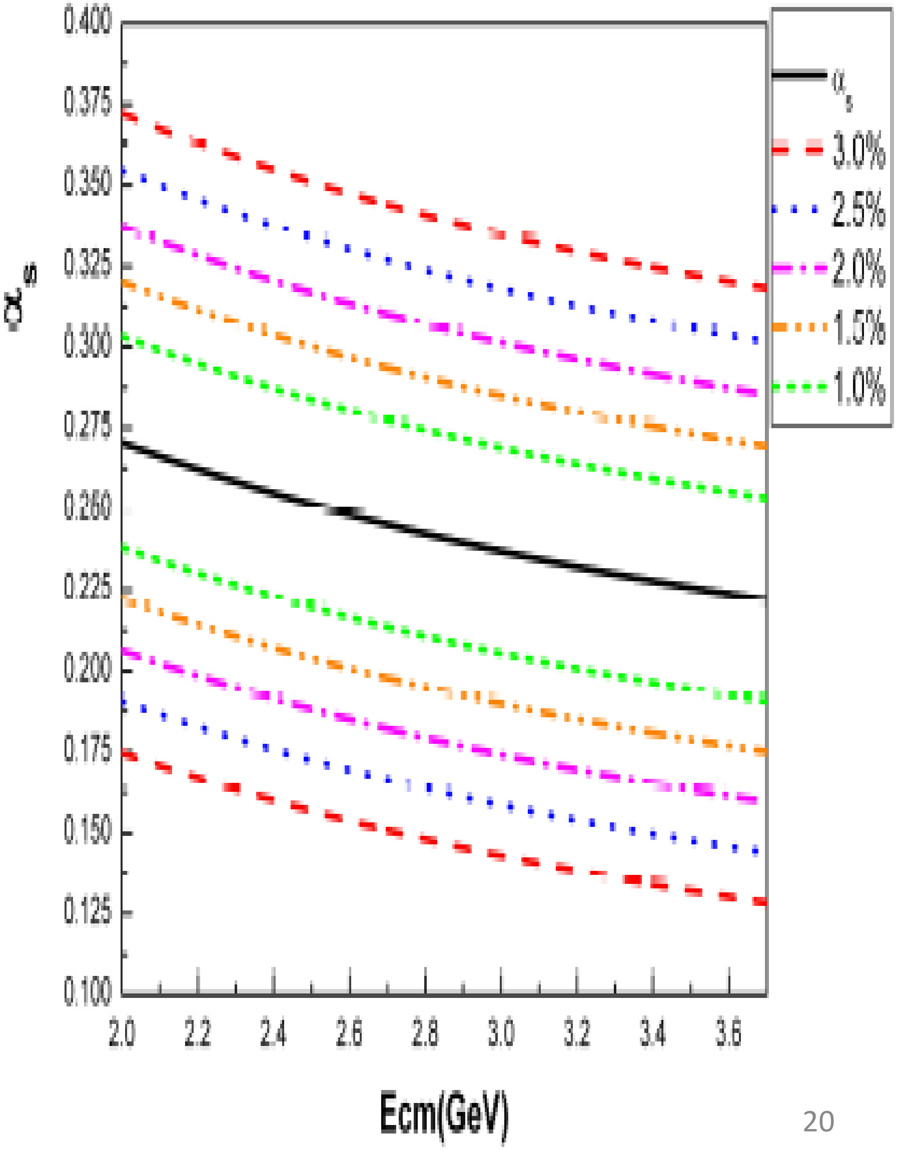
So, α_s can be determined based on R, and independent of any model, but the error of α_s larger than that of R value, it is not an “economical” way.

R value error → error of α_s

Uncertainty range of R within 1σ



Uncertainty range of α_s within 1σ



Data samples of R – QCD scan

R&QCD scan data taking plan

- Phase I: test run (2012)

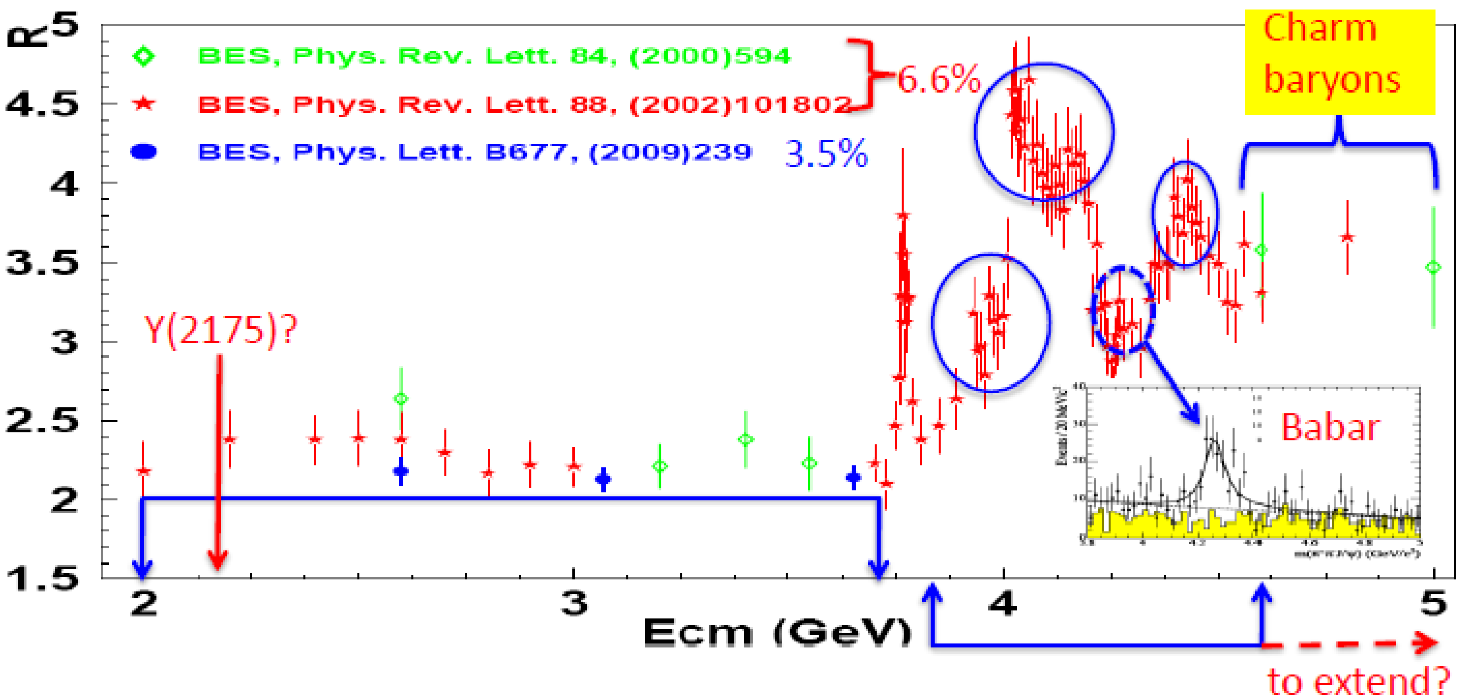
  @ Ecm = 2.232, 2.400, 2.800, 3.400 GeV , 4 energy points, ~12/pb

- Phase II: fine scan for heavy charm resonant line shape (2013–2014)

  @ 3.800 – 4.590 GeV, 104 energy points, ~ 800/pb

- Phase III: R&QCD scan (2015)

  @ 2.000 – 3.080 GeV, 19+2 energy points, ~ 500/pb

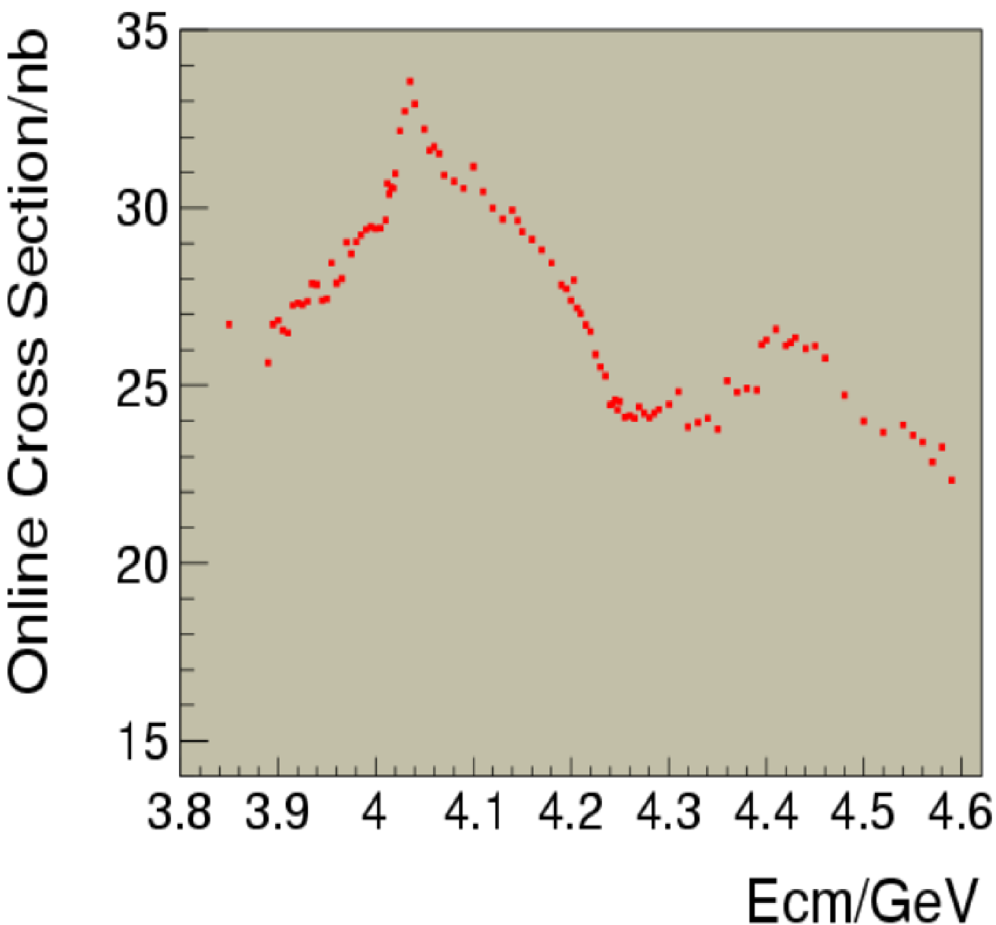


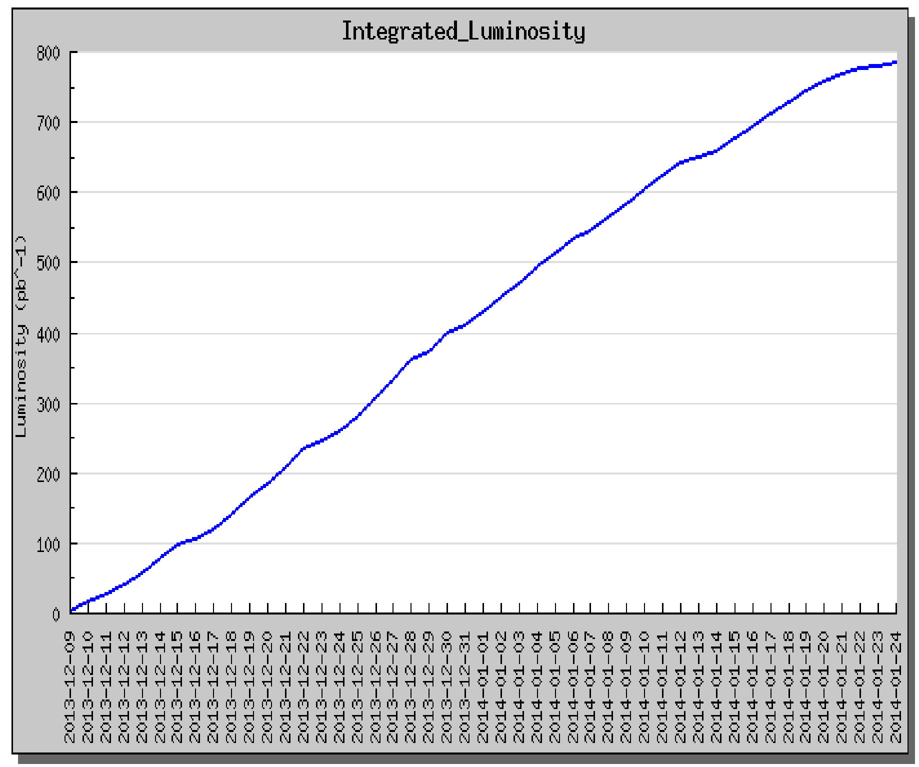
Phase I: R-QCD scan below open charm

- BESIII collected data at 2.23, 2.4, 2.8 and 3.4 GeV during June 8–16, 2012;
- Total integrated luminosity ~12 pb-1;
- Useful information for BEPCII/BESIII at low energy;
- The data being used for MC generator tuning;
- Necessary to establish analysis chain;
- R value measurement ;
- Baryon and meson form factors;
- fragmentation function study.

Phase II: R line shape scan between 3.8 - 4.6 GeV

- Data taken 2013.12.9 - 2014.1.24;
- 104 energy points in total, ~800 pb^{-1};
- >100k hadronic events each points.





Phase III: R scan between 2.0 – 3.08 GeV

- Data taken at: 19+2 points, ~500 pb^{-1};
- Precision of R measurement expected: ~3%;
- Nucleon form factors: 9-15% accuracy;
- Suspicious structures in the $p\bar{p}$ invariant mass;
- Hyperon form factor studies;
- Studies of threshold effects (Λ, Σ, Ξ);
- Determination of α_s and charm quark mass;
- Quark fragmentation functions;
- ……

Third run: R scan between 2.0 – 3.08 GeV

Data samples between 2.0 – 3.08 GeV collected in 2015

E_{cm} (GeV)	E_{th} (GeV)	L_{Needed} (pb^{-1})	t_{beam} ($days$)	Purpose
2.0		≥8.95	14.6	Nucleon FFs
2.1		10.8	14.8	Nucleon FFs
2.15		2.7	2.29	Y(2175)
2.175		10(+)	8.5	Y(2175)
2.2		13	11	Nucleon FFs, Y(2175)
2.2324	2.2314	11	4	Hyp threshold ($\Lambda\bar{\Lambda}$)
2.3094	2.3084	20	16	Nucleon & Hyp FFs Hyp Threshold ($\Sigma^0\bar{\Lambda}$)
2.3864	2.3853	20	8.7	Hyp Threshold ($\Sigma^0\bar{\Sigma}^0$) Hyp FFs
2.3960	2.3949	≥64	27.8	Nucleon & Hyp FFs Hyp Threshold ($\Sigma^-\bar{\Sigma}^+$)
2.5		0.4895	8h	R scan
2.6444	2.6434	65	18	Nucleon & Hyp FFs Hyp Threshold ($\Xi^-\bar{\Xi}^+$)
2.7		0.5542	4.2h	R scan
2.8		0.6136	4h	R scan
2.9		100	18.5	Nucleon & Hyp FFs
2.95		15	2.8	$m_{p\bar{p}}$ step
2.981		15	2.8	η_c , $m_{p\bar{p}}$ step
3.0		15	2.8	$m_{p\bar{p}}$ step
3.02		15	2.8	$m_{p\bar{p}}$ step
3.08		120	13.2	Nucleon FFs (+30 pb^{-1})

Data: 19+2 energy points

Main goals

1. R value
2. Form factors
3. New phenomenon?
4. New states?

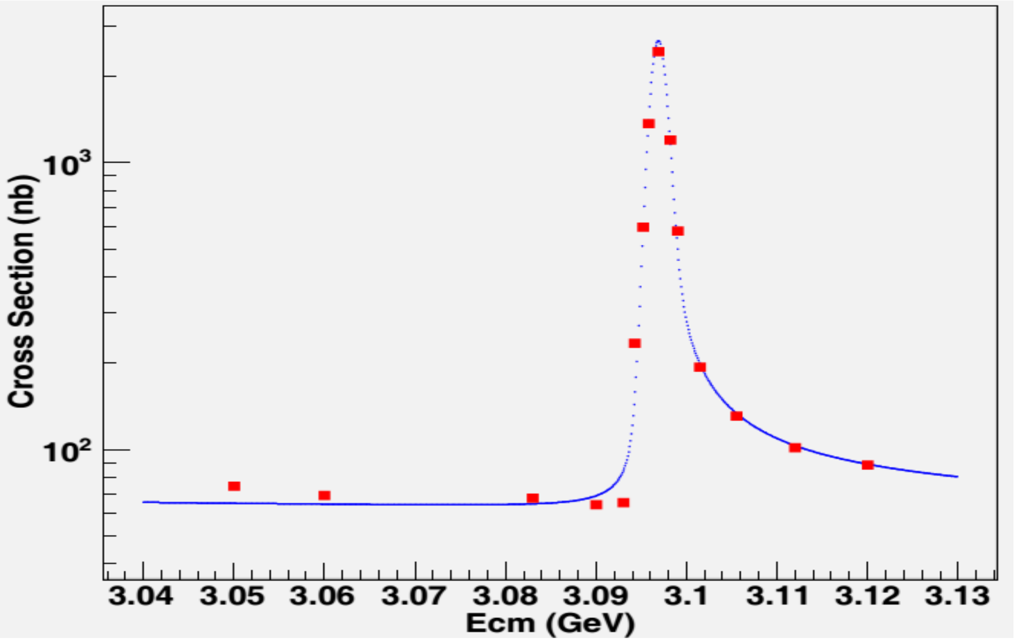
See
Yadi and Yaqian's talks

J/psi line shape scan between 3.0500– 3.1200 GeV

Data have been taken around the J/psi peak at 12 energy points in 2012

Req Ecm (GeV)	Int Lum (nb^{-1})
3.0500	14918 ± 169
3.0600	15059 ± 170
3.0830	4768 ± 58
3.0900	15558 ± 173
3.0930	14909 ± 160
3.0943	2143 ± 25
3.0952	1816 ± 22
3.0958	2134 ± 25
3.0969	2069 ± 26
3.0982	2203 ± 27
3.0990	756 ± 11
3.1015	1612 ± 21
3.1055	2106 ± 25
3.1120	1720 ± 21
3.1200	1264 ± 17

On line cross section and J/psi line-shape

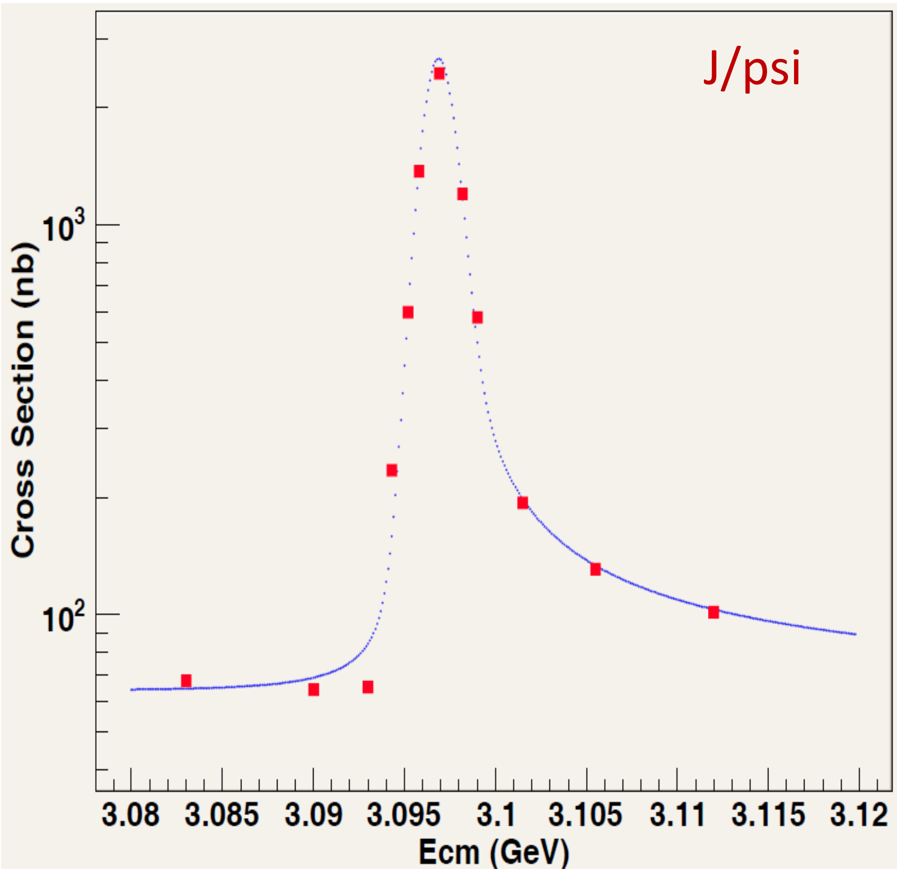


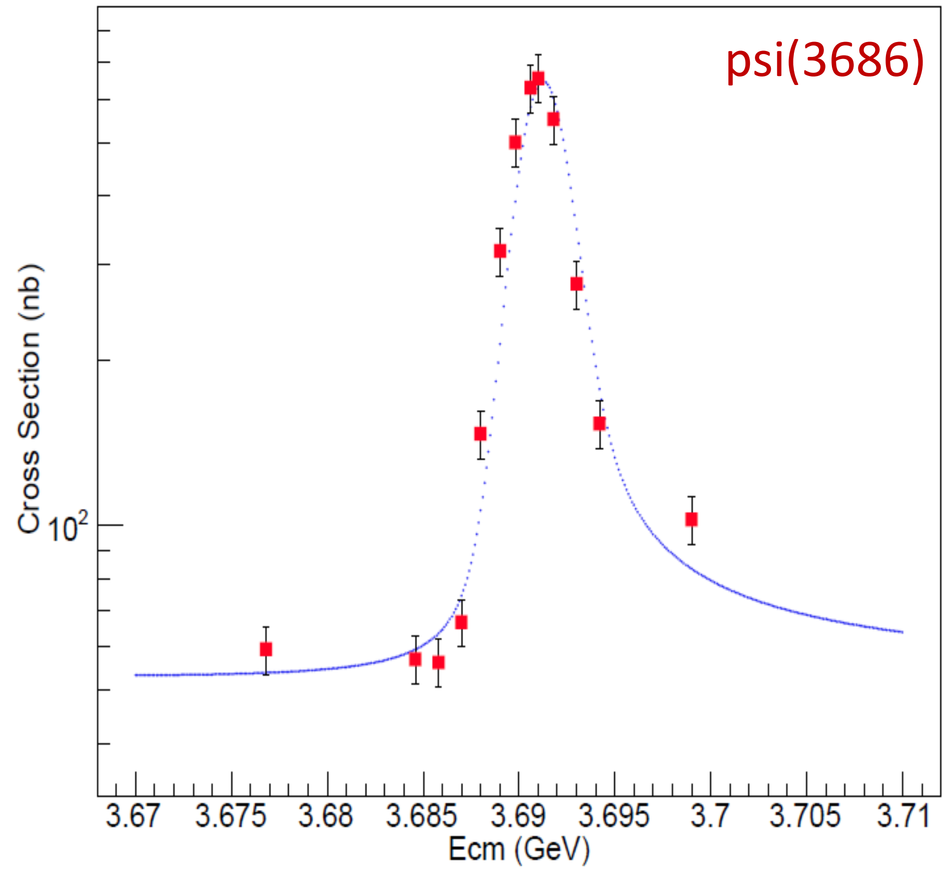
Physical goal: measure the leptonic, hadronic and total widths of J/psi by following channels:

1. $e^+e^- \rightarrow e^+e^-$
2. $e^+e^- \rightarrow \mu^+\mu^-$
3. $e^+e^- \rightarrow$ hadrons

Energy calibration

During the data taking, sever times J/psi and psi(3686) fast scan were done, and fit the on line cross section to calibrate the beam energy.





$$\Delta E_{cm} = M_{J/\Psi}^{FIT} - M_{J/\Psi}^{PDG}$$

$$\Delta E_{cm} = M_{psi(3686)}^{FIT} - M_{psi(3686)}^{PDG}$$

Calibration:

$$E_{cm}^{set} = E_{cm}^{preset} + \Delta E_{cm}$$

$$E_{beam}^{set} = E_{beam}^{preset} + \Delta E_{beam}$$

Data samples taken at BESIII

Taking data	Total Num. / Lum.	Taking time
J/ψ	225+1086 M	2009+2012
$\psi(2S)$	106+350 M	2009+2012
$\psi(3770)$	2916 pb^{-1}	2010~2011
τ scan	24 pb^{-1}	2011
Y(4260)/Y(4230)/Y(4360)/scan	806/1054/523/488 pb^{-1}	2012~2013
4600/4470/4530/4575/4420	506/100/100/42/993 pb^{-1}	2014
J/ψ line-shape scan	100 pb^{-1}	2012
R scan (2.23, 3.40) GeV	12 pb^{-1}	2012
R scan (3.85, 4.59) GeV	795 pb^{-1}	2013~2014
R scan (2.0, 3.08) GeV	~525 pb^{-1}	2014~2015
Y(2175)	~100 pb^{-1}	2015

Status of R value measurement

R value measurement with data

In experiment, R values are measured with

$$R = \frac{1}{\sigma_{\mu+\mu-}} \cdot \frac{N_{had} - N_{bg}}{L \cdot \varepsilon_{had} \cdot (1+\delta)}$$

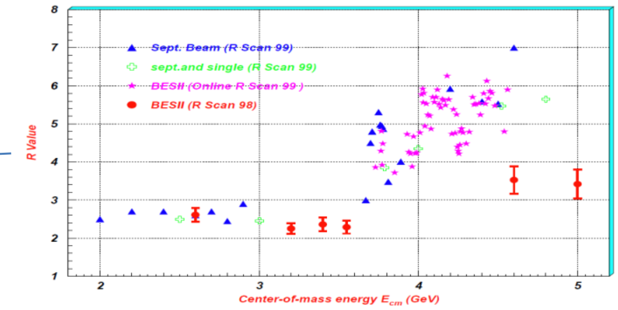
Tasks in experiment:

- N_{had} observed hadronic events
- N_{bg} background events
- L integrated luminosity
- ε_{had} detection efficiency for hadronic events
- $1+\delta$ radiative correction factor
- $\sigma_{\mu\mu}$ Born cross section of μ pair production in QED.

The efficiency and ISR factor correction

Observed cross section (no physics):

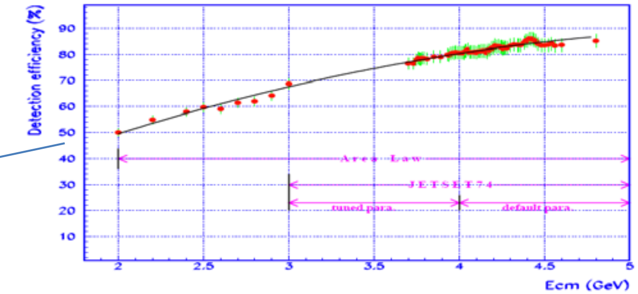
$$\sigma^T_{obs} = \frac{N_{had}}{L}$$



Efficiency corection:

→ total cross section (physics)

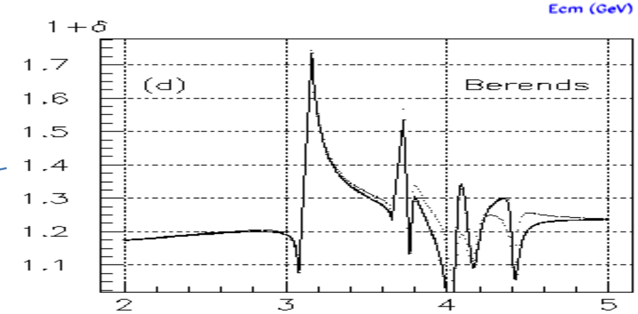
$$\sigma^T = \frac{\sigma^T_{obs}}{\bar{\epsilon}} = \frac{N_{had}}{L\bar{\epsilon}}$$



ISR factor (1+δ) correction:

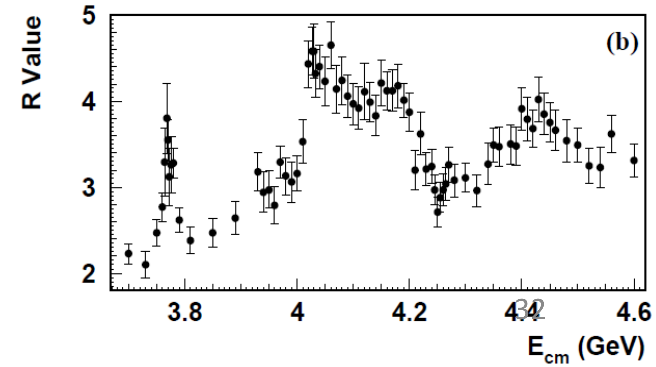
→ Born cross section

$$\sigma^0 = \frac{N_{had}}{L\bar{\epsilon}(1+\delta)}$$



R value:

$$R = \frac{N_{had}}{\sigma^0_{\mu\mu} L\bar{\epsilon}(1+\delta)}$$



Present status of R value measurement

$$R = \frac{1}{\sigma_{\mu+\mu-}} \cdot \frac{N_{had} - N_{bg}}{L \cdot \varepsilon_{had} \cdot (1+\delta)}$$

N_{had} , N_{bg} $\rightarrow$ event selection:

below open charm finished, above open charm in progress.

L $\rightarrow$ integrated luminosity:

finished, error ~ 1%.

ε_{had} $\rightarrow$ hadronic generator LUARLW tuning:

two schemes are doing, cross check, largest error source?

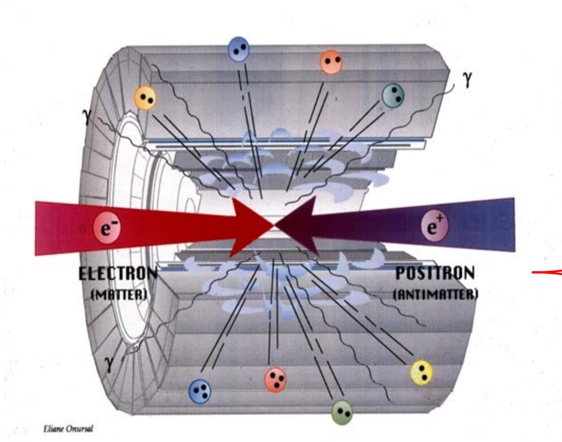
$1+\delta$ $\rightarrow$ theoretical calculations:

finished, error ~1.5%, including the contribution from $\Delta\sigma^0_{had}$

Error analysis:

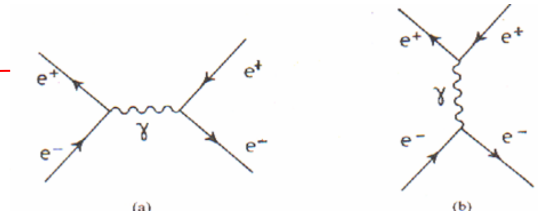
on going, final goal $\Delta R/R$ ~2.5–3.0%

The generators used in R measurement

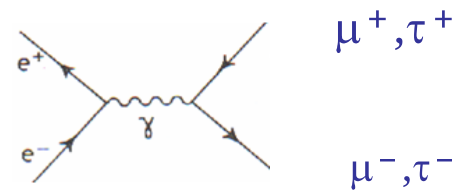


processes

generators

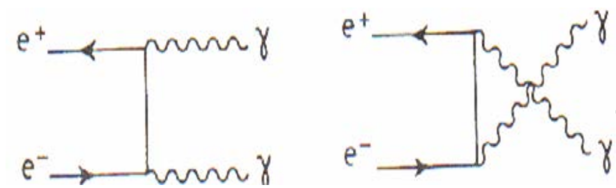


$e^+e^- \to e^+e^-$ BABAYAGA (OK)

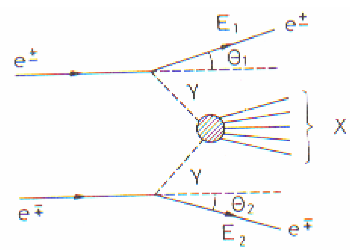


$e^+e^- \to \mu^+\mu^-$ BABAYAGA (OK)

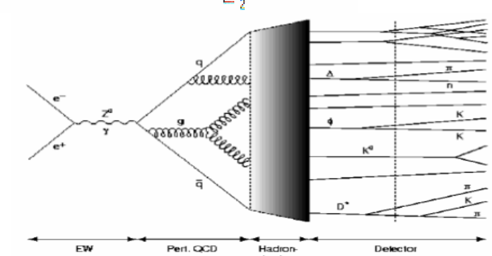
$e^+e^- \to \tau^+\tau^-$ KKMC (OK)



$e^+e^- \to \gamma\gamma$ BABAYAGA (OK)



$e^+e^- \to e^+ e^- X$ TWOPHOTON (need check)



$e^+e^- \to$ hadrons LUARLW (need tuning)

Functions of LUARLW

LUARLW can simulate ISR inclusive continuous channels and $J^{PC} = 1^{--}$ resonances from 2–5 GeV, phenomenological parameters need tuning.

$$e^+e- \Rightarrow \gamma^* \Rightarrow \rho(770), \omega(782), \phi(1020), \omega(1420), \rho(1450), \omega(1650), \phi(1680), \rho(1700)$$

$$e^+e^- \Rightarrow \gamma^* \Rightarrow \begin{cases} q\bar{q} \Rightarrow \text{string} \Rightarrow \text{hadrons} \\ gq\bar{q} \Rightarrow \text{string} + \text{string} \Rightarrow \text{hadrons} \\ ggq\bar{q} \Rightarrow \text{string} + \text{string} + \text{string} \Rightarrow \text{hadrons} \end{cases}$$

$$e^+e^- \Rightarrow \gamma^* \Rightarrow J/\psi \Rightarrow \begin{cases} \gamma^* \Rightarrow e^+e^-,\ \mu^+\mu^- \\ q\bar{q} \Rightarrow \text{string} \Rightarrow \text{hadrons} \\ ggg \Rightarrow \text{string} + \text{string} + \text{string} \Rightarrow \text{hadrons} \\ \gamma gg \Rightarrow \gamma + \text{string} + \text{string} \Rightarrow \gamma + \text{hadrons} \\ \gamma\eta_c \end{cases}$$

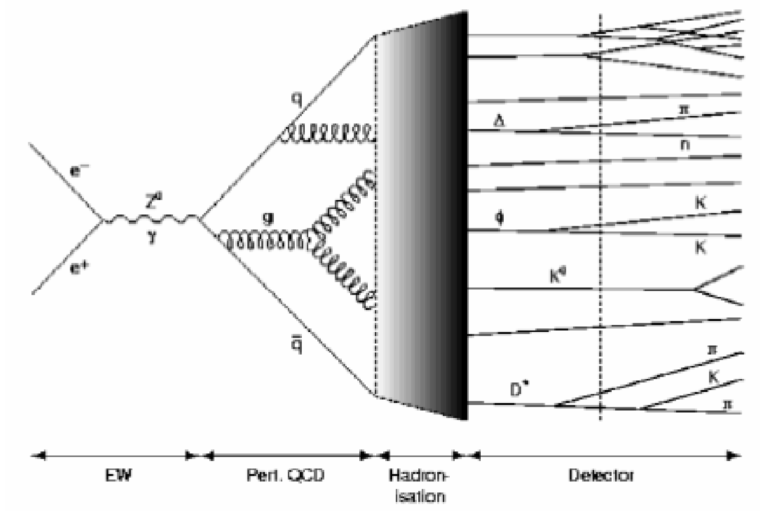
$$e^+e^- \Rightarrow \gamma^* \Rightarrow \psi(2S) \Rightarrow \begin{cases} \gamma^* \Rightarrow e^+e^-,\ \mu^+\mu^-,\ \tau^+\tau^- \\ \gamma^* \Rightarrow q\bar{q} \Rightarrow \text{string} \Rightarrow \text{hadr} \\ ggg \Rightarrow \text{string} + \text{string} + \text{string} \Rightarrow \text{hadrons} \\ \gamma gg \Rightarrow \gamma + \text{string} + \text{string} \Rightarrow \gamma + \text{hadrons} \\ \pi^+\pi^- J/\psi,\ \pi^0\pi^0 J/\psi,\ \pi^0 J/\psi,\ \eta J/\psi,\ \gamma\chi_{cJ},\ \phi\eta \end{cases}$$

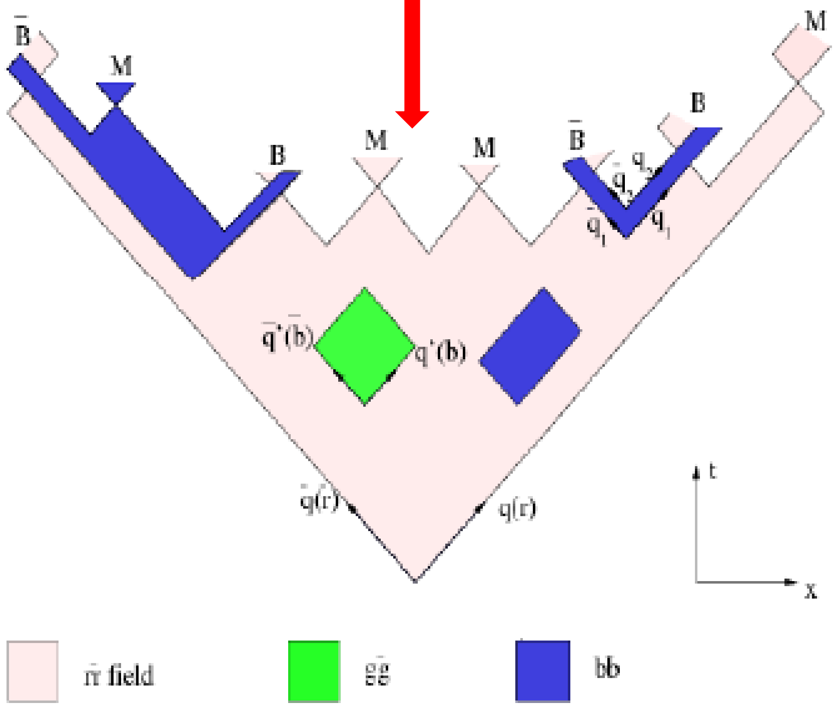
$$e^+e^- \Rightarrow \gamma^* \Rightarrow \psi(3770) \Rightarrow \begin{cases} \gamma^* \Rightarrow e^+e^-,\ \mu^+\mu^-,\ \tau^+\tau^- \\ D^0\bar{D}^0,\ D^+\bar{D}^- \\ \gamma^* \Rightarrow q\bar{q} \Rightarrow \text{string} \Rightarrow \text{hadrons} \\ ggg \Rightarrow \text{string} + \text{string} + \text{string} \Rightarrow \text{hadrons} \\ \gamma gg \Rightarrow \gamma + \text{string} + \text{string} \Rightarrow \gamma + \text{hadrons} \\ \pi^+\pi^- J/\psi,\ \pi^0\pi^0 J/\psi,\ ,\ \pi^0 J/\psi,\ \eta J/\psi,\ \gamma\chi_{cJ} \end{cases}$$

$$e^+e^- \Rightarrow \gamma^* \Rightarrow \begin{cases} \psi(4040) \Rightarrow D\bar{D}, D^*\bar{D}^*, D\bar{D}^*, \bar{D}D^*, D_s\bar{D}_s; \\ \psi(4160) \Rightarrow D\bar{D}, D^*\bar{D}^*, D\bar{D}^*, \bar{D}D^*, D_s\bar{D}_s, D_s\bar{D}_s^*; \\ \psi(4415) \Rightarrow D\bar{D}, D^*\bar{D}^*, D\bar{D}^*, \bar{D}D^*, D_s\bar{D}_s, D_s\bar{D}_s^*, D_s^*\bar{D}_s^*. \end{cases}$$

$$e^+e- \Rightarrow \gamma^* \Rightarrow X(4160), X(4260)\cdots \quad \text{with} \quad J^{PC} = 1^{--}$$

Picture of Lund string fragmentation





Basic formula of LUARLW

The lowest cross section for the exclusive channel

$$\sigma(e^+e^- \to m_1, m_2, \cdots m_n) = \int d\Omega_{q\bar{q}} \frac{d\sigma(e^+e^- \to q\bar{q})}{d\Omega_{q\bar{q}}} \cdot \wp_n(q\bar{q} \to m_1, m_2, \cdots m_n; s)$$

The QED cross section for quark pair production

$$\frac{d\sigma(e^+e^- \to q\bar{q})}{d\Omega_{q\bar{q}}} = N_c \frac{\alpha^2}{4s} \cdot e_q^2 \beta [1 + \cos^2\theta + (1-\beta^2)\sin^2\theta]$$

The string fragmentation probability in Lund area law

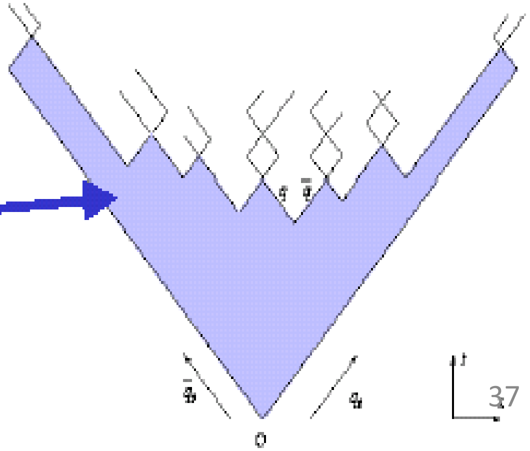
$$d\wp_n(q\bar{q} \to m_1, m_2, \cdots m_n; s) = \cdot(2\pi)^4 \delta\left(1 - \sum_{j=1}^{n} \frac{m_{\perp j}^2}{s z_j}\right) \cdot \delta\left(1 - \sum_{j=1}^{n} z_j\right) \cdot \delta^{(2)}\left(\sum_{j=1}^{n} \vec{k}_j\right) \cdot \overline{\sum} |\hat{\mathcal{T}}_{con}^{(n)f}|^2 d\Phi_n$$

$$d\Phi_n = \prod_{j=1}^{n} d^2 \vec{k}_j \frac{dz_j}{z_j}$$

$$\hat{\mathcal{T}}_{con}(q\bar{q} \to m_1, m_2, \cdots m_n) \equiv \hat{\mathcal{T}}_{con}^{(n)f} = \cdot N^n \cdot \hat{\mathcal{T}}_{con\perp}^{(n)f} \cdot \hat{\mathcal{T}}_{con//}^{(n)f}$$

$$\hat{\mathcal{T}}_{con\perp}^{(n)f} = exp\left(-\sum_{j=1}^{n} \vec{k}_j^{\,2}\right) \qquad \vec{k}_j \equiv \frac{\vec{p}_{\perp j}}{2\sigma}$$

$$\hat{\mathcal{T}}_{con//}^{(n)f} = exp(i\xi \mathcal{A}_n). \qquad \xi = \frac{1}{2\kappa} + i\frac{b}{2}.$$

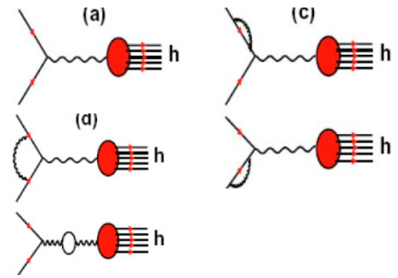


ISR sampling in LUARLW simulation

In the MC simulation, the events are classed into two types

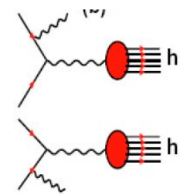
① non real radiation: tree level, virtual and soft radiations events.

Weight: $$\sigma^{VSB} = \sigma^0(s)[1+\beta \ln k_0 + \delta_{AR}]$$



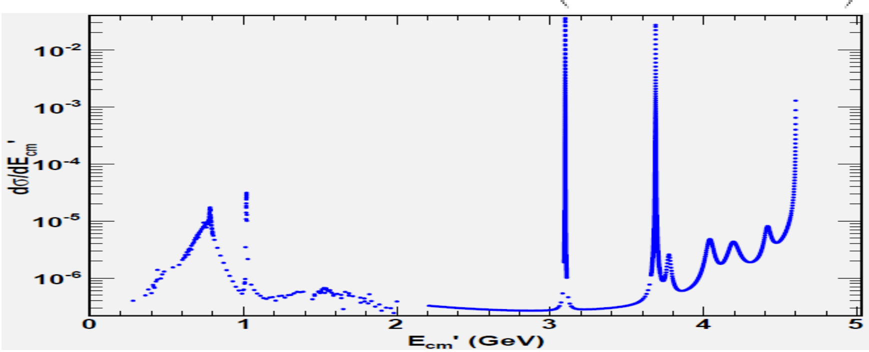
② real radiation: hard bremsstrahlung events.

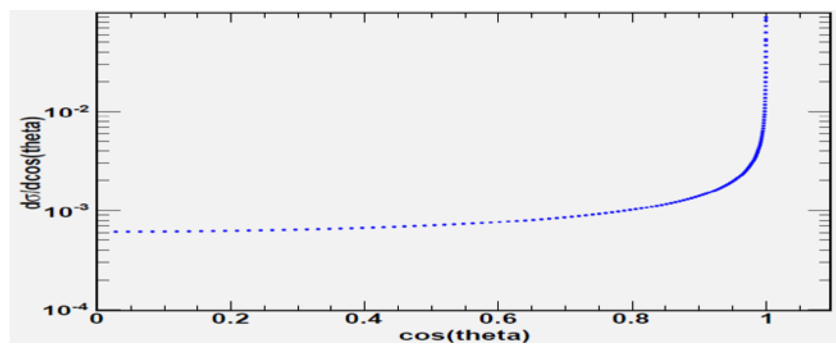
Weight: $$\sigma^{HB} = \int_{k_0}^{k_m} dk \frac{\partial \sigma^{HB}}{\partial k}$$



The energy and polar angle distribution of real emission photon

$$d\sigma^{HB}(s) = \frac{\alpha}{\pi^2} \frac{\sin^2\theta}{(1-a^2\cos^2\theta)} \frac{dk\, d\Omega_\gamma}{k} (1-k+\frac{k^2}{2}) d\sigma^0(s')$$





Parameters for primary hadron multiplicity

N-particle system partial function in Lund area law

$$Z_n = s \int d\Phi_n \exp(-b\mathcal{A}_n)$$

Multiplicity distribution for preliminary fragmentation hadrons

$$P_n = Z_n / \sum Z_r$$

Approximate expression

$$P_n(s) = \frac{\mu^n}{n!} \exp[c_0 + c_1(n-\mu) + c_2(n-\mu)^2]$$

μ predicted by pQCD

$$\mu = \alpha + \beta \exp(\gamma\sqrt{s})$$

c_0, c_1, c_2 and α, β, γ are free parameters to be tuned.

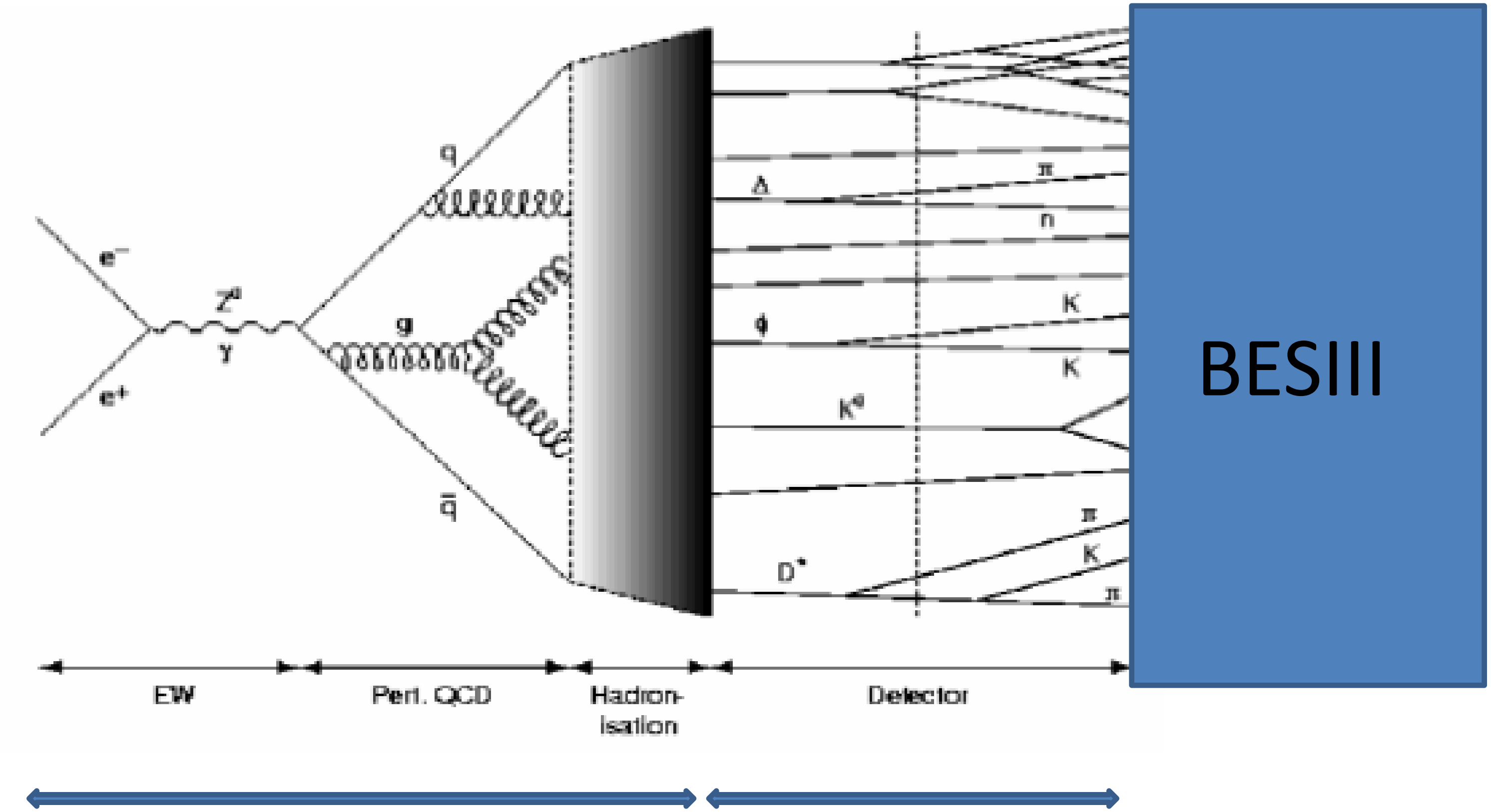
Parameters for string fragmentaion hadrons

Related to ratio of baryon and meson with different quantum number

parameter	default	tuned	meaning
PARJ(1)	0.10	0.10	diquark/quark production ratio (baryon suppression) (B/M)
PARJ(2)	0.30	0.28	s/(u,d) production ratio (strange meson suppression K/π)
PARJ(3)	0.40	0.55	extra strange diquark suppression (strange baryon suppression (Λ/p))
PARJ(4)	0.05	0.07	extra suppression of spin 1 diquark compared to spin 0 ones
PARJ(11)	0.50	0.55	suppression of light meson has spin 1 compared to spin 0 (ρ/π)
PARJ(12)	0.60	0.55	suppression of strange meson has spin 1 compared to spin 0 (K^*/K)
PARJ(13)	0.75	0.75	suppression of charm meson has spin 1 compared to spin 0 (D^*/D)
PARJ(14)	0.00	0.09	probability that a spin s=0 and orbital L=1 with total J=1 meson
PARJ(15)	0.00	0.07	probability that a spin s=1 and orbital L=1 with total J=0 meson
PARJ(16)	0.00	0.09	probability that a spin s=1 and orbital L=1 with total J=1 meson
PARJ(17)	0.00	0.14	probability that a spin s=1 and orbital L=1 with total J=2 meson

By comparing data with MC, it is found that in BEPC energy region, some parameters in the table are not constants, they are slightly energy dependent.

Simulation of hadron production and decay



Production: LUARLW

Decay: BesEvtGen

Detector: GEANT4

Parameter tuning and optimization of LUARLW

Z. Phys. C 26, 157 (1984)
Z. Phys. C 41, 359(1988)
Eur. Phys. J. C 65 , 331 (2010)

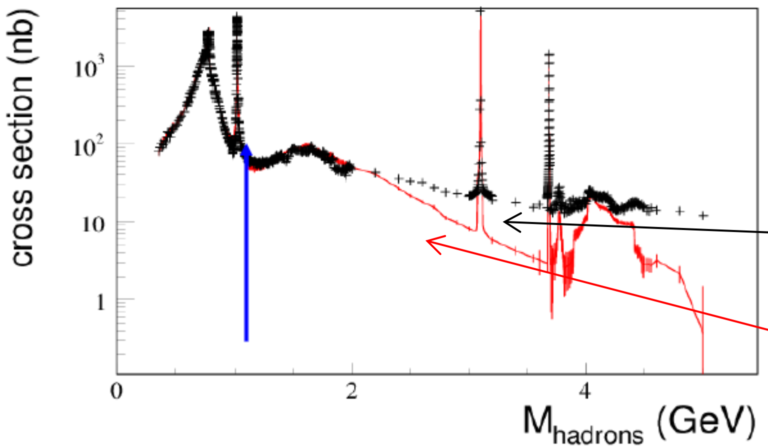
Scheme A: optimization fit

- Assume LUARLW is approximately described by a parameterized response function

$$f(\boldsymbol{p}_0+\delta\boldsymbol{p},x)=a_0^{(0)}(x)+\sum_{i=1}^{n}a_i^{(1)}(x)\delta p_i+\sum_{i=1}^{n}\sum_{j=1}^{n}a_{ij}^{(2)}(x)\delta p_i\delta p_j \approx MC(\boldsymbol{p}_0+\delta\boldsymbol{p},x)$$

The phenomenological parameters in LUARLW are treated as free numbers in fit, the optimal values are obtained by simultaneously fit this function to the data.

- The channels ever measured by experiments use the experimental values, and the unmeasured channels use LUARLW.



+ total hadronic cross section,
+ sum of the cross section ever measured exclusive channels

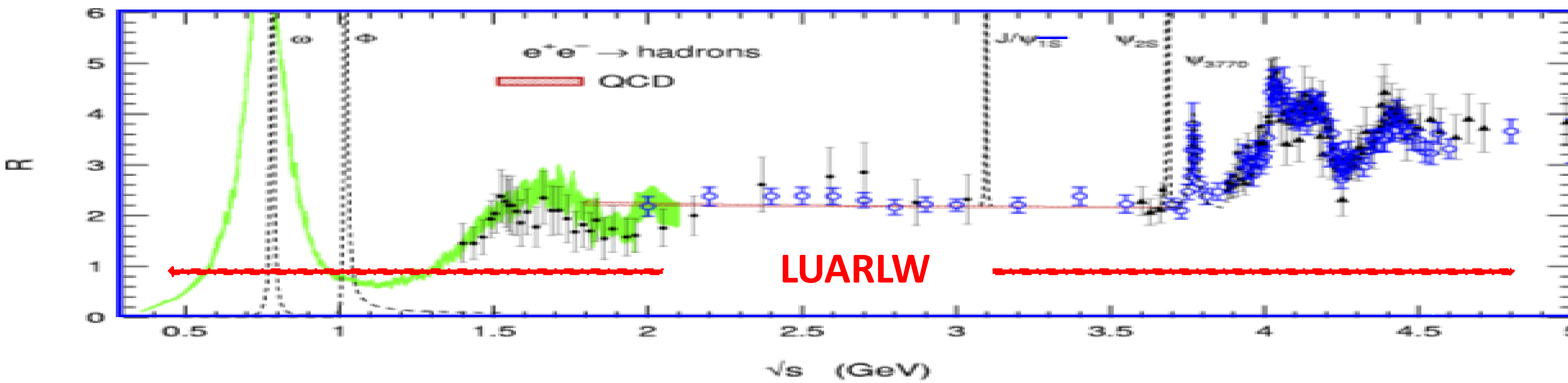
Unknown channels, simulate by LUARLW

Known channels, simulate by exclusive method

Parameter tuning and optimization of LUARLW

Scheme B: manual tuning first, optimization fit last

Choose about 30 final state distributions, such as, charged and neutral multiplicity, cosθ, deposit energy, momentum, ratios of mesons and baryons, et al. Compare the differences between data and MC which only using LUARLW, tune the corresponding parameters within the reasonable ranges, again and again, until obtain a set of reasonable parameters, then use scheme A to optimize them.

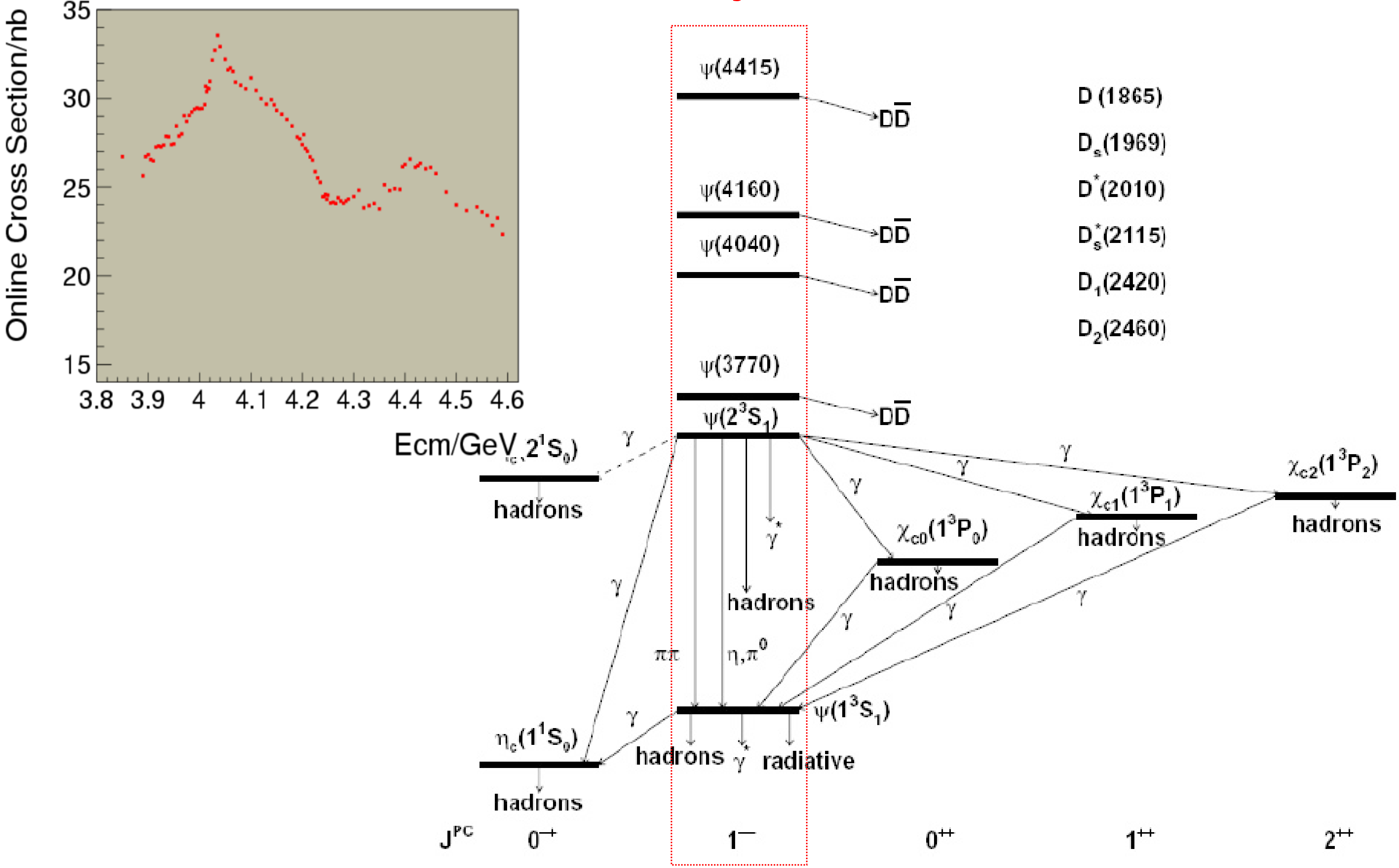


At present, the differences of the hadronic efficiency estimated by the two schemes are about ~2%.

Next, more effort have to do, until systematic error of the efficiency no exceed 2%.

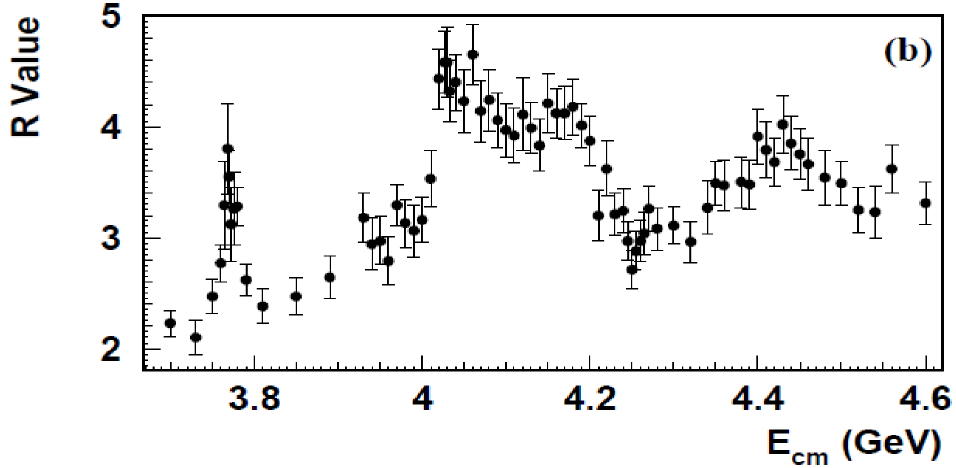
Heavy vector charmonia line shape

Confirmed charmoniums family in BESII era



Aim to understand resonant structure

Phys. Rev. Letts. 88 (2002)101802



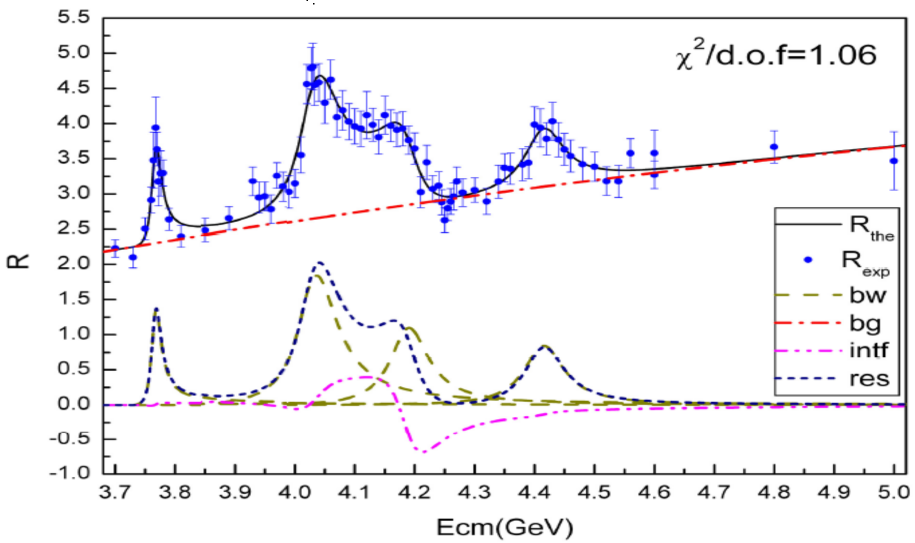
Fit

$$\chi^2 = \sum_i \frac{(f \cdot \widetilde{R}_{exp}(s_i) - \widetilde{R}_{the}(s_i))^2}{(f \cdot \Delta \widetilde{R}_{exp}^{(i)})^2} + \frac{(f-1)^2}{\sigma_f^2}$$

$$\widetilde{R}_{exp} = \frac{N_{had}^{obs} - N_{bg} - \sum_l N_{ll} - N_{\gamma\gamma}}{\sigma_{\mu\mu}^0 \cdot L \cdot \epsilon_{trg} \cdot \epsilon_{had}(0)}$$

$$\widetilde{R}_{the} = (1 + \delta_{obs}) \cdot R_{the}$$

Phys. Lett. B660 (2008)315



R values

↓

Fit

↓

Resonant parameters

Theoretical problems in resonant parameters fit

The measurement of R value and the resonant parameters are closely related and affected by the following theoretical factors:

- ✓ What is the correct Breit-Wigner form for wide resonance?
- ✓ How to introduce intrinsic/effective initial phase angle?
- ✓ How amplitudes interfere between final states?
- ✓ How guarantee the unitary of the interference?
- ✓ How the total widths depend on energy?
- ✓ How to express the continuous charm backgrounds in fit?

Parameters of the excited charmonia resonances

Similar work like did at BESII, but improved measurement at BESIII

At BESII, parameters (M, Γ_{tot}, Γ_{ee}) of the $J^{PC} = 1^{--}$ conventional charmonia ψ(3770), ψ(4040), ψ(4160), ψ(4415) remain quite uncertain and model dependent:

	M, MeV	Γ_{tot}, MeV	Γ_{ee}, keV	δ, deg	
ψ(3770)	3772.92 ± 0.35	27.3 ± 1.0	0.265 ± 0.018		PDG09
	3772.0 ± 1.9	30.4 ± 8.5	0.22 ± 0.05	0	BES08
ψ(4040)	4039 ± 1	80 ± 10	0.86 ± 0.07		PDG09
	4039.6 ± 4.3	84.5 ± 12.3	0.83 ± 0.20	130 ± 46	BES08
ψ(4160)	4153 ± 3	103 ± 8	0.83 ± 0.07		PDG09
	4191.7 ± 6.5	71.8 ± 12.3	0.48 ± 0.22	293 ± 57	BES08
ψ(4415)	4421 ± 4	62 ± 20	0.58 ± 0.07		PDG09
	4415.1 ± 7.9	71.5 ± 19.0	0.35 ± 0.12	234 ± 88	BES08

PDG2012

$\psi(4040)$ $\qquad I^G(J^{PC}) = 0^-(1^{--})$

$\psi(4040)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
4039 ± 1 OUR ESTIMATE				
4039.6 ± 4.3	[1] ABLIKIM	08D	BES2	$e^+e^- \to$ hadrons

$\psi(4040)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
80 ±10 OUR ESTIMATE				
84.5±12.3	[5] ABLIKIM	08D	BES2	$e^+e^- \to$ hadrons

$\psi(4040)$ PARTIAL WIDTHS

$\Gamma(e^+e^-)$ $\qquad \Gamma_1$

VALUE (keV)	DOCUMENT ID		TECN	COMMENT
0.86 ±0.07 OUR ESTIMATE				
0.83 ±0.20	[9] ABLIKIM	08D	BES2	$e^+e^- \to$ hadrons

[1] Reanalysis of data presented in BAI 02C. From a global fit over the center-of-mass energy region 3.7–5.0 GeV covering the $\psi(3770)$, $\psi(4040)$, $\psi(4160)$, and $\psi(4415)$ resonances. Phase angle fixed in the fit to $\delta = (130 \pm 46)^\circ$.

PDG2012

$\psi(4160)$

$I^G(J^{PC}) = 0^-(1^{--})$

$\psi(4160)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
4153 ± 3 OUR ESTIMATE				
4191.7 ± 6.5	[1] ABLIKIM	08D	BES2	$e^+e^- \rightarrow$ hadrons

$\psi(4160)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
103 ± 8 OUR ESTIMATE				
71.8 ± 12.3	[5] ABLIKIM	08D	BES2	$e^+e^- \rightarrow$ hadrons

$\psi(4160)$ PARTIAL WIDTHS

$\Gamma(e^+e^-)$ Γ_1

VALUE (keV)	DOCUMENT ID		TECN	COMMENT
0.83 ± 0.07 OUR ESTIMATE				
0.48 ± 0.22	[9] ABLIKIM	08D	BES2	$e^+e^- \rightarrow$ hadrons

[5] Reanalysis of data presented in BAI 02C. From a global fit over the center-of-mass energy region 3.7–5.0 GeV covering the $\psi(3770)$, $\psi(4040)$, $\psi(4160)$, and $\psi(4415)$ resonances. Phase angle fixed in the fit to $\delta = (293 \pm 57)^\circ$.

PDG2012

$\psi(4415)$

$I^G(J^{PC}) = 0^-(1^{--})$

$\psi(4415)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
4421 ± 4 OUR ESTIMATE				
4415.1 ± 7.9	[1] ABLIKIM	08D	BES2	$e^+e^- \to$ hadrons

$\psi(4415)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
62 ±20 OUR ESTIMATE				
71.5±19.0	[6] ABLIKIM	08D	BES2	$e^+e^- \to$ hadrons

$\psi(4415)$ PARTIAL WIDTHS

$\Gamma(e^+e^-)$ Γ_{16}

VALUE (keV)	DOCUMENT ID		TECN	COMMENT
0.58±0.07 OUR ESTIMATE				
0.35±0.12	[11] ABLIKIM	08D	BES2	$e^+e^- \to$ hadrons

[1] Reanalysis of data presented in BAI 02C. From a global fit over the center-of-mass energy region 3.7–5.0 GeV covering the $\psi(3770)$, $\psi(4040)$, $\psi(4160)$, and $\psi(4415)$ resonances. Phase angle fixed in the fit to $\delta = (234 \pm 88)^\circ$.

PDG2014

$\psi(4160)$

$I^G(J^{PC}) = 0^-(1^{--})$

$\psi(4160)$ MASS

VALUE (MeV)		*DOCUMENT ID*	*TECN*	*COMMENT*
4191 ± 5	**OUR AVERAGE**			
4191^{+9}_{-8}		AAIJ 13BC	LHCB	$B^+ \to K^+ \mu^+ \mu^-$
4191.7 ± 6.5		[1] ABLIKIM 08D	BES2	$e^+ e^- \to$ hadrons

$\psi(4160)$ WIDTH

VALUE (MeV)		*DOCUMENT ID*	*TECN*	*COMMENT*
70 ±10	**OUR AVERAGE**			
65^{+22}_{-16}		AAIJ 13BC	LHCB	$B^+ \to K^+ \mu^+ \mu^-$
71.8 ± 12.3		[5] ABLIKIM 08D	BES2	$e^+ e^- \to$ hadrons

$\psi(4160)$ PARTIAL WIDTHS

$\Gamma(e^+ e^-)$ Γ_1

VALUE (keV)	*DOCUMENT ID*	*TECN*	*COMMENT*
0.48±0.22	[9] ABLIKIM 08D	BES2	$e^+ e^- \to$ hadrons

Summary

- Data taking plans of phaseI-III finished, data sets for R scan and QCD study between 2.0 – 4.6 GeV have been collected.
- Data analysis for R value measurement between 2.2324-3.671 GeV are almost finished, but the analysis for other data samples need further optimization.
- The LUARLW parameter tuning are in progress, which is a tough and challenge work, and could be the largest error source (1.5-2.0%) for R value measurement.
- The related theoretical study about the heavy charmonia line shape fit are doing, which are crucial for obtaining reliable values.
- Preliminary results of R measurement between 2.2324-3.671 GeV have reported inside BES Collaboration, the analysis for other energy points are in going.