# Measurement of Hadron Form Factor at BESIII

**Bingxin Zhang**

**On behalf of BESIII Collaboration**

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湖北宜昌三峡大学

# Outline

① Introduction

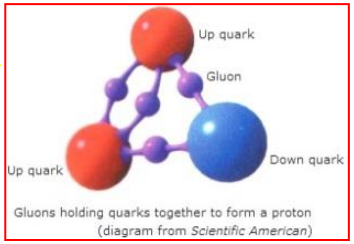
② BESIII experiment

③ Measurement of hadron form factor

④ Summary and prospect

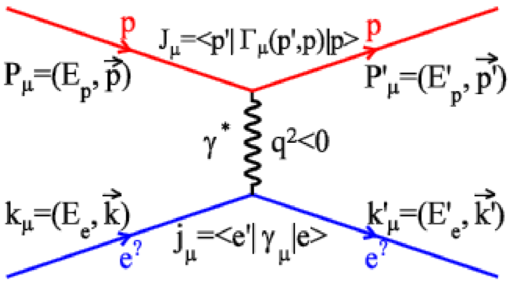
# Motivation

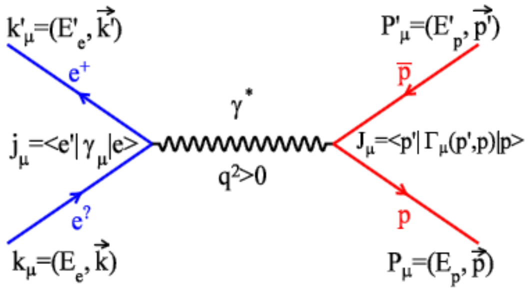
The valence-quark picture of proton in quark model:




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

$e^{\pm}p \to e^{\pm}p$ (space-like $q^2<0$)    $e^+e^- \to p\bar{p}$    (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 : $G_M(q^2) = F_1(q^2) + \kappa_p F_2(q^2)$

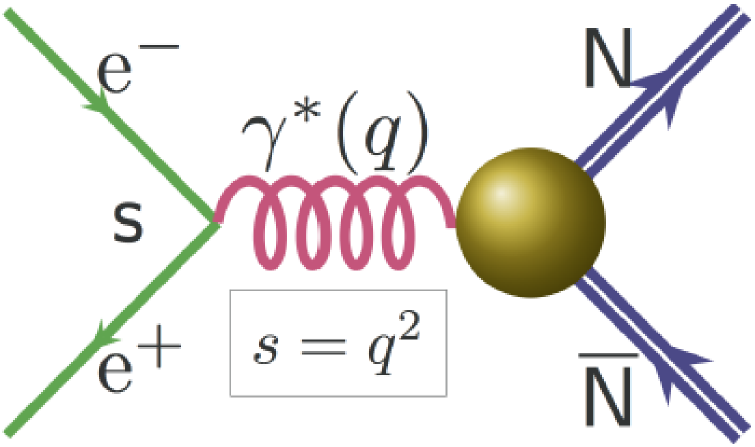
$$\tau = \frac{q^2}{4m_p^2}, \quad \kappa_p = \frac{g_p - 2}{2} = \mu_p - 1$$

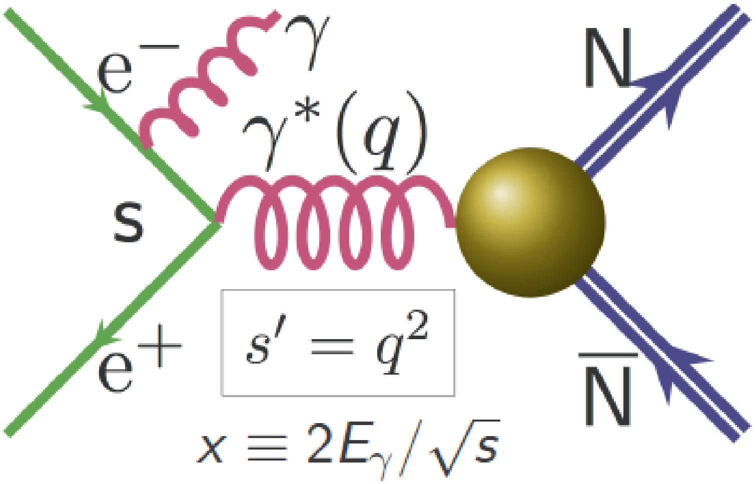
More directly perceived through the senses, $G_E$ and $G_M$ relate to the spatial distribution of charge and magnetization in Breit frame, e.g, the charge density distribution.

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

# Two methods

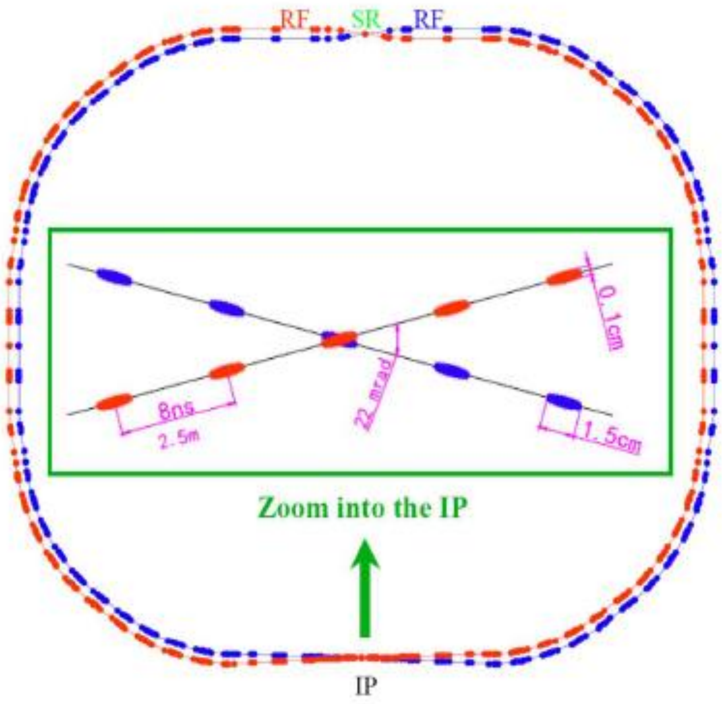
For time-like process




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

# BEPCII storage rings

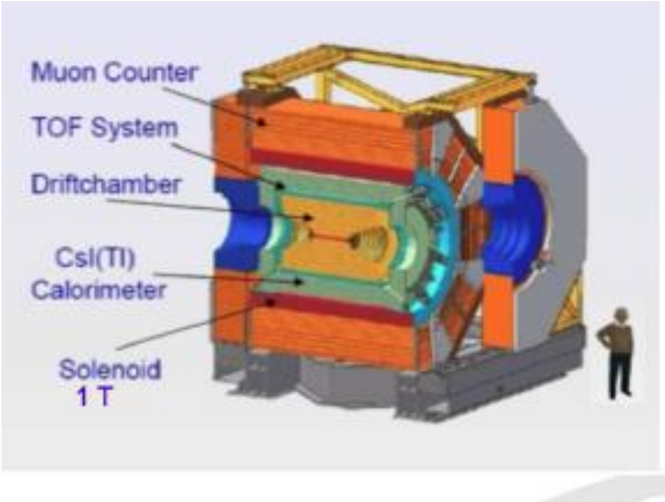



Double-ring $e^+e^-$ collider

- ✓ Beam energy : 1.0 -2.3GeV
- ✓ Crossing angle: 11 mrad
- ✓ Design Luminosity:$1X10^{33}cm^{-2}s^{-1}$
- ✓ Achieved the goal
- ✓ Energy spread: $5.16X10^{-4}$
- ✓ Optimum energy:1.89 GeV

# BESIII detector

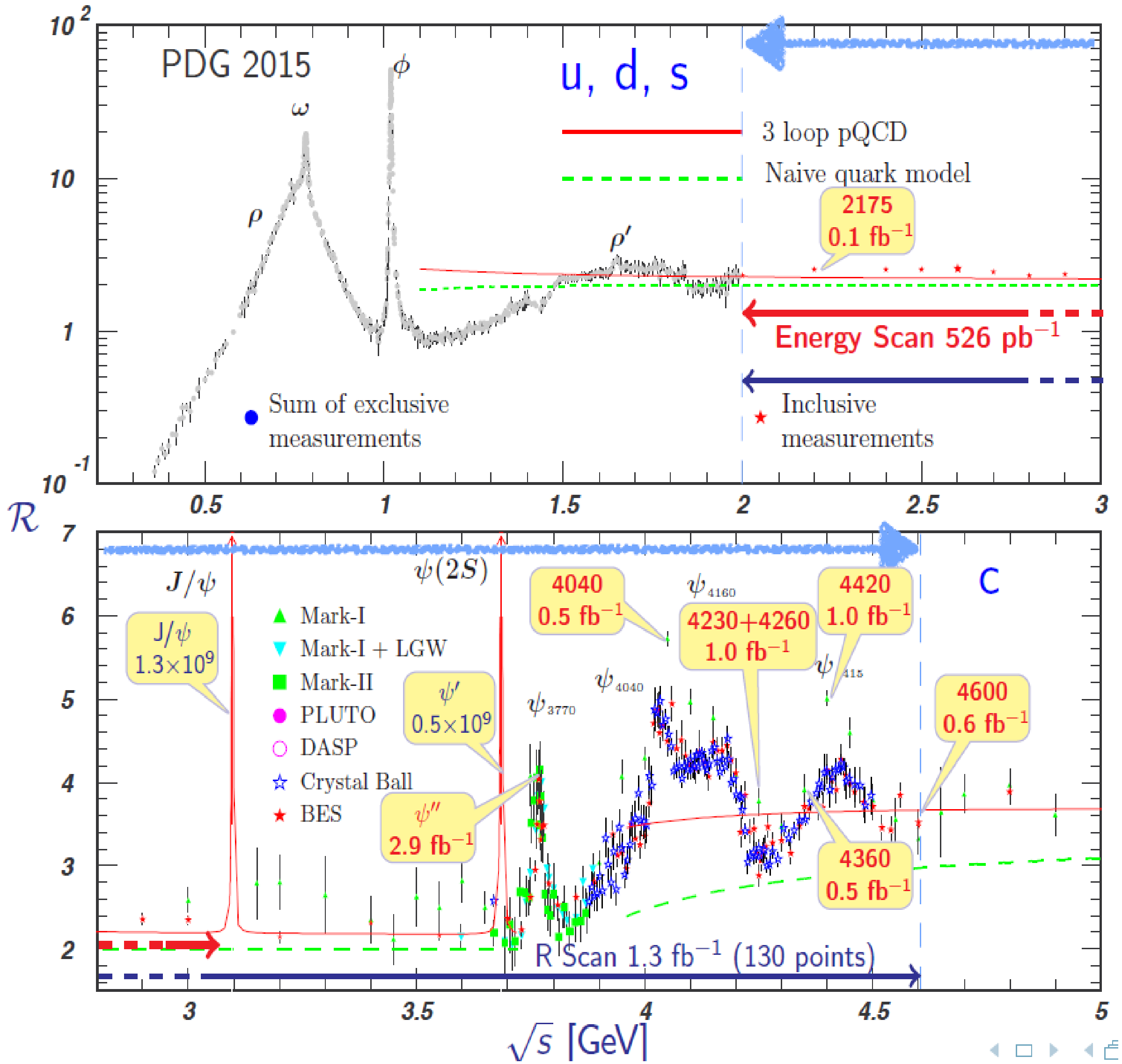
- MDC: main drift chamber (60%He +40% propane)
- TOF: time of flight (two layer plastic scintillators)
- EMC: electronic magnetic calorimeter(CsI(TI))
- MUC: muon system (resistive plate chambers)




Performance :

| Expt. | MDC wire resolution | MDC dE/dx resolution | EMC Energy resolution | | TOF time resolution |
|---|---|---|---|---|---|
| CLEO | 110um | 5% | 2.2-2.4% | CDF | 100ps |
| BABAR | 125um | 7% | 2.67% | Belle | 90ps |
| Belle | 130um | 5.6% | 2.2 % | | |
| **BESIII** | **115um** | **<5%** | **2.3%** | **BESIII** | **80ps(Barrel)**<br>**110ps (ETOF)** |

# BESIII data sample




**Phase 1: test run at 2012**
**Ecm =[2.2324-3.400]GeV**
**4 energy points ~12 /pb**

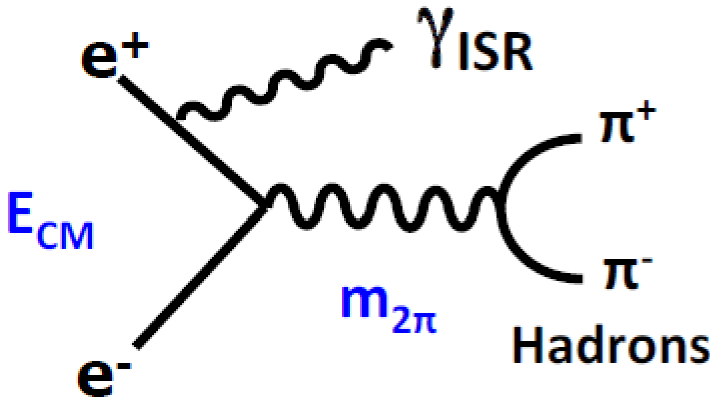
**Phase 2: fine scan for heavy charm resonant at 2013-2014**
**Ecm=[3.850 ,4.590] GeV**
**104 energy points 800 /pb.**

**Phase 3: R & QCD scan at 2015**
**Ecm=[2.00-3.080]GeV 21 energy points ~ 550 /pb**

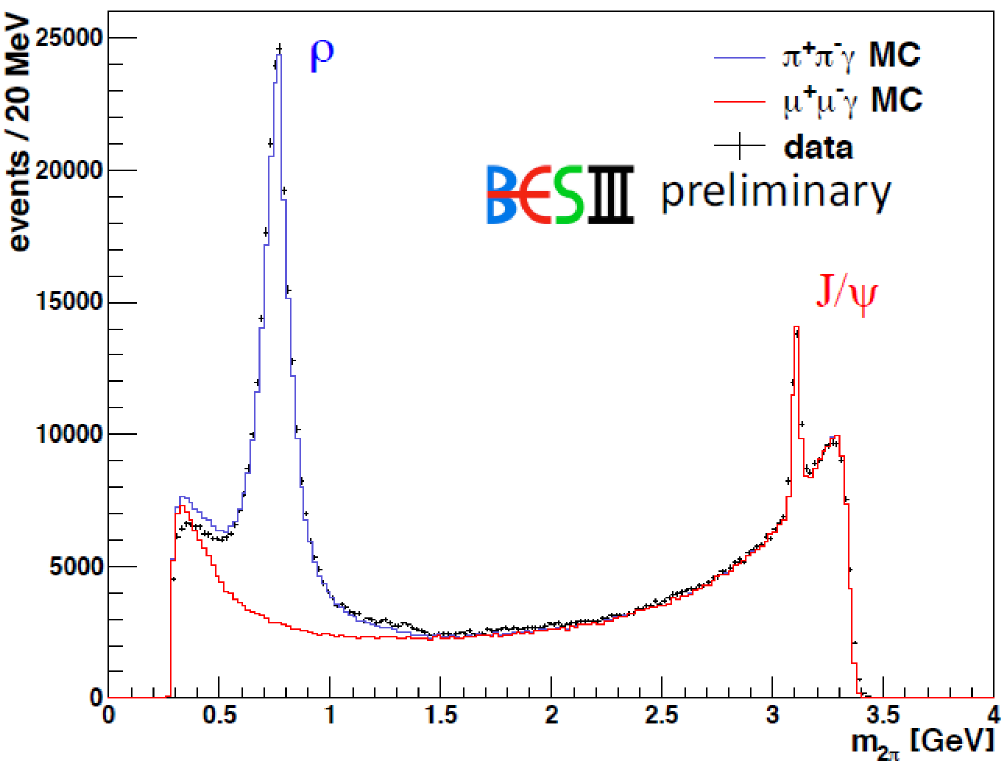
# Measurement of pion Form Factor

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

**Initial State Radiation**
**aka Radiative Return**
A.D., W. Kluge, G.Venanzoni
Phokhara event generator
[H,Kuhn]

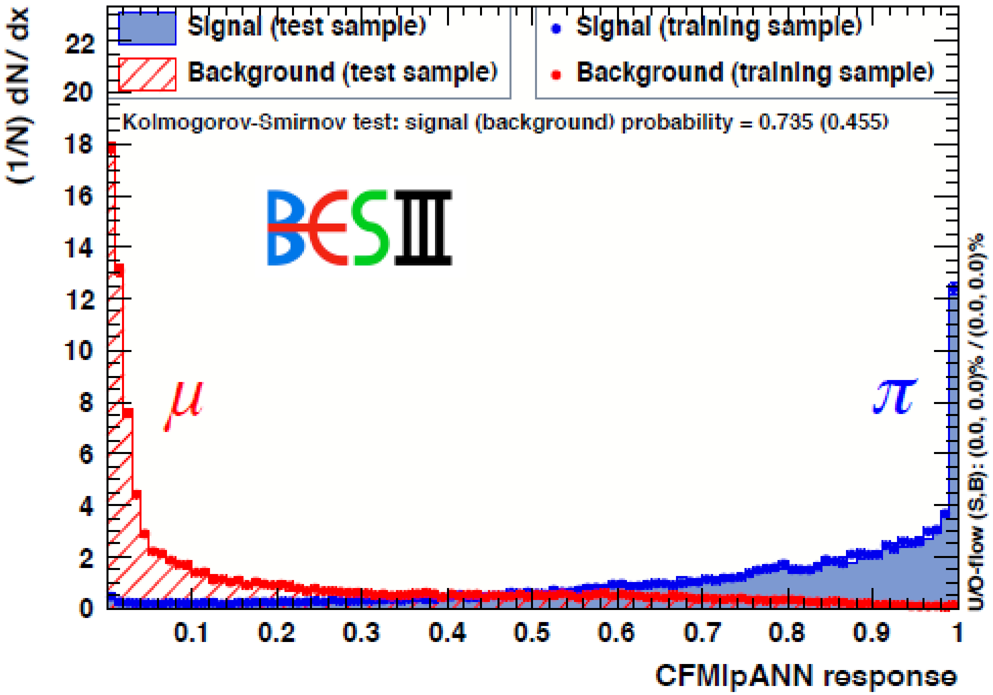



Event yield after acceptance cuts **only**

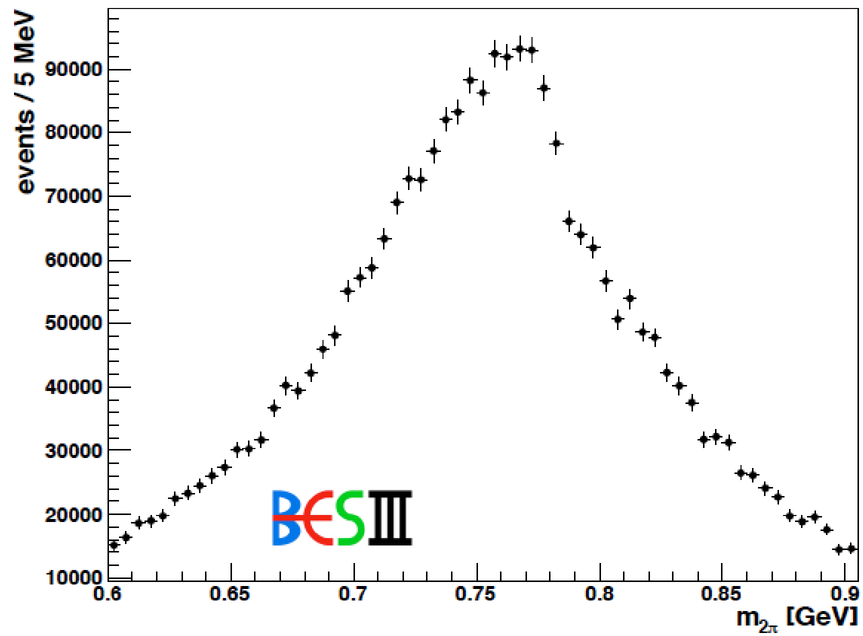



**Pion Muon Separation needed**
**→TMVA methods !**

# π-μ Separation




Event yield ππγ after π-μ separation

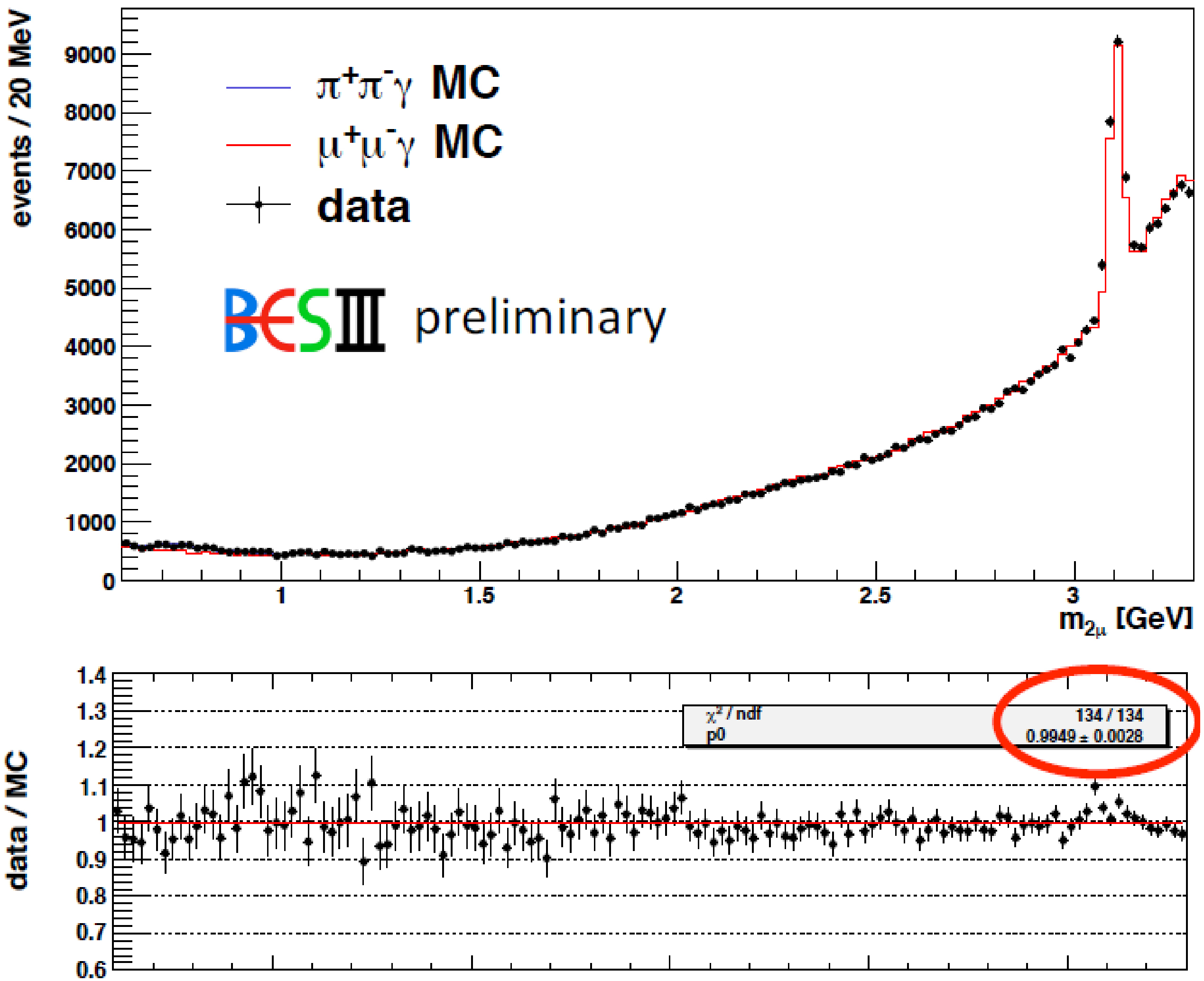



TMVA method (Neural Network)

- trained using μμγ and ππγ MC events
- Information based on track level
- Efficiency matrix(p,Θ) for data MC
- Correct for data –MC differences
- Cross checked for different TMVA methods

# Data vs. MC comparison

Event yield $\mu\mu\gamma$ after $\pi$-$\mu$ separation (ANN)




**Features:**

- background from $\pi\pi\gamma$ very small
- PHOKHARA accuracy <0.5%
- luminosity measurement based on Bhabha ev., 1.0% accuracy

→ excellent agreement with QED

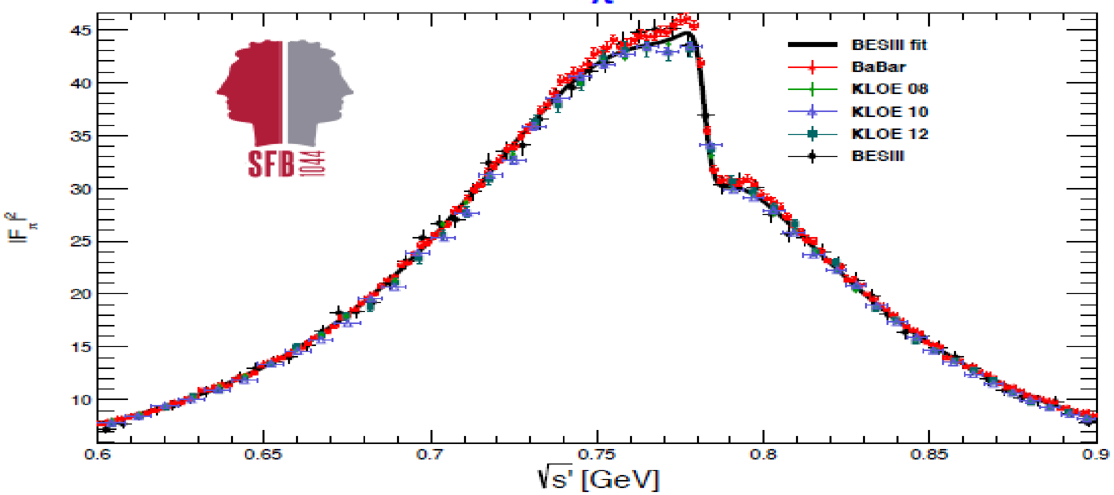
**Δ(MC/QED-data) -1 = (0.51 ± 0.28) %**

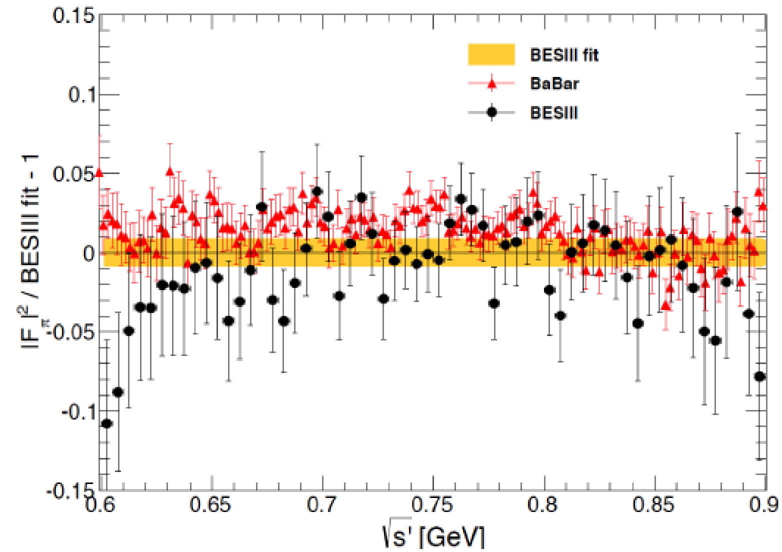
→ accuracy on 1% level as needed to be competitive !

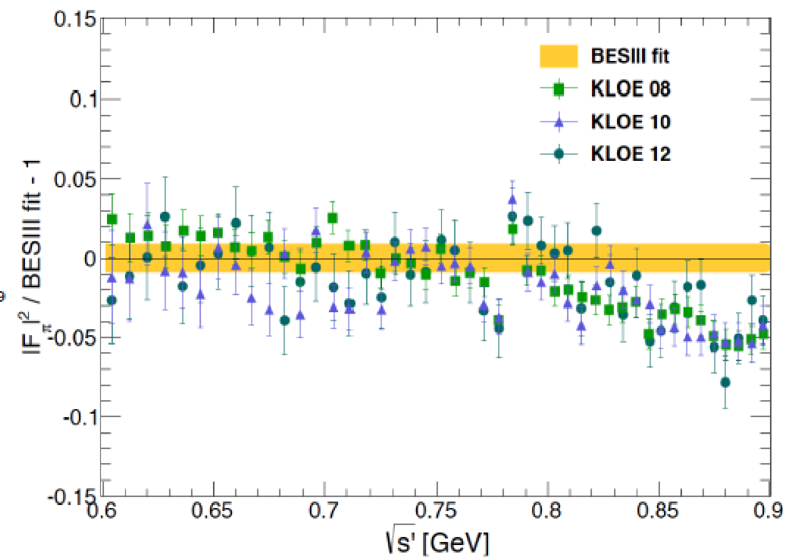
# Comparison with existing Data

- 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 $\alpha_\mu$
  - ➢ $\alpha_\mu^{\pi\pi,LO}(0.6 - 0.9\ \text{GeV}) = \frac{1}{4\pi^3}\int_{0.6}^{0.9} ds K(s)\sigma^{bare}_{\pi\pi}$

**Pion Form Factor $F_\pi$**

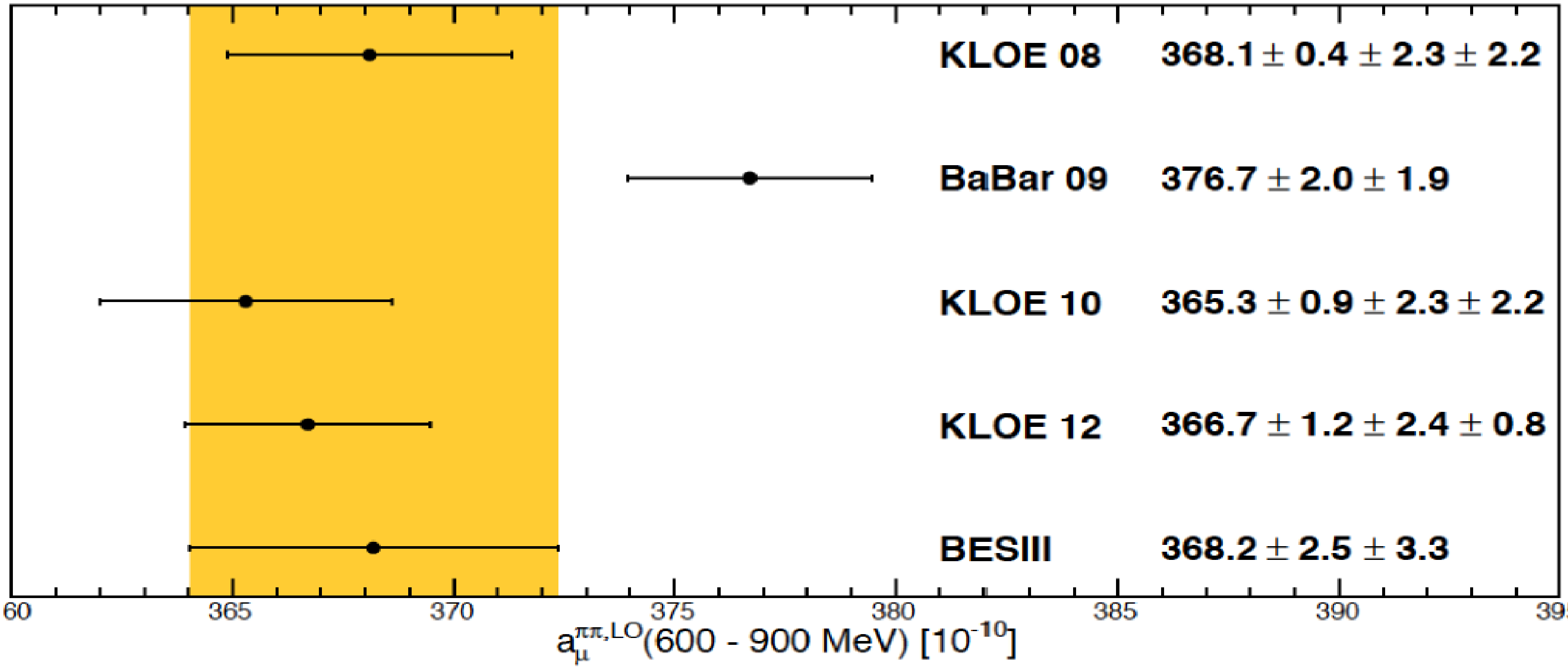



**0.9% accuracy normalization to luminosity/radiator function**

# Impact on Hadronic Vacuum Polarization




**Good agreement found with KLOE !**

**BESIII confirms the deviation at 3… 4 sigma level !!!**

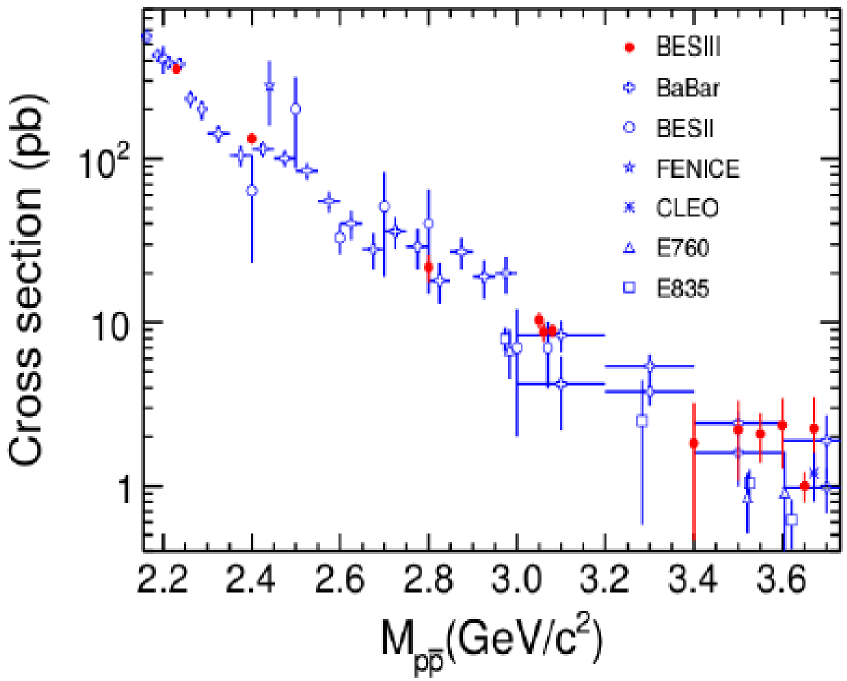
**Phy. Lett. B753 （2016） 629-632**

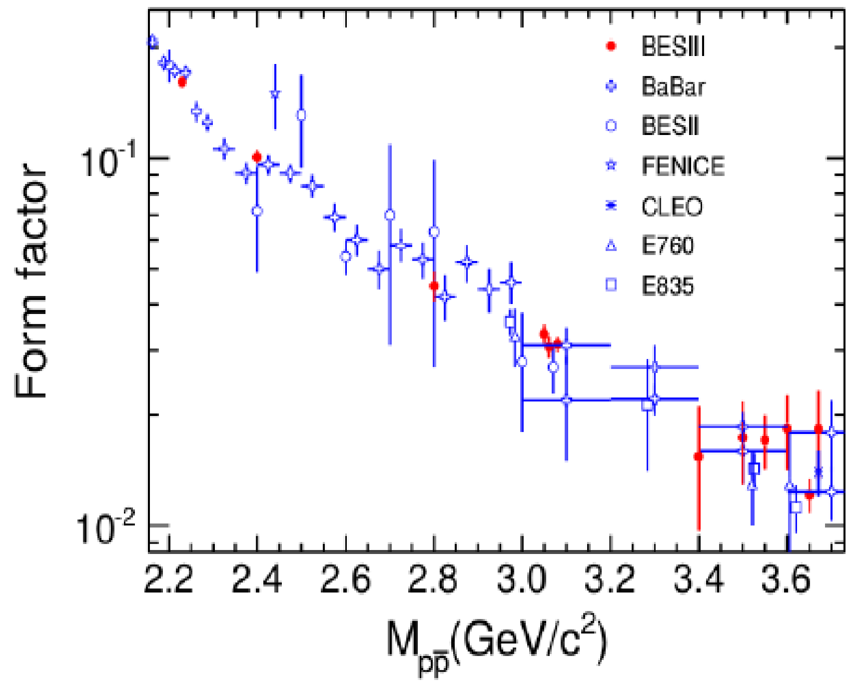
# Measurement of  proton Form Factor

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

Extraction of $\sigma^{Born}(ee \to p\bar{p})$ and |G| for each scan point:

$$\sigma^{\mathrm{Born}}(q) = \frac{N_{\mathrm{obs}(q)} - N_{\mathrm{bg}(q)}}{L \cdot \epsilon(q) R(q)} \longrightarrow |G(q^2)| = \sqrt{\frac{\sigma^{\mathrm{Born}}(q^2)}{(1+\frac{2M^2}{q^2})(\frac{4\pi\alpha^2\beta C}{3q^2})}}$$




**Overall uncertainty improved by 30%**

# Extraction of $R_{em}$=|$G_E$/$G_M$| and |$G_M$|

- From **a 2-parameter fit** to the proton angular distribution in center-of-mass:

$$\frac{dN}{\epsilon \cdot (1+\delta) \cdot d\cos\theta_p} = N_{\text{norm}} \boxed{|G_M|^2} \times [\frac{q^2}{4M_p^2} \cdot (1+\cos\theta_p^2) + \boxed{R^2} \sin\theta_p^2]$$

$$N_{norm} = \frac{2M_p^2 \cdot L \cdot \hbar c \cdot \pi\alpha^2 \cdot \beta C}{q^4}$$

- From the **measurement of the expectation value (method of moments)**:

$$<\cos^2\theta_p> = \frac{N_{norm} \cdot |G_M|^2}{N_{tot}} \int \epsilon \cdot (1+\delta) \cdot [\frac{q^2}{4M_p^2}(1+\cos^2\theta_p) + R_{em}^2 \sin^2\theta_p] d\cos\theta_p$$

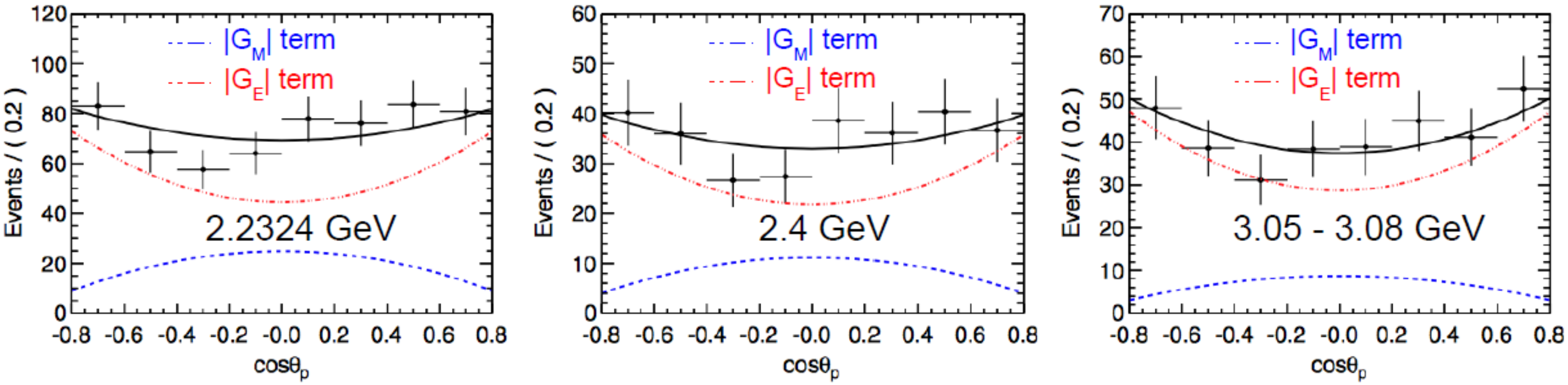
For $\cos\theta_p$ within [-0.8,0.8]:

$$R = \sqrt{\frac{s}{4M_p^2} \frac{<\cos^2\theta_p> -0.243}{0.108 - 0.648 <\cos^2\theta_p>}}$$

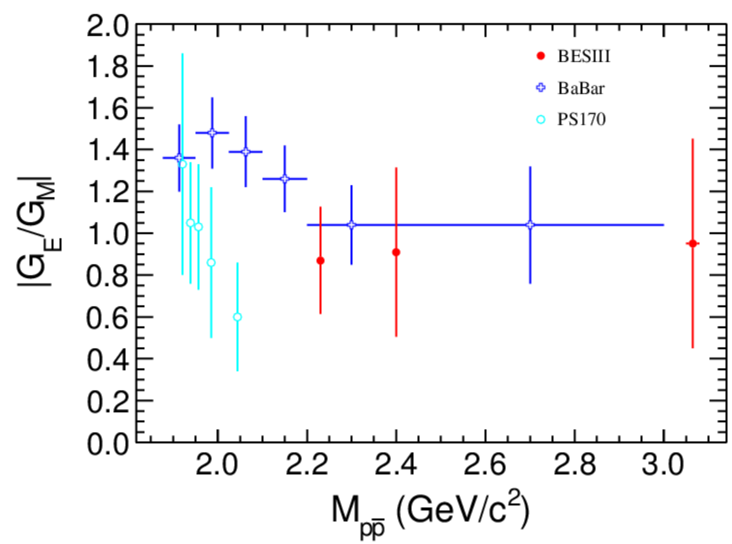
$$\sigma_R = \frac{0.0741}{R(0.167 - <\cos^2\theta_p>)^2} \frac{s}{4M_p^2} \sigma_{<\cos^2\theta_p>}$$

|$G_M$| extracted from the integral of angular differential cross section and R

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



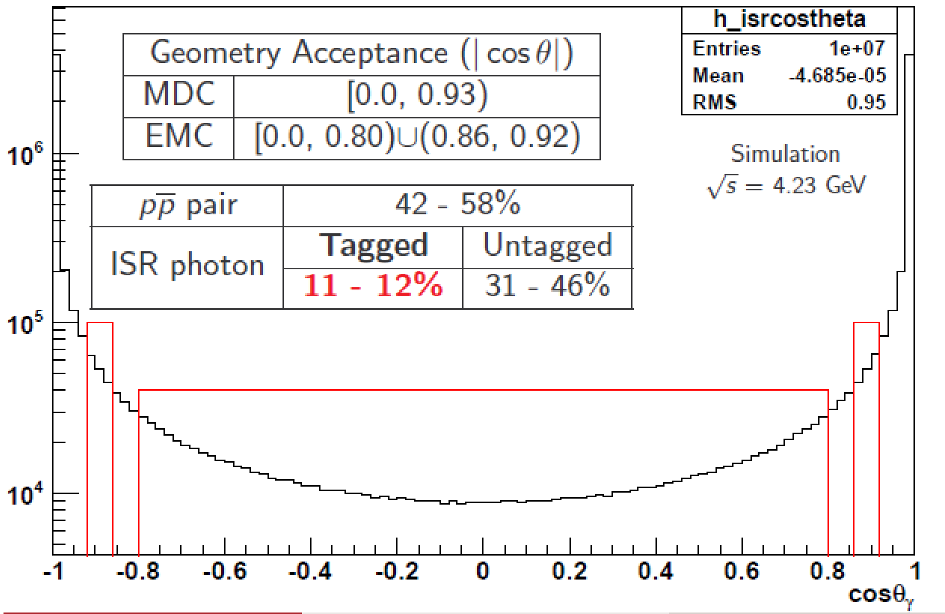

| $\sqrt{s}(MeV)$ | $\lvert G_E/G_M \rvert$ | $\lvert G_M \rvert(\times 10^{-2})$ |
|---|---|---|
| | Fitting | |
| 2232.4 | 0.87±0.24±0.05 | 18.42±5.09±0.98 |
| 2400.0 | 0.91±0.38±0.12 | 11.30±4.73±1.53 |
| (3050.0, 3080.0) | 0.95±0.45±0.21 | 3.61±1.71±0.82 |
| | Method of moments | |
| 2232.4 | 0.83±0.24 | 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 |



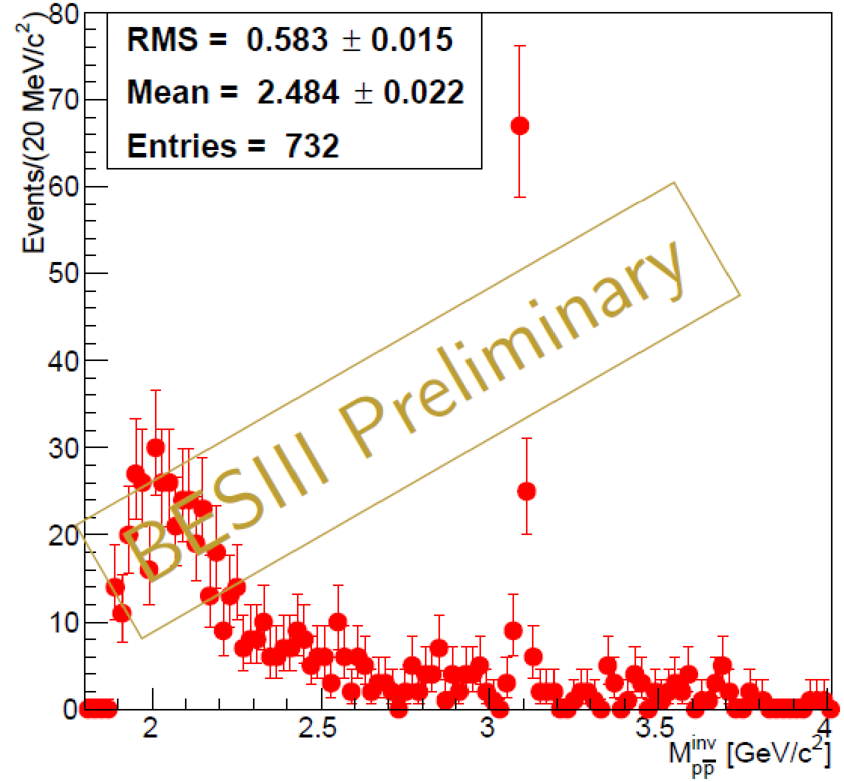

- **R=|$G_E$|/|$G_M$| consistent with 1**
- **|$G_M$|(and |$G_E$| extracted for the first time** **Phys. Rev. D91, 112004 (2015)**
- **Precision between 11% and 28%**

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

$\gamma_{ISR}$ Angular Distribution




$p\bar{p}$ Invariant Mass

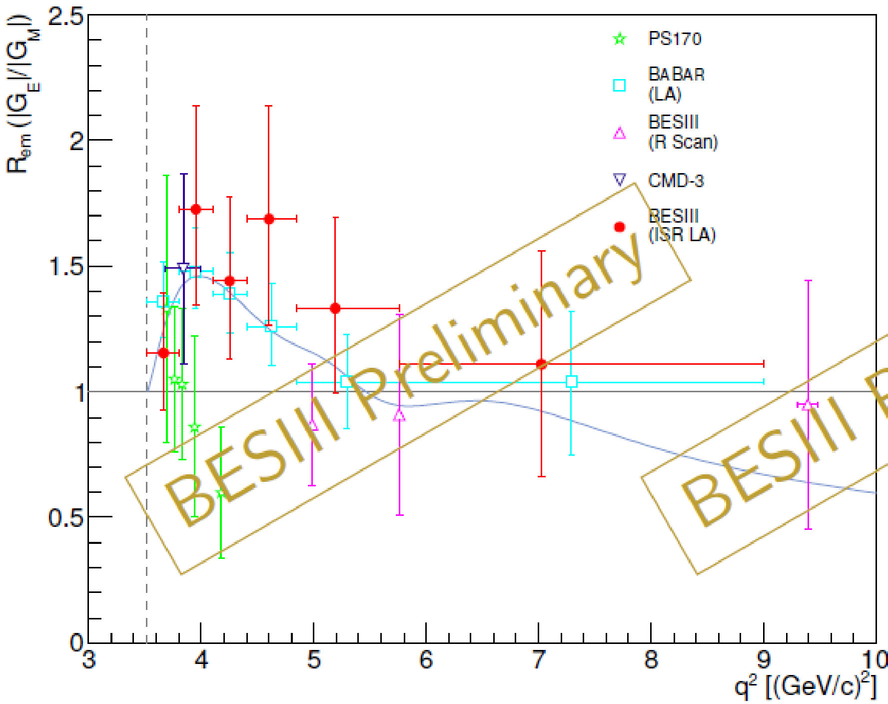


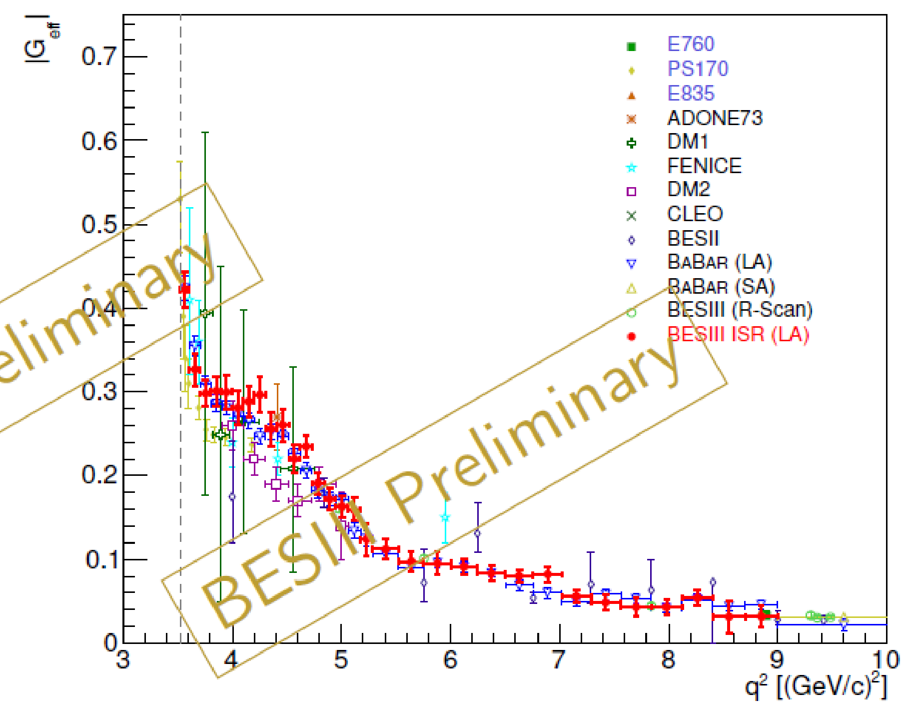

- 7 data samples ($\geq$ 3.773 GeV)
- Total luminosity 7.4 $fb^{-1}$
- Event selction:
  - Two charged tracks from vertex
  - One high energy shower in EMC
  - Kinematic constraints applied
- Background evaluation

**Data at the energy 4.23 GeV**

$p\bar{p}$ invariant mass spectrum from threshold

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




- Background subtraction and efficiency dividing
- Combine the seven data samples
- The proton FFs extracted between th. – 3.0 GeV
- Systematic uncertainty included

| | $\frac{\delta R_{em}}{R_{em}}$ | $\frac{\delta G_{eff}}{G_{eff}}$ |
|---|---|---|
| stat. | 16% - 34% | 5% - 32% |
| syst. | 5% - 22% | 2% - 30% |

LA: **L**arge polar **A**ngle of ISR photon

SA: **S**mall polar **A**ngle of ISR photon

# Measurement of Λ Form Factor

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

Two channels for 2.2324GeV:

- Charged channel: $\Lambda \to p\pi^+$, $\Lambda \to p\pi^-$
- Neutral channel: $\Lambda \to n\pi^0$

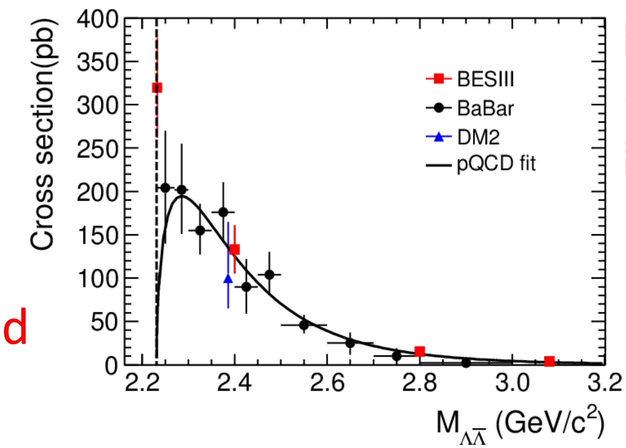
Only charged channel for other data:

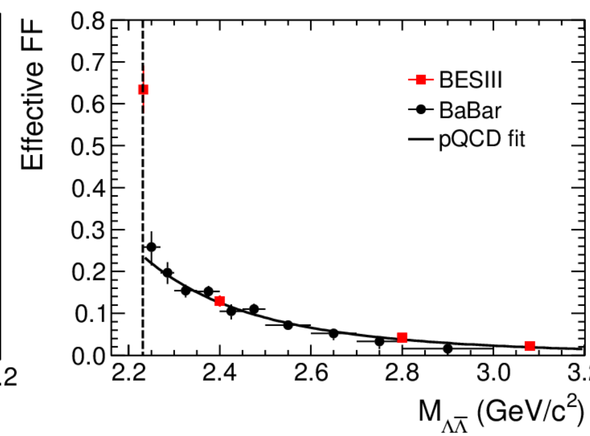
Full reconstruction for 4 tracks

Kinematic constraints applied

| $\sqrt{s}$ GeV | Reconstruction | $\sigma_{Born}$ (pb) | $\lvert G\rvert$ ($\times 10^{-2}$) |
|---|---|---|---|
| 2.2324 | $\Lambda \to p\pi^-, \bar{\Lambda} \to \bar{p}\pi^+$ | $325 \pm 53 \pm 46$ | |
| | $\bar{\Lambda} \to \bar{n}\pi^0$ | $(3.0 \pm 1.0 \pm 0.4) \times 10^2$ | |
| | combined | $320 \pm 58$ | $63.4 \pm 5.7$ |
| 2.40 | | $133 \pm 20 \pm 19$ | $12.93 \pm 0.97 \pm 0.92$ |
| 2.80 | | $15.3 \pm 5.4 \pm 2.0$ | $4.16 \pm 0.73 \pm 0.27$ |
| 3.08 | | $3.9 \pm 1.1 \pm 0.5$ | $2.21 \pm 0.31 \pm 0.14$ |

$$\sigma = \frac{4\pi\alpha^2\beta}{3q^2}\left[\lvert G_M^2(q^2)\rvert + \frac{1}{2\tau}\lvert G_E^2(q^2)\rvert\right]$$




Preliminary results for Λ

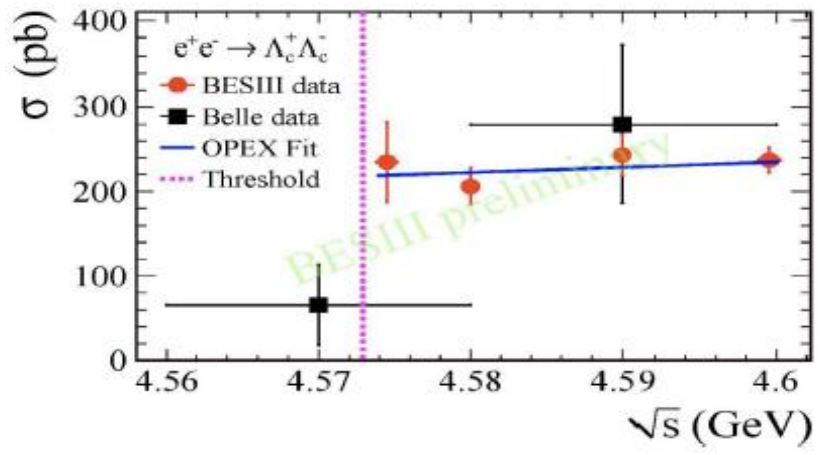
Non-zero behavior at threshold

Precision improved by 10%

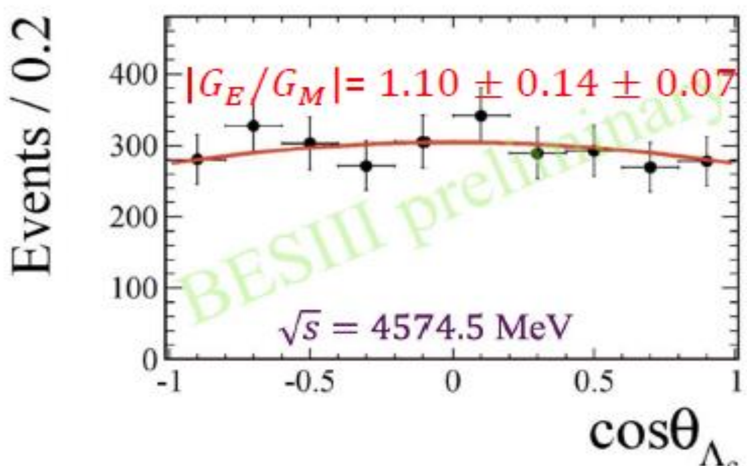
# Measurement of Λc Form Factor

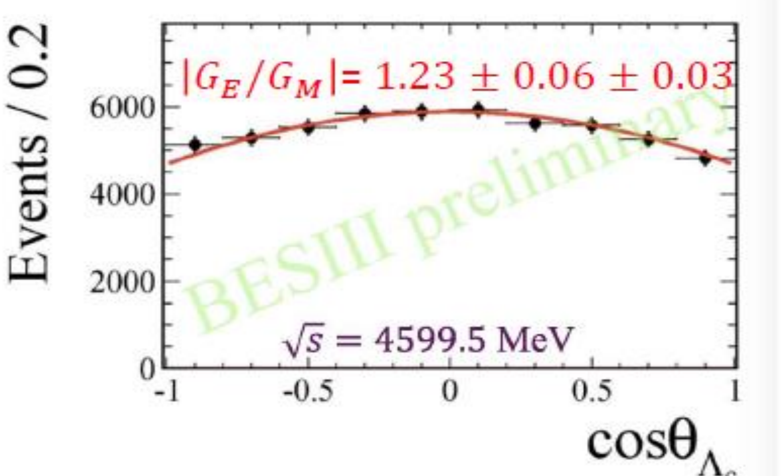
## $e^+e^- \rightarrow \Lambda_c^+\bar{\Lambda}_c^-$

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



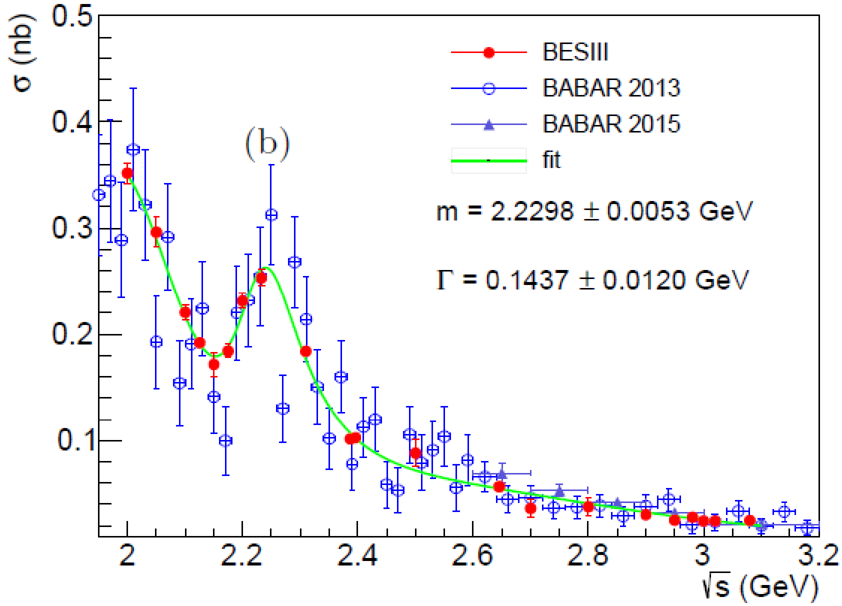

- Angular distribution of $\Lambda_c^+$ is studied at 4.575 and 4.600 GeV.

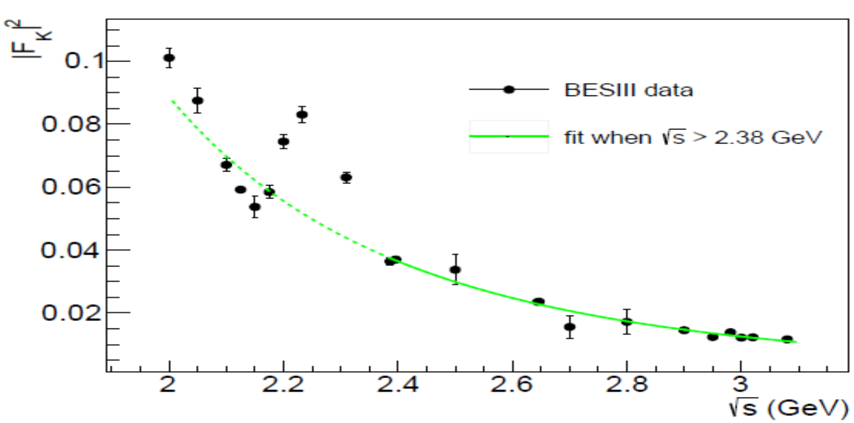


# Measurement of kaon Form Factor

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




- Cross sections of $e^+e^- \to K^+K^-$ measured with BESIII data at 2-3 GeV are consistent with those of previous experiments but with higher precision
- A structure near 2.2 GeV is observed with
  M=2229.8 ±5.3±17.2 MeV
  Γ =143.7±12.0±7.8 MeV

- Form factor extraction:

$$|F_K|^2(s) = \frac{3s}{\pi\alpha(0)^2\beta_K^3}\frac{\sigma_{KK}(s)}{C_{FS}}$$

$$\sigma_{KK}(s) = \sigma^0_{KK}(s)\left(\frac{\alpha(s)}{\alpha(0)}\right)^2 \qquad C_{FS} = 1+\frac{\alpha}{\pi}\eta_K(s)$$

- Form factor fitting function

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

$n = 1.94 \pm 0.09$

(agreement with pQCD prediction $n = 2$)

# BESIII Summary and prospect

- With ISR method

✓ $\sigma(e^+e^- \to \pi^+\pi^-)$ is measured with <1% uncertainty ; the deviation of $(g-2)_\mu$ is confirmed.

✓ Proton form factor is measured.

- Use Energy Scan method

✓ proton and $\Lambda$ , $\Lambda_c$ form factors are measured.

- A structure near 2.2GeV is observed in $e^+e^- \to K^+K^-$
- Form Factors of Neutron and other Hyperons will be studied in the near future.

*Thanks for your attention !*