IJCLab Irène Joliot-Curie
Orsay, France
8th to 12th September 2025

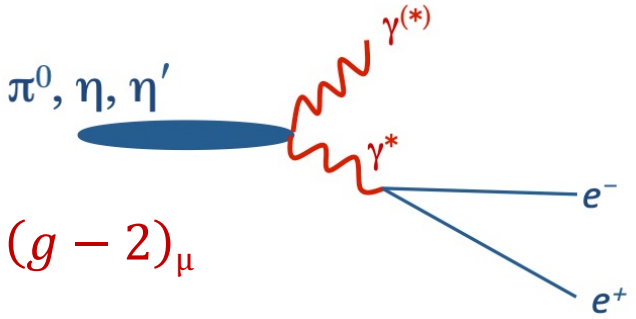
A high-precision measurement of the Transition Form Factor of the π^0 at A2/MAMI

Lena Heijkenskjöld
Sergey Prakhov
Achim Denig
JGU Mainz

Importance of Transition Form Factors

Electromagnetic (EM) Transition Form Factors (TFFs) of light mesons *M*

$$M \leftrightarrow \gamma^{(*)}\gamma^{*}$$



→ understanding their intrinsic structure

→ input to the hadronic light-by-light contribution to $(g-2)_\mu$

JHEP 09, 074 (2015) JHEP 10, 141 (2018)

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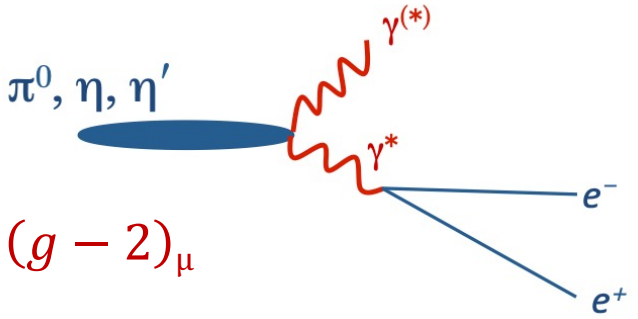

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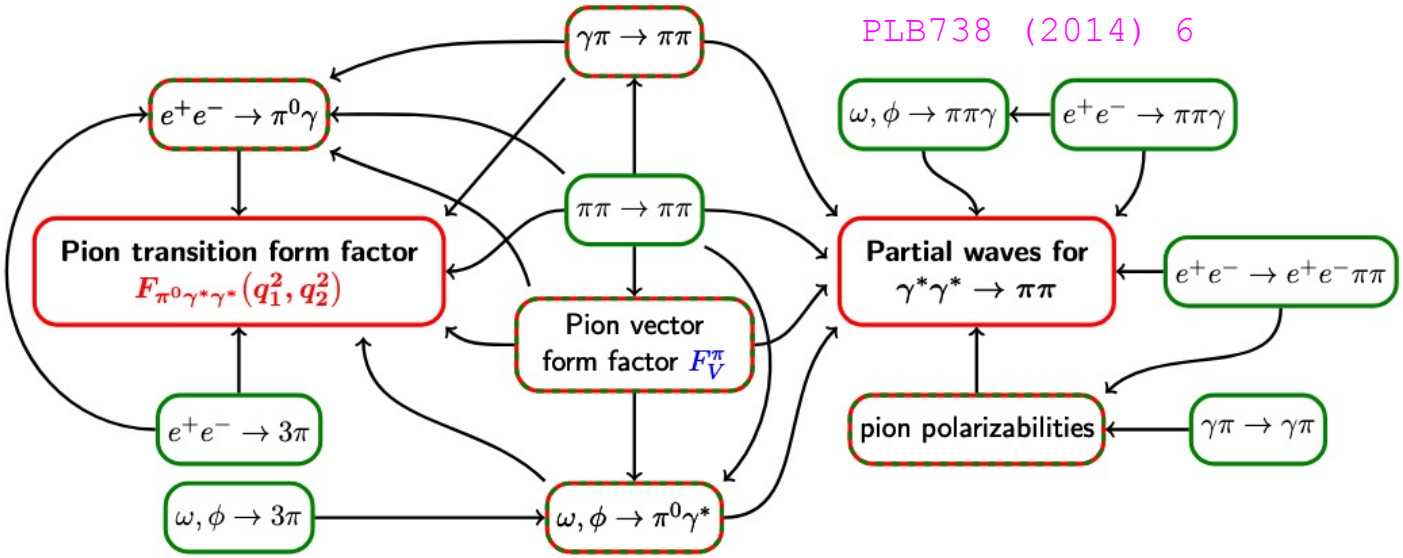
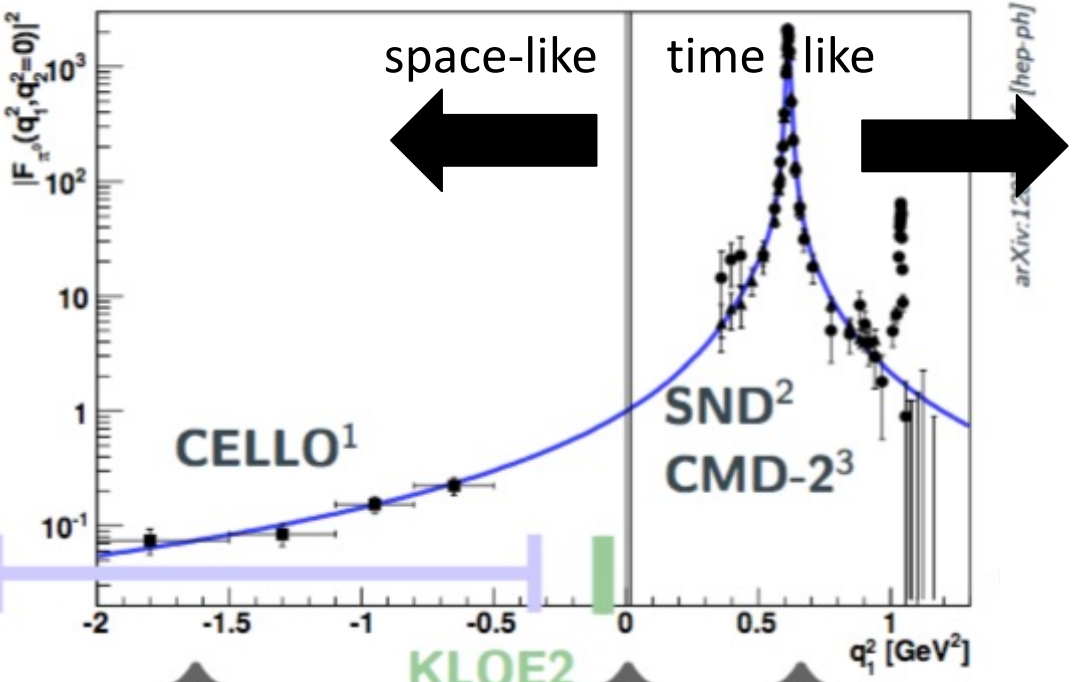
PLB738 (2014) 6



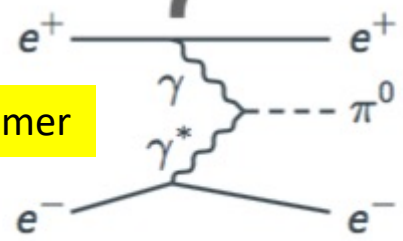
Important to check internal cosistency

Access to Transition Form Factors (TFFs)

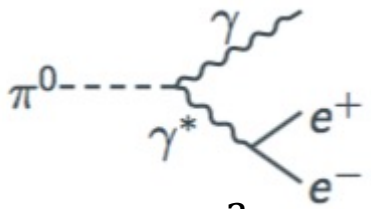
Pion TFF



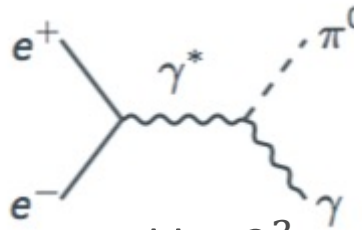
talk Ch. Redmer



space-like $Q^2 < \sqrt{s}$



time-like $Q^2 < M_P$



time-like $Q^2 = \sqrt{s}$

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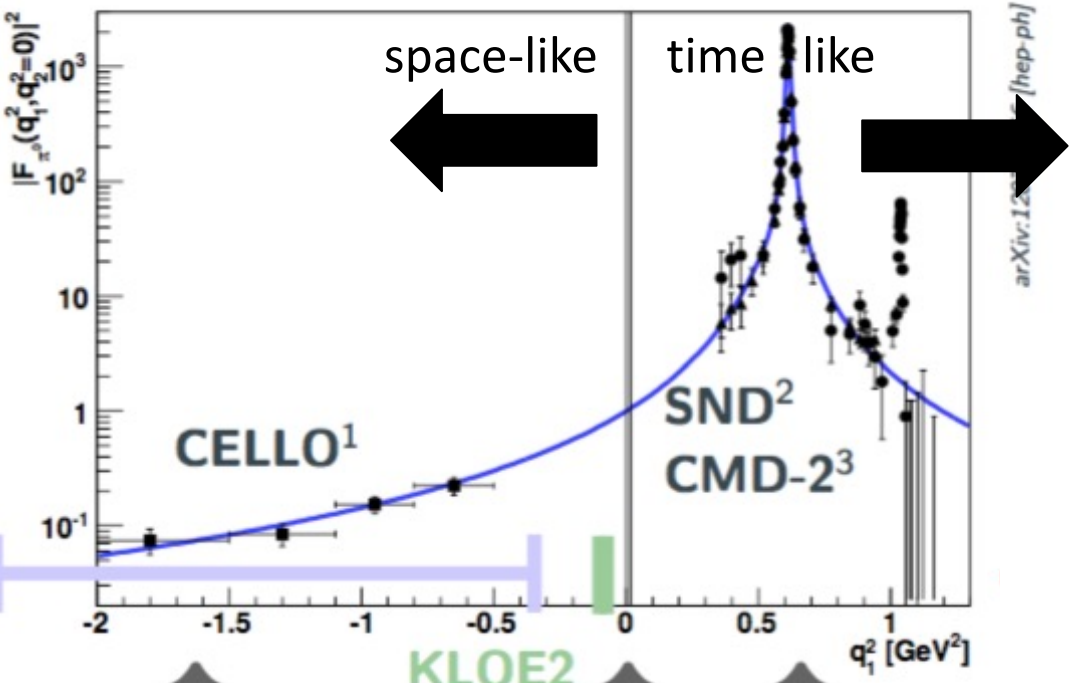

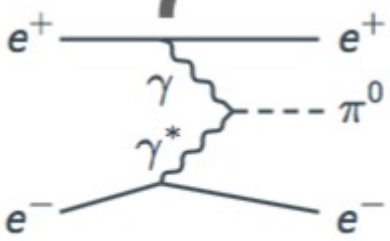

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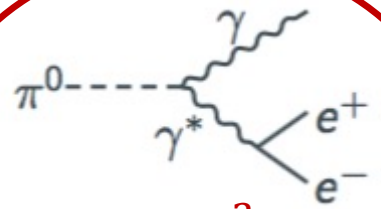

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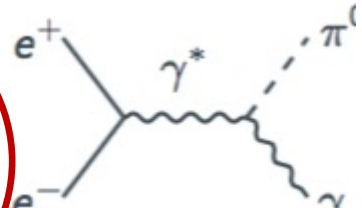


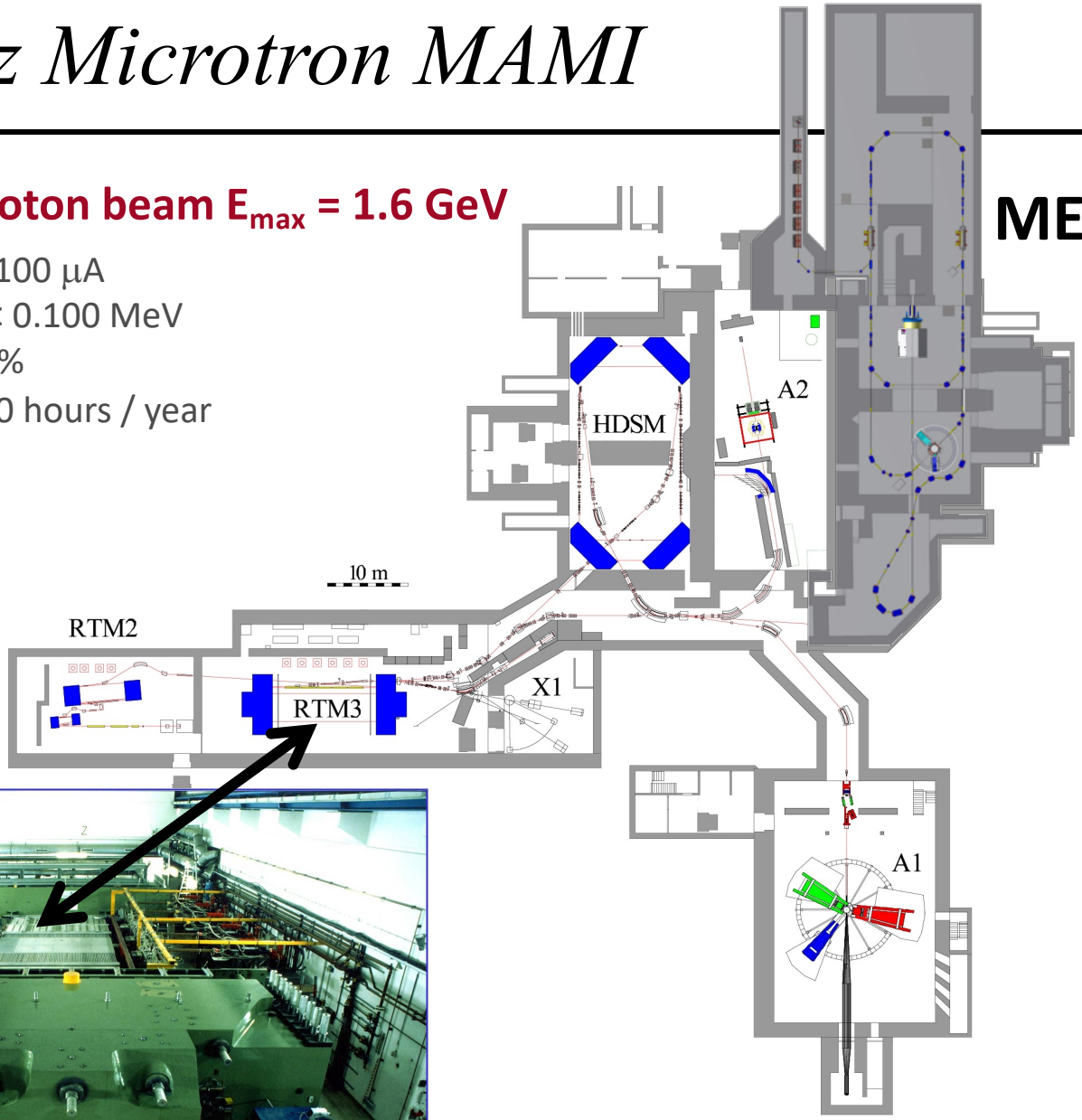
time-like $Q^2 = \sqrt{s}$

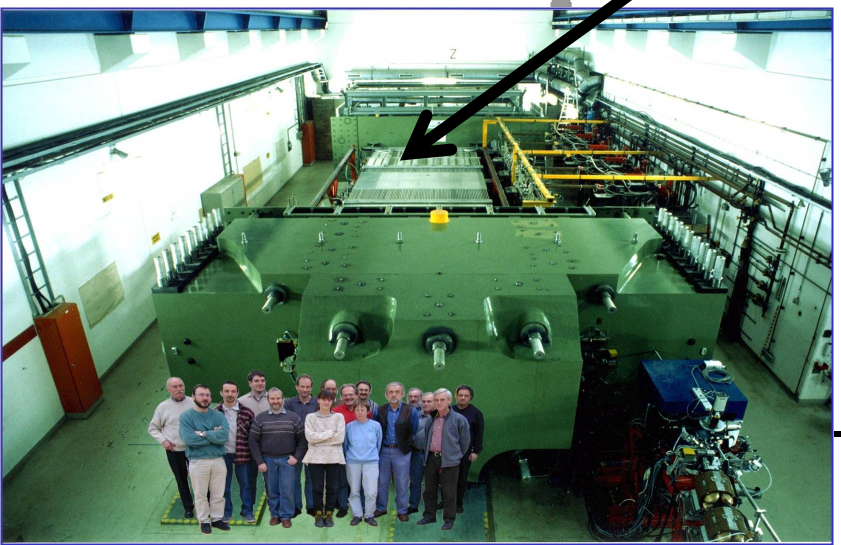
Mainz Microtron MAMI

Electron / Photon beam E_{max} = 1.6 GeV

- Intensity max. 100 μA
- Resolution σ_E < 0.100 MeV
- Polarization 85%
- Reliability: 7000 hours / year

MESA





Experiment A2: Photon Beam Line

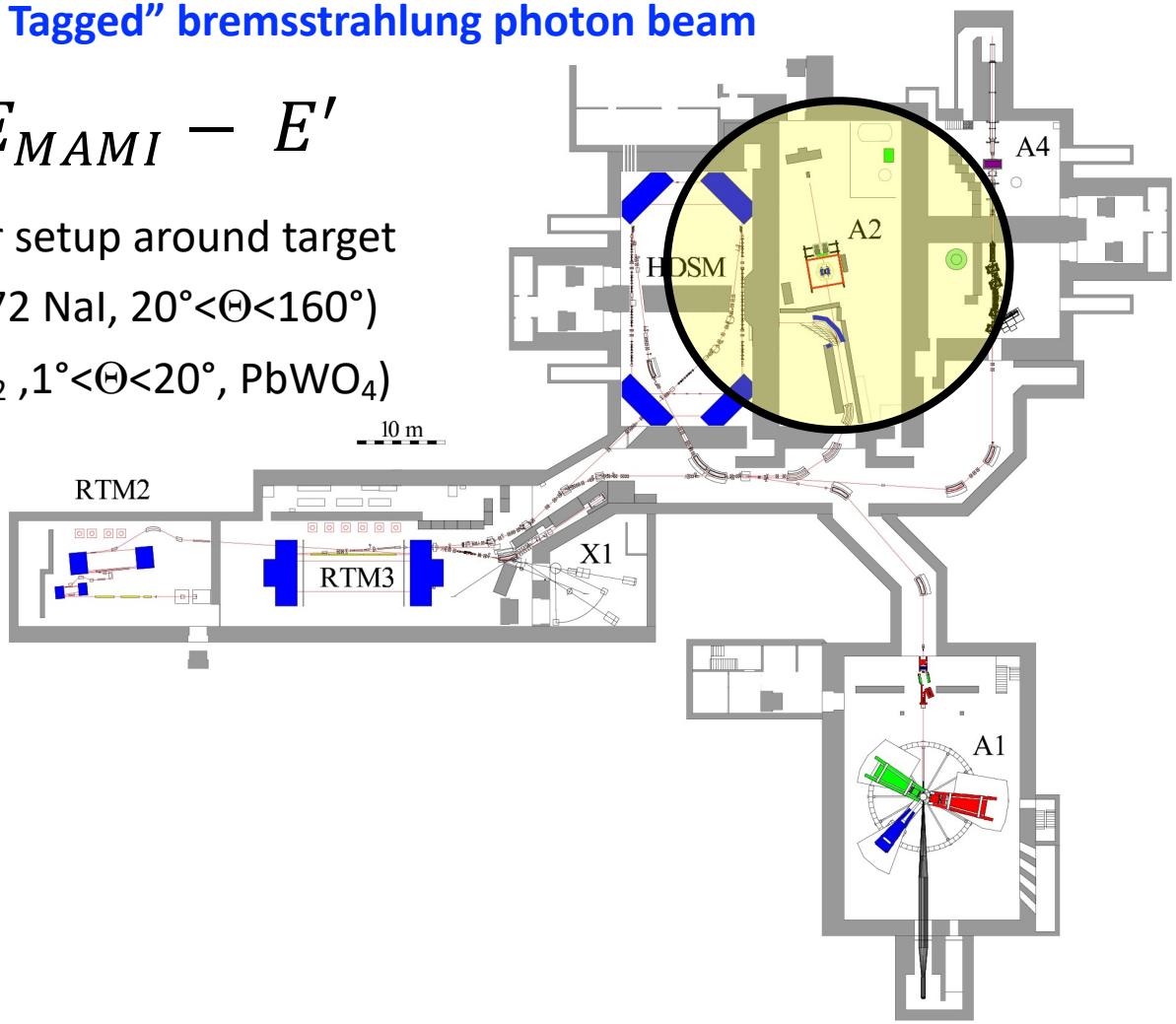
Experiment A2: Tagged" bremsstrahlung photon beam

$$E_\gamma = E_{MAMI} - E'$$

- 4π calorimeter setup around target

  Crystal Ball (672 NaI, 20°<Θ<160°)

  TAPS (384 BaF_2 ,1°<Θ<20°, $PbWO_4$)



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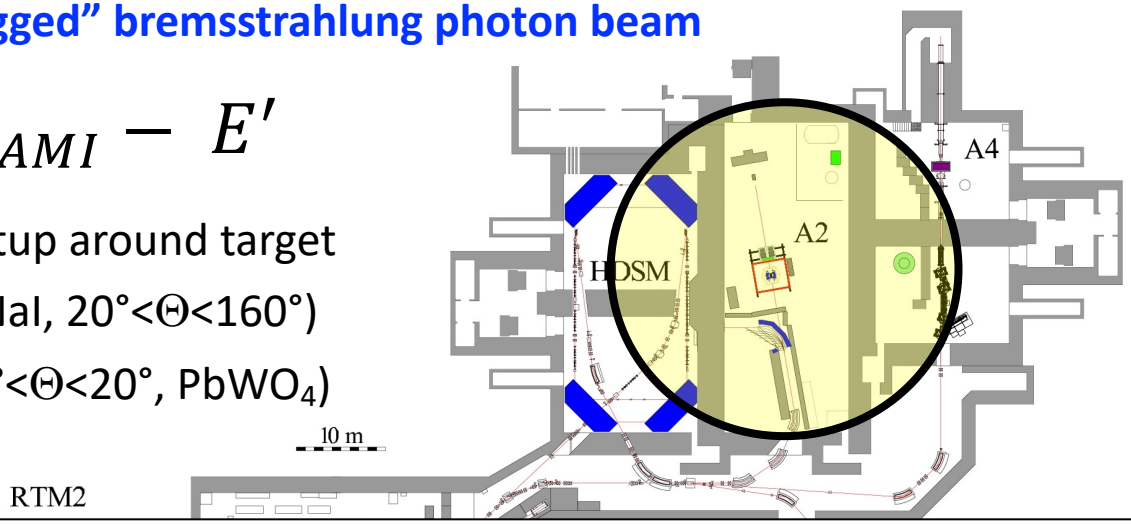

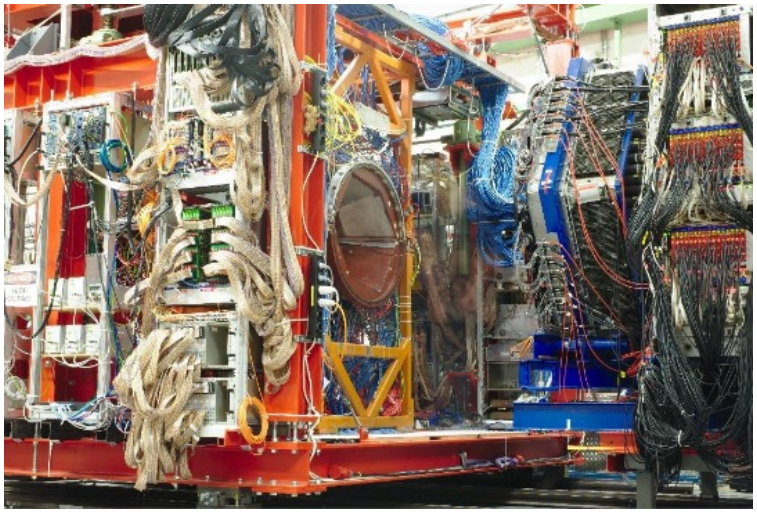

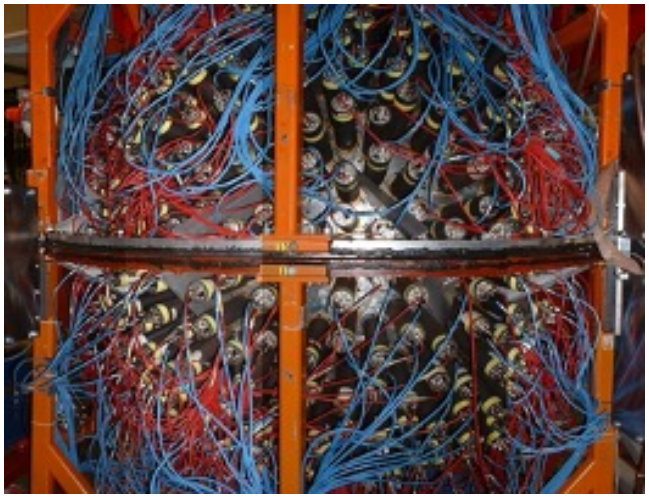

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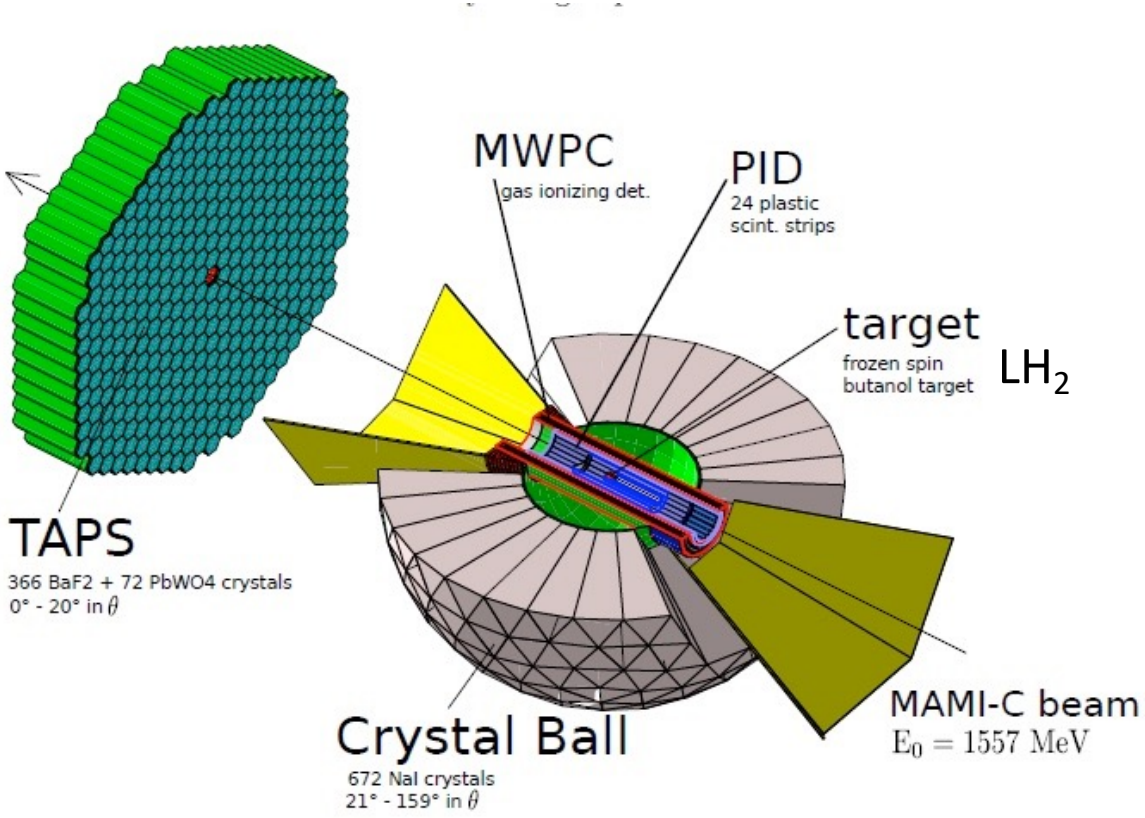

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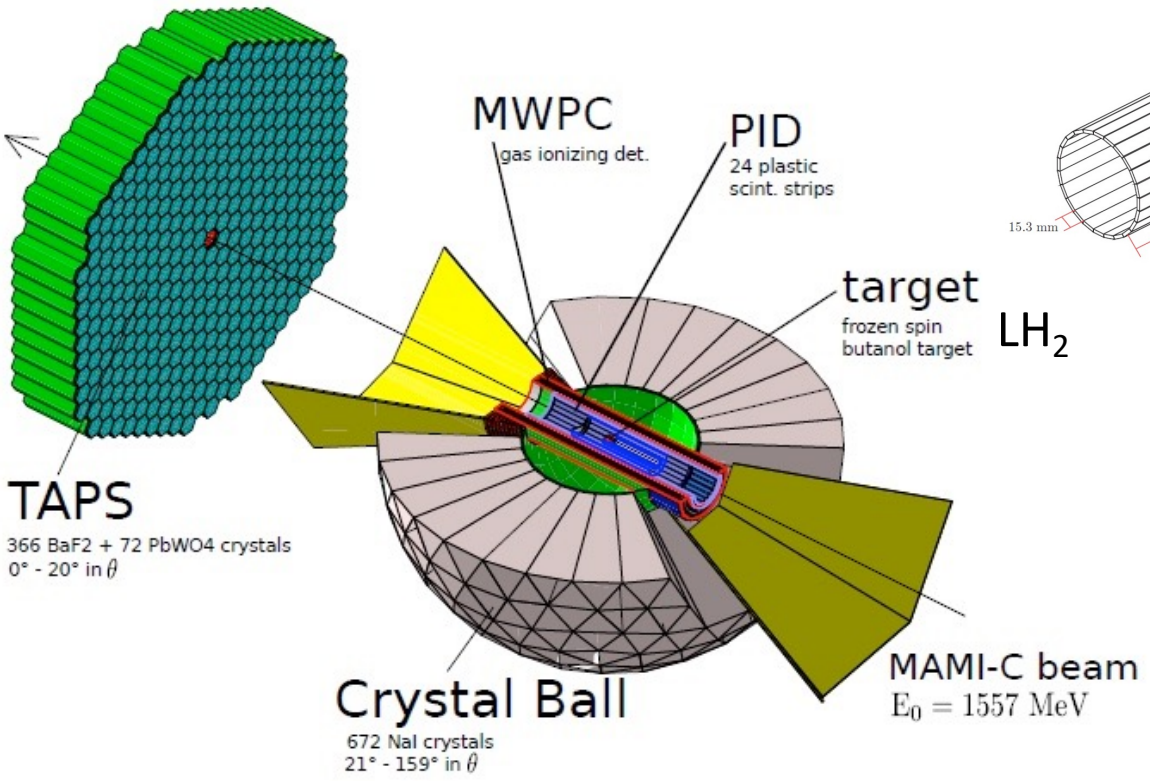
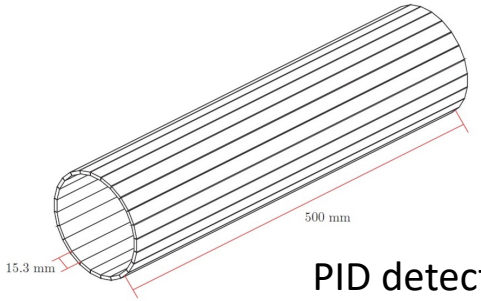


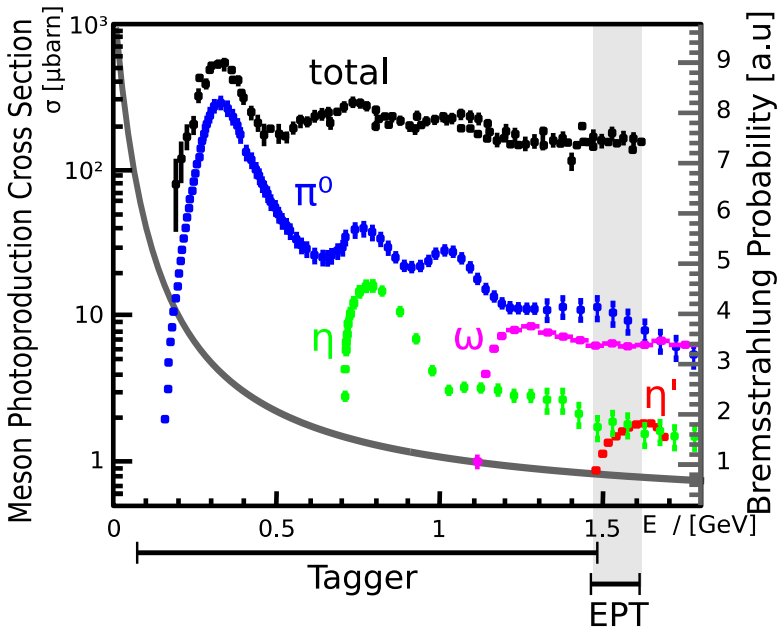


PID detector for separation of charged particles / photons

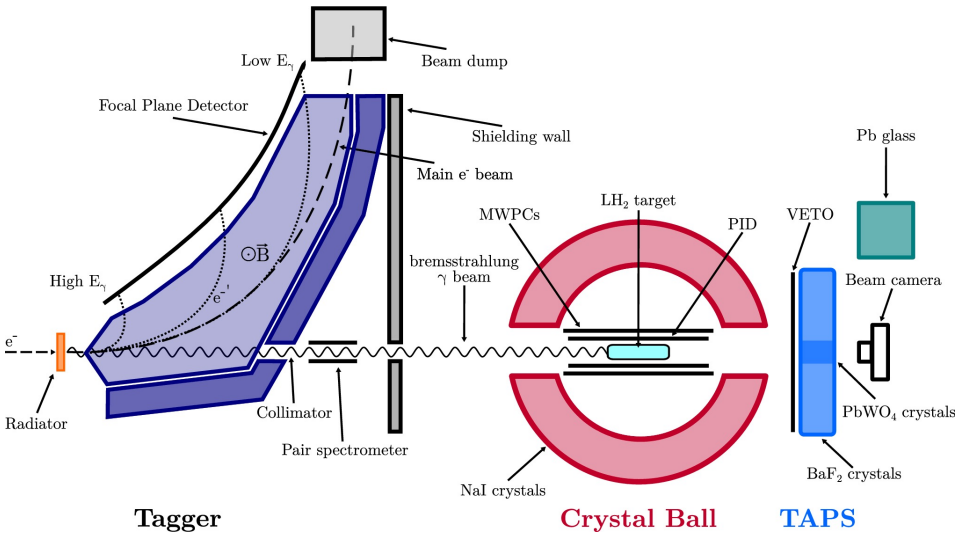
Non-magnetic detector →
Separation of charged and neutral particles on basis of
PID and tracking detector surrounding the LH_2 target

Experiment A2: Photon Beam Line

MAMI is a Meson factory: $\gamma p \rightarrow M\gamma$



A2 setup ideally suited for detection of meson decays



Depending on photon energy, extremely large cross sections for meson production on p target:

~ 10^7 ... 10^9 mesons/beam time (corresponding to ~3 weeks)

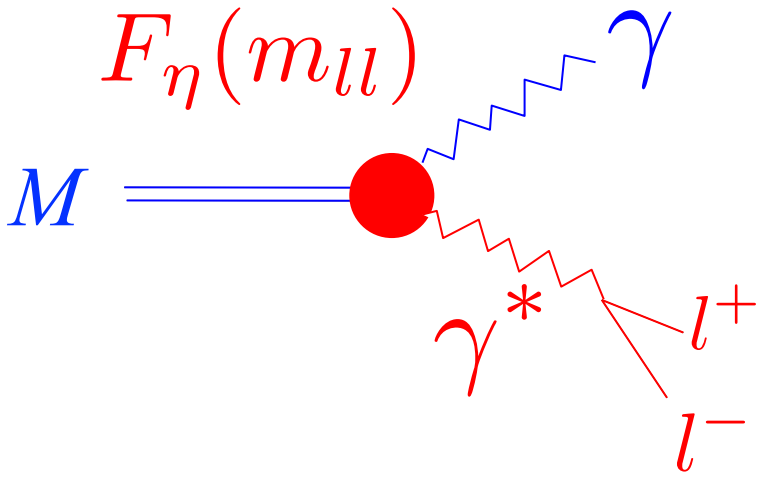
Target: LH_2

A Meson Factory for Measurements of TFFs

Meson Dalitz decays, normalized to γγ decays:

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

pointlike meson M



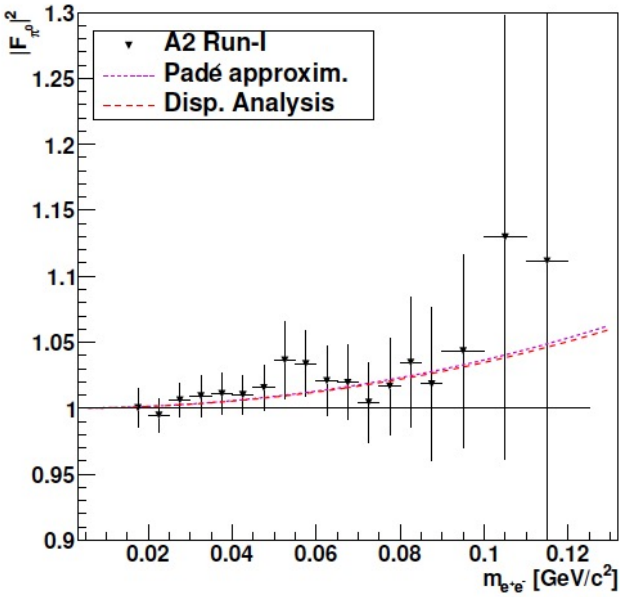
Parametrization of TFF in one-pole parametrization:

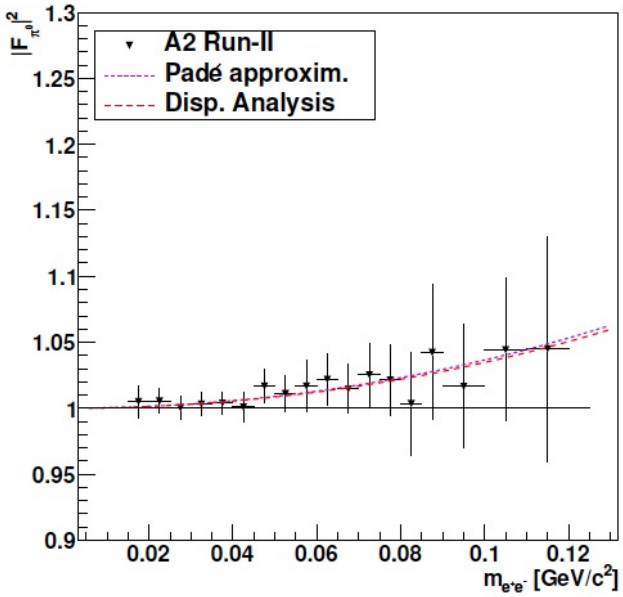
$$F(m_{ll}) = \frac{1}{1-\frac{m_{ll}^2}{\Lambda^2}}$$

Slope factor Λ

Theoretical predictions based on dispersion relations as well as Padé approximants

A2 Timelike Pion TFF: $\pi^0 \to e^+e^-\gamma$

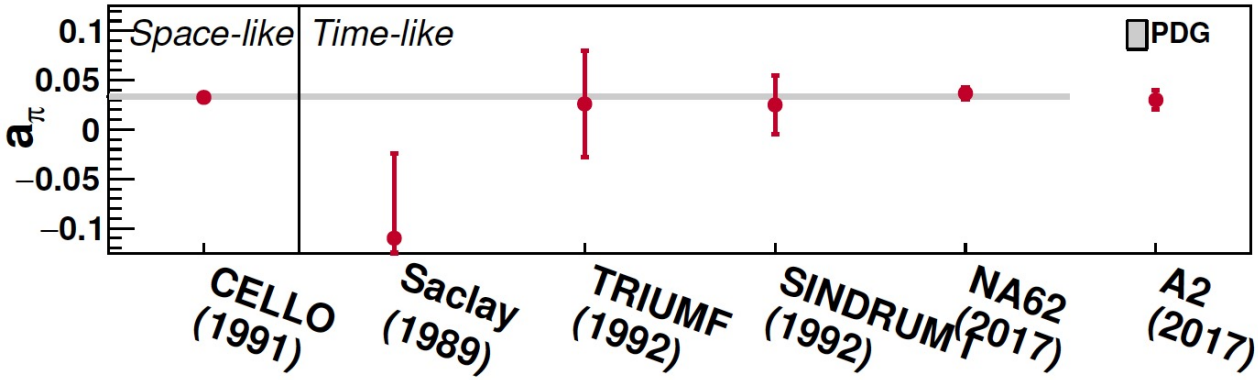




$$F_{\pi^0\gamma}(m_{ee}) = 1 + a_\pi \frac{m_{ee}^2}{m_{\pi^0}^2}$$

Feasibility study already lead to first publication

- $4 \cdot 10^5$ $\pi^0 \to e^+e^-\gamma$ events
- slope paramete
  $a_\pi = 0.030 \pm 0.010$
  with $a_\pi \sim m_\pi^2/({m_\rho}^2 + {m_\omega}^2)$
- competitive with world's most precise NA62 analysis
  $a_\pi = 0.0368 \pm 0.0051$



Phys. Rev. C95 (2017)02502

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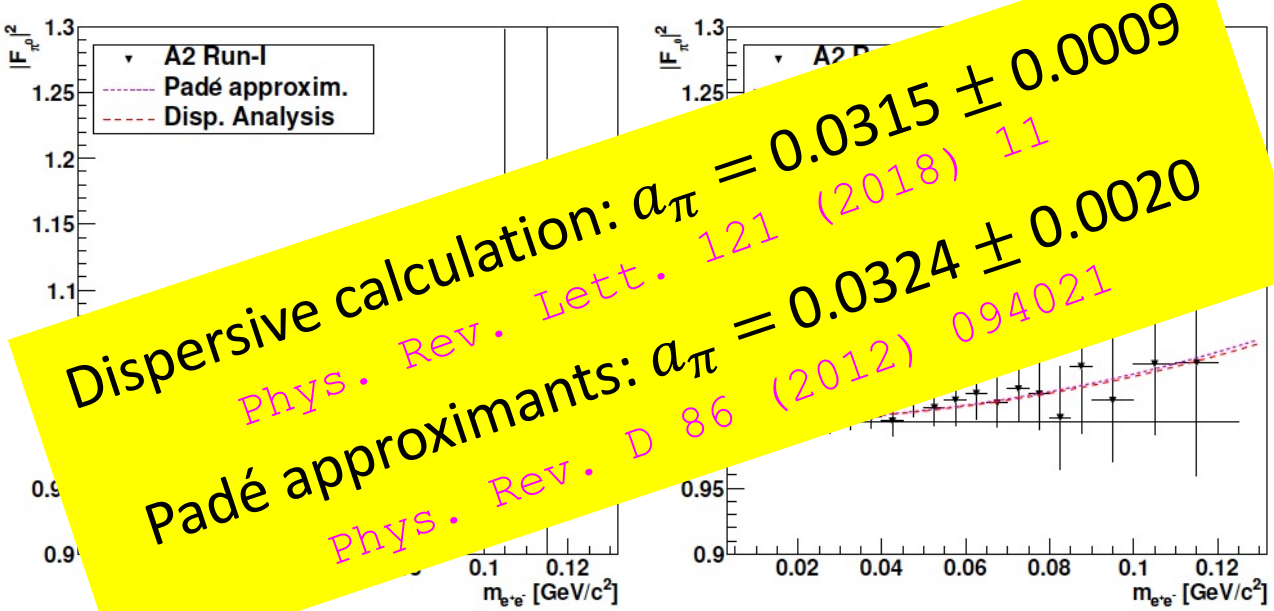

Dispersive calculation: $a_\pi = 0.0315 \pm 0.0009$
Phys. Rev. Lett. 121 (2018) 11

Padé approximants: $a_\pi = 0.0324 \pm 0.0020$
Phys. Rev. D 86 (2012) 094021

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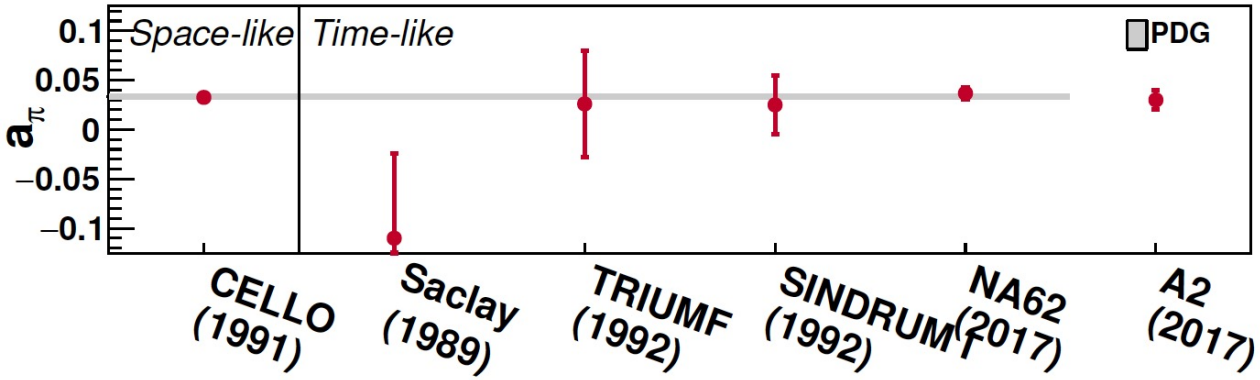
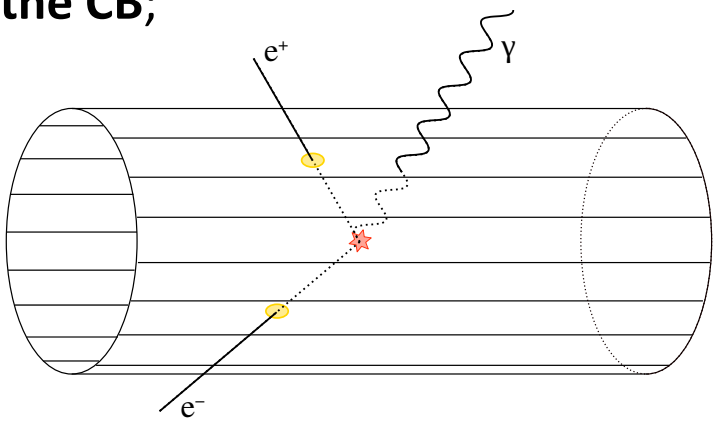


Phys. Rev. C95 (2017)02502

New A2 Measurement of $\pi^0 \to e^+e^-\gamma$

Analysts:
Lena Heijkenskjöld
Sergey Prakhov

- Dedicated data taking in 2018 allowed to **improve statistics by factor of ~6** with respect to previous result
- Searching for $\pi^0 \to e^+e^-\gamma$ in **3- and 4-cluster events**
- **Kinematic fitting just assuming $\gamma p \to 3\gamma p$** (electron mass irrelevant);
  Photon and e^+e^- clusters detected **only by the CB**;
  PID detector is used to identify e^+ and e^-



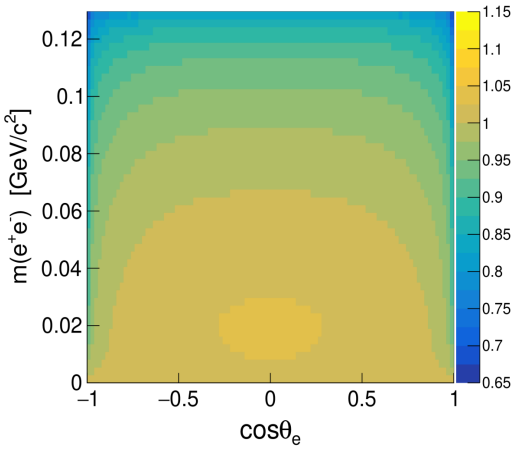
- **Background contributions**:
  random and empty-target runs subtracted directly;
  most important background: **$\pi^0 \to \gamma\gamma$ with γ converting in detector material into e^+e^-** (conversion)
  → suppressed by **detecting e^+ and e^- in different PID detector elements**;

Monte-Carlo for $\gamma p \to \pi^0 p \to e^+e^-\gamma p\,/\,\gamma\gamma p$

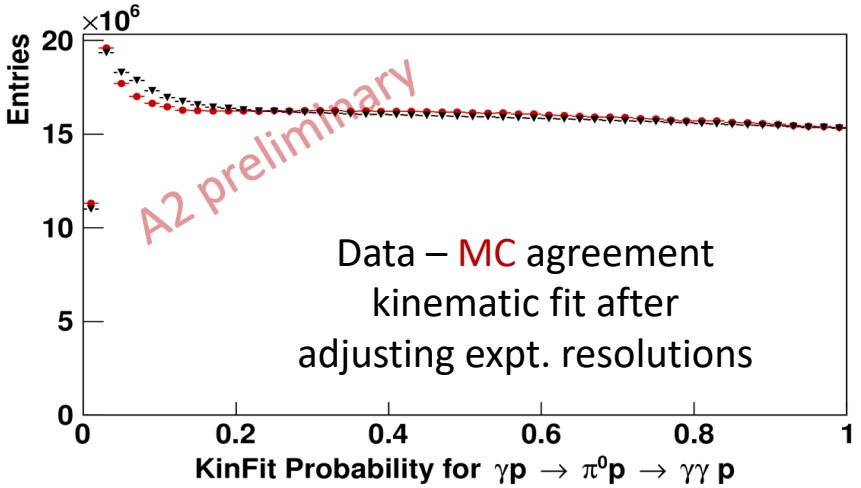
MC simulation constructed according to the actual $\gamma p \to \pi^0 p \to \gamma\gamma p$ spectra measured in the same experiment,

$d\Gamma(\pi^0 \to e^+e^-\gamma)/dm_{ee} = |QED_\pi| \cdot |F_\pi(m_{ee})|^2$ dependence and angular decay distribution $f(\theta_e) = 1 + \cos^2\theta_e + (2m_e/m_{ee})^2 \sin^2\theta_e$ folded with radiative corrections, where θ_e is the angle between one lepton in the dilepton rest frame and the dilepton direction in the π^0 rest frame

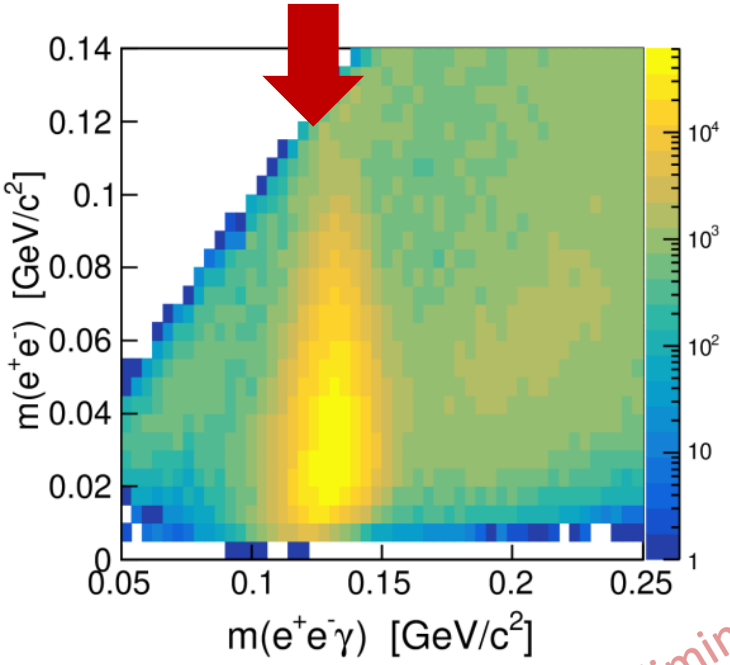
magnitude radiative corrections

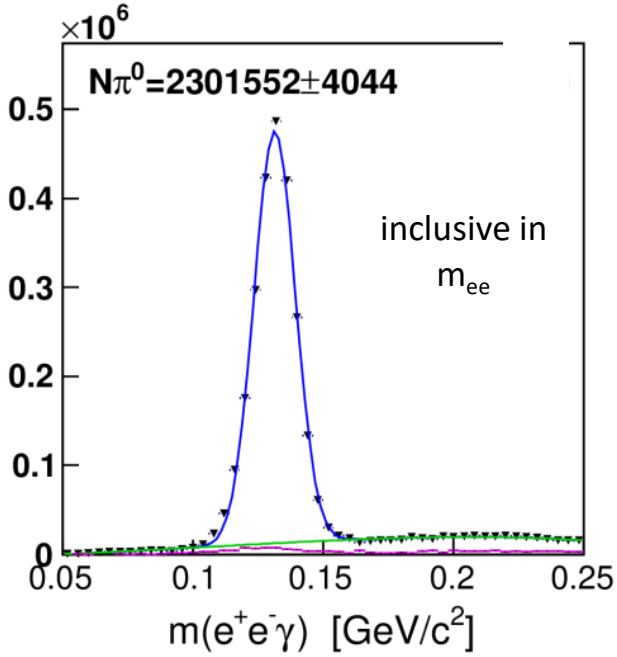


Phys.Rev.D92(2015)054027



Invariant Masses $\pi^0 \to e^+e^-\gamma$





A2 preliminary

Low background contribution

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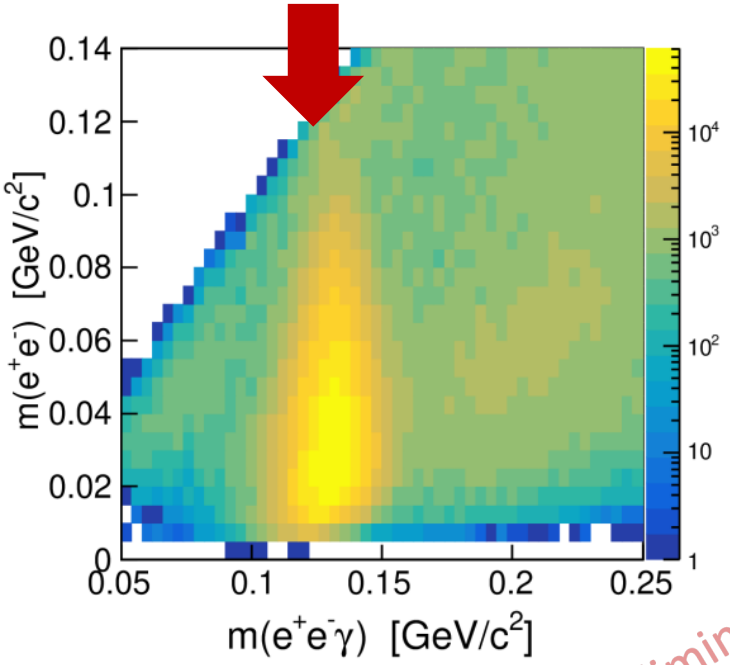
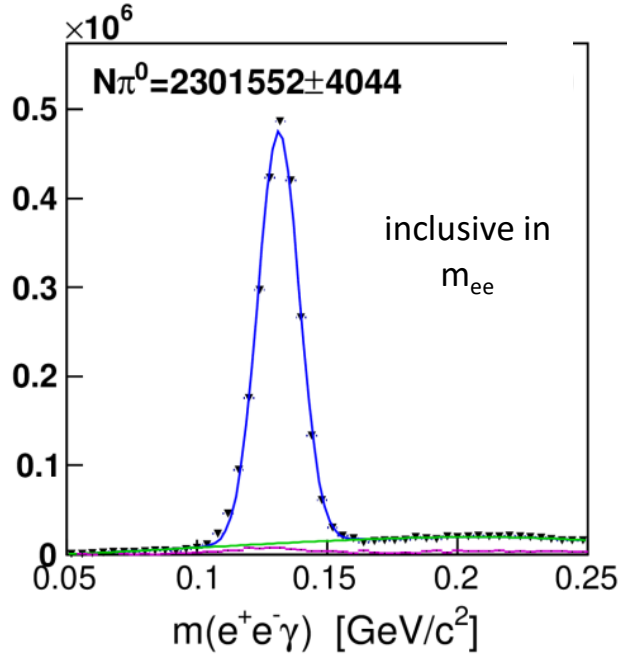




A2 preliminary

Low background contribution

Analysis strategy: fit π^0 peak (MC spectrum) over background in m_{ee} bins
event selection based on different selections cuts –> different background levels

- vary cuts on PID dE/dx
- vary cuts on kinematic fit CL (1%, 2%, 5%, 10%)

Monte-Carlo Templates $\pi^0 \to e^+e^-\gamma$

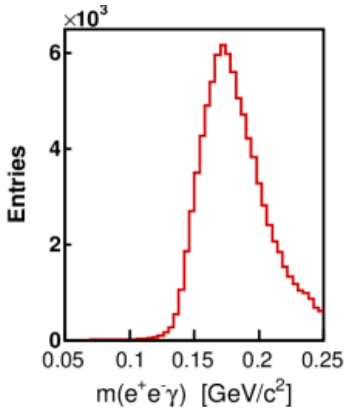
$40 < m_{ee} < 45$ MeV

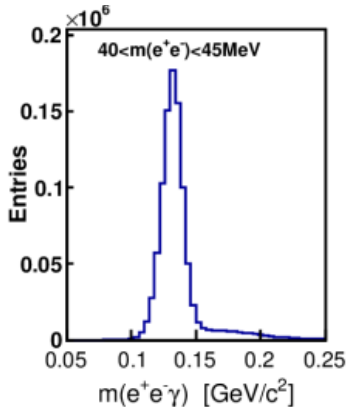
background MC $\pi^0 \to \gamma\gamma$

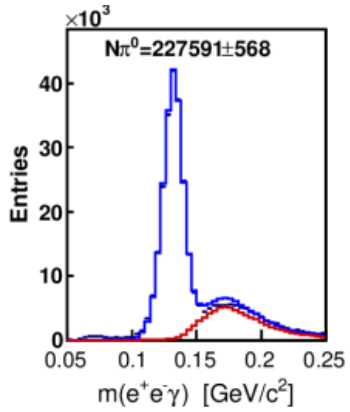
signal MC $\pi^0 \to e^+e^-\gamma$

Fit Data MC-sum

without PID dE/dx

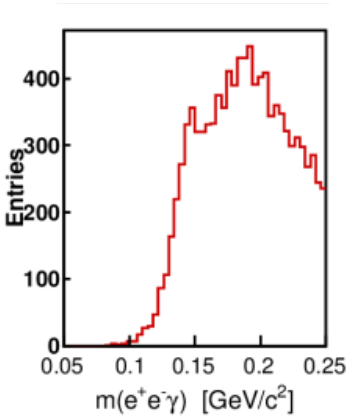


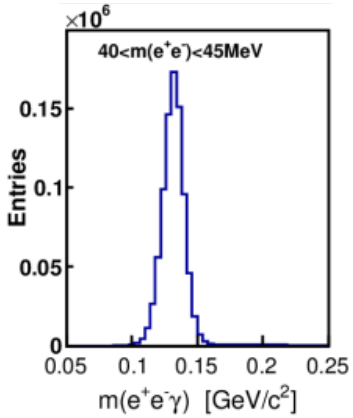


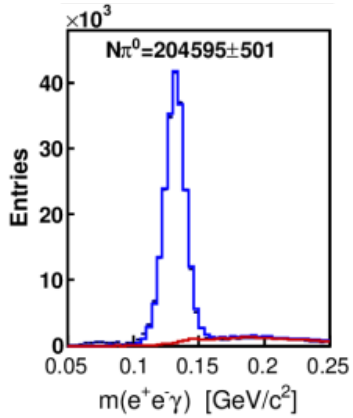


A2 preliminary

with PID dE/dx







Monte-Carlo Templates $\pi^0 \to e^+e^-\gamma$

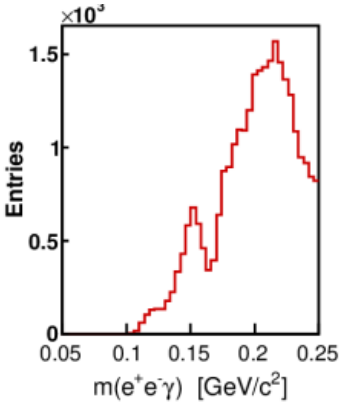
$100 < m_{ee} < 105$ MeV

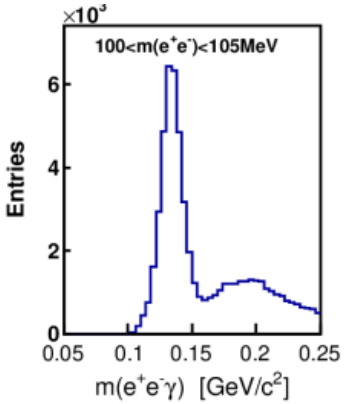
background MC $\pi^0 \to \gamma\gamma$

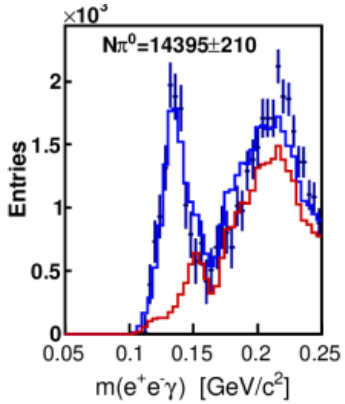
signal MC $\pi^0 \to e^+e^-\gamma$

Fit Data MC-sum

without PID dE/dx







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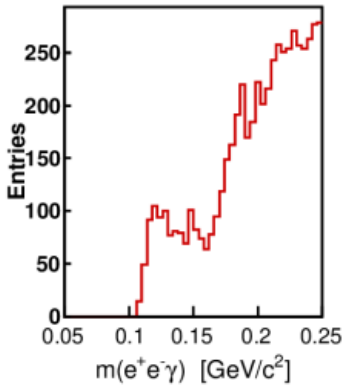
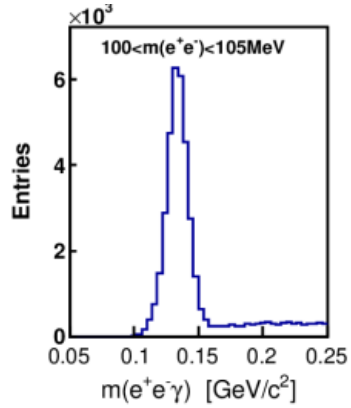
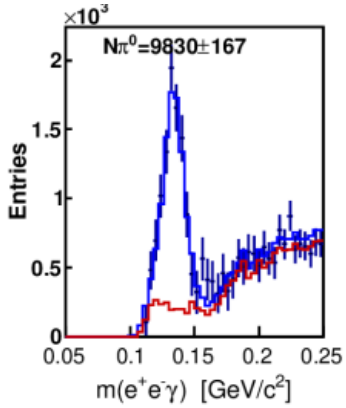


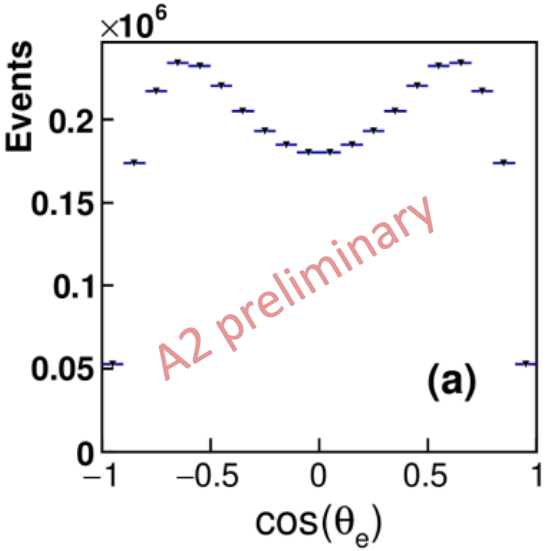




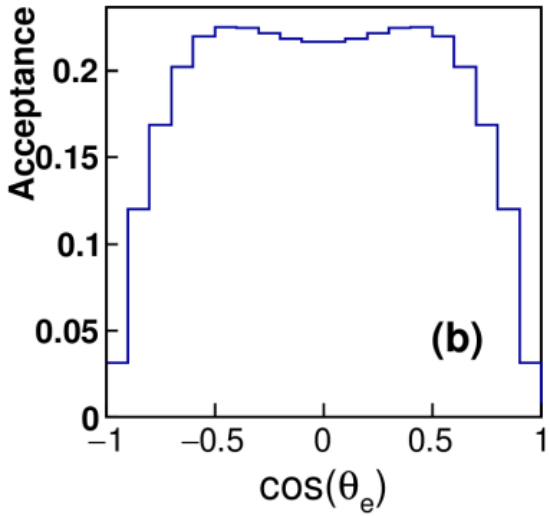
Angular Distribution $\pi^0 \to e^+e^-\gamma$

$15 < m_{ee} < 60$ MeV

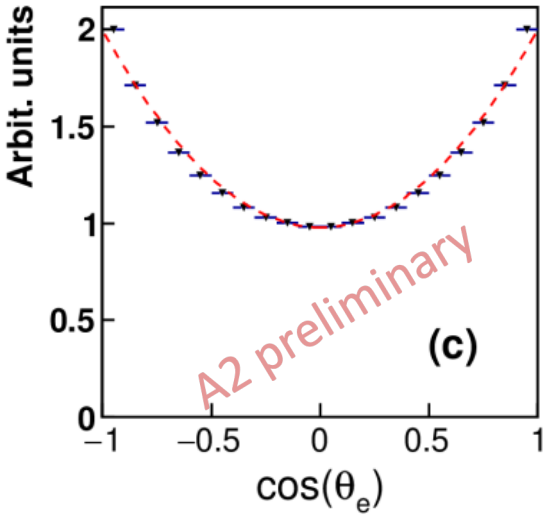
Experimental distribution



Monte-Carlo acceptance

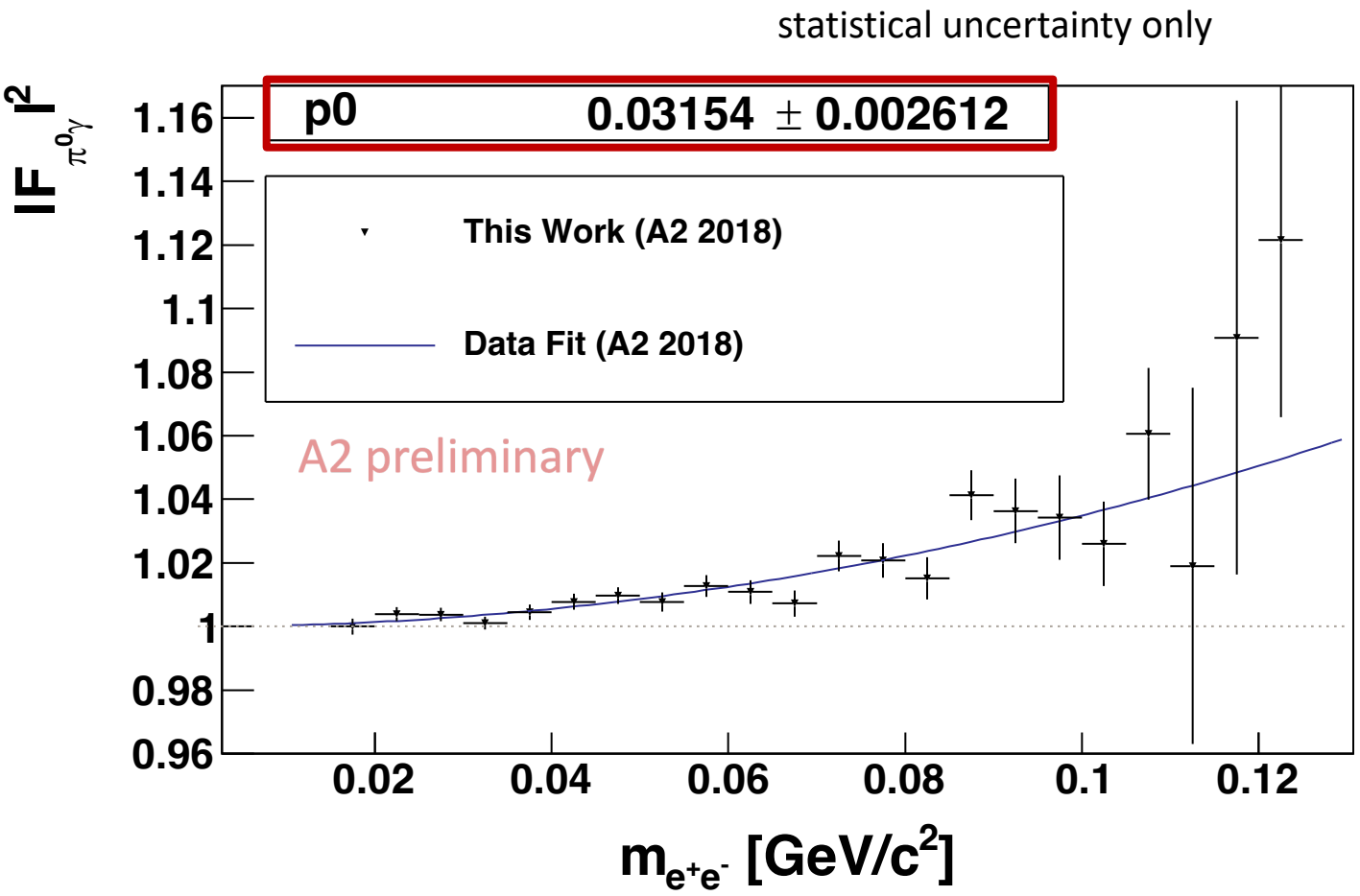


Acceptance-corrected data – theory comparison



Excellent agreement !

New π^0 Transition Form Factor Result



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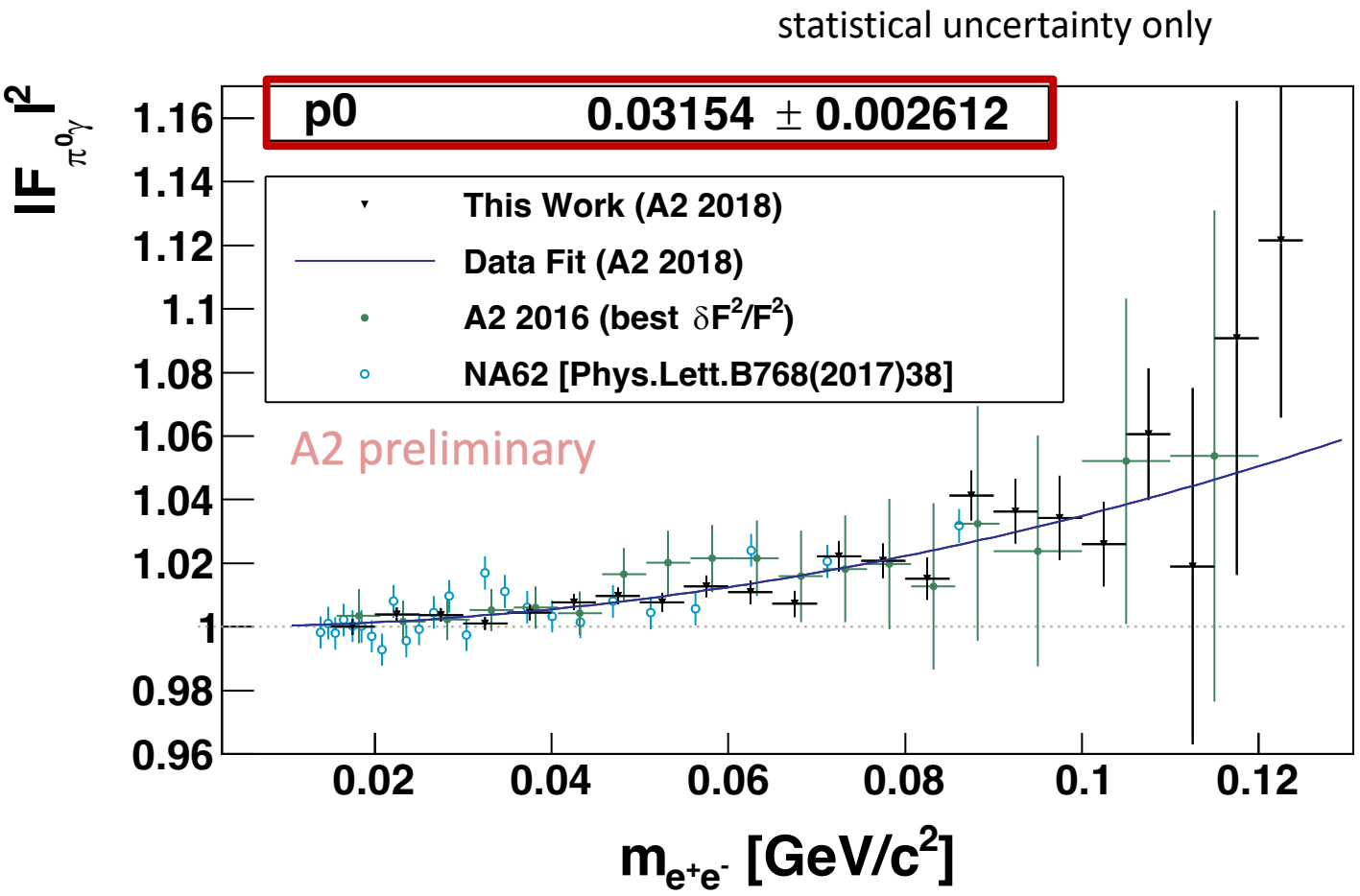

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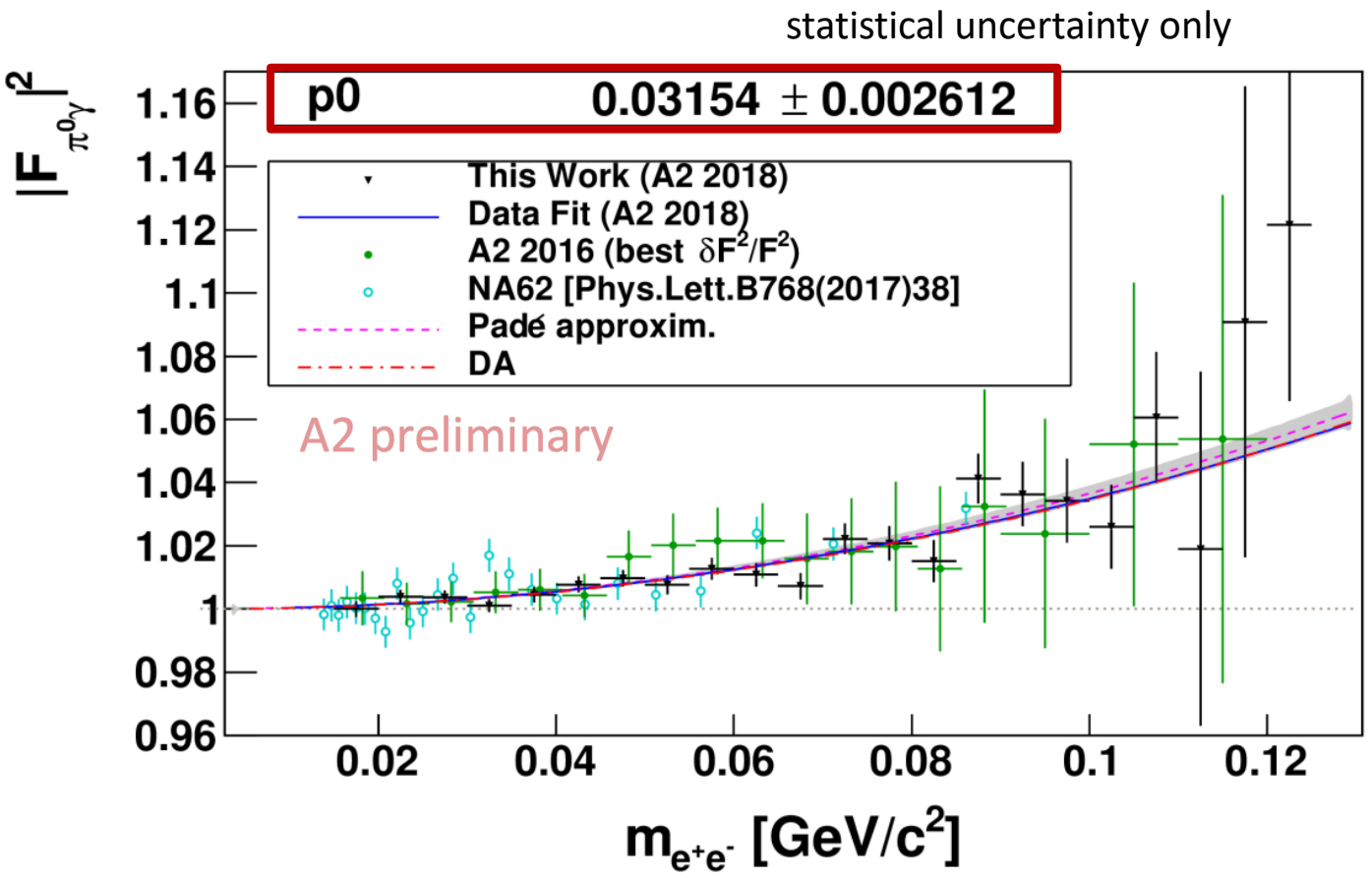


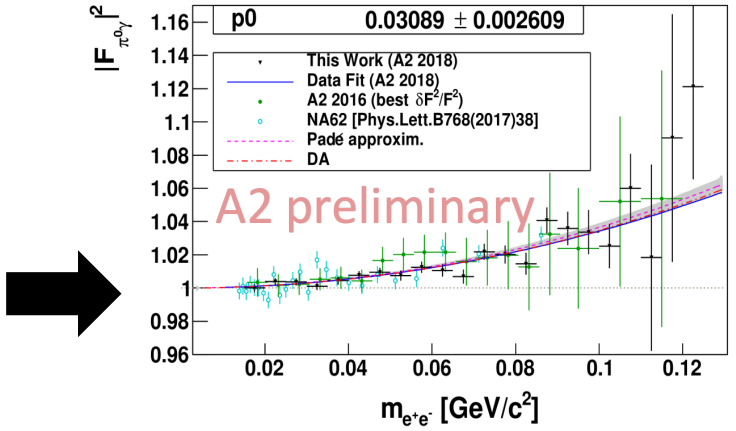
Comparison to experimental data from NA62 (2017) and A2/MAMI (2016) and theoretical predictions within Padé approximants and dispersive Analysis

→ world's most precise measurement – agreement with previous data/theory

Systematic Uncertainties

Systematic uncertainty in a_π evaluated by :

- changing selection criteria (see before)
- excluding radiative corrections from the Monte Carlo simulation used to determine the experimental acceptance.



The rms of all results obtained for a_π was used as systematic uncertainty.

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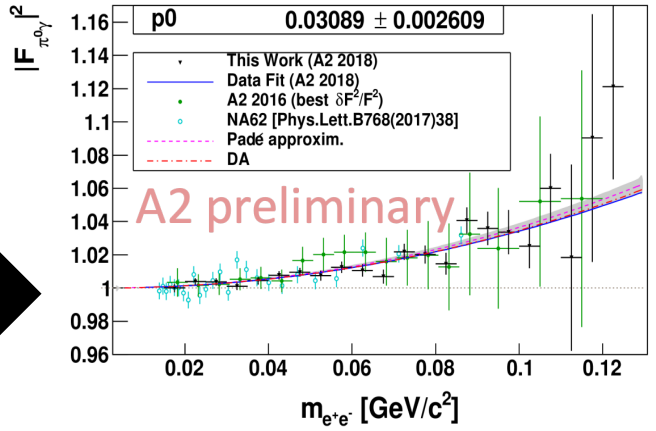

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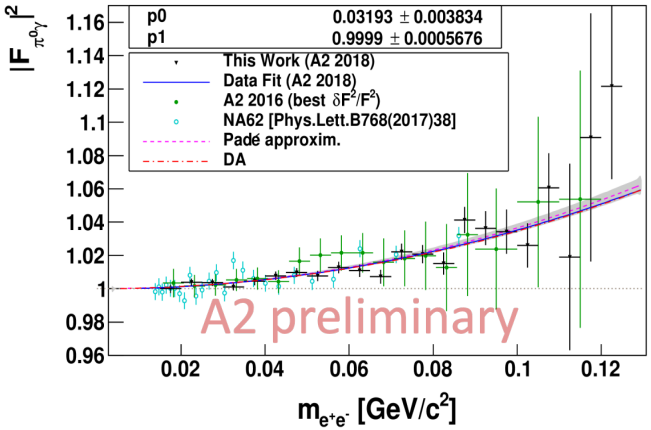


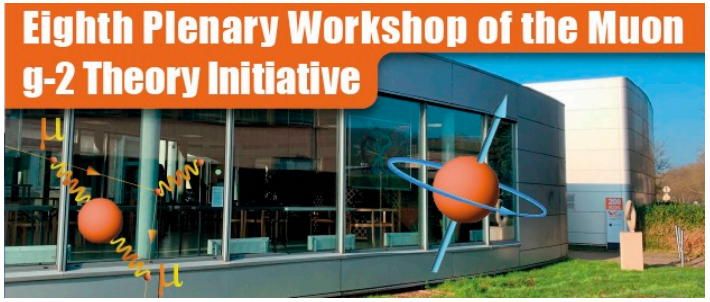
$$a_\pi = 0.0315 \pm 0.0026_{stat} \pm 0.0010_{syst}$$

Fit without constraining TFF = 1 for zero momentum transfer

Summary

A2 preliminary

$$a_\pi = 0.0315 \pm 0.0026_{stat} \pm 0.0010_{syst}$$

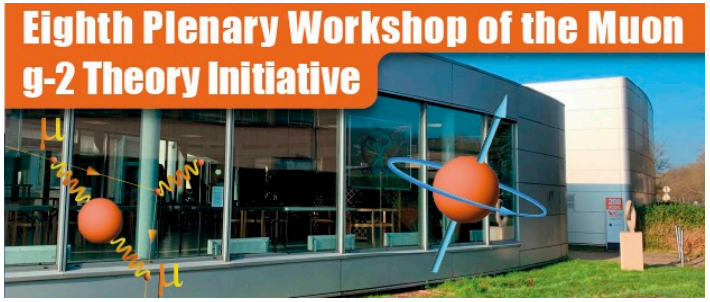


- New A2 result improves the experimental uncertainty of the previous A2 measurement by a factor of four, and by a factor of two the NA62 result $a_\pi = 0.0368 \pm 0.0057_{tot}$.
- Paper draft under internal review.
- Excellent agreement with the theoretical calculations within Padé approximants [$a_\pi = 0.0324 \pm 0.0020$] and the Dispersive Analysis [$a_\pi = 0.0315 \pm 0.0009$]. Experimental accuracy approaching those of the predictions.

Summary

A2 preliminary

$$a_\pi = 0.0315 \pm 0.0026_{\text{stat}} \pm 0.0010_{\text{syst}}$$



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New MAMI result for timelike TFF together with spacelike measurement from BESIII → internal consistency check of pion pole contribution to HLbL currently used for $(g\text{-}2)_\mu$

Backup

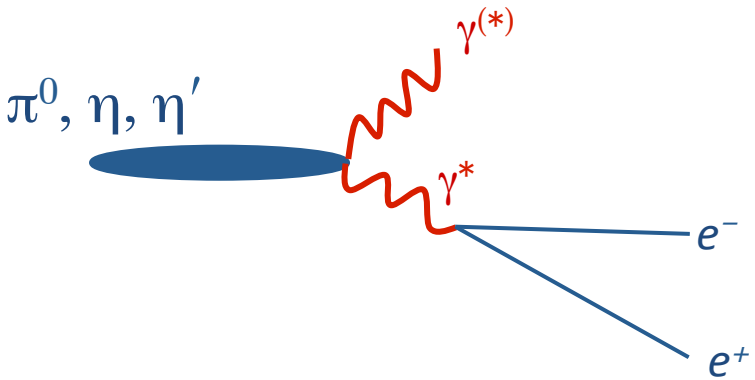
Importance of Transition Form Factors

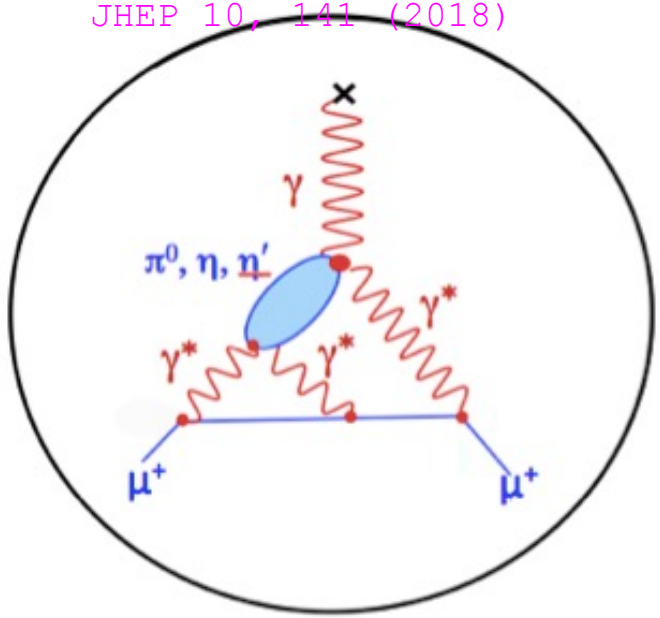
Determination of electromagnetic (EM)
Transition Form Factors (TFFs) of light mesons *M*

$$M \leftrightarrow \gamma^{(*)}\gamma^{*}$$

→ understanding their intrinsic structure
→ input to the hadronic light-by-light contribution to $(g-2)_\mu$
(dispersive approach)

Whitepaper 25, Phys. Reports
JHEP 09, 074 (2015)
JHEP 09, 074 (2015)
JHEP 10, 141 (2018)



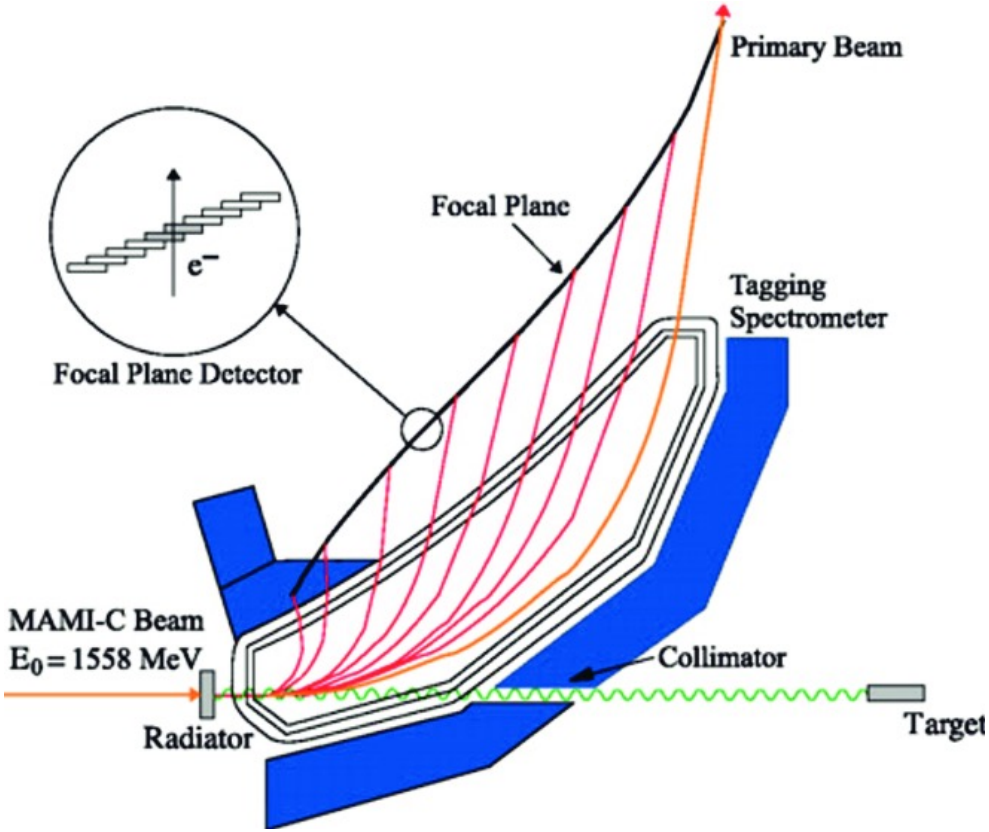


Pion pole contribution dominating
Low virtualities important

Photon Beam Line at MAMI

Converting MAMI electron beam into *tagged* photon beam via bremsstrahlung process
Energy of electron after bremsstrahlung process measured in tagger

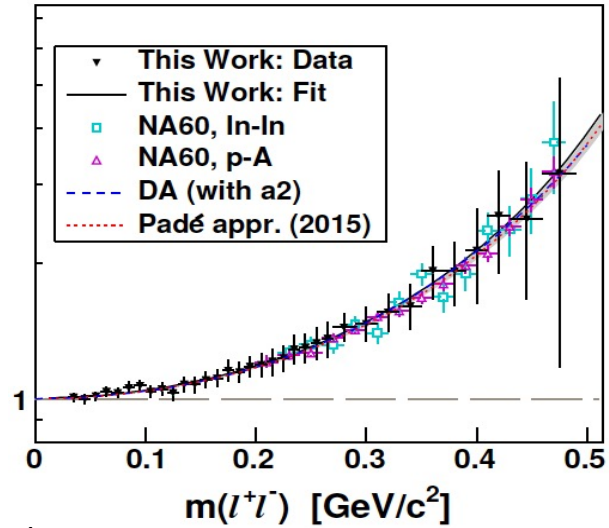
$$E_\gamma = E_{MAMI} - E'$$



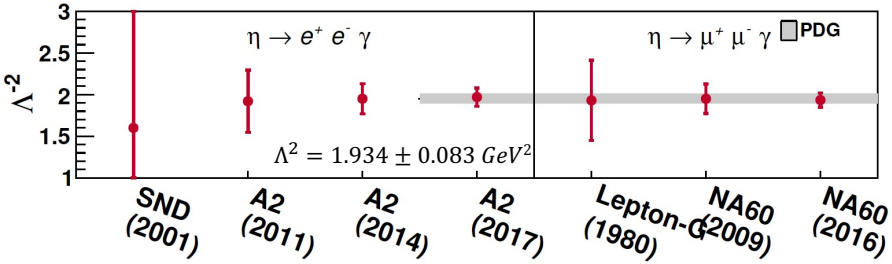
Timelike η and $\omega\pi^0$ TFFs

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

tool to study light-quark dynamics

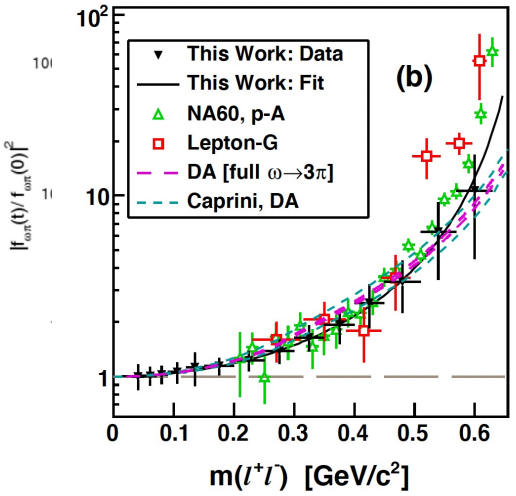


- $5.4 \cdot 10^4$ $\eta \to e^+e^-\gamma$ events, most precise e^+e^-
- slope parameter: $\Lambda^2 = 1.97 \pm 0.11\ GeV^2$



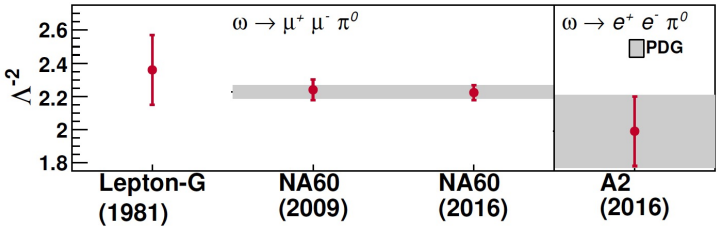
$\omega \to \pi^0 e^+e^-$

large deviation between NA60 and theoretical models?!



1100 $\pi^0e^+e^-\gamma$ events

- A2 data not yet competitive with NA60
- at given statistics no conflict with theory



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

Leading contributions are pole contribution from π^0, η, η'

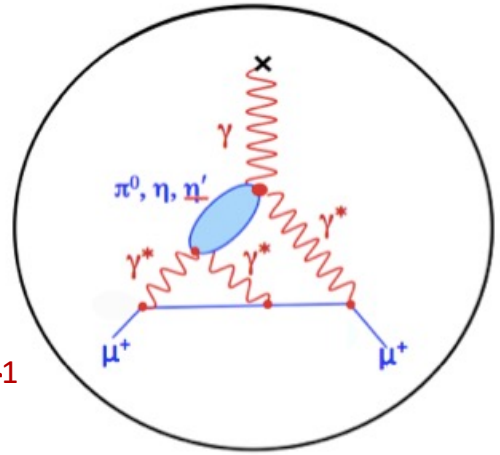
2D integral representation

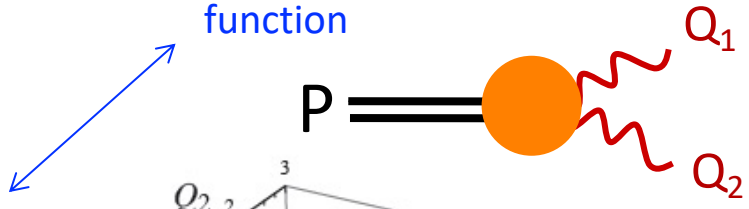
$$a_\mu^{\mathrm{HLbL};\pi^0} = \int_0^\infty dQ_1 \int_0^\infty dQ_2 \sum_i w_i(Q_1, Q_2)\, f_i(Q_1, Q_2)$$

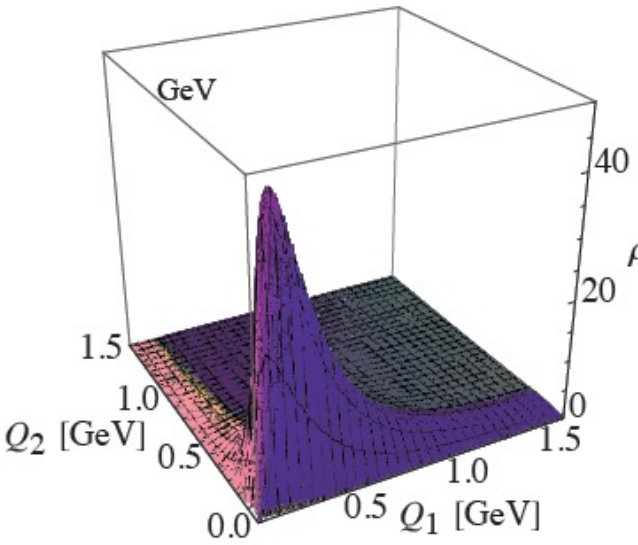
weighting function

form factor

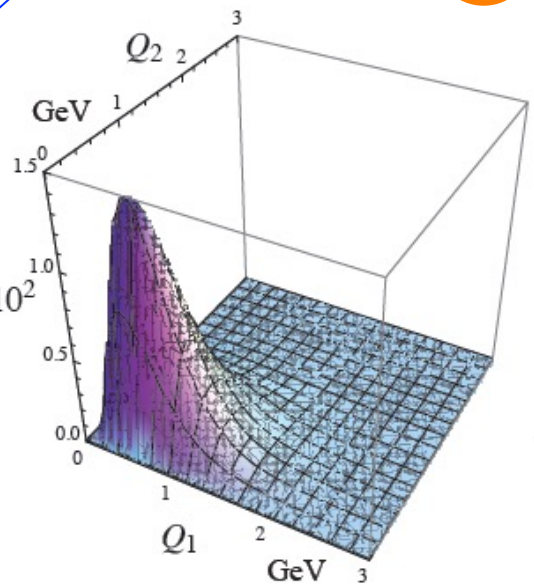
[Knecht, Nyffeler 2002]







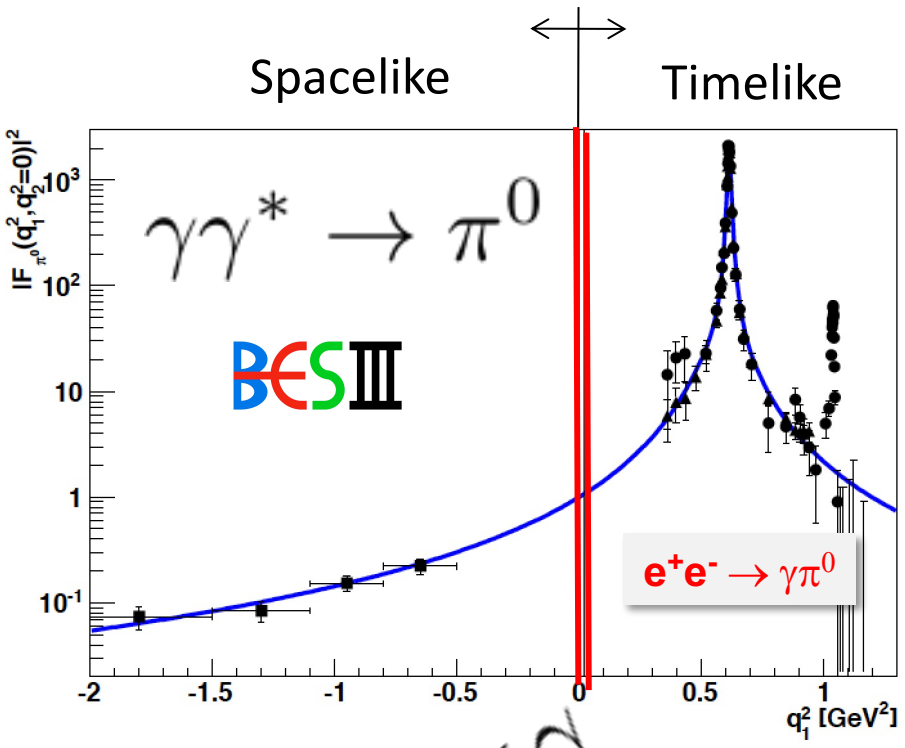
Pseudoscalar Mesons

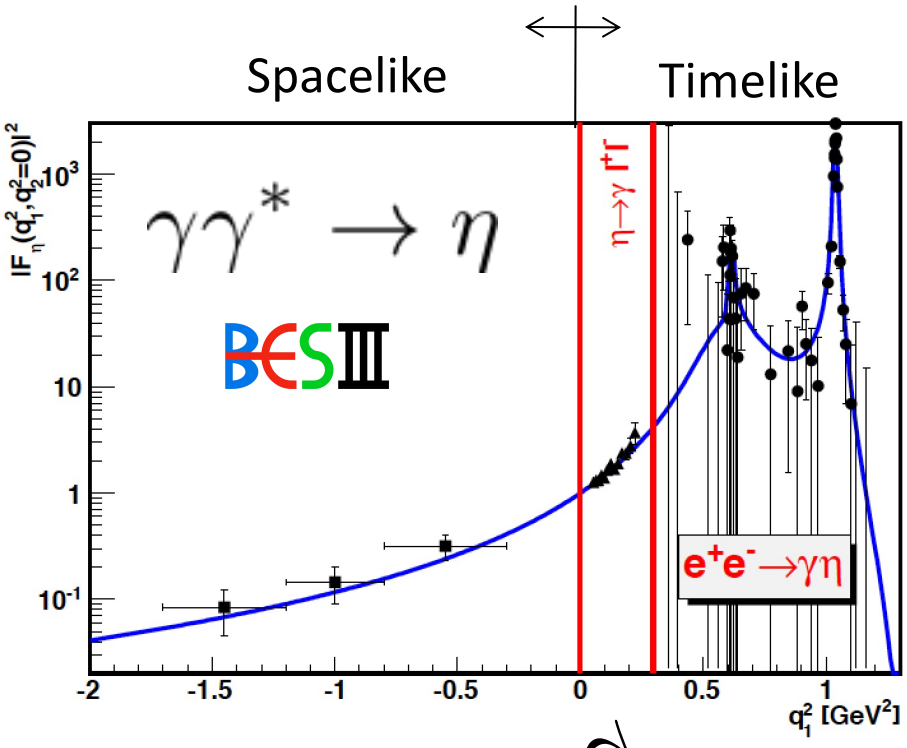


Axial Vector Mesons

→ **Need doubly virtual form factors of π^0, η, η' at low Q^2**

Transition Form Factors





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

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