UCONN

Muon g-2 Theory Initiative, March 13, 2018
Hadronic Light-by-Light working group workshop

Experimental Input to HLbL from BESIII and A2/MAMI

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JG|U

SFB 1044 THE LOW-ENERGY FRONTIER OF THE STANDARD MODEL

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

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

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

$$a_\mu^{SM} = a_\mu^{QED} + a_\mu^{weak} + a_\mu^{had} = (\,11\,659\,182.05 \pm 3.56\,) \cdot 10^{-10}$$

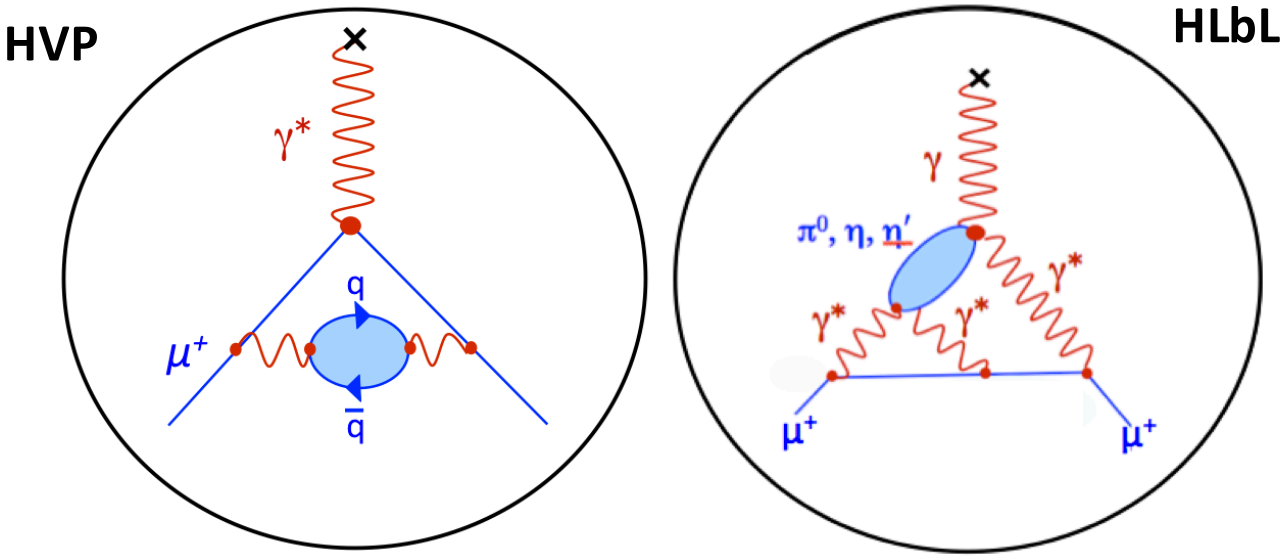
[Keshavarzi, Nomura, Teubner 2018]

Teubner et al. '11

→ **HVP**: Hadronic Vacuum Polarization (693.27 ± **2.46**) · 10^{-10}

NLO (-9.82 ± **0.04**) · 10^{-10}

→ **HLbL**: Hadronic Light-by-Light (10.5 ± **2.6**) · 10^{-10}



Hadronic Light-by-Light $(g-2)_\mu$

Leading contributions are pole contribution from $\pi^{0,}$ η, η'

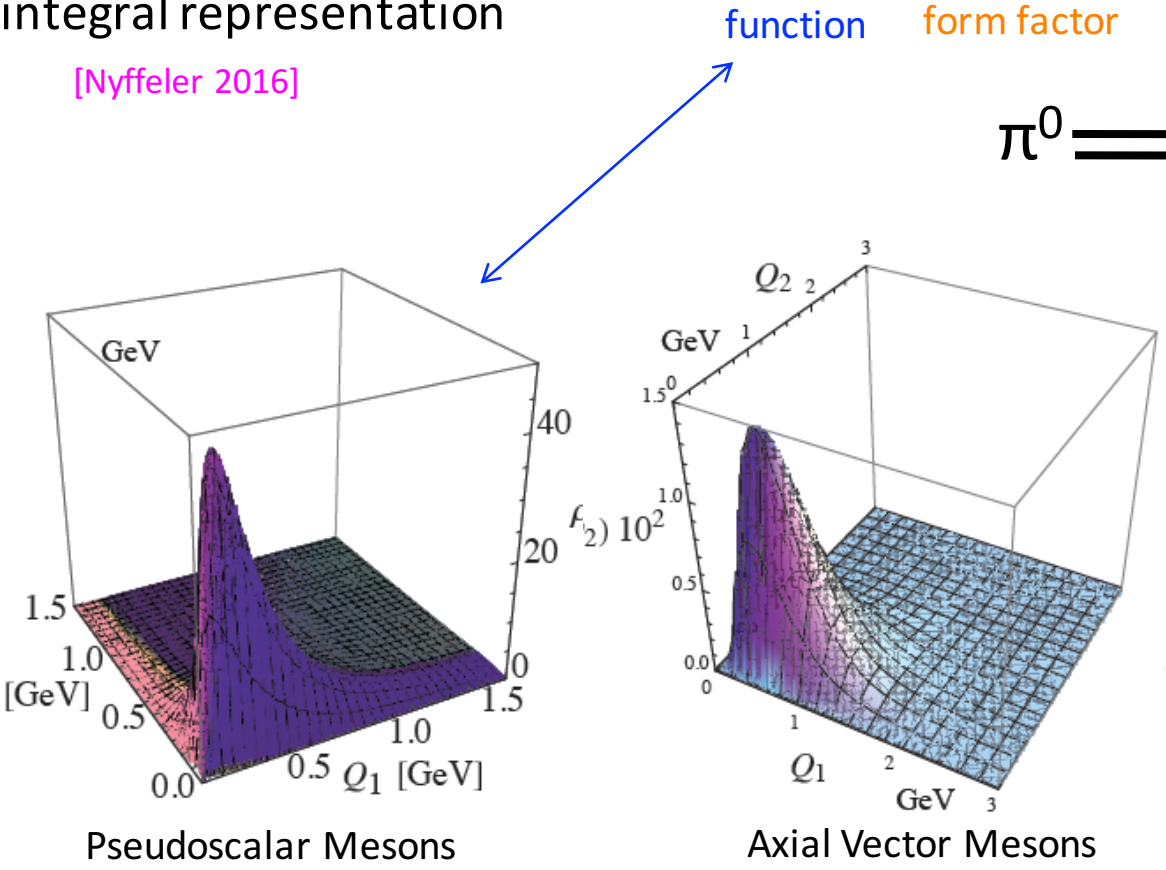
$$a_\mu^{\mathrm{HLbL};\pi^{0(1)}} = \int_0^\infty dQ_1 \int_0^\infty dQ_2 \int_{-1}^{1} d\tau\, w_1(Q_1, Q_2, \tau) \mathcal{F}_{\pi^0\gamma^*\gamma^*}(-Q_1^2, -(Q_1+Q_2)^2) \mathcal{F}_{\pi^0\gamma^*\gamma^*}(-Q_2^2, 0)$$

weighting function

transition form factor

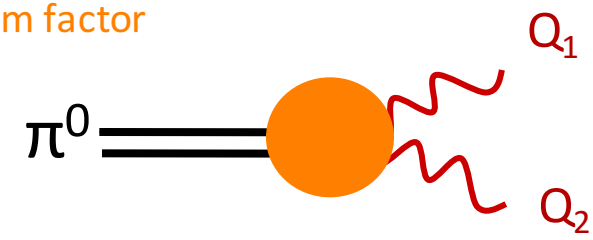
3D integral representation

[Nyffeler 2016]



Pseudoscalar Mesons

Axial Vector Mesons



→ **Need doubly virtual form factors of $\pi^{0,}$ η, η' at low Q^2**

Data-Driven Approaches $F(Q^2,0)$

Padé Approximants

[Escribano, Masjuan 2012, 2015]

- Parametrize TFF by series of rational approximants
- Fit free parameters to experimental data
- Spacelike and timelike data can be used
- **Provides access to Q^2 range currently not or poorly covered**

Dispersive Approaches for a_μ^{HLbL}

[Colangelo, Hoferichter, Kubis, ...2014, 2015,...]
[Pauk, Vanderhaeghen, 2015, 2016]

- Describe dominating contributions with dispersion relations
- Remaining contributions calculated classically (model-dependent)
- Relate to measurable quantities
- Relate singly-virtual TFFs with double-virtual TFFs
- Goal: 10 … 20% of HLbL uncertainty
- **Reduced model-dependence**

Access to Transition Form Factors

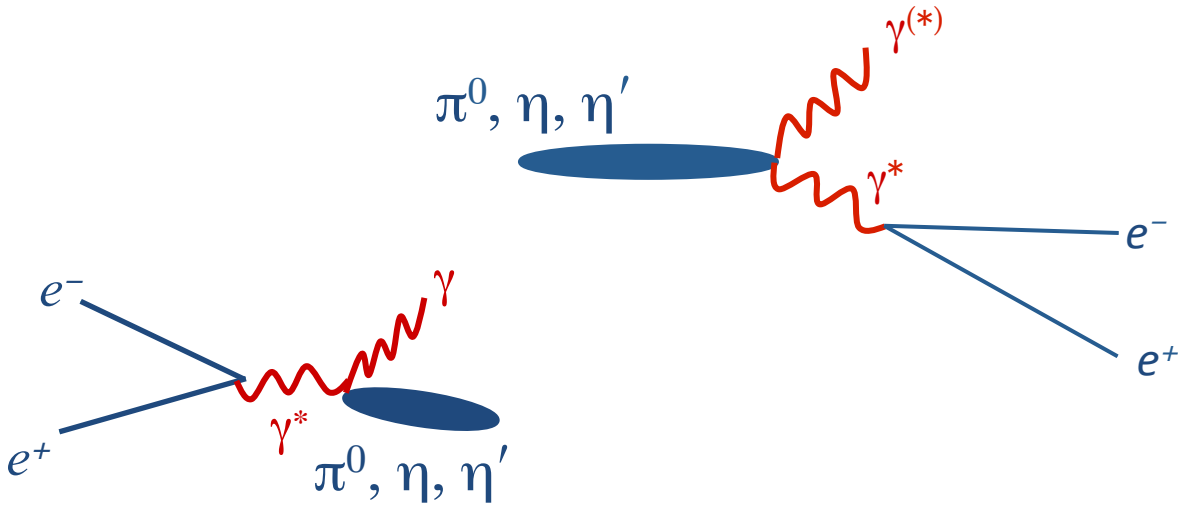
Time – like Transition Form Factors:

- Dalitz decays

  $0 < q^2 < M^2$

- Annihilation process

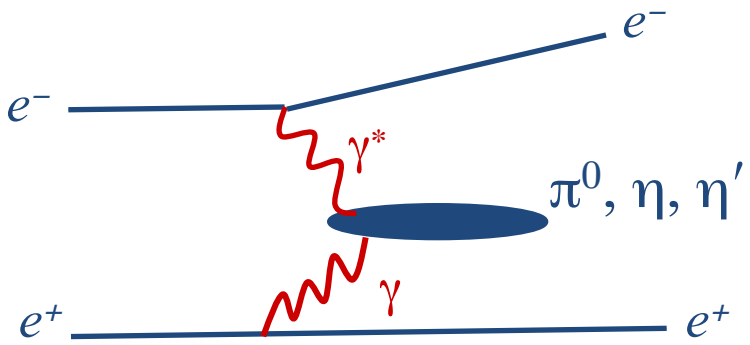
  $q^2 = s > M^2$

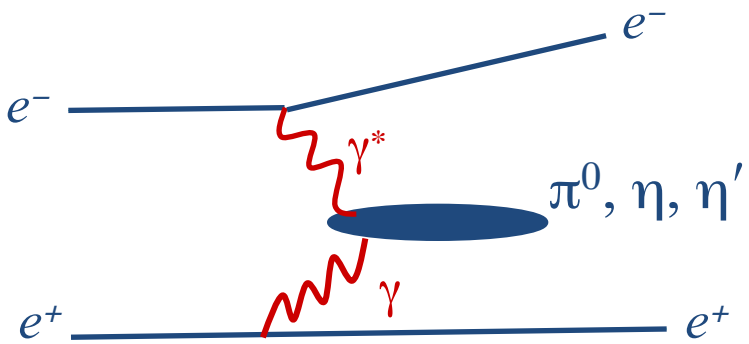


Space – like Transition Form Factors:

- Two-photon production of mesons

  $F(Q_1^2, Q_2^2), \quad Q^2 = -q^2$





Spacelike Transition Form Factor Measurements

BESIII

BESIII Experiment @ BEPCII

Operated at BEPCII collider

$2.0 \leq \sqrt{s}\ [\mathrm{GeV}] \leq 4.6$

Design luminosity achieved

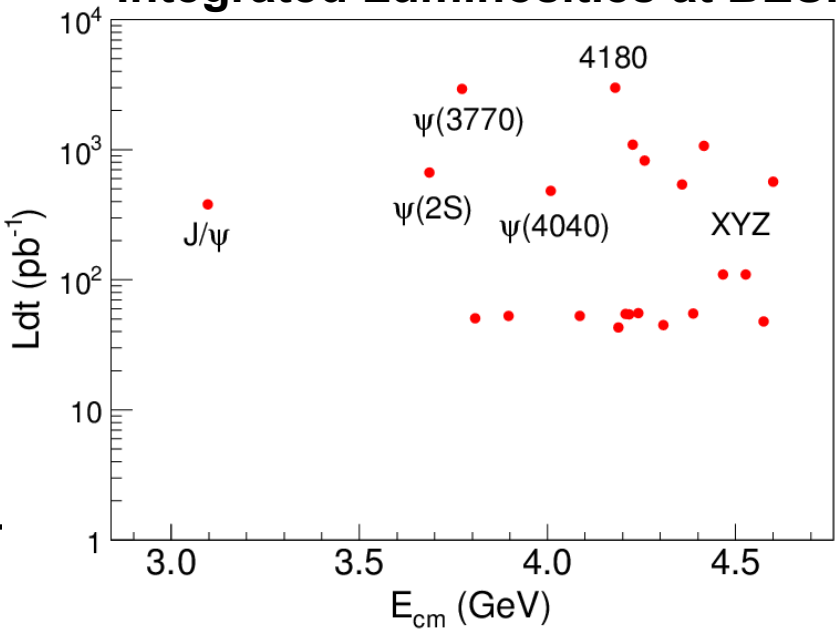
$\mathcal{L} = 1.0 \times 10^{33}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ at $\psi(3770)$

Large data sets for

- Charmonium spectroscopy
- Charm physics
- Light hadrons
- τ and R-scan, QCD physics

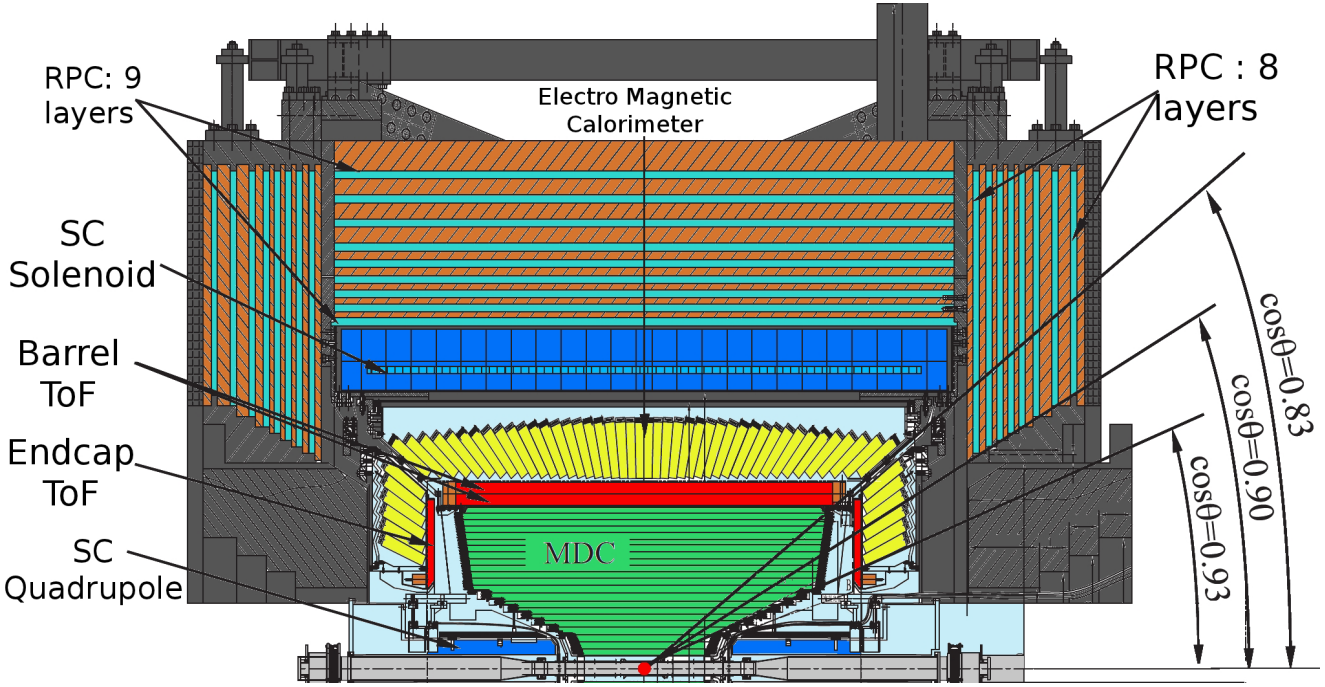
$\gamma\gamma$ studies mainly on 2.9 fb^{-1} at $\psi(3770)$

Integrated Luminosities at BESIII



BESIII Experiment

NIM A614 (2010) 345



- Main Drift Chamber (MDC)
  σ(p)/p = 0.5%
- Time-of-flight system (TOF)
  σ(t) = 90ps (barrel)
  σ(t) = 110ps (endcap)
- EMC
  6240 CsI(Tl) crystals
  σ(E)/E = 2.5%
- Muon Chambers
  8 – 9 layers of RPC

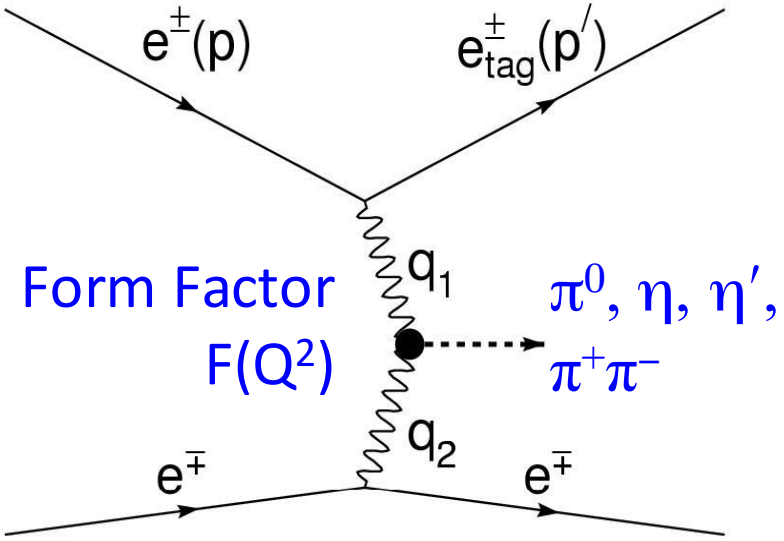
Spacelike FFs $\gamma\gamma^* \rightarrow P$

Single Tag Method

Selection criteria

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

→ **cut on angle of missing momentum**

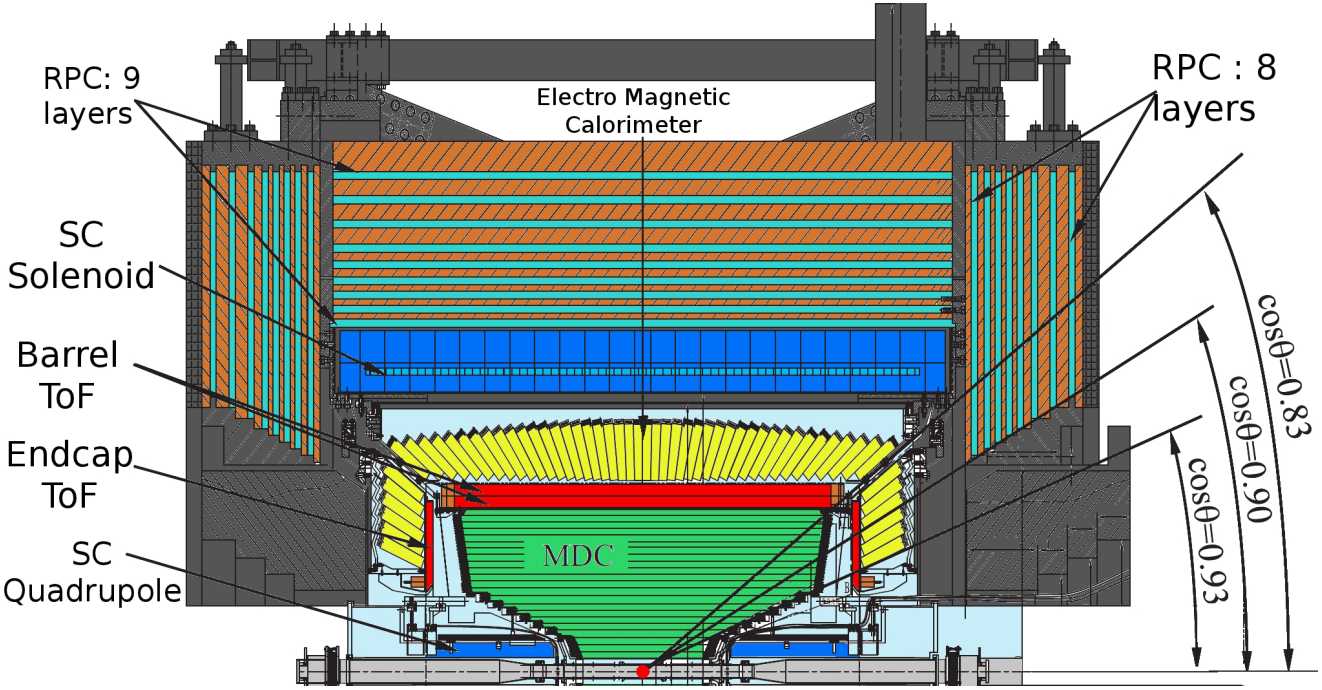


Momentum transfer

- 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

Coverage of Momentum Transfer

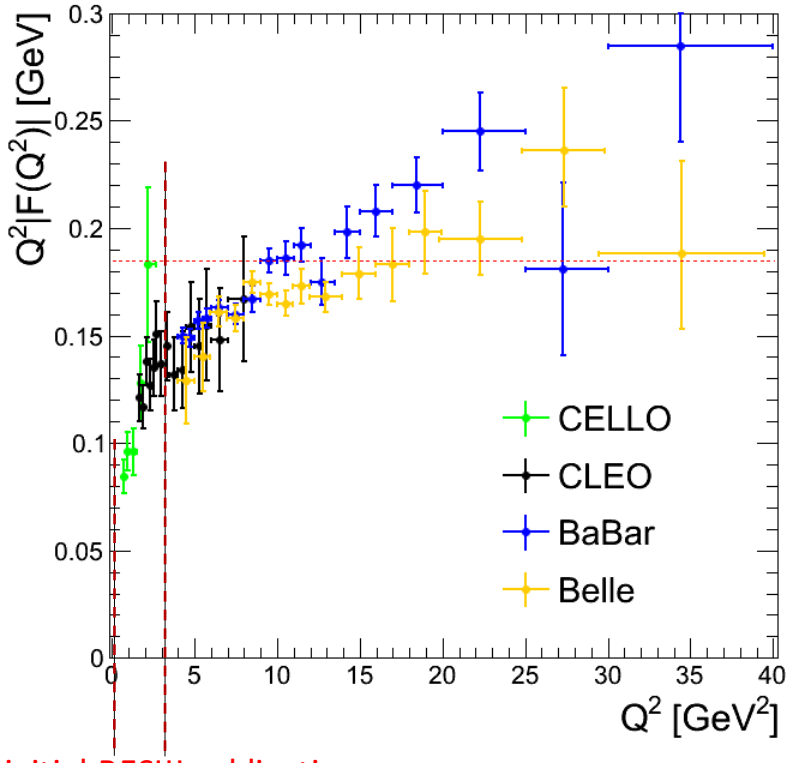


$$Q^2 = 4 \cdot E \cdot E' \cdot \sin^2(\theta/2)$$

Acceptance of detector allows for Q^2 coverage above 0.2 GeV^2

Existing Data on SL Transition FFs

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



initial BESIII publication
< 3.1 GeV^2

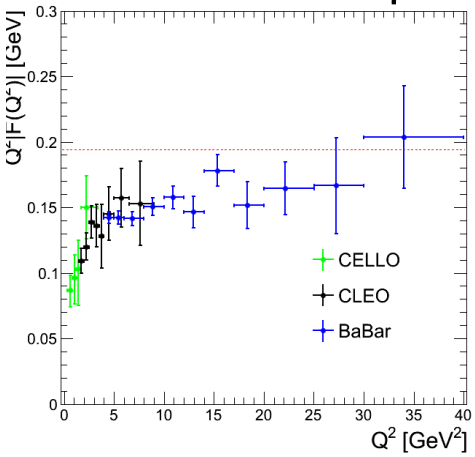
Features:

- 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

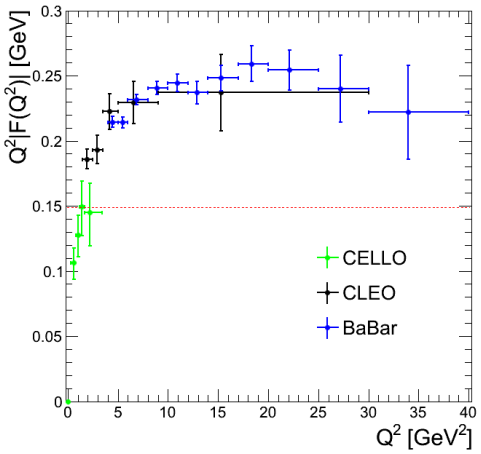
→ low Q^2 range not covered
most relevant for HLbL contribution to $(g-2)_\mu$

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

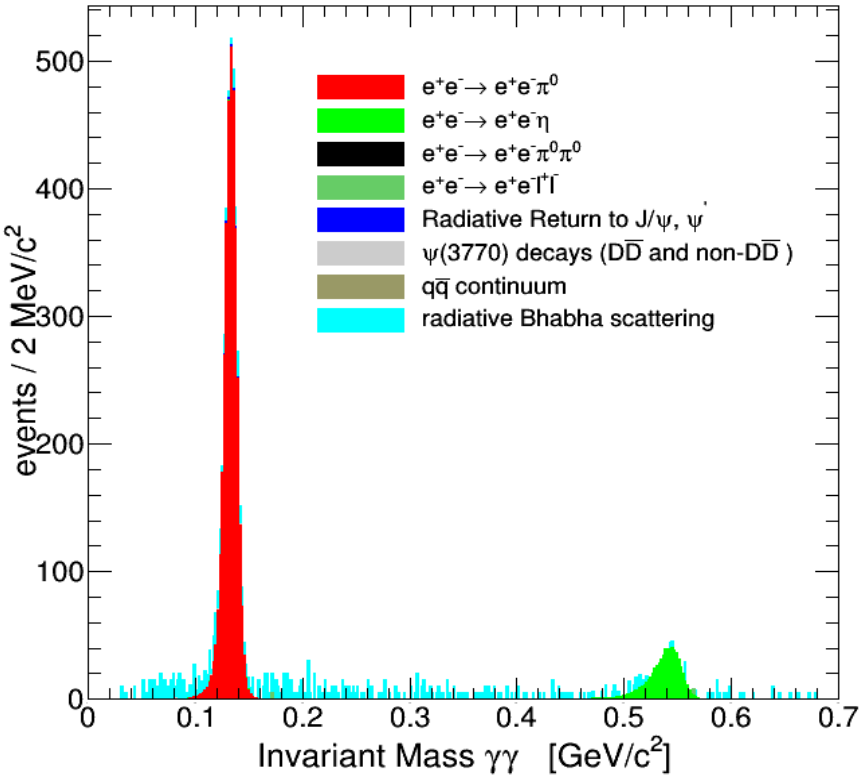
$e^+e^- \to e^+e^- \eta$



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



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



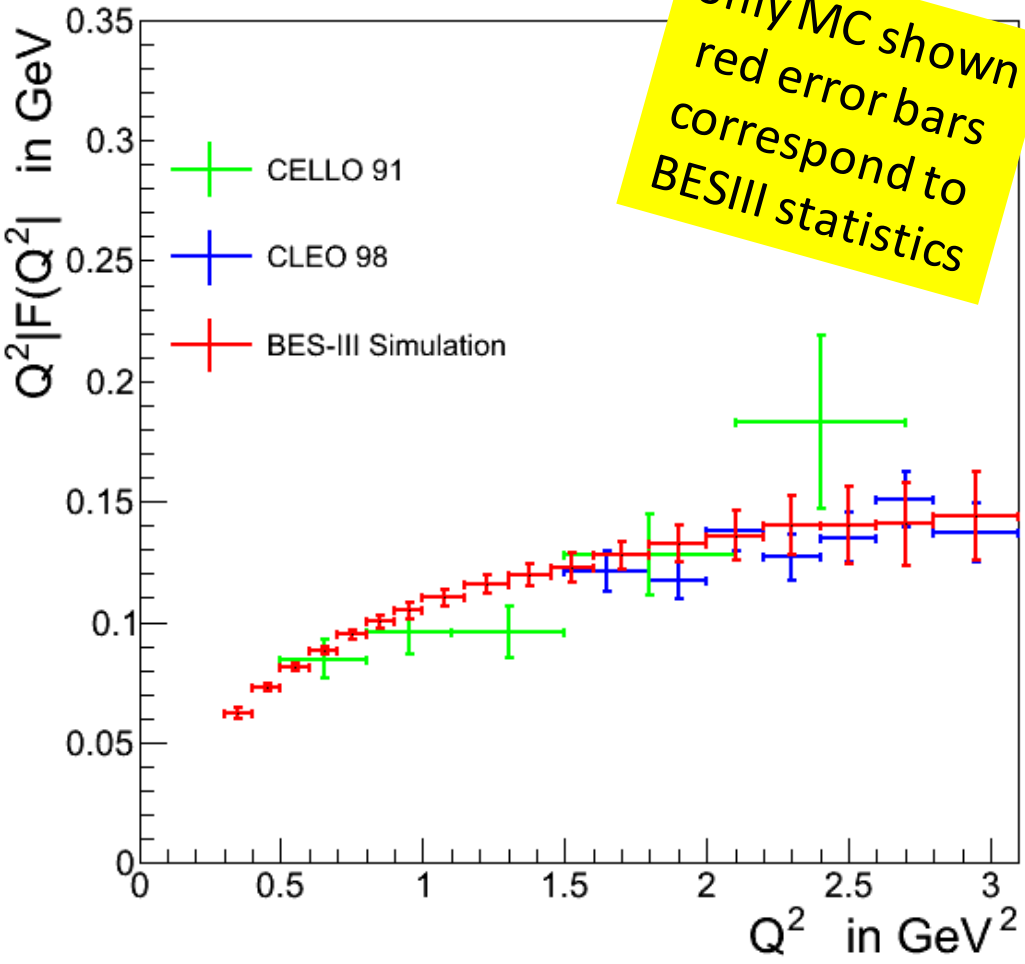
Event Selection:

- 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: $\gamma\,\gamma^* \rightarrow \pi^0$

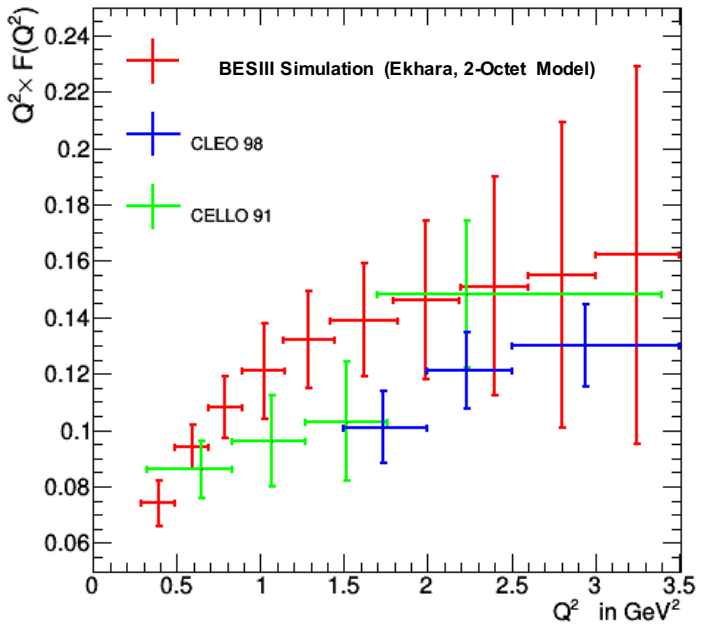


- Full Simulation
  - L_{int}: 2.92 fb^{-1}
  - Single Tag with both, $e^{\pm}$
- Extract TFF for $0.3 \leq Q^2[\text{GeV}^2] \leq 3.1$

→ **Unprecedented $Q^2 < 1.5$ GeV^2**

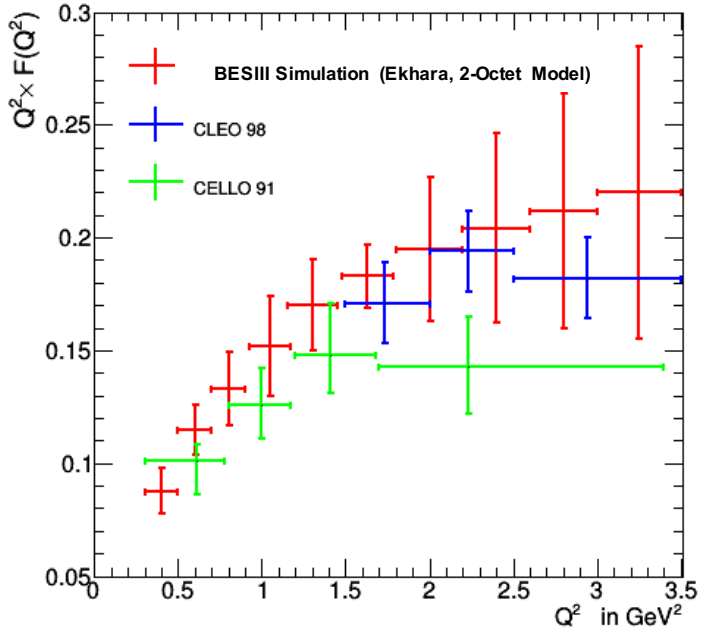
BES III Analysis: $\gamma\,\gamma^* \to \eta,\ \eta'$

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



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

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



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

- Statistics compatible to previous measurements
  - only one decay channel of η and η' analyzed at BESIII
  - more data available (×3.5)
- Systematic studies to be done

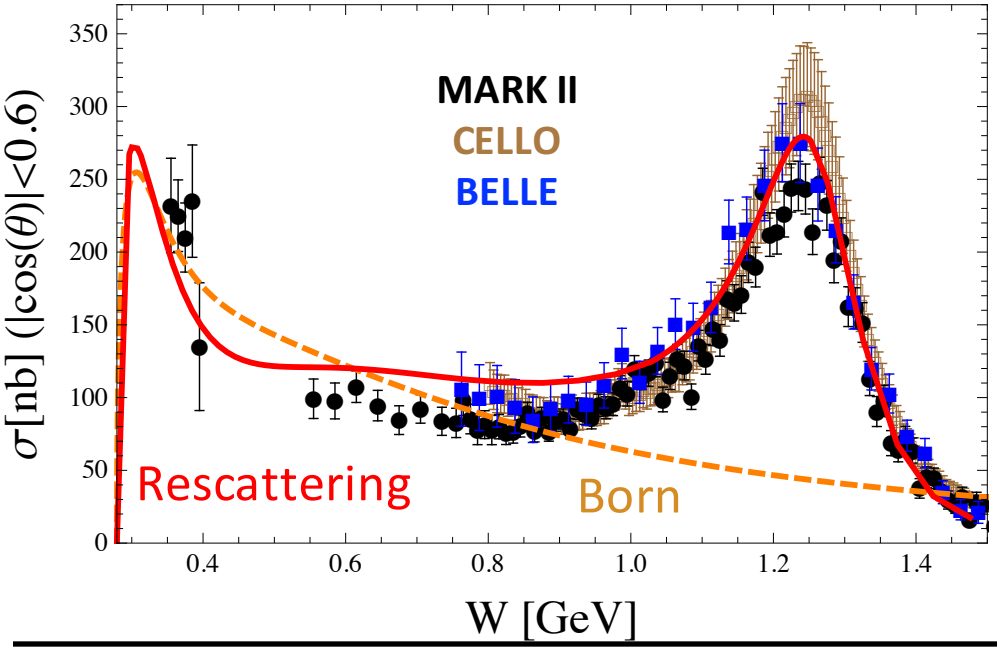
BES III Analysis: $\gamma\,\gamma^* \rightarrow \pi^+\pi^-$

Motivations:

- Essential for dispersive framework Colangelo, Hoferichter, Procura, Stoffer
- Resonance parameters
- Pion polarizabilities, pion structure
- Rescattering effects in low mass region

Until recently only untagged measurements, recent BELLE result single-tagged

Phys. Rev. D93 (2016) 032003



MarkII, Phys. Rev. D42 (1990) 5

CELLO, Z. Phys. C56 (1992) 381

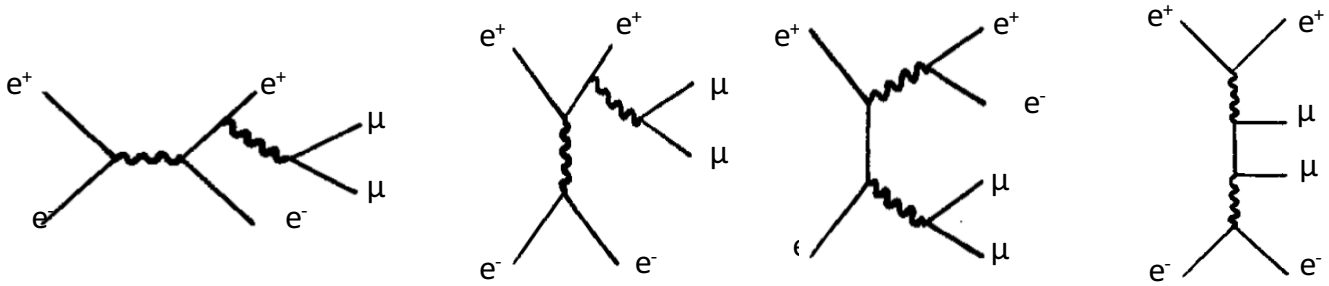
Belle, Phys. Rev D75 (2007) 051101

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

- At BESIII: Single-Tag measurement

  Major Backgrounds:

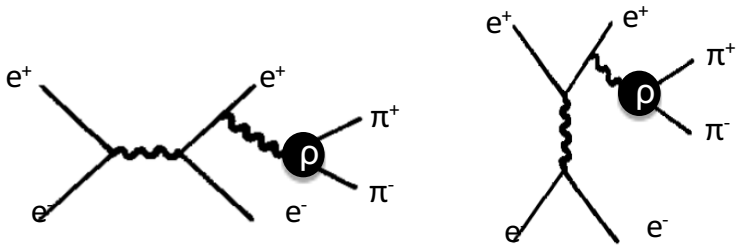
  - $e^+e^- \rightarrow e^+e^-\mu^+\mu^-$



  - Radiative Bhabha scattering coupling to ρ (s + t channel)

    MC generators being developed

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



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

- Multivariate methods to suppress muon background
- Subtract ρ contribution

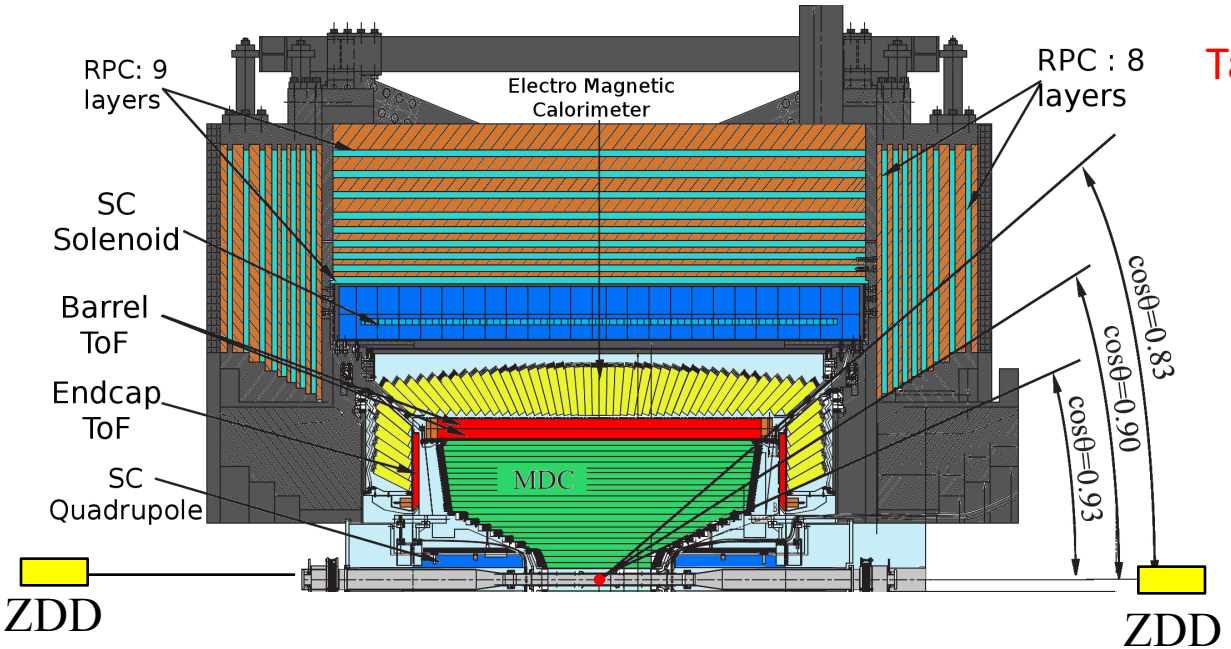
  Fit peak in data using shape from theory
- Study $\pi^+\pi^-$ invariant mass in bins of Q^2 and $\cos\theta^*$

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

Conclusions Spacelike TFF's

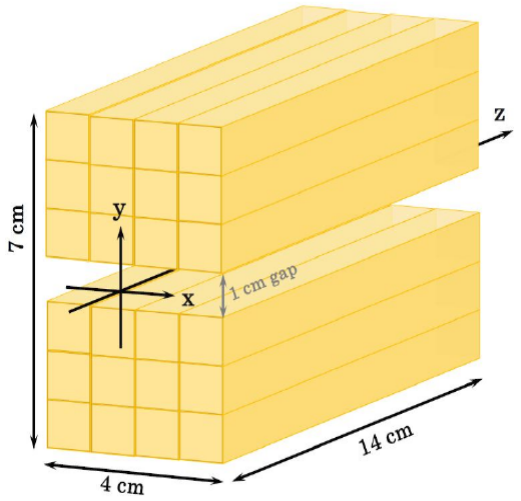
- Highly competitive BES III results to be expected in Q^2 range 0.2 ... 3 GeV^2
- Expect to have preliminary results for $\gamma\gamma^* \to \pi^0$ by June meeting @ Mainz
- Expect to have preliminary results for $\gamma\gamma^* \to \pi^+\pi^-$ by end of the year
- An analysis on $\gamma\gamma^* \to \pi^0\pi^0$ has started in addition
- Results also exist for $\gamma\gamma^* \to \eta$ and $\gamma\gamma^* \to \eta'$ (internal)
  Will include more decay channels to reduce uncertainties
- First preliminary results exist for $\gamma^*\gamma^* \to \pi^0$
  Presently only very coarse binning in (Q_1^2 , Q_2^2) possible
  Cannot make definite statement regarding reliability of different models
- Plans for upcoming years: collect ~ factor 7 higher statistics @ 3.77 GeV

Crystal Zero-Degree-Detector (cZDD)



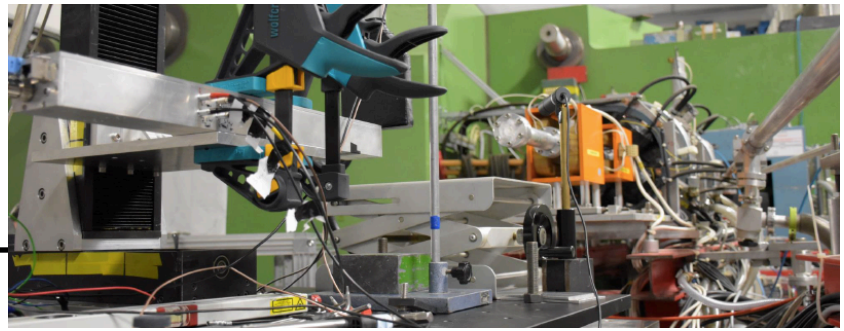
Tagging of leptons at small angles:

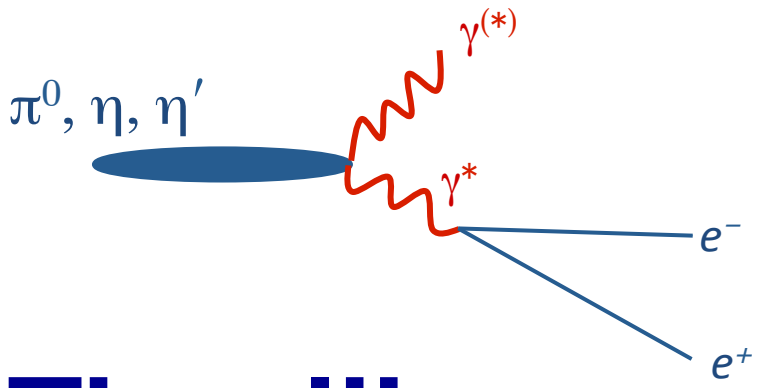
- Polar angle range : 1-10 mrad
- High rate environnement due to Bhabha scattering.



cZDD Detector:

- Two arrays of 12 LYSO crystals on each side
- Readout by Silicon Photomultipliers
- Gap to reduce $e^+e^- \rightarrow e^+e^-\gamma$ contamination
- Promising test beam results (MAMI)





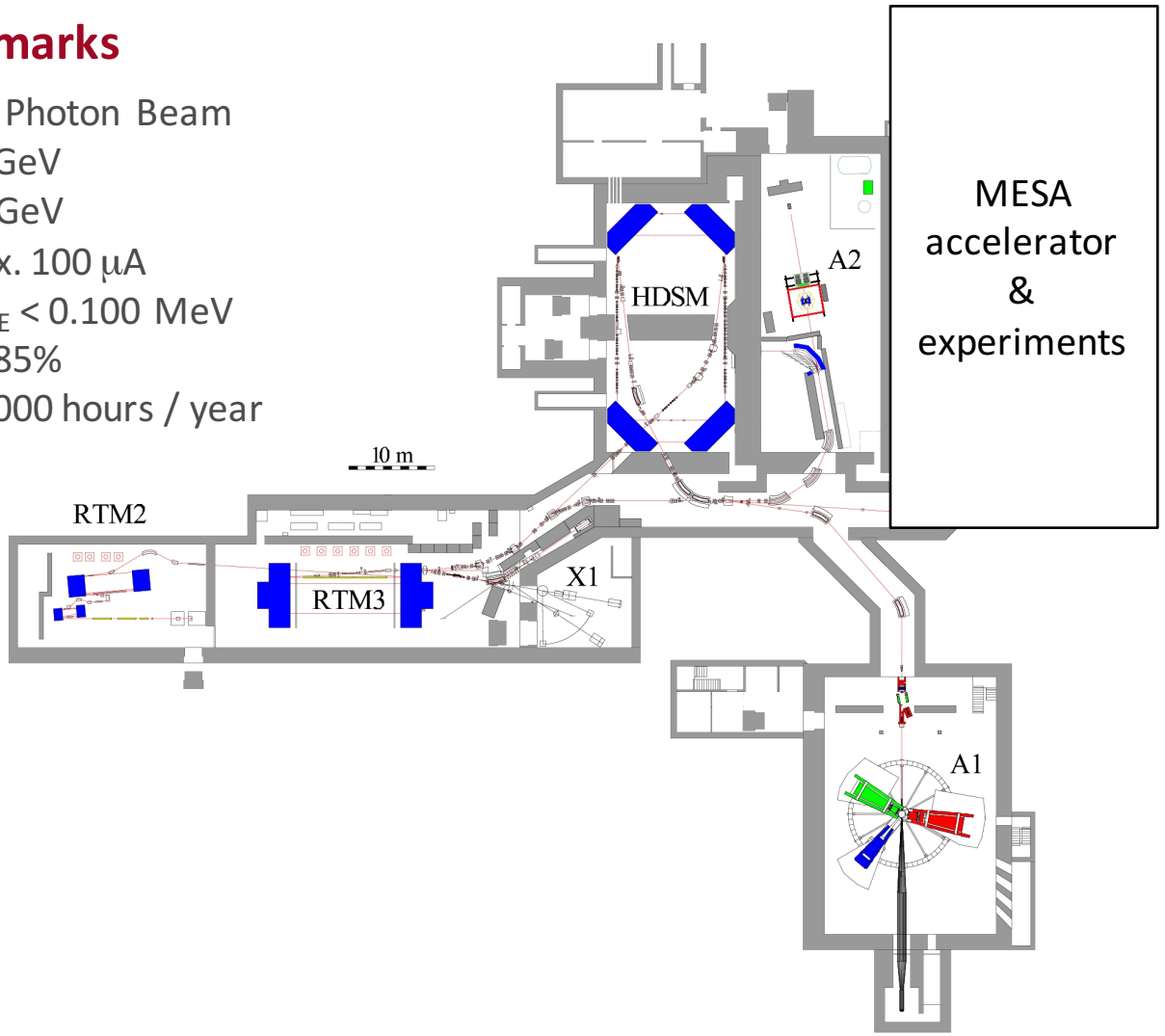
Timelike Transition Form Factor Measurements

A2 BESIII

Mainz Microtron MAMI

MAMI Hallmarks

- Electron and Photon Beam
  E_{min} = 0.185 GeV
  E_{max} = 1.604 GeV
- Intensity max. 100 μA
- Resolution σ_E < 0.100 MeV
- Polarization 85%
- Reliability: 7000 hours / year



Experiment A2: Photon Beam Line

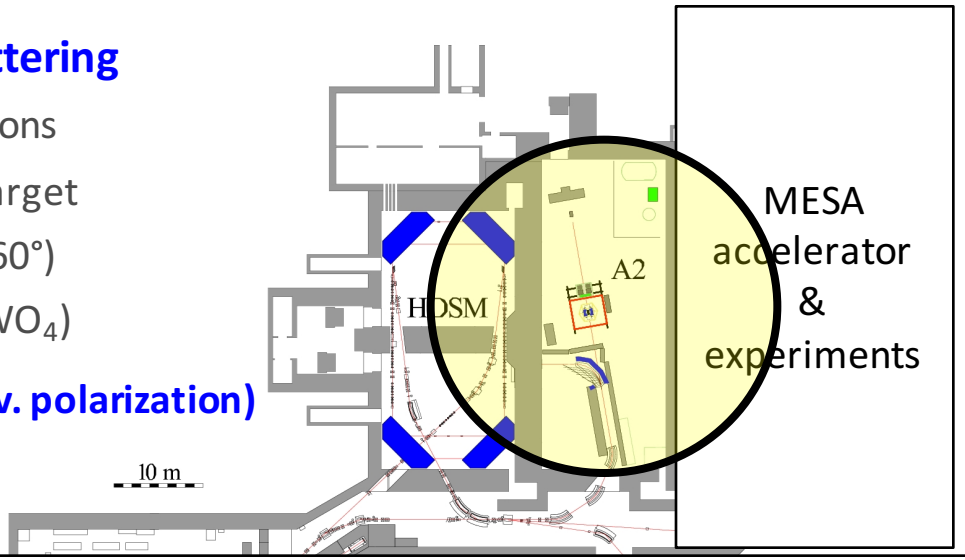
Experiment A2: Photon Scattering

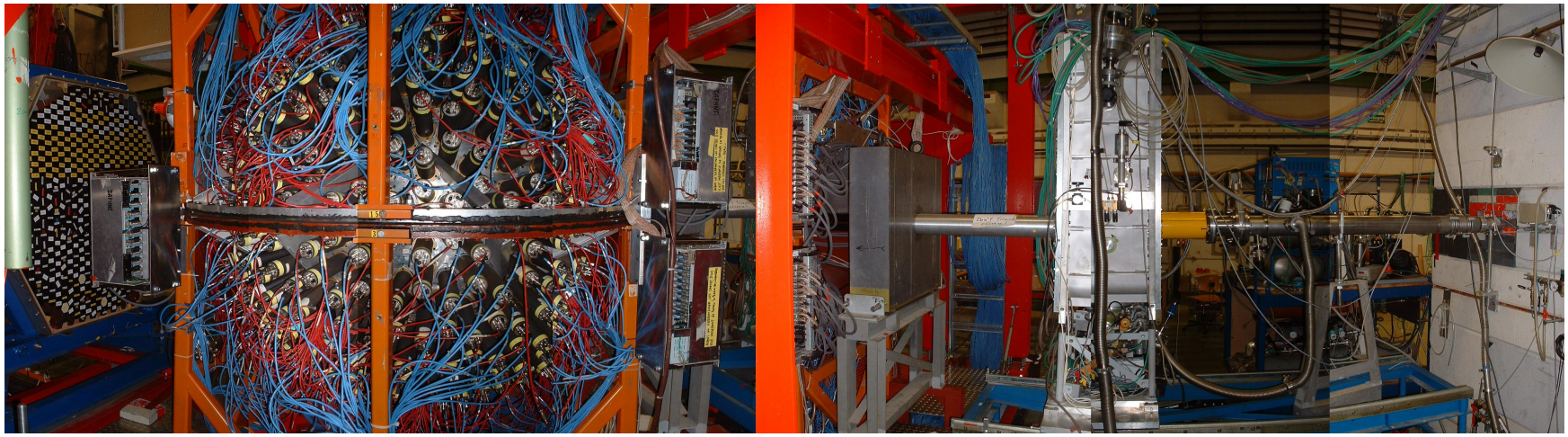
- "Tagged" bremsstrahlung photons
- 4π calorimeter setup around target

Crystal Ball (672 NaI, 20°<Θ<160°)

TAPS (384 BaF_2 ,1°<Θ<20°, $PbWO_4$)

Polarized Target (long. + transv. polarization)



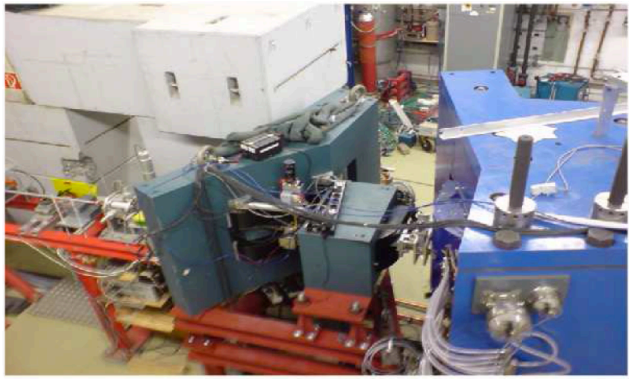


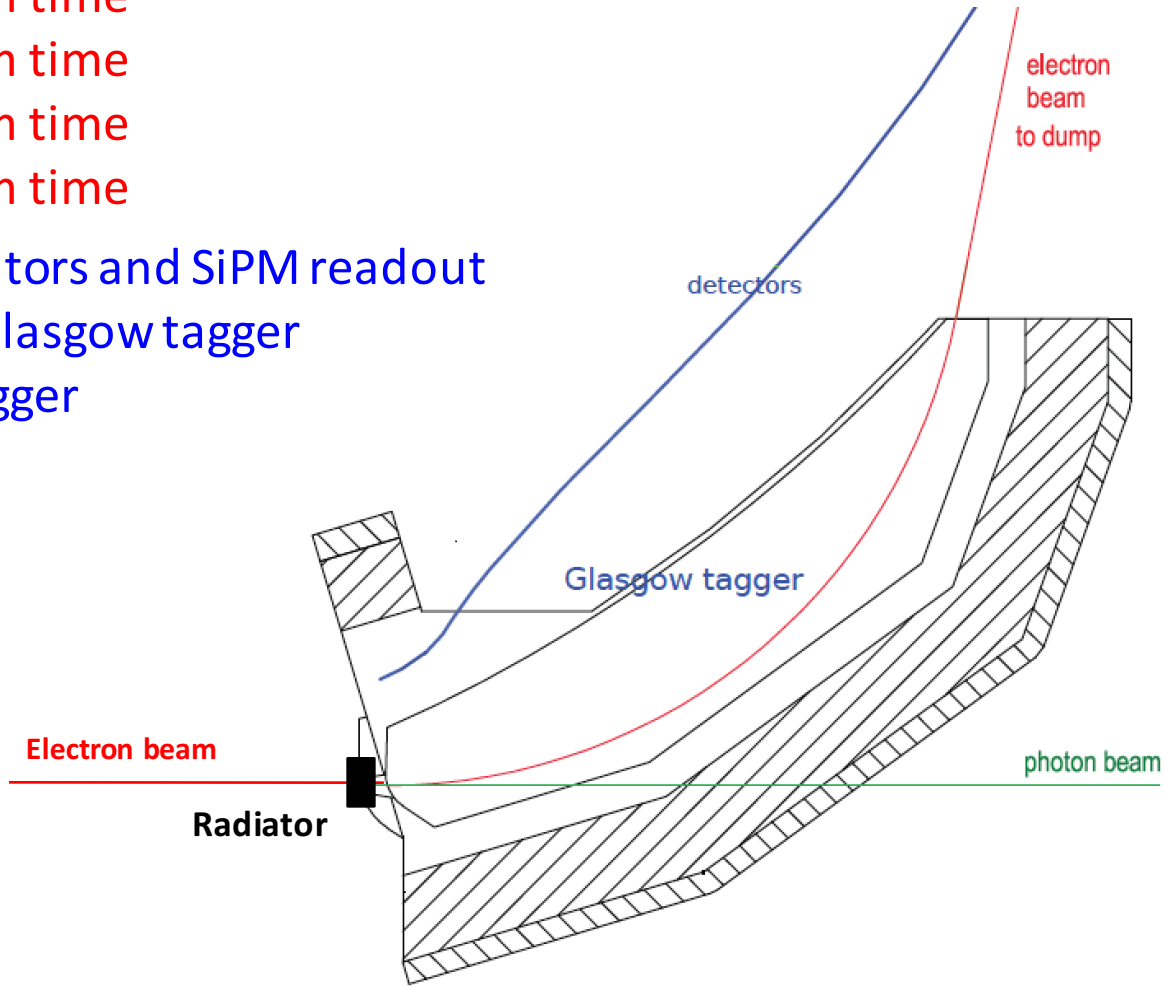
Photoproduction Pseudoscalar Mesons

Production rates:

π^0: ~ 10^9 events / beam time
η: ~ 10^8 events / beam time
η': ~ 10^7 events / beam time
ω: > 10^7 events / beam time

- Installation of new scintillators and SiPM readout for focal plane of Mainz - Glasgow tagger
- Installation of endpoint tagger

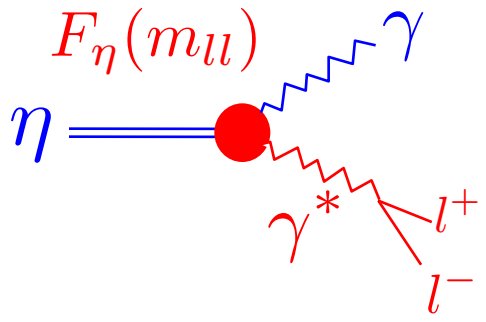




Timelike EM Form Factor: $\eta \to e^+e^-\gamma$

$$\frac{d\Gamma(\eta \to l^+l^-\gamma)}{dm_{ll}\Gamma(\eta \to \gamma\gamma)} = [QED] \cdot |F_\eta(m_{ll})|^2$$

pointlike eta



30<m(e+e-) < 100 MeV

- First result from **2011 (PLB)**
- **2014 result (PRC)** based on factor 10 higher statistics (18,000 events); kinematic fit used for selection
- **New analysis** based on **54,000 events**, yet improved selection

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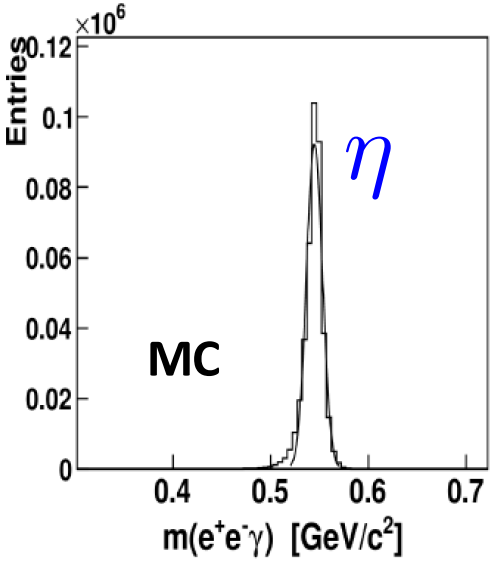
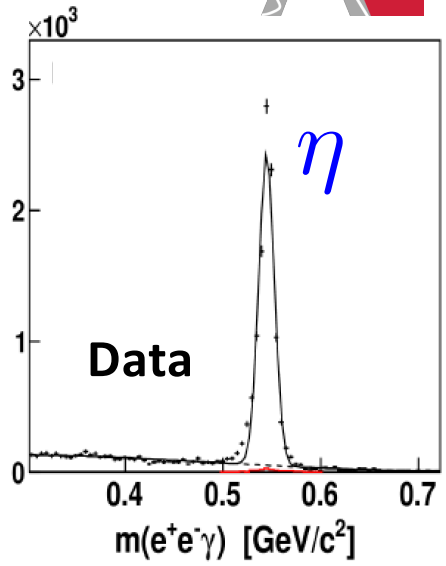
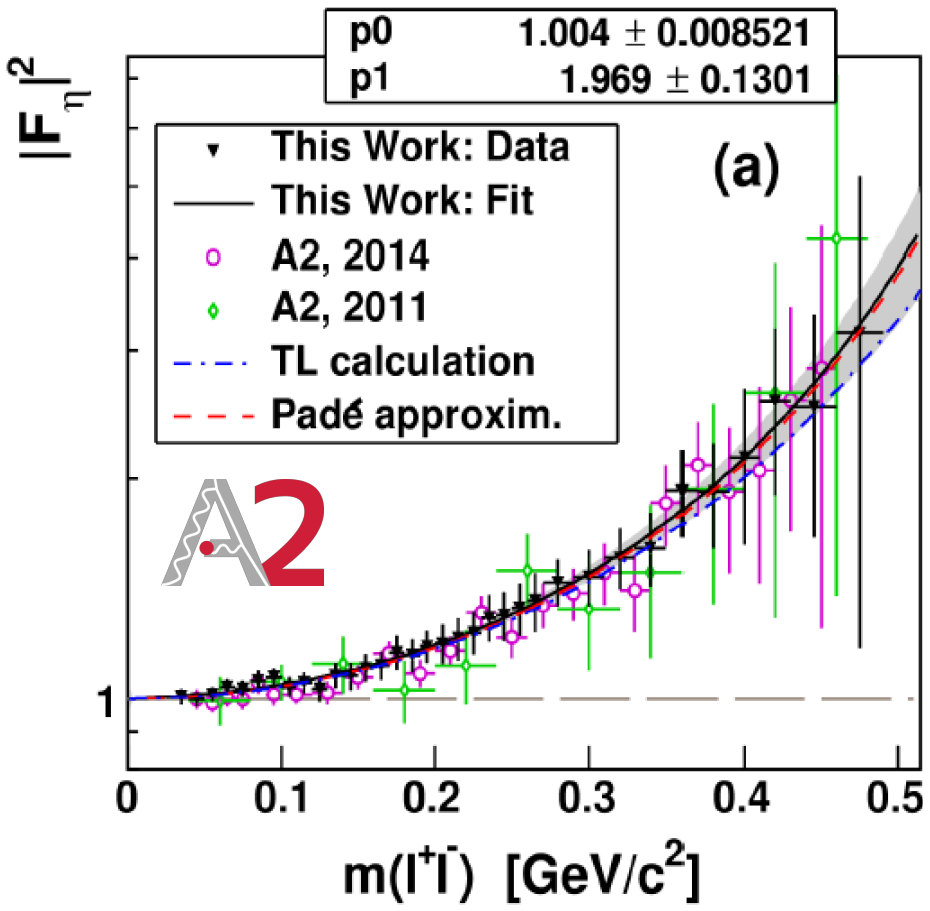




Timelike EM Form Factor: $\eta \to e^+e^-\gamma$



Vector Meson Dominance model:

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

$\Lambda^{-2}=(1.97 \pm 0.13_{tot})$ GeV^{-2}

in good agreement with all previous results

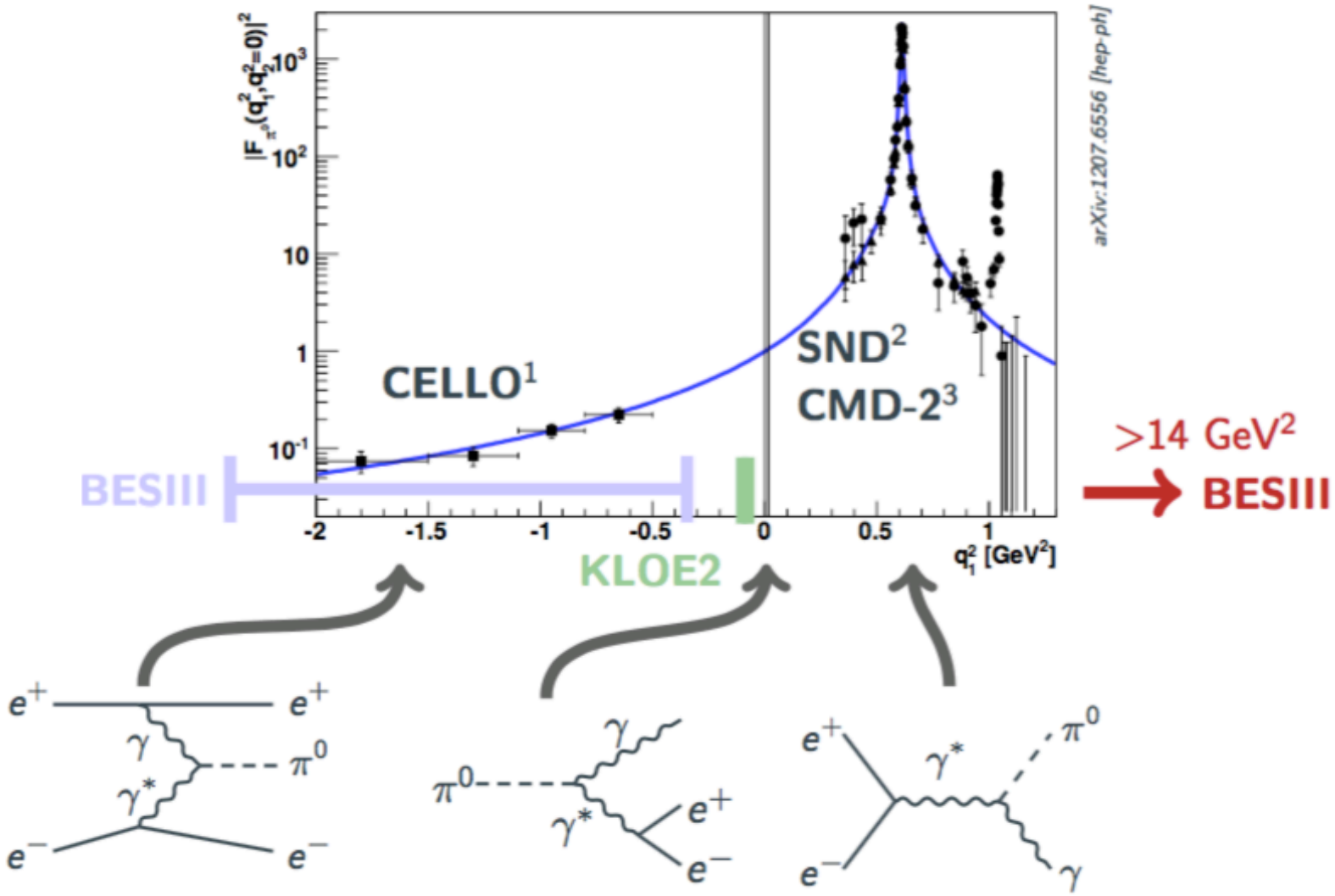
A2 (2014):	$\Lambda^{-2}=(1.95\pm0.18)$ GeV^2;
A2 (2011):	$\Lambda^{-2}=(1.92\pm0.37)$ GeV^2;
NA60(In-In):	$\Lambda^{-2}=(1.95\pm0.17)$ GeV^2;
NA60(p-A):	$\Lambda^{-2}=(1.934\pm0.08)$ GeV^2.

Very good agreement among previous A2 and NA60 ($\mu^+\mu^-\gamma$) experiments

VMD prediction ✔

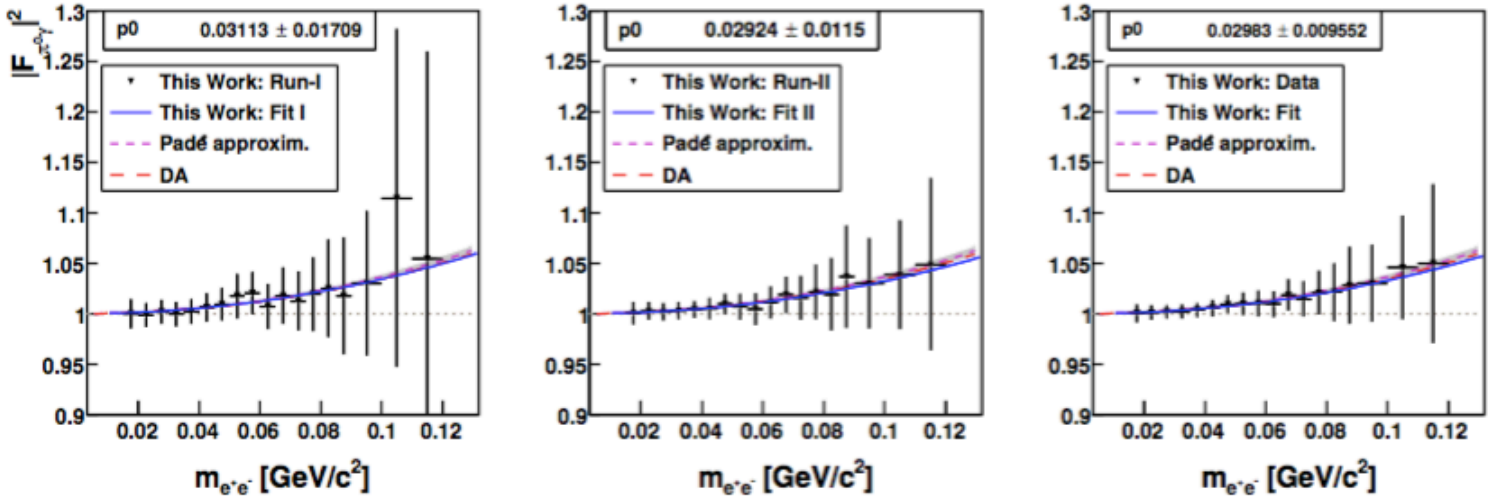
TL calculation: S. Leupold, C. Terschlüsen
Padé calculation: R. Escribano, P. Masjuan, P. Sanches-Puertas

Timelike EM Form Factor: $\pi^0 \to e^+e^-\gamma$



Timelike EM Form Factor: $\pi^0 \to e^+e^-\gamma$

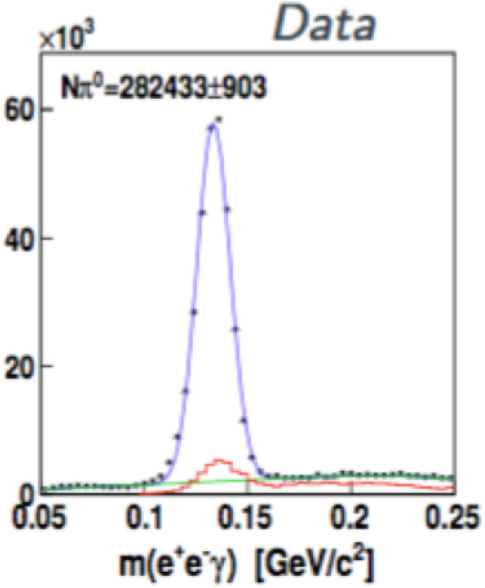
PRC 95 (2017) 025202



VMD inspired fit $F(q^2,0) \approx 1 + \frac{a_\pi}{m^2_{\pi^0}} q^2$

Total uncertainty dominated by fit uncertainties
→statistics

QED includes radiative corrections
Husek, Kampf, Novotny (PRD 2015)



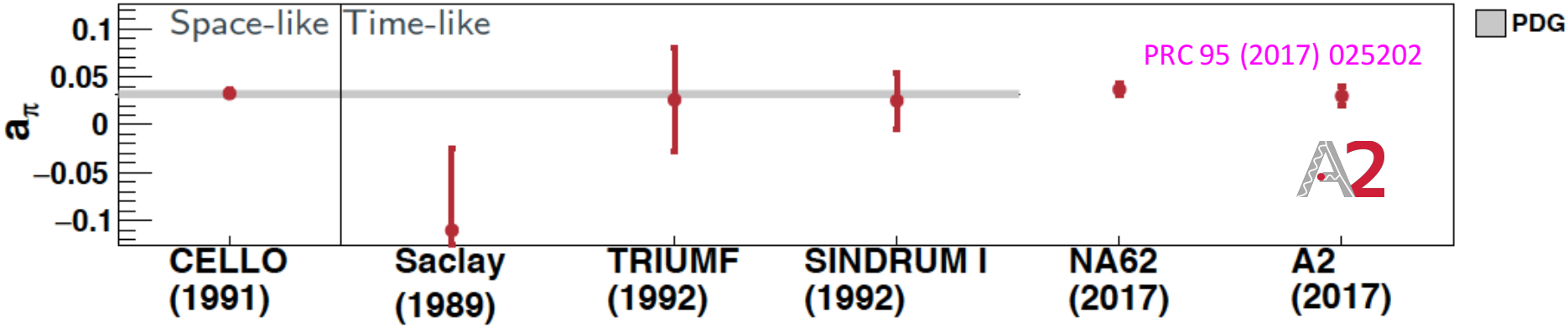
Timelike EM Form Factor: $\pi^0 \to e^+e^-\gamma$

Experiment:

A2/MAMI result $a_\pi = 0.03 \pm 0.01_{tot}$

NA62 result $a_\pi = 0.0368(57_{tot})$ PLB 768 (2017) 38

PDG average $a_\pi = 0.032(4)$



Theory:

Dispersion analysis $a_\pi = 0.0307(6)$ EPJC74 (2014) 3180

Padé approximants $a_\pi = 0.0324(12)_{stat}(19)_{sys}$ PRD 86 (2012) 094021

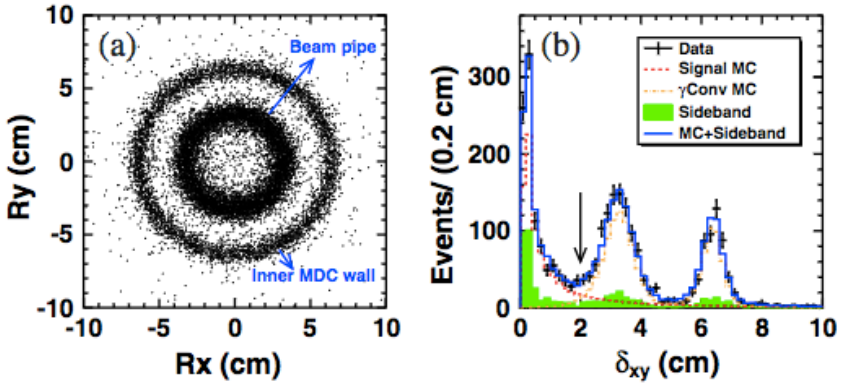
New experiment scheduled at A2/MAMI for spring 2018 (6 weeks)

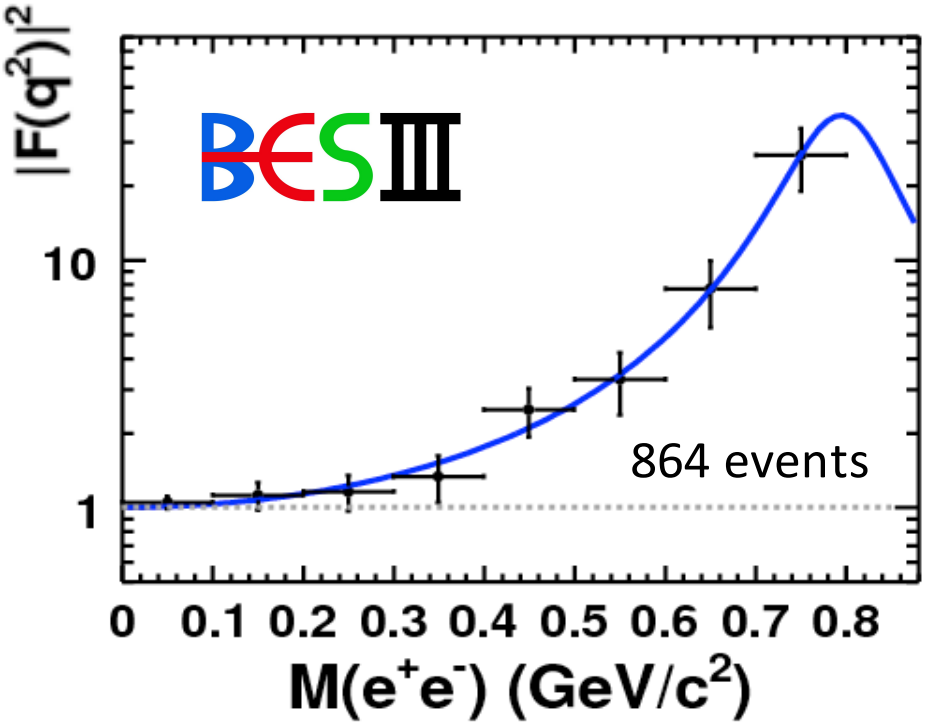
Target accuracy: PDG error

Timelike EM Form Factor: $\eta' \to e^+e^-\gamma$

$$e^+e^- \to J/\psi \to \eta'\gamma$$

World's largest data sample
1.3 billion J/ψ events





$$b = \left.\frac{dF}{dq^2}\right|_{q^2=0} = \Lambda^{-2}$$

pole
width

$$|F(q^2)|^2 = \frac{\Lambda^2(\Lambda^2+\gamma^2)}{(\Lambda^2-q^2)^2+\Lambda^2\gamma^2}$$

$$\Lambda_{\eta'} = (0.79 \pm 0.05)\text{GeV}$$
$$\gamma_{\eta'} = (0.13 \pm 0.06)\text{GeV}$$
$$b_{\eta'} = (1.7 \pm 0.4)\text{GeV}^{-2}$$

Conclusions Timelike TFF's

- Significant progress in measurements from Dalitz decays
  Still not sufficient to distinguish between various models

- Puzzling situation regarding $\omega \to \pi^0 e^+ e^-$ FF
  theory versus NA60, NA60 vs. A2/MAMI PRD 92 (2015) 012001

- Upcoming new measurements at KLOE-2, A2/MAMI, BES III, CLAS, NA60, ...

- BES III measuring timelike FF in annihilation reactions at Q^2 ~20 GeV^2

$$e^+ e^- \to \pi^0 \gamma$$
$$e^+ e^- \to \eta \gamma$$
$$e^+ e^- \to \eta' \gamma$$

Thank you for the attention and stay tuned!