JG|U

SFB 1044 THE LOW-ENERGY FRONTIER OF THE STANDARD MODEL

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

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Institute for Nuclear Physics

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ISR, γγ, and R Scan Measurements at BESIII

(and relevant for $(g-2)_\mu$)

BESIII

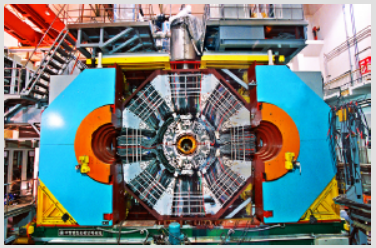
September 14-18, 2014

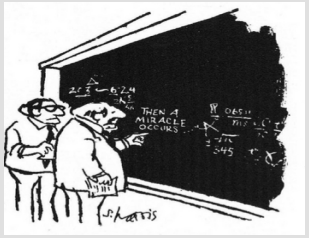
Aachen, Germany

The 13th Intl. Workshop on tau Lepton Physics

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

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





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

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

Perturbative Calculations (Theory)

Hadronic Vacuum Polarization

Hadronic Light-by-Light Scattering

Electroweak Contribution

White Paper:
arXiv:1311.2198

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

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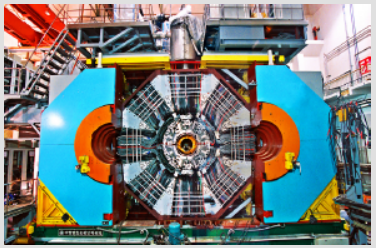

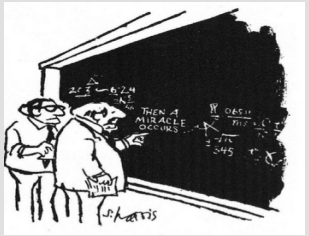

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$(g-2)_\mu$ Experiments

$(g-2)_\mu$ Interpretation

White Paper:
arXiv:1311.2198

Outline

Hadronic Vacuum Polarization <-> R_{had}

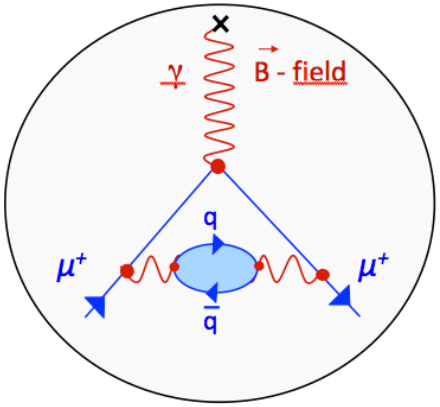
- Overview hadronic cross section measurements
- BES III ISR Program, Status e+e- → π+π-γ analysis
- R Scan > 2 GeV

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}



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

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

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

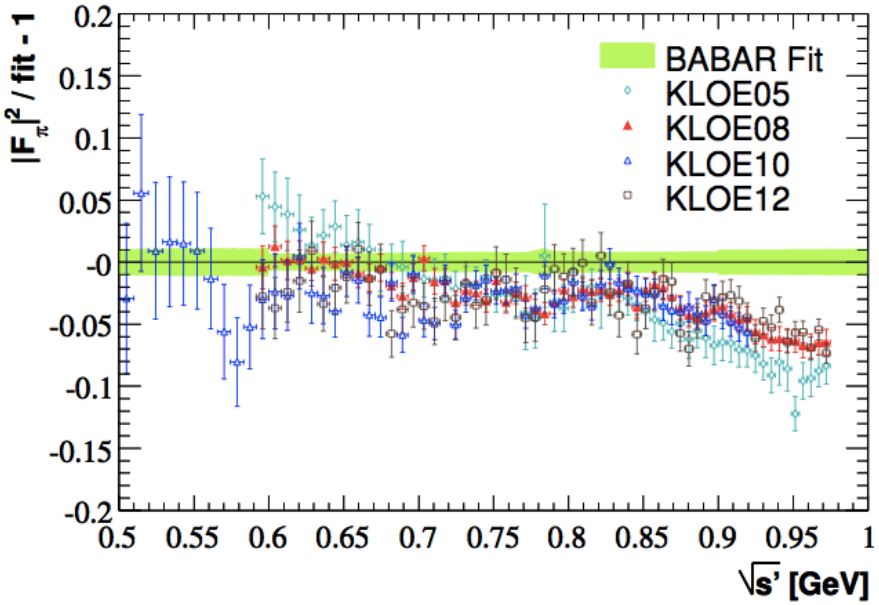
T. Teubner et al., arXiv: 1105.3149

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!



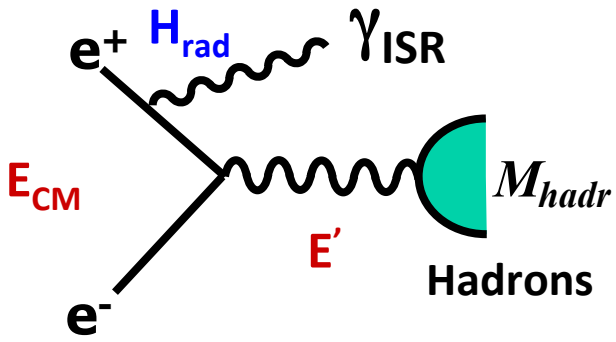
***Note**: KLOE05 superseded by KLOE08*

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

Initial State Radiation

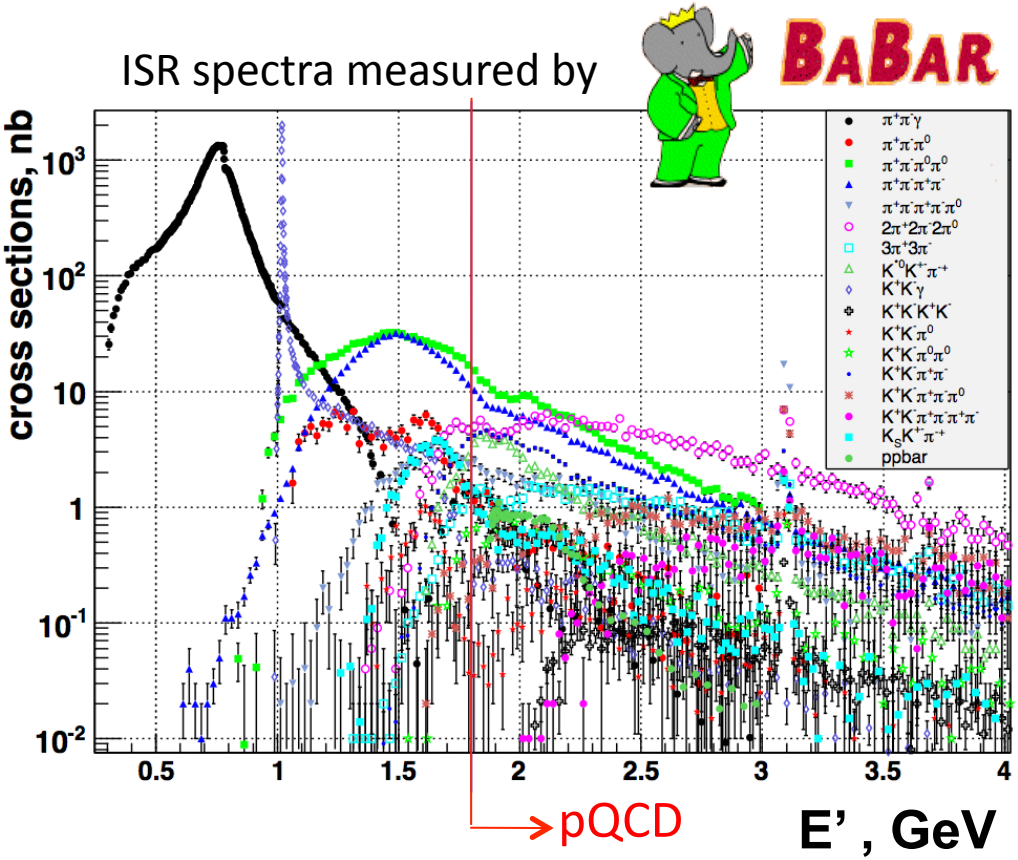
Rev. Mod. Phys. 83, 1545–1588 (2011)

Initial State Radiation (ISR) aka Radiative Return



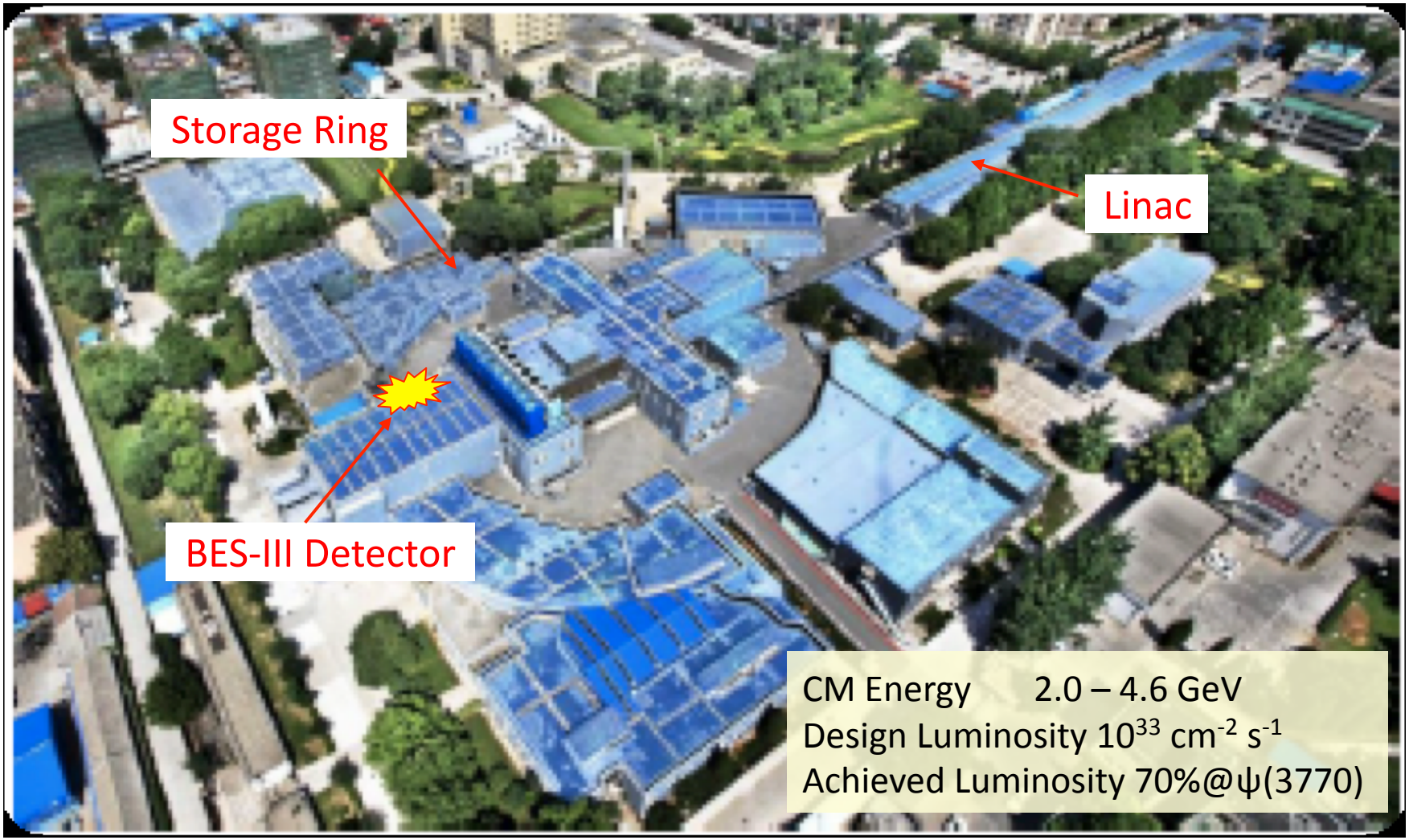
- Needs **no** systematic variation of beam energy
- High statistics thanks to high integrated luminosities
- Precise knowledge of radiative corrections mandatory (H_{rad})

PHOKHARA event generator Czyż, Kühn, et al.



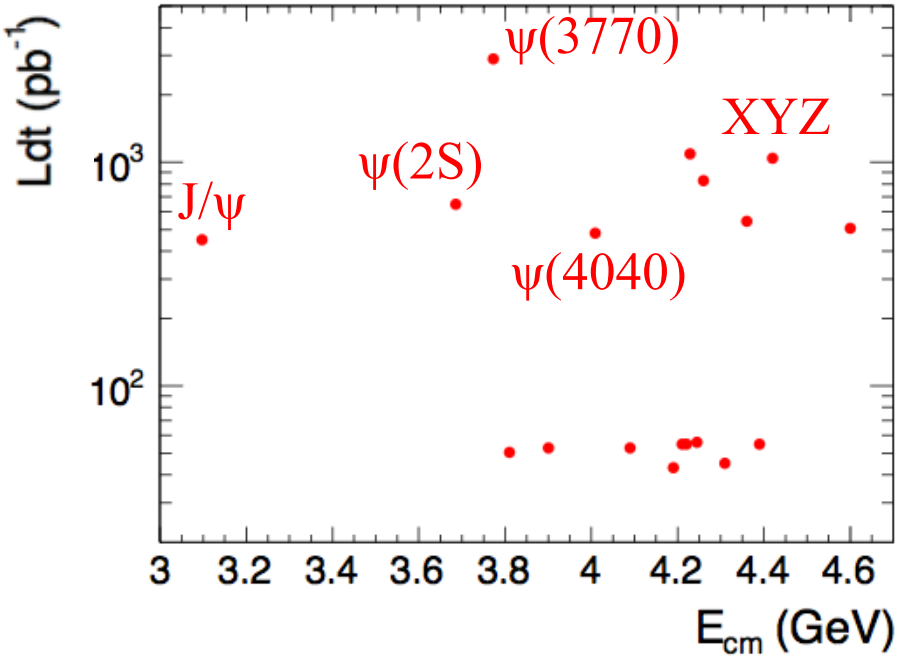
→ **Entire E range <E_{CM} accessible**

BEPC II Project



Data Samples for ISR Physics

Integrated luminosities BESIII



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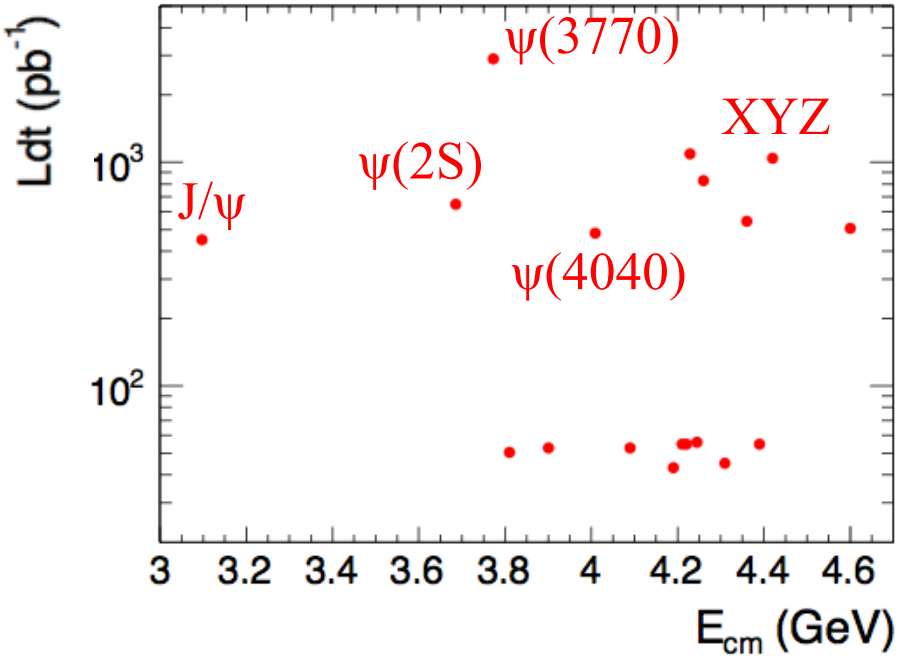
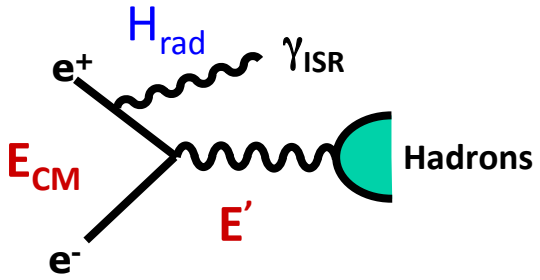
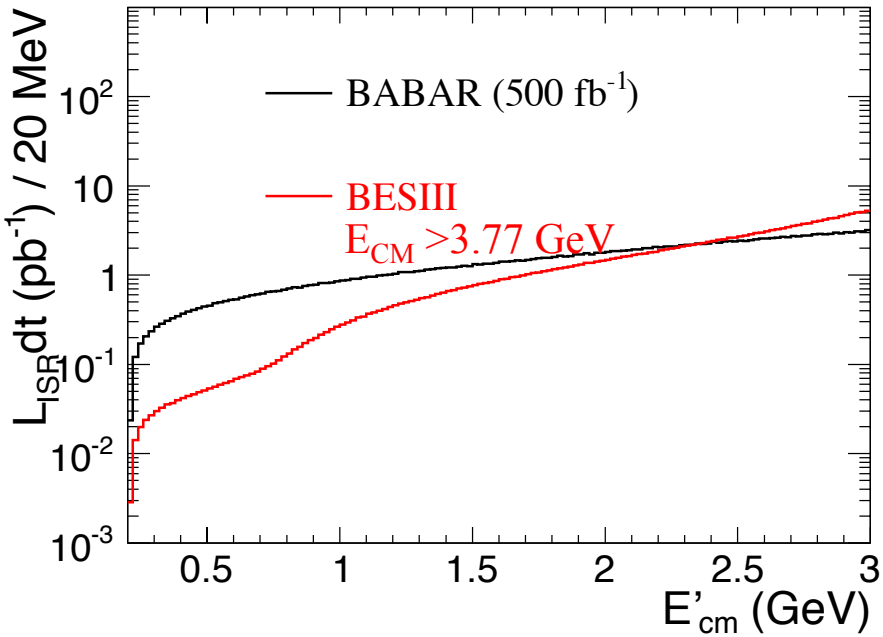
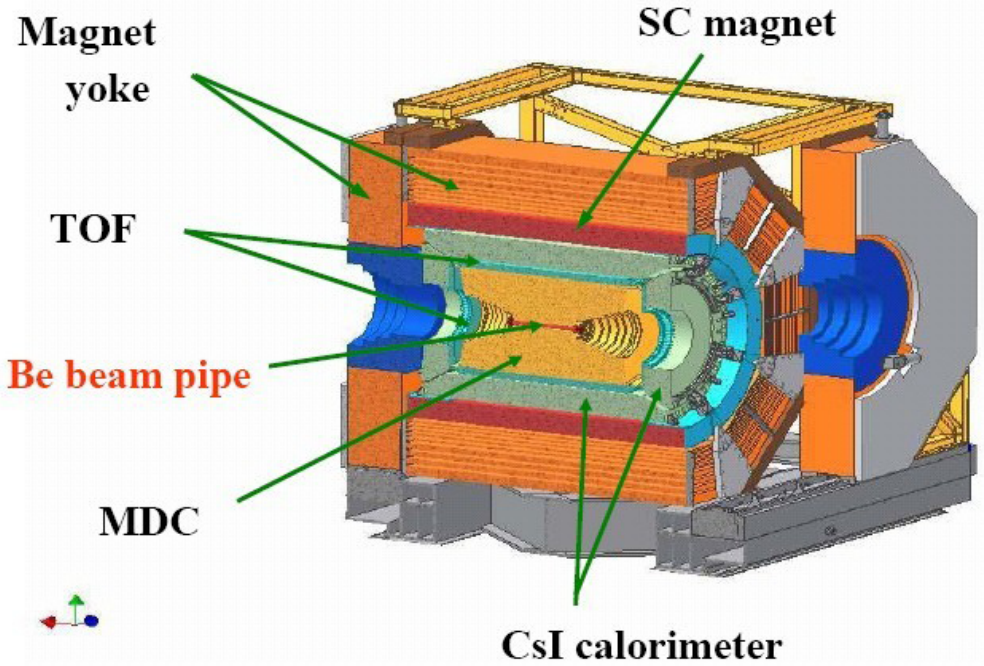




ISR luminosity = Ldt x H_{rad}



BES III Detector



Main Drift Chamber (MDC)

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

Time-of-flight system (TOF)

- σ(t) = 80ps (barrel)
- σ(t) = 120ps (endcap)

EMC

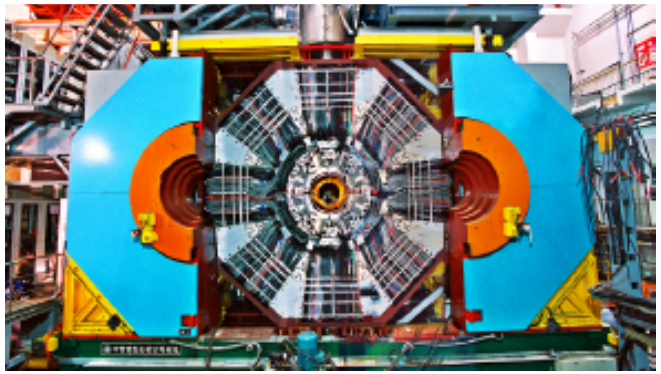
- 6240 CsI(Tl) crystals
- σ(E)/E = 2.5%
- $\sigma_{Z\Phi}$(E) = 0.5 – 0.7 cm

Muon Chambers

- 8 – 9 layers of RPC
- p>400 MeV/c
- δRΦ = 1.4 ~ 1.7 cm

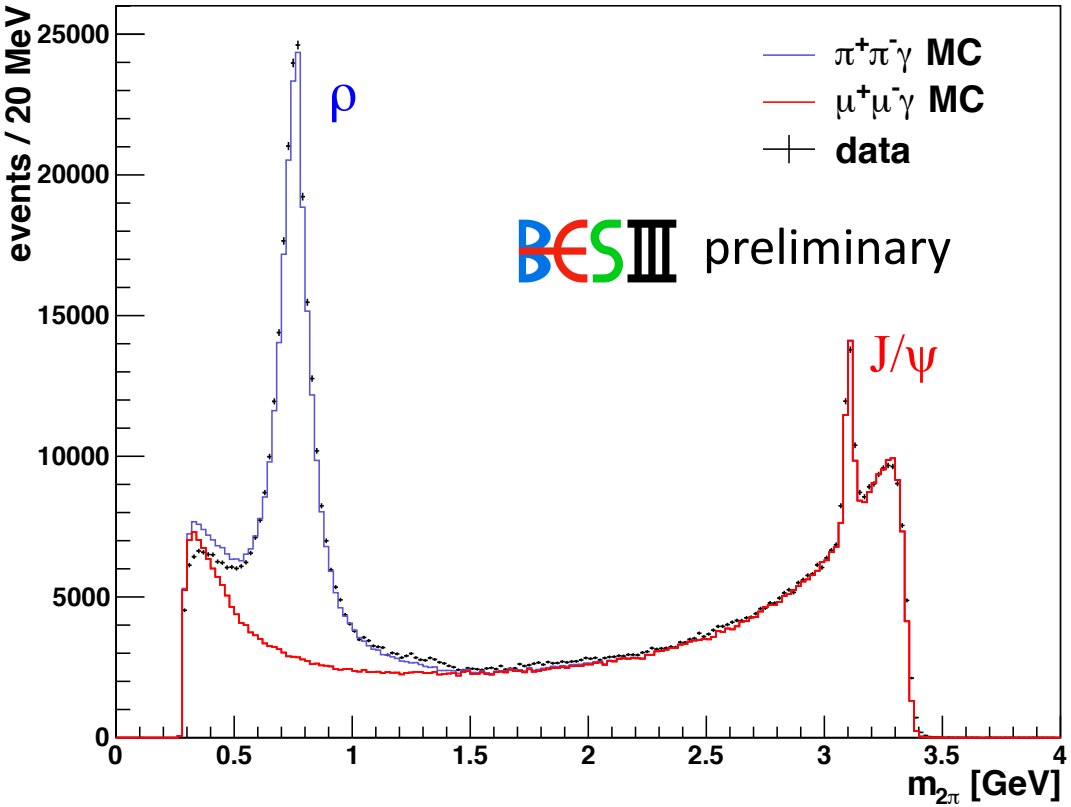
Superconducting Magnet

- 1 T magnetic field



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

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

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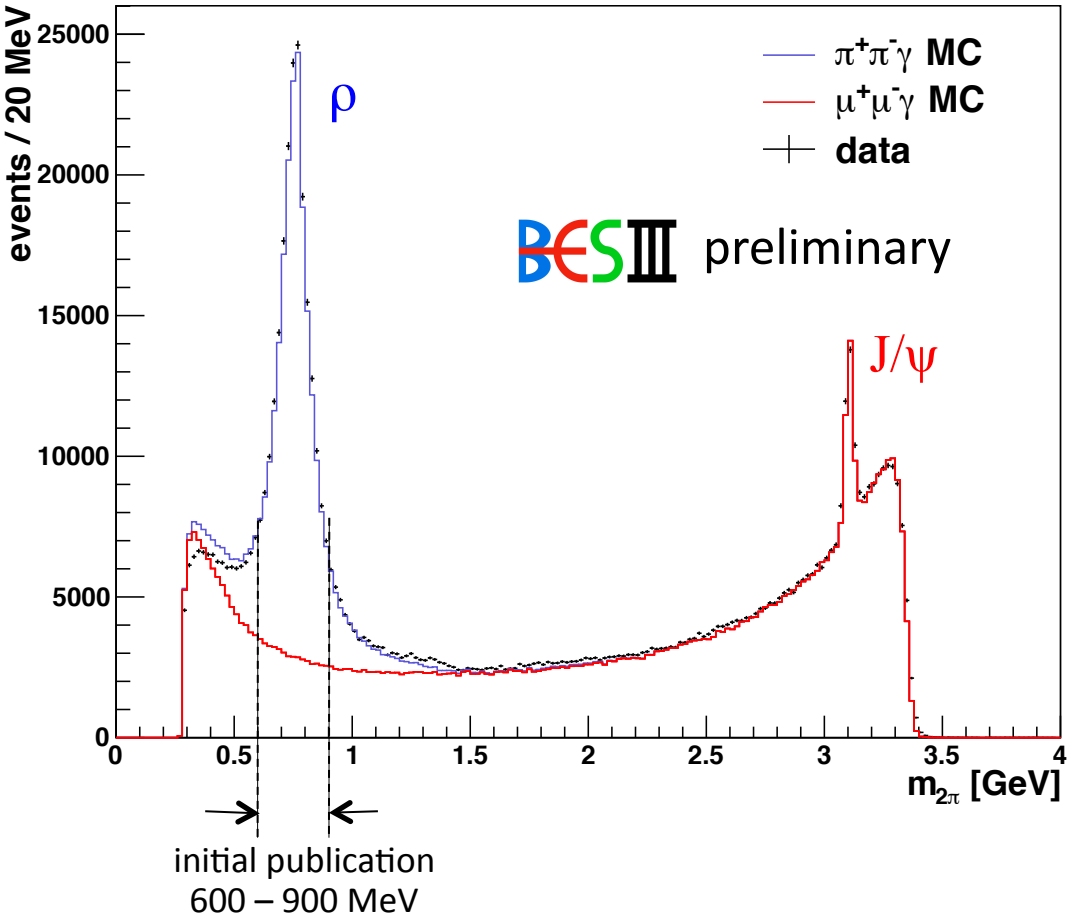

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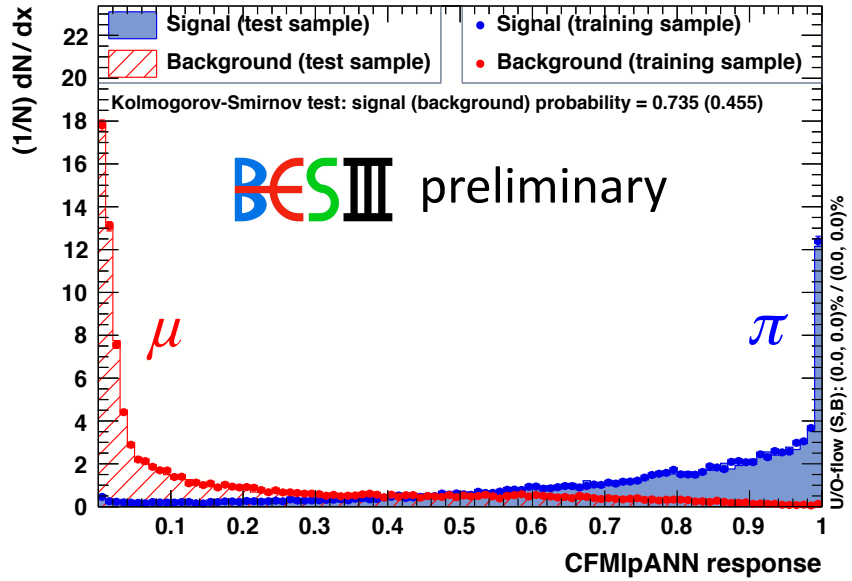
$e^+e^- \to \pi^+\pi^-\gamma_{ISR}$: π - μ Separation



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

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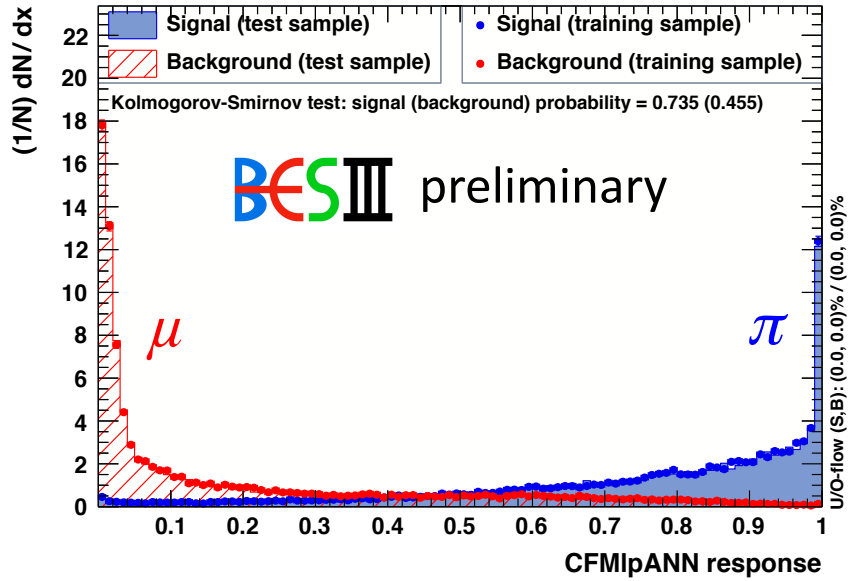

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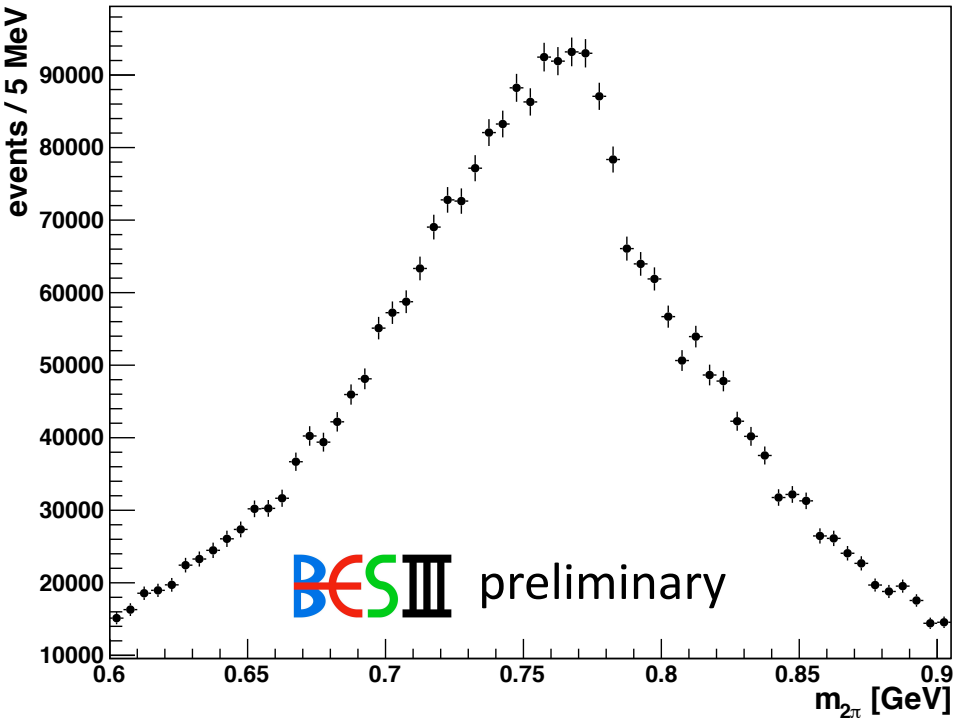
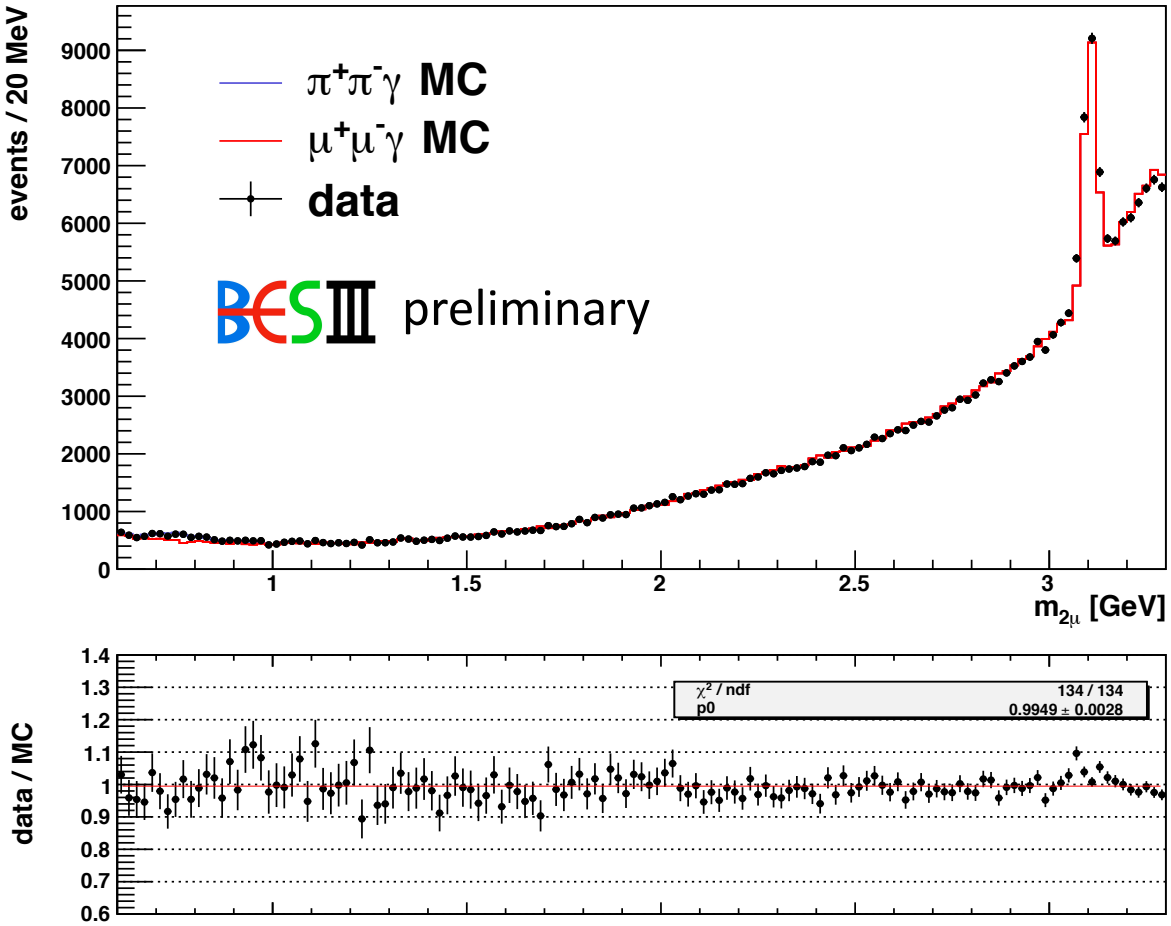
Event yield ππγ after π-μ separation



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

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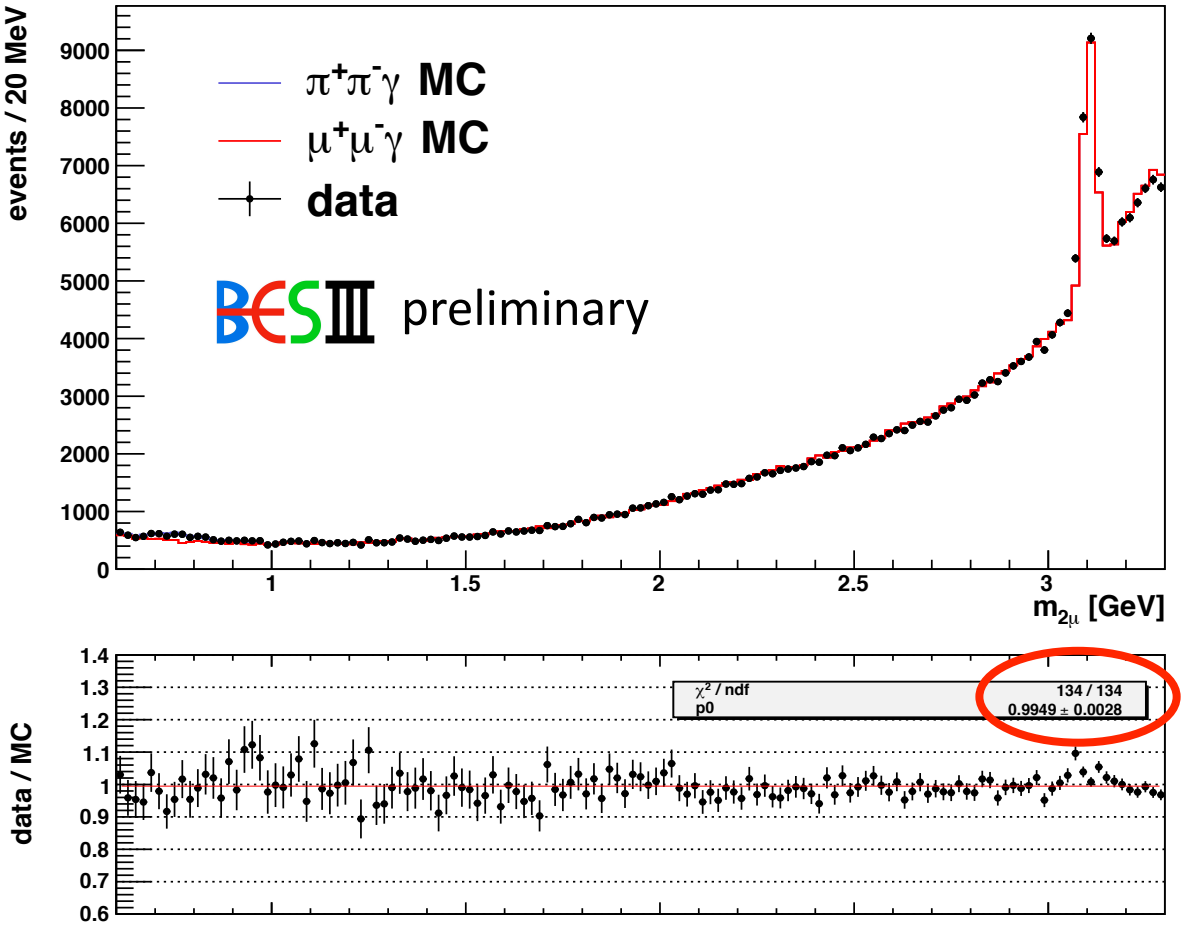

Features:

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- luminosity measurement based on Bhabha ev., 1.0% accuracy

→ excellent agreement with QED

Δ(MC/QED-data) = (0.51 ± 0.28) %

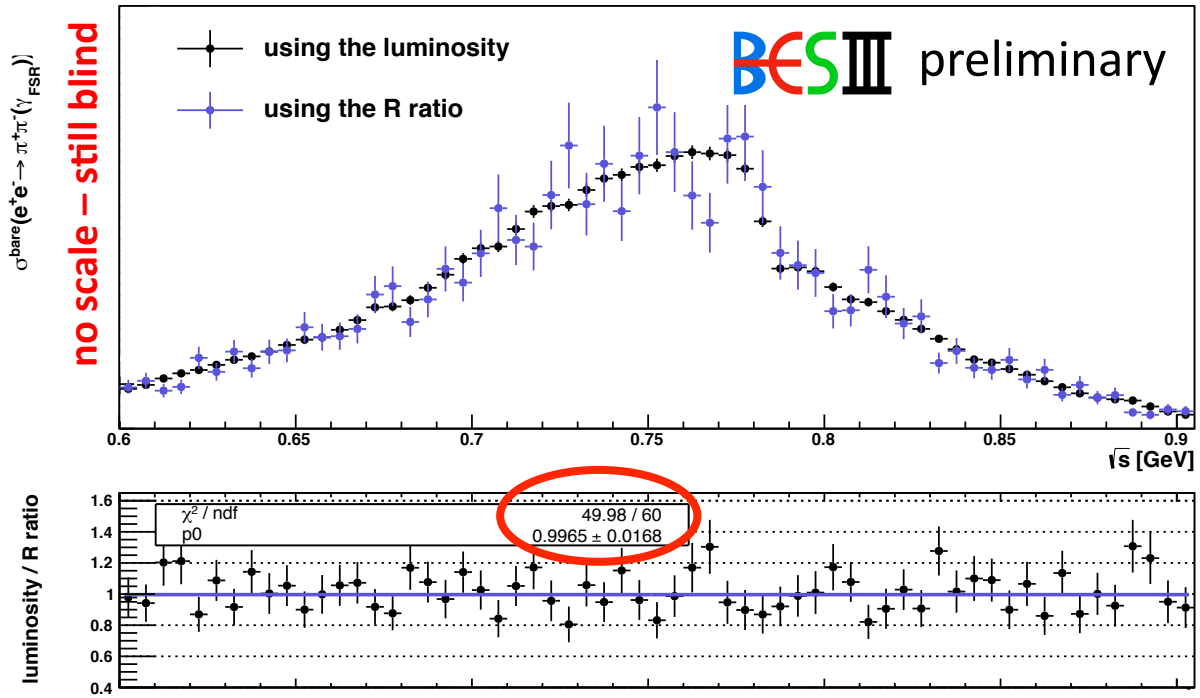
→ accuracy on 1% level as needed to be competitive !

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

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 -1
= (0.35 ± 1.68) %

limited by low μμγ statistics

New R Scan 2.0 - 4.6 GeV (2013++)

R measurement foreseen in 3 phases

- R_{incl} in range 2 – 4.6 GeV
  ~1% statistical, 3% systematic accuracy
  → improve $\alpha_{QED}(m_Z^2)$ by factor 2 (✔)
- R in range 2 – 3 GeV, high statistics
  → Improve nucleon $|G_E|/|G_M|$ ratio
- Fine binning R ratio in charmonium region → charmonium spectroscopy ✔

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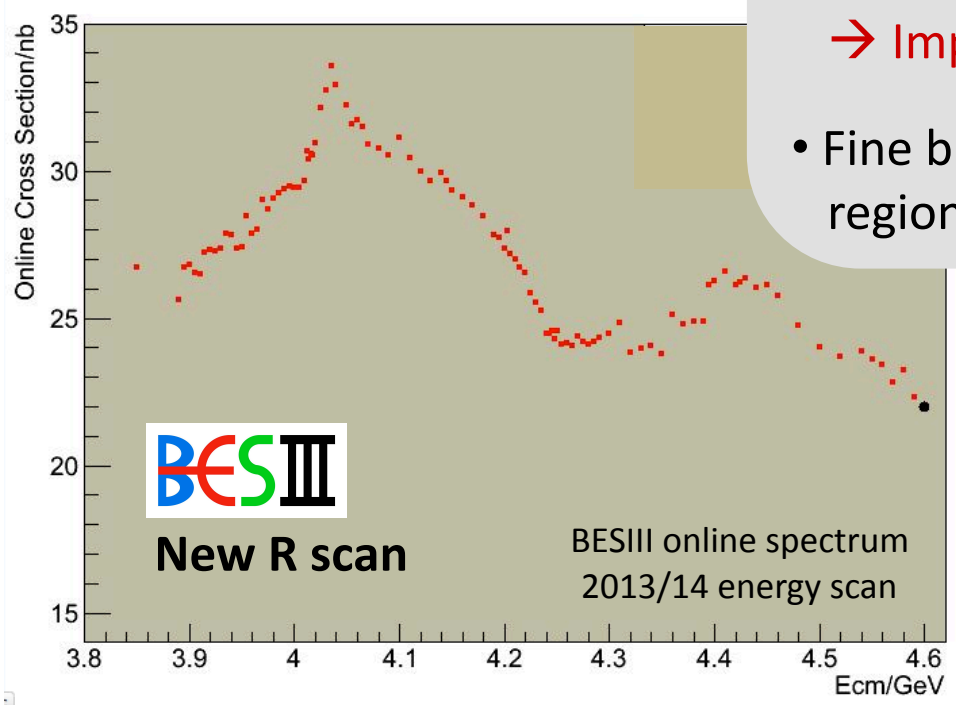


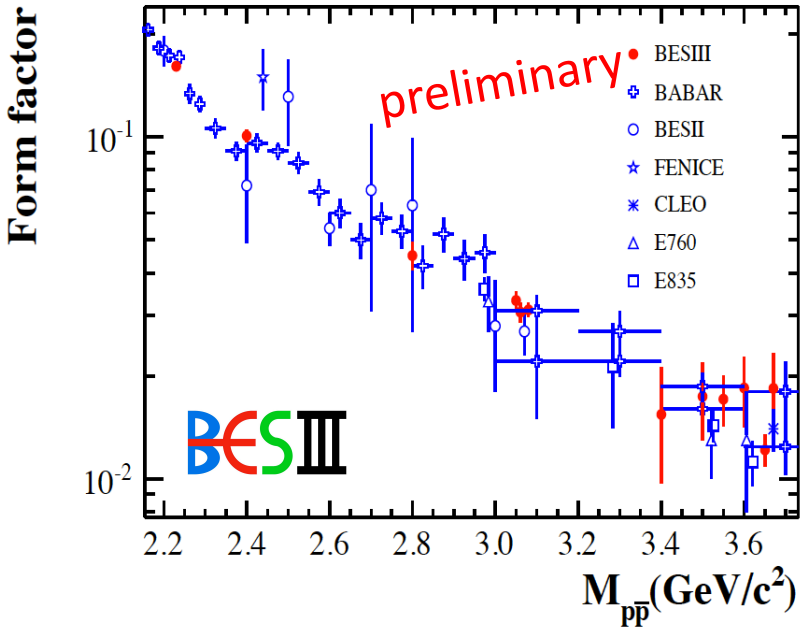
BES: 3-5% stat. accuracy
BESIII: <<1%

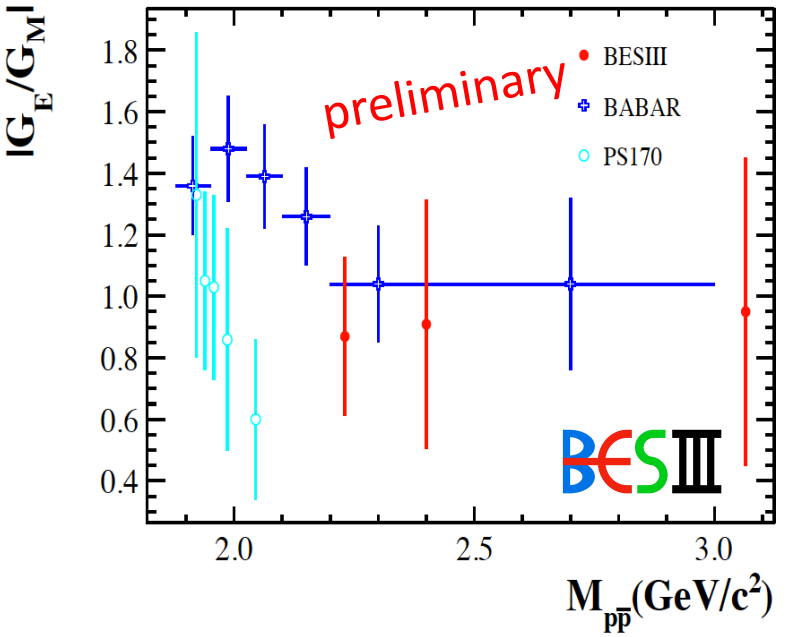
Prelim. Proton FF from Mini R Scan

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

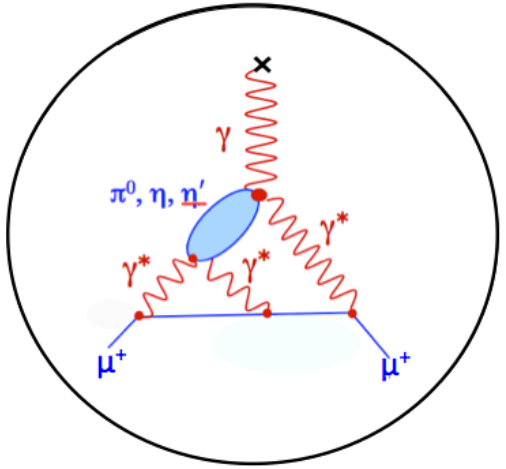
E_{cm}/GeV	L_{int} / pb^{-1}
2.23	2.6
2.40	3.4
2.80	3.8
3.05, 3.06, 3.08	60.7
3.40, 3.50, 3.54, 3.56	23.3
3.60, 3.65, 3.67	63.0





Meson Transition Form Factors

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



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

arXiv:1408.2517 (G. Colangelo et al.)

arXiv:1409.0819 (M. Vanderhaeghen et al.)

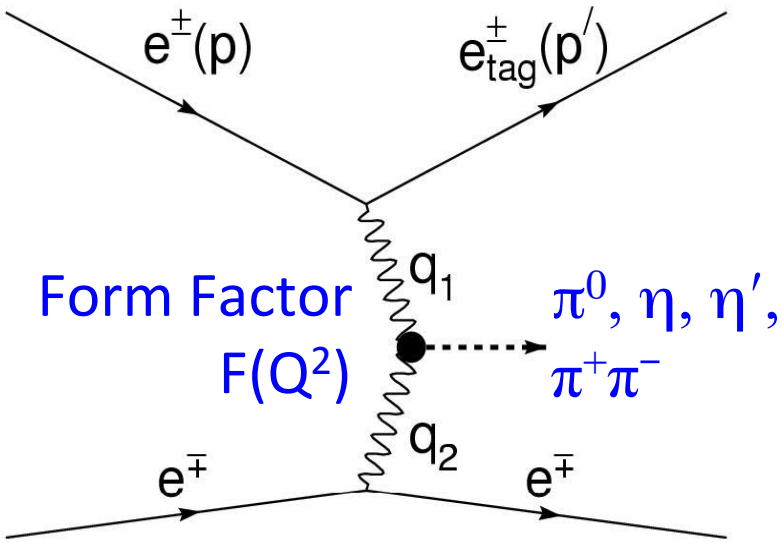
Space-Like FFs $\gamma\gamma^* \rightarrow P$

Single Tag Method

Selection criteria

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

→ cut on angle of missing momentum



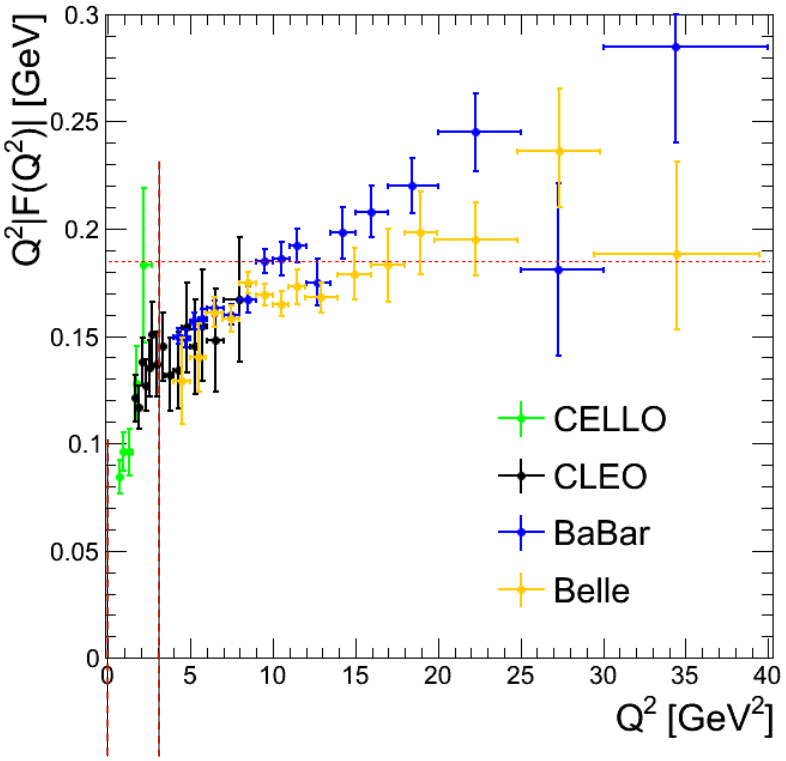
Momentum transfer

- 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 FFs

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



initial BESIII publication
< 3.1 GeV^2

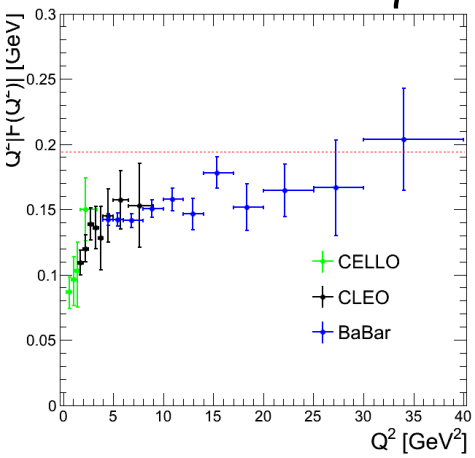
Features:

- 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

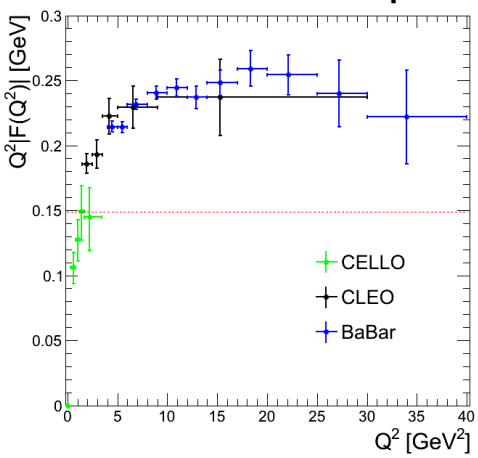
→ low Q^2 range not covered
most relevant for HLbL contribution to $(g-2)_\mu$

→ most relevant channels: π^0, η, η', $\pi\pi$

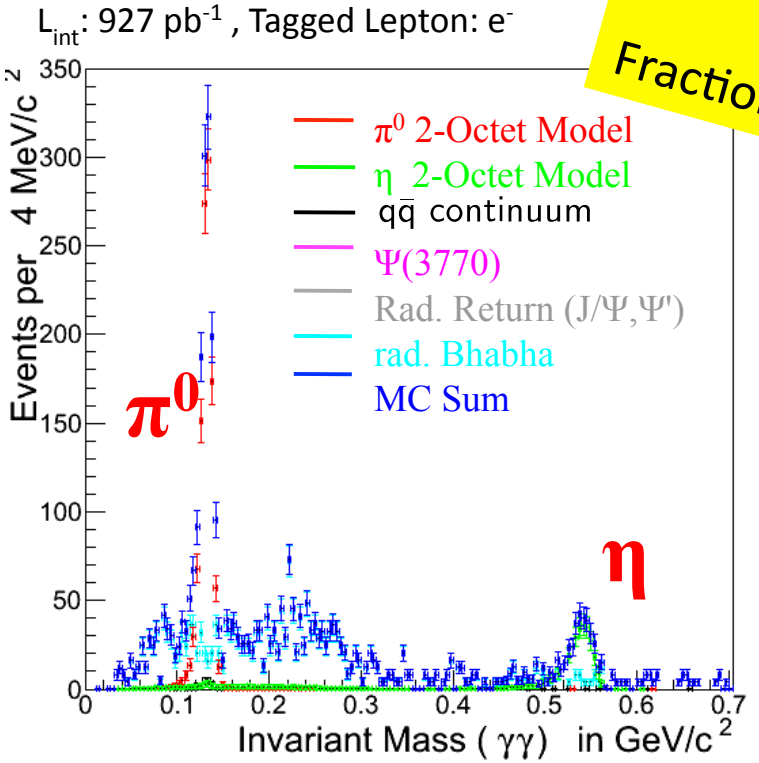
$e^+e^- \to e^+e^- \eta$



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



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



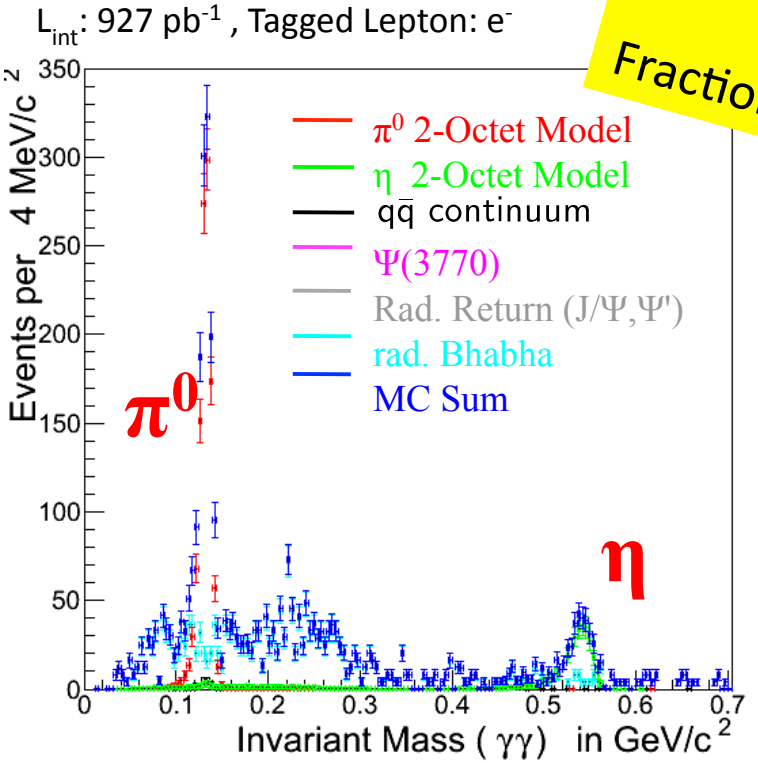
MC only
Fraction of full statistics

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

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



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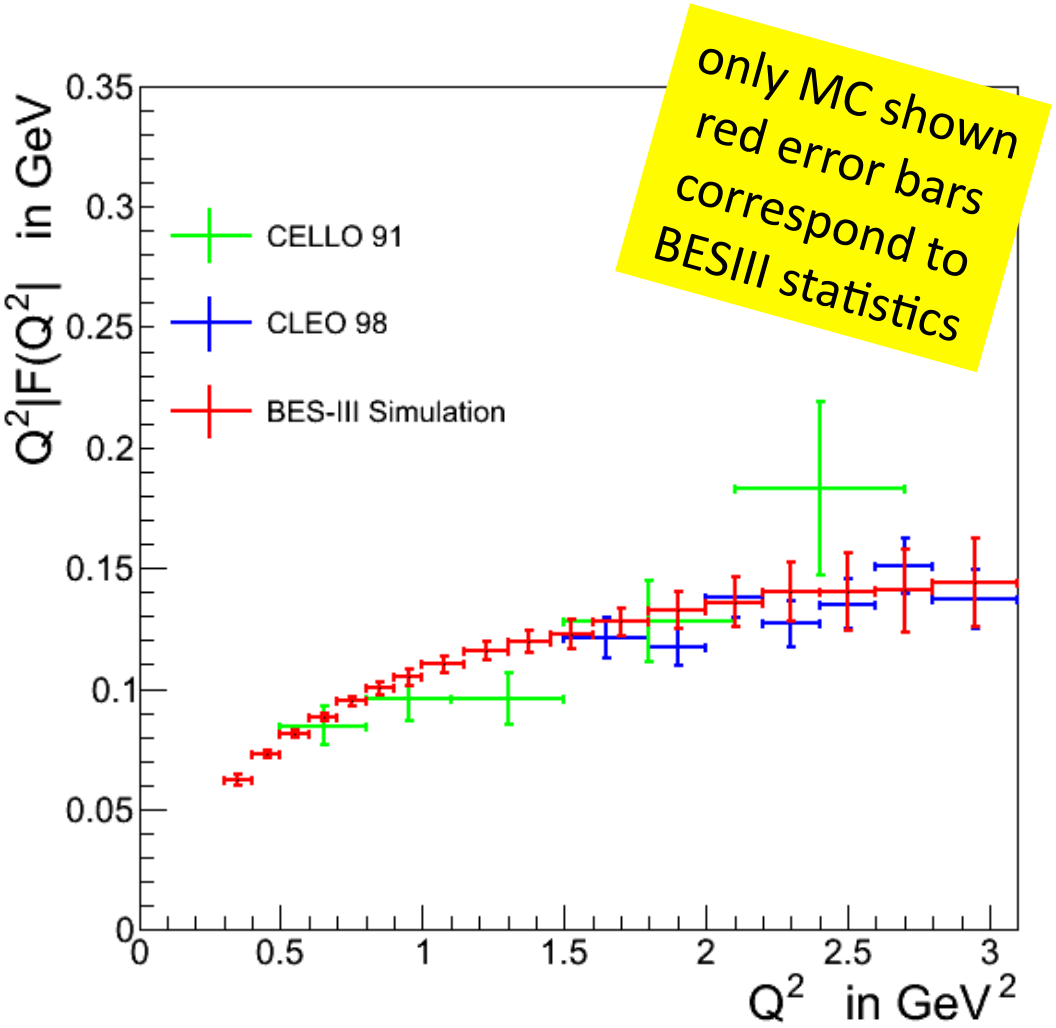
Strategy: Count π^0 yield in bins of Q^2 → $d\sigma/dQ^2$ → Form factor $F(Q^2)$

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 $0.3 \leq Q^2[\text{GeV}^2] \leq 3.1$

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

Conclusions

&

Outlook

Conclusions and Outlook

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

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

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

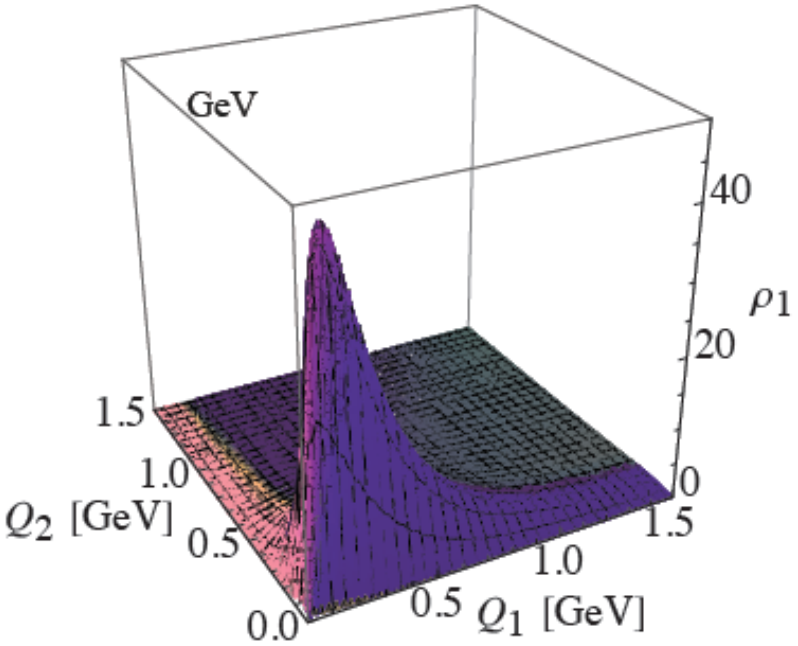
What accuracy can be achieved for a_μ^{had} ?

Reduction of factor 2 of uncertainty in reach

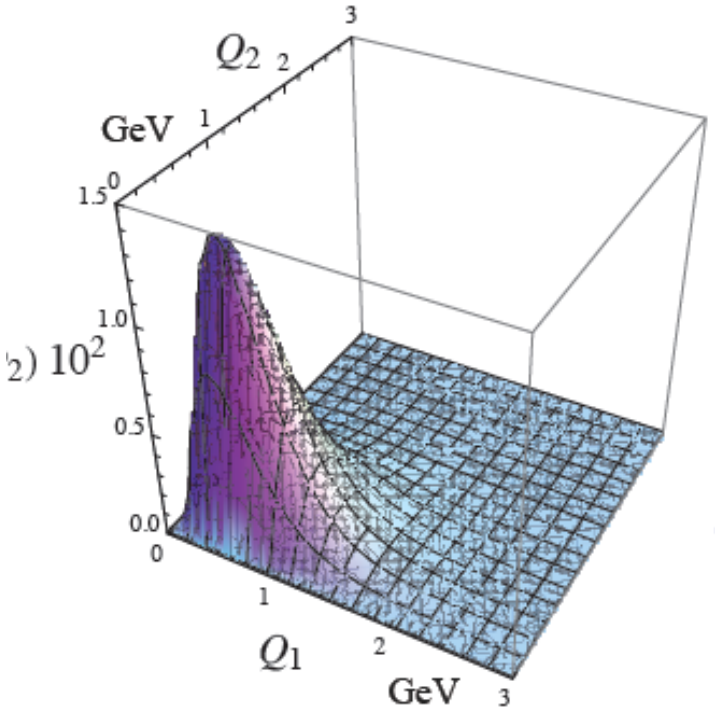
Additional slides

Relevance for HLbL

Pseudoscalar Mesons



Axial Vector Mesons

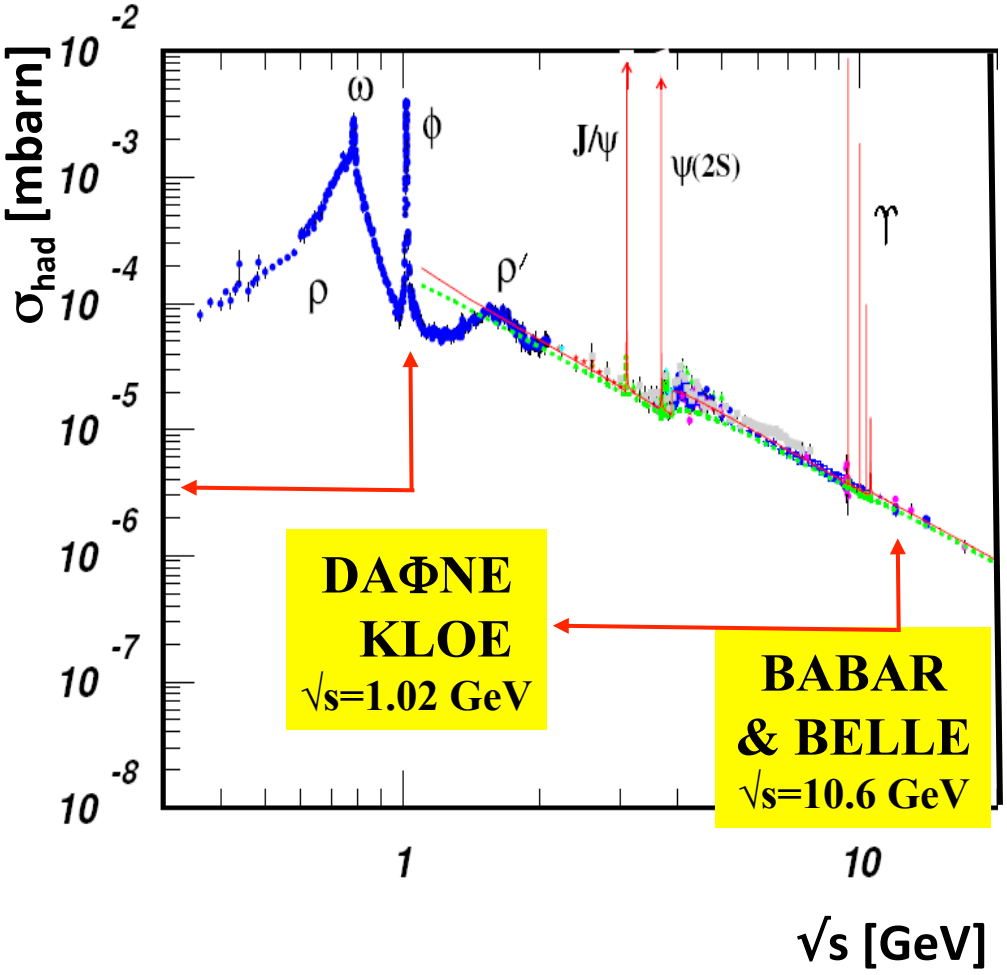


Weighting functions dominate at low Q < 2 GeV !

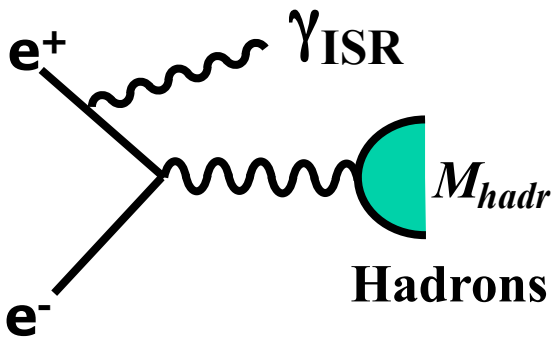
courtesy: V. Pauk, JGU

*Hadronic Cross Section via **Radiative Return***

Rev. Mod. Phys. 83, 1545–1588 (2011)



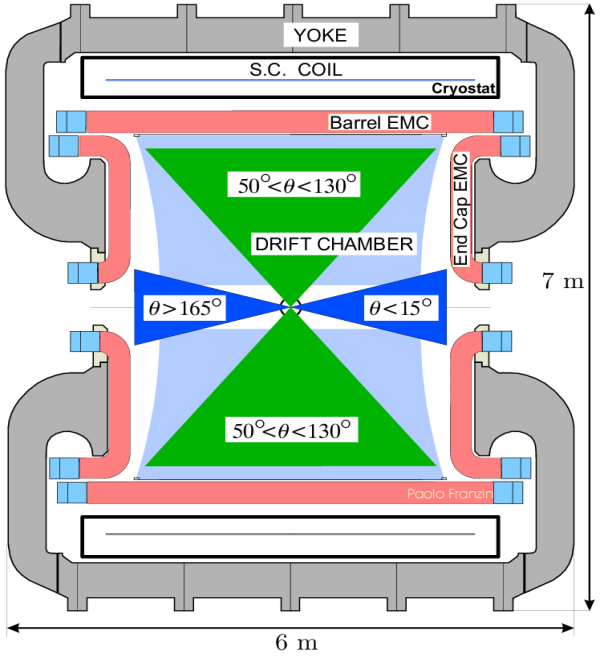
Initial State Radiation (ISR)
aka Radiative Return



- Possible at modern particle factories
- Needs no systematic variation of beam energy
- High statistics thanks to high integrated luminosities

→ **Entire E range <√s accessible**

KLOE: ISR at 1.02 GeV (DAΦNE)



$$\sigma(e^+e^- \to \pi^+\pi^-\gamma_{ISR})$$

Tagged analysis:
ISR photon measured in KLOE-Calorimeter
- Increased amount of Final State Radiation (FSR)

Untagged analysis:
No ISR detection; cut on missing momentum
- Threshold mass region not accessible

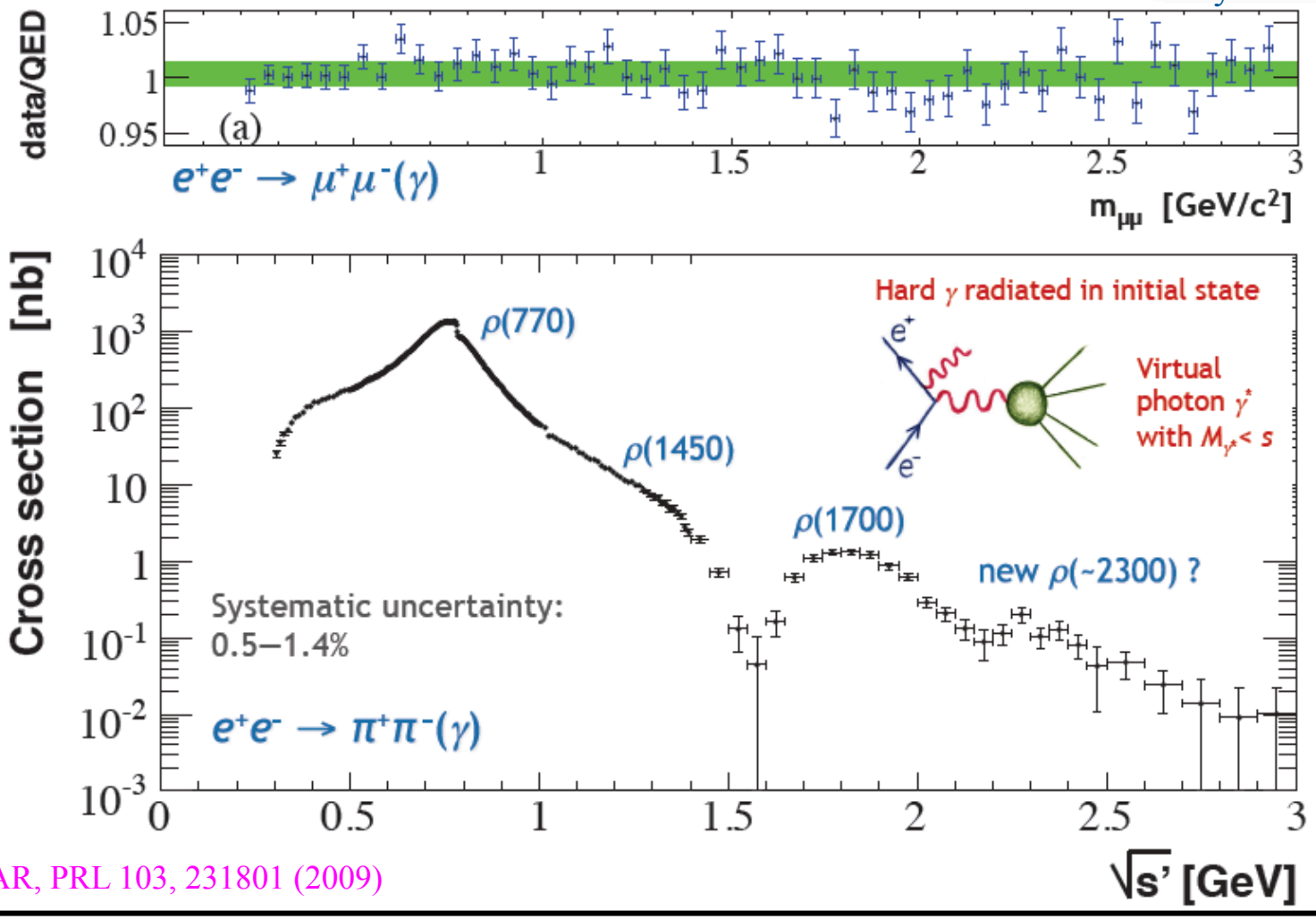
*full KLOE statistics 2,500 pb^{-1}

Publication	Mode	Normalization	Int. Luminosity*
Phys.Lett. B606 (2005) 12	untagged	Radiator	141 pb^{-1}
Phys.Lett. B670 (2009) 285	untagged	Radiator	240 pb^{-1}
Phys.Lett. B700 (2011) 102	tagged	Radiator	232 pb^{-1}
Phys.Lett. B720 (2013) 336	untagged	$\mu^+\mu^-\gamma$	240 pb^{-1}

BABAR: Pion Form Factor

< 1% systematic. uncertainty

Normalization to muon yield!

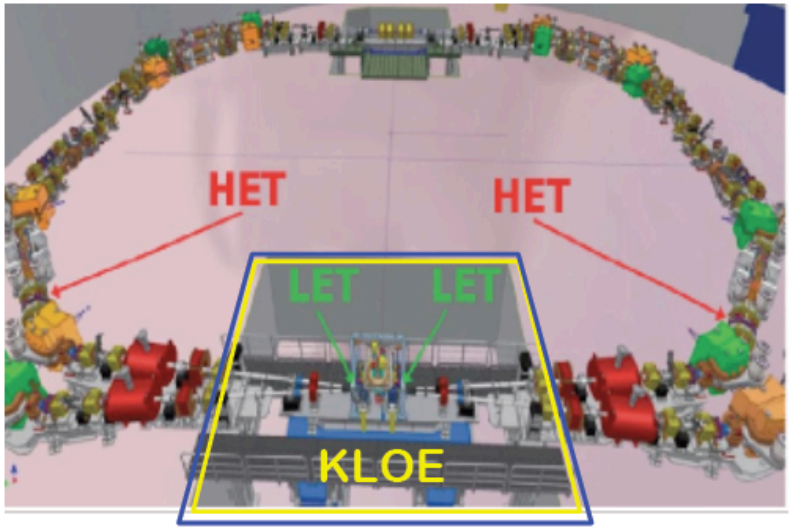


BABAR, PRL 103, 231801 (2009)

Impact of KLOE-II

Future

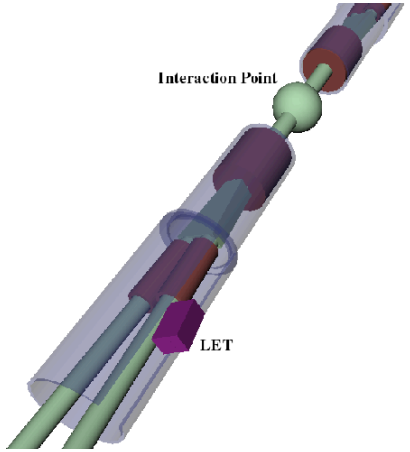
Installation of dedicated tagging detectors close to beam pipe



$e^+e^- \rightarrow e^+e^- + X$

taggers

KLOE

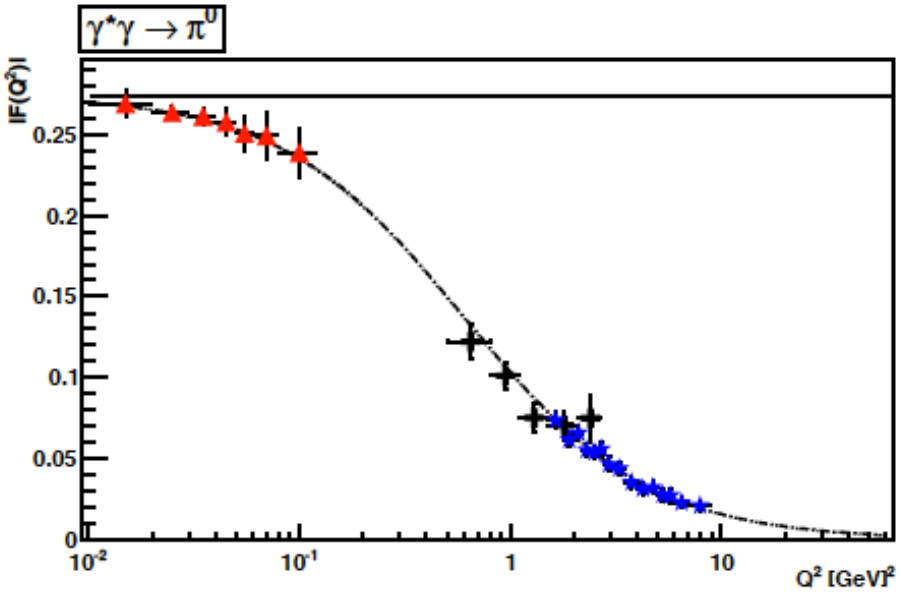


LET (Low Energy tagger)

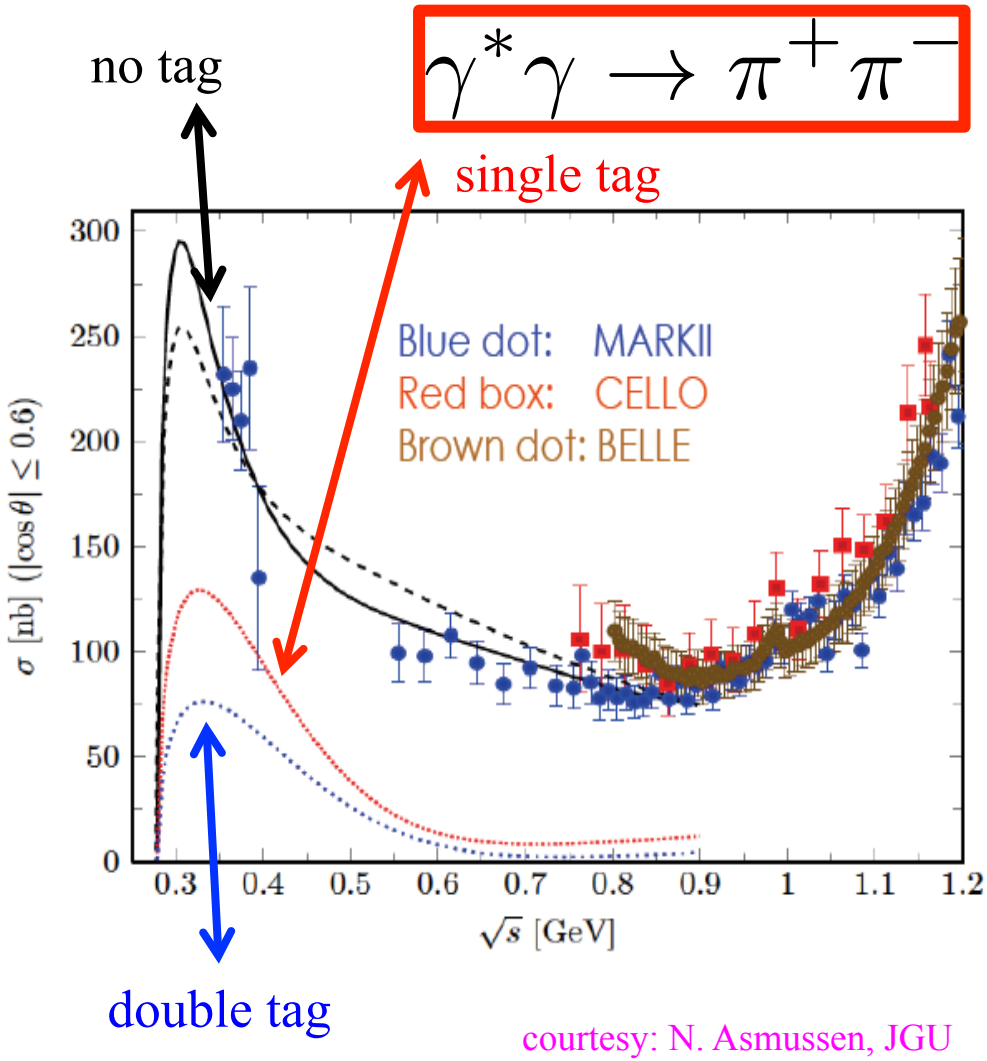
- inside KLOE (1 m from IP)
- energy range = 160-400 MeV

HET (High Energy tagger)

- after 1st dipole (11 m from IP)
- energy range = 420-495 MeV



Impact of BESIII



courtesy: N. Asmussen, JGU

Single tag analysis:

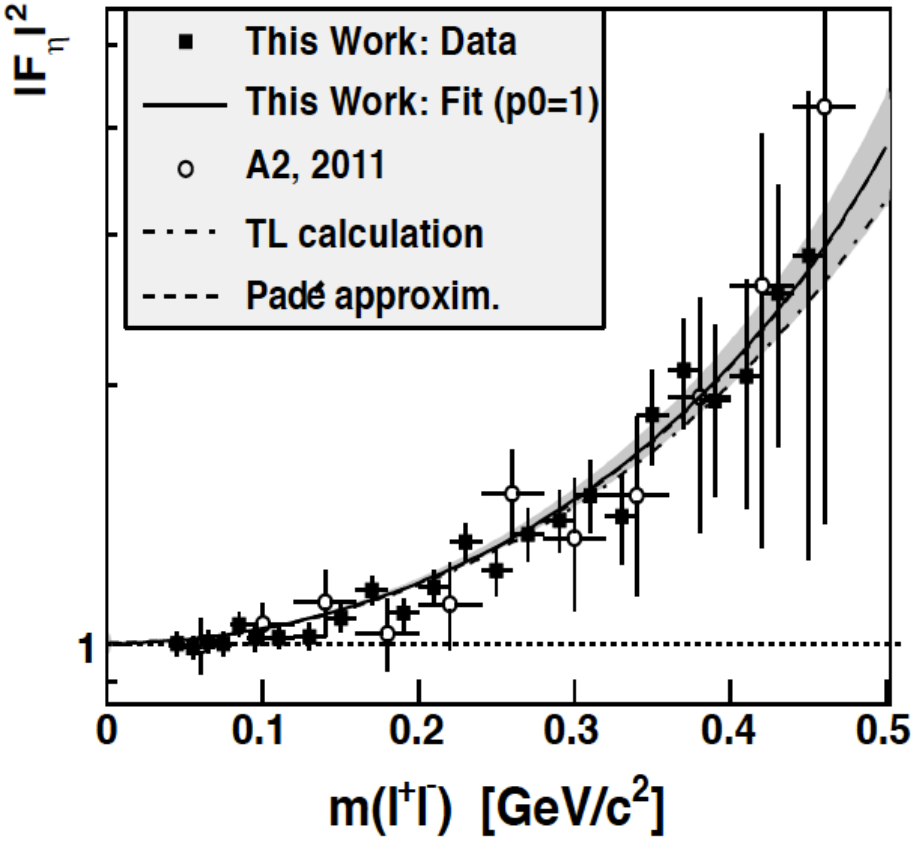
- Q^2 range above 0.3 GeV^2 accessible
- $M_{\pi\pi}$ mass spectrum down to threshold
- Background from di-muon and radiative Bhabha evts.
- Improved vs. of EKHARA needed
- Goal: 5 … 10% accuaracy

Timelike (TL) FFs $P \to \gamma\gamma^*$

Meson Factories

A2 / MAMI: TL FF $\eta \to e^+e^-\gamma$

Accepted by Phys. Rev. C:
S. Prakhov, M. Unverzagt et al. (A2 collab.)



TL calculation: S. Leupold, C. Terschlüsen
Padé calculation: R. Escribano, P. Masjuan, P. Sanches-Puertas

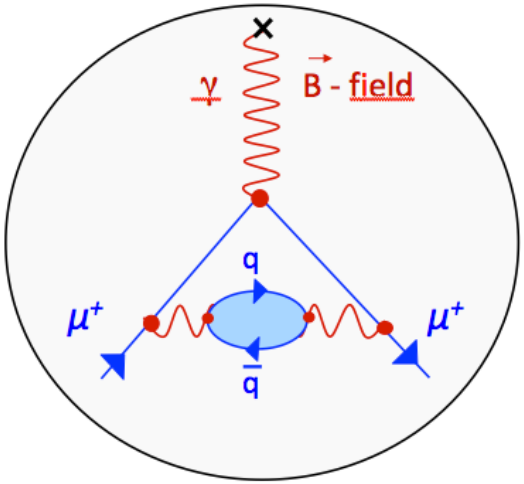
Vector Meson Dominance model:

$$F(m_{ll}) = \frac{1}{1 - \frac{m_{ll}^2}{\Lambda^2}}$$

$\Lambda^{-2} = (1.95 \pm 0.15_{stat} \pm 0.10_{syst})$ GeV^{-2}

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

Hadronic Vacuum Polarization

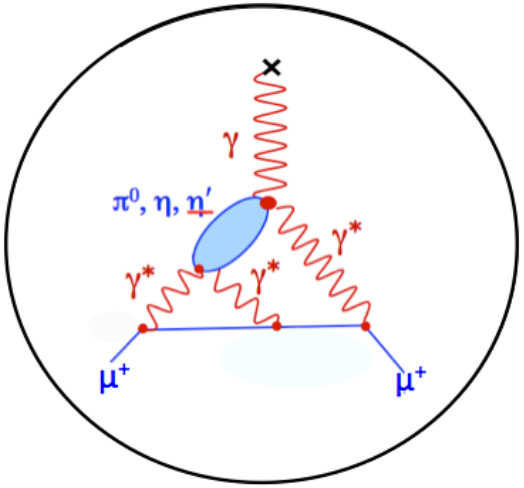


$a_\mu^{had,VP} = (692.3 \pm 4.2) \cdot 10^{-10}$ Davier et al.

Measurement of the R_{had} ratio, i.e. the hadronic cross section

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

Hadronic Light-by-Light Scattering



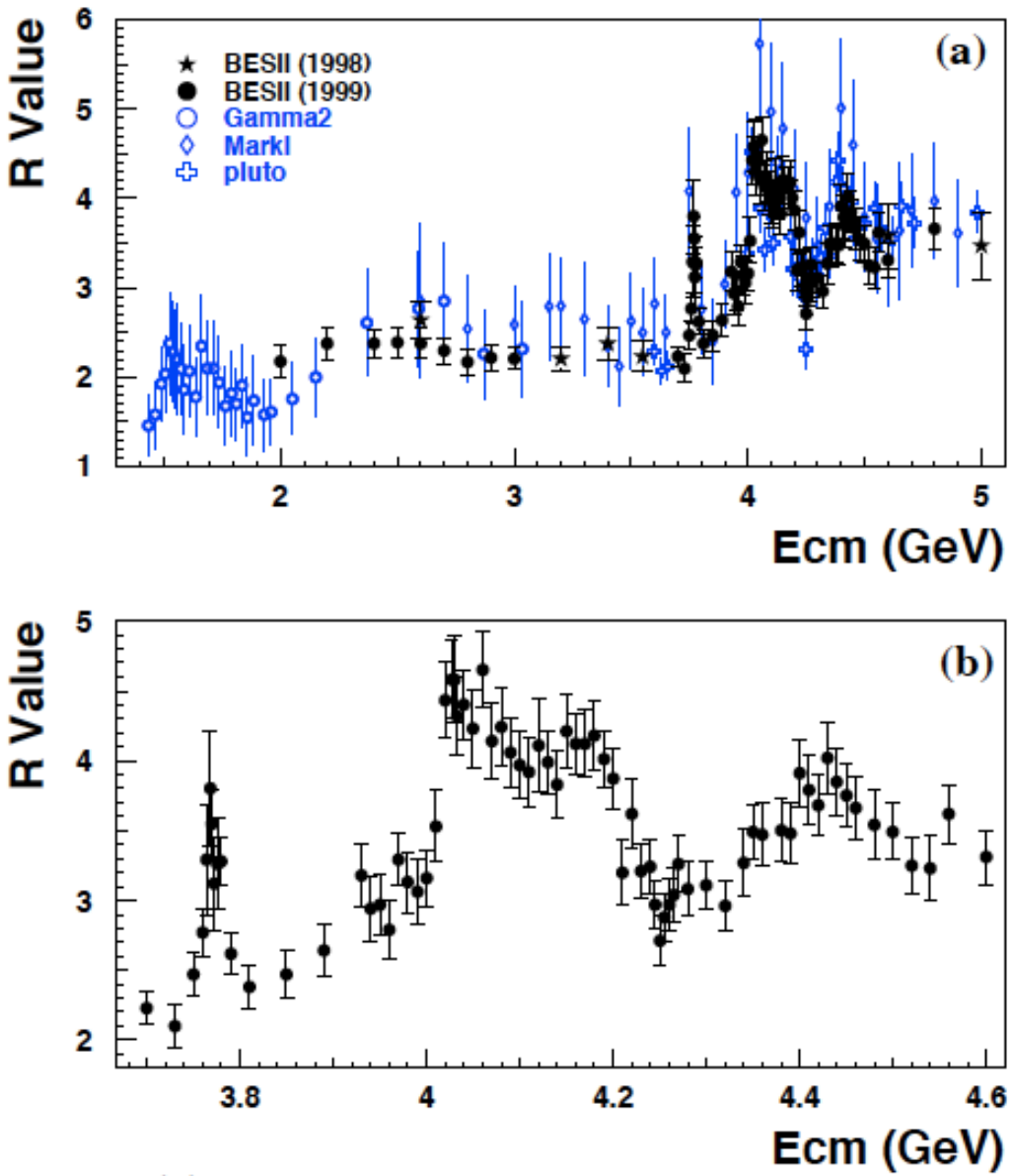
$a_\mu^{had,LbL} = (10.5 \pm 2.6) \cdot 10^{-10}$ Prades et al.

$(11.6 \pm 4.0) \cdot 10^{-10}$ Nyffeler

Measurements of meson transition form factors $|F(Q^2,Q^2)|$

➔ $\gamma^{(*)}\gamma^{(*)} \rightarrow$ *Meson(s)*

$BEPC: \sigma_{incl}(e^+e^- \rightarrow Hadrons)$



arXiv:hep-ex/9908046
arXiv:hep-ex/0102003

Results

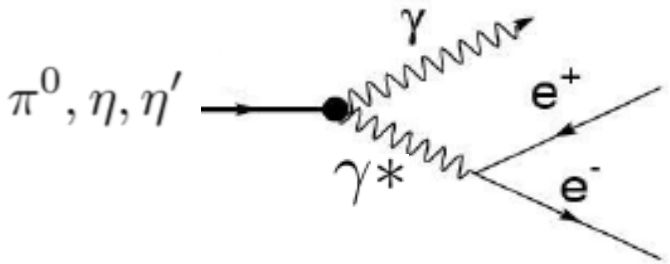
- 3-5 % statistical accuracy per scan point
- Systematic uncertainty: ~5 …8%
- Later few additional point with even smaller uncertainty

- **Major improvement of R**
- **Best measurement to date**
- **Important QCD test**
- **Of utmost importance for $\alpha_{em}(m_Z^2)$**

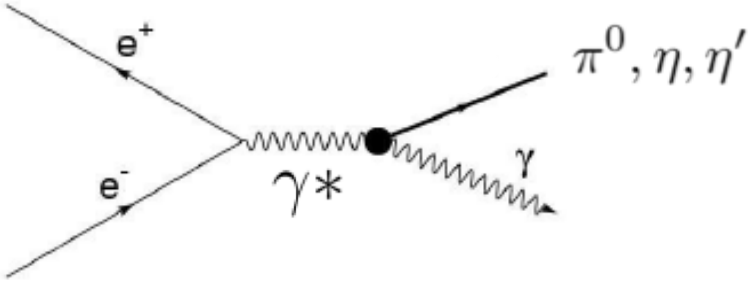
Meson Transition Form Factors $P \to \gamma^*\gamma^{(*)}$

Time-like transition form factors:

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

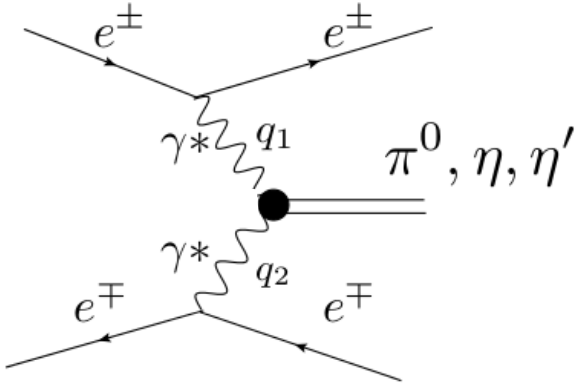


- Annihilation process
  - $q^2 = s > M_P^2$

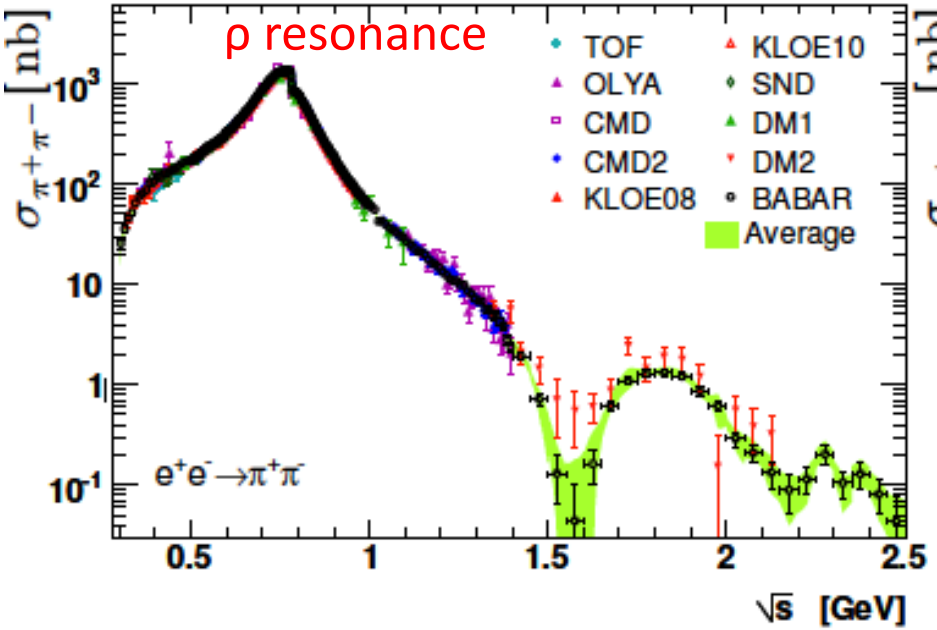


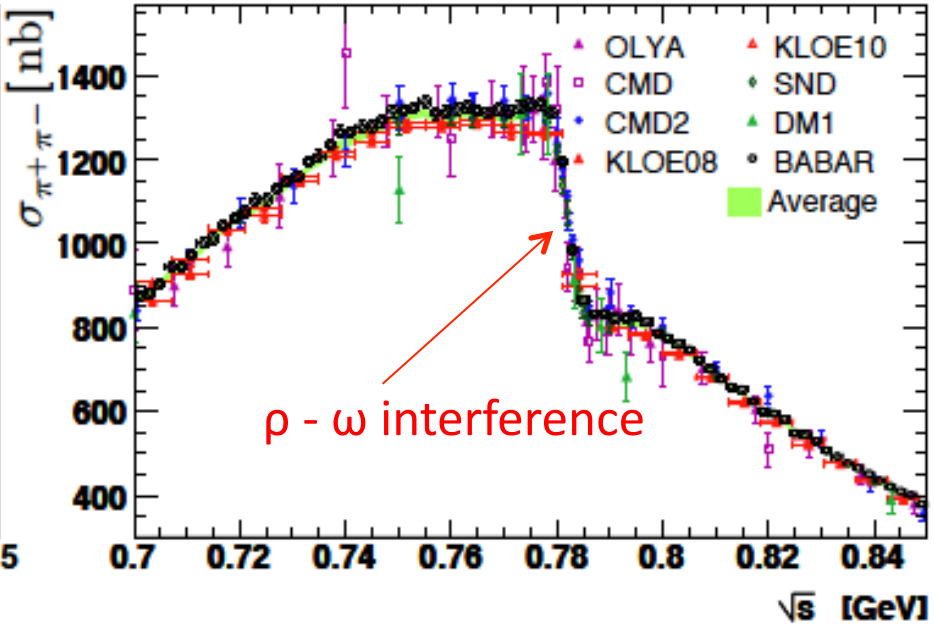
Space–like transition form factors:

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



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



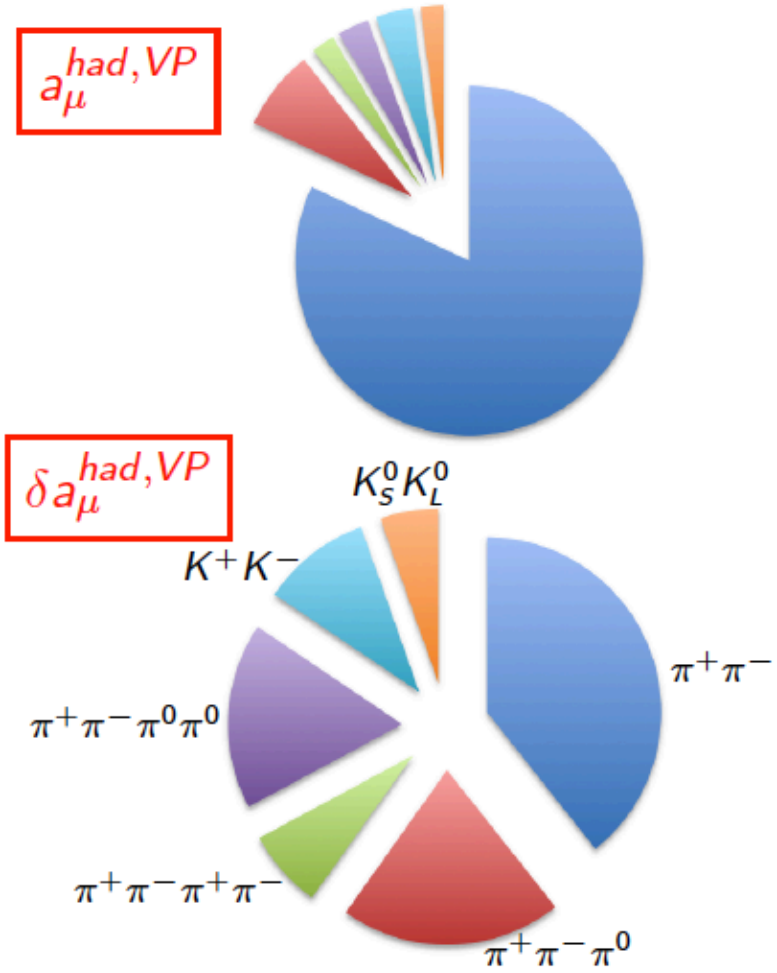


Systematic Uncertainties

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

* limited in addition by statistics

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