



JOHANNES GUTENBERG
UNIVERSITÄT MAINZ



THE LOW-ENERGY FRONTIER
OF THE STANDARD MODEL



Hadronic and Transition Form Factor Measurements at **BESIII**

February 27, 2019 | Christoph Florian Redmer
for the BESIII Collaboration

PhiPsi19 – 12th International Workshop on e^+e^- Collisions from Phi to Psi, Novosibirsk

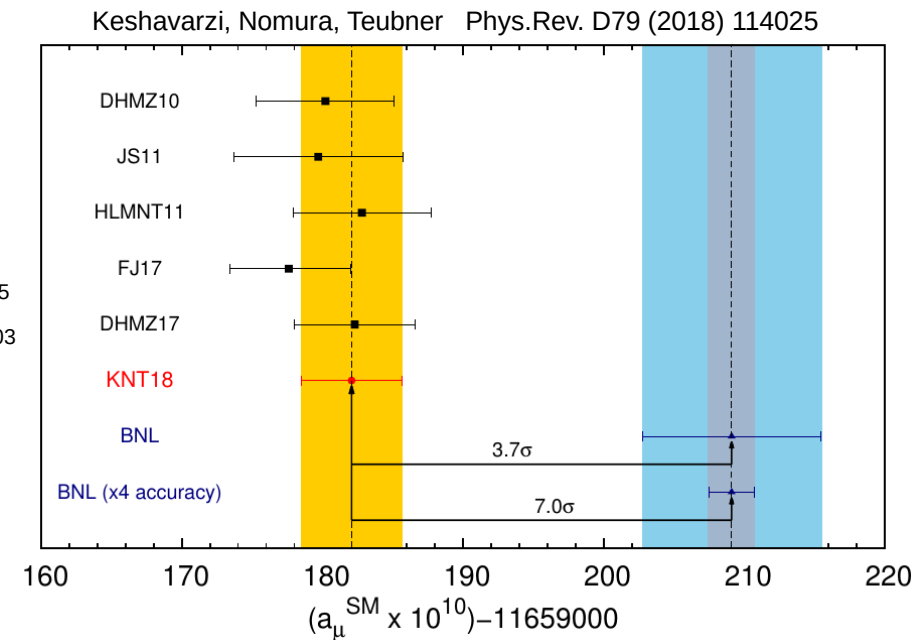
JGU Anomalous magnetic moment of the μ

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

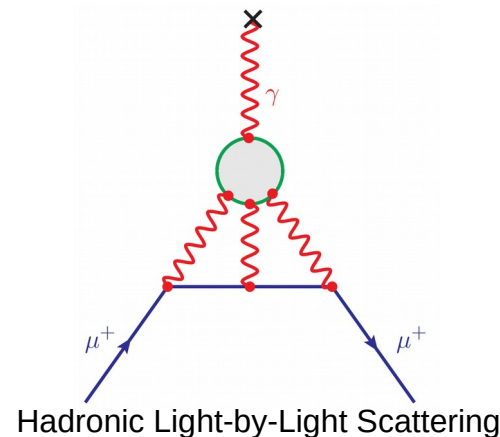
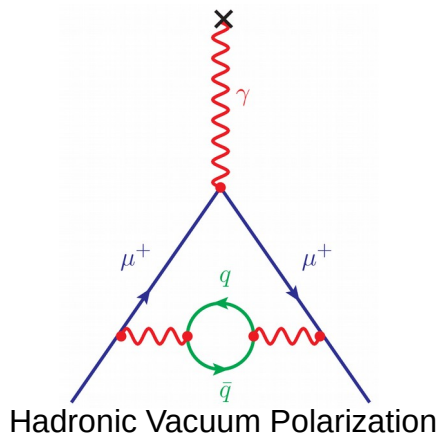
- Known to 0.5 ppm in theory and experiment

Standard Model (SM)	$(11659182.04 \pm 3.65) \cdot 10^{-10}$	Phys. Rev D97 (2018) 114025
Experiment (BNL)	$(11659208.9 \pm 6.3) \cdot 10^{-10}$	Phys. Rev. D73 (2006) 072003

- Discrepancy between SM prediction and measurement!
- New measurements at FermiLab and J-PARC
- Improvement of SM prediction necessary

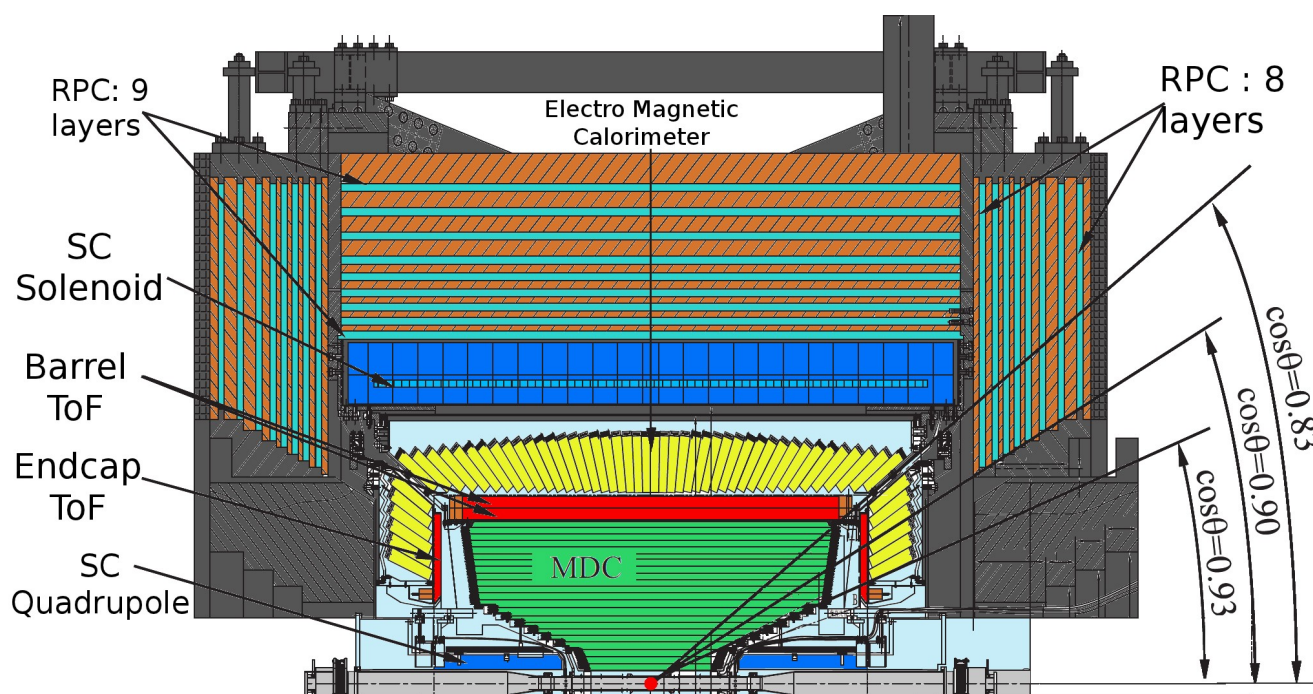


Uncertainty of SM prediction completely limited by hadronic contributions!



Use input from experiments to improve SM prediction!

NIM A614 (2010) 345



Muon Chambers

- 8 – 9 layers of RPC
- $p > 400 \text{ MeV}/c$
- $\delta R\Phi = 1.4 \sim 1.7 \text{ cm}$

Superconducting Magnet

- 1 T magnetic field

EM Calorimeter (EMC)

- 6240 CsI(Tl) crystals
- $\sigma(E)/E = 2.5\%$
- $\sigma_{Z,\Phi}(E) = 0.5 - 0.7 \text{ cm}$

Time-of-flight system (TOF)

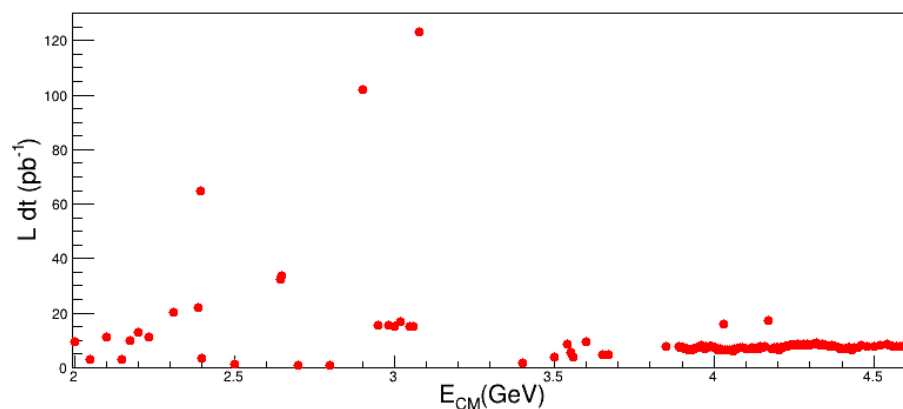
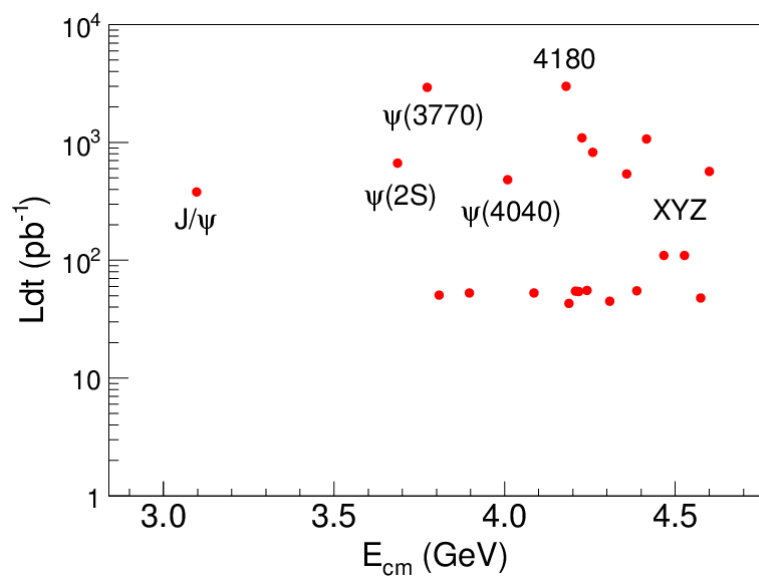
- $\sigma(t) = 90\text{ps}$ (barrel)
- $\sigma(t) = 110\text{ps}$ (endcap)

Drift Chamber (MDC)

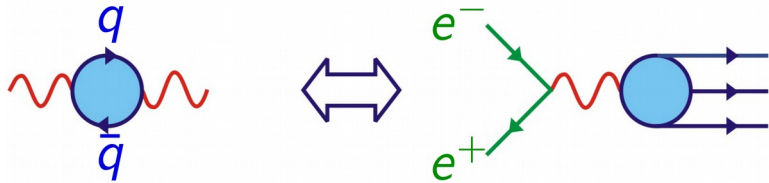
- $\sigma(p)/p = 0.5\%$
- $\sigma_{dE/dx} = 6.0\%$



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

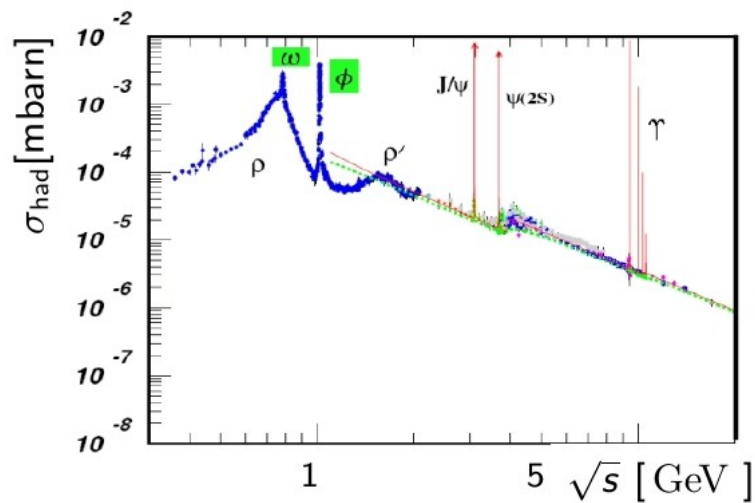


Related to hadronic cross sections by optical theorem

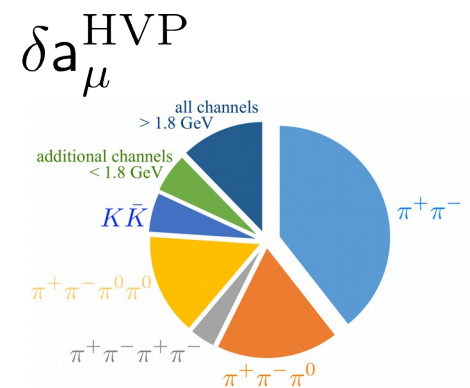
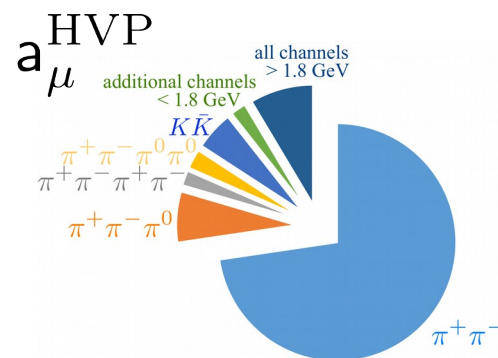


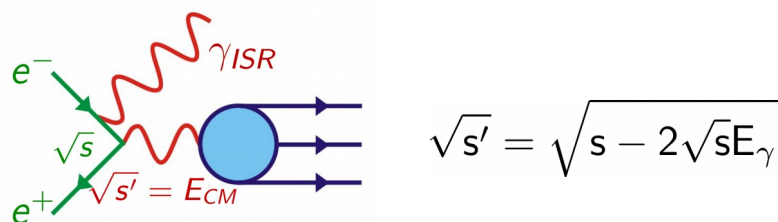
Dispersion integral :

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

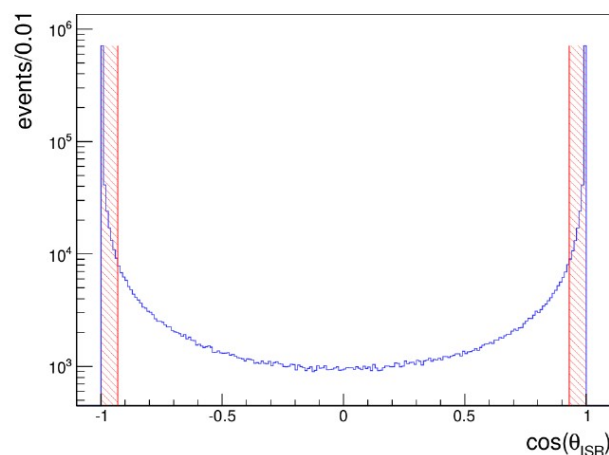


$$\left. \begin{aligned} K(s) &\sim \frac{1}{s} \\ \sigma(e^+e^- \rightarrow \text{hadr}) &\sim \frac{1}{s} \end{aligned} \right\} \text{Low energy contributions dominate !}$$



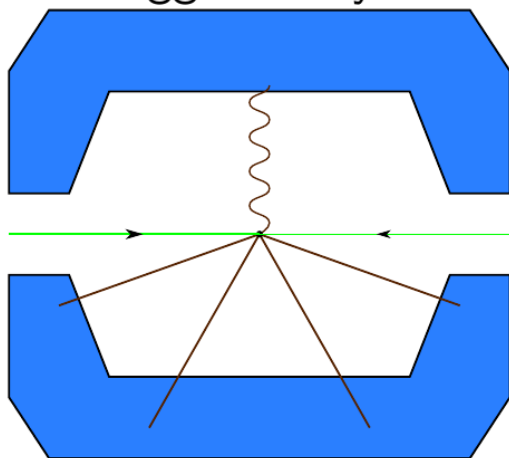


polar angle distribution of ISR photons (MC)

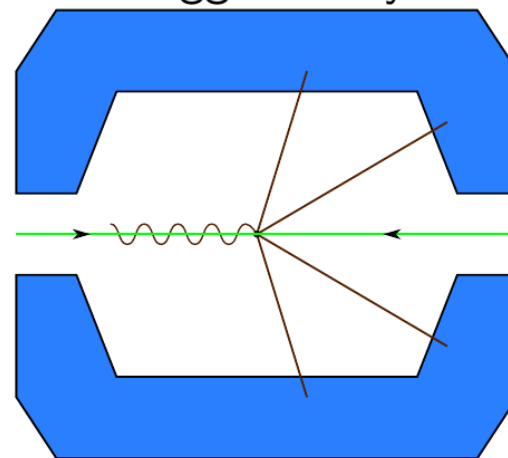


- Detect hadronic system
- ISR photon detected
 - Acceptance from $\pi^+\pi^-$ threshold
 - Large background contamination at high $\sqrt{s'}$
- ISR photon undetected
 - High statistics
 - Acceptance for $\sqrt{s'} > 1$ GeV
 - Small background contamination

Tagged analysis



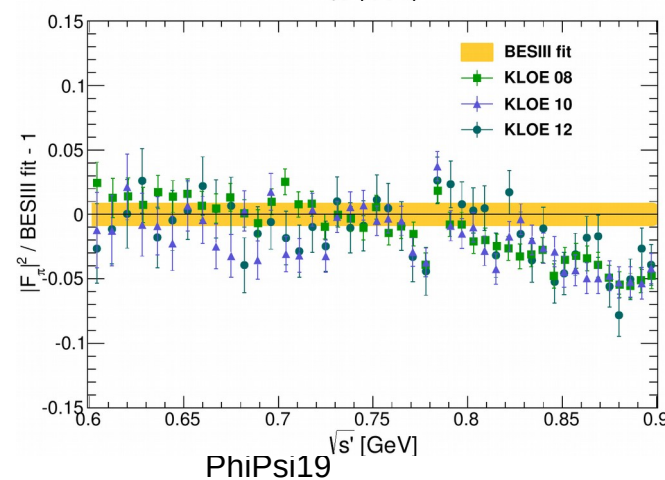
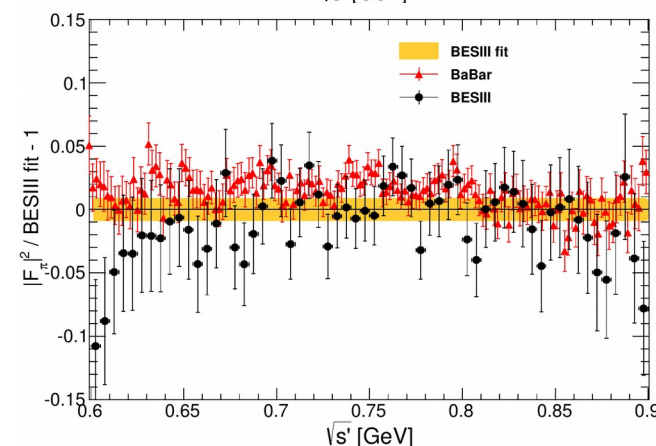
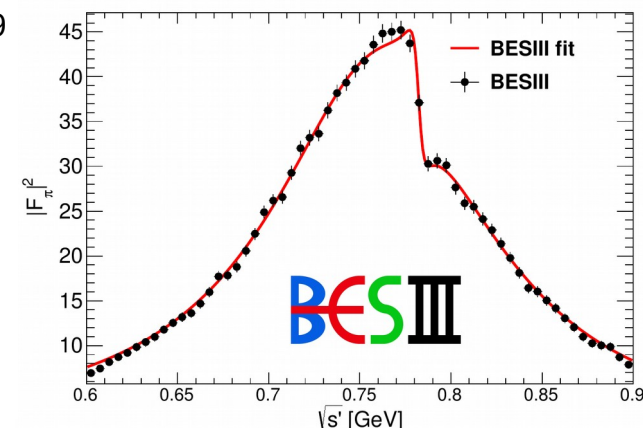
Untagged analysis



$$e^+e^- \rightarrow \pi^+\pi^-$$

Phys.Lett.B753 (2016) 629

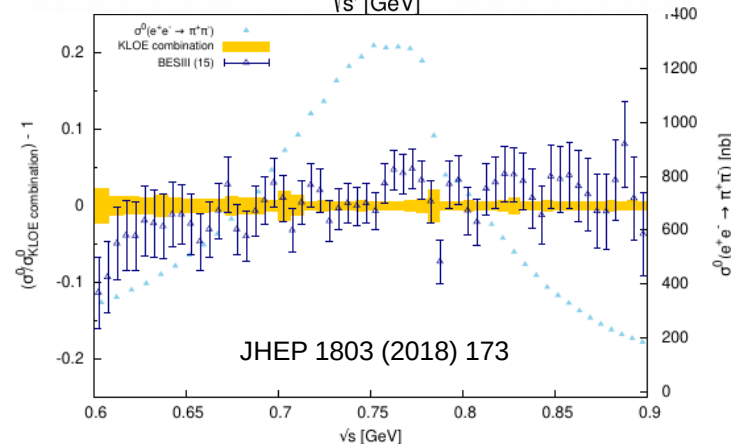
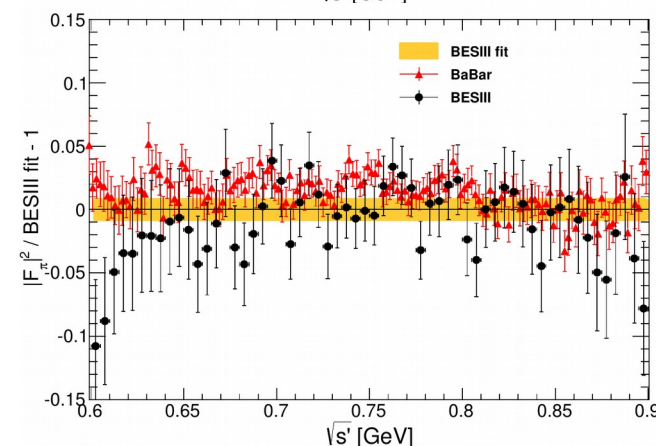
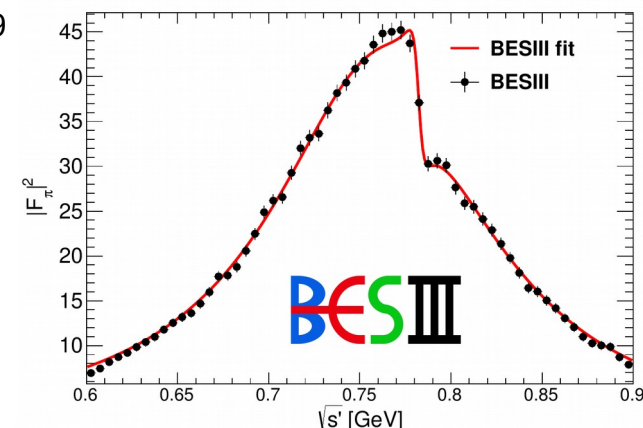
- Tagged ISR technique
- Based on 2.9 fb^{-1} at 3.773 GeV
- $\mu - \pi$ separation with Artificial Neural Network
- Focus on $0.6 \leq m_{\pi\pi} \leq 0.9$
- Normalized to integrated luminosity
- Careful evaluation of systematics
 - Total uncertainty of 0.9% achieved
 - Dominated by
 - Luminosity (0.5%)
 - Radiator function (0.5%)
- Deviations to previous measurements observed
- Ongoing activities
 - Extend analysis to new data sets
 - Investigate $m_{\pi\pi} \geq 1 \text{ GeV}$
 - Untagged ISR analysis



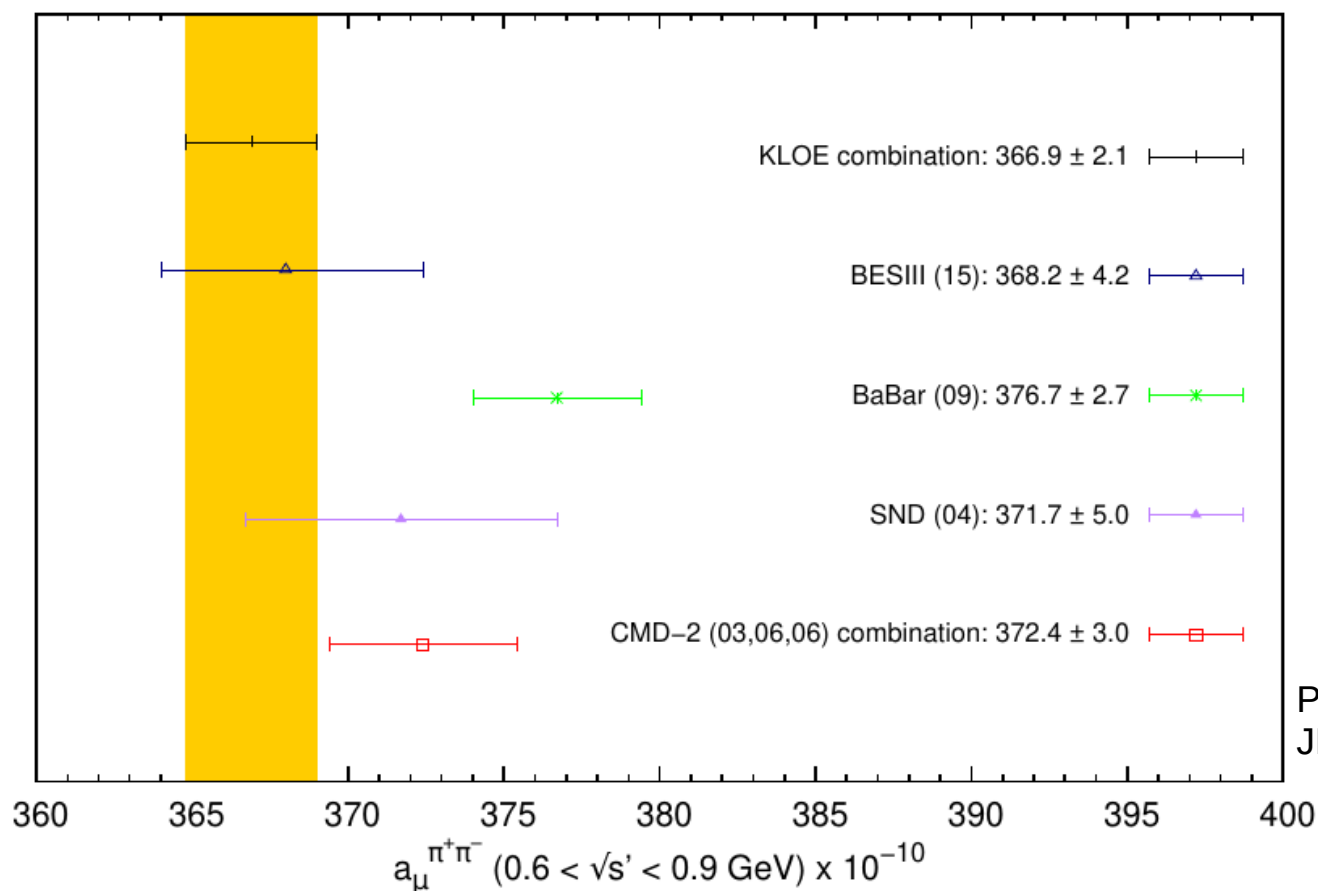
$$e^+e^- \rightarrow \pi^+\pi^-$$

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$$e^+e^- \rightarrow \pi^+\pi^-$$



- 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

Tagged ISR method

Untagged ISR method

ISR photon observed?

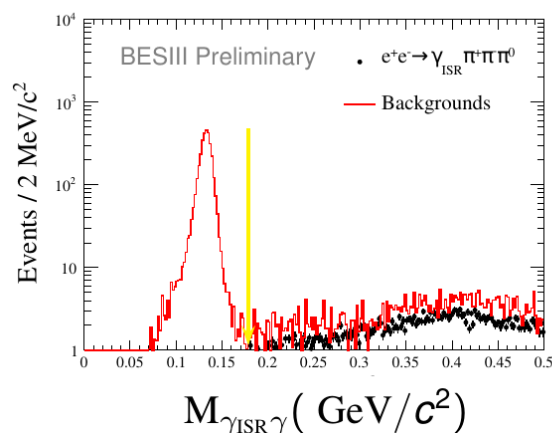
5C kinematic fit

2C kinematic fit

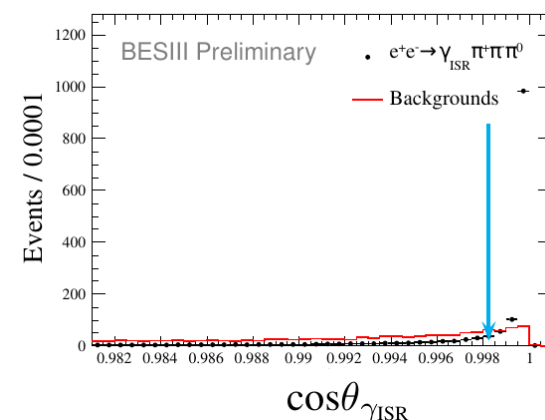
 π^0 veto

Polar angle

Combination of the ISR photon and any other photon



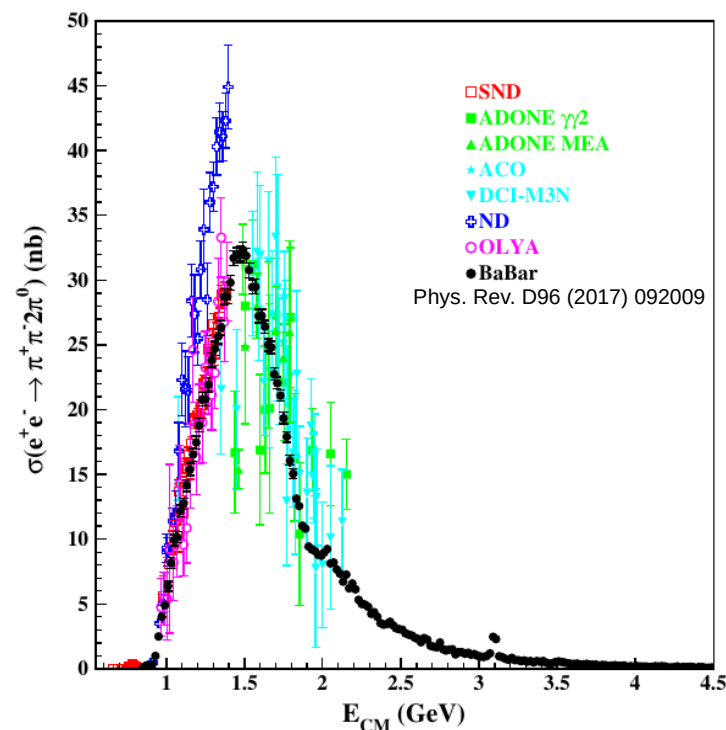
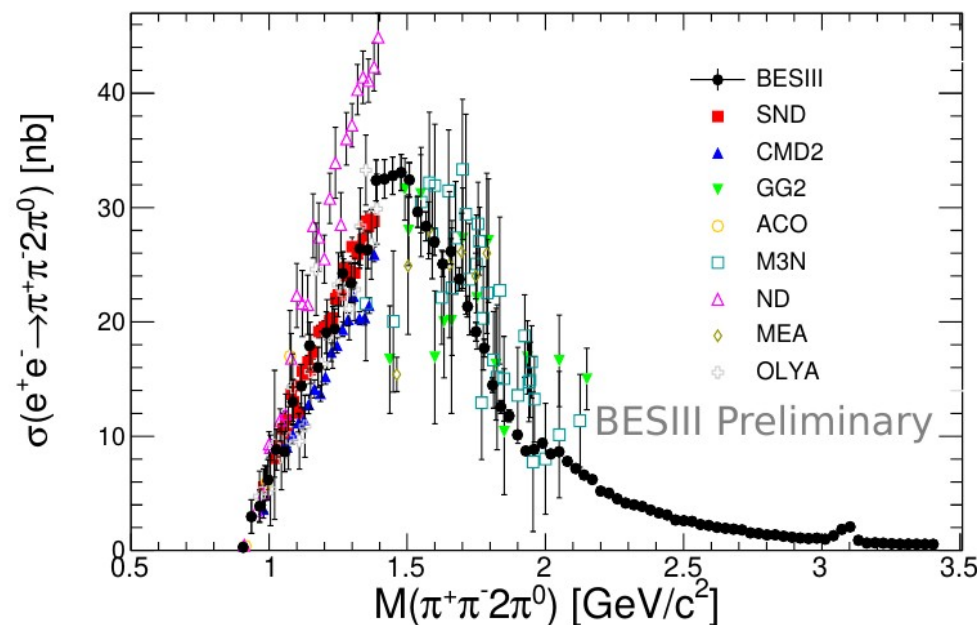
Polar angle of the ISR photon



Scheme successfully applied to measure $e^+e^- \rightarrow \pi^+\pi^-\pi^0/\pi^+\pi^-2\pi^0/\pi^+\pi^-3\pi^0$!

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

BESIII

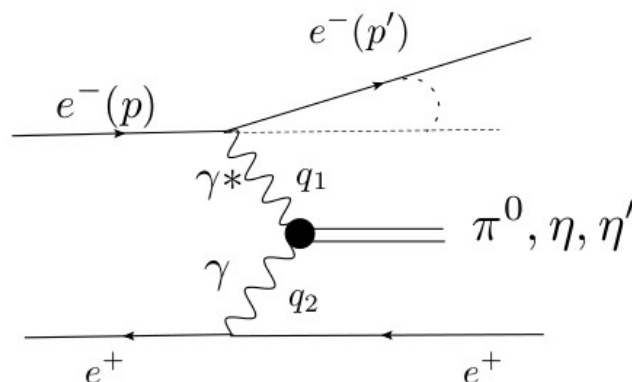


- Error weighted mean of tagged and untagged results
- Good agreement with BaBar measurement
- Improved precision (approx. 3% syst. uncertainty)

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

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

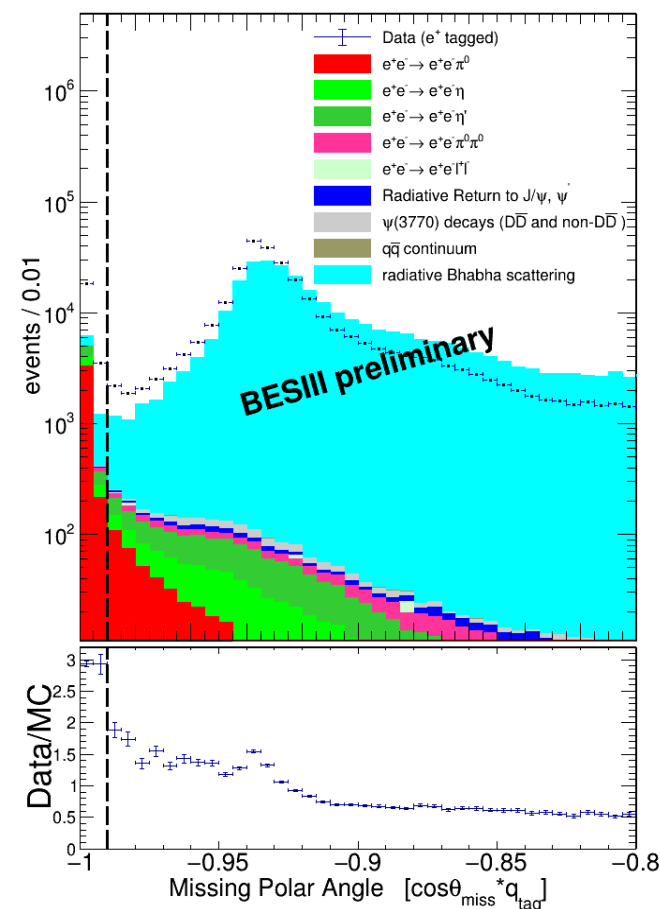
- Transition form factors (TFF) as input for HLbL calculations
- Cross section of $\gamma\gamma$ processes proportional to square of TFF
- Single-tagged measurements to study momentum dependence of TFFs



- Reconstruct:
 - only one scattered lepton
 - produced system
 - unmeasured lepton from momentum conservation
- Require scattering angle of missing momentum to be small
 - Small virtuality of exchanged photon
 - $F(Q_1^2, Q_2^2) \rightarrow F(Q_1^2, 0)$

Reject events with $q_{\text{tag}} \cdot \cos(\theta_{\text{miss}}) > -0.99$

q_{tag} : Charge of tagged lepton in units of [e]



JGU Space-like π^0 Transition Form Factor



■ Based on 2.9 fb^{-1} at 3.773 GeV

■ Select:

- Exactly one lepton
- At least two photons

■ Apply:

- Single-tag condition
- Helicity angle of photons

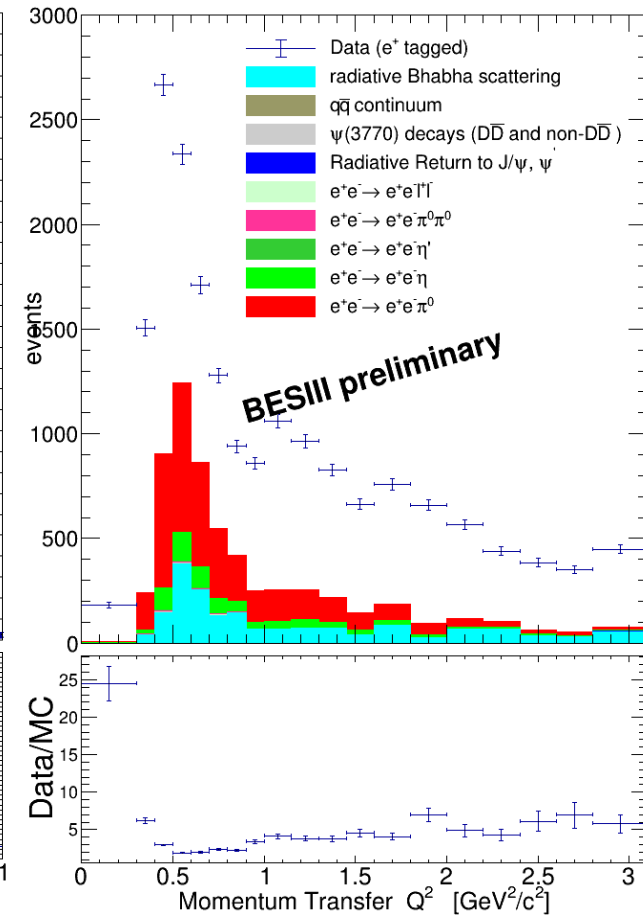
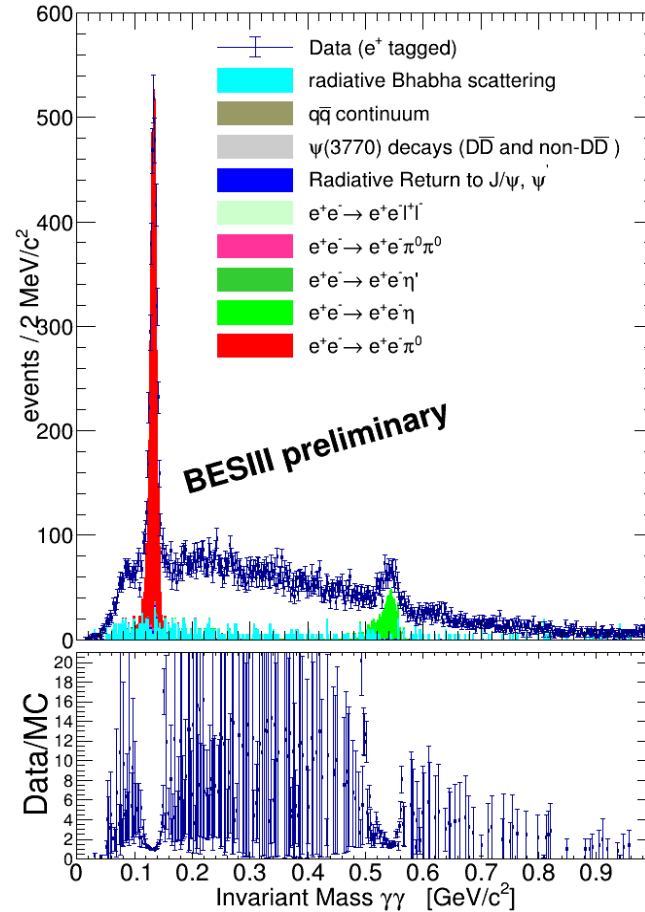
$$R_\gamma = \frac{\sqrt{s} - E_{e^\pm \pi^0}^{\text{CMS}} - p_{e^\pm \pi^0}^{\text{CMS}}}{\sqrt{s}} > 0.05$$

■ Clear signals of π^0 and η

■ Incomplete MC description

- Data-driven background subtraction

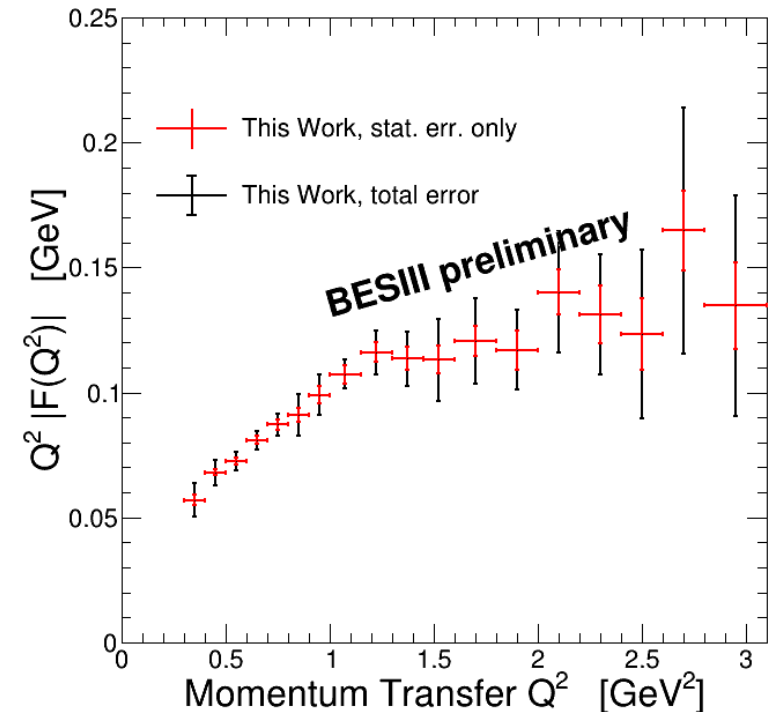
■ Divide out point-like cross section using MC distributions



Systematic Uncertainties of $|F(Q^2)|$

Error propagation: $\Delta|F(Q^2)|_i = \frac{1}{2} \frac{1}{\sqrt{(|F(Q^2)|^2)_i}} \Delta(|F(Q^2)|^2)_i$

	Source	Contribution
External	Tracking efficiency	0.25%
	Photon detection efficiency	1%
	Luminosity	0.25%
Analysis	$q_{\text{tag}} \cdot \cos \theta_{\text{miss}} < -0.99$	0.1% – 3.1%
	$\cos \theta_{\text{H}} < 0.8$	0.2% – 4.5%
	$ \Delta\phi_{\gamma\gamma} < \frac{\pi}{2}$	negligible
	$ \Delta\theta_{\gamma\gamma} - 0.01q_{\text{tag}} > 0.02$	0.3% – 9.8%
	$R_\gamma < 0.05$	1.0% – 7.7%
Background subtraction	Reconstruction efficiency	1.6% – 17.2%
	Signal shape	0.1% – 1.9%
	Event counting	0.1% – 11.1%
	Background shape	0.2% – 21.0%
Total		3.9% – 30.0%



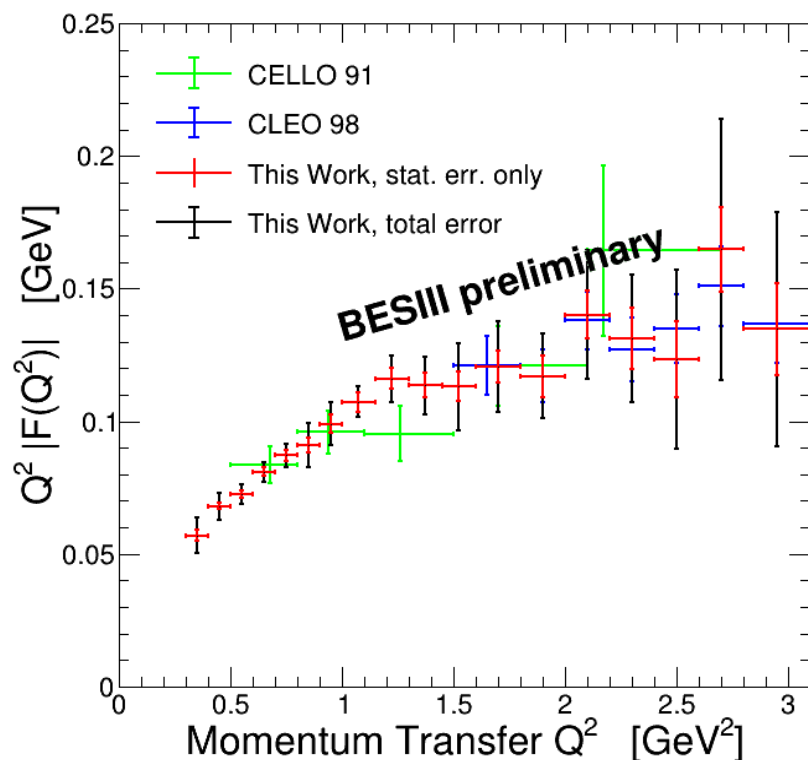
- Contributions added in quadrature
- Full correlation between contributions of analysis conditions and background subtraction assumed

Error estimate does not consider radiative effects

- To be evaluated with recently released Ekhara 3.0

Comp. Phys. Commun. 234 (2019) 245

Comparison to previous measurements

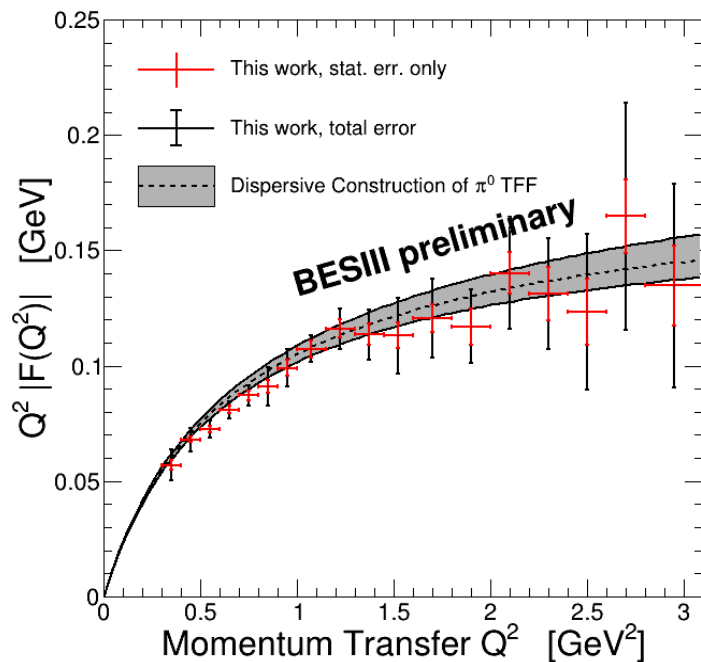


- First measurement below 0.5 GeV²
- Unprecedented accuracy below $Q^2 = 1.5$ GeV²
- Competitive accuracy up to 3.1 GeV²

CELLO: Z. Phys. C49 (1991) 401
CLEO: Phys. Rev. D57 (1998) 33

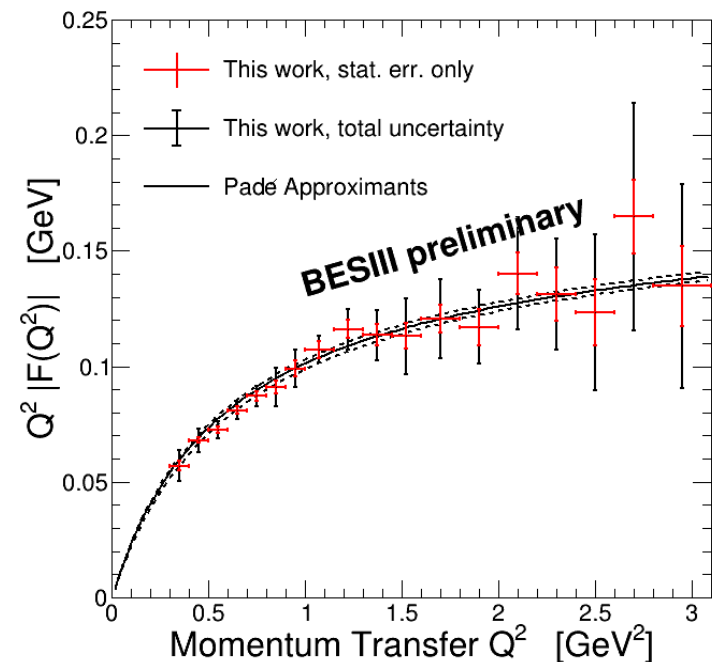
Comparison to Theory

Data-driven Approaches:



- Construction of space-like TFF using time-like experimental results in dispersive calculations

Hoferichter et al., Phys. Rev. Lett 121 (2018) 112002



- Fit previous measurements with Padé approximants

Masjuan et al., Phys. Rev. D86, 094021

- Model independent (mathematical technique)
- Provides estimate of systematic uncertainties

First HLbL estimate including these data: Danilkin, CFR, Vanderhaeghen arxiv:1901.10346

JGU Space-like $\pi^+\pi^-$ Transition Form Factor



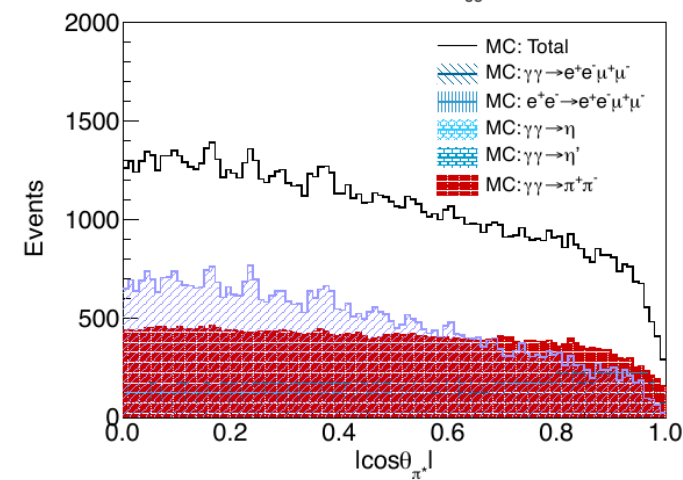
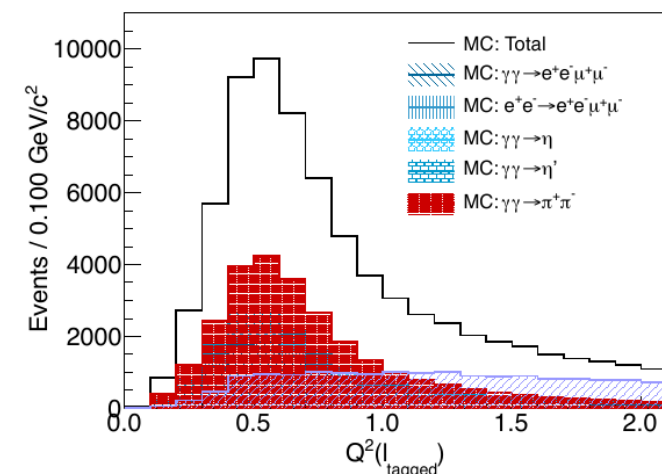
Single-Tag measurement

- Event selection analogous to single pseudoscalar analysis
- Multivariate methods to suppress muon background $e^+e^- \rightarrow e^+e^-\mu^+\mu^-$
- Subtraction of ρ contribution in $e^+e^- \rightarrow e^+e^-\pi^+\pi^-$
 - Fit peak in data using shape from theory
- Study $\pi^+\pi^-$ invariant mass in bins of Q^2 and $\cos\theta^*$

■ First single-tag measurement of $\pi^+\pi^-$!

■ Access to:

- low momentum transfers $0.2 < Q^2 [\text{GeV}^2] < 2.0$
- low invariant masses $m_{\pi^+\pi^-} < M [\text{GeV}] < 2.0$
- full coverage of $\cos\theta^*$



- Single-tagged measurements
 - Complete TFF studies of single mesons (η, η')
 - Extend two-meson studies to neutral channels ($\pi^0\pi^0, \pi^0\eta, \eta\eta$)
 - Investigate higher multiplicity final states ($3\pi, 4\pi, \dots$)
 - Axial and tensor contributions to a_μ
- Double-tagged measurements
 - Complementary to BaBar measurement of η' TFF
 - Cover all single pseudoscalar states for $Q^2 < 2 \text{ GeV}^2$
 - Feasibility studies successful
 - Development and installation of dedicated taggers

BESIII is a perfect laboratory for hadron physics!

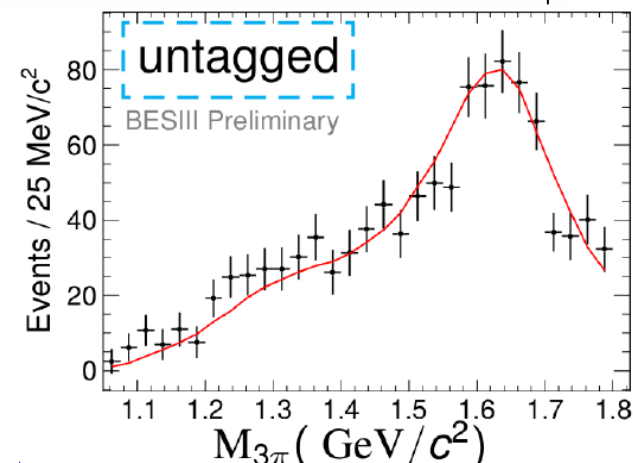
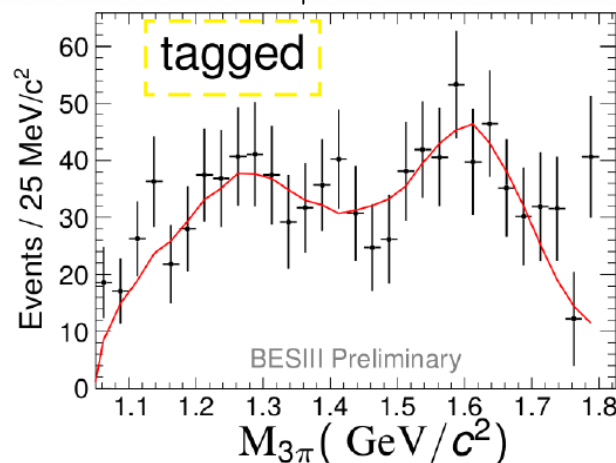
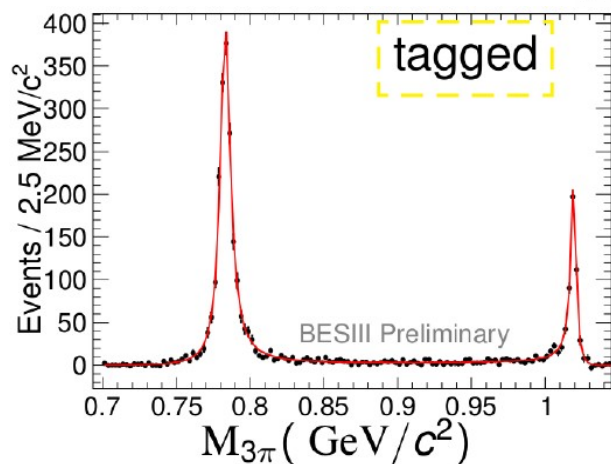
- Hadronic cross section measurements with ISR
 - Information from hadronic threshold to tau-charm region
 - Competitive accuracy
 - $\pi^+\pi^-$ result confirms $a_\mu^{\text{theo,SM}} - a_\mu^{\text{exp}} > 3\sigma$, extending investigations to $m_{\pi\pi} \geq 1 \text{ GeV}$
 - Preliminary results on $e^+e^- \rightarrow \pi^+\pi^-\pi^0, e^+e^- \rightarrow \pi^+\pi^-\pi^0\pi^0$
- Two-photon physics program
 - Single-tag measurements
 - π^0, η , and η' transition form factors with unprecedented accuracy ($Q^2 < 1.5 \text{ GeV}^2$)
 - $\pi^0\pi^0, \pi^0\eta, \eta\eta$
 - First measurement at low Q^2
 - Covers masses from threshold and the full helicity angle
 - First double-tagged measurement $\gamma^*\gamma^* \rightarrow \pi^0$ started

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

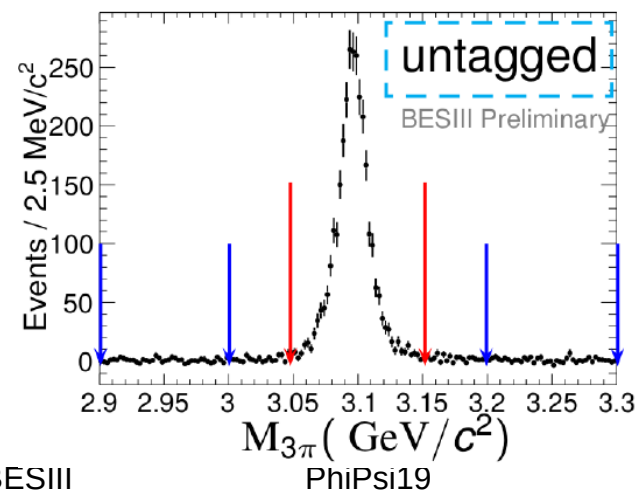
$\pi^+\pi^-\pi^0$ invariant mass spectra

- Below 1.8 GeV: Fit $\frac{dN}{dm} = \sigma(m) \cdot \frac{dL}{dm} \cdot \varepsilon$

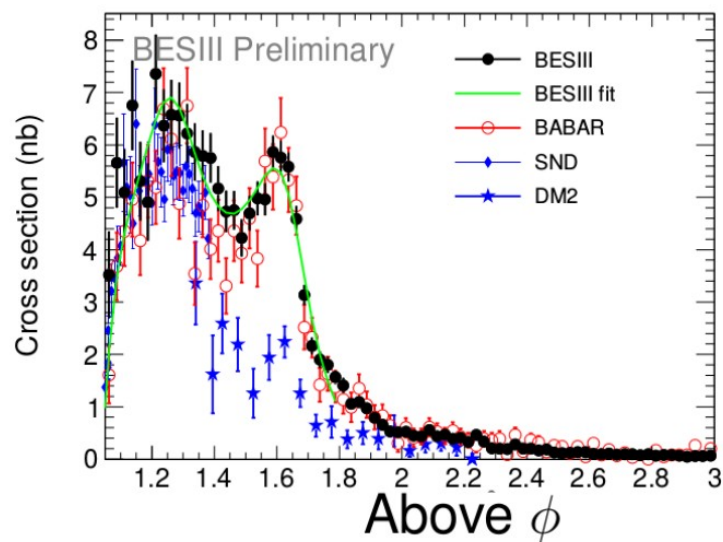
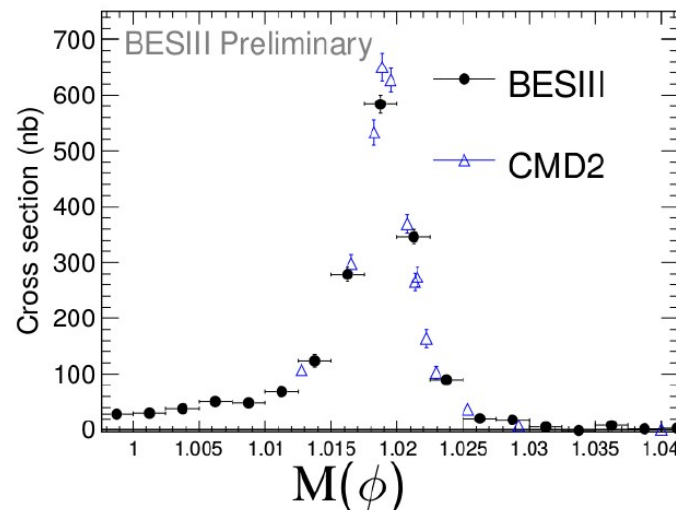
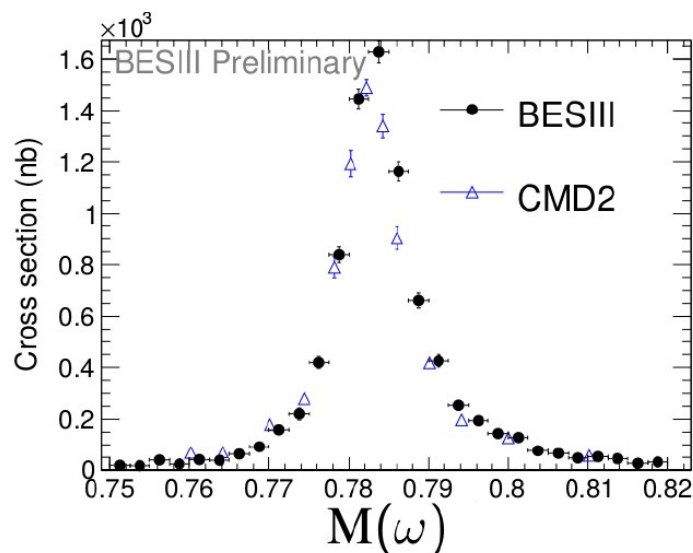
$$\sigma(m) = \frac{12\pi}{m^3} F_{\rho\pi}(m) \left| \sum_{V=\omega, \phi, \omega', \omega''} \frac{\Gamma_V m_V^{\frac{3}{2}} \sqrt{\Gamma_V^{ee} \mathcal{B}(V \rightarrow 3\pi)}}{D_V(m)} \frac{e^{i\varphi_V}}{\sqrt{F_{\rho\pi}(m_V)}} \right|^2$$



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



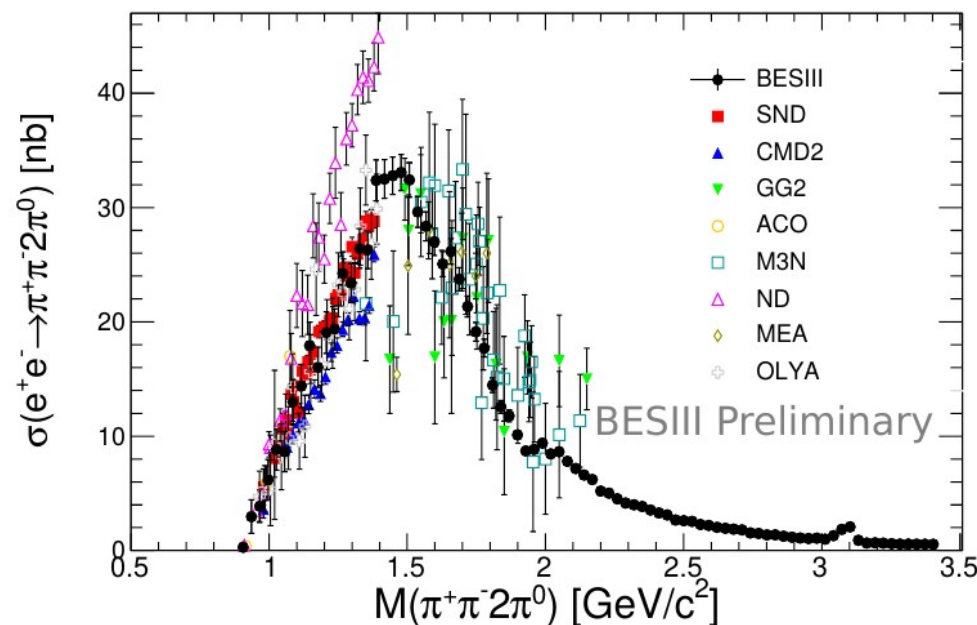
$$e^+e^- \rightarrow \pi^+\pi^-\pi^0$$



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

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

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



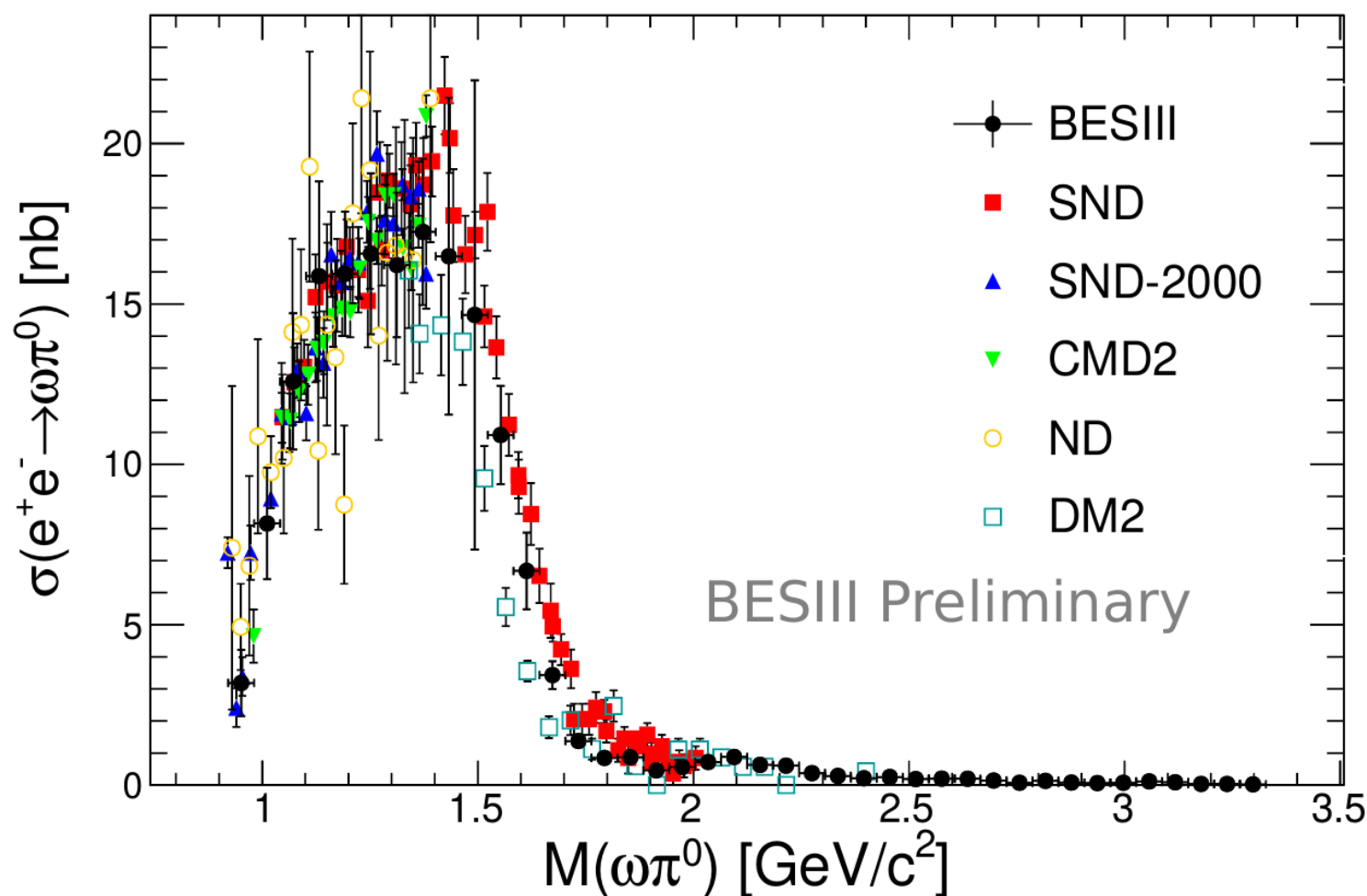
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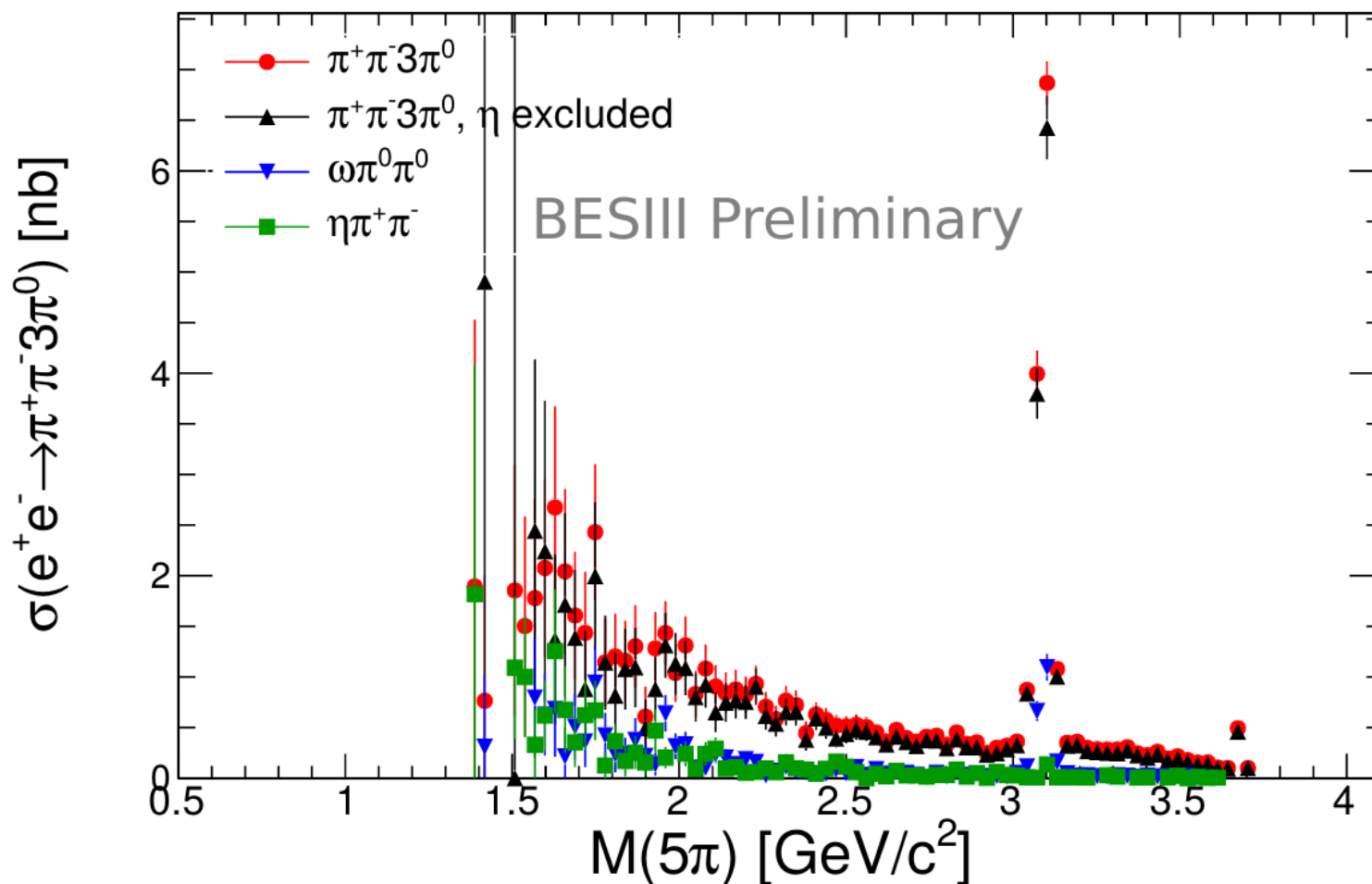
	$a_{\mu}^{\pi^+\pi^-\pi^0, \text{LO}} / 10^{-10}$
BESIII (preliminary)	$18.63 \pm 0.27 \pm 0.57$

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

- 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



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

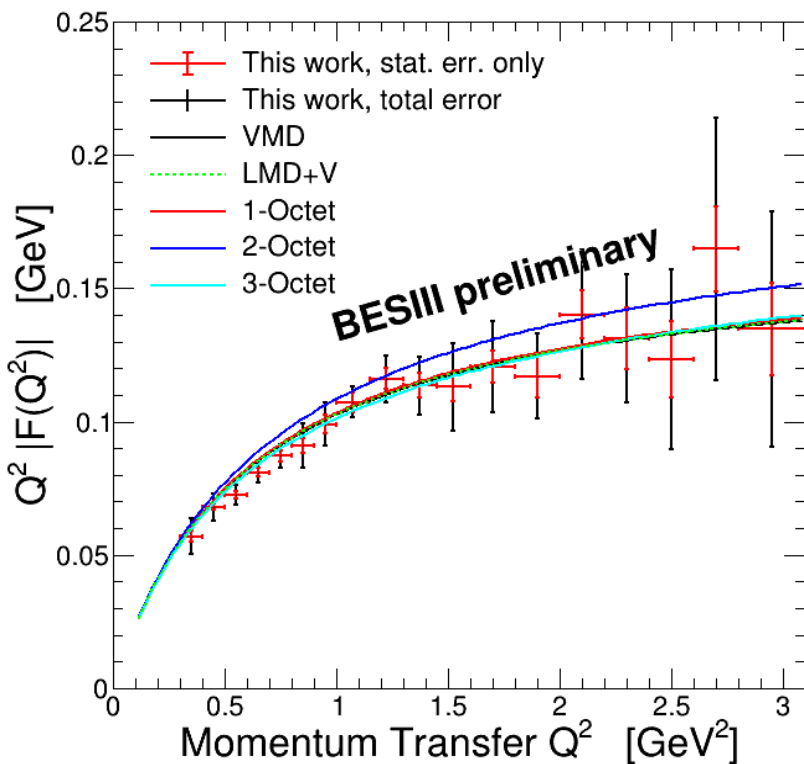


- From background evaluation of $e^+e^- \rightarrow \pi^+\pi^-\pi^0\pi^0$
- Good agreement calculations using isospin relations

Comparison to Theory (I)



Models:



$$F_{\text{VMD}}(Q^2) = -\frac{N_c}{12\pi^2 F_\pi} \frac{M_V^2}{M_V^2 + Q^2}$$

$$F_{\text{LMD+V}}(Q^2) = -\frac{F_\pi}{3} \frac{h_1 Q^4 - h_5 Q^2 + h_7}{(M_{V1}^2 + Q^2)(M_{V1}^2 + Q^2)M_{V1}^2 M_{V2}^2}$$

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

$$F_{n=1,2-\text{Octet}}(Q^2) = -\frac{N_c}{12\pi^2 F_\pi} + \sum_{i=1}^n \frac{4\sqrt{2}h_{Vi}f_{Vi}}{3F_\pi} Q^2 (D_{\rho_i} - D_{\omega_i})$$

Czyz et al. Phys. Rev. D55 (2012) 094010

$$F_{3-\text{Octet}}(Q^2) = -\frac{N_c}{12\pi^2 F_\pi} + \sum_{i=1}^3 \frac{4\sqrt{2}h_{Vi}f_{Vi}}{3F_\pi} Q^2 (D_{\rho_i} + F_{\omega_i} H_{\omega_i} D_{\omega_i} + A_i^{\pi^0} F_{\phi_i} D_{\phi_i})$$

Czyz et al. Phys. Rev. D97 (2018) 016006

Parameters of models fixed according to publications

Comparison to Theory (III)

Lattice QCD:

BESIII

