30TH ANNIVERSARY OF THE QCD MONTPELLIER CONFERENCE

QCD 15

MONTPELLIER FRANCE - 29 june 3 july 2015

30th Anniversary

Measurement of hadron pair production cross sections at BESIII

Haiming HU (IHEP,CAS)

On behalf of BESIII Collaboration

Outline

- Motivation
- Data samples with BEPCII/BESIII
- $e^+e^- \to p\bar{p}$
  - measurement of cross section
  - extraction of form factors
- $e^+e^- \to \pi^+\pi^-\gamma$
  - measurement of cross section
  - extraction of form factor
- Summary and prospect

Data samples of BESIII

Till June, 2015

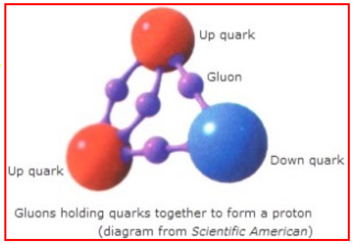
Taking data	Total Num. / Lum.	Taking time
J/ψ	225+1086 M	2009+2012
$\psi(2S)$	106+350 M	2009+2012
$\psi(3770)$	2916 pb^{-1}	2010~2011
τ scan	24 pb^{-1}	2011
Y(4260)/Y(4230)/Y(4360)/scan	806/1054/523/488 pb^{-1}	2012~2013
4600/4470/4530/4575/4420	506/100/100/42/993 pb^{-1}	2014
J/ψ line-shape scan	100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

Part 1

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

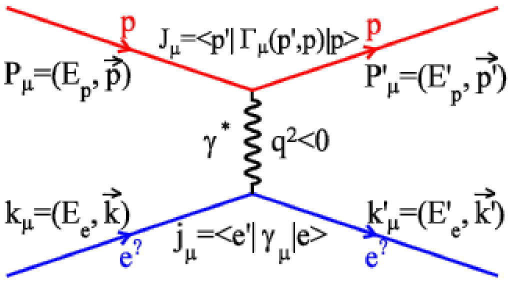
Motivation

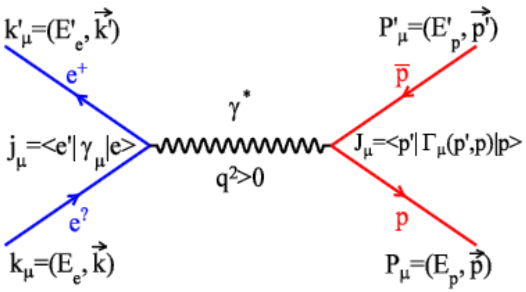
The valence-quark picture of proton in quark model:



The dynamic 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

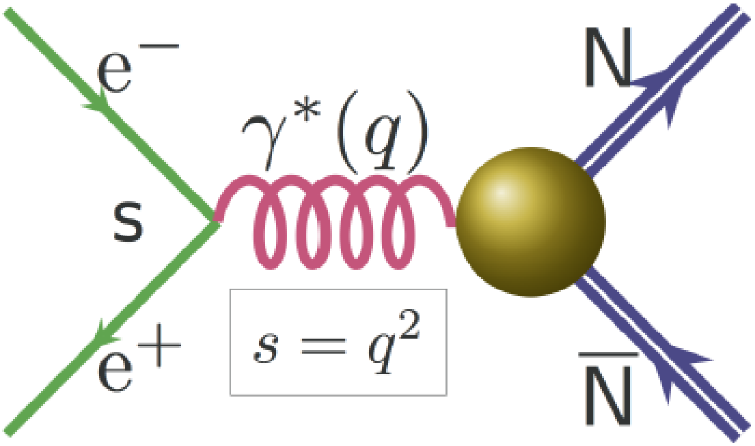
- Electronic: $G_E(q^2) = F_1(q^2) + \tau\kappa_p F_2(q^2)$
- Magnetic : $G_M(q^2) = F_1(q^2) + \kappa_p F_2(q^2)$

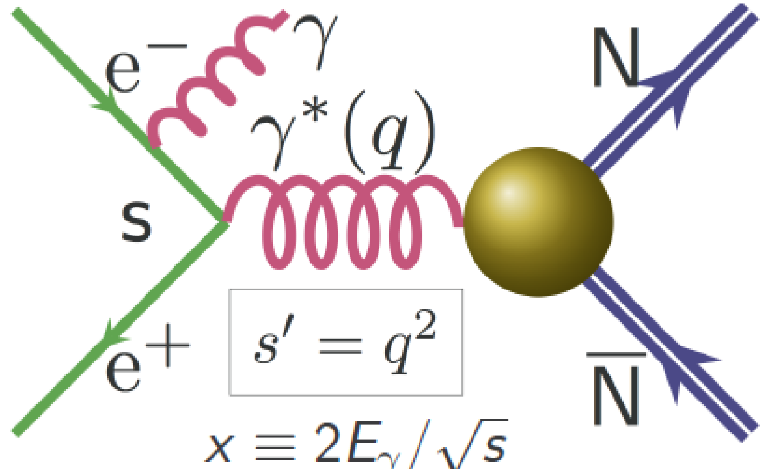
$\tau = \frac{q^2}{4m_p^2}$, $\kappa_p = \frac{g_p - 2}{2} = \mu_p - 1$

More directly perceived through the senses, G_E and G_M relate to the spetial distribution of charge and magnetization in Breit frame,
e.g, 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





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

This talk

In progress

Cross section

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

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

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

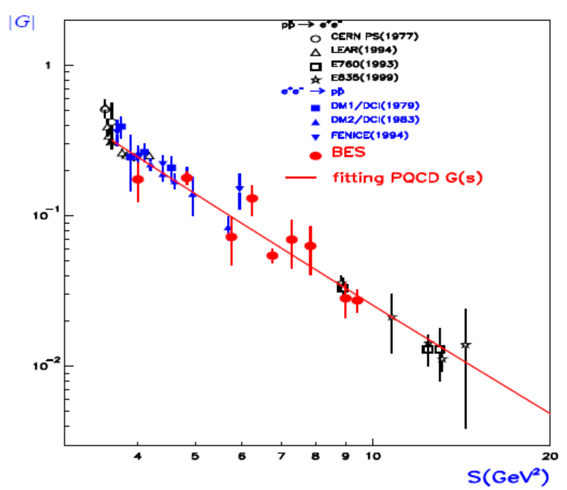
the Born cross section

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

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)

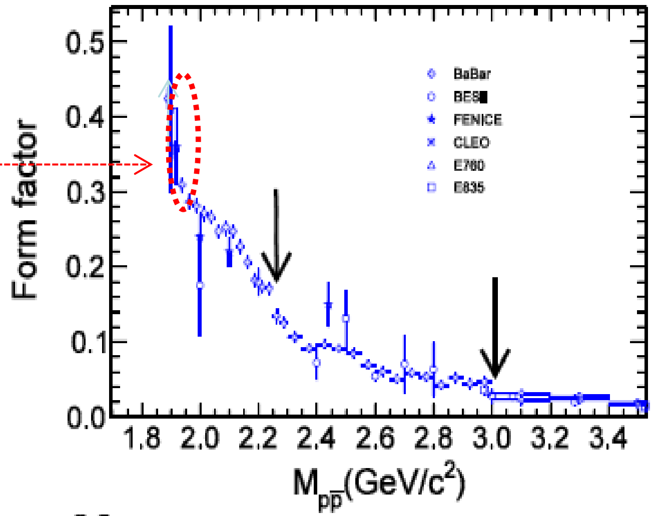
$$|G(s)| = \frac{A}{s^2\ln^2(s/\Lambda^2)}$$

Some question to make clear

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

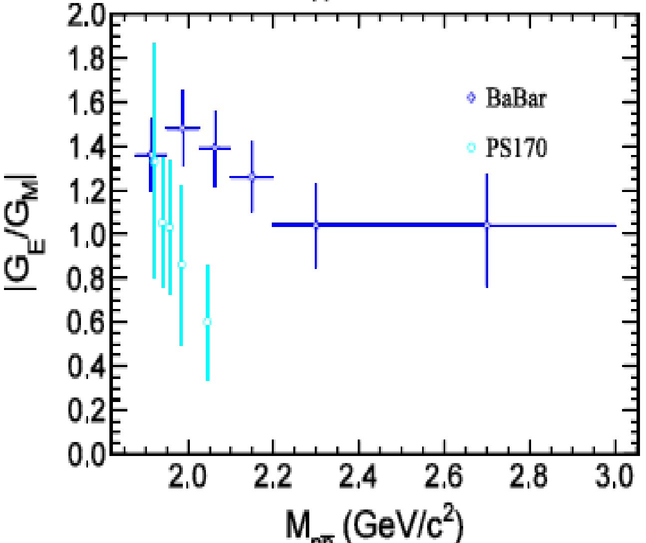
- Steep rise toward threshold ?
- Two rapid decreases around 2.25 and 3.0 GeV ?

  Are they true?



- Ratio $|G_E/G_M|$ disagreement by PS170 and BaBar
- Poor precision (~11%, 43%)
- Limited energy range

  which one is reliable?

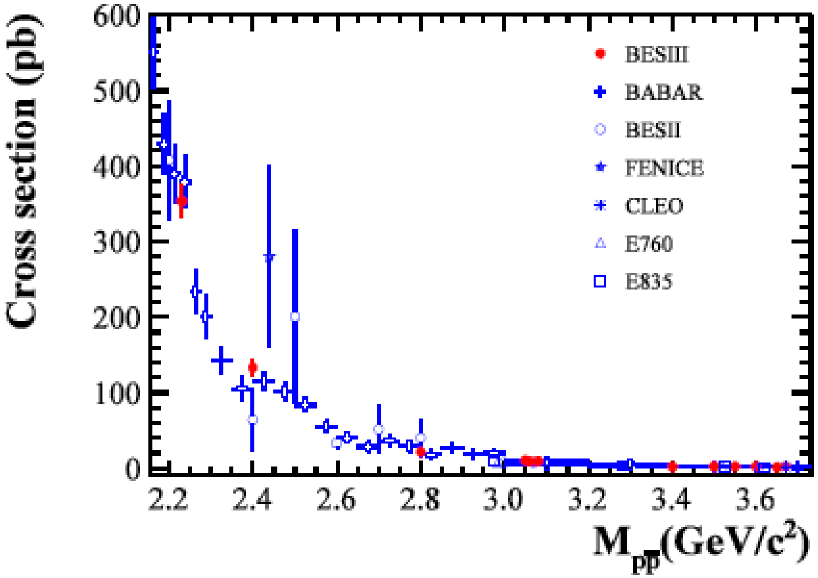


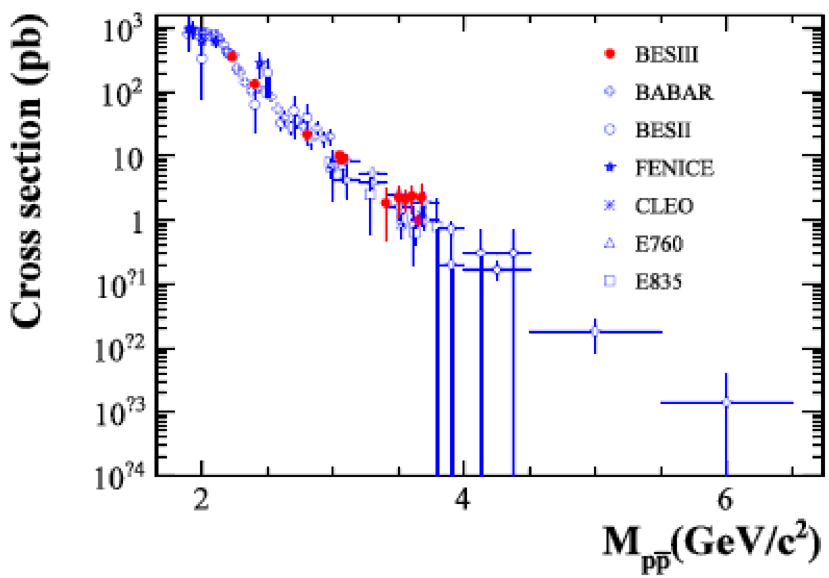
Measurement of cross section

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





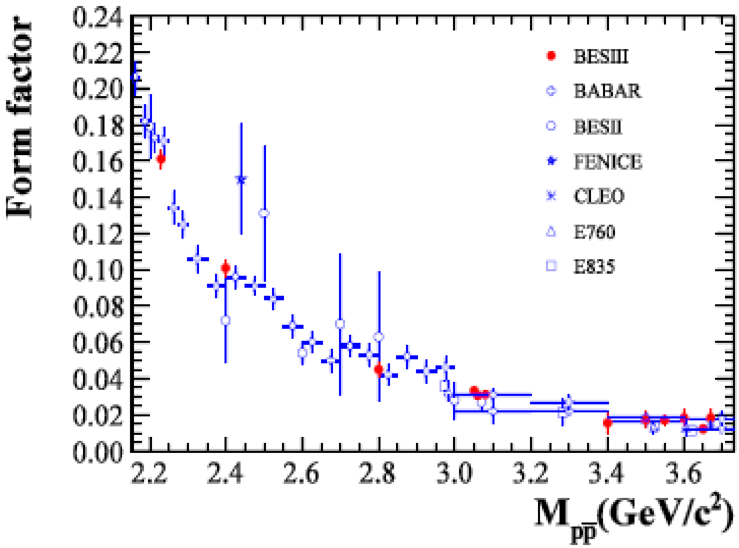
Extraction of effective form factor

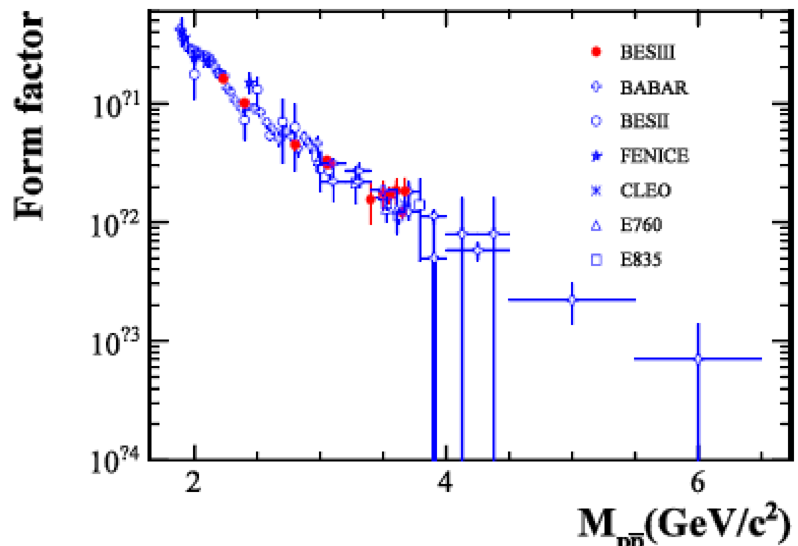
In order to compare with earlier measurements, we still assume $|G_E|=|G_M|\equiv|G_{eff}|$, and the cross section reads

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

Then the effective form factor could be extracted

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





The result with BESIII data 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

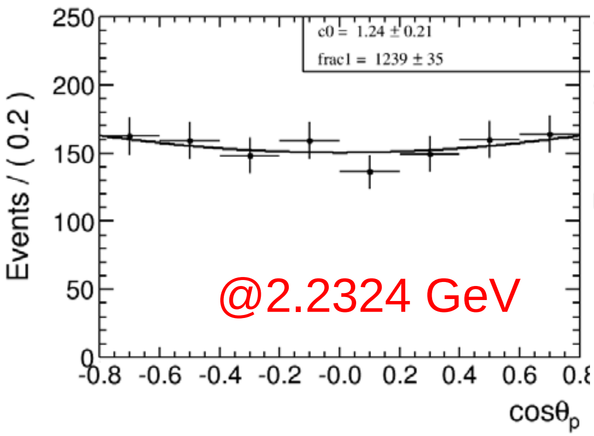
- Fit function:

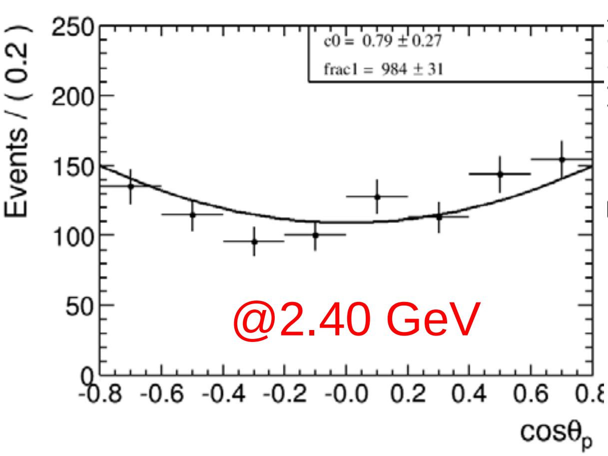
$$\frac{dN}{d\cos\theta_p} = N_{norm}\left[\left(1+\cos^2\theta_p\right) + R_{em}^2\frac{1}{\tau}\sin^2\theta_p\right]$$

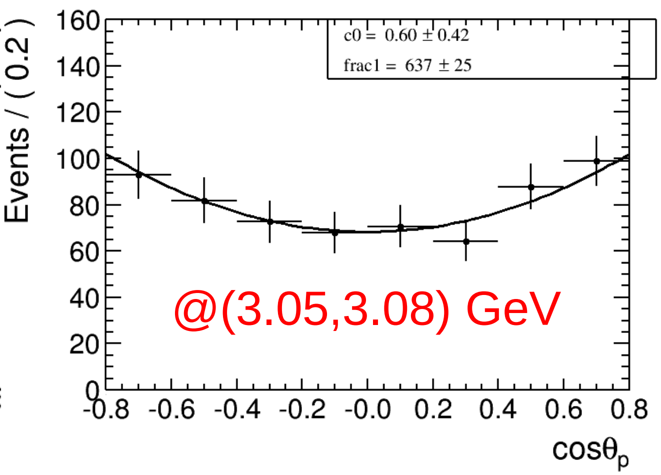
the overall normalization

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

- Results:





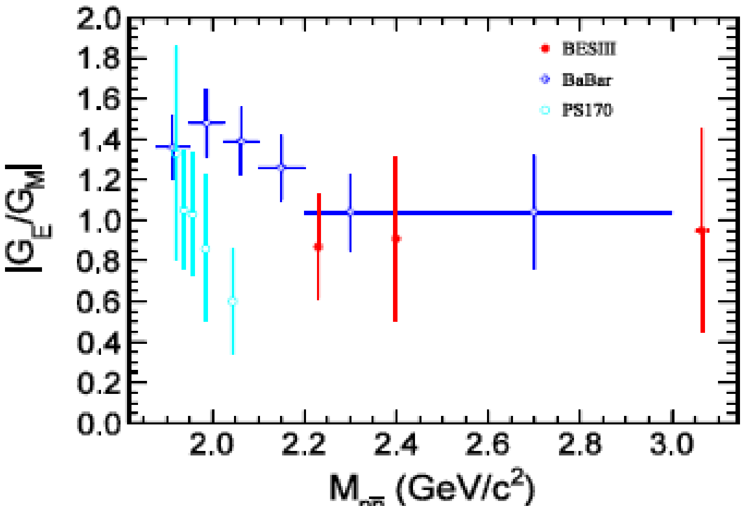


Extraction of electromagnetic $|G_E/G_M|$ ratio

- Method of moment:

- 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:



Result measured with BESIII is consistent with BaBar's, but not with PS170.

Extraction of electromagnetic ratio $|G_E/G_M|$

$\sqrt{s}$ (MeV)	$\|G_E/G_M\|$	$\|G_M\|$ ($\times 10^{-2}$)	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

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

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

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

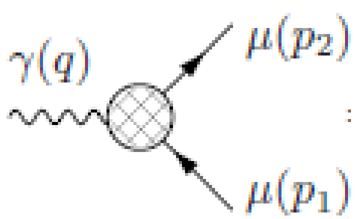
define Bohr magneton:

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

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):

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

= 

$= \text{(QED)} \quad (11\,658\,470.35 \pm 0.28)10^{-10}$ (5-loop!)

$+ \text{(had,LO)} \quad (684.7 \text{ to } 709.0 \pm 6)10^{-10}$ (Big spread, largest error)

$+ \text{(had,HO)} \quad (-10.0 \pm 0.6)10^{-10}$

$+ \text{(had,LBL)} \quad (8.0 \pm 4.0)10^{-10}$ (sign change since 1998)

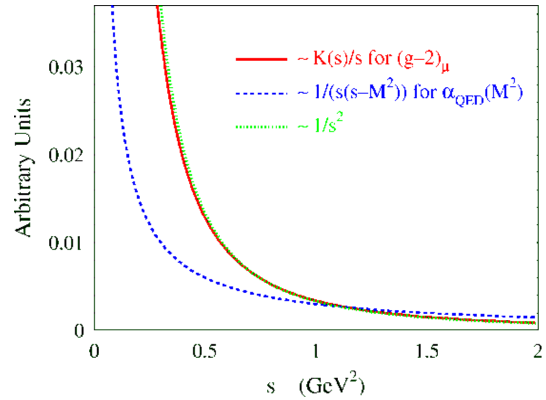
$+ \text{(weak)} \quad (15.4 \pm 0.2)10^{-10}$ (2-loop)

$a_\mu^{had,LO}$ 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

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).

Motivation

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

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

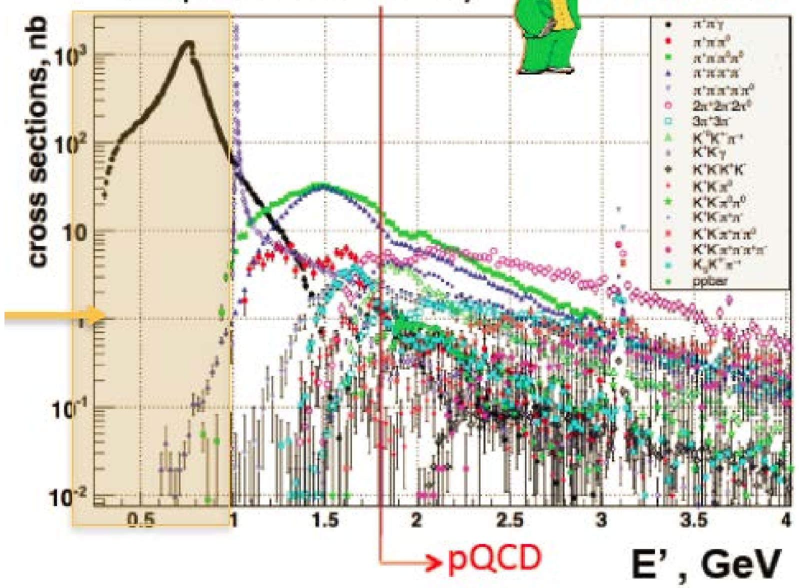
$$a_\mu^{had,LO} = \frac{1}{4\pi^3}\int_{4m_\pi^2}^{\infty} \sigma_{had}^{0}(s)K(s)ds$$

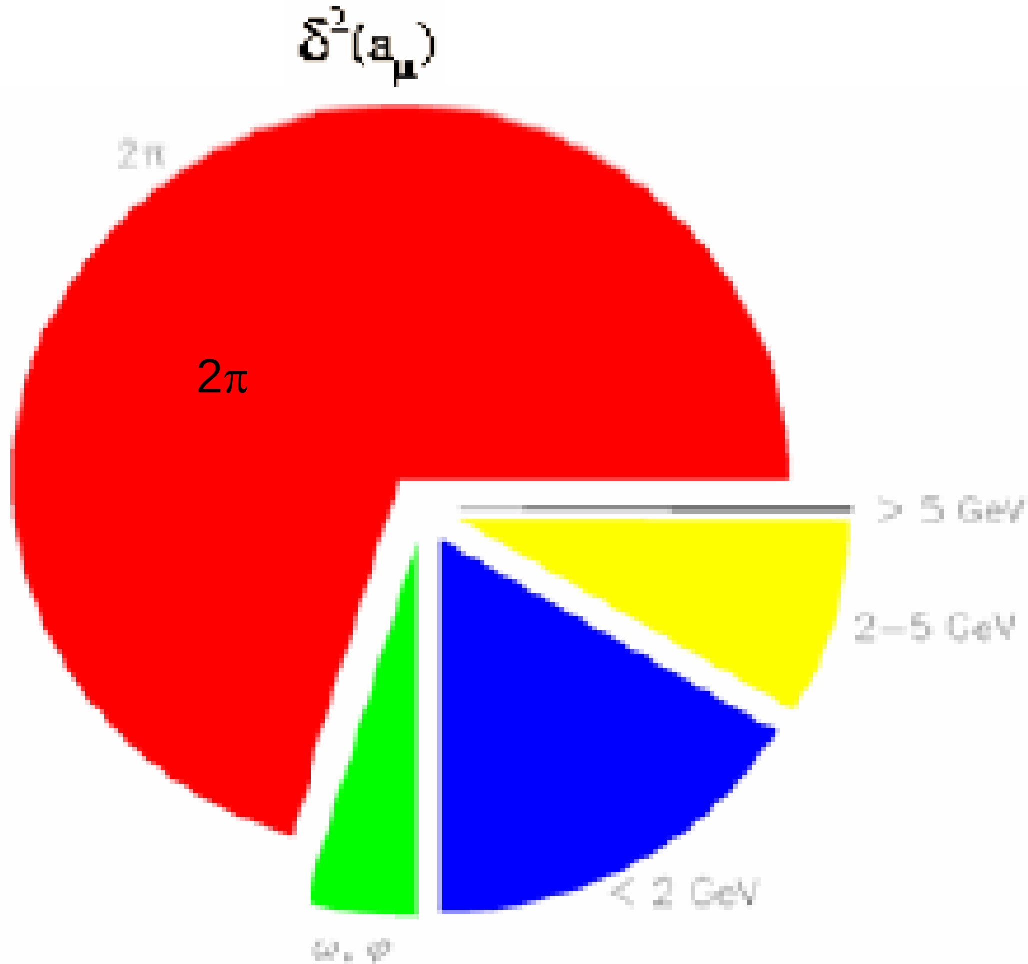
$K(s) \propto 1/s \qquad \sigma(s) \propto 1/s$

The largest contribution is below 1 GeV.

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

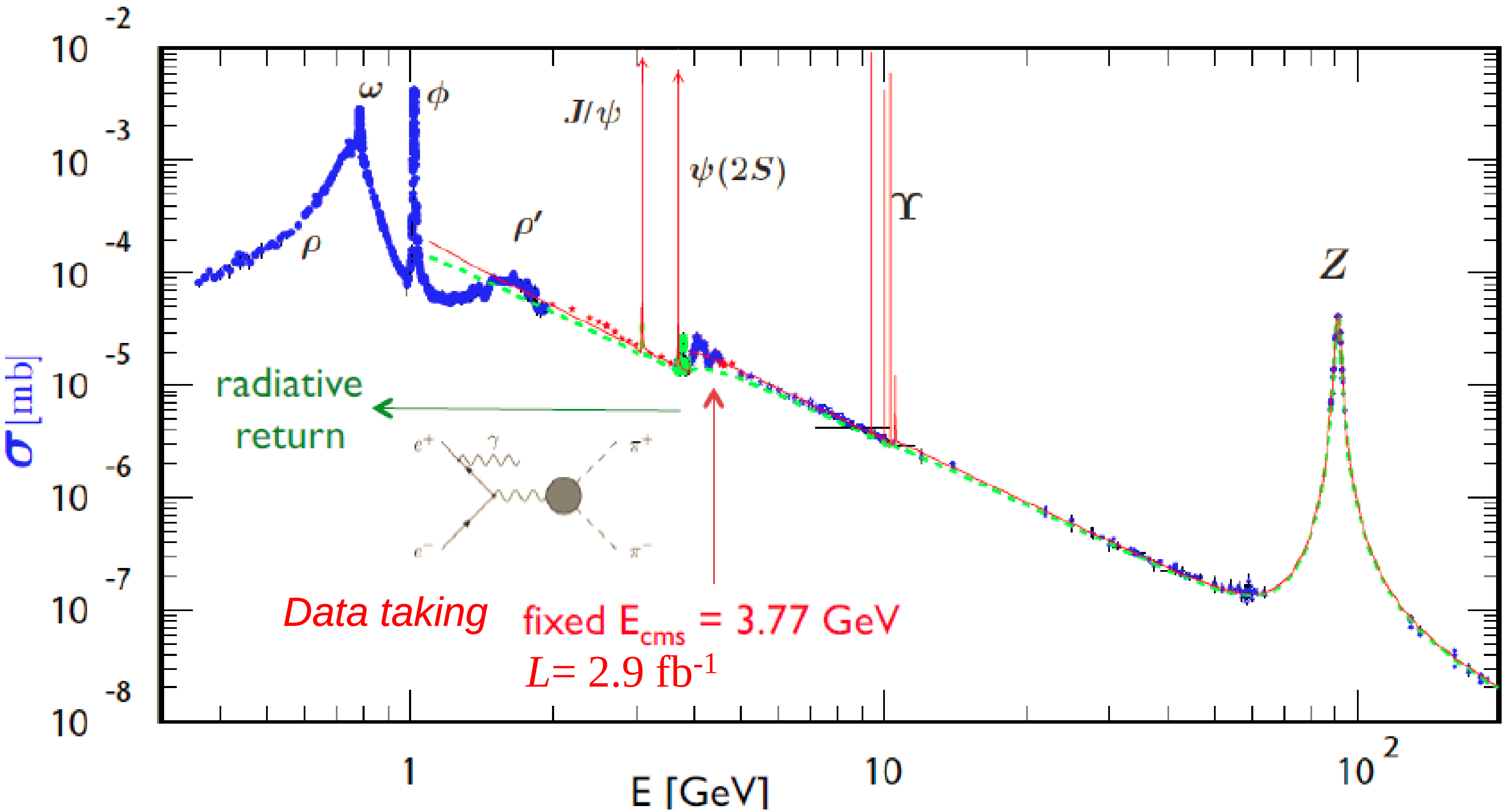
ISR spectra measured by BaBar



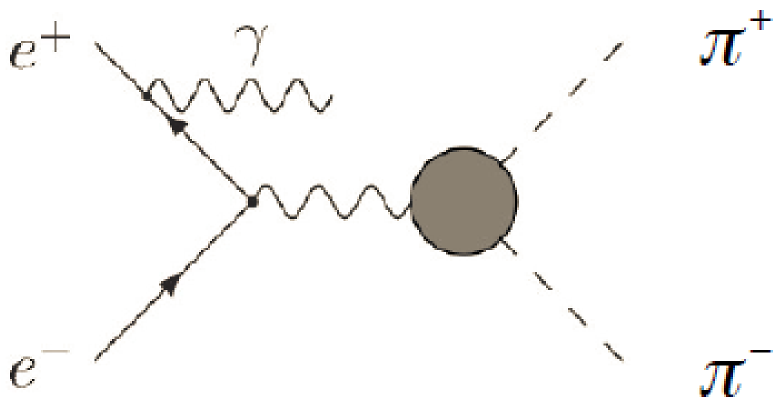


Initial state radiation

In the $e^{\pm}$ collider, photon emitted from initial $e^{\pm}$ decrease the effective $s' = s(1 - E_\gamma/E)$ continuously, this makes measurement at lower different energies possible .



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

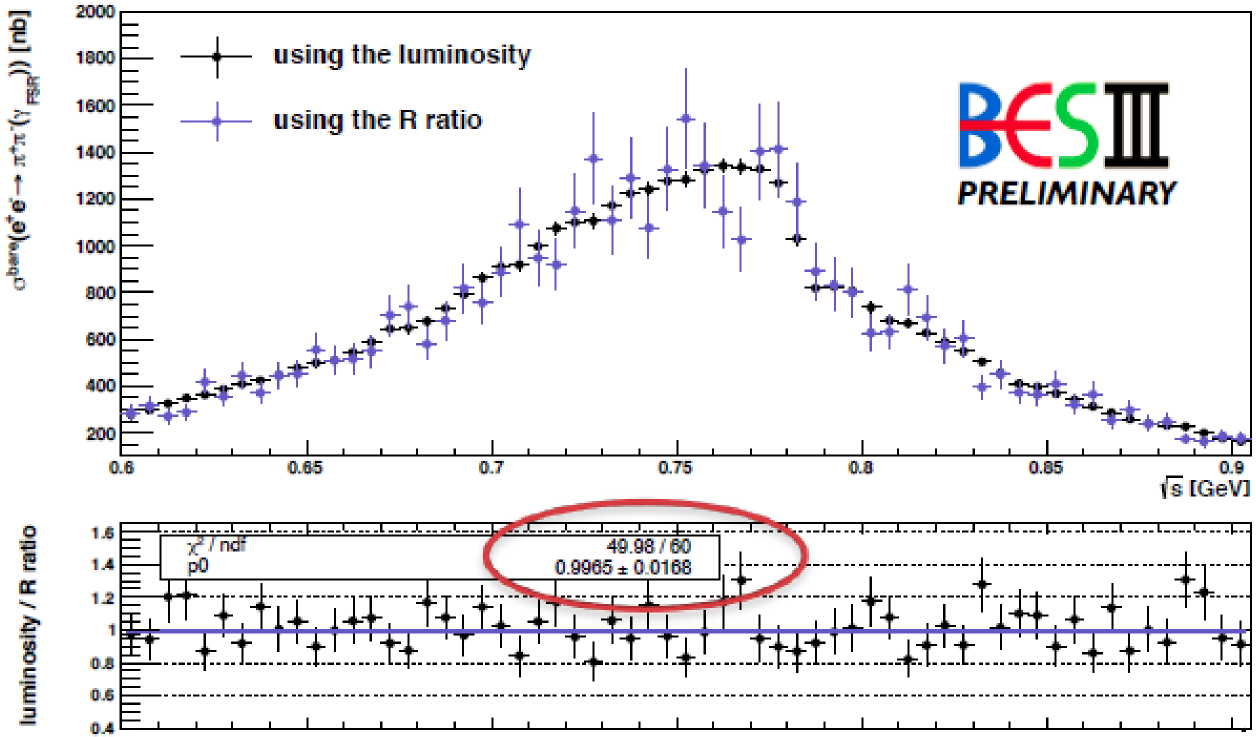
Two normalization methods

- Normalization to integrated luminosity

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

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

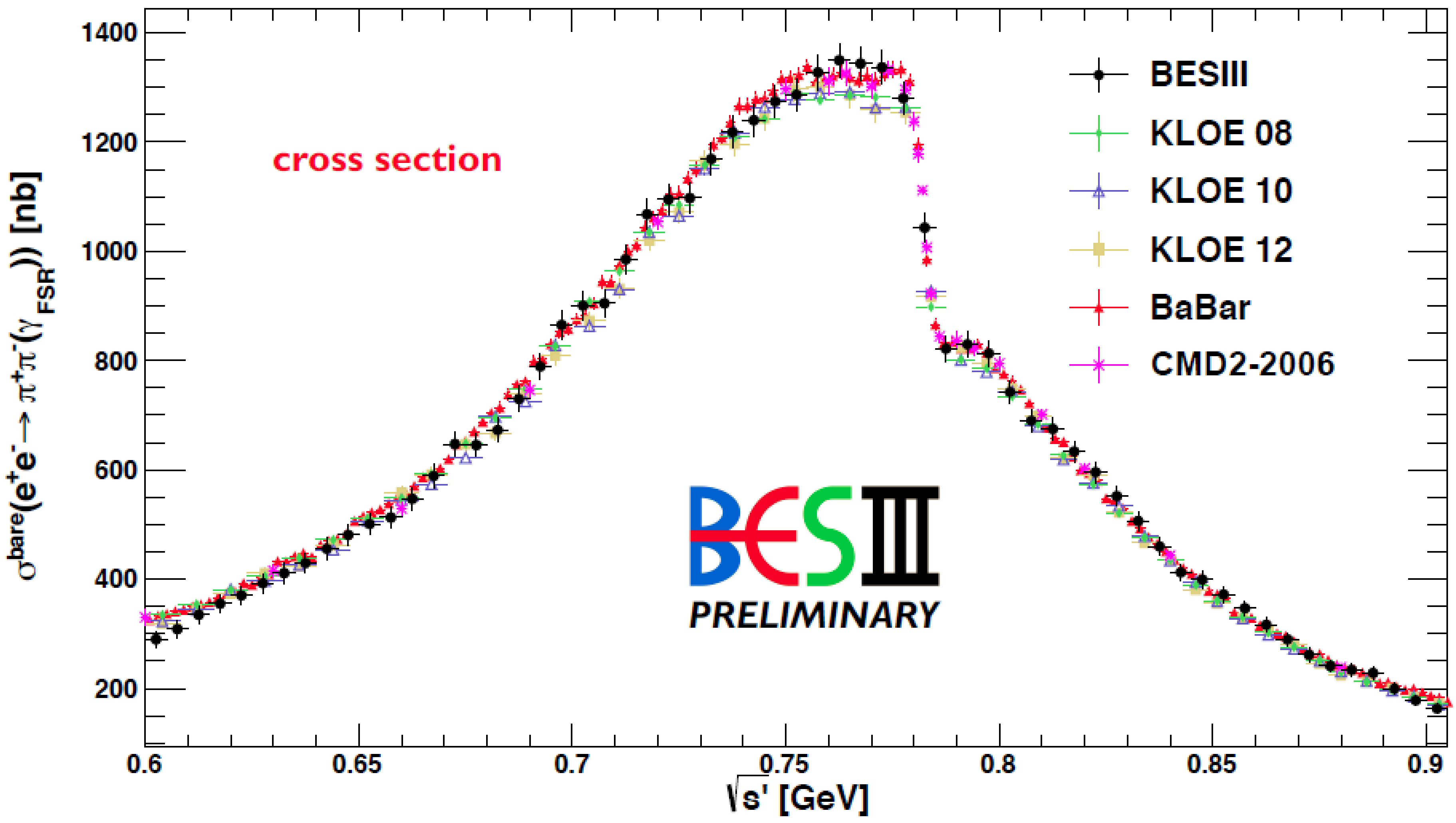
  ⟶ L_{int}, H_{rad}, δ_{vac} canceled



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

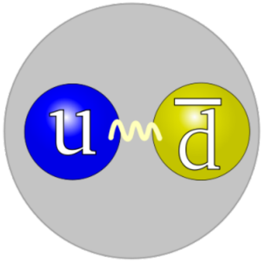
limited by $\mu^+\mu^-\gamma$ statistics

Cross section



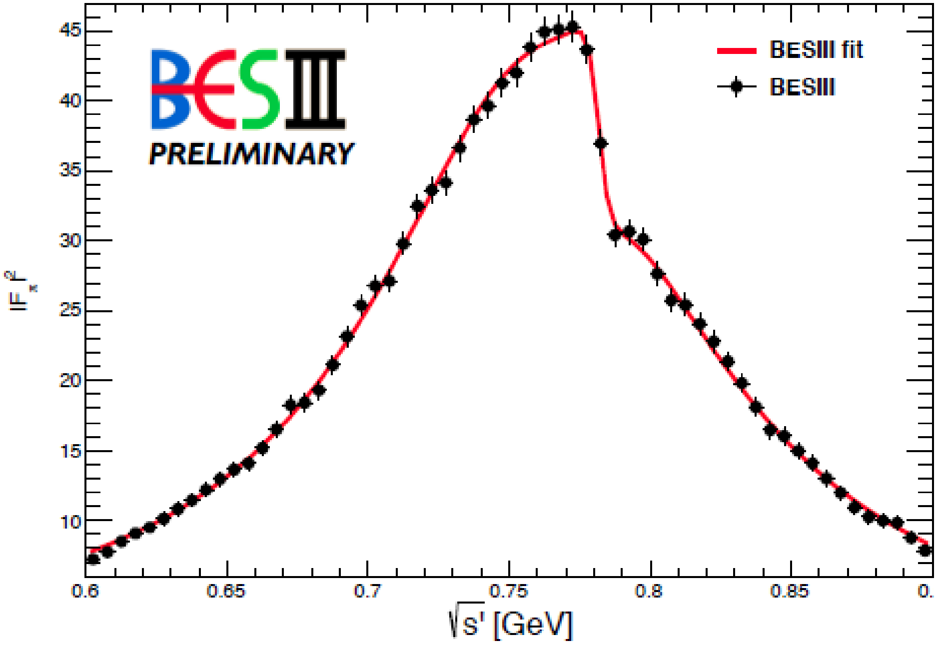
Extraction of form factor

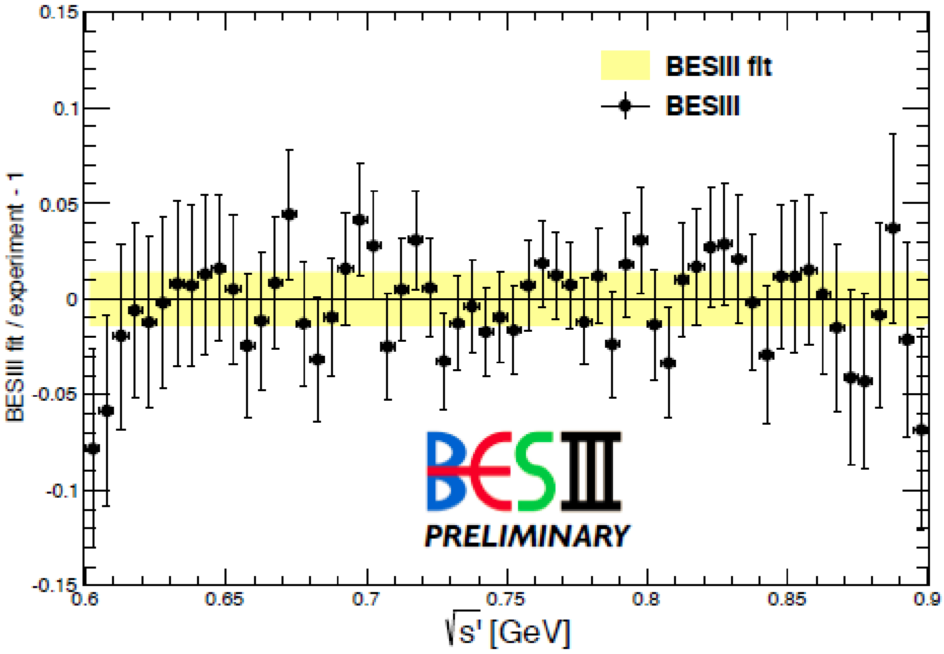
The picture of pion structure in quark model:



Not a point-like particle ⇒ pion form factor

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

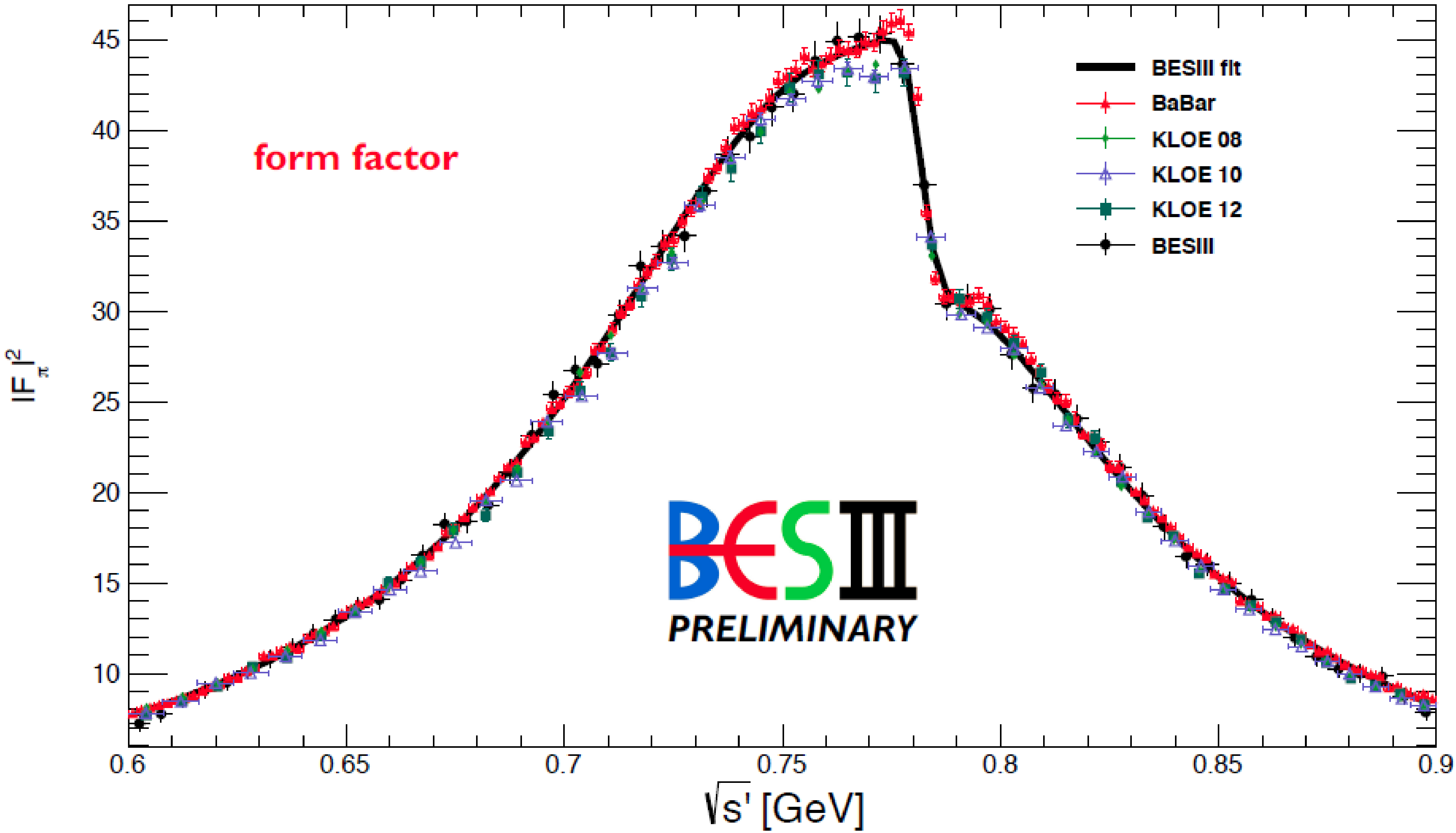




Fit function: Gounaris-Sakurai Parameterization

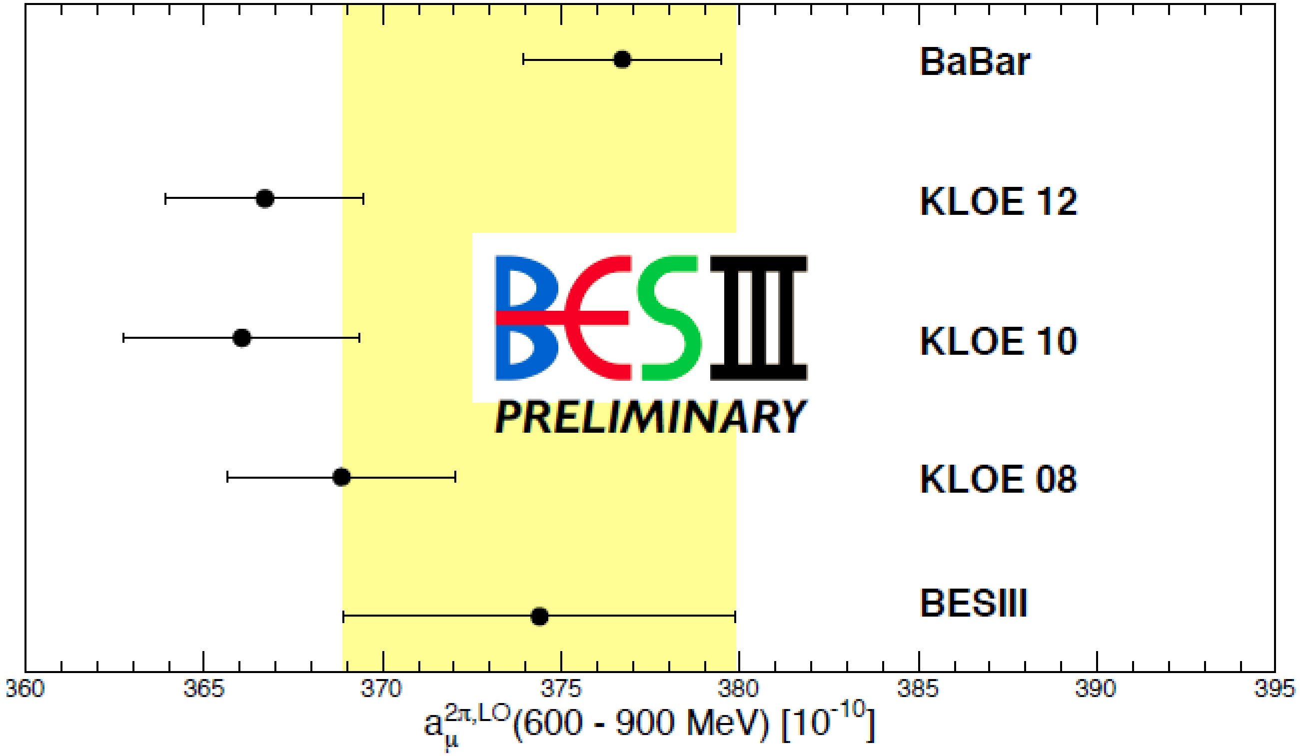
χ^2 / ndf = 33.2 / 51

Form factor



form factor
BESIII fit
BaBar
KLOE 08
KLOE 10
KLOE 12
BESIII
BESIII
PRELIMINARY
$|F_\pi|^2$
$\sqrt{s'}$ [GeV]
45
40
35
30
25
20
15
10
0.6
0.65
0.7
0.75
0.8
0.85
0.9

Result for (g-2)



Experiment	$a_\mu^{2\pi,LO}$ (600 – 900 MeV) [10^{-10}]
BaBar	$376.7 \pm 2.0_{stat} \pm 1.9_{sys}$
KLOE 08	$368.9 \pm 0.4_{stat} \pm 2.3_{sys,exp} \pm 2.2_{sys,theo}$
KLOE 10	$366.1 \pm 0.9_{stat} \pm 2.3_{sys,exp} \pm 2.2_{sys,theo}$
KLOE 12	$366.7 \pm 1.2_{stat} \pm 2.4_{sys,exp} \pm 0.8_{sys,theo}$
BESIII (preliminary)	$374.4 \pm 2.6_{stat} \pm 4.9_{sys}$

Summary

♦ proton pairs

- The effective form factors are measured with improved errors.
- The ratio $|G_E/G_M|$ were extracted at three energy points with uncertainty of 25% – 30% (statistic error dominant).
- The ratio $|G_E/G_M|$ are close to unity in 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 (~1.3%) still dominant.

Prospect

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. Cross section
2. Form factors
3. New states
4. R value

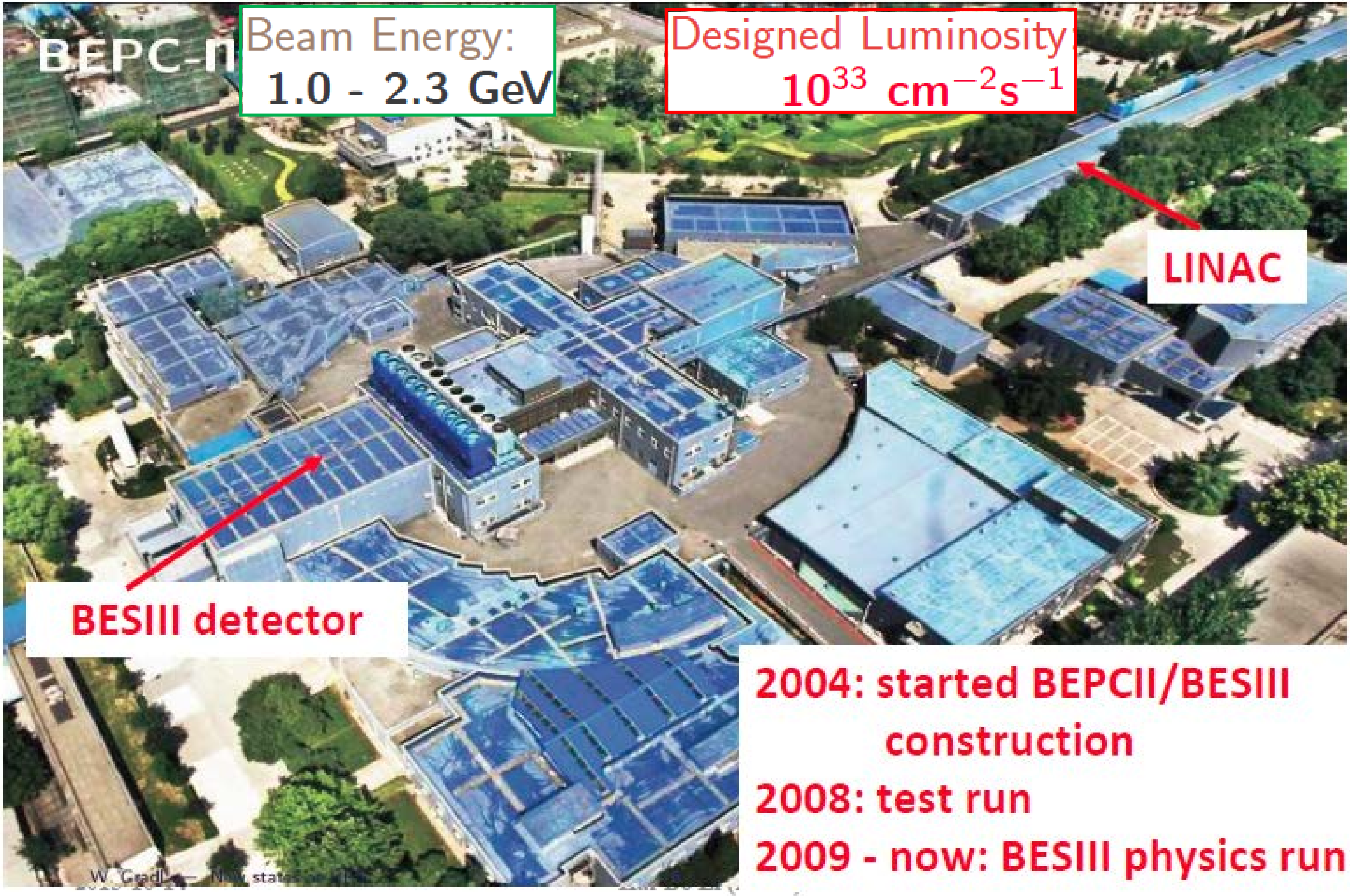
Prospect

- New data samples with larger statistics (~525pb^{-1}) between 2.0–3.08 GeV at 21 energy points have collected in 2015.
- It may expect that more new results about handron production will be obtained at BESIII.

Thank you for your attention

Back up

Beijing Electron-Positron Collider II (BEPCII)

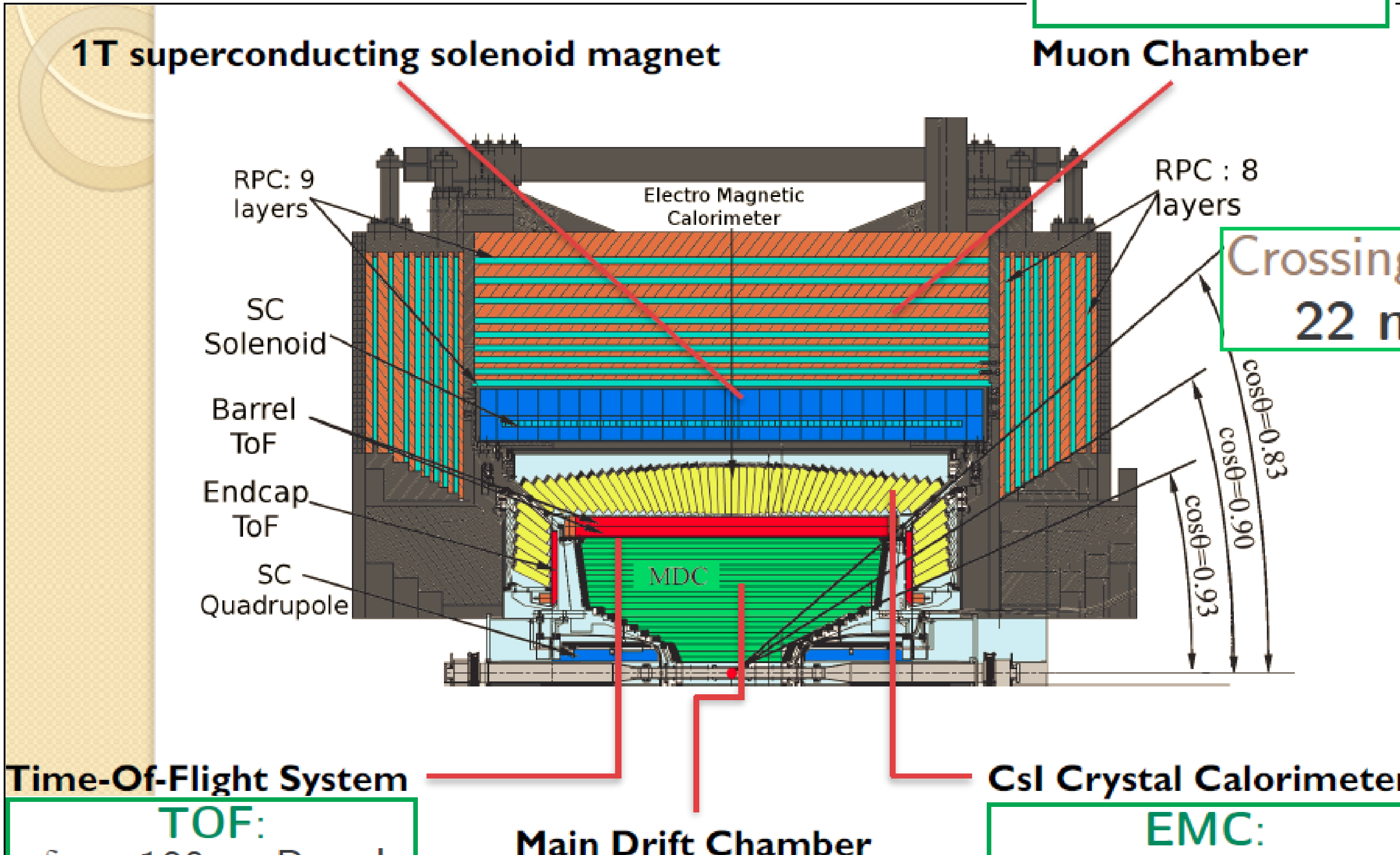


Beijing Spectrometer III (BESIII)

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

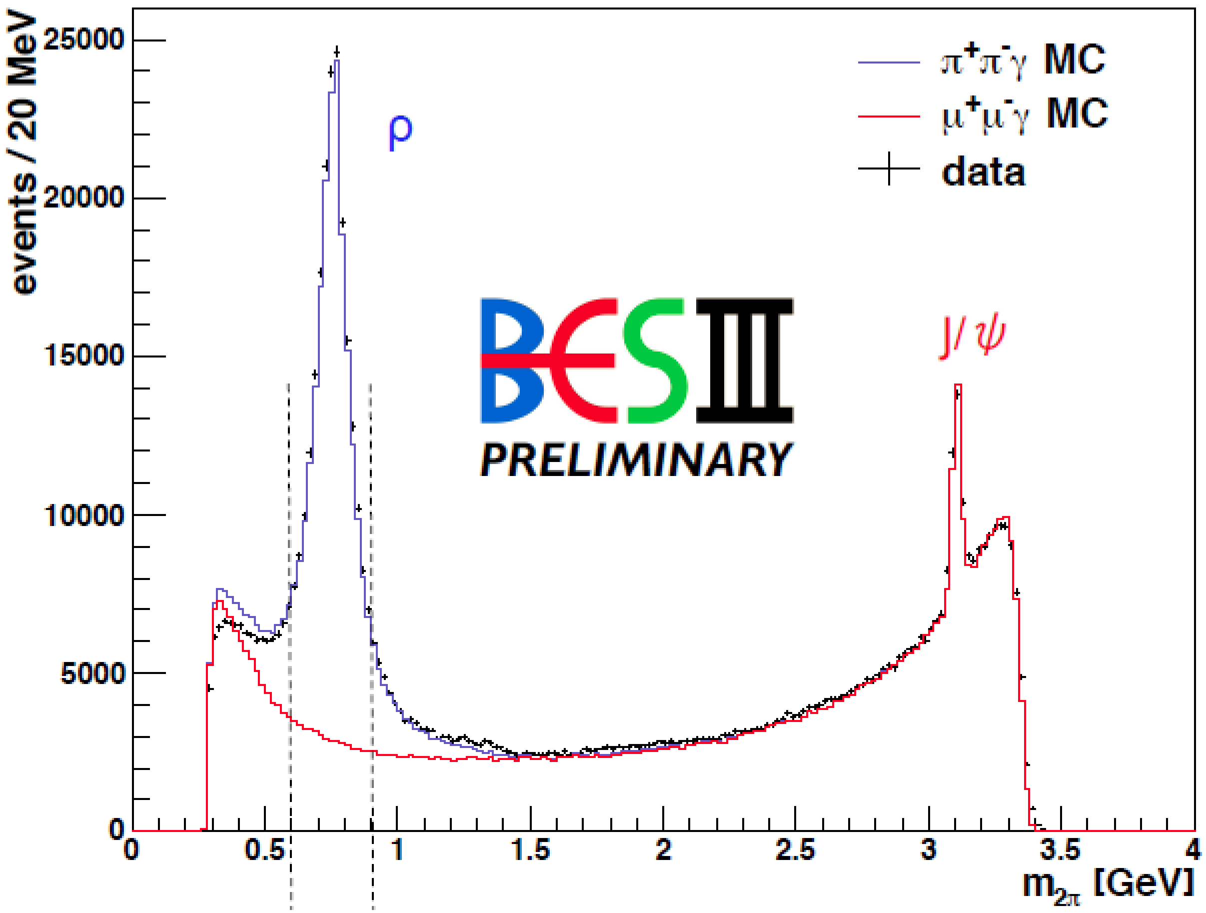
$\delta z = 0.6/\sqrt{E}$

Overview of measurements of proton form factors

Some experiments measured proton form factors in scan and ISR return methods:

Process	Date	Experiment	q^2 (GeV^2/c^4)	q^2 point	Event	Precision
$e^+e^- \to p\bar{p}$	1972	FENICE/ADONE [17]	4.3	1	27	15%
	1979	DM1/ORSAY-DCI [18]	3.75-4.56	4	70	25.0%
	1983	DM2/ORSAY-DC1 [19]	4.0-5.0	6	100	19.6%
	1998	FENICE/ADONE [20]	3.6-5.9	5	76	19.3%
	2005	BES/BEPC [21]	4.0-9.4	10	80	21.2%
	2006	CLEO/ [22]	13.48	1	16	33.3%
$p^+p^- \to e^+e^-$	1976	PS135/CERN [24]	3.52	1	29	15.7%
	1994	PS170/CERN [25]	3.52-4.18	9	3667	6.1%
	1993	E760/Fermi [26]	8.9-13.0	3	29	33.8%
	1999	E835/Fermi [27]	8.84-18.4	6	144	10.3%
	2003	E835/Fermi [28]	11.63-18.22	4	66	21.1%
$e^+e^- \to \gamma + p\bar{p}$	2006	BaBar/SLAC-PEPII [30]	3.57-19.1	38	3261	9.8%
	2013	BaBar/SLAC-PEPII [31]	3.57-19.1	38	6866	6.7%
	2013	BaBar/SLAC-PEPII [32]	9.61-36.0	8	140	18.4%

ISR return analysis



initial publication 600-900 MeV

- data: 2.9fb^{-1}@ψ(3773)
- detect ISR γ
- BG: $\mu^+\mu^-\gamma$
- Initial publication

Systematic uncertainties

source	uncertainty (%)
photon efficiency correction	0.2
pion tracking efficiency correction	0.3
pion ANN efficiency correction	0.2
pion e-PID efficiency correction	0.2
ANN	negl.
angular acceptance	0.1
muon background subtraction	0.06
non-muon background subtraction	0.03
unfolding	0.2
FSR correction δ_{FSR}	0.2
vacuum polarization correction δ_{vac}	0.2
radiator function	0.5
Luminosity $\mathcal{L}$	1.0
sum	**1.3**

dominant