Form Factor Measurements at BESIII for an Improved Standard Model Prediction of the muon g-2

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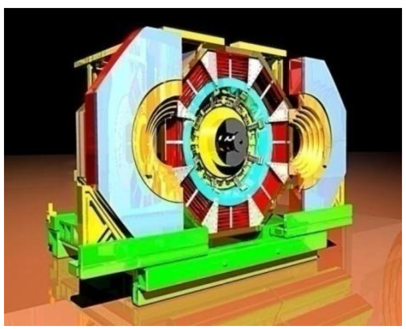
on behalf of the BESIII Collaboration



PANIC 2017

21st Particles & Nuclei International Conference

Beijing, China

September 1-5, 2017

Overview

- Introduction

Muon magnetic moment

BEPCII and the BESIII experiment

BESIII dataset

- Physics results

$\pi^+\pi^-$

$\pi^+\pi^-\pi^0$

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

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

Two-photon physics

} BESIII Preliminary

- Summary

Muon Magnetic Moment

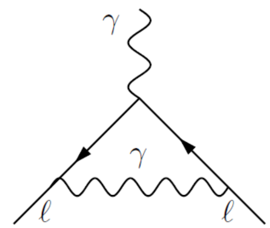
Lepton magnetic moment: $\bar{\mu} = g \frac{Qe}{2m} \bar{s}$

Dirac theory pediction: $g = 2(1 + a)$

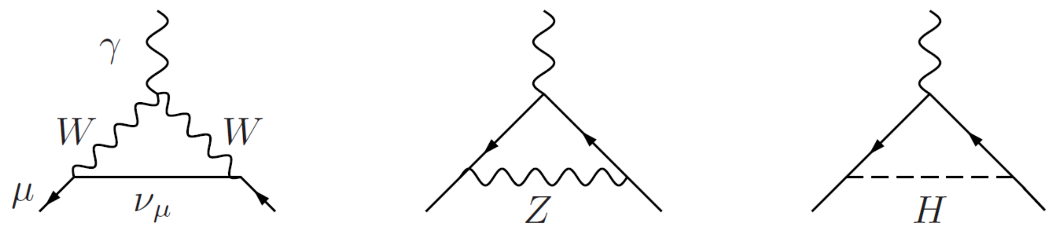
$$a_\mu = \frac{g_\mu - 2}{2}$$

Muon anomaly arises from quantum fluctuations

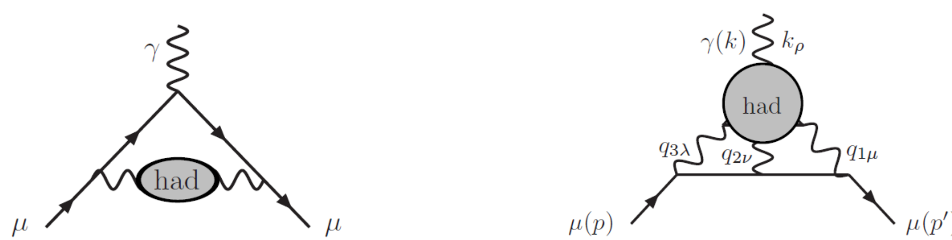
QED contribution (largest):



Weak contribution:



Hadronic contribution:



Muon Magnetic Moment

$$a_\mu = \frac{g_\mu - 2}{2} = \frac{\alpha}{2\pi} + \cdots = 0.001161$$

$$a_\mu^{theo} = a_\mu^{QED} + a_\mu^{weak} + a_\mu^{hadr}$$

Contribution	Results in 10^{-10} units		
QED (leptons)	11658471.885	± 0.004	Kinoshita et al. (2012)
Weak	15.4	± 0.2	Czamecki et al. (2003)
HVP (LO)	692.3	± 4.2	Davier et al. (2001)
HVP (HO)	-9.84	± 0.07	Hagiwara et al. (2009)
HLBL	11.6	± 4.0	Jegerlehner, Nyffler (2009)
Total	11659181.3	± 5.8	
Experiment	11659208.9	± 6.3	

Discrepancy: 27.6

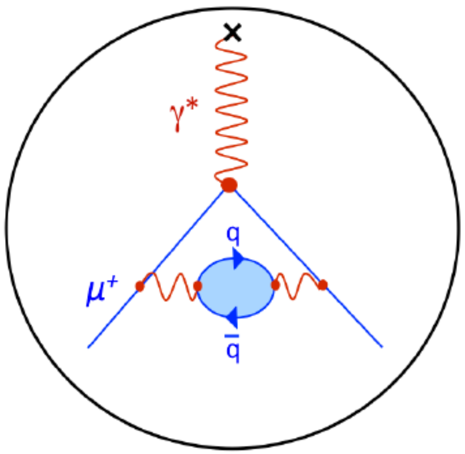
Prediction limited by hadronic contributions

Perturbative method cannot be applied in the relevant energy regime

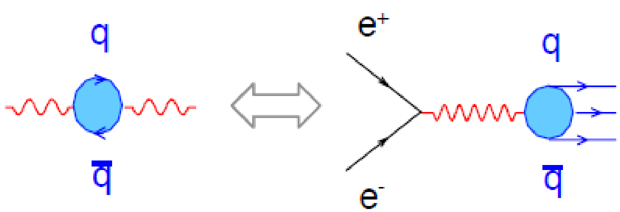
Muon Magnetic Moment

Hadronic Contributions

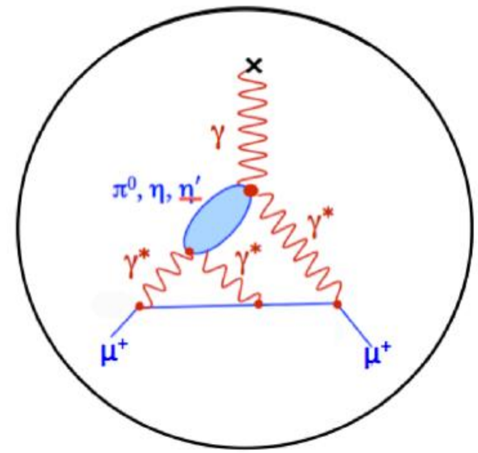
Hadronic Vacuum Polarization



Optical theorem



Hadronic Light-by-Light



Two-photons collisions

Dispersion integral: $a_{\mu,LO}^{HVP} = \frac{1}{4\pi^3}\int_{m_{\pi^0}}^{\infty} ds\, K(s)\, \sigma_{had}(s)$

Muon Magnetic Moment

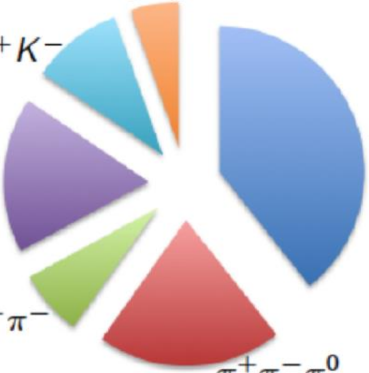
Hadronic Contributions

Vacuum Polarization

M. Ripka, *Initial State Radiation Measurement at BESIII*, PhiToPsi2017 proceedings, in press

$a_\mu^{had,VP}$

$\delta a_\mu^{had,VP}$



KLOE[1] and BABAR[2] measurement discrepancy 3-5%

Another high precision measurement needed -> BESIII

Wider mass range than KLOE

Closer to $\sqrt{s} \lesssim 2$ GeV than BABAR -> lower suppression of ISR events

Untagged ISR mode can be used above $\sqrt{s} \gtrsim 1$ GeV
-> no problem for ≥ 4π

ISR measurement of baryon Form Factors:
see presentation of Zhaoxia Meng

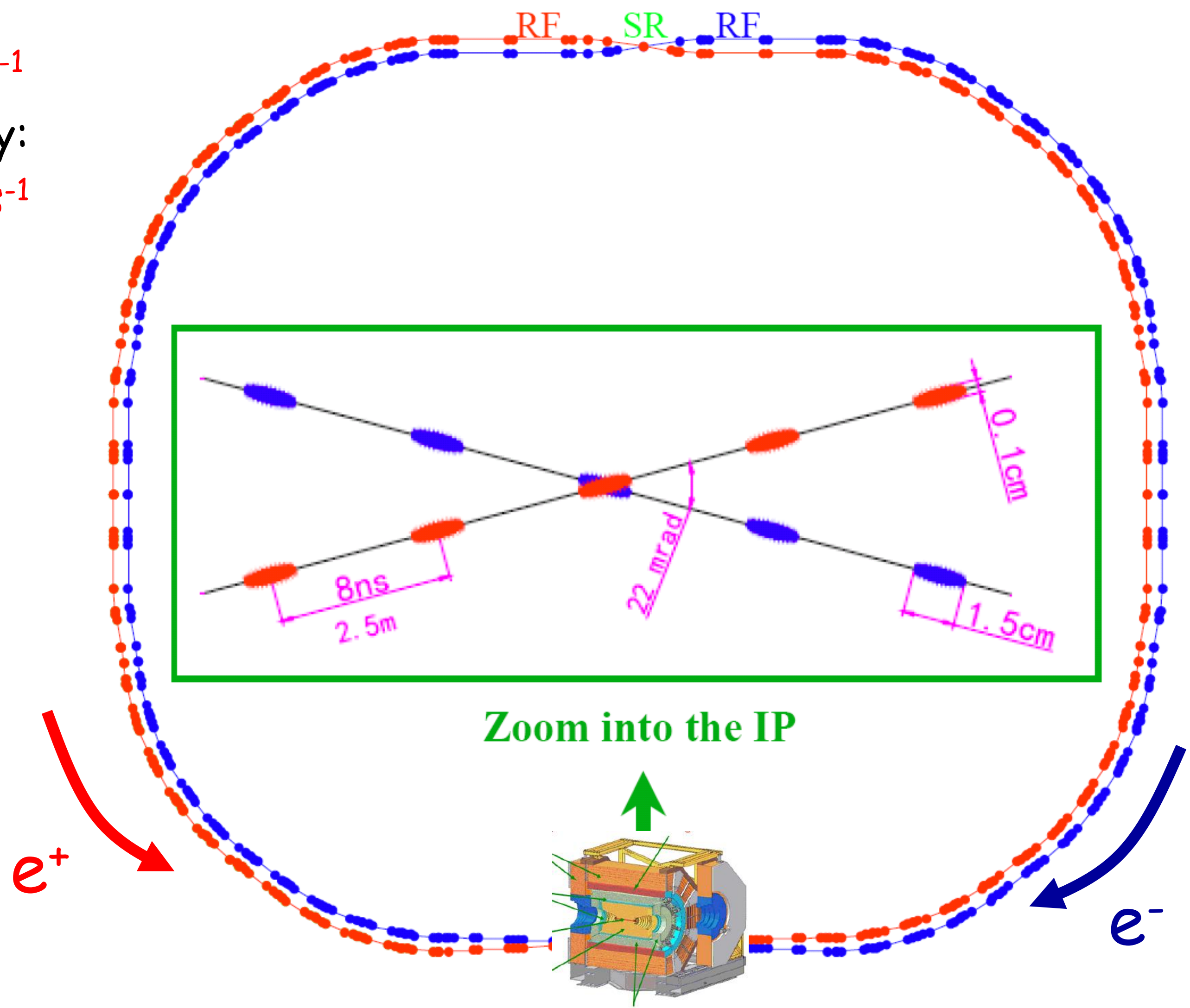
[1] B. Aubert et al., Phys. Rev. Lett. 103, 231801 (2009). J.P. Lees et al., Phys. Rev. D86, 032013 (2012)

[2] F. Ambrosino et al. Phys. Lett. B 670, 285 (2009). F. Ambrosino et al. Phys. Lett. B 700, 102-110 (2011). D. Babusci et al. Phys. Lett. B 720, 336-343 (2013).

BEPCII Storage Rings

- Beam energy:
  1.0-2.3 GeV
- Design Luminosity:
  1×10^{33} $cm^{-2}s^{-1}$
- Achieved Luminosity:
  $\sim 1\times10^{33}$ $cm^{-2}s^{-1}$
- Optimum energy:
  1.89 GeV
- Energy spread:
  5.16×10^{-4}
- No. of bunches:
  93
- Bunch length:
  1.5 cm
- Total current:
  0.91 A
- Circumference:
  237m

Beijing Electron-Positron Collider II

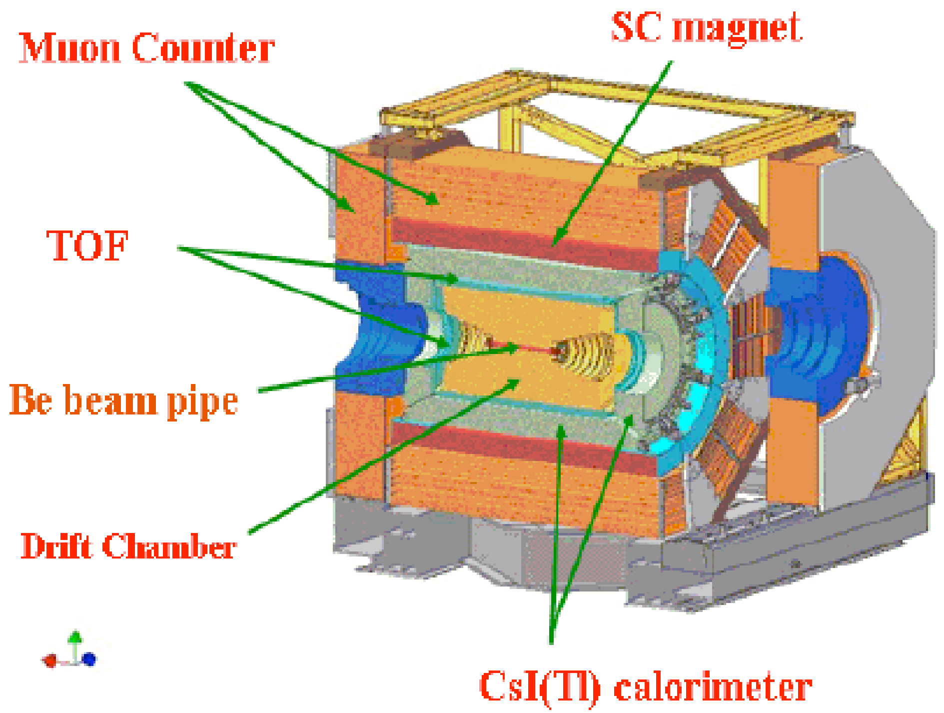


The BESIII Spectrometer @ IHEP

BEijing Spectrometer III

e^+e^- collisions

$\sqrt{S}$ tuned depending on energy

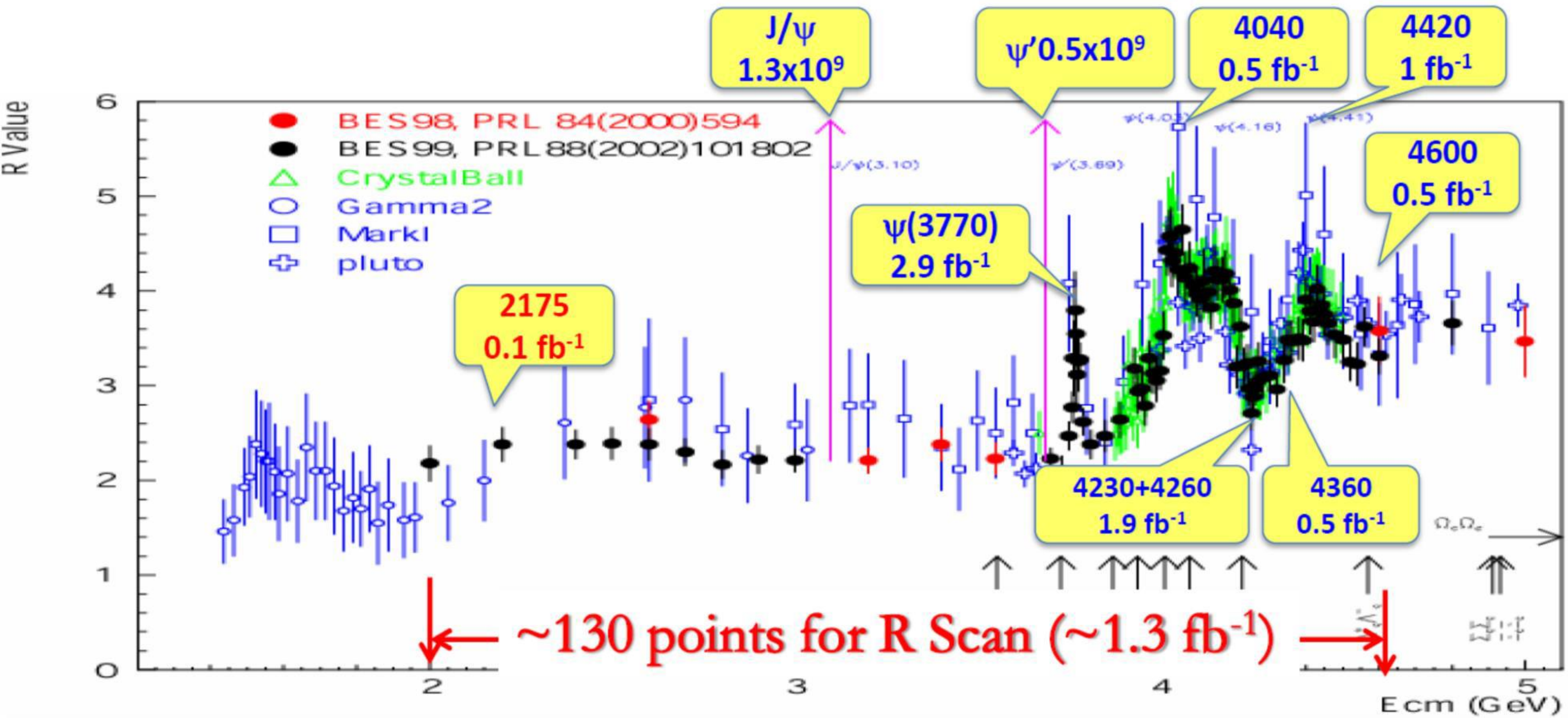


Physics program

- Charmonium Physics
- D-Physics
- Light Hadron Spectroscopy
- τ-Physics
- ...

D.M. Asner et al, Physics at BES-III, arXiv:0809.1869v1 [hep-ex] (2008)

BESIII Dataset



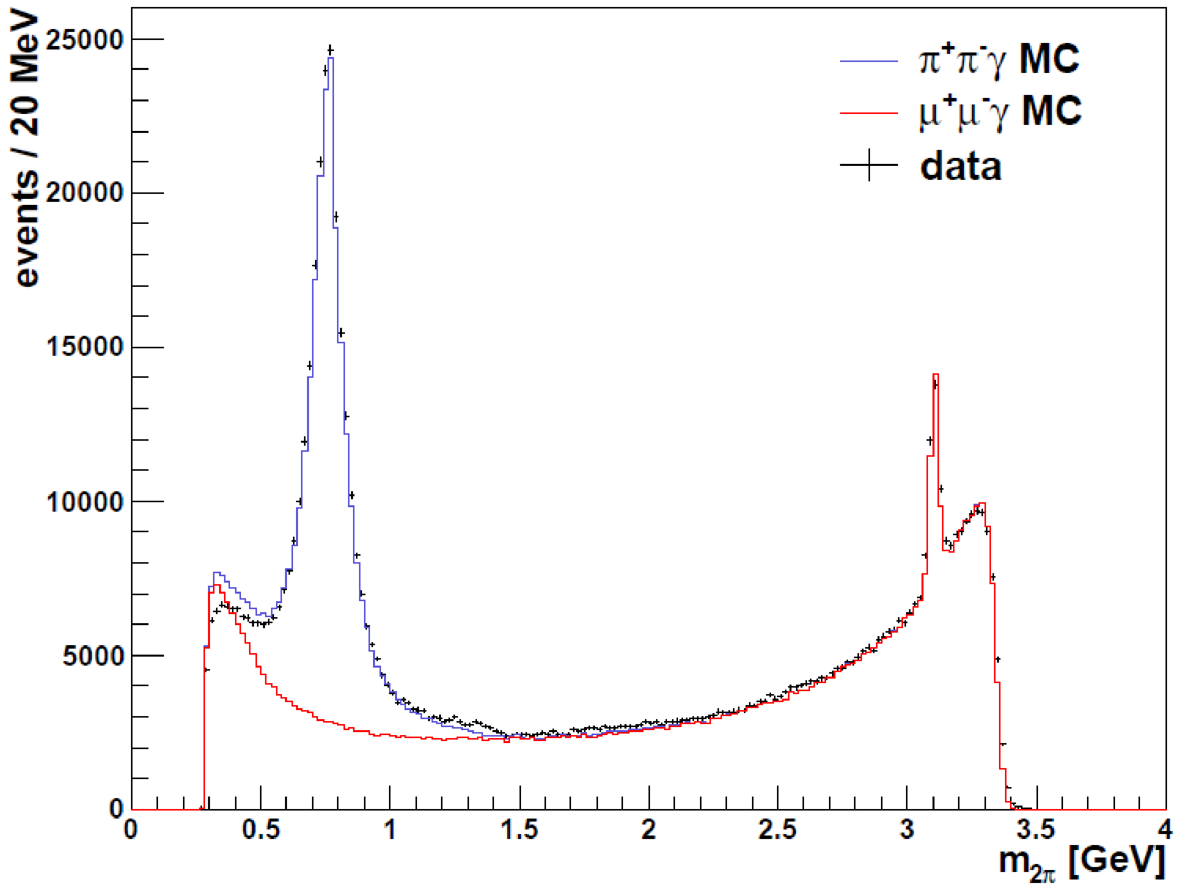
- World largest data sample on J/ψ, ψ(2S), ψ(3770), Y(4260)… in e^+e^- collisions
- From light meson spectroscopy to $\Lambda_c\bar{\Lambda}_c$
- Fine and coarse scan of the accessible energy region

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

PLB 753, 629 (2016)

Particle Identification

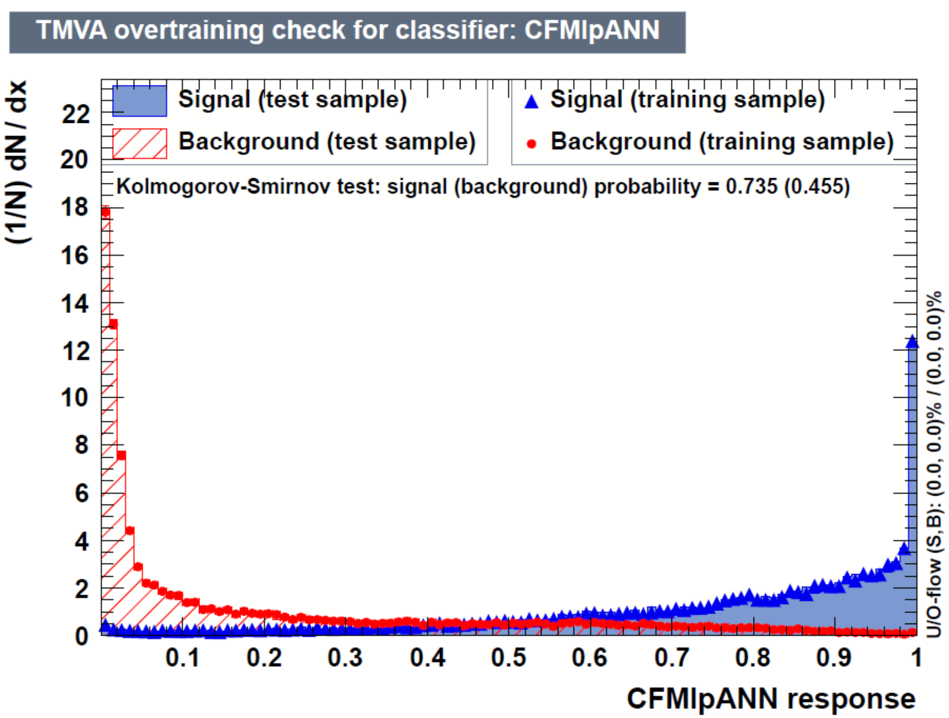
- Tagged ISR mode only
- Kinematic fit for $\pi^+\pi^-\gamma_{ISR}$ final state
- Standard BESIII PID system for electron rejection
- Muon-pion separation needed

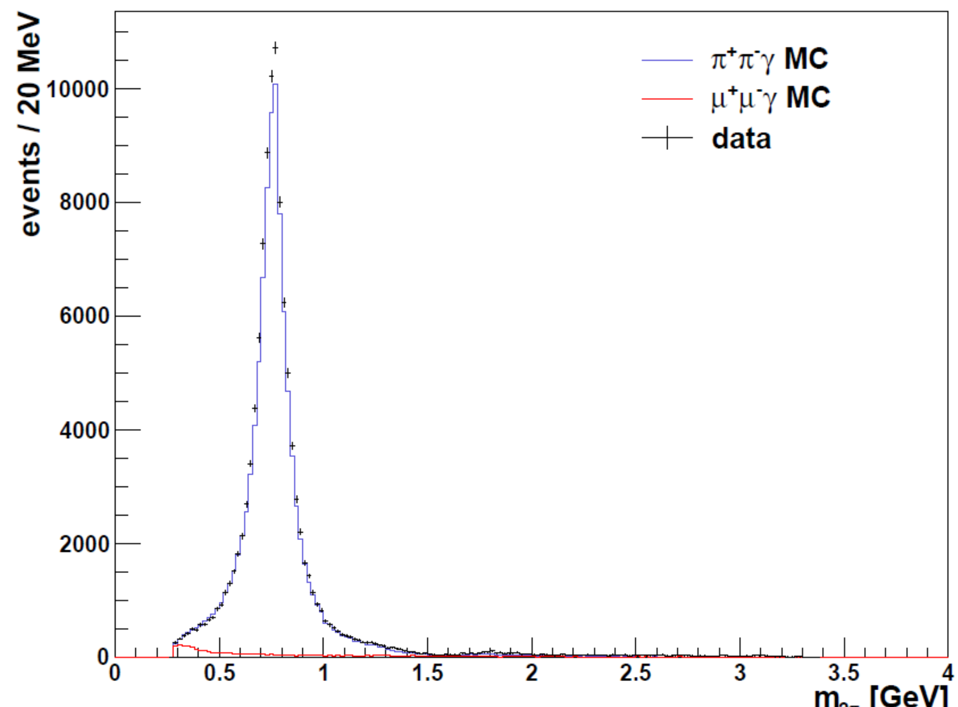


$e^+e^- \to \gamma\pi^+\pi^-$ Selection

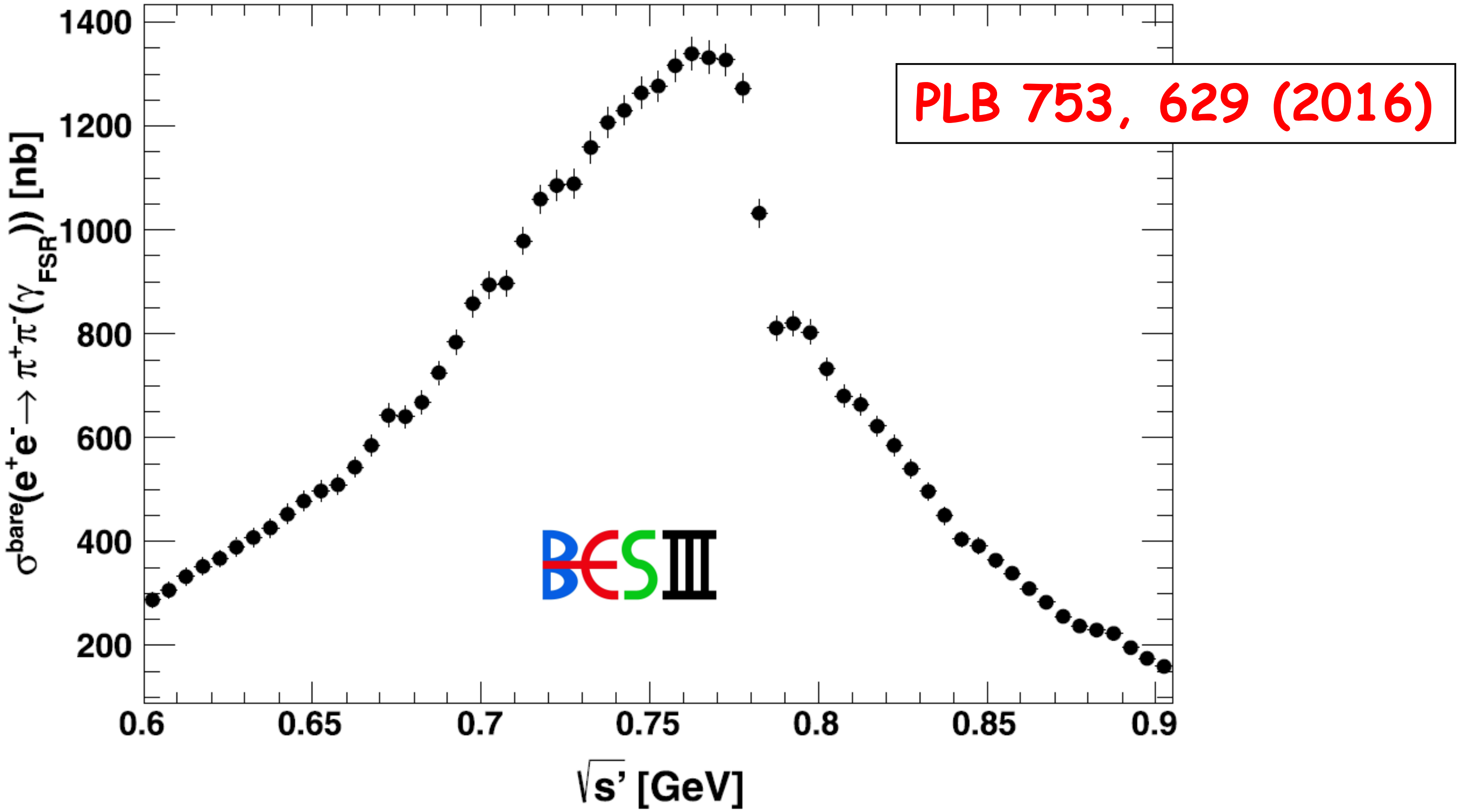
PLB 753, 629 (2016)

- Muons and pions have different shower shape in EMC
- Artificial Neural Network (ANN) for μ-π separation
- Very clean sample after ANN
- ρ-ω interference clearly visible





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



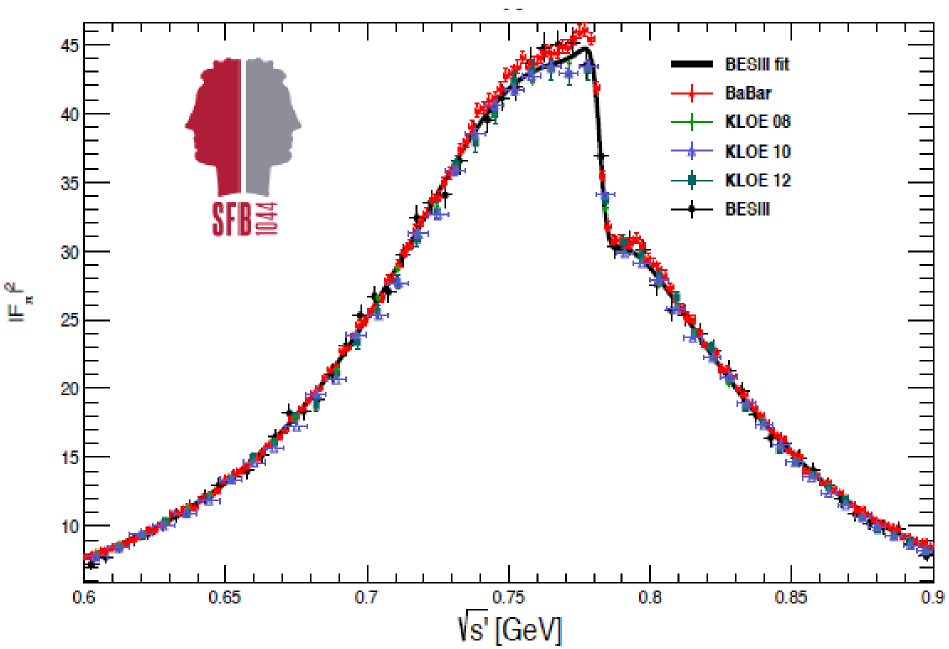
$$\sigma^{bare}\left(\sqrt{s'}\right) = \frac{1}{\frac{2\sqrt{s'}}{s} W(s,x)\epsilon\left(\sqrt{s'}\right)\mathcal{L}\delta_{vac}\delta_{FSR}} \frac{dN}{d\sqrt{s'}}$$

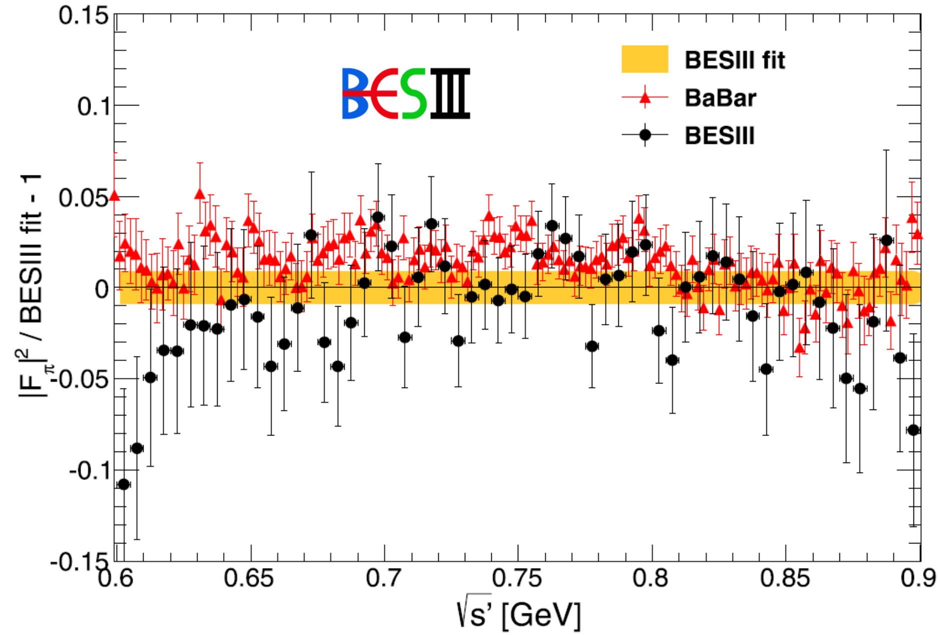
ρ-ω interference clearly visible

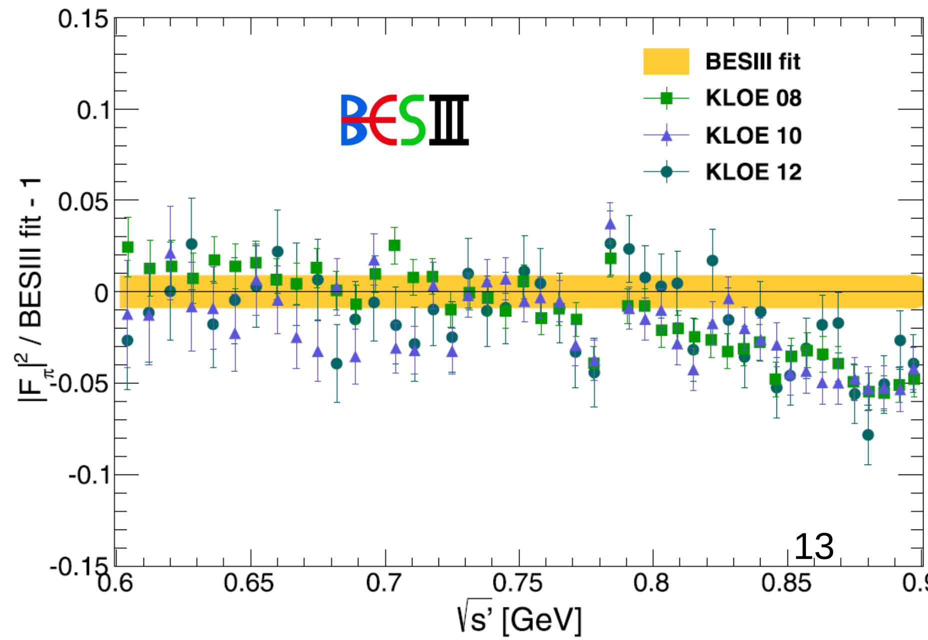
Comparison of $\pi^+\pi^-$ Form Factor

PLB 753, 629 (2016)

Pion Form Factor F_π







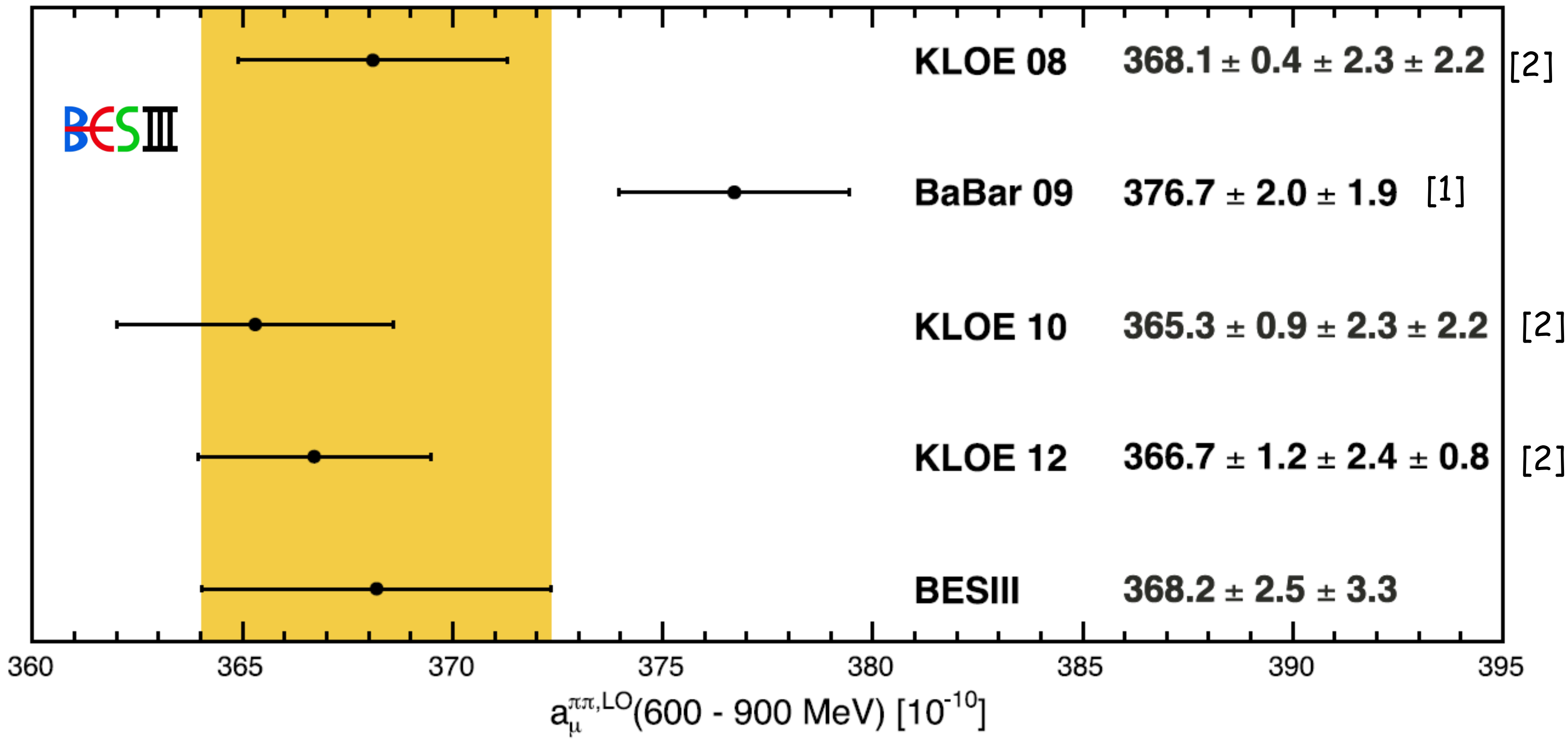
- New BESIII measurement agrees with KLOE[1] and BABAR[2]
- Small shift wrt BABAR above ρ-ω interference

[1] B. Aubert et al., Phys. Rev. Lett. 103, 231801 (2009).
J.P. Lees et al., Phys. Rev. D86, 032013 (2012)

[2] F. Ambrosino et al. Phys. Lett. B 670, 285 (2009).
F. Ambrosino et al. Phys. Lett. B 700, 102-110 (2011).
D. Babusci et al. Phys. Lett. B 720, 336-343 (2013).

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

PLB 753, 629 (2016)



- Precision compatible with previous measurements
- $a_\mu^{\pi\pi,LO}(600 - 900\ \mathrm{MeV}) = (368.2 \pm 2.5_{stat} \pm 3.3_{syst}) \cdot 10^{-10}$
- Confirmation of deviation of > 3σ between experiment and theory

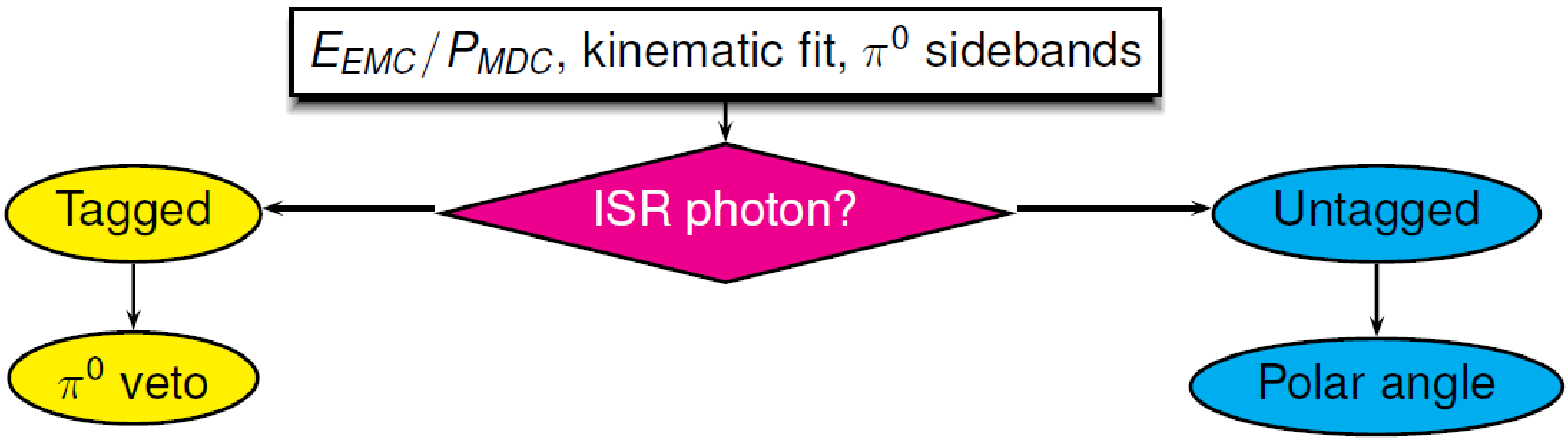
[1] B. Aubert et al., Phys. Rev. Lett. 103, 231801 (2009). J.P. Lees et al., Phys. Rev. D86, 032013 (2012)

[2] F. Ambrosino et al. Phys. Lett. B 670, 285 (2009). F. Ambrosino et al. Phys. Lett. B 700, 102-110 (2011). D. Babusci et al. Phys. Lett. B 720, 336-343 (2013).

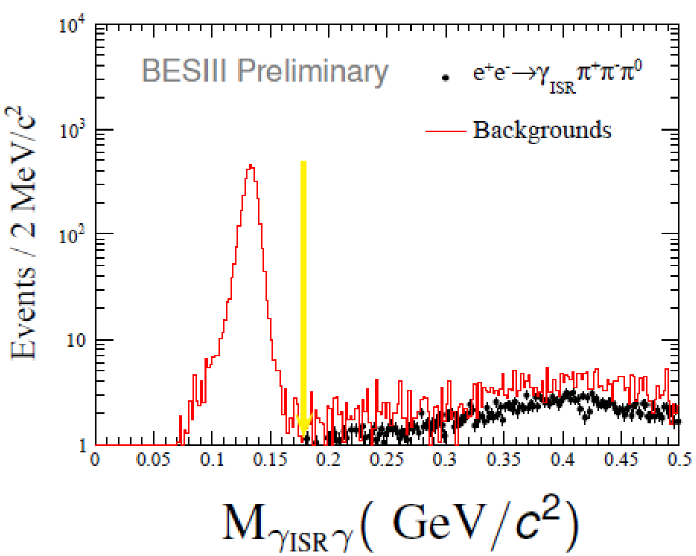
$e^+e^- \to \gamma\pi^+\pi^-\pi^0$

PRELIMINARY

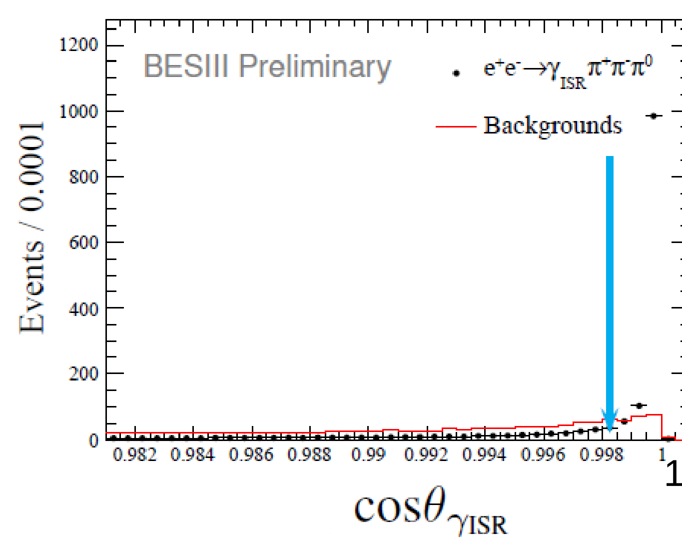
Event Selection



Combination of the ISR photon and any other photon

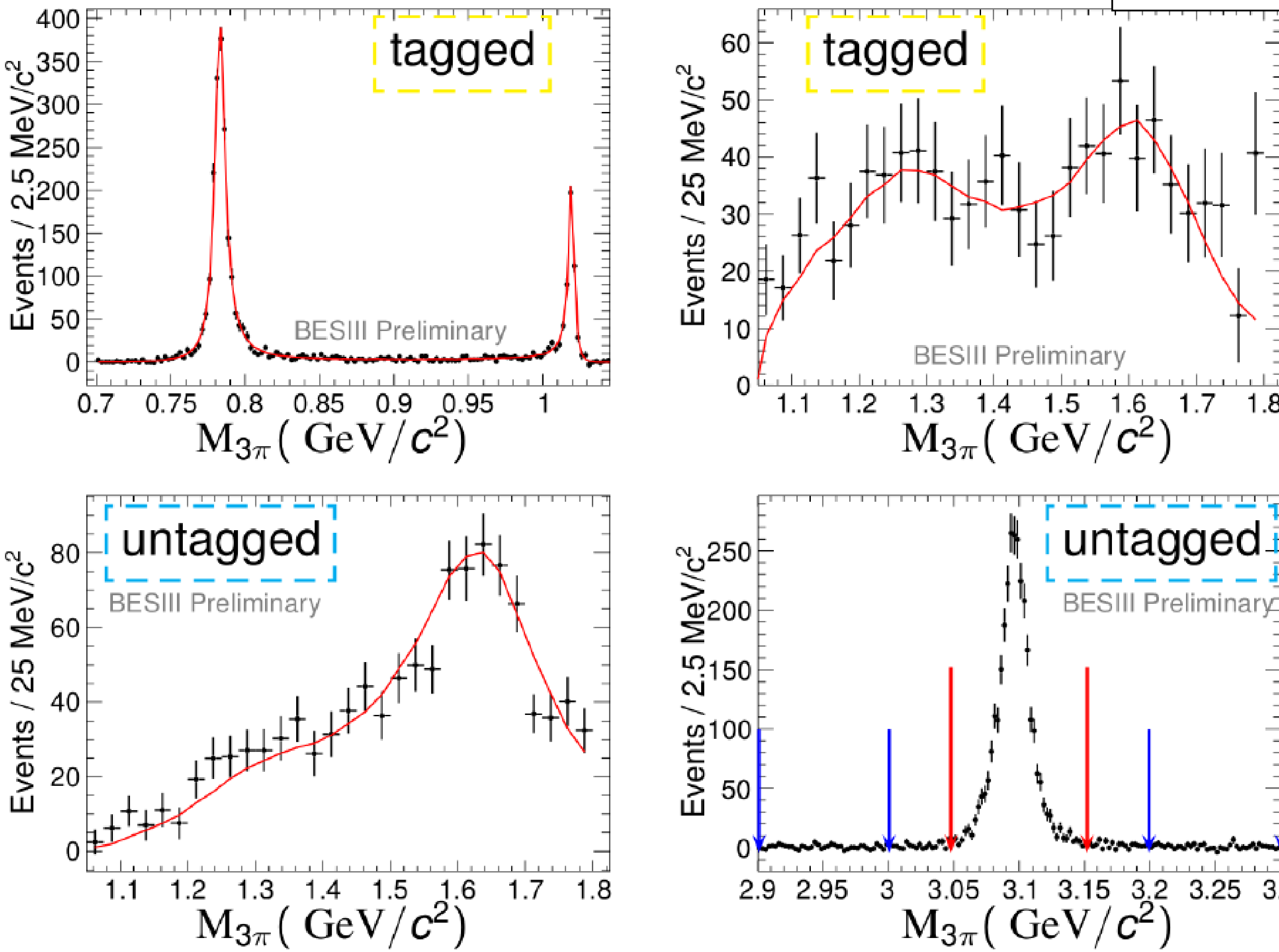


Polar angle of the ISR photon



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

PRELIMINARY



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

Fit Results of $\gamma\pi^+\pi^-\pi^0$

PRELIMINARY

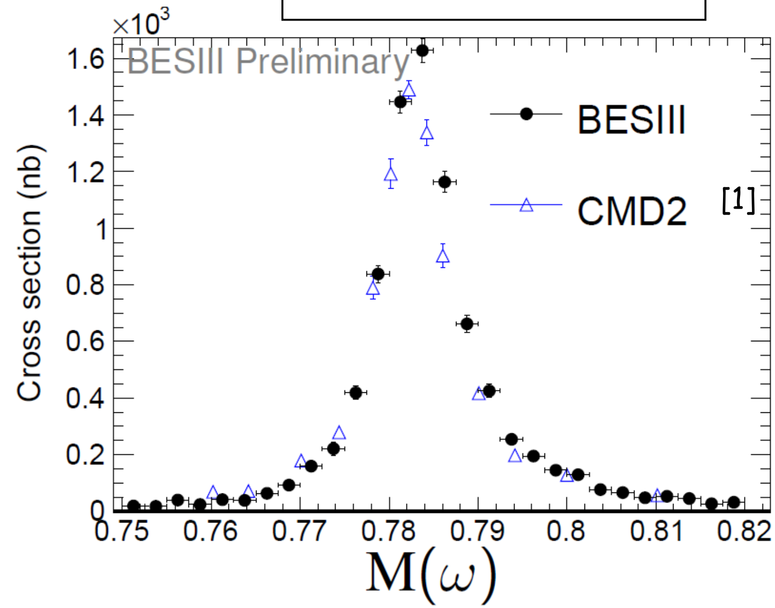
BESIII Preliminary

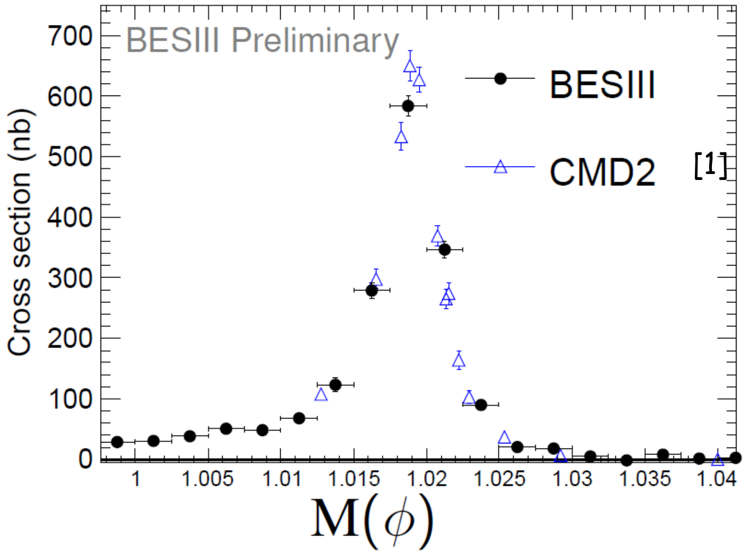
Parameters	PDG	This result
χ^2/NDF	-	443/390
m_ω (MeV/c^2)	782.65 ± 0.12	$783.20 \pm 0.07 \pm 0.23$
m_ϕ (MeV/c^2)	1019.46 ± 0.02	$1020.00 \pm 0.06 \pm 0.30$
$m_{\omega'}$ (MeV/c^2)	$1400 \sim 1450$	$1388 \pm 39 \pm 52$
$m_{\omega''}$ (MeV/c^2)	1670 ± 30	$1699 \pm 9 \pm 6$
Γ_ω (MeV/c^2)	8.49 ± 0.08	PDG
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	$2.18 \pm 0.03 \pm 0.06$

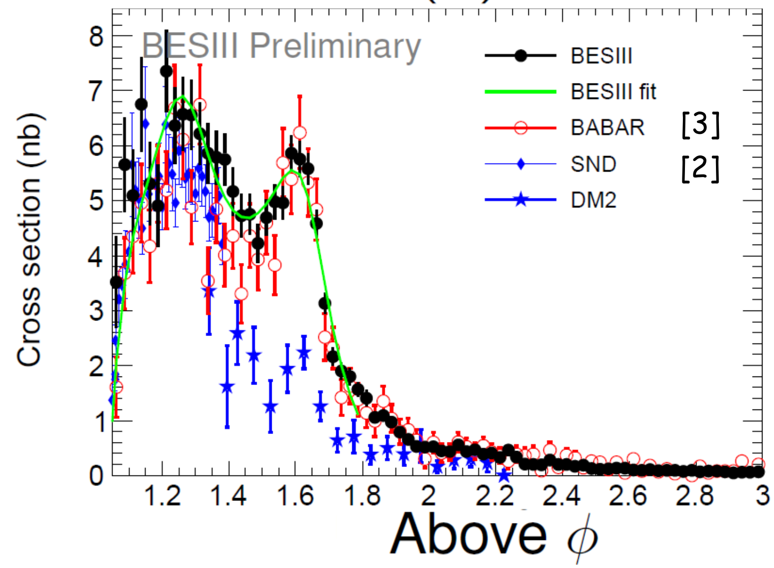
$\pi^+\pi^-\pi^0$ Cross Section

PRELIMINARY

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







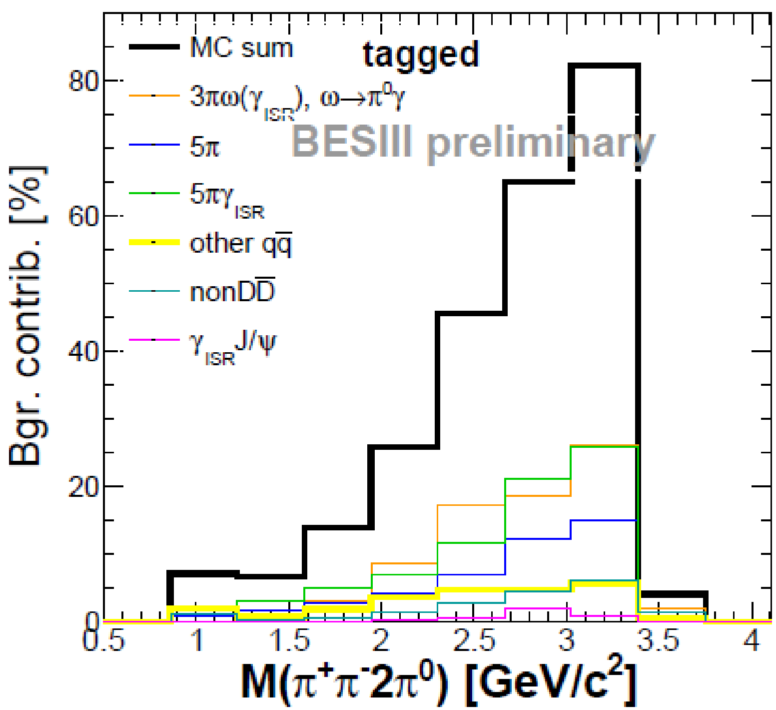
[1] R. R. Akhmetshin et al., Phys. Lett. B 476, 33 (2000). R. R. Akhmetshin et al., Phys. Lett. B 642, 203 (2006).
[2] M. N. Achasov et al., Phys. Rev. D 68, 052006 (2003). M. N. Achasov et al., Phys. Rev. D 66, 032001 (2002).
[3] B. Aubert et al., Phys. Rev. D 70, 072004 (2004).

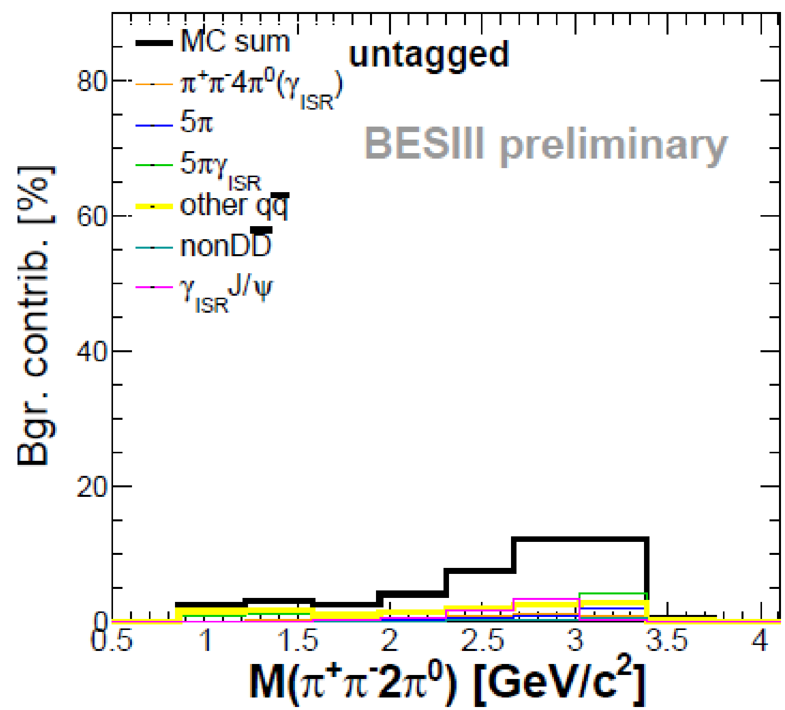
$e^+e^- \rightarrow \gamma\pi^+\pi^-2\pi^0$

PRELIMINARY

Event Selection

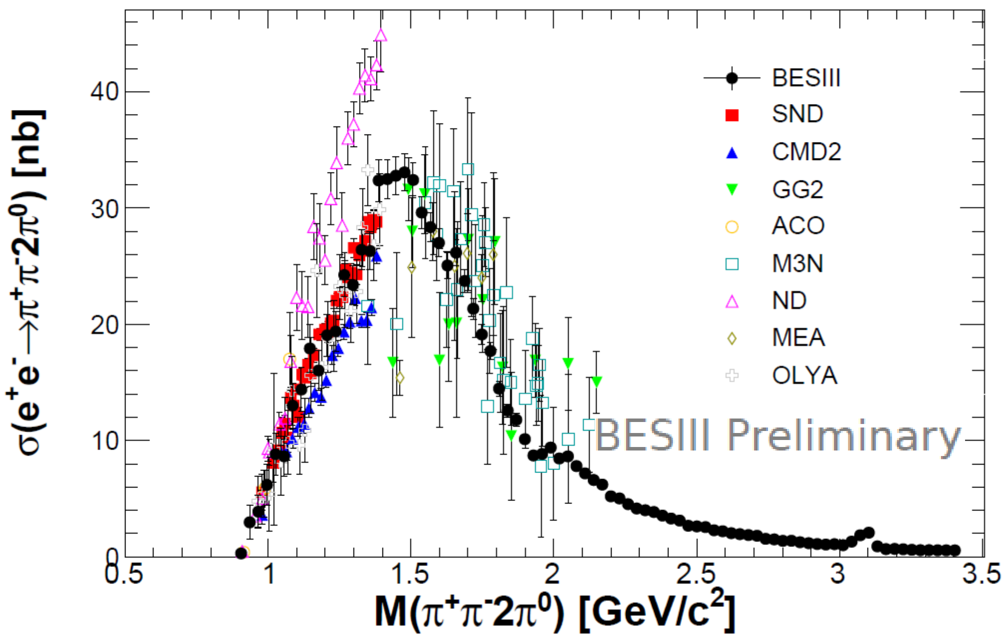
- Tagged and untagged analysis performed separately
- Tagged: kinematic fit, π^0 veto for ISR photon
- Untagged: $|\cos\theta_{ISR}| > 0.995$
- Main background from $\pi^+\pi^-3\pi^0(\gamma_{ISR})$
- Partial wave analysis with HelPWA for $\pi^+\pi^-3\pi^0$
- Correct MC background according to data

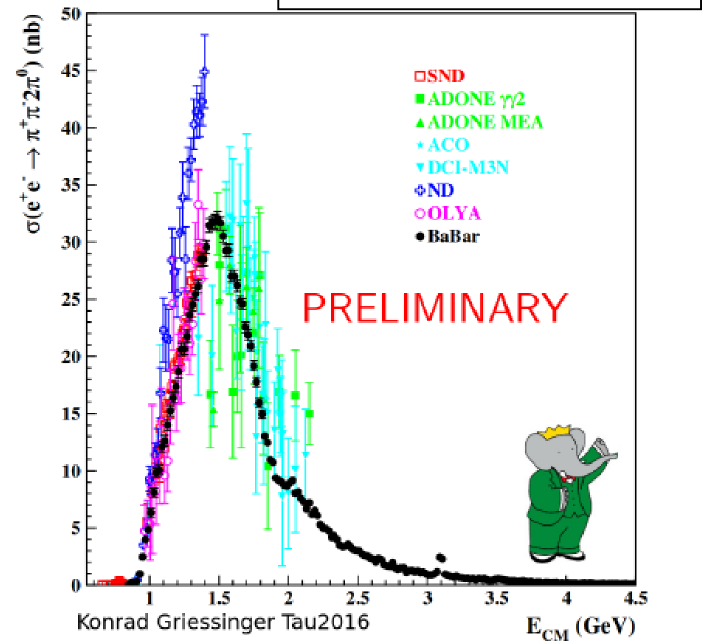




$\pi^+\pi^-2\pi^0$ Combined Cross Section

PRELIMINARY





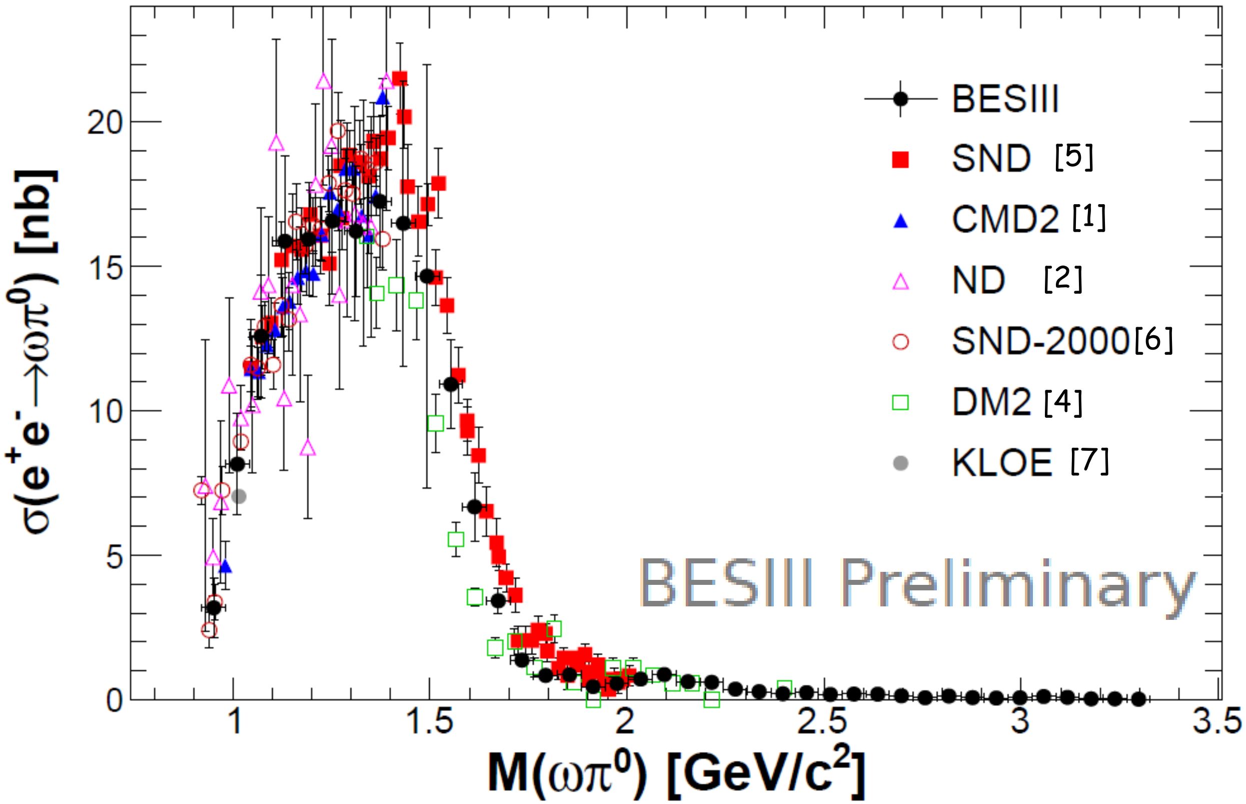
- Error: weighted mean of tagged and untagged events
- ≈ 3% precision like BABAR

	$a_\mu^{\pi^+\pi^-2\pi^0[0.92-1.8\,GeV],LO}/10^{-10}$
BESIII (preliminary)	18.63 ± 0.27 ± 0.57
BABAR (preliminary)	17.9 ± 0.1 ± 0.6

[1] R. R. Akhmetshin et al., Phys. Lett. B 466, 392 (1999).
[2] S. I. Dolinsky et al., Phys. Rept. 202, 99 (1991).
[3] C. Bacci et al., Nucl. Phys. B 184, 31 (1981).
[4] L. M. Kurdadze et al., J. Exp. Theor. Phys. Lett. 43 643 (1986).
[5] M. N. Achasov et al., Preprint BUDKER-INP-2001-34 (Novosibirsk, 2001).
[6] G. Cosme et al., Phys. Lett. B 63, 349 (1976).
[7] G. Cosme et al., Nucl. Phys. B 152 215 (1979).
[8] B. Esposito et al., Lett. Nuovo Cim. 31, 445 (1981).

$\omega\pi^0$ Cross Section

PRELIMINARY



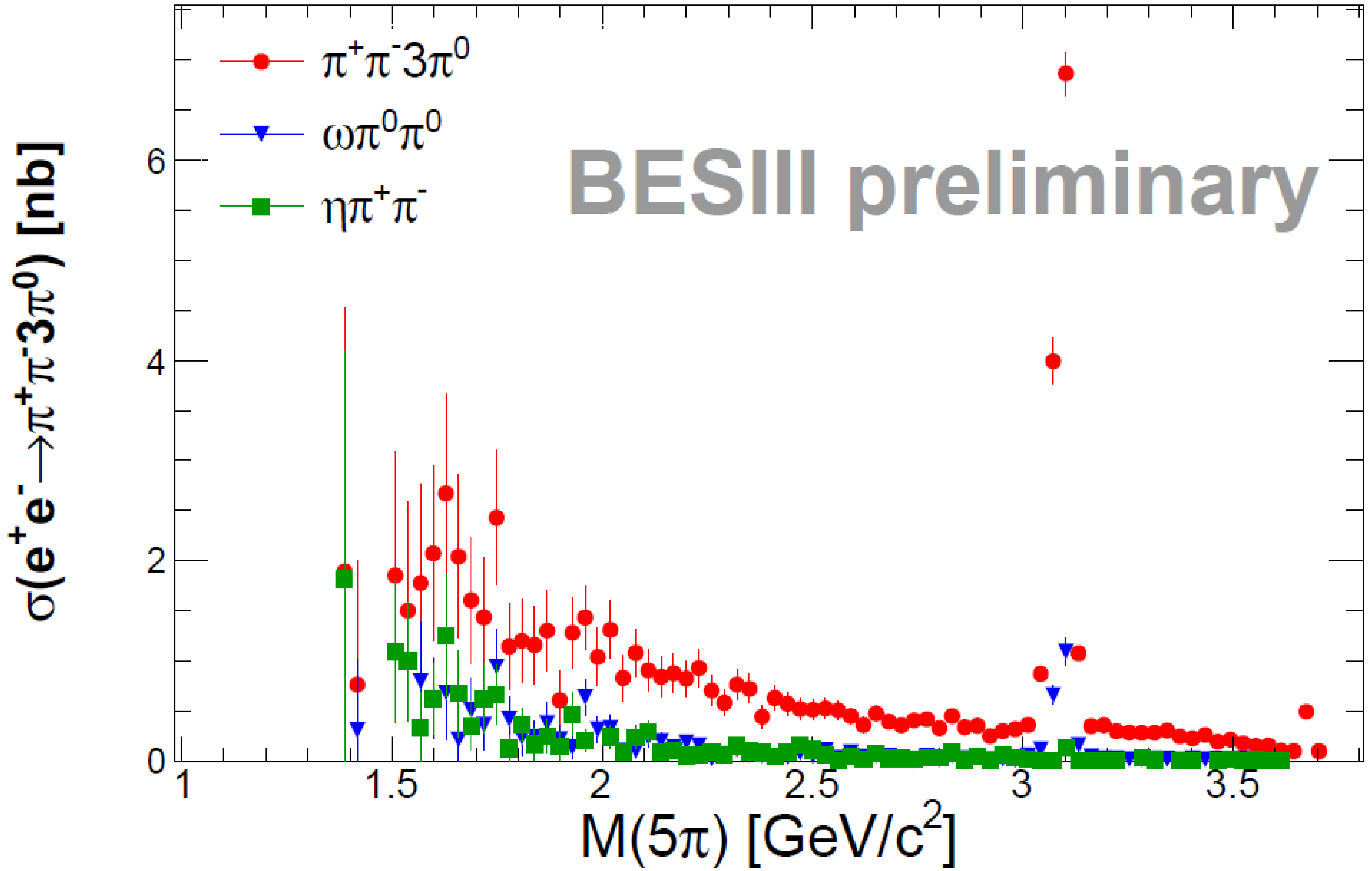
Fit of *M(3π)* distibution with double Gaussian for ω plus third order polynomial for non-ω in each $M(\pi^+\pi^- 2\pi^0)$ bin

[1] R. R. Akhmetshin et al., Phys. Lett. B 466, 392 (1999).
[2] S. I. Dolinsky et al., Phys. Rept. 202, 99 (1991).
[3] C. Bacci et al., Nucl. Phys. B 184, 31 (1981).
[4] D. Bisello et al., Preprint LAL-90-35 (Orsay, 1990).
[5] M. N. Achasov et al., Phys. Lett. B 486, 29 (2000).
[6] M. N. Achasov et al., arXiv:1610.00235 [hep-ex].
[7] F. Ambrosino et al., Phys. Lett. B 669, 223 (2008).

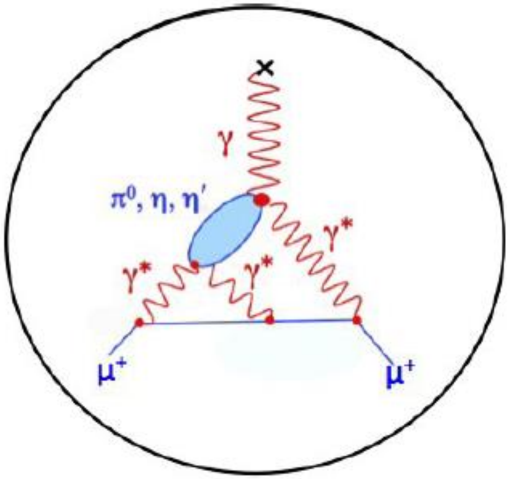
$\pi^+\pi^-3\pi^0$ Cross Section

PRELIMINARY

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



Hadronic Light-by-Light Contribution



Interaction of virtual mesons with real/virtual photons

a_μ^{hLBL} not directly related to measurable quantities

- Hadronic models
  - ChPT at lowest energies
  - pQCD at high energies
  - Intermediate region?

Glasgow Consensus, arXiv:0901.0306
Jegerlehner/Nyffeler, Phys. Rept. 477,1

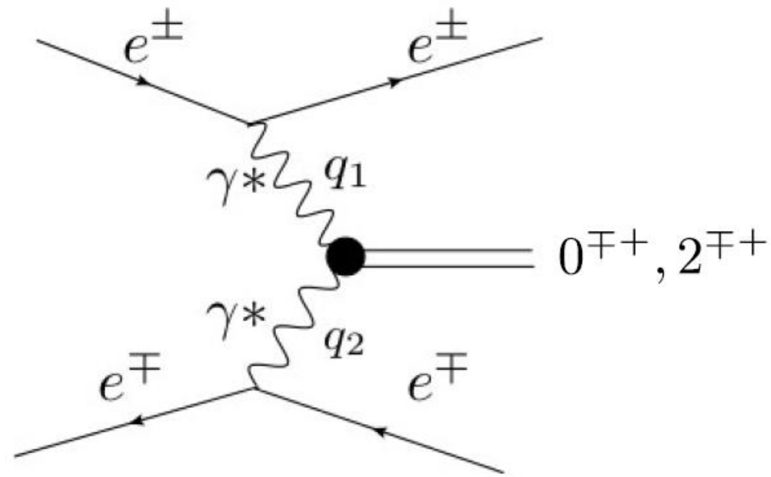
- Data driven approaches
  - Based on dispersion relations
  - Reduce model dependency
  - Reliable error estimates

Colangelo, Hoferichter et al. (Bern)
Vanderhaeghen, Pauk et al. (Mainz)

- Transition FF as experimental input

Two-Photon Collisions

- Exchange of 2 photons in e^+e^- collisions
- Pseudoscalar, axial, and tensor states accessible
- $M_x \ll \sqrt{s}$
- $\sigma \propto \alpha^2 \ln^2 E$
- $\sigma \propto F^2(Q_1^2, Q_2^2)$, with $Q_1^2 = -q_i^2$
- Forward peaked kinematic
  - Experimentally challenging
  - Special tagging detectors



Contributions to a_μ

- Current accuracy of a_μ: ~ $6.3 \cdot 10^{-10}$
- Contribution of π^0: ~ $7 \cdot 10^{-10}$

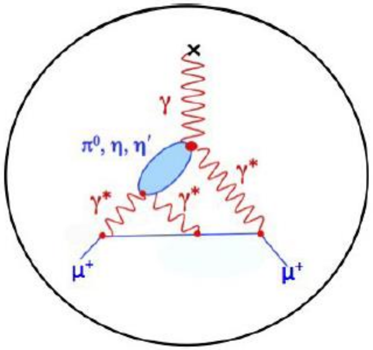
Knecht, Nyffeler
Phys. Rev. D65, 073034 (2002)

- Expected accuracy of new experiments at FNAL and J-PARC: ~ $1.6 \cdot 10^{-10}$
- Contribution of η and η' relevant!

η ~ $1.5 \cdot 10^{-10}$

η' ~ $1.5 \cdot 10^{-10}$

Knecht, Nyffeler
Phys. Rev. D65, 073034 (2002)



Two-photons physics program exstabilished at BESIII

Untagged, single-tagged, and double-tagged measurements are ongoing

Summary

- High precision measurements of $\pi^+\pi^-$, $\pi^+\pi^-\pi^0$, $\pi^+\pi^-2\pi^0$ cross sections

  Results compatible with previous experiments

  Improved BR measurements

  Further measurements will reduce the a_μ^{VP} uncertainty

- Near future

  Two-photon physics program

  Include all BESIII data sets

  Investigate more final states ($2\pi^+2\pi^-$, etc…)

- Stay tuned for new results!!

Backup Slides

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

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**

$\pi^+\pi^-\pi^0$ Systematic Uncertainties

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

$\pi^+\pi^-2\pi^0$ Systematic Uncertainties

- 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

BESIII Detector

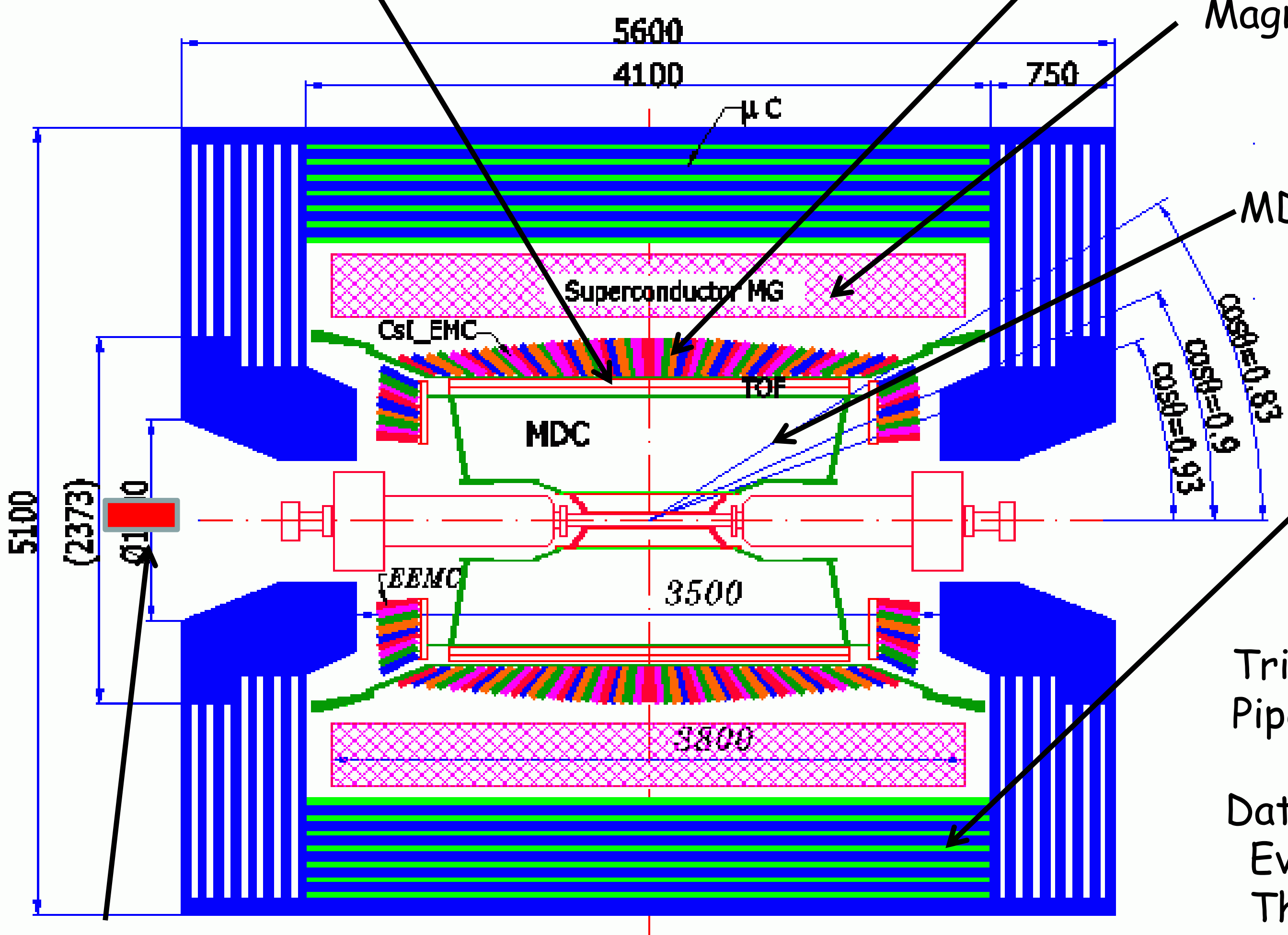
TOF:
σ_T = 80 ps Barrel
110 ps Endcap

EMC: CsI crystals, 28 cm
$\Delta E/E$ = 2.5% @1 GeV
σ_z = 0.6 cm/$\sqrt{E}$

Magnet: 1T Superconducting

MDC: small cell & He gas
σ_{xy}= 130 μm
σ_p/p = 0.5% @1GeV
dE/dx = 6%

Muon: 9 layer RPC

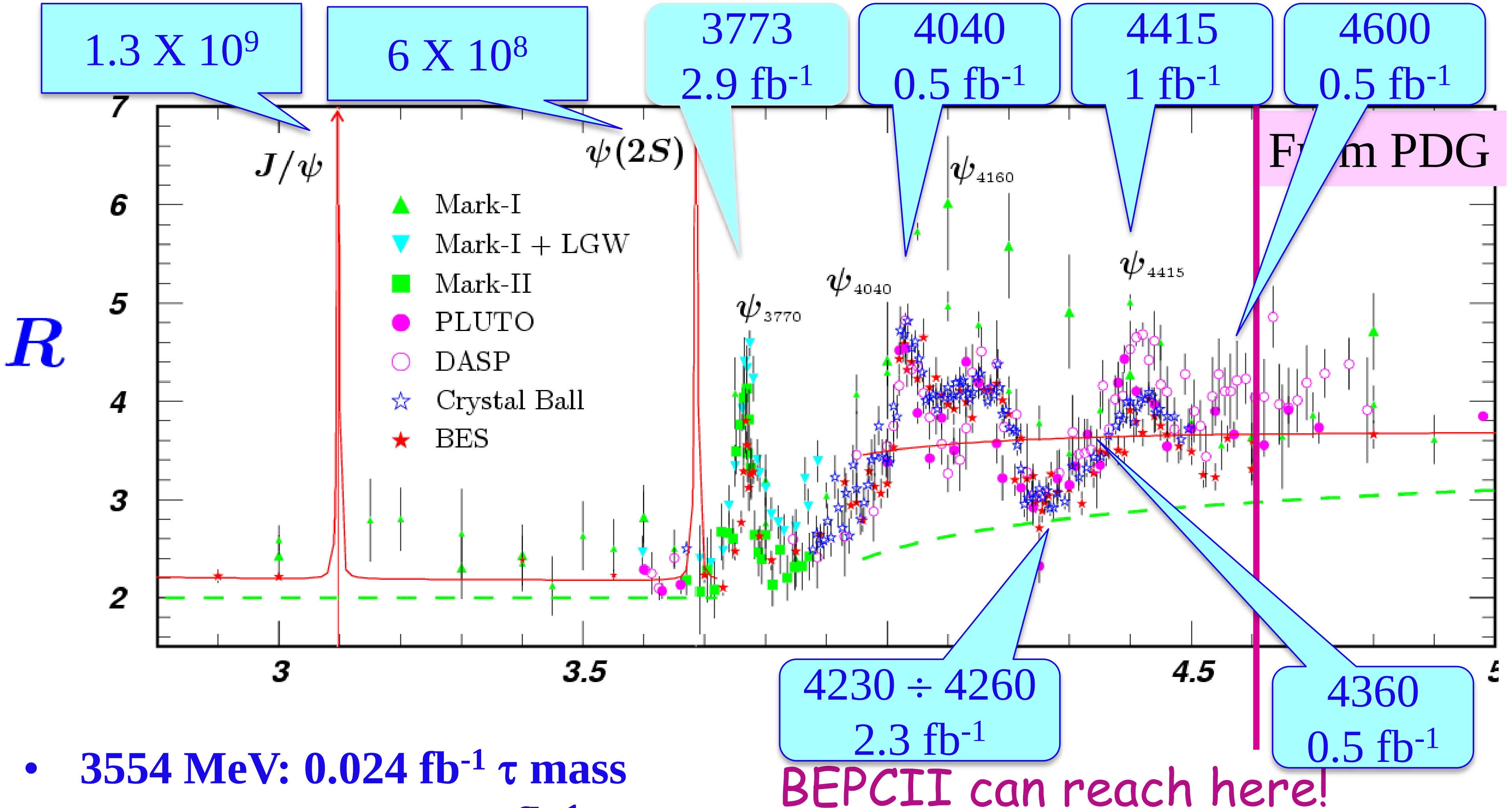


Zero Degree Detector (ISR)

Trigger: Tracks & Showers
Pipelined; Latency = 2.4 ms

Data Acquisition:
Event rate = 3 kHz
Thruput ~ 50 MB/s

BESIII Production of Charmonium(like) states



- **3554 MeV: 0.024 fb^{-1} τ mass**
- **4100 ÷ 4400 MeV: 0.5 fb^{-1} coarse scan**
- **3850 ÷ 4590 MeV: 0.5 fb^{-1} fine scan**

BESIII: Baryon Production

- Charmonium decays offer complementary information to existing data
  - Coupling of unobserved states through conventional production channels could be small, but coupling may be large to gggN:
    $\psi \to N\bar{N}(\pi/\eta/\eta'/\omega/\varphi)$, $\bar{p}\Sigma\pi$, $\bar{p}\Lambda K$
  - High statistics available at BESIII