March 21, 2018
International Workshop on
Hadron Structure and Spectroscopy
IWHSS 2018, Bonn, Germany

Studying Low-Energy QCD via Radiative Meson Decays

JG|U

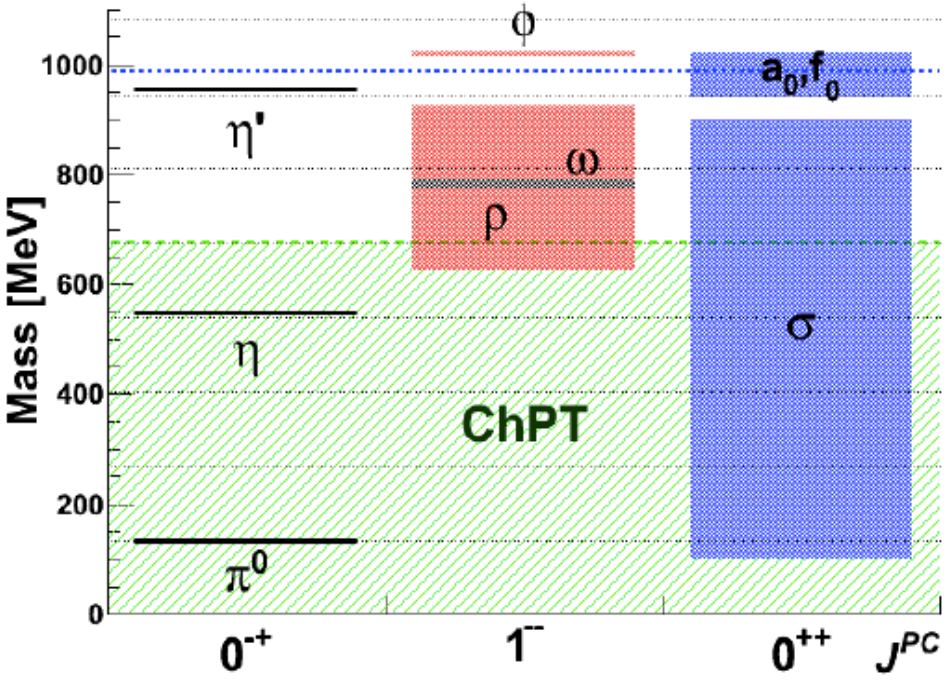
SFB 1044
THE LOW-ENERGY FRONTIER OF THE STANDARD MODEL

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

Achim Denig, JGU Mainz

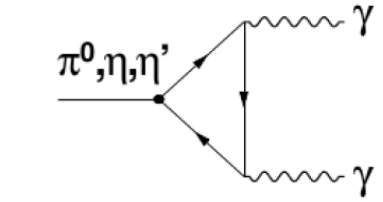
Light Meson Degrees of Freedom

Hadron Spectroscopy

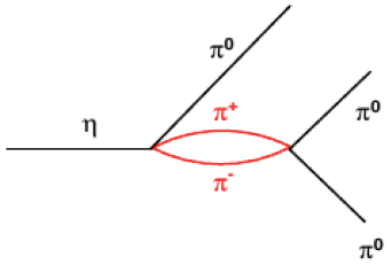


Pseudo-scalar | Vector | Scalar

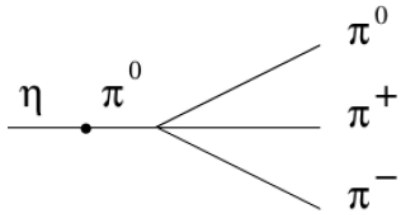
Hadron Structure/Dynamics



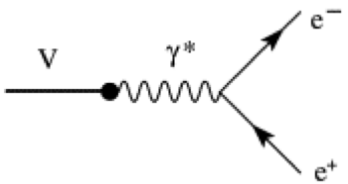
Anomalous Processes



Rescattering Effects



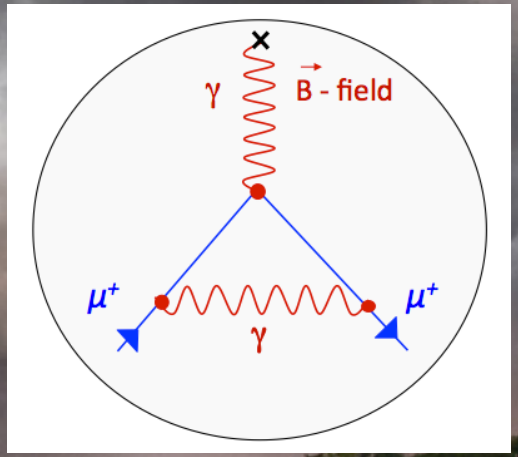
Isospin Breaking

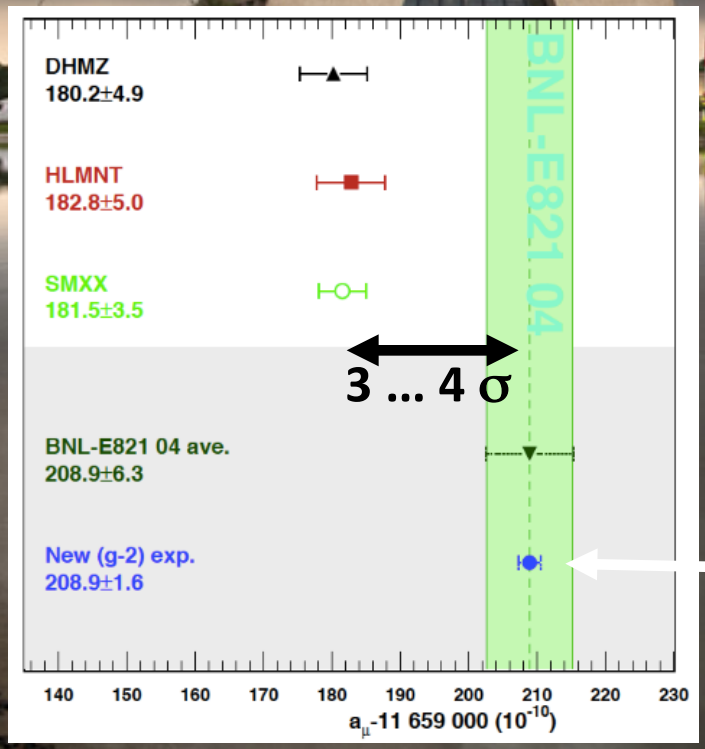


Vector Meson Dominance

Muon Anomalous Magnetic Moment Puzzle

$(g-2)_\mu$





New $(g-2)_\mu$ experiment at FNAL has started data taking

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

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

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

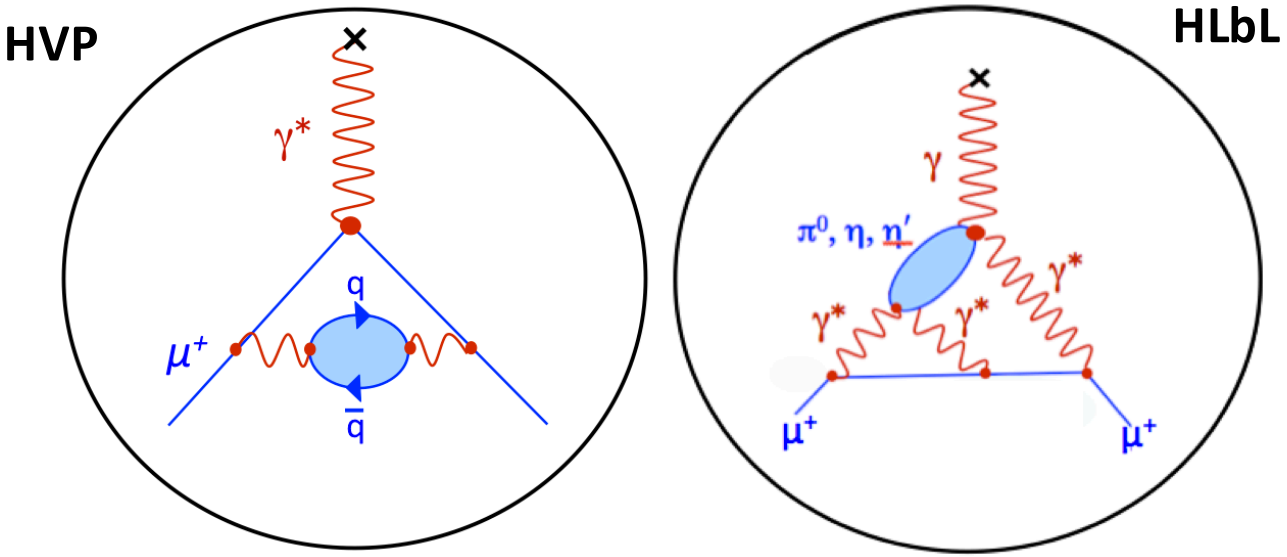
[Keshavarzi, Nomura, Teubner 2018]

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 π^0, η, η'

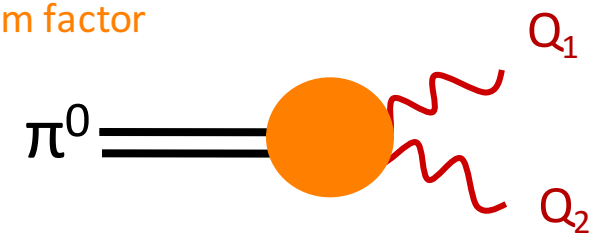
$$a_\mu^{\mathrm{HLbL};\pi^{0(1)}} = \int_0^\infty dQ_1 \int_0^\infty dQ_2 \int_{-1}^1 d\tau \; w_1(Q_1, Q_2, \tau) \mathcal{F}_{\pi^0\gamma^*\gamma^*}(-Q_1^2, -(Q_1+Q_2)^2) \mathcal{F}_{\pi^0\gamma^*\gamma^*}(-Q_2^2, 0)$$

weighting function

transition form factor

3D integral representation

[Nyffeler 2016]



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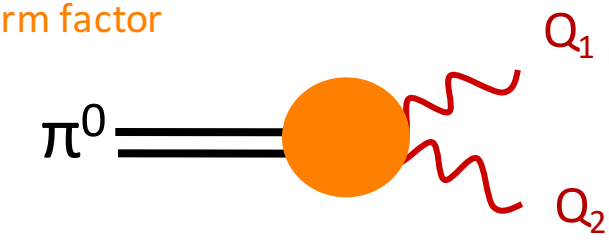
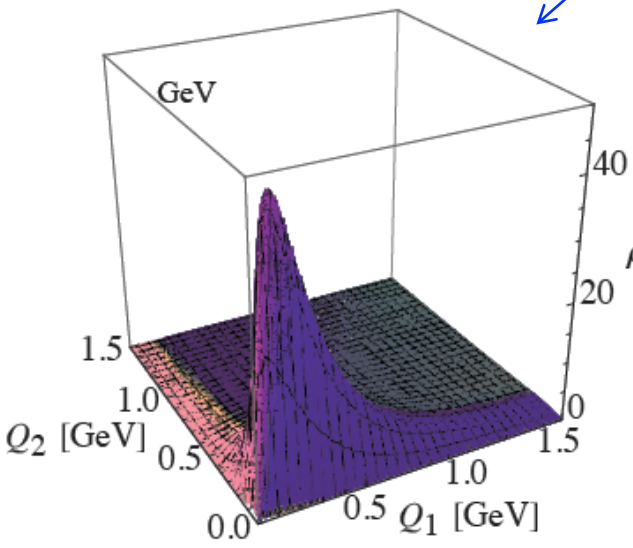
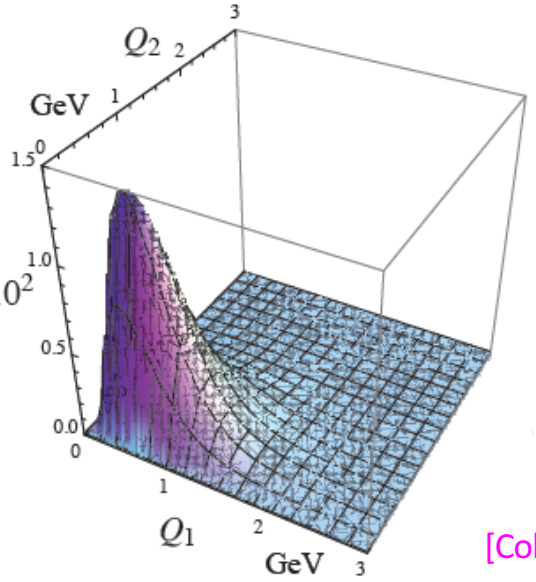




Pseudoscalar Mesons

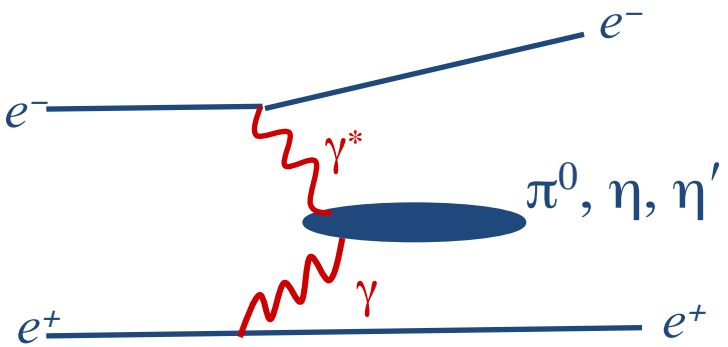


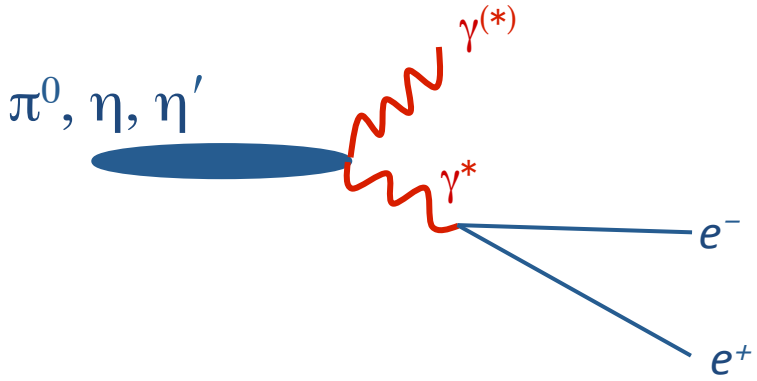
Axial Vector Mesons

→ **Dispersion theory: Relate singly-virtual form factor to doubly-virtual one**

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

Transition Form Factors (TFF)





Spacelike Measurement

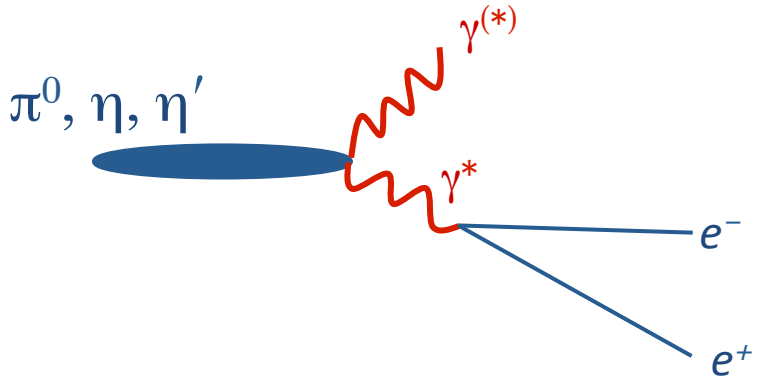
at BES III: $Q^2 = 0.3 – 3.1\ GeV^2$
no previous precision data

Timelike Measurement

$Q^2 < M^2_{Meson}$

Outline

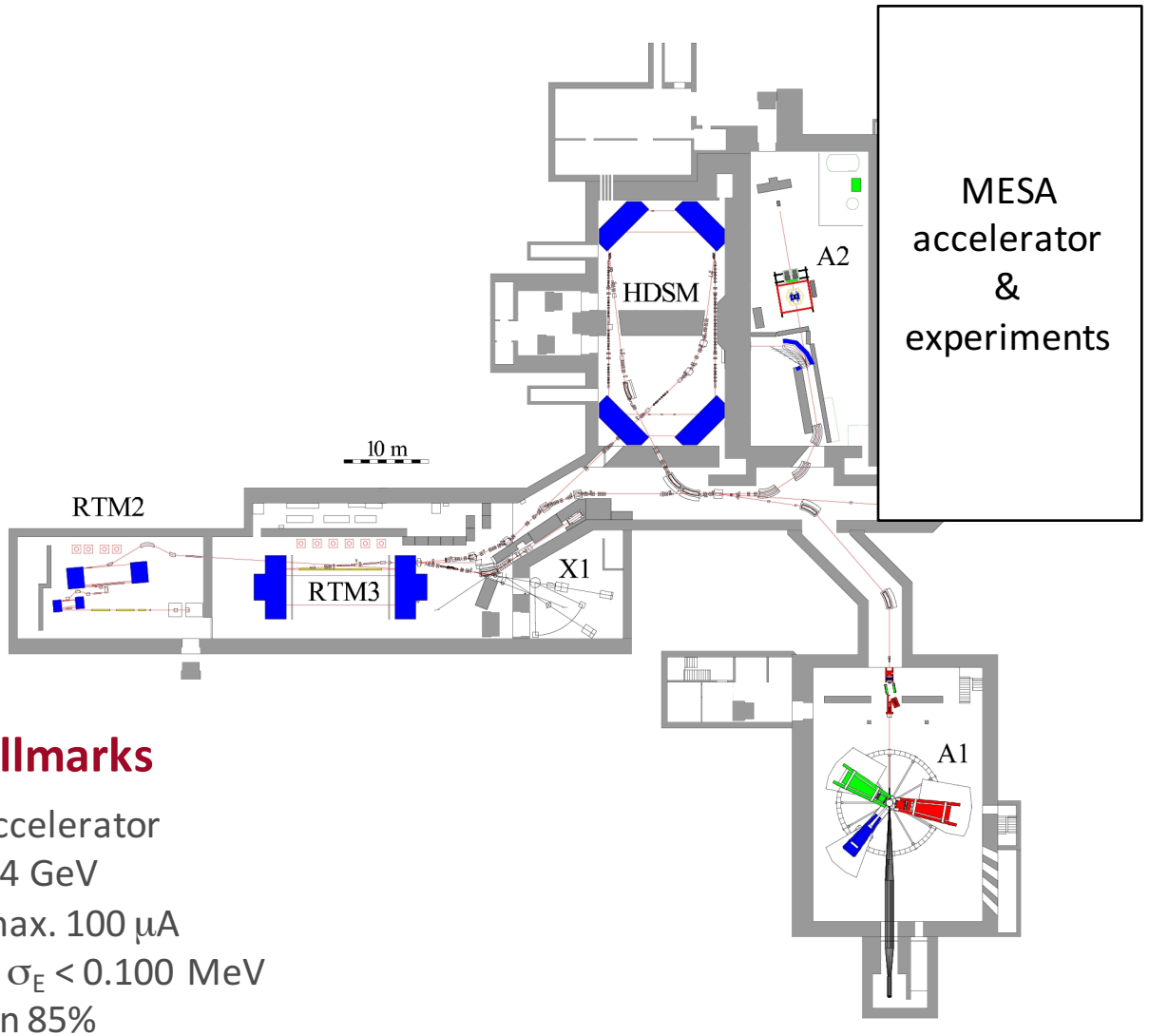
- Transition Form Factor Measurements at A2/MAMI
- Gamma-Gamma-Programme at BES III
- Anomalous Decay $\eta' \rightarrow \pi^+\pi^-\gamma$ at BES III



Transition Form Factor Measurements at

A2

Experiment A2: Photon Beam Line



MAMI Hallmarks

- Electron Accelerator
- E_{max} = 1.604 GeV
- Intensity max. 100 μA
- Resolution σ_E < 0.100 MeV
- Polarization 85%

Experiment A2: Photon Beam Line

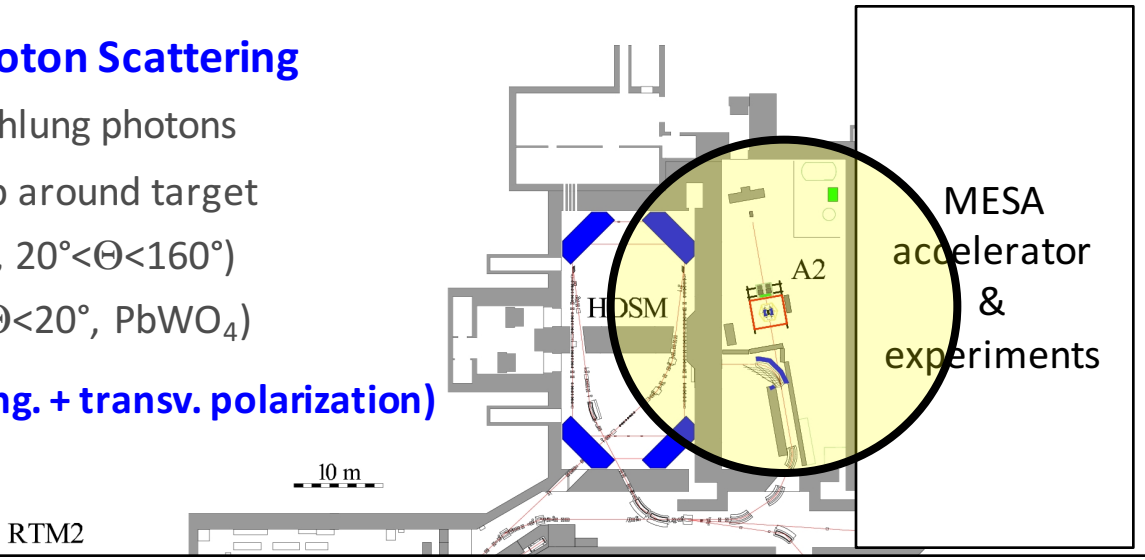
Experiment A2: Photon Scattering

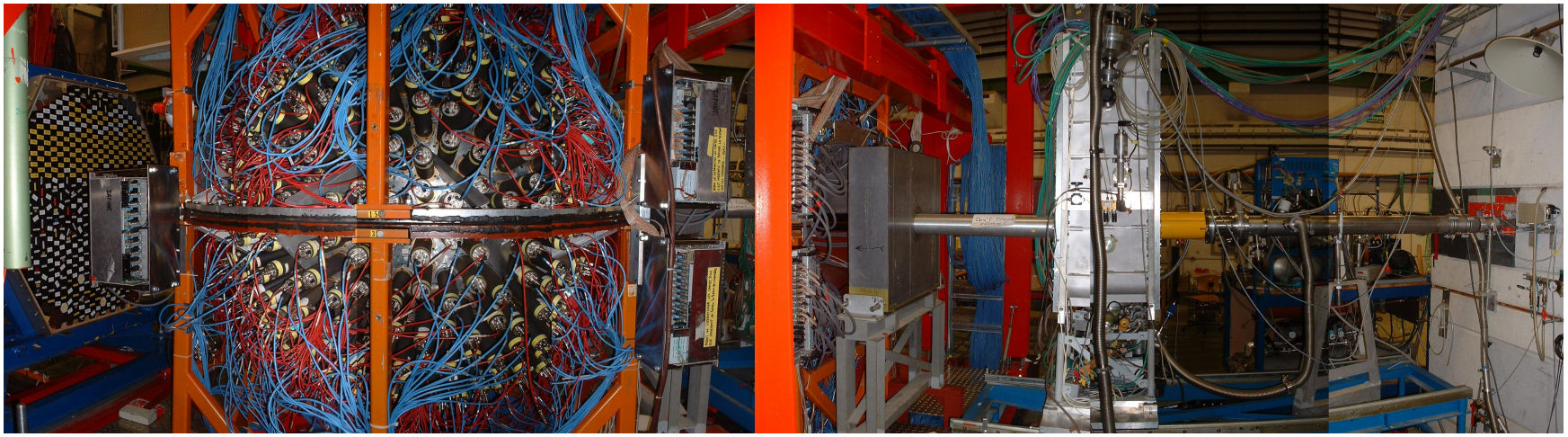
- "Tagged" bremsstrahlung photons
- 4π calorimeter setup around target

Crystal Ball (672 NaI, 20°<Θ<160°)

TAPS (384 BaF_2 ,1°<Θ<20°, $PbWO_4$)

Polarized Target (long. + transv. polarization)



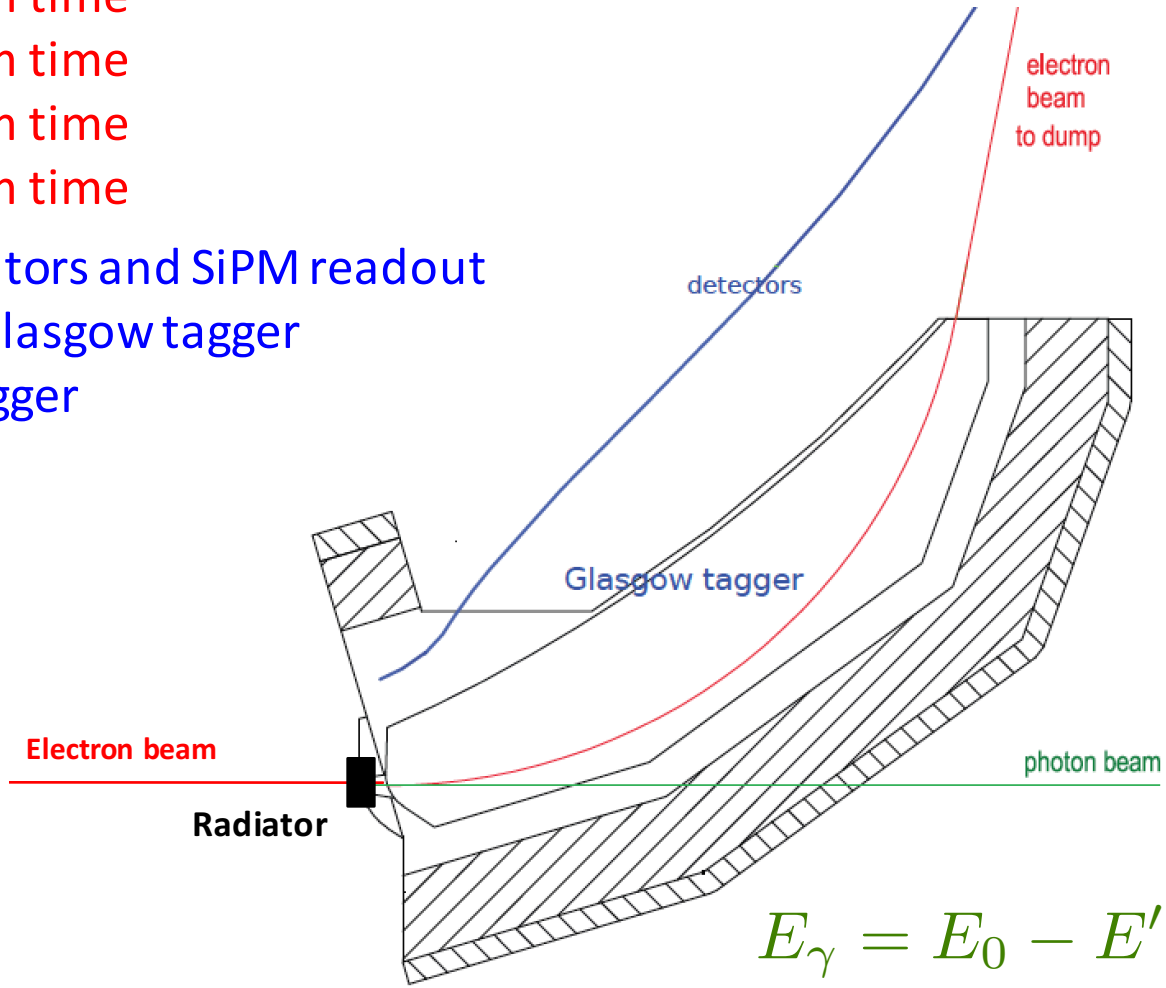


Photoproduction Pseudoscalar Mesons

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



$$E_\gamma = E_0 - E'$$

A2 Programme on TFF Measurements

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

Phys.Lett. B701 (2011) 562

Phys. Rev. C 89 (2014) 044608

Phys.Rev. C95 (2017) 035208

$$\omega \to \pi^0\gamma^* \to \pi^0 e^+ e^-$$

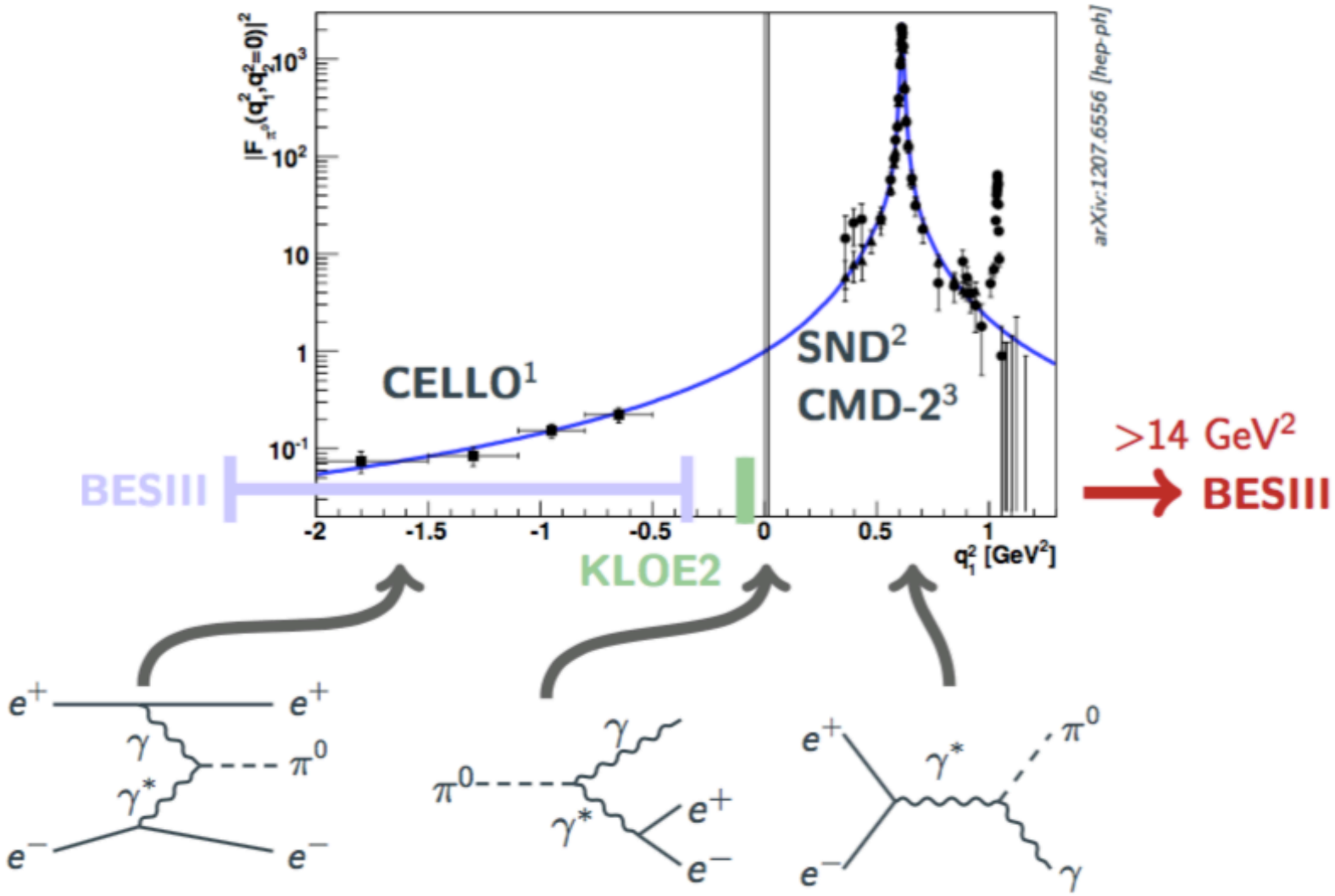
Phys.Rev. C95 (2017) 035208

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

Phys. Rev. C95 (2017) 025202

In preparation: $\eta' \to \gamma\gamma^* \to \gamma e^+ e^-$

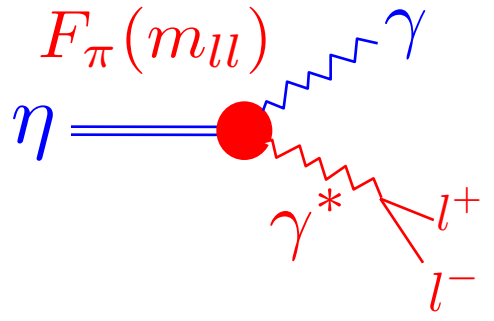
Timelike EM Form Factor: $\pi^0 \to e^+e^-\gamma$



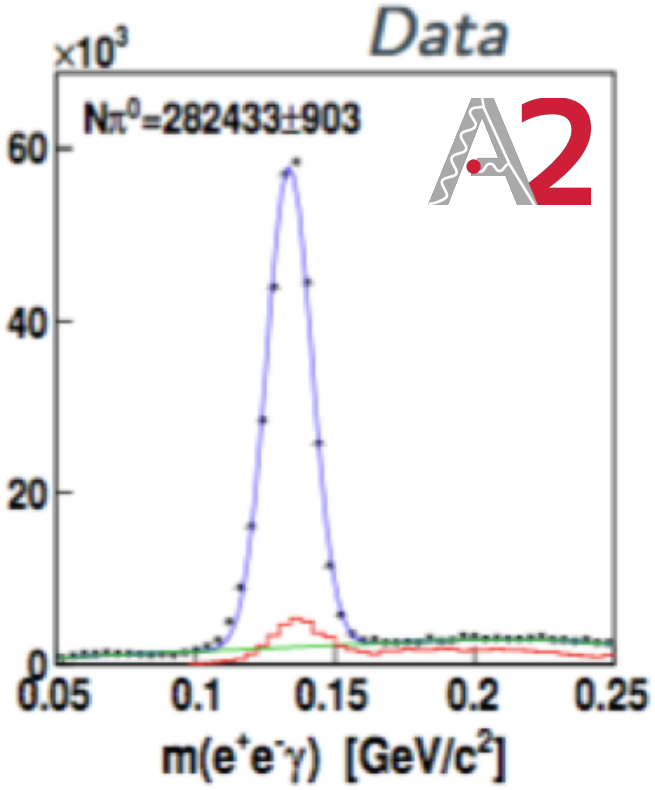
Timelike EM Form Factor: $\eta \to e^+e^-\gamma$

$$\frac{d\Gamma(\pi^0 \to e^+e^-\gamma)}{dm_{ee}\Gamma(\pi^0 \to \gamma\gamma)} = [\mathrm{QED}] \cdot |F_\pi(m_{ee})|^2$$

pointlike pi0

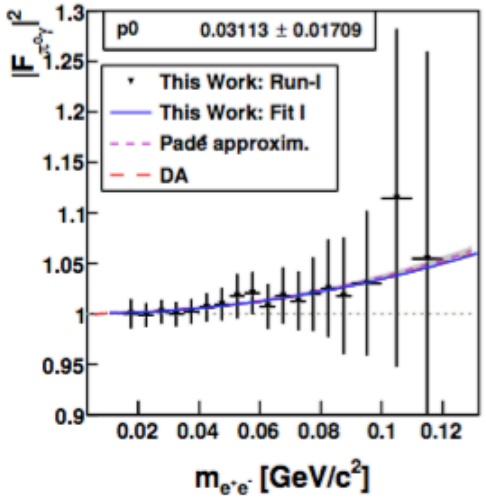


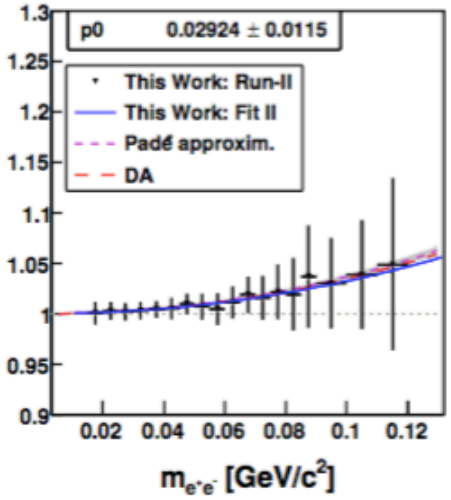
- 2 Runs
  - 1.5 weeks in 2008, E_{beam} = 855 MeV
  - 3 weeks in 2013, E_{beam} = 1557 MeV
- Non-magnetic calorimeter
  → PID detector
- Select 3 or 4 cluster events
  → 4 • 10^5 Dalitz events

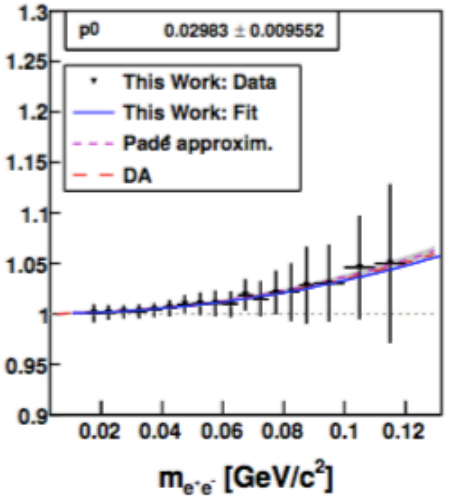


Timelike EM Form Factor: $\pi^0 \to e^+e^-\gamma$

PRC 95 (2017) 025202







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

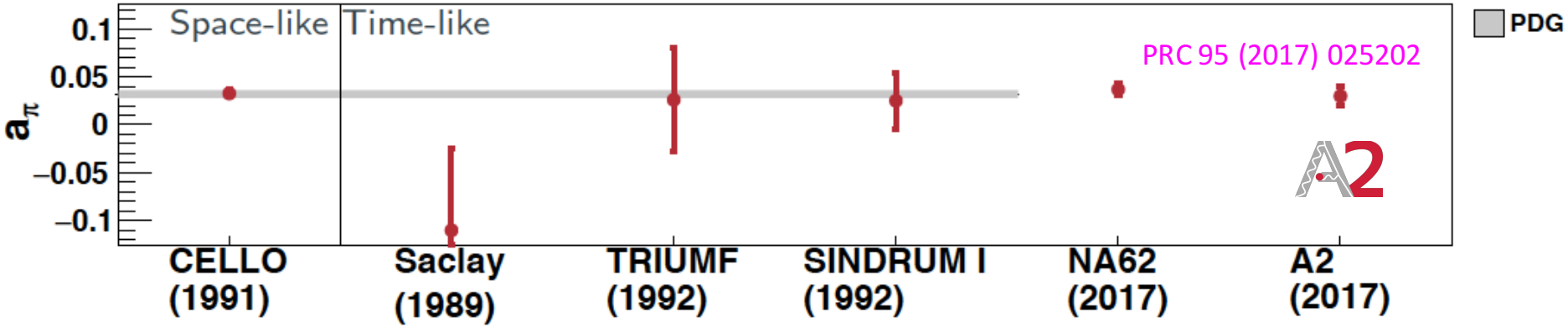
Total uncertainty dominated by fit uncertainties
→statistics

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

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

Experiment:

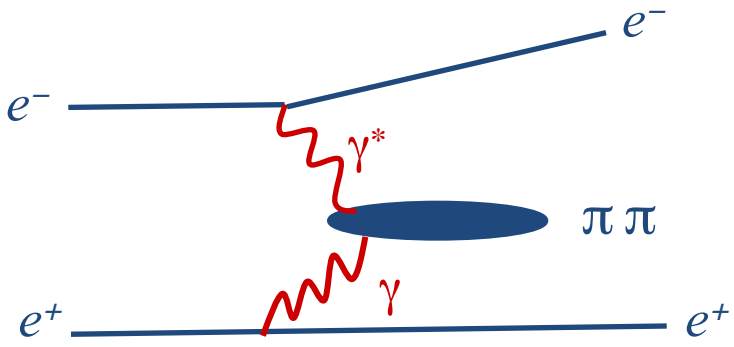
A2/MAMI result	$a_\pi = 0.03 \pm 0.01_{tot}$
NA62 result	$a_\pi = 0.0368(57_{tot})$ PLB 768 (2017) 38
PDG average	$a_\pi = 0.032(4)$



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

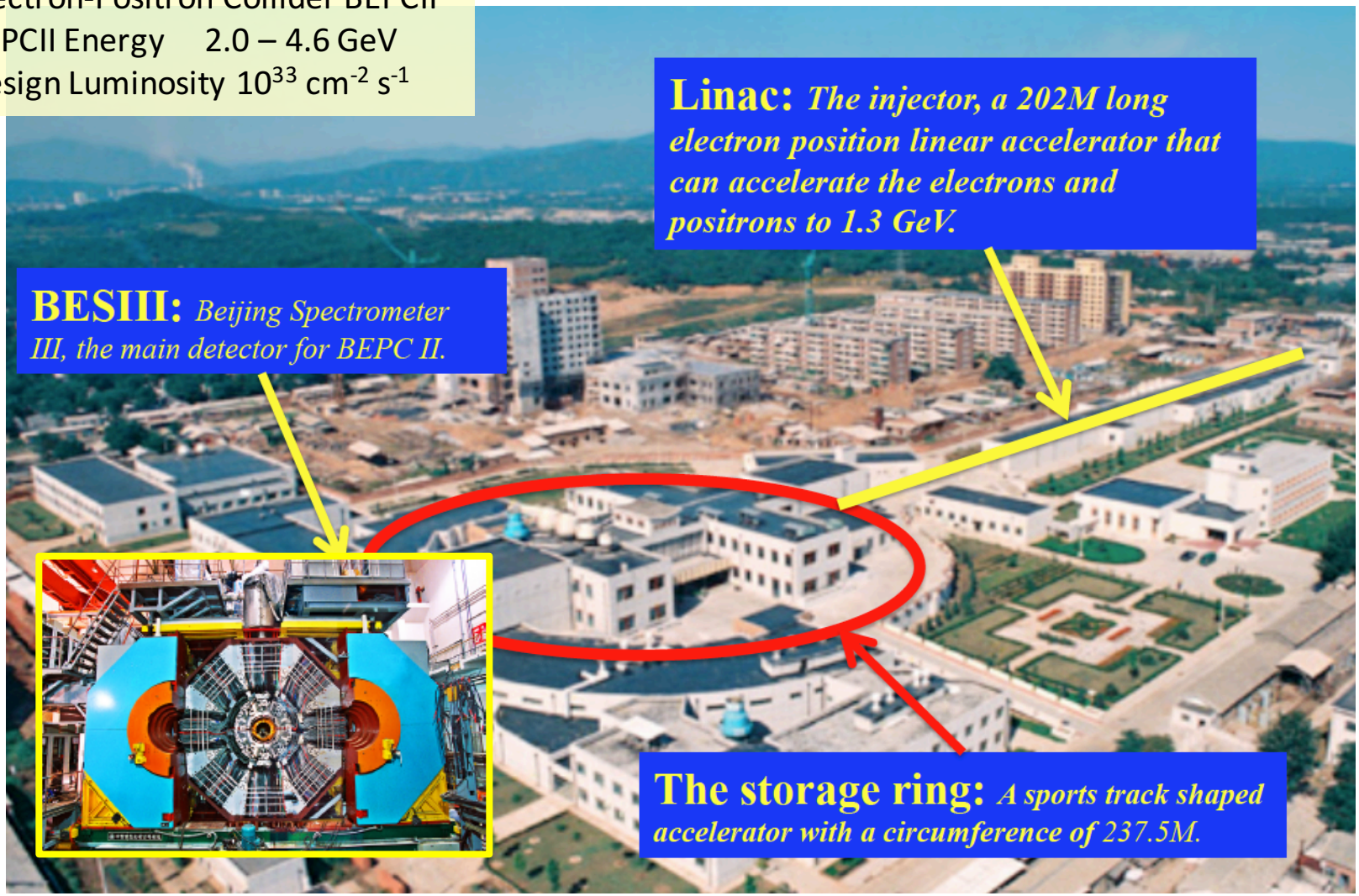
New experiment scheduled at A2/MAMI for spring 2018 (6 weeks)
Target accuracy: PDG error from 2.2 Million Dalitz decays



gamma – gamma Interactions at BESIII

BESIII Experiment @ BEPCII

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



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

Single Tag Method

Selection criteria

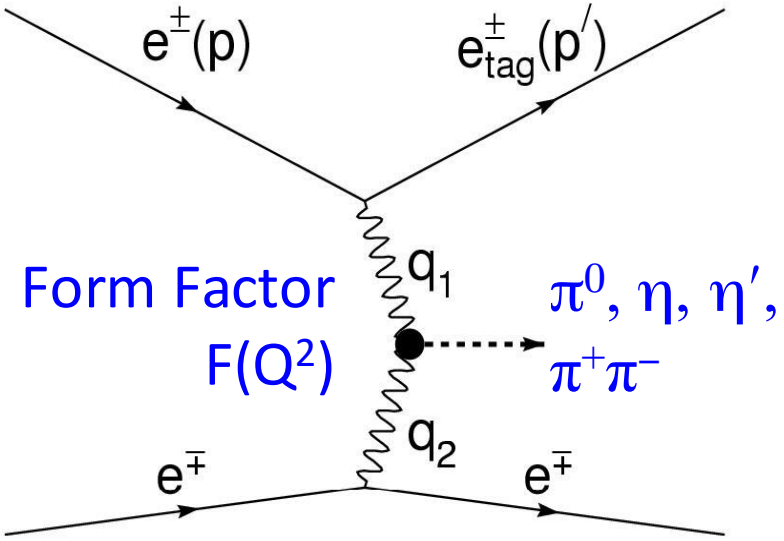
- 1 electron (positron) detected
- 1 positron (electron) along beam axis
- Meson fully reconstructed

→ **cut on angle of missing momentum**

Momentum transfer

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

EKHARA event generator
Czyż, Ivashyn, Trascz

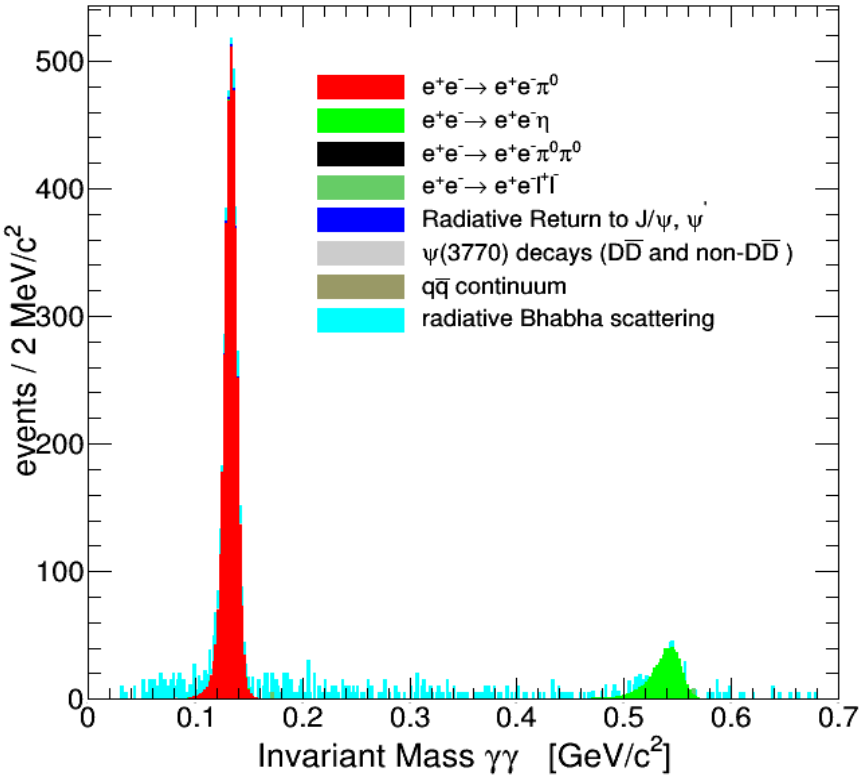


Event Selection:

- exactly one lepton candidate
- fully reconstruct hadronic sysem
- 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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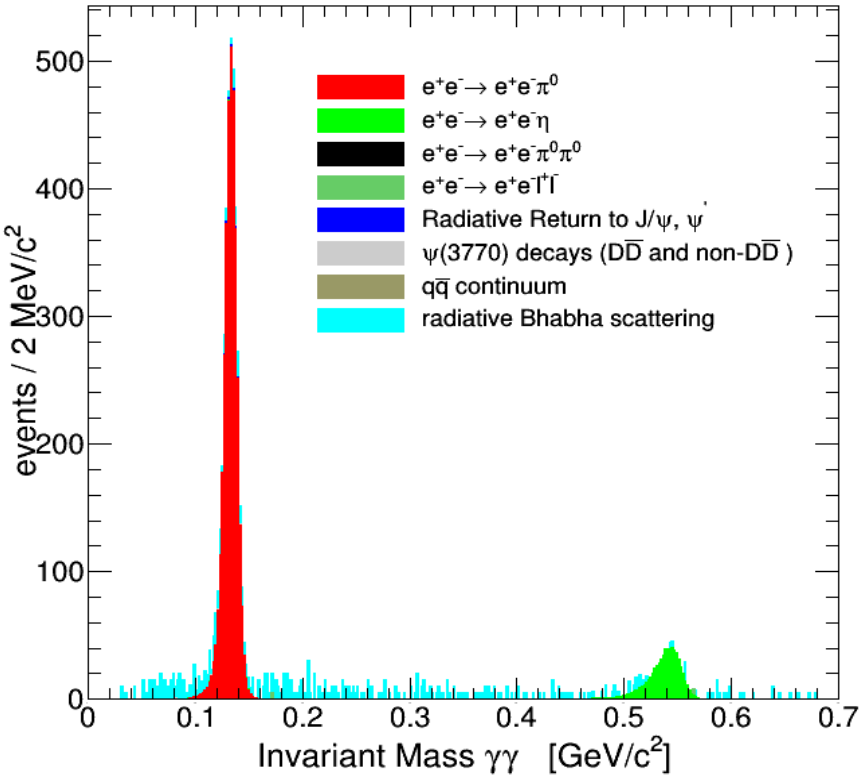

Strategy:

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

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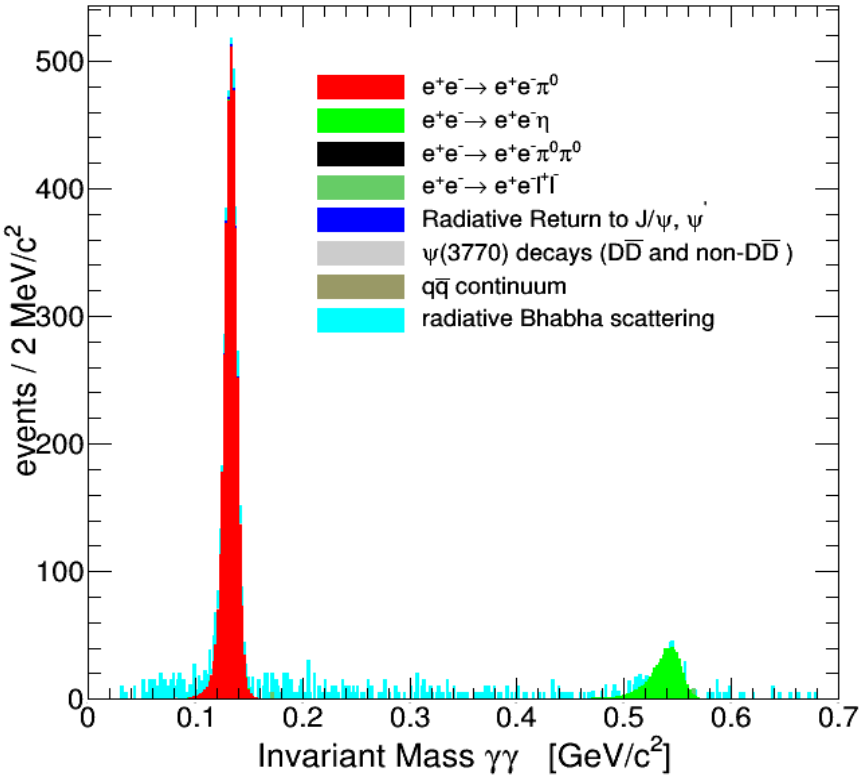

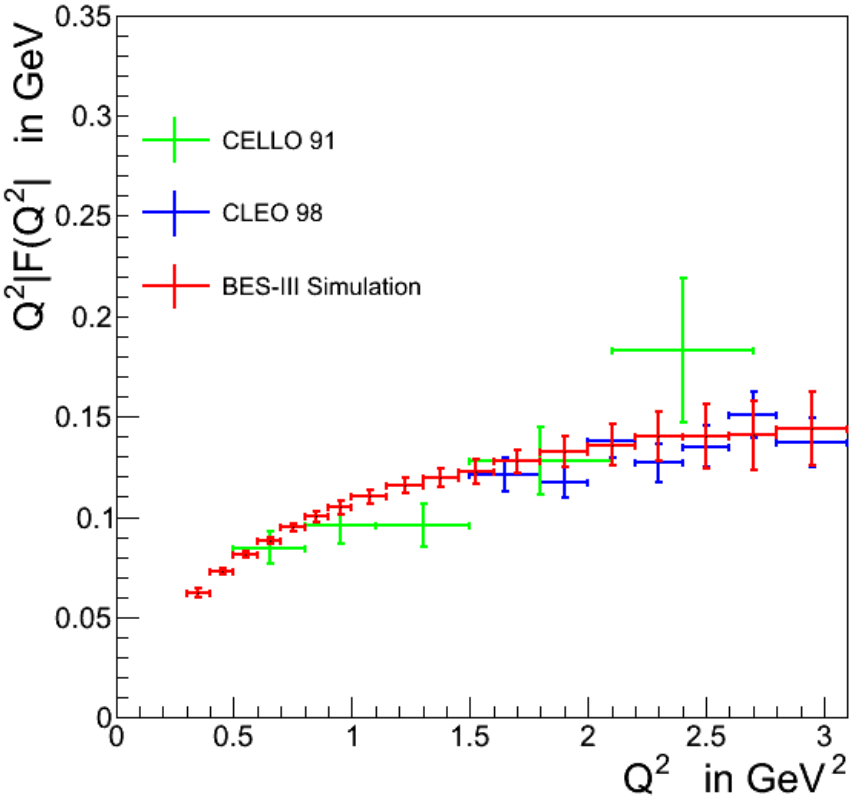

Strategy:

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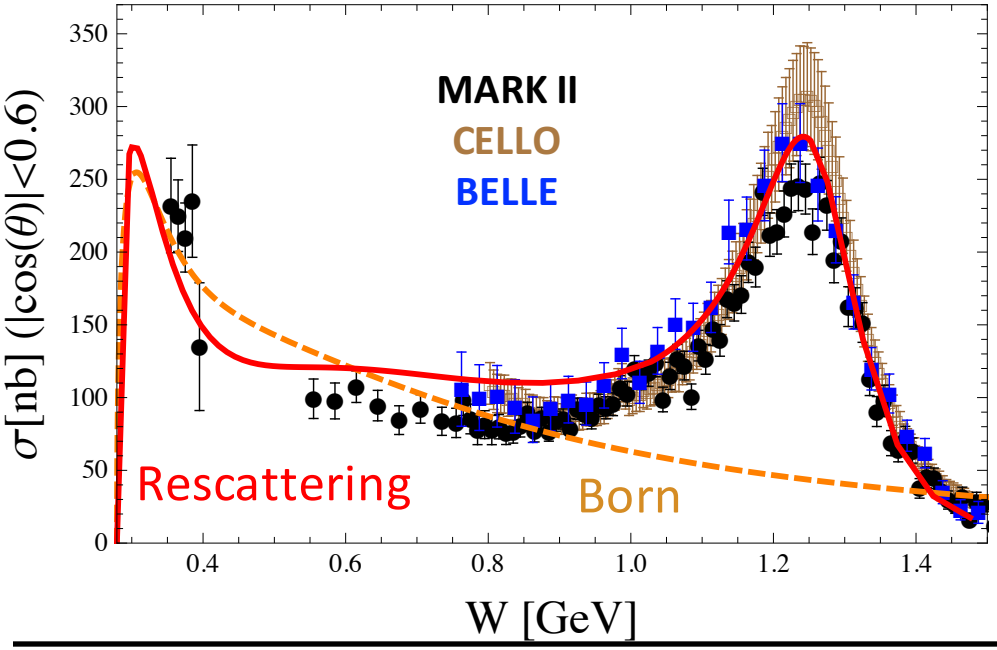
BES III Analysis: $\gamma\,\gamma^* \rightarrow \pi^+\pi^-$

Motivations:

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

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

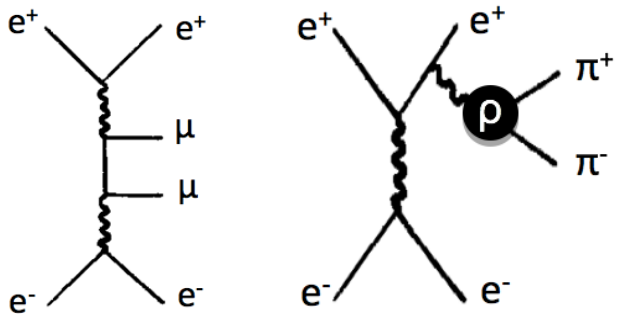
Belle, Phys. Rev D75 (2007) 051101

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

- Multivariate methods to suppress muon background

- Subtract ρ contribution

  Fit peak in data using shape from theory



- First single-tag measurement of $\gamma\gamma^* \to \pi^+\pi^-$!

  - low momentum transfers $0.2 < Q^2\,[\mathrm{GeV}^2] < 2.0$

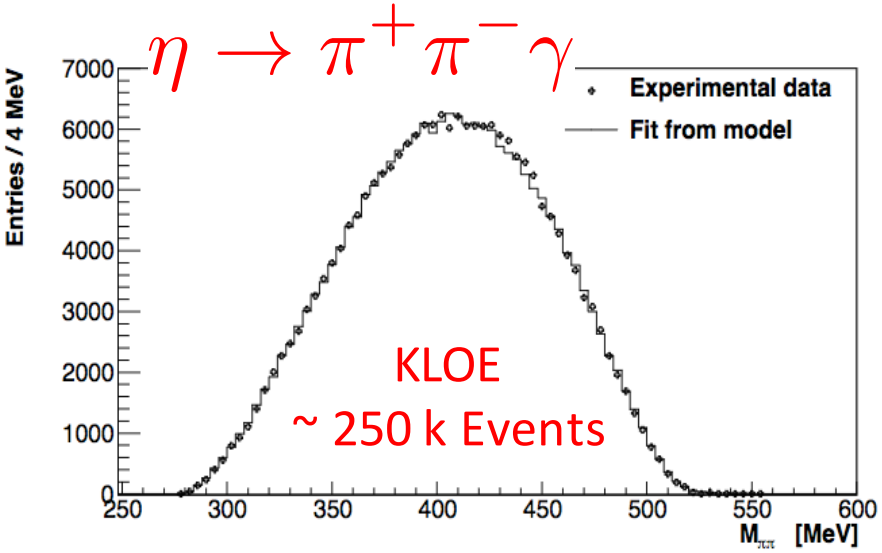
  - low invariant masses $m_{\pi+\pi-} < M\,[\mathrm{GeV}] < 2.0$

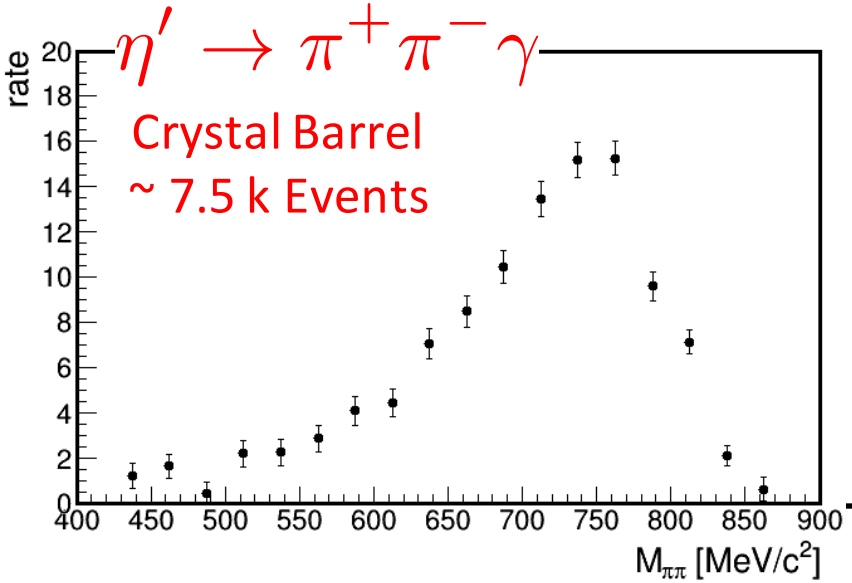
  - full coverage of cosθ*

  - Polarizability contribution beyond Born term

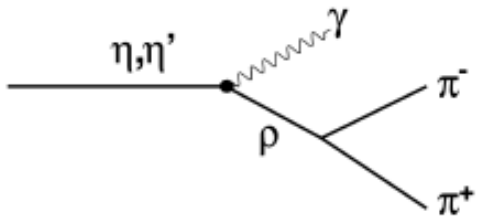
Decay Dynamics in $\eta' \to \pi^+\pi^-\gamma$ Decays

Description of the $\eta^{(\prime)} \to \pi^+\pi^-\gamma$ Decay

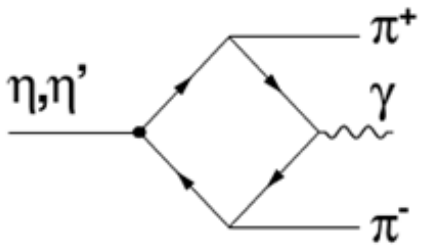




Vector Meson Dominance Model



Wess-Zumino box anomaly contribution



Model – independent approach based on ChPT and dispersion relations

Stollenwerk et al. , PLB (2012)

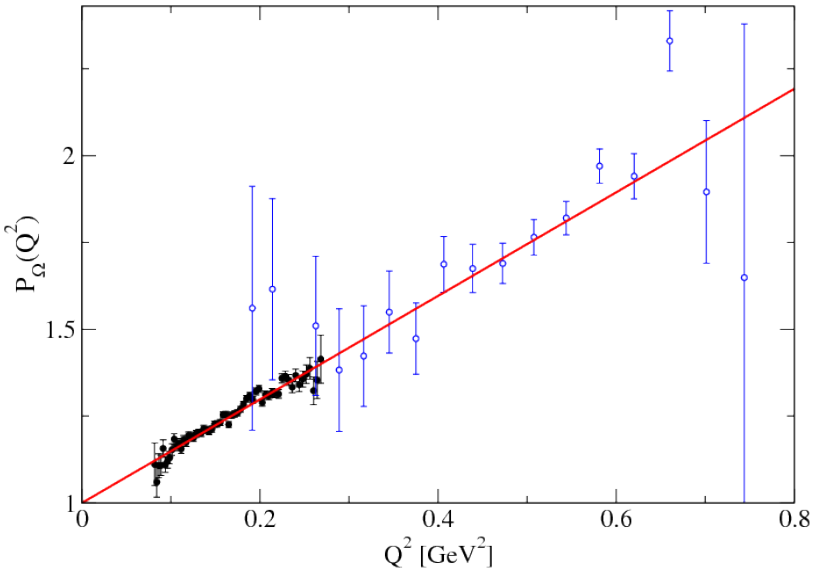
$$\frac{d\Gamma}{ds} = |A(1 + \alpha s + \ldots)F_V(s)|^2 K_P(s)$$

pion vector form factor

Relation to η Transition FF

Hanhart et al. , PRD (2013)

Fit to $\eta \to \pi^+\pi^-\gamma$ works well with linear term only, also good agreement with old Crystal Barrel data on $\eta' \to \pi^+\pi^-\gamma$



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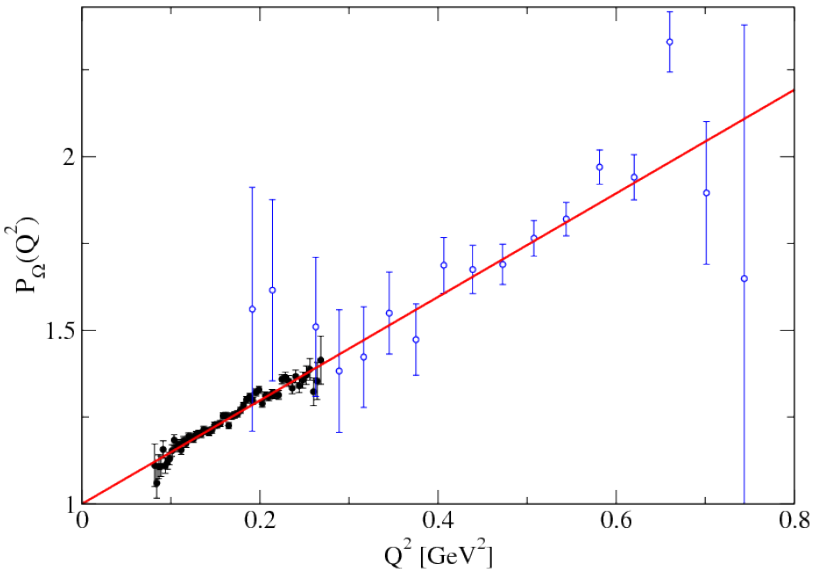
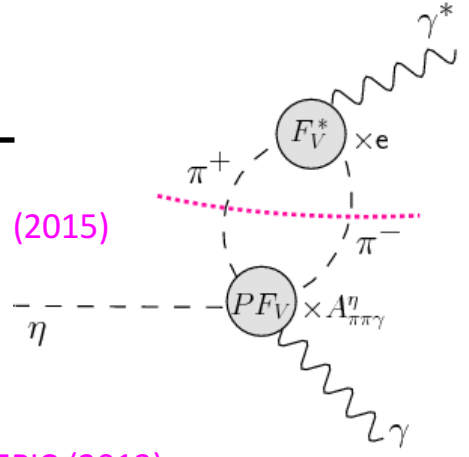
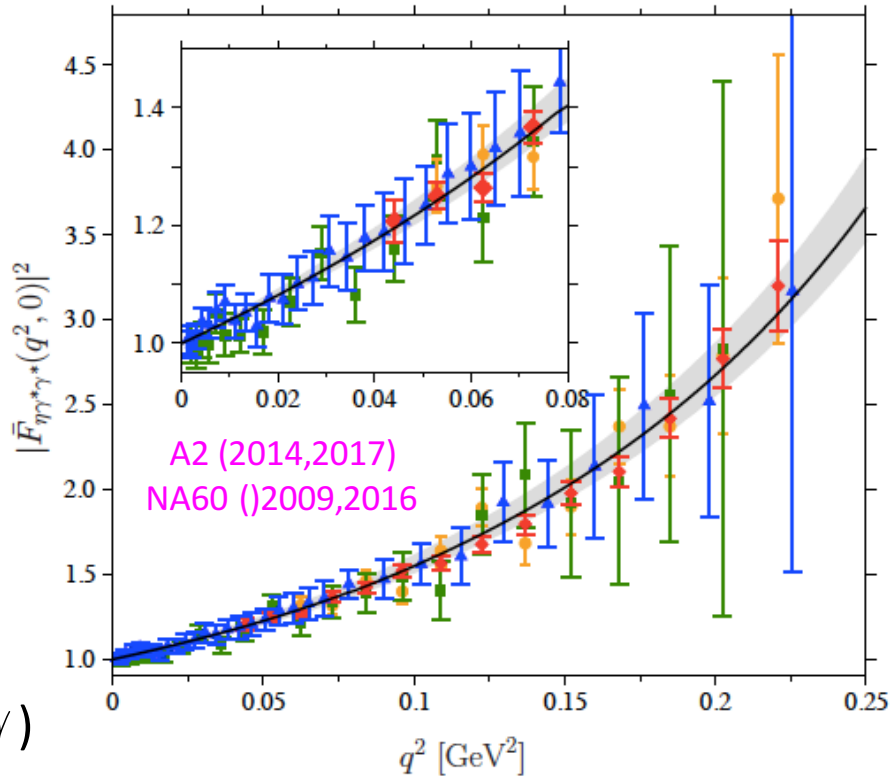


Kubis, Plentner, EPJC (2015)



Hanhart et al. , EPJC (2013)

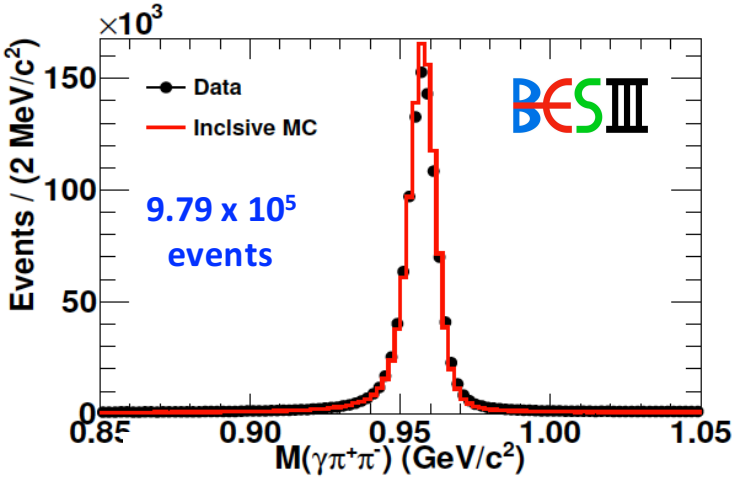


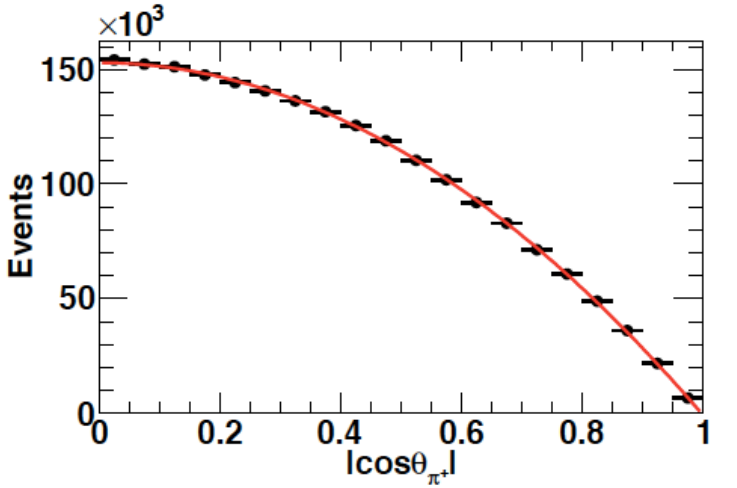
Allows to extract the eta TFF

Input: $F_V(s)$, slope parameter,

BR($\eta \to \pi^+\pi^-\gamma$), BR($\eta \to \gamma\gamma$)

BES III Analysis of $\eta' \to \pi^+\pi^-\gamma$



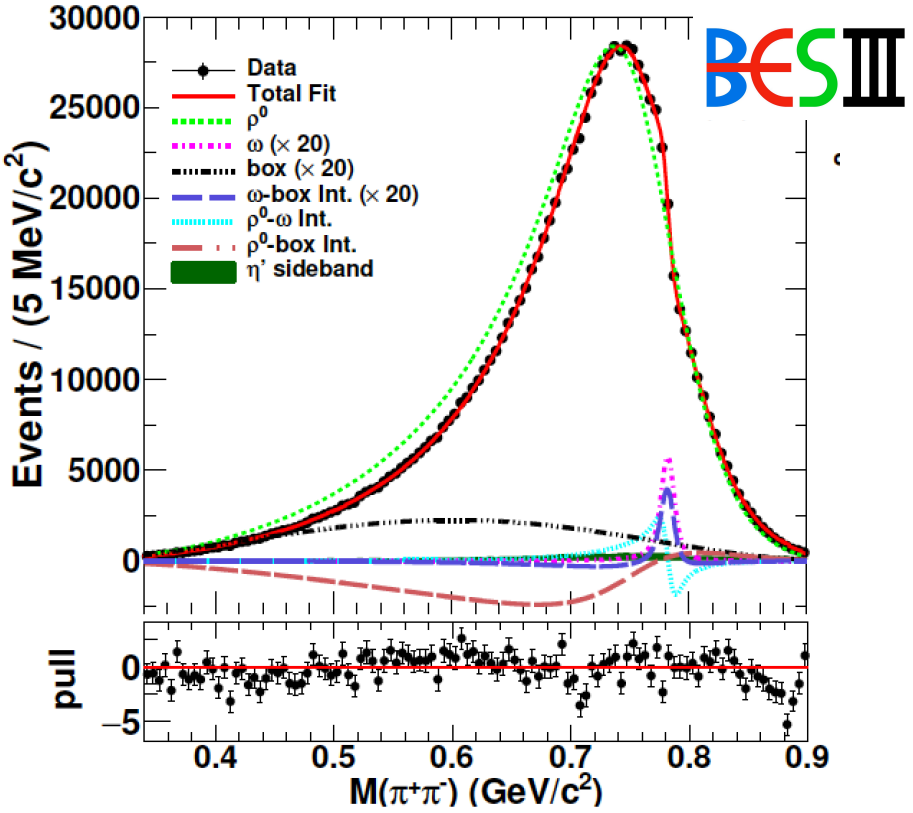


eta' sample from radiative J/ψ decays:

- world's largest sampe 1.6 Billion
- 5×10^{-3} branching ration in eta'

Search for Box Anomaly in $\eta' \to \pi^+\pi^-\gamma$

arxiv:1712.01525



Fit to M(ππ) requires definitely:

- rho(770) and omega(782) contributions
- rho + omega interference

Fit to M(ππ) including in addition:

- box anomaly contribution → χ2/ndf = 207/107
- rho(1450) contribution → χ2/ndf = 303/106
- rho(1450) + box anomaly contribution → χ2/ndf = 134/105, but unstable fits

Model-independent Fit to $\eta' \to \pi^+\pi^-\gamma$

Include also the omega contribution to theoretical description

$$P(s) = 1 + \kappa \cdot s + \lambda \cdot s^2 + \xi \cdot BW_\omega$$

mixing term rho-omega

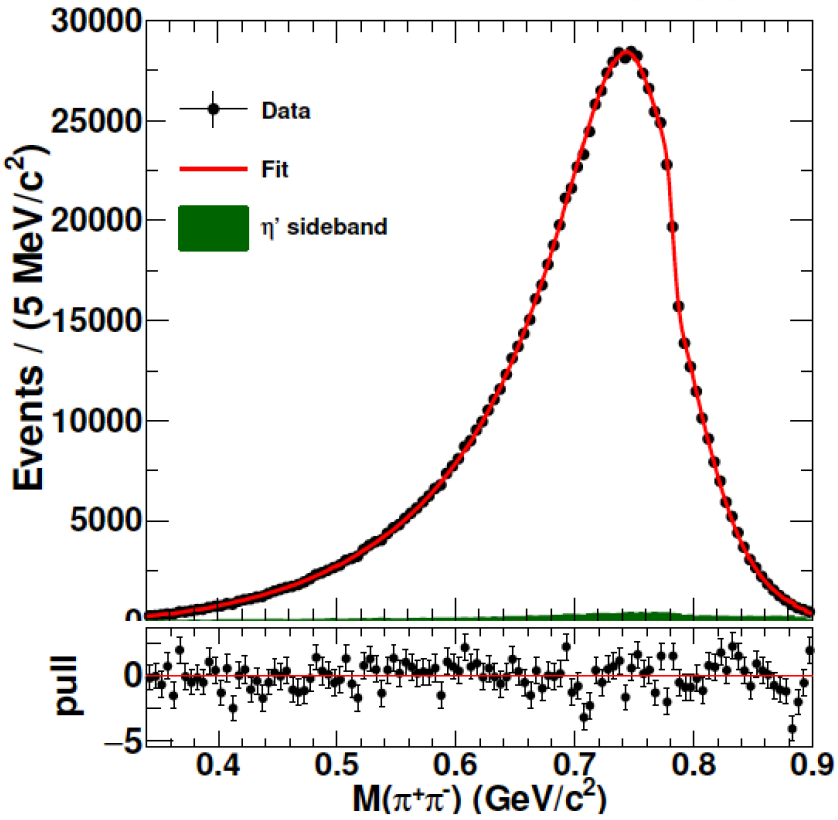
$$\kappa = 0.992 \pm 0.039_{\text{stat}} \pm 0.067_{\text{syst}} GeV^{-2}$$
$$\lambda = -0.523 \pm 0.039_{\text{stat}} \pm 0.066_{\text{syst}} GeV^{-2}$$
$$\xi = 0.199 \pm 0.006_{\text{stat}} \pm 0.011_{\text{syst}} \quad 4$$

Omega contribution is definitely needed, it seems a quadratic term as well

Precision data from BES III allows to cross check different data sets for vector form factor $F_V(s)$

Hanhart et al. , EPJC (2017)

arxiv:1712.01525



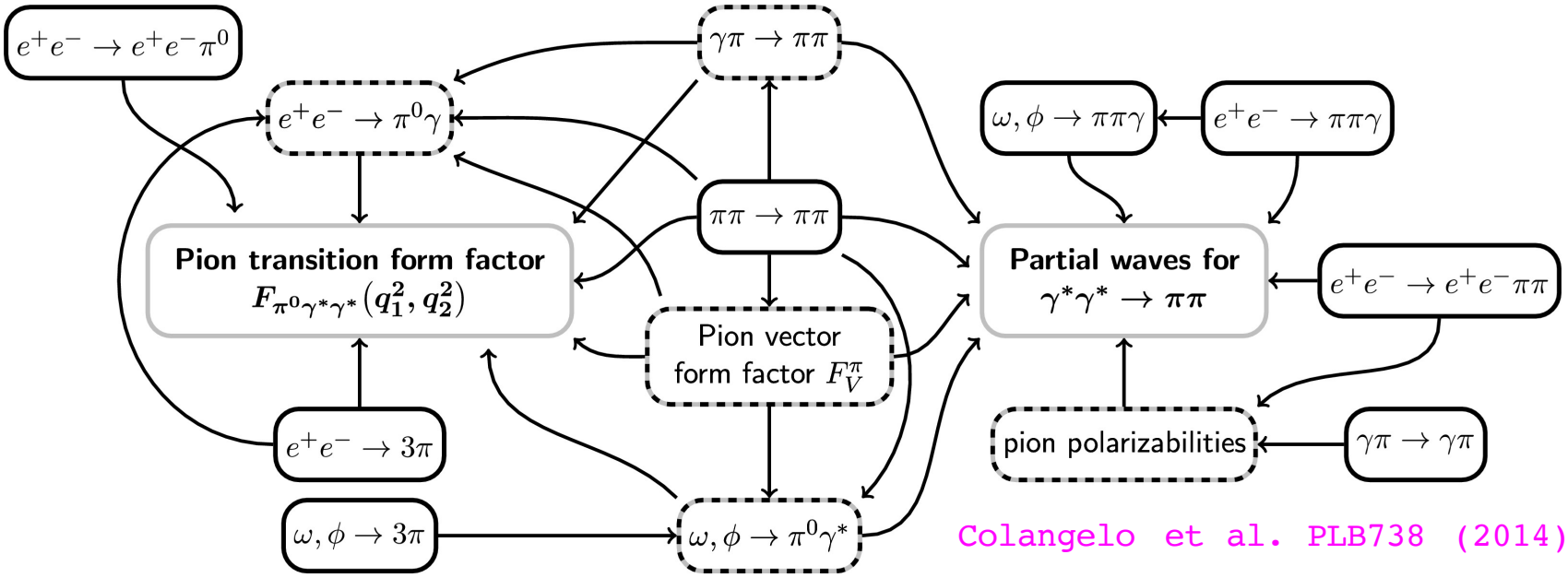
Good fit obtained with this ansatz:
$\chi 2/ndf = 145/109$

Radiative Decays of Light Mesons

Allowing for deep insights into dynamics of pseudoscalar mesons and treatment of spin; Challenge hadronic models/theories

Input to precision observables of the Standard Model of particle physics
$(g\text{-}2)_\mu$

High quality data



Colangelo et al. PLB738 (2014) 6