JOHANNES GUTENBERG UNIVERSITÄT MAINZ

SFB 1044 THE LOW-ENERGY FRONTIER OF THE STANDARD MODEL

PRISMA

Measurements of Hadronic Cross Sections at BESIII

May 30, 2018 | Christoph Florian Redmer
for the BESIII Collaboration

CIPANP2018 – 13th Conference on the Intersections of Particle and Nuclear Physics

Anomalous magnetic moment of the μ

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

a_μ	in units of 10^{-10}		
Standard Model	11659182.3 ± 4.3	Davier et al.	EPJC 77 (2017) 827
Direct Measurement	11659209.1 ± 6.3	BNL-E821	PRD 73 (2006) 072003
Difference	26.8 ± 7.6		

→ More than three standard deviations !

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Indication of New Physics?

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

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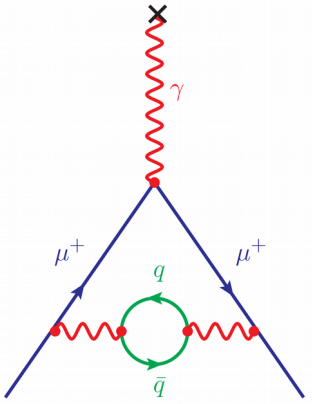
Hadronic contributions completely dominate the uncertainty of the Standard Model prediction!

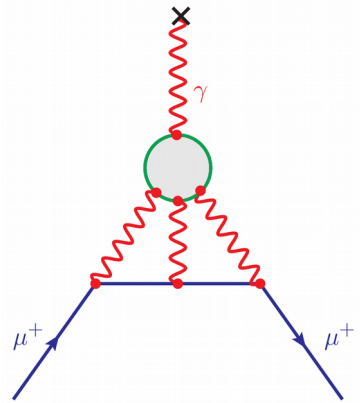
HVP (LO): $(693.1 \pm 3.4)\ 10^{-10}$ EPJC 77 (2017) 827

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

Use input from experiments!

Hadronic Vacuum Polarization

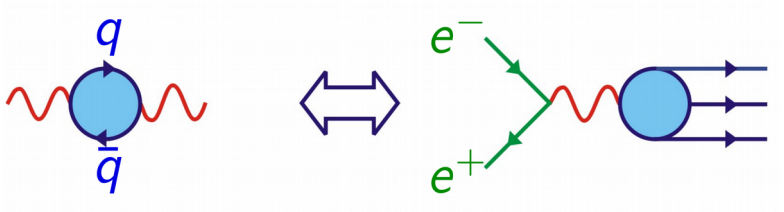




Hadronic Light-by-Light Scattering

Hadronic Vacuum Polarization

Related to hadronic cross sections by optical theorem

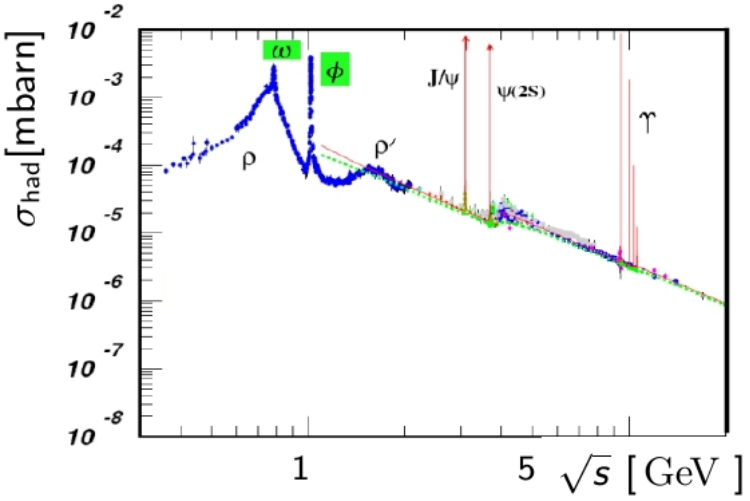


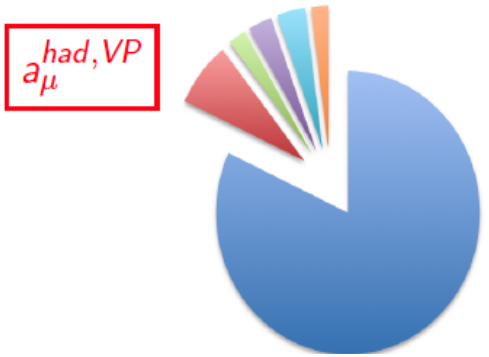
Dispersion integral :

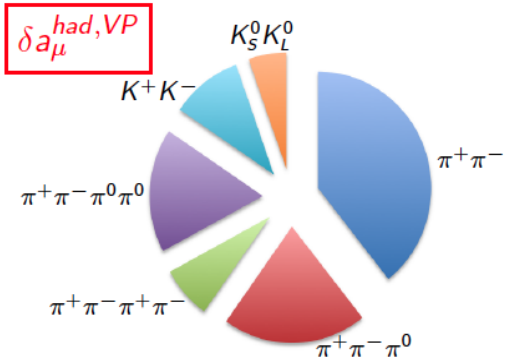
$$a_\mu^{hVP,LO} = \frac{1}{4\pi^3} \int_{4m_\pi^2}^{\infty} K(s)\sigma(e^+e^- \to \text{hadr})\text{d}s$$

$$K(s) \sim \frac{1}{s}$$
$$\sigma(e^+e^- \to \text{hadr}) \sim \frac{1}{s}$$

Low energy contributions dominate !

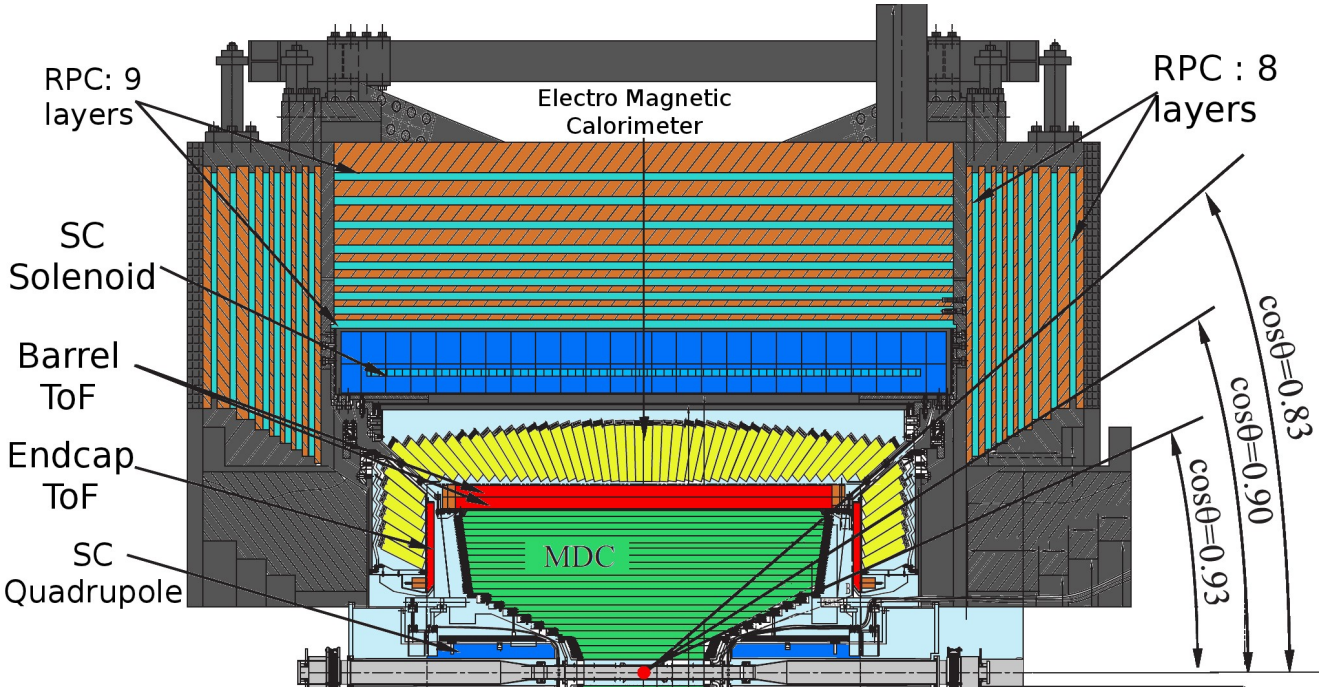






BESIII at BEPCII

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

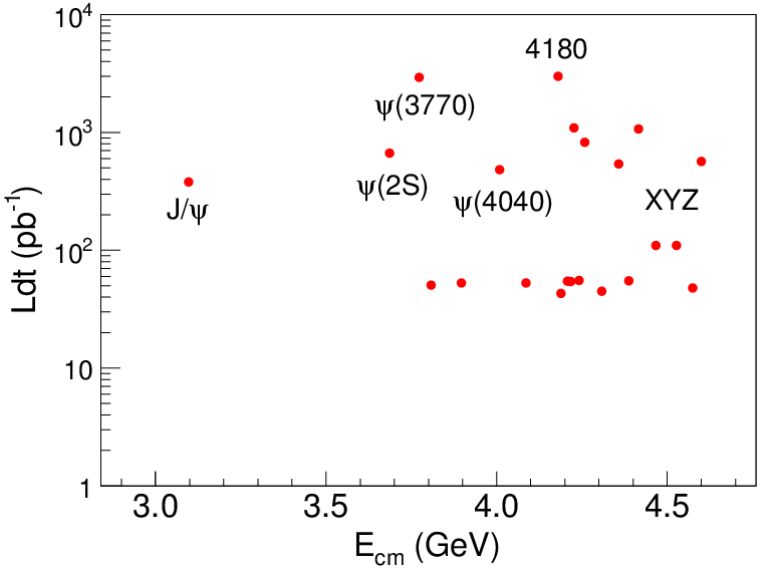
EM Calorimeter (EMC)
- 6240 CsI(Tl) crystals
- σ(E)/E = 2.5%
- $\sigma_{Z,\Phi}$(E) = 0.5 – 0.7 cm

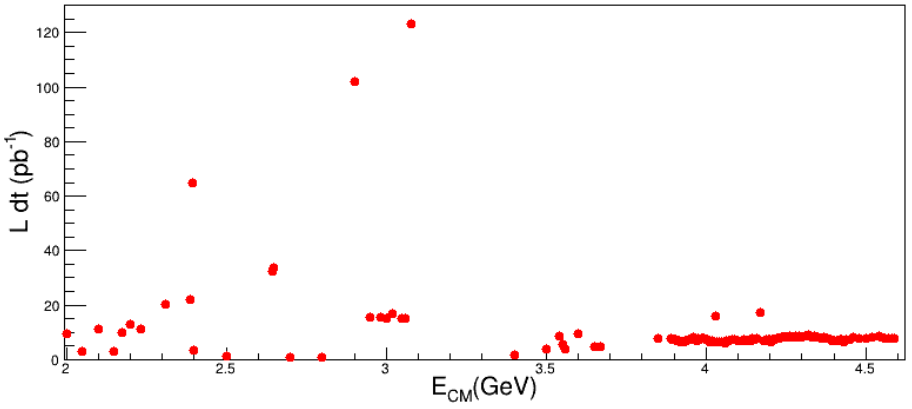
Time-of-flight system (TOF)
- σ(t) = 90ps (barrel)
- σ(t) = 110ps (endcap)

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

BESIII at BEPCII

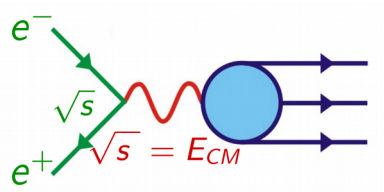
- Operated at BEPCII collider
  - $2.0 \leq \sqrt{s}\ [\mathrm{GeV}] \leq 4.6$
  - Design luminosity achieved
    - $\mathcal{L} = 1.0 \times 10^{33} \mathrm{cm}^{-2} \mathrm{s}^{-1}$ at $\psi(3770)$
- Data taking for
  - Charmonium spectroscopy
  - Charm physics
  - Light hadrons
  - τ and R-scan



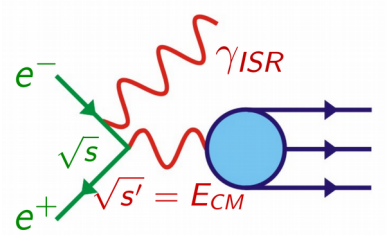


Hadronic Cross Sections

- Exclusive Cross Sections
  - Direct scan



  - Initial State Radiation



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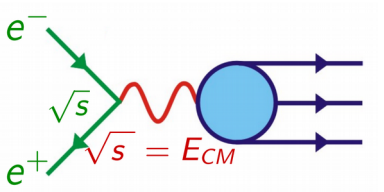
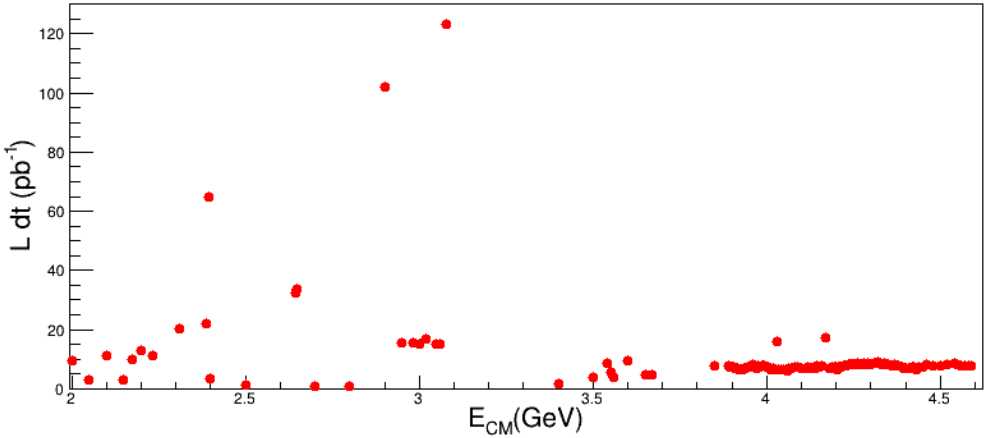


R Measurement

- 130 energy scan points
- 2 GeV ≤ √s ≤ 4.6 GeV
- $N_{had} > 10^5$ at each point



$$R = \frac{1}{\sigma_{\mu\mu}} \cdot \frac{N_{had} - N_{bkg}}{\mathcal{L} \cdot \varepsilon_{had} \cdot (1+\delta)}$$

- Luminosity
  - Determined from large angle Bhabha events
  - 0.8 % uncertainty

Chin.Phys. C41 (2017) 063001

- Radiative Corrections
  - Two schemes tested:
    - Feynman diagram
    - Structure functions
  - Agreement within 1.2%

- Background Contributions
  - Evaluated with MC
    - e^+e^- : Babayaga
    - $\mu^+\mu^-$: Babayaga, Phokhara
    - $\tau^+\tau^-$: KKMC
    - $\gamma\gamma$: Babayaga
    - $e^+e^- \rightarrow e^+e^- + X$
      - Dominant channels according to Phys. Rep. 4 (1975) 81
      - BdkRC, Diag36, Galuga, Ekhara
  - Beam related background

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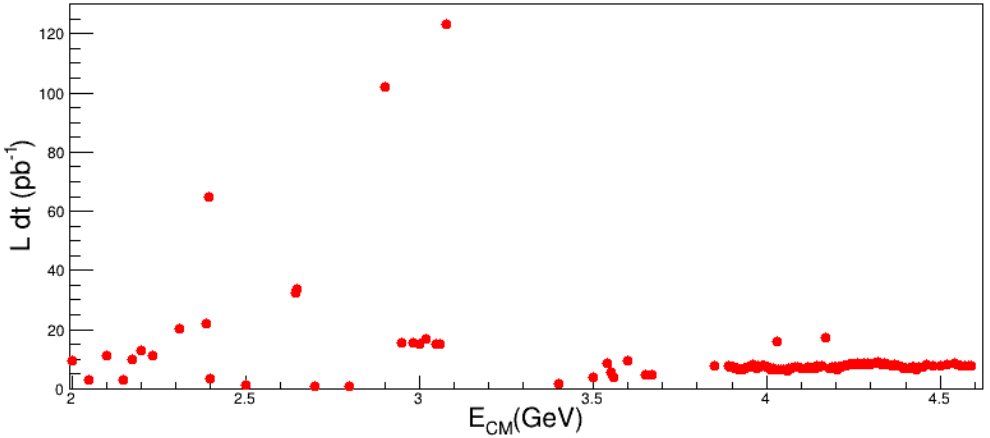

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Chin.P C41 (2017) 063001

- Background Contributions
  - Evaluated with MC
    - e^+e^- : Babayaga
    - $\mu^+\mu^-$: Babayaga, Phokhara
    - KMC
    - abayaga
    - $e^+e^- + X$

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ep. 4 (1975) 81
, Diag36, Galuga, Ekhara

- Agreement within 1.2%
- Beam related background

Aiming at total uncertainty of R measurement < 3%

- Dominated by uncertainty of event generator

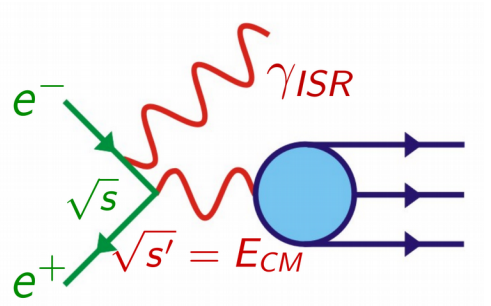
Initial State Radiation

- Reduces effective CMS energy

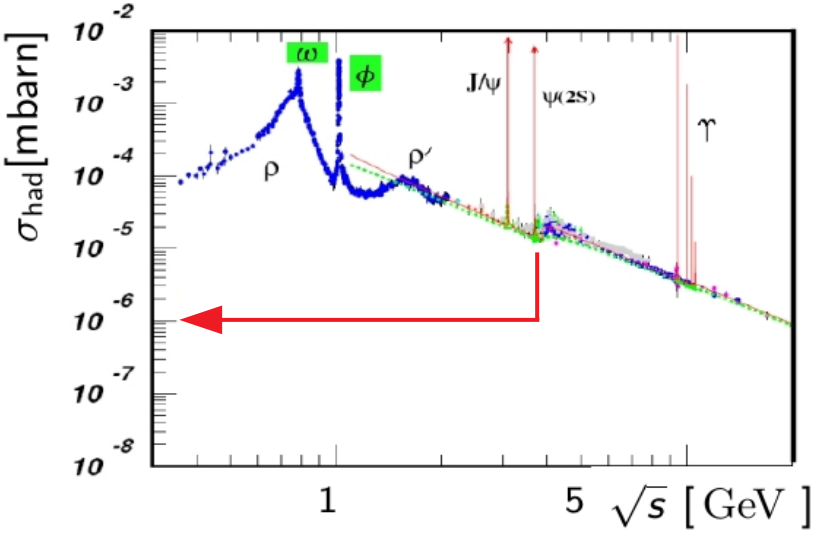
$$\sqrt{s'} = \sqrt{s - 2\sqrt{s}E_\gamma}$$

- Radiator function relates to non-radiative process

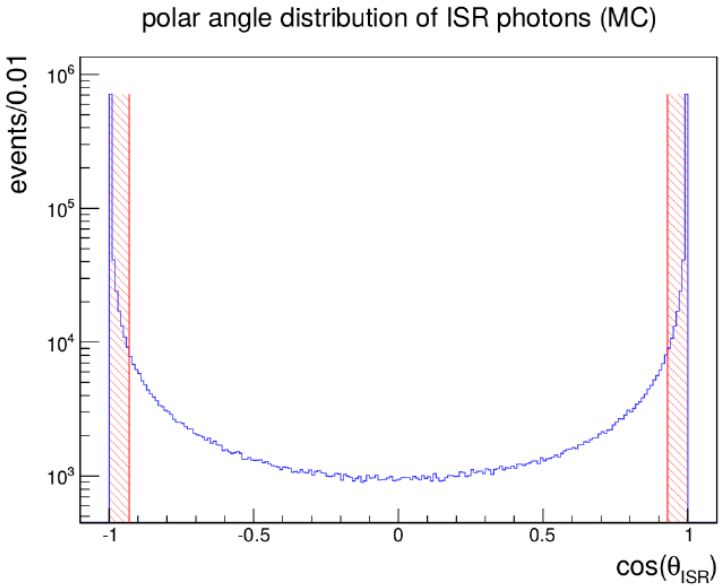
$$\frac{d\sigma_{had+\gamma}}{dm_\gamma} = \frac{2m_{had}}{s} W(s, E_\gamma, \theta_\gamma)_{had}$$



- Emission of ISR suppressed by $\frac{\alpha}{\pi}$
- Large integrated luminosity needed for precision studies
  - Studies based on 2.93 fb^{-1} at $\psi(3770)$

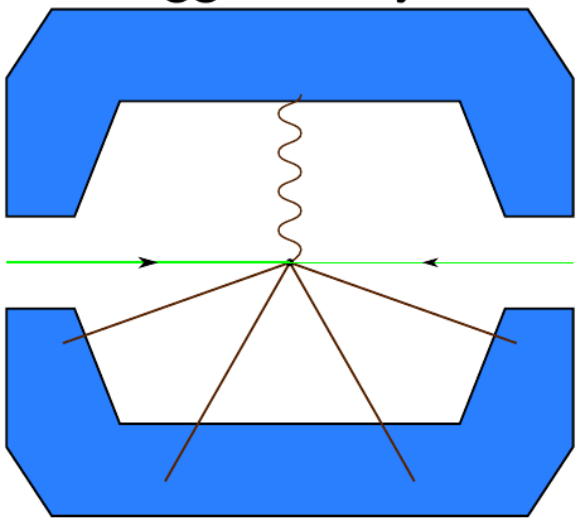


ISR Measurements

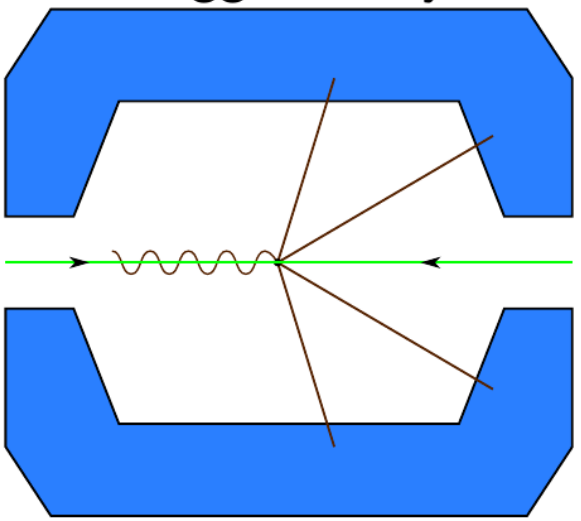


- Detect hadronic system
- ISR photon detected
  - Acceptance from $\pi^+\pi^-$ threshold
  - Large background contamination at high $\sqrt{s'}$
- ISR photon undetected
  - High statistics
  - Acceptance for $\sqrt{s'} > 1$ GeV
  - Small background contamination

Tagged analysis

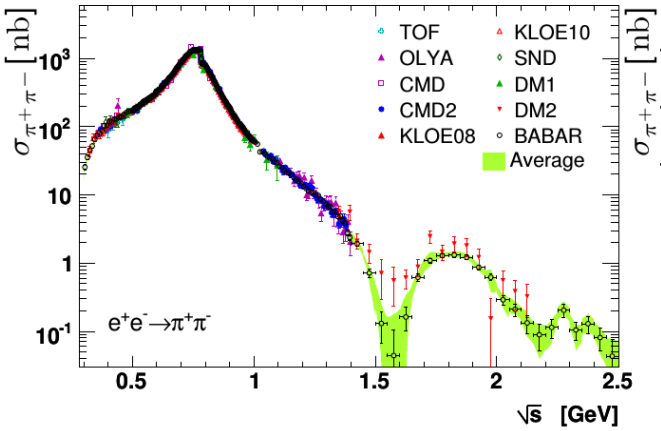


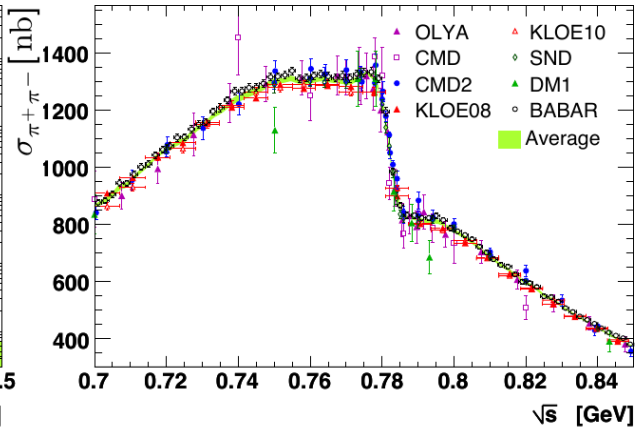
Untagged analysis



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

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



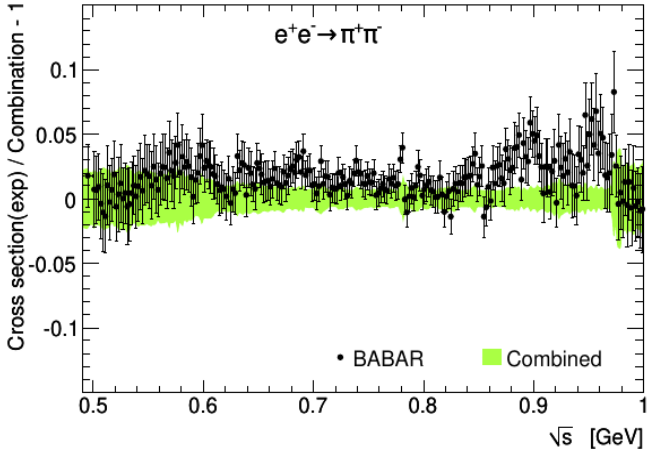


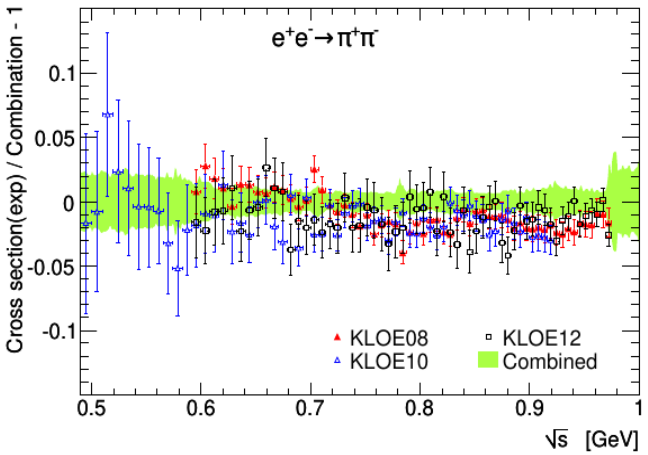
Systematic uncertainties:

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

} Limited by statistics

KLOE and BaBar measurements dominate world average



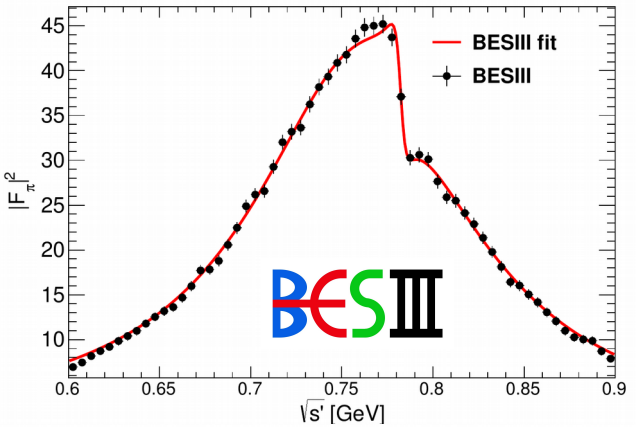


systematic differences ⟶ large uncertainty for a_μ^{hVP}

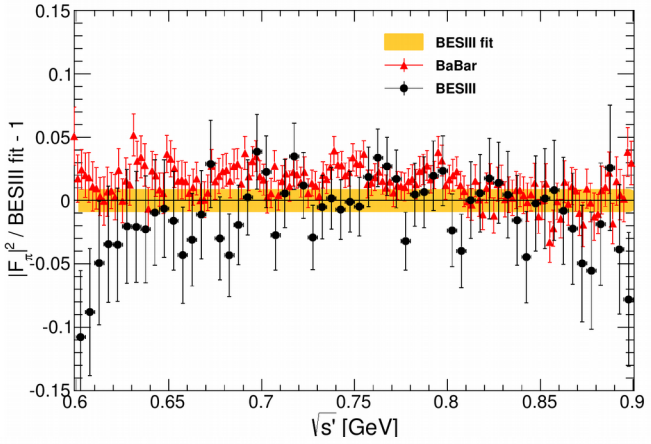
$e^+e^- \to \pi^+\pi^-$

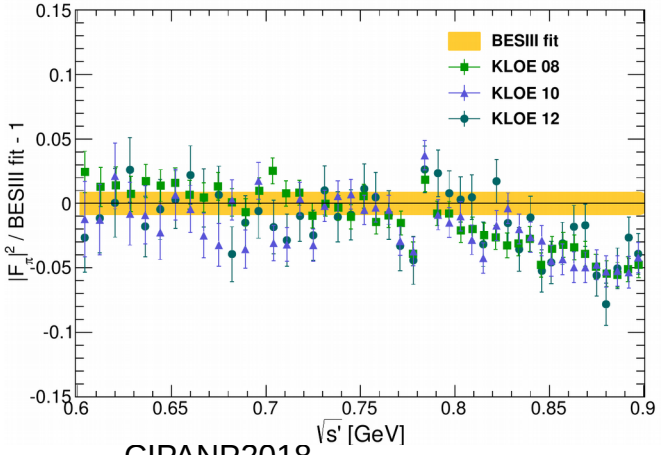
Phys.Lett.B753 (2016) 629

- Tagged ISR technique
- $\mu - \pi$ separation with Artificial Neural Network
- Normalized to integrated luminosity
- 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 wrt BaBar
  - above ρ/ω interference wrt KLOE

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

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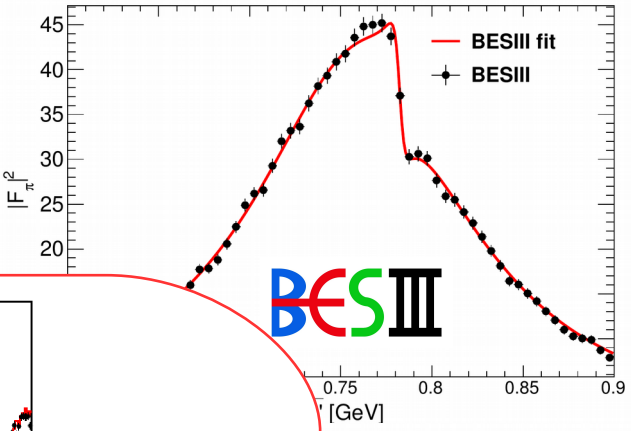

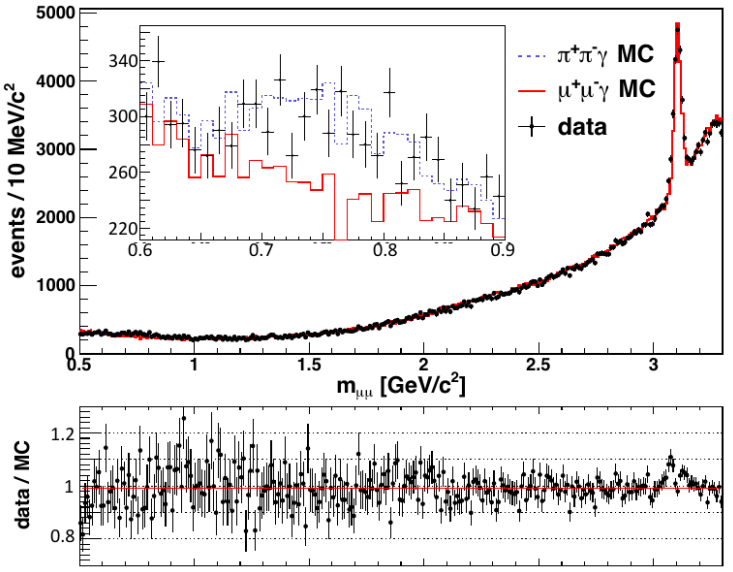

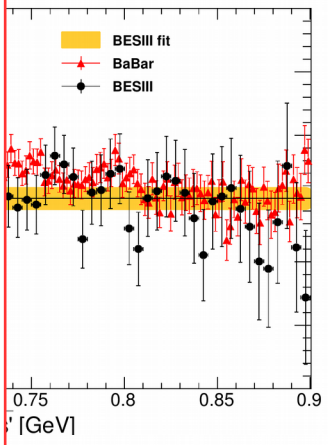

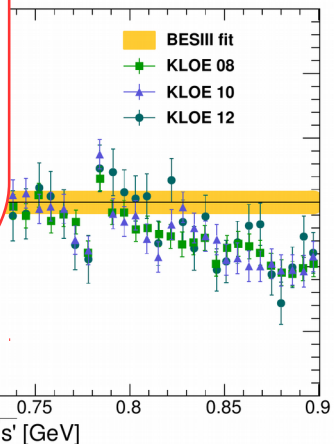

- Use ANN to select muons
- Compare to QED prediction
- Excellent agreement!
- Spin-off: Electronic width of J/ψ Phys.Lett.B761 (2016) 98

$$\Gamma_{ee}(J/\psi) = (5.58 \pm 0.05_{stat} \pm 0.08_{syst})\ \text{keV}$$

Comparison
- Systematic
  - below ρ/ω in
  - above ρ/ω interference wrt KLOE

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

Phys.Lett.B753 (2016) 629

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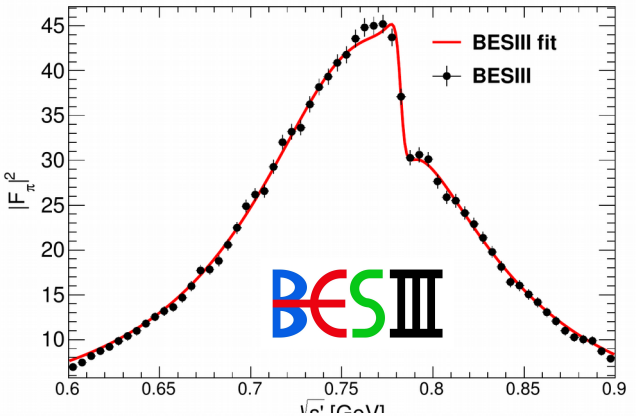

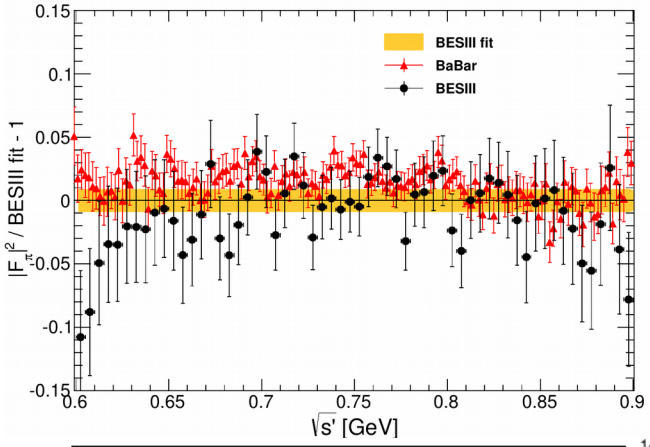

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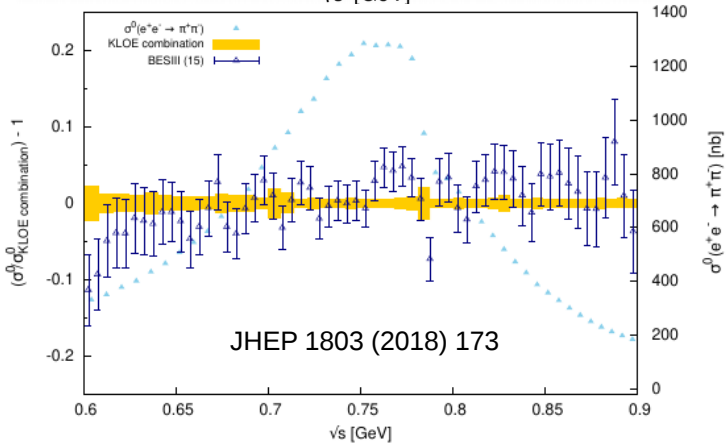

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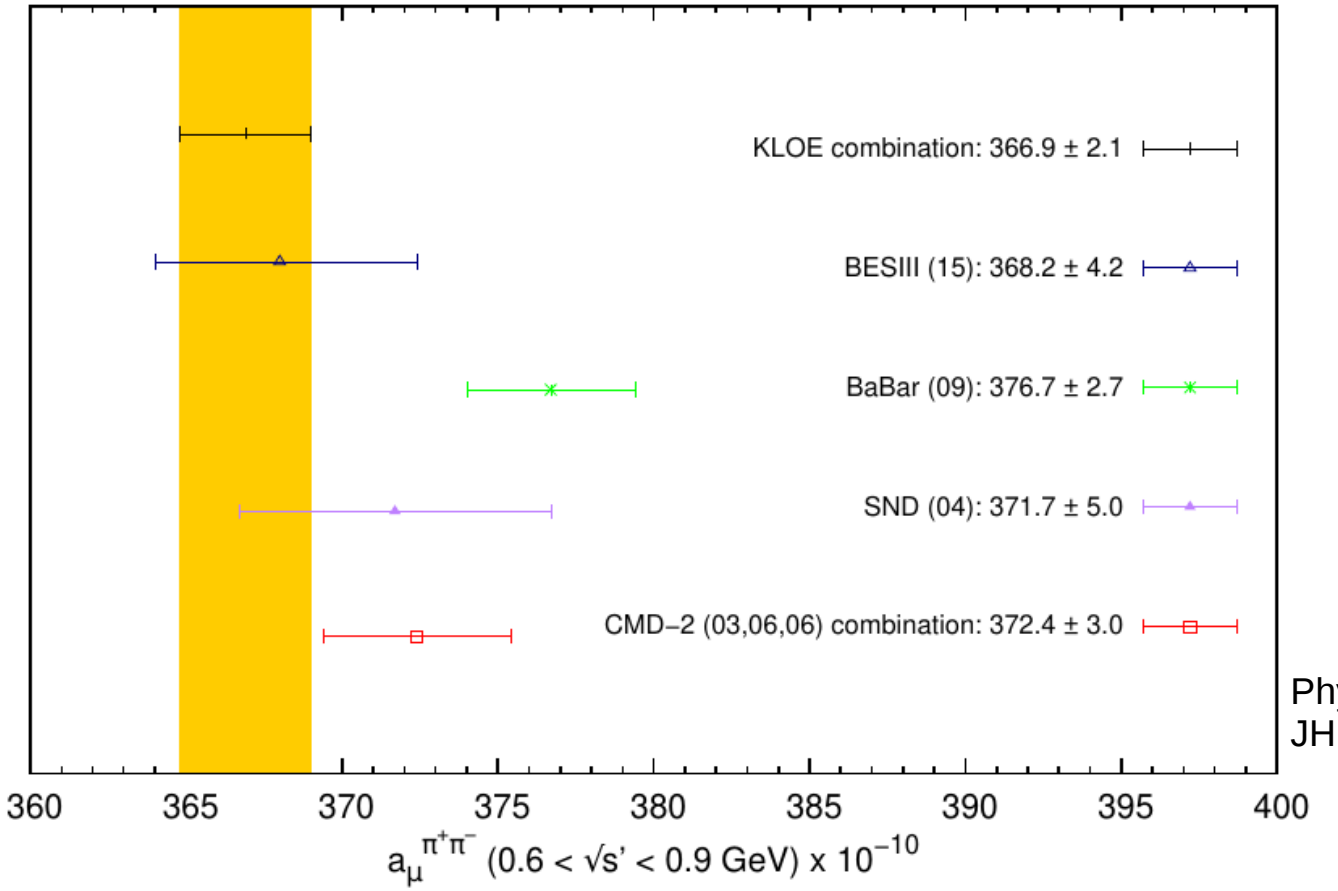


Phys.Lett.B753 (2016) 629
JHEP 183 (2018) 173

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

EPJ C77 (2017), 820

$e^+e^- \to \pi^+\pi^-\pi^0$

Tagged ISR method

ISR photon observed?

Untagged ISR method

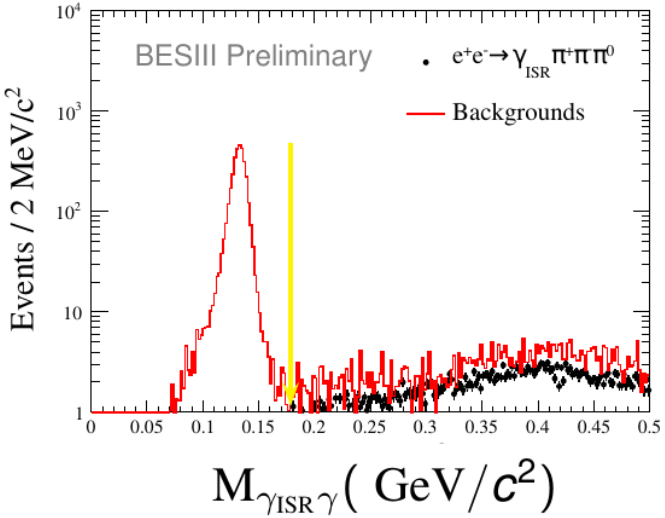
5C kinematic fit

π^0 veto

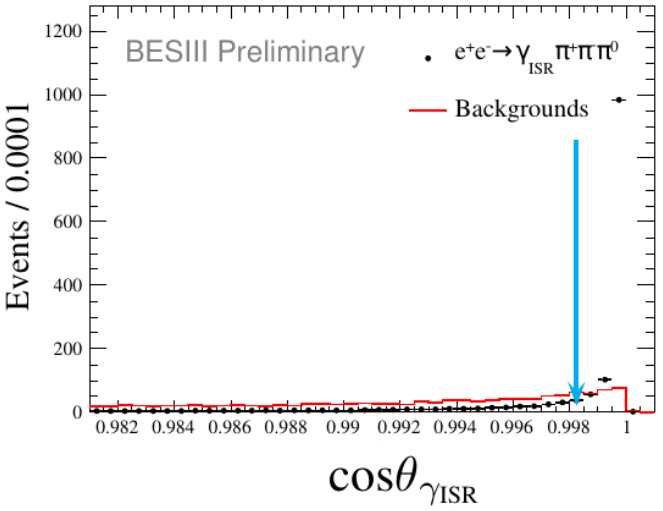
2C kinematic fit

Polar angle

Combination of the ISR photon and any other photon



Polar angle of the ISR photon



Measure $e^+e^- \to \pi^+\pi^-\pi^0\pi^0(\gamma)$ to correct background description

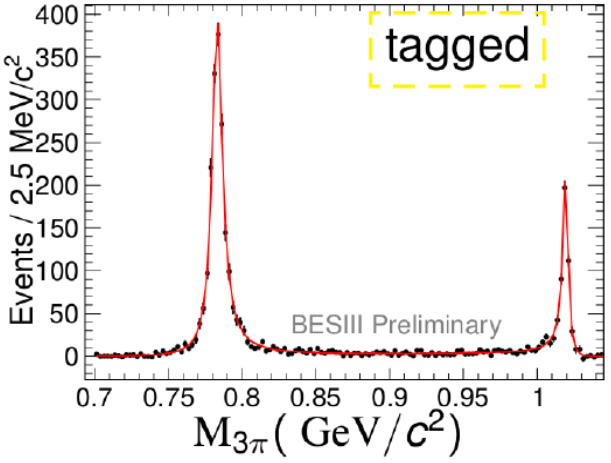
$e^+e^- \to \pi^+\pi^-\pi^0$

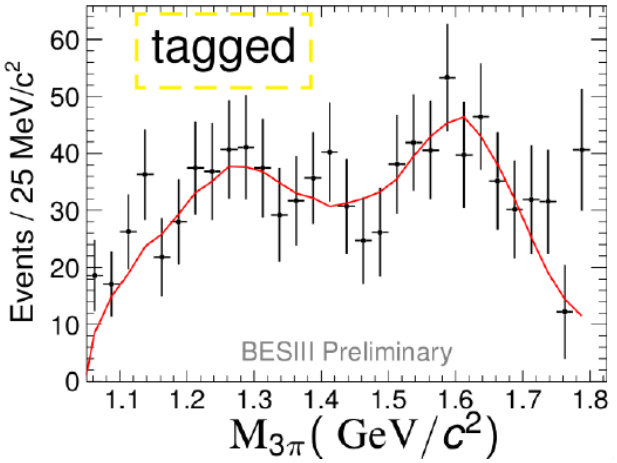
$\pi^+\pi^-\pi^0$ invariant mass spectra

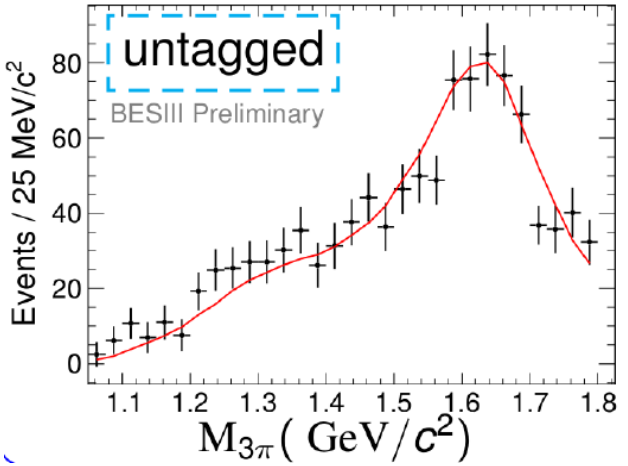
- Below 1.8 GeV: Fit

$$\frac{dN}{dm} = \sigma(m) \cdot \frac{dL}{dm} \cdot \varepsilon$$

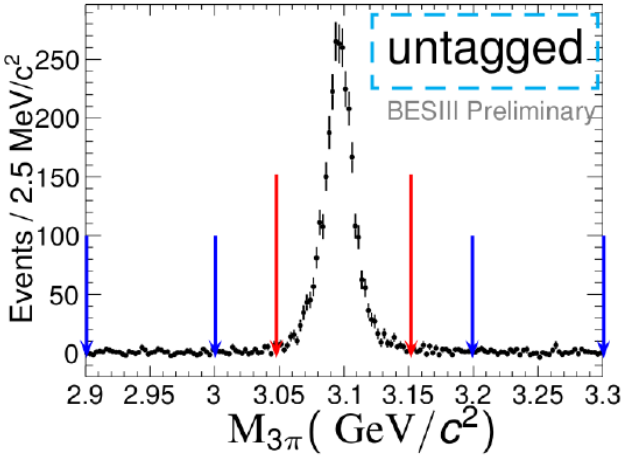
$$\sigma(m) = \frac{12\pi}{m^3} F_{\rho\pi}(m) \left| \sum_{V=\omega,\phi,\omega',\omega''} \frac{\Gamma_V m_V^{\frac{3}{2}} \sqrt{\Gamma_V^{ee} \mathcal{B}(V \to 3\pi)}}{D_V(m)} \frac{e^{i\varphi_V}}{\sqrt{F_{\rho\pi}(m_V)}} \right|^2$$



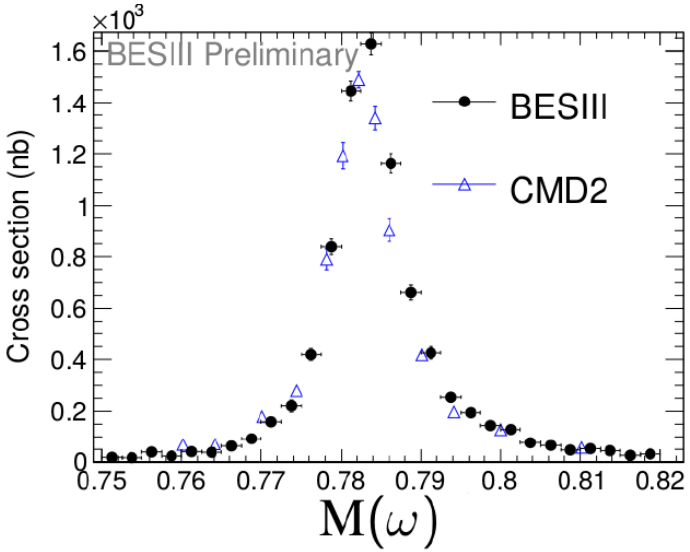


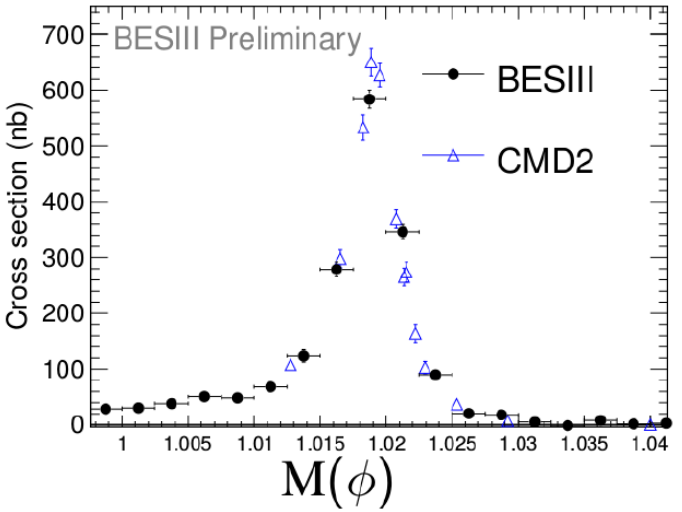


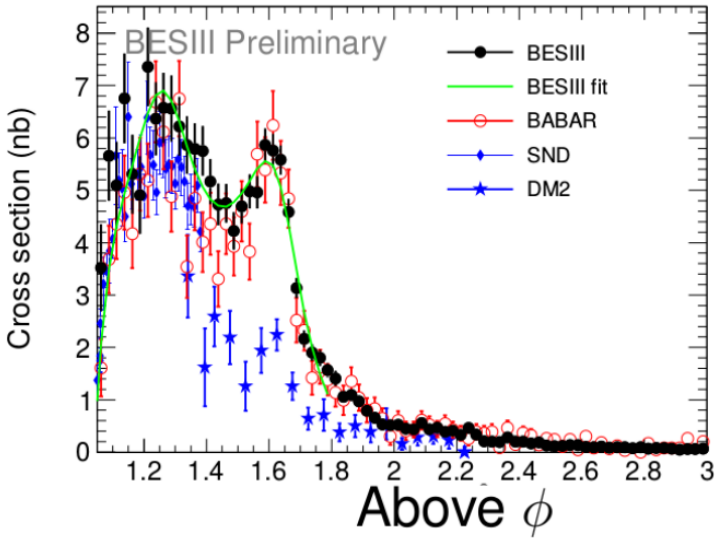
- Above 3 GeV: Determine $\mathcal{B}(J/\psi \to \pi^+\pi^-\pi^0)$



$e^+e^- \to \pi^+\pi^-\pi^0$



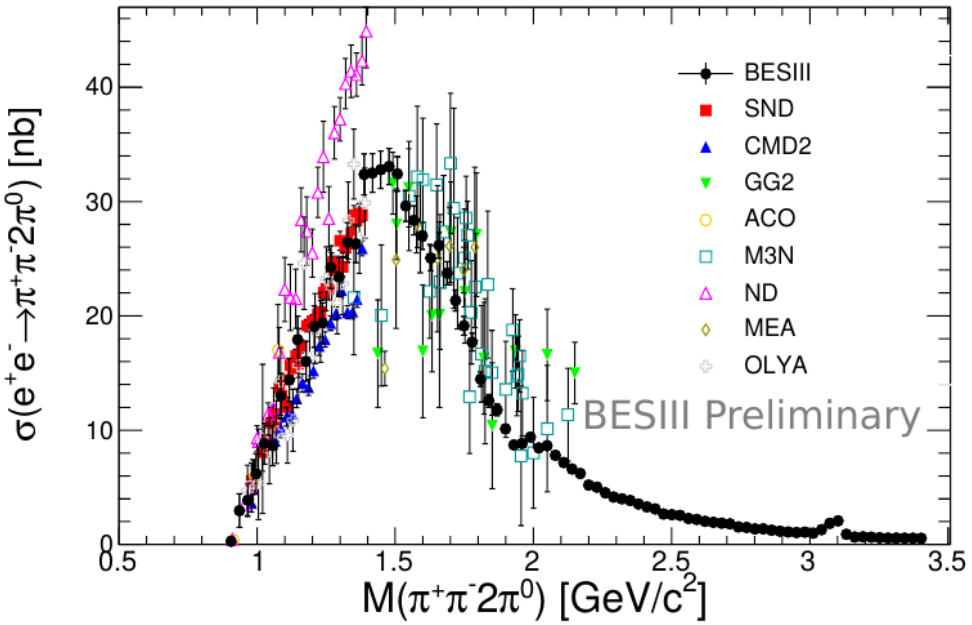




- Good agreement with previous measurements
- Improved precision
  - ~ 3% syst. uncertainty in full mass range
  - < 2% at narrow resonances
- Confirms BaBar result at ω''
- To be used to evaluate a_μ^{hVP}

$e^+e^- \to \pi^+\pi^-\pi^0\pi^0$

Strategy similar to $e^+e^- \to \pi^+\pi^-\pi^0\gamma$ analysis

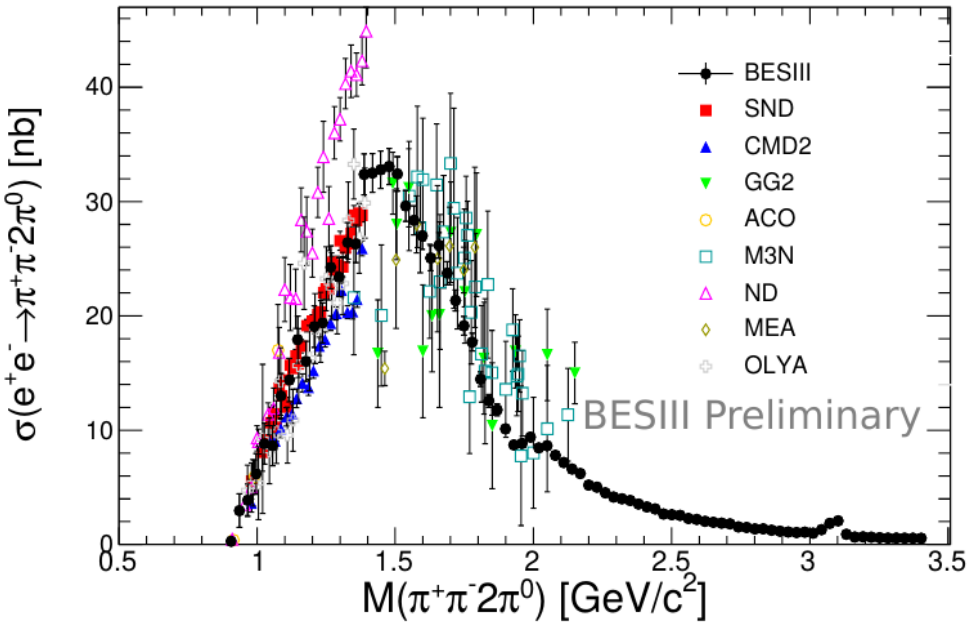


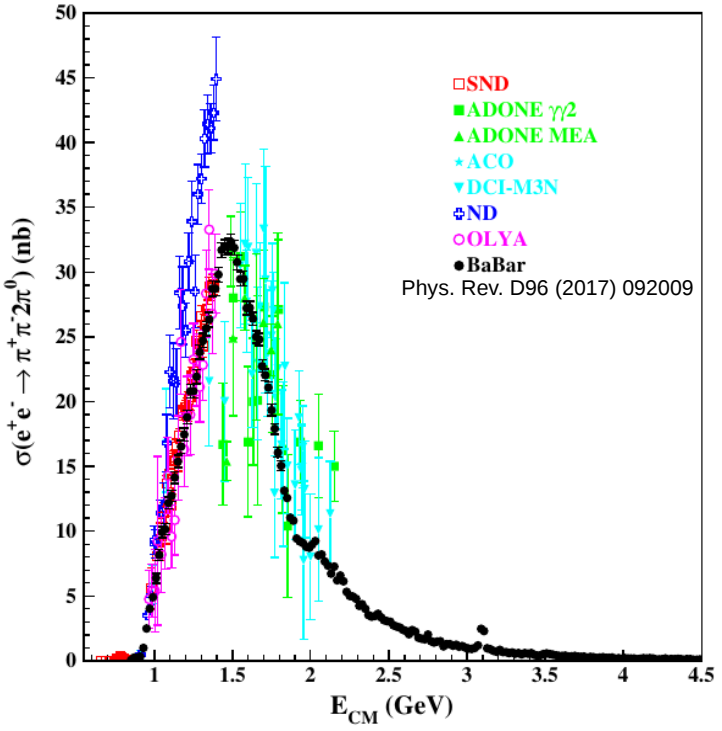
- Error weighted mean of tagged and untagged results
- Good agreement with previous measurements
- Improved precision (approx. 3% syst. uncertainty)

$$a_\mu^{\pi^+\pi^-2\pi^0,\mathrm{LO}} = \frac{1}{4\pi^3} \int_{(4m_\pi)^2}^{(1.8\,\mathrm{GeV})^2} ds\, K(s)\sigma_{\pi^+\pi^-2\pi^0}(s)$$

	$a_\mu^{\pi^+\pi^-2\pi^0,\mathrm{LO}}/10^{-10}$
BESIII (preliminary)	$18.63 \pm 0.27 \pm 0.57$

$e^+e^- \to \pi^+\pi^-\pi^0\pi^0$





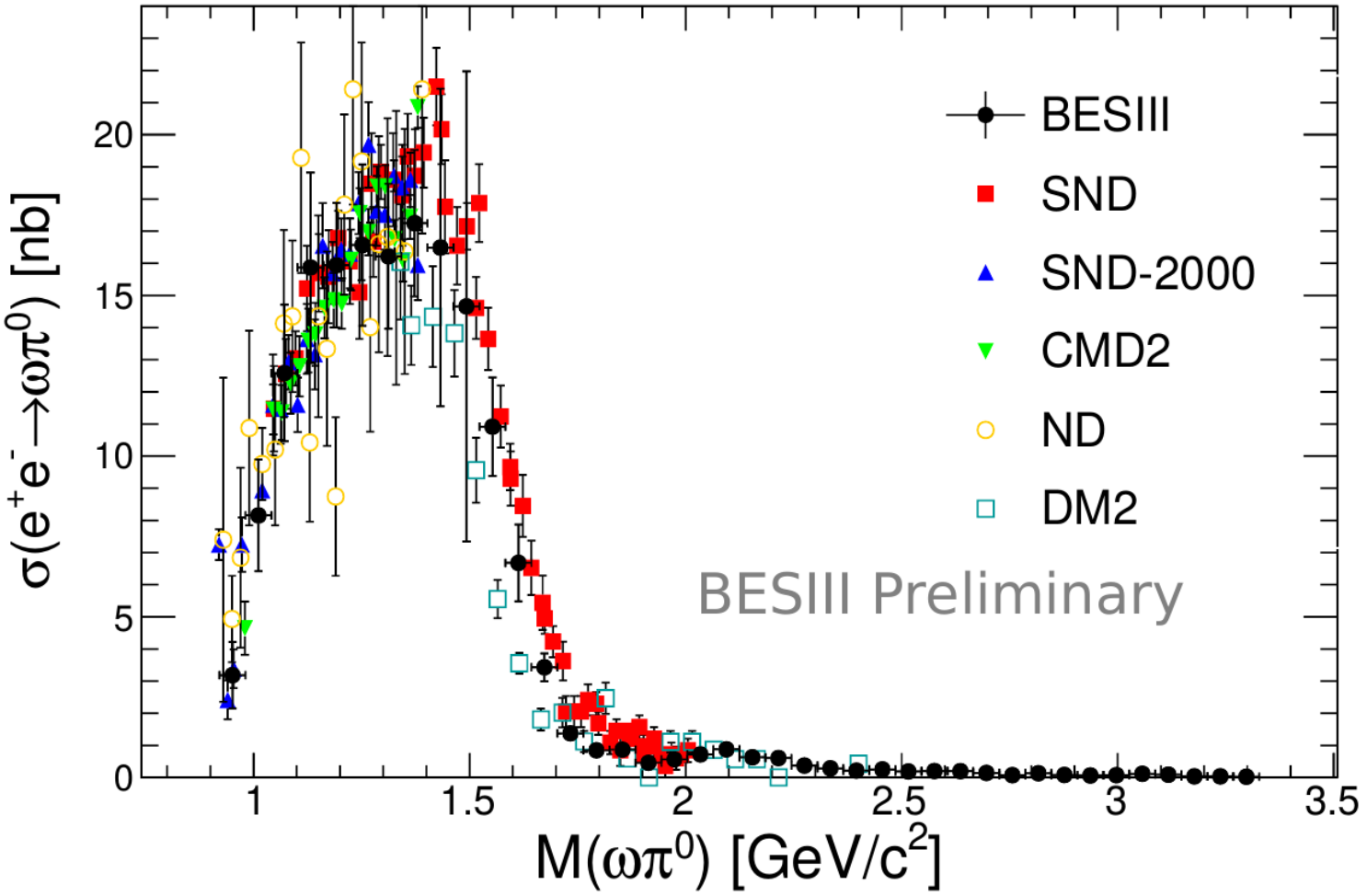
- Error weighted mean of tagged and untagged results
- Good agreement with previous measurements
- Improved precision (approx. 3% syst. uncertainty)

$$a_\mu^{\pi^+\pi^-2\pi^0,\mathrm{LO}} = \frac{1}{4\pi^3} \int_{(4m_\pi)^2}^{(1.8\,\mathrm{GeV})^2} ds\, K(s)\sigma_{\pi^+\pi^-2\pi^0}(s)$$

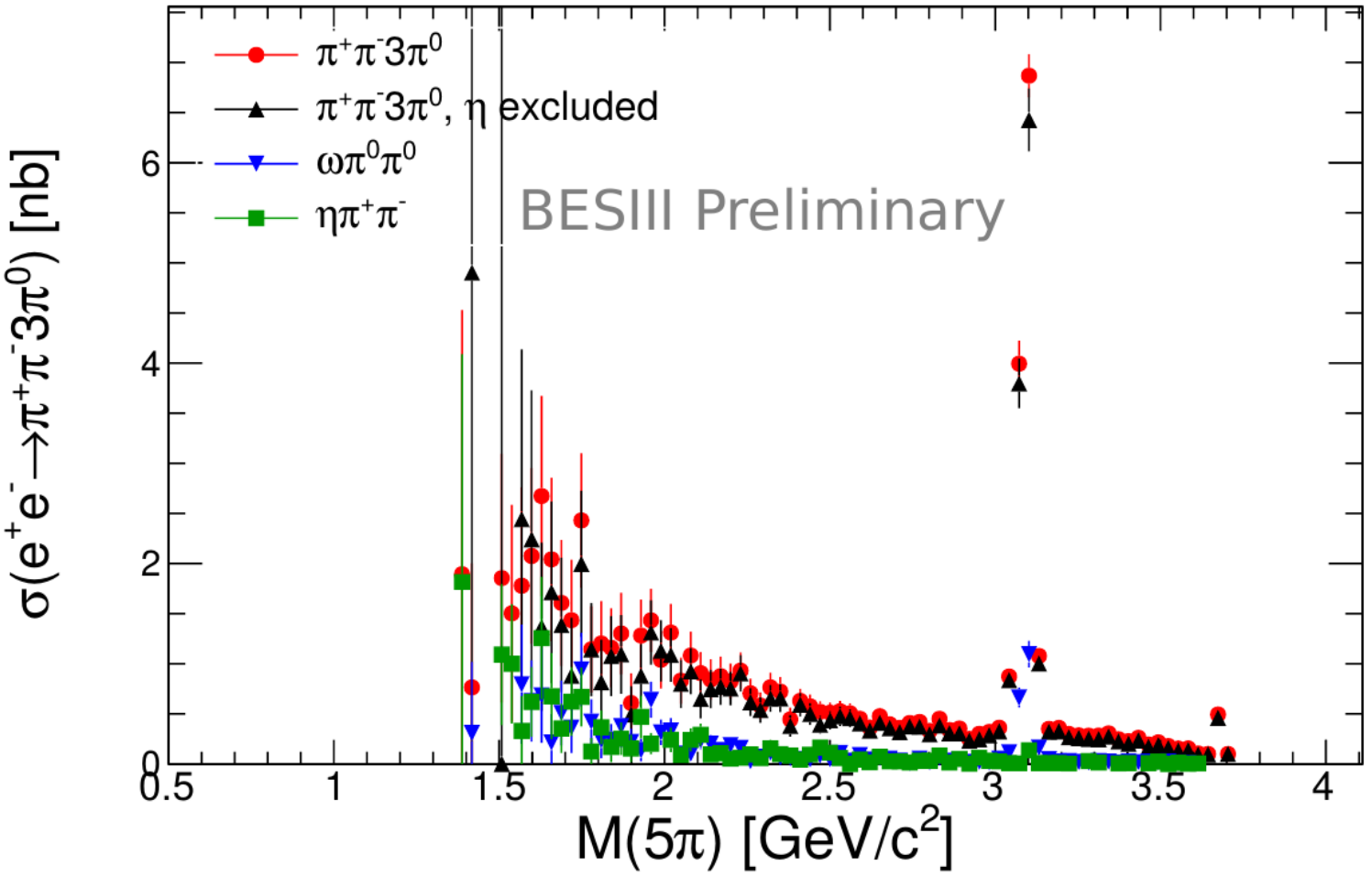
	$a_\mu^{\pi^+\pi^-2\pi^0,\mathrm{LO}}/10^{-10}$
BESIII (preliminary)	$18.63 \pm 0.27 \pm 0.57$
BABAR	$17.9 \pm 0.1 \pm 0.6$

$e^+e^- \to \omega\pi^0$

- Fit ω signal on smooth background in every bin of $M_{\pi^+\pi^-\pi^0\pi^0}$
- Approx. 4% syst. uncertainty
- Good agreement with previous measurements



$e^+e^- \to \pi^+\pi^-\pi^0\pi^0\pi^0$



- From background evaluation of $e^+e^- \to \pi^+\pi^-\pi^0\pi^0$
- Good agreement calculations using isospin relations

Summary

- Hadronic cross section measurements at BESIII
  - Scan, tagged and untagged ISR methods
  - Competitive accuracy
  - $\pi^+\pi^-$result confirms $a_\mu^{\text{theo,SM}} - a_\mu^{\text{exp}} > 3\sigma$
  - Preliminary results on $e^+e^- \to \pi^+\pi^-\pi^0$, $e^+e^- \to \pi^+\pi^-\pi^0\pi^0$and $e^+e^- \to \pi^+\pi^-3\pi^0$
  - Measurement of R value ongoing, 3% accuracy targeted
  - Pion form factor to be evaluated in additional mass regions from ISR and scan data
  - Additional exclusive final states in preparation