XLVII International Symposium on Multiparticle Dynamics

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Measurements of hadronic form factors at BESIII

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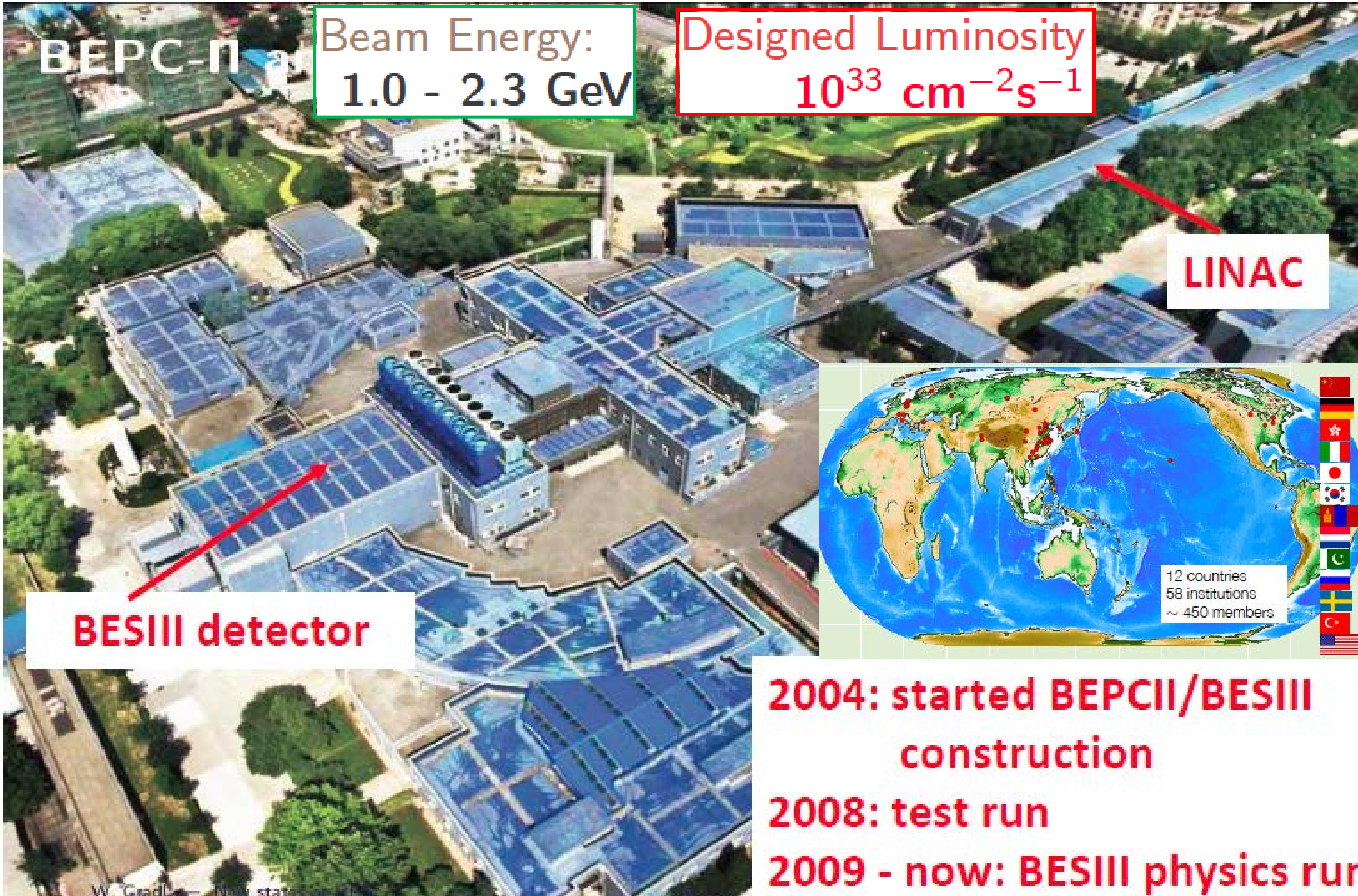
On behalf of BESIII Collaboration

Outline

- ☞ **Motivations**
- ☞ **Data samples**
- ☞ **Measurement of cross sections**
- ☞ **Extraction of form factors**
  - $e^+e^- \to p\bar{p}$
  - $e^+e^- \to \pi^+\pi^-$
  - $e^+e^- \to \Lambda_c^+\bar{\Lambda}_c^-$
- ☞ **Summary**

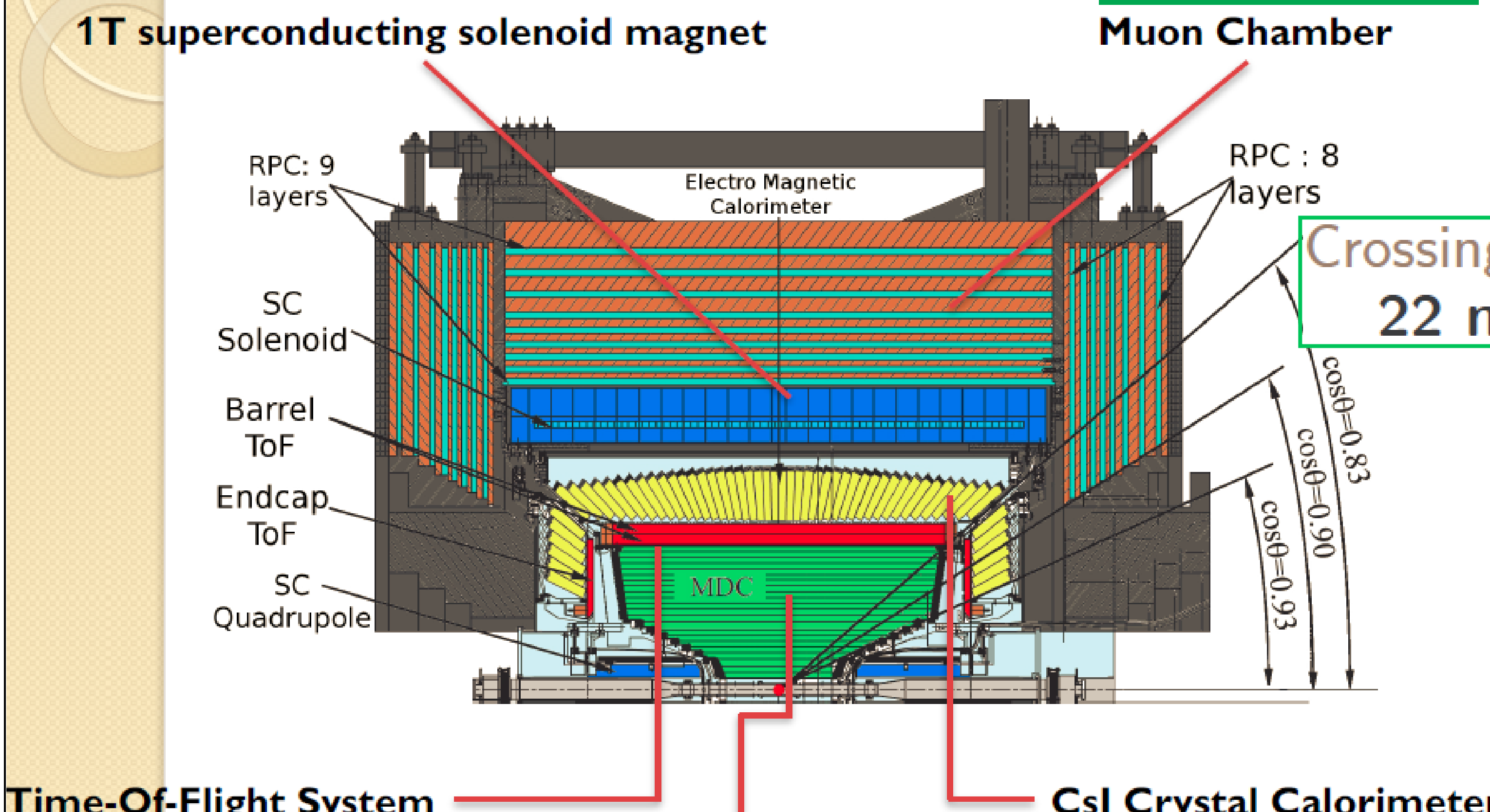
Beijing Electron-Positron Collider II (BEPCII)



Beijing Spectrometer III (BESIII)

MUC:

$\delta(xy) < 2$ cm



Crossing angle 22 mrad

TOF:

$\delta t = 100$ ps Barrel

$\delta t = 110$ ps Endcap

Main Drift Chamber

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

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

Data samples of 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

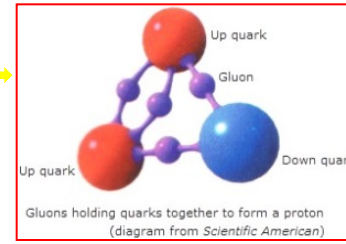
Other newly collected data samples

Part 1

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

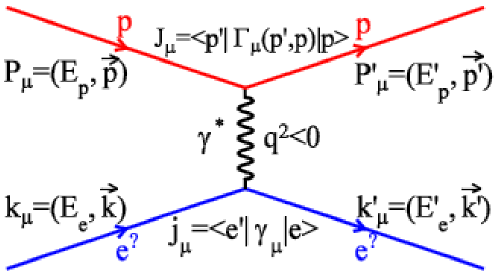
Motivation

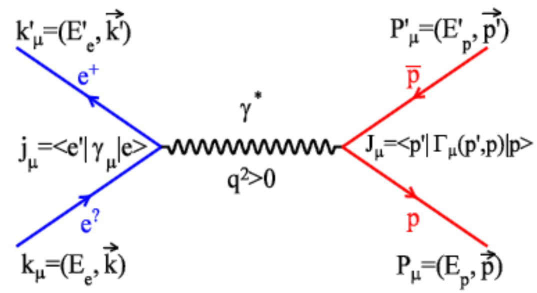
- The valence-quark picture of proton in quark model:



- The structure of proton can be measured in two processes:

$e^{\pm}p \rightarrow e^{\pm}p$ (space-like $q^2<0$) $e^+e^- \rightarrow p\,\bar{p}$ (time-like $q^2>0$)





BESIII

- Vector current of the interaction vertex with hadronic structure

$$\Gamma_\mu(p',p)=\gamma_\mu F_1(q^2)+\frac{i\sigma_{\mu\nu}q^\nu}{2m_p}F_2(q^2)$$

- Structure functions F_1 and F_2 can be recombined into two form factors
  - Electronic: $G_E(q^2)=F_1(q^2)+\tau\kappa_p F_2(q^2)$
  - Magnetic : $G_M(q^2)=F_1(q^2)+\kappa_p F_2(q^2)$

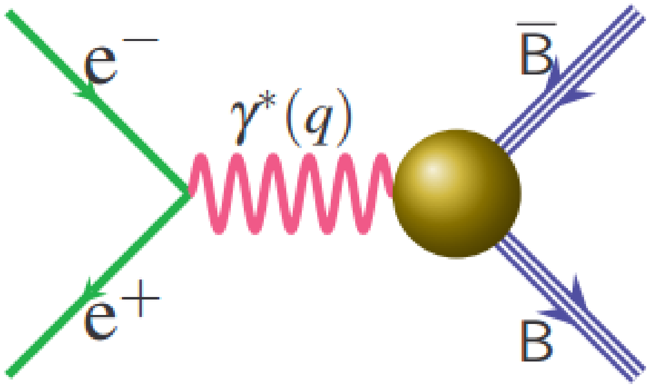
$\tau=\frac{q^2}{4m_p^2}$, $\kappa_p=\frac{g_p-2}{2}=\mu_p-1$

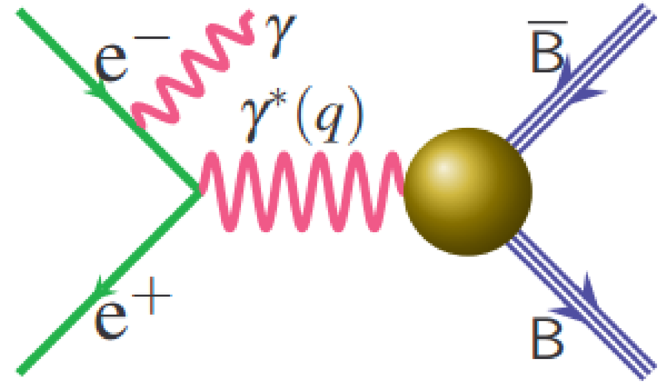
- G_E and G_M relate to the spatial distribution of charge and magnetization in Breit-frame, the charge density distribution:

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

Two methods

For time-like process





$x \equiv 2E_\gamma/\sqrt{s}$

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

This talk

In progress

Cross section

- For the reaction $e^+e^- \to p\bar{p}$, differential cross section:

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2\beta}{4s} C[|G_M(s)|^2(1+\cos^2\theta) + \frac{1}{\tau}|G_E(s)|^2\sin^2\theta]$$

$$\beta = \sqrt{1-4M^2/s}$$
$$\tau = s/4M^2;$$
$$y = \pi\alpha M/\beta\sqrt{s}$$

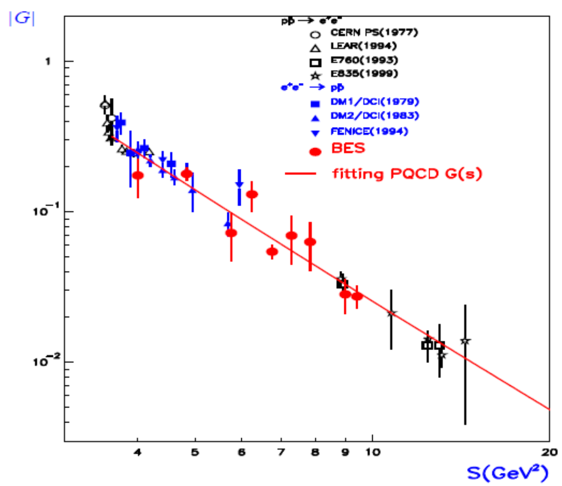
- the Born cross section

$$\sigma = \frac{4\alpha^2\pi\beta}{3s} C[|G_M(s)|^2 + \frac{1}{2\tau}|G_E(s)|^2]$$

- Coulomb correction C is subtle and important near threshold ($\beta \to 0$).

$$C = \frac{y}{1-exp(-y)}$$

- Due to the limited statistics, early experiments assume $|G_E| = |G_M| \equiv |G|$



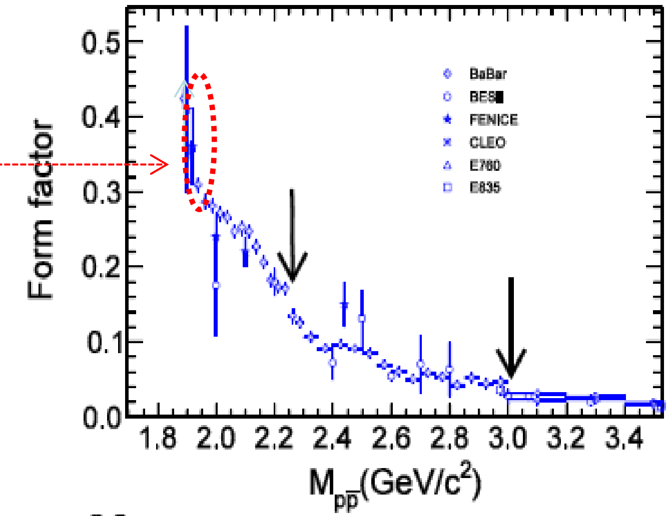
BES Collaboration, Phys. Lett. **B630**, (2005)14

- BESII measured |G| and parameterized as (Λ: QCD scale, A: free parameter)

$$|G(s)| = \frac{A}{s^2\ln^2(s/\Lambda^2)}$$

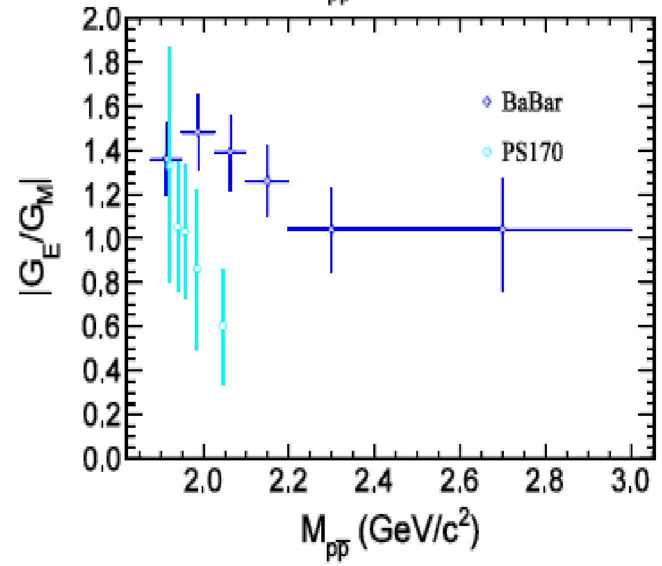
Some question to make clear

- Recent years, statistics of data samples increased, the behavior of form factor seems clear, but some questions still left:



- steep rise toward threshold ?
- two rapid decreases around 2.25 and 3.0 GeV ?

Are they true?



- ratio $|G_E/G_M|$ disagreement by PS170 and BaBar
- poor precision (~11%, 43%)
- limited energy range

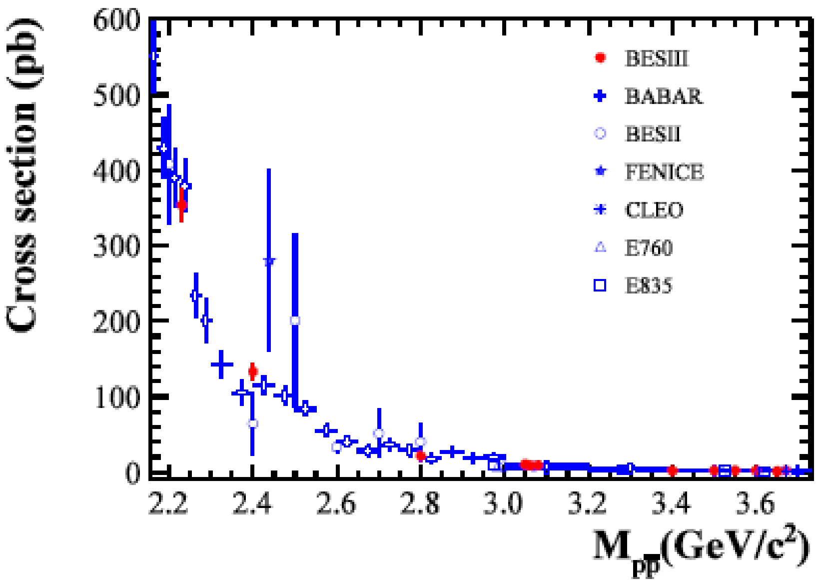
which one is reliable?

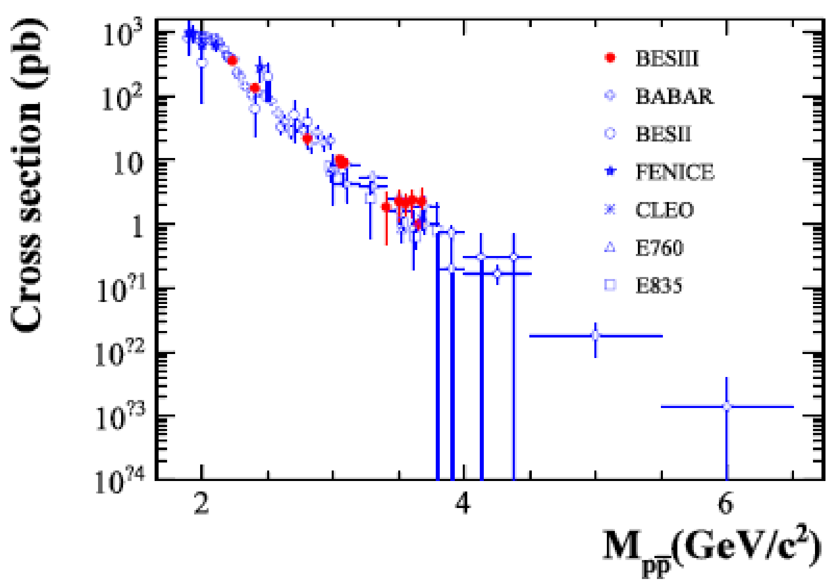
Measurement of cross section

Experimental formula for cross section:

$$\sigma_{Born} = \frac{N_{obs} - N_{bkg}}{L \cdot \varepsilon \cdot (1+\delta)}$$

- N_{obs}: the observed number of signal in data
- N_{bkg}: the number of background evaluated from MC
- L: the integral luminosity
- ε: detection efficiency by MC sample, with Conexc generator
- (1+δ): radiative correction factor





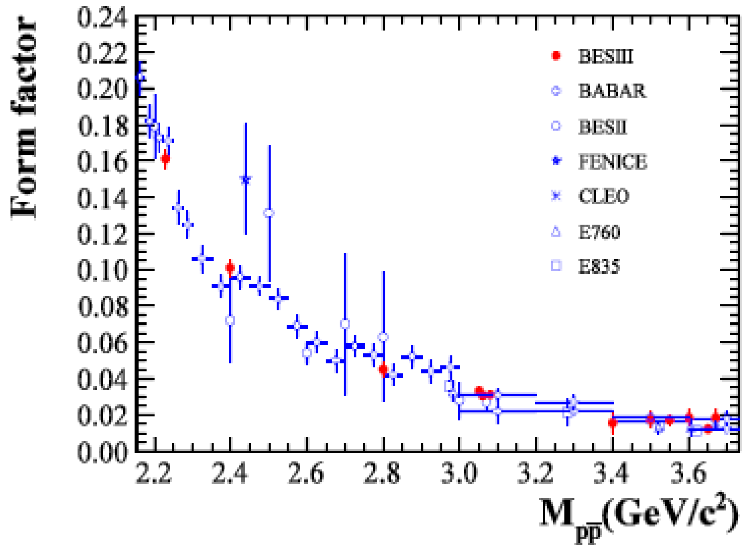
Extraction of effective form factor

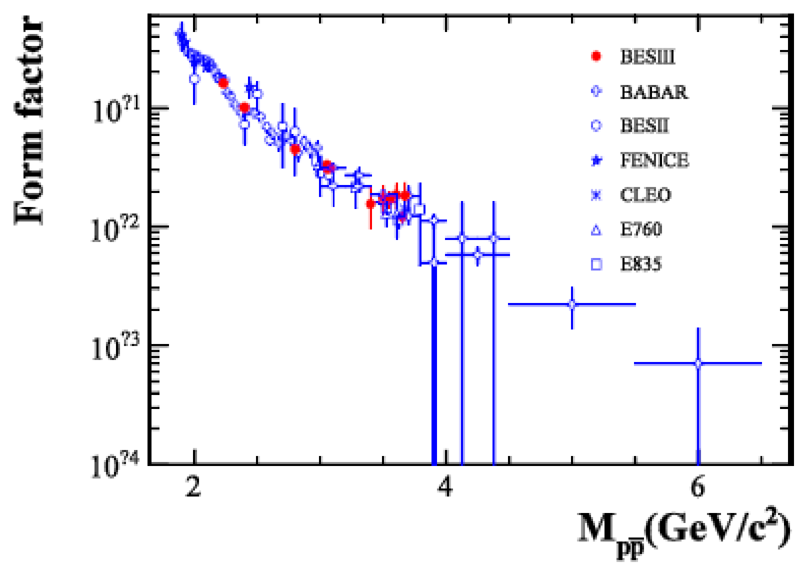
- In order to compare with earlier measurements, it is still assumed $|G_E|=|G_M|\equiv|G_{eff}|$, and the cross section reads

$$\sigma = \frac{\pi\alpha^2}{3m_p^2\tau}\left[1+\frac{1}{2\tau}\right]|G_{eff}|^2$$

- The effective form factor could be extracted

$$G_{eff} = \sqrt{\frac{\sigma_{Born}}{86.83\cdot\frac{\beta}{s}\left(1+\frac{2m_p^2}{s}\right)}}$$





- The BESIII results are consistent with other measurements within errors.

Extraction of electromagnetic $|G_E/G_M|$ ratio

- Angular distribution:

$$\frac{d\sigma}{d\Omega}(q^2) = \frac{\alpha^2\beta}{4s}|G_M(s)|^2\left[\left(1+\cos^2\theta_p\right) + R_{em}^2\frac{1}{\tau}\sin^2\theta_p\right]$$

  - $R_{em} = G_E(q^2)/G_M(q^2)$
  - θ_p : polar angle of proton

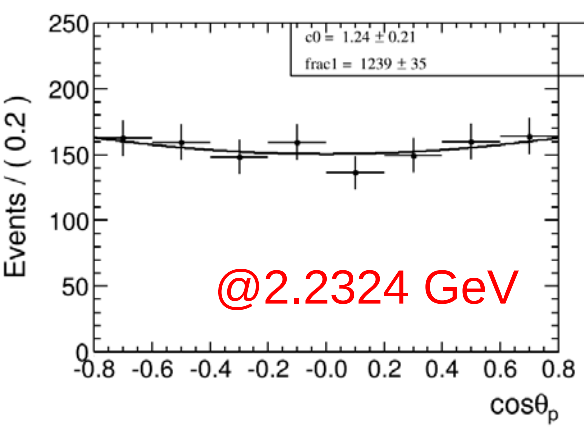
- Fit function:

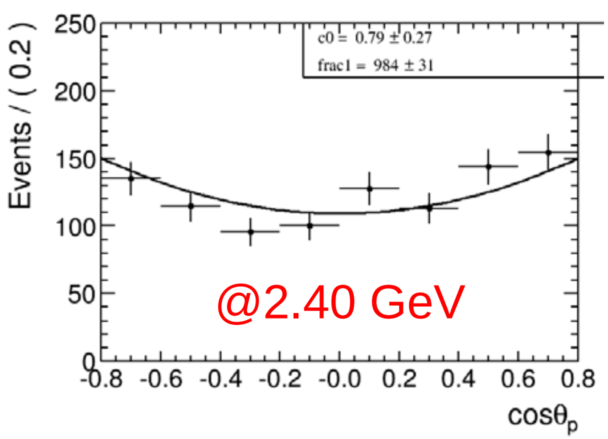
$$\frac{dN}{d\cos\theta_p} = N_{norm}\left[\left(1+\cos^2\theta_p\right) + R_{em}^2\frac{1}{\tau}\sin^2\theta_p\right]$$

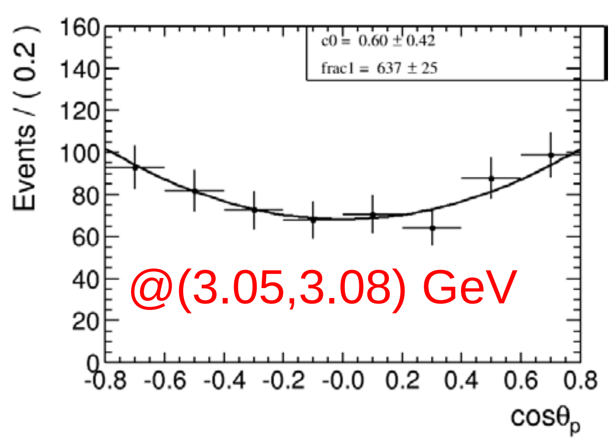
the overall normalization

$$N_{norm} = \frac{2\pi\alpha^2\beta L}{4s}\left[1.94 + 5.04\frac{m_p^2}{s}R^2\right]G_M(s)^2$$

- Results:







Extraction of electromagnetic $|G_E/G_M|$ ratio

- Moment method:

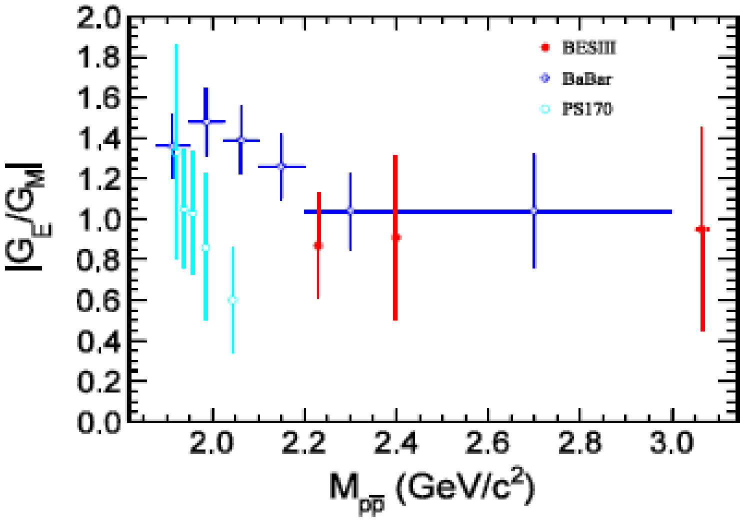
- second moment of $\cos\theta_p$: $\langle\cos^2\theta_p\rangle = \frac{1}{N_{norm}}\int \cos^2\theta_p \frac{d\sigma}{d\Omega} d\cos\theta_p$

- Estimator of $\cos\theta_p$: $\langle\cos^2\theta_p\rangle = \overline{\cos^2\theta_p} = \frac{1}{N}\sum_{i=1}^{N}\cos^2\theta_p/\varepsilon_i$

- Extraction of $|G_E/G_M| = R = \sqrt{\frac{s}{4m_p^2}\frac{\langle\cos^2\theta_p\rangle - 0.243}{0.108 - 0.648\langle\cos^2\theta_p\rangle}}$

- Uncertainty: $\langle\cos^2\theta_p\rangle$: $\sigma_{\langle\cos^2\theta_p\rangle} = \sqrt{\frac{1}{N-1}[\langle\cos^4\theta_p\rangle - \langle\cos^2\theta_p\rangle]}$

- Result:



- BESIII measurements are consistent with BaBar's, but not with PS170.

The electromagnetic ratio $|G_E/G_M|$

$\sqrt{s}$ (MeV)	$\lvert G_E/G_M \rvert$	$\lvert G_M \rvert$ ($\times 10^{-2}$)	χ^2/ndf
	Fit on $\cos\theta_p$		
2232.4	$0.87 \pm 0.24 \pm 0.05$	$18.42 \pm 5.09 \pm 0.98$	1.04
2400.0	$0.91 \pm 0.38 \pm 0.12$	$11.30 \pm 4.73 \pm 1.53$	0.74
(3050.0, 3080.0)	$0.95 \pm 0.45 \pm 0.21$	$3.61 \pm 1.71 \pm 0.82$	0.61
	method of moment		
2232.4	0.83 ± 0.24	18.60 ± 5.38	-
2400.0	0.85 ± 0.37	11.52 ± 5.01	-
(3050.0, 3080.0)	0.88 ± 0.46	3.34 ± 1.72	-

Phys. Rev. D 91, 112004. (June 9, 2015)

Part 2

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

Motivation

The Dirac equation of a charged fermion in electromagnetic field ($\vec{A}$,$\vec{B}$)

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

- point-like fermion has magnetic moment

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

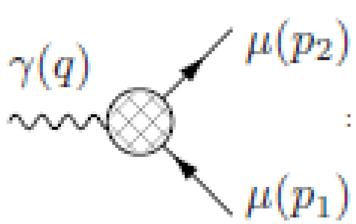
- define Bohr magneton:

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

- 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: $a_\mu = (g_\mu - 2)/2$

Motivation

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) $(684.7 \text{ to } 709.0 \pm 6)10^{-10}$ (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)

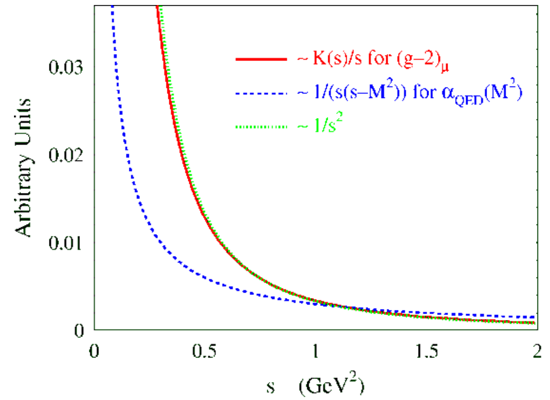
+ (weak) $(15.4 \pm 0.2)10^{-10}$ (2-loop)

$a_\mu^{had,LO}$ 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 $e^+e^- \to$ hadrons, i.e. taking out radiative corrections.
QED kernel $K(s) \sim m_\mu^2/3s$, gives strong weight to low energy data.



Motivation

Ratio of the contribution to theoretical uncertainty of (g-2) from the measured hadronic cross section in different energy region:

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

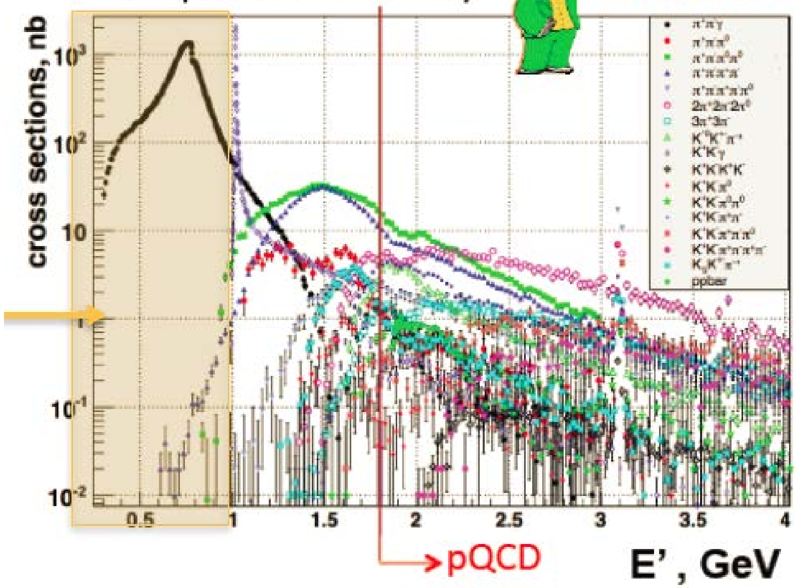
$$a_\mu^{had,LO} = \frac{1}{4\pi^3}\int_{4m_\pi^2}^{\infty} \sigma_{had}^0(s)K(s)ds$$

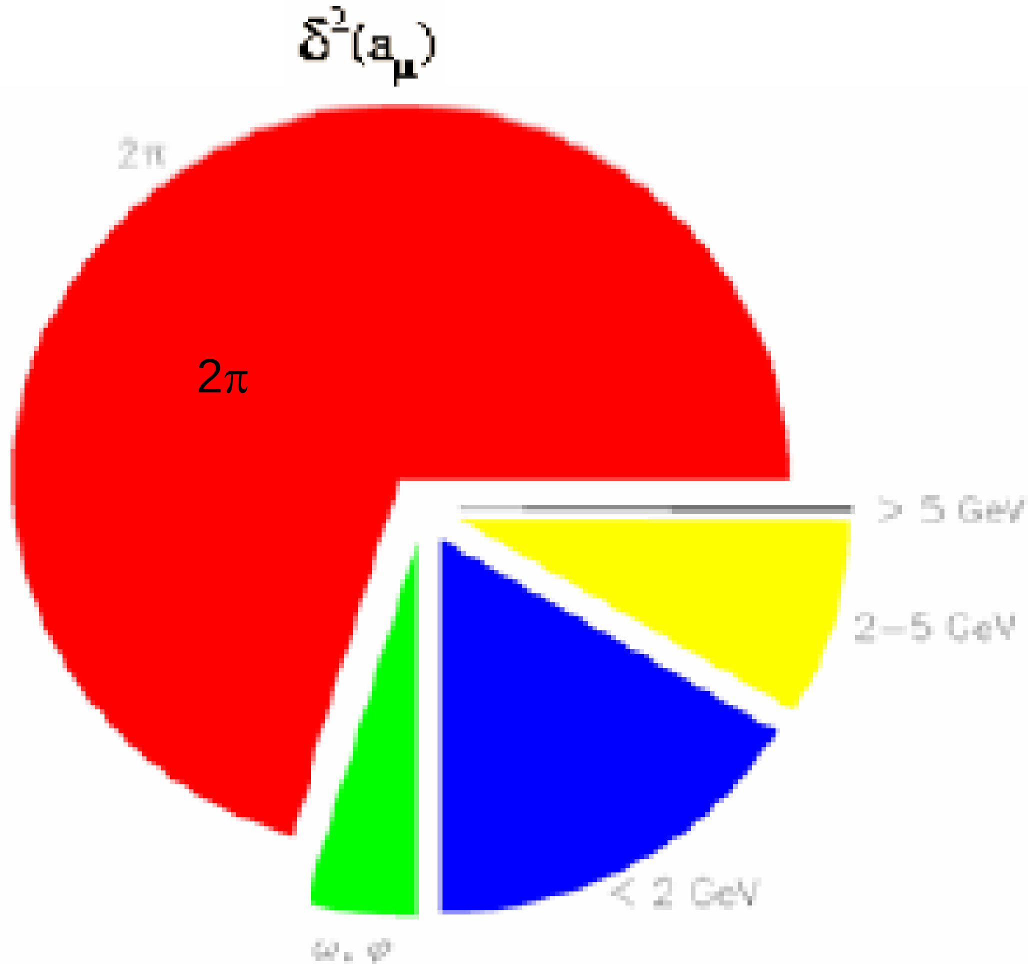
$K(s) \propto 1/s \qquad \sigma(s) \propto 1/s$

The largest contribution is below 1 GeV.

Channel $e^+e^- \rightarrow \pi^+\pi^-$ is the most important one

ISR spectra measured by BABAR





Motivation

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)

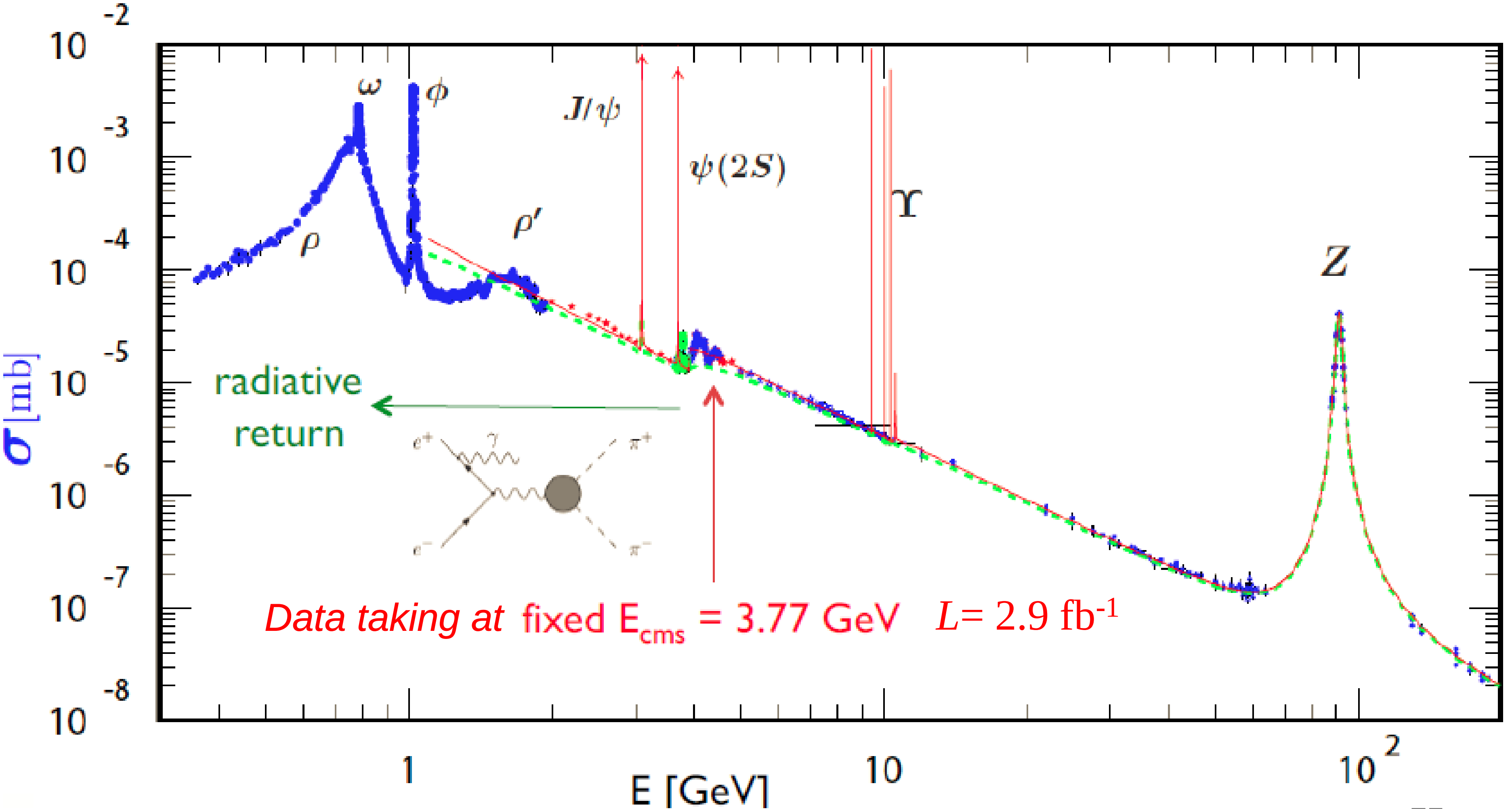
	$a_\mu^{SM} \times 10^{11}$	$(\Delta a_\mu = a_\mu^{EXP} - a_\mu^{SM}) \times 10^{11}$	σ
[1]	116 591 773 (53)	316 (82)	3.8
[2]	116 591 782 (59)	307 (86)	3.6
[3]	116 591 834 (49)	255 (80)	3.2
[4]	116 591 773 (48)	316 (79)	4.0
[5]	116 591 929 (52)	160 (82)	2.0

with a_μ^{HHO}(lbl) = 105 (26) x 10^{-11}

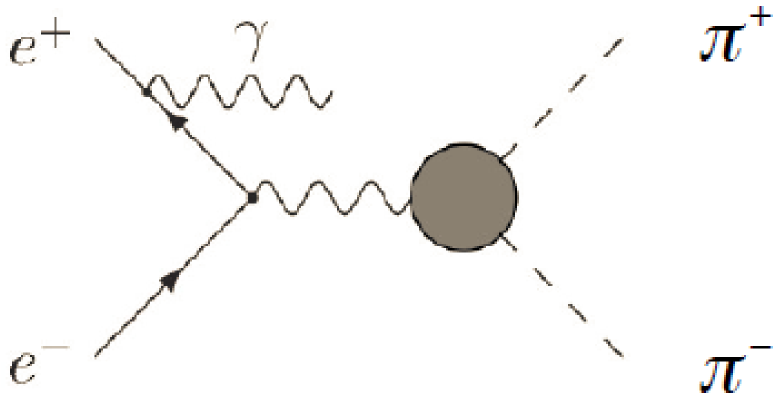
[1] HMNT06, PLB649 (2007) 173.
[2] F. Jegerlehner and A. Nyffeler, arXiv:0902.3360.
[3] Davier et al, arXiv:0908.4300 August 2009 (includes BaBar)
[4] Hagiwara, Liao, Martin, Nomura, Teubner, Oct '09 (preliminary)
[5] Davier et al, arXiv:0906.5443v2 August 2009 (τ data).

Initial state radiation (ISR return)

For e^+e^- collision, photons emitting from initial $e^\pm$ decrease the effective energy $s' = s(1 - E_\gamma/E)$ continuously, this makes measurement at lower energies possible (ISR return).



Initial state radiation (ISR return)



Study the channel

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

to measure the cross section of $e^+e^- \rightarrow \pi^+\pi^-$

via

$$\frac{d\sigma_{ISR}(M_{2\pi})}{dM_{2\pi}} = \frac{2M_{2\pi}}{s} W(s,x,\theta_\gamma) \cdot \sigma(M_{2\pi})$$

(neglecting FSR)

invariant mass of 2π

Radiator function

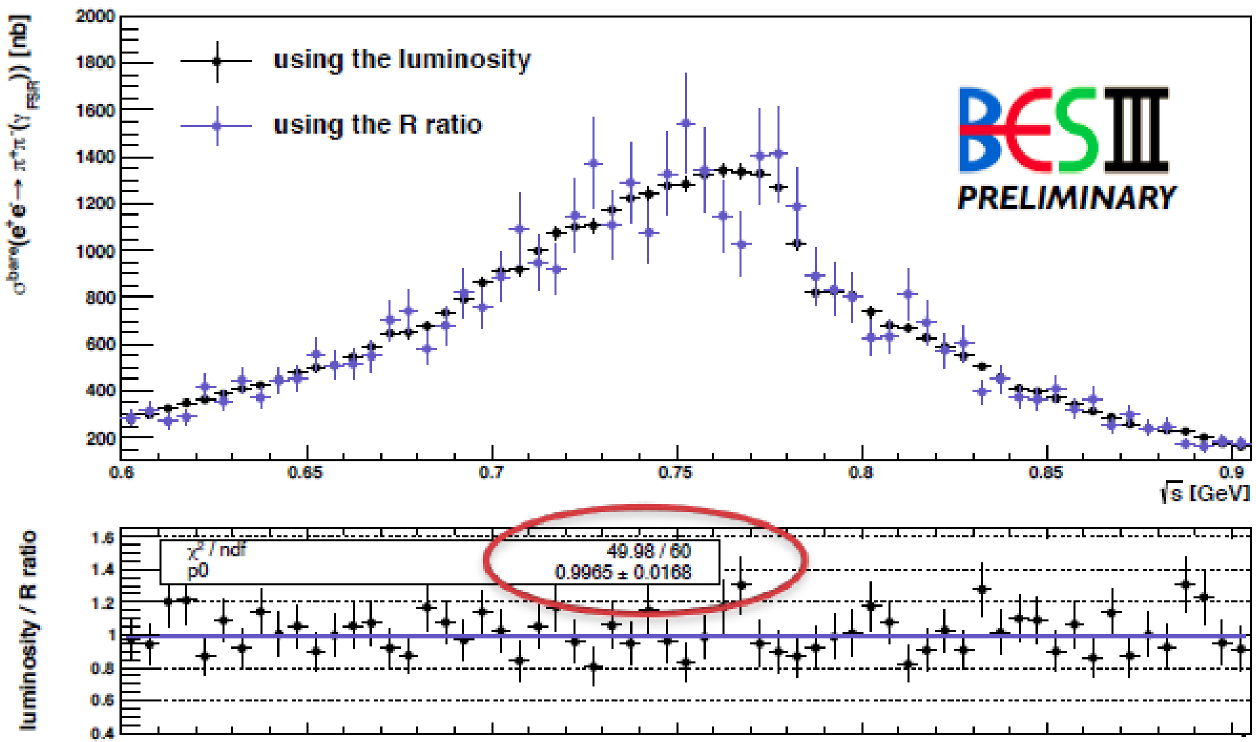
Two normalization methods

- Normalization to integrated luminosity

$$\sigma^{bare}(e^+e^- \to \pi^+\pi^-(\gamma_{FSR})) = \frac{N_{\pi\pi\gamma}/\varepsilon}{L_{int}\cdot H_{rad}\cdot \delta_{vac}\cdot(1+\delta_{FSR})}$$

- Normalization to $\mu^+\mu^-\gamma$ events, i.e. *R* ration $\pi^+\pi^-\gamma/\mu^+\mu^-\gamma$

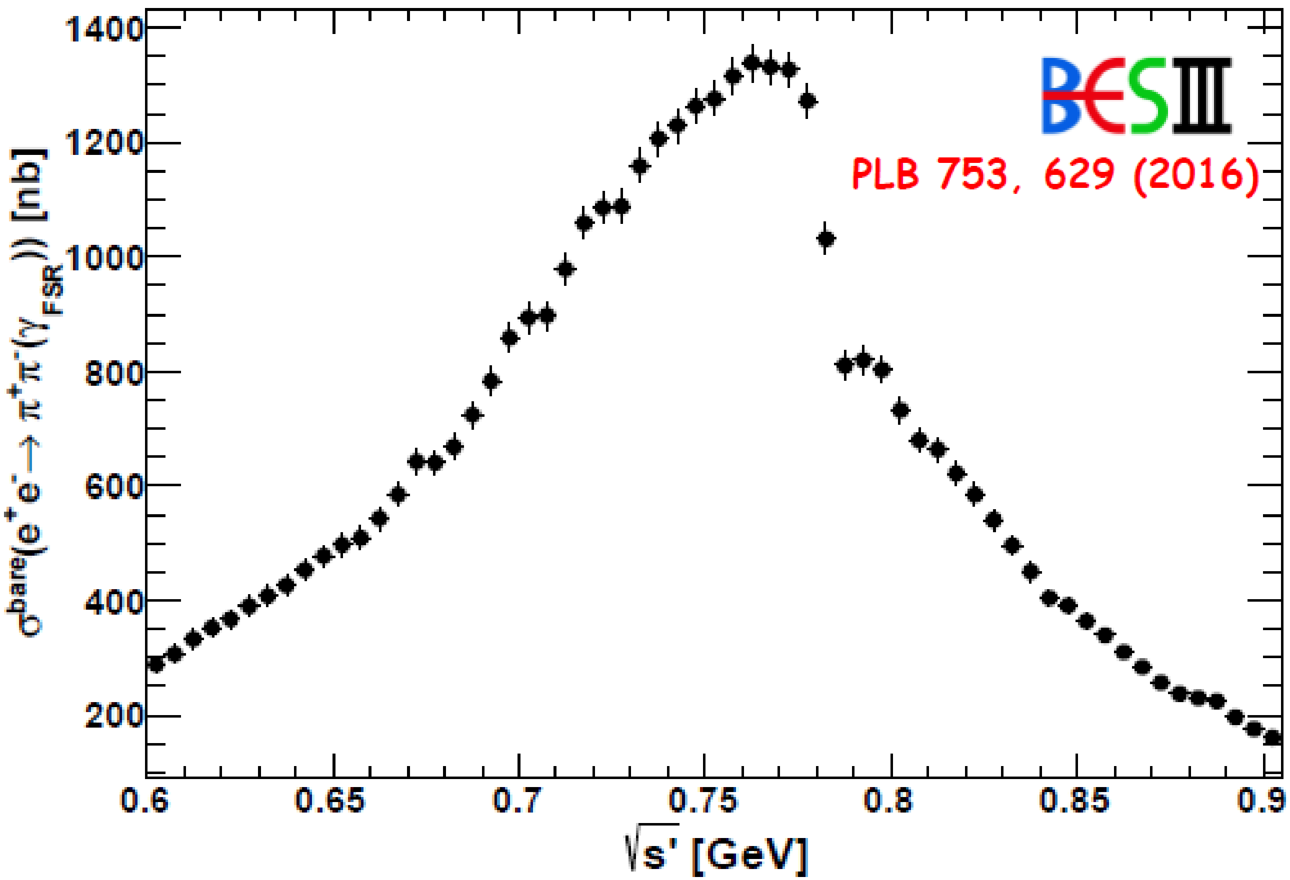
  → L_{int}, H_{rad}, δ_{vac} canceled, uncertainty decreased.



Luminosity / R ratio – 1 = (0.35 ± 1.68) %

limited by $\mu^+\mu^-\gamma$ statistics

Cross section of $\pi^+\pi^-$

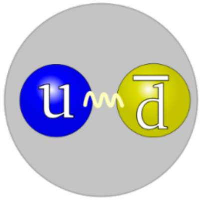


$$\sigma^{bare}\left(\sqrt{s'}\right) = \frac{1}{\frac{2\sqrt{s'}}{s} W(s,x)\epsilon\left(\sqrt{s'}\right)\mathcal{L}\delta_{vac}\delta_{FSR}} \frac{dN}{d\sqrt{s'}}$$

- ρ–ω interference clearly visible

Extraction of form factor

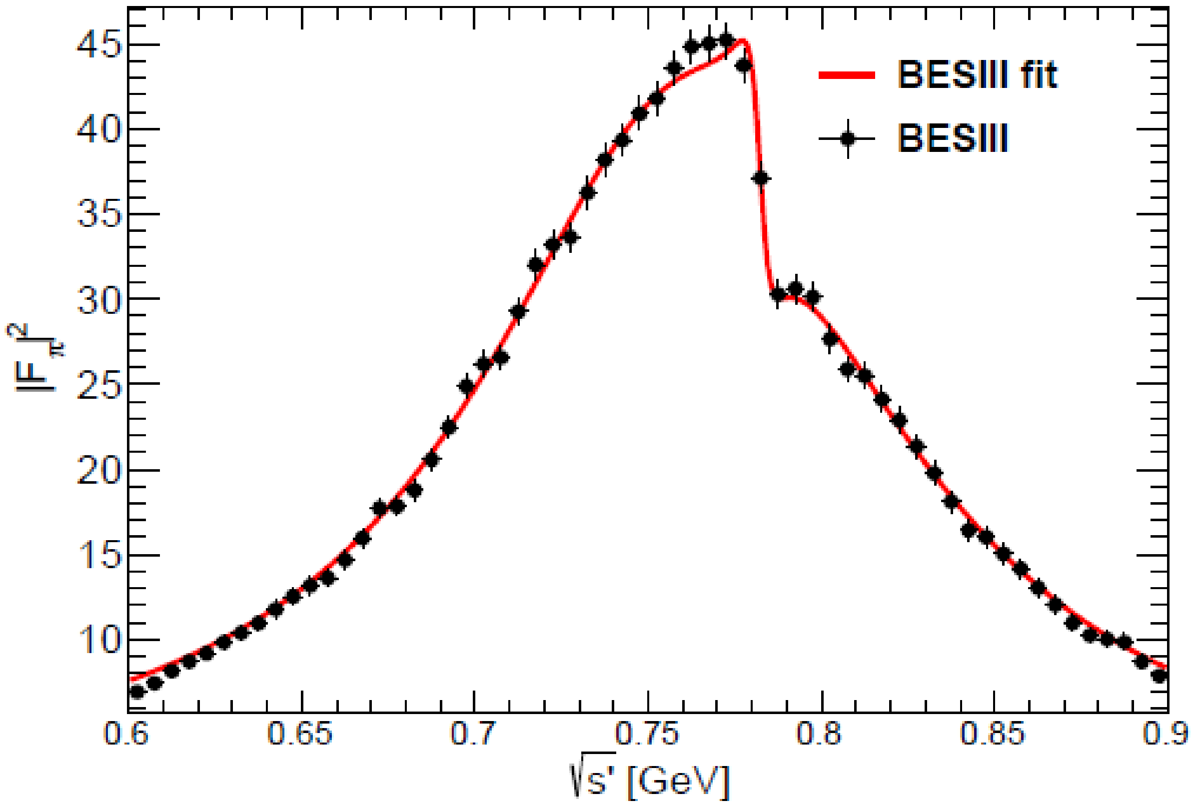
- The picture of pion structure in quark model:



π^+

- Non point-like particle ⇒ pion form factor:

$$|F_\pi|^2(s') = \frac{3s'}{\pi\alpha\beta_\pi^3(s')}\sigma(e^+e^- \to \pi^+\pi^-)(s') \quad , \quad \beta_\pi(s') = \sqrt{1-\frac{4m_\pi^2}{s'}}$$

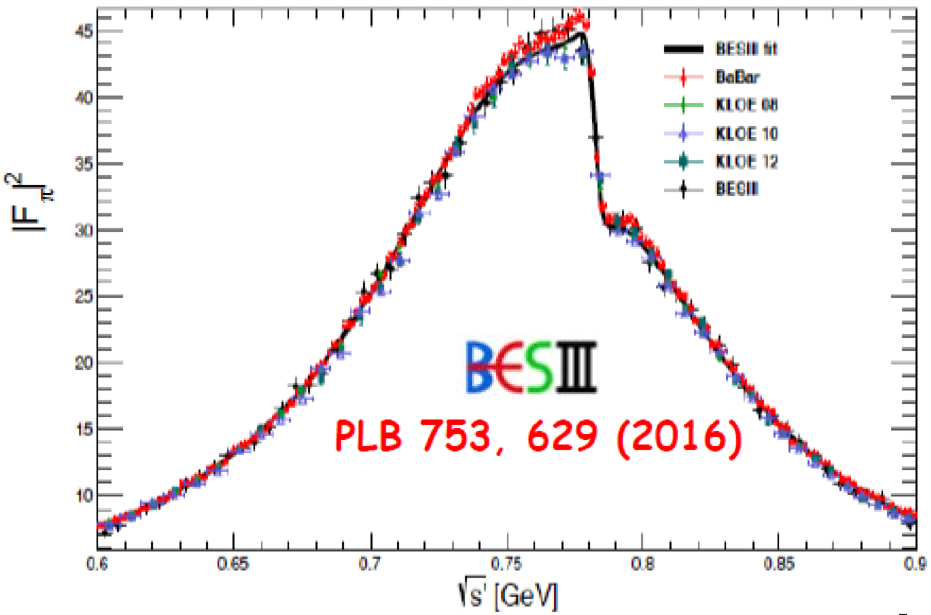


Fit function: Gounaris-Sakurai Parameterization

χ^2 / ndf = 33.2 / 51

Comparisons between BESIII and BaBar/ KLOE

- Pion form factor F_π

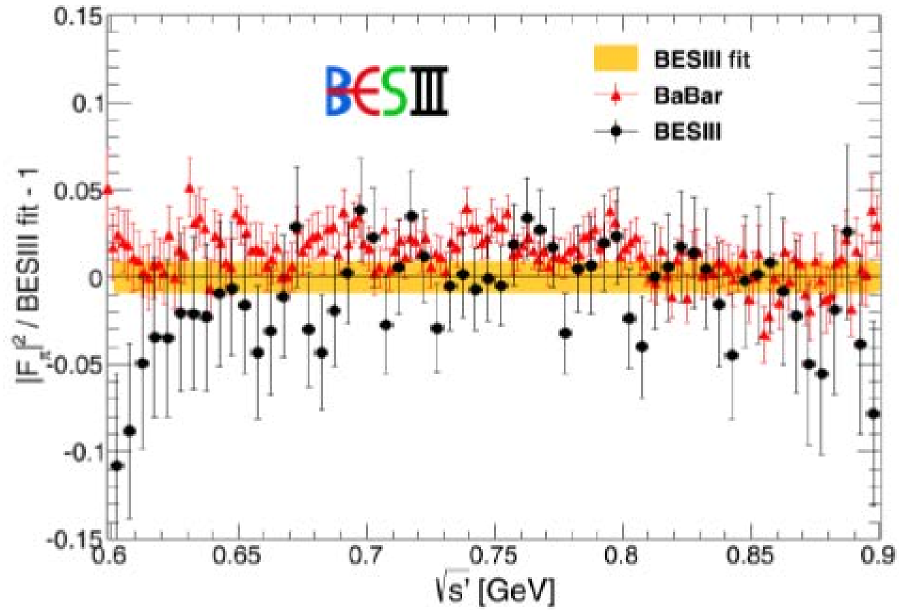


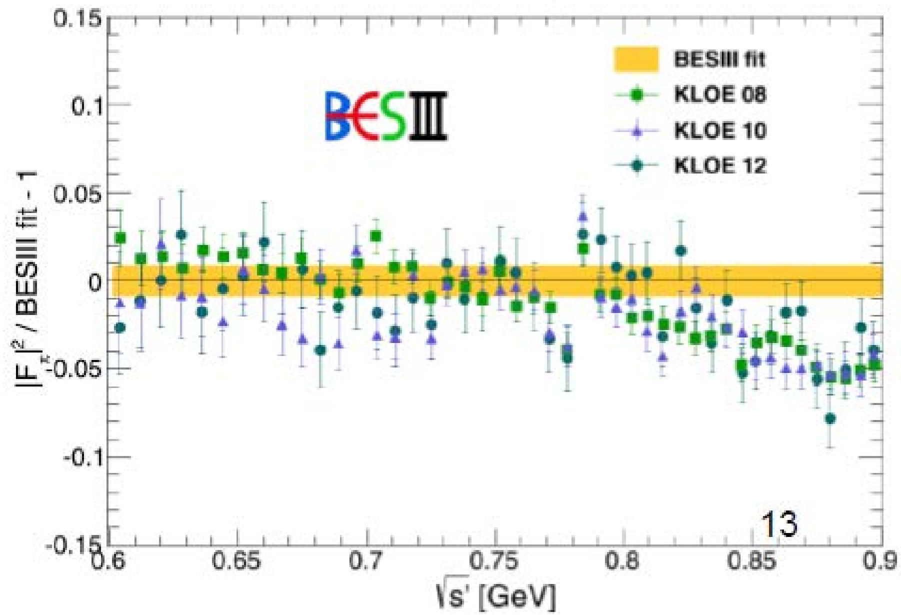
- New BESIII measurement agree with KLOE[1] and BaBar [2]

- Small shift wrt BaBar's results above ρ–ω interference

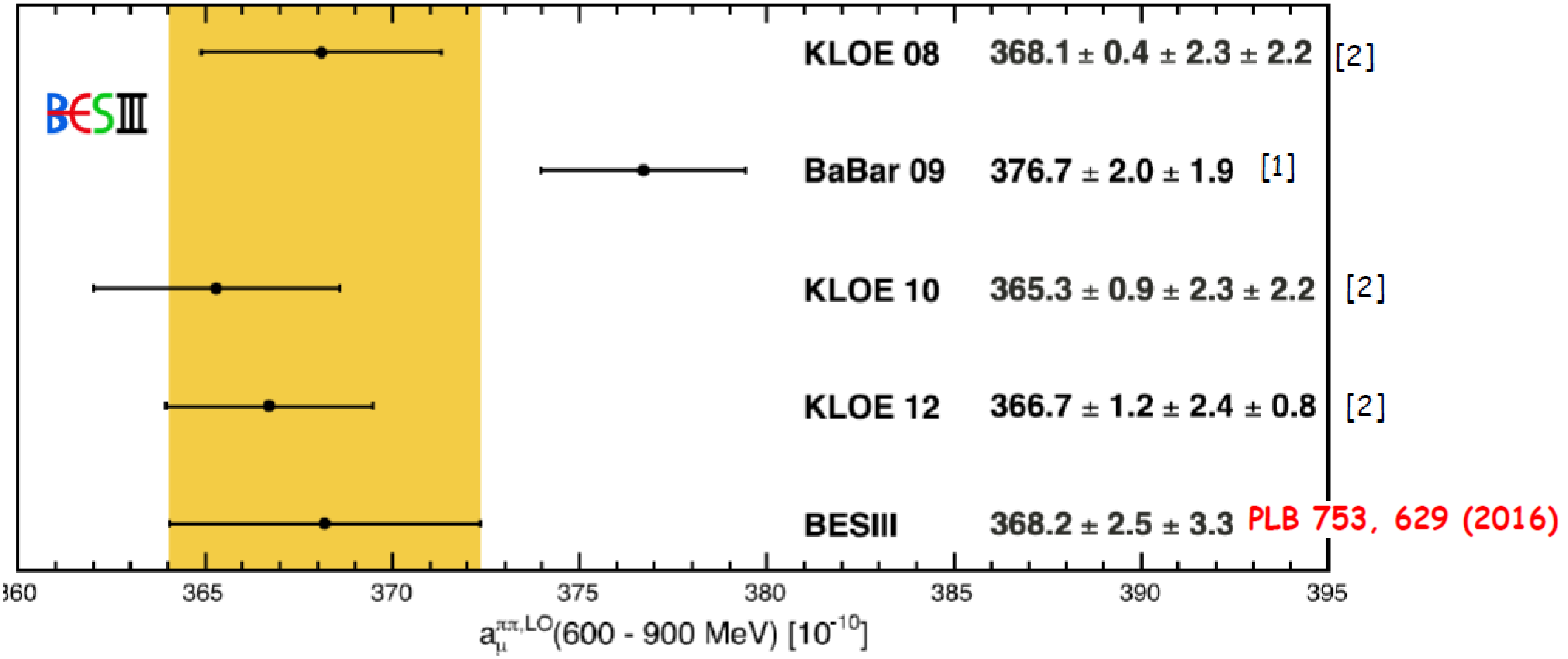
[1] B. Aubert et al., Phys. Rev. Lett. 103, 231801 (2009).
J.P. Lees et al., Phys. Rev. D86, 032013 (2012)

[2] F. Ambrosino et al. Phys. Lett. B 670, 285 (2009).
F. Ambrosino et al. Phys. Lett. B 700, 102-110 (2011).
D. Babusci et al. Phys. Lett. B 720, 336-343 (2013).





Contribution of $\pi^+\pi^-$ to a_μ



- Precision compatible with previous measurements
- $a_\mu^{(\pi\pi,LO)} = (370.0 \pm 2.5_{stat} \pm 3.3_{sys})\times 10^{-10}$
- Confirm deviation of (g-2) between experiment and theory larger than 3σ

[1] B. Aubert et al., Phys. Rev. Lett. 103, 231801 (2009). J.P. Lees et al., Phys. Rev. D86, 032013 (2012)

[2] F. Ambrosino et al. Phys. Lett. B 670, 285 (2009). F. Ambrosino et al. Phys. Lett. B 700, 102-110 (2011). D. Babusci et al. Phys. Lett. B 720, 336-343 (2013).

Part 3

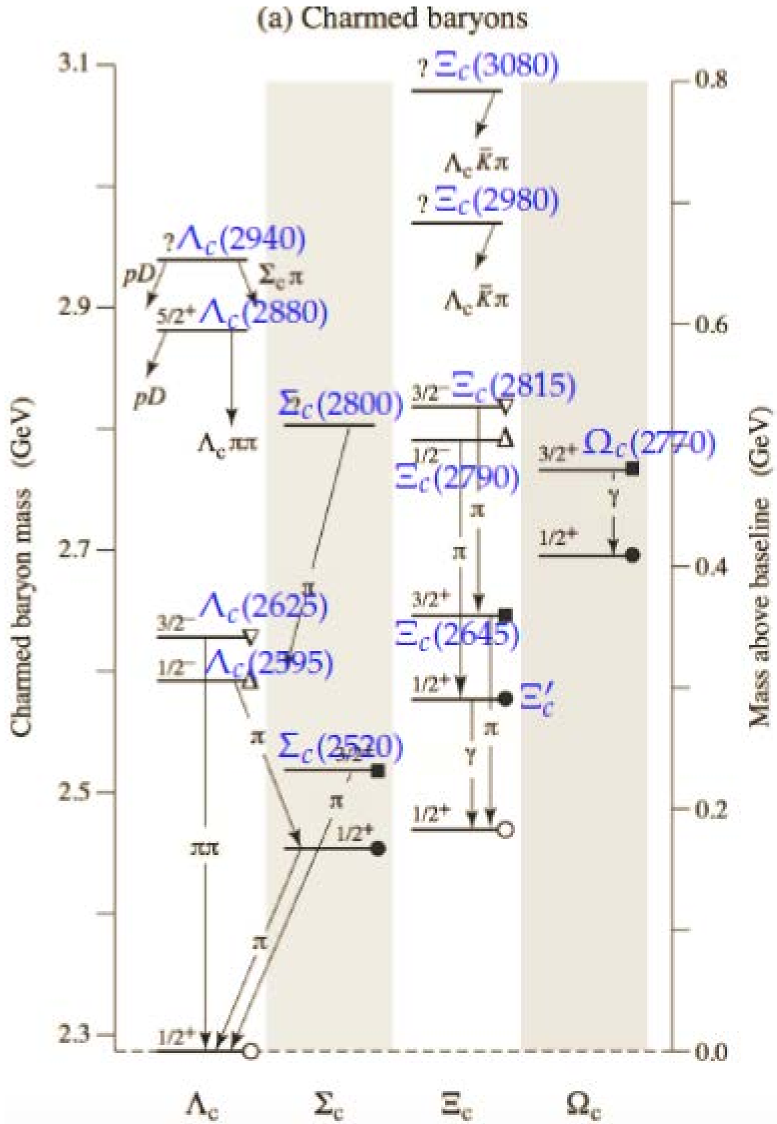
$$e^+e^- \rightarrow \Lambda_c^+ \bar{\Lambda}_c^-$$

Charmed baryon family

- Singly charmed baryongs
  - ground states: $\Lambda_c^+,\ \Sigma_c,\ \Xi_c^{(\prime)},\ \Omega_c$
  - excited states

- LHCb Collaboration observed doubly charmed baryon Ξ_{cc}^{++} via decay $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$, $\Lambda_c^+ \to p K^- \pi^+$ arXiv:1707.01621

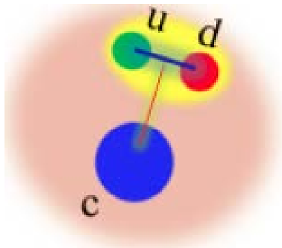
- No triply charmed baryon observed



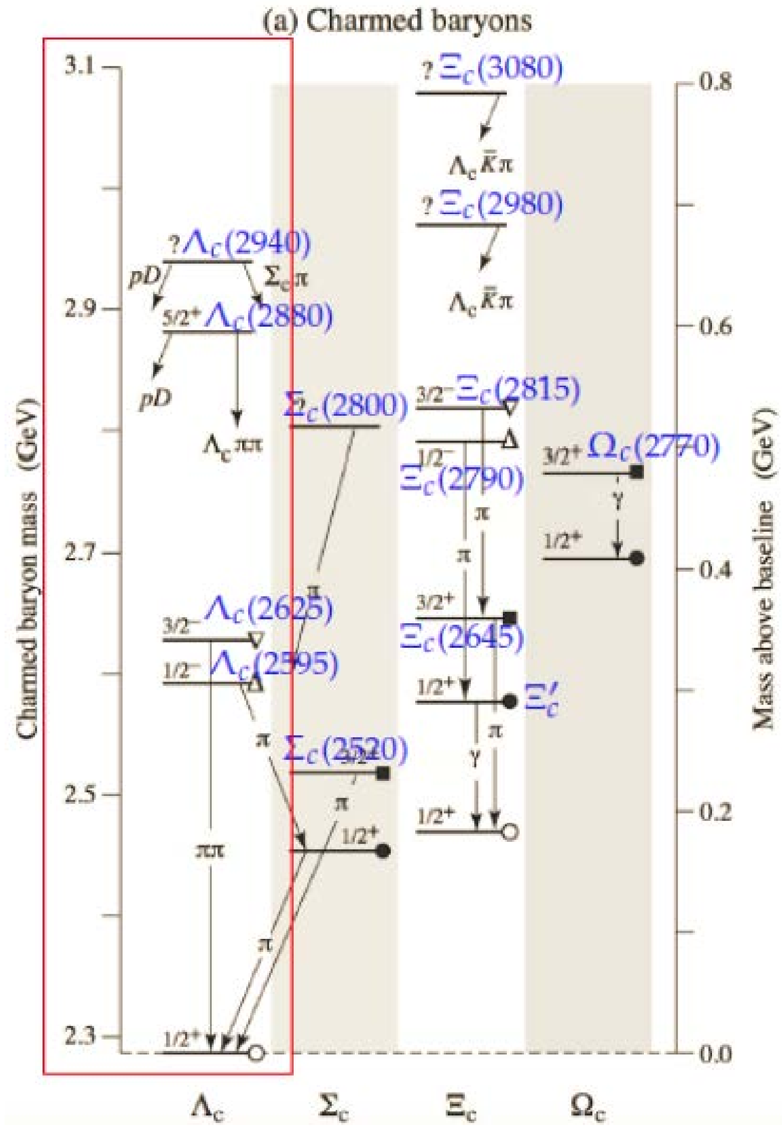
- ☐ Λ_c^+: decays only weakly
- ☐ Σ_c: $B(\Sigma_c \to \Lambda_c^+ \pi) \sim 100\%$
- ☐ Ξ_c: decays only weakly; no absolute BF measured, most are ratios relative to $\Xi^- \pi^+ (\pi^+)$
- ☐ Ω_c: decays only weakly; no absolute BF measured

Λ_c^+: Charmed baryon family

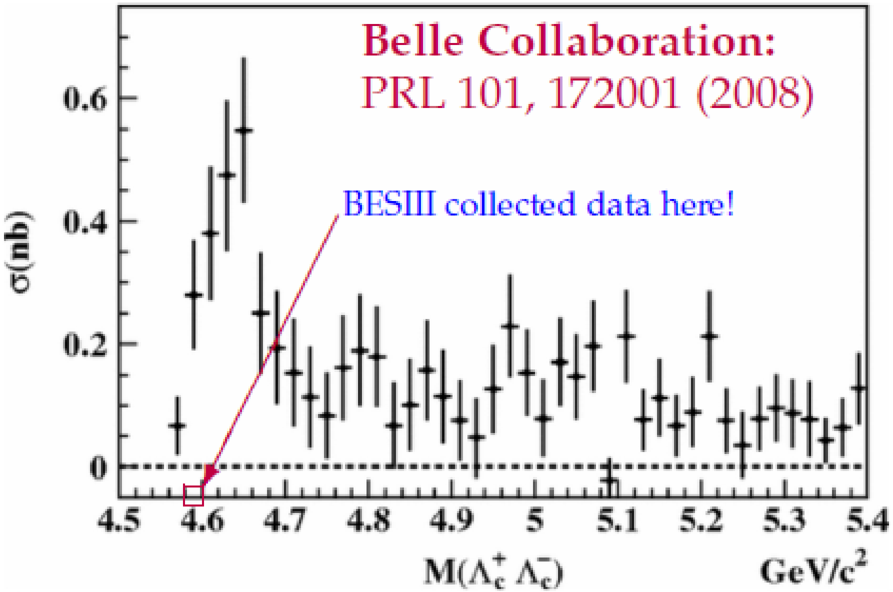
- Quark component: ud-c



- The lightest charmed baryon:
  $m_{\Lambda_c} = 2286.48$ MeV
- Most of charmed baryons decay to Λ_c
- Λ_c is important tagging charmed baryon in high energy production.
- $Br(\Lambda_c \to pK^- \pi^+)$ contributes dominant error for V_{ub} via Λ_b decay



Data samples used for $\Lambda_c^+\bar{\Lambda}_c^-$ measurements



BESIII data samples

$\sqrt{s}$ (GeV)	$\mathcal{L}_{int}$ (pb^{-1})
4.5745	47.67
4.580	8.545
4.590	8.162
4.5995	566.9

- At $\sqrt{s} = 4.5995$ GeV, the hadronic, semi-leptonic and inclusive decays of Λ_c^+ can be measured directly
- The samples make precise measurement of the Born cross section line-shape of $e^+e^- \to \Lambda_c^+\bar{\Lambda}_c^-$ near threshold possible
- At $\sqrt{s} = 4.5745$ and 4.5995 GeV, the polar angular distribution of Λ_c can be studied and the $|G_E|/|G_M|$ ratios can be extracted

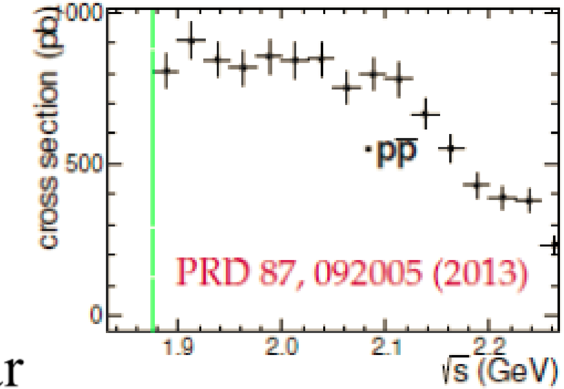
Production cross sections of baryon pairs

- Born cross section for the process $e^+e^- \to \gamma^* \to B\bar{B}$

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

  - Baryon speed $\beta = \sqrt{1 - 4m_B^2c^4/q^2}$, $\tau = q^2/(4m_B^2c^4)$

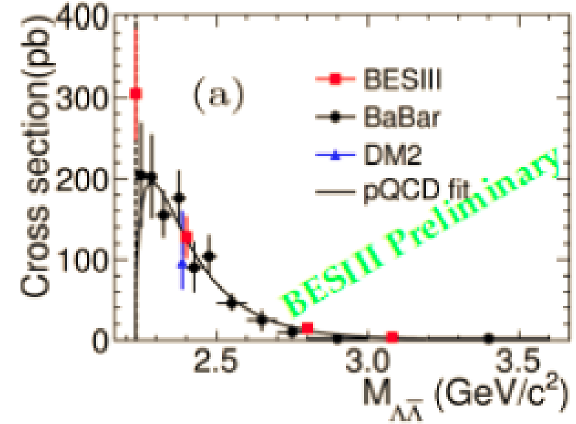
  - Coulomb factor C results in a non-zero cross section at threshold



- $e^+e^- \to p\bar{p}$: an enhancement and wide plateau

- $e^+e^- \to \Lambda\bar{\Lambda}$: non-zero cross section near threshold

- It could be anticipated that behaviour of Λ_c is similar to that of proton

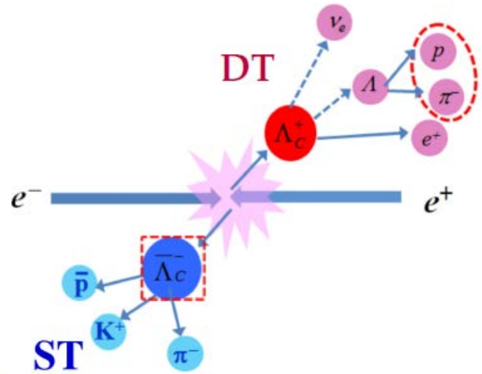


- Belle Collaboration has measured the cross section of $e^+e^- \to \Lambda_c^+\bar{\Lambda}_c^-$ using ISR return method PRL101, 172001(2008)

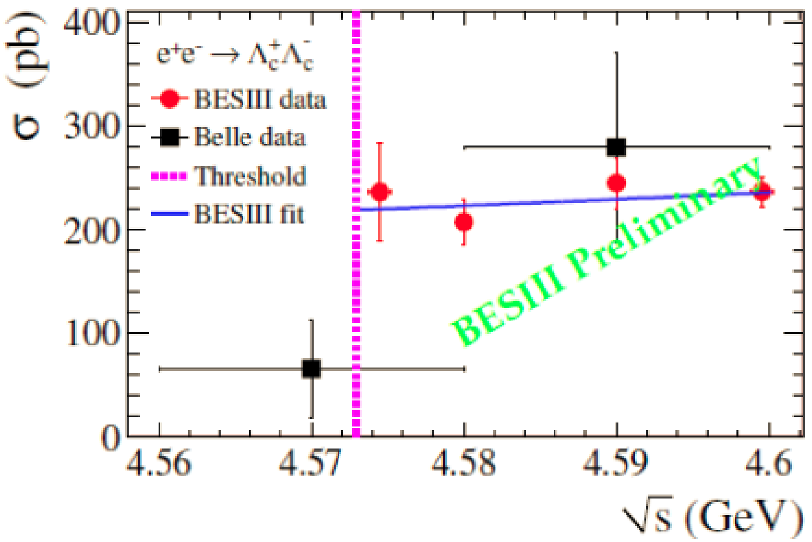
Cross section of $\Lambda_c^+\bar{\Lambda}_c^-$

BESIII preliminary results:

$\sqrt{s}$ (GeV)	σ (pb)
4.5745	$236 \pm 11 \pm 46$
4.580	$207 \pm 17 \pm 13$
4.590	$245 \pm 19 \pm 16$
4.5995	$237 \pm 3 \pm 15$

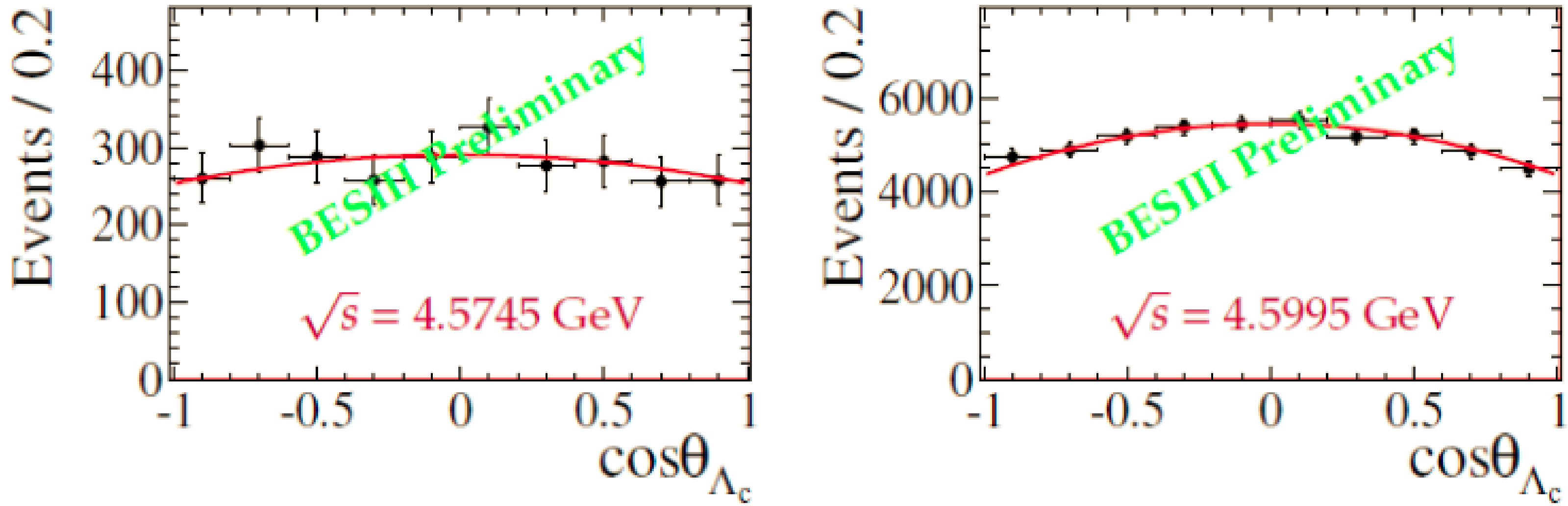


- 10 hadronic decays of Λ_c are employed
- Single Tag method (ΔE & M_{BC}) is used
- Λ_c^+ and $\bar{\Lambda}_c^-$ are reconstructed independently
- Total cross sections are obtained from weighted average



- The cross sections are measured with unprecedented precision
- Enhanced cross section of process $e^+e^- \to \Lambda_c^+\bar{\Lambda}_c^-$ close to threshold is discerned for the first time
- The enhancement: the Coulomb effect or dynamics?

Fit of angular distribution of $\Lambda_c^+\bar{\Lambda}_c^-$



- Studied at 4.5745 and 4.5995 GeV only
- The bin-by-bin efficiency correction is applied on the total yields
- Combined the corrected yields from Λ_c^+ and $\bar{\Lambda}_c^-$ bins
- The χ^2 fit on the angular distribution with shape $1 + \alpha_{\Lambda_c} \cos^2\theta$

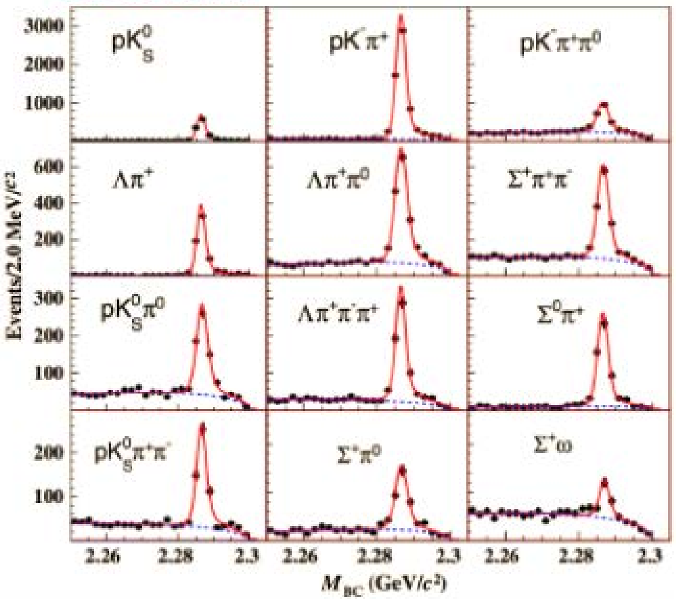
- BESIII preliminary fit

$\sqrt{s}$ (MeV)	α_{Λ_c}	$\lvert G_E/G_M \rvert$
4.5745	$-0.13 \pm 0.12 \pm 0.08$	$1.14 \pm 0.14 \pm 0.07$
4.5995	$-0.20 \pm 0.04 \pm 0.02$	$1.23 \pm 0.05 \pm 0.03$

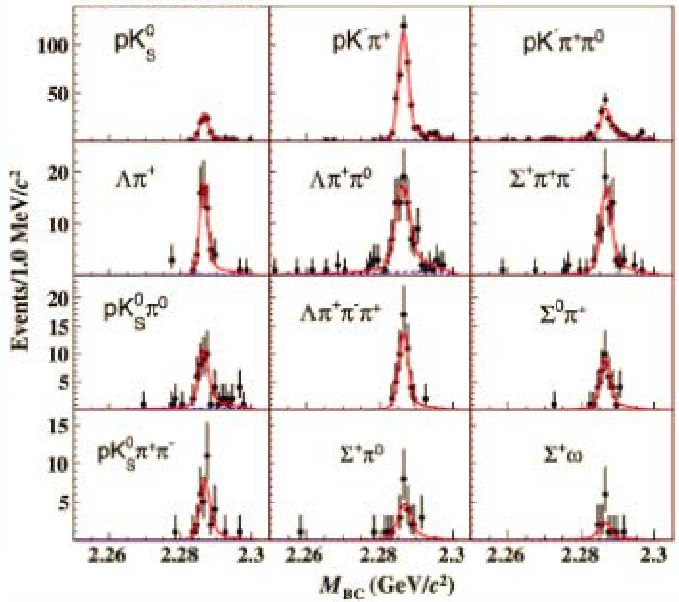
- First time that ratios $|G_E/G_M|$ of Λ_c are measured near threshold

Cabibbo Favored hadronic decays of Λ_c^+

ST events:



DT events:



- $N_j^{ST} = N_{Tot.}\mathcal{B}_j\varepsilon_j$
- $N_{ij}^{DT} = N_{Tot.}\mathcal{B}_i\mathcal{B}_j\varepsilon_{ij}$
- $\mathcal{B}_i = \frac{N_{ij}^{DT}}{N_j^{ST}}\frac{\varepsilon_j}{\varepsilon_{ij}}$

PRL 116, 052001 (2016)

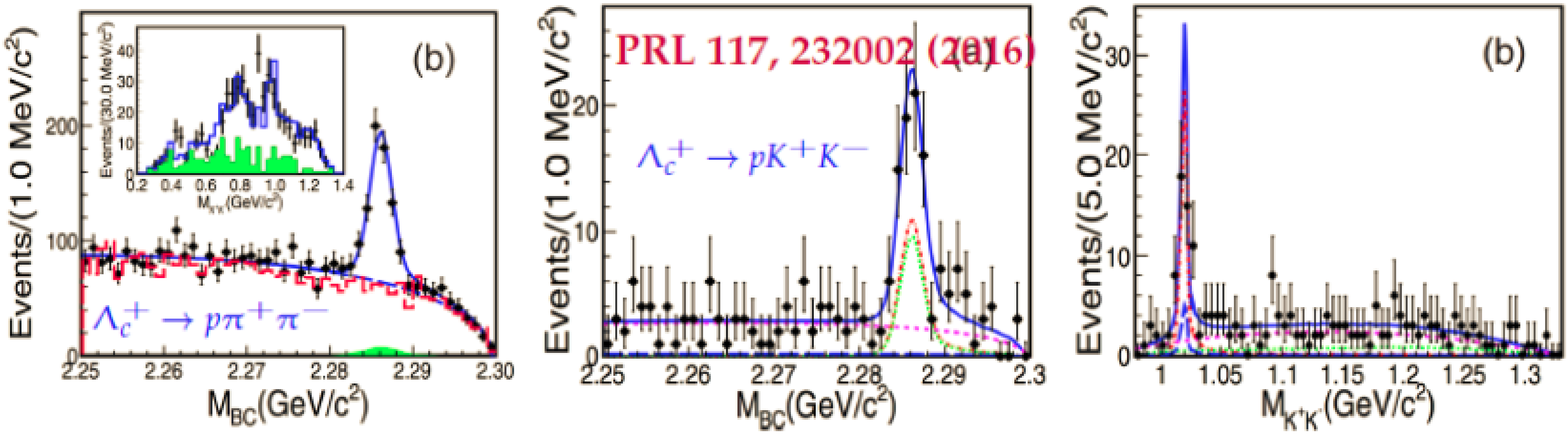
Branch ratios $\mathcal{B}_i$ of Λ_c^+ hadronic decay

Mode	This work (%)	PDG (%)
pK_S^0	$1.52 \pm 0.08 \pm 0.03$	1.15 ± 0.30
$pK^-\pi^+$	$5.84 \pm 0.27 \pm 0.23$	5.0 ± 1.3
$pK_S^0\pi^0$	$1.87 \pm 0.13 \pm 0.05$	1.65 ± 0.50
$pK_S^0\pi^+\pi^-$	$1.53 \pm 0.11 \pm 0.09$	1.30 ± 0.35
$pK^-\pi^+\pi^0$	$4.53 \pm 0.23 \pm 0.30$	3.4 ± 1.0
$\Lambda\pi^+$	$1.24 \pm 0.07 \pm 0.03$	1.07 ± 0.28
$\Lambda\pi^+\pi^0$	$7.01 \pm 0.37 \pm 0.19$	3.6 ± 1.3
$\Lambda\pi^+\pi^-\pi^+$	$3.81 \pm 0.24 \pm 0.18$	2.6 ± 0.7
$\Sigma^0\pi^+$	$1.27 \pm 0.08 \pm 0.03$	1.05 ± 0.28
$\Sigma^+\pi^0$	$1.18 \pm 0.10 \pm 0.03$	1.00 ± 0.34
$\Sigma^+\pi^+\pi^-$	$4.25 \pm 0.24 \pm 0.20$	3.6 ± 1.0
$\Sigma^+\omega$	$1.56 \pm 0.20 \pm 0.07$	2.7 ± 1.0

- The first direct measurement of the Λc near the production threshold
- Branch ratio of $pK^-\pi^+$ is consistent with Belle's results
- Measurements of the 11 modes of semi-leptonic decay improved

Decay $\Lambda_c^+ \to p\pi^+\pi^-$ and pK^+K^-

- Sensitive to nonfactorizable contributions from W-exchange diagrams
- $\Lambda_c^+ \to p\phi$ is particular interest due to only internal W-emission diagrams



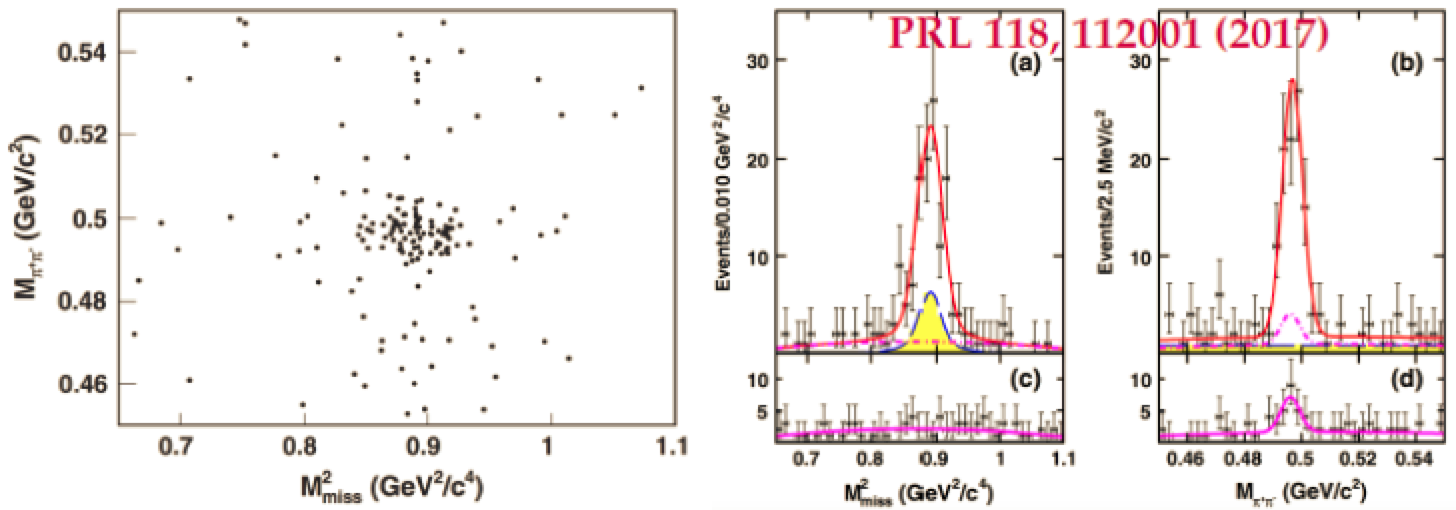
Decay modes	$\mathcal{B}_{mode}/\mathcal{B}_{ref}$ (This work)	$\mathcal{B}_{mode}/\mathcal{B}_{ref}$ (PDG average)
$\Lambda_c^+ \to p\pi^+\pi^-$	$(6.70 \pm 0.48 \pm 0.25) \times 10^{-2}$	$(6.9 \pm 3.6) \times 10^{-2}$
$\Lambda_c^+ \to p\phi$	$(1.81 \pm 0.33 \pm 0.13) \times 10^{-2}$	$(1.64 \pm 0.32) \times 10^{-2}$
$\Lambda_c^+ \to pK^+K^-$ (non-ϕ)	$(9.36 \pm 2.22 \pm 0.71) \times 10^{-3}$	$(7 \pm 2 \pm 2) \times 10^{-3}$
–	$\mathcal{B}_{mode}$ (This work)	$\mathcal{B}_{mode}$ (PDG average)
$\Lambda_c^+ \to p\pi^+\pi^-$	$(3.91 \pm 0.28 \pm 0.15 \pm 0.24) \times 10^{-3}$	$(3.5 \pm 2.0) \times 10^{-3}$
$\Lambda_c^+ \to p\phi$	$(1.06 \pm 0.19 \pm 0.08 \pm 0.06) \times 10^{-3}$	$(8.2 \pm 2.7) \times 10^{-4}$
$\Lambda_c^+ \to pK^+K^-$ (non-ϕ)	$(5.47 \pm 1.30 \pm 0.41 \pm 0.33) \times 10^{-4}$	$(3.5 \pm 1.7) \times 10^{-4}$

- Single tag method is used
- Using the decay $pK^-\pi^+$ as the reference mode

- First observation of the singly Cabibbo suppressed decay $\Lambda_c^+ \to p\,\pi^+\pi^-$
- precision of decays $\Lambda_c \to p\,K^+K^-$ (non-ϕ) and $\Lambda_c \to p\phi$ improved

Decay $\Lambda_c^+ \to n K_S \pi^+$

- A precision test for the isospin symmetry and final states interaction
- DT method: $M^2_{miss} \equiv E^2_{miss}/c^4 - |\vec{p}_{miss}|^2/c^2$

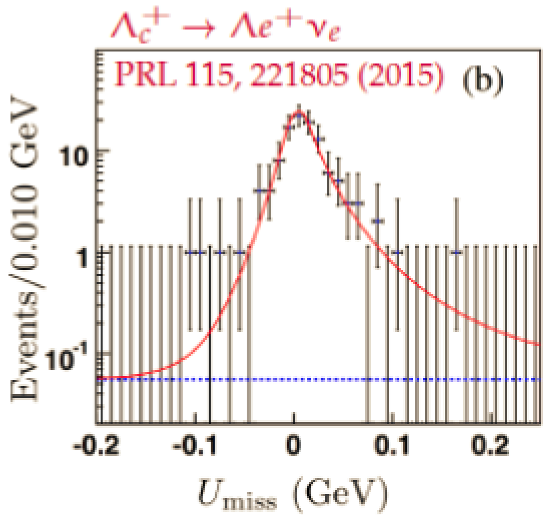


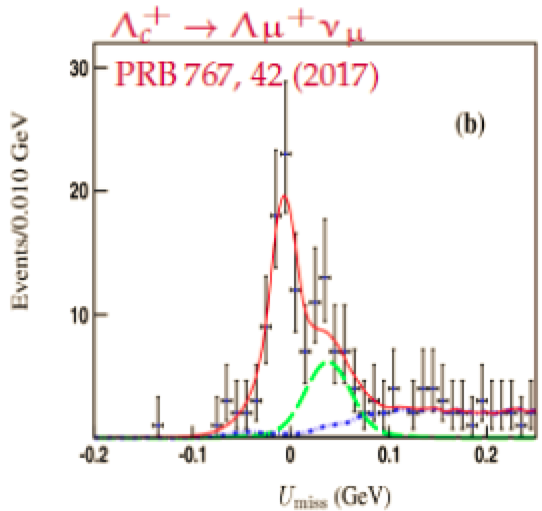
- $\mathcal{B}(\Lambda_c^+ \to n K_S^0 \pi^+) = (1.82 \pm 0.23 \pm 0.11)\%$
- $\mathcal{B}(\Lambda_c^+ \to n \bar{K}^0 \pi^+)/\mathcal{B}(\Lambda_c^+ \to p K^- \pi^+) = 0.62 \pm 0.09$
- $\mathcal{B}(\Lambda_c^+ \to n \bar{K}^0 \pi^+)/\mathcal{B}(\Lambda_c^+ \to p \bar{K}^0 \pi^0) = 0.97 \pm 0.16$

The first direct measurement of Λ_c^+ decay involving neutron in final state

Decay $\Lambda_c^+ \to \Lambda l^+ \nu_l$

- A stringent test for nonperturbative aspects of strong interaction theory
- The key ingredient in calibrating Lattice QCD calculations
- There is no absolute measurement of Λ_c^+ semi-leptonic decay yet
- Mutually confirm and test the leptonic university





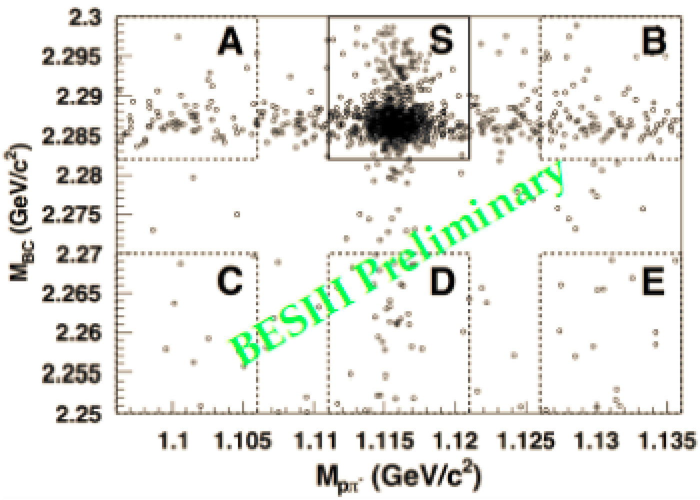
- DT method is used, 11 modes are tagged
- missing mass technique at threshold
- $U_{\rm miss} = E_{\rm miss} - c|\vec{p}_{\rm miss}|$

- $\mathcal{B}(\Lambda_c^+ \to \Lambda e^+ \nu_e) = (3.63 \pm 0.38 \pm 0.20)\%$
- $\mathcal{B}(\Lambda_c^+ \to \Lambda \mu^+ \nu_\mu) = (3.49 \pm 0.46 \pm 0.27)\%$
- $\mathcal{B}(\Lambda_c^+ \to \Lambda e^+ \nu_e)/\mathcal{B}(\Lambda_c^+ \to \Lambda \mu^+ \nu_\mu) = 0.96 \pm 0.16 \pm 0.04$

The first direct measurement of Λ_c^+ semi-leptonic decay

Decay $\Lambda_c^+ \to \Lambda X$

- This decay is mediated by $c \to s$ and dominates the lifetime of Λ_c^+
- Help to understand the quark structure and decay dynamics of Λ_c^+
- Provide an essential input for decays of b-flavored hadrons



- DT method is used, modes $\bar{p}K^+\pi^-$ and $\bar{p}K_S^0$ are singly tagged.
- $\mathcal{A}_{cp} \equiv \frac{\mathcal{B}(\Lambda_c^+ \to \Lambda + X) - \mathcal{B}(\bar{\Lambda}_c^- \to \bar{\Lambda} + X)}{\mathcal{B}(\Lambda_c^+ \to \Lambda + X) + \mathcal{B}(\bar{\Lambda}_c^- \to \bar{\Lambda} + X)}$

Preliminary result:

$$\mathcal{B}(\Lambda_c^+ \to \Lambda + X) = (38.2^{+2.8}_{-2.2} \pm 0.6)\% \text{ and } \mathcal{A}_{cp} = (2.1^{+7.0}_{-6.6} \pm 1.1)\%$$

- Sum of known exclusive decays $\Lambda_c^+ \to \Lambda X_i$ is (24.5±2.1)%, which means other unknown decays
- No CPV is observed at current precision

Summary

♦ Proton pairs

- The effective form factors are measured with improved errors
- The ratio $|G_E/G_M|$ are extracted with uncertainty of 25% – 30%
- The ratio $|G_E/G_M|$ are close to unity between 2.2 – 3.08 GeV

♦ Pion pairs

- The cross section and form factor are measured with ISR return
- The difference of Δa_μ between experiments and theory is confirmed
- Systematic uncertainty (~0.9%) still dominant.

♦ $\Lambda_c^+\Lambda_c^-$ pairs

- Cross section and form factor close to threshold are measured
- Absolute branch ratio of Λ_c decays are studied