Initial State Radiation Measurements at BESIII

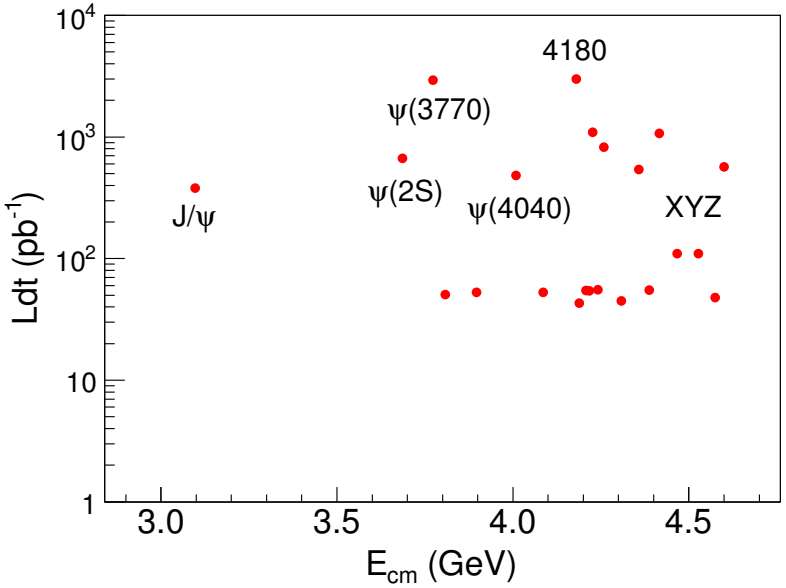
Martin Ripka on behalf of the BESIII-Collaboration

Outline

1. BESIII Detector
2. Initial State Radiation Technique
3. $e^+e^- \to \pi^+\pi^-\gamma_{ISR}$
4. $e^+e^- \to \pi^+\pi^-\pi^0\gamma_{ISR}$
5. $e^+e^- \to \pi^+\pi^-2\pi^0\gamma_{ISR}$
6. $e^+e^- \to \pi^+\pi^-3\pi^0\gamma_{ISR}$
7. Summary

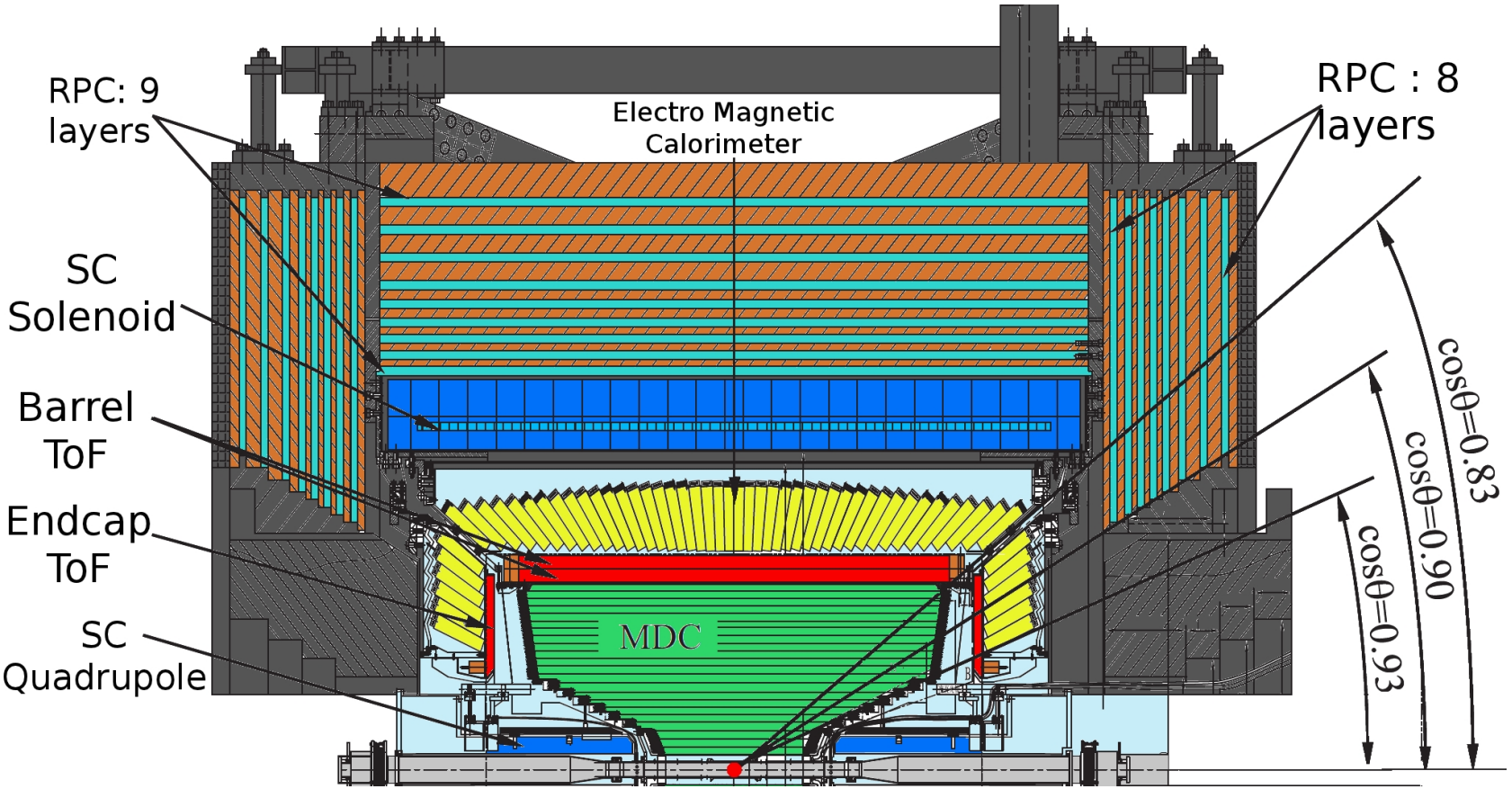
The BESIII Detector

BEPCII



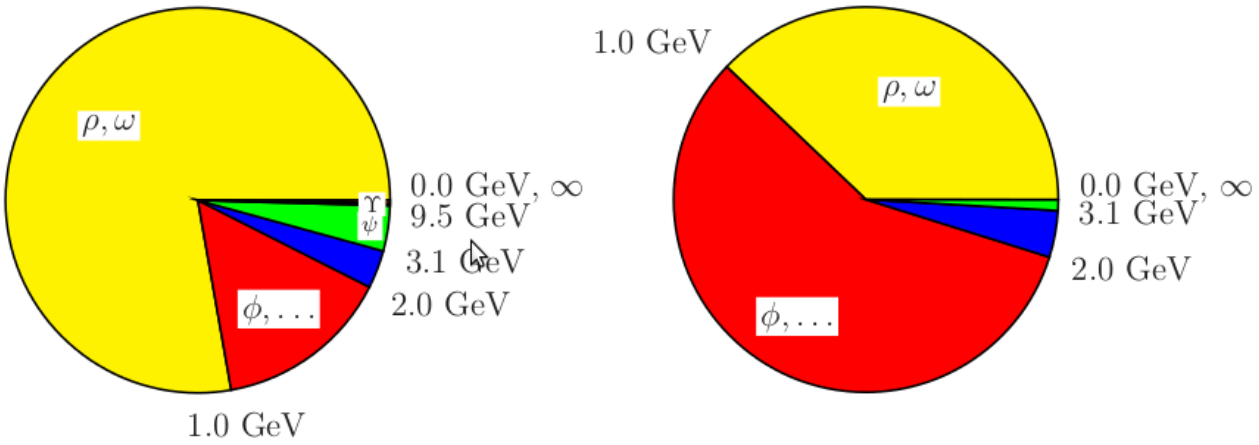
- τ-charm factory
- Energy range: 2 - 4.6 GeV
- Design luminosity: $10^{33}\,\mathrm{cm}^{-2}s^{-1}$ (at 3.77 GeV)
- Design luminosity reached in 2016 but data taking ongoing
- $\psi(3770)$ data set dominantly used for ISR program

BESIII Detector



- Multilayer Drift Chamber (MDC) $\Delta p/p \approx 0.5\%$
- Time of Flight system (ToF)
- Electromagnetic Calorimeter (EMC) $\Delta E/E \approx 2.5\%$
- Super Conducting magnet 1 Tesla (SC)
- Resistive Plate Chamber (RPC) for muon detection

Introduction: Why ISR Measurements at BESIII?

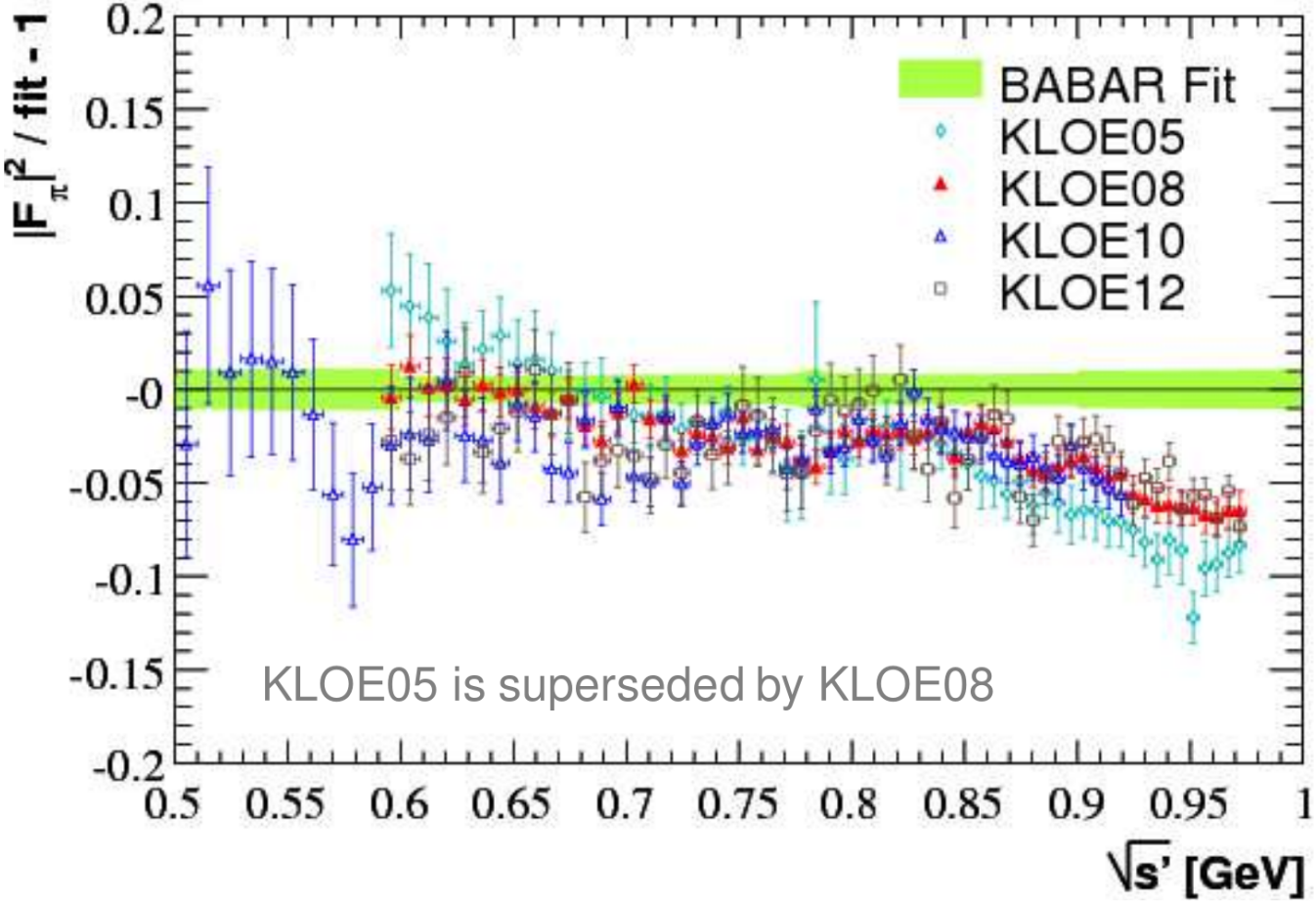


M. Davier, A. Hoecker, B. Malaescu and Z. Zhang, Eur. Phys. J. C **71** 1515 (2011)

- Cover wider mass range than KLOE
- Closer to interesting energy range $\sqrt{s} \lesssim 2$ GeV than Babar
  $\rightarrow$ less suppression of ISR events by radiator function
- Untagged ISR mode can be used above $\sqrt{s} \gtrsim 1$ GeV
  $\rightarrow$ no problem for $\geq 4\pi$
- ISR measurements of baryon form factors not topic of this talk

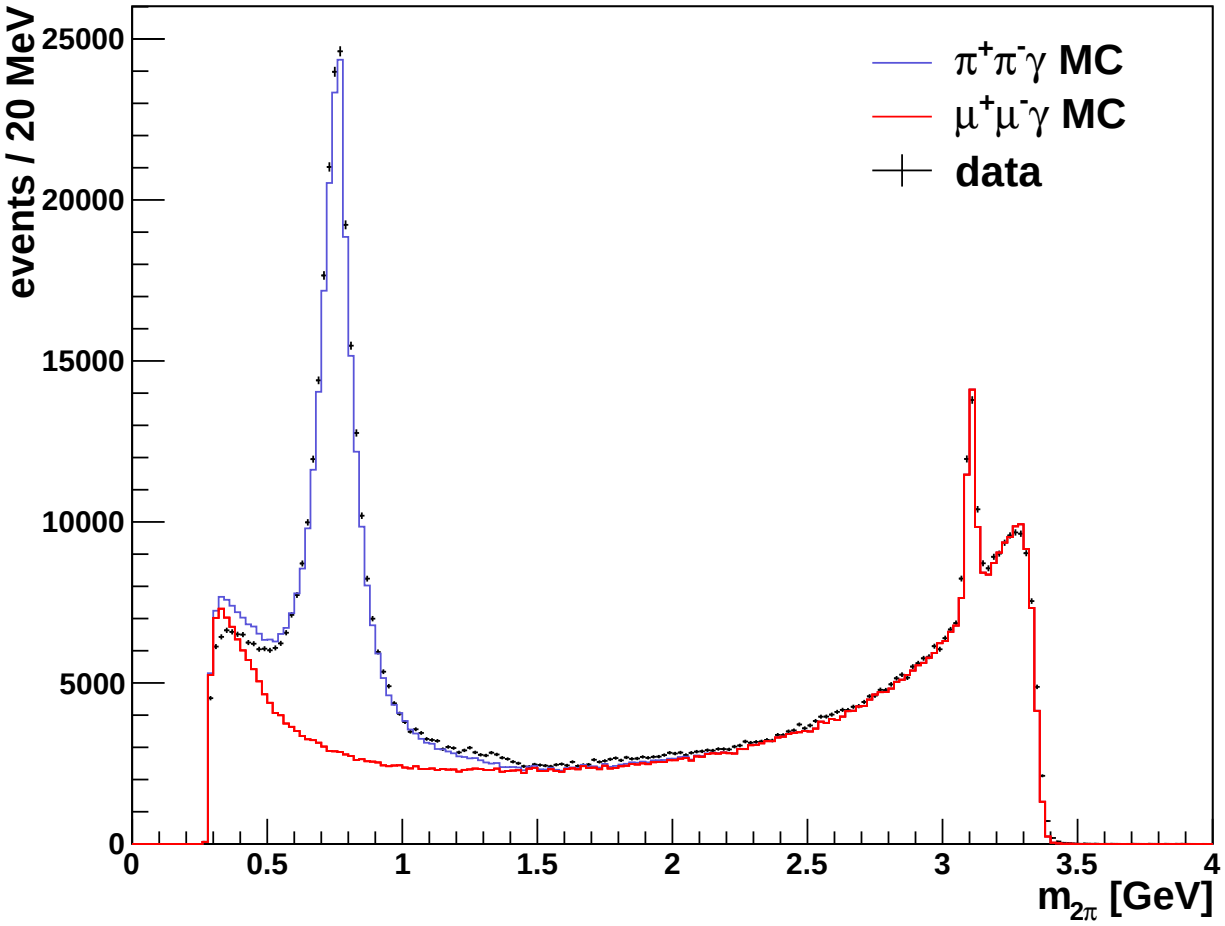
$$e^+e^- \to \pi^+\pi^-\gamma_{ISR}$$

$\pi^+\pi^-$ at Babar and Kloe



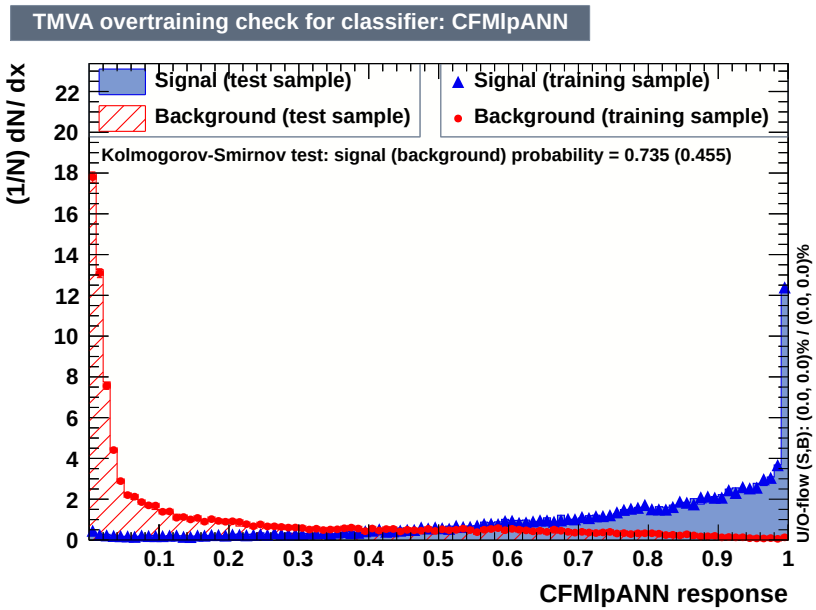
- Babar and Kloe each claim sub-percent precision
- Measurements do not agree with each other
- Another high precision measurement needed $\Rightarrow$ BESIII

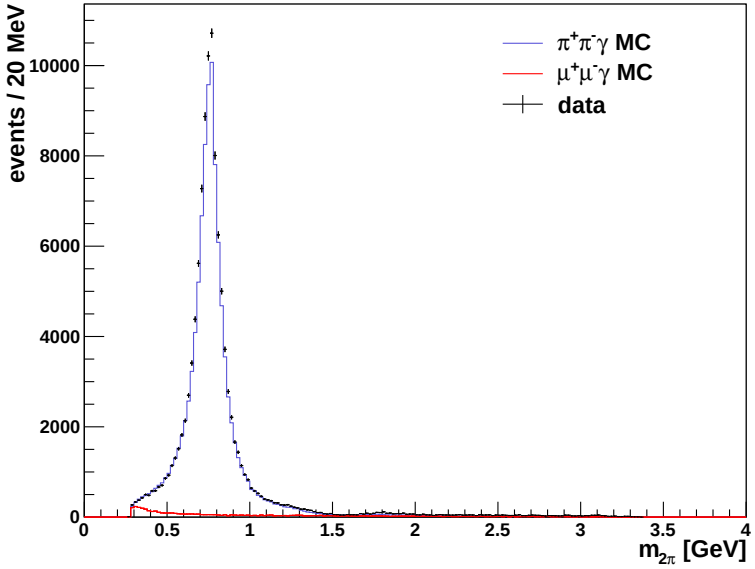
Event Selection and Particle Identification (PID) of $\pi^+\pi^-$



- Tagged ISR mode only
- Kinematic Fit for $\pi^+\pi^-\gamma_{ISR}$ final state
- Standard BESIII PID system for electron rejection
- Muon-pion separation needed

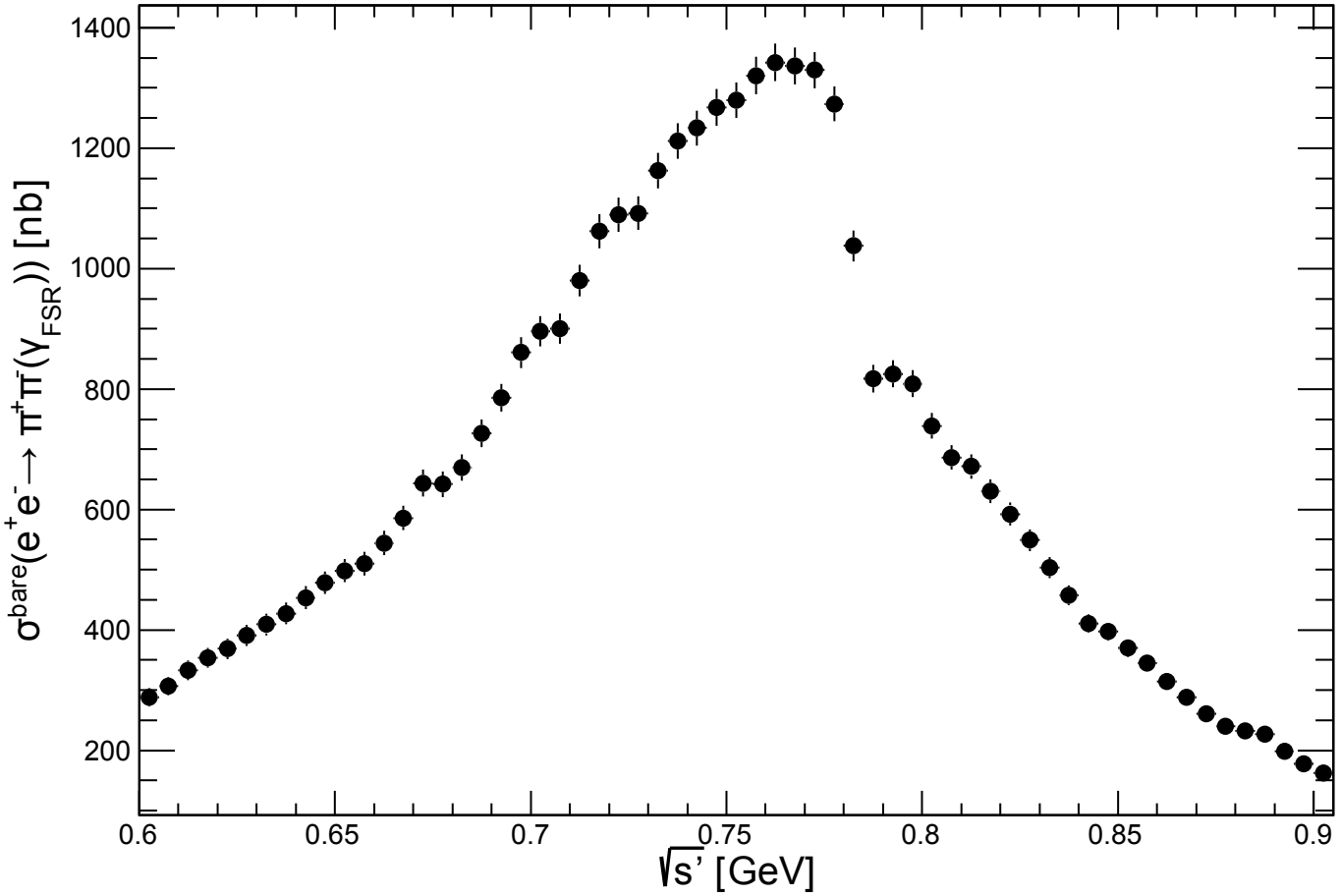
Event Selection and Particle Identification (PID) of $\pi^+\pi^-$





- Muons, pions have different shower shape in EMC
- Artificial Neuronal Network (ANN) for $\mu - \pi$ separation
- Very clean sample After ANN

$\pi^+\pi^-$ Cross Section

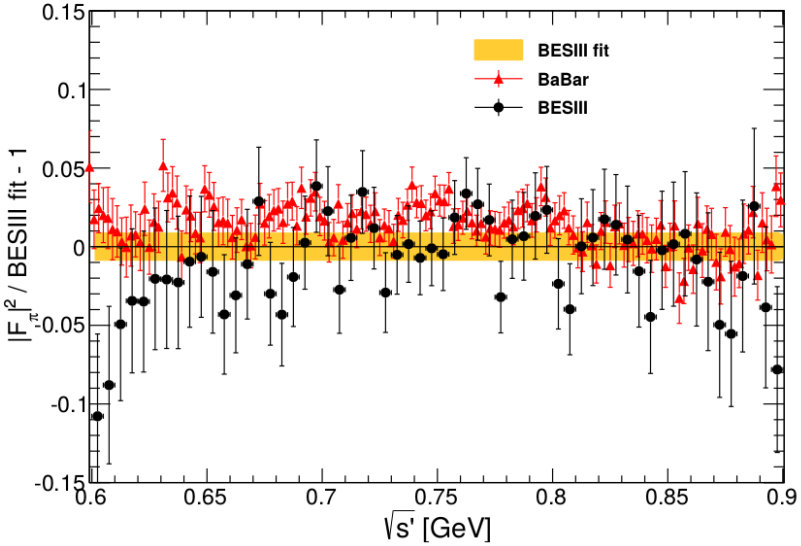


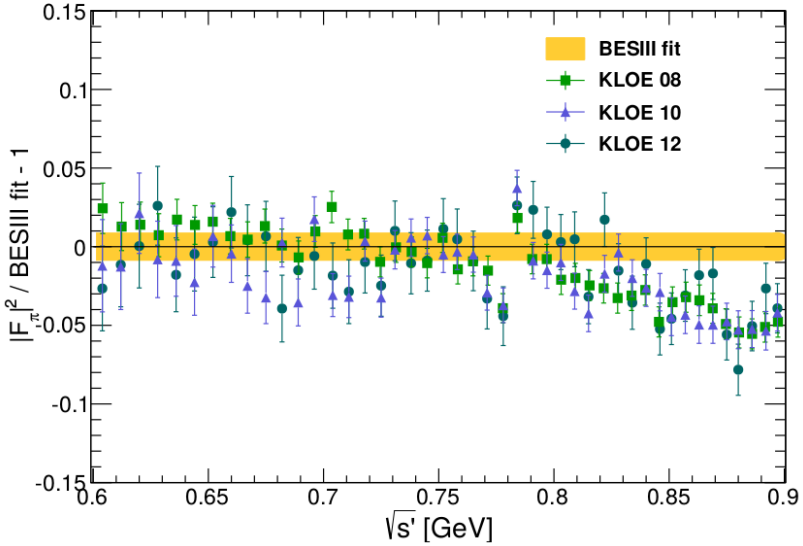
- $\sigma^{\mathbf{bare}}(\sqrt{s'}) = \frac{1}{\frac{2\sqrt{s'}}{s} W(s,x)\epsilon(\sqrt{s'})\mathcal{L}\delta_{vac}\delta_{FSR}} \frac{dN}{d\sqrt{s'}}$
- ρ-ω interference clearly visible

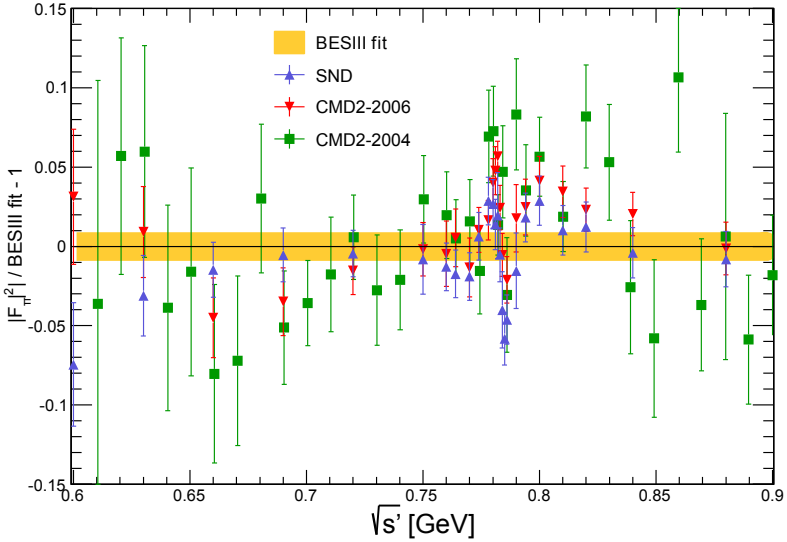
Systematic Uncertainties of $\pi^+\pi^-$

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
Background subtraction	0.1
Unfolding	0.2
FSR correction δ_{FSR}	0.2
Vacuum polarisation correction δ_{vac}	0.2
Radiator function	0.5
Luminosity $\mathcal{L}$	0.5
Sum	**0.9**

Comparison to Other $\pi^+\pi^-$ Measurements

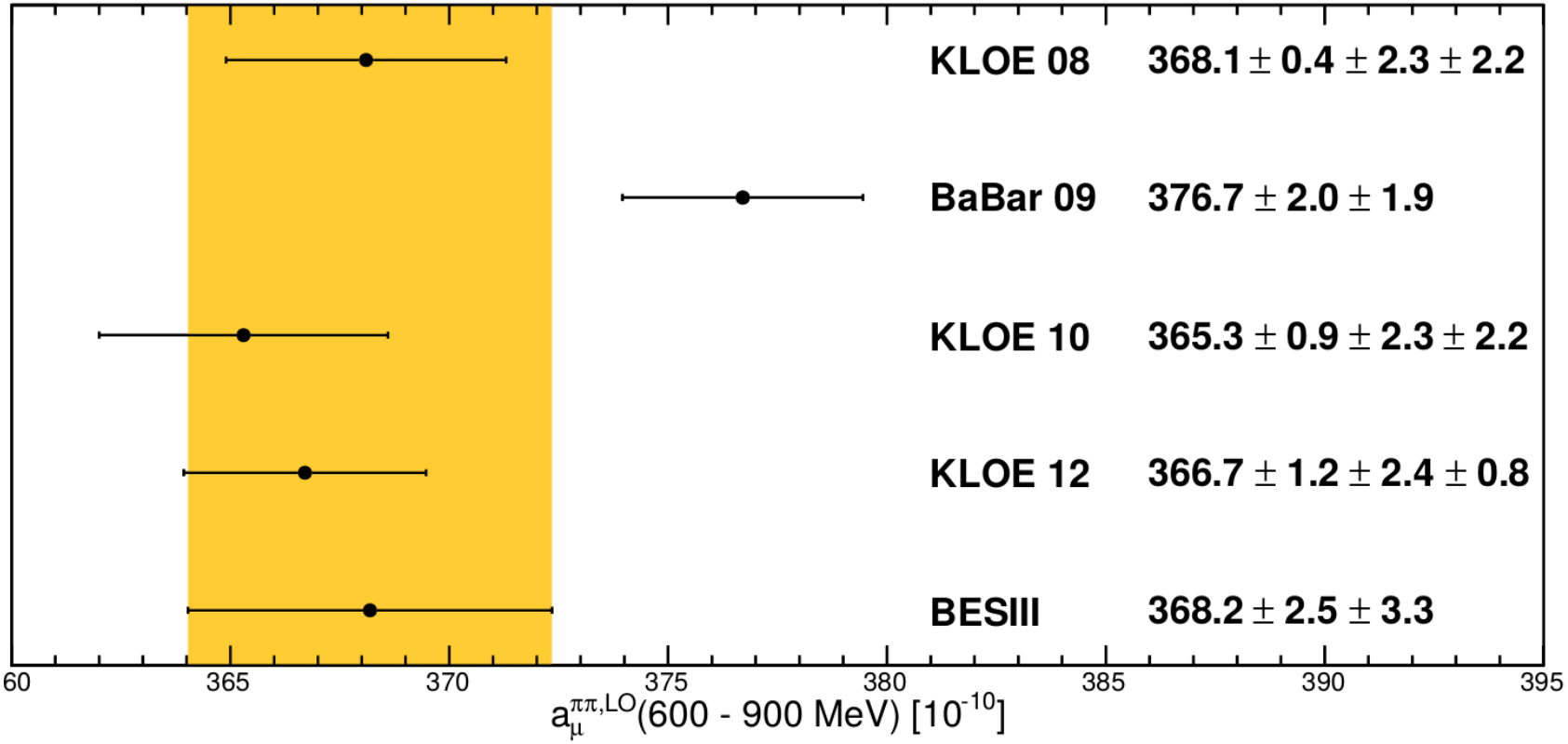






- In agreement with BaBar above $\sqrt{s} \gtrsim 0.8$ GeV
- In agreement with KLOE below $\sqrt{s} \lesssim 0.8$ GeV

Final Result: Contribution of $\pi^+\pi^-$ to $a_\mu^{\mathrm{VP,LO}}$

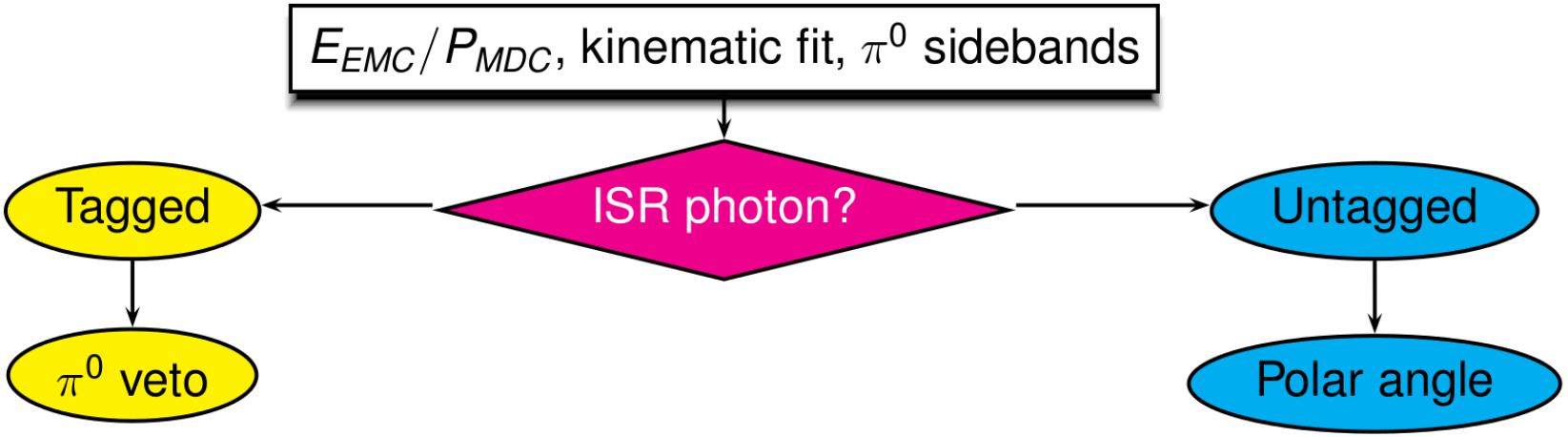


- Precision competitive with previous measurements
- $a_\mu^{\pi\pi,\mathrm{LO}}(600-900\,\mathrm{MeV}) = (368.2 \pm 2.5_{\mathrm{stat}} \pm 3.3_{\mathrm{sys}}) \cdot 10^{-10}$
- Confirms deviation of $> 3\sigma$ between experiment and theory
- Published in PLB 753, 629 (2016)

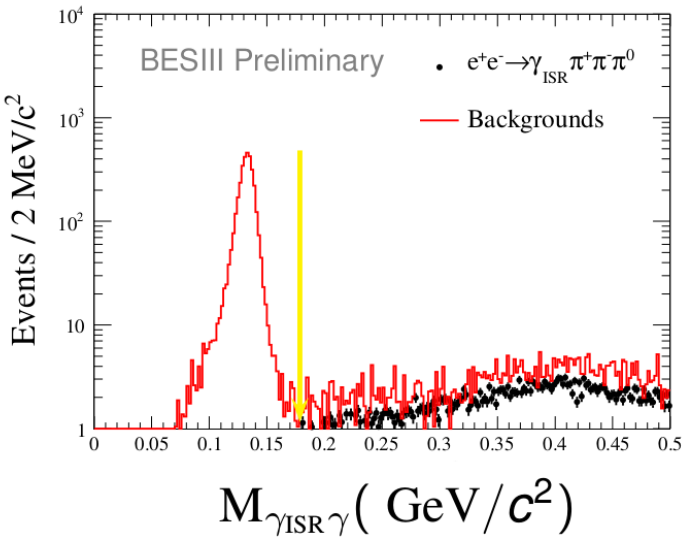
$e^+e^- \to \pi^+\pi^-\pi^0\gamma_{ISR}$

(Preliminary)

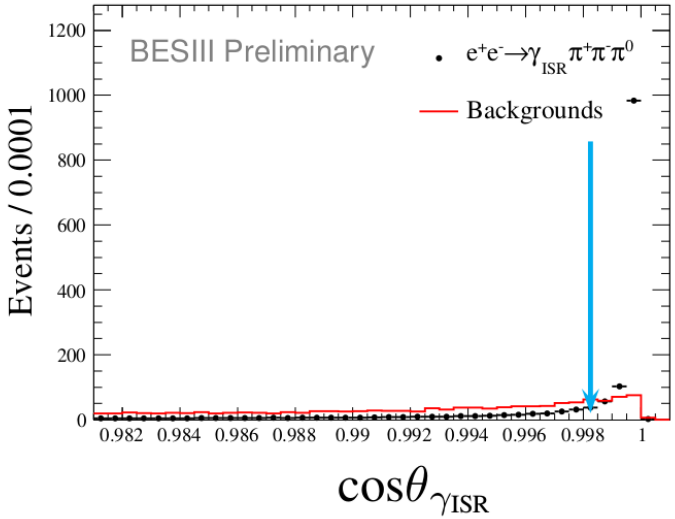
Event Selection of $\pi^+\pi^-\pi^0\gamma_{ISR}$



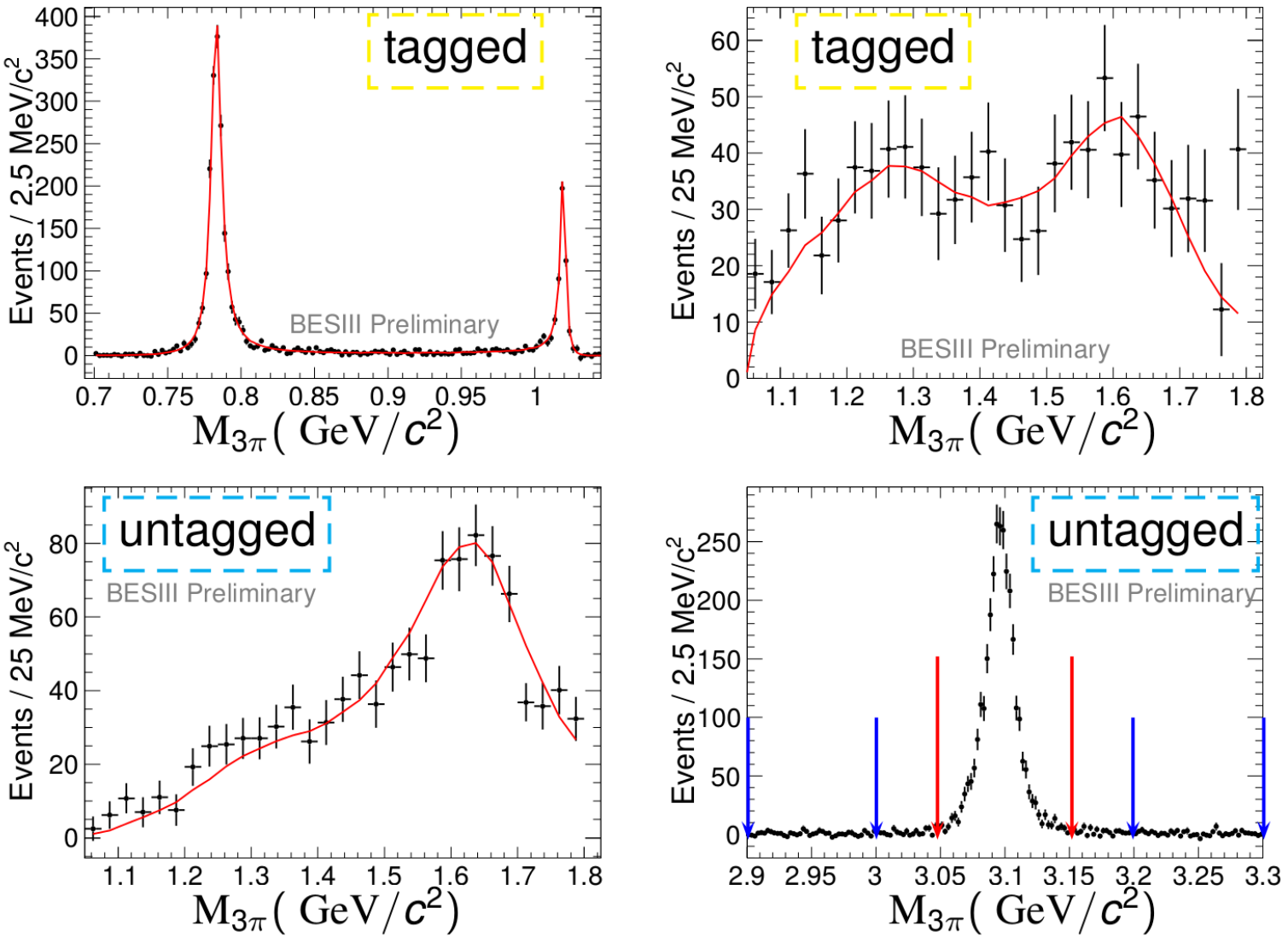
Combination of the ISR photon and any other photon



Polar angle of the ISR photon



Fit to $\pi^+\pi^-\pi^0$ Mass Spectrum



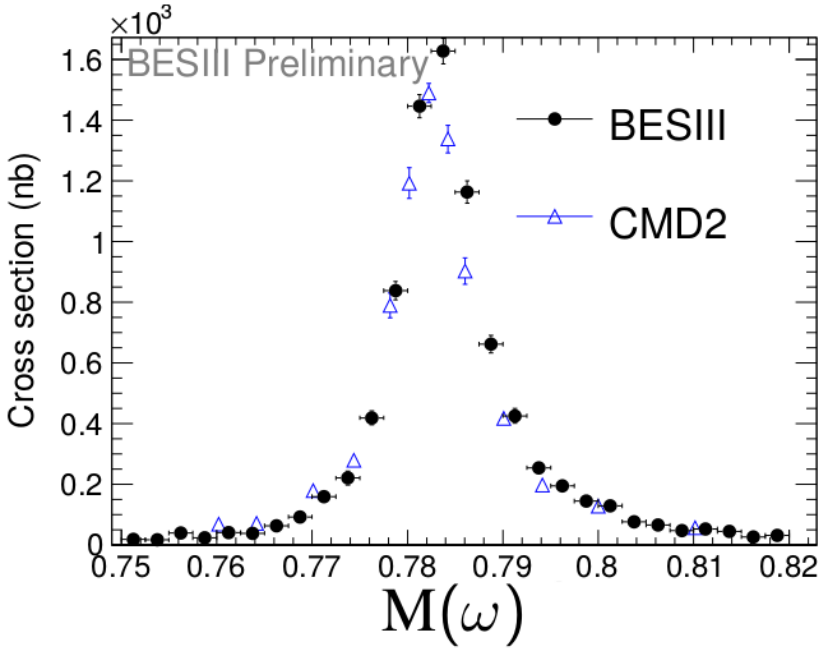
$$\sigma(m) = \frac{12\pi}{m^3} F_{\rho\pi}(m) \left| \sum_{V=\omega,\phi,\omega',\omega''} \frac{\Gamma_V m^{\frac{3}{2}} \sqrt{\Gamma_V^{ee} \mathcal{B}(V \to 3\pi)}}{D_V(m)} \frac{e^{i\varphi_V}}{\sqrt{F_{\rho\pi}(m_V)}} \right|^2$$

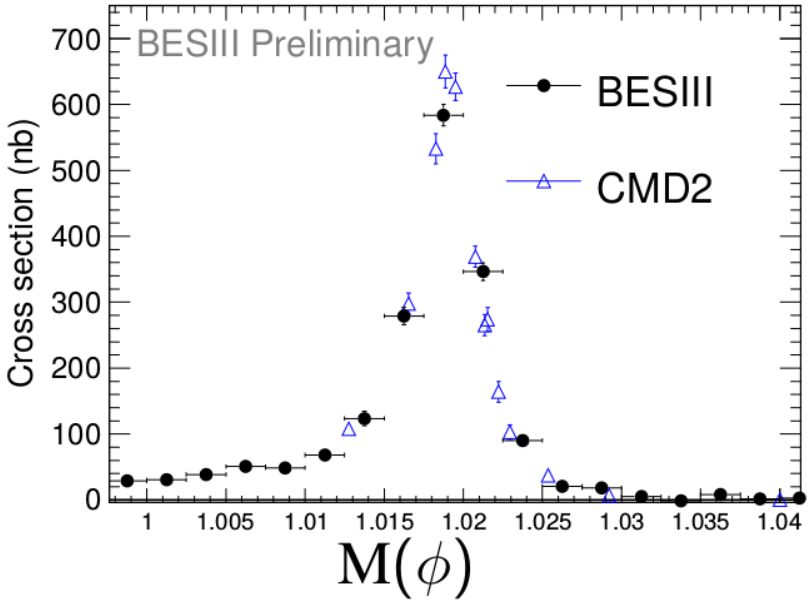
Fit Results of $\pi^+\pi^-\pi^0$ Mass Spectrum

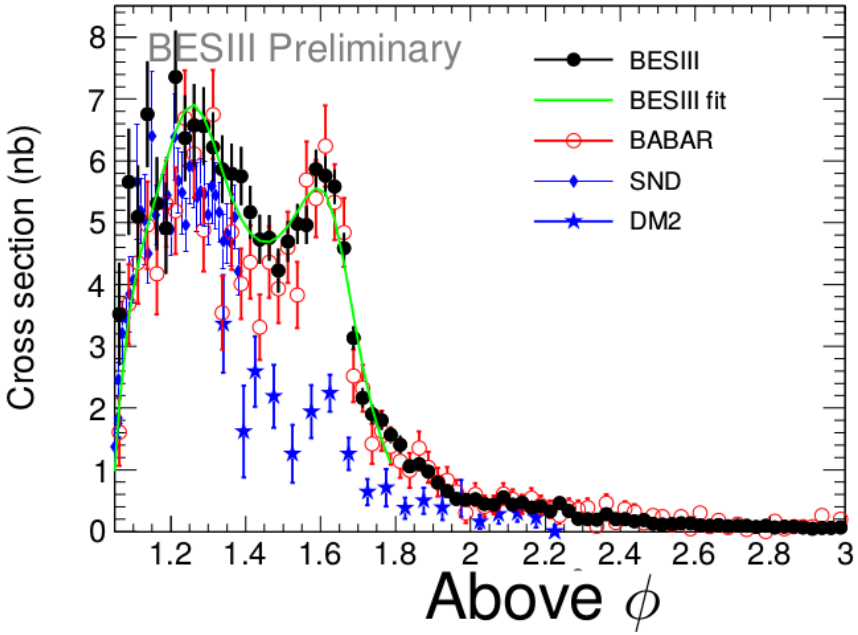
BESIII Preliminary

Parameters	PDG	This result
χ^2/NDF	-	443/390
m_ω (MeV/c^2)	782.65 ± 0.12	$783.20 \pm 0.07 \pm 0.23$
m_ϕ (MeV/c^2)	1019.46 ± 0.02	$1020.00 \pm 0.06 \pm 0.30$
$m_{\omega'}$ (MeV/c^2)	$1400 \sim 1450$	$1388 \pm 39 \pm 52$
$m_{\omega''}$ (MeV/c^2)	1670 ± 30	$1699 \pm 9 \pm 6$
Γ_ω (MeV/c^2)	8.49 ± 0.08	PDG
Γ_ϕ (MeV)	4.26 ± 0.04	PDG
$\Gamma_{\omega'}$ (MeV)	$180 \sim 250$	$629 \pm 155 \pm 212$
$\Gamma_{\omega''}$ (MeV)	315 ± 35	$331 \pm 40 \pm 28$
$(\mathcal{B}_{\omega\to e^+e^-} \times \mathcal{B}_{\omega\to 3\pi})$ (10^{-5})	6.49 ± 0.11	$6.94 \pm 0.08 \pm 0.17$
$(\mathcal{B}_{\phi\to e^+e^-} \times \mathcal{B}_{\phi\to 3\pi})$ (10^{-5})	4.53 ± 0.10	$4.20 \pm 0.08 \pm 0.17$
$(\mathcal{B}_{\omega'\to e^+e^-} \times \mathcal{B}_{\omega'\to 3\pi})$ (10^{-6})	0.82 ± 0.08	$0.84 \pm 0.09 \pm 0.09$
$(\mathcal{B}_{\omega''\to e^+e^-} \times \mathcal{B}_{\omega''\to 3\pi})$ (10^{-6})	1.30 ± 0.20	$1.14 \pm 0.15 \pm 0.15$
$\mathcal{B}_{J/\psi\to 3\pi}(\%)$	2.11 ± 0.07	$2.18 \pm 0.03 \pm 0.06$

$\pi^+\pi^-\pi^0$ Cross Section







- BESIII results clearly support BaBar measurement
- Improved precision
- Can be used as input for $a_\mu^{3\pi,\mathrm{LO}}$

Systematic Uncertainties of $\pi^+\pi^-\pi^0\gamma_{ISR}$

BESIII Preliminary

Data samples	Data I		Data II	
Source	Tagged	Untagged	Tagged	Untagged
Tracking	0.4-1.0	0.4-0.9	0.4-0.7	0.4-0.7
Photon reconstruction	0.9	0.6	0.9	0.6
E/P	0.7-0.9	0.4	0.4	0.4
π^0 side band	0.6-0.9	0.4	0.4	0.4
Kinematic fit (χ^2 cut)	1.0-1.4	0.4	0.6	0.4
Veto π^0 for $\gamma_{\rm ISR}$	0.6	-	0.5-1.0	-
$\cos\theta^{2C}_{\gamma_{\rm ISR}}$	-	1.5	-	1.5
Vertex	-	0.2	-	0.2
BG subtraction	0.0-19	0-12	0.04-26	0-6.1
Vacuum polarization	0.02-0.23	0.02-0.07	0.02-0.23	0.02-0.07
Unfolding	0.91-1.7	1.3	0.61-0.93	0.77
Radiative function	0.5	0.5	0.5	0.5
Luminosity	1.1	1.1	1.1	1.1
Total	> 2.4	> 2.6	> 2.0	> 2.4

in unit [%]

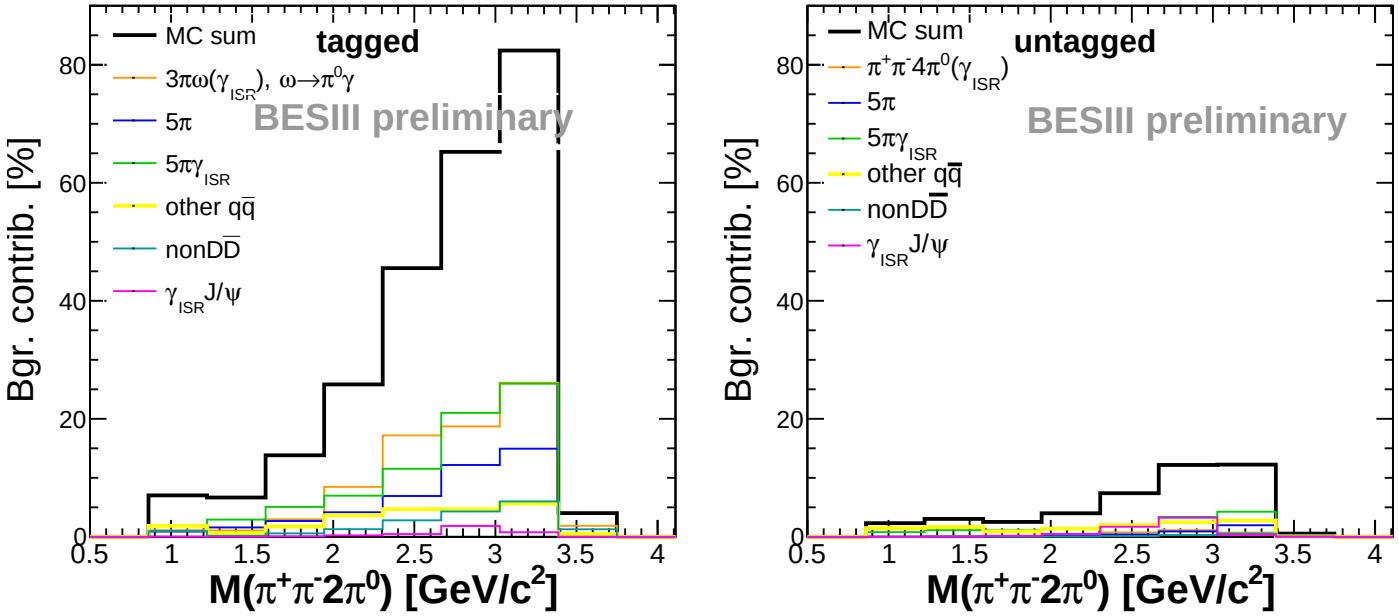
- Systematic error $< 2\%$ in the resonance regions

$e^+e^- \to \pi^+\pi^- 2\pi^0 \gamma_{ISR}$

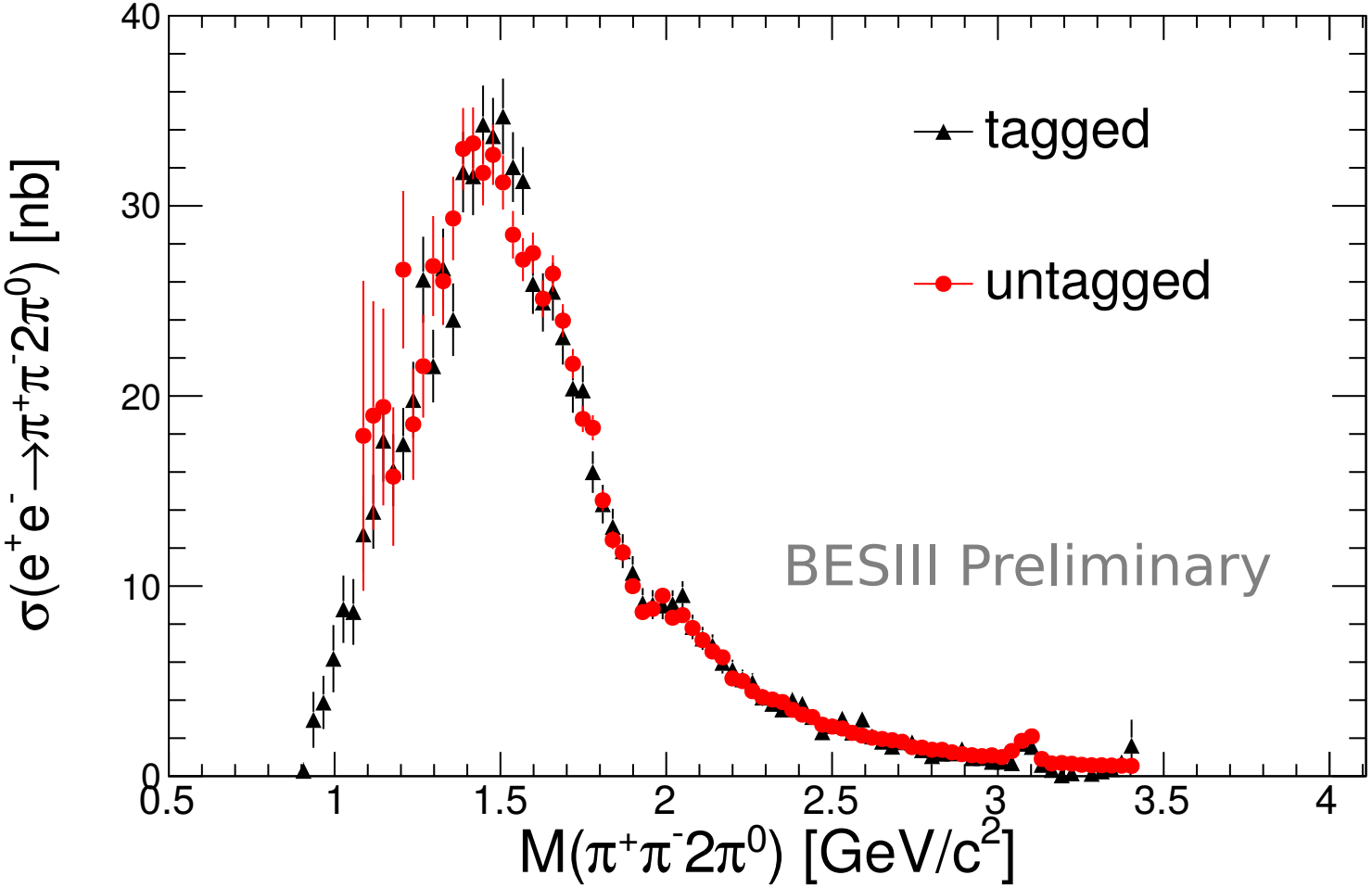
(Preliminary)

Event Selection of $\pi^+\pi^-2\pi^0\gamma_{ISR}$

- Perform tagged and untagged analyses separately
- Most important selection criteria:
  - Tagged: Kinematic fit, π^0 veto for ISR photon
  - Untagged: $|\cos\theta_{ISR}| > 0.995$
- Main background from $\pi^+\pi^-3\pi^0(\gamma_{ISR})$
- Perform measurements of $\pi^+\pi^-3\pi^0$ and $\pi^+\pi^-3\pi^0\gamma_{ISR}$ backgrounds
- Partial wave analysis with HelPWA for $\pi^+\pi^-3\pi^0$
- Correct background MC according to data



$\pi^+\pi^-2\pi^0$ Cross Section



$$\sigma(m) = \frac{1}{\frac{2m}{s} W(s,x)\epsilon(m)\mathcal{L}\delta_{VP}\delta_{FSR}} \frac{dN}{dm}$$

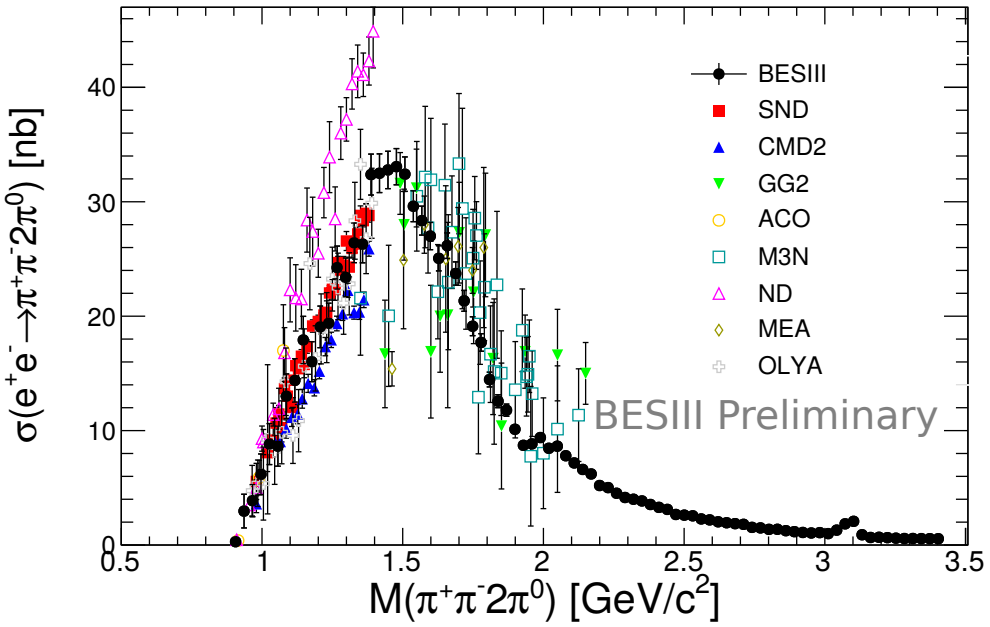
Systematic Uncertainties Summary

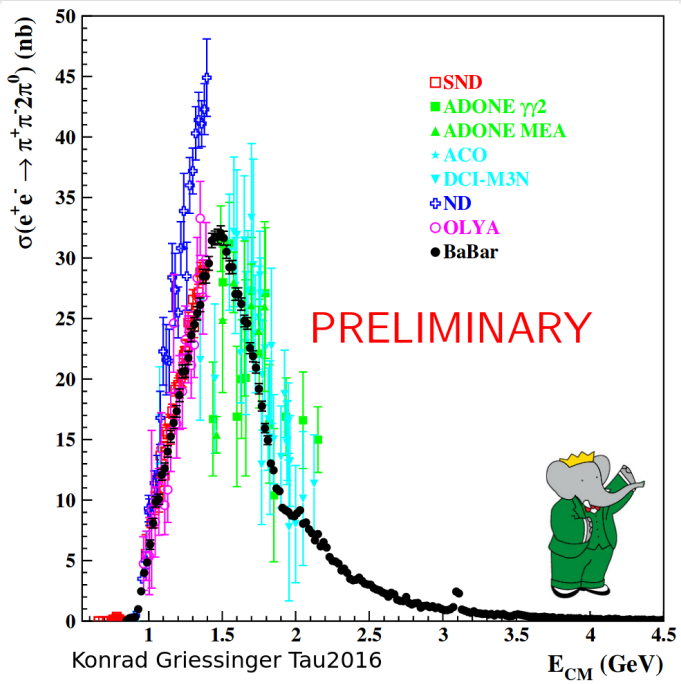
- Background uncertainties are mass dependent

Region	Mass range [GeV]
R1	$0.5 < M(4\pi) < 1.5$
R2	$1.5 < M(4\pi) < 2.0$
R3	$2.0 < M(4\pi) < 3.0$
R4	$3.0 < M(4\pi) < 3.8$

Source	Tagged [%]				Untagged [%]			
	R1	R2	R3	R4	R1	R2	R3	R4
Luminosity	0.50				0.50			
Tracking	0.60				0.60			
VP correction	0.05				0.05			
FSR correction	0.20				0.20			
Radiator Function	0.50				0.50			
ISR Photon Eff.	0.30				-			
π^0 Eff.	2.57				2.52			
Signal Eff.	0.58				0.61			
Kin. fit	0.42				0.45			
Event selection	0.60		1.46		0.64			
Bgr. Subrt. 5π	0.01	0.13	2.47	3.23	0.00	0.01	0.08	0.15
Bgr. Subrt. $5\pi\gamma_{ISR}$	0.48	0.47	7.77	10.27	0.59	0.25	0.65	0.71
Bgr. Subrt. $q\bar{q}$	0.50	0.98	12.68	21.05	0.58	0.22	0.82	0.76
Bgr. Subrt. other	0.05	0.14	2.31	5.34	0.01	0.02	0.30	0.32
ω fits (only for $\omega\pi^0$)	2.26				2.26			
$\pi^+\pi^-2\pi^0$ Total	2.97	3.09	15.58	24.45	2.95	2.85	3.04	3.04
$\omega\pi^0$ Total	3.80	4.84	7.71	3.73	3.91	3.70	4.48	3.68

Combined $\pi^+\pi^-2\pi^0$ Cross Section

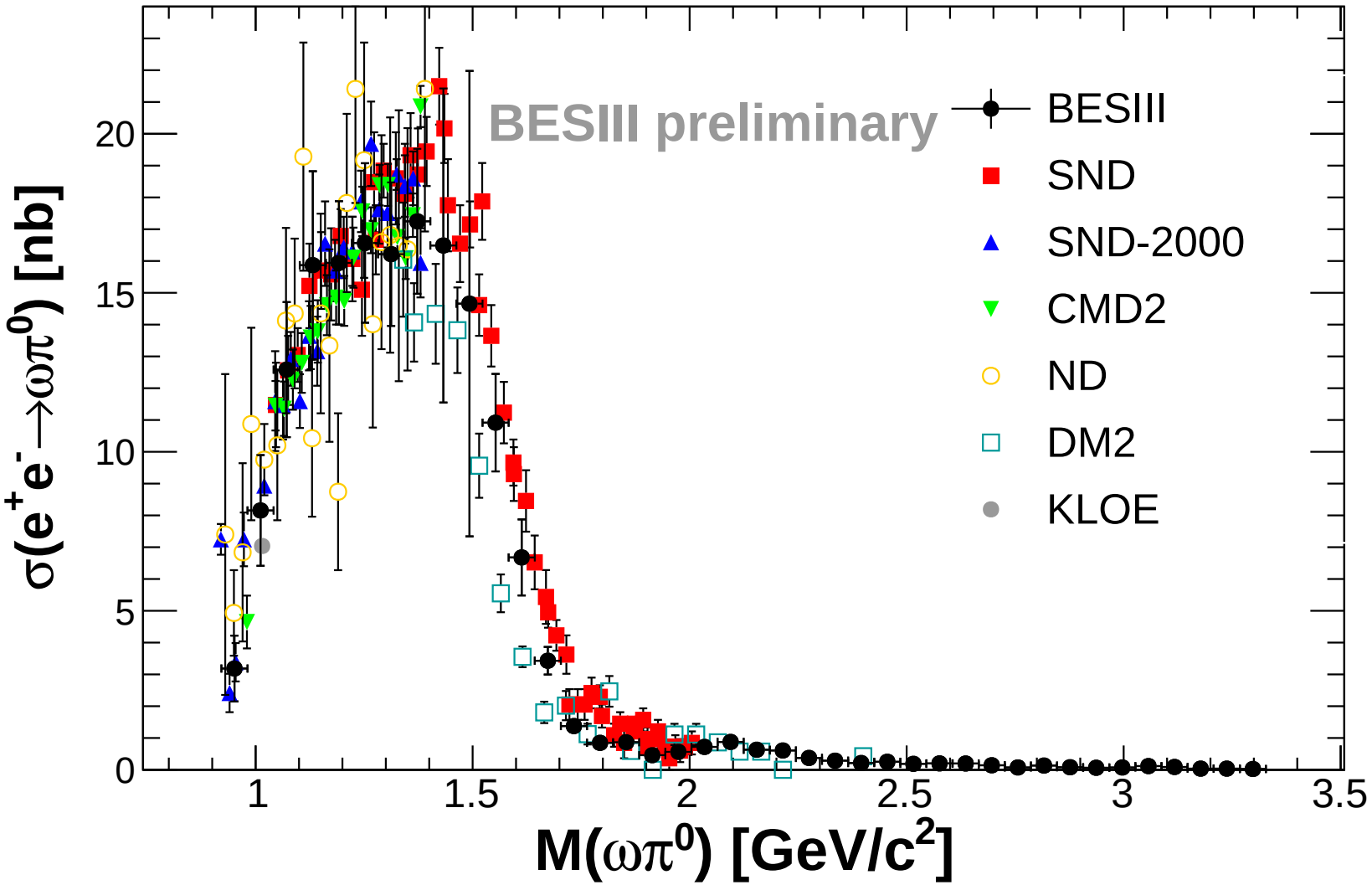




- Error weighted mean of tagged and untagged
- $\approx 3\%$ precision like Babar
- $a_\mu^{\pi^+\pi^-2\pi^0,\mathrm{LO}} = \frac{1}{4\pi^3}\int_{(4m_\pi)^2}^{(1.8\,\mathrm{GeV})^2} ds\, K(s)\sigma_{\pi^+\pi^-2\pi^0}(s)$

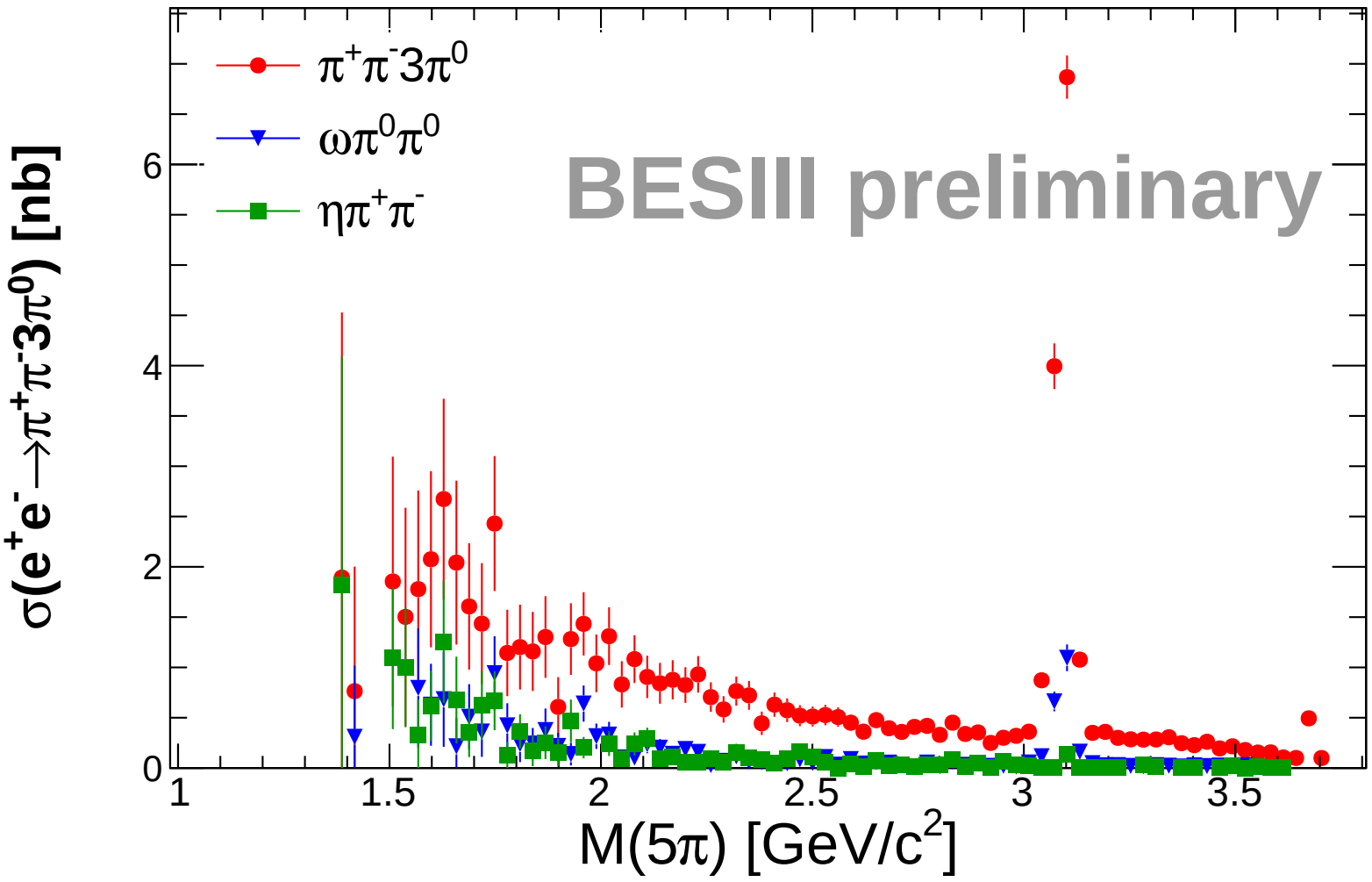
	$a_\mu^{\pi^+\pi^-2\pi^0,\mathrm{LO}}/10^{-10}$
BESIII (preliminary)	$18.6 \pm 0.3 \pm 0.6$
BABAR (preliminary)	$17.9 \pm 0.1 \pm 0.6$

$\omega\pi^0$ Cross Section



- Perform Fit of the $M(3\pi)$ distributions with double Gaussian for *omega* plus third order polynomial for non-ω in each $M(\pi^+\pi^-2\pi^0)$ bin

$\pi^+\pi^-3\pi^0$ Cross Section



- From $\pi^+\pi^-2\pi^0\gamma_{ISR}$ background study
- Systematic uncertainty: 13.8%

Summary, Conclusion and Outlook

Summary

- Deviation $> 3\sigma$ between experiment and Standard model prediction of $(g-2)_\mu$
- BESIII contributes with high precision measurements of 2π, 3π and $\pi^+\pi^-2\pi^0$ cross sections

Conclusion

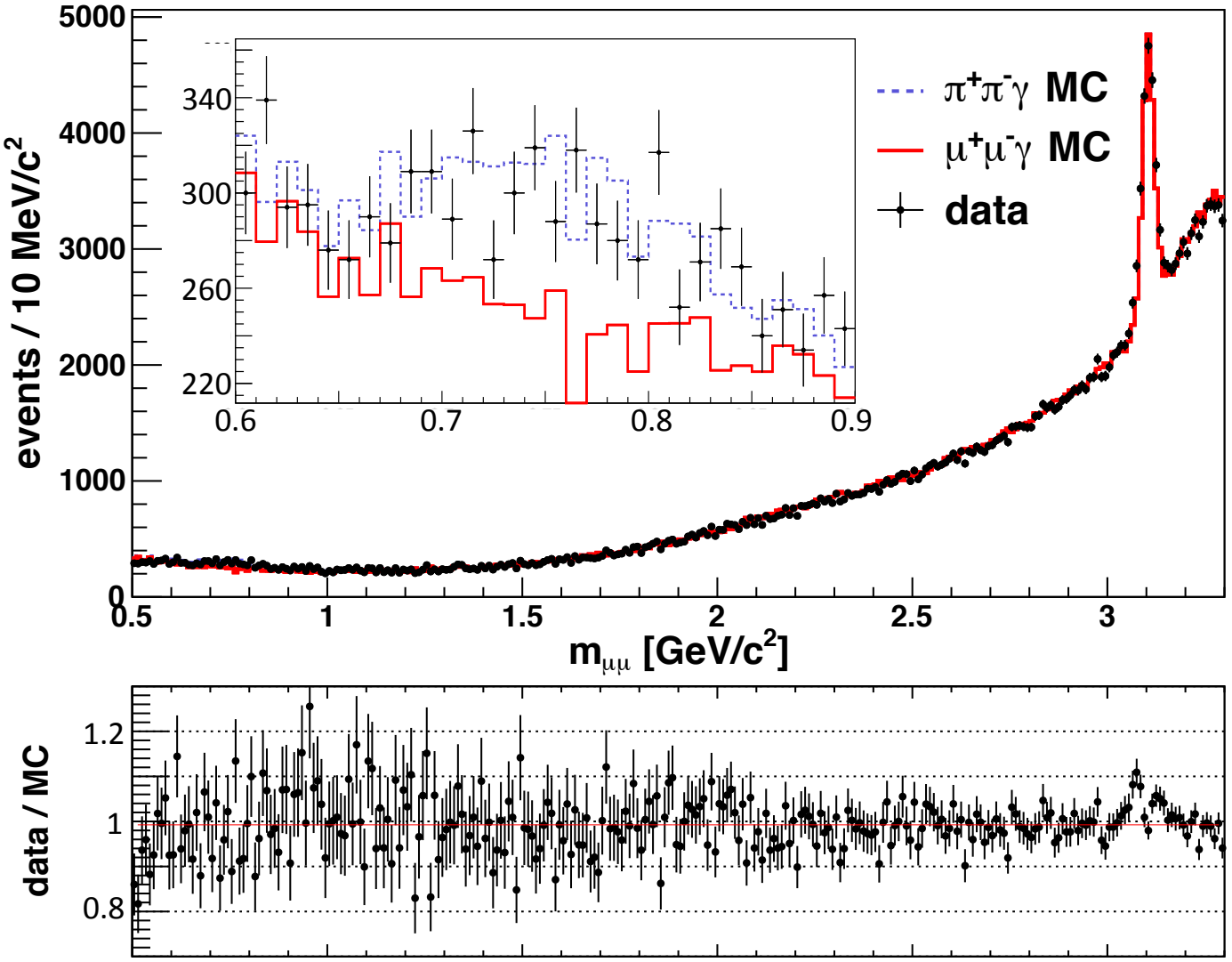
- BESIII provides competitive results
- Uncertainty of a_μ^{VP} can be reduced with further measurements
- Improved branching fraction measurements and spectroscopy

Outlook

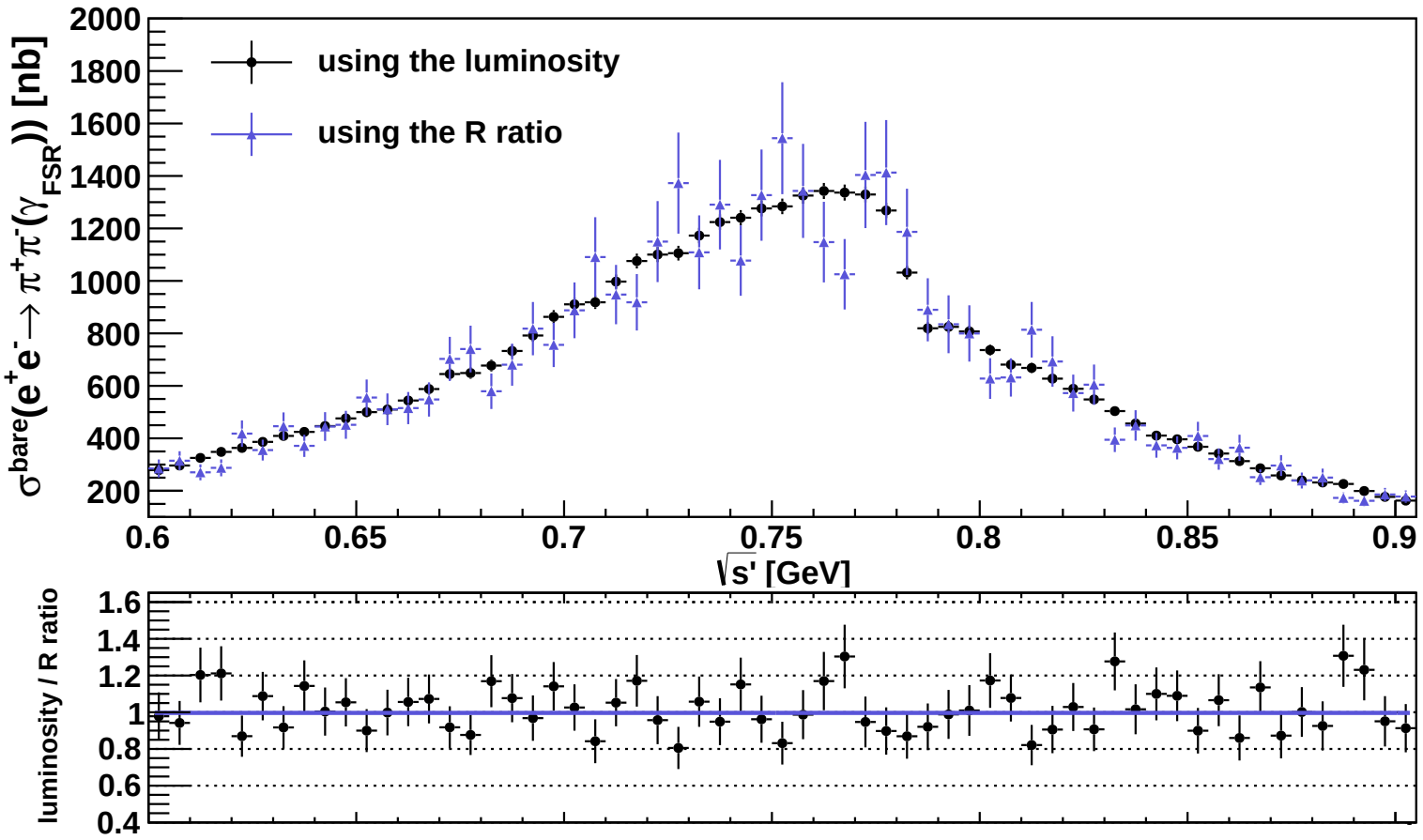
- Use all BESIII data sets
- Improve accuracy of $\pi^+\pi^-$ in the peak region
- Investigate $\pi^+\pi^-$ analysis in full mass range
- Measure more final states

Backup

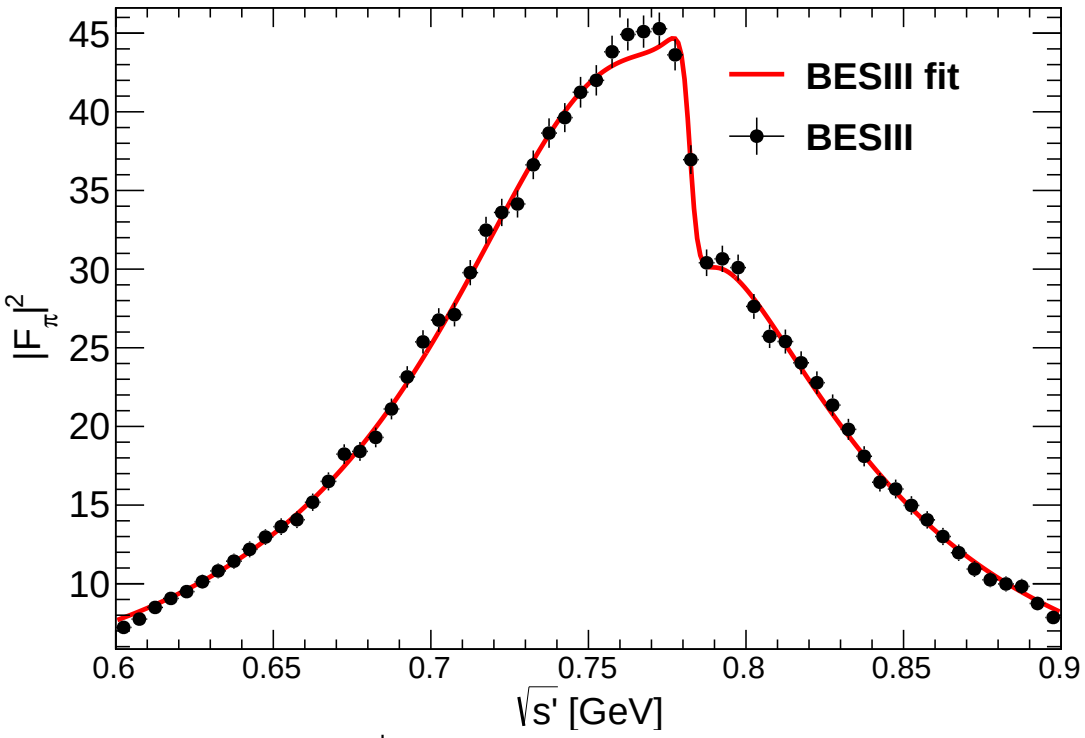
$\pi^+\pi^-$ Cross Section with Muon Normalization I



$\pi^+\pi^-$ Cross Section with Muon Normalization II

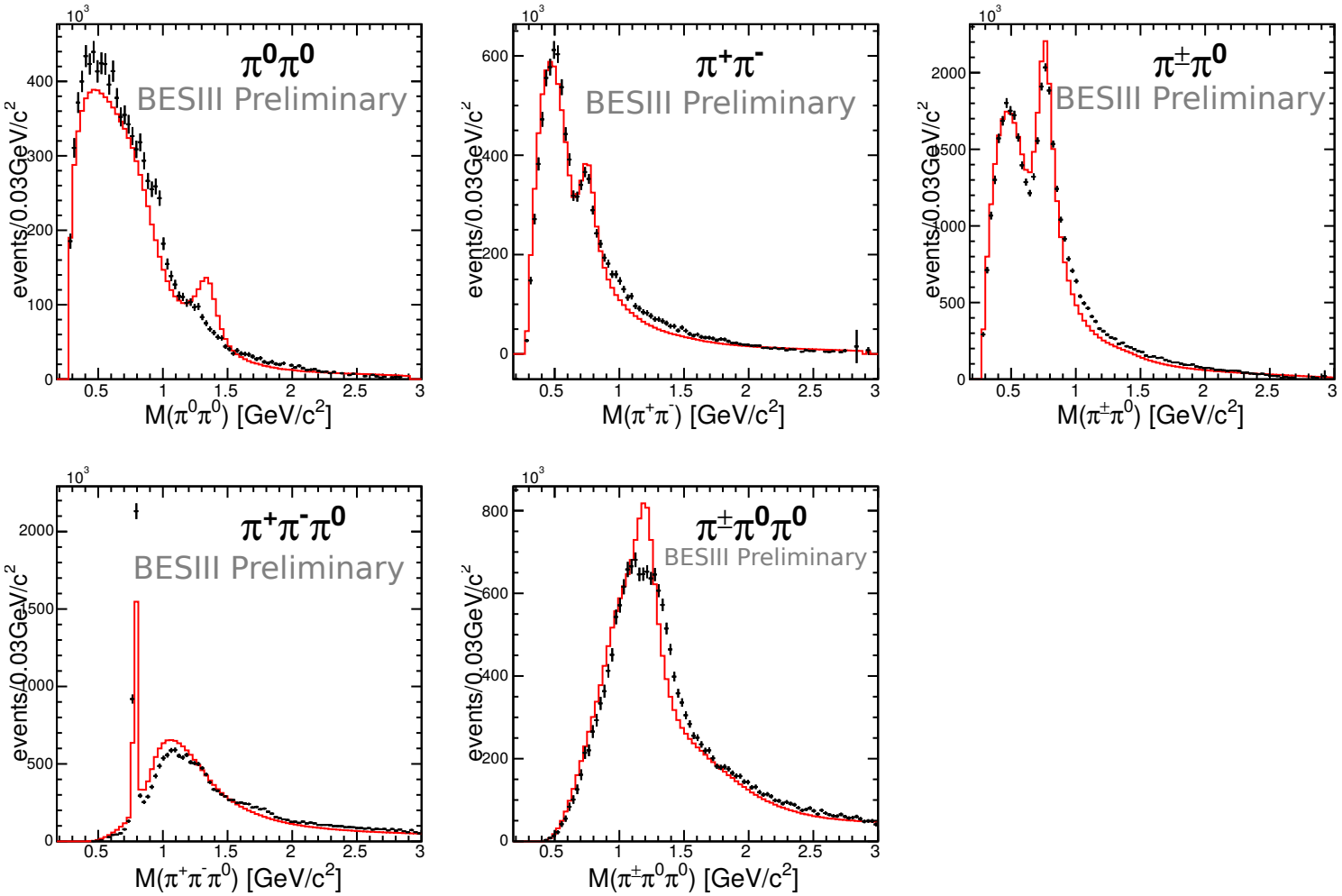


$\pi^+\pi^-$ Form Factor (Gounaris-Sakurai Parametrisation)



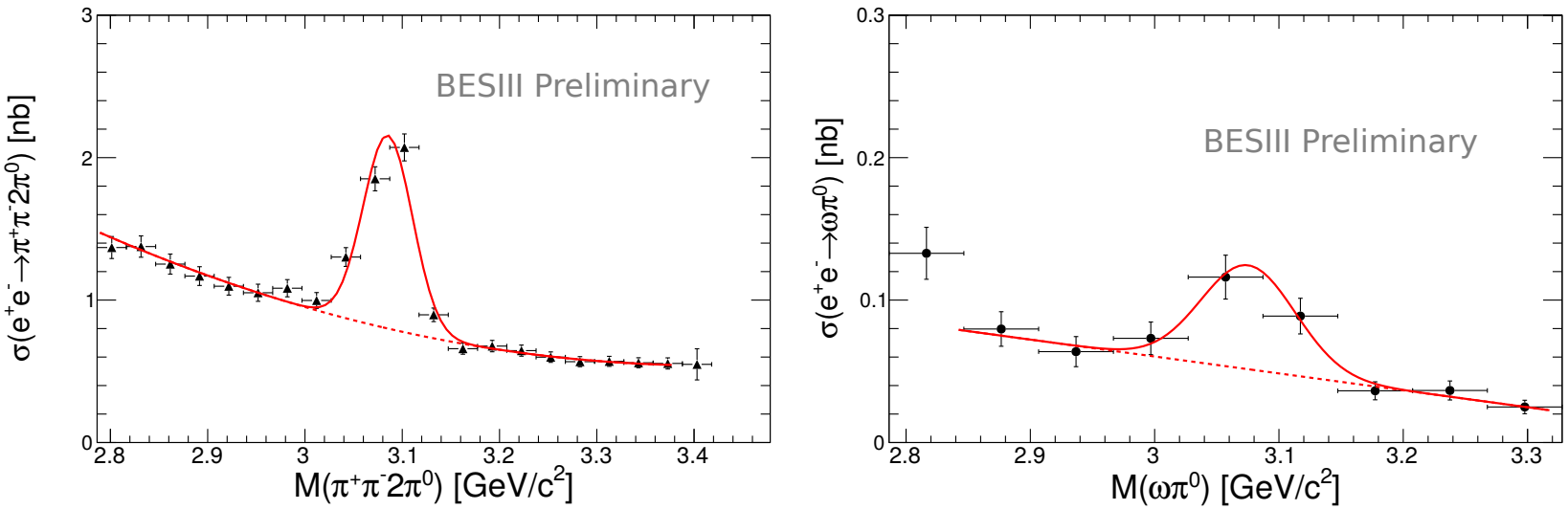
parameter	BESIII value	PDG 2014
m_ρ [MeV/c^2]	774.8 ± 0.4	775.26 ± 0.25
Γ_ρ [MeV]	151.1 ± 0.7	147.8 ± 0.9
m_ω [MeV/c^2]	782.1 ± 0.6	782.65 ± 0.12
Γ_ω [MeV]	fixed to PDG	8.49 ± 0.08
$\lvert c_\rho \rvert$ [10^{-3}]	1.7 ± 0.2	-
$\lvert \phi_\omega \rvert$ [rad]	0.04 ± 0.13	-

$\pi^+\pi^-2\pi^0$ Intermediate Structures



- Most intermediate structures are described very well

J/ψ Branching Fraction



- $\sigma^{\text{int}}_{R\to f} = \int dm\, \sigma(m^2)_{R\to f} = \mathcal{B}(R\to f)\frac{6\pi^2\Gamma^R_{ee}}{M_R^2}C$
- $\mathcal{B}(R\to f) = \frac{\sigma^{\text{int}}_{R\to f}M_R^2}{6\pi^2\Gamma^R_{ee}C}$

final state	χ^2/ndf	$\sigma^{\text{int}}_{R\to f}$ [nb GeV]	$\mathcal{B}(J/\psi\to f)/10^{-3}$	PDG $/10^{-3}$
$\pi^+\pi^-2\pi^0$	1.14	0.0861 ± 0.0057	$6.46 \pm 0.43_{\text{stat}} \pm 0.27_{\text{sys}}$	-
$\omega\pi^0$	0.51	0.0069 ± 0.0017	$0.52 \pm 0.12_{\text{stat}} \pm 0.03_{\text{sys}}$	0.45 ± 0.05
$\pi^+\pi^-3\pi^0$	1.55	0.347 ± 0.012	$26.0 \pm 0.9_{\text{stat}} \pm 3.4_{\text{sys}}$	-
$\omega\pi^0\pi^0$	1.11	0.057 ± 0.007	$4.8 \pm 0.6_{\text{stat}} \pm 0.8_{\text{sys}}$	3.4 ± 0.8
$\eta\pi^+\pi^-$	0.66	0.0027 ± 0.0010	$0.61 \pm 0.23_{\text{stat}} \pm 0.08_{\text{sys}}$	0.40 ± 0.17