Overview on QCD studies at BESIII

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Outline

- The BESIII experiment
- Baryon structure, form factor measurement
- Hadron spectroscopy
- Precision test on Standard Model, $(g-2)_\mu$
- Lineshape of J/ψ resonance
- Summary

Beijing Electron Positron Collider

E_{beam}: 1.0-2.3 GeV

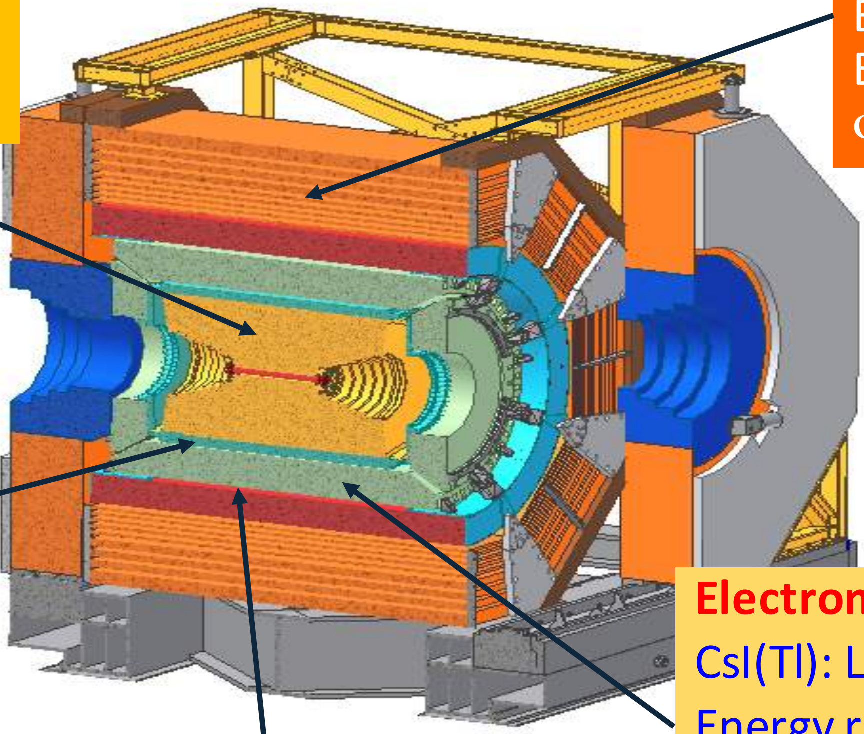
σ_E: 5.16×10^{-4}

L: 1.0×10^{33} cm^{-2}s^{-1} @3770

BEijing Spectrometer III

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

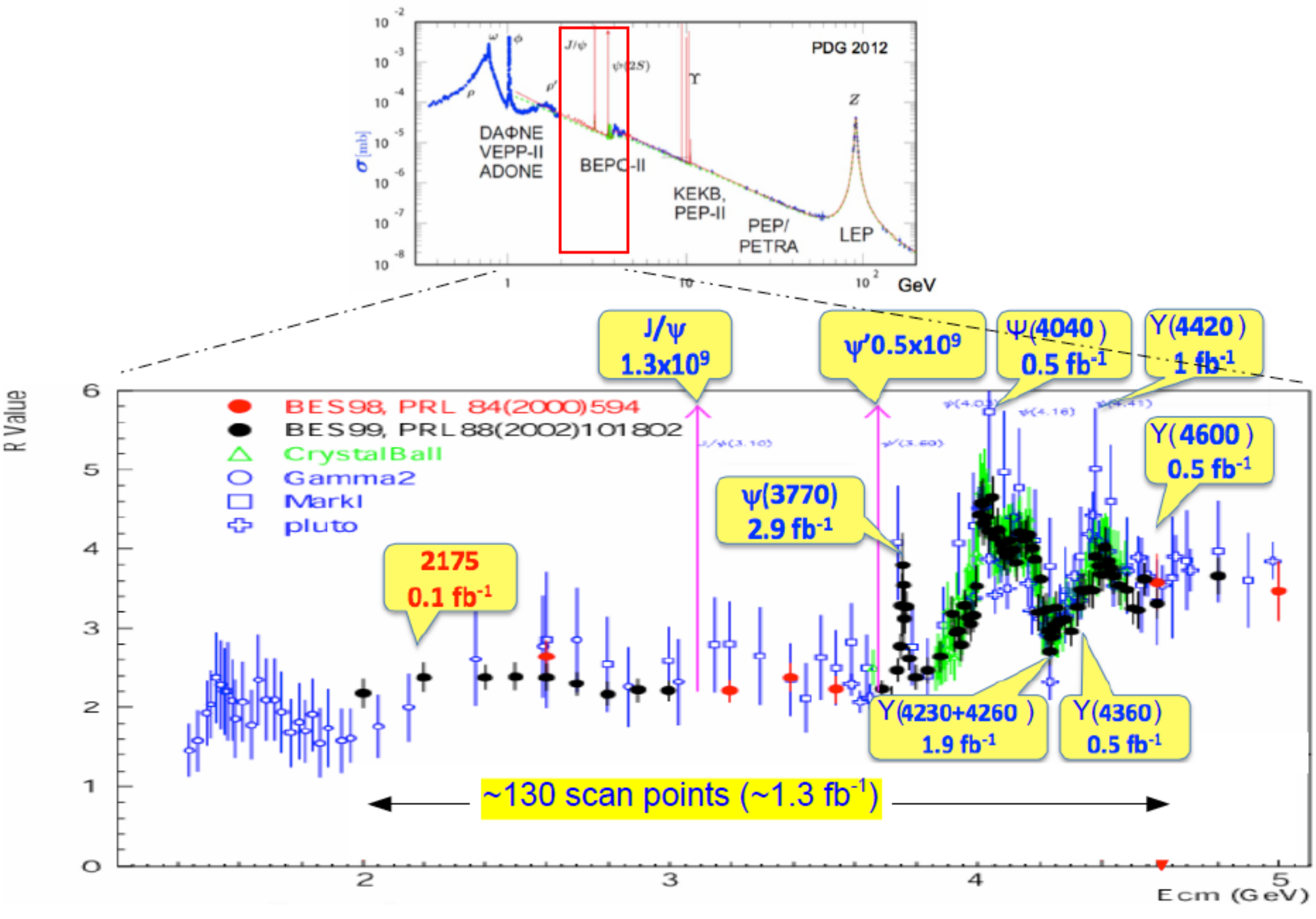


Time Of Flight
Plastic scintillator
σ_T(barrel): 80 ps
σ_T(endcap): 110 ps

SC Magnet 1.0T

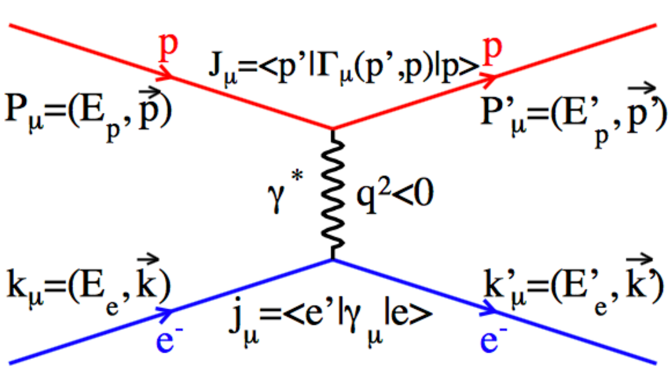
Electromagnetic Calorimeter
CsI(Tl): L=28 cm ($15X_0$)
Energy range: 0.02-2GeV
Barrel σ_E 2.5%, σ_l 6mm
Endcap σ_E 5.0%, σ_l 9mm

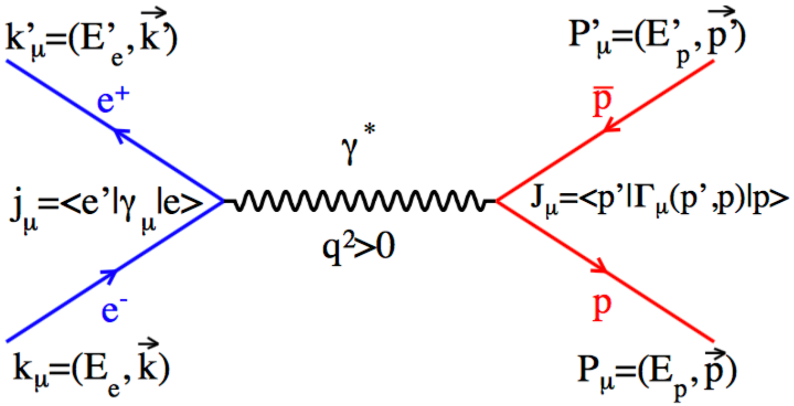
The BESIII data sample



Baryon form factor

- The FFs are measured in space-like (SL) region or time-like (TL) region. The proton electromagnetic vertex Γ_μ describing the hadron current





- $\Gamma_\mu(p',p) = \gamma_\mu F_1(q^2) + \frac{i\sigma_{\mu\nu}q^\nu}{2m_p}F_2(q^2)$
- $G_E(q^2) = F_1(q^2) + \tau\kappa_p F_2(q^2)$
- $G_M(q^2) = F_1(q^2) + \kappa_p F_2(q^2)$
- $\tau = \frac{q^2}{4m_p^2}, \quad \kappa_p = \frac{g_p - 2}{2} = \mu_p - 1$
- At $q^2=0$,
  proton: $F_1=F_2=1 \quad G_E=1,\ G_M=\mu_p$
  neutron: $F_1=0,\ F_2=1,\ G_E=1,\ G_M=\mu_n$

- G_E and G_M can be interpreted as Fourier transforms of spatial distributions of charge and magnetization of nucleon in the Breit frame

i.e $\rho(\vec{r}) = \int \frac{d^3q}{2\pi^3} e^{-i\vec{q}\cdot\vec{r}} \frac{M}{E(\vec{q})} G_E(\vec{q}^2)$

Baryon form factor

- The Born cross section for $e^+e^- \to \gamma^* \to B\bar{B}$, can be expressed in terms of electromagnetic form factor G_E and G_M :

$$\sigma_{B\bar{B}}(q) = \frac{4\pi\alpha^2 C\beta}{3q^2}\left[|G_M(q)|^2 + \frac{1}{2\tau}|G_E(q)|^2\right]$$

- The Coulomb factor C=

$$C = \begin{cases} \frac{\pi\alpha}{\beta}\frac{1}{1-\exp(-\frac{\pi\alpha}{\beta})} & \text{for a charged } B\bar{B} \text{ pair} \\ 1 & \text{for a neutral } B\bar{B} \text{ pair} \end{cases}$$

	Energy Scan	Initial State Radiation
E_{beam}	discrete	fixed
$\mathcal{L}$	low at each beam energy	high at one beam energy
σ	$\frac{d\sigma_{p\bar{p}}}{d(\cos\theta)} = \frac{\pi\alpha^2\beta C}{2q^2}[\|G_M\|^2(1+\cos^2\theta) + \frac{4m_p^2}{q^2}\|G_E\|^2\sin^2\theta]$	$\frac{d^2\sigma_{p\bar{p}\gamma}}{dq^2 d\theta_\gamma} = \frac{1}{s}W(s,x,\theta_\gamma)\sigma_{p\bar{p}}(q^2)$ $W(s,x,\theta_\gamma) = \frac{\alpha}{\pi x}(\frac{2-2x+x^2}{\sin^2\theta_\gamma} - \frac{x^2}{2})$
q^2	single at each beam energy	from threshold to s

$\sim \frac{1}{400}$

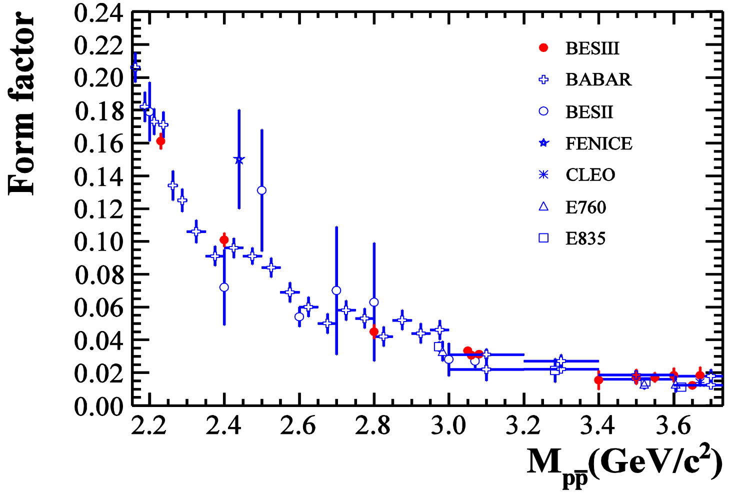
Both techniques, energy scan and initial state radiation. can be used at BESIII

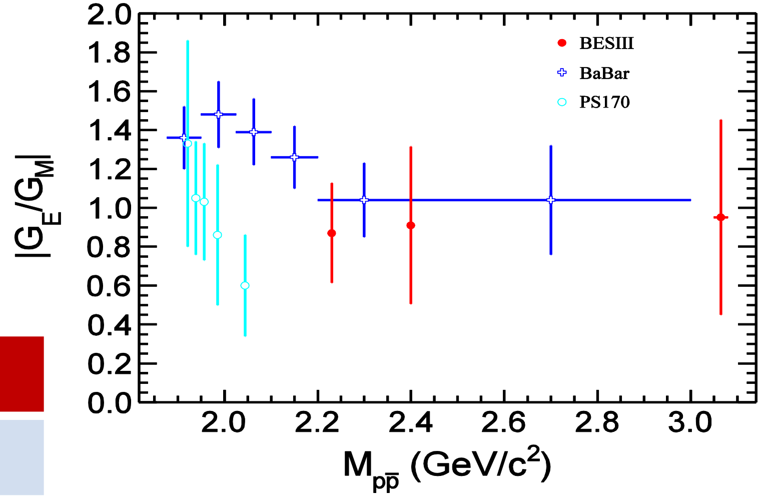
$e^+e^- \rightarrow p\bar{p}$

Phys.Rev.D 91, 112004(2015)

- Using 12 c.m. energies from 2.2324 to 3.671 GeV, total luminosity 156.9 pb^{-1}
- Cross section
  - $\sigma_{Born} = \frac{N_{obs} - N_{bkg}}{L \cdot \varepsilon \cdot (1+\delta)}$
- Effective FF
  - $\sigma = \frac{4\pi\alpha^2\beta C}{3q^2}\left(|G_M|^2 + \frac{1}{2\tau}|G_E|^2\right)$
  - $G_{eff} = \sqrt{\frac{3q^2}{4\pi\alpha^2\beta C} \cdot \frac{\sigma}{1+1/2\tau}}$
- Ratio extraction
  - Fit function:
  - $\frac{dN}{d\cos\theta_p} = N_{norm}\left[\left(1+\cos^2\theta_p\right) + R_{em}^2 \frac{1}{\tau}\sin^2\theta_p\right]$

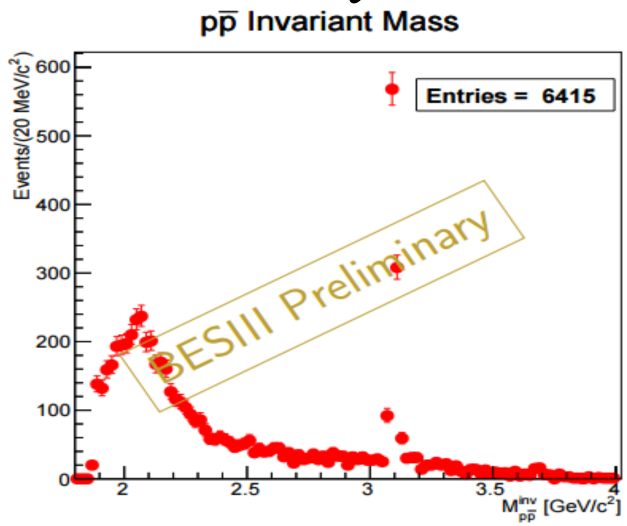
	$\delta R_{em}/R_{em}$	$\delta G_{eff}/G_{eff}$
Stat. with Sys.	**25% - 50%**	**3% - 37%**



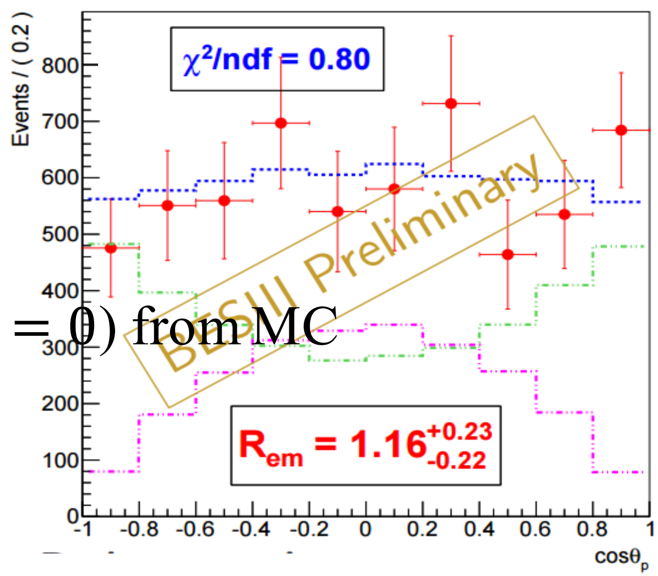


$e^+e^- \rightarrow \gamma_{ISR} p\bar{p}$

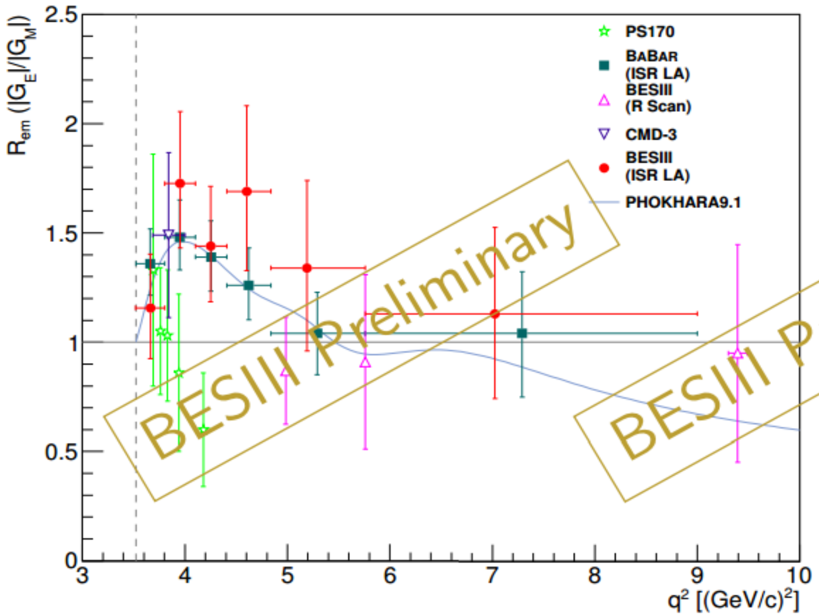
- Combination of 7 data sets (≥3.773 GeV), total luminosity 7.4 fb^{-1}.
- Event selection:
  - Two charged tracks from vertex
  - One high energy shower in EMC (ISR-tagged)
  - Kinematic constraints applied
  - Background subtraction from weighted MC

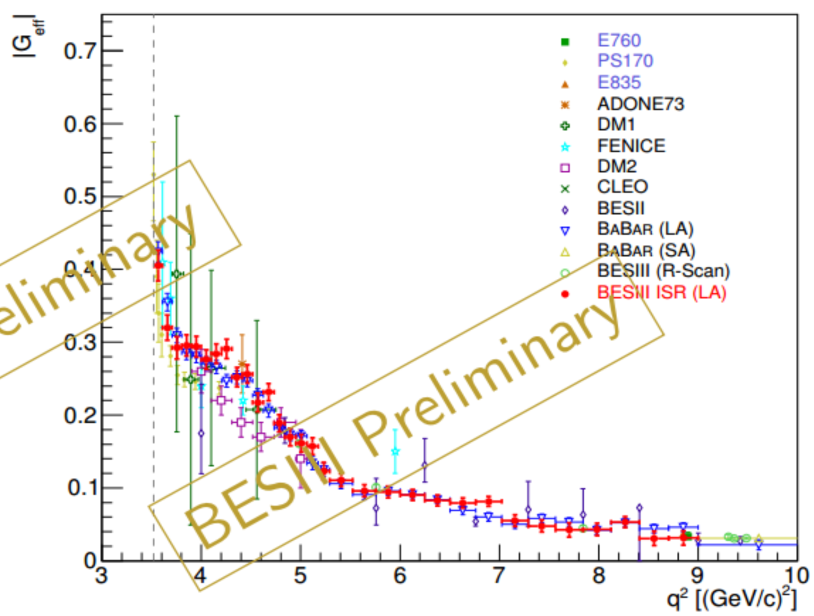


- Cross section
  - $\sigma^{Born}_{p\bar{p}}(M_{p\bar{p}}) = \frac{(dN/dM_{p\bar{p}})corr}{dL/dM_{p\bar{p}}}$
- Ratio extraction
  - $\frac{d\sigma}{dcos\theta} = A\left[H_M(cos\theta, q^2) + \frac{R^2_{em}}{\langle\tau\rangle} H_E(cos\theta, q^2)\right]$
  - $H_M(cos\theta, q^2)$ $(G_E = 0)$ and $H_E(cos\theta, q^2)$ $(G_M = 0)$ from MC



$e^+e^- \rightarrow \gamma_{ISR} p\bar{p}$



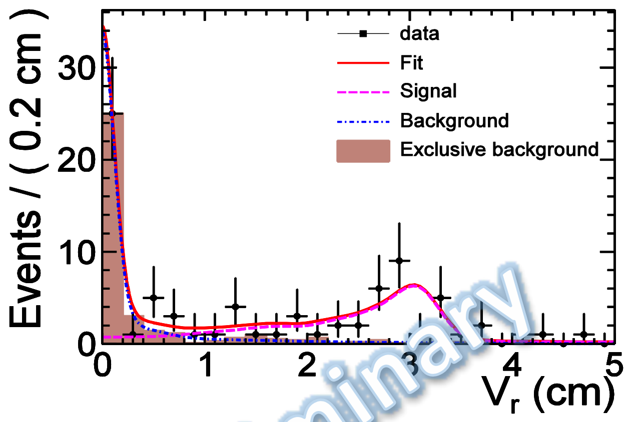


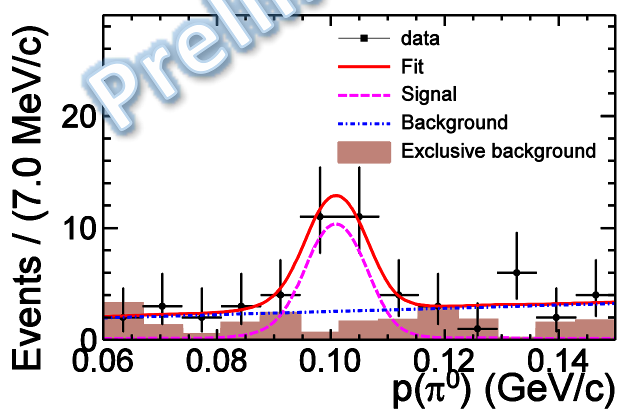
- Background subtraction and efficiency dividing
- The proton FFs extracted between threshold to 3.0 GeV

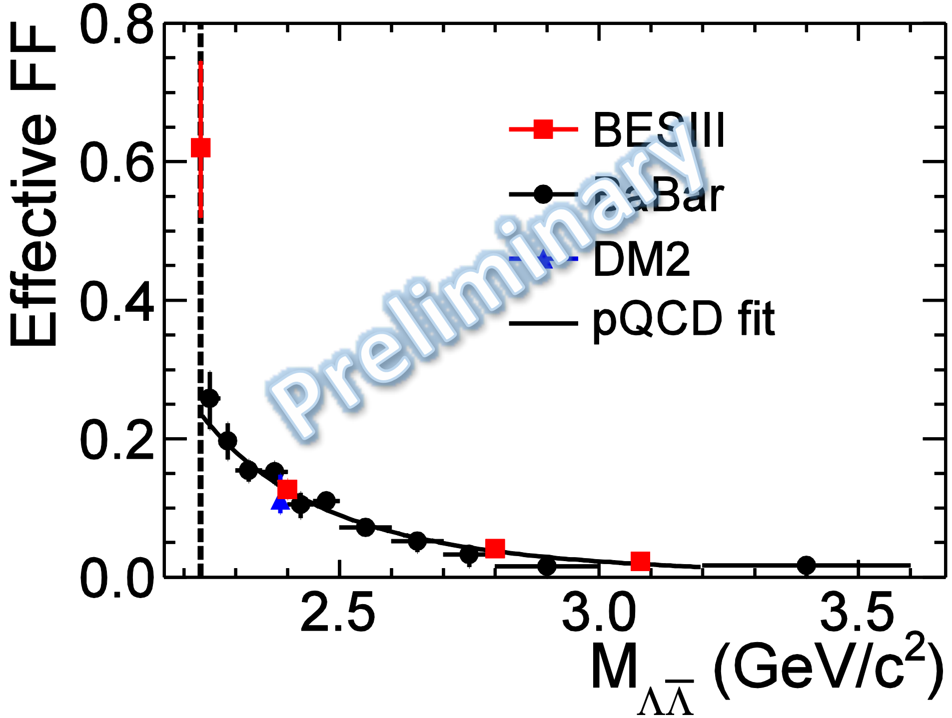
	$\delta R_{em}/R_{em}$	$\delta G_{eff}/G_{eff}$
Stat.	**18.5 – 33.6%**	**4.1 - 31.6%**
Syst.	**4.2- 15.6%**	**1.6 - 12%**

$e^+e^- \to \Lambda\bar{\Lambda}$

- Using 4 c.m. energies from 2.2324 to 3.08 GeV, total luminosity 40.5 pb^{-1}
- $e^+e^- \to \Lambda\bar{\Lambda}$ at the first energy point, 2.2324 GeV, which is 1.0 MeV above the $\Lambda\bar{\Lambda}$ mass threshold,is reconstructed final final states of $p\bar{p}\pi^+\pi^-$ and $\bar{n}\pi^0 + X$. The Born cross section is measured to be $305 \pm 45^{+66}_{-36}$ pb

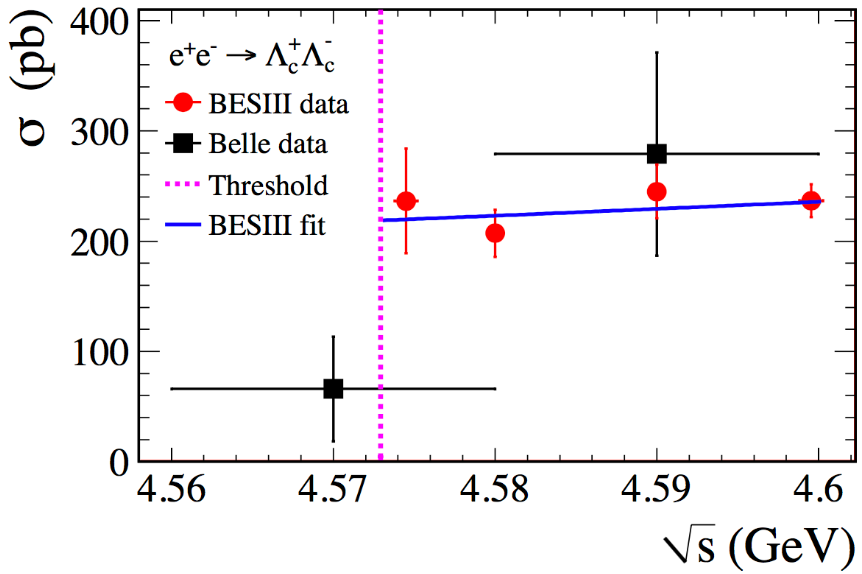




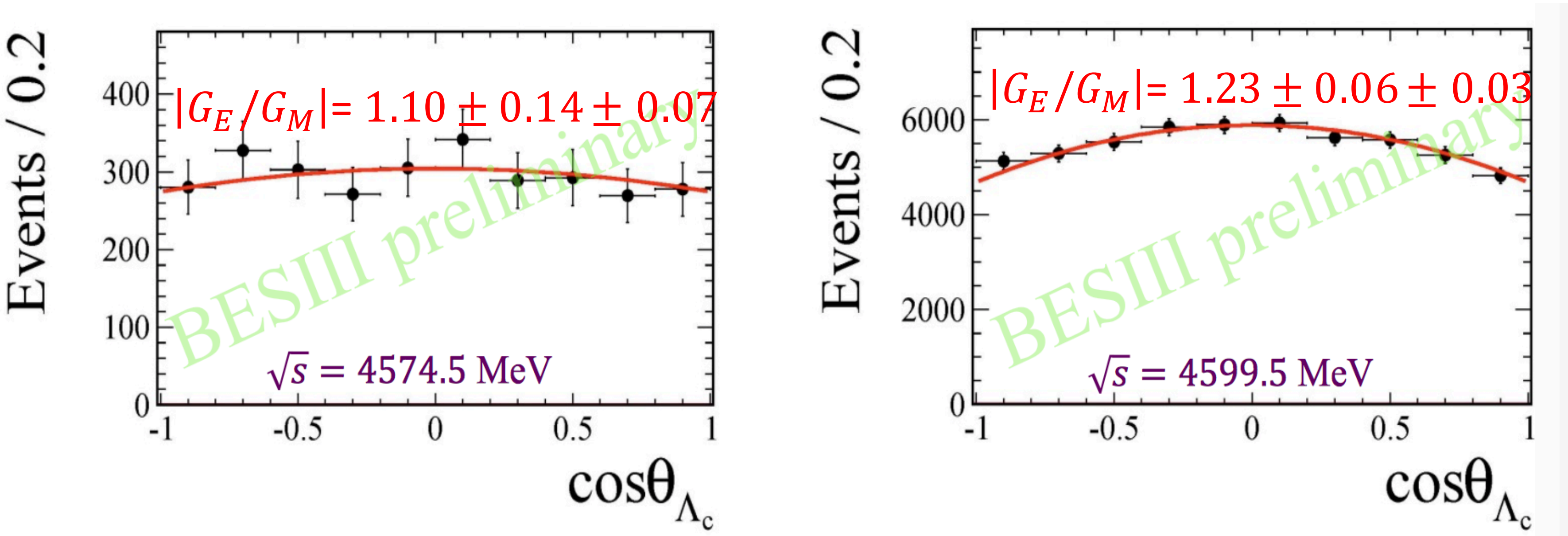


$e^+e^- \rightarrow \Lambda_c^+\overline{\Lambda}_c^-$

- Using 4 c.m. energies, 4.575, 4.580, 4.590 and 4.600 GeV, total luminosity 631.3 pb^{-1}
- $e^+e^- \rightarrow \Lambda_c^+\overline{\Lambda}_c^-$ is reconstructed by tagging 10 decay modes of Λ_c^+



- Angular distribution of Λ_c^+ is studied at 4.575 and 4.600 GeV.



Hadron spectroscopy

- Cross section of $e^+e^- \to K^+K^-$ inBaBar
  - Possible resonance near 2.2 GeV:ρ(2150), φ(2170)/Y(2175), …

Y(2175)	As 2 $^3D_1$ $s\bar{s}$ quarkonium		As $s\bar{s}g$ hybrid	As 3 $^3S_1$ $s\bar{s}$ quarkonium
	Γ_{LJ} in $^3P_0$ model	Γ_{LJ} in Flux Tube Model	in Flux Tube Model	in $^3P_0$ model
Γ_{KK}(MeV)	9.8	23.1	0	0
Γ_{tot}(MeV)	167.21	211.9	148.7	378

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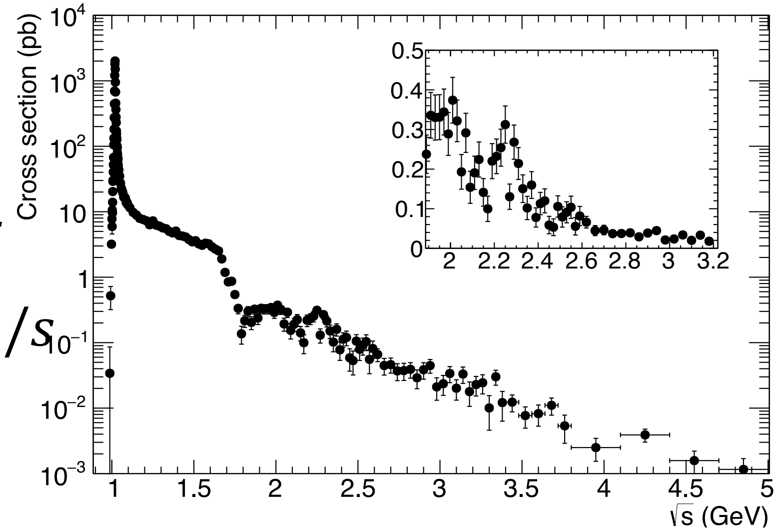


- Form factor of kaon
  - Charge distribution: $F(q^2) = \int d^3r\rho(r)e^{iq\cdot r}$
  - Check pQCD predictions: $F_K = 16\pi\alpha_s(s)f_K^2/s$

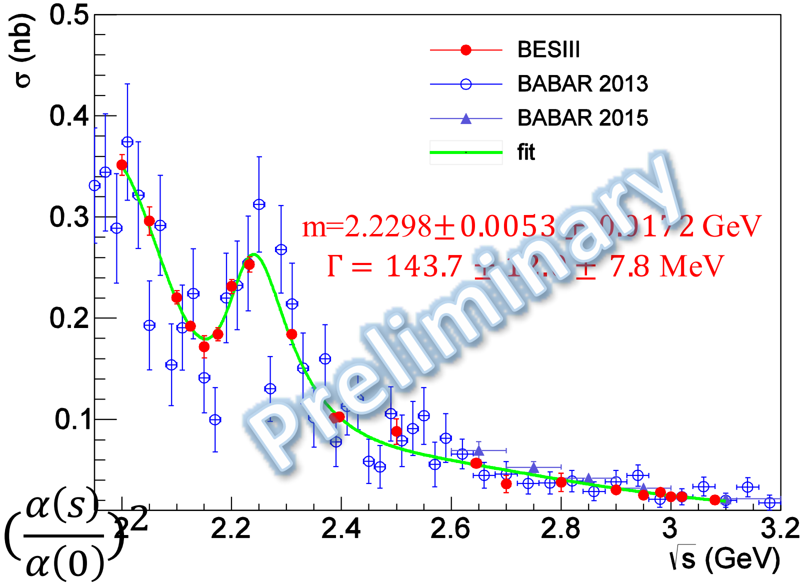
$e^+e^- \to K^+K^-$

- R scan data from 2.0 to 3.08 GeV, total luminosity ~651 pb^{-1}
- A structure near 2.2 GeV is measured by:

  $\sigma = |A_K|^2,$

  $A_K = \sum_r c_r \cdot BW_r + c_{con} \cdot s^{-\alpha} \cdot e^{i\theta}$

  r : ρ, ω, φ and their excited states



- Form factor extraction:

  $$|F_K|^2(s) = \frac{3s}{\pi\alpha(0)^2\beta^3}\frac{\sigma_{KK}(s)}{C_{FS}}; \quad \sigma_{KK}(s) = \sigma^0_{KK}(s)\left(\frac{\alpha(s)}{\alpha(0)}\right)^2$$

  $\sigma_{KK}(s)$: dressed cross section; $\sigma^0_{KK}(s)$: bare cross section

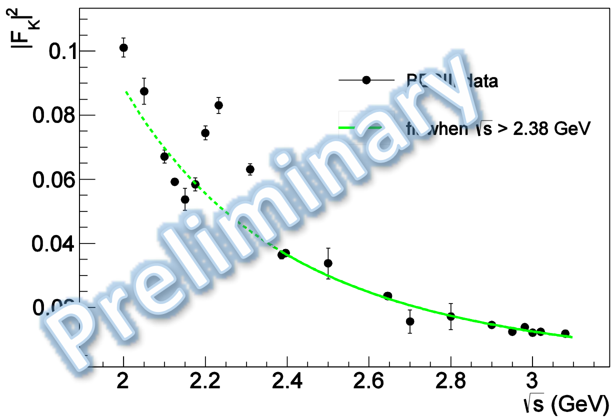
  C_{FS}: final-state correction

- Form factor fitting function:

  $|F_K|^2 = A\alpha_s^2(s)/s^n$

  $n = 1.94 \pm 0.09$

  (agreement with pQCD prediction $n = 2$)



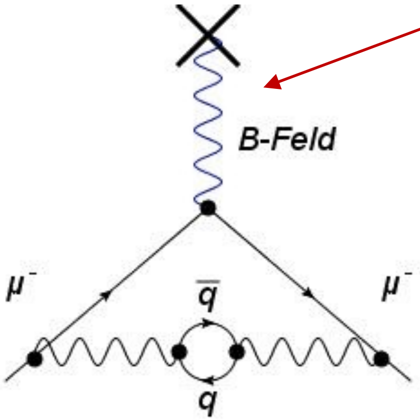
Precision tests of the Standard Model

- The anomalous magnetic moment $\alpha_\mu = \frac{g_\mu - 2}{2}$
  - ➢ Experimental measurement: $\alpha_\mu^{exp} = (11659208.9 + 6.3) \cdot 10^{-10}$ PRD 73, 072(2006)
  - ➢ Theoretical prediction: $\alpha_\mu^{SM} = (11659580.2 + 4.9) \cdot 10^{-10}$ Eur. Phys. J. C71, 1515(2011)

  =>discrepancy: 3.6 standard deviations

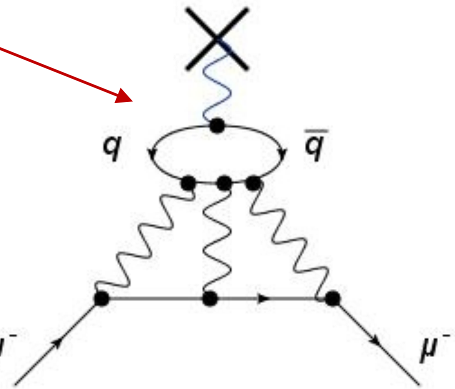
- $\alpha_\mu^{\mathrm{SM}} = \alpha_\mu^{\mathrm{QED}} + \alpha_\mu^{\mathrm{weak}} + \alpha_\mu^{\mathrm{hadr}}$

can not be calculated by means of perturbative calculations



Hadronic vacuum polarization

$\alpha_\mu^{hadr,VP} = (692.2 \pm 4.2) \cdot 10^{-10}$

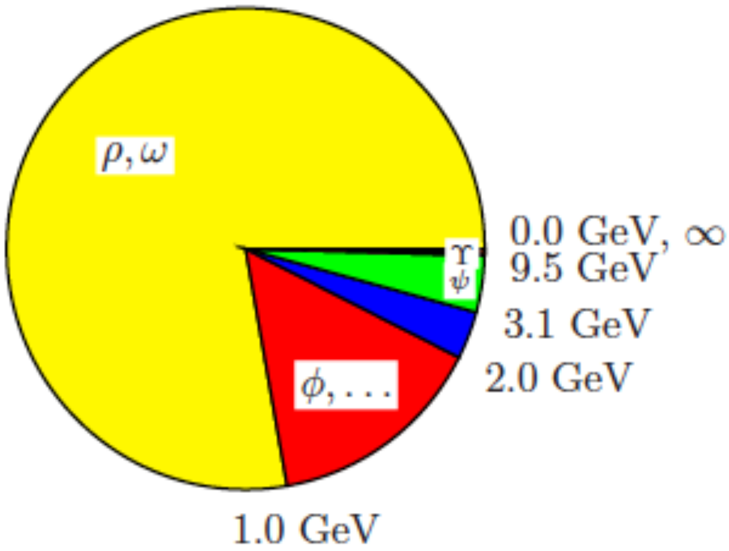


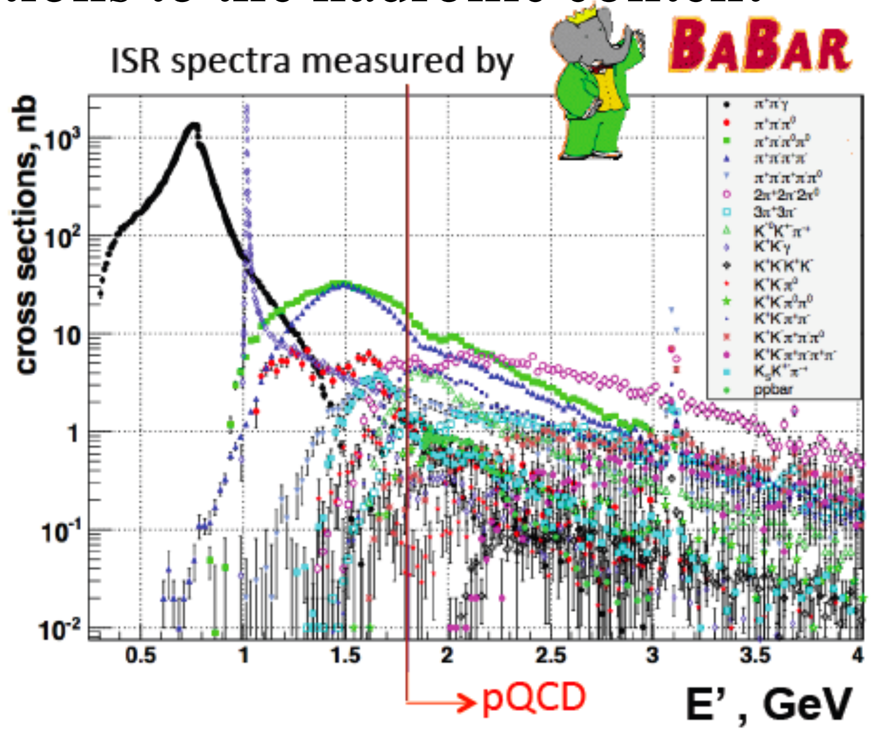
Hadronic light-by-light scattering

$\alpha_\mu^{hadr,LBL} = (10.5 \pm 2.6) \cdot 10^{-10}$

Precision tests of the Standard Model

- Hadronic vacuum polarization
  - $\alpha_\mu^{had,LO} = \frac{\alpha^2(0)}{3\pi^2}\int_{4m_\pi^2}^{\infty} ds\, \frac{K(s)}{s} R(s)$ $\quad\quad R(s) = \frac{\sigma(e^+e^-\to hadrons)}{\sigma(e^+e^-\to\mu^+\mu^-)}$
- Contributions of hadronic cross sections to the hadronic content α_μ^{hadr}





- The largest contribution is below 1 GeV ($e^+e^- \to \pi^+\pi^-$)
- $e^+e^- \to \pi^+\pi^-\pi^0$ contribution > 6%

$e^+e^- \rightarrow \gamma_{ISR}\pi^+\pi^-$

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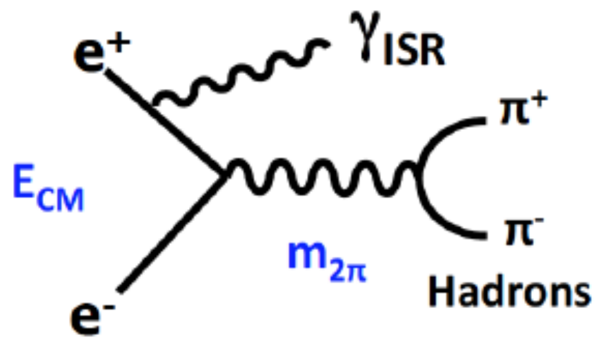
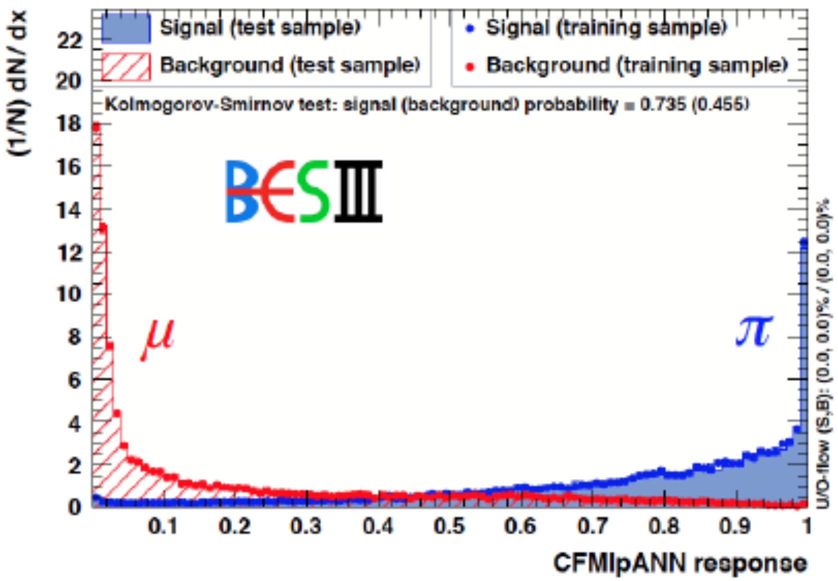
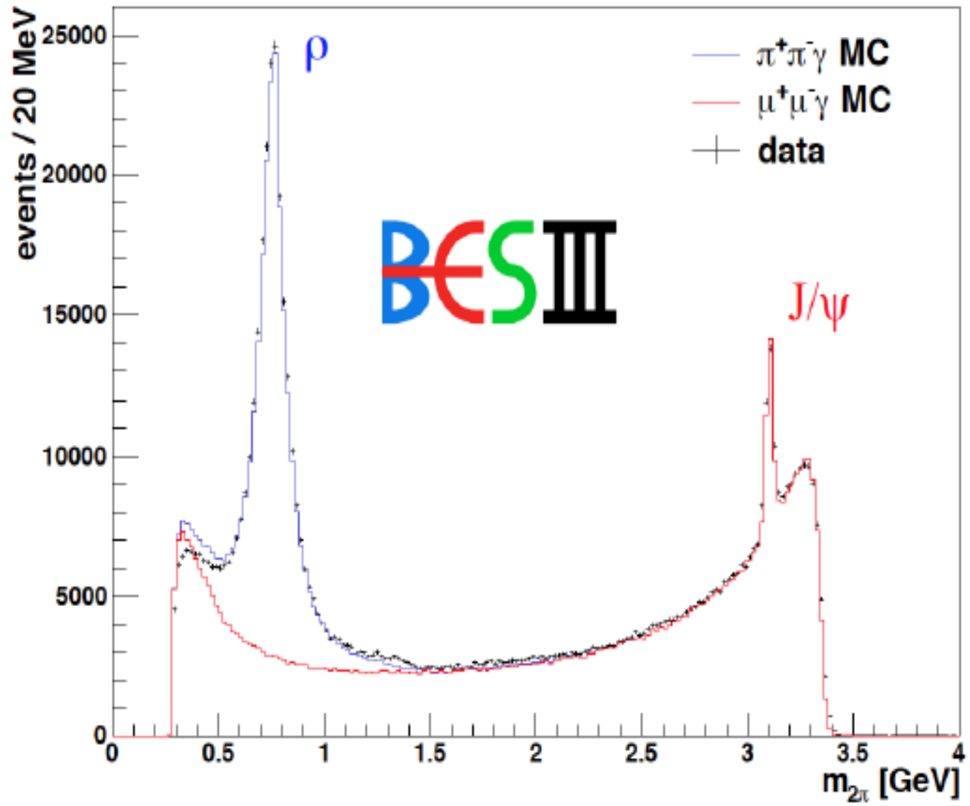
- Data: 2.9 fb^{-1}@3.773 GeV
- Detected ISR photon
- MC produced with Phokhara
- Main background: $\mu^+\mu^-\gamma$
  - TMVA method (Neutral Network)
- Systematic uncertainty: 0.9%







$e^+e^- \rightarrow \gamma_{ISR}\pi^+\pi^-$

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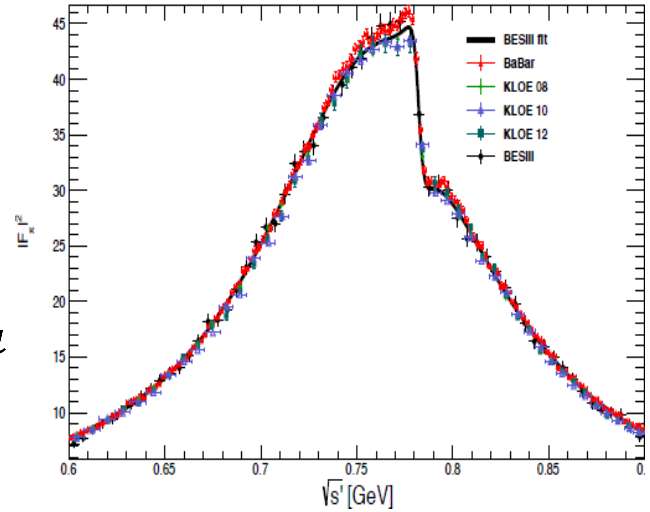
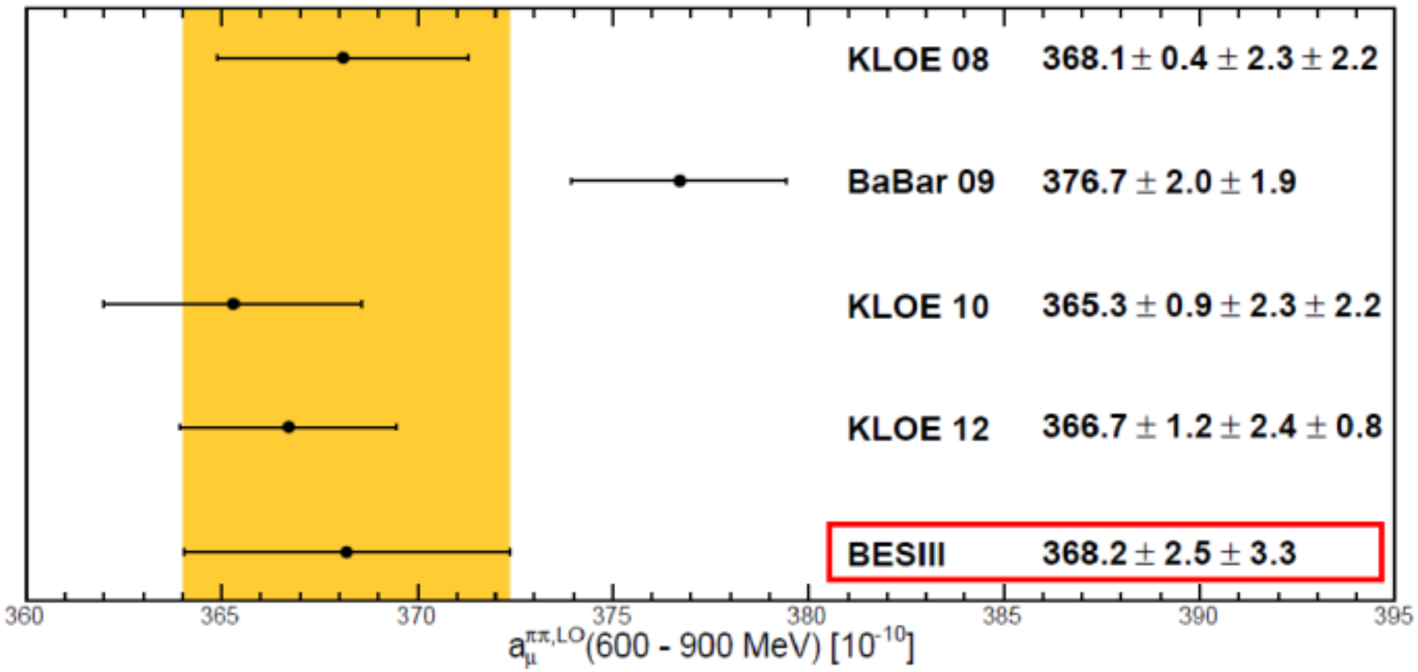
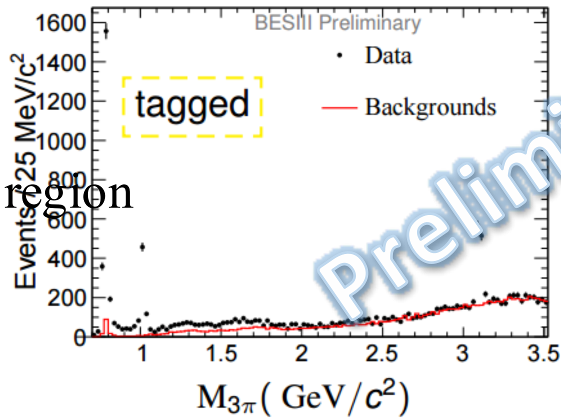
- Cross section: $\sigma^{bare}_{\pi\pi(\gamma_{FSR})} = \frac{N_{\pi\pi\gamma}\cdot(1+\delta^{\pi\pi}_{FSR})}{L\cdot\epsilon^{\pi\pi\gamma}_{global}\cdot H(s)\cdot\delta_{vac}}$
- Form factor: $|F_\pi|^2 = \frac{3s}{\pi\alpha^2\beta^3}\sigma^{dressed}_{\pi\pi}$
- Contribution to the hadronic contribution of α_μ
  - $\alpha_\mu^{\pi\pi,LO}(0.6-0.9\text{ GeV}) = \frac{1}{4\pi^3}\int_{0.6}^{0.9} ds K(s)\sigma^{bare}_{\pi\pi}$

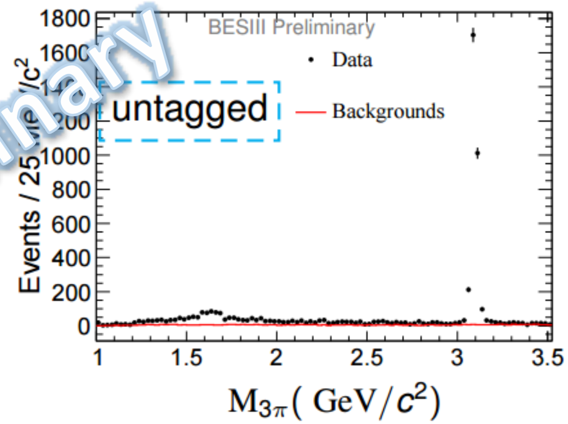




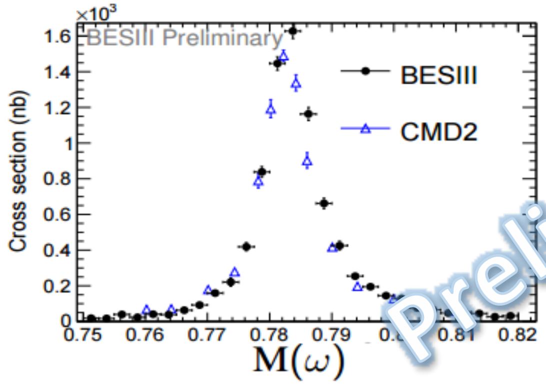
$e^+e^- \to \gamma_{ISR}\pi^+\pi^-\pi^0$

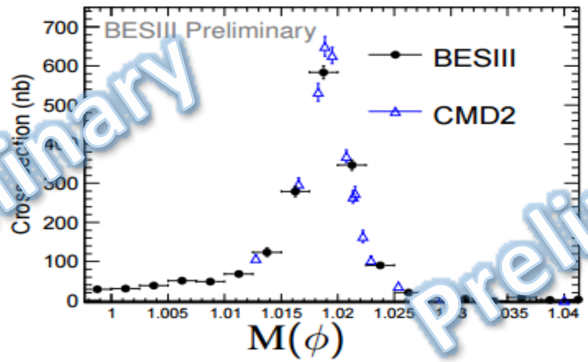
- Data: 2.9 fb^{-1}@3.773 GeV
- ISR tagged:
  - Clear ω and φ signals
  - Huge background in high mass region
- ISR untagged
  - Limited by acceptance
  - Negligible background

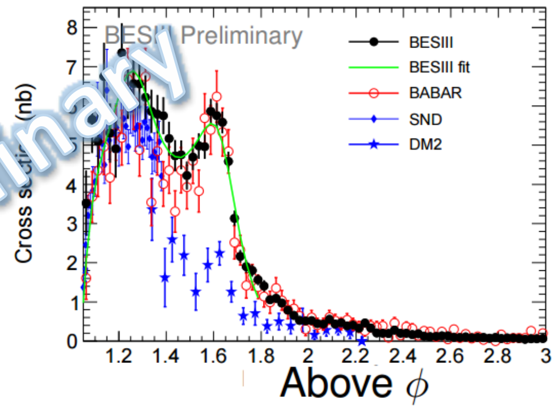




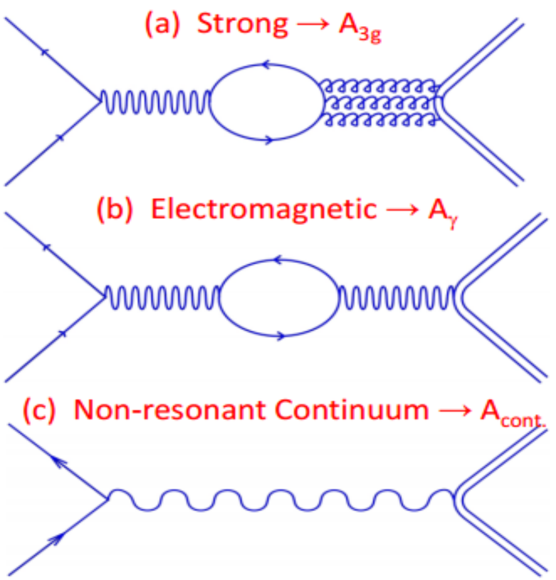
- Below 1.8 GeV, fit with VMD model
  - $\sigma(m) = \frac{12\pi}{m^3} F_{\rho\pi}(m) \left| \sum_{V=\omega,\varphi,\omega'\omega''} \frac{\Gamma_V m_V^{3/2} \sqrt{B(V \to e^+e^-) B(V \to 3\pi)}}{D_V(m)} \frac{e^{i\varphi V}}{\sqrt{F_{\rho\pi}(m_V)}} \right|^2$
  - Branching fraction for $\omega, \varphi, \omega'\omega''$ consistent with PDG







Lineshape of J/ψ resonance



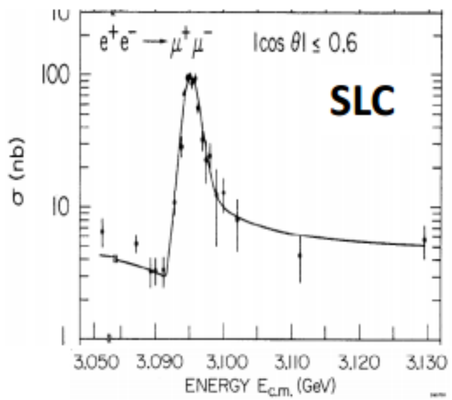
(a) $e^+e^- \to J/\psi \to$ hadrons via strong mechanism;

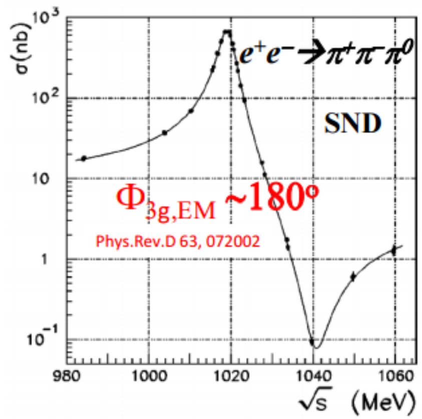
(b) $e^+e^- \to J/\psi \to$ hadrons via EM mechanism;

(c) non-resonant $e^+e^- \to$ hadrons via a virtual photon.

$$\sigma_{Born} = \left|A_{3g} + A_\gamma + A_{cont}\right|^2$$
$$= \left||A_{3g}|e^{i\Phi_{3g,EM}} + |A_\gamma|e^{i\Phi_{\gamma,cont.}} + |A_{cont.}|\right|^2$$

- Model dependent experimental evidences:
  - SU3 and SU3 breaking in 1^-0^-[1], 0^-0^-[1], 1^-1^-[1], 1^+0^-[2] decay show the phase between A_{3g} and A_{EM} is $\Phi_{3g,EM} \sim 90^\circ$
  - If $A(e^+e^- \to n\bar{n}) \sim -A(e^+e^- \to p\bar{p})$, $\frac{B(n\bar{n})}{B(p\bar{p})} = 0.98 \pm 0.08 \to \Phi_{3g,EM} \sim 89^\circ \pm 8^\circ$[3]
  - Other baryon pairs: $\Phi_{3g,EM} \sim -85.9^\circ \pm 1.7^\circ$ or $90.8^\circ \pm 1.6^\circ$[4]
  - The phase angle between A_{EM} and A_{cont}: $\Phi_{\gamma,cont.} = 0^\circ$ from $e^+e^- \to \mu^+\mu^-$
  - The interference between φ and ω was observed at SND, $\Phi_{3g,EM} \sim 180^\circ$



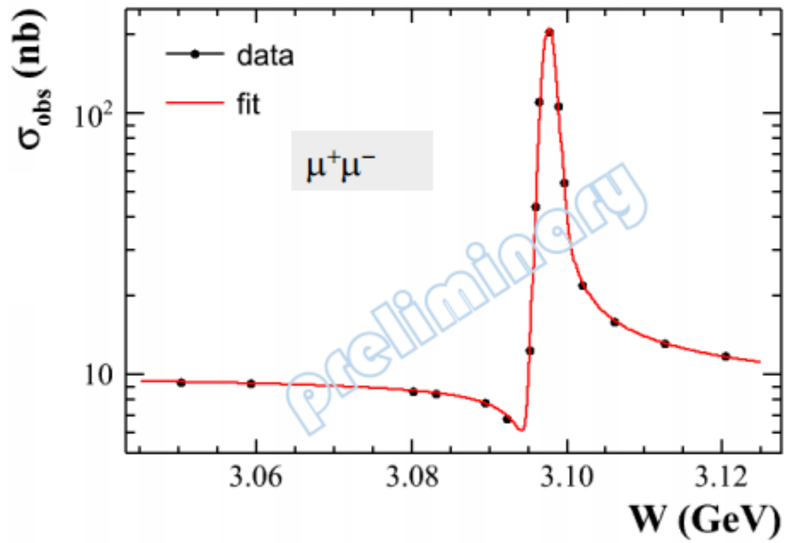


[1] M. Suzuki et al., Phys. Rev. D60, 051501 (1999).
[2] M. Suzuki et al. Phys. Rev. D63, 054021 (2001).
[3] M. Ablikim et al. (BESIII), Phys. Rev. D86, 032014 (2012).
[4] K. Zhu et al., Int. J Mod. Phys. A30, 1550148 (2015).

$e^+e^- \to \mu^+\mu^-$

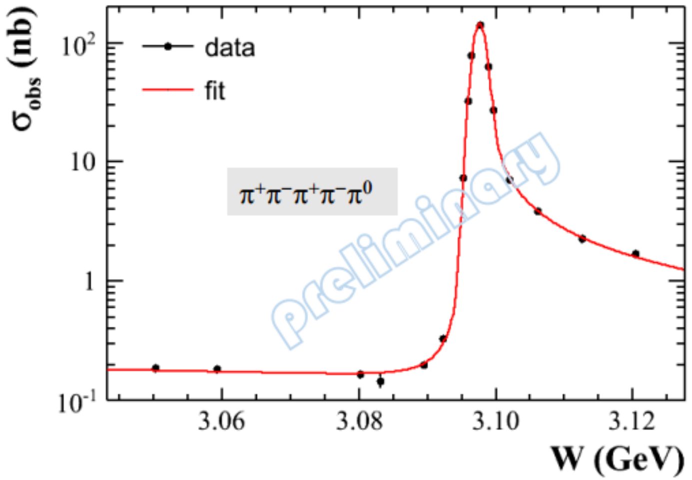
- Data at 16 energy points around J/ψ peak, integrated luminosity~100.5 pb^{-1}
- Observed cross section: $\sigma_i = \frac{N_i}{\epsilon_i L_i (B)}$
- Theoretically prediction of Born cross section: $\sigma^0(W) = \frac{4\pi\alpha^2}{W^2}\left|1 + \frac{3W^2\sqrt{\Gamma_{ee}\Gamma_{\mu\mu}}e^{i\gamma,cont}}{\alpha M(W^2 - M^2 + iM\Gamma)}\right|^2$
- Considering ISR : $\sigma'(W) = \int_0^{1-(\frac{W_m}{W})^2} dxF(x,W)\sigma^0(W)$
- Considering energy spread S_E: $\sigma''(W) = \int_{W-nS_E}^{W+nS_E} \frac{1}{\sqrt{2\pi}S_E} \exp(\frac{W'-W}{2S_E^2})\sigma'(W')dW'$
- Minimization method: $\chi^2 = \sum_{i=1}^{16} \frac{[\sigma^{obs}(W_i) - \sigma''(W_i)]^2}{(\Delta\sigma^{obs}W_i)^2 + \left[\Delta W_i \cdot \frac{d\sigma''}{dW}(W_i)\right]^2}$

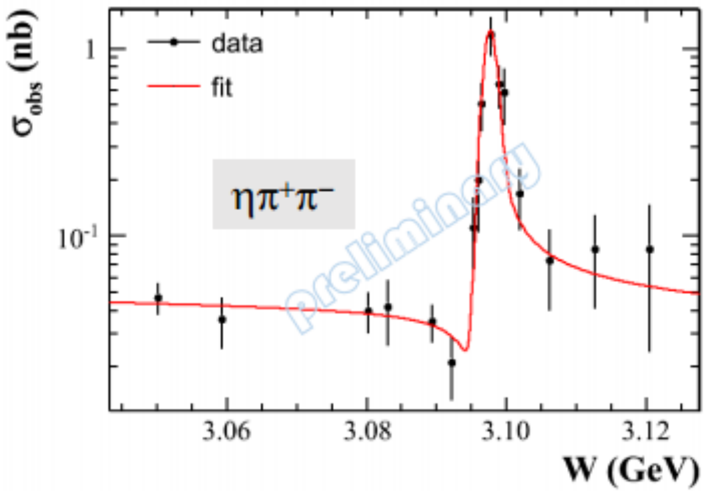
$\Phi_{\gamma,cont.} = (-5 \pm 9.7)^\circ$, consistent with zero
Energy spread: $S_E = (0.911 \pm 0.026)$MeV
Energy shift: $\Delta M = (0.548 \pm 0.041)$MeV



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

- For $\pi^+\pi^-\pi^+\pi^-\pi^0$ process: $\sigma^0(W) = (\frac{A}{W^2})^2\frac{4\pi\alpha^2}{W^2}\left|1 + \frac{3W^2\sqrt{\Gamma_{ee}\Gamma_{\mu\mu}}(1+Ce^{i\Phi_{3g,EM}})}{\alpha M(W^2-M^2+iM\Gamma)}\right|^2$
  - $\Phi_{3g,EM} = 83.4^\circ \pm 4.3^\circ$ or $-83.5^\circ \pm 4.2^\circ$
  - $\Gamma_{5\pi} = (\frac{A}{W^2})^2\Gamma_{\mu\mu}\left|1 + Ce^{i\Phi_{3g,EM}}\right|^2$
  - $\mathrm{Br}(J/\psi \rightarrow \pi^+\pi^-\pi^+\pi^-\pi^0) = \frac{\Gamma_{5\pi}}{\Gamma} = (\mathbf{4.27 \pm 0.52})\%$, consistent with PDG value
- For $\eta\pi^+\pi^-(\eta \rightarrow \pi^+\pi^-\pi^0)$ process, the formula is similar with that for $\mu^+\mu^-$
  - No A_{3g} due to G violation
  - $\Phi_{\gamma,cont.} = (-2 \pm 39)^\circ$, consistent with zero
  - $\mathrm{Br}(J/\psi \rightarrow \eta\pi^+\pi^-) = \frac{\Gamma_{\eta\pi^+\pi^-}}{\Gamma} = (\mathbf{3.6 \pm 0.7})\times\mathbf{10^{-4}}$, much improved than PDG value.





J/ψ decay width

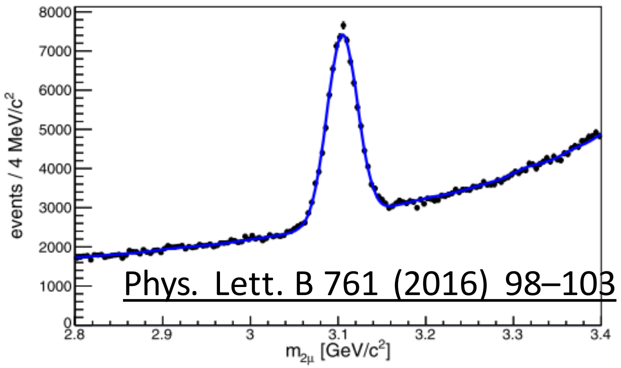
- ISR method
- $2.93\ \text{fb}^{-1}$ data at 3.773 GeV
- Channel: $e^+e^- \to \gamma_{ISR}\mu^+\mu^-$
- Generator: Phokhara
- $\sigma_{J/\psi\gamma}(s) = \frac{N_{J/\psi}}{\epsilon \cdot L} = \Gamma_{ee} \cdot B_{\mu\mu} \cdot I(s)$

$$I(s) = \int_{m_{min}}^{m_{max}} \frac{2m_{2\mu}}{s} W(s, m_{2\mu}) \frac{BW'(m_{2\mu})}{B_{\mu\mu}\Gamma_{ee}} dm_{2\mu}$$

$$BW(m_{2\mu}) = \frac{12\pi B_{\mu\mu}\Gamma_{ee}\Gamma_{tot}}{(m_{2\mu}^2 - m_{J/\psi}^2)^2 + m_{J/\psi}^2 \Gamma_{tot}^2}$$

- Fit function:

$$f(x) = N_{J/\psi}[M(x) \otimes G(x)] + (N_{total} - N_{J/\psi})p(x)$$



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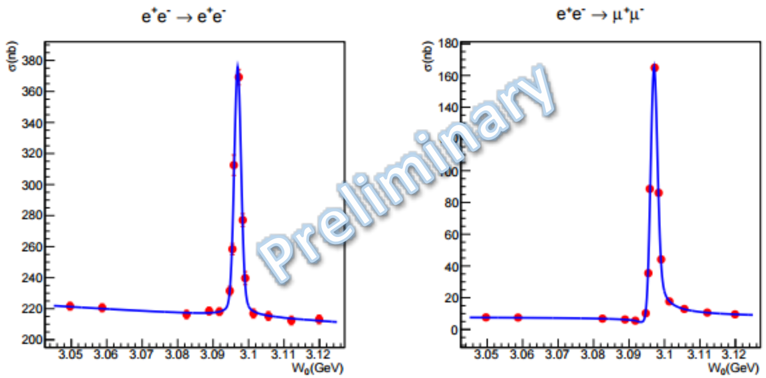
- $\Gamma_{ee} \cdot B_{\mu\mu} = (333.4 \pm 2.5 \pm 4.4)$ eV

- Energy Scan method
- Data at 15 energy points around J/ψ peak, integrated luminosity ~83 pb^{-1}
- Channels: $e^+e^- \to e^+e^-$ and $e^+e^- \to \mu^+\mu^-$
- $\sigma_{ll}^{the} = \sigma_{ll}^{the}(W_0, M, \Gamma_{tot}, \Gamma_{ee}\Gamma_{ll}/\Gamma_{tot}, \sqrt{\Gamma_{ee}\Gamma_{ll}}, \sigma_W)$ with ll = ee or μμ



Collaboration	Year	Γ_{tot} (keV)	Γ_{ll} (keV)
BABAR	2004	94.7±4.4	5.61±0.21
CLEO	2006	96.1±3.2	5.71±0.16
KEDR	2010	94.1±2.7	5.59±0.12
PDG	2014	92.9±2.8	5.55±0.14
BESIII(ISR)	2016	—	5.58±0.09
This Work	2016	94.4±1.9	5.64±0.10

Summary

- Fruitful results from e^+e^- annihilation at BESIII, both energy scan and ISR methods are performed.
- More precise baryon form factor on proton, Λ and Λ_c, threshold effect observed near the mass threshold of baryon pair.
- A vector structure observed in K^+K^- spectrum, with m=2.2298$\pm$0.0053$\pm$ 0.0172 GeV and $\Gamma = 143.7 \pm 12.0 \pm 7.8$ MeV.
- Progress been made in vacuum polarization calculation from $\gamma_{ISR}\pi^+\pi^-$ and $\gamma_{ISR}\pi^+\pi^-\pi^0$ processes.
- First measurement for the phase between J/ψ strong and EM amplitude concern multi-hadron final state.
- ISR and ES methods performed to extract Γ_{ll} and Γ_{tot} on J/ψ and achieved the best accuracy.

Thank you!

Obrigado!

谢谢!