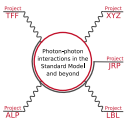
Funded by
DFG Deutsche Forschungsgemeinschaft
German Research Foundation

Meson decay studies from the A2 Collaboration at MAMI

ECT* workshop:
Precise tests of fundamental physics with light mesons

Edoardo Mornacchi
Johannes Gutenberg University of Mainz

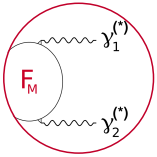
Villazzano (Trento), June 13th 2023



FOR 5327

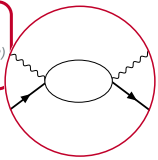
A2 physics program

Meson decays

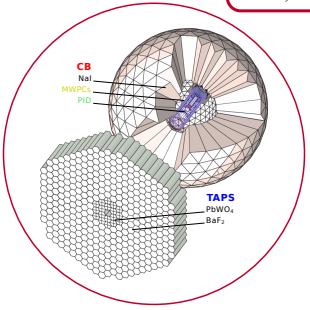


Compton scattering

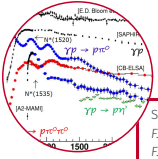
See Refs.:
E. Mornacchi et al., PRL 129 (2022)
E. Mornacchi et al. [A2], PRL 128 (2022)
D. Paudyal et al. [A2], PRC 102 (2020)



A2@MAMI

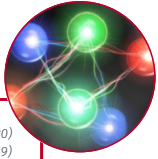


Baryon spectroscopy



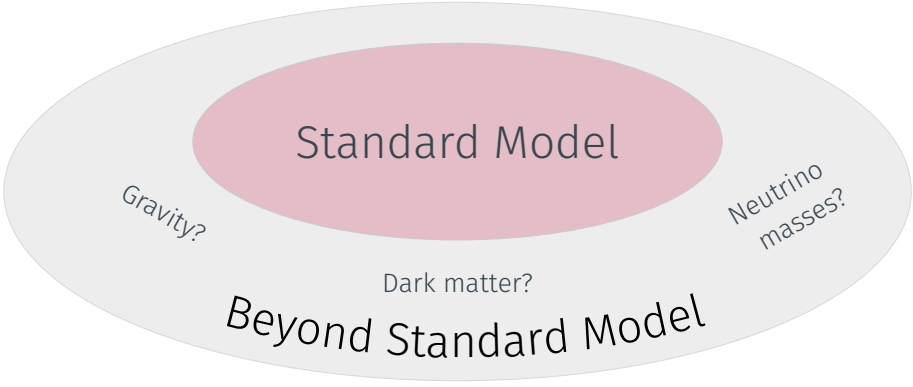
See Refs.:
F. Cividini et al. [A2], EPJA 58 113 (2022)
F. Afzal et al. [A2], to be submitted
D. Ghosal et al. [A2], to be submitted

Di-baryon spectroscopy



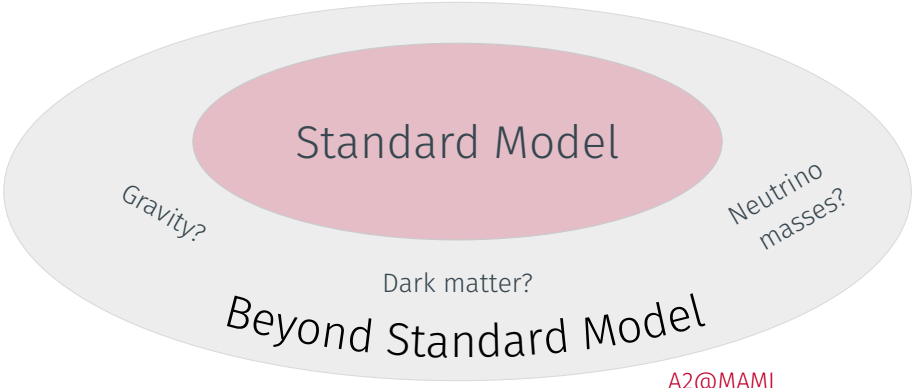
See Refs.:
M. Bashkanov et al. [A2], PRL 124 (2020)
M. Bashkanov et al. [A2], PLB 789 (2019)
M. Bashkanov et al. [A2], submitted to PLB

The frontiers of the Standard Model

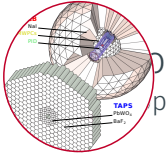


High Energy	High Precision	Cosmological
e.g. TeV scale	Precision tests	Astrophysics
	Rare processes/small effects	

The frontiers of the Standard Model



A2@MAMI



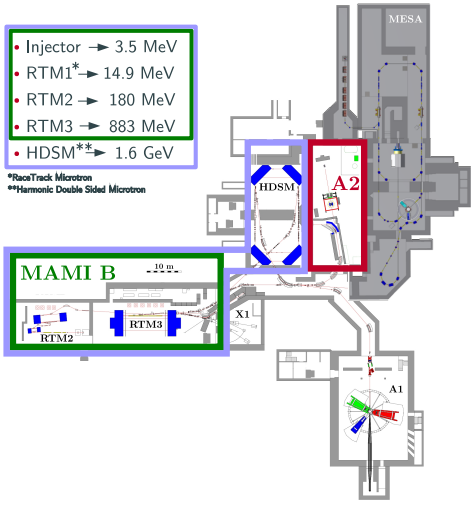
High Energy
e.g. TeV scale

High Precision
Precision tests
Rare processes/small effects

ological
physics

MAinz MIcrotron (MAMI)

- 4-stage microtron
- Continuous polarized or unpolarized electron beam
- $I_{e^-}^{\max} = 20\ \mu A$ or $100\ \mu A$ (pol/unpol)
- Linac & 3 RTMs (MAMI B) $\rightarrow$ 883 MeV
- HDSM (MAMI C) $\rightarrow$ 1604 MeV



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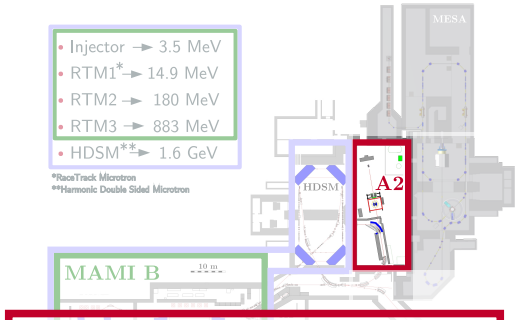
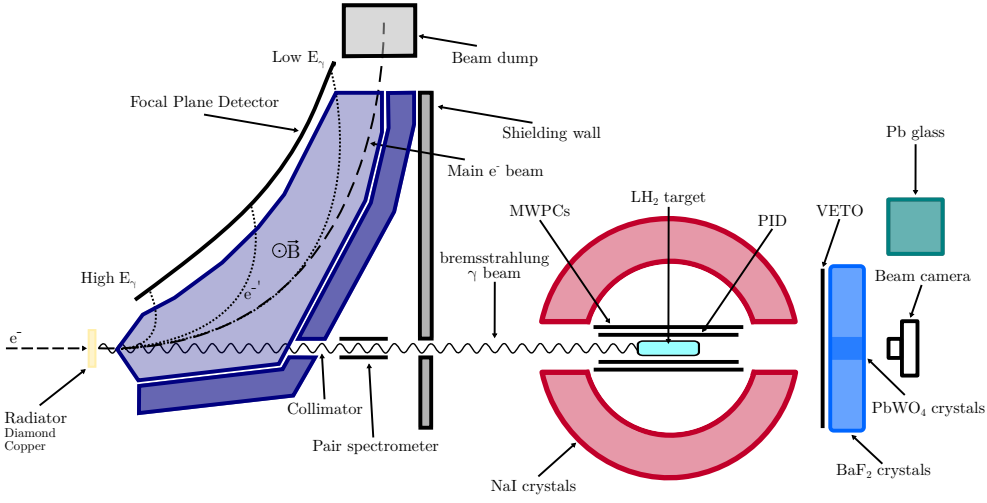
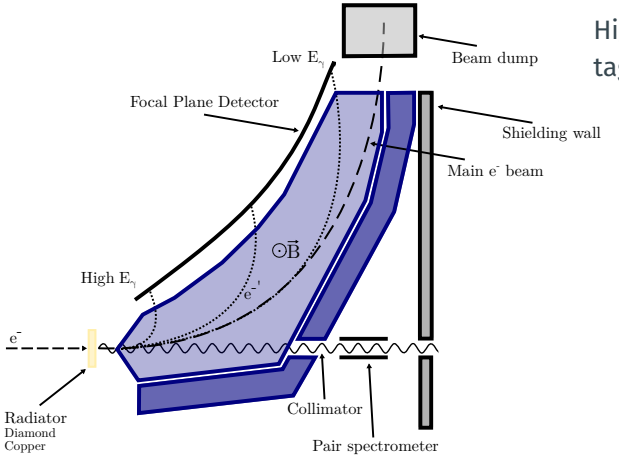


A2 setup


Low E$_\gamma$
Beam dump
Focal Plane Detector
Shielding wall
Main e$^-$ beam
Pb glass
MWPCs
LH$_2$ target
PID
VETO
$\odot\vec{B}$
High E$_\gamma$
e$^-$'
bremsstrahlung
γ beam
Beam camera
e$^-$
Radiator
Diamond
Copper
Collimator
Pair spectrometer
PbWO$_4$ crystals
NaI crystals
BaF$_2$ crystals
Tagger
Crystal Ball
TAPS

Photon tagging system

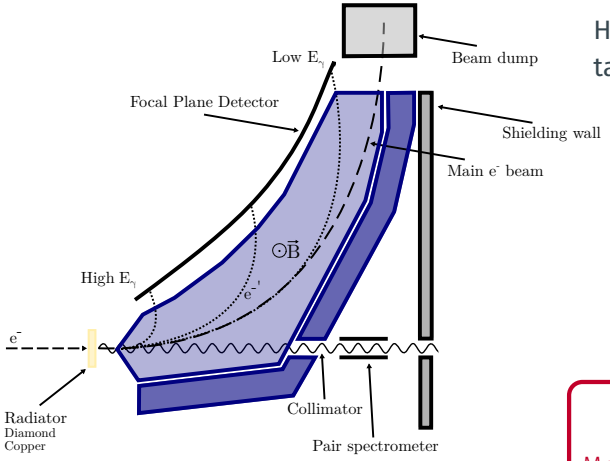


Tagger

High intensity (linearly polarized) tagged photon beam:

- $E_\gamma = E_0 - E_{e^-}$
- For $E_0 = 883$ MeV:
  - $E_\gamma = 40 - 800$ MeV
- For $E_0 = 1604$ MeV:
  - $E_\gamma = 70 - 1500$ MeV
- γ flux on target $\sim 3 \times 10^7 \gamma/s$

Photon tagging system



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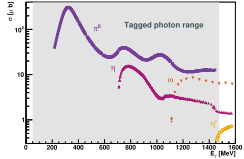
Meson factory!



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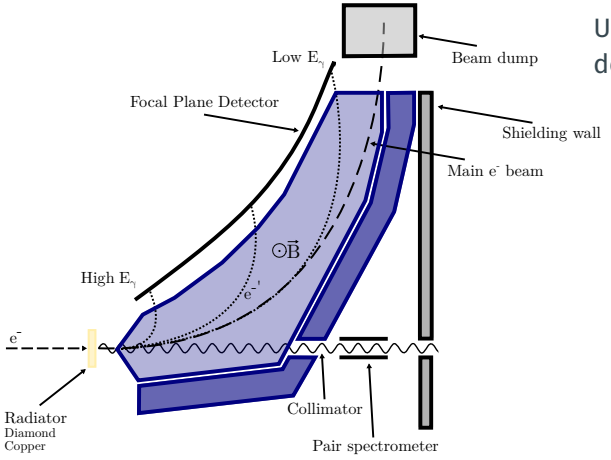
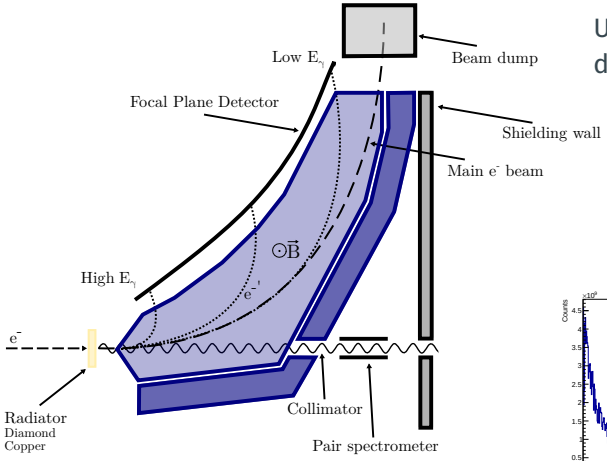


Tagger

Upgrade of the focal plane detector:

- Higher electron flux
- Higher efficiency
- Better control of systematic

Photon tagging system



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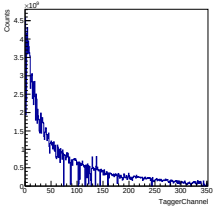

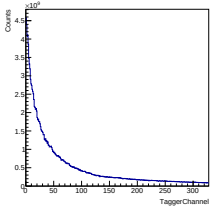

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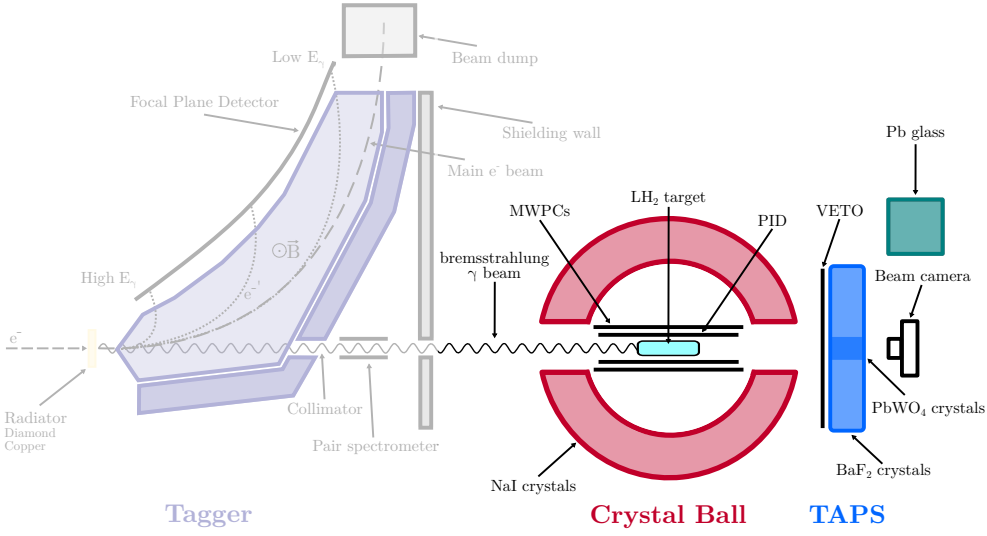
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Beam dump
Focal Plane Detector
Shielding wall
Main e$^-$ beam
High E$_\gamma$
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Radiator
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Pair spectrometer
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MWPCs
LH$_2$ target
PID
VETO
Pb glass
Beam camera
PbWO$_4$ crystals
BaF$_2$ crystals
NaI crystals
Tagger
Crystal Ball
TAPS

Detection apparatus

Crystal Ball

Highly segmented EM calorimeter

$\Delta E/E = 0.020 \cdot E[\text{GeV}]^{0.36}$

$\sigma_\phi = \sigma_\theta / \sin\theta$

$\sigma_\theta = 2 - 3^\circ$

TARGET

Liquid Hydrogen

10-cm capton cell

TAPS

Highly segmented EM calorimeter

$\Delta E/E = 0.018 + 0.008/E[\text{GeV}]^{0.5}$

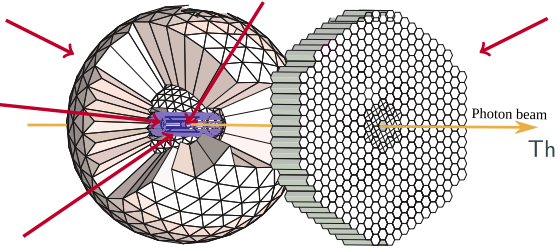
$\sigma_\phi = 14 \ldots 0.95^\circ$

$\sigma_\theta < 1^\circ$

Particle ID

Barrel of thin scintillators

$\Delta\phi = 15^\circ$



TAPS-Veto

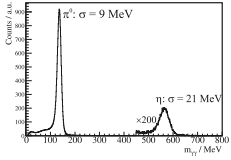
Thin scintillators before each TAPS crystal

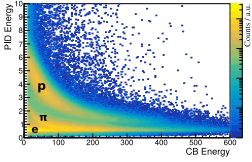
Multiwire Proportional Chambers

Precise charged tracking/positioning

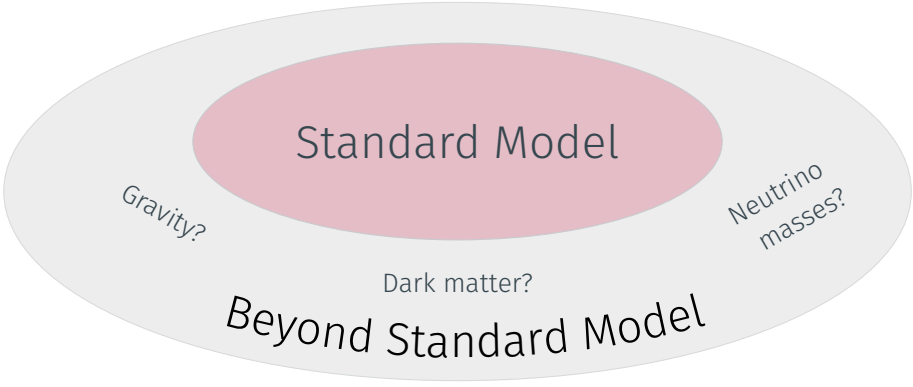
$\sigma_\theta \sim 2^\circ$

$\sigma_\phi \sim 3^\circ$





The frontiers of the Standard Model



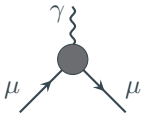
High Energy
e.g. TeV scale

High Precision
$(g-2)_\mu$ Precision tests
Rare processes/small effects

Cosmological
Astrophysics

Muon anomalous magnetic moment

Magnetic moment: $\vec{\mu} = g\frac{Qe}{2m}\vec{s}$

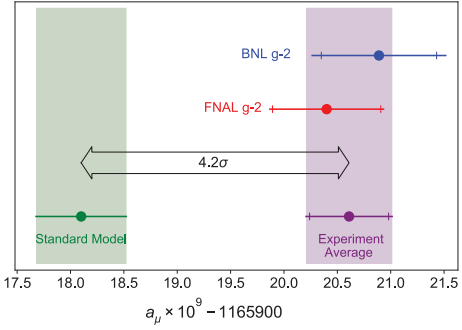


The anomaly: $a_\mu = \frac{g-2}{2} \neq 0$

	$a_\mu(\sigma_{a_\mu})[10^{-11}]$	
Experiment	116 592 061	(41)
Standard Model	116 591 810	(43)
QED	116 584 718.93	(0.1)
EW	153.6	(1.0)
Strong		
HVP	6845	(40)
HLbL	92	(18)

T. Aoyama et al., Phys. Rept. ***887****, 1-166 (2020)*

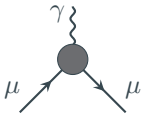
Muon g-2 Coll., Phys. Rev. Lett. ***126****, 141801 (2021)*



Increase precision of $a_\mu^{SM} = a_\mu^{QED} + a_\mu^{EW} + a_\mu^{Strong}$

Muon anomalous magnetic moment

Magnetic moment: $\vec{\mu} = g\frac{Qe}{2m}\vec{s}$



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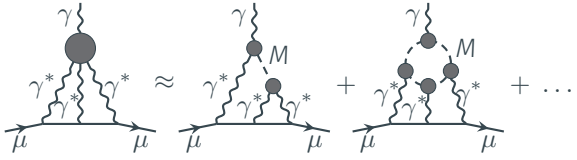
Hadronic Light-by-Light scattering:



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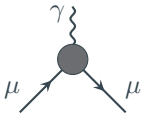

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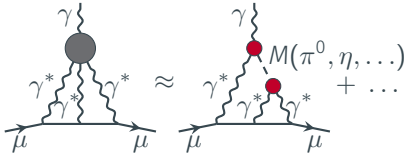


● : $\mathcal{A}\left(M \to \gamma^{(*)}\gamma^{(*)}\right)$

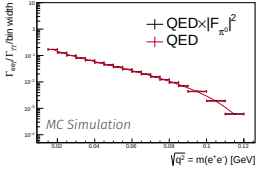
$\rightarrow$ Meson transition form factor

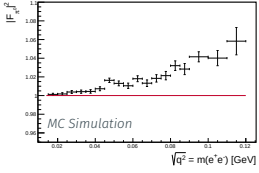
Time-like transition form factor

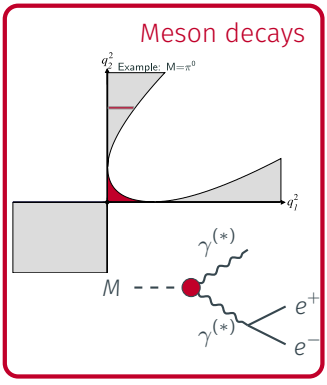
Accessing the TFF — Momentum transfer spectrum of the decay rate

$$\frac{d\Gamma(A \to Be^+e^-)}{dq^2\Gamma(A \to B\gamma)} = [QED]\left|\frac{\mathcal{F}_{AB}(q^2)}{\mathcal{F}_{AB}(0)}\right|^2 = [QED]\left|F_{AB}(q^2)\right|^2$$

Example $A = \pi^0$ $\quad \frac{d\Gamma(\pi^0 \to \gamma e^+ e^-)}{dq^2\Gamma(\pi^0 \to \gamma\gamma)}$ $\quad |F_{\pi^0}(q^2)|^2$







Compare results — VMD-inspired parametrisation

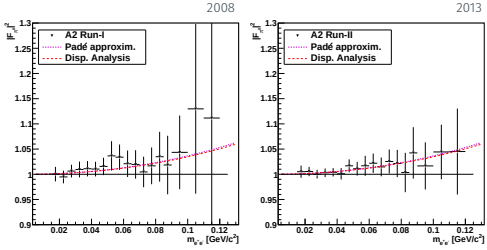
$$F(q^2) = \frac{\Lambda_V^2}{\Lambda_V^2 - q^2 - i\Gamma_V\Lambda_V} \overset{q^2<\Lambda_V}{\approx} 1 + \Lambda^{-2}q^2$$

A2 measurement (2008 and 2013):

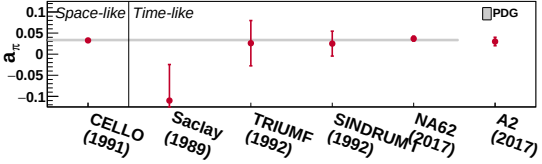
*A2 Collaboration, Phys. Rev. C **95**, 025202 (2017)*

- Two separate data sets with different running conditions
- 18 bins in $m_{e^+e^-} = [15 - 120]$ MeV
- 4.0×10^5 Dalitz decay events
- Uncertainties dominated by statistics

Significant improvement of direct time-like measurements



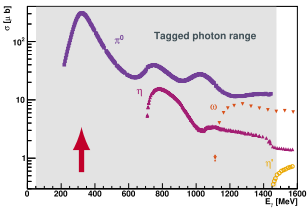
Plot: L. Heijkenskjöld



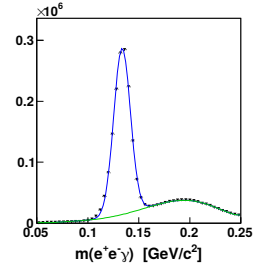
$\pi^0 \to e^+e^-\gamma$ - A2 ongoing measurement

First dedicated data taking in 2018:

- 6 weeks of beam
- Polarization peak placed in $\Delta(1232)$ region
- Higher rate thanks to upgraded system
- Experimental trigger tuned to the best conditions



Preliminary results:



First estimates:

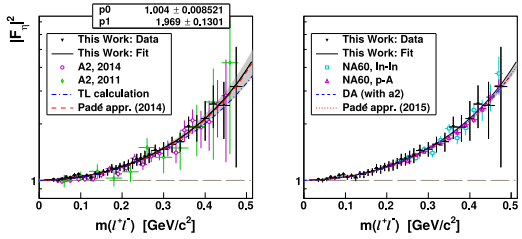
- $\sim 2.2 \times 10^6$ signal events collected
- 6 times improvement compared to previous measurement!

World leading precision of time-like measurement!

A2 measurement (2007 and 2009):

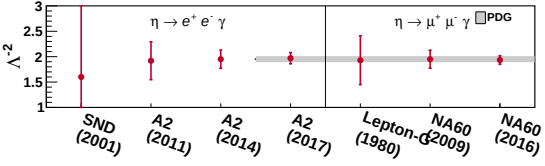
A2 Collaboration, Phys. Rev. C ***95****, 035208 (2017)*

- 34 bins in $m_{e^+e^-} = [30 - 490]$ MeV
- 5.4×10^4 Dalitz decay events
- Double statistics compared to previous A2 result



Good agreement between theory and experiment

Plot: L. Heijkenskjöld

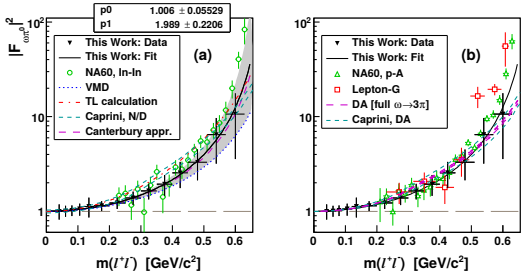


$\omega \to e^+e^-\pi^0$ - A2 existing measurement

A2 measurement (2007 and 2009):

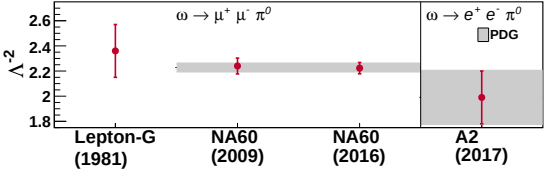
A2 Collaboration, Phys. Rev. C ***95****, 035208 (2017)*

- 14 bins in $m_{e^+e^-} = [30 - 630]$ MeV
- 1.1×10^3 Dalitz decay events
- Total uncertainties dominated by the fit



Plot: L. Heijkenskjöld

Lower than previous measurements, but still in agreement due to the bigger uncertainties



$\omega \to e^+e^-\pi^0$ - A2 planned measurement

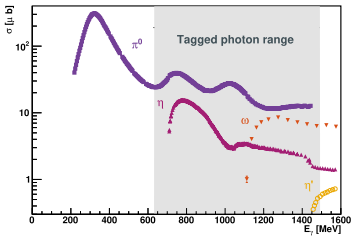
First dedicated data taking in 2019:

- 6 weeks of beam
- $E_{e^-} = 1604$ MeV
- Unpolarized photon beam with 10-cm LH_2 target

3 times more ω Dalitz decays produced!

After some preparatory studies, collection of an even larger data sample is planned:

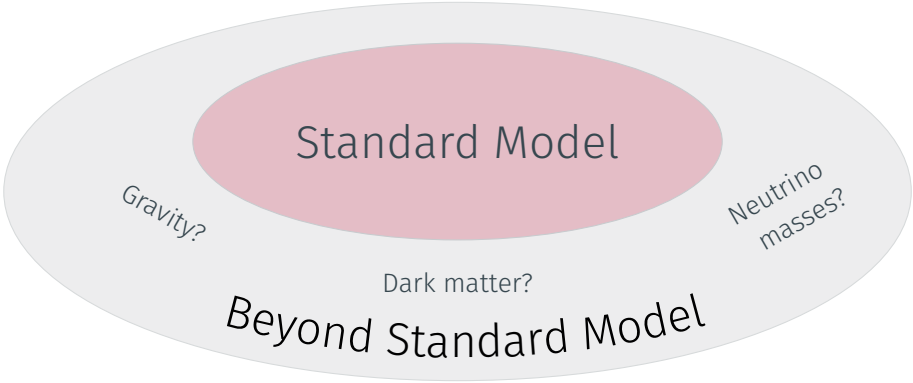
Total improvement of ~ 9 times compared to previous measurement



FOR 5327

Provide experimental input to understand the discrepancy between $\mu^+\mu^-\pi^0$ and $e^+e^-\pi^0$ extractions

The frontiers of the Standard Model



High Energy
e.g. TeV scale

High Precision
Precision tests

Rare processes/small effects

Cosmological
$\eta \to \pi^0\gamma\gamma$

$\eta \to \pi^0\pi^0\pi^0$

$\eta' \to \eta\pi^0\pi^0$

Rare decay - $\eta \to \pi^0\gamma\gamma$

Excellent χPT probe:

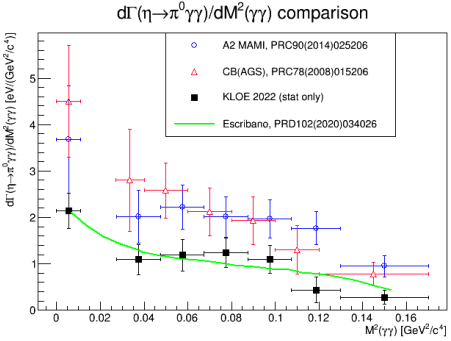
- $\mathcal{O}(p^2)$ and $\mathcal{O}(p^4)$ tree level terms vanish
- π and K loops at $\mathcal{O}(p^4)$ are heavily suppressed
- Major contribution to $d\Gamma(\eta \to \pi^0\gamma\gamma)$ comes from $\mathcal{O}(p^6)$ counter terms

Searches for possible new physics:

- Exclusion limit for Leptophobic $U(1)_B$-boson

$$\eta \to B\gamma \to \pi^0\gamma\gamma$$

R. Escribano, S. Gonzàlez-Solís, R. Jora and E. Royo, Phys. Rev. D 102, 034026 (2020)
Taken from: P. Gauzzi [KLOE-2], PoS **ICHEP2022**, 791 (2022)



The experimental situation needs to be clarified (JEF, REDTOP, A2@MAMI)

A2 measurement (2007 and 2009):

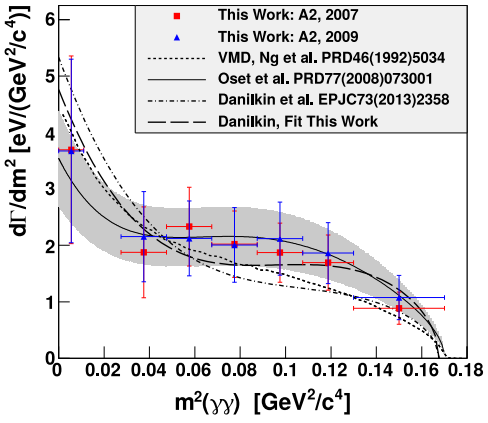
*A2 Collaboration, Phys. Rev. C **90**, 025206 (2014)*

- 6.0×10^7 η mesons produced
- 1.2×10^3 $\eta \to \pi^0\gamma\gamma$ measured

✓ Most precise (at the moment) $d\Gamma(\eta \to \pi^0\gamma\gamma)/dm^2(\gamma\gamma)$ measurement

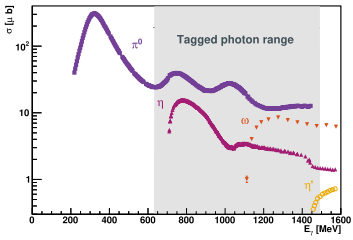
× Combination of two data sets with different running conditions

× Trigger not fully optimized for this reaction channel



Dedicated data taking in 2019:

- 6 weeks of beam
- $E_{e^-} = 1604$ MeV
- Unpolarized photon beam with 10-cm LH_2 target



Improvements:

- ✓ Upgraded A2 system: two times higher photon flux, faster DAQ
- ✓ Same conditions in both beamtimes

↓

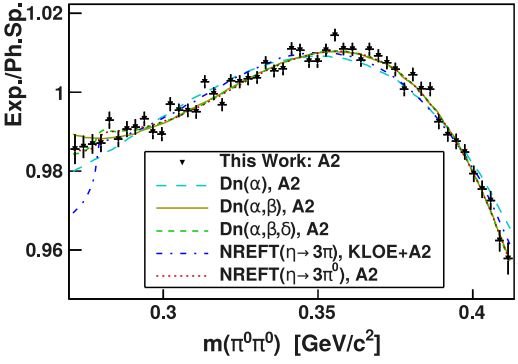
3 times more η produced! →

World-leading $d\Gamma(\eta \to \pi^0\gamma\gamma)/dm^2(\gamma\gamma)$ and $d\Gamma(\eta \to \pi^0\gamma\gamma)/dm^2(\pi^0\gamma)$ measurements

A2 measurement (2007 and 2009):

*A2 Collaboration, Phys. Rev. C **97**, 065203 (2018)*

- 7.0×10^7 η events measured
- Most precise study of dynamics
  - parametrization of Dalitz plot density
  - Cusp from $\pi^+\pi^- - \pi^0\pi^0$



Searches for possible new physics:

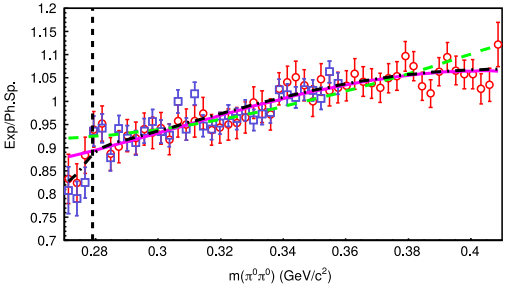
- Exclusion limit for up/hadrophilic scalar S-boson

$$\eta \to \pi^0 S \to \pi^0\pi\pi$$

A2 measurement (2007 and 2009):

A2 Collaboration, Phys. Rev. D **98**, *012001 (2018)*

- 1.2×10^5 η' events measured
- Most precise study of dynamics
  - parametrization of Dalitz plot density
  - Cusp from $\pi^+\pi^- - \pi^0\pi^0$



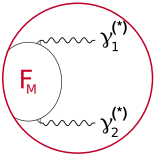
Searches for possible new physics:

- Exclusion limit for up/hadrophilic scalar S-boson

$$\eta' \to \eta S \to \eta\pi\pi$$

Summary

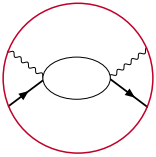
Meson decays



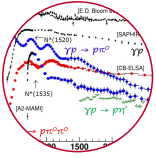
A2@MAMI

Contributes to and tests the SM precision frontiers!

Compton scattering



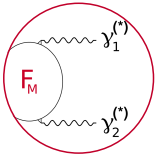
Baryon spectroscopy



Di-baryon spectroscopy

Summary

Meson decays

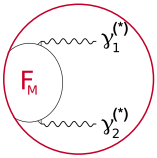


Time-like Transition form factors:

- $\pi^0 \to e^+e^-\gamma$
  - high quality data set collected and calibrated
  - analysis on going to extract TFF
- $\omega \to e^+e^-\pi^0$
  - 6 weeks of new data calibrated
  - much more data to come

Summary

Meson decays



Time-like Transition form factors:

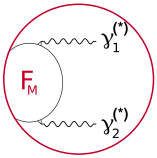
- $\pi^0 \to e^+e^-\gamma$
  - high quality data set collected and calibrated
  - analysis on going to extract TFF

Rare decays and small effects:

- $\eta \to \pi^0\gamma\gamma$:
  - new high quality data set collected and calibrated
  - analysis on going to extract $\pi^0\gamma$ and $\gamma\gamma$ distributions
  - results can provide new inputs for understanding experimental situation
- $\omega \to e^+e^-\pi^0$
  - 6 weeks of new data calibrated
  - much more data to come
- Published results on:
  - $\eta \to \pi^0\pi^0\pi^0$
  - $\eta' \to \eta\pi^0\pi^0$

Summary

Meson decays



Time-like Transition form factors:

- $\pi^0 \to e^+e^-\gamma$
  - high quality data set collected and calibrated
  - analysis on going to extract $\pi^0\gamma$ and $\gamma\gamma$ distributions
  - results can provide new inputs for understanding experimental situation
- $\to e^+e^-\pi^0$
  - 6 weeks of new data calibrated
  - much more data to come
- Published results on:
  - $\eta \to \pi^0\pi^0\pi^0$
  - $\eta' \to \eta\pi^0\pi^0$

Thanks for your attention!