HIM
Helmholtz-Institut Mainz

BESIII

PRISMA
Cluster of Excellence

Hardon Form Factors at BESIII

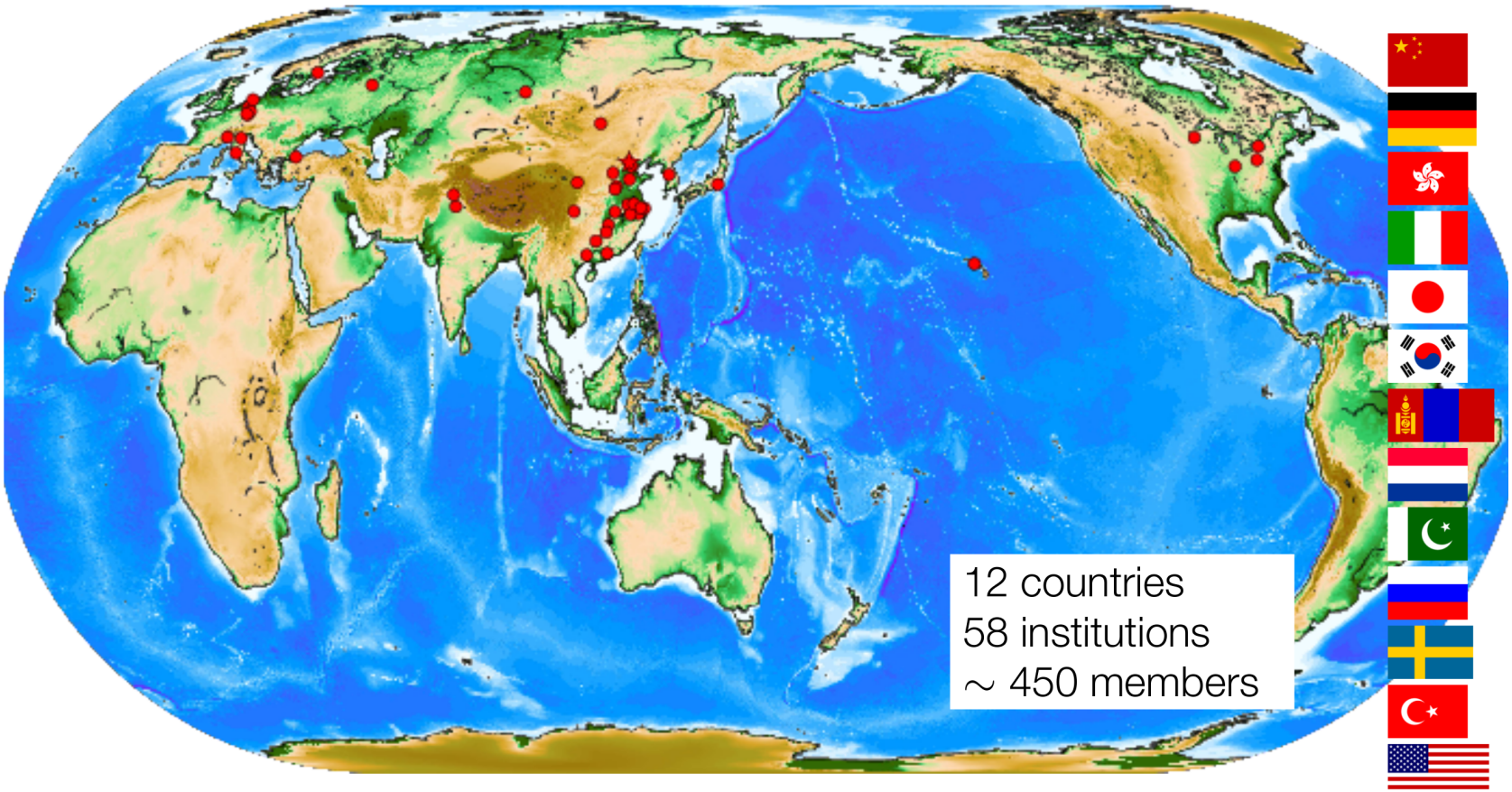
Paul Larin (Helmholtz Institute Mainz)
on behalf of the **BESIII-Collaboration**

- BESIII experiment
- Introduction to electromagnetic form factors
- Hadron form factors at BESIII
- Summary

September 25th - 29th, 2017, Salamanca, Spain

The BESIII Collaboration

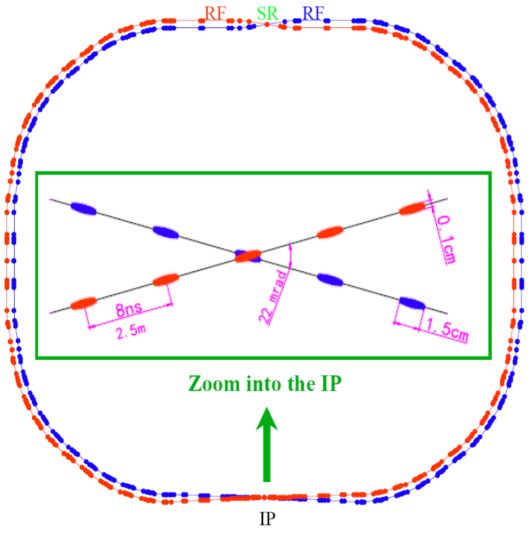
From 2009 to 2016



BEPC-II and BESIII Detector

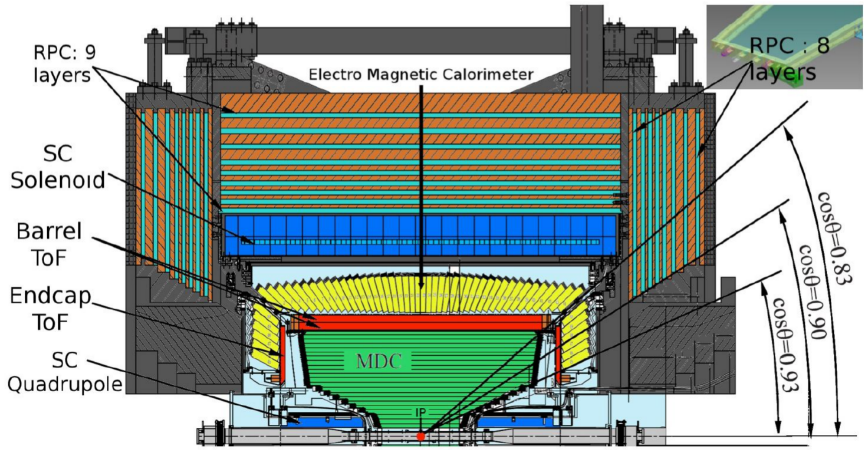
Beijing, China

Beijing Electron Positron Collider



- Symmetric e^+e^- collider
- Beam energy: 1.0 - 2.3 GeV
- Optimum energy: 1.89 GeV
- Design luminosity: 10^{33} cm^{-2} s^{-1}
- Crossing angle: 22 mrad

BESIII detector



Electromagnetic Calorimeter
$\sigma_E/\sqrt{E}(\%)$=2.5% (1 GeV),
(CsI) $\sigma_{z,\phi}$(cm)=0.5-0.7 cm/$\sqrt{E}$

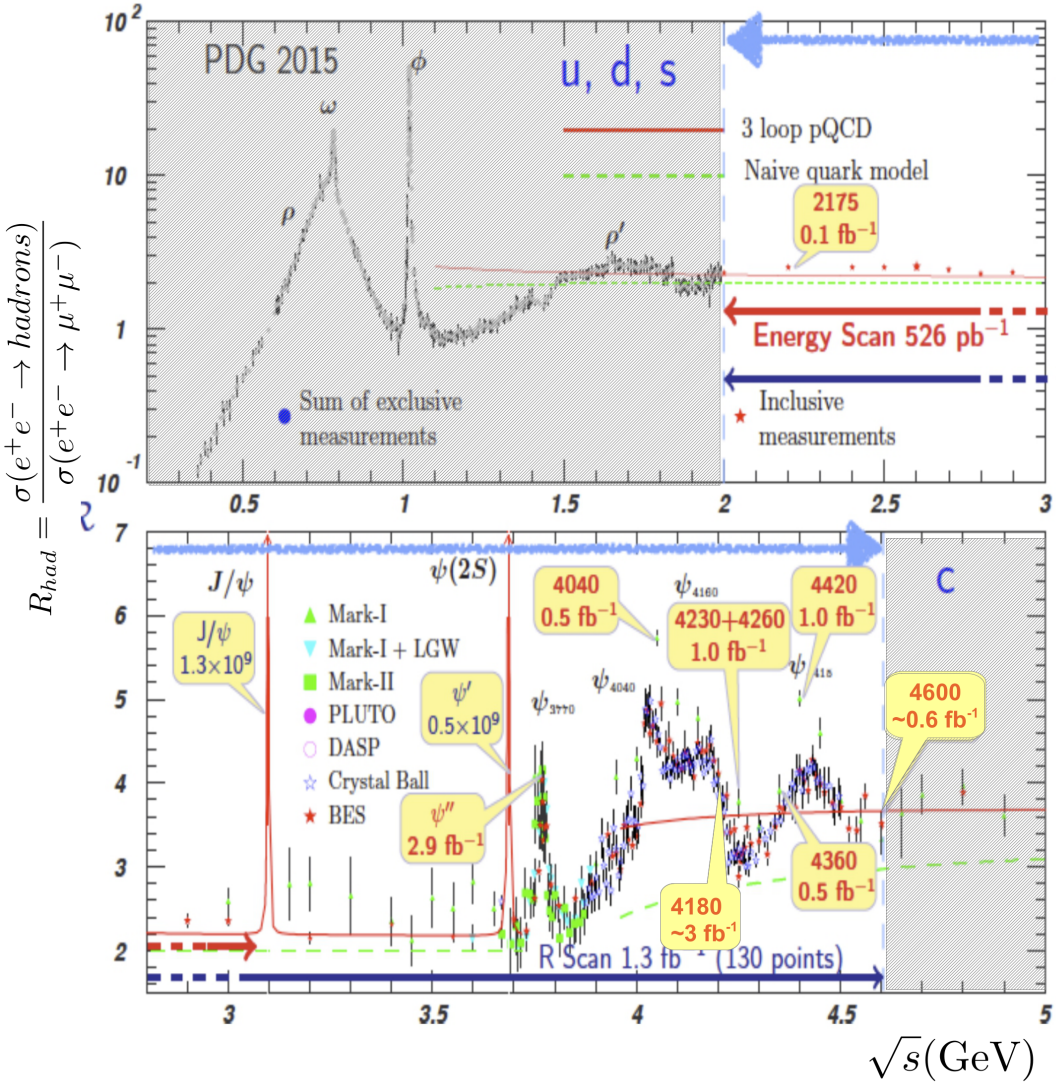
Muon Counter
σ_{xy}<2 cm

Time Of Flight
σ_T(barrel)=90 ps
σ_T(endcap)=70 ps

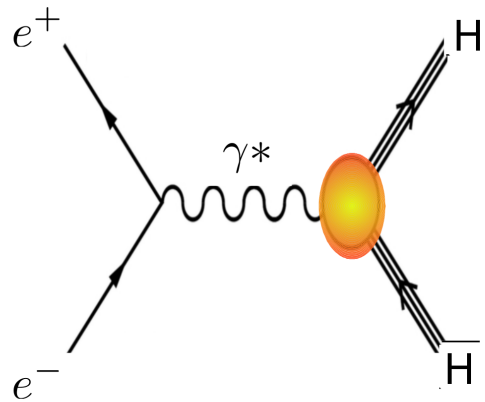
Main Drift Chamber
σ_{xy}=130 mm, dE/dx~6%
σ_p/p = 0.5% at 1 GeV

BESIII Data Samples

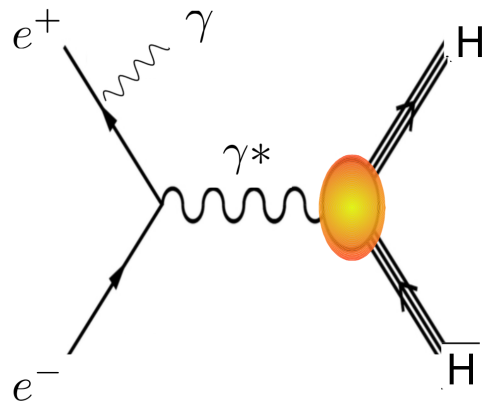
From 2009 to 2016



From scan data:

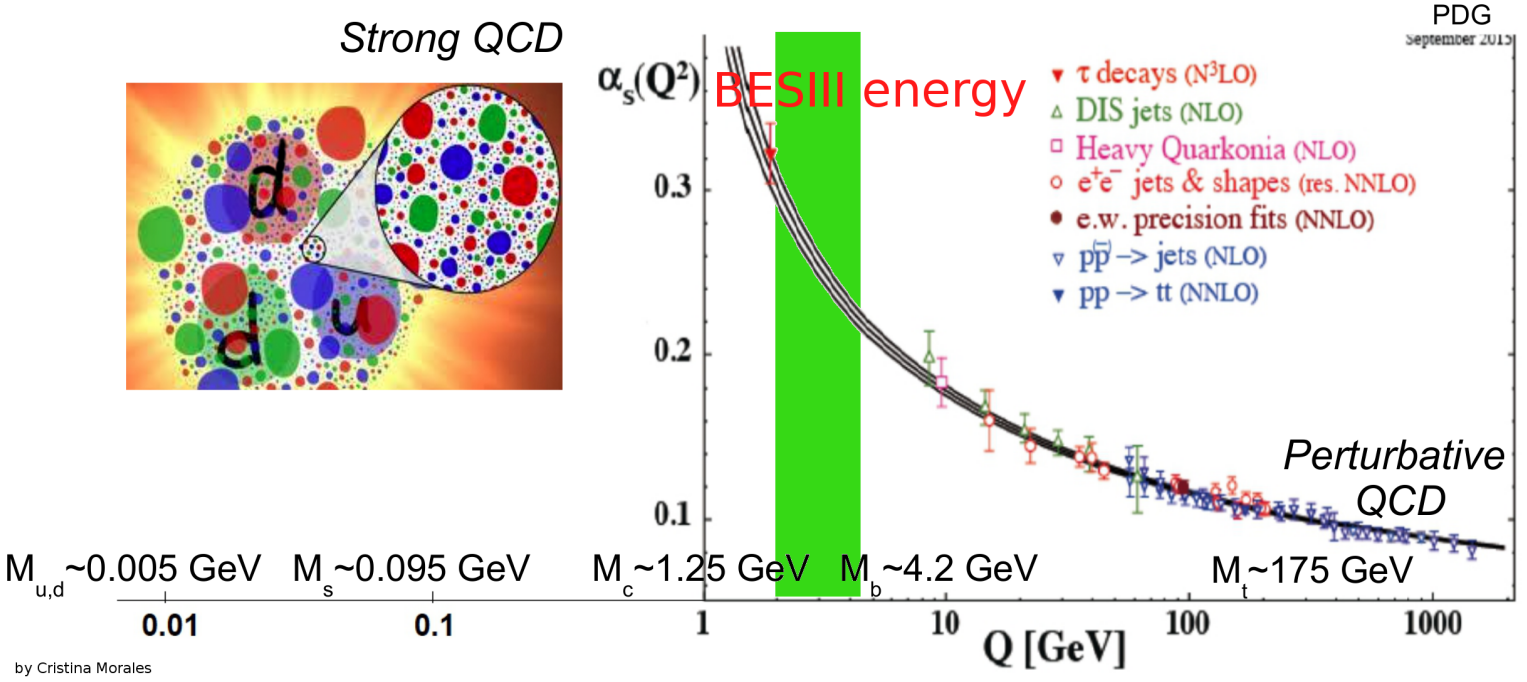


From data at the resonances:



Hadron Form Factors

Why are we interested in Form Factors?



- Hadrons are non-point-like objects $\rightarrow$ have structure!
- Structure and internal dynamics parametrized in form factors
- Understanding hadrons' structure helps **understanding QCD**
- Other topics: charge radius, QCD scaling, threshold behaviour, ...

Hadron Form Factors

More Motivation? The Anomalous Magnetic Moment of the Muon

- Experimental results: $\alpha_\mu^{exp} = (11659208.9 \pm 6.3) \cdot 10^{-10}$
- Theoretical prediction: $\alpha_\mu^{SM} = (11659580.2 \pm 4.9) \cdot 10^{-10}$

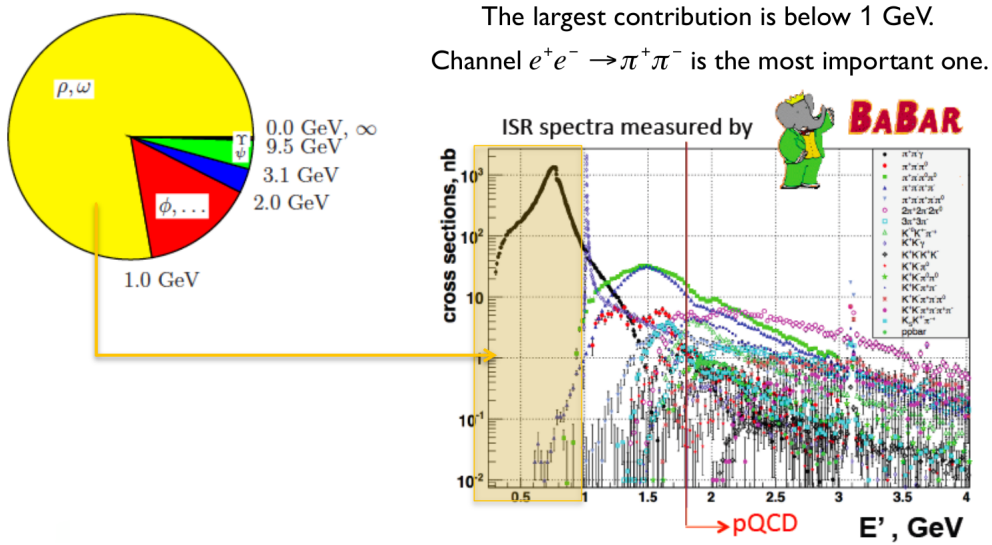
$\rightarrow$ discripancy: 3.6 standard deviations

- Goal: **hadronic vacuum polarization contribution to** $\alpha_\mu = \frac{g_\mu - 2}{2}$

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

- Largest contribution to α_μ^{hadr} below 1 GeV: $\sigma\left(e^+e^- \rightarrow \pi^+\pi^-\right)$

$$|F_\pi|^2(s^2) = \frac{3s^2}{\pi\alpha^2\beta^3}\sigma_{\pi^+\pi^-}^{dressed}(s^2)$$

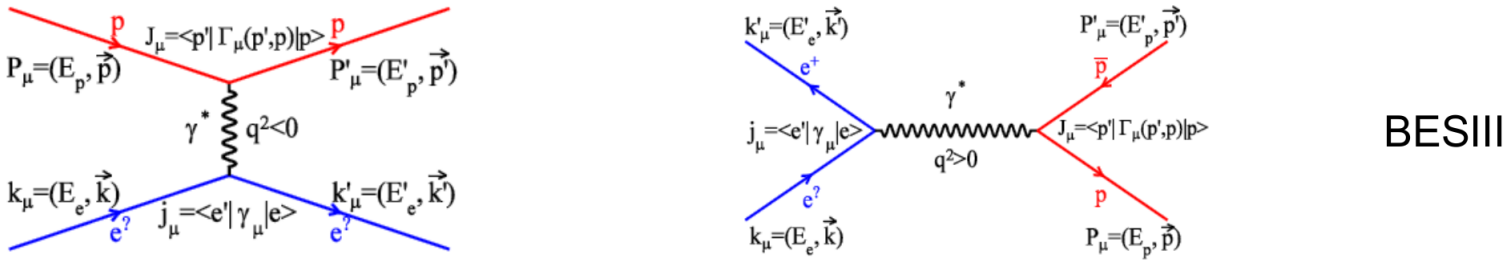


Hadron Form Factors

Theoretical Framework for Hadron Form Factors

Internal structure of hadrons can be measured in two processes:

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



BESIII

Left: $e-p$ scattering; $\quad$ Right: $p\bar{p}$ production

- Vector current of the interaction vertex with hadron structure:

$$\Gamma_\mu(p',p) = \gamma_\mu F_1(q2) + \frac{i\sigma_{\mu\nu}q^\nu}{2m}F_2(q^2)$$

- Structure functions F_1, F_2 can be recombined into e.m. form factors:

$$\text{Electric:} \quad G_E(q^2) = F_1(q^2) + \tau\kappa F_2(q^2)$$

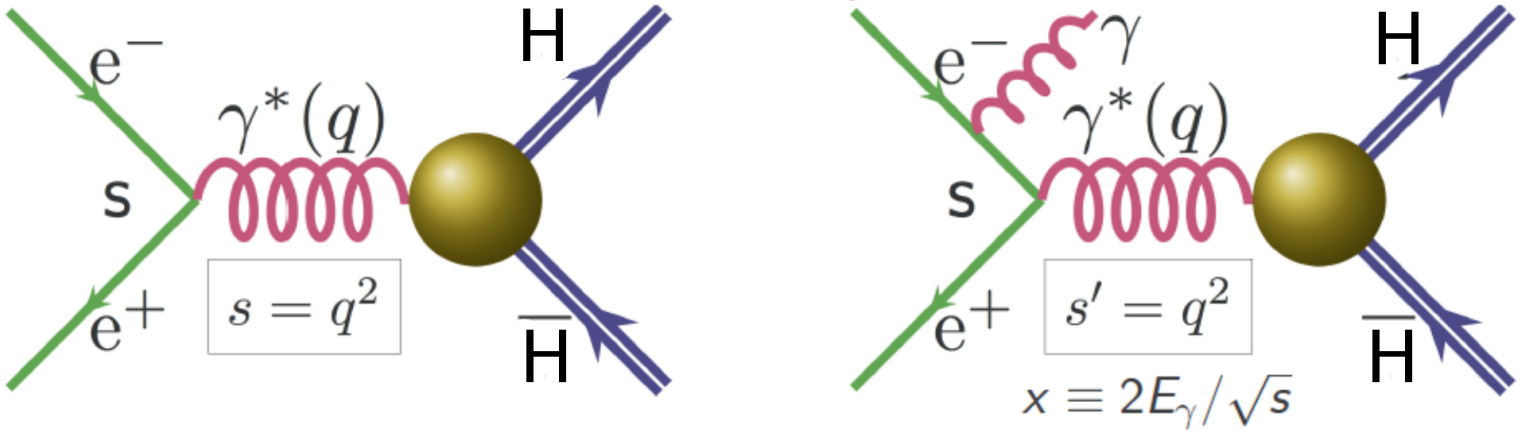
$$\text{Magnetic:} \quad G_M(q^2) = F_1(q^2) + \kappa F_2(q^2)$$

Hadron Form Factors

Two Methods to Measure Hadron Form Factors

Two methods

For time-like process



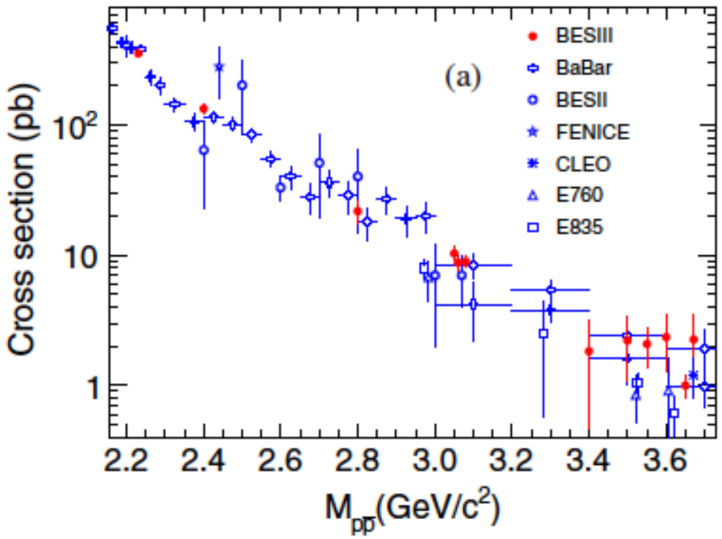
	Energy Scan	Initial State Radiation
E_{beam}	discrete	fixed
$\mathcal{L}$	low at each beam energy	high at one beam energy
σ	$\frac{d\sigma_{p\bar{p}}}{d(\cos\theta)} = \frac{\alpha^2\beta C}{4q^2}[\lvert G_M\rvert^2(1+\cos^2\theta) + \frac{4m_p^2}{q^2}\lvert G_E\rvert^2\sin^2\theta]$	$\frac{d^2\sigma_{p\bar{p}\gamma}}{dx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

Measurement of $e^+e^- \longrightarrow p\bar{p}$

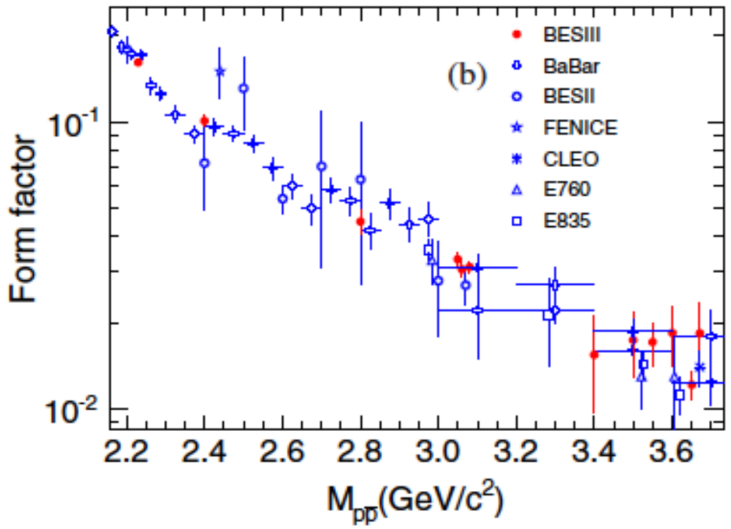
Phys. Rev. D91, 112004 (2015), Scan Data (2011/12)

Analysis of **157 pb^{-1}** data in 12 scan points between **2.23 - 3.71 GeV**

(a) The Born cross section



(b) The effective FF ($|G_E|=|G_M|$)



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

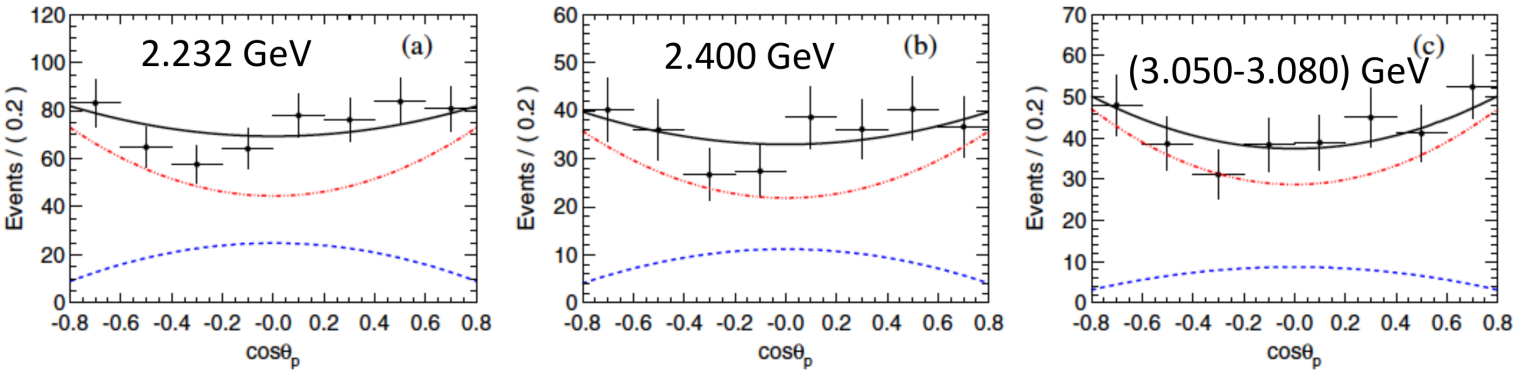
$$|G_{eff}| = \sqrt{\frac{3q^2\sigma_{Born}}{4\pi\alpha^2\beta C(1+1/2\tau)}}$$

- N_{obs}: secevted number of data; N_{bkg}: background from MC; L: luminosity; $\mathcal{E}$: signal efficiency; $(1+\delta)$: radiative corrections; C: Coulomb factor
- Born cross section and effective FF in good agreement with previous experiments, **overall uncertainty improved by $\sim$ 30%**

Measurement of $e^+e^- \longrightarrow p\bar{p}$

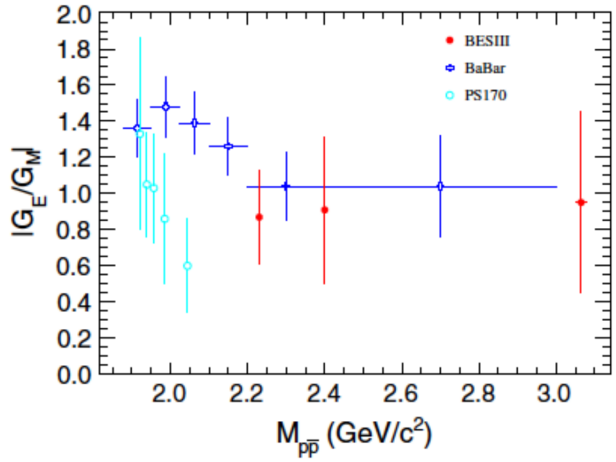
Phys. Rev. D91, 112004 (2015), Scan Data (2011/12)

Extraction of the electromagnetic $R=|G_E|/|G_M|$ ratio



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

$\sqrt{s}$ (MeV)	$\lvert G_M\rvert$ ($\times 10^{-2}$)
	Fit on $\cos\theta_p$
2232.4	$18.42 \pm 5.09 \pm 0.98$
2400.0	$11.30 \pm 4.73 \pm 1.53$
(3050.0, 3080.0)	$3.61 \pm 1.71 \pm 0.82$



- $R = |G_E| / |G_M|$ consistent with BaBar and $R = 1$
- Relative precision (stat. and syst.) $\delta R_{em}/R_{em}$: **25% - 50%**

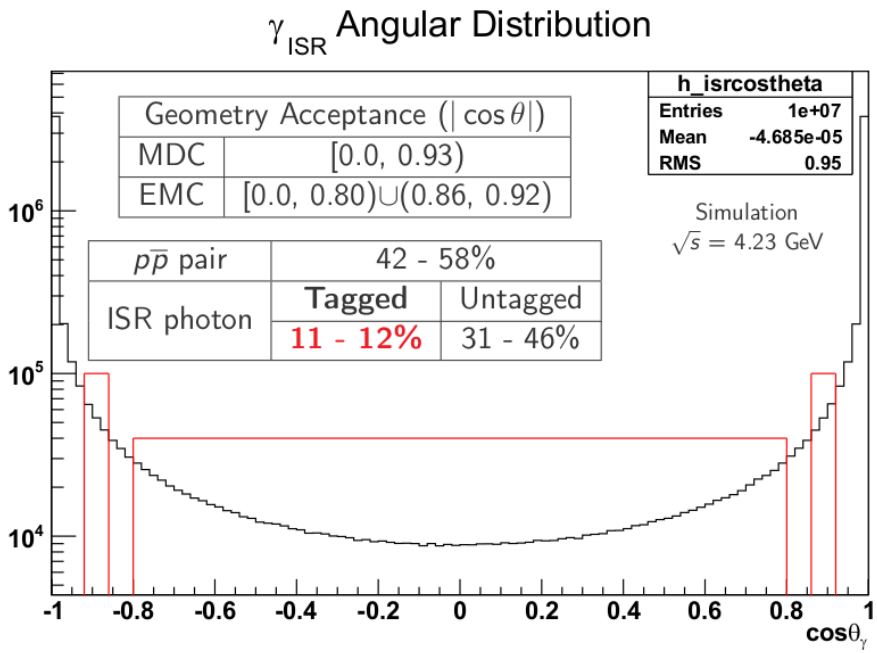
Measurement of $e^+e^- \rightarrow p\bar{p}\gamma_{ISR}$

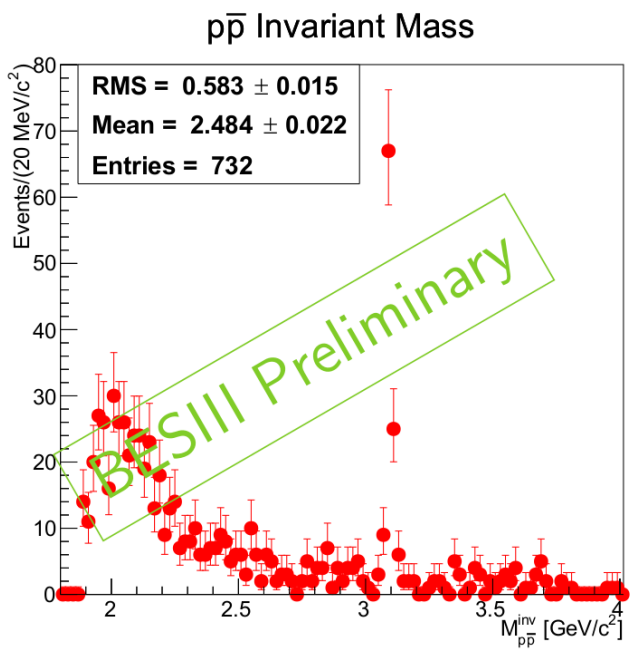
Tagged + Untagged γ_{ISR}, Resonance Data (2010 - 14)

Analysis of 7 data sets between **3.773 - 4.6 GeV**, luminosity **7.4 fb^{-1}**

Tagged method: γ is detected

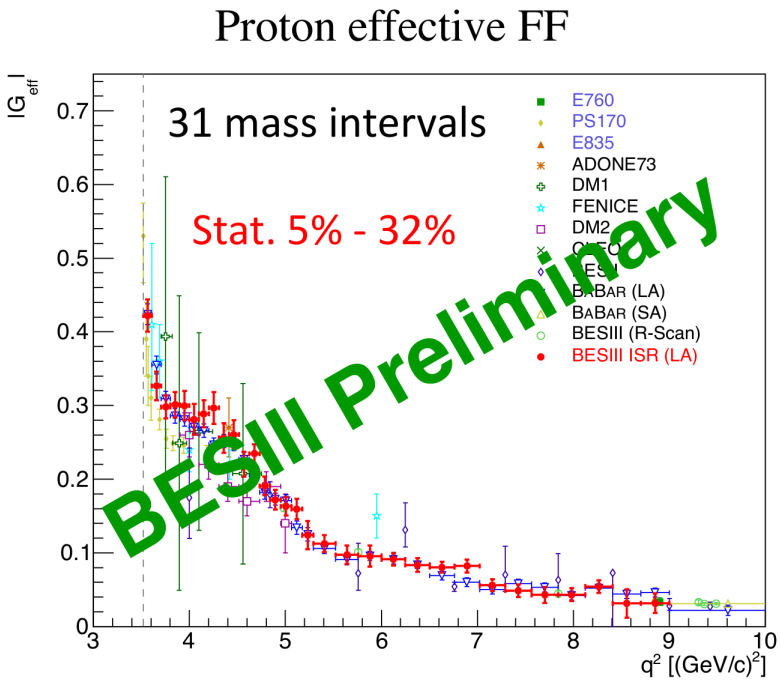
- Two charged tracks from vertex
- One high energetic shower in EMC (ISR-tagged)
- Kinematic constraints applied
- Background subtraction from weighted MC

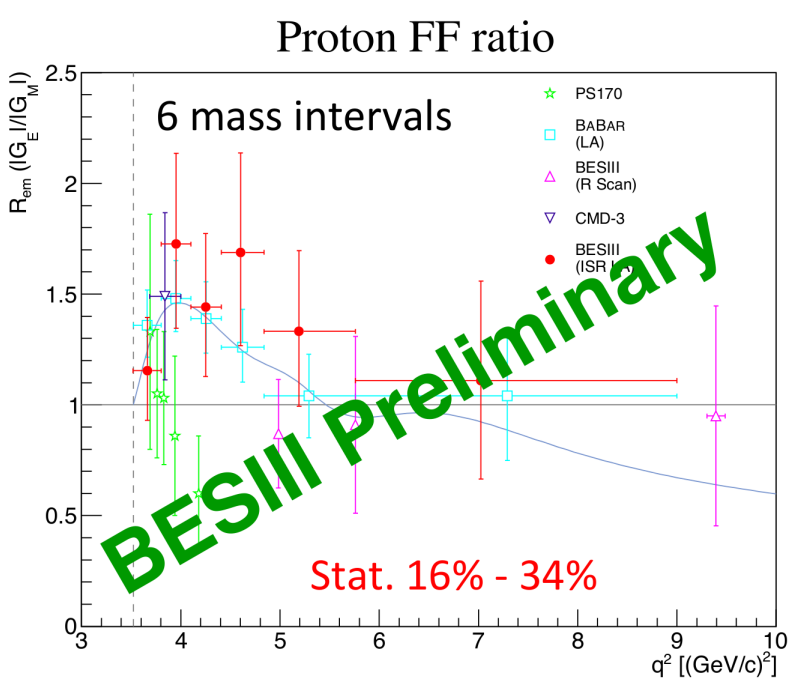




Measurement of $e^+e^- \to p\bar{p}\gamma_{ISR}$

Tagged + Untagged γ_{ISR}, Resonance Data (2010 - 14)





- Proton FFs extracted between threshold and 3.0 GeV
- **Effective FF measurement** consistent with previous measurements
- Relative precision $\delta G_{eff}/G_{eff}$: **5.4%** - **34.2%**
- **R measurement** consistent with BaBar and BESIII R-Scan results
- Relative precision $\delta R_{em}/R_{em}$: **16.5%** - **35.0%**

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

From Scan Data collected 2011/2012

Analysis of 4 data sets between **2.23 - 3.08 GeV**, luminosity **40.5 pb^{-1}**

Two modes for 2.23 GeV:

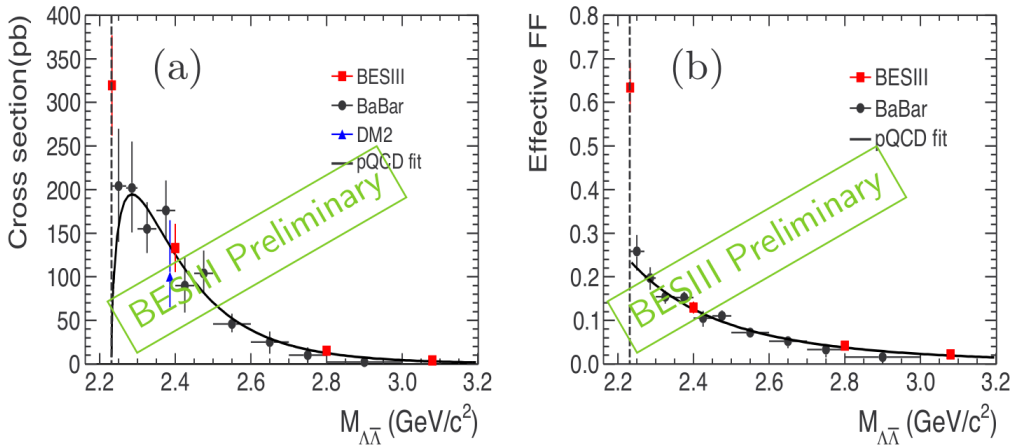
- Charged mode: $\bar{\Lambda} \to \bar{p}\pi^+$ and $\Lambda \to p\pi^-$
- Neutral mode: $\bar{\Lambda} \to \bar{n}\pi^0$

One mode for $>$ 2.23 GeV:

- Charged mode: $\bar{\Lambda} \to \bar{p}\pi^+$ and $\Lambda \to p\pi^-$

Interesting Behaviour:

- Non-Zero at threshold
- Precision improved by 10%



$\sqrt{s}$ GeV	Reconstruction	σ_{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 ± 58	63.4 ± 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		$3.9 \pm 1.1 \pm 0.5$	$2.21 \pm 0.31 \pm 0.14$

$$\sigma = \frac{4\pi\alpha^2\beta}{3q^2}[1 + \frac{1}{2\tau}]|G_{eff}(q^2)|^2$$

Measurement of $e^+e^- \longrightarrow \Lambda_c^+\overline{\Lambda}_c^-$

From new Scan Data collected 2014/15

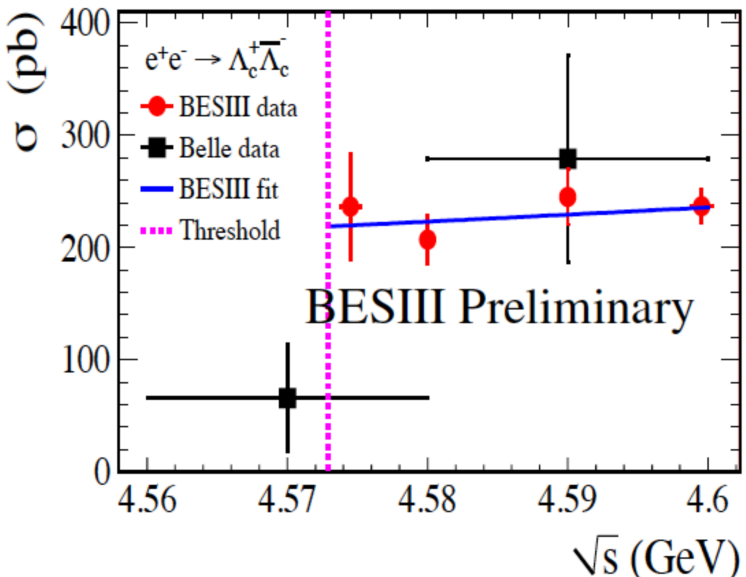
Analysis of 4 data sets between **4.5 - 4.6 GeV**, luminosity **631.3 pb^{-1}**

Main features:

- First direct measurement of Λ_c FF
- Data very close to threshold
- Born cross section with **unpredicted statistical accuracy** (∼1.3% at 4.6 GeV)
- Possible determination of the Λ_c FF ratio at 4.57 and 4.6 GeV

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

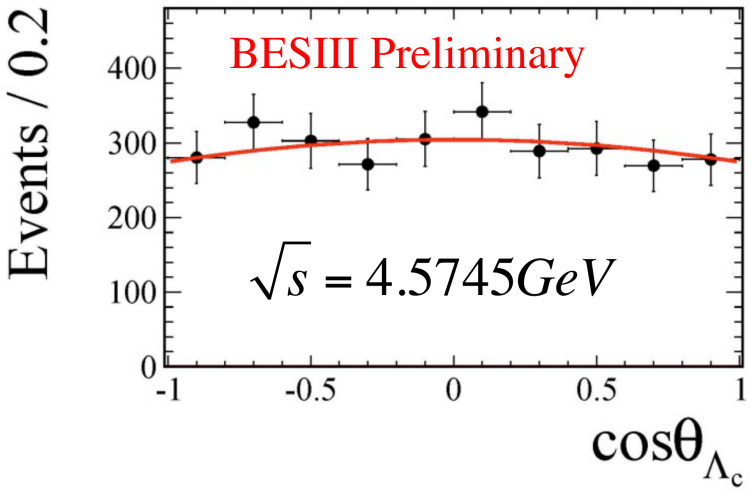
$\sqrt{s}$ [GeV]	Luminosity [pb^{-1}]
4.5745	47.67
4.580	8.545
4.590	8.162
4.5995	566.9

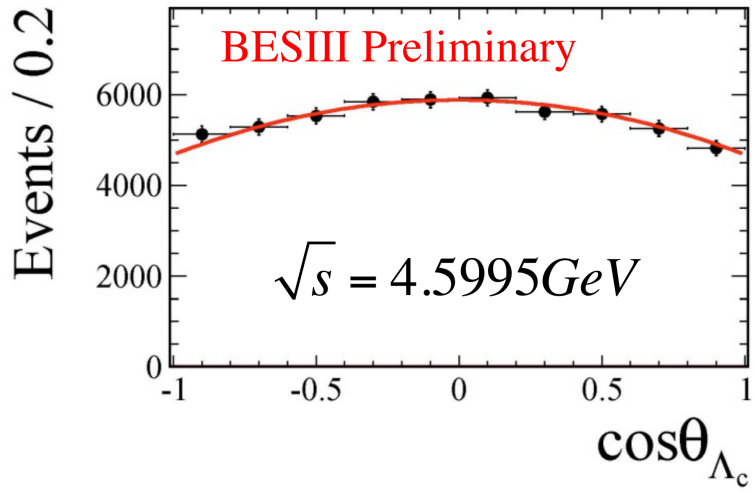


Measurement of $e^+e^- \to \Lambda_c^+ \bar{\Lambda}_c^-$

From Scan Data collected 2014

Measurement of angular distribution at **4.5745 and 4.5995 GeV**





First time measurement of the Λ_c^+ form factor ratio

$\sqrt{s}$ [GeV]	Luminosity [pb^{-1}]	$\lvert G_E\rvert/\lvert G_M\rvert$
4.5745	47.67	1.14 ± 0.14 ± 0.07
4.580	8.545	
4.590	8.162	
4.5995	566.9	1.23 ± 0.05 ± 0.03

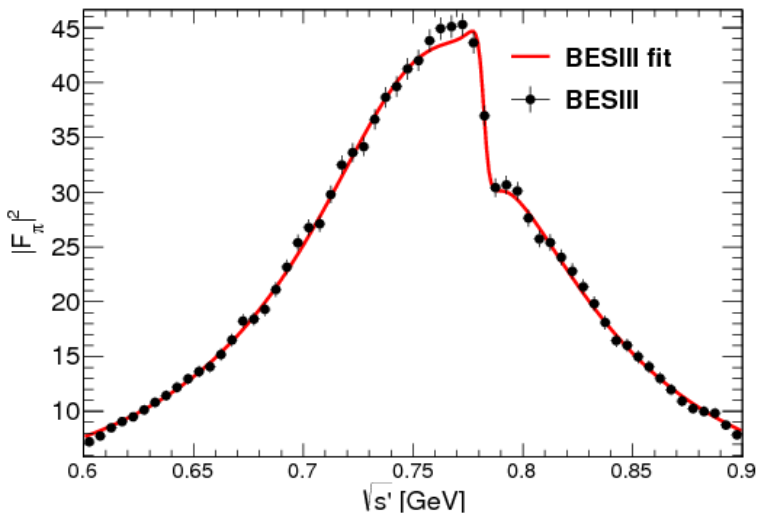
Measurement of $e^+e^- \rightarrow \pi^+\pi^-\gamma_{ISR}$

Phys. Lett. B, Vol. 753, P. 629-638 (2016), Res. Data (2010/11)

Pion cross section and FF at **3.773 GeV**, luminosity **2.9 fb^{-1}**

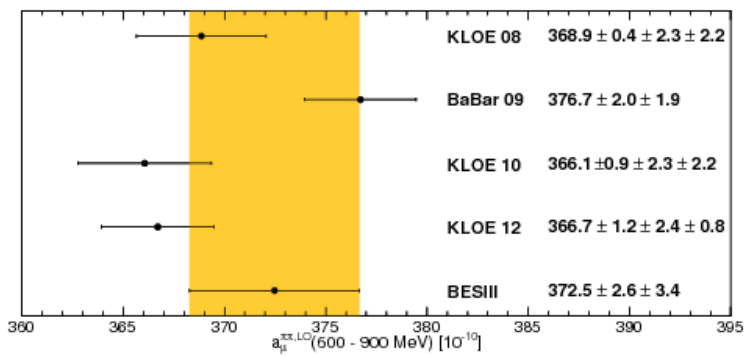
Features:

- Studied range: 600 - 900 MeV
- Main bgk: $\mu^+\mu^-\gamma_{ISR}$, ($< 1\%$)
- Luminosity from BhaBha $\rightarrow$ 0.5%
- Radiative corrections: Phokhara8.0
- FF: $|F_\pi|^2(s^2) = \frac{3s^2}{\pi\alpha^2\beta^3}\sigma^{dressed}_{\pi^+\pi^-}(s^2)$



Summary of Results:

- Syst. uncertainty in XS: 0.9%
- Results inbetween KLOE and BaBar
- Clear confirmation of $\sim 4\sigma$ deviation wrt $(g_\mu\text{-}2)^{SM}$



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

From new Scan Data collected 2014/15

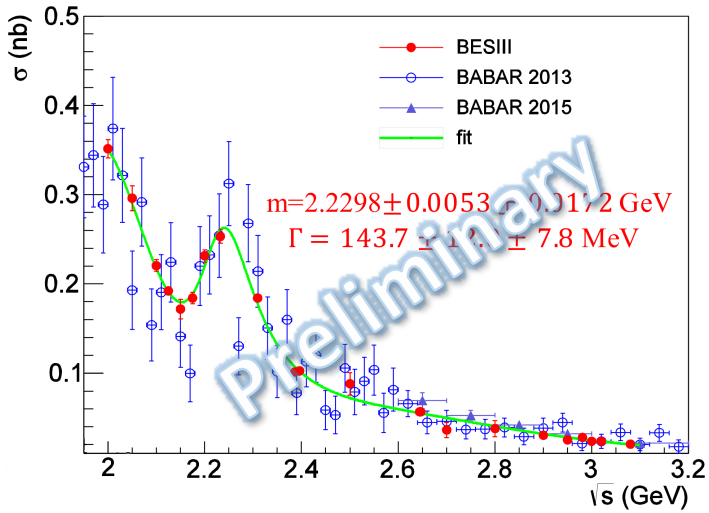
R scan data from **2.0 - 3.08 GeV**, luminosity $\sim$**651 pb**$^{-1}$

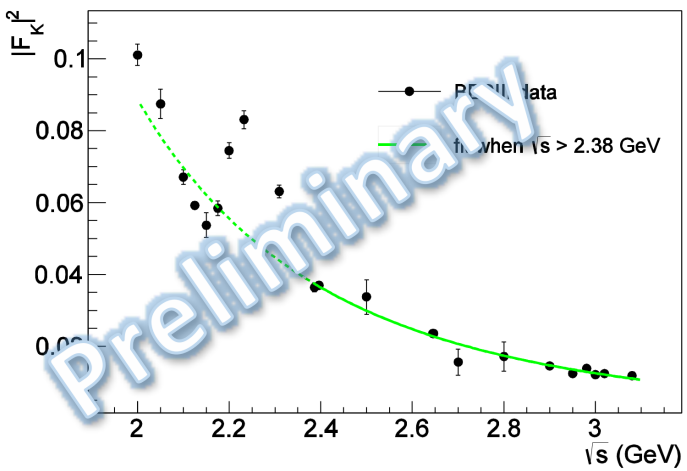
Form Factor from $e^+e^- \to K^+K^-$:

- $|F_K|^2(s) = \frac{3s}{\pi\alpha(0)^2\beta^2}\frac{\sigma_{KK}^{dressed}(s)}{C_{FS}}$
- $\sigma_{KK}^{dressed} = \sigma_{KK}^{0}(s)\left[\frac{\alpha(s)}{\alpha(0)}\right]^2$
- σ_{KK}^{0}: bare cross section
- C_{FS}: final state correction
- $\beta_K = \sqrt{1-4m_K^2/s}$

Features:

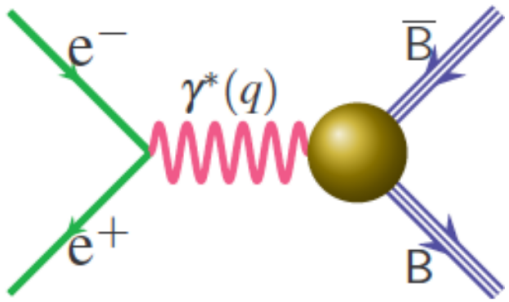
- Consistent with BaBar
- Improve uncertainty
- Confirms QCD prediction: $|F_K|$ decreases with $1/s$

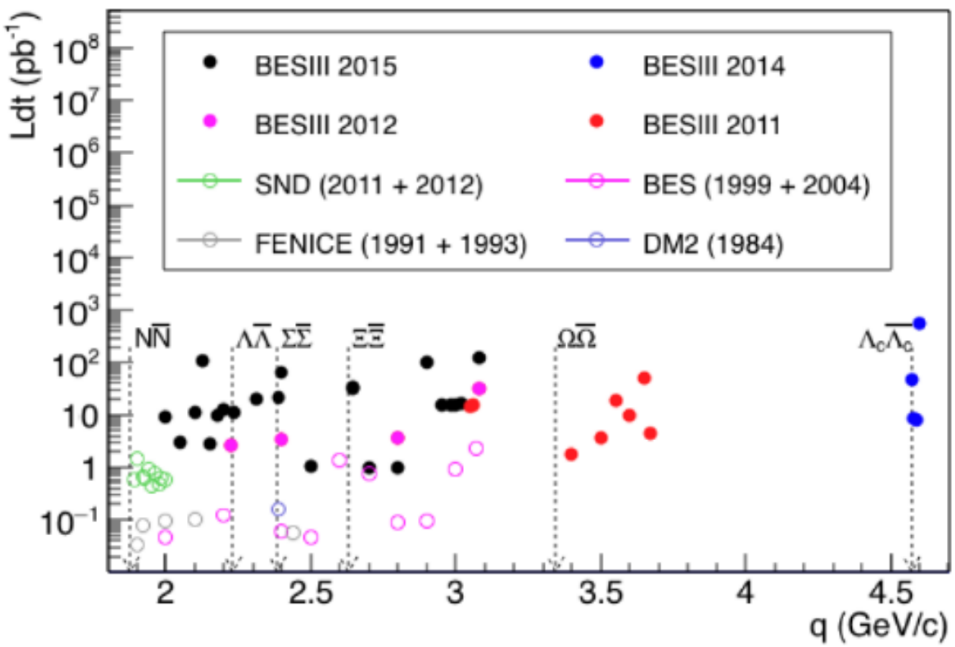




Prospects:

Scan data 2015 between 2 and 3.08 GeV (552 pb^{-1})





Unprecedented determination of baryons (proton, neutron, hyperons) form factors with a direct production of baryon pairs

Prospects:

Proton form factors

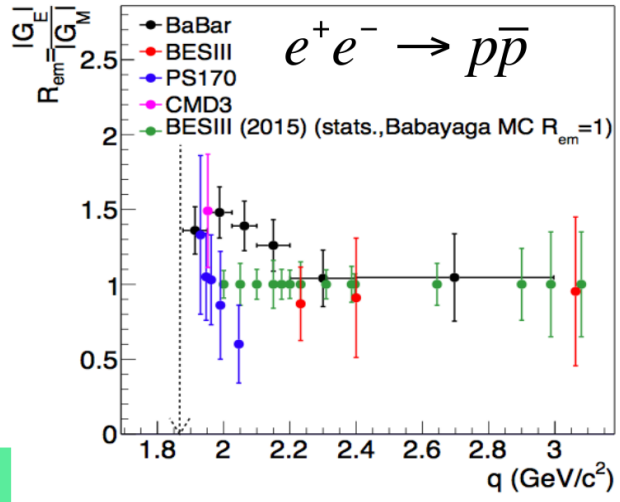
- Precise measurement of proton FFs ($|G_M|$ and $|G_E|$) in narrow q^2-bins
- Expected (MC) statistical accuracies on $R=|G_E|/|G_M|=1$, between 9 % and 35%

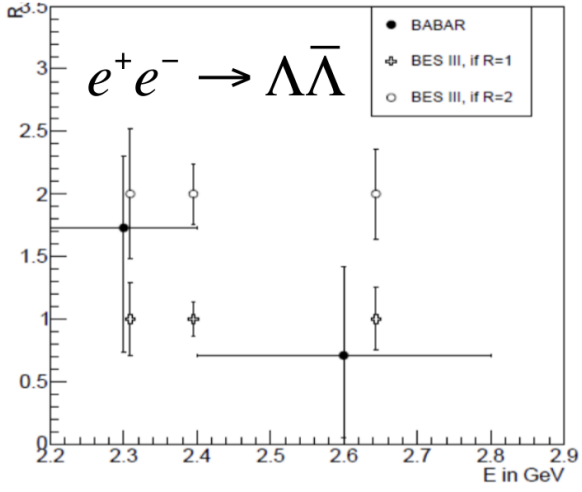
Λ form factors:

- 6 points between 2.23 -2.9 GeV: unprecedented data samples.
- First determination of the ralative phase ϕ between G_E and G_M at 2.396 GeV
- Enough statistics at 4 energy points to extract $R=|G_E|/|G_M|$

Neutron Form Factors:

- Neutron FFs with Scan- and ISR method





Summary:

- BESIII published important results in hadron FFs measurement
- **Baryon FFs:**
  - Proton, Λ, Λ_c results published and preliminary
  - Expected new results from 2015 scan data
- **Meson FFs:**
  - Published results on π FF
  - Preliminary results on K FF
  - Expected new results f.e. on neutral K from 2015 scan data

Summary:

- **Proton FFs** measured at 12 c.m. energies based on 2012 scan data:
  - Effective FF measurements are in good agreement with previous experiments, **improving uncertainty by $\sim$30%**
  - $|G_E|/|G_M|$ **ratio is extracted at 3 energy points**, with total uncertainty between 25% - 50% (dominated by statistics)
- Preliminary results on the proton FF measurement from **tagged-ISR** analysis have been shown. **Untagged-ISR** analysis soon ready.
- Preliminary results on Λ FF measurement based on 2012 scan data
- First measurement on Λ_c **FFs (effective FF and FF ratio)** in direct baryon pair production
- $e^+e^- \to \pi^+\pi^-$ cross section measured via ISR technique with $<$1% uncertainty, **deviation of (g-2)$_\mu$ is confirmed**
- A structure near 2.2 GeV is observed in $e^+e^- \to K^+K^-$ cross section
- **The measurements of baryon and meson FFs will be significantly improved with the 2015 energy scan data from 2.0 GeV to 3.08 GeV**
- Measurements on Neutron and other Hyperons FFs are ongoing

Thank You For Your Attention!