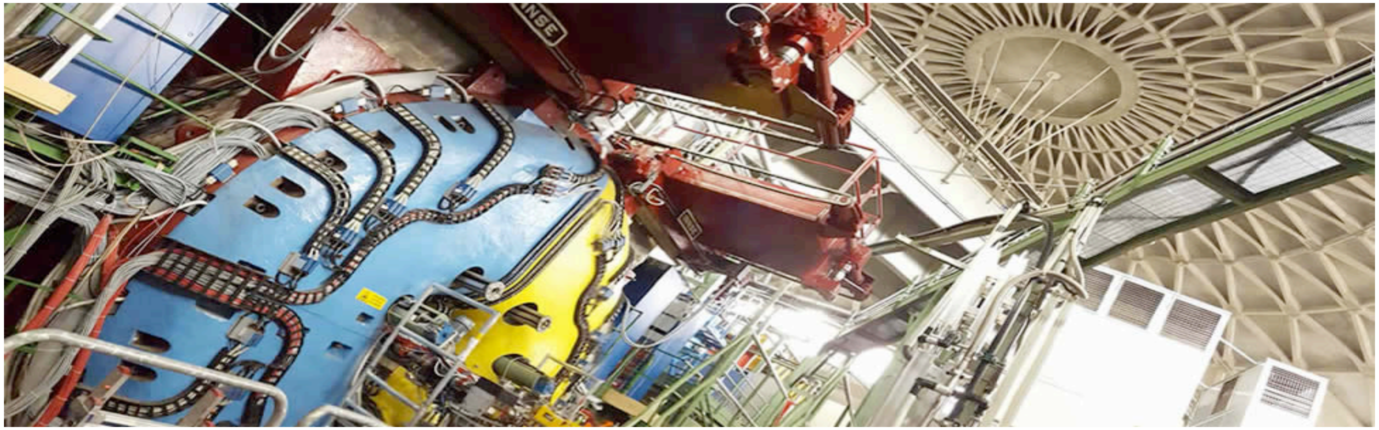
*KLOE 2 workshop on e+e- physics at 1 GeV, LNF, October 26-28, 2016*



# Selected topics of e+e- physics outside the phi region (BES III)

SFB 1044

PRISMA Cluster of Excellence

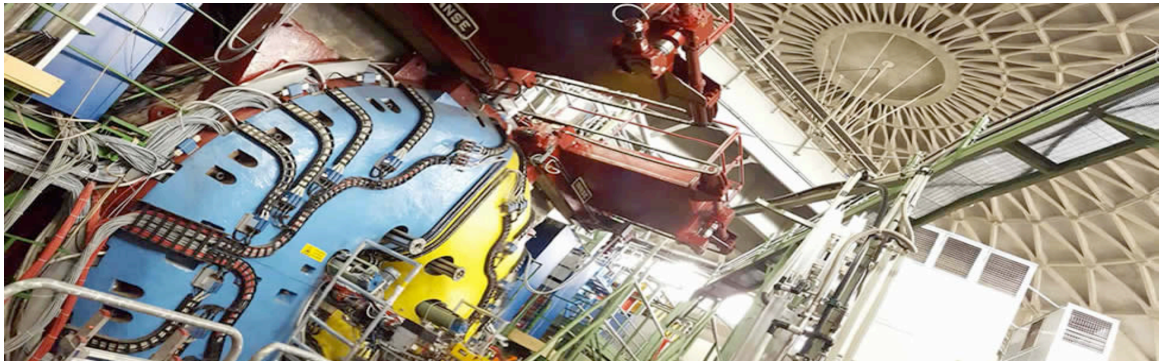
mami MAINZER MIKROTRON

*Achim Denig*

*Institute for Nuclear Physics*

*JGU Mainz*

# Outline




- Hadronic Cross Section Measurements at BES III
  ISR and R Scan

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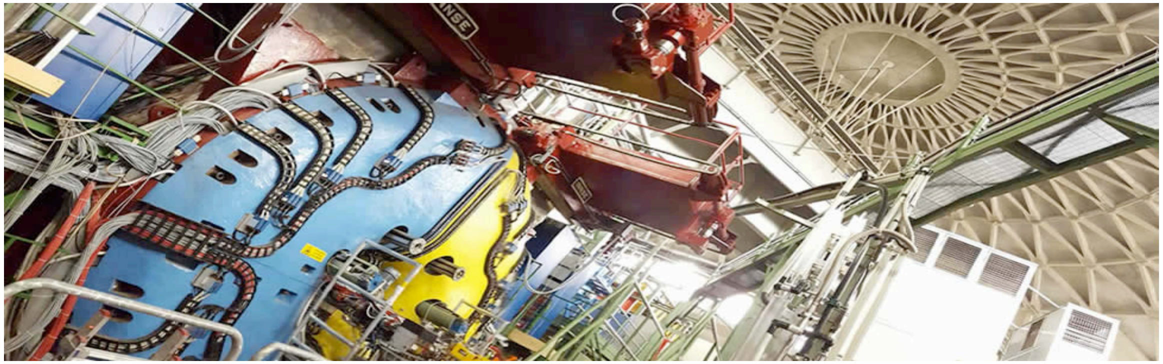
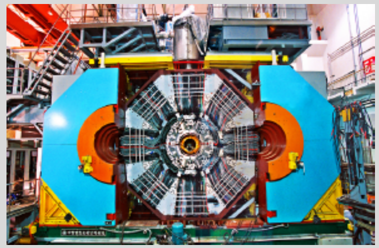
- Production of $J^{PC} = 1^{++}$ states in e+e- annihilation
  $\chi_{c1}$ and X(3872)



# *Hadron Production in $e^+e^-$ Annihilation*

# *The Hadronic Contribution to $(g\text{-}2)_\mu$*

**$(g\text{-}2)_\mu$ Standard Model Theory**



*$R_{had}$ ratio, i.e.*
*$\sigma_{had} = \sigma(e^+e^- \rightarrow Hadrons)$*

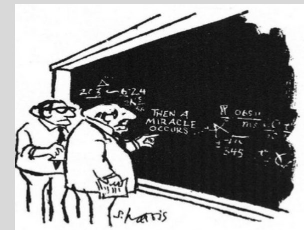
↓

***Hadronic Vacuum Polarization***

*Meson transition form factors $|F(Q_1^2, Q_2^2)|$*

↓

***Hadronic Light-by-Light Scattering***



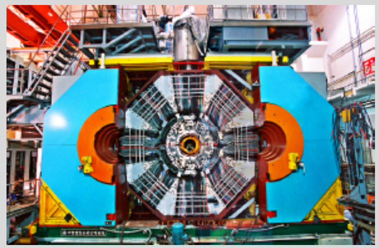

*Perturbative Calculations (Theory)*

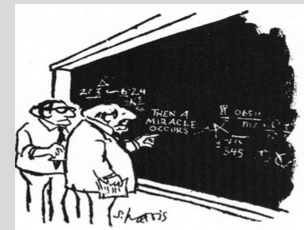
↓

***Electroweak Contribution***

# The Hadronic Contribution to $(g-2)_\mu$

## $(g-2)_\mu$ Standard Model Theory






$R_{had}$ ratio, i.e. $\sigma_{had} = \sigma(e^+e^- \rightarrow Hadrons)$

→ **Hadronic Vacuum Polarization**

Meson transition form factors $|F(Q_1^2,Q_2^2)|$

→ **Hadronic Light-by-Light Scattering**

Perturbative Calculations (Theory)

→ **Electroweak Contribution**

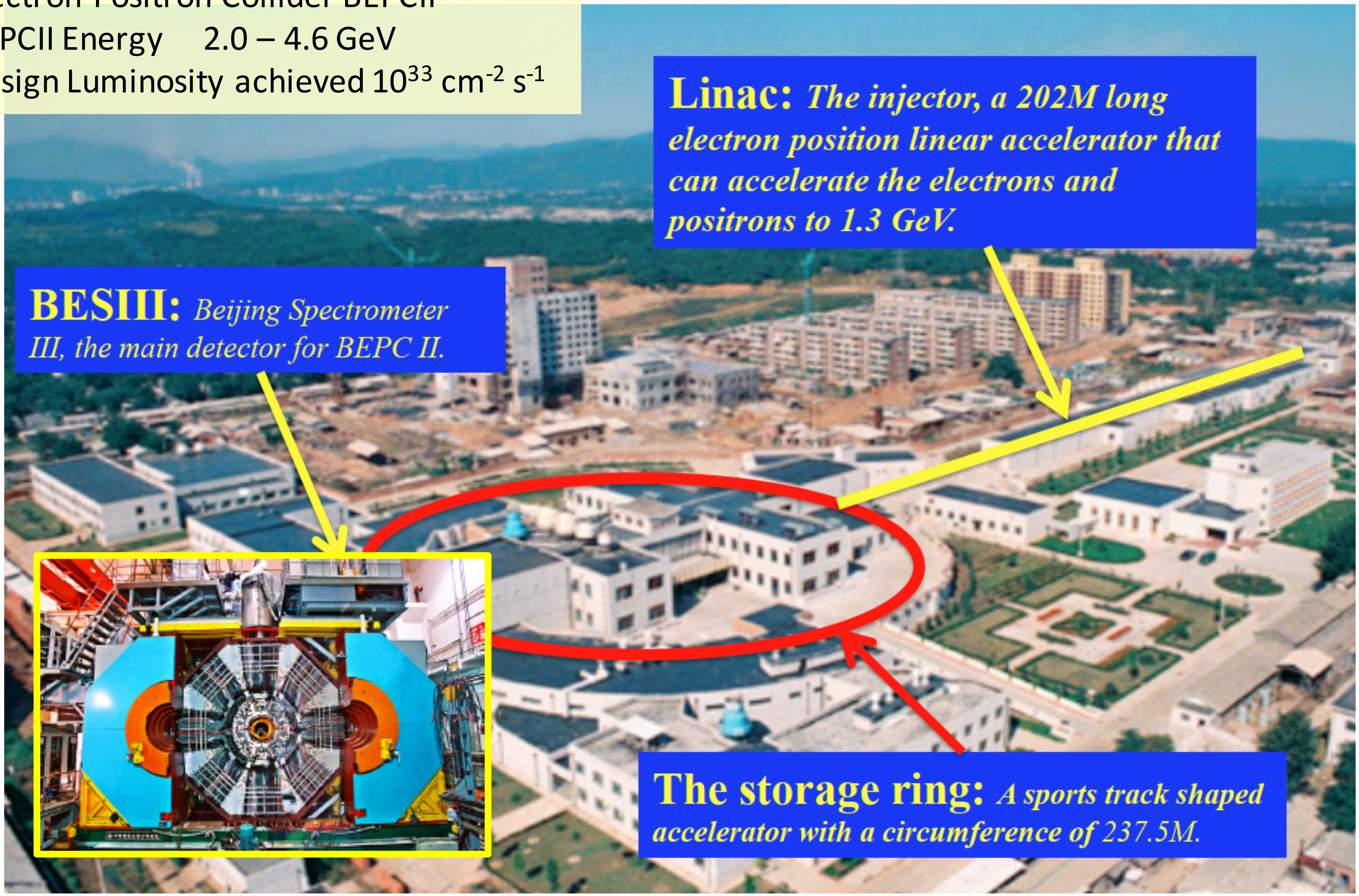
## $(g-2)_\mu$ Experiments


$(g-2)_\mu$ Interpretation

White Paper: arXiv:1311.2198

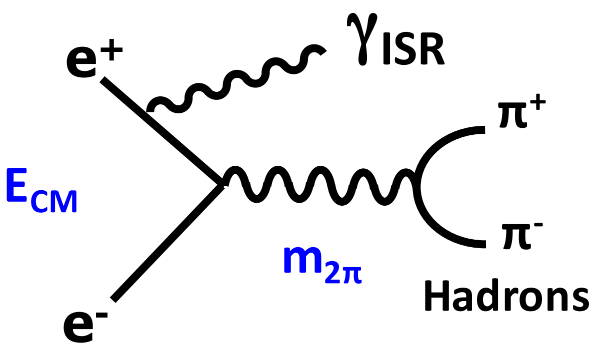
# BESIII Experiment @ BEPCII

Electron-Positron Collider BEPCII
BEPCII Energy 2.0 – 4.6 GeV
Design Luminosity achieved $10^{33}$ cm$^{-2}$ s$^{-1}$

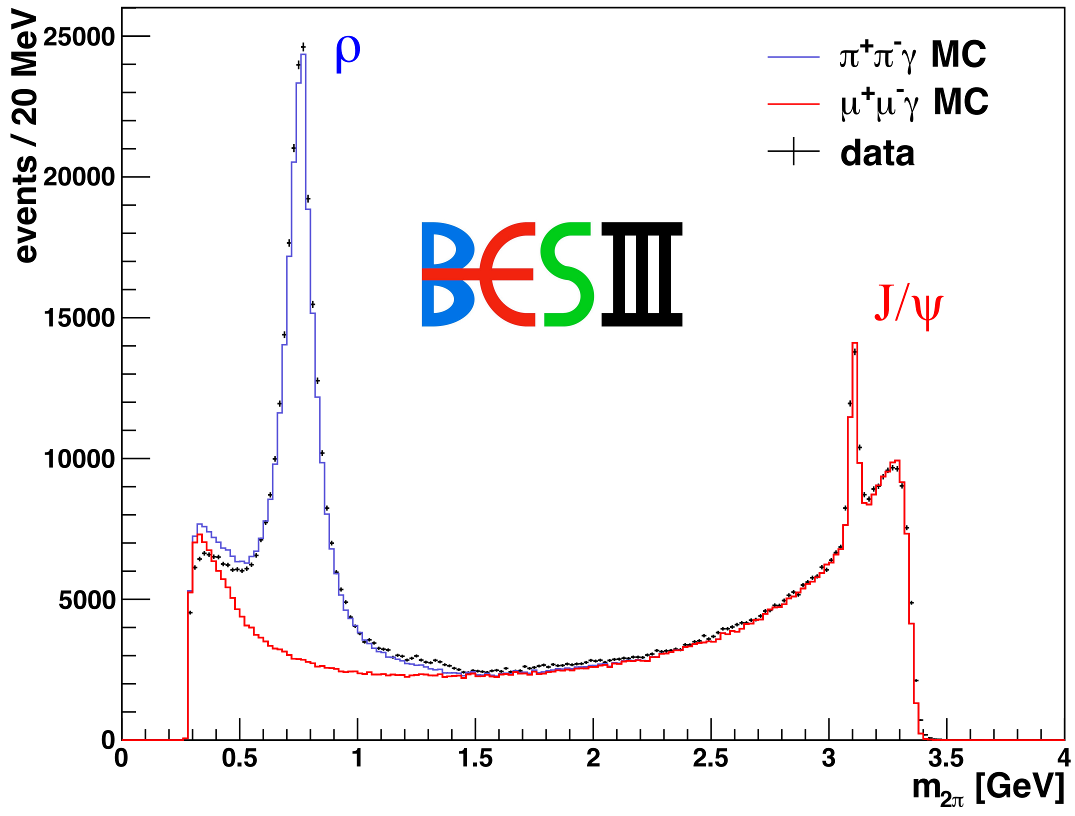


# BESIII ISR Analysis: $e^+e^- \rightarrow \pi^+\pi^-\gamma_{ISR}$

## Initial State Radiation




Event yield after acceptance cuts **only**

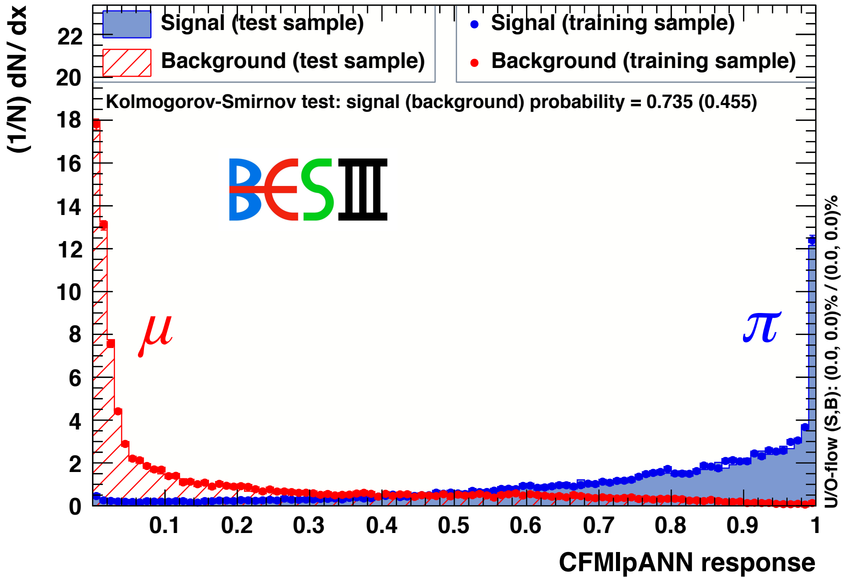



**Features**:

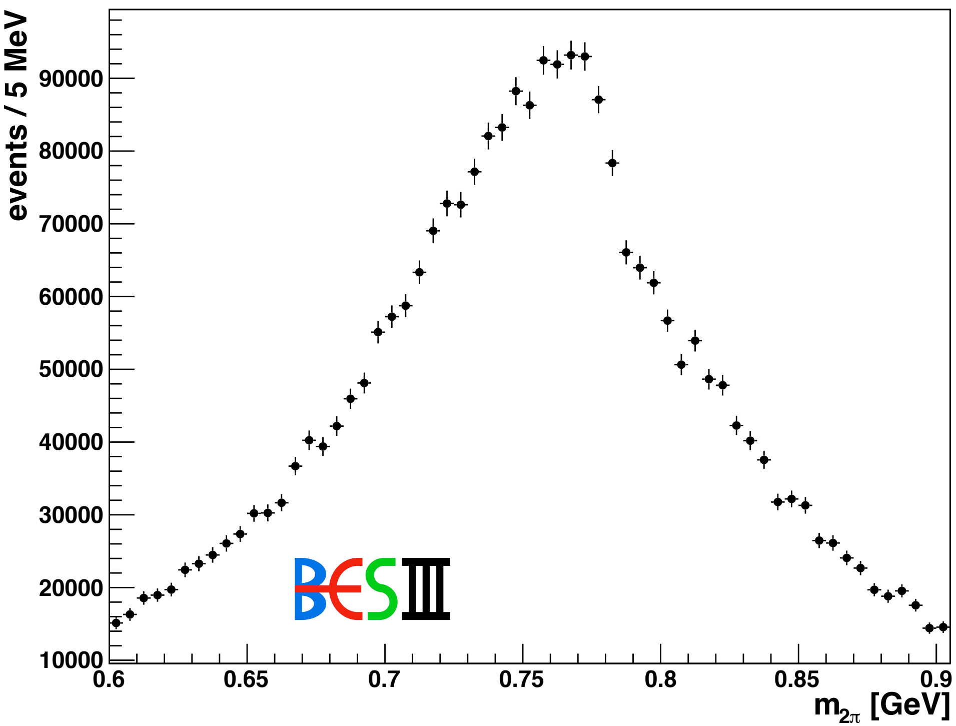
- $\psi(3770)$ data only (2.9 fb$^{-1}$)
- no dedicated background subtraction
- tagged ISR photon

**Pion Muon Separation needed**
**→ TMVA methods!**

# $e^+e^- \rightarrow \pi^+\pi^-\gamma_{ISR}$: $\pi$ - $\mu$ Separation




Event yield ππγ after π-μ separation

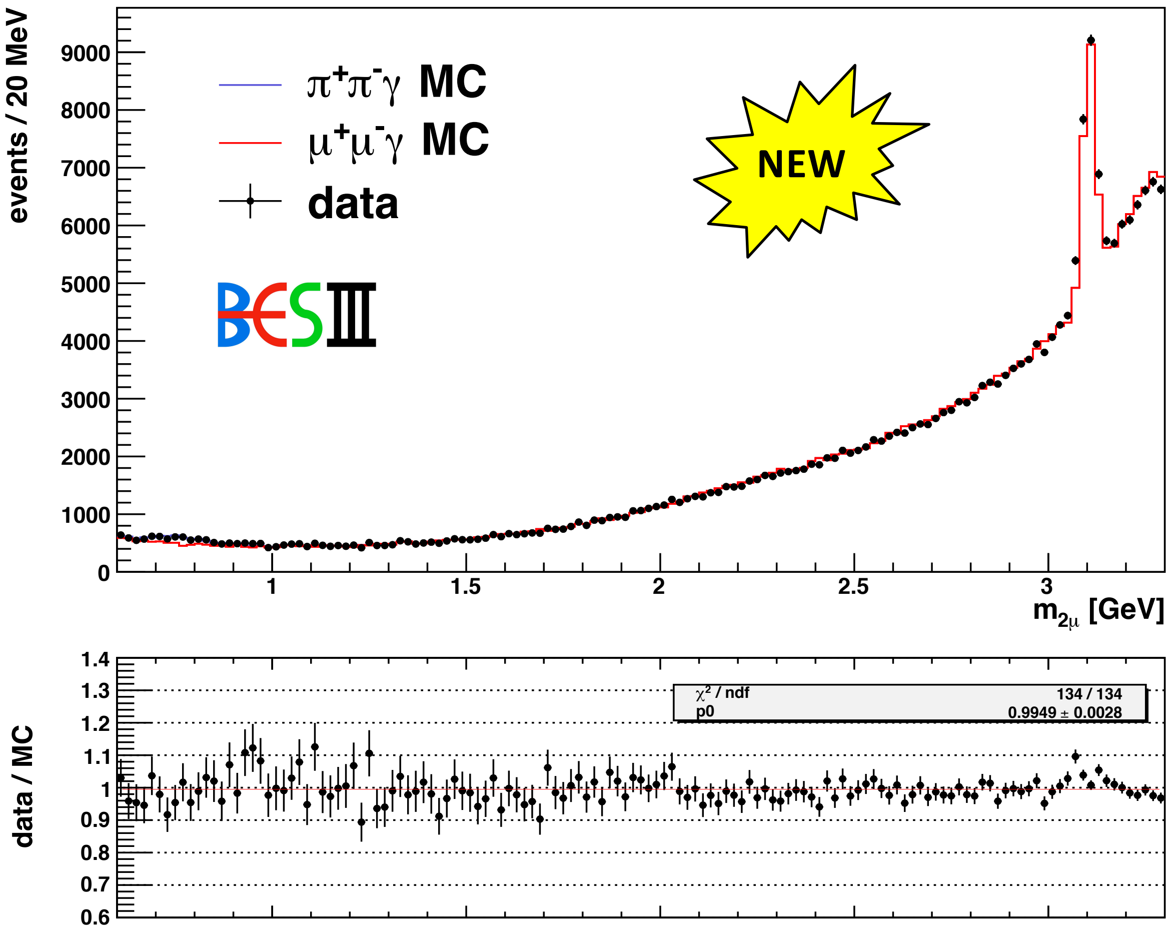



**TMVA method (Neural Network)**:

- trained using μμγ and ππππγ MC events
- information based on track level
- efficiency matrix (p,Θ) for data, MC
- corrected for data - MC differences
- cross checked for different TMVA methods

# Measurement of $\mu^+\mu^-\gamma$: Data vs. QED

Event yield $\mu\mu\gamma$ after $\pi$-$\mu$ separation (ANN)

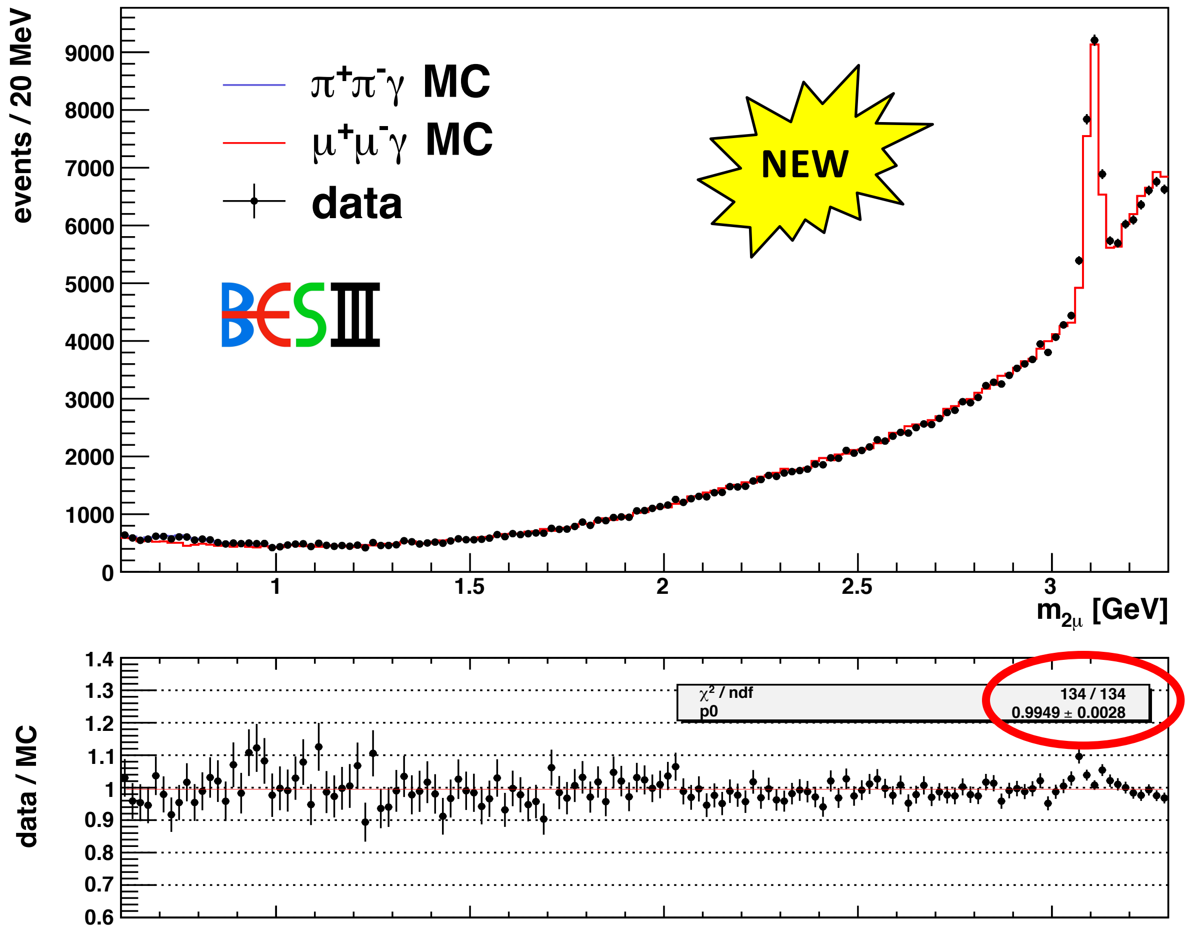



**Features**:

- background from $\pi\pi\gamma$ very small
- PHOKHARA accuracy <0.5%
- luminosity measurement based on Bhabha ev., 0.5% accuracy

# Measurement of $\mu^+\mu^-\gamma$: Data vs. QED

Event yield μμγ after π-μ separation (ANN)




**Features**:

- background from ππγ very small
- PHOKHARA accuracy <0.5%
- luminosity measurement based on Bhabha ev., 0.5% accuracy

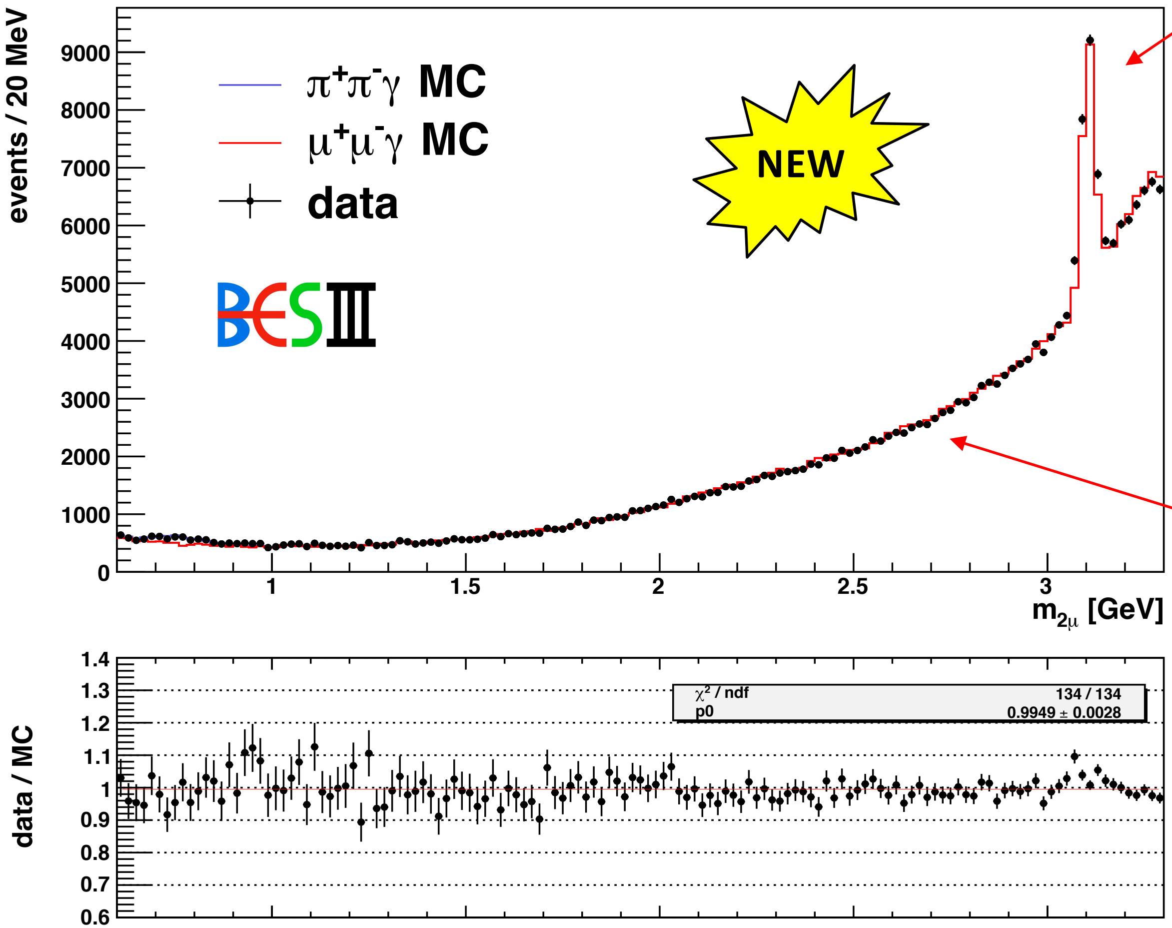
→ excellent agreement with QED

**Δ(MC/QED-data) -1 = (0.51 ± 0.28) %**

→ accuracy on 1% level as needed to be competitive !

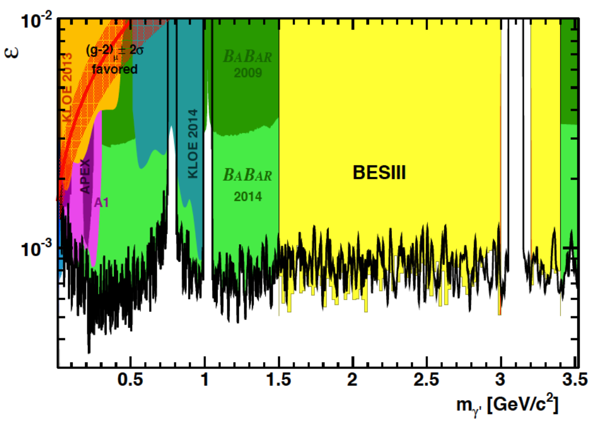
# $e^+e^- \to \mu^+\mu^-\gamma$: Spin-Off Analyses

Event yield $\mu\mu\gamma$ after $\pi$-$\mu$ separation (ANN)




$\Gamma_{ee}$ ($J/\psi$) / keV =
$5.58 \pm 0.05_{stat} \pm 0.08_{syst}$
BES III, PLB 04/2016

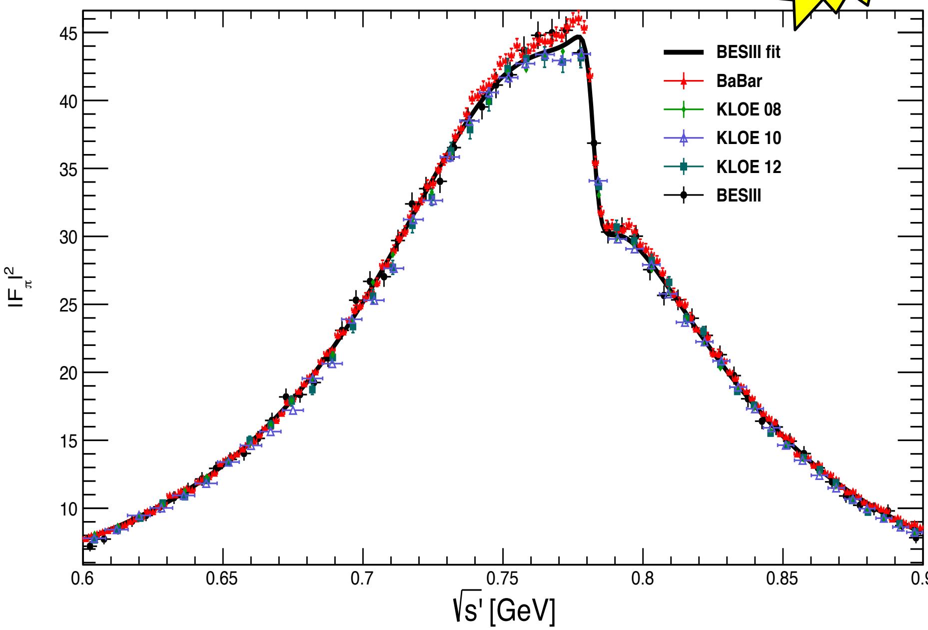
Dark Photon Search

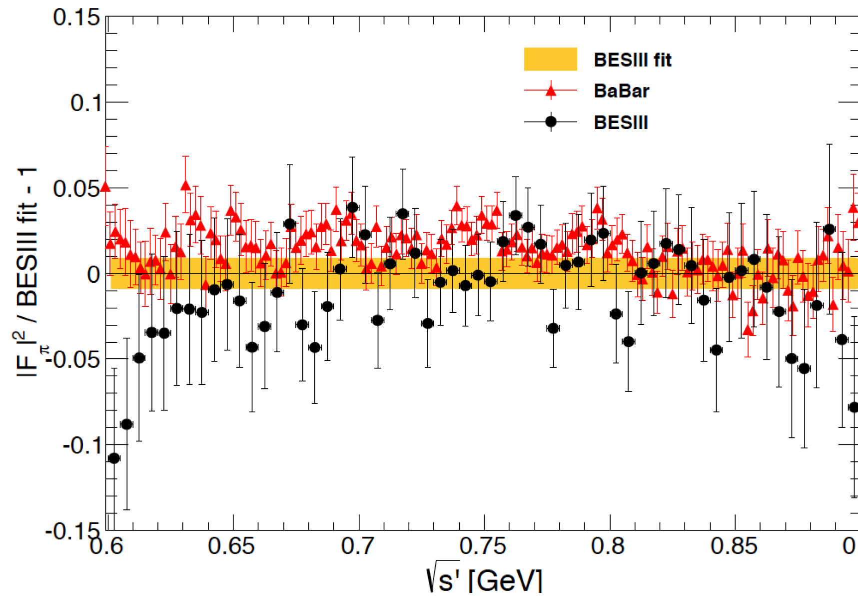


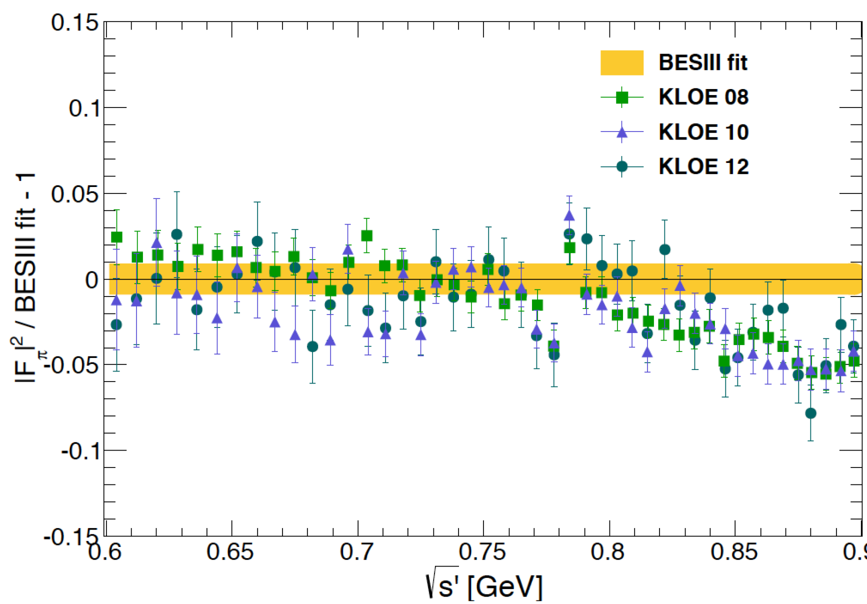
# Comparison with existing Data

**NEW**

## Pion Form Factor $F_\pi$



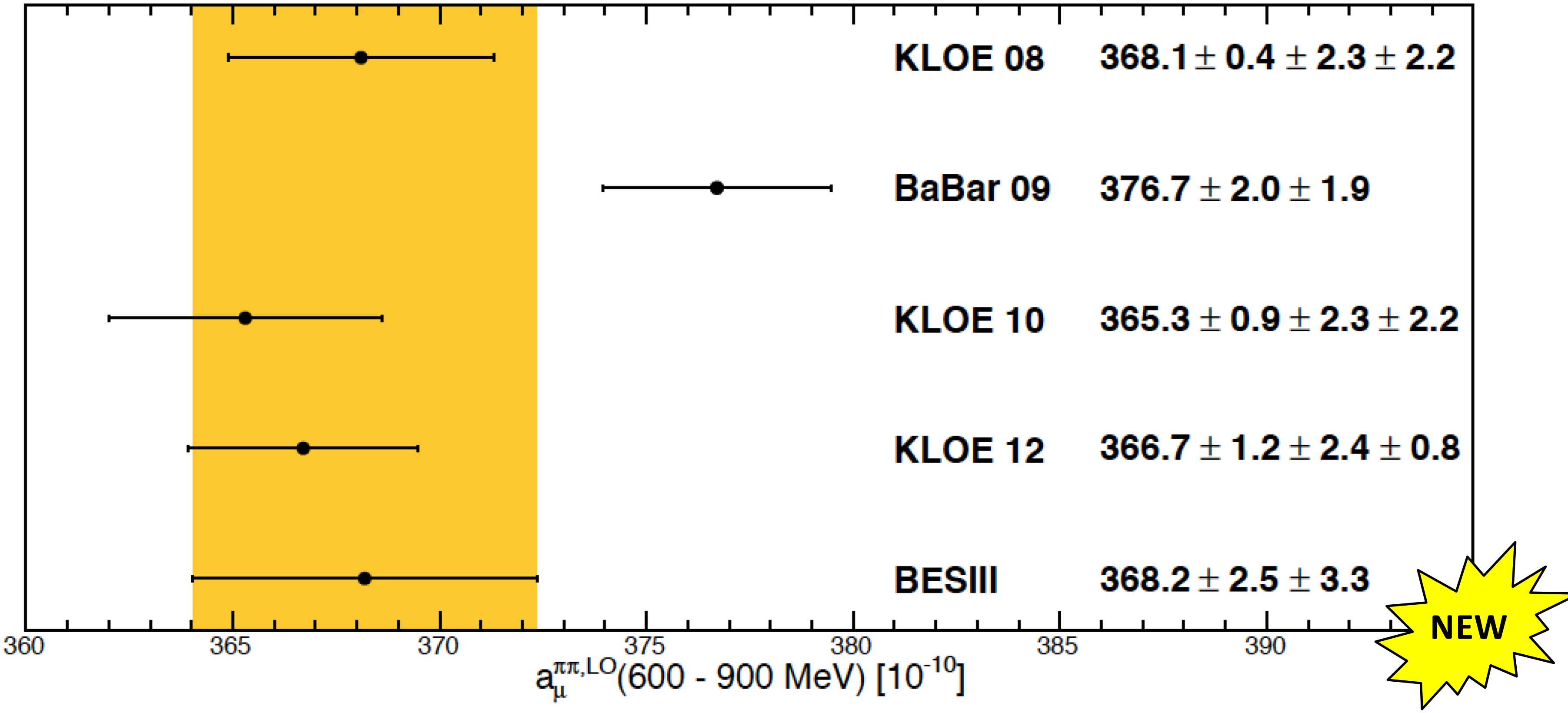




**0.9 % accuracy**

normalization to luminosity / radiator function

# *Impact on Hadronic Vacuum Polarization*

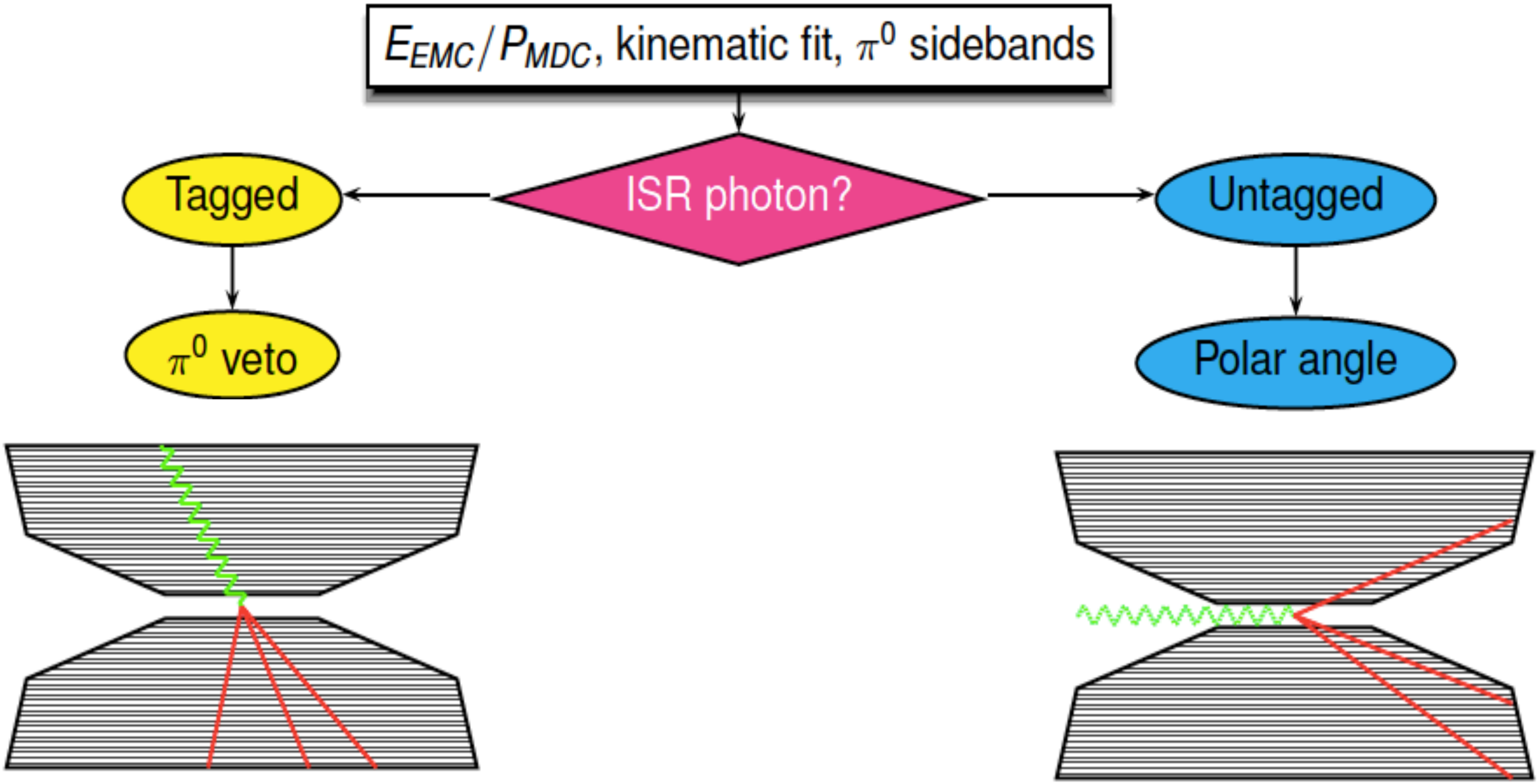
PLB753 (2016)




**Good agreement with KLOE found !**

**BES III confirms the $(g\text{-}2)_\mu$ deviation at 3 …4 sigma level !!!**

# BESIII ISR Analysis: $e^+e^- \rightarrow \pi^+\pi^-\pi^0\gamma_{ISR}$



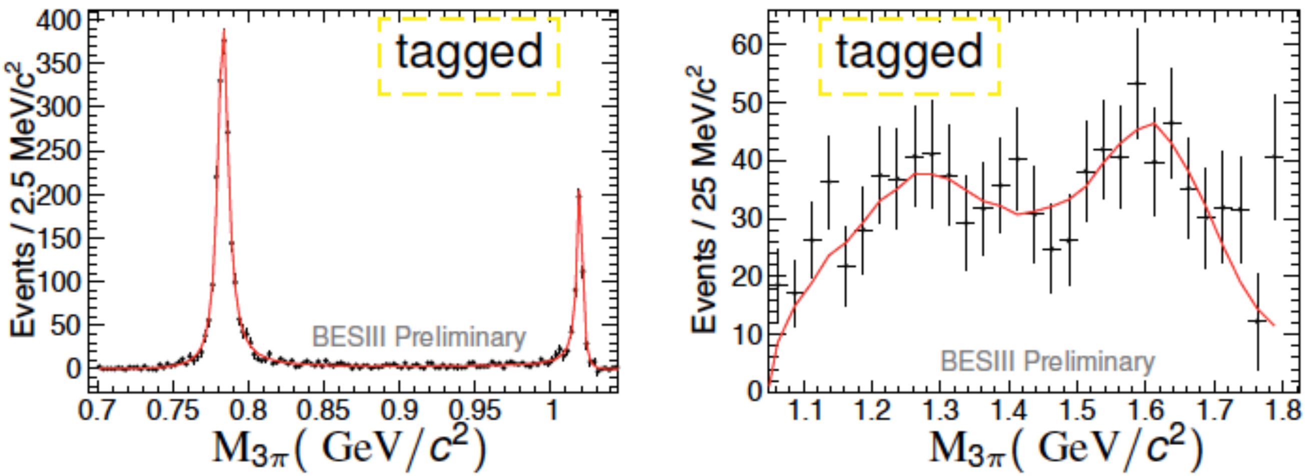

Cover full mass range
Flat efficiency curve
Huge background > 1.5 GeV

Kinematically allowed > 1 GeV
Efficiency increases with mass
Much reduced background

# *Tagged Analysis:* $e^+e^- \rightarrow \pi^+\pi^-\pi^0\gamma_{ISR}$

JG|U

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

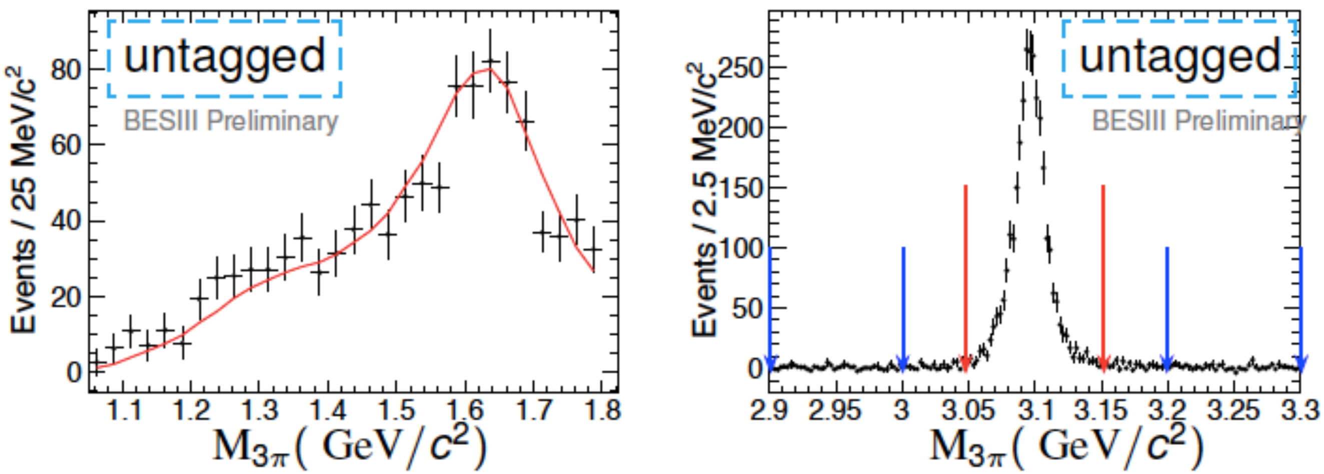



**NEW**

- Toy MC study to check effect of background
- Mass, width of $\omega$ and $\phi$ in agreement with PDG
- Branching ratios of $\omega$ and $\phi$ into $3\pi$ in agreement with PDG
- Clear indication for $\omega(1420)$ and $\omega(1650)$

# *Untagged Analysis:* $e^+e^- \rightarrow \pi^+\pi^-\pi^0\gamma_{ISR}$

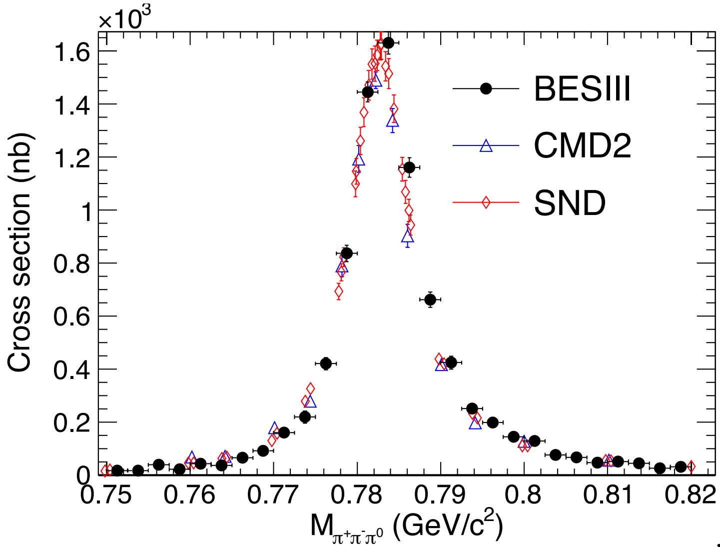
$$\mathcal{B}(J/\psi \to \pi^+\pi^-\pi^0) = \frac{N_{\rm sig}}{N_{J/\psi}\times\epsilon\times\mathcal{B}(\pi^0\to\gamma\gamma)}$$

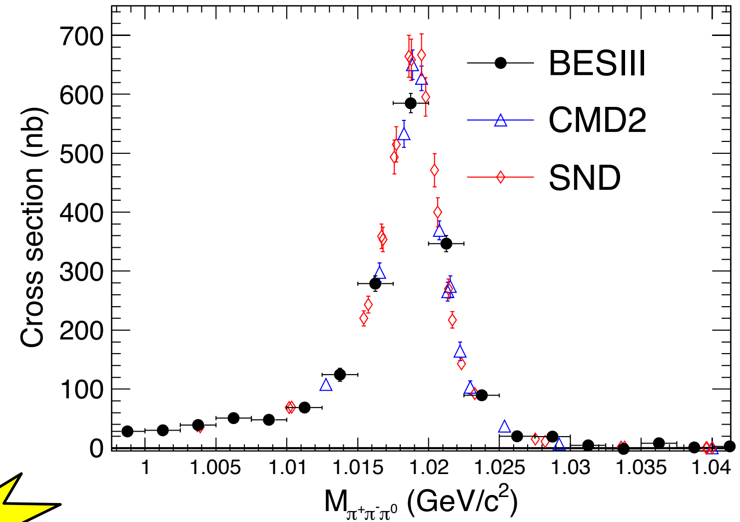



NEW

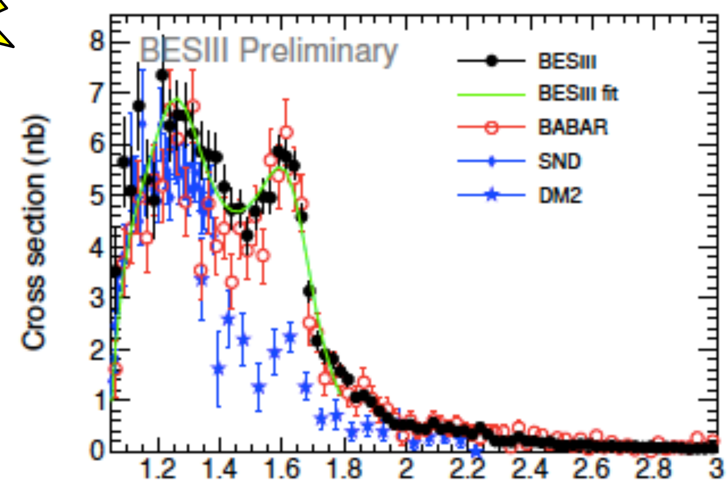
- Extract the J/ψ branching ratio to 3π
- Effect of interference found to be small
- BES III: BR(J/ψ → 3π) = ( 2.18 ± 0.03 ± 0.06 ) %
- PDG: ( 2.11 ± 0.07 ) %

# *Comparison with existing Data (preliminary)*




NEW



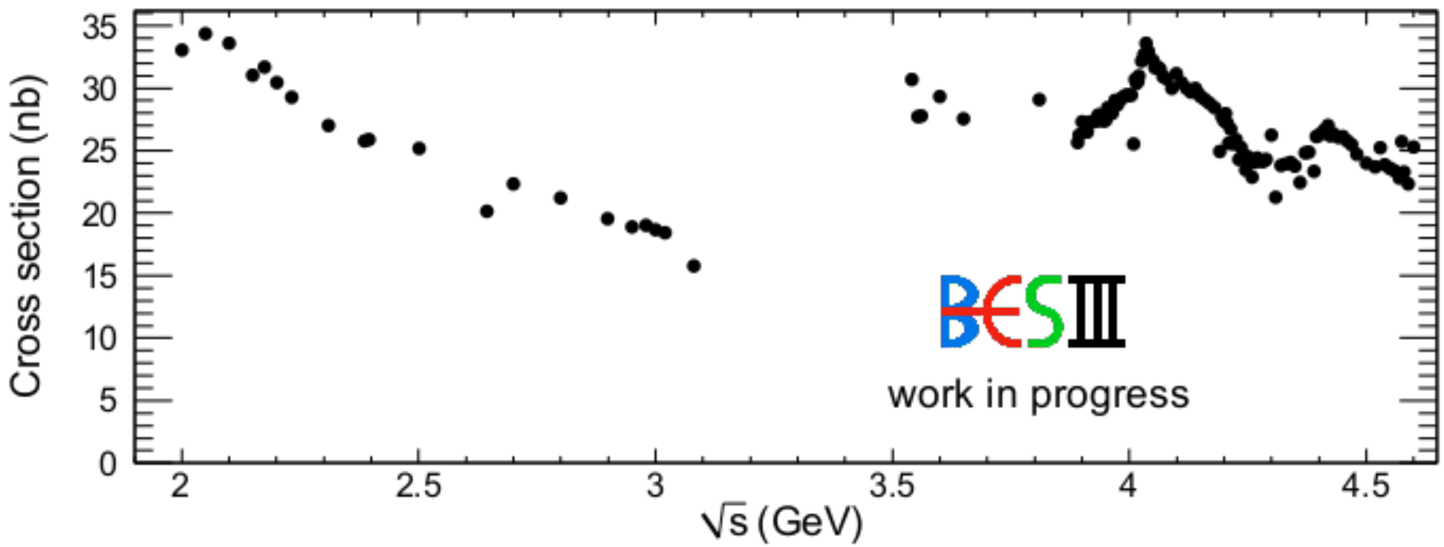

Above $\phi$

- Systematic uncertainty < 1 GeV ~2%
- Larger binning wrt. CMD-2/SND
- Above 1 GeV in agreement with BABAR
- Hope to publish results shortly

# *New R Scan 2.0 - 4.6 GeV finished*

**Reducing the uncertainty of $\alpha_{em}(M_Z^2)$ by a factor 2**
**→ A new quantity of electroweak precision fits**

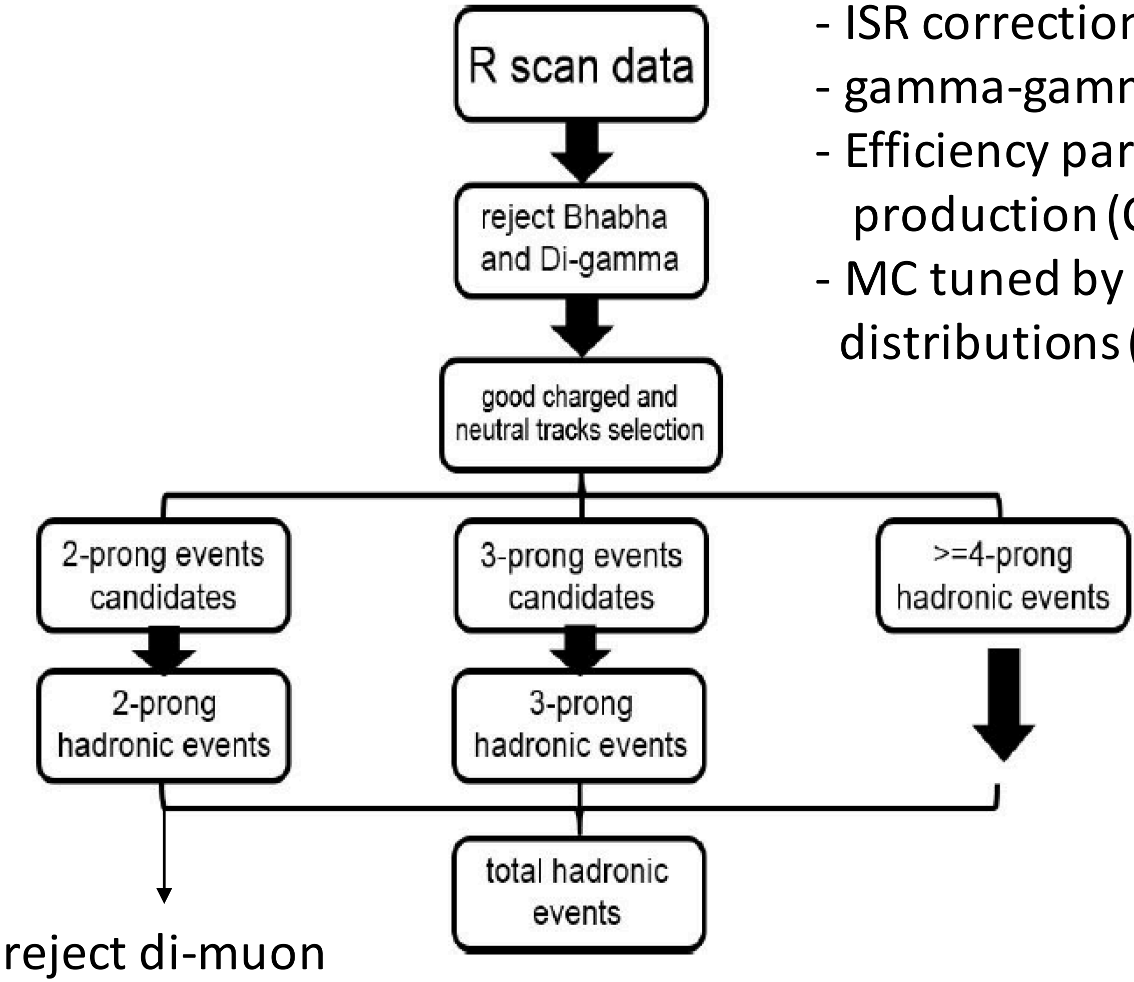
**Online spectrum of R scan recently finished**




**$R_{incl} = \sigma_{had}/\sigma_{\mu\mu}$ ratio with targeted 3% systematic accuracy (statistical error <<1%)**

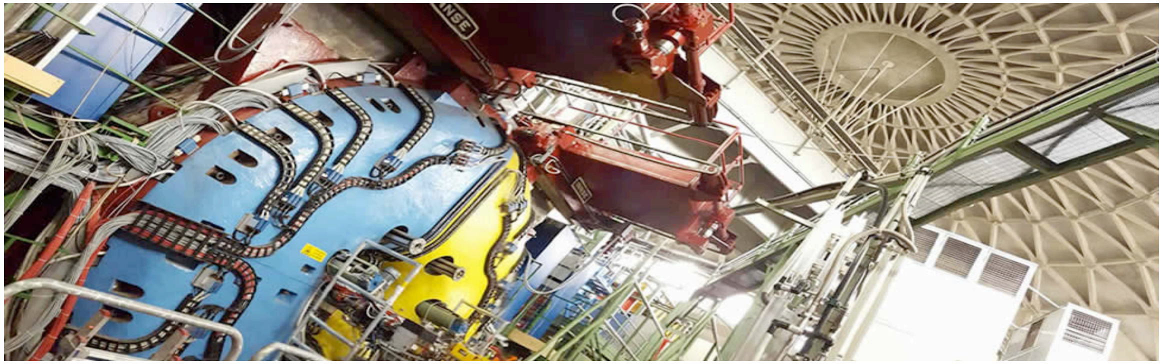
- World's best measurement so far from BES /BESII with 5 ...8 % total error (with 3 ... 5% statistical error)

# *Inclusive R Measurement*




**Issues:**

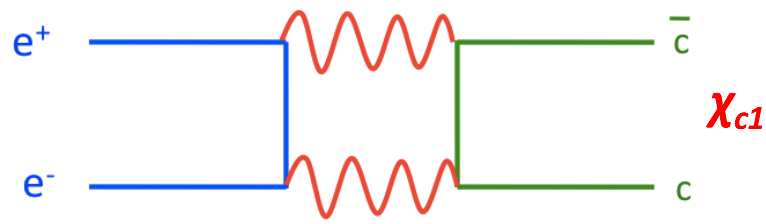
- ISR corrections ("Radiative Return")
- gamma-gamma background
- Efficiency partly obtained from excl. MC production (ConExc) based on phase space
- MC tuned by comparison with kinematic distributions ($N_{trk}$, $p_{trk}$, $E_\gamma$, Yields of $\pi^0$, $K_S$)



# *Production of Non-Vector-Resonances in $e^+e^-$ Annihilation*

# Production $e^+e^- \to \chi_{c1}$

$$e^+e^- \to 1^{++}$$




- $\chi_{c1}$ **Parameters:** Mass $\chi_{c1}$ = 3.5107 GeV
  Width $\chi_{c1}$ = 0.86 MeV
  Main decay channel (35% BR): $\chi_{c1} \to \gamma\, J/\Psi$

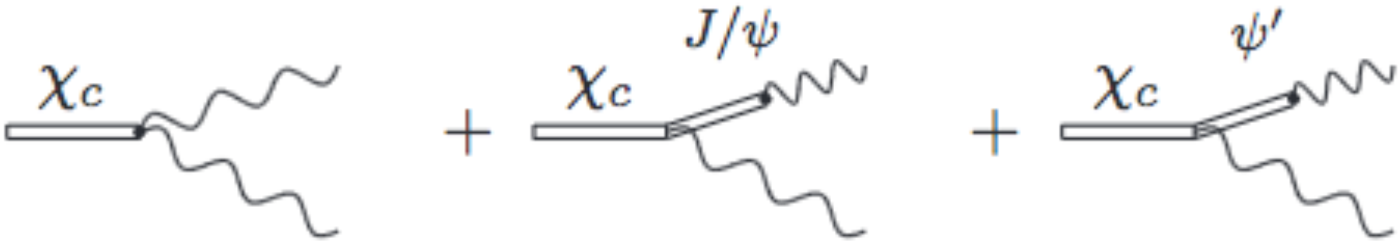
→ **Signal process:** $e^+e^- \to \gamma\, J/\psi \to \gamma\, \mu^+\mu^-$

Irreducible background process: ISR production of $J/\psi$

# *Electronic Width of* $\chi_{c1}$

Czyz, Kühn, Trasc, arXiv:1605.06803

Interference effects lead to a value for $\Gamma_{ee}$ for $\chi_{c1}$ of 0.41 eV




J. Kaplan, H.Kühn, PLB78 (1978) 252

Vector Meson Dominance (without $\psi$') predicts $\Gamma_{ee}$ for $\chi_{c1}$ of 0.46 eV

used for our beam time proposal

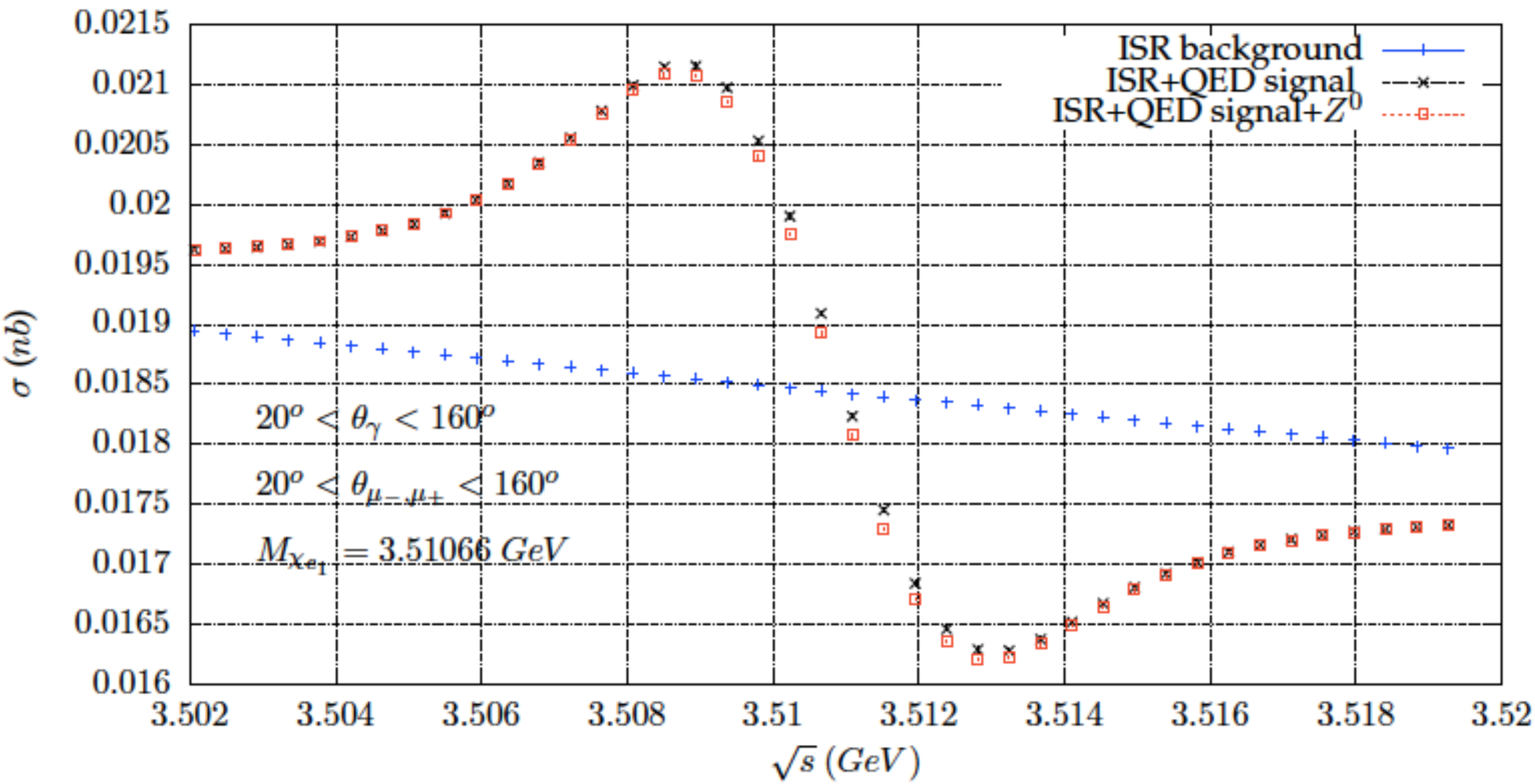
N. Kivel and M. Vanderhaeghen, JHEP 02, 032 (2016)

Soft Collinear Theory $\Gamma_{ee}$ for $\chi_{c1}$ is 0.09 eV

A.D., F.-K. Guo, C. Hanhart, A. Nefediev, PLB 736, 221 (2016)

Vector Meson Dominance (without $\psi$') predicts $\Gamma_{ee}$ for $\chi_{c1}$ of 0.1 eV

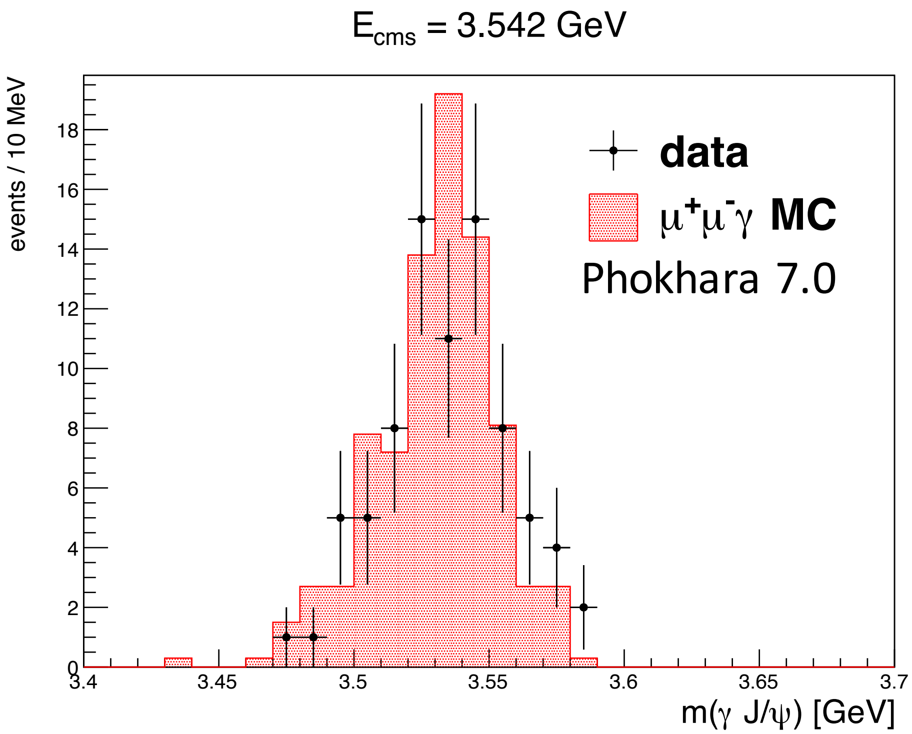
# *Signal Cross Section* $e^+e^- \to \chi_{c1}$



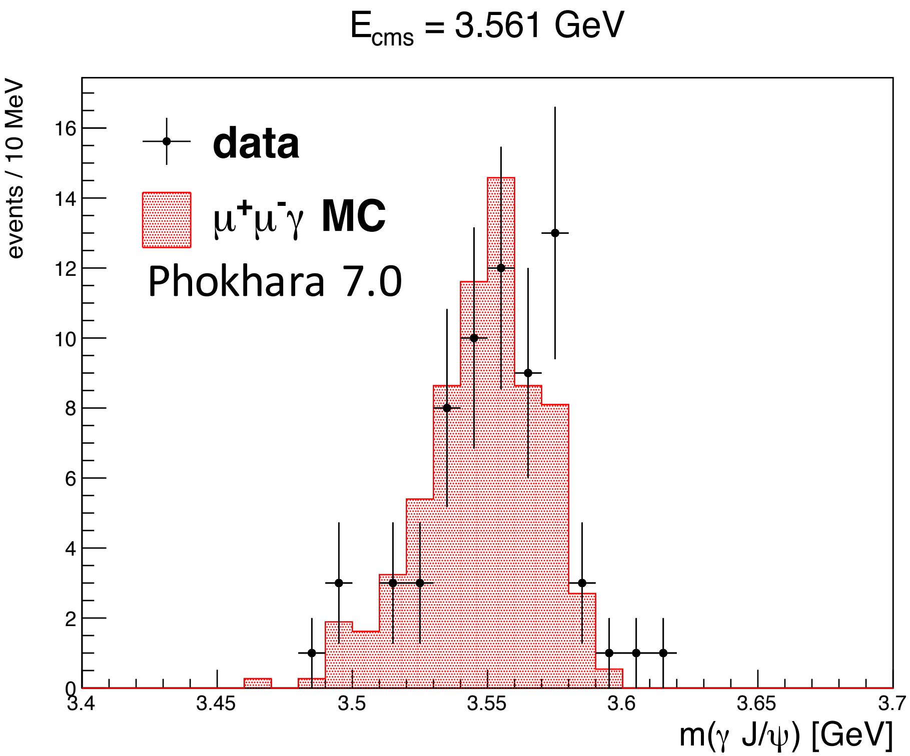

Effect of the resonance ~ 10%

# ISR Background $e^+e^- \rightarrow \mu^+\mu^-\gamma_{ISR}$

31 MeV above signal




50 MeV above signal



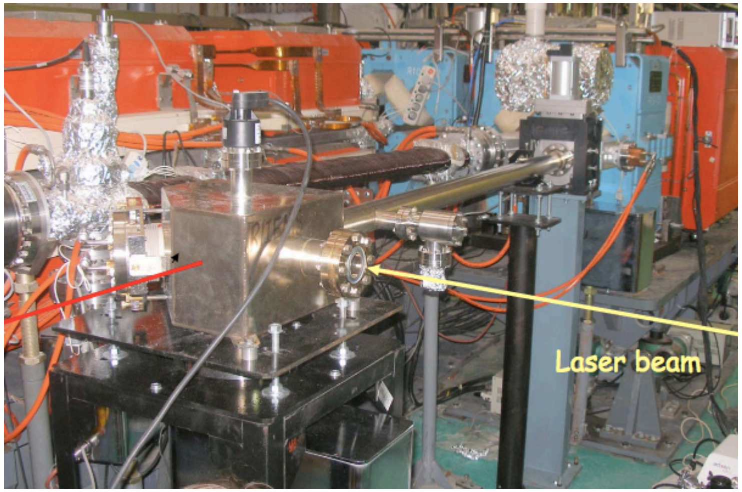

- excellent agreement, no indication of additional background
- effective cross section background 20.6 pb

# *Data Taking Plan at BES III* $e^+e^- \rightarrow \chi_{c1}$

- Start of data taking campaign 2016/2017 (beginning of 12/16)
  → 2 weeks of data taking (> 300 $pb^{-1}$)
  → Additional 10 days of data taking in case of >2sigma observed

- Potential to observe 5 sigma effect (assuming no phase!)
  Beam energy spread, ISR effects included in calculation

- Beam Energy Measurement System
  Compton Backscattering developed by Novosibirsk group will be in place
  <<$10^{-4}$ accuracy



# *Data Taking Plan at BES III* $e^+e^-$ $\chi_{c1}$

- Start of data taking campaign 2016/2017
  (beginning of 12/16)
  → 2 weeks of data taki
  → Additiona

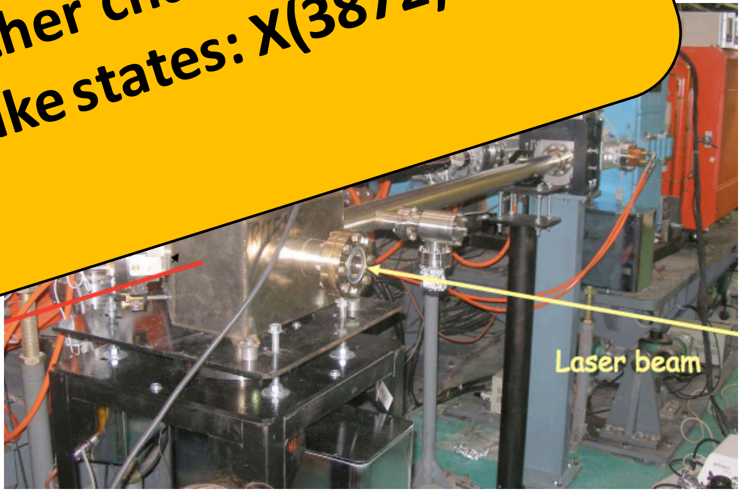
- Pot
  Bear

- Beam
  Compt
  Novosib
  <<$10^{-4}$ ac

**Historically first measurement in e+e-**
**of a production of a non-vector state**

**Test two-photon coupling of**
**mesons, all virtualities**

**Can be applied to other charmonium**
**and charmonium-like states: X(3872)**

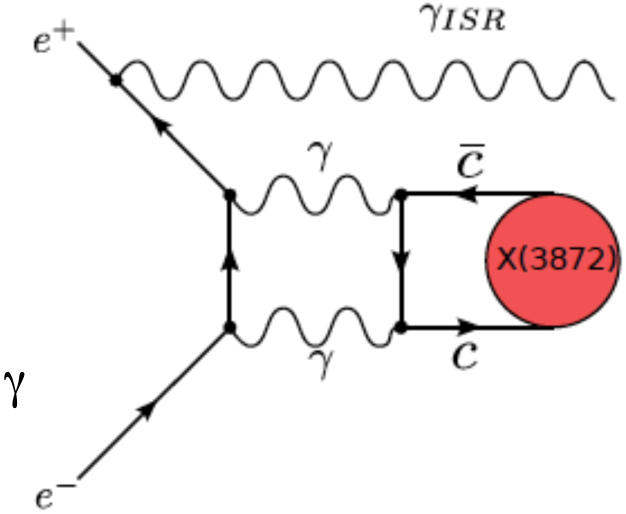


# *Upper Limit of* $\Gamma_{ee}$( X(3872) )

- Search for X(3872), $J^{PC}=1^{++}$, via
  Initial State Radiation ISR

- Fully available BESIII data set

- Small angle ISR photon
  At large angle production via Y(4260)→ X(3872) γ



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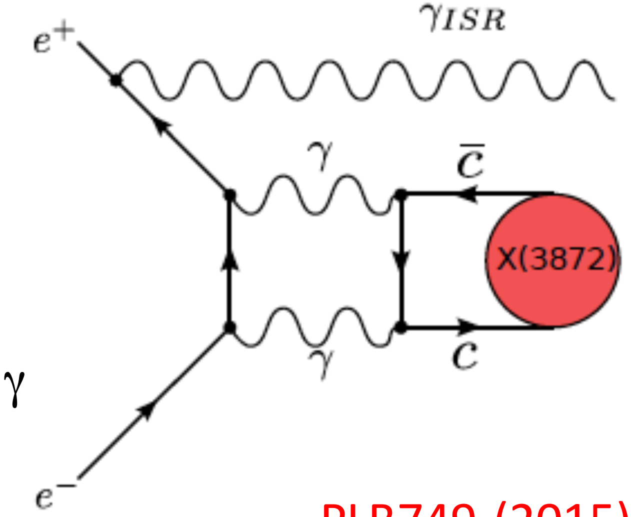
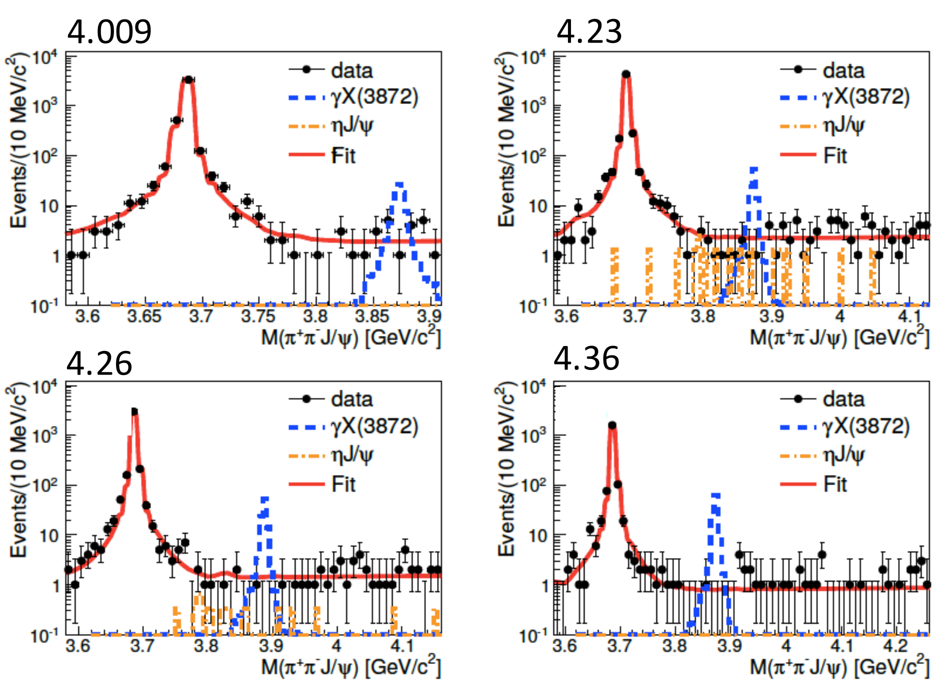
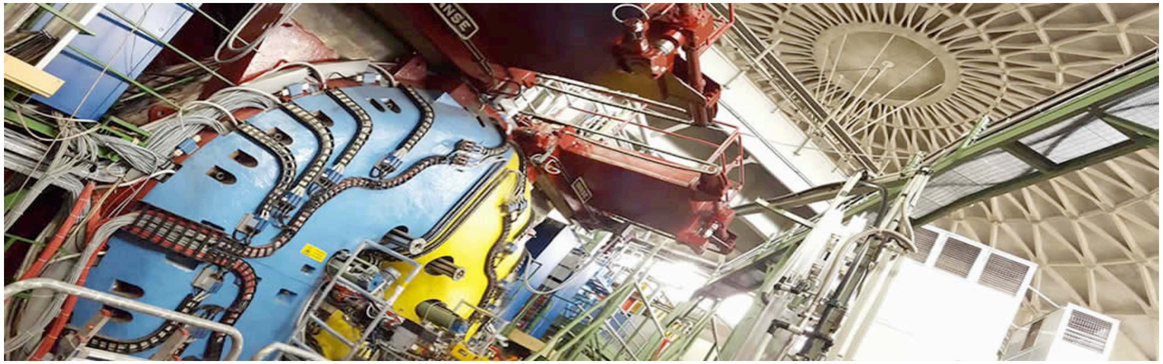



PLB749 (2015)

$\Gamma_{ee}$ ( X(3872) ) < 4.3 eV
Factor ~50 improvement

$\Gamma_{ee}$ ( ψ(2S) ) =
( 2213 ± 18 ± 99 ) eV
World's most precise measurement



# *Conclusions*

# *Topics of $e^+e^-$ physics outside the phi*

Break down of top-100 cited papers of BABAR collaboration

| Physics topic BABAR | Nr. of publications |
|---|---|
| B decays and CP violation | 51 |
| Heavy quark spectroscopy | 25 |
| Hadron form factors | 12 |
| Flavour physics and LFV studies | 7 |
| Searches for BSM particles + Symmetry tests | 5 |

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our field

**Field of form factor measurements important part of the programme of low-energy particle physics with many implications (from Nucleon Structure, QCD tests to New Physics searches)**

# International Workshop on $e^+e^-$ collisions from Phi to Psi 2017

26-29 June 2017
Schloss Waldthausen
Europe/Berlin timezone

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

- **Overview**
- Scientific Programme
- Timetable
- Contribution List
- Speaker List
- Registration
  - Registration Form
- Registration Fee
- Participant List
- Advisory Committee
- Accommodation
- Venue & Social Events
- Travel Information
- Previous Editions


Woodcarving of Franz Behem, 1565 (Stadtarchiv Mainz)

The 11th edition of the "International worksh... by the Institute for Nuclear Physics ... Schloss Waldthausen, an ... city limits, on June ...

PhiP... (1996) and in No... theorists to review in detail the stat... developments, and discuss the potential of ex...

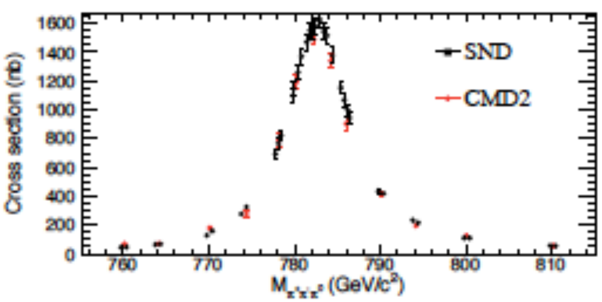
The w... meeting of the Working Group on Radiative Corrections and Monte ... Energies (RadioMonteCarLOW), held on June 30th / July 1st. The aim of this W... to bring together theorists and experimentalists in order to discuss the current status of ... corrections and Monte Carlo generators at low energies.

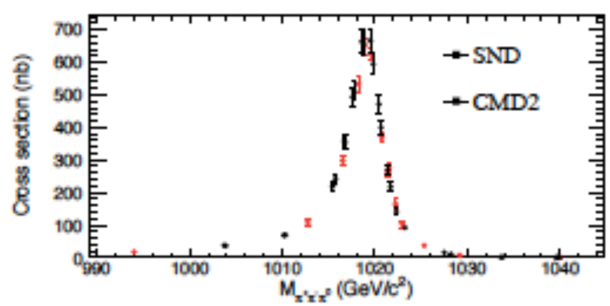
**Save the date: PHIPSI 2017**
**June 26 - 29**

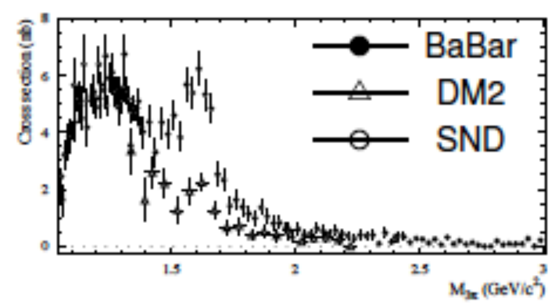
# BACKUP

# BESIII ISR Analysis: $e^+e^- \rightarrow \pi^+\pi^-\pi^0\gamma_{ISR}$

- History of $\sigma$ for $e^+e^- \rightarrow \pi^+\pi^-\pi^0$ :
  - $\sqrt{s} \lesssim 1$ GeV: $\omega(782)$ and $\phi(1020)$
  - Published results above $\phi$ :
    - SND : up to 1.4 GeV
    - DM2 : 1.34 $\sim$ 2.40 GeV
    - BaBar : 1.05 $\sim$ 3.00 GeV

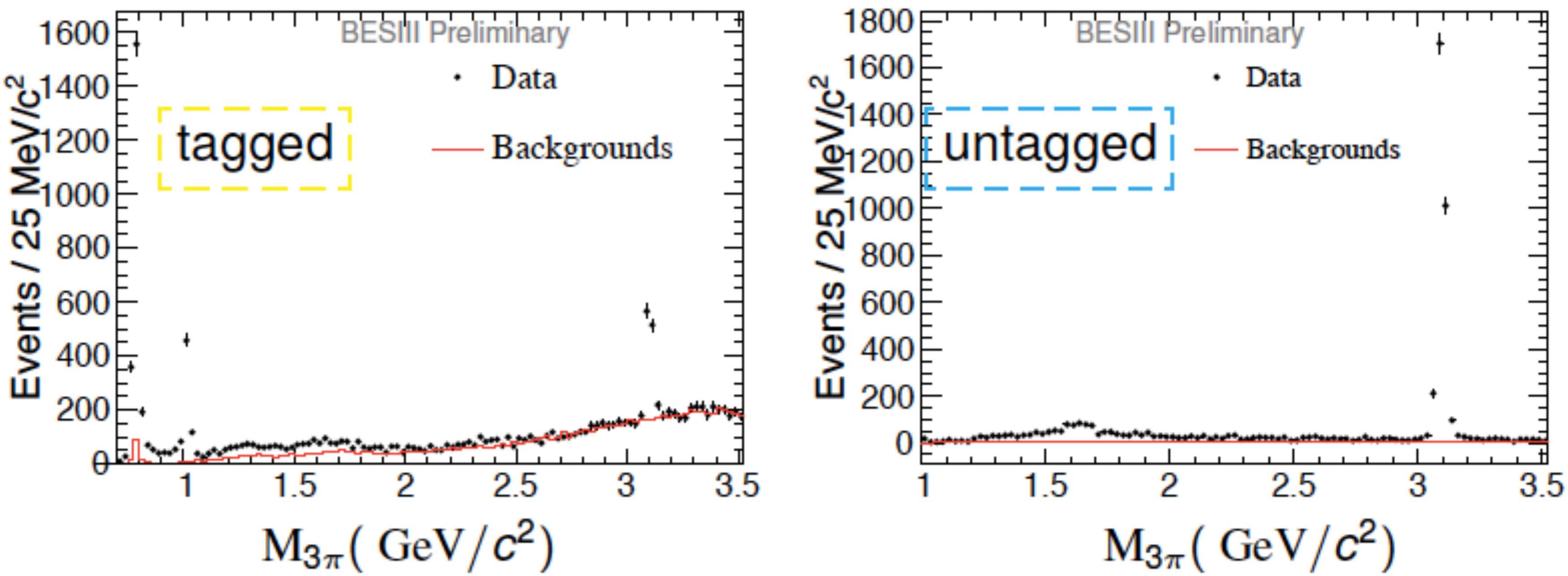


# BESIII ISR Analysis: $e^+e^- \rightarrow \pi^+\pi^-\pi^0\gamma_{ISR}$

Data-driven background estimation: $e^+e^- \rightarrow (\gamma_{ISR})\pi^+\pi^-\pi^0\pi^0$




- Clear $\omega$ and $\phi$ signals
- Huge BG in high mass region

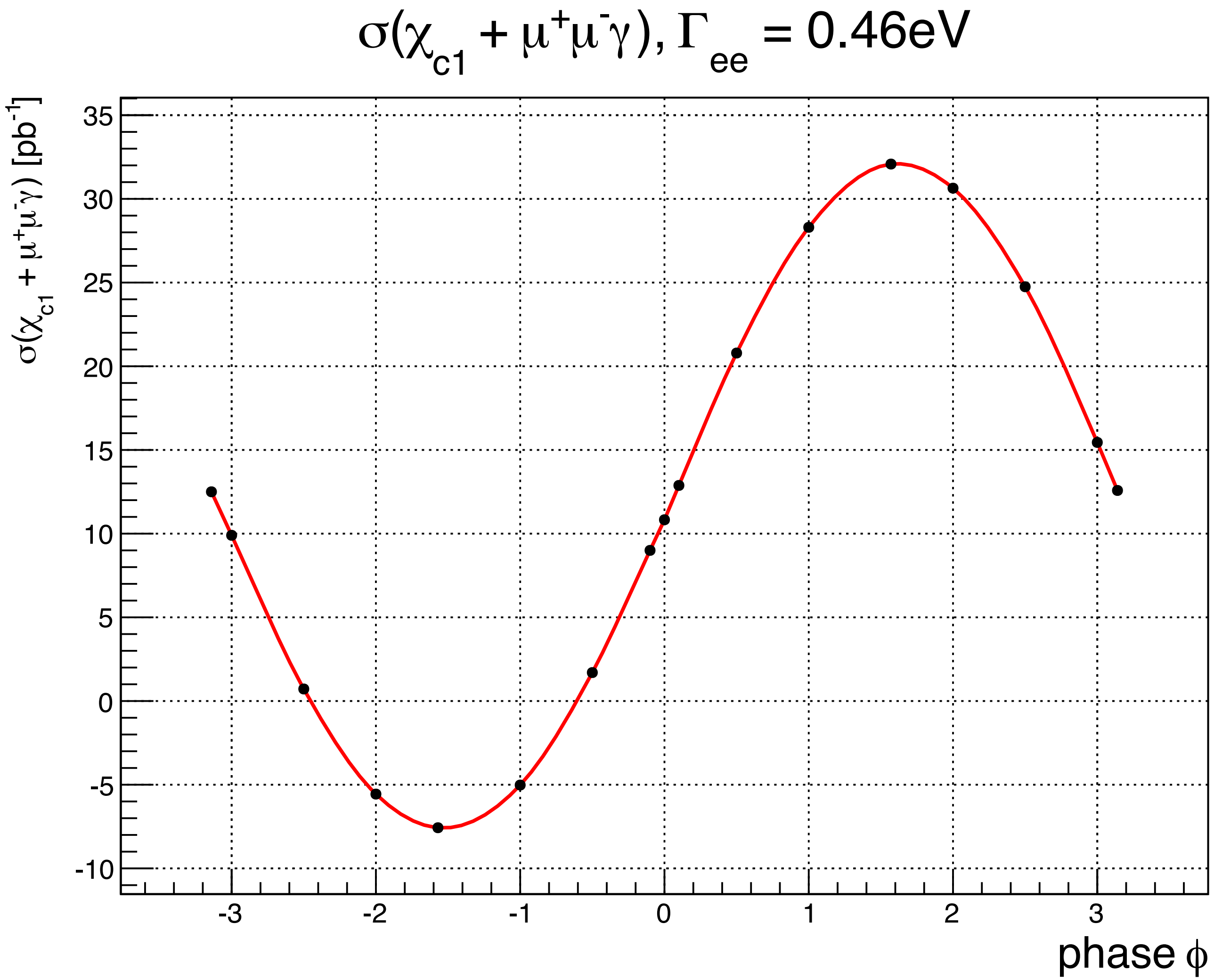
- Limited by acceptance
- Negligible BackGround

# BESIII ISR Analysis: $e^+e^- \rightarrow \pi^+\pi^-\pi^0\gamma_{ISR}$

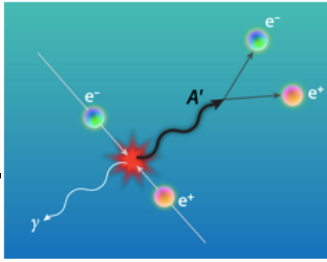
BESIII Preliminary

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

# Signal Cross Section $e^+e^- \to \chi_{c1}$

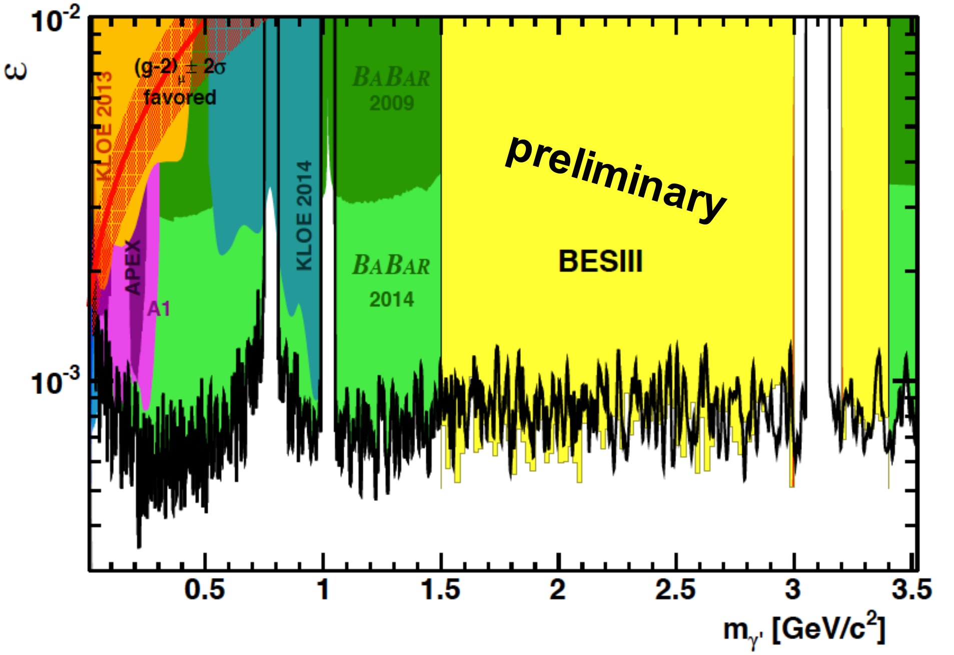


# *Channel $\mu^+\mu^-\gamma$: Dark Photon Search*




$$\frac{\sigma_i(e^+e^- \to \gamma'\gamma_{\mathrm{ISR}} \to l^+l^-\gamma_{\mathrm{ISR}})}{\sigma_i(e^+e^- \to \gamma^*\gamma_{\mathrm{ISR}} \to l^+l^-\gamma_{\mathrm{ISR}})} = \frac{3\pi}{2N_f^{l^+l^-}} \cdot \frac{\varepsilon^2}{\alpha} \cdot \frac{m_{\gamma'}}{\delta_m^{l^+l^-}}$$

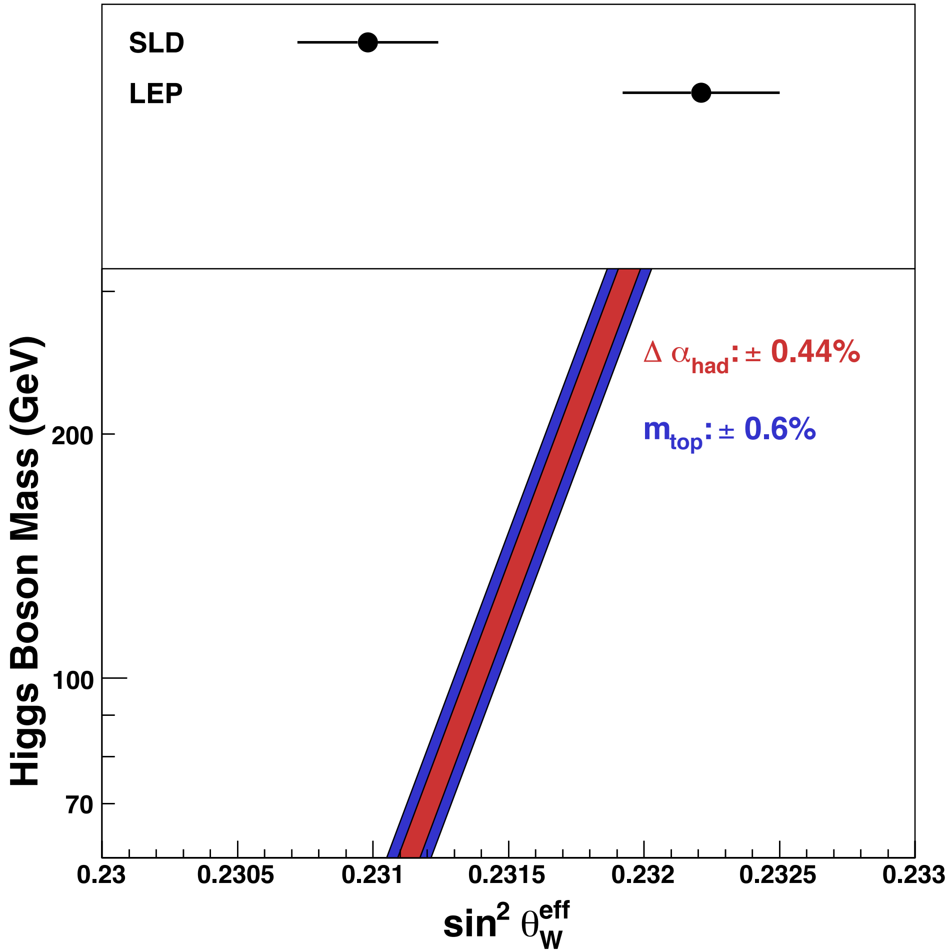
- Include also t-channel Bhabha events
- Data from 2 years of data taking (2.9 $fb^{-1}$)
- Analysis of full data set will yield world's most precise limits > 1 GeV



# *Electroweak Precision Physics*

## $\alpha_{em}(M_Z^2)$ limiting electroweak precision fits

→ Test overall consistency of the electroweak Standard Model
→ Since the discovery of the Higgs boson more timely than ever

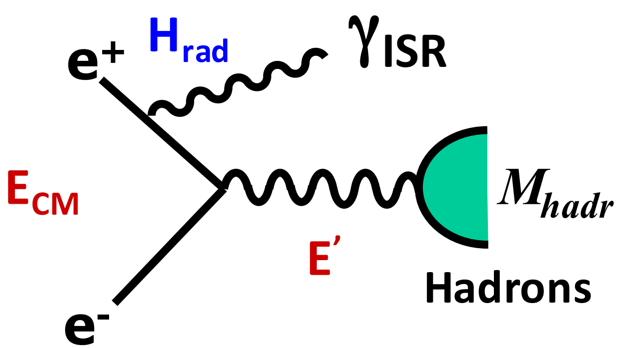



SM running $\sin^2\Theta_W$ ($M_{Higgs}$) limited by $\alpha_{em}$

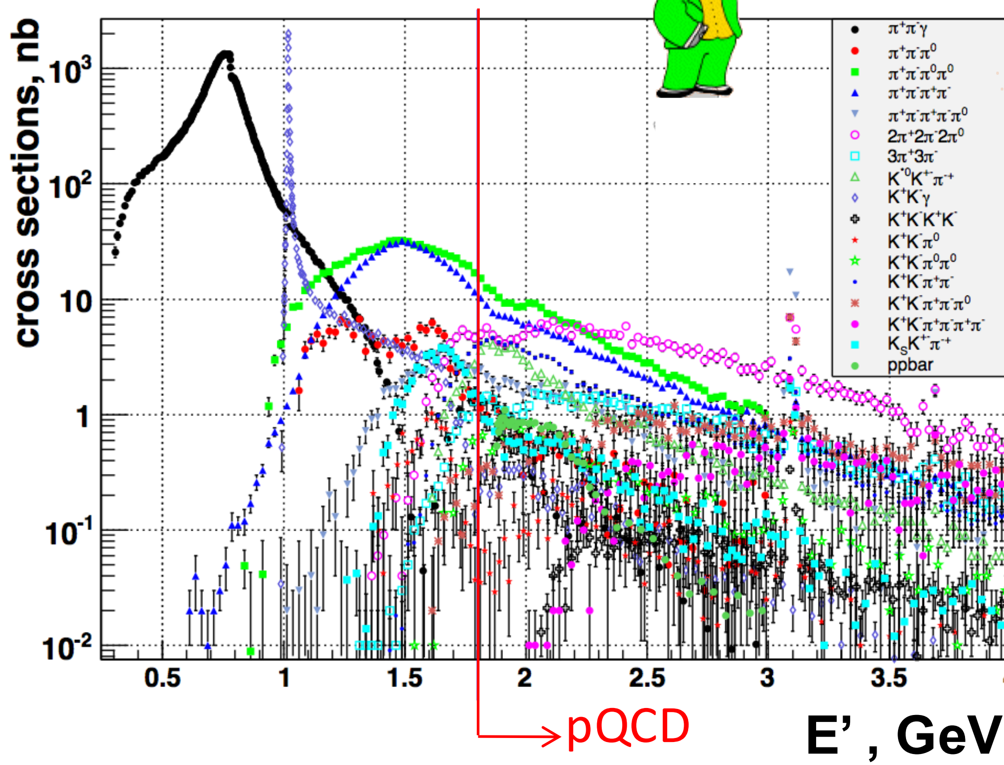
# Initial State Radiation

Rev. Mod. Phys. 83, 1545–1588 (2011)

## Initial State Radiation (ISR) aka Radiative Return




ISR spectra measured by BaBar




- Needs **no** systematic variation of beam energy
- High statistics thanks to high integrated luminosities
- Precise knowledge of radiative corrections mandatory ($H_{rad}$)

PHOKHARA event generator Czyż, Kühn, et al.

**→ Entire E range <$E_{CM}$ accessible**

# *Inclusive R Measurement and $\alpha_{em}(M_Z^2)$*

## Running of $\alpha_{em}$ (s) with s due to vacuum polarization corrections

- Leptonic Vacuum Polarization calculable within QED
- Hadronic Vacuum Polarization not accessible in pQCD → **Dispersion relation**

$$\alpha_{\rm em}(s) \;=\; \frac{\alpha(0)}{(1-\Delta\alpha_{\rm em}(s))}$$

$$\alpha^{-1}(M_Z^2) = 128.962 \pm 0.014$$

Davier, et al.( 2010)

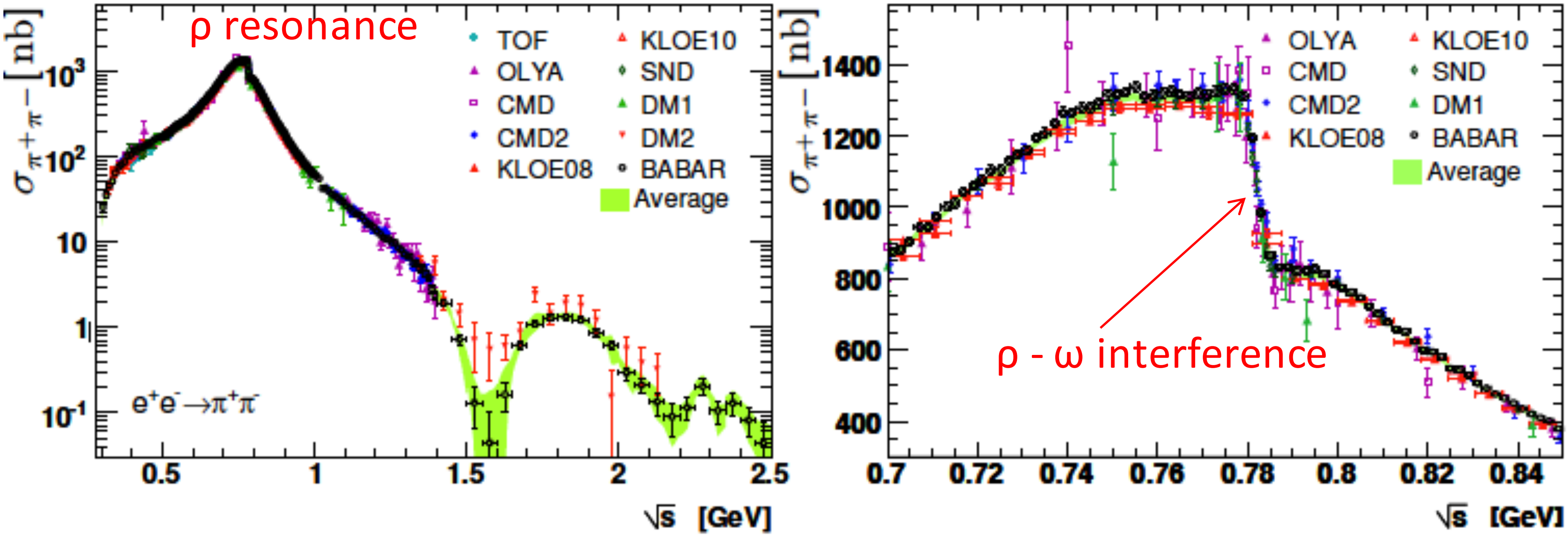
*QED* $\Delta\alpha_{\rm lep}(M_Z^2) \;=\; 314.97686 \cdot 10^{-4}$

*strong* $\Delta\alpha_{\rm had}(M_Z^2) = (274.2 \pm 1.0) \cdot 10^{-4}$

dispersion integral relates $\sigma_{had}$ with $\Delta\alpha_{em}^{had}$

**→ R data up to few GeV essential, above use pQCD !**

# *Most relevant Channel: $e^+e^- \rightarrow \pi^+\pi^-$*

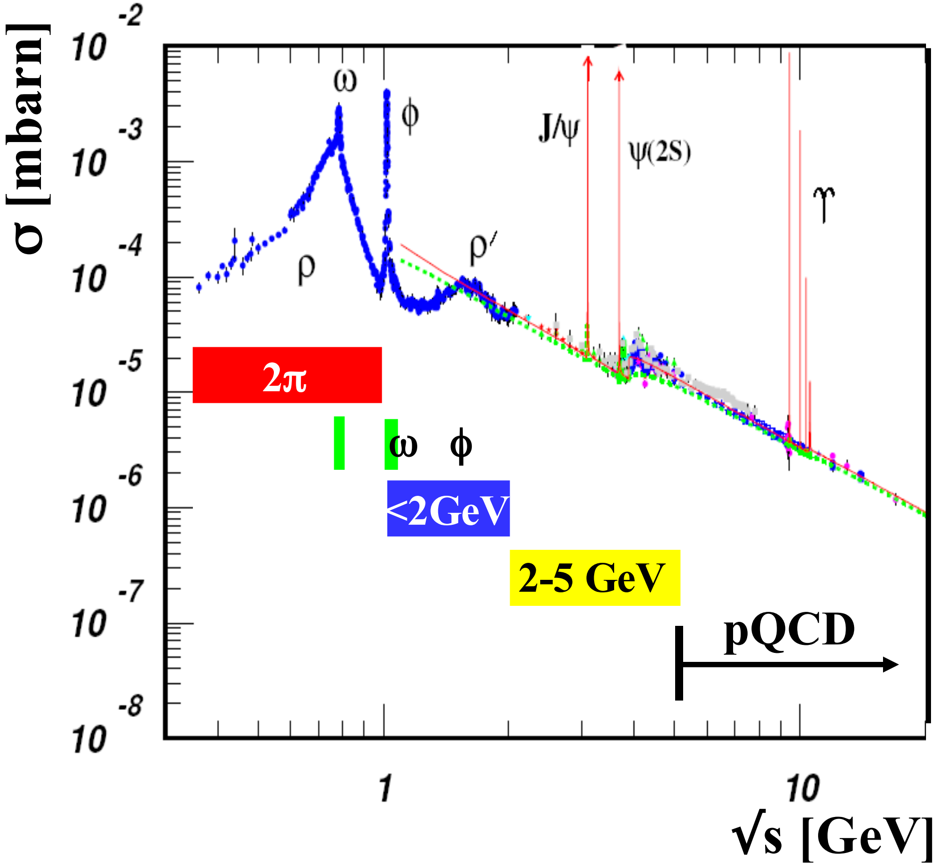



**Systematic Uncertainties**

- BABAR 0.5%
- KLOE 0.8%
- CMD2 0.8%*
- SND 1.5%*

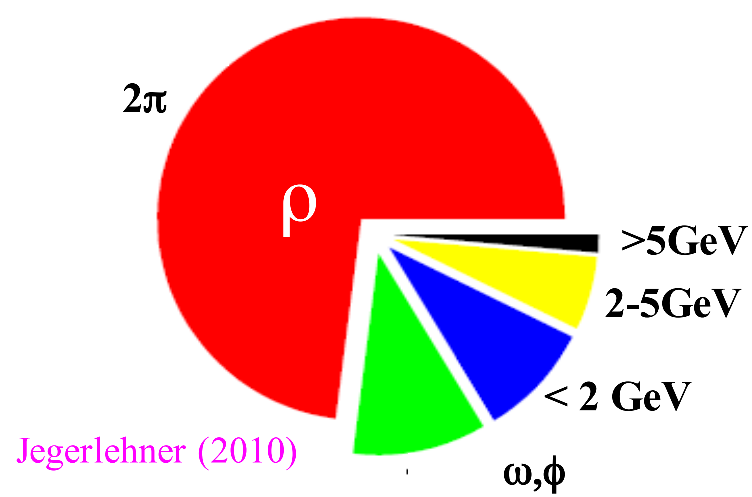
* limited in addition by statistics

# *Hadronic Cross Section Data and $(g\text{-}2)_\mu$*



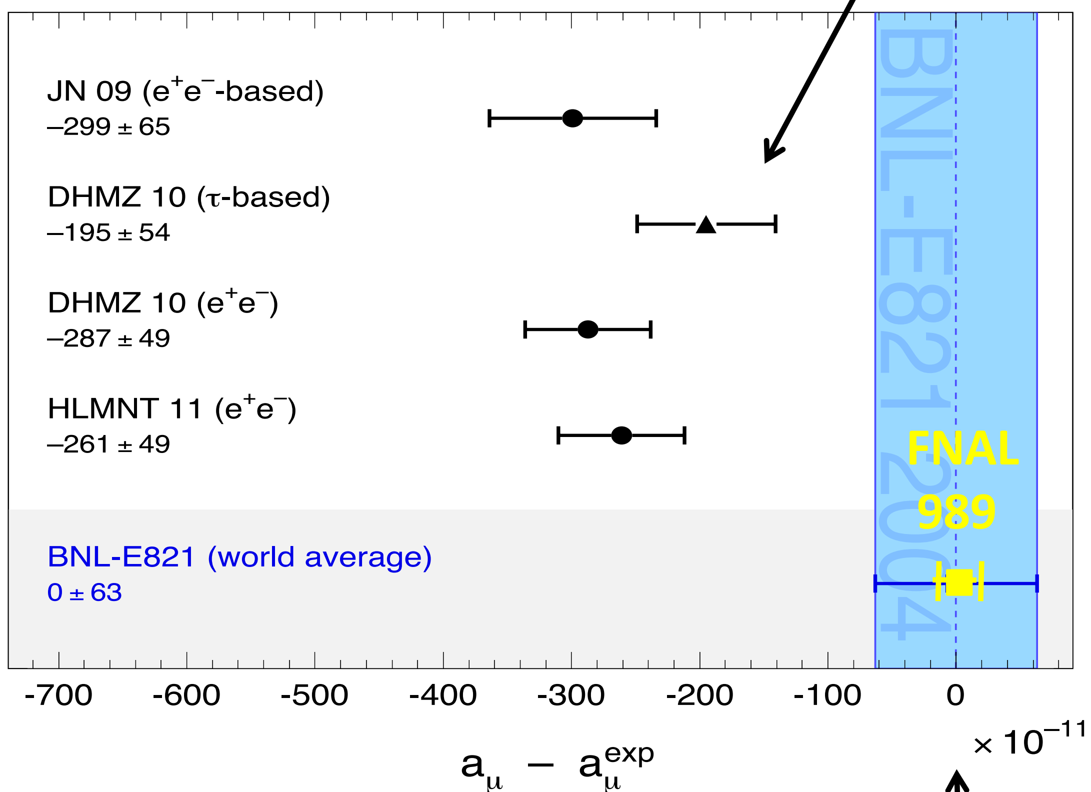

$$a_\mu^{had} = \frac{1}{4\pi^3} \int_{4m_\pi^2}^{\infty} ds\, K(s)\, \sigma_{had}$$

Intrinsic ~ $1 / s^2$
**low energy contributions**
especially important!



# *Muon Anomaly $(g-2)_\mu$*

**Standard Model predictions $(g-2)_\mu$**




**E821 measurement of $(g-2)_\mu$**

**$\Delta a_\mu = a_\mu^{exp} - a_\mu^{SM} =$**

**$(28.7 \pm 8.0) \cdot 10^{-10}$ $(3.6\ \sigma)$**

**Error(s) or New Physics ?**

**New FNAL 989 $(g-2)_\mu$ measurement (2015):**

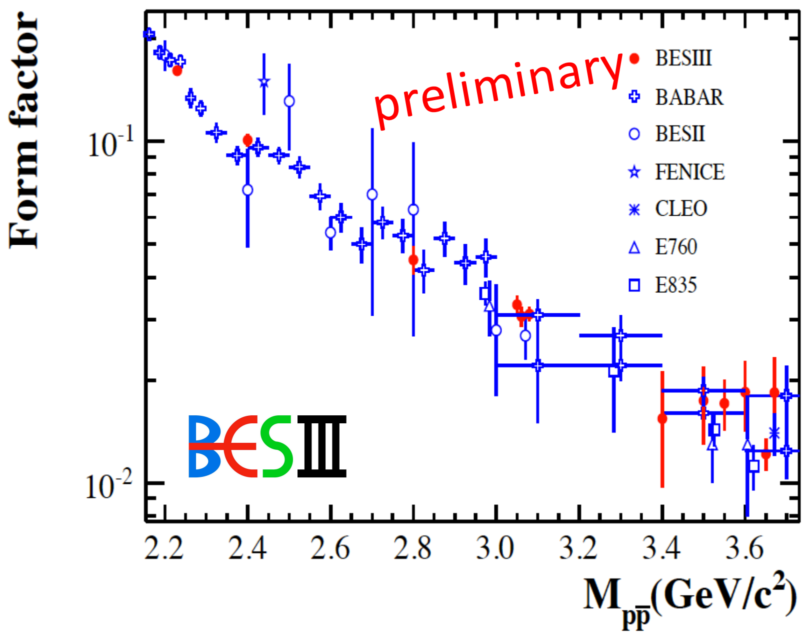
Factor 4 improvement in experimental error

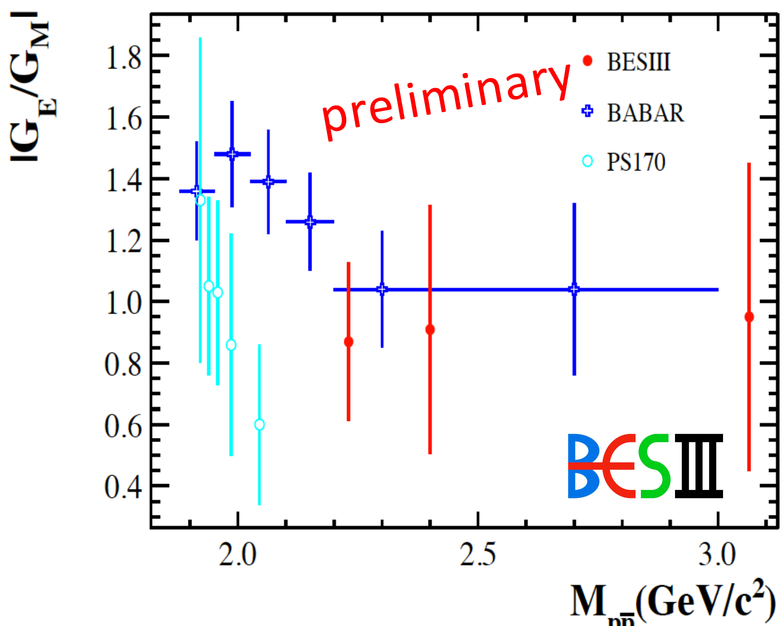
# *Prelim. Proton FF from Mini R Scan*

**Analysis Features**:

- Radiative corrections from Phokhara8.0 (scan)
- Normalization to e+e- → e+e-, e+e- →γγ (BABAYAGA 3.5)
- Efficiencies 60% (2.23 GeV) .... 3% (~4 GeV)
- $|G_E/G_M|$ ratio obtained for 3 cm energies

| $E_{cm}$/GeV | $L_{int}$ / $pb^{-1}$ |
|---|---|
| 2.23 | 2.6 |
| 2.40 | 3.4 |
| 2.80 | 3.8 |
| 3.05, 3.06, 3.08 | 60.7 |
| 3.40, 3.50, 3.54, 3.56 | 23.3 |
| 3.60, 3.65, 3.67 | 63.0 |



# Muon Anomaly $(g\text{-}2)_\mu$

**Magnetic Moment:** $\vec{m} = \mu_B\, g\, \vec{S}$ *$\mu_B$: Bohr magneton, g: gyromagnetic factor ~ 2*

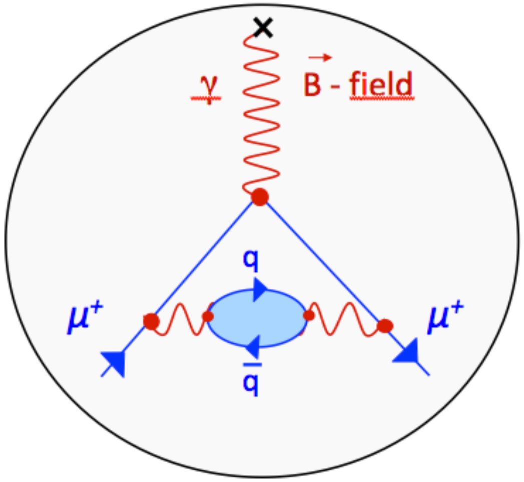
**Muon Anomaly:** $a_\mu = (g-2)_\mu / 2 = \alpha_{em} / 2\pi + \ldots = 0.001161\ldots.$

- **Standard Model (SM) prediction $a_\mu^{SM}$:**

  - QED: $a_\mu^{QED} = (11\,658\,471.809 \pm 0.015) \cdot 10^{-10}$
  - weak: $a_\mu^{weak} = (15.4 \pm 0.2) \cdot 10^{-10}$
  - hadronic: $a_\mu^{hadr} =$ **$(693.0 \pm 4.9) \cdot 10^{-10}$**

  $$a_\mu^{SM} = (\,11\,659\,180.2 \pm 4.9\,) \cdot 10^{-10}$$ Davier et al., 2010

  **SM prediction** entirely limited by **hadronic contribution**!




- **Direct measurement BNL-E821 $a_\mu^{exp}$:**

  $$a_\mu^{exp} = (\,11\,659\,208.9 \pm 6.3\,) \cdot 10^{-10}$$