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R_{had} , $\gamma\gamma$ Form Factors and the Standard Model Prediction of the Muon Anomaly

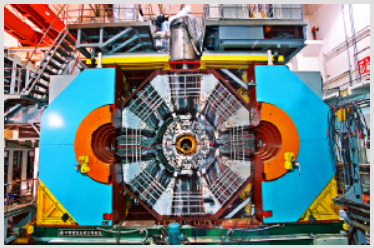
July 21-24, 2014

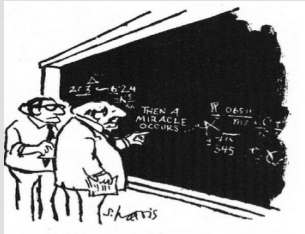
Centerville, Cape Cod, USA

5th Intl. Symposium on Lepton Moments

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

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





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

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

Perturbative
Calculations (Theory)

Hadronic Vacuum Polarization

Hadronic Light-by-Light Scattering

Electroweak Contribution

$(g\text{-}2)_\mu$ Experiment

$(g\text{-}2)_\mu$ Interpretation

Outline

Hadronic Vacuum Polarization <-> R_{had}

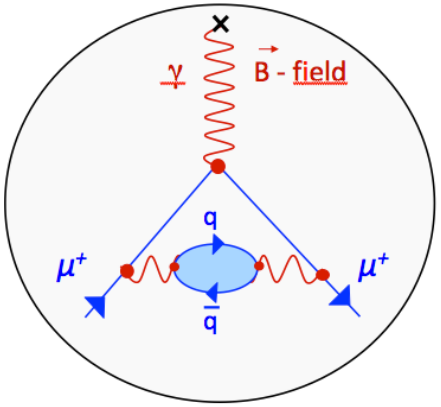
- Overview hadronic cross section measurements
  Initial State Radiation: KLOE vs. BABAR
- BES III status and expectations

Hadronic Light-by-Light <-> $F(Q_1^2,Q_2^2)$

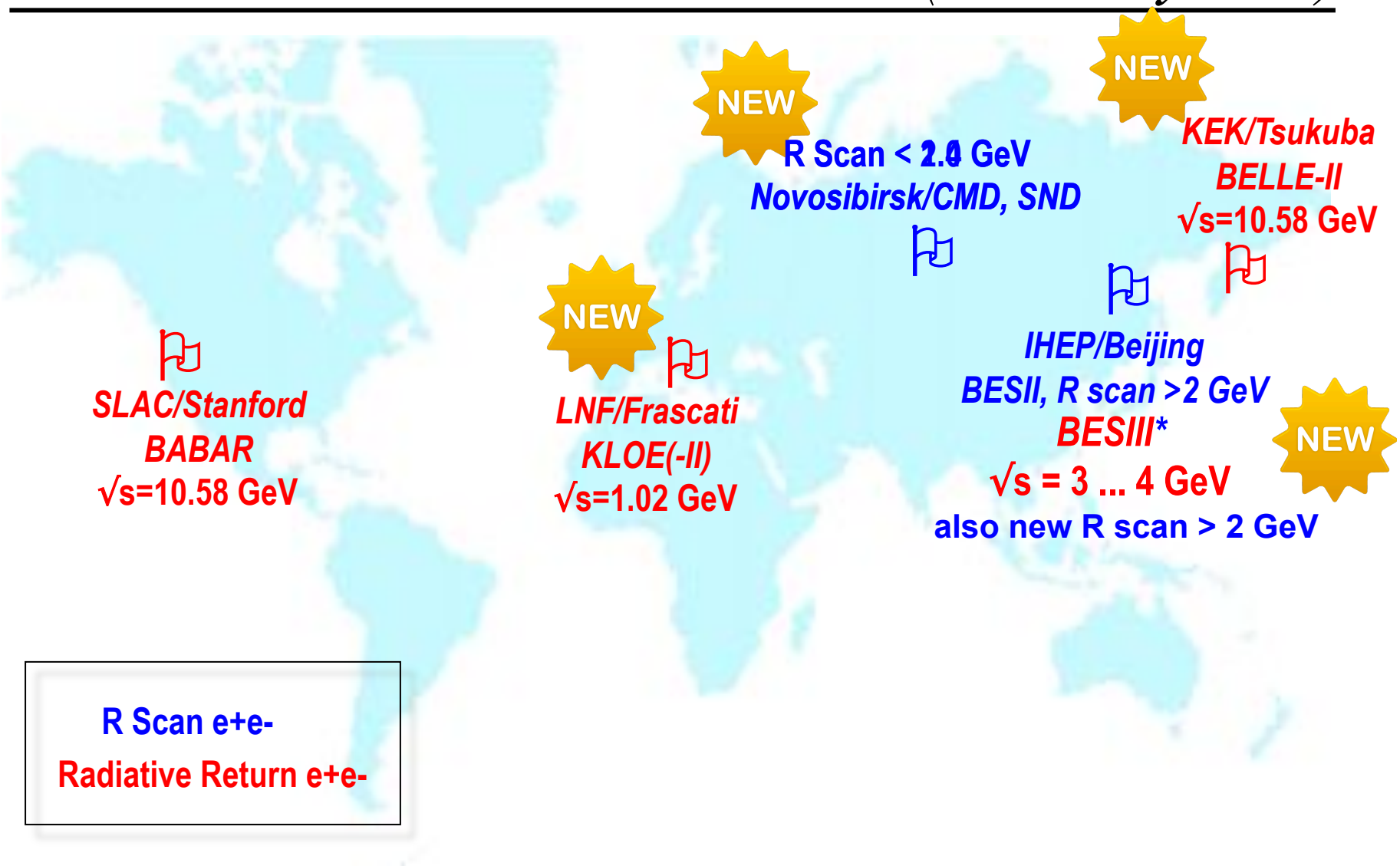
- Overview meson transition form factors
- BES III status and expectations

Conlusions & Outlook

R_{had}
Hadronic Cross Section
σ_{had}



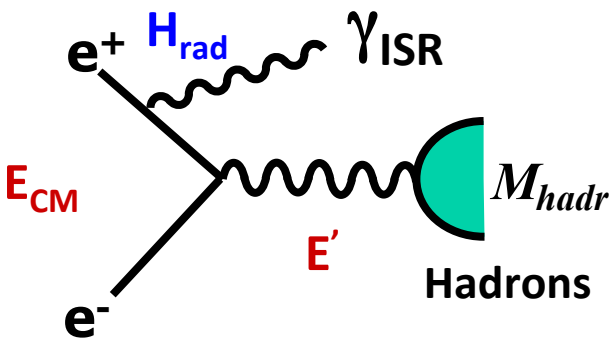
Hadronic Cross Section Data (last 20 years)



Initial State Radiation

Rev. Mod. Phys. 83, 1545–1588 (2011)

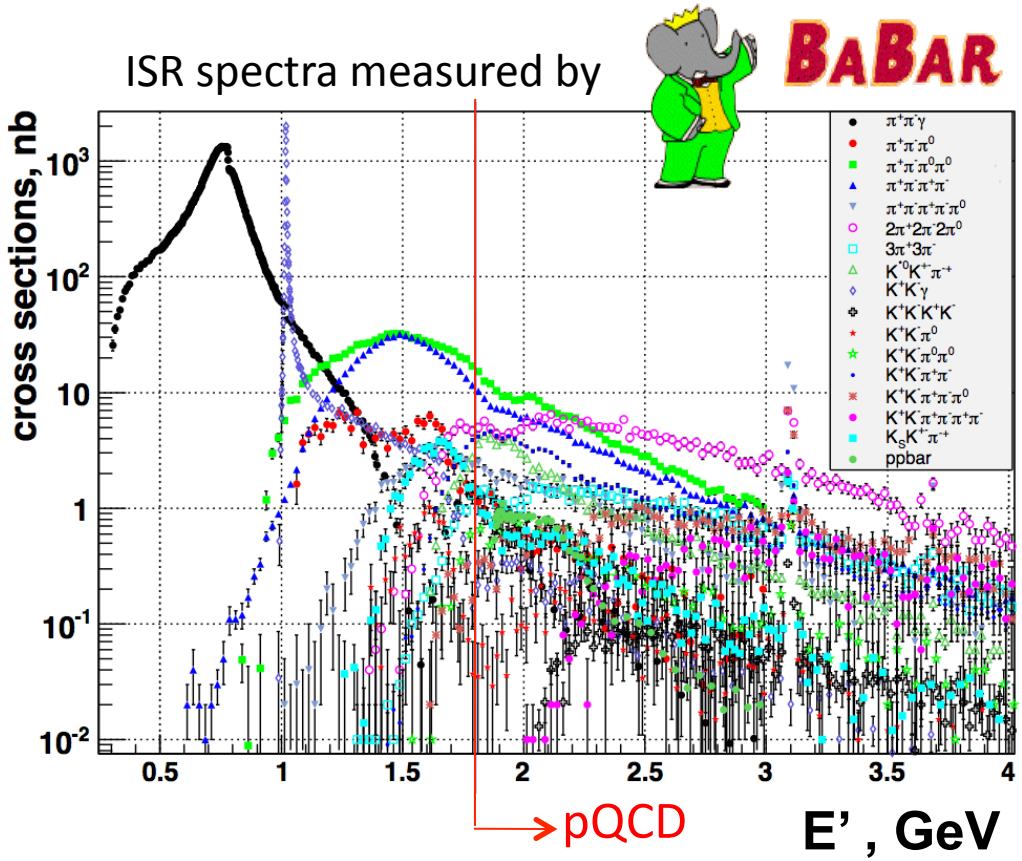
Initial State Radiation (ISR)
aka Radiative Return



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

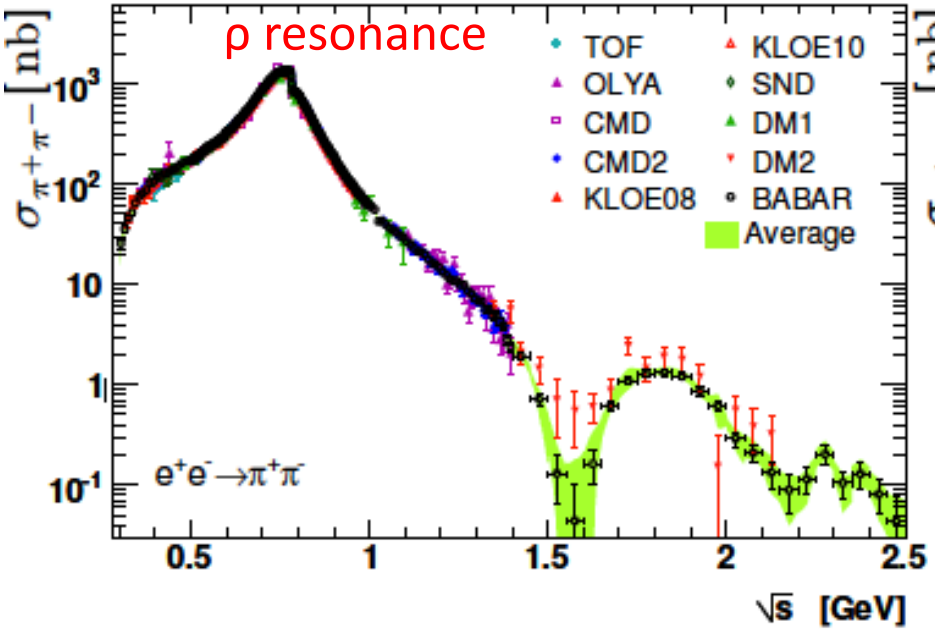
PHOKHARA event generator Czyż, Kühn, et al.

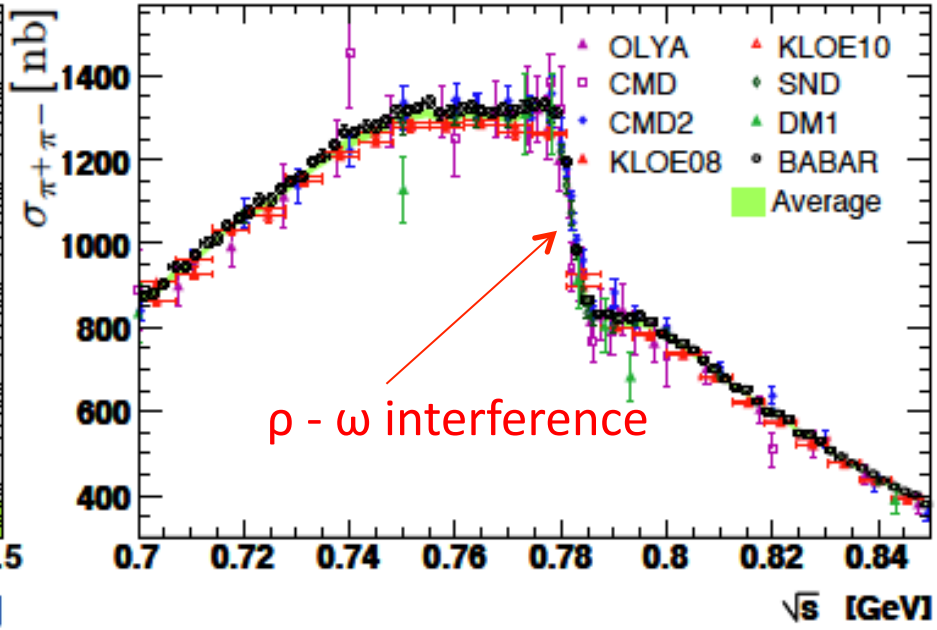
ISR spectra measured by



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

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



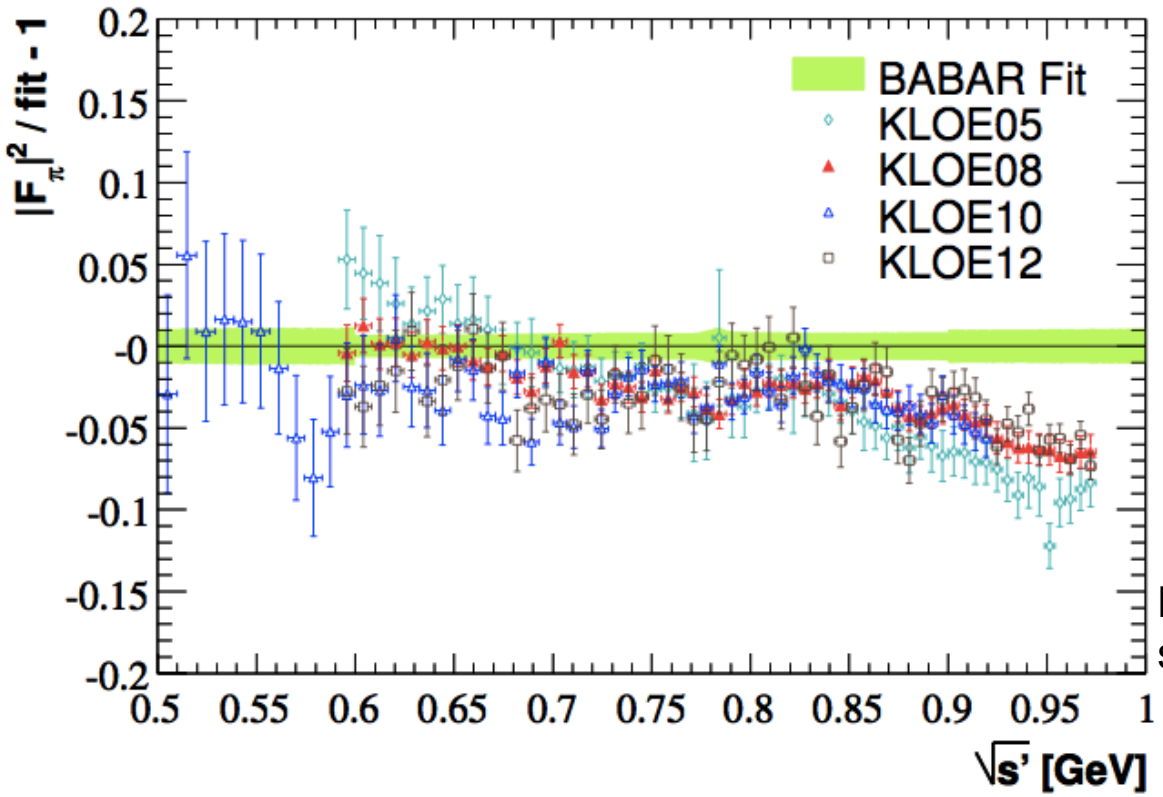


Systematic Uncertainties

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

* limited in addition by statistics

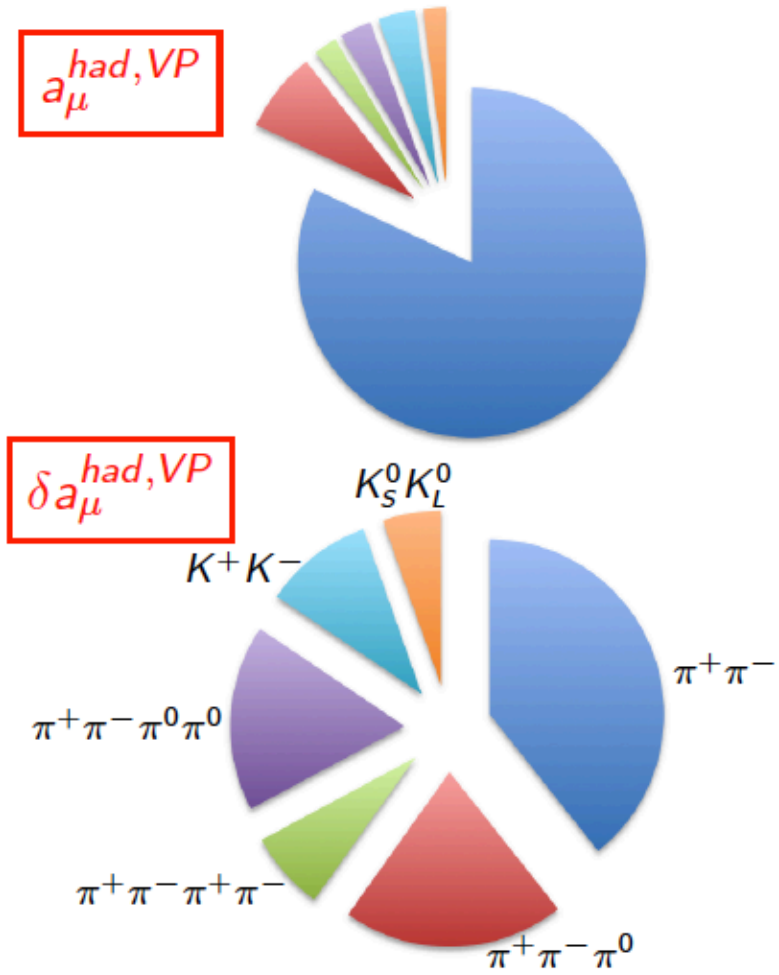
Most relevant Channel: $e^+e^- \rightarrow \pi^+\pi^-$



Note: KLOE05 superseded by KLOE08

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

Status Hadronic Vacuum Polarization



Future improvement of a_μ^{had} ?

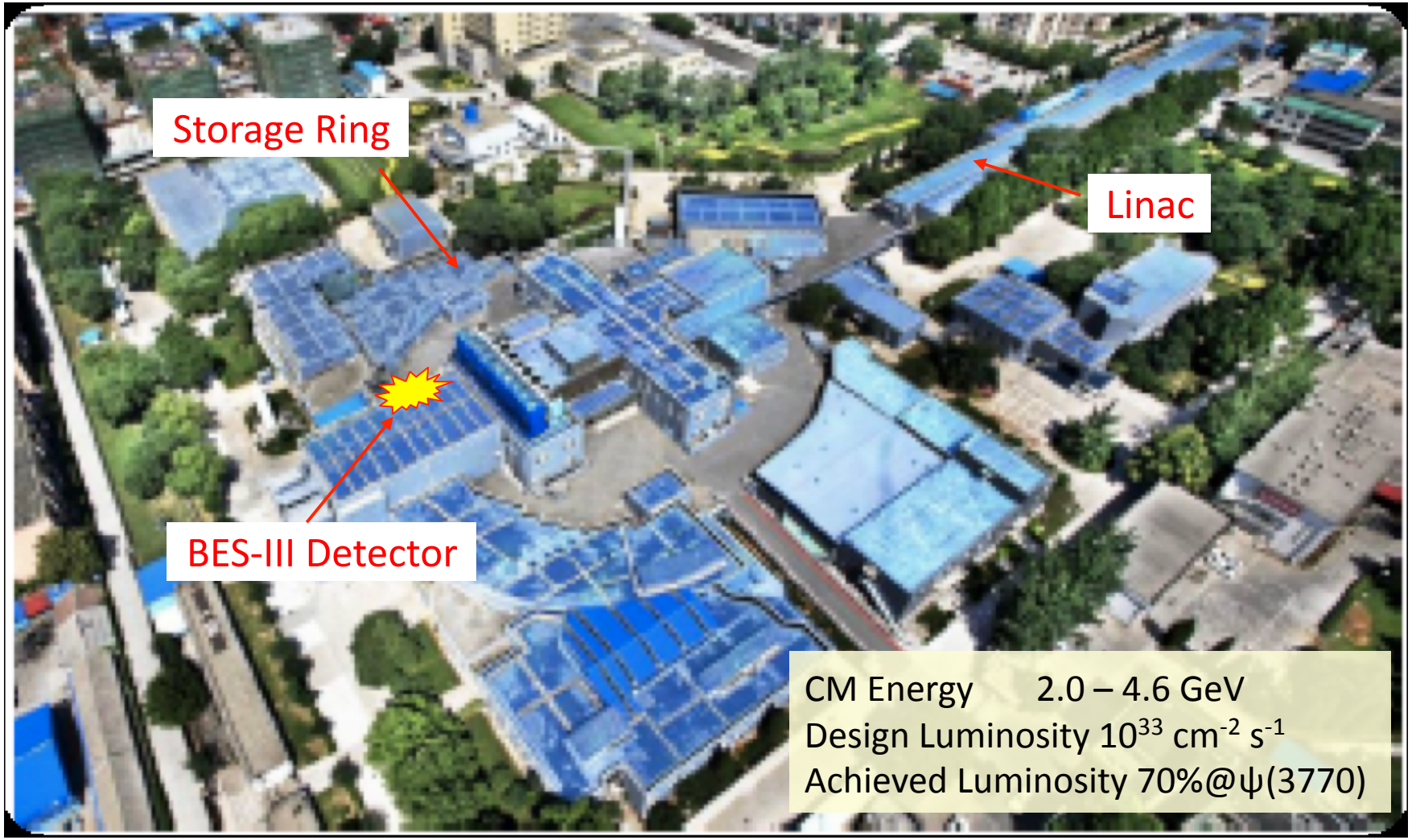
1st priority:
Clarify situation regarding $\pi+\pi-$
(KLOE vs. BABAR puzzle)

2nd priority:
Measure 3π, 4π channels

Ongoing ISR analyses
BESIII, BEPC-II collider

3rd priority:
$K\bar{K}$ and higher multiplicities

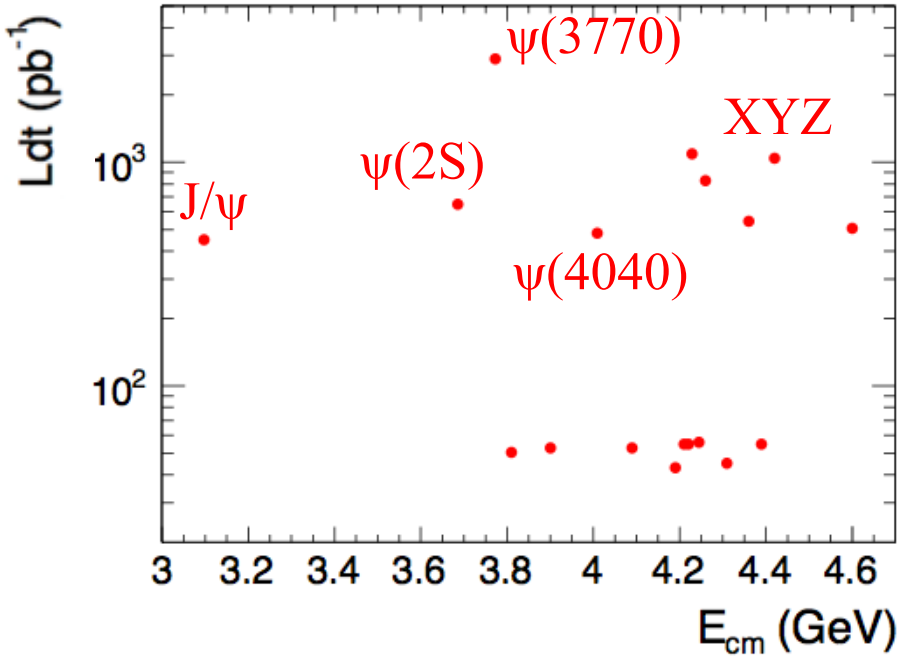
BEPC II Project

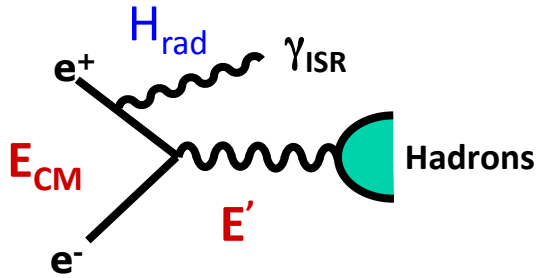


CM Energy 2.0 – 4.6 GeV
Design Luminosity 10^{33} cm^{-2} s^{-1}
Achieved Luminosity 70%@ψ(3770)

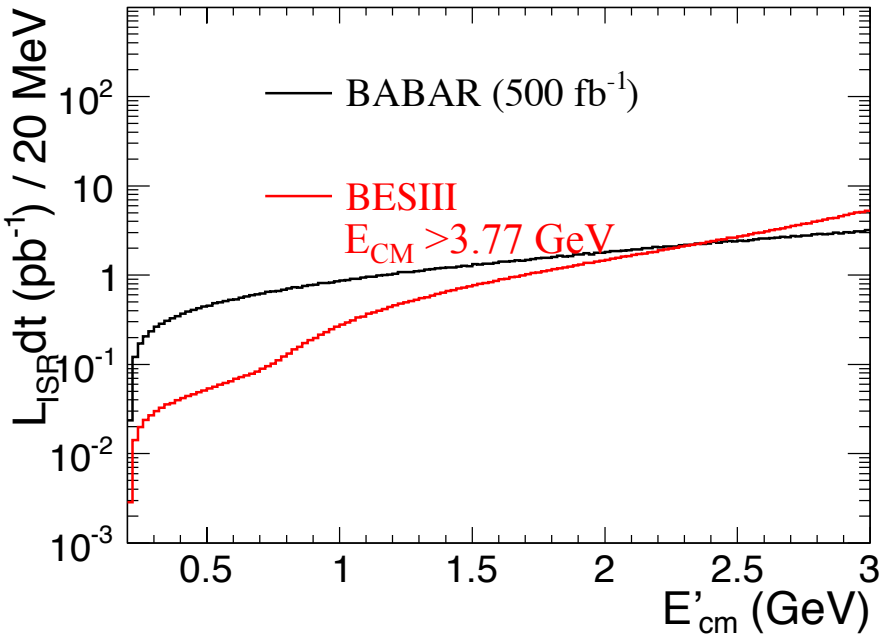
Data Samples for ISR Physics

Integrated luminosities BESIII

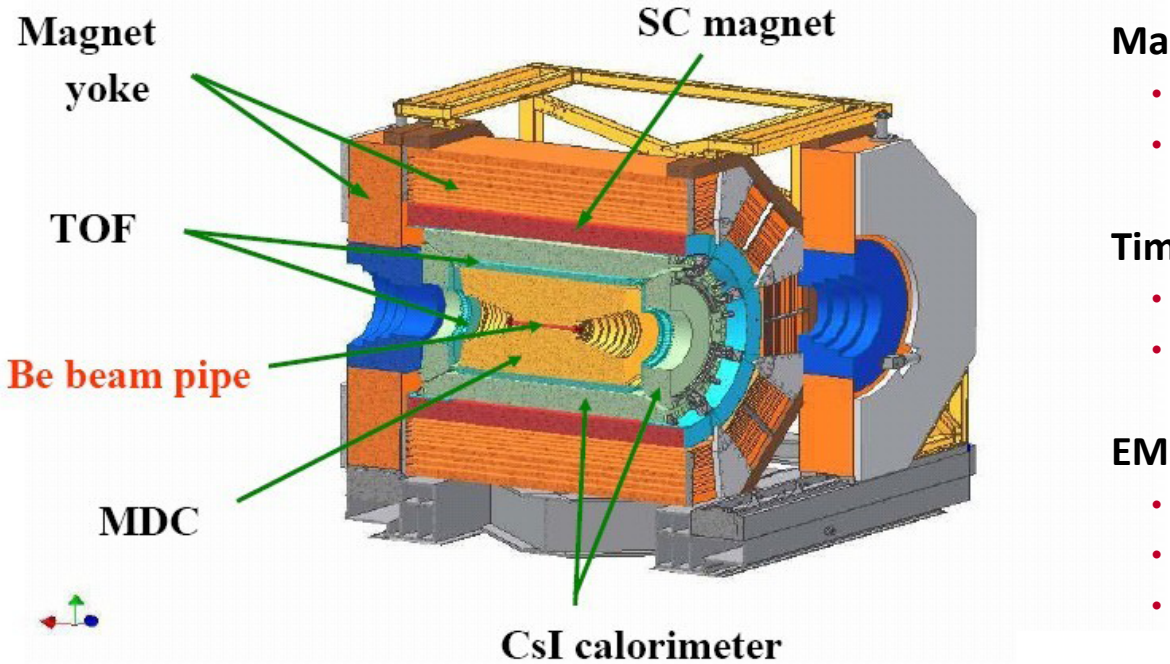




ISR luminosity = Ldt x H_{rad}



BES III Detector



Main Drift Chamber (MDC)

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

Time-of-flight system (TOF)

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

EMC

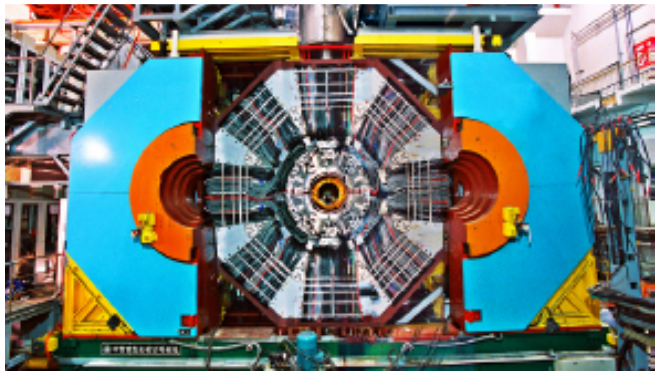
- 6240 CsI(Tl) crystals
- $\sigma(E)/E = 2.5\%$
- $\sigma_{Z.\Phi}(E) = 0.5 – 0.7$ cm

Muon Chambers

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

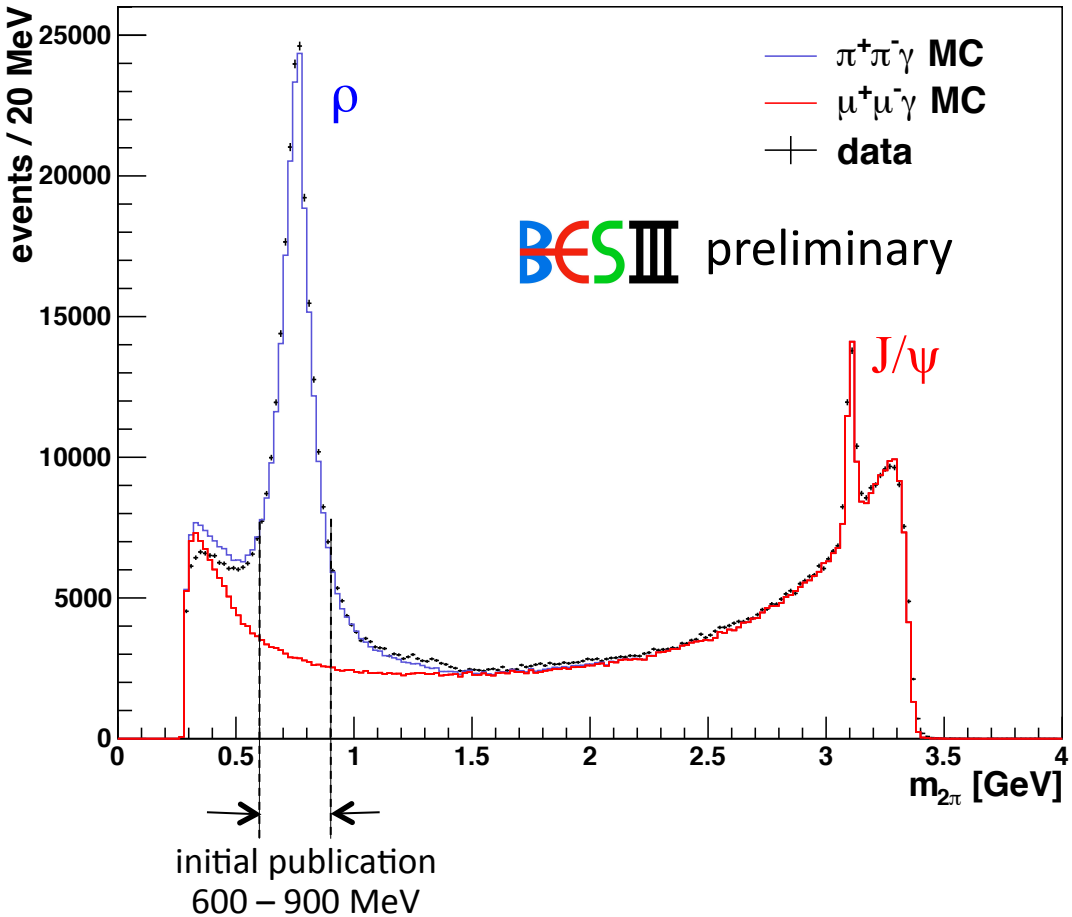
Superconducting Magnet

- 1 T magnetic field



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

Event yield after acceptance cuts **only**

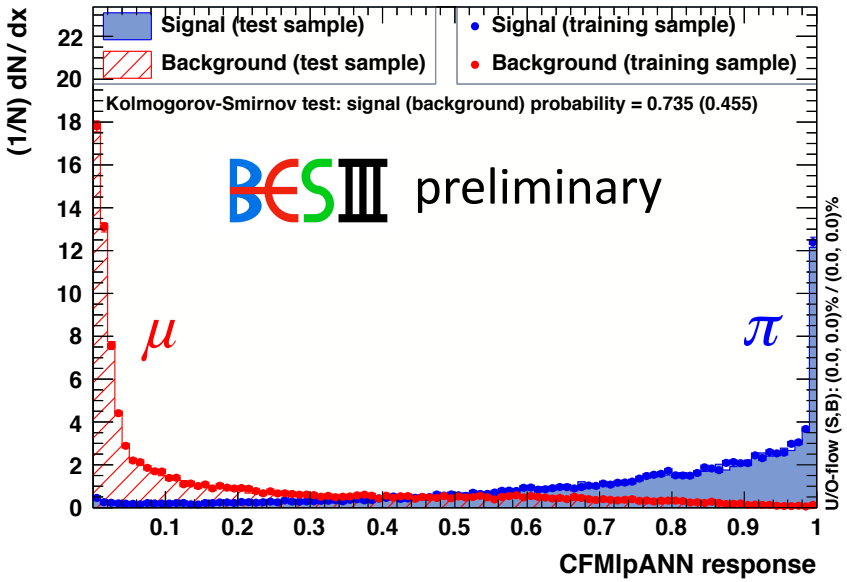


Features:

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

→ large statistics of e+e- → ππγ events
→ background dominated by e+e- → μμγ
→ data – MC differences visible

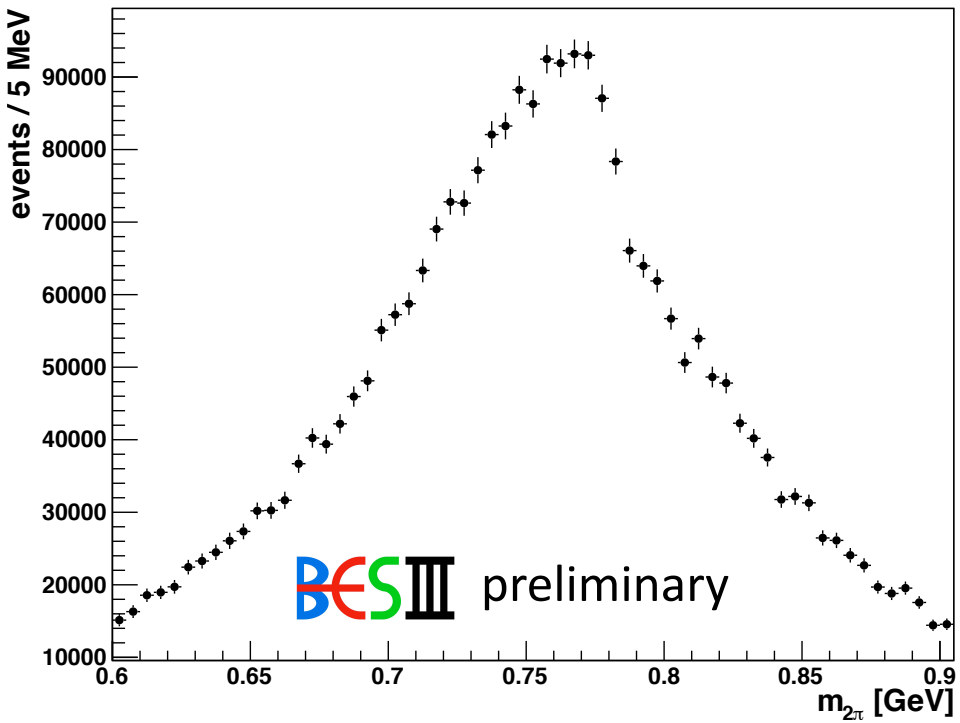
$e^+e^- \rightarrow \pi^+\pi^-\gamma_{ISR}$: π - μ Separation



TMVA method (Neural Network):

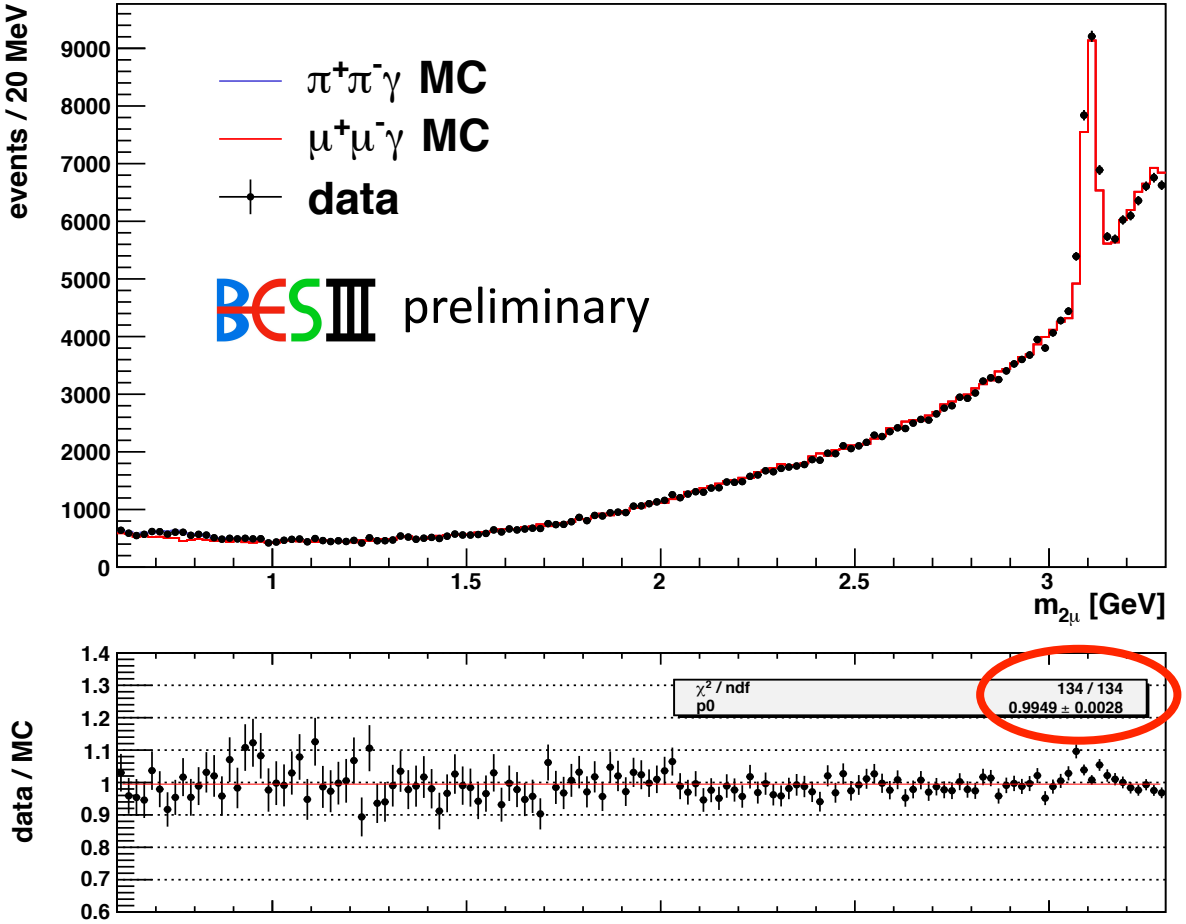
- trained using μμγ and ππππγ MC events
- information based on track level
- efficiency matrix (p,Θ) for data, MC
- correct for data - MC differences
- cross checked for different TMVA methods

Event yield ππγ after π-μ separation



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

Event yield μμγ after π-μ separation
and all efficiency corrections



Features:

- background from ππγ very small
- PHOKHARA accuracy <0.5%
- luminosity measurement based on Bhabha ev., 1.0% accuracy

→ excellent agreement with QED

Δ(MC/QED-data) = (0.51 ± 0.28) %

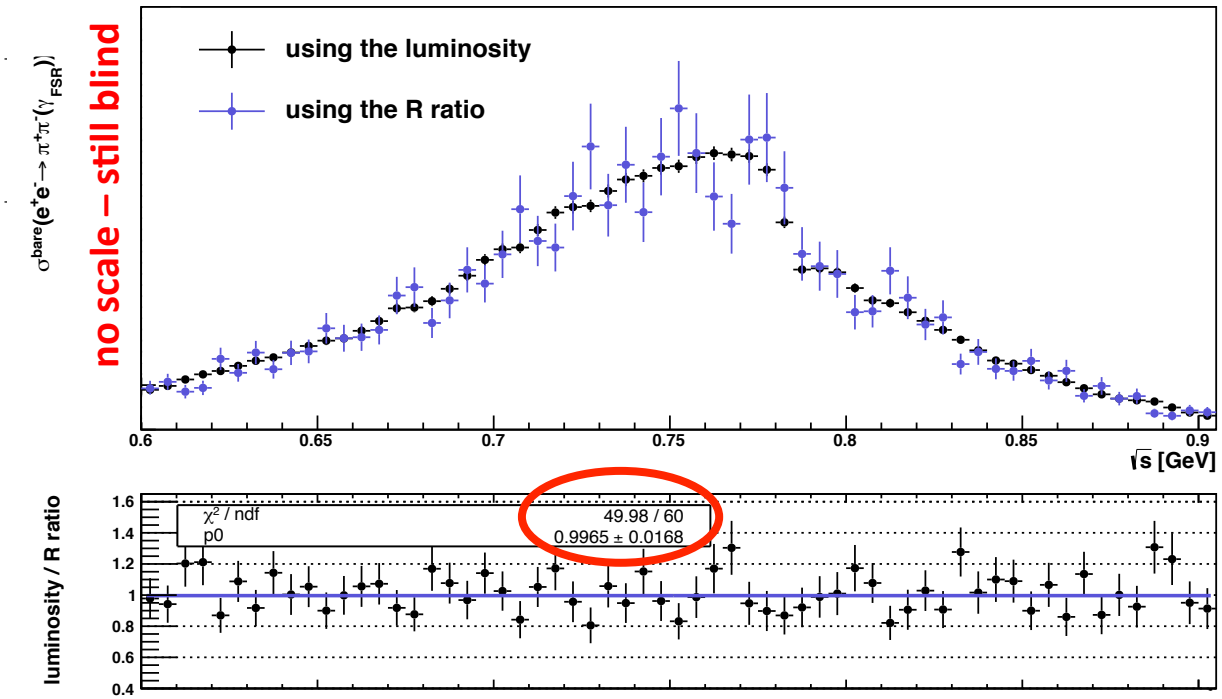
→ accuracy on 1% level as needed to be competitive !

Result (still blind): $\sigma(e^+e^- \to \pi^+\pi^-)$

2 normalization methods: 1) normalization to L_{int} (obtained from Bhabha events)

$$\sigma_{bare}(e^+e^- \to \pi^+\pi^-) = \frac{N_{\pi\pi\gamma}/\epsilon_{exp}}{L_{int} \cdot H_{rad} \cdot \delta_{vac} \cdot (1+\delta_{FSR})}$$

2) normalization to μμγ events, i.e. R ratio (ππγ/μμγ)
→ L_{int}, H_{rad}, δ_{vac} cancel in ratio!

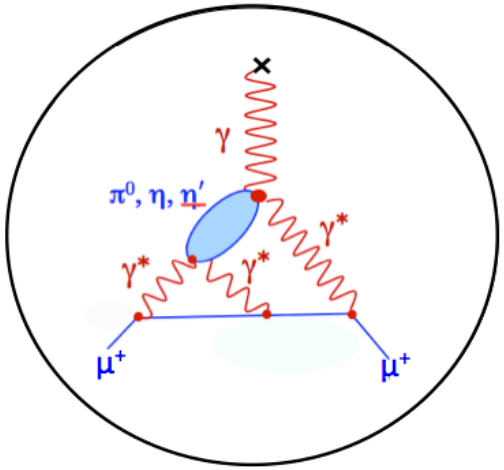


luminosity / R ratio = (0.35 ± 1.68) %

limited by low μμγ statistics

Meson Transition Form Factors

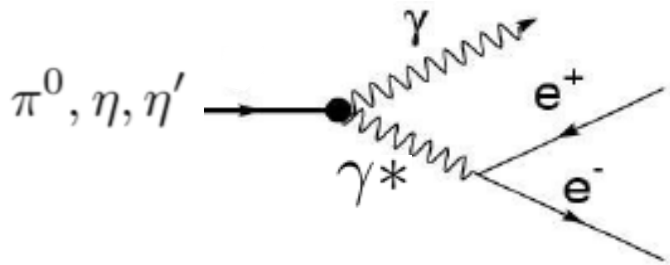
$F(Q_1^2, Q_2^2)$



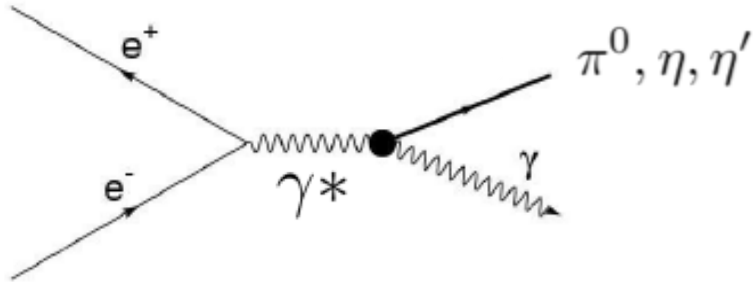
Meson Transition Form Factors P→ γ γ(*)*

Time-like transition form factors:

- Dalitz decays
  - $0 < q^2 < M_P^2$

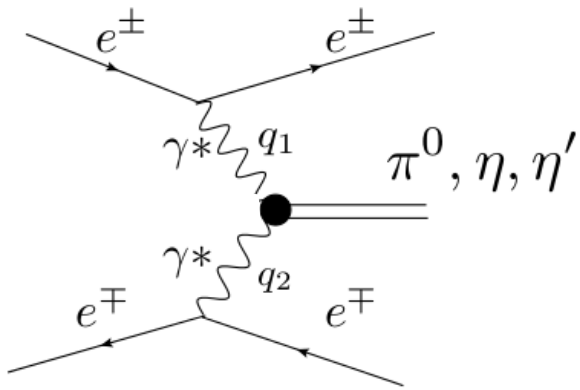


- Annihilation process
  - $q^2 = s > M_P^2$



Space–like transition form factors:

- Two-photon production of mesons in e+e-



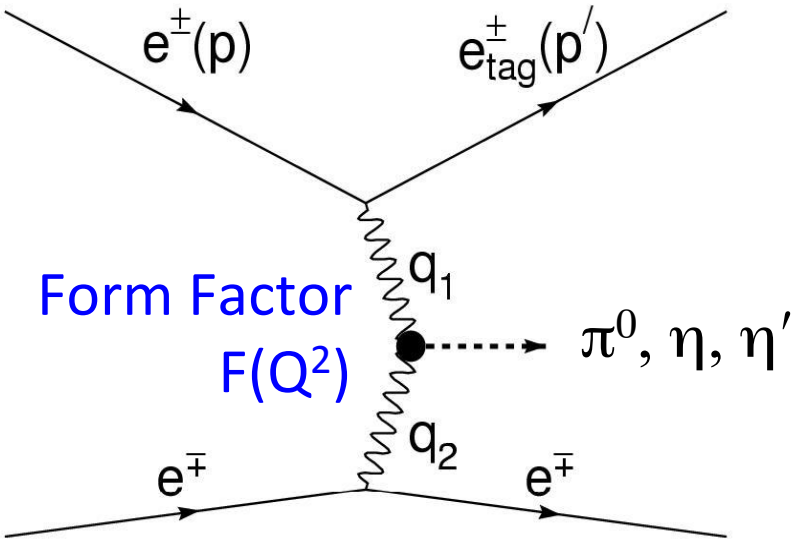
Space-Like FFs $\gamma\gamma^* \rightarrow P$

Single Tag Method

Selection criteria

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

→ cut on angle of missing momentum



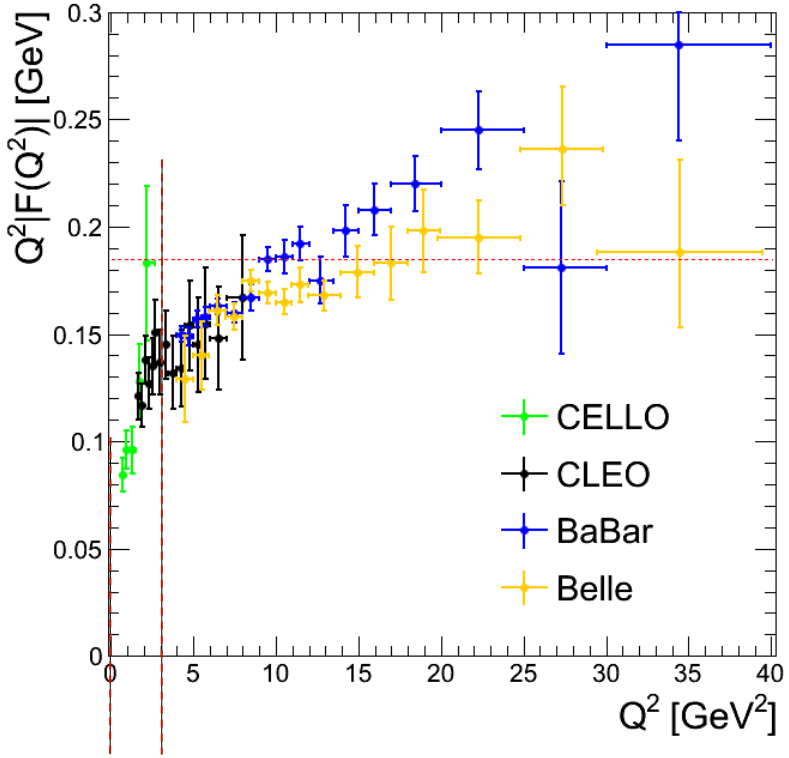
Momentum transfer

- 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 Form Factors

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



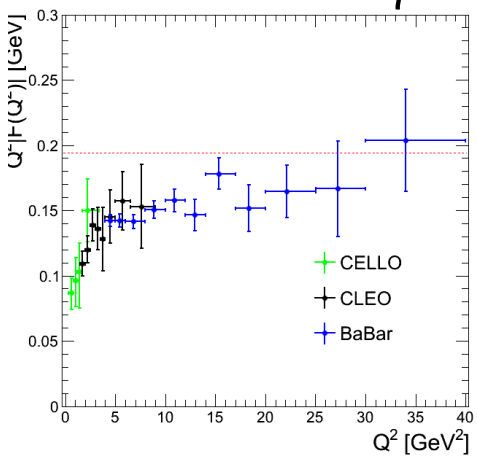
initial BESIII publication
< 3.1 GeV^2

Features:

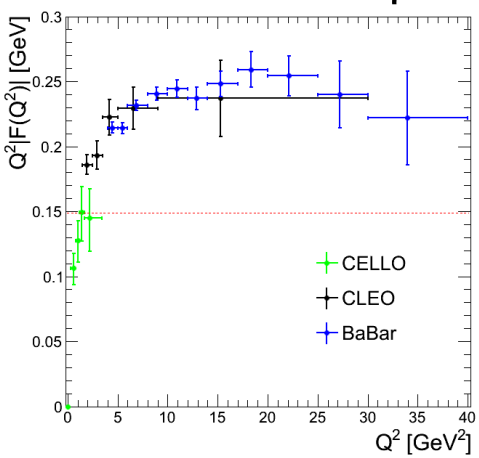
- recent high-Q^2 data from BABAR and BELLE $Q^2 > 4$ GeV^2
- above 1.5 GeV^2 data from CLEO
- below 1.5 GeV^2 data from CELLO, very poor accuracy

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

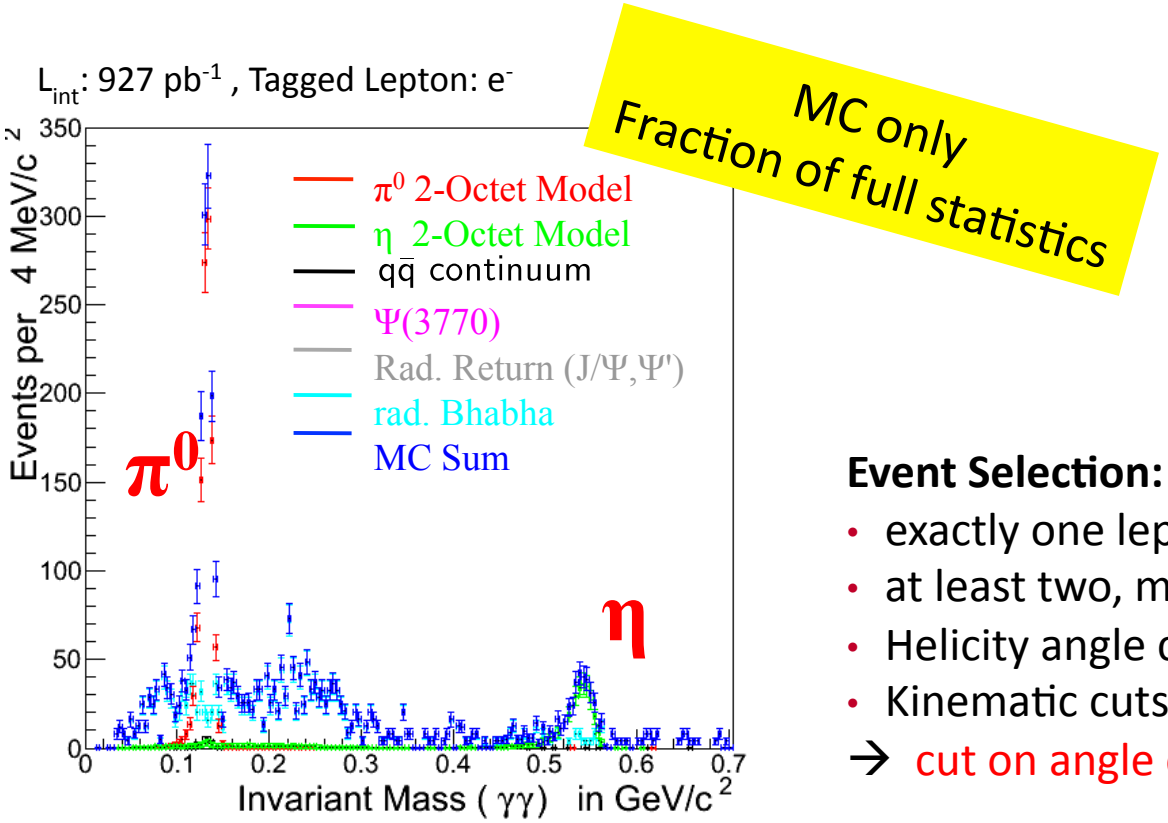
$e^+e^- \to e^+e^- \eta$



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



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



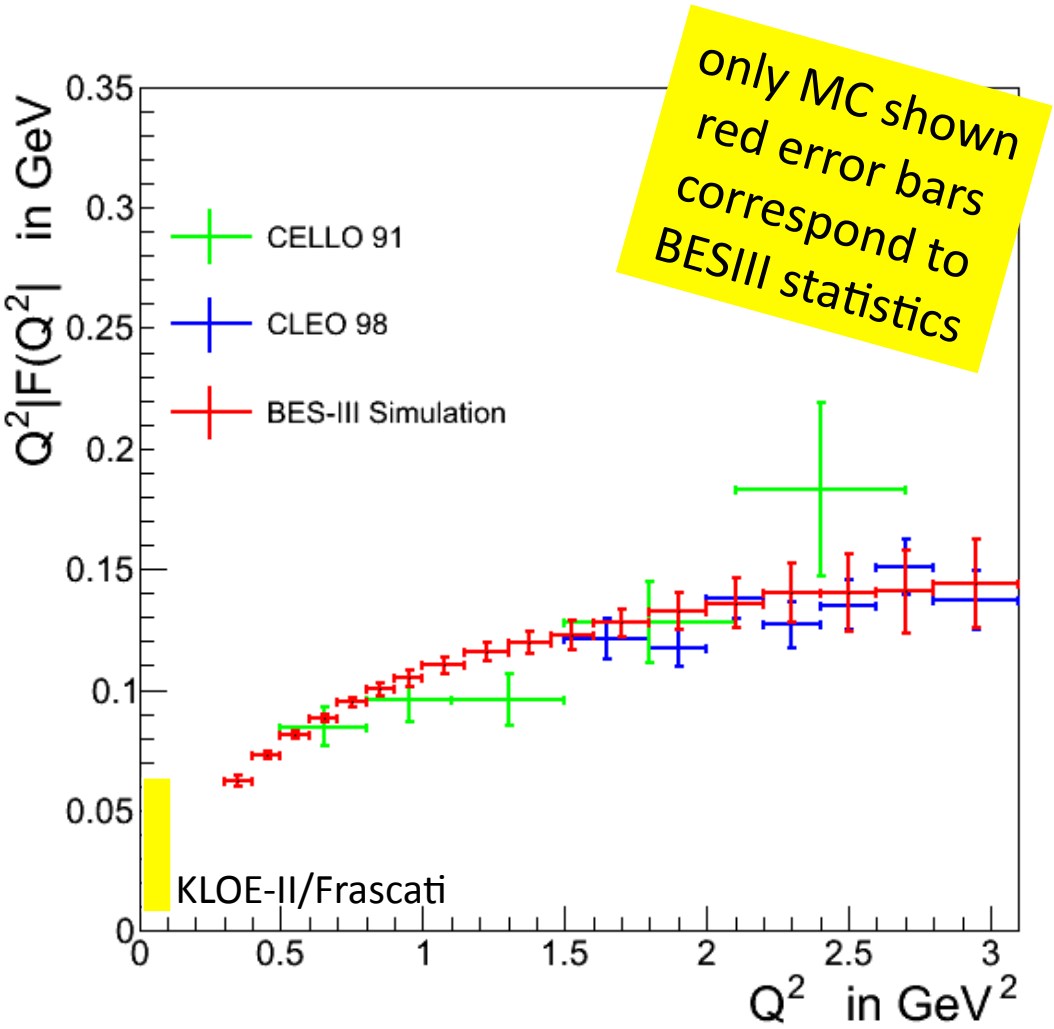
Event Selection:

- 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 π^0 yield in bins of Q^2 → $d\sigma/dQ^2$ → Form factor $F(Q^2)$

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



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

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

Conclusions

&

Outlook

Conclusions and Outlook

The Muon $(g-2)$ Theory Value: Present and Future

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November 12, 2013 arXiv:1311.2198

Hadronic contributions to the muon anomalous magnetic moment: strategies for improvements of the accuracy of the theoretical prediction

April 1–5, 2014 in Waldthausen Castle, Mainz, Germany

AND

$(g-2)_\mu$: Quo vadis?

April 7–10, 2014 in Mainz, Germany

Mini Proceedings arXiv:1407.4021

- Exciting results to be expected from BESIII
  → Precision R measurements relevant for HVP contribution to $(g\text{-}2)_\mu$
  → Space-like transition form factors of meson(s)

- Competing experiments ongoing in Frascati, Novosibirsk, soon BELLE-II (?)

What accuracy can be achieved for a_μ^{had} ?

Reduction of factor 2 of uncertainty in reach

Anomalous Magnetic Moment of the Muon

Let's speculate ☺

assume new exptl. measurement will be 1 sigma lower than today's value

assume we observe New Physics in (g-2)$_\mu$

→ without change in theoretical uncertainty: **$\Delta a_\mu = a_\mu^{exp} - a_\mu^{SM}$ = 4.3 sigma**

→ reduction of theoretical uncertainty of factor 2: **Δa_μ = 7.7 sigma**