

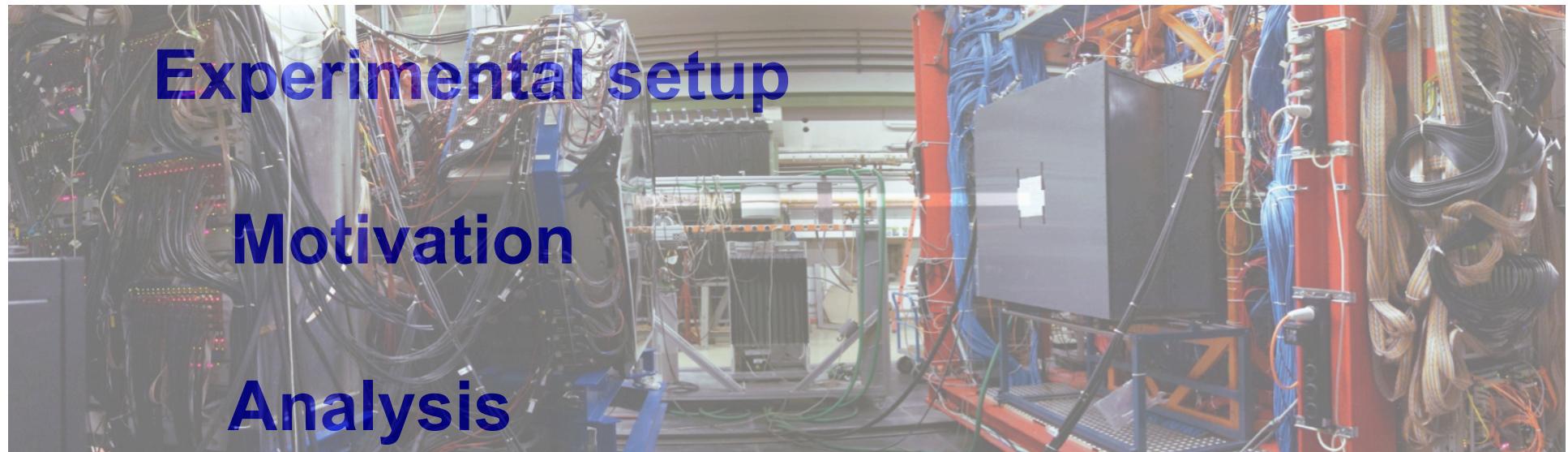


Recent Results on Meson Decays from A2

Patrik Adlarson
on behalf of the A2 collaboration at MAMI
KLOE-2 Workshop – Oct 26 – Oct 28, 2016

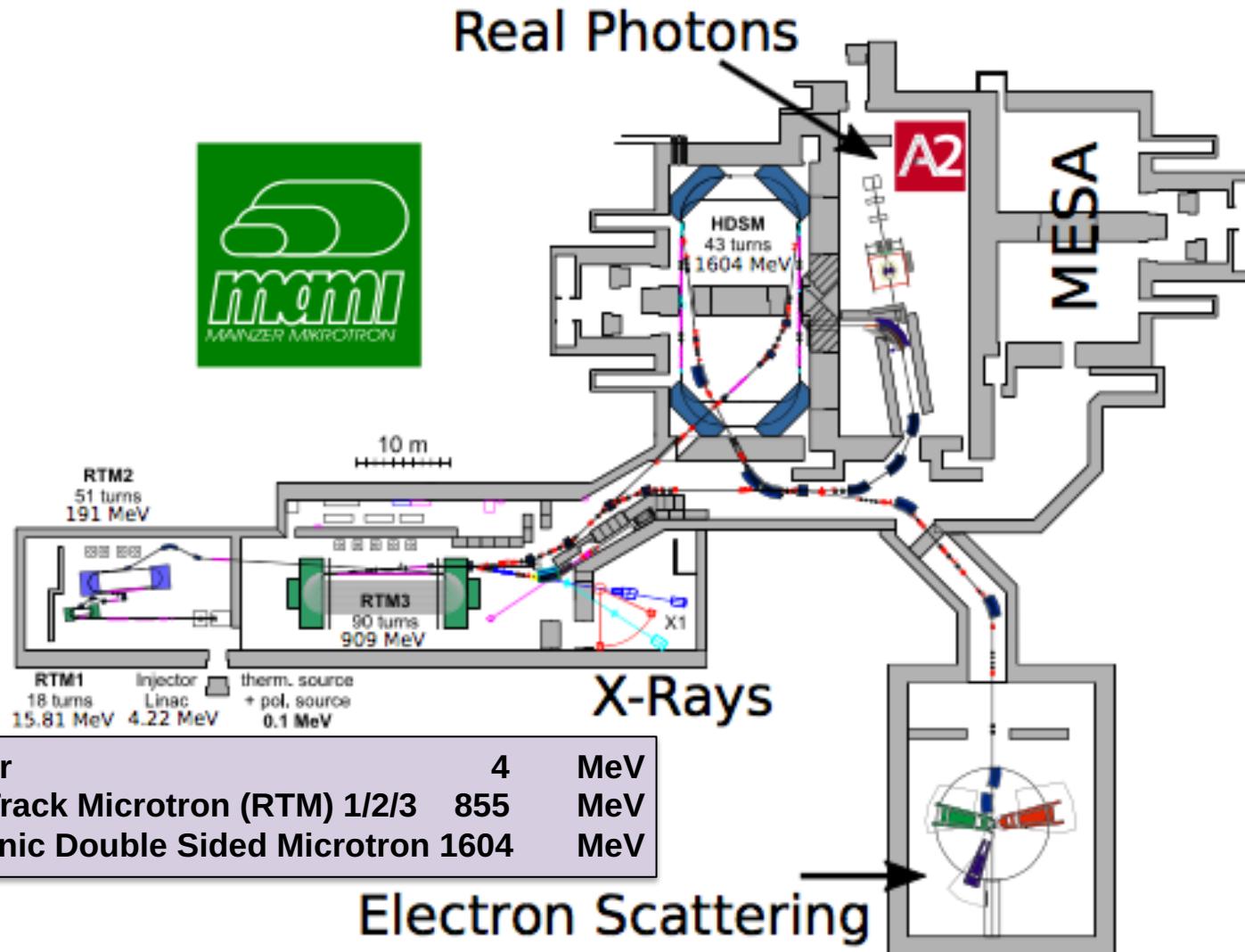
KLOE-2 Workshop on e^+e^- collision physics at 1 GeV, Oct 26 - 28, 2016

Outline

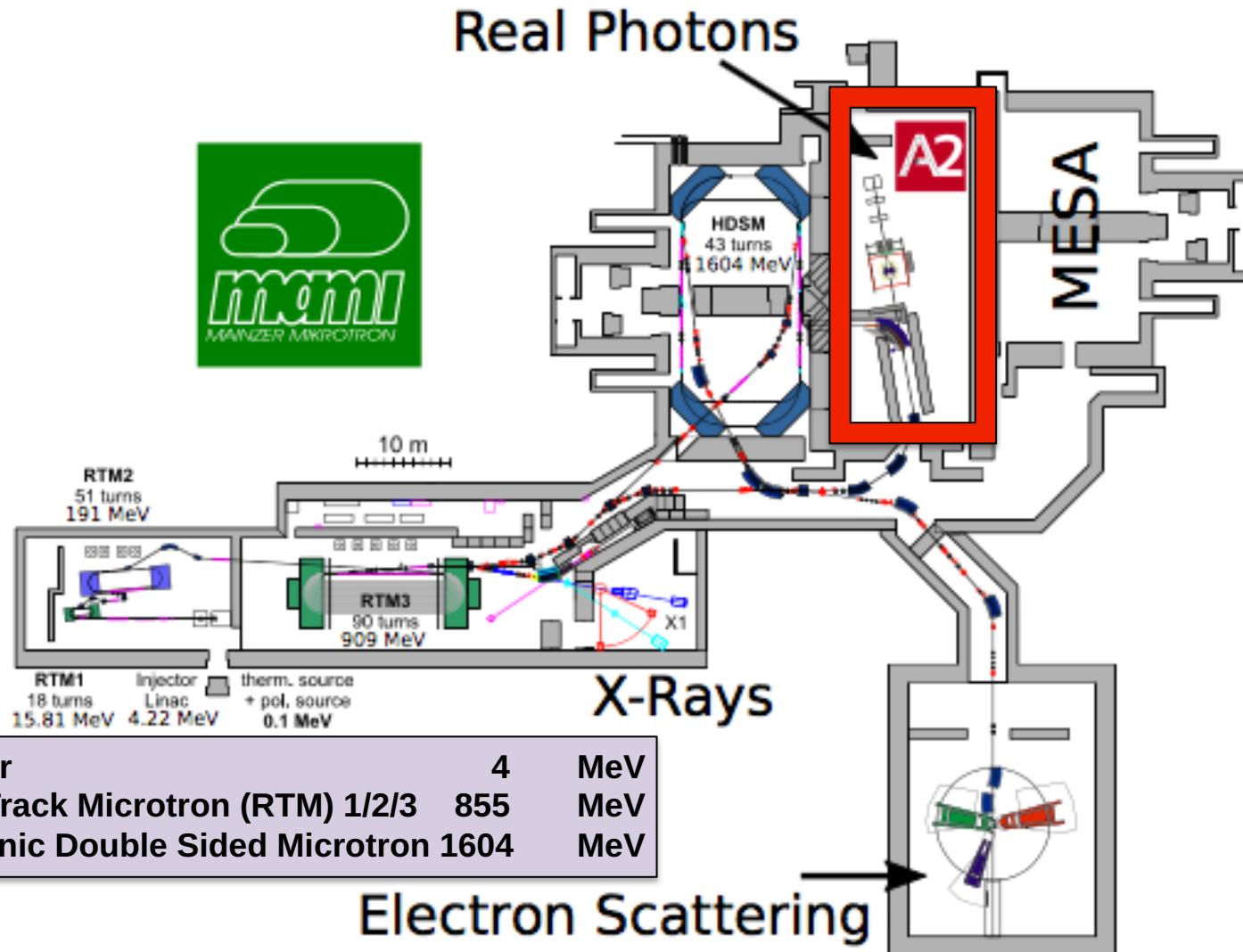


A2 Result

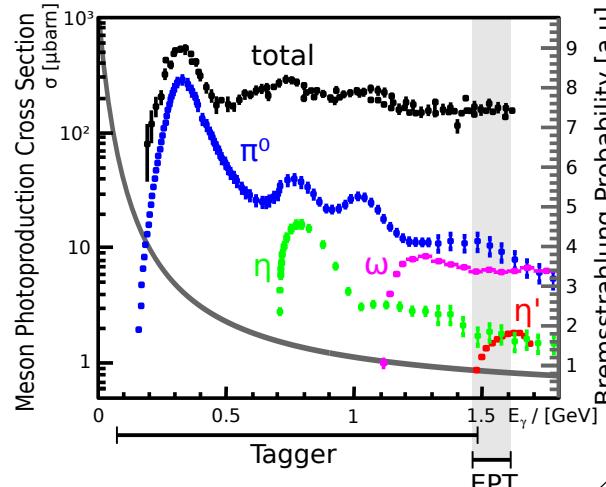
Experiments at MAMI



Experiments at MAMI



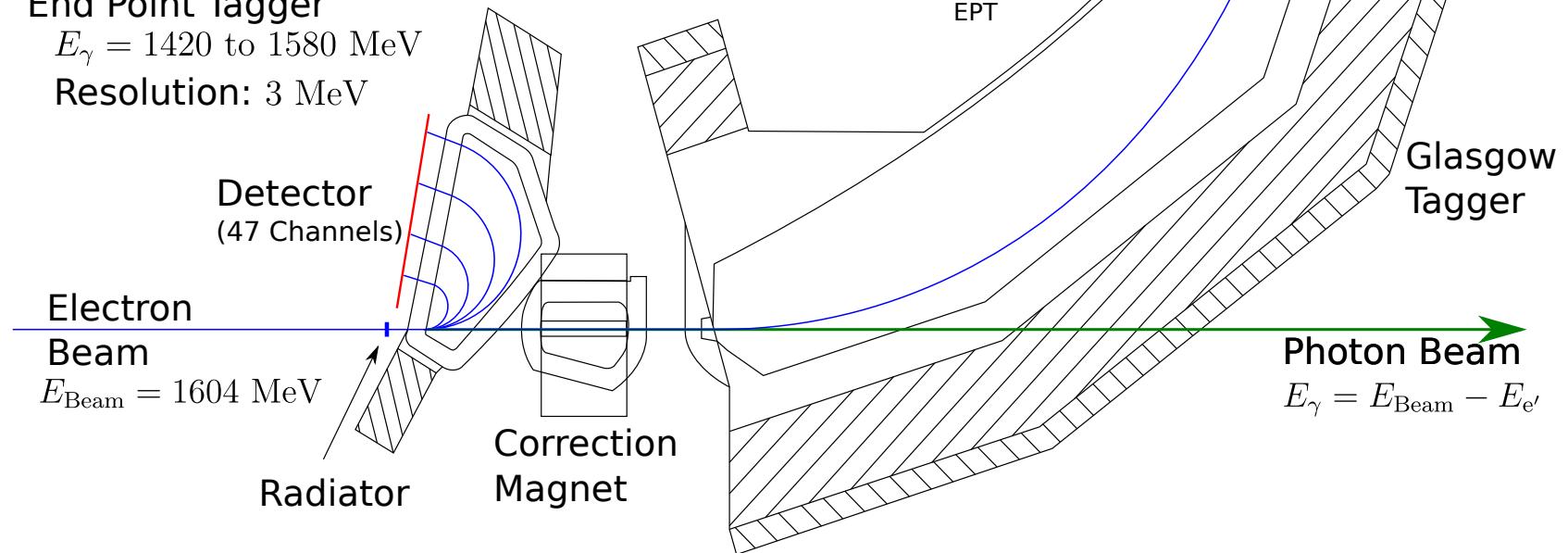
Taggers



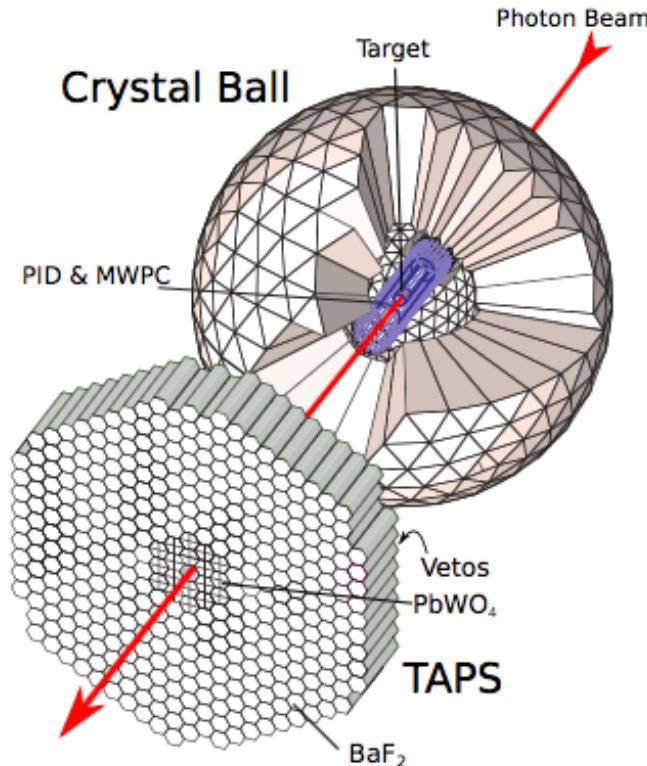
End Point Tagger

$E_\gamma = 1420$ to 1580 MeV

Resolution: 3 MeV



Exp setup CB-TAPS



CB – TAPS - 4π detector
Typical LH_2 target length 5 or 10 cm

Central Part

CB - 672 NaI(Tl) crystals
PID - 24 plastic scintillators

Forward Part

TAPS - 366 BaF_2 , 72 PbWO_4 crystals
Veto - 384 plastic scintillators

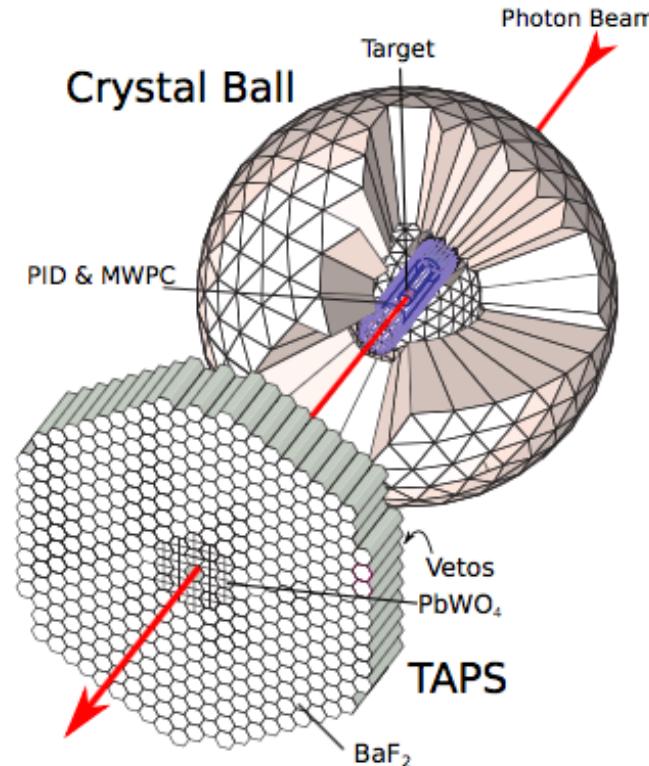
$$\Delta E / E = 2 \% / (\text{E[GeV]})^{0.36}$$

(CB)

$$\Delta E / E = 1.8 \% + 0.8 \% / (\text{E[GeV]})^{0.5}$$

(TAPS)

Exp setup CB-TAPS



CB – TAPS - 4π detector
Typical LH₂ target length 5 or 10 cm

Central Part

CB - 672 NaI(Tl) crystals
PID - 24 plastic scintillators

Forward Part

TAPS - 366 BaF₂, 72 PbWO₄ crystals
Veto - 384 plastic scintillators

$$\Delta E / E = 2 \% / (E[\text{GeV}])^{0.36}$$
$$\Delta E / E = 1.8 \% + 0.8 \% / (E[\text{GeV}])^{0.5}$$

(CB)
(TAPS)

The anomalous magnetic moment of muon known to very high precision

$$a_{\mu}^{\text{exp}} = 11\ 659\ 208.9 \pm 6.3 \cdot 10^{-10}$$

BNL, PRD 73, 072(2006)

$$a_{\mu}^{SM} = 11\ 659\ 180.2 \pm 4.9 \cdot 10^{-10}$$

Eur Phys J C71, 1515(2011)

$$\Delta a_{\mu}^{\text{exp}-SM} = 28.7 \pm 8.0 \cdot 10^{-10}$$

3.6 σ discrepancy...Beyond Standard Model Physics?

$$a_{\mu}^{QED} = (11\ 658\ 471.809 \pm 0.015) \cdot 10^{-10}$$

$$a_{\mu}^{W,Z} = (15.4 \pm 0.2) \cdot 10^{-10}$$

$$a_{\mu}^{hadr} = (692.3 \pm 4.2) \cdot 10^{-10} + (10.5 \pm 2.6) \cdot 10^{-10} + \dots$$

Future experimental measurements at Fermilab and J-PARC
expected to reduce uncertainty to $da_{\mu} \sim 1.6 \times 10^{-10}$

The uncertainty of the SM calculation dominated
by hadronic contributions and soon greatest limiting factor

$(g-2)_\mu$ HLbL contribution

$$a_\mu^{hadr} =$$

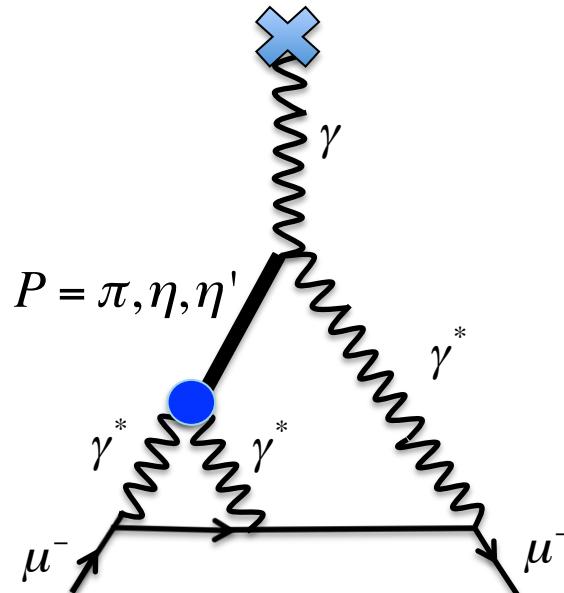
$$(692.3 \pm 4.2) \cdot 10^{-10} +$$

$$(10.5 \pm 2.6) \cdot 10^{-10}$$

J. Prades, E. de Rafael, A. Vainshtein, arXiv:0901.0306

$$(11.6 \pm 3.9) \cdot 10^{-10}$$

F. Jegerlehner and A. Nyffeler, Phys. Rept. 477, 1 (2009)



Interaction of virtual mesons with γ^*

No direct relation to measurable quantities-
model dependence

Off-shell P form factors not accessible
experimentally...but any aspiring theory/model
should be able to correctly describe also the
on-shell scenario

TFF used as experimental input

Based on dispersion relations

Provide direct link between HLbL contribution and experimental data

More reliable theoretical uncertainties

Approach based on analytic structure on HLbL tensor:

G. Colangelo, M. Hoferichter, M. Procura, and P. Stoffer
arXiv: 1402.7081v2 , 1408.2517v2, 1410.491v2 [hep-ph]

Approach based on analytic properties of the EM vertex function of muon:

V. Pauk and M. Vanderhaeghen
arXiv: 1403.7503 , 1409.0819 [hep-ph]

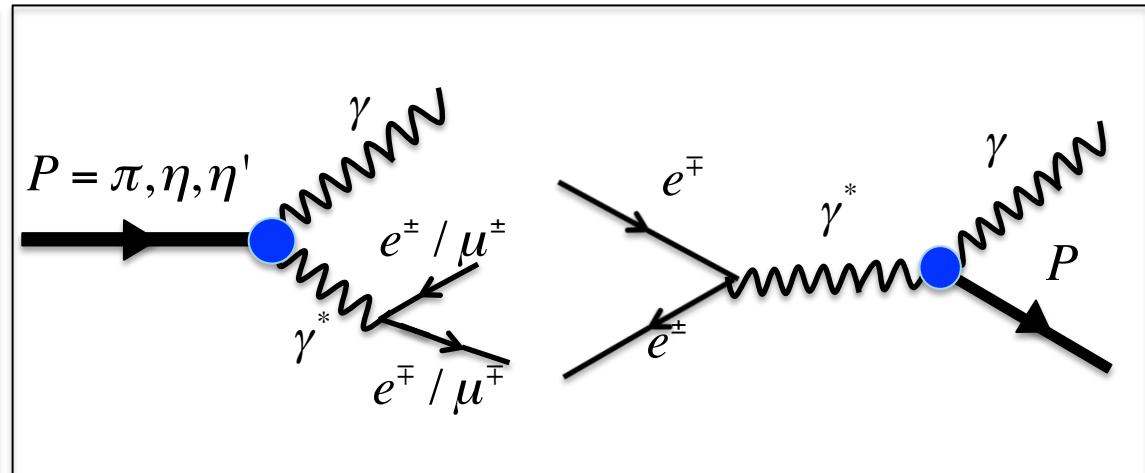
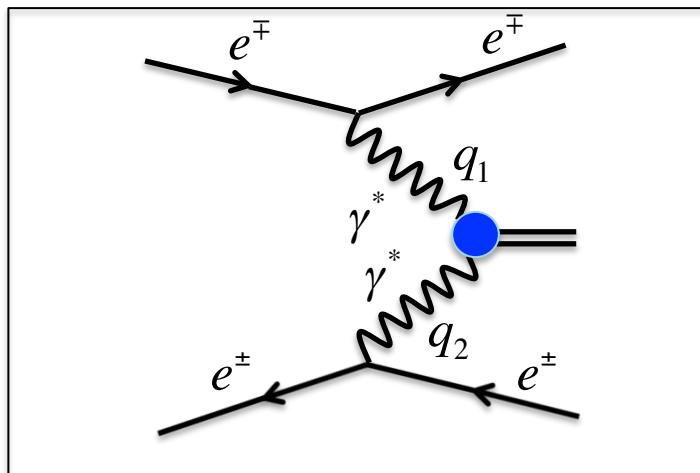
**On the precision of a data-driven estimate of HLbL in muon g-2:
pseudoscalar-pole contribution**

A.Nyffeler
arXiv:1602.03398 [hep-ph]

Space & Time-like Form Factors

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The Form Factor $F(q^2)$ expresses influence of hadronic internal structure on scattering cross-section
Meson TFF accessed in kinematical regions of (transferred squared four-momentum) q^2 through study of space- and time like processes



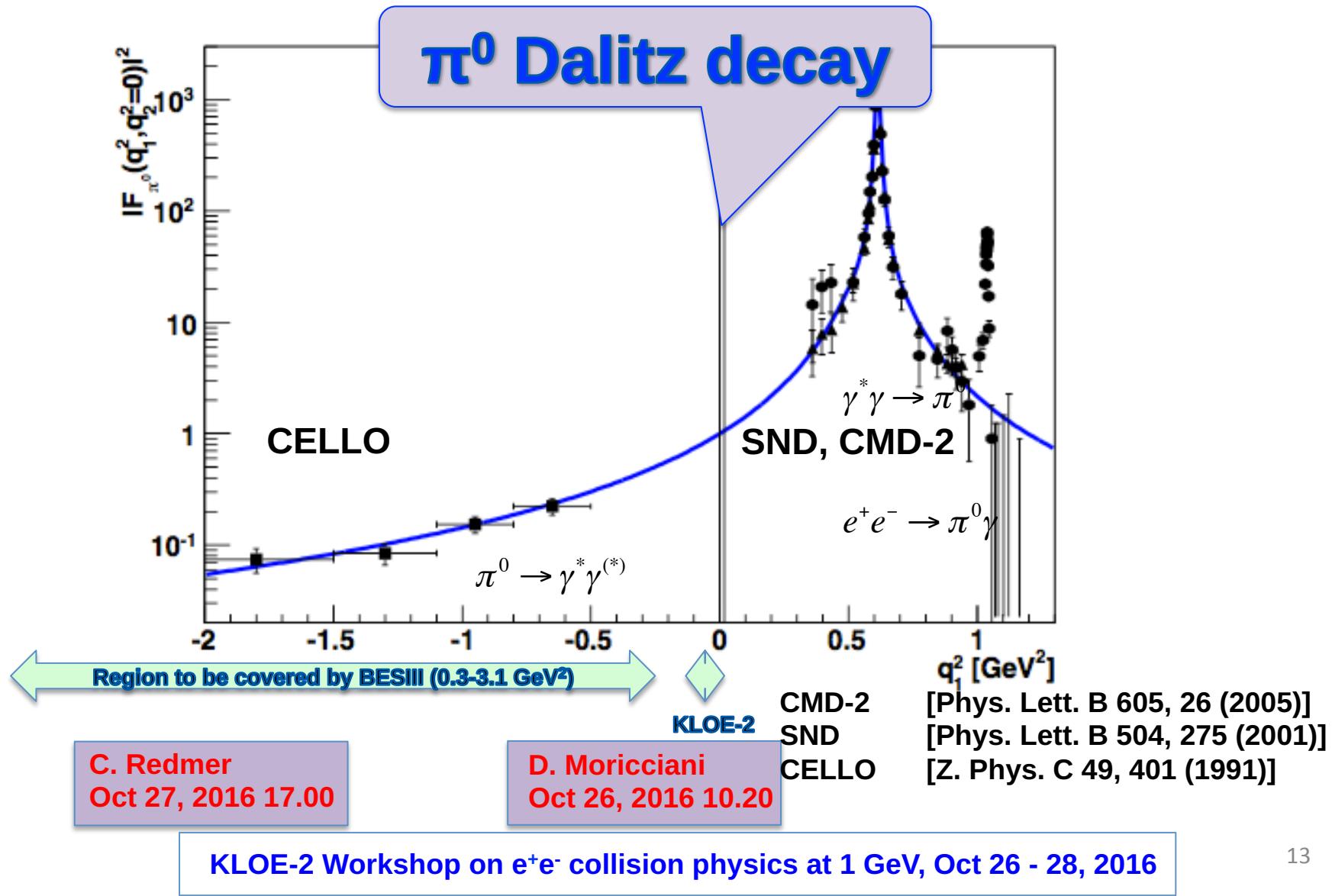
Space-like $q^2 < 0$

Photon-photon fusion
Accessed at e^+e^- colliders

Time-like $q^2 > 0$

Single or double Dalitz decay, $4m_l^2 < q^2 < m_P^2$
Annihilation process, $q^2 > m_P^2$

$\pi^0\gamma$ Transition Form Factor



π^0 Dalitz Decay

Observable: slope parameter a_π

$$\text{FF} = (1 - a_\pi x)^{-1} \sim 1 + a_\pi x \text{ for small } a_\pi$$

Theory

VMD	+0.031
ChPT 2 –loop	+0.029(5)
Kampf, Knecht, Novotný, EPJ C46 (2006) 191	

"...we think that a precise measurement of a_π which would not rely on any kind of extrapolation remains an interesting issue."

Dispersive approach +0.0307(6)
Hoferichter, et al. EPJ C74, 3180 (2014)

Padé approximants +0.0324(22)
P. Masjuan, Phys. Rev. D 86, 094021 (2012).

Experiment time-like

SINDRUM-I Coll. +0.025(14)_{stat}(26)_{syst} 54k
Drees et al Phys.Rev.D 45 (1992) 1439

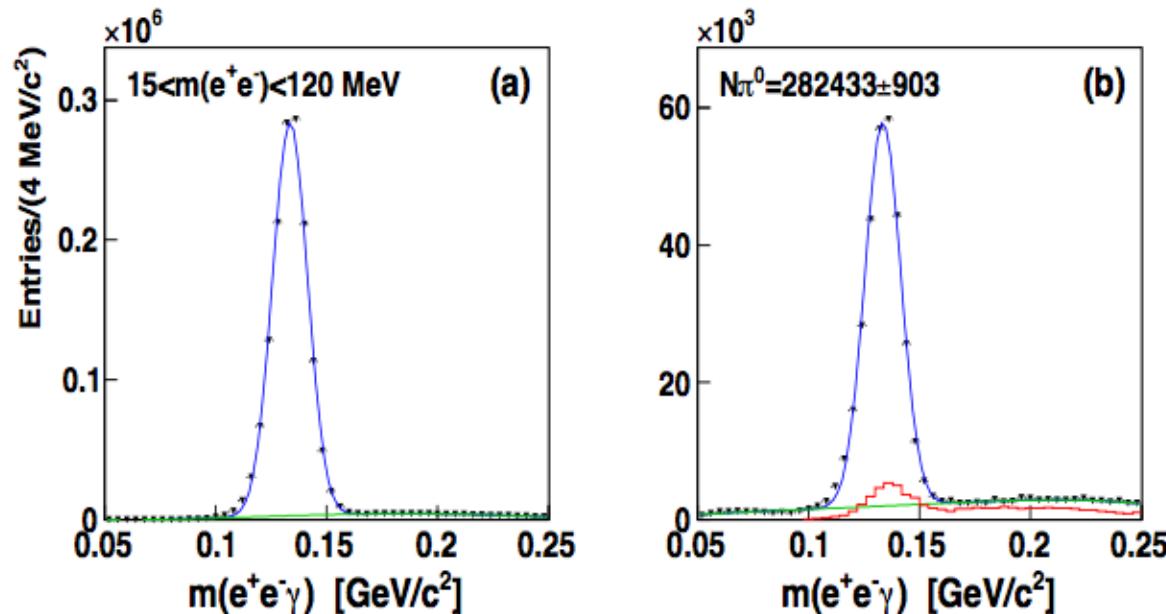
NA48/2 prel +0.0370(53)_{stat}(36)_{syst} 1050k
1609.02952

Extrapolation space-like region

CELLO +0.0326(26)_{stat}(26)_{syst}
Behrend et al (CELLO) Z. Phys.C 49 (1991) 401
CLEO +0.0303(8)_{stat}(9)_{syst}(12)
Gronberg et al (CLEO) Phys.Rev.D 57 (1998) 33

BESIII forthcoming

π^0 Dalitz Decay at A2



A2 result based on 4.0×10^5 Dalitz decays from 15-120 MeV in $m(e^+e^-)$ from two different beam times

Dalitz decay searched in 3 and 4 cluster events and identified from charged hits in PID and kinematical fit

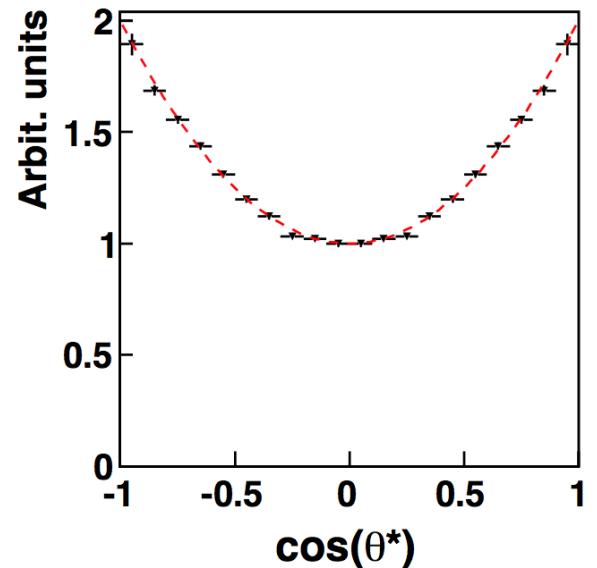
Different systematics compared to NA48/2

$$\frac{\Gamma(\pi^0 \rightarrow e^+ e^- \gamma)}{dm_{e^+ e^-} \Gamma(\pi^0 \rightarrow \gamma\gamma)} = |QED(m_{e^+ e^-})| |F_{\pi^0 \gamma}(m_{e^+ e^-})|^2$$

QED with radiative corrections taken into account
T. Husek, K. Kampf, and J. Novotny , Phys. Rev. D 92, 054027 (2015).

Low background content, normalization to $\pi^0 \rightarrow 2\gamma$

Data points dominated by statistical uncertainties



Angle between direction of one of leptons in dilepton rest frame and direction of the dilepton system

π^0 Dalitz Decay results A2

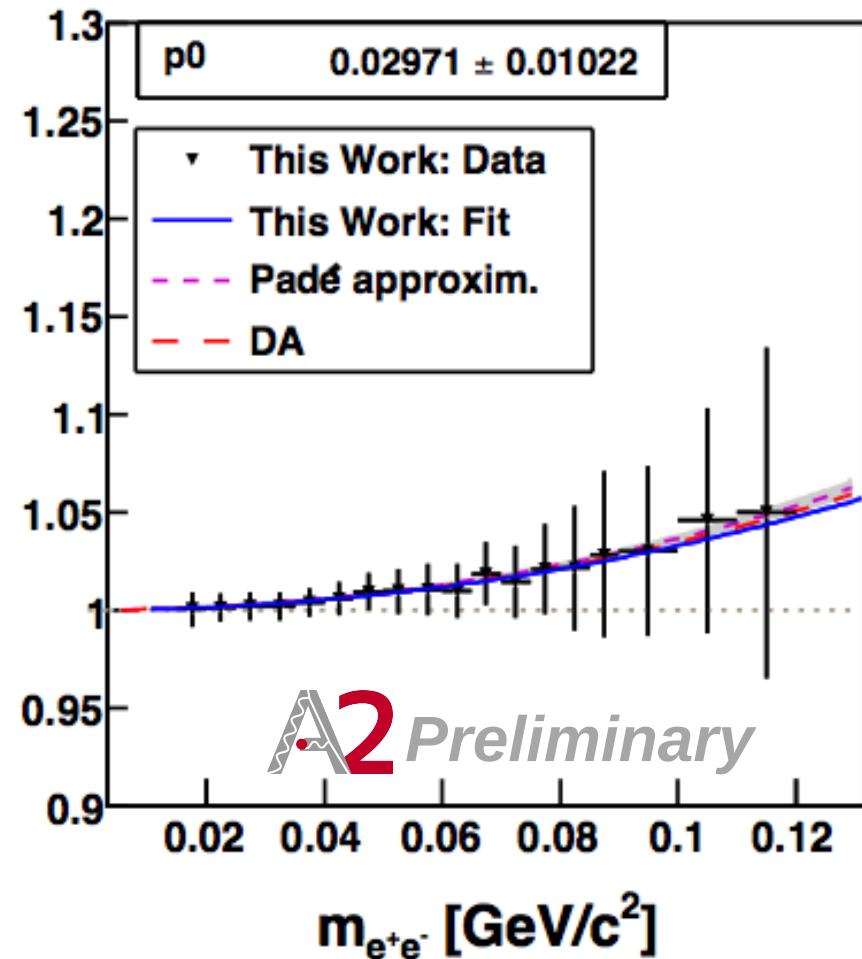
A2 Preliminary

$$a_\pi = 0.030(10)_{\text{tot}}$$

Good agreement with current theoretical estimates

18 data points with total uncertainties provided

To appear on arXiv in coming weeks

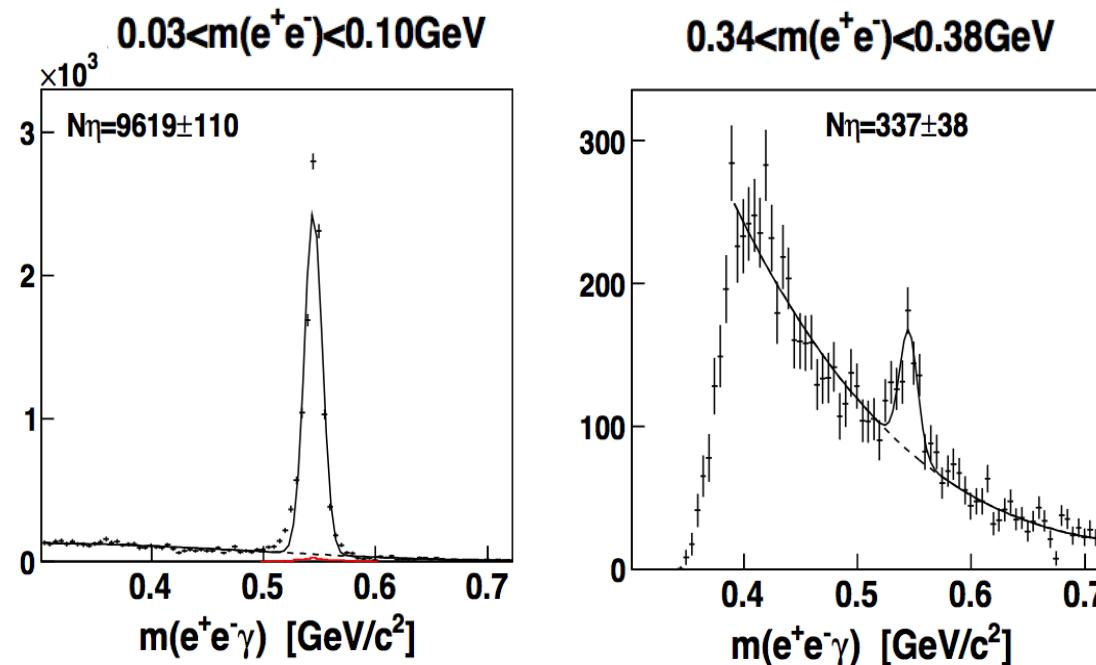


η Dalitz Decay

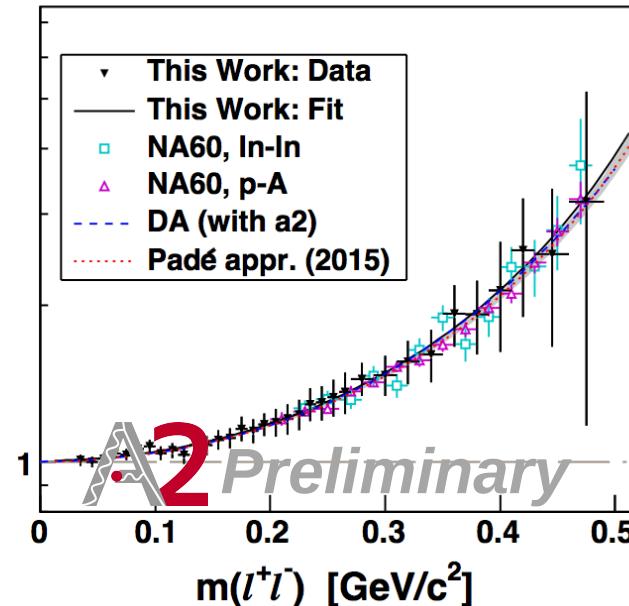
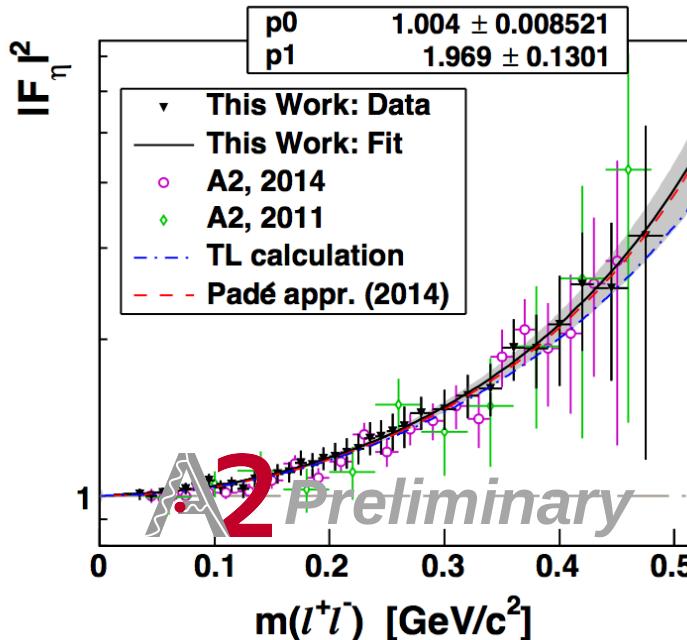
Previous result based on 2.2×10^4 Dalitz decays from A2

$$F(m_{ll}) = \left(1 - \frac{m_{ll}^2}{\Lambda^2}\right)^{-1} \quad \Lambda_{\eta\gamma}^{-2} = 1.95(15)_{stat}(10)_{syst} \text{ GeV}^{-2}$$

More than double the statistics with new result, 5.4×10^4



η Dalitz Decay results



A2	$\Lambda^{-2} = 1.97(13)_{\text{tot}} \text{ GeV}^{-2}$	[arXiv:1609.04503 (2016)]
	$ F_\eta ^2 = 1.004(8) \text{ compatible with 1 within } 1\sigma$	submitted to PRC
NA60	$\Lambda^{-2} = 1.934(67)_{\text{stat}} (50)_{\text{syst}} \text{ GeV}^{-2} (I = \mu)$	[Phys.Lett. B757 (2016) 437]



Good agreement with theory and NA60.
Data points with (improved) total uncertainties provided

V-P Transition Form Factors

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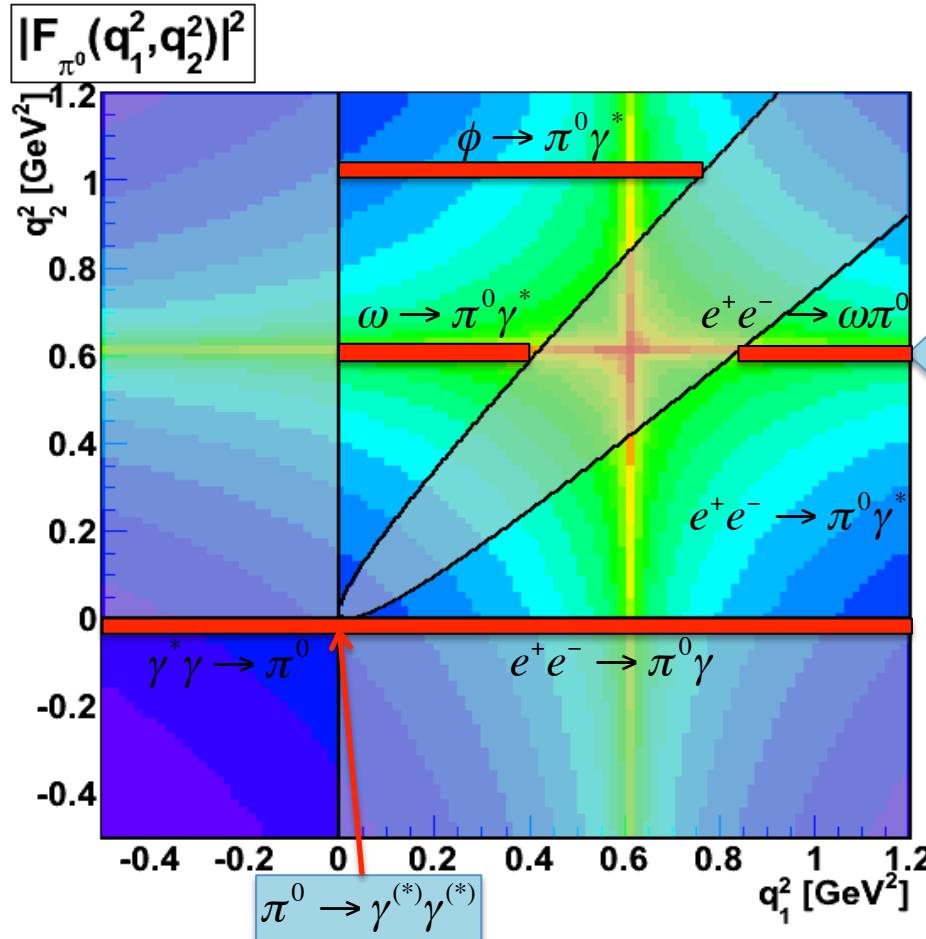


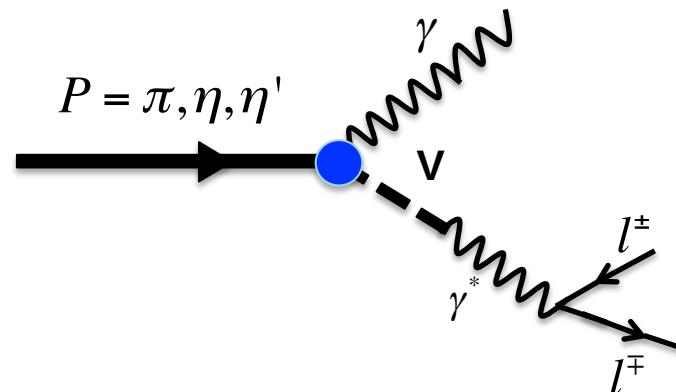
Figure by A. Kupsc, Uppsala University

Since Vector mesons act as intermediate states for TFF of Pseudoscalar mesons, also information obtained by studying TFF of Vector mesons to Pseudoscalar mesons are of interest.

- | | |
|-------|---------------------------------|
| NA60 | [Phys. Lett. B 677, 260 (2009)] |
| SND | [Phys. Lett. B 486, 29 (2000)] |
| CMD-2 | [Phys. Lett. B 562, 173 (2003)] |
| KLOE | [Phys. Lett. B 669, 223 (2008)] |

Vector Meson Dominance

In Vector Meson Dominance (VMD), virtual photon couples to intermediate vector meson state: $\rho, \omega, \phi, \dots J^P = 1^-$



Effect of VMD seen in annihilation process when q^2 approaches the resonant region of the vector meson

[L. G. Landsberg, Phys. Rept. 128, 301 (1985)]

$\omega\pi^0$ TFF and VMD

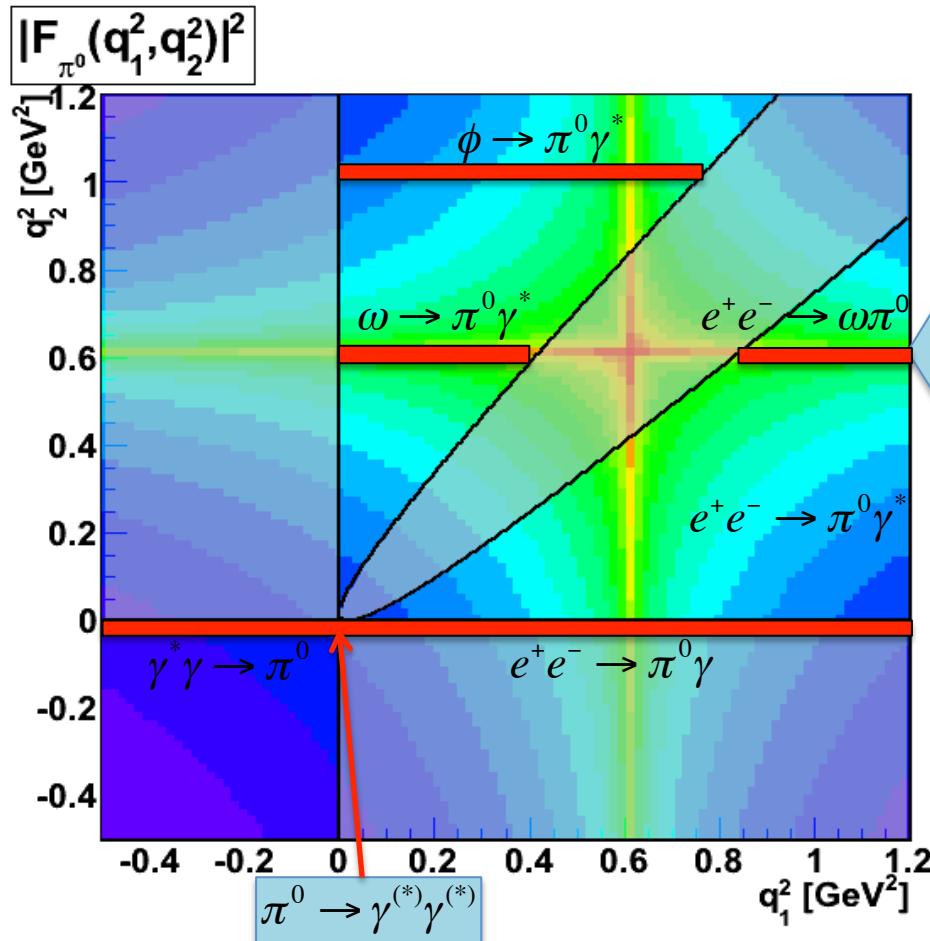


Figure by A. Kupsc, Uppsala University

VMD description fails to reproduce data

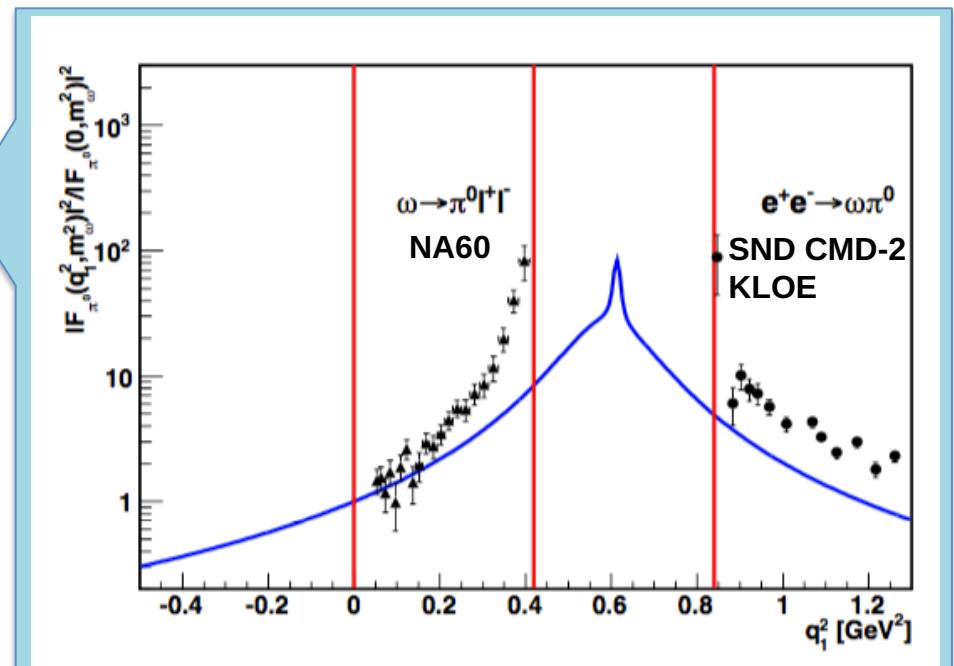


Figure from arXiv:1207.6556

- | | |
|-------|---------------------------------|
| NA60 | [Phys. Lett. B 677, 260 (2009)] |
| SND | [Phys. Lett. B 486, 29 (2000)] |
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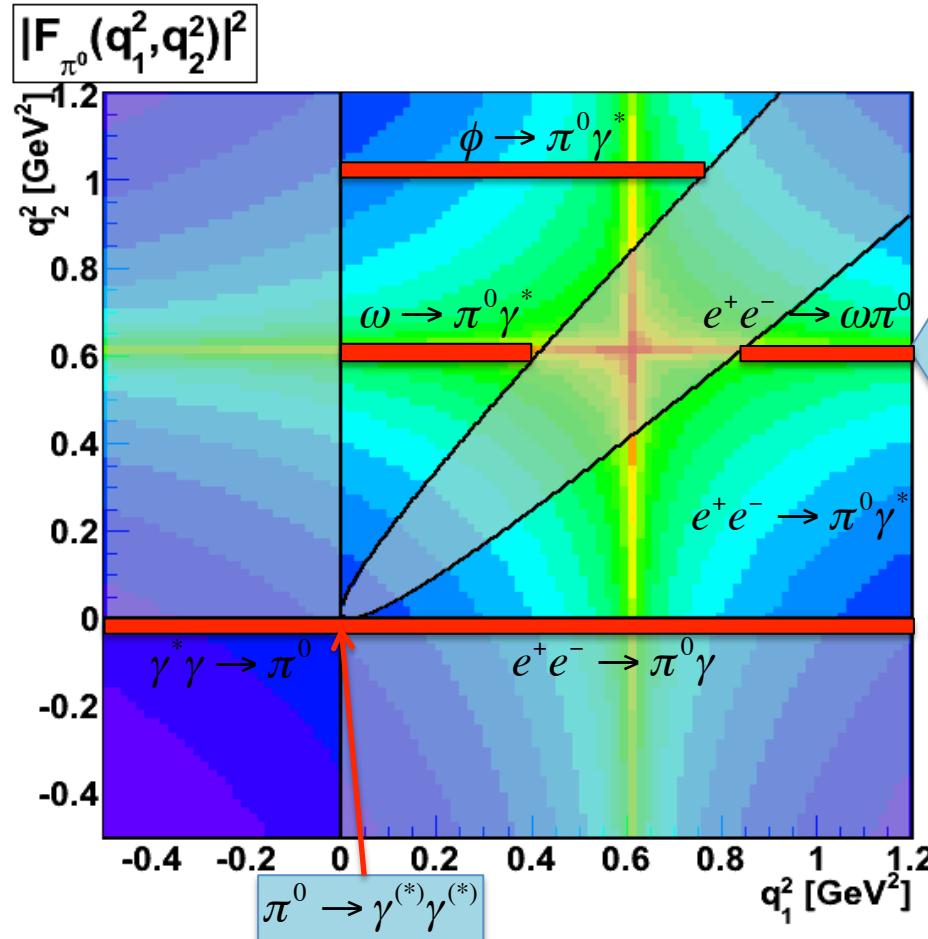
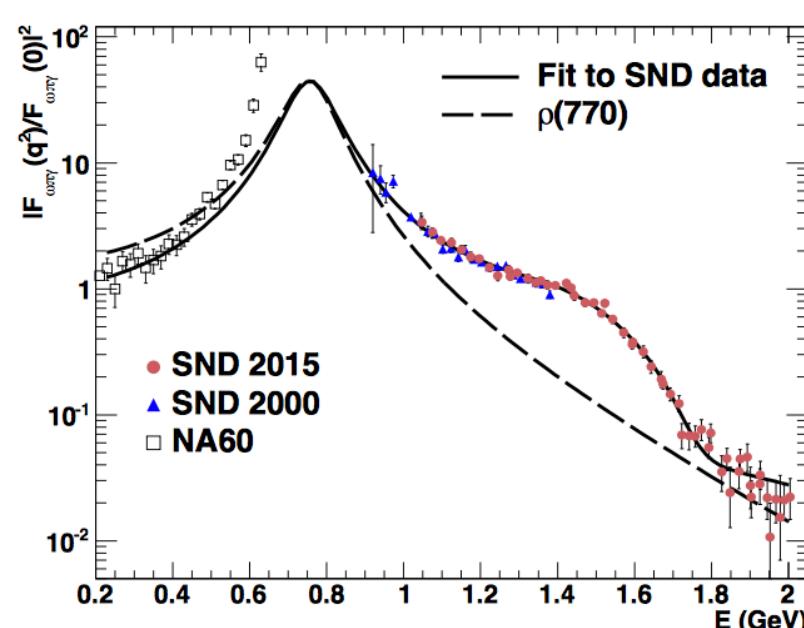


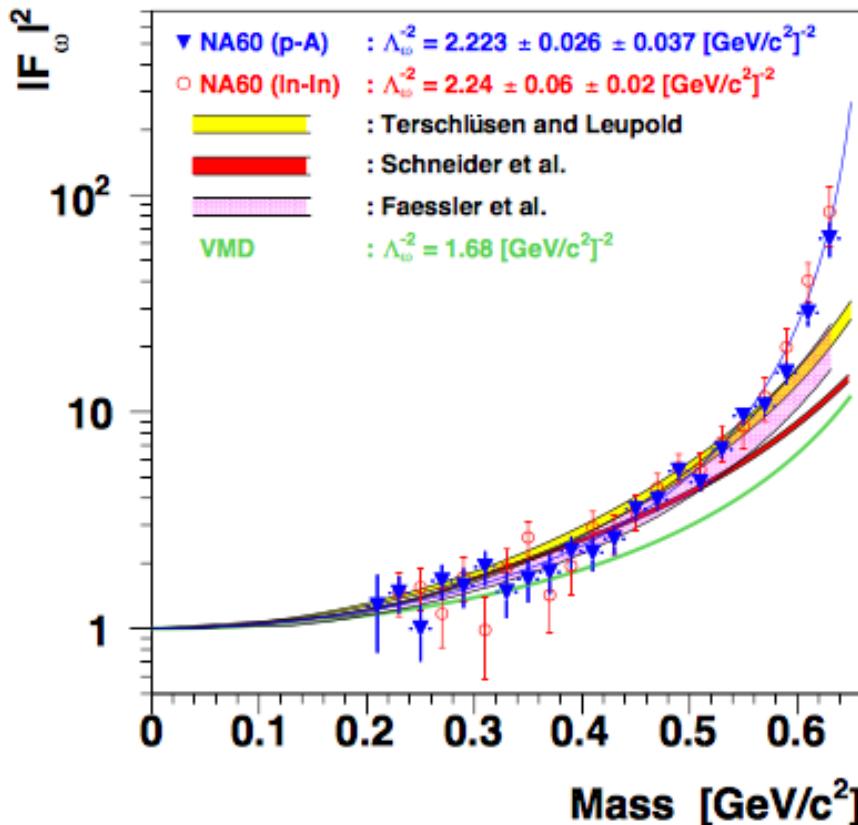
Figure by A. Kupsc, Uppsala University

Recent measurement 1.05 – 2 GeV

SND [arXiv: 1610.00235]

Fit to data found by using VMD fit with $\rho(770)$, $\rho(1450)$, $\rho(1700)$

NA60 Phys.Lett. B757 (2016) 437



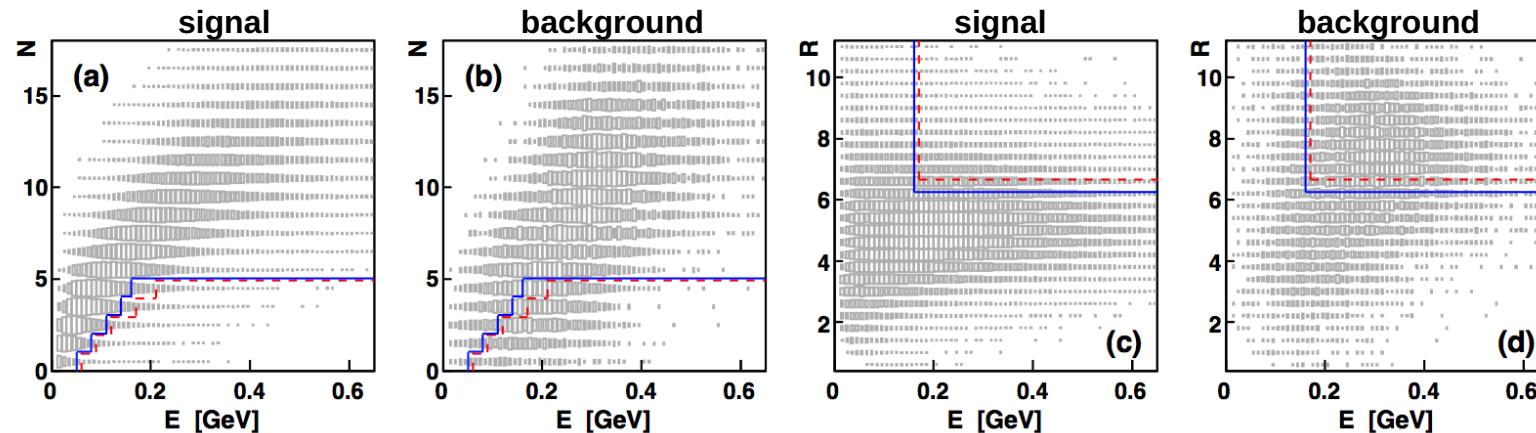
No theoretical approach which reproduce TFF data for η , and other mesons, can describe TFF data based on the $\omega \rightarrow \pi^0 \mu^+ \mu^-$ decay at large $m(\mu^+ \mu^-)$.

$$\Lambda_{\omega \pi^0}^{-2} = 2.223(26)_{\text{stat}}(37)_{\text{syst}} \text{ GeV}^{-2}$$

NA60 discrepancy solidified...independent results needed

Result based on two beam times. Parallel with η Dalitz decay analysis

More challenging background situation



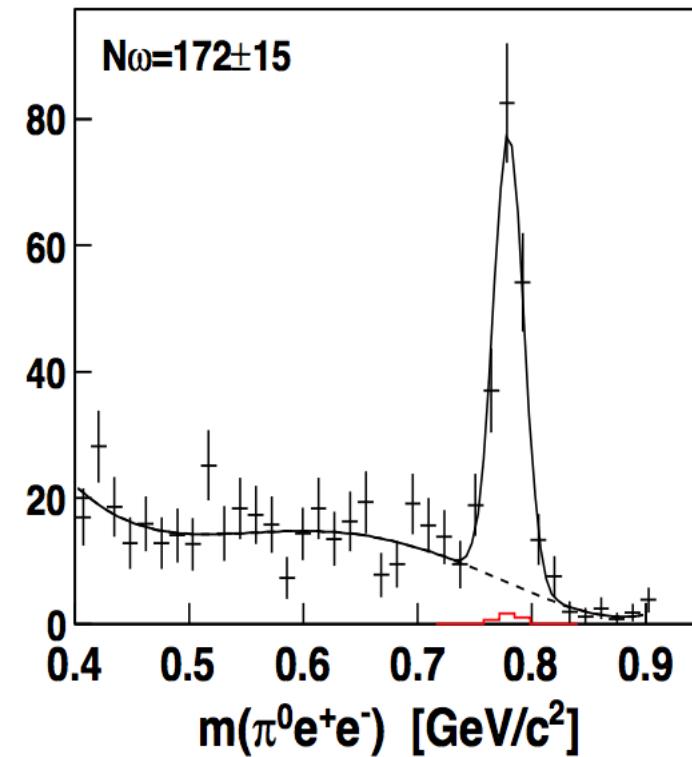
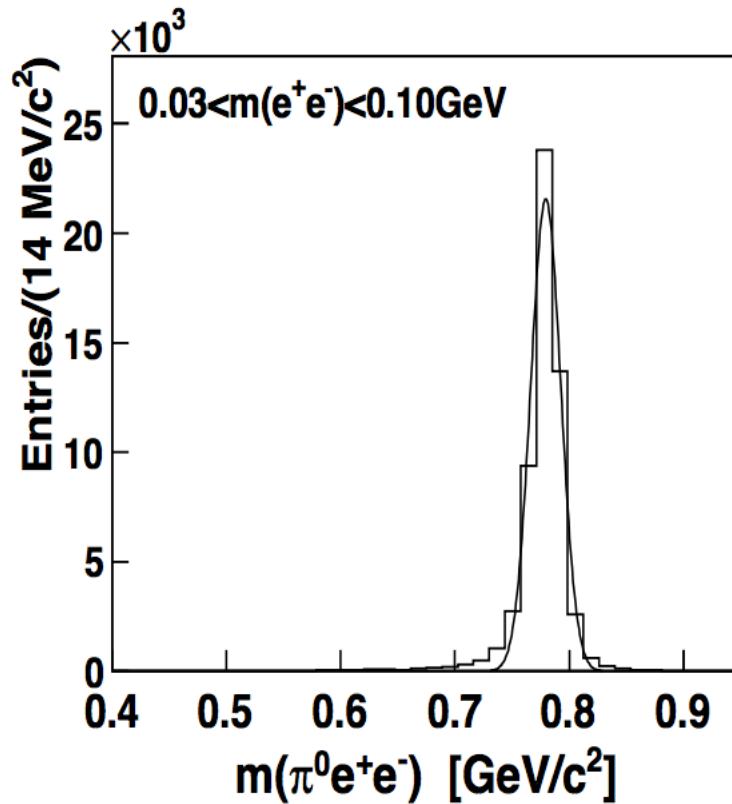
$\omega \rightarrow \pi^+ \pi^- \pi^0$ removed by cut on E vs N_{clust} & E vs Radius

General analysis method validated via η Dalitz decay analysis

In sum 1100 $\omega \rightarrow \pi^0 e^+ e^-$ decays based off 2.27×10^7 produced ω

$\omega \rightarrow \pi^0 e^+ e^-$ with A2

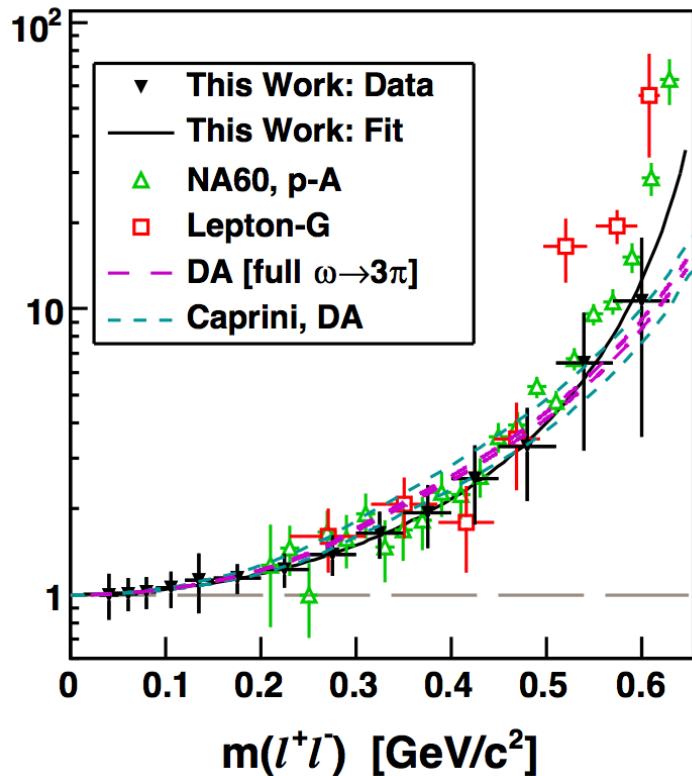
A2 arXiv:1609.04503



$m(\pi^0 e^+ e^-)$ split up into different regions in $m(e^+ e^-)$ and extracted with polynomial + Gaussian

$\omega \rightarrow \pi^0 e^+ e^-$ with A2

A2 Preliminary



NA60

$$\Lambda_{\omega\pi^0}^{-2} = 2.223(26)_{stat}(37)_{syst} \text{GeV}^{-2}$$

A2

$$\Lambda_{\omega\pi^0}^{-2} = 1.99(22)_{tot} \text{GeV}^{-2}$$

A2 arXiv:1609.04503
submitted to PRC

In agreement with theoretical descriptions, e.g. dispersive approaches

S. P. Schneider, B. Kubis, and F. Niecknig, Phys. Rev. D 86, 054013 (2012).

I. Caprini, Phys. Rev. D 92, 014014 (2015).

Slightly lower compared to NA60 but more experimental results needed

η' campaign 2014- special tagger built for this purpose
covering E_γ 1420-1585 MeV
Outcome: more than $6 \times 10^6 \eta'$ collected

Production mechanism:



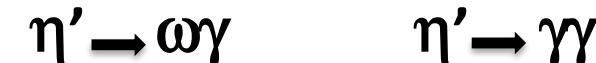
QCD:



Transition Form Factors



Branching ratios, Chiral EFT



Forbidden / Suppressed decays



η' Dalitz decay

First observation of η' Dalitz decay
Based on 1.3×10^9 J/ Ψ events from BESIII

$$\text{BR}(\eta' \rightarrow e^+e^-\gamma) = (4.69 \pm 0.20 \pm 0.23) \times 10^{-4}$$

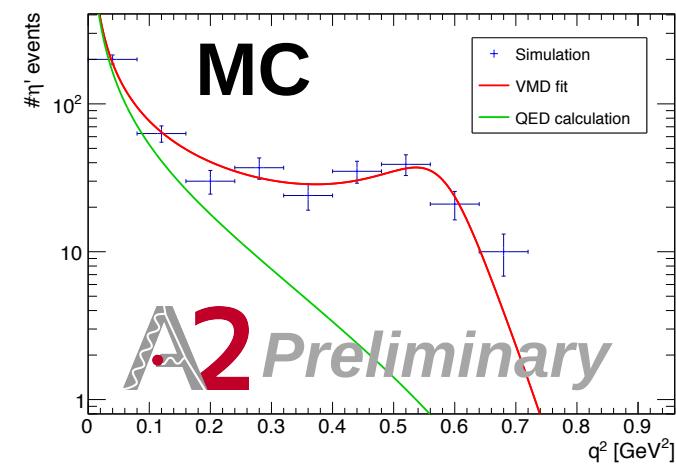
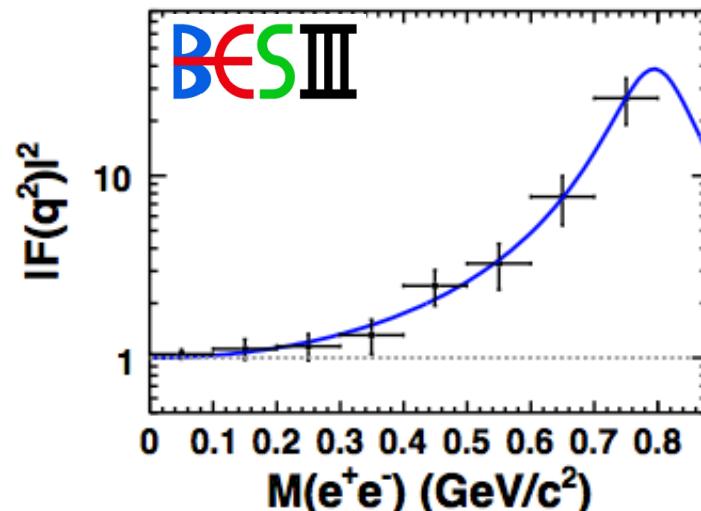
Pole is inside kinematical boundary
Form Factor parametrization

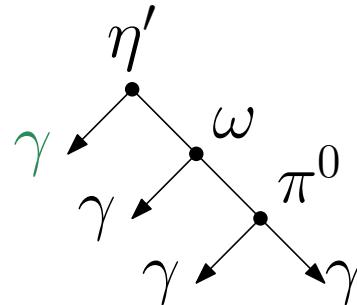
$$|F(q^2)|^2 = \frac{\Lambda^2(\Lambda^2 + \gamma^2)}{(\Lambda^2 - \gamma^2)^2 + \Lambda^2\gamma^2}$$

Λ, γ : mass and width of Breit-Wigner
effective contributing V meson

$\Lambda^2 = b = 1.60(17)(8)$	GeV^{-2}	BESIII
$\Lambda^2 = b = 1.45$	GeV^{-2}	VMD
$\Lambda^2 = b = 1.60$	GeV^{-2}	ChPT
$\Lambda^2 = b = 1.53^{+0.08}_{-0.15}$	GeV^{-2}	Disp

Phys. Rev. D 92, 012001 (2015)

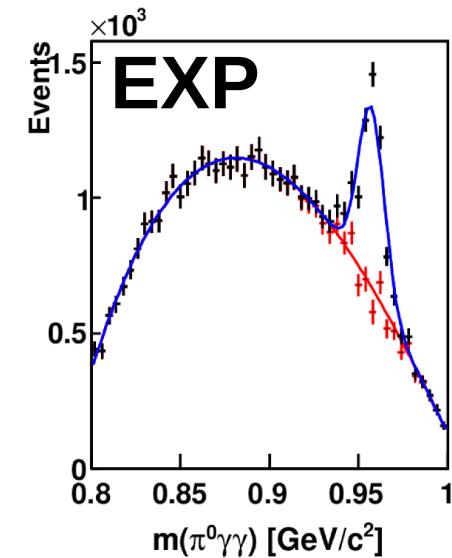
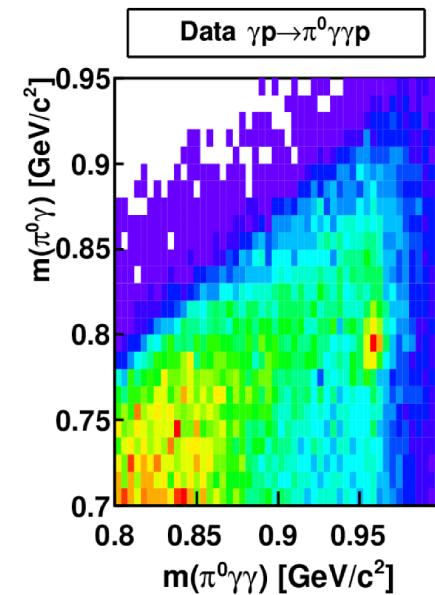
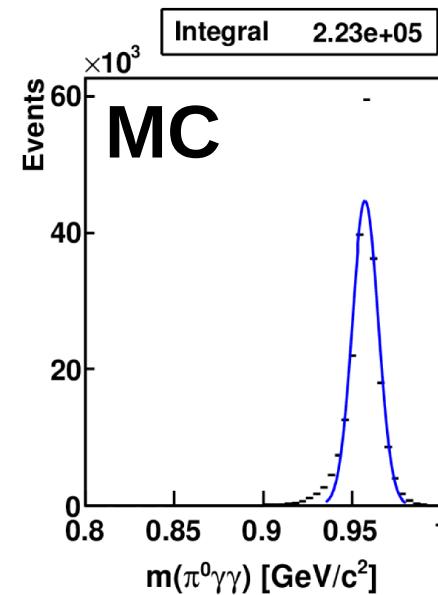
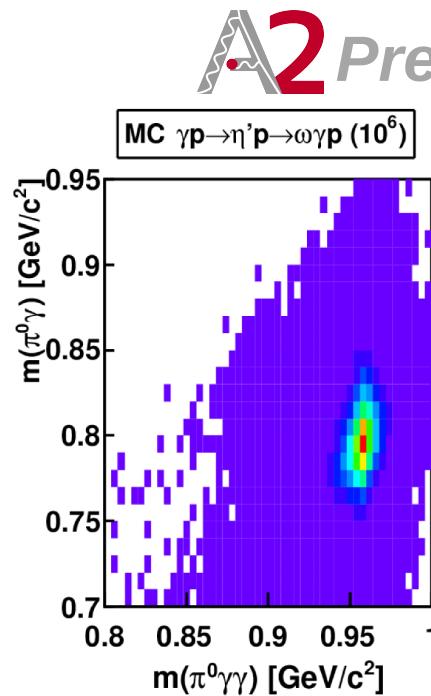




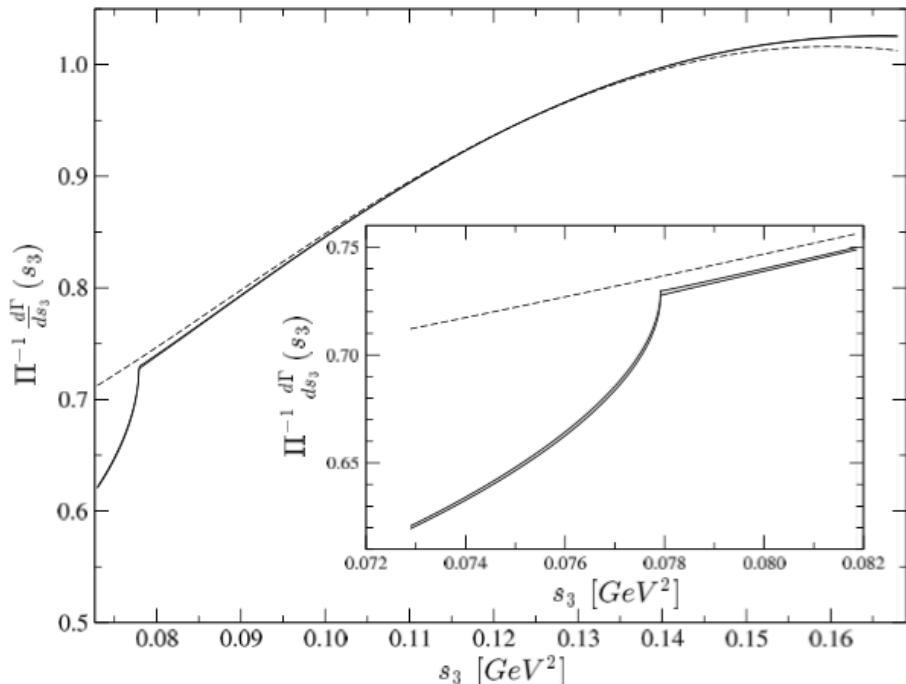
Pseudoscalar-Vector (PV) γ interaction input for Eff Field Theory

Objective: A framework of pseudoscalar and vector mesons

Experimental result A2: Branching ratios $\eta' \rightarrow \omega\gamma$ $\omega \rightarrow \eta\gamma$



Motivation $\eta' \rightarrow \eta \pi^0 \pi^0$



Cusp effect due to $\pi^+ \pi^- \rightarrow \pi^0 \pi^0$ rescattering

First seen in $K^+ \rightarrow \pi^0 \pi^0 \pi^+$ by NA48/2 coll

Predicted in $\eta / K_L \rightarrow 3\eta^0$ having few % effect

Figure from Eur.Phys.J. C62 (2009) 511

From study of cusp effect one can extract S-wave $\pi\pi$ scattering lengths

Prediction from Kubis, Schneider cusp is $6\% < m_{\pi^+ \pi^-}$ threshold for $\eta' \rightarrow \eta \pi^0 \pi^0$

Motivation $\eta' \rightarrow \eta \pi^0 \pi^0$

ChPT is low energy effective field theory of QCD – π , K , η
 η' not included as external d.o.f due to axial anomaly. Works well
below the resonance region m_σ

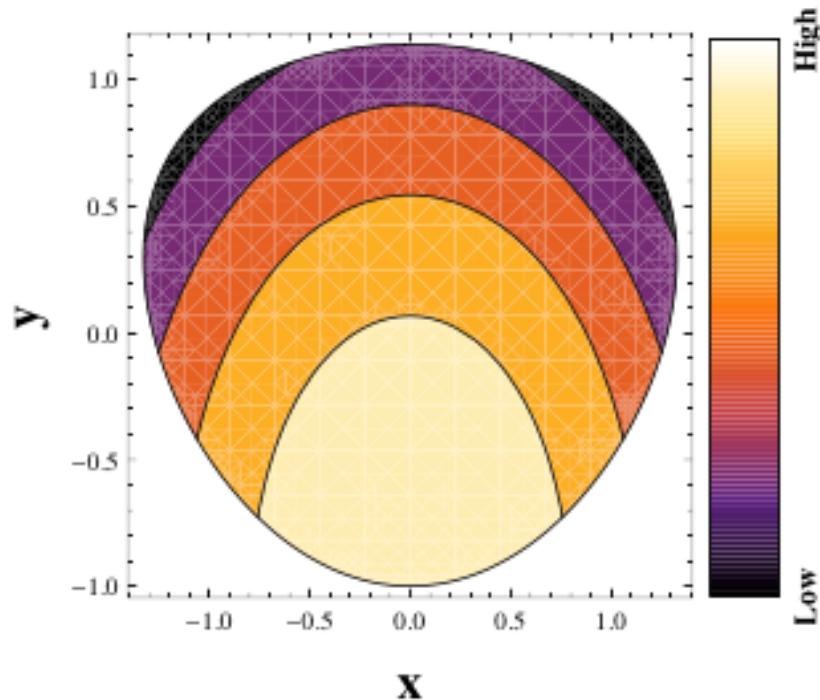
large N_C ChPT: axial anomaly absent $U(3)_L \times U(3)_R$ with π , K , η , η'
included. Does not include resonances as external states, but in LEC
[R. Kaiser and H. Leutwyler, Eur. Phys. J. C 17, 623 (2000)]

Resonance ChPT: takes resonances into account explicitly - ρ , σ , a_1
included

G. Ecker, J. Gasser, H. Leutwyler, A. Pich and E. de Rafael, Phys. Lett. B 223 (1989) 425

Tests ChPT extensions by Escrivano, Masjuan, Sanz-Cillero [JHEP 1105 (2011) 094]
with $\eta' \rightarrow \eta \pi \pi$ as probe

Dalitz plot $\eta' \rightarrow \eta \pi\pi$



Dalitz plot to compare theory and exp

$$X = \frac{\sqrt{3}(T_{\pi_1} - T_{\pi_2})}{Q} \quad Y = \frac{(m_\eta + 2m_\pi)}{m_\pi} \frac{T_\eta}{Q} - 1$$

$$Q = T_{\pi_1} + T_{\pi_2} + T_\eta = m_{\eta'} - m_\eta - 2m_\pi$$

$$|A(X,Y)|^2 = |N|^2 [1 + aY + bY^2 + cX + dX^2]$$

Dalitz plot parameters **a, b, c, d, ...**

In isospin limit neutral and charged decay should give same result

Charged decay BESIII collaboration 4.3×10^4 [Phys.Rev. D83 (2011) 012003]

Neutral decay GAMS4π collaboration 1.5×10^4 [Phys Atomic Nucl, 2009, Vol. 72, 231]

Dalitz plot $\eta' \rightarrow \eta \pi\pi$

Exp / Th	a	b	c	d
VES	-0.127(18)	-0.106(31)	-	-0.082(19)
BESIII	-0.047(11)	-0.069(21)	0.019(11)	-0.073(12)
GAMS4 π	-0.066(16)	-0.064(29)	-	0.067(20)
LN _C ChPT	-0.098(48)*	-0.050(1)	0	-0.092(8)
RChPT	-0.098(48)*	-0.033(1)	0	-0.072(1)

Dalitz plot to compare theory and exp

$$X = \frac{\sqrt{3}(T_{\pi_1} - T_{\pi_2})}{Q} \quad Y = \frac{(m_\eta + 2m_\pi)}{m_\pi} \frac{T_\eta}{Q} - 1$$

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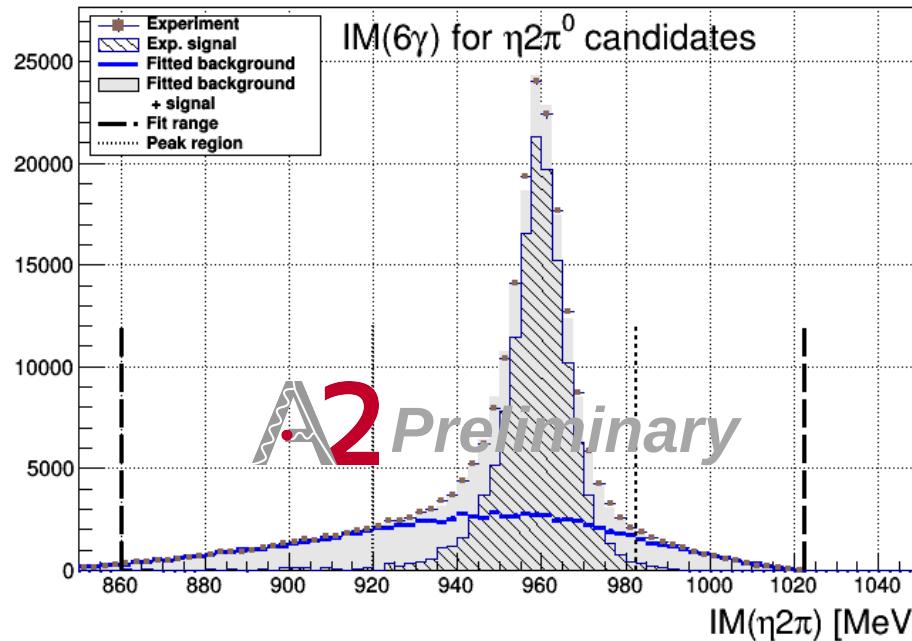
$$|A(X, Y)|^2 = |N|^2 [1 + aY + bY^2 + cX + dX^2]$$

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Kinematical fit with z-vertex in fit

Removal of background by kinfit with mass constraints

Largest background contribution $3\pi^0, \eta\pi^0$

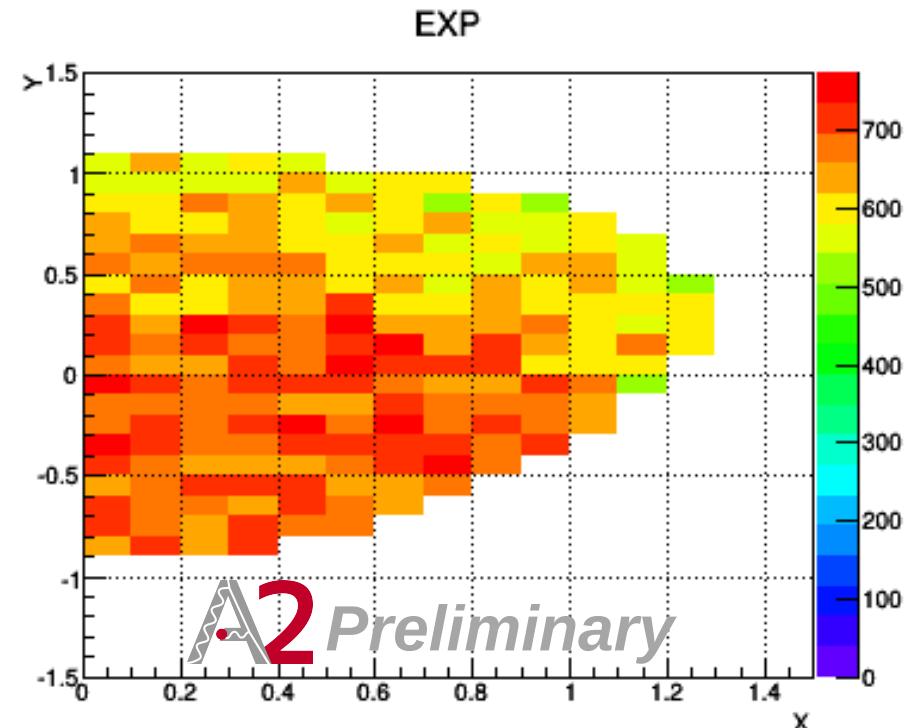
Almost one order of magnitude greater statistics compared to GAMS4 π
- 130 000 events

Charged decay BESIII collaboration 4.3×10^4 [Phys.Rev. D83 (2011) 012003]

Neutral decay GAMS4 π collaboration 1.5×10^4 [Phys Atomic Nucl, 2009, Vol. 72, 231]

Bin-by-bin background subtracted Dalitz plot compared to theoretical distribution multiplied by efficiency

Exp / Th	a	b	c	d
VES	-0.127(18)	-0.106(31)	-	-0.082(19)
BESIII	-0.047(11)	-0.069(21)	0.019(11)	-0.073(12)
GAMS4 π	-0.066(16)	-0.064(29)	-	0.067(20)
LN _C ChPT	-0.098(48)*	-0.050(1)	0	-0.092(8)
RChPT	-0.098(48)*	-0.033(1)	0	-0.072(1)
A2 prel	-0.073(8)	-0.072(13)	-	-0.054(11)



Cusp region under study and systematical cross-checks

Summary A2 results

Several new results from A2 collaboration on time-like TFF. Prepared for theoreticians by giving data points with total uncertainties



η' campaign in 2014. Several Ph.D. and post-docs working on the analyses. Preliminary results on $\eta' - \eta \pi^0 \pi^0$ Dalitz plot

Outlook: Exciting results from A2 in the upcoming years.

THANK YOU