# BESIII Inputs for $(g-2)_\mu$

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HC2NP – 2nd Workshop on Hadronic Contributions to New Physics Searches
Puerto de la Cruz, Tenerife

# Anomalous magnetic moment of the μ

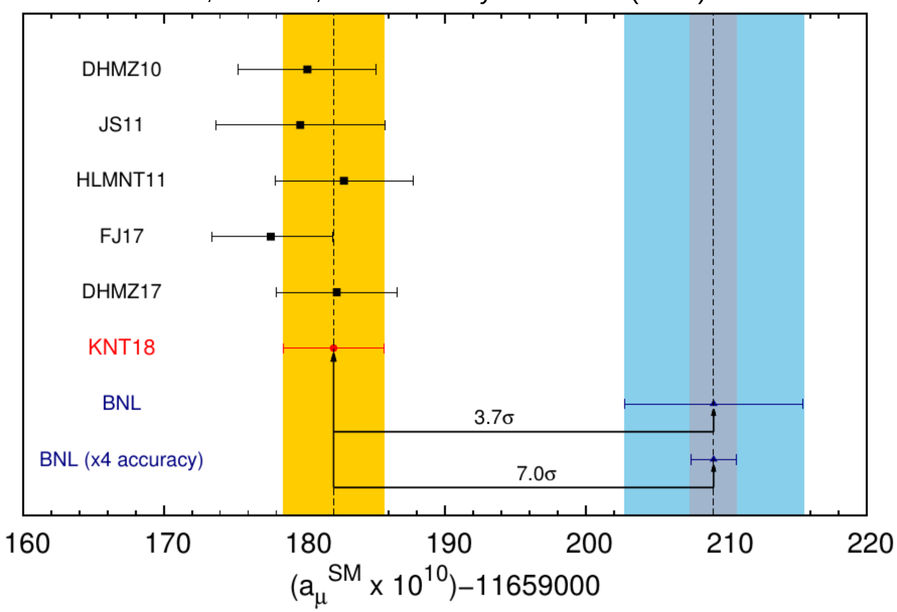
Muon anomaly: $a_\mu = \frac{g_\mu - 2}{2}$

- Known to 0.5 ppm in theory and experiment

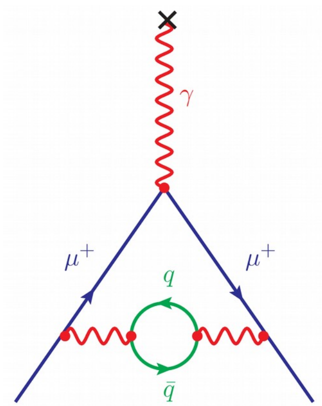
| | | |
|---|---|---|
| Standard Model (SM) | $(11659182.04 \pm 3.65)\ 10^{-10}$ | Phys. Rev D97 (2018) 114025 |
| Experiment (BNL) | $(11659208.9 \pm 6.3)\ 10^{-10}$ | Phys. Rev. D73 (2006) 072003 |

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

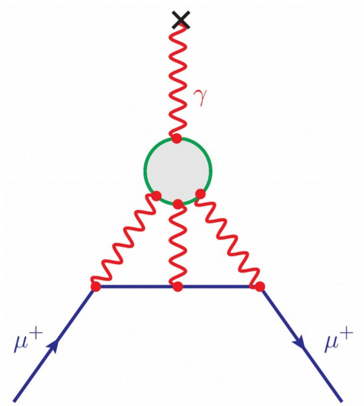
Keshavarzi, Nomura, Teubner Phys.Rev. D79 (2018) 114025




Uncertainty of SM prediction completely limited by hadronic contributions!




Hadronic Vacuum Polarization

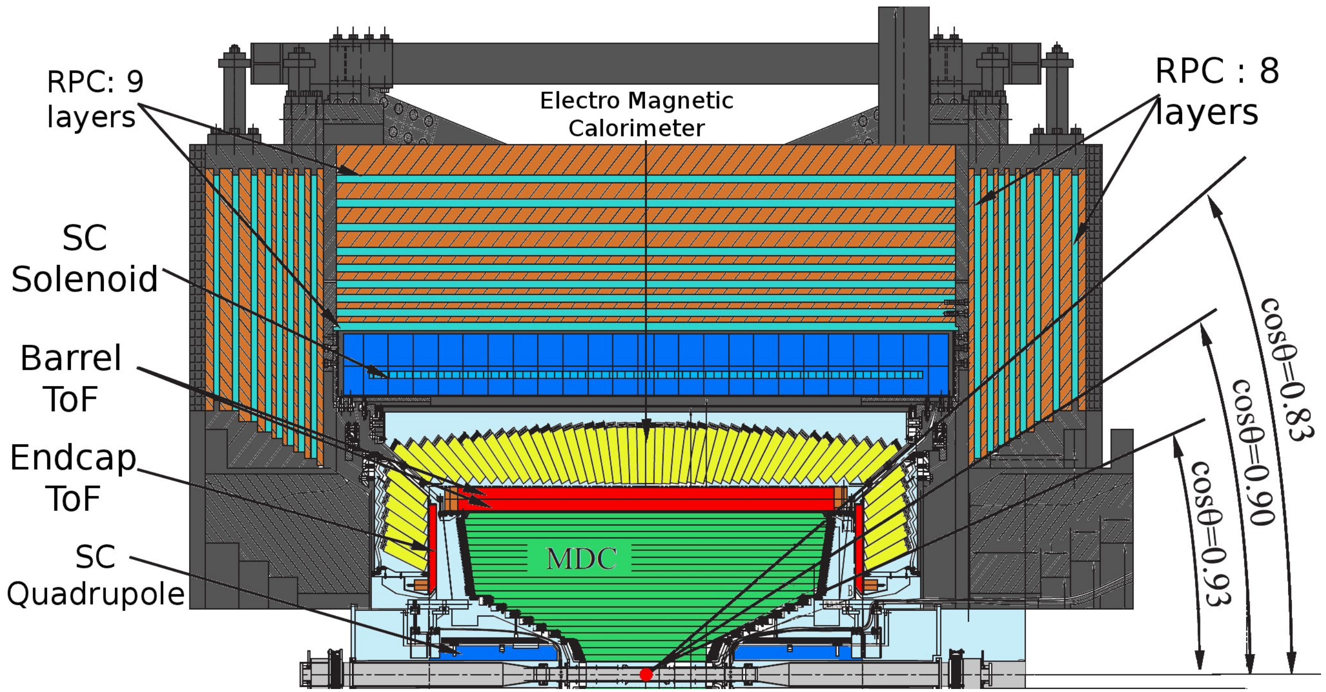



Hadronic Light-by-Light Scattering

Use input from experiments to improve SM prediction!

# 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

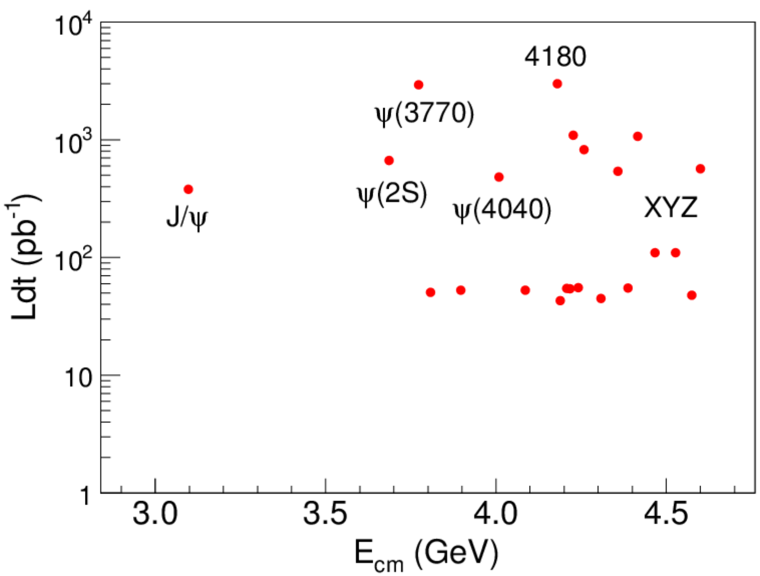
**EM Calorimeter (EMC)**
- 6240 CsI(Tl) crystals
- $\sigma(E)/E = 2.5\%$
- $\sigma_{Z,\Phi}(E) = 0.5 – 0.7$ cm

**Time-of-flight system (TOF)**
- $\sigma(t) = 90$ps (barrel)
- $\sigma(t) = 110$ps (endcap)

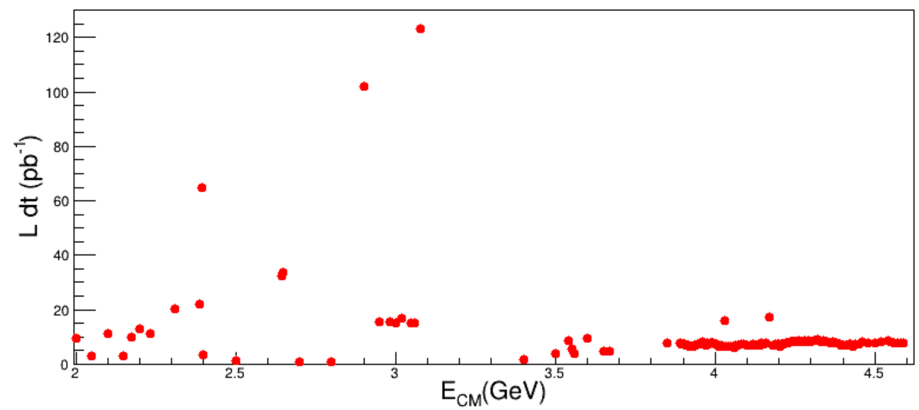
**Drift Chamber (MDC)**
- $\sigma(p)/p = 0.5\%$
- $\sigma_{dE/dx} = 6.0\%$

# 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 $\psi(3770)$

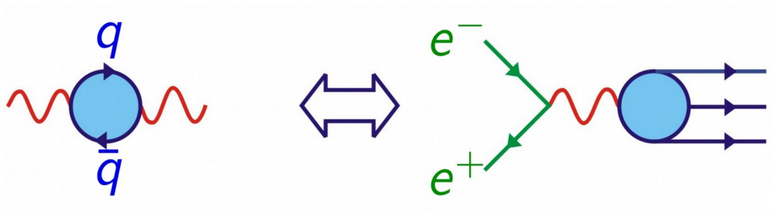



- Data taking for
  - Charmonium spectroscopy
  - Charm physics
  - Light hadrons
  - τ and R-scan



# Hadronic Vacuum Polarization

Related to hadronic cross sections by optical theorem



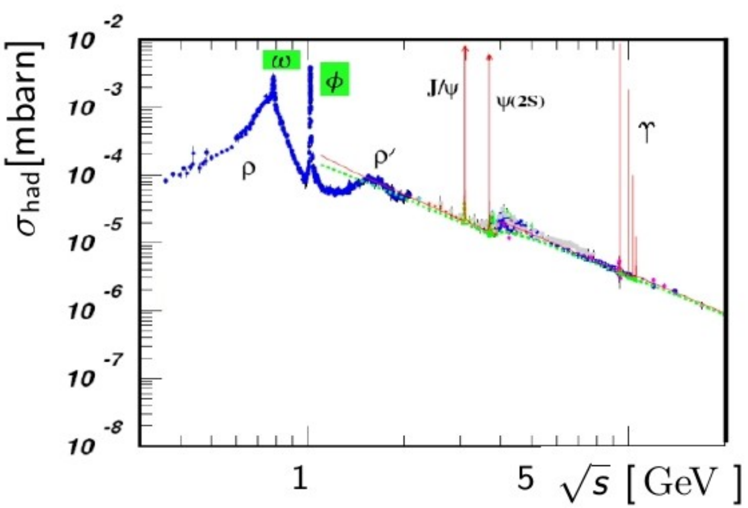

Dispersion integral :

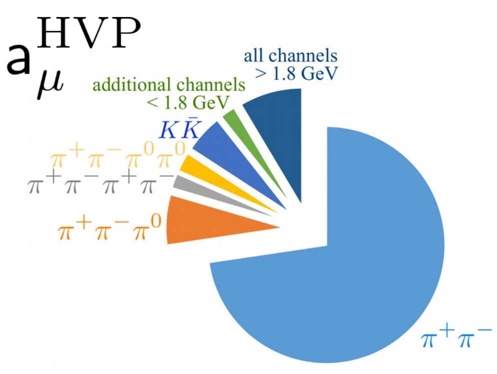
$$a_\mu^{hVP,LO} = \frac{1}{4\pi^3}\int_{4m_\pi^2}^{\infty} K(s)\sigma(e^+e^- \to \mathrm{hadr})\mathrm{d}s$$

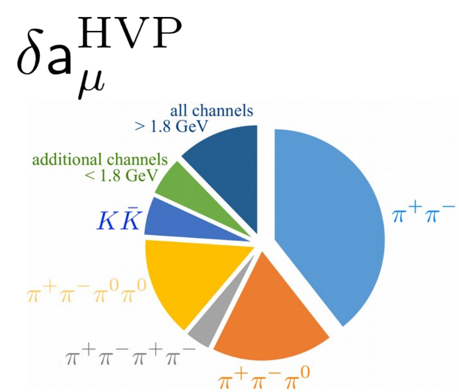
$$K(s) \sim \frac{1}{s}$$

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

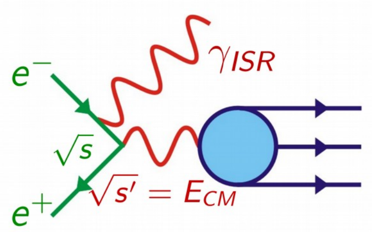
} Low energy contributions dominate !



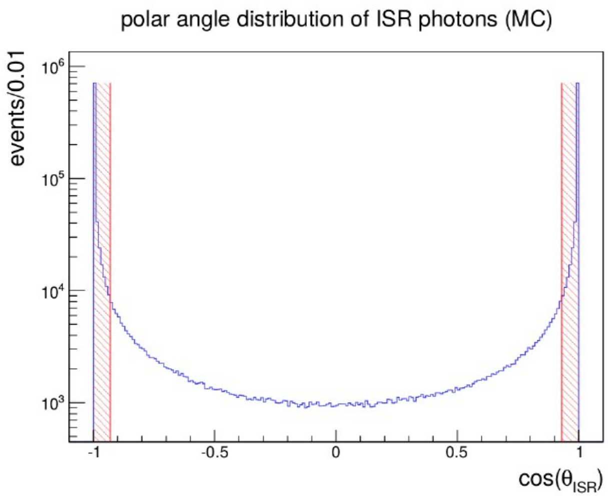



# ISR Measurements at BESIII

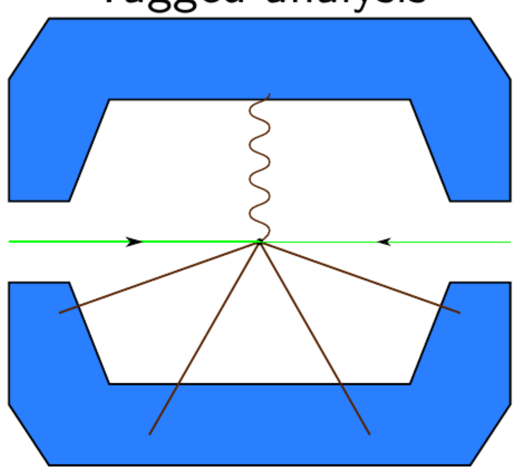



$$\sqrt{s'} = \sqrt{s - 2\sqrt{s}E_\gamma}$$

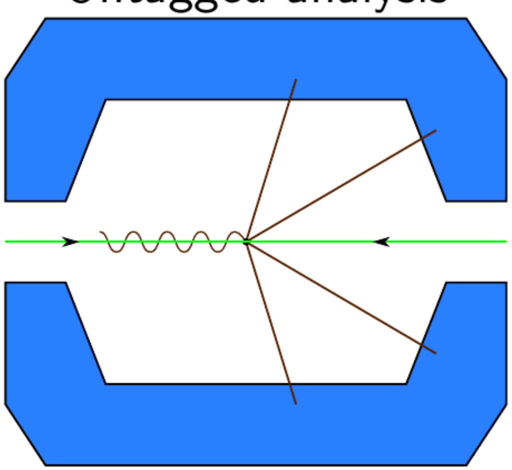



- Detect hadronic system
- ISR photon detected
  - Acceptance from $\pi^+\pi^-$ threshold
  - Large background contamination at high $\sqrt{s'}$
- ISR photon undetected
  - High statistics
  - Acceptance for $\sqrt{s'} > 1$ GeV
  - Small background contamination

Tagged analysis



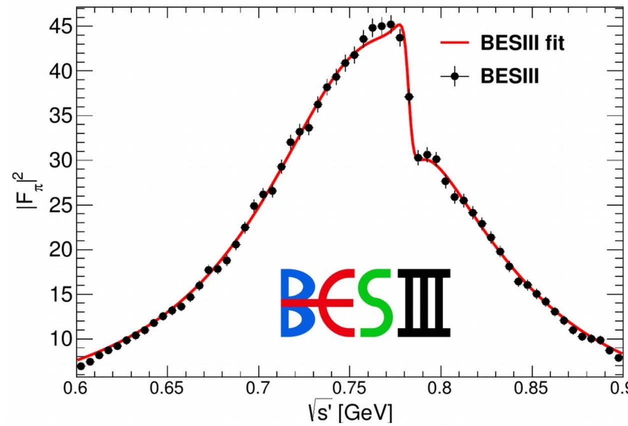
Untagged analysis

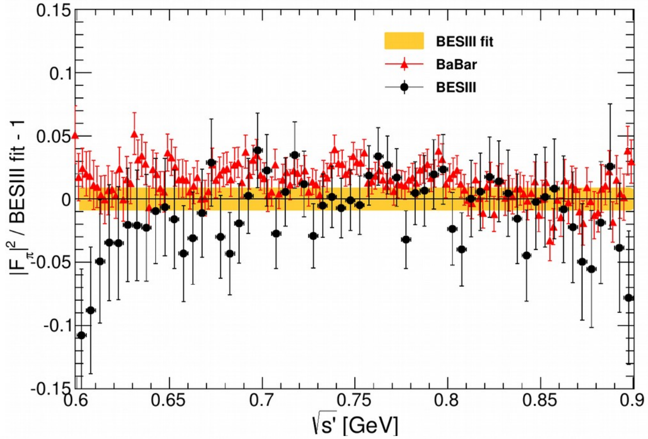


# $e^+e^- \rightarrow \pi^+\pi^-$

Phys.Lett.B753 (2016) 629

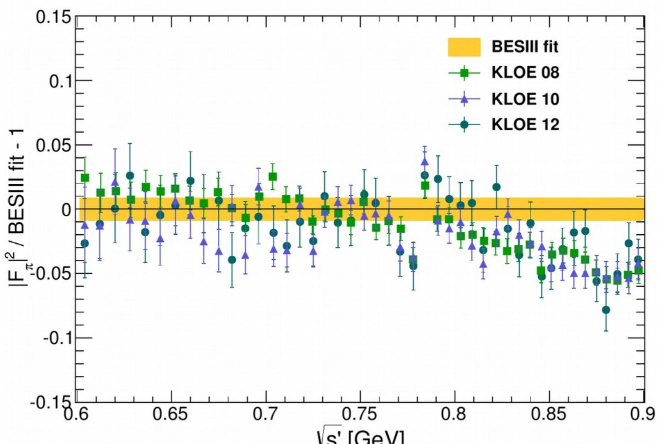
- Tagged ISR technique
- Based on 2.9 fb$^{-1}$ at 3.773 GeV
- $\mu - \pi$ separation with Artificial Neural Network
- Focus on $0.6 \leq m_{\pi\pi} \leq 0.9$
- Normalized to integrated luminosity
- Careful evaluation of systematics
  - Total uncertainty of 0.9% achieved
  - Dominated by
    - Luminosity (0.5%)
    - Radiator function (0.5%)




- Deviations to previous measurements observed

- Ongoing activities
  - Extend analysis to new data sets
  - Investigate $m_{\pi\pi} \geq 1$ GeV
    - Untagged ISR analysis



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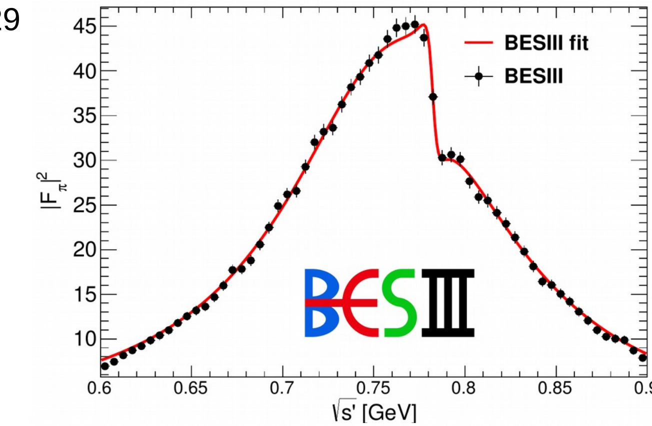
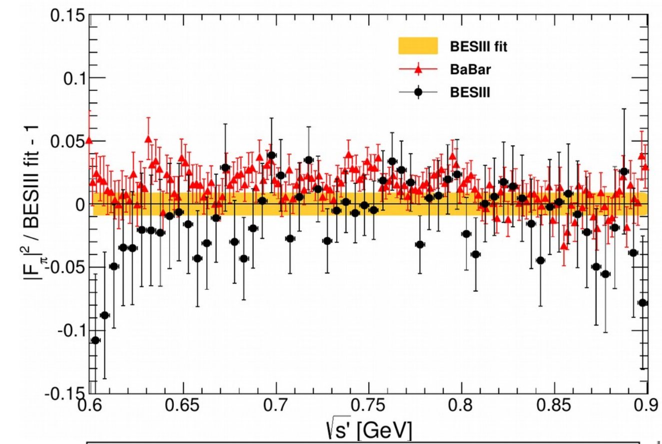
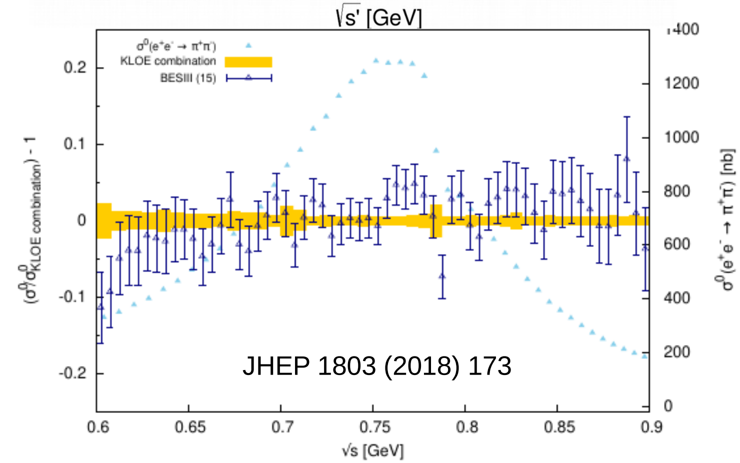
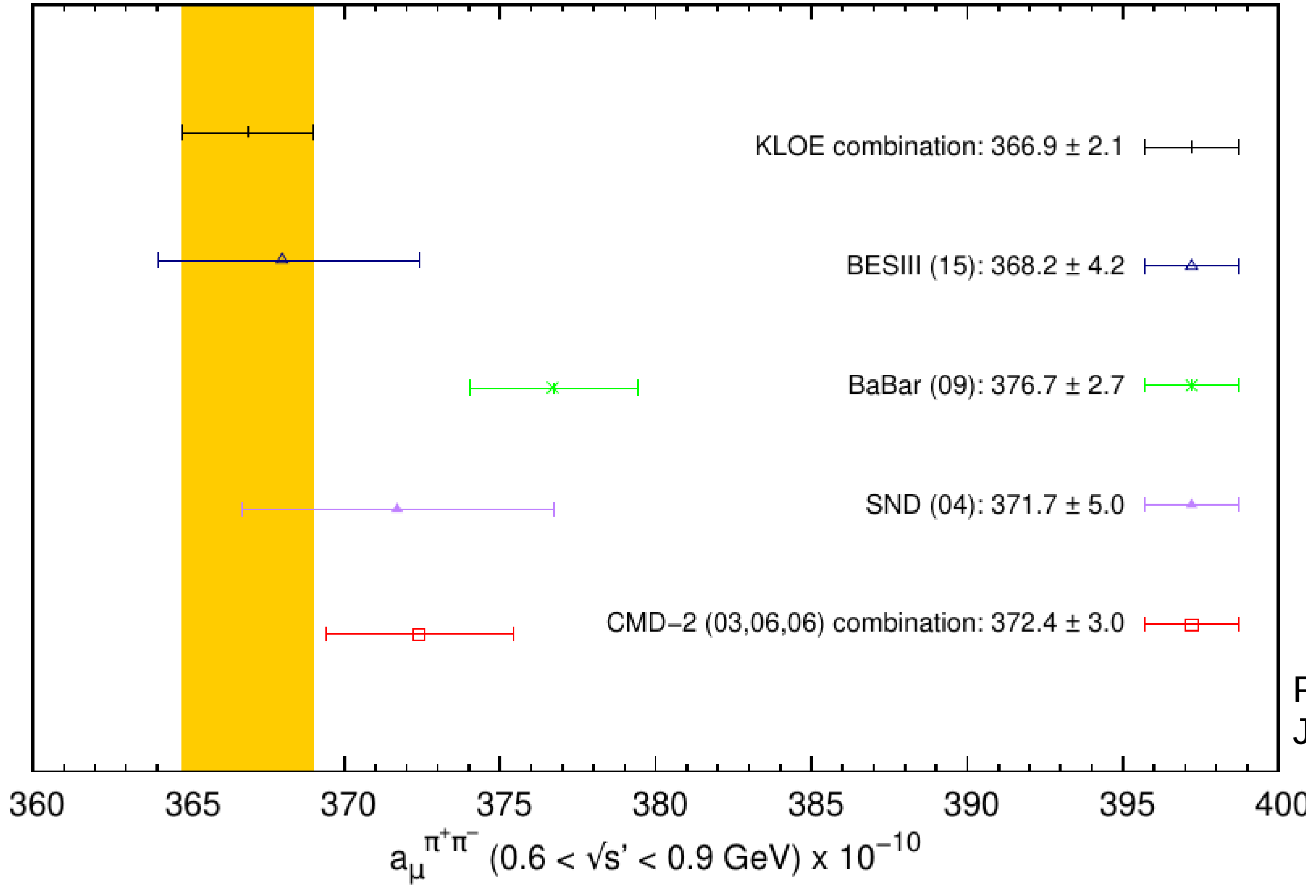


# $e^+e^- \to \pi^+\pi^-$




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 $a_\mu^{\text{hVP}}$ including BESIII result improve accuracy by 20%

EPJ C77 (2017), 820

# Higher pion multiplicities

Tagged ISR method

ISR photon observed?

Untagged ISR method

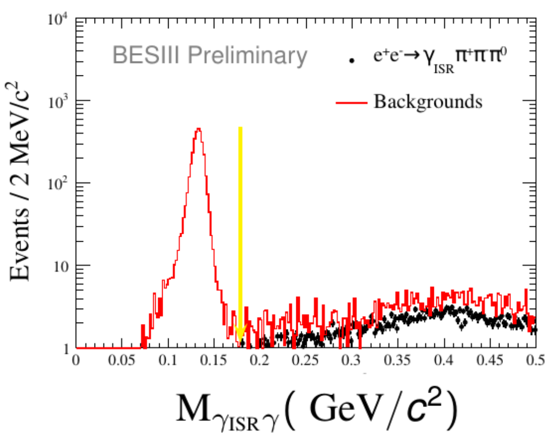
5C kinematic fit

$\pi^0$ veto

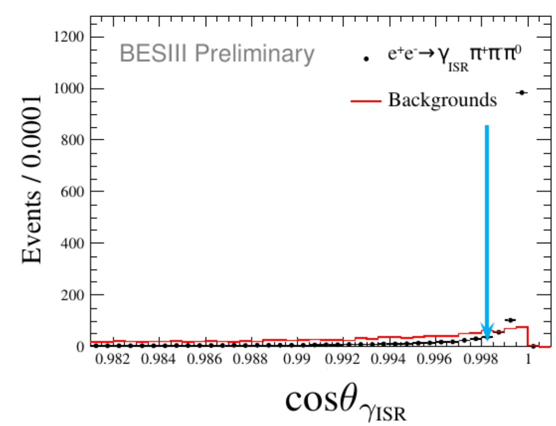
2C kinematic fit

Polar angle

Combination of the ISR photon and any other photon

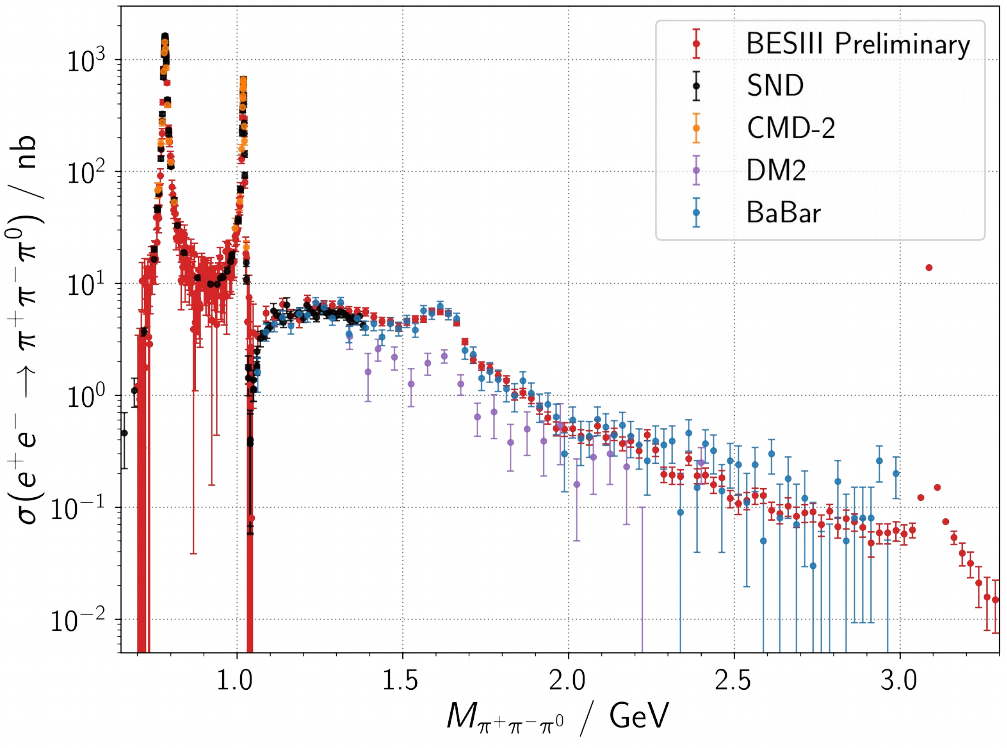


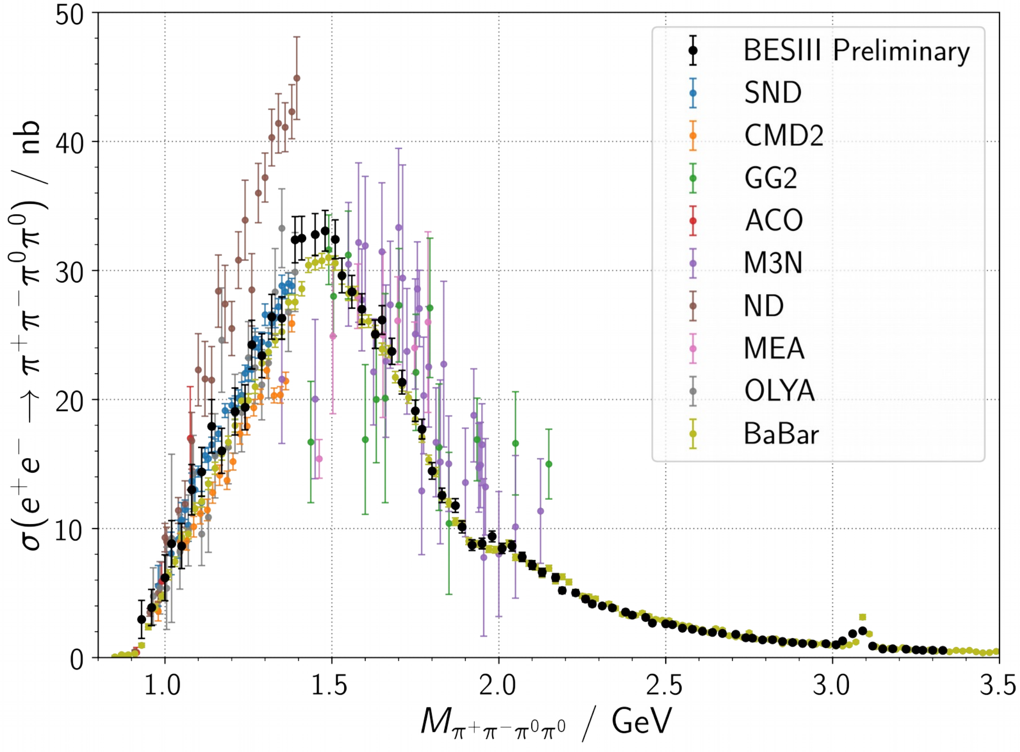

Polar angle of the ISR photon




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

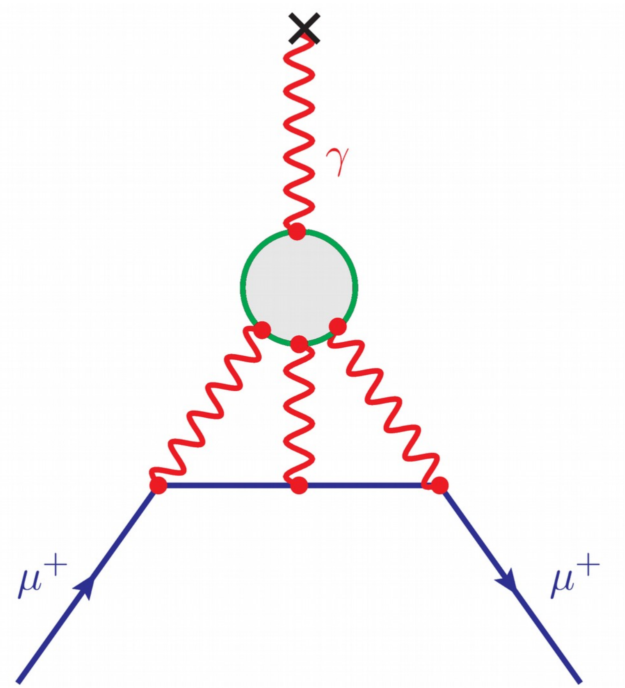
# Higher pion multiplicities



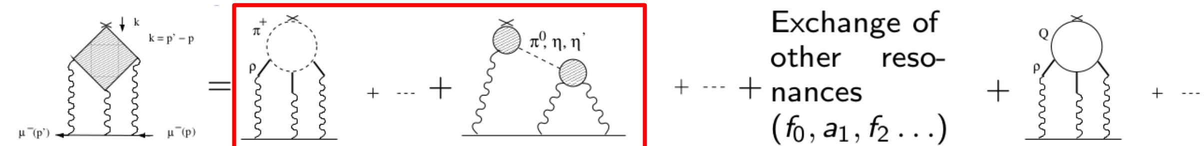




- Error weighted mean of tagged and untagged results
- Improved precision (syst. uncertainties of approx. 3% and 4%, respectively)
- Determination of LO contribution to $a_\mu^{HVP}$
- Measurement of branching fractions of $J/\psi$

# Hadronic Light-by-Light Scattering




Counting scheme for contributions to $a_\mu^{\text{HLbL}}$ (de Rafael, Phys.Lett.B322, 239, 1994)




| | | | | |
|---|---|---|---|---|
| Chiral counting | $p^4$ | $p^6$ | $p^8$ | $p^8$ |
| $N_C$-counting: | 1 | $N_C$ | $N_C$ | $N_C$ |

Dominating contributions:
- PS meson exchange
- Pion loops

**Dispersive Approaches**

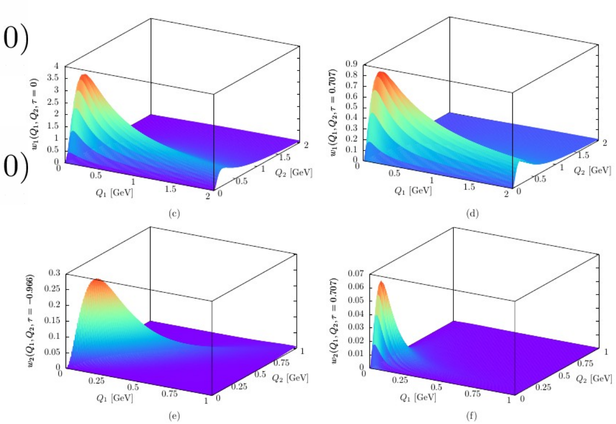
| | |
|---|---|
| Bern | Colangelo *et al.* |
| Mainz | Vanderhaeghen *et al.* |

3D integral representation for PS-pole contribution: ( Nyffeler, Phys.Rev.D94,053006, 2016 )

$$a_\mu^{HLbL;\pi^0(1)} = \int_0^\infty dQ_1 \int_0^\infty dQ_2 \int_{-1}^1 d\tau\; w_1(Q_1,Q_2,\tau)\mathcal{F}_{\pi^0\gamma^*\gamma^*}(-Q_1^2,-(Q_1+Q_2)^2)\mathcal{F}_{\pi^0\gamma^*\gamma^*}(-Q_2^2,0)$$

$$a_\mu^{HLbL;\pi^0(2)} = \int_0^\infty dQ_1 \int_0^\infty dQ_2 \int_{-1}^1 d\tau\; w_2(Q_1,Q_2,\tau)\mathcal{F}_{\pi^0\gamma^*\gamma^*}(-Q_1^2,-Q_2^2)\mathcal{F}_{\pi^0\gamma^*\gamma^*}(-(Q_1+Q_2)^2,0)$$

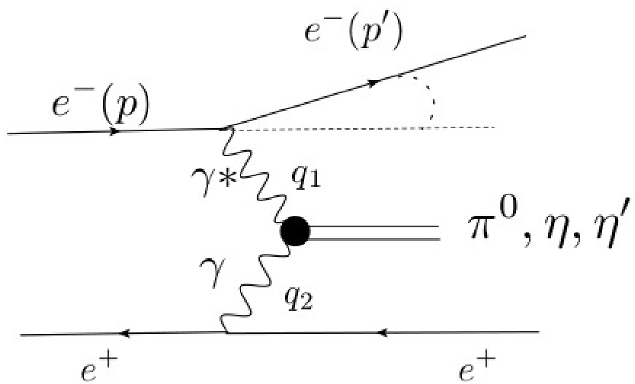
Universal weight functions $w_1$, $w_2$ Form factor dependence F

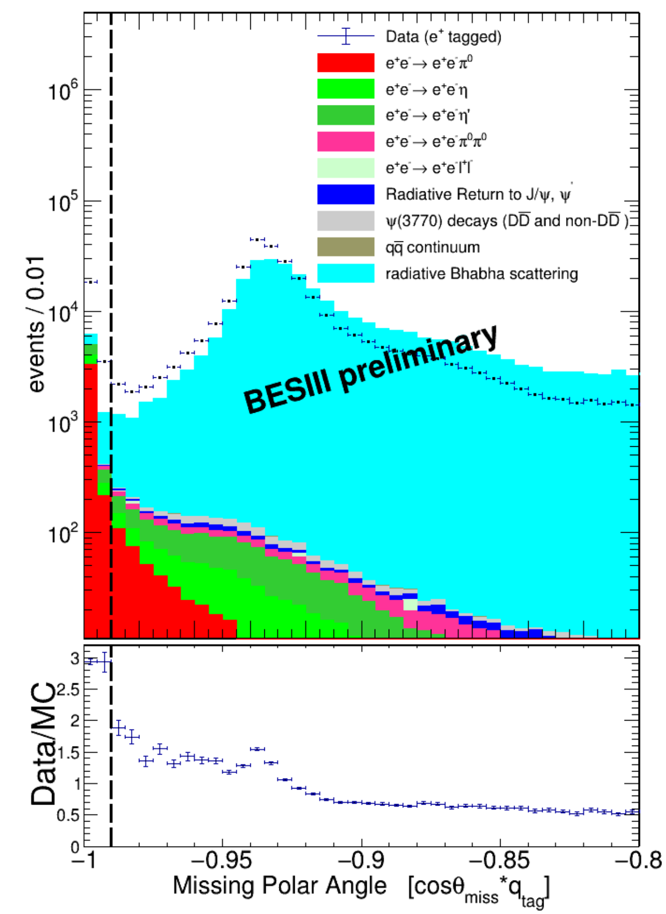


Relevant momentum region: 0.25 – 1.25 GeV

# Two-photon Physics

- Cross section of $\gamma\gamma$ processes proportional to square of TFF
- Single-tagged measurements to study momentum dependence of TFF



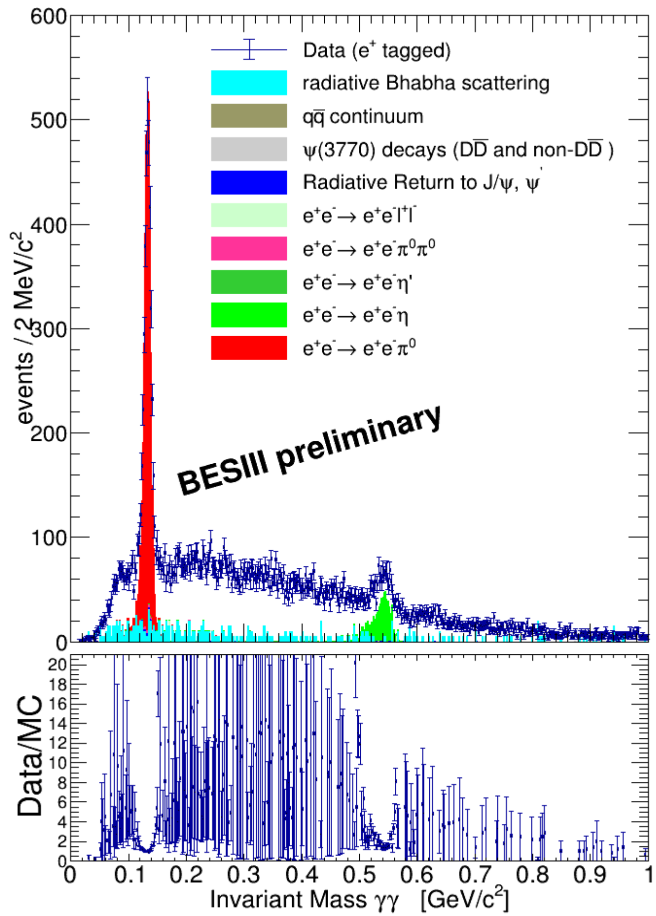

- Reconstruct:
  - only one scattered lepton
  - produced system
  - unmeasured lepton from momentum conservation
- Require scattering angle of missing momentum to be small
  - Small virtuality of exchanged photon
  - $F(Q_1^2, Q_2^2) \rightarrow F(Q_1^2, 0)$

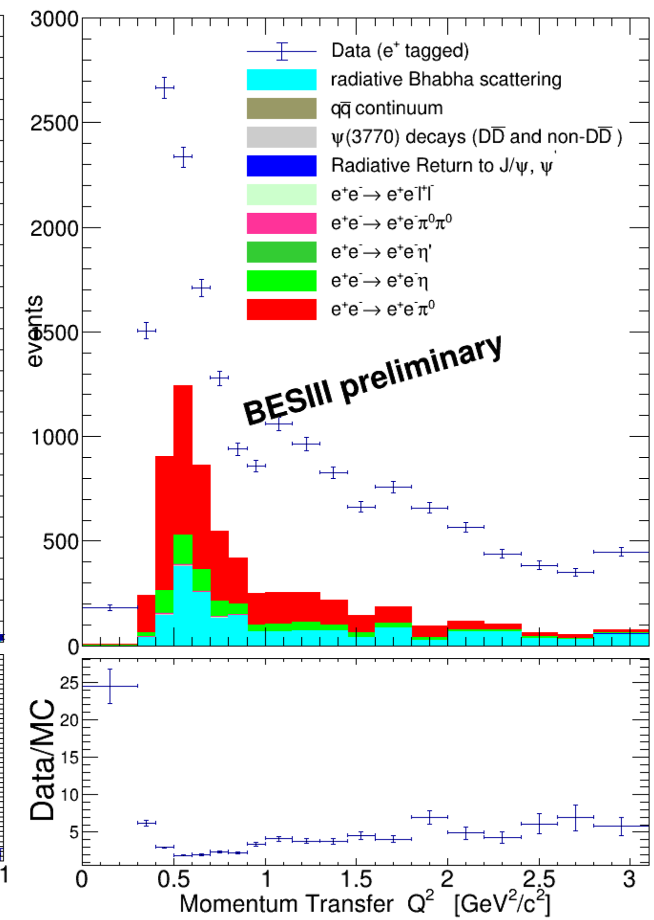
Reject events with $q_{\text{tag}} \cdot \cos(\theta_{\text{miss}}) > -0.99$

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

# Space-like $\pi^0$ 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
  - $R_\gamma = \frac{\sqrt{s} - E^{\text{CMS}}_{e^\pm\pi^0} - p^{\text{CMS}}_{e^\pm\pi^0}}{\sqrt{s}} > 0.05$



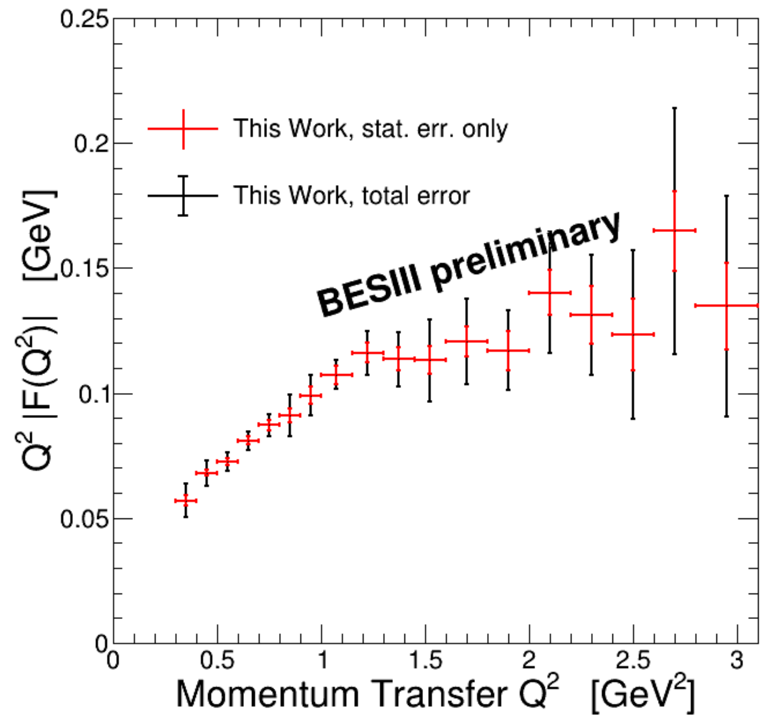

- Clear signals of $\pi^0$ and $\eta$
- Incomplete MC description
  - Data-driven background subtraction
- Divide out point-like cross section using MC distributions

# Space-like $\pi^0$ Transition Form Factor

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

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

| | 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% |
| | $\lvert\Delta\phi_{\gamma\gamma}\rvert < \frac{\pi}{2}$ | negligible |
| | $\lvert\Delta\theta_{\gamma\gamma} - 0.01 q_{\text{tag}}\rvert > 0.02$ | 0.3% – 9.8% |
| | $R_\gamma < 0.05$ | 1.0% – 7.7% |
| | Reconstruction efficiency | 1.6% – 17.2% |
| Background subtraction | 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

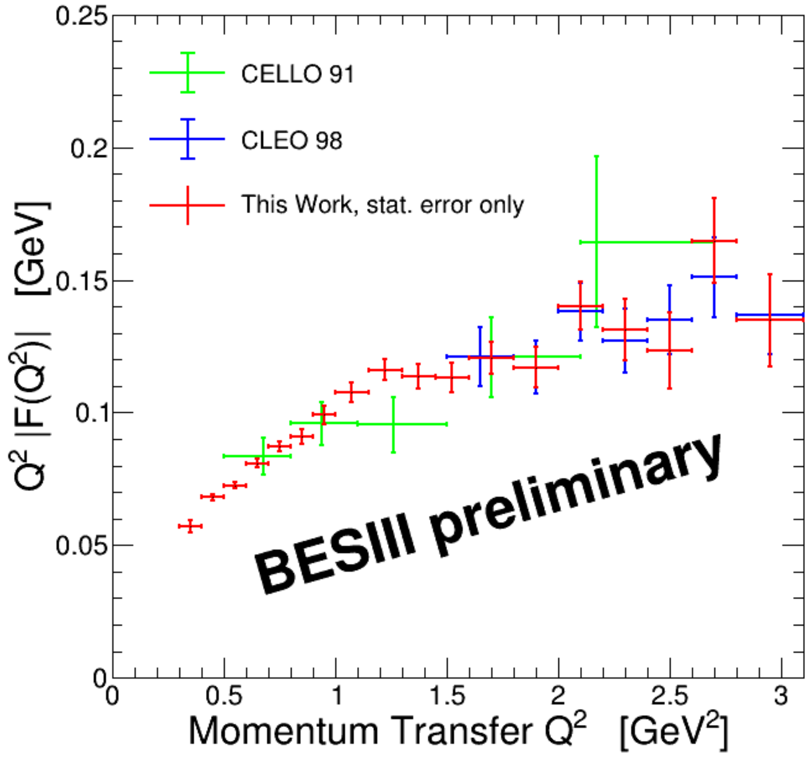
Error estimate does not consider radiative effects

- To be evaluated with recently released Ekhara 3.0

Comp. Phys. Commun. 234 (2019) 245

# Space-like $\pi^0$ Transition Form Factor

## Comparison with previous measurements



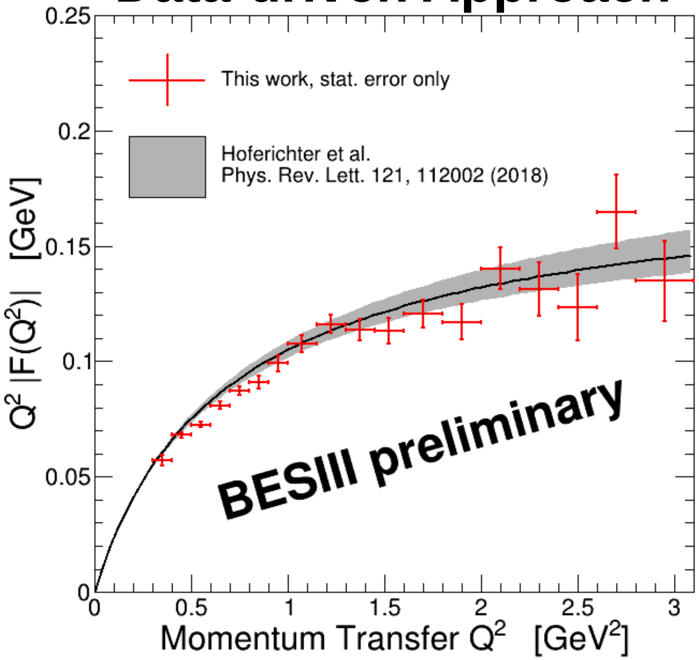

- Competitive accuracy up to 3.1 GeV²
- Unprecedented accuracy below $Q^2 = 1.5$ GeV²
- First measurement below 0.5 GeV²
  - Limited by acceptance for $\pi^0 \to \gamma\gamma$

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

# Space-like $\pi^0$ Transition Form Factor

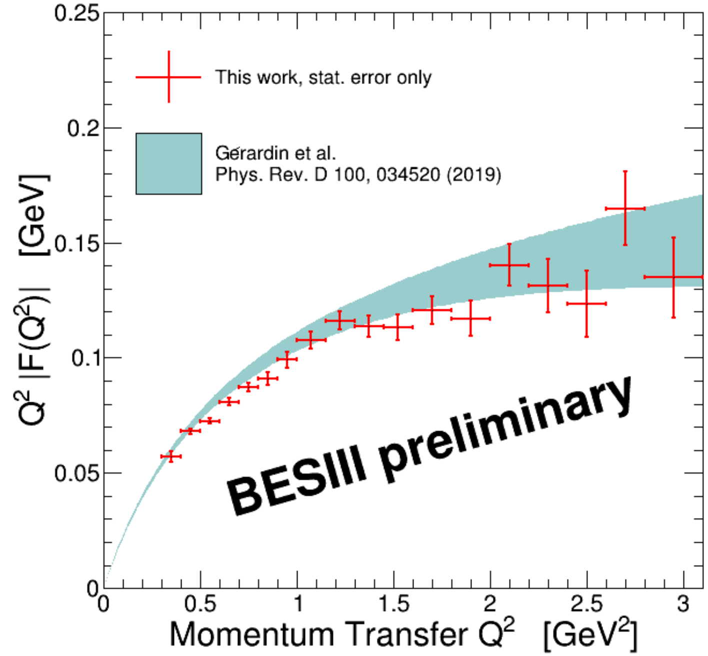
## Comparison with Theory

### Data-driven Approach




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

### Lattice QCD



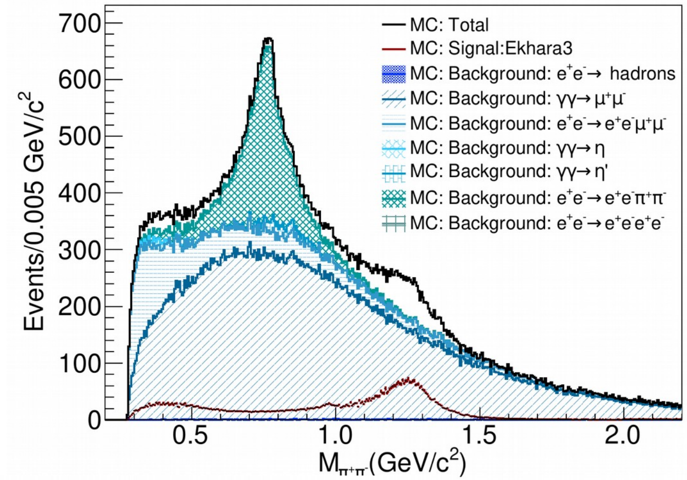

- “Mainz approach”
  - $N_f$ = 2+1 Wilson fermions

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

## Single-Tag measurement

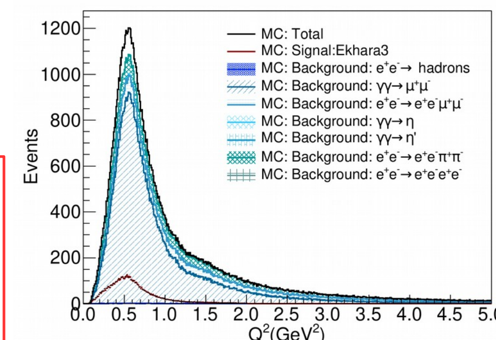
- Combine 7.5 $fb^{-1}$ from 3.773 GeV to 4.6 GeV
- Event selection analogous to single pseudoscalar analysis
- Machine learning tools to suppress $e^+e^- \to e^+e^-\mu^+\mu^-$
- Subtraction of $\rho$ contribution in $e^+e^- \to e^+e^-\pi^+\pi^-$
  - Fit peak in data using shape from theory

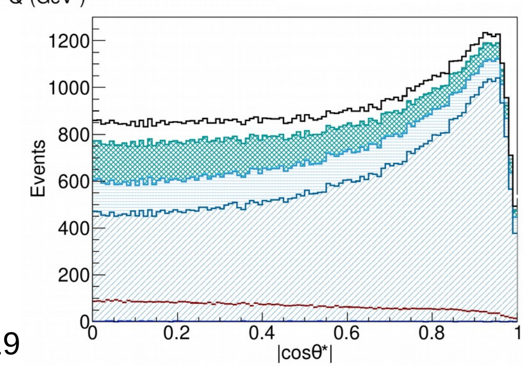
Full simulation of 1 $fb^{-1}$ at 4.23 GeV




- Study $\pi^+\pi^-$ invariant mass in bins of $Q^2$ and cosθ*

- First single-tag measurement of $\pi^+\pi^-$ !
  - Access to:
    - low momentum transfers $0.2 < Q^2\ [GeV^2] < 2.0$
    - low invariant masses $m_{\pi+\pi-} < M\ [GeV] < 2.0$
    - full coverage of cosθ*



# Outlook

- Single-tagged measurements
  - Complete TFF studies of single mesons $(\eta, \eta')$
  - Extend two-meson studies to neutral channels $(\pi^0\pi^0, \pi^0\eta, \eta\eta)$
  - Investigate higher multiplicity final states $(3\pi, 4\pi, ...)$
    - Axial and tensor contributions to $a_\mu$
  - Exploit additional data sets to increase $Q^2$ range

- Double-tagged measurements
  - Complementary to BaBar measurement of $\eta'$ TFF
  - Cover all single pseudoscalar states for $Q^2 < 2$ GeV$^2$
  - Feasibility studies successful
  - Development and installation of dedicated taggers

# Summary

## BESIII provides important input to (g-2)µ calculations!

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

# Backup

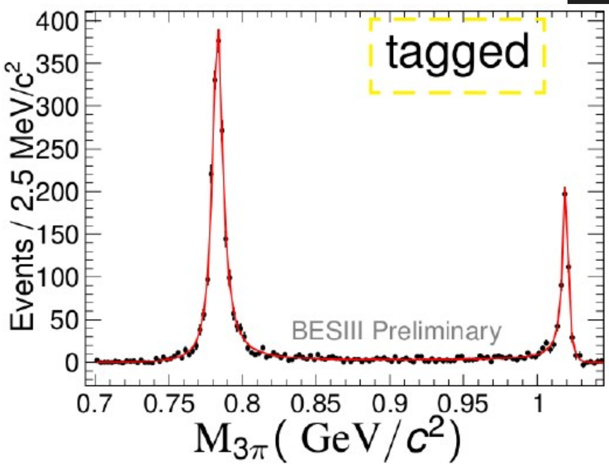
JG|U

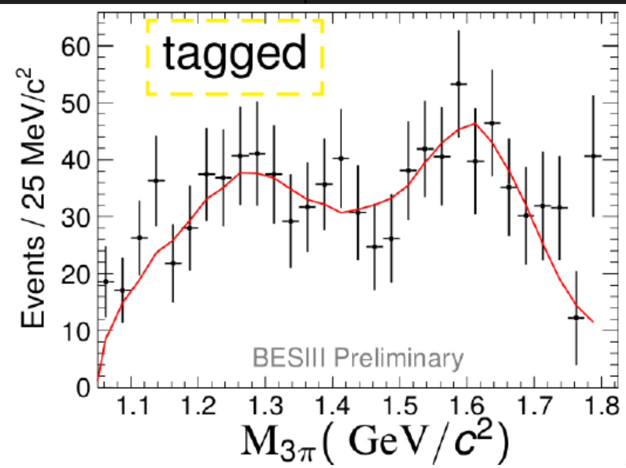
# $e^+e^- \rightarrow \pi^+\pi^-\pi^0$

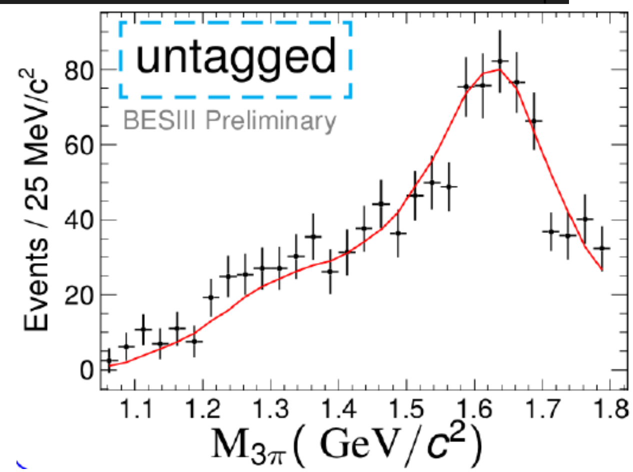
## $\pi^+\pi^-\pi^0$ invariant mass spectra

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

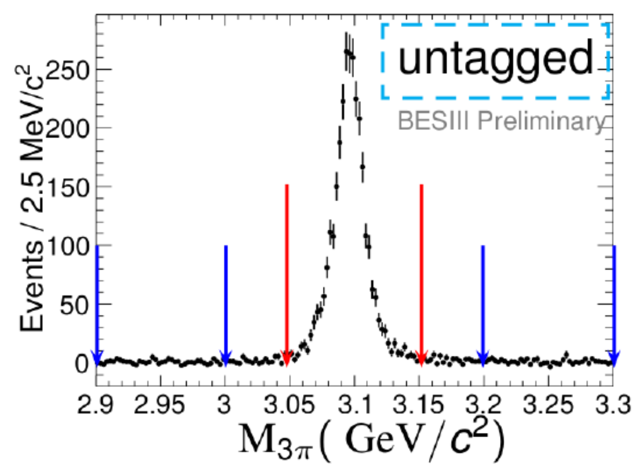
[redacted]



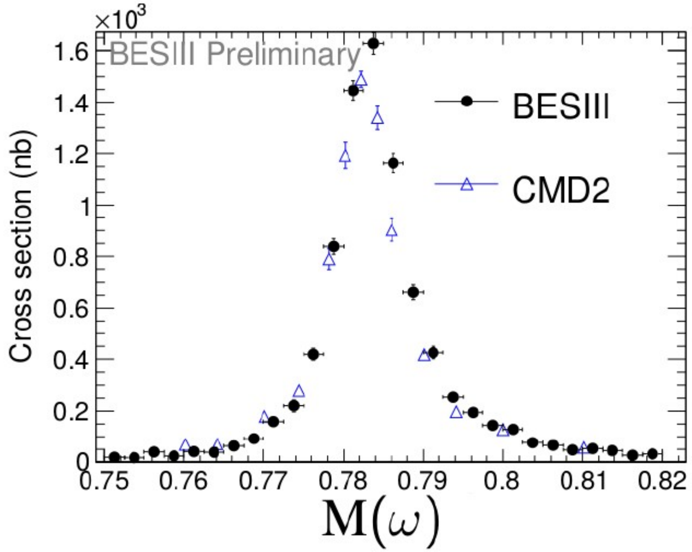



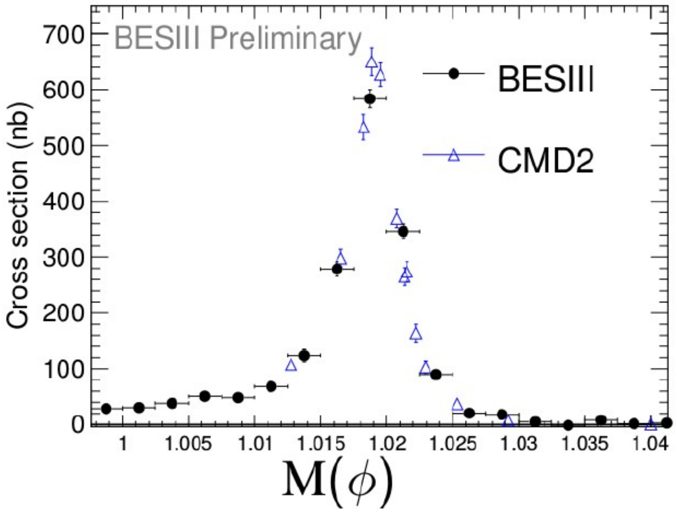



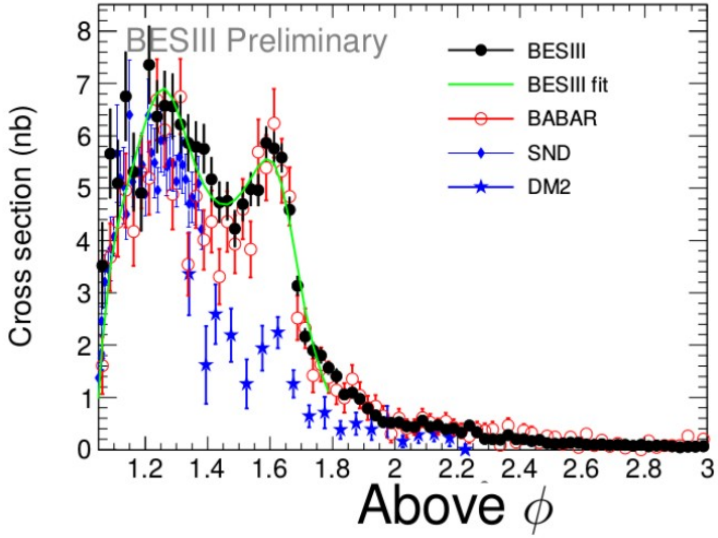

- Above 3 GeV: Determine $\mathcal{B}(J/\psi \rightarrow \pi^+\pi^-\pi^0)$



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



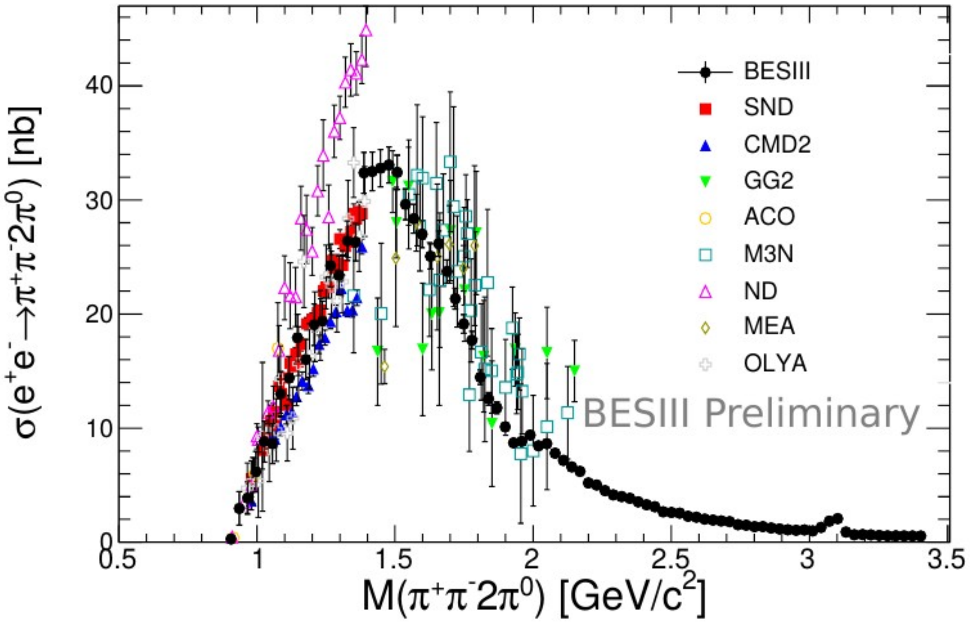




- Good agreement with previous measurements
- Improved precision
  - ~ 3% syst. uncertainty in full mass range
  - < 2% at narrow resonances
- Confirms BaBar result at $\omega''$
- To be used to evaluate $a_\mu^{hVP}$

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

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



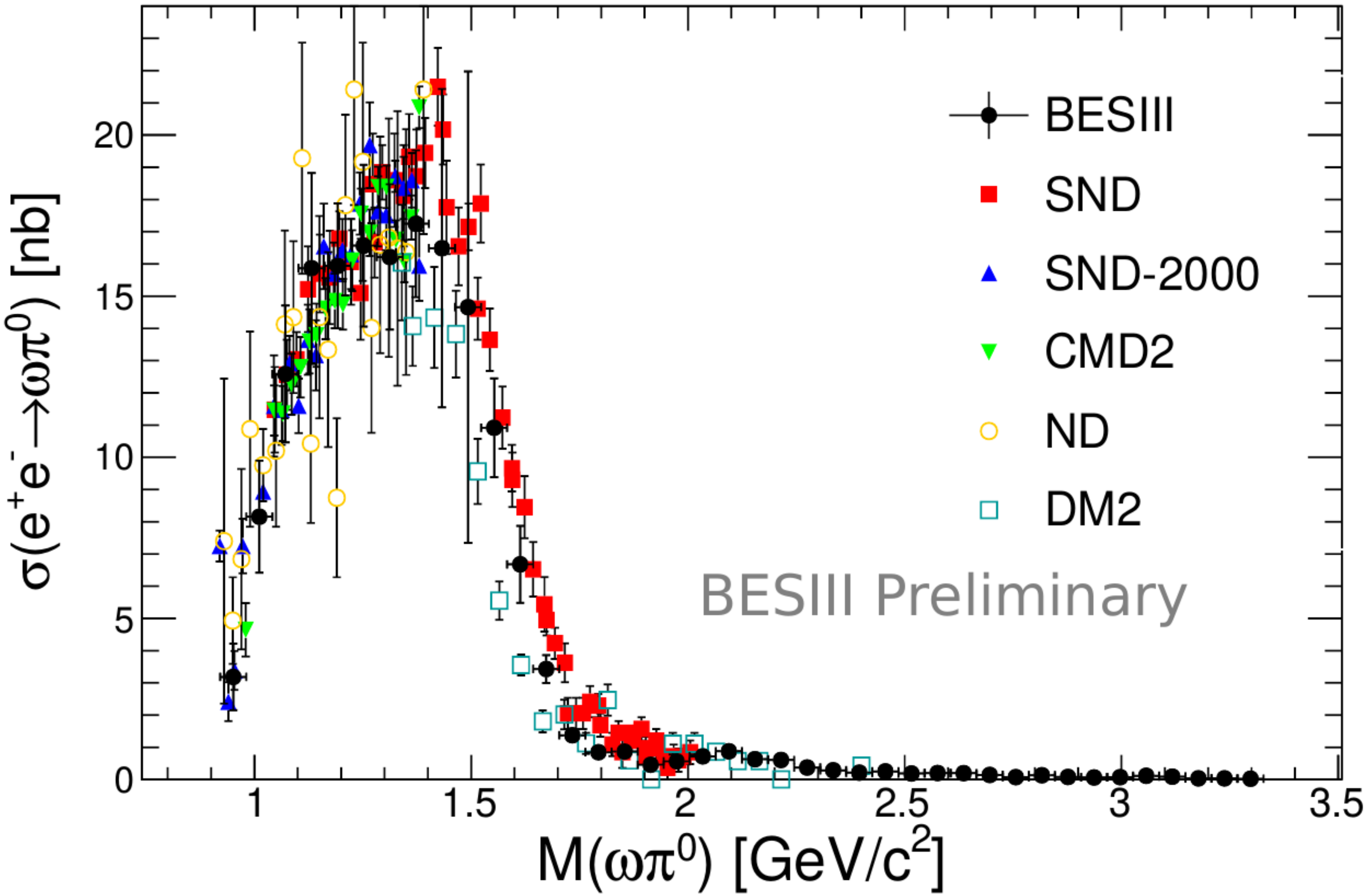

- Error weighted mean of tagged and untagged results
- Good agreement with previous measurements
- Improved precision (approx. 3% syst. uncertainty)

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

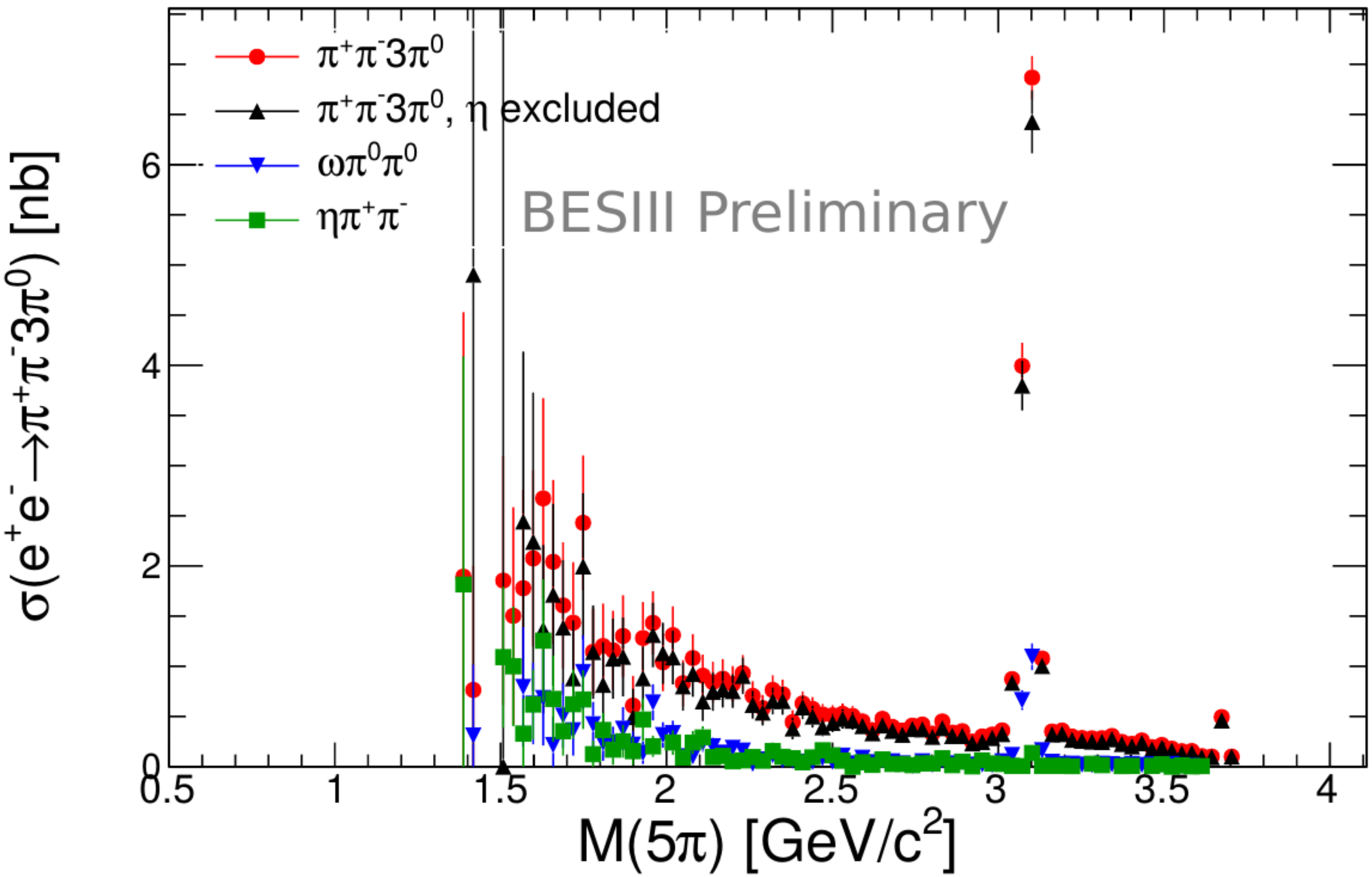
| | $a_\mu^{\pi^+\pi^-2\pi^0,\mathrm{LO}}/10^{-10}$ |
|---|---|
| BESIII (preliminary) | $18.63 \pm 0.27 \pm 0.57$ |

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

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



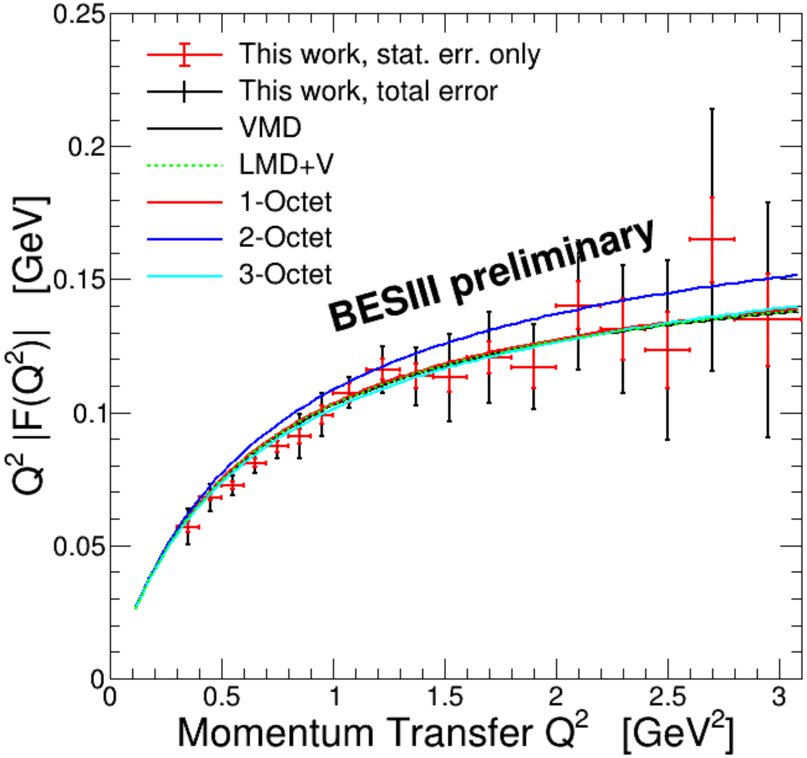
# $e^+e^- \to \pi^+\pi^-\pi^0\pi^0\pi^0$




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

# Space-like $\pi^0$ Transition Form Factor

**Models:**




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

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

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

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

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

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

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

Parameters of models fixed according to publications