JOHANNES GUTENBERG UNIVERSITÄT MAINZ

SFB 1044 THE LOW-ENERGY FRONTIER OF THE STANDARD MODEL

PRISMA

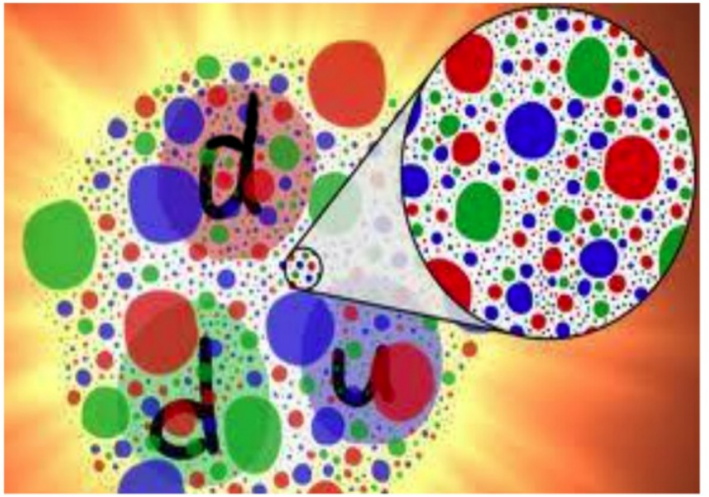
Measurement of hadron form factors at BESIII

June 26, 2018 | Christoph Florian Redmer
for the BESIII Collaboration

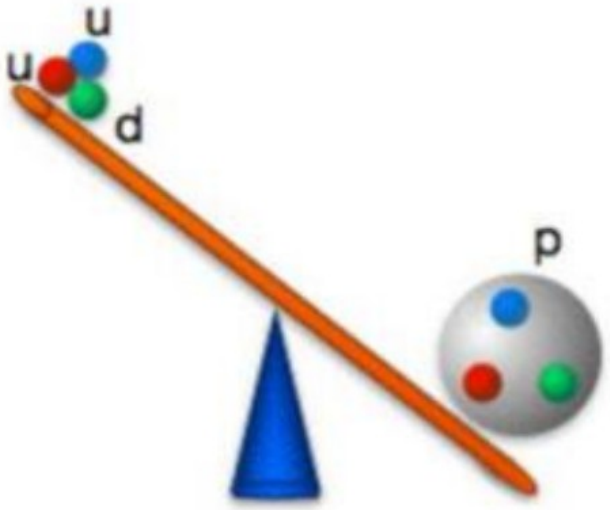
QCD@Work - International Workshop on QCD Theory and Experiment
Matera, 2018

Why measuring hadron form factors?

- Hadrons not point-like
  - Internal stucture



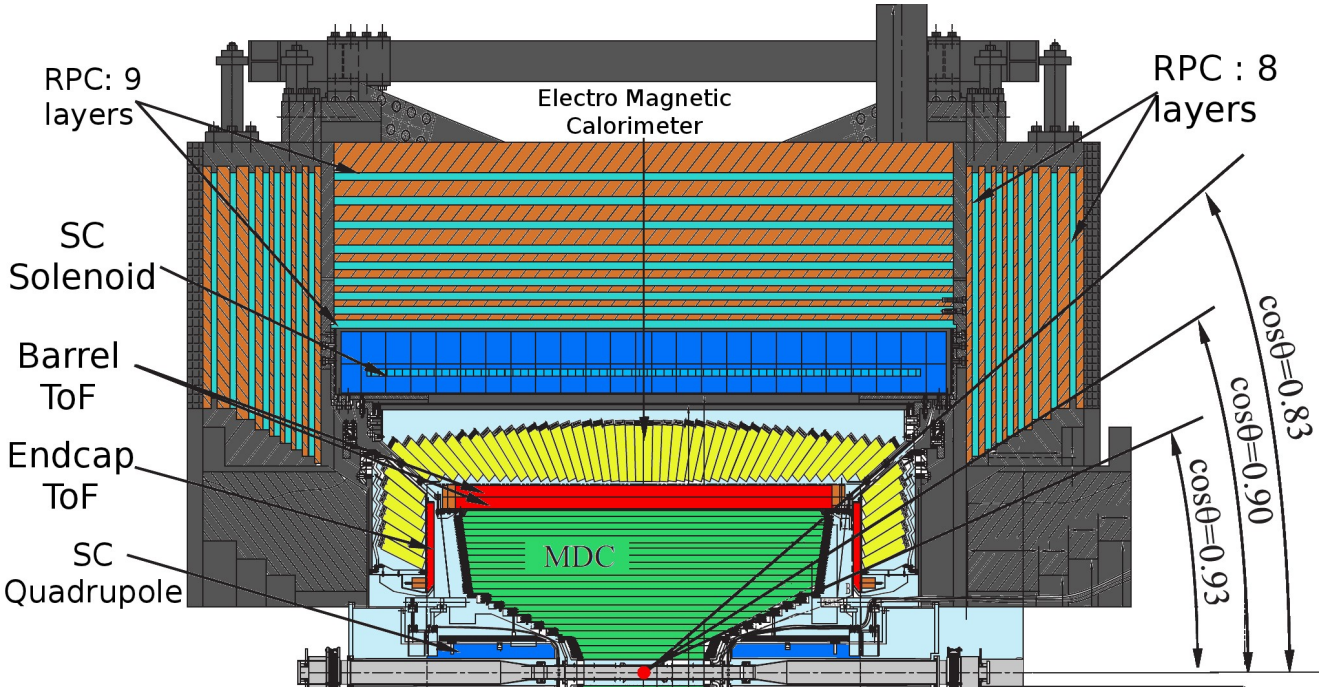
- Sum of valence quark masses not hadron mass
  - Internal dynamics



Form factors as parametrization of structure and internal dynamics of hadrons

BESIII Detector

NIM A614 (2010) 345



Muon Chambers
- 8 – 9 layers of RPC
- p>400 MeV/c
- δRΦ = 1.4 ~ 1.7 cm

Superconducting Magnet
- 1 T magnetic field

EM Calorimeter (EMC)
- 6240 CsI(Tl) crystals
- σ(E)/E = 2.5%
- $\sigma_{Z,\Phi}$(E) = 0.5 – 0.7 cm

Time-of-flight system (TOF)
- σ(t) = 90ps (barrel)
- σ(t) = 110ps (endcap)

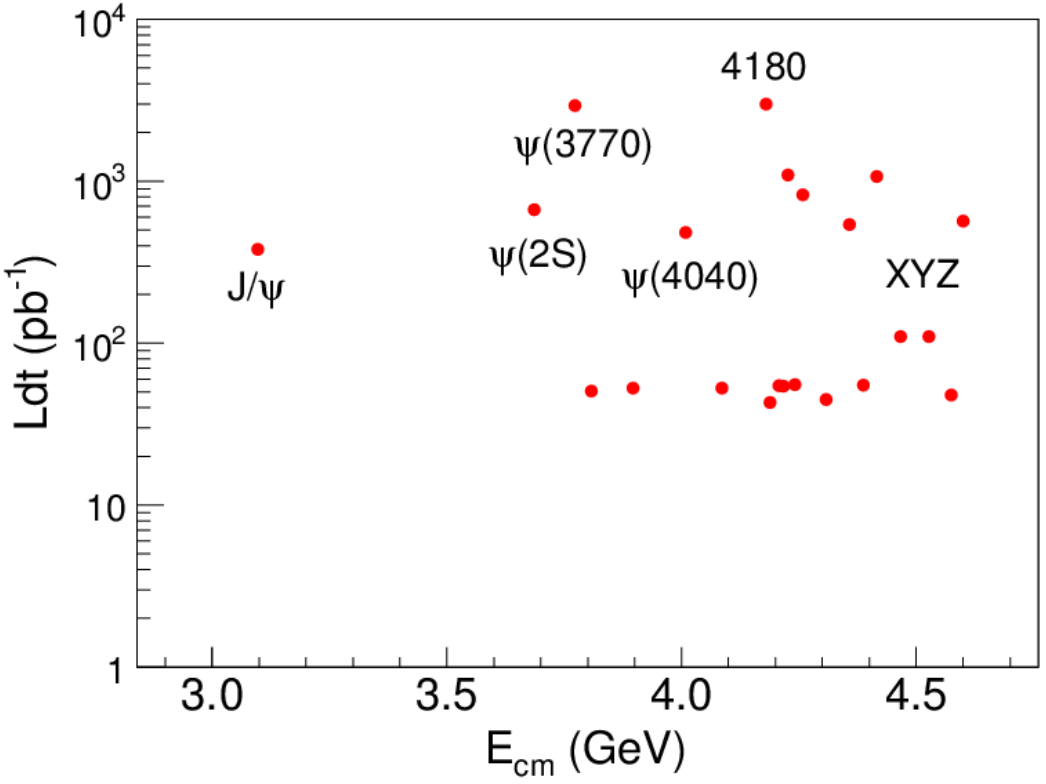
Drift Chamber (MDC)
- σ(p)/p = 0.5%
- $\sigma_{dE/dx}$ = 6.0%

BESIII at BEPCII

Operated at BEPCII collider in Beijing

- $2.0 \leq \sqrt{s}\ [\mathrm{GeV}] \leq 4.6$
- Design luminosity achieved

$$\mathcal{L} = 1.0 \times 10^{33} \mathrm{cm}^{-2} \mathrm{s}^{-1} \text{ at } \psi(3770)$$

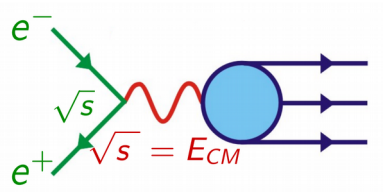


Large data sets for

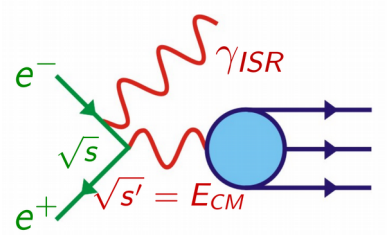
- Charmonium spectroscopy
- Charm physics
- Light hadrons
- τ-mass and R-scan

Hadronic Cross Sections

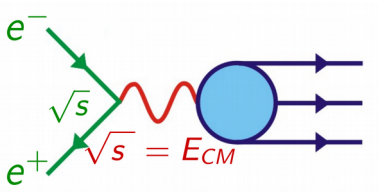
- Exclusive Cross Sections
  - Direct scan



  - Initial State Radiation



- Inclusive Cross Sections
  - Direct scan



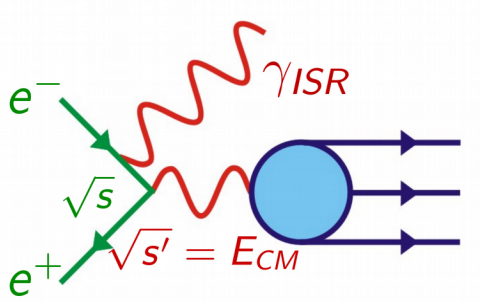
Initial State Radiation

- Reduces effective CMS energy

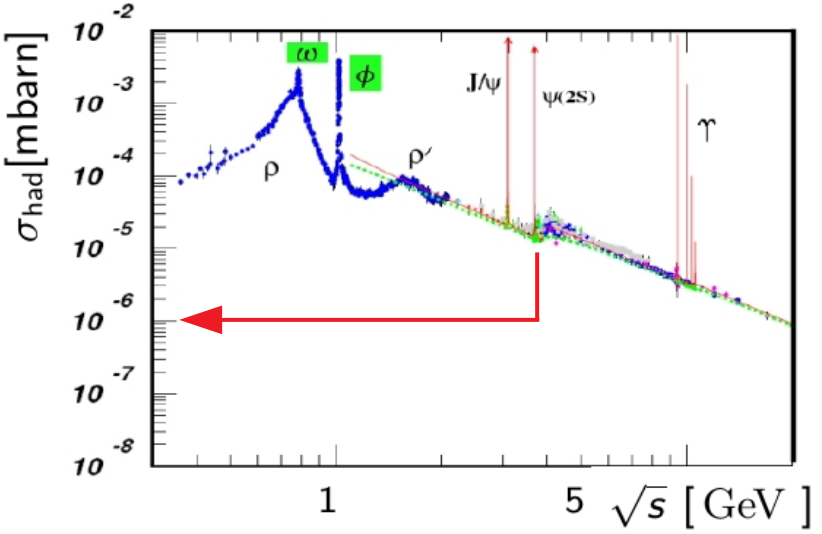
$$\sqrt{s'} = \sqrt{s - 2\sqrt{s}E_\gamma}$$

- Radiator function relates to non-radiative process

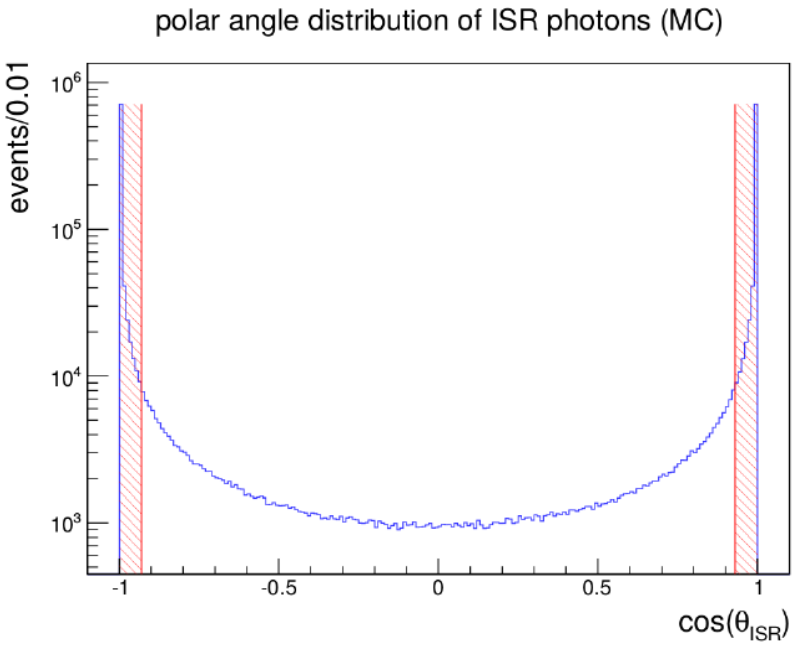
$$\frac{d\sigma_{had+\gamma}}{dm_\gamma} = \frac{2m_{had}}{s} W(s, E_\gamma, \theta_\gamma)_{had}$$



- Emission of ISR suppressed by $\frac{\alpha}{\pi}$
- Large integrated luminosity needed for precision studies
  - > 10 fb^{-1} at BESIII with 3.77 ≤ √s[GeV] ≤ 4.6

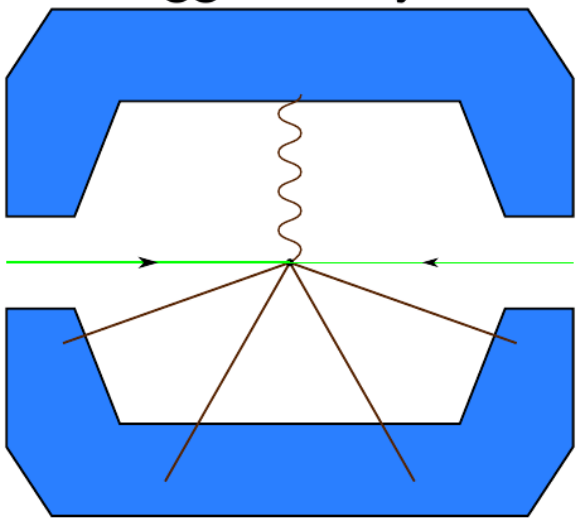


Measurement Strategy

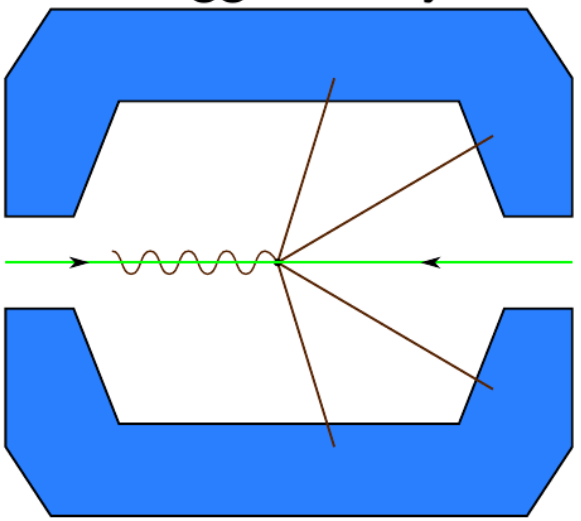


- Detect hadronic system
- ISR photon detected
  - Acceptance from $\pi^+\pi^-$ threshold
  - Large background contamination at high $\sqrt{s'}$
- ISR photon undetected
  - High statistics
  - Acceptance for $\sqrt{s'} > 1$ GeV
  - Small background contamination

Tagged analysis



Untagged analysis



Anomalous Magnetic Moment of μ

Muon anomaly: $a_\mu = \frac{g_\mu - 2}{2}$

a_μ	in units of 10^{-10}
Standard Model	11659182.3 ± 4.3
Direct Measurement	11659209.1 ± 6.3
Difference	26.8 ± 7.6

Davier et al. EPJC 77 (2017) 827

BNL-E821, PRD 73 (2006) 072003

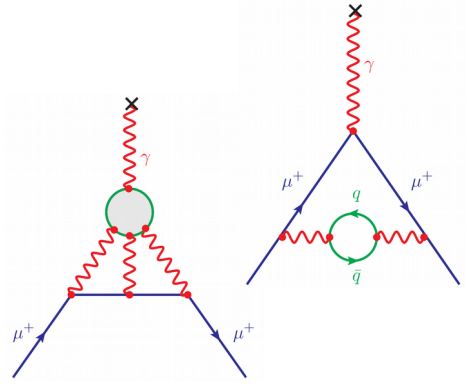
→ More than three standard deviations !

Indication of New Physics?

Theory uncertainty completely dominated by hadronic contributions!

New experiments at Fermilab and J-PARC aim at fourfold improvement of accuracy

Hadronic Vacuum Polarization



Hadronic Light-by-Light Scattering

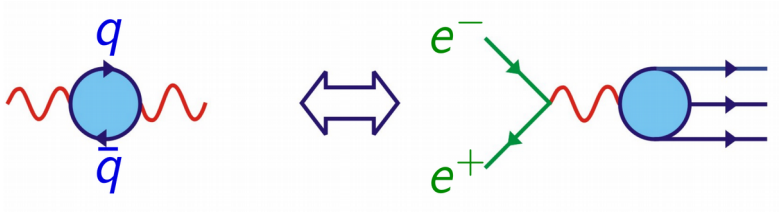
HVP (LO): $(693.1 \pm 3.4)\ 10^{-10}$ EPJC 77 (2017) 827

HLBL : $(10.5 \pm 2.6)\ 10^{-10}$ Adv. Ser. Direct. High Energy Phys. 20, 303 (2009)

Use input from experiments!

Hadronic Vacuum Polarization

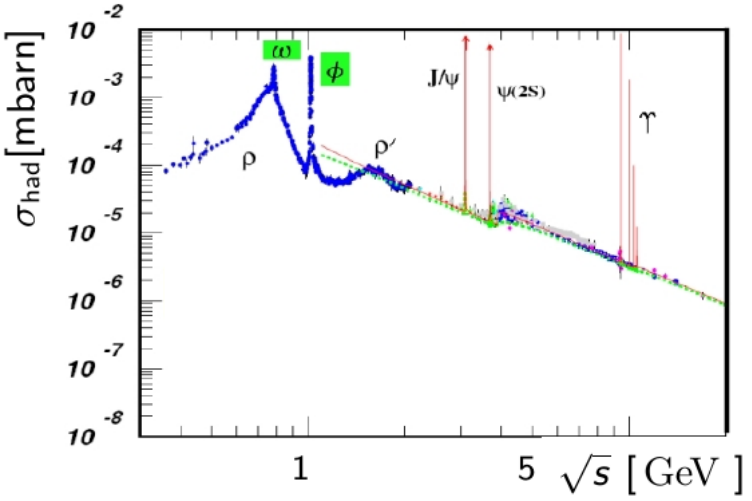
Related to hadronic cross sections by optical theorem

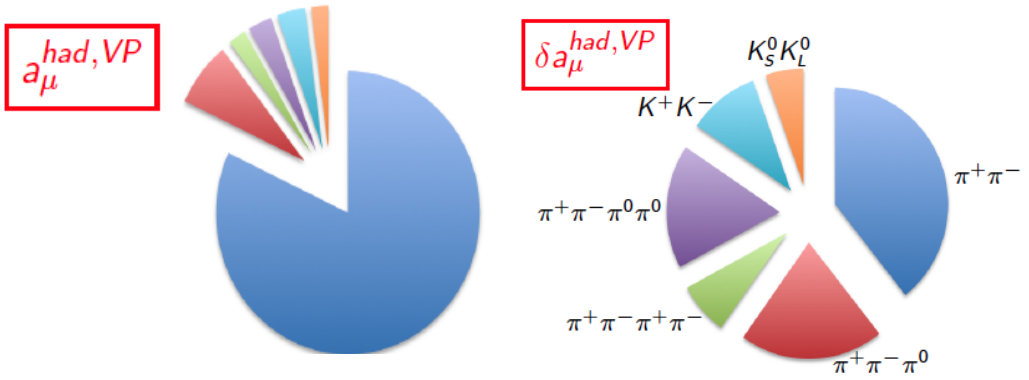


Dispersion integral :

$$a_\mu^{hVP,LO} = \frac{1}{4\pi^3} \int_{4m_\pi^2}^{\infty} K(s)\sigma(e^+e^- \to \text{hadr})\text{d}s$$

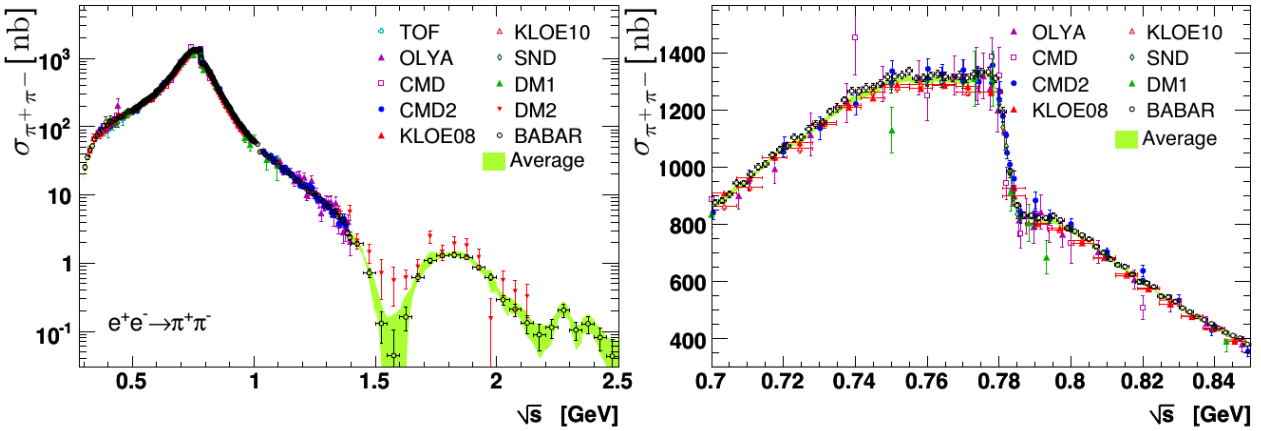
$$\left.\begin{aligned} K(s) &\sim \frac{1}{s} \\ \sigma(e^+e^- \to \text{hadr}) &\sim \frac{1}{s} \end{aligned}\right\} \text{Low energy contributions dominate !}$$





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

Accounts for 75% of a_μ^{hVP} ⟶ Good knowledge important !

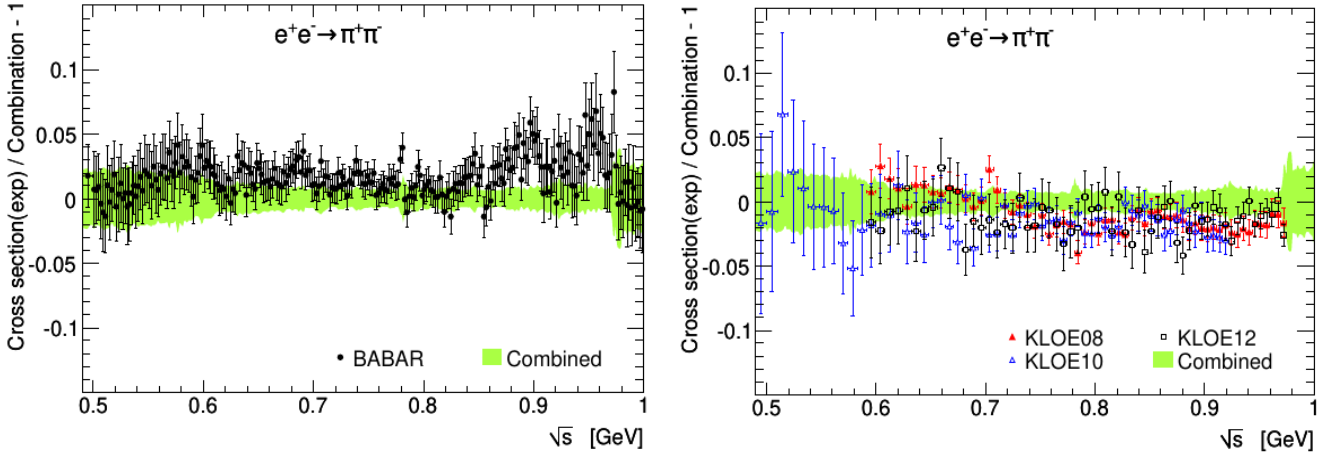


Systematic uncertainties:

0.5%	BaBar
0.8%	KLOE
0.8%	CMD
1.5%	SND

} Limited by statistics

KLOE and BaBar measurements dominate world average



systematic differences ⟶ large uncertainty for a_μ^{hVP}

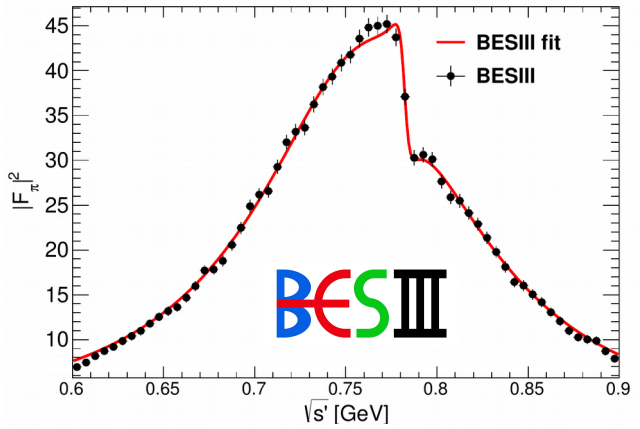
$e^+e^- \to \pi^+\pi^-$

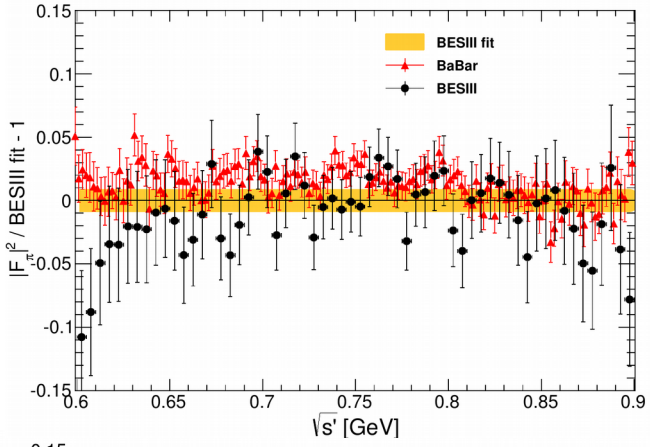
Phys.Lett.B753 (2016) 629

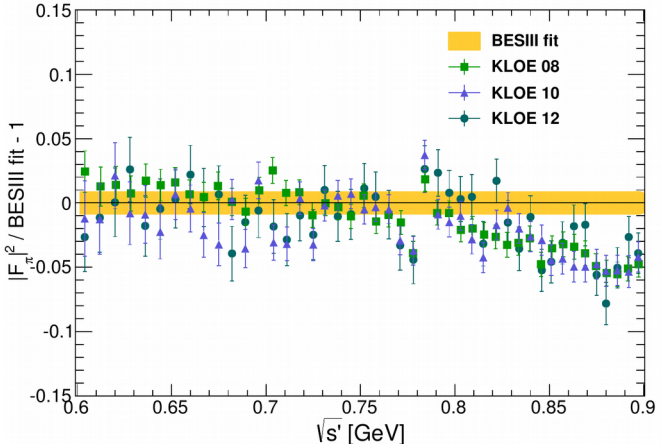
- Tagged ISR technique
- $\mu - \pi$ separation with Artificial Neural Network
- careful evaluation of systematics
  - Total uncertainty of 0.9% achieved
  - Dominated by
    - Luminosity (0.5%)
    - Radiator function (0.5%)

- evaluation for $0.6 \leq m_{\pi\pi} \leq 0.9$
  - 70% of total 2π contribution
  - 50% of a_μ^{hVP} contribution

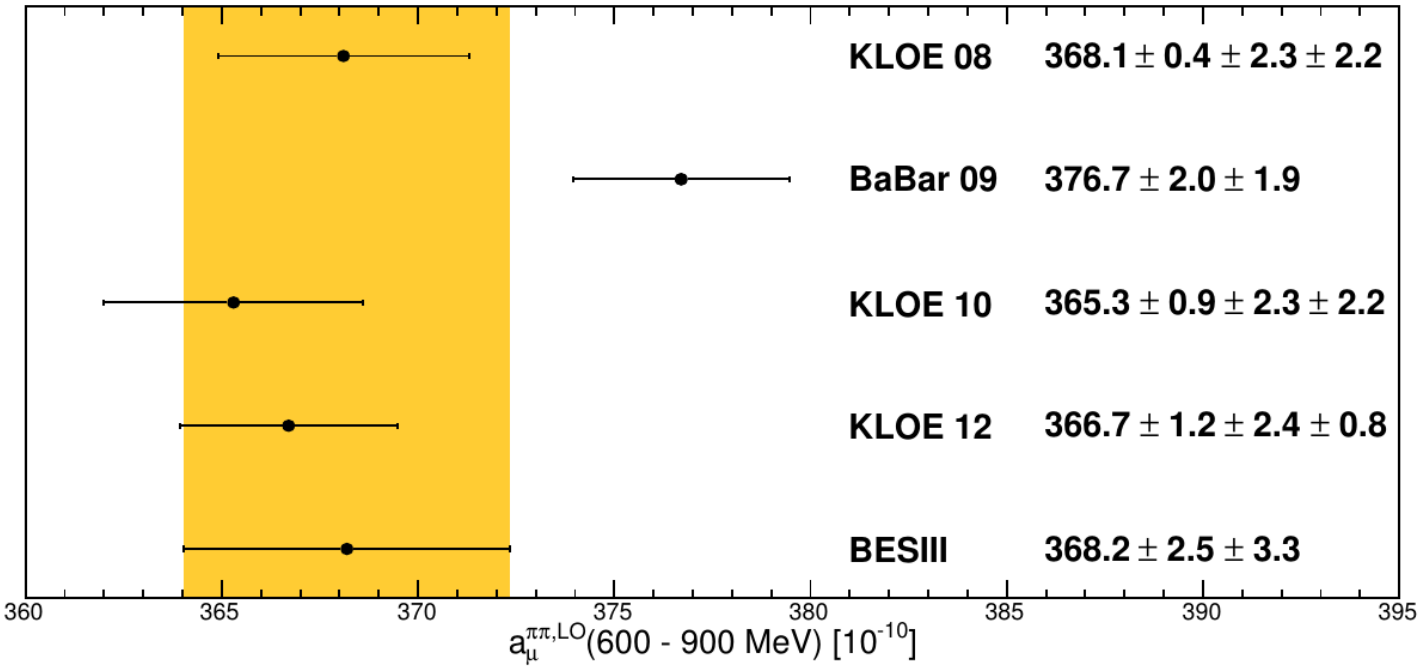
Comparison to previous measurements:
Systematic shift in pion form factor
- below ρ/ω interference w.r.t. BaBar
- above ρ/ω interference w.r.t. KLOE







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



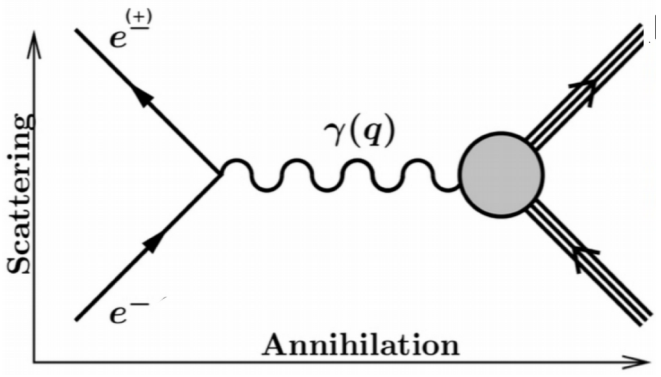
Ablikim et al., Phys.Lett.B753 (2016) 629

- Precision competitive to measurements by BaBar and KLOE
- Good agreement with all KLOE results
- BESIII result confirms $a_\mu^{theo,SM} - a_\mu^{exp} > 3\sigma$
- Reevaluations of a_μ^{hVP} including BESIII result improve accuracy by 20%

EPJ C77 (2017), 820

Baryon EM Form Factors

BESIII: Time-like EM form factors (EMFF)



- Hadronic vector currents → (2s+1) EMFF
- 2 EMFF for baryons
  - Pauli and Dirac FF

$$\Gamma^\mu = \gamma^\mu F_1(q^2) \frac{i\sigma^{\mu\nu} q_\nu}{2M_B} F_2(q^2$$

- Sachs parametrization: $G_E(q^2) = F_1(q^2) + \frac{q^2}{4M_B} F_2(q^2) \qquad G_M(q^2) = F_1(q^2) + F_2(q^2)$
- Differential cross section: $\frac{\mathrm{d}\sigma_{BB}^{\mathrm{Born}}}{\mathrm{d}\Omega} = \frac{\alpha^2\beta^2 C}{4q^2}\left[(1+\cos^2\theta_{\mathrm{B}}^{\mathrm{CM}})|G_M(q^2)|^2 + \frac{1}{\tau}|G_E(q^2)|^2 \sin^2\theta_{\mathrm{B}}^{\mathrm{CM}}\right]$
- Total cross section: $\sigma_{BB}^{\mathrm{Born}} = \frac{4\pi\alpha^2\beta^2 C}{3q^2}\left[|G_M(q^2)|^2 + \frac{1}{2\tau}|G_E(q^2)|^2\right]$
  - Effective EMFF: $|G_{\mathrm{eff}}(q^2)| = \sqrt{\frac{\sigma_{BB}^{\mathrm{Born}}}{(1+\frac{1}{2\tau})\frac{4\pi\alpha^2\beta^2 C}{3q^2}}}$, assuming $|G_M(q^2)| = |G_E(q^2)|$

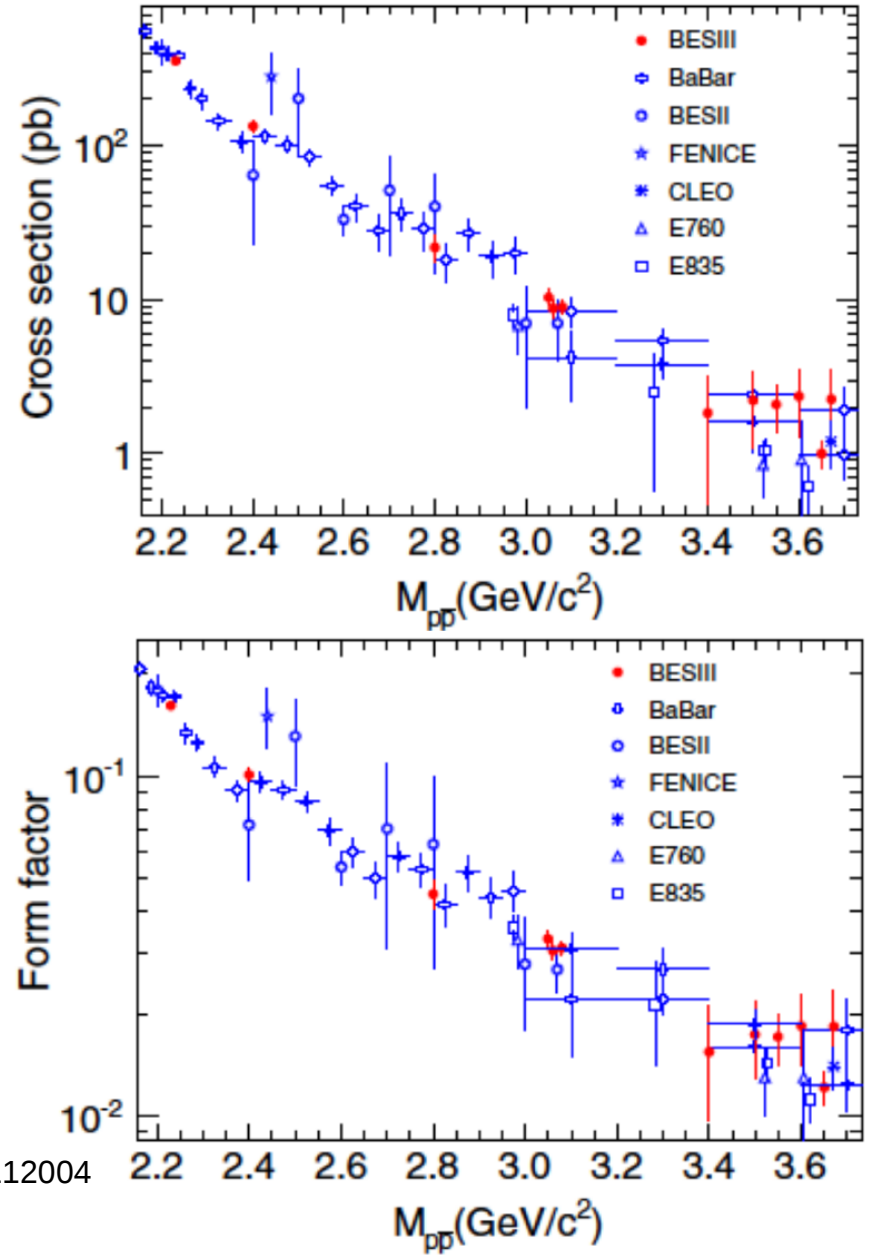
Proton EMFF from Scan

- ‘pilot scan’ analyzed
  - 157 pb^{-1} at 12 scan points 2232.4 ≤ √s[MeV] ≤ 3671.0
- Two tracks, PID by dE/dx and TOF
- Kinematic constraints to reduce background

$$\sigma^{\mathrm{Born}} = \frac{N_{\mathrm{obs}} - N_{bkg}}{\mathcal{L}\varepsilon(1+\delta)}$$

luminosity, efficiency, rad. corrections

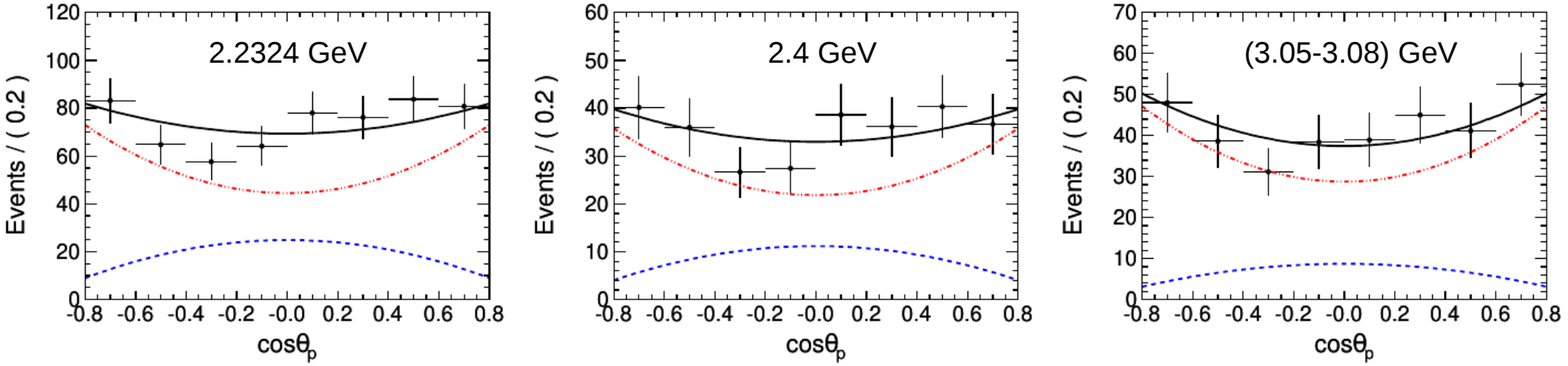
- Cross section and effective EMFF
  - Good agreement with previous measurements
  - Overall improvement of uncertainties by ~ 30%



Phys.Rev. D91 (2015) 112004

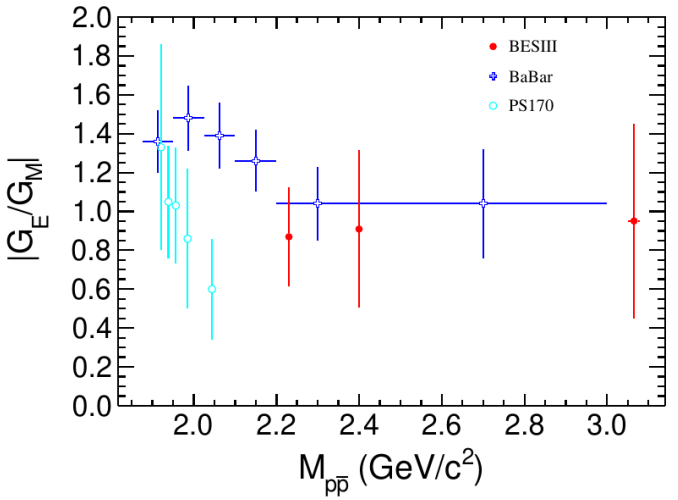
Proton EMFF from Scan

Extraction of EMFF ratio $R = |G_E|/|G_M|$ at scan points with largest statistics



$\sqrt{s}$ (MeV)	$\lvert G_E/G_M\rvert$	$\lvert G_M\rvert$ ($\times 10^{-2}$)
		Fit on $\cos\theta_p$
2232.4	$0.87 \pm 0.24 \pm 0.05$	$18.42 \pm 5.09 \pm 0.98$
2400.0	$0.91 \pm 0.38 \pm 0.12$	$11.30 \pm 4.73 \pm 1.53$
(3050.0, 3080.0)	$0.95 \pm 0.45 \pm 0.21$	$3.61 \pm 1.71 \pm 0.82$
		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

Phys.Rev. D91 (2015) 112004



- EMFF ratio consistent with 1
- Agreement with BaBar measurement
- BESIII result statistics limited
  - New high statistics scan data under evaluation

Proton EMFF from ISR

- 7.4 fb^{-1} at 3.773 ≤ √s[GeV] ≤ 4.6 analyzed
- Both ISR analysis schemes exploited!

Tagged [large angle(LA)]

- Two tracks, one cluster
- 4C kinematic fit
- 5C veto fit with additional γ

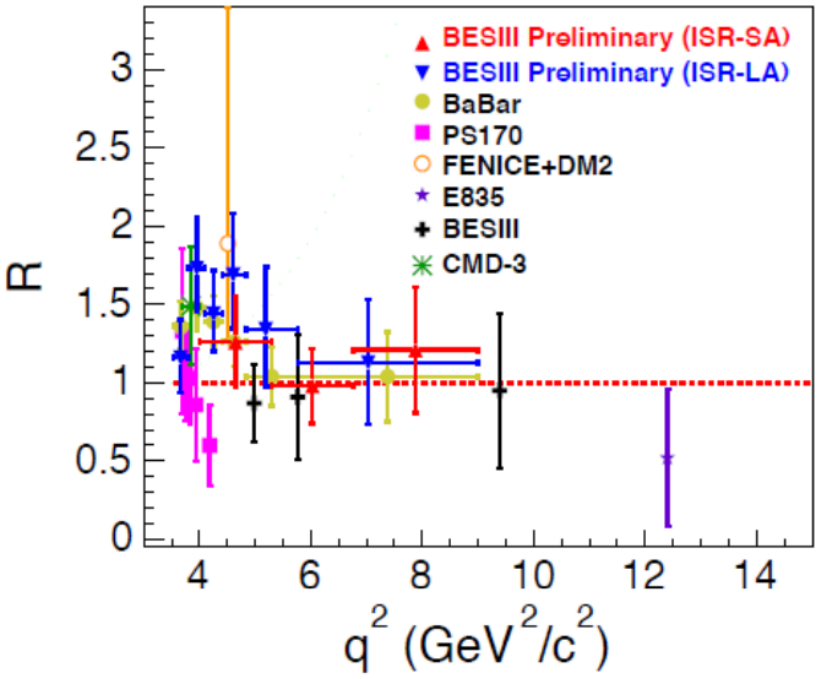
Untagged [small angle (SA)]

- Two tracks, PID by dE/dx and TOF
- Small polar angle of missing momentum
- Missing mass squared

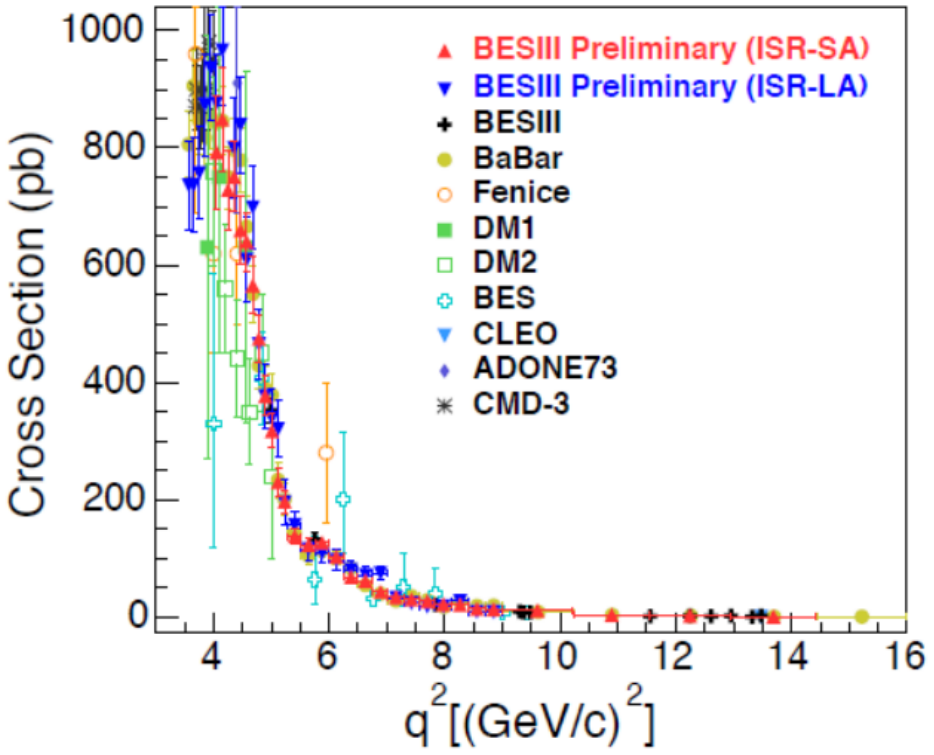
Determination of EMFF ratio:

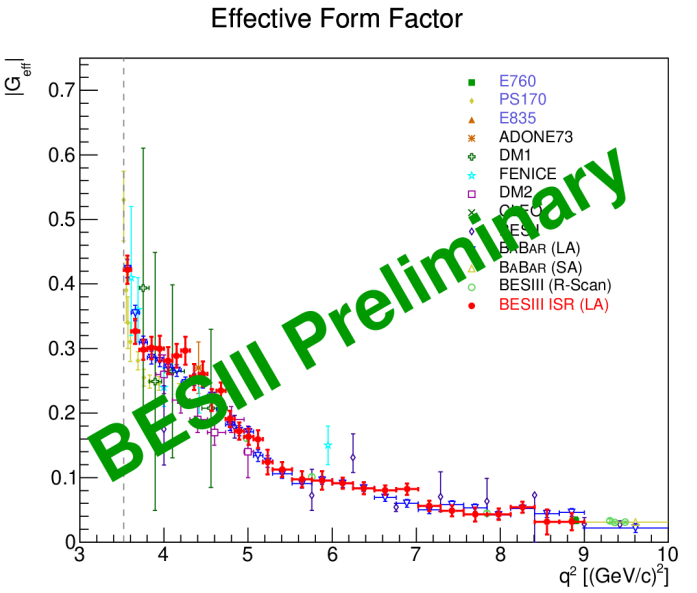
- Tagged: 6 bins in 1.877 ≤ √s[GeV] ≤ 3.0
- Untagged: 3 bins in 2.0 ≤ √s[GeV] ≤ 3.0

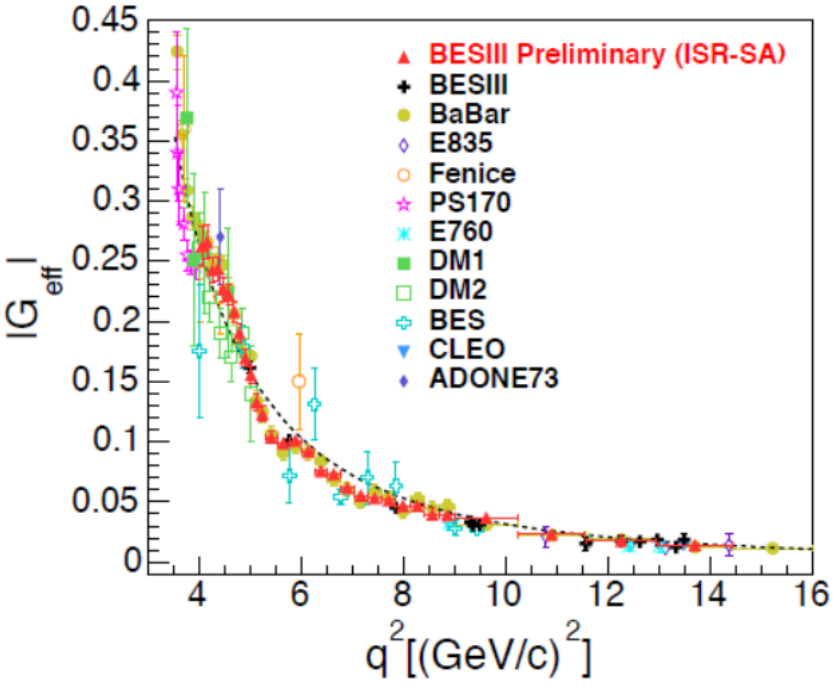
- Competitive accuracy
- Agreement with BaBar and BESIII scan



Proton EMFF from ISR







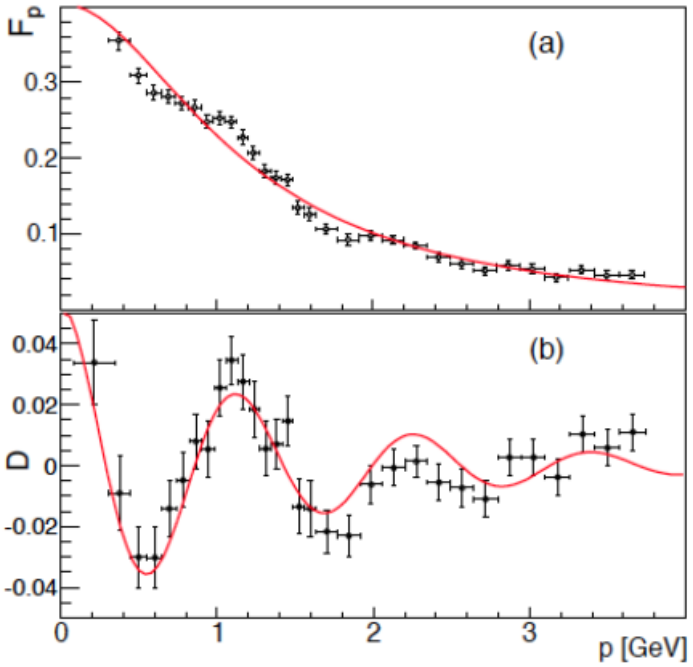
- Measurement of cross section and effective EMFF
  - Tagged: 31 bins in 1.877 ≤ √s[GeV] ≤ 3.0
  - Untagged: 30 bins in 2.0 ≤ √s[GeV] ≤ 3.8
- Consistent with previous measurements
- Untagged ISR competitive in statistics with BaBar

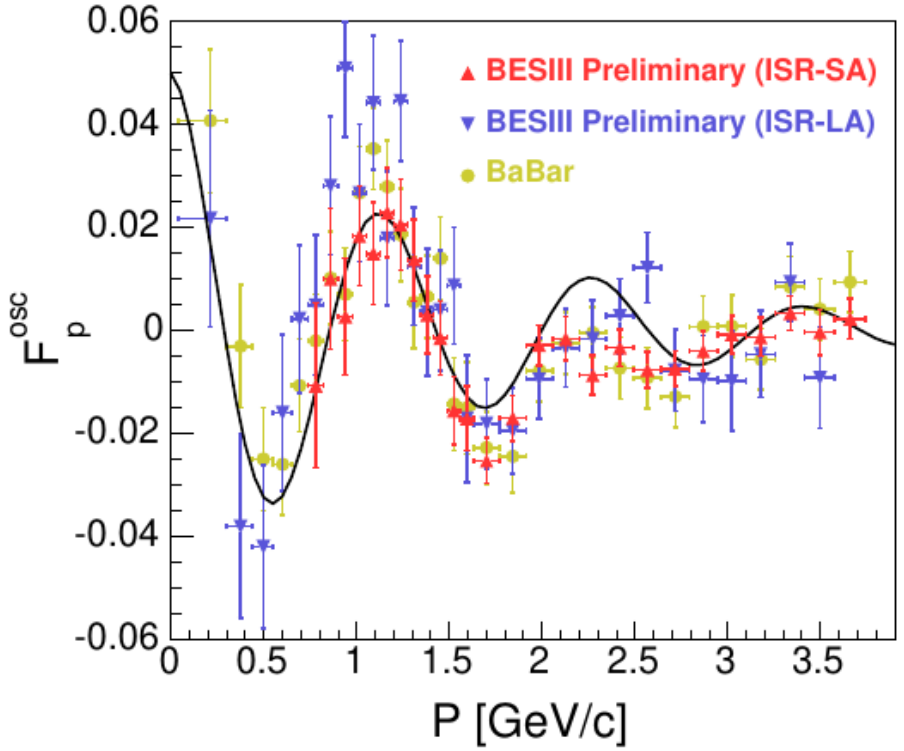
Stuctures in Effective Proton FF

Effective EMFF as a function of three-momentum of the relative motion of the protons

- Damped oscillation pattern in $F^{\mathrm{osc}} = |G_{\mathrm{eff}}| - F^{0}$
  - F^0 : regular behavior of $|G_{eff}|$ over long range of $M_{p\bar{p}}$

A. Bianconi, E. Tomasi-Gustafsson
Phys.Rev.Lett. 114 (2015) 232301
Phys.Rev. C93 (2016) 035201





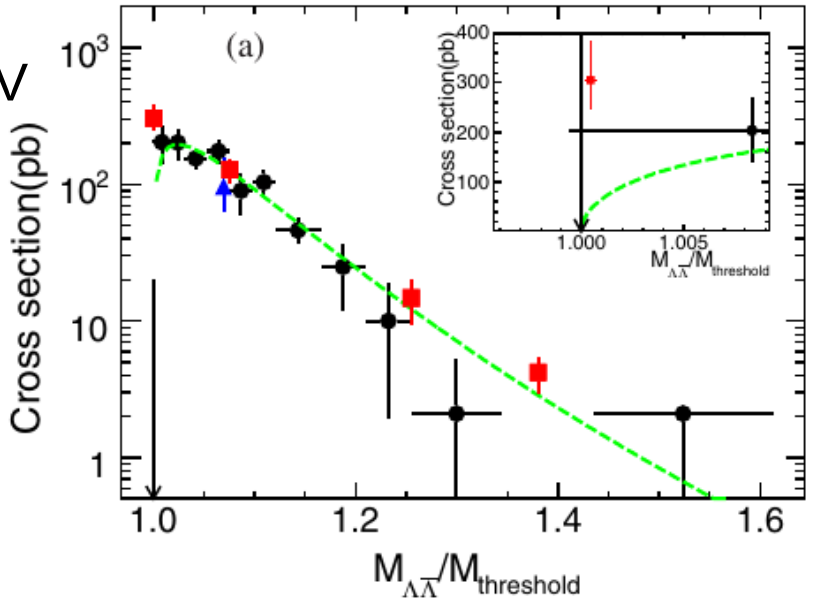
- Observed in BaBar results of $|G_{eff}|$
- Confirmed by BESIII result

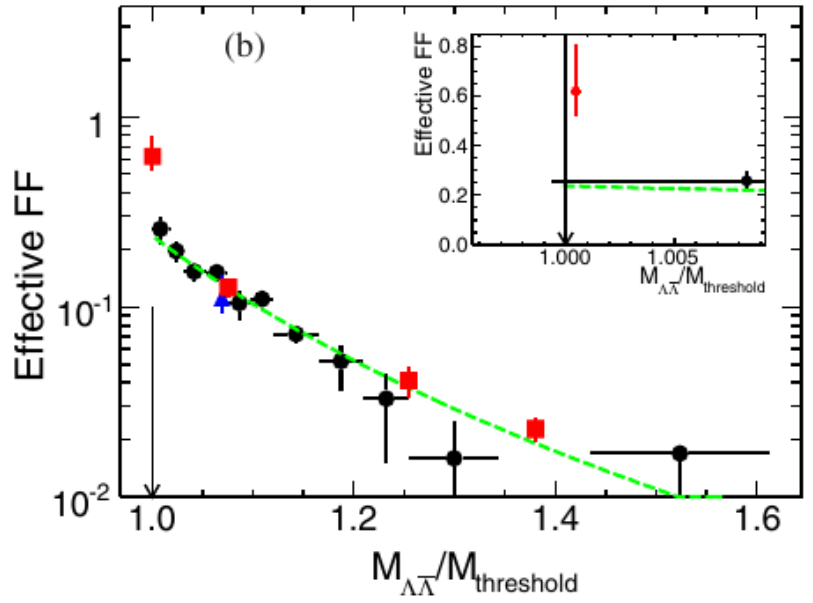
Hyperons

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

- Four scan points: 2232.4, 2400, 2800, 3080 MeV
  - 1 MeV above threshold: $\Lambda \to p\pi, \Lambda \to \bar{n}\pi^0$
    - Indirect reconstruction (nucleons stopped in beam pipe)
  - Other: $\Lambda \to p\pi^-, \bar{\Lambda} \to \bar{p}\pi^+$
- Cross section and effective EMFF determined
- Unexpected enhancement at threshold!

Phys. Rev. D97 (2018) 032013





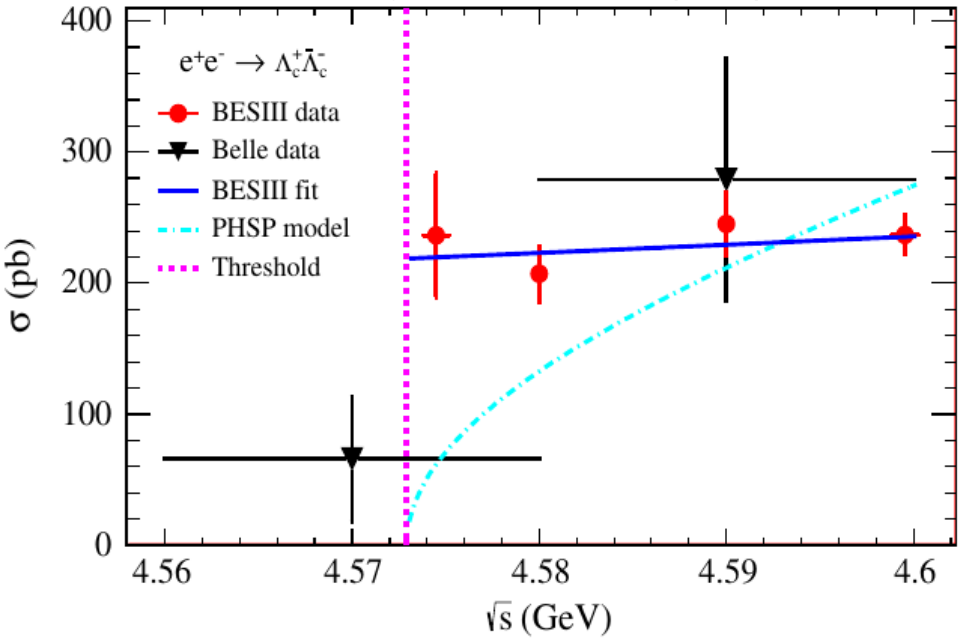
$\sqrt{s}$ (GeV)	$\mathcal{L}_{int}$ (pb^{-1})	N_{obs}	$\epsilon(1+\delta)$ (%)	σ^B (pb)	$\lvert G\rvert$ ($\times 10^{-2}$)
2.2324_1	2.63	43 ± 7	12.9	$312 \pm 51^{+72}_{-45}$	
2.2324_2	2.63	22 ± 6	8.25	$288 \pm 96^{+64}_{-36}$	
2.2324_c				$305 \pm 45^{+66}_{-36}$	$61.9 \pm 4.6^{+18.1}_{-9.0}$
2.400	3.42	45 ± 7	25.3	$128 \pm 19 \pm 18$	$12.7 \pm 0.9 \pm 0.9$
2.800	3.75	8 ± 3	36.1	$14.8 \pm 5.2 \pm 1.9$	$4.10 \pm 0.72 \pm 0.26$
3.080	30.73	13 ± 4	24.5	$4.2 \pm 1.2 \pm 0.5$	$2.29 \pm 0.33 \pm 0.14$

Hyperons

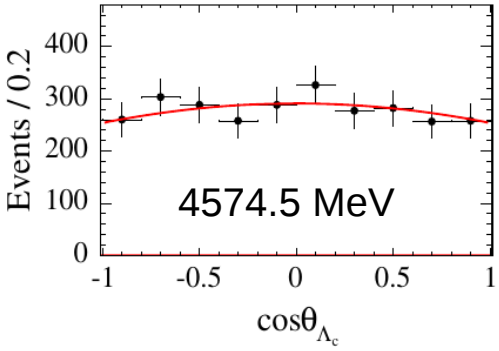
$e^+e^- \to \Lambda_c^+ \bar{\Lambda}_c^-$

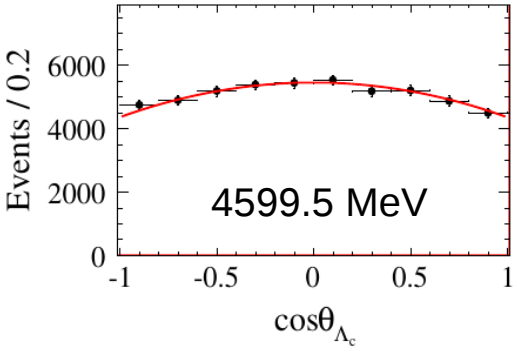
- Four scan points: 4574.5 , 4580.0, 4590.0, 4599.5 MeV
- 10 Cabbibo-favored decay modes (+c.c.)
- Cross section as weighted average
- Plateau at threshold observed
- Tension with Belle result

Phys. Rev. Lett. 120 (2018) 132001



- EMFF ratio extracted for the first time!

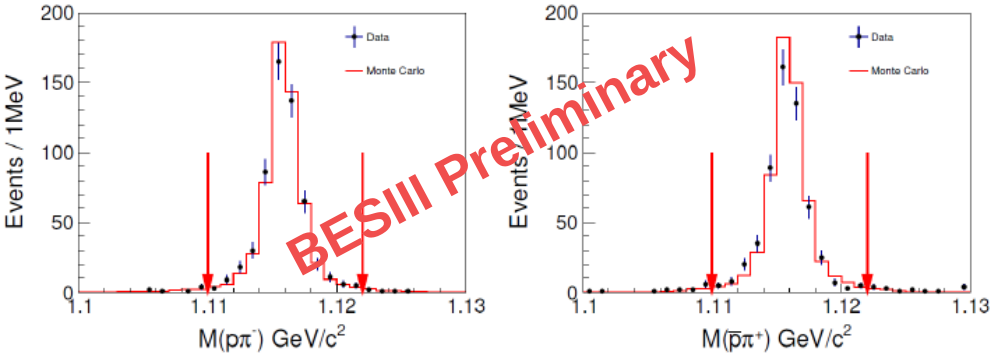




$\sqrt{s}$ (MeV)	α_{Λ_c}	$\lvert G_E/G_M \rvert$
4574.5	$-0.13 \pm 0.12 \pm 0.08$	$1.14 \pm 0.14 \pm 0.07$
4599.5	$-0.20 \pm 0.04 \pm 0.02$	$1.23 \pm 0.05 \pm 0.03$

Hyperons

- Weak decay of Λ self analyzing: Access to phase information!
- High statistics sample at 2.396 GeV
- $e^+e^- \to \Lambda\bar{\Lambda}$
  - Four charged tracks, PID by momentum
  - Mass windows to select Λ



- $\sigma^{Born} = 119.0 \pm 5.3_{\rm stat} \pm 7.3_{syst}$
- $|G_{\rm eff}| = 0.123 \pm 0.003_{\rm stat} \pm 0.004_{syst}$

BESIII Preliminary

  - Compatible with previous measurements by BaBar and BESIII

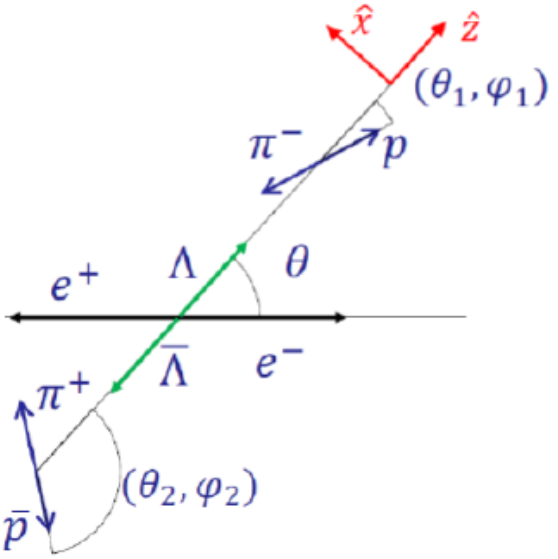
- Relative phase from fit to decay distributions

Relative Phase of Λ EMFF

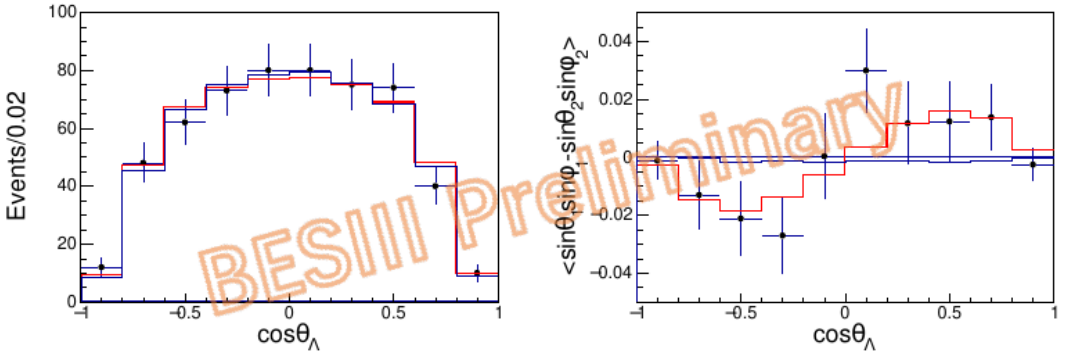
Fäldt, Kupsc Phys. Lett. B772 (2017) 16

$$\mathcal{W}(\xi) = \mathcal{T}_0(\xi) + \eta\,\mathcal{T}_5(\xi) - \alpha_\Lambda^2\left(\mathcal{T}_1(\xi) + \sqrt{1-\eta^2}\cos(\Delta\Phi)\,\mathcal{T}_2(\xi) + \eta\,\mathcal{T}_6(\xi)\right) + \alpha_\Lambda\sqrt{1-\eta^2}\sin(\Delta\Phi)\left(\mathcal{T}_3(\xi) - \mathcal{T}_4(\xi)\right).$$

$$\mathcal{T}_0(\xi) = 1$$
$$\mathcal{T}_1(\xi) = \sin^2\theta\sin\theta_1\sin\theta_2\cos\phi_1\cos\phi_2 + \cos^2\theta\cos\theta_1\cos\theta_2$$
$$\mathcal{T}_2(\xi) = \sin\theta\cos\theta\,(\sin\theta_1\cos\theta_2\cos\phi_1 + \cos\theta_1\sin\theta_2\cos\phi_2)$$
$$\mathcal{T}_3(\xi) = \sin\theta\cos\theta\sin\theta_1\sin\phi_1$$
$$\mathcal{T}_4(\xi) = \sin\theta\cos\theta\sin\theta_2\sin\phi_2$$
$$\mathcal{T}_5(\xi) = \cos^2\theta$$
$$\mathcal{T}_6(\xi) = \cos\theta_1\cos\theta_2 - \sin^2\theta\sin\theta_1\sin\theta_2\sin\phi_1\sin\phi_2$$



Unbinned maximum log likelihood fit with relative phase $\Delta\Phi$ and $\eta = \dfrac{\tau - R^2}{\tau + R^2}$ as free parameters



$$R = 0.94 \pm 0.16_{\rm stat} \pm 0.03_{\rm syst} \pm 0.02_{\alpha_\Lambda}$$

$$|\Delta\Phi| = 42^\circ \pm 16^\circ_{\rm stat} \pm 8^\circ_{\rm syst} \pm 6^\circ_{\alpha_\Lambda}$$

BESIII Preliminary

First measurement!

Summary

- Form factors contain valuable information on hadron structure
- BESIII perfect laboratory to study hadron FF's
  - Scan, tagged, and untagged ISR
  - Mesons
    - Important input to calculations of a_μ^{hVP}
    - Precision measurement of $e^+e^- \to \pi^+\pi^-$ Phys. Lett. B753 (2016) 629
    - Higher multiplicities $(\pi^+\pi^-\pi^0, \pi^+\pi^-\pi^0\pi^0, ...)$ in internal review
  - Baryons
    - First measurements of p, Λ, Λ_c Phys. Rev. D91 (2015) 112004 Phys. Rev. D97 (2018) 032013 Phys. Rev. Lett. 120 (2018) 132001
      - Intriguing enhancements at threshold
      - Oscillating behavior of p effective FF
    - High statistics scan data available
      - First measurement of relative phase of EMFF in Λ
      - Measurements of nucleon (p and n!) form factors in internal review
    - Prospects for Λ_c: Potential energy upgrade of the accelerator