Cluster of Excellence Precision Physics, Fundamental Interactions and Structure of Matter
PRISMA

SFB 1044
THE LOW-ENERGY FRONTIER OF THE STANDARD MODEL


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# Experimental Input to Standard Model Prediction of $(g-2)_\mu$

MAMI MAINZER MIKROTRON

BESIII

*March 10, 2016*

*MITP Mainz, Germany*

*Determination of Fundamental Parameters in QCD*

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

Hadronic contribution **non-perturbative,** the **limiting** contribution

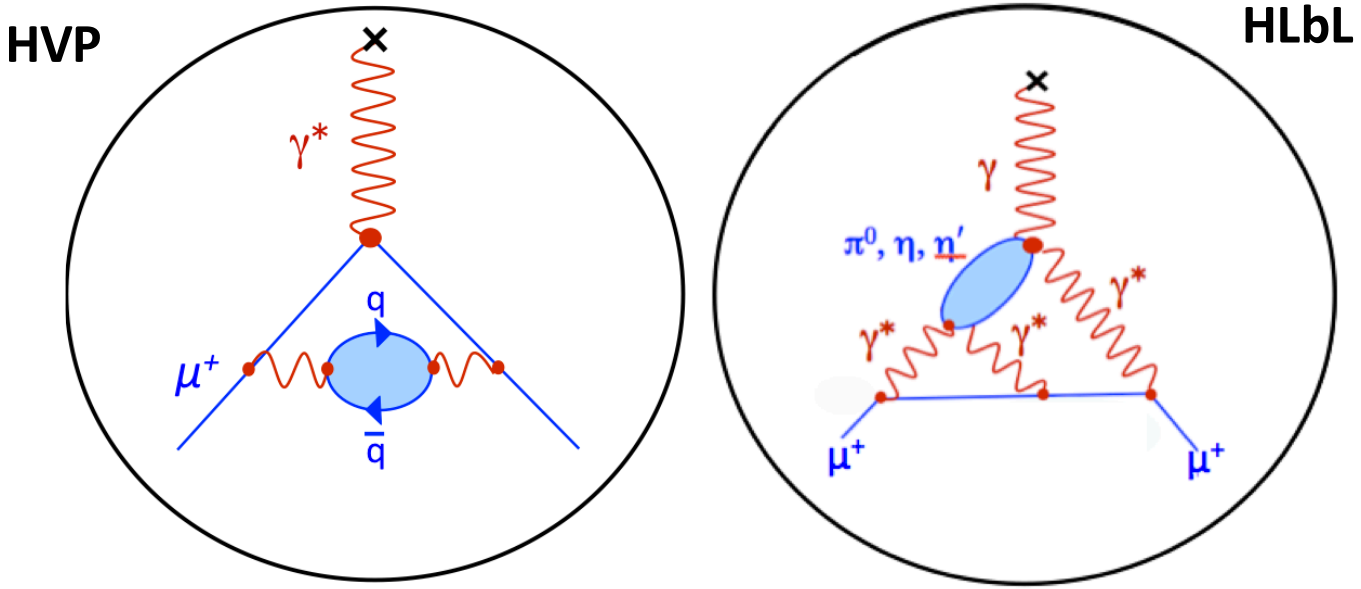
$$a_\mu^{SM} = a_\mu^{QED} + a_\mu^{weak} + a_\mu^{had} = (\,11\,659\,180.2 \pm 4.9\,) \cdot 10^{-10}$$

Teubner et al. '11

→ **HVP**: Hadronic Vacuum Polarization $(\,692.3 \pm \mathbf{4.2}\,) \cdot 10^{-10}$

NLO $(\,-9.8 \pm \mathbf{0.1}\,) \cdot 10^{-10}$ ; NNLO $(\,1.2 \pm \mathbf{0.01}\,) \cdot 10^{-10}$ )

→ **HLbL**: Hadronic Light-by-Light $(\,10.5 \pm \mathbf{2.6}\,) \cdot 10^{-10}$



# *Outline*

**Hadronic Vacuum Polarization <-> Hadronic Cross Section $R_{had}$**

- Overview hadronic cross section measurements
- BES III ISR Program, Status $e^+e^- \rightarrow \pi^+\pi^-\gamma$ analysis
- R Scan > 2 GeV

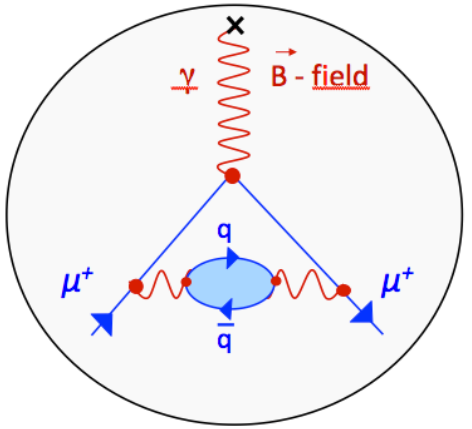
**Hadronic Light-by-Light <-> Transition Form Factors $F(Q_1^2,Q_2^2)$**

- Overview meson transition form factors
- BES III status and expectations

**Conclusions**

[ • Dark Photon as a possible solution for $(g-2)_\mu$ discrepancy ]

# $R_{had}$
# Hadronic Cross Section $\sigma_{had}$




**Relation to $(g-2)_\mu$ HVP:**

M. Davier et al., Eur. Phys. J. C71 (2011) 1515

F. Jegerlehner, Acta Phys. Pol. B40 (2009) 3097

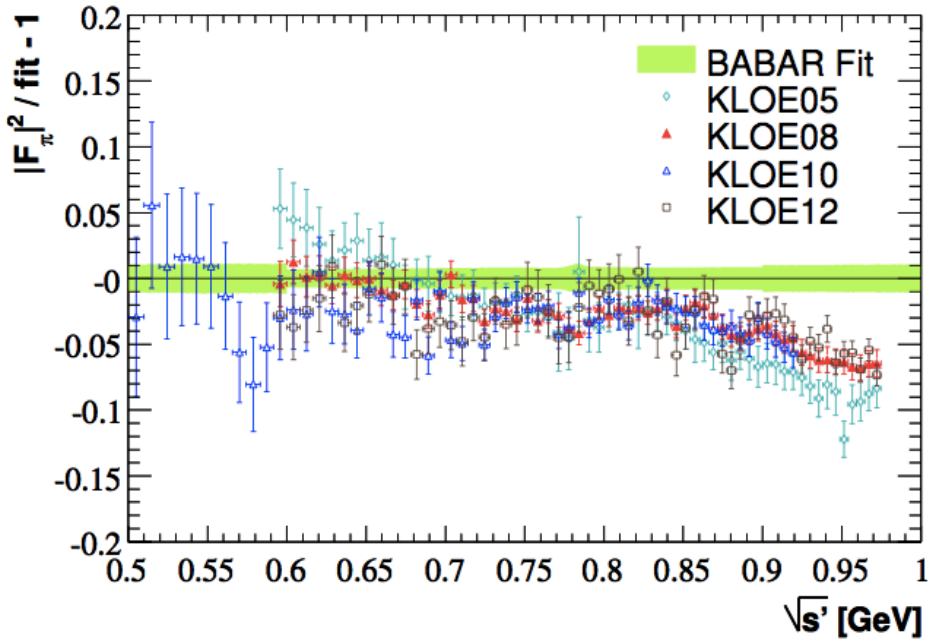
T. Teubner et al., arXiv: 1105.3149

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

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

$\sigma_{had} = \sigma(e^+e^- \rightarrow hadrons)$

~ 1/s → Data below ~3 GeV needed!



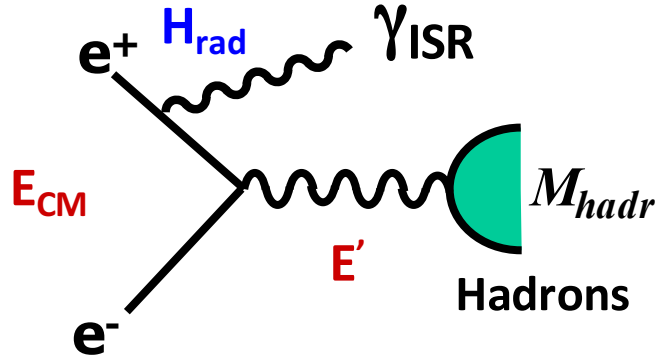

***Note**: KLOE05 superseded by KLOE08*

- KLOE and BABAR dominate the world average
- Relatively large systematic differences, esp. above ρ peak
- Knowledge of $a_\mu^{had}$ dramatically limited due to this difference

# *Initial State Radiation*

Rev. Mod. Phys. 83, 1545–1588 (2011)

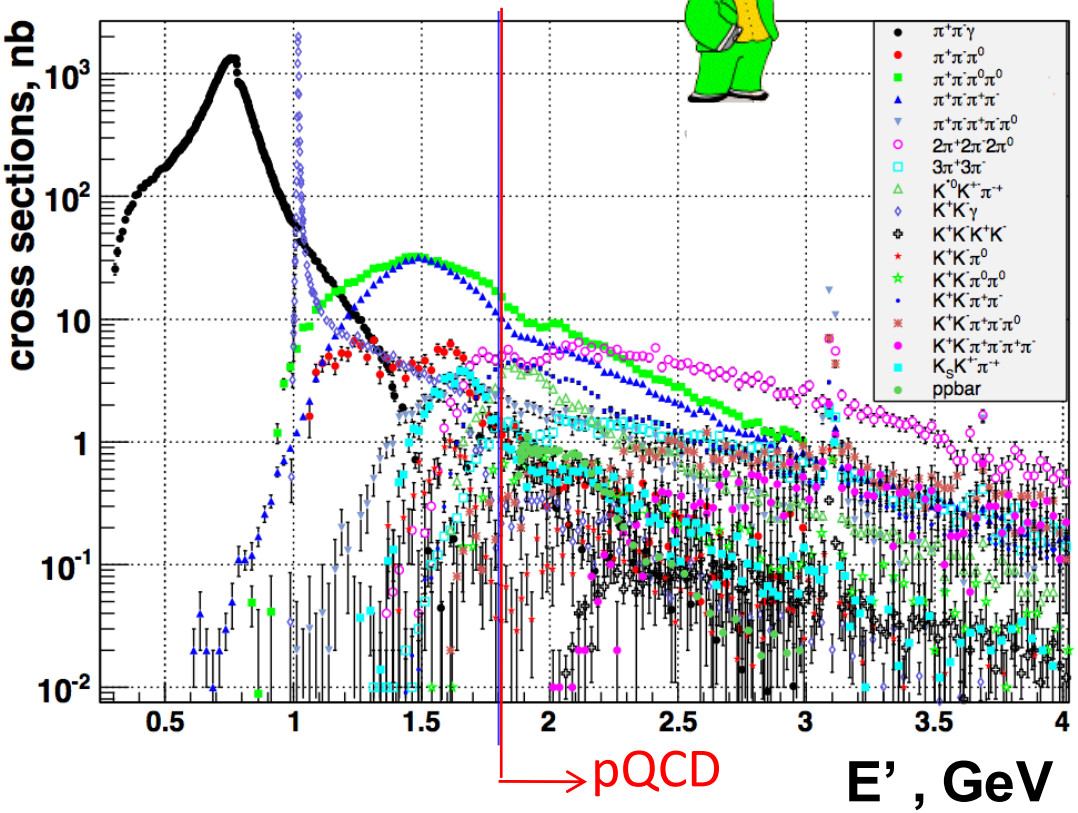
## Initial State Radiation (ISR) aka Radiative Return




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

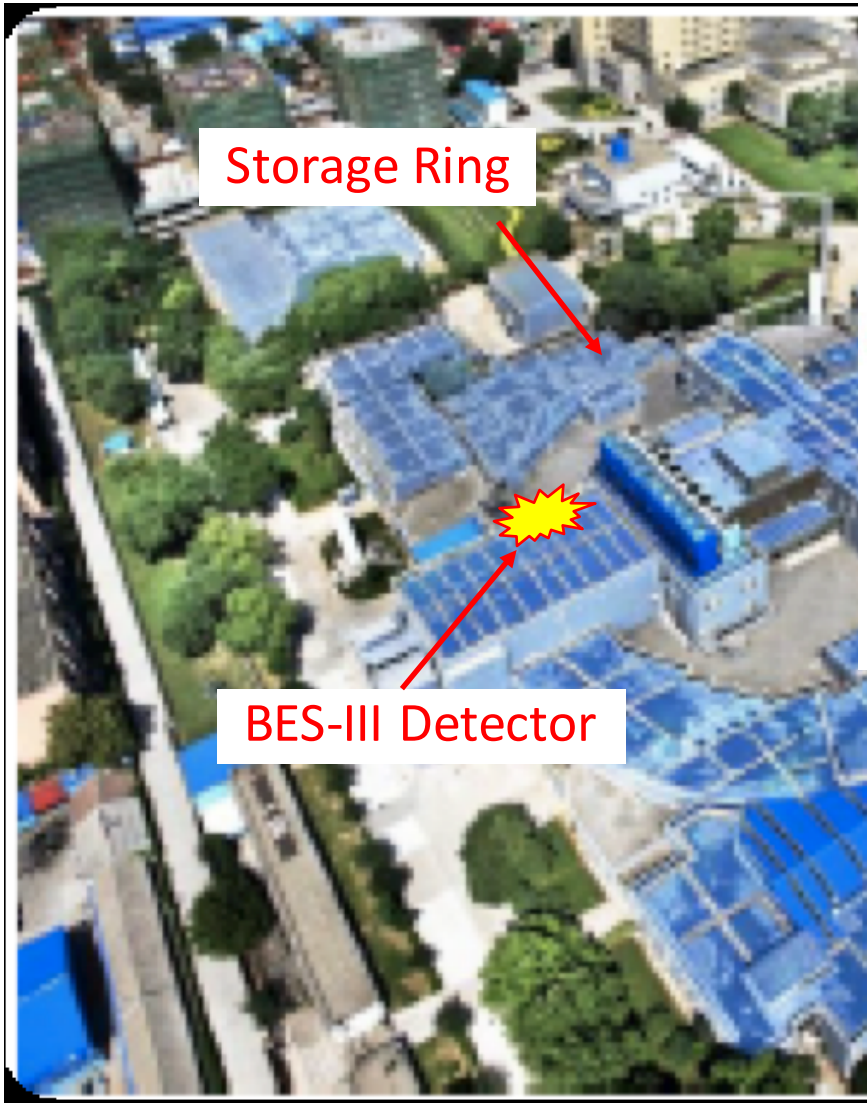
PHOKHARA event generator Czyż, Kühn, et al.

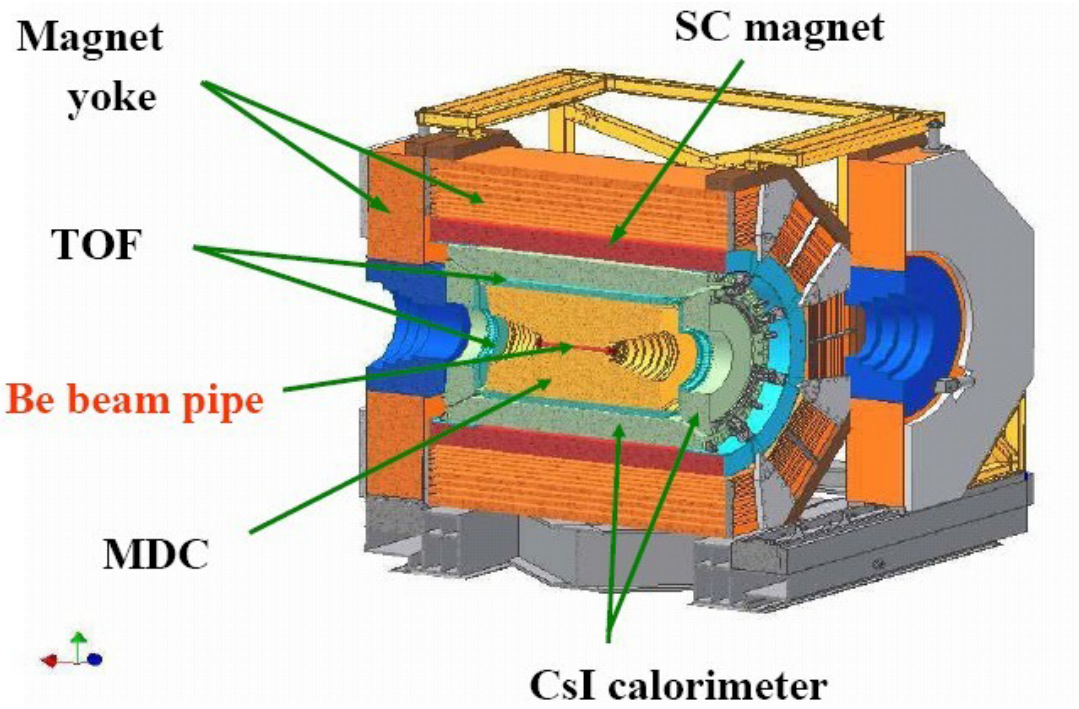
ISR spectra measured by BABAR




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

# BEPC II Project

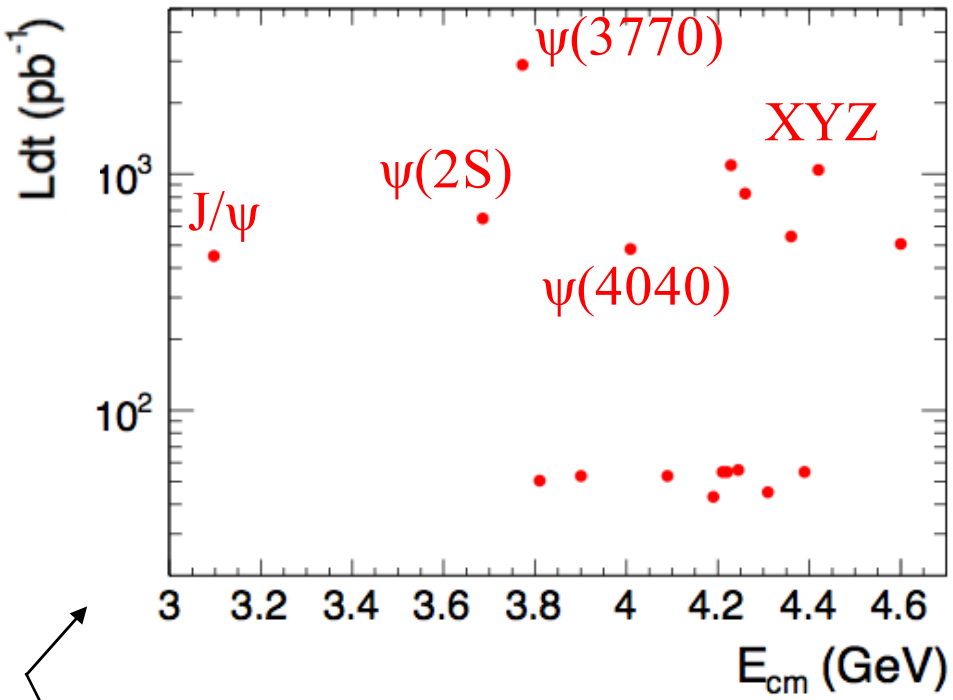


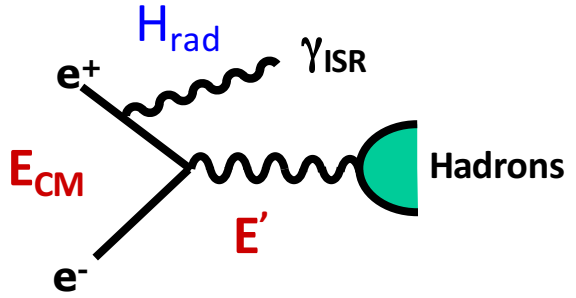

CM Energy 2.0 – 4.6 GeV
Design Luminosity $10^{33}$ $cm^{-2}$ $s^{-1}$
Achieved Luminosity 70%@ψ(3770)

# *Data Samples for ISR Physics*

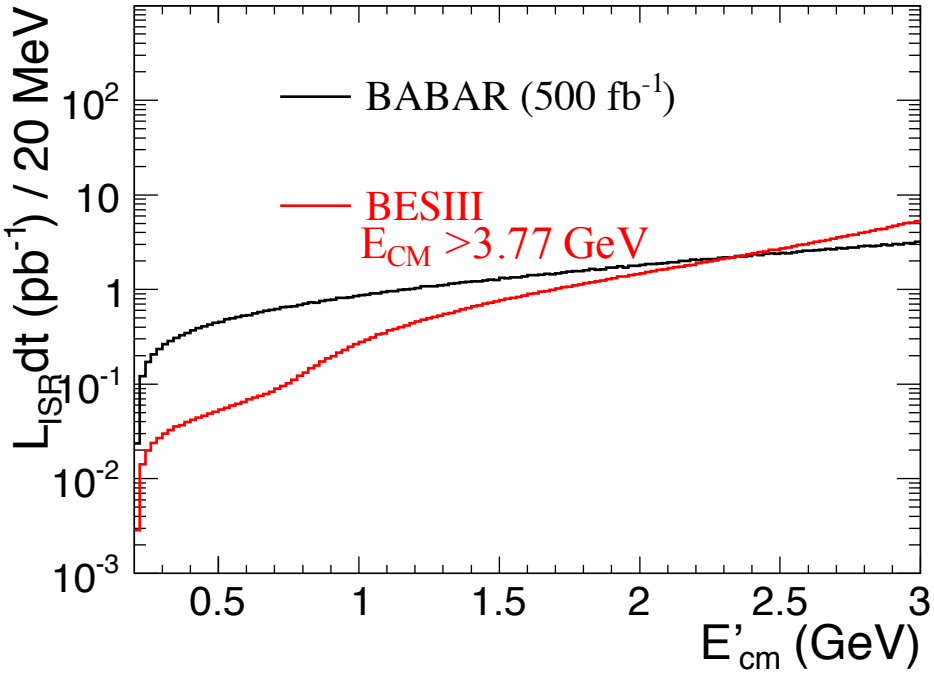
Integrated luminosities BESIII




Energy Scan < 3.08 GeV
→ later

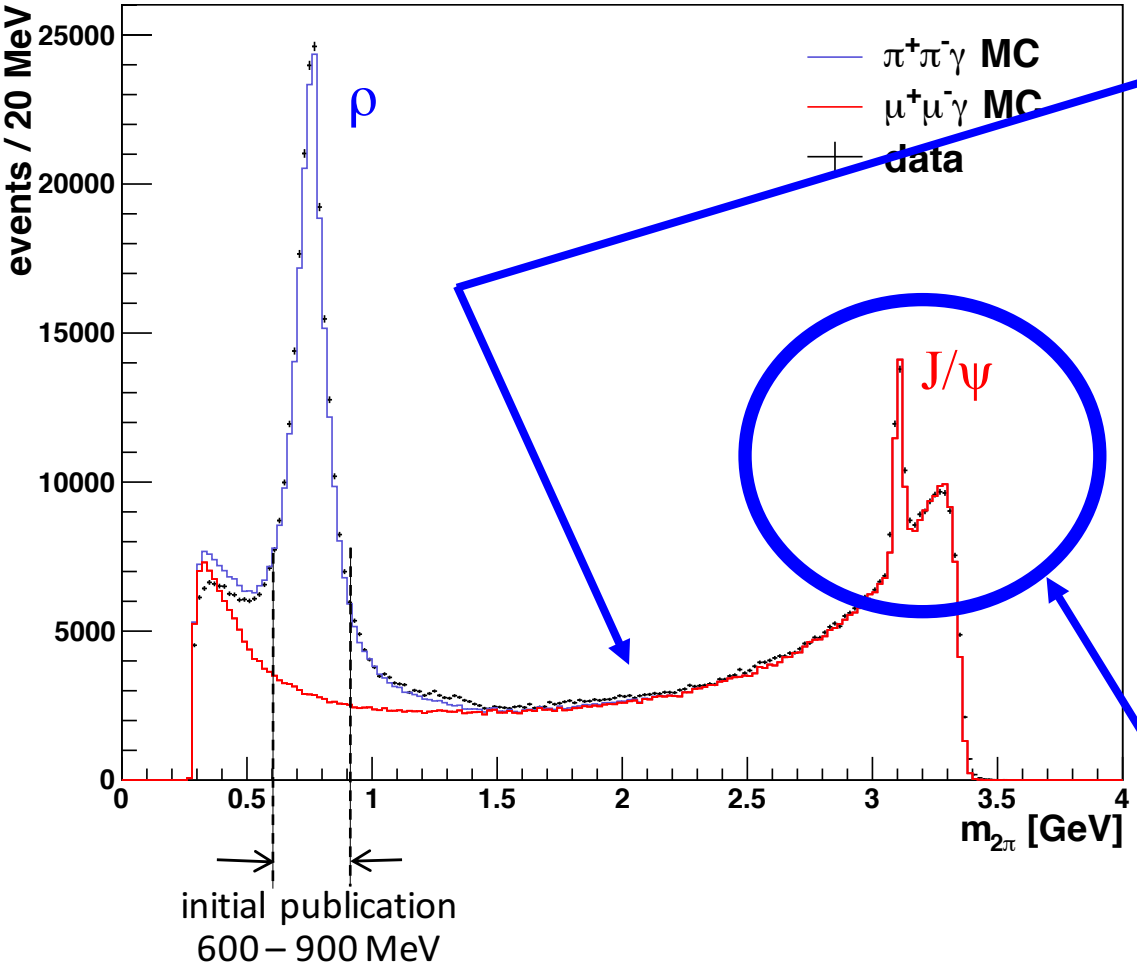



ISR luminosity = Ldt x $H_{rad}$



# *Flagship ISR Analysis: $e^+e^- \to \pi^+\pi^-\gamma_{ISR}$*

Event yield after acceptance cuts **only**




Competitive limit
for Dark Photon search

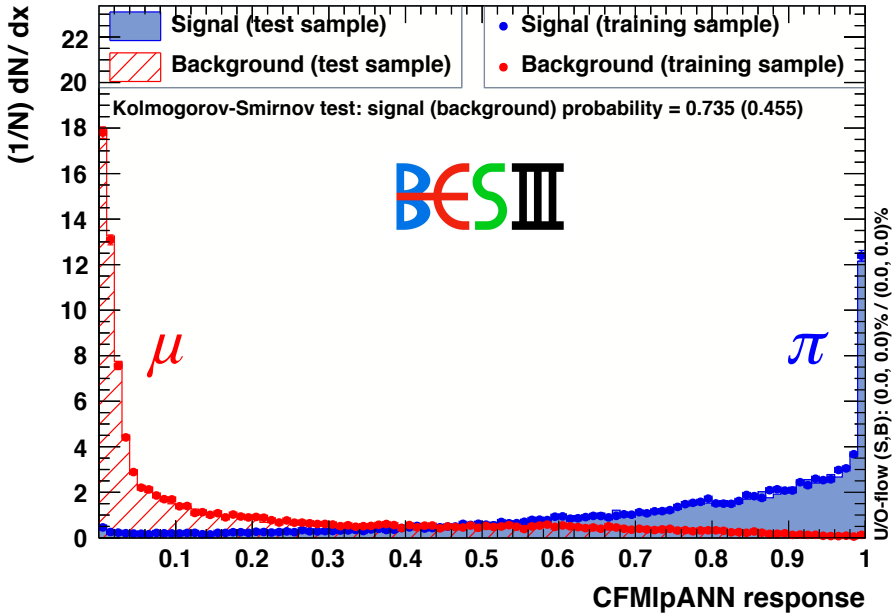
**Features**:

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

→ large statistics of e+e- → $\pi\pi\gamma$ events
→ background dominated by e+e- → $\mu\mu\gamma$
→ data – MC differences visible

World's best measurement
of $\Gamma_{ee}$ of J/ψ (to appear soon)

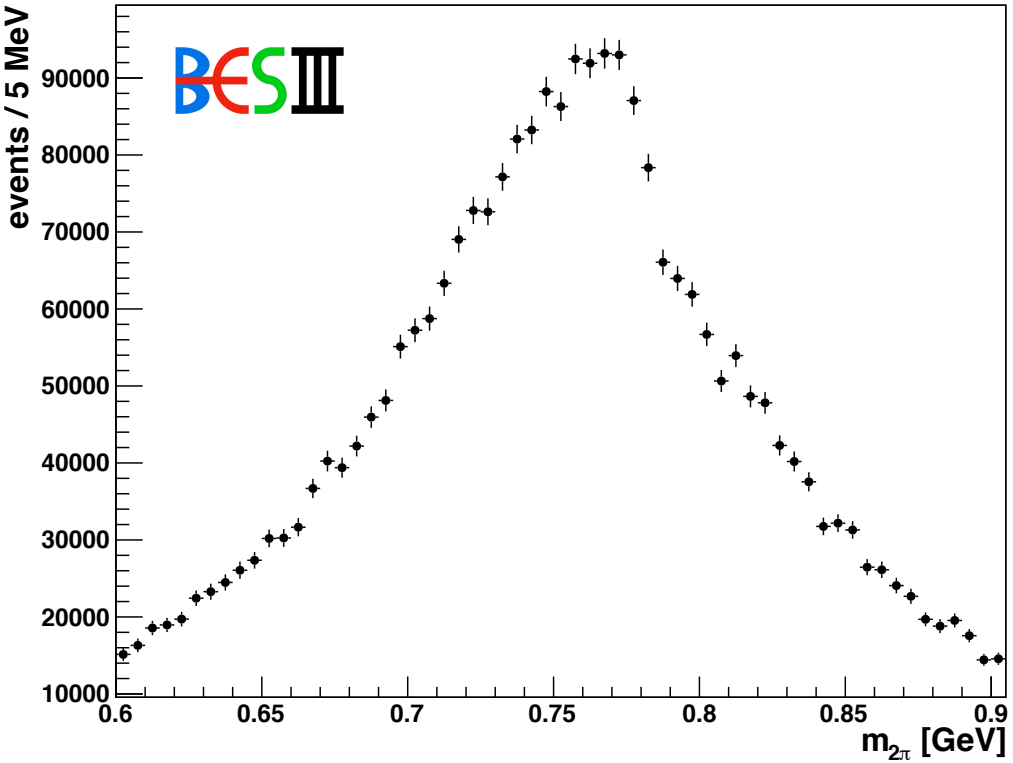
# $e^+e^- \rightarrow \pi^+\pi^-\gamma_{ISR}$: $\pi$ - $\mu$ Separation




**TMVA method (Neural Network)**:

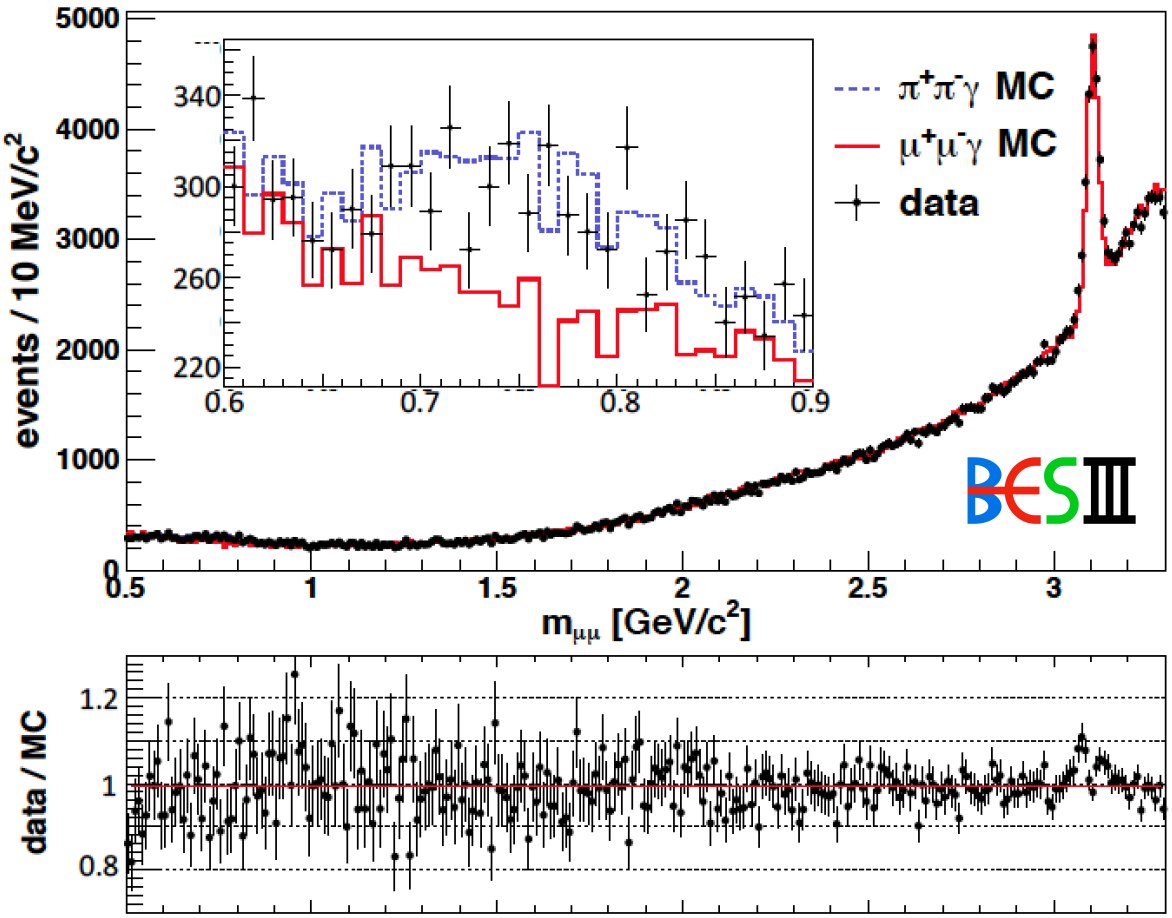
- trained using μμγ and ππππγ MC events
- information based on track level
- efficiency matrix (p,Θ) for data, MC
- correct for data - MC differences
- cross checked for different TMVA methods

Event yield ππγ after π-μ separation



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

Event yield $\mu\mu\gamma$ after $\pi$-$\mu$ separation
and all efficiency corrections




**Features**:

- background from $\pi\pi\gamma$ very small
- PHOKHARA accuracy <0.5%
- luminosity measurement based on Bhabha ev., 1.0% accuracy

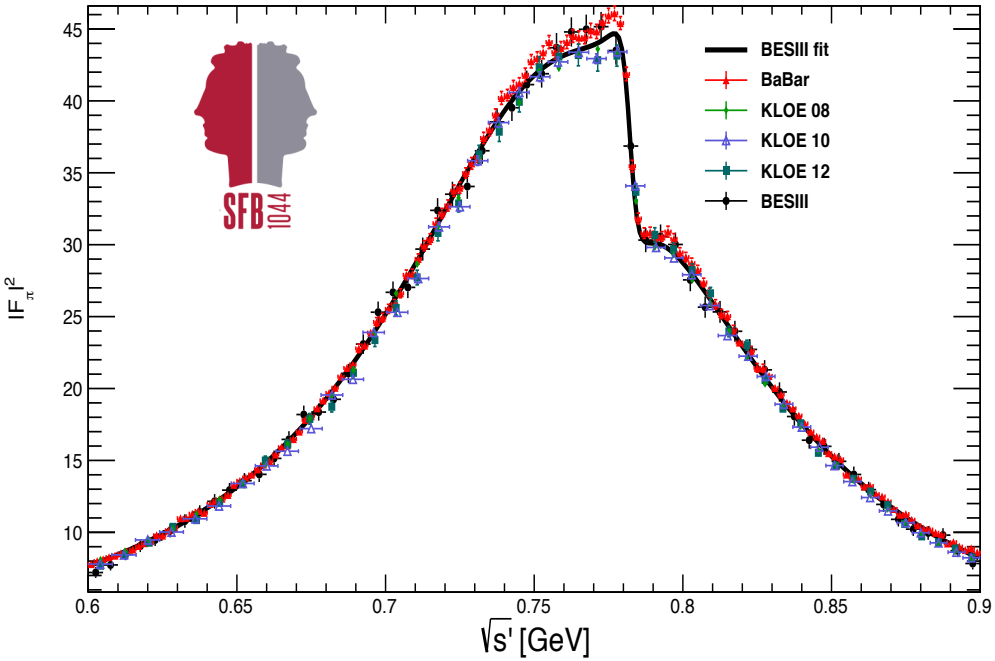
→ excellent agreement with QED

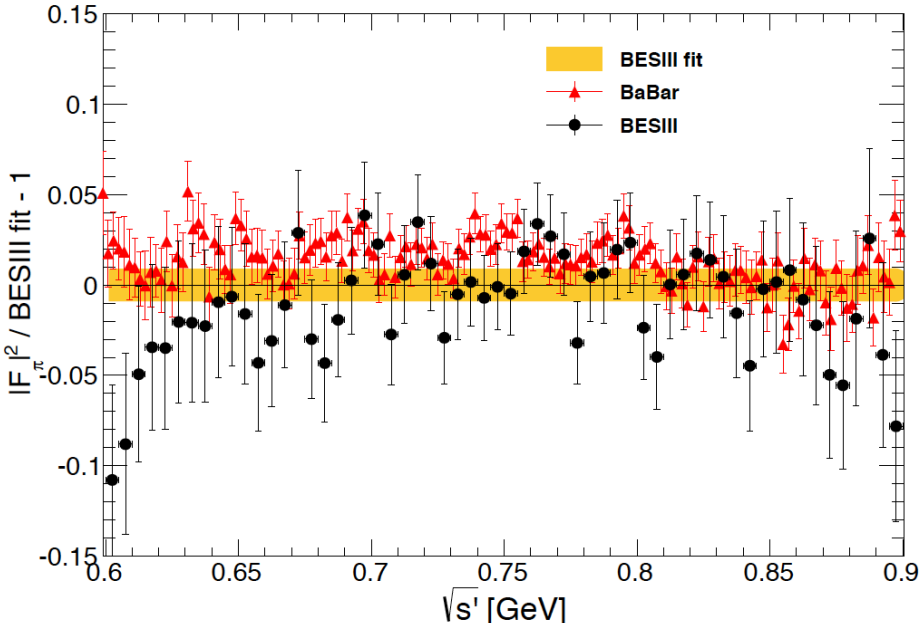
**$\Delta$(MC/QED-data) -1 =**
**$(1.0 \pm 0.3_{stat} \pm 0.9_{syst})$ %**

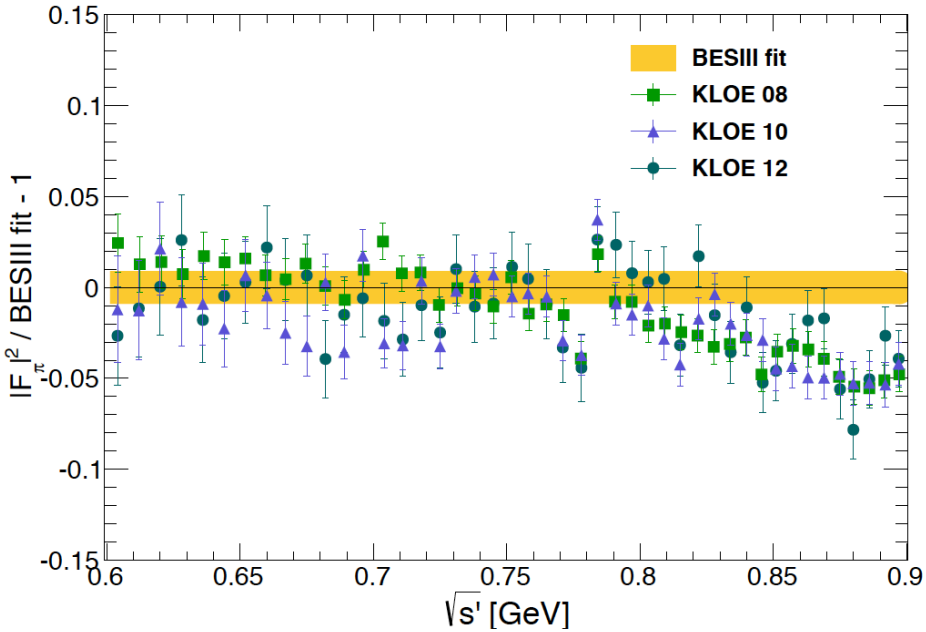
→ accuracy on 1% level as needed to be competitive !

# Comparison with existing Data

## Pion Form Factor $F_\pi$



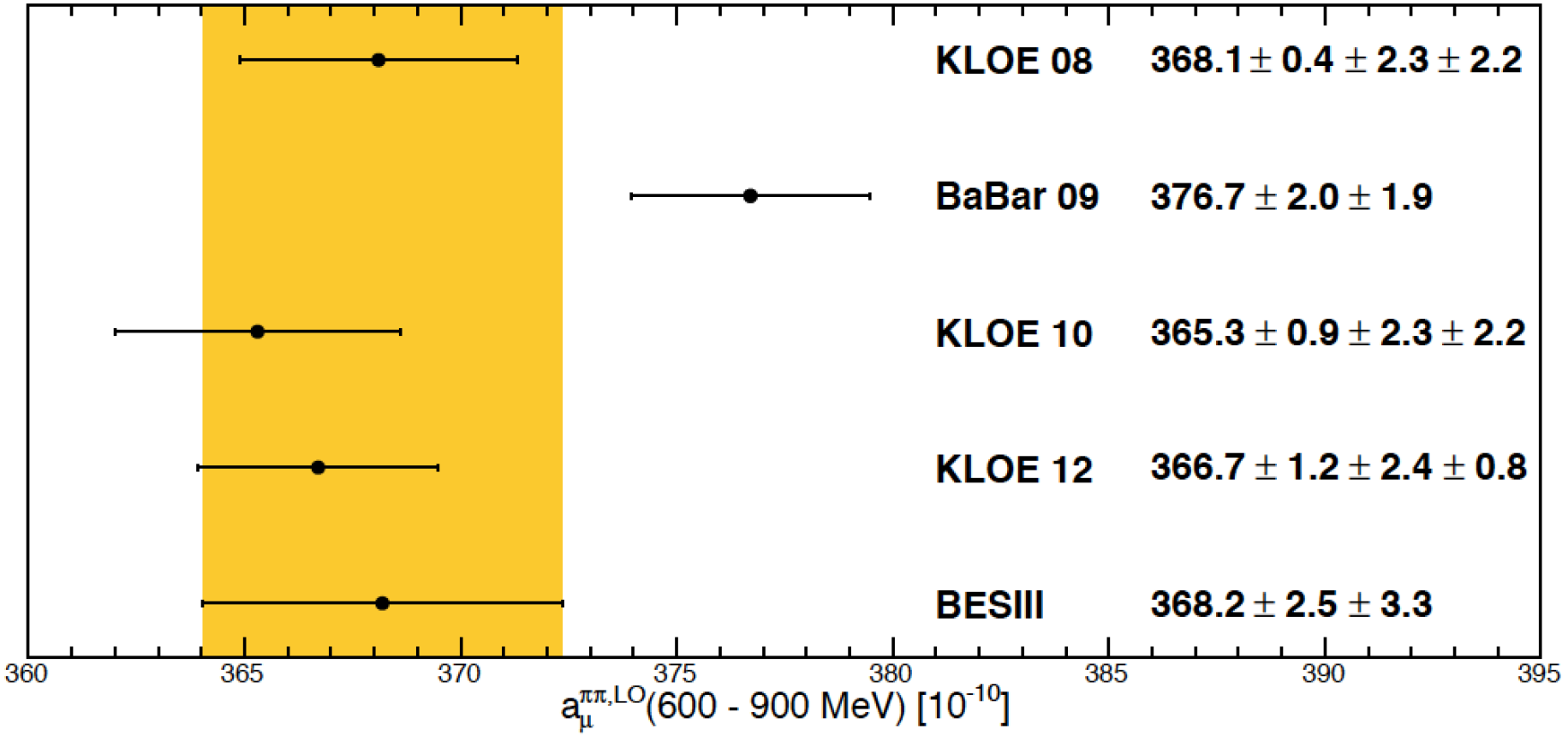




0.9 % accuracy (dominated by theory)
Normalization to luminosity / radiator function

Cross check with R=ππγ/μμγ ratio

# *Impact on Hadronic Vacuum Polarization*

Phys. Lett. B753 (2016) 629

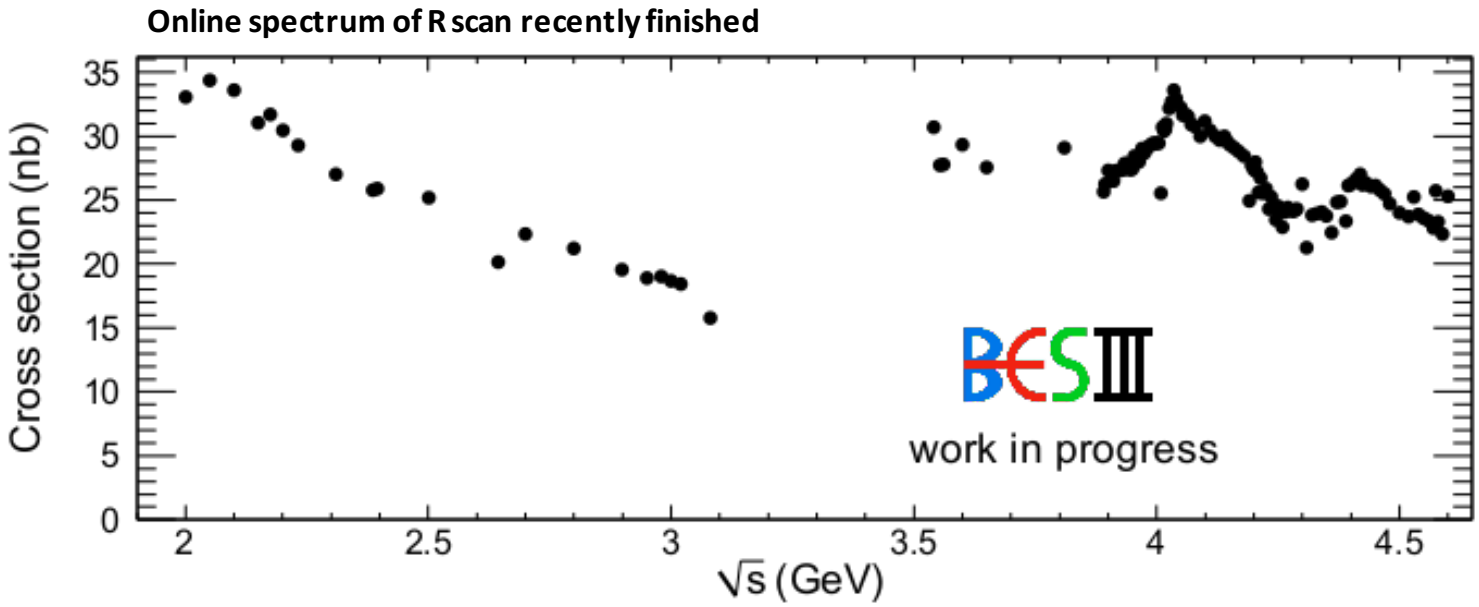



**→ BES III confirms ~4 sigma deviation in $(g-2)_\mu$!**

**→ Also 3π and 4π channels in preparation**

# *R Scan 2 – 4.6 GeV recently completed*

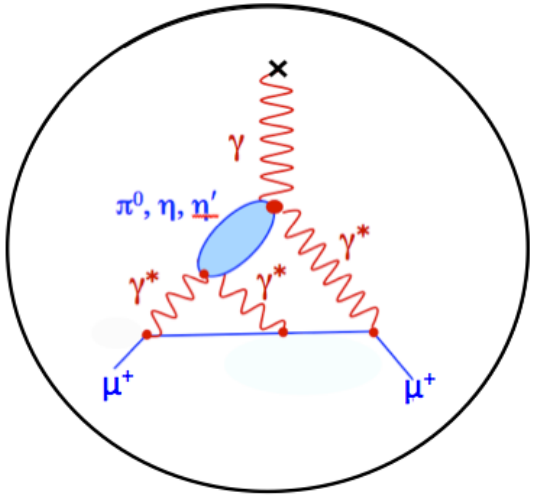
**Reducing the uncertainty of $\alpha_{em}(M_Z^2)$ by a factor of 2**
**→ A new quantity of electroweak precision fits**




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

- 125 scan points with >$10^5$ hadronic events each → statistical error negligible
- World's best measurement so far from BES /BESII with 5 …8 % total error (with 3 … 5% statistical error)

# Meson Transition Form Factors $F(Q^2)$




**Relation to $(g-2)_\mu$ HLbL:**

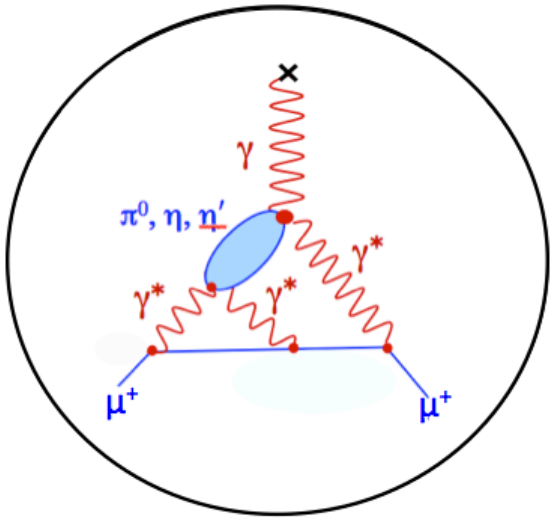
arXiv:1408.2517 (G. Colangelo et al.)

arXiv:1409.0819 (M. Vanderhaeghen et al.)

# *Hadronic Light-by-Light Scattering*

**HLbL:** ( 10.5 ± **2.6** ) · $10^{-10}$
Prades, de Rafael, Vainshtein '09

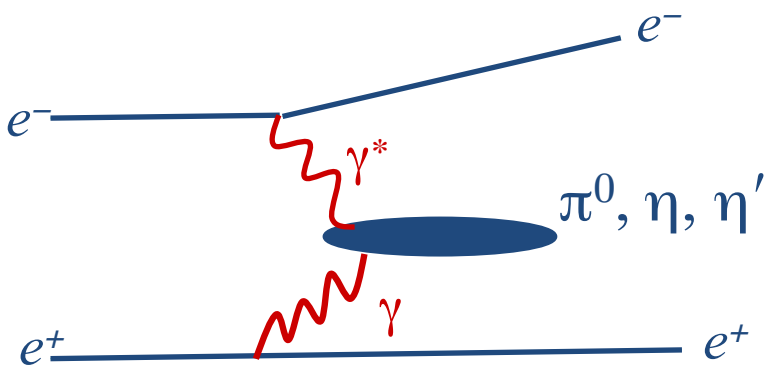
( 18.8 ± **0.4**$_{stat}$ ) · $10^{-10}$
Goeke, Fischer, Williams '11



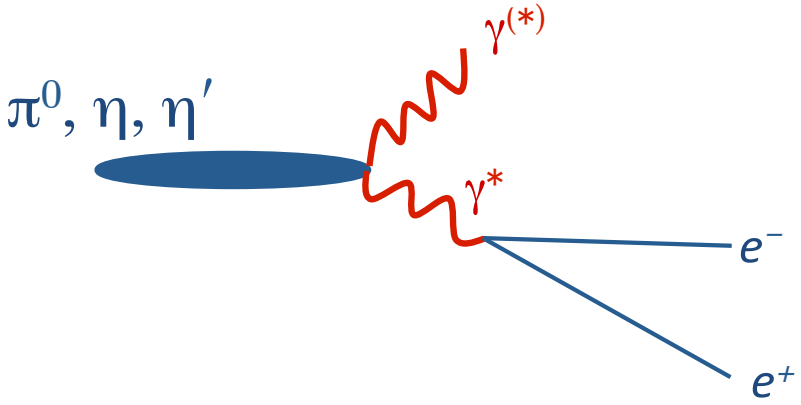

**Relation ?**

⇔

**Exp. Input !**
**Transition**
**Form Factors**
**F(Q²)**








**Future: data-driven approach**!

Dispersion Relations being developed using experimental measurements of meson transition form factors!

Colangelo et al '14; Pauk, Vanderhaeghen '14

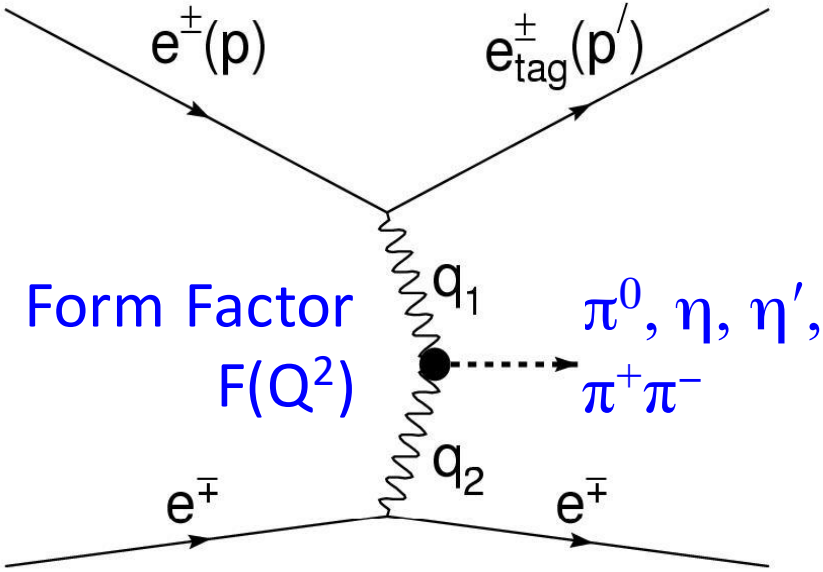
# *Spacelike FFs* $\gamma\gamma^* \rightarrow P$

## Single Tag Method

Selection criteria

- 1 electron (positron) detected
- 1 positron (electron) along beam axis
- Meson fully reconstructed

→ cut on angle of missing momentum



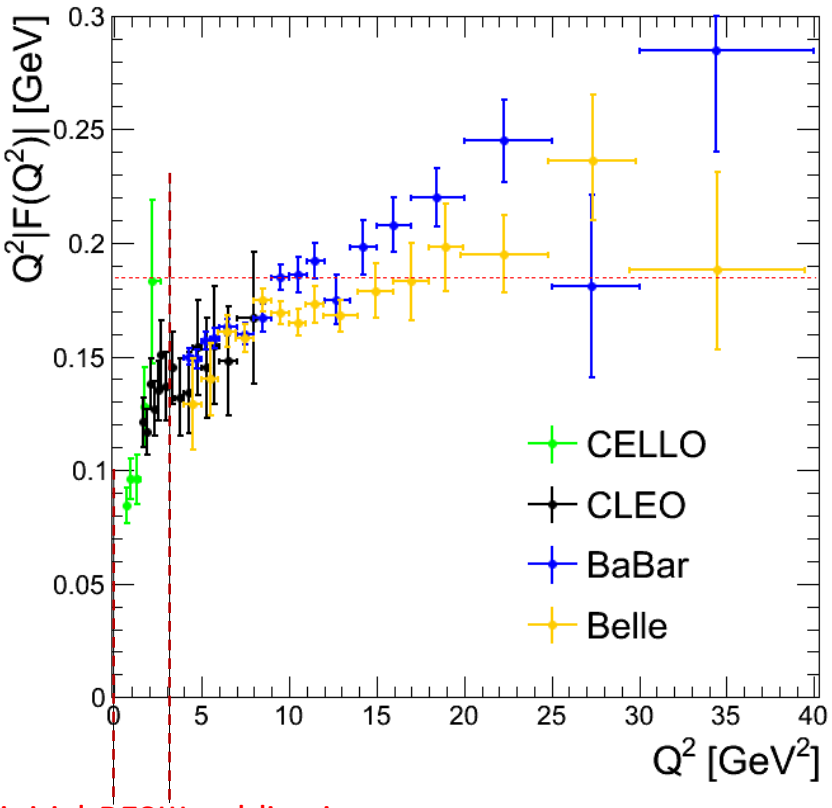

Momentum transfer

- tagged: $Q^2 = -q_1^2 = -(p - p')^2$
  → Highly virtual photon
- untagged: $q^2 = -q_2^2 \sim 0$ GeV$^2$
  → Quasi-real photon

EKHARA event generator
Czyż, Ivashyn

# Existing Data on SL Transition FFs

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



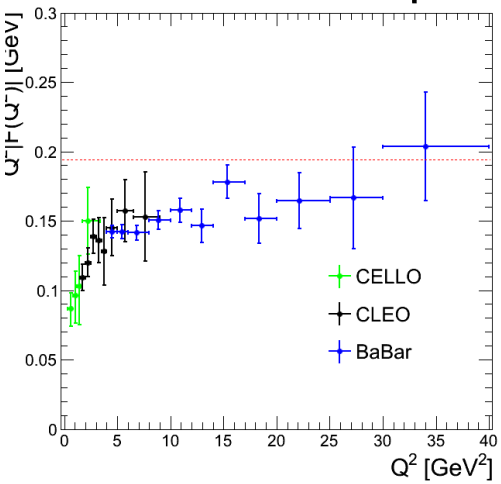

initial BESIII publication
< 3.1 GeV$^2$

**Features**:

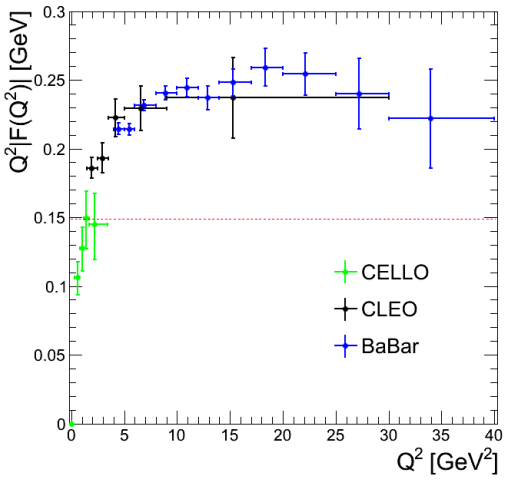
- recent high-$Q^2$ data from BABAR and BELLE $Q^2 > 4$ GeV$^2$
- above 1.5 GeV$^2$ data from CLEO
- below 1.5 GeV$^2$ data from CELLO, very poor accuracy

→ low $Q^2$ range not covered
most relevant for HLbL contribution to $(g-2)_\mu$
→ most relevant channels: $\pi^0$, $\eta$, $\eta'$, $\pi\pi$

$e^+e^- \to e^+e^- \eta$

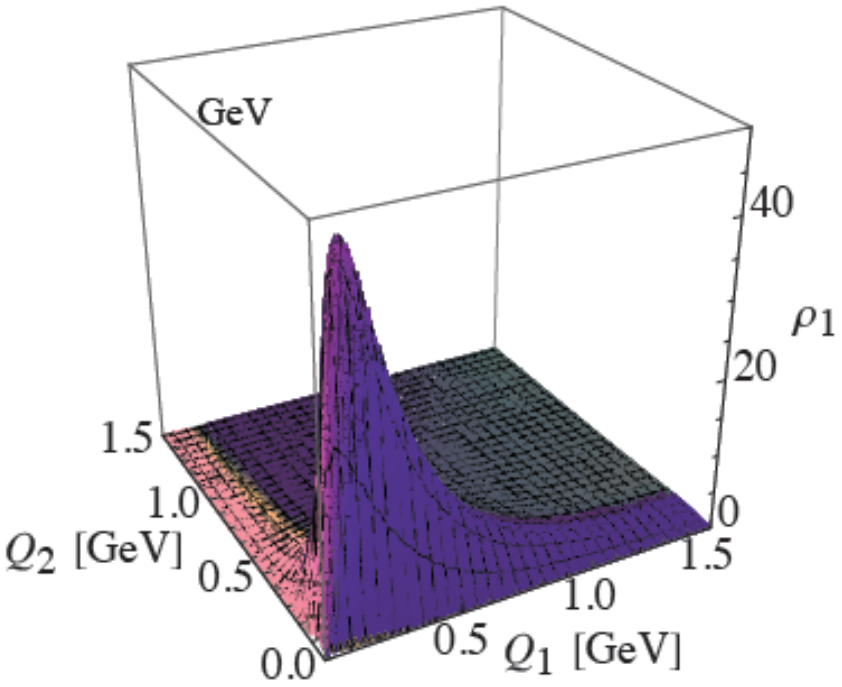



$e^+e^- \to e^+e^- \eta'$

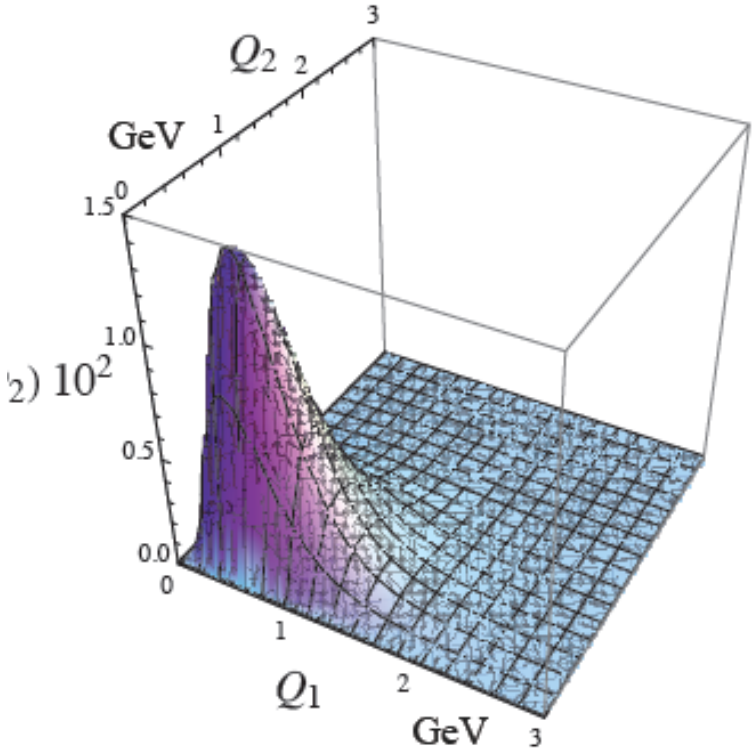


# *Relevance for HLbL*

Pseudoscalar Mesons



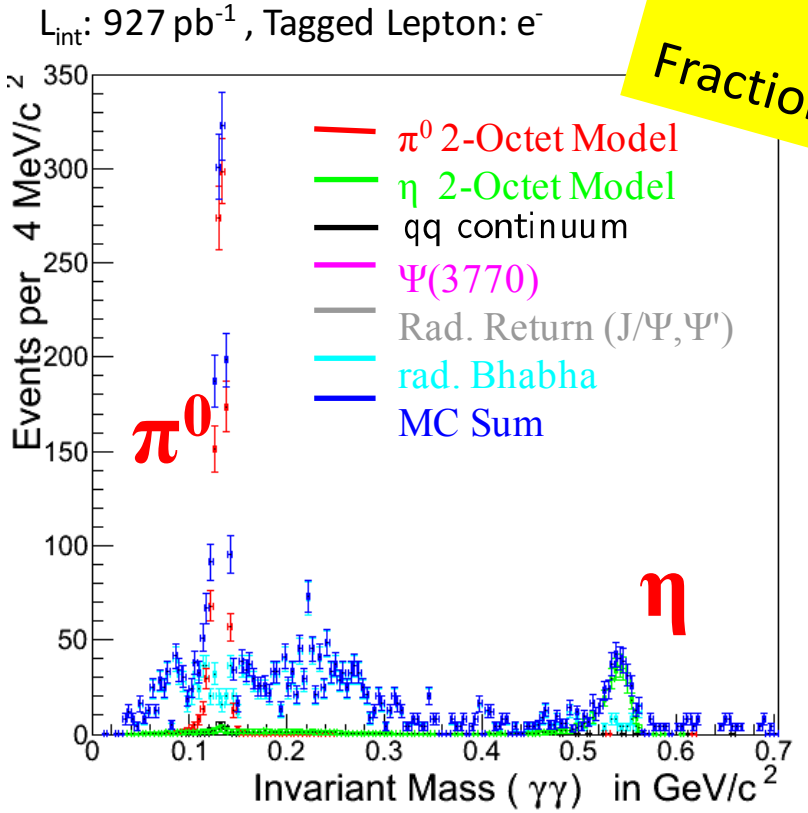

Axial Vector Mesons




**Weighting functions dominate at low Q < 2 GeV !**

courtesy: V. Pauk, JLAB

# BES III Analysis: $e^+e^- \rightarrow e^+e^- \pi^0$




MC only
Fraction of full statistics

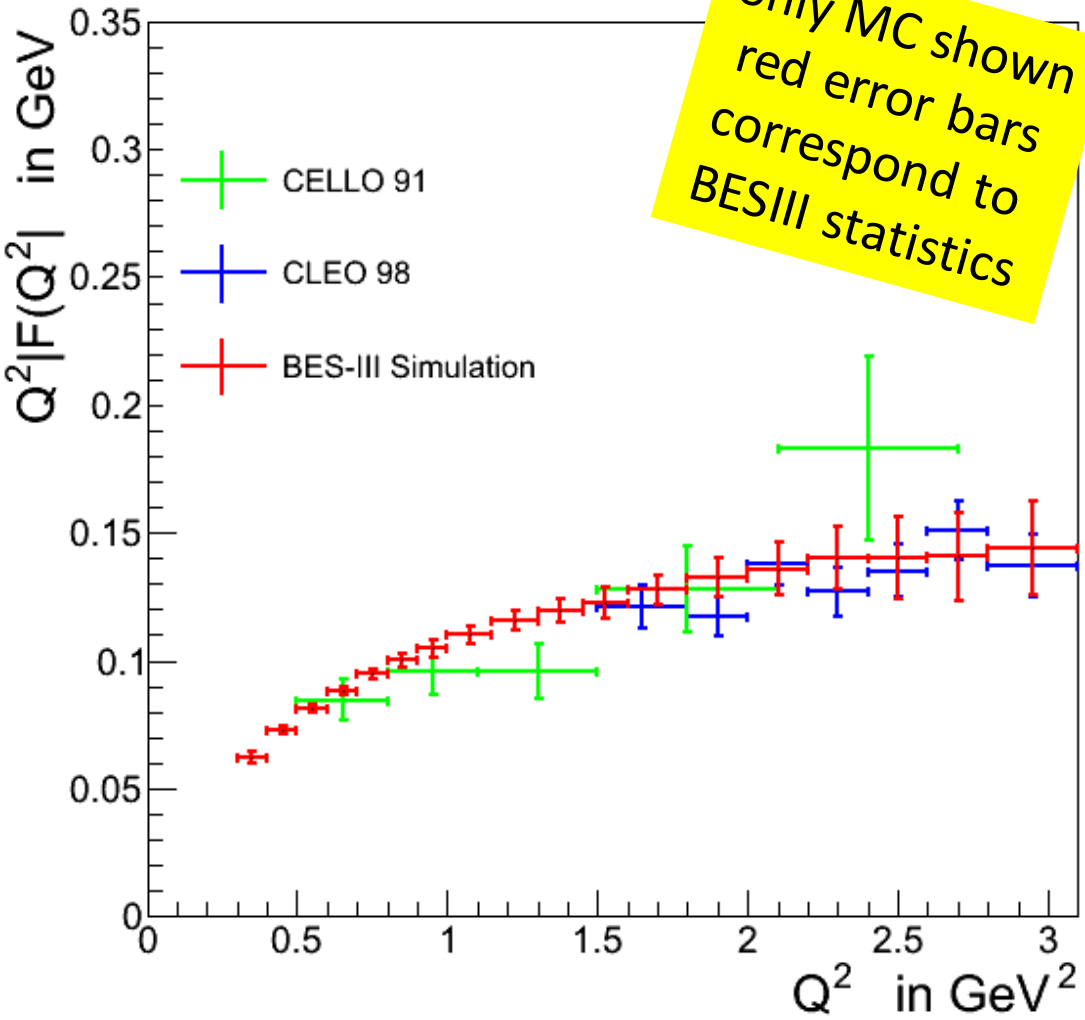
**Event Selection:**

- exactly one lepton candidate
- at least two, max four photons
- Helicity angle cos $\Theta_H > 0.8$
- Kinematic cuts to reject ISR background

→ cut on angle of missing momentum

**Strategy:** Count $\pi^0$ yield in bins of $Q^2$ → $d\sigma/dQ^2$ → Form factor $F(Q^2)$

# BES III Analysis: $\gamma\,\gamma^* \rightarrow \pi^0$

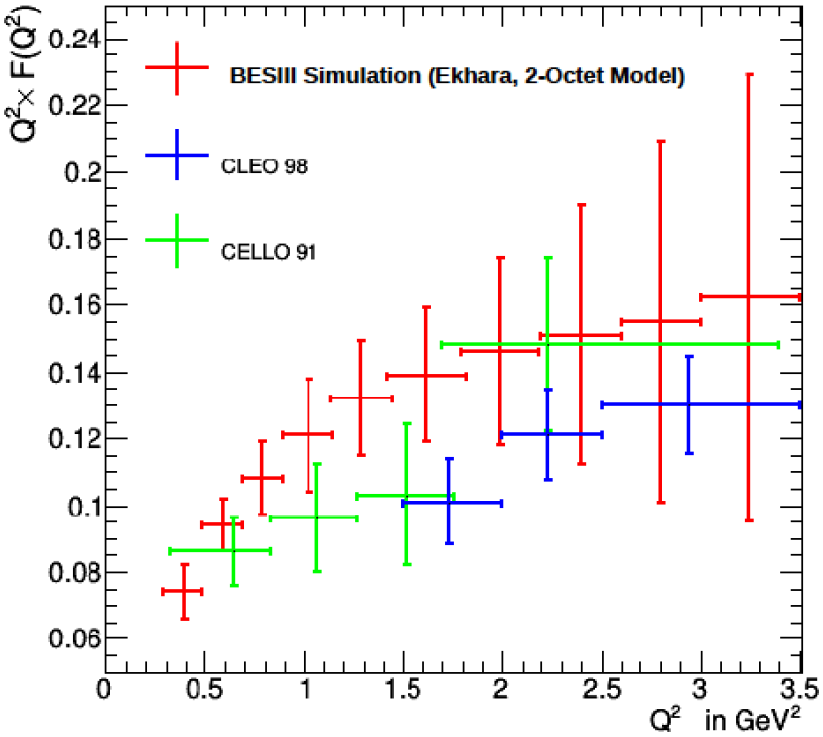



- Full Simulation
  - $L_{int}$: 2.92 fb$^{-1}$
  - Single Tag with both, $e^{\pm}$
- Extract TFF for $0.3 \leq Q^2[\text{GeV}^2] \leq 3.1$

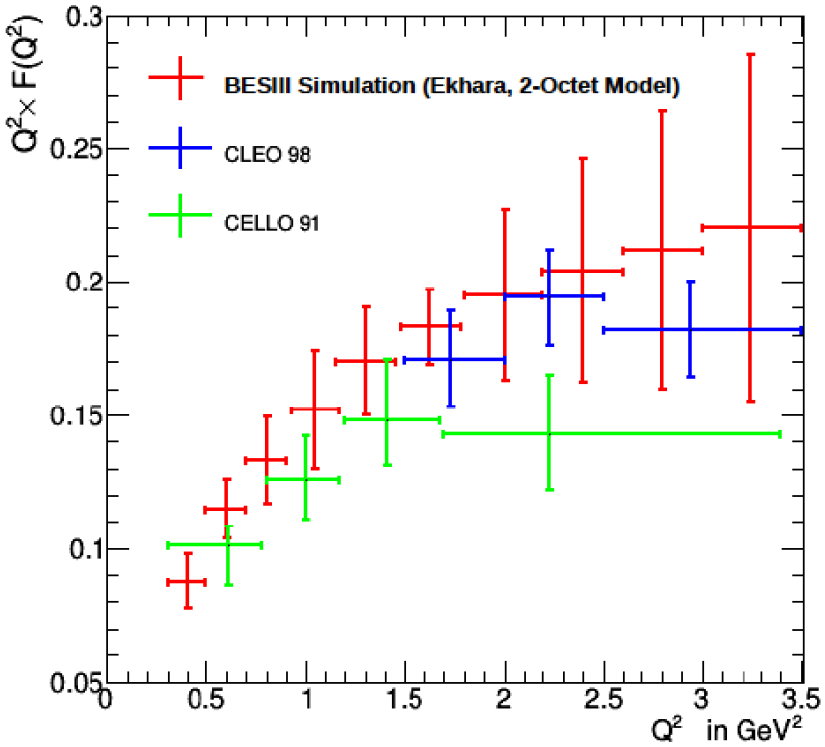
→ **Unprecedented $Q^2 < 1.5$ GeV$^2$ Input for $(g-2)_\mu$**

# BES III Analysis: $\gamma\,\gamma^* \rightarrow \eta\,/\,\eta'$

$F_{\eta,\gamma,\gamma^*}(Q^2)$

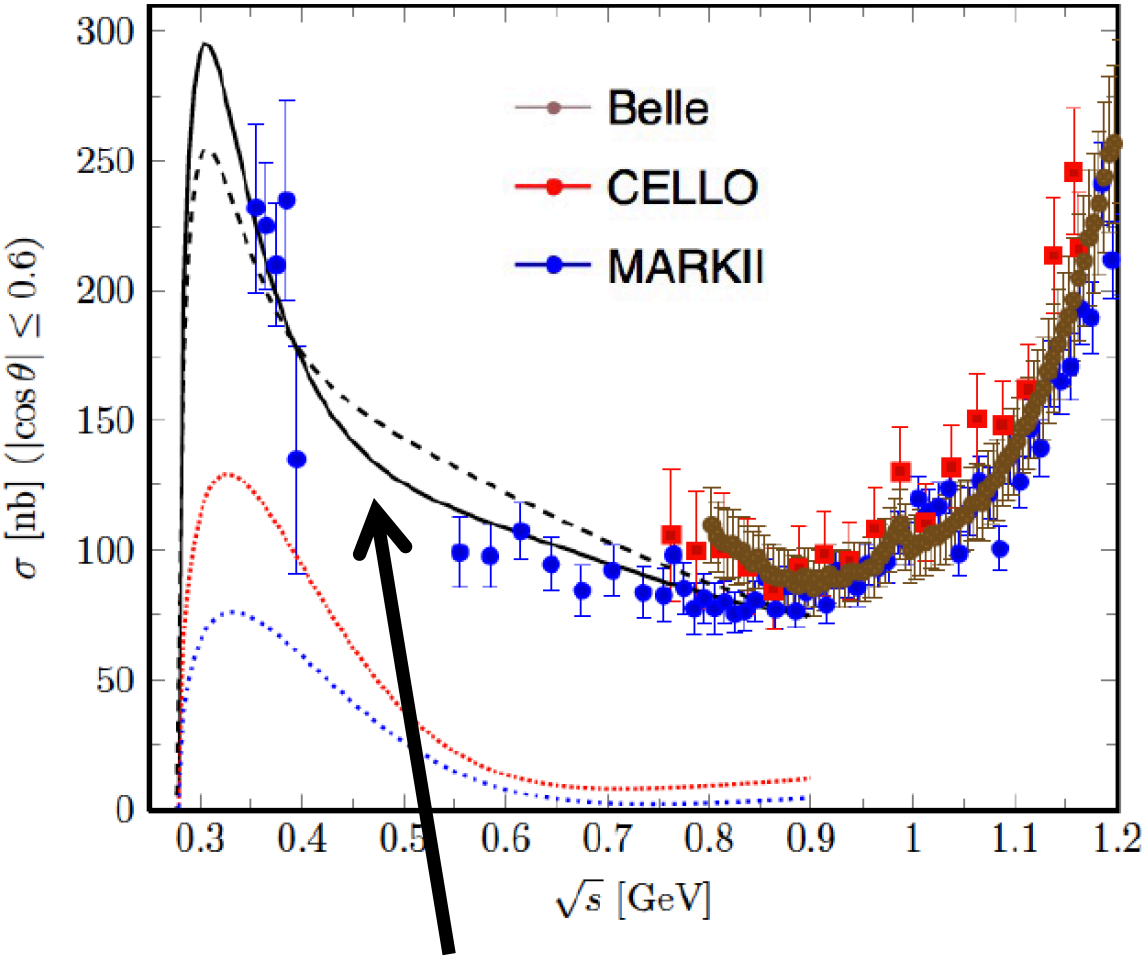



$F_{\eta',\gamma,\gamma^*}(Q^2)$




only MC shown - red error bars correspond to BESIII statistics
increase statistics by taking into account more decay channels

# *BES III Analysis: $\gamma\,\gamma^* \rightarrow \pi^+\pi^-$*




Calculations by Assmussen, Masjuan, Vanderhaegen

Untagged
Single-Tag ($Q^2 = 0.5$ GeV$^2$)
Double-Tag ($Q_1^2 = Q_2^2 = 0.5$ GeV$^2$)

Measure mass range $\sqrt{s} = M_{\pi\pi} < 800$ MeV

# Conclusions

# &

# Outlook

# *Conclusions and Outlook*

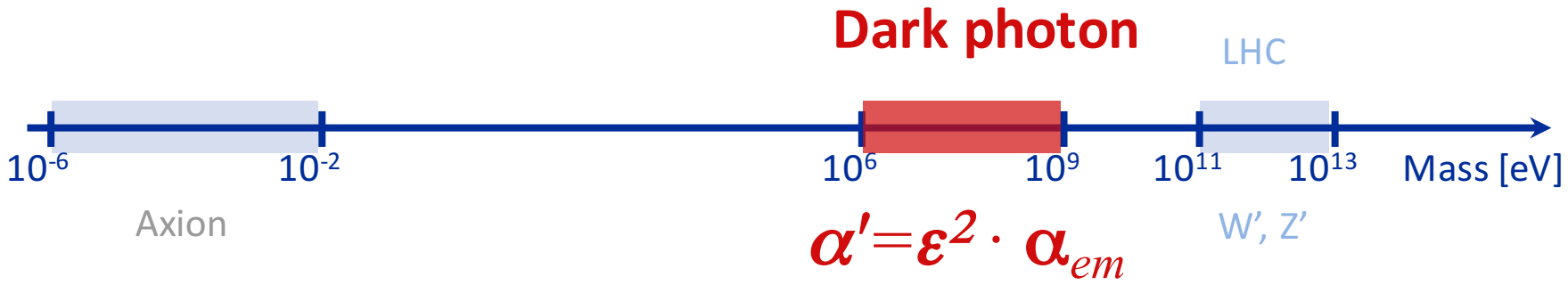
- Important results (to be expected) from BESIII for SM prediction of $(g-2)_\mu$
  - → Precision R measurements relevant for HVP contribution
  - → Space-like transition form factors of meson(s) relevant for HLbL contribution
- Competing experiments ongoing in Frascati, Novosibirsk, soon BELLE-II (?)

What accuracy can be achieved for $a_\mu^{had}$ ?

**Reduction of factor of 2 of uncertainty of SM prediction in reach**

# *Dark Photon*

**New massive force carrier of extra $U(1)_d$ gauge group; predicted in almost all string compactifications**

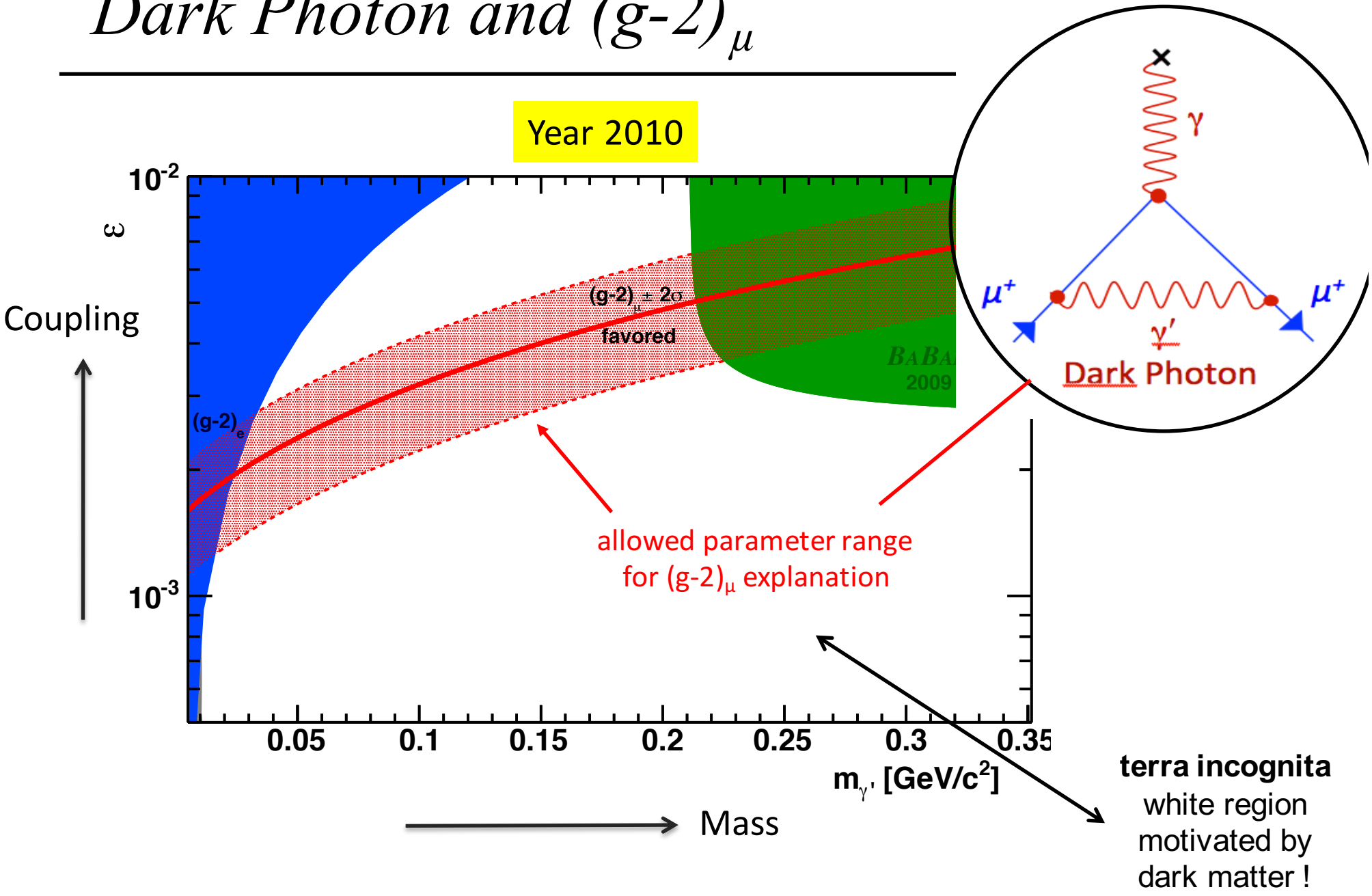



**Search for the O(GeV/$c^2$) mass scale in a world-wide effort**

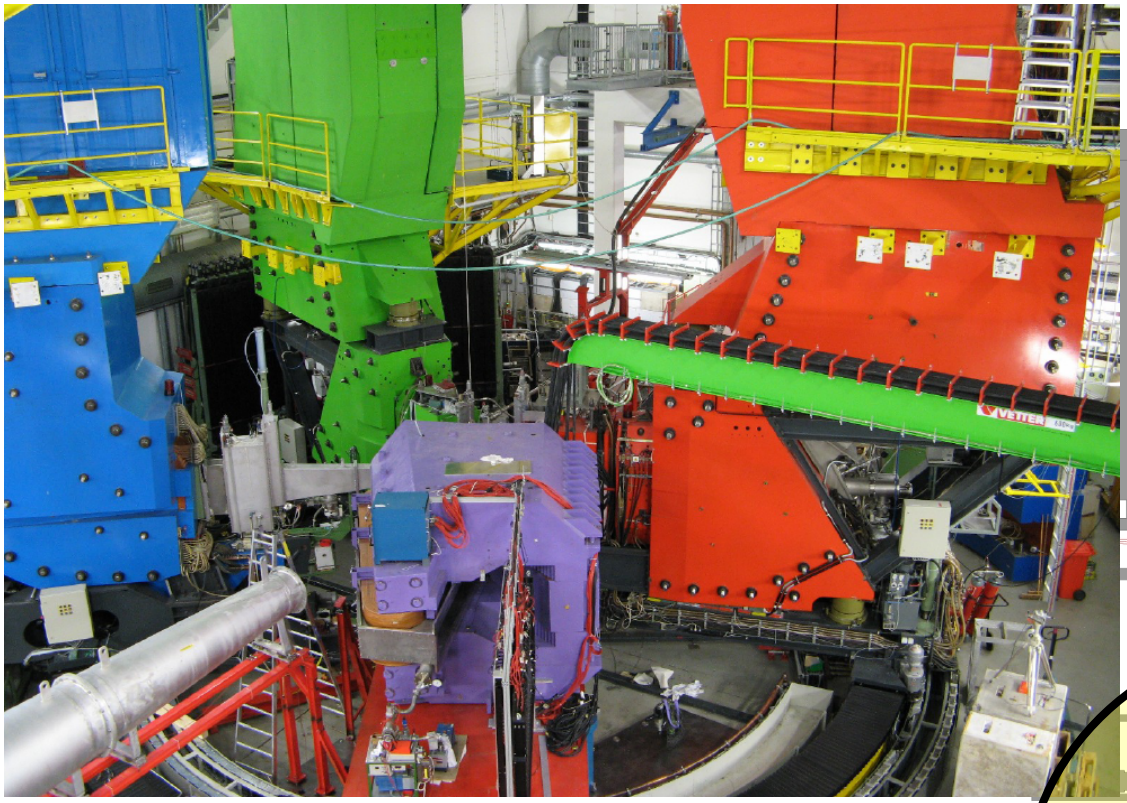
- Could explain large number of **astrophysical anomalies**
  Arkani-Hamed et al. (2009)
  Andreas, Ringwald (2010); Andreas, Niebuhr, Ringwald (2012)

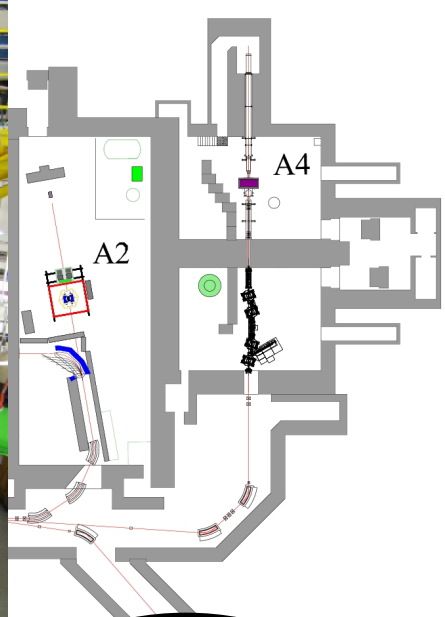
- Could explain presently seen **deviation of 3.6σ between $(g-2)_\mu$** Standard Model prediction and direct $(g-2)_\mu$ measurement
  Pospelov(2008)

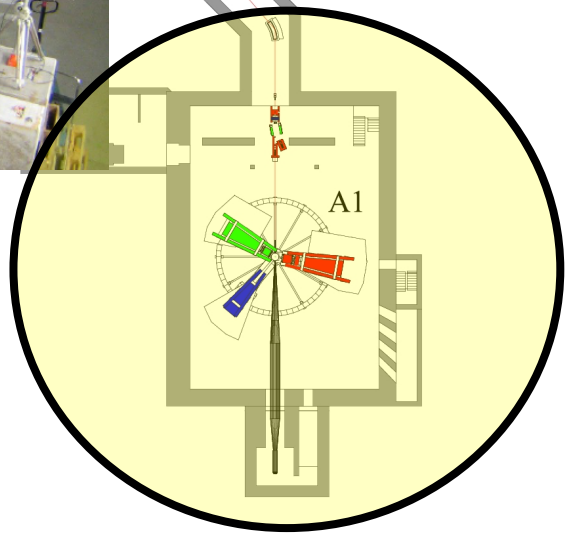
# *Dark Photon and $(g-2)_\mu$*



# *Experiment A1: High-Resolution Spectrometers*






**Experiment A1: Electron Scattering**

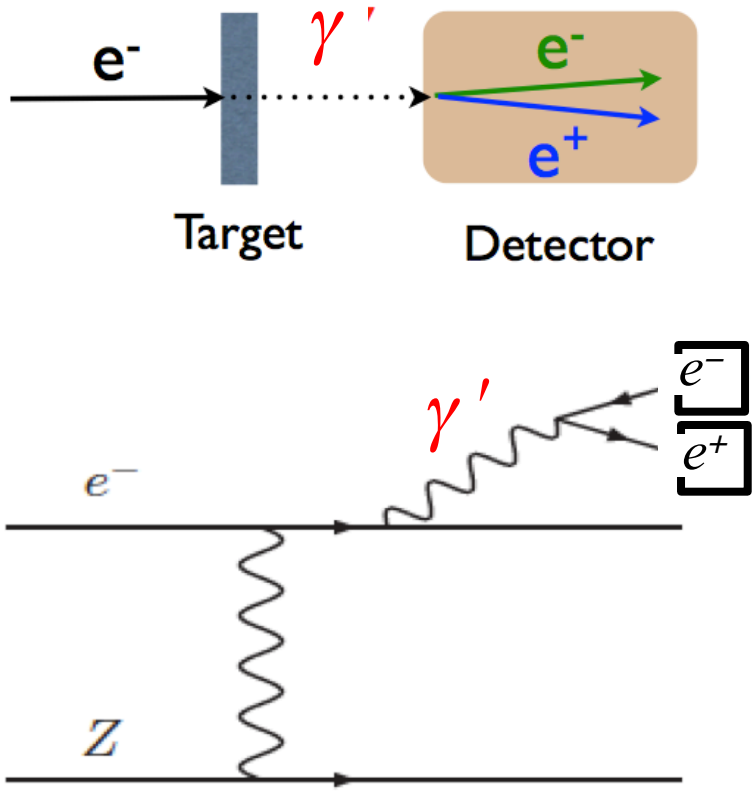
- 4 magnetic focussing spectrometers
- Resolution: $\delta p/p < 10^{-4}$
- Angular acceptance: <30 mrad

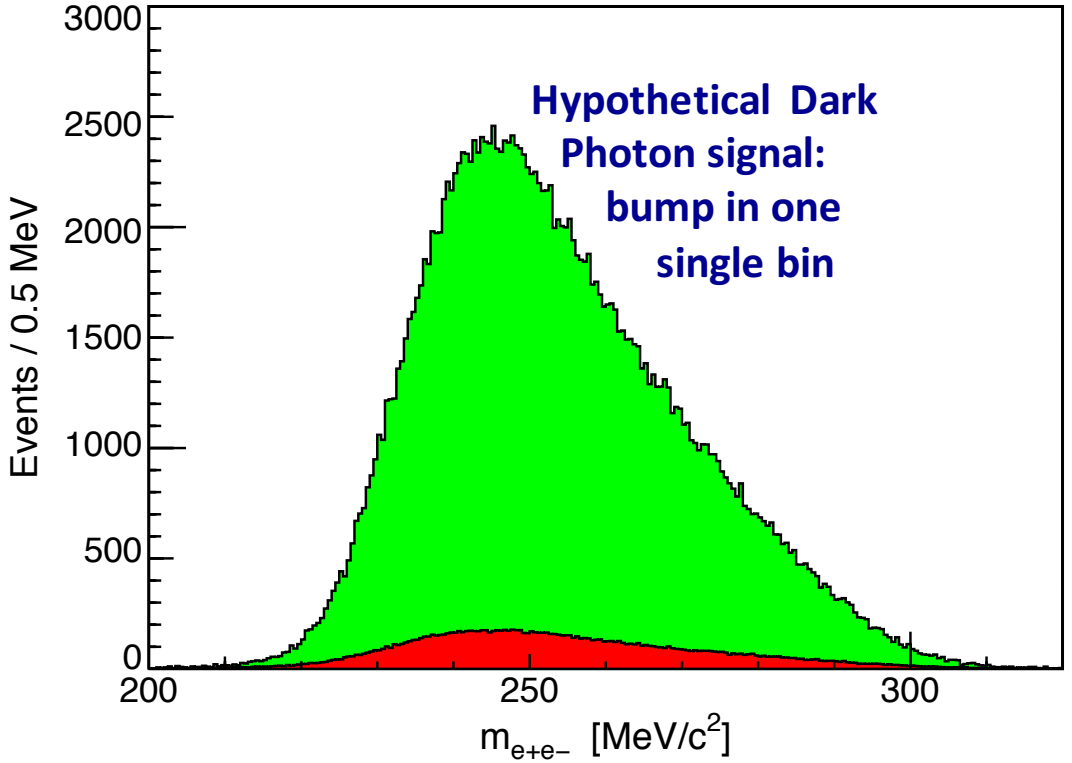
# *Results from A1*

**Low-Energy Electron Accelerators with high Intensity ideally suited for Dark Photon search**

Bjorken et al. (2009)

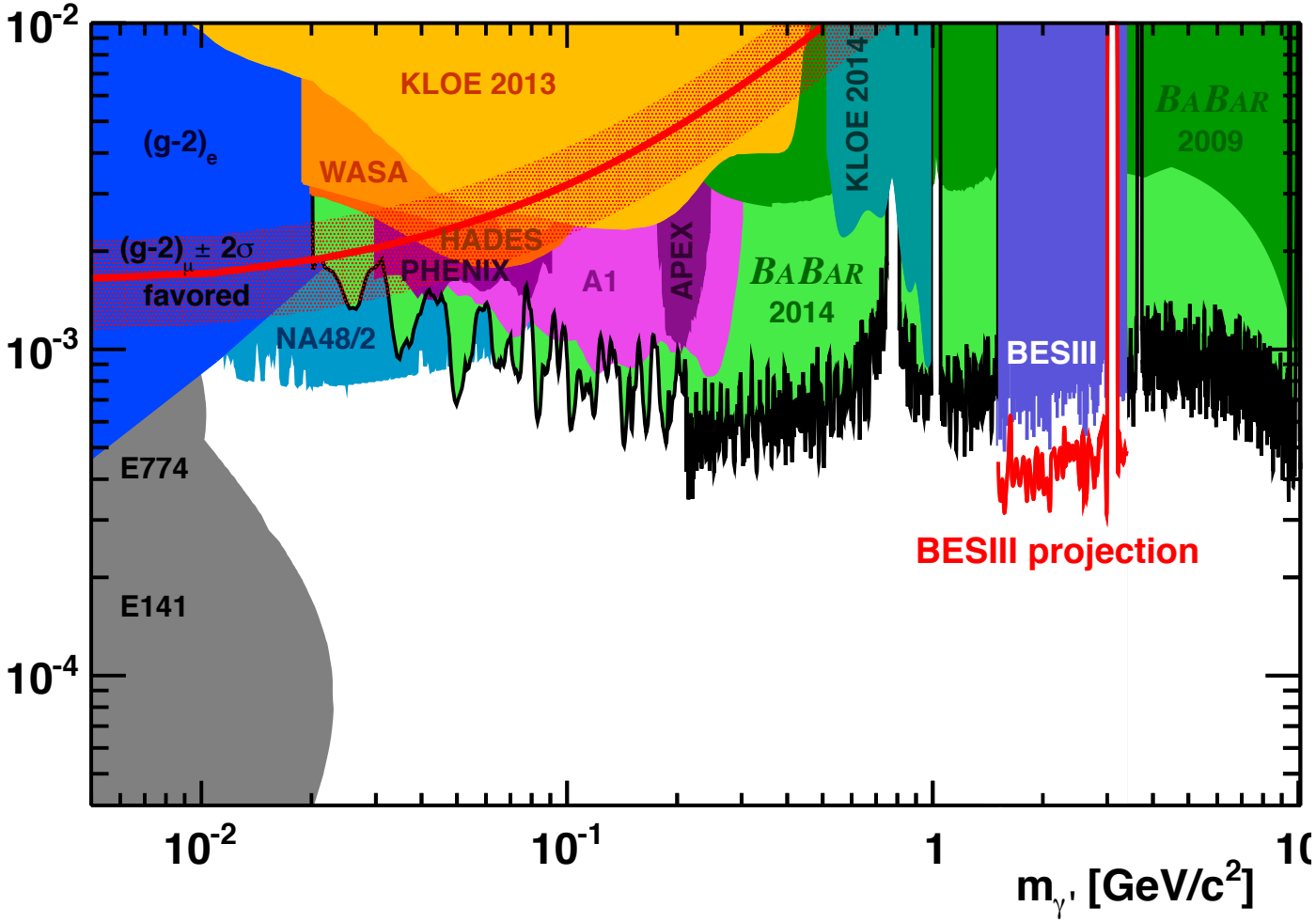
## Signal processes



# *Results from A1 @ MAMI*

Merkel et al. [A1]
PRL '11
PRL '14




- $E_{beam}$ 180 - 855 MeV
- 100 µm beam current
- Stack of Ta targets
- 22 kinematic settings
- coincidence between 2 spectrometers for e-, e+

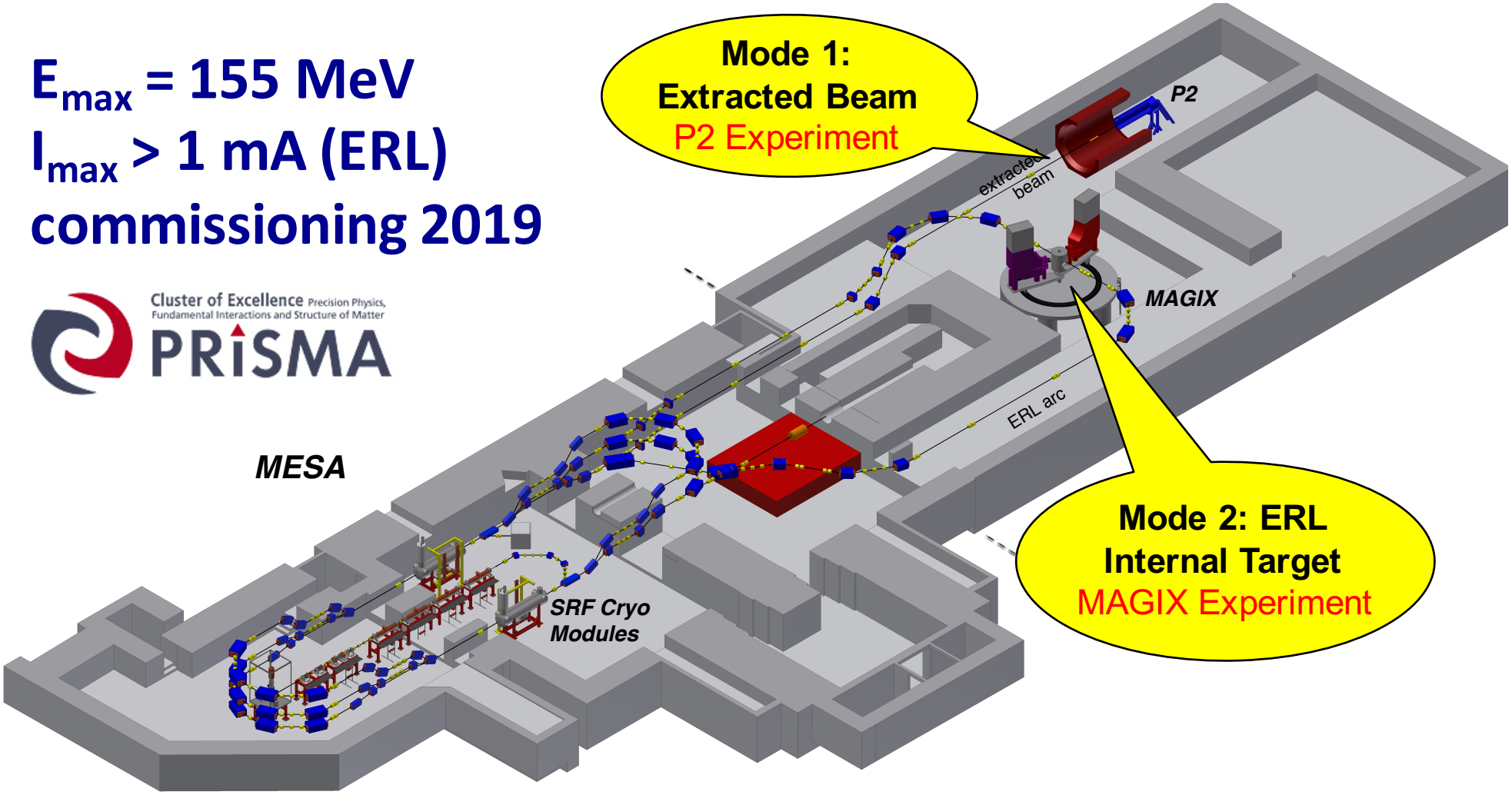
→ **at time of publication most stringent limit ruling out major part of the parameter range motivated by $(g-2)_\mu$**

# *Low-Energy Electron Accelerator MESA*

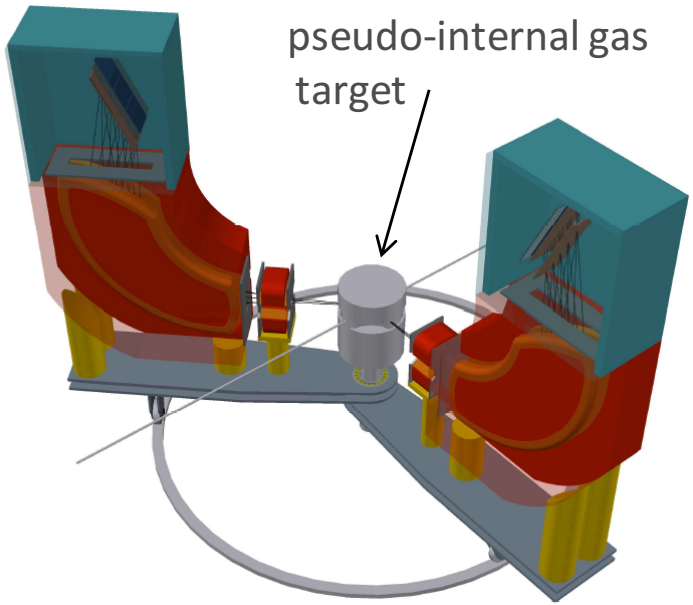
## Mainz Energy-Recovering Superconducting Accelerator

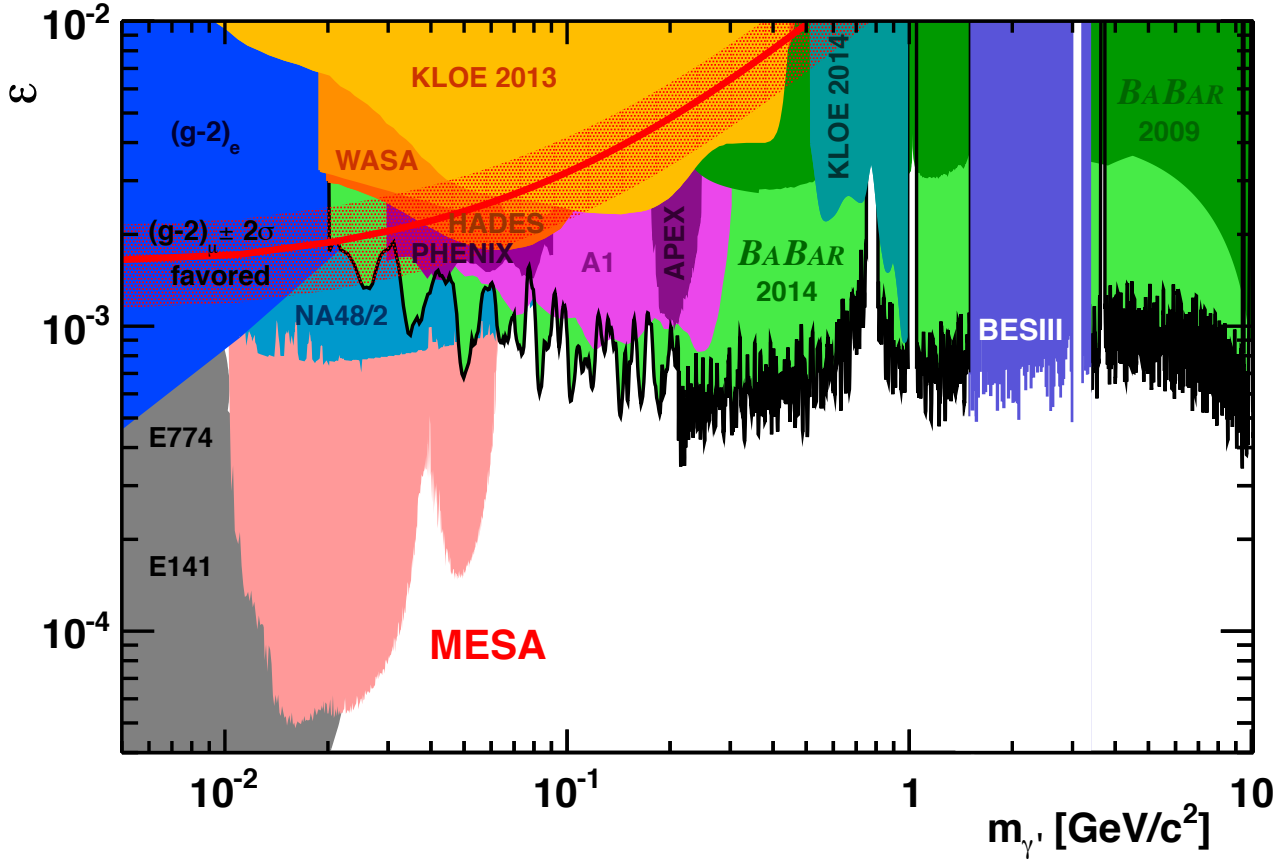
**$E_{max}$ = 155 MeV**
**$I_{max}$ > 1 mA (ERL)**
**commissioning 2019**

Cluster of Excellence Precision Physics, Fundamental Interactions and Structure of Matter
PRISMA



# *Outlook: Dark Photon at MAGIX @ MESA*




## MAGIX / MESA

**Model 1: Dark Photon coupling to SM particles**

→ parameter range motivated by Dark Photon relation to Dark Matter

**Model 2: Dark Photon not coupling to SM particles**

→ could still explain $(g-2)_\mu$ discrepancy

→ search possible thanks to excellent momentum resolution of MAGIX spectrometers via missing mass