HLbL from an experimentalist perspective

Andrzej Kupsc
Uppsala University

Study of Strongly Interacting Matter
HadronPhysics

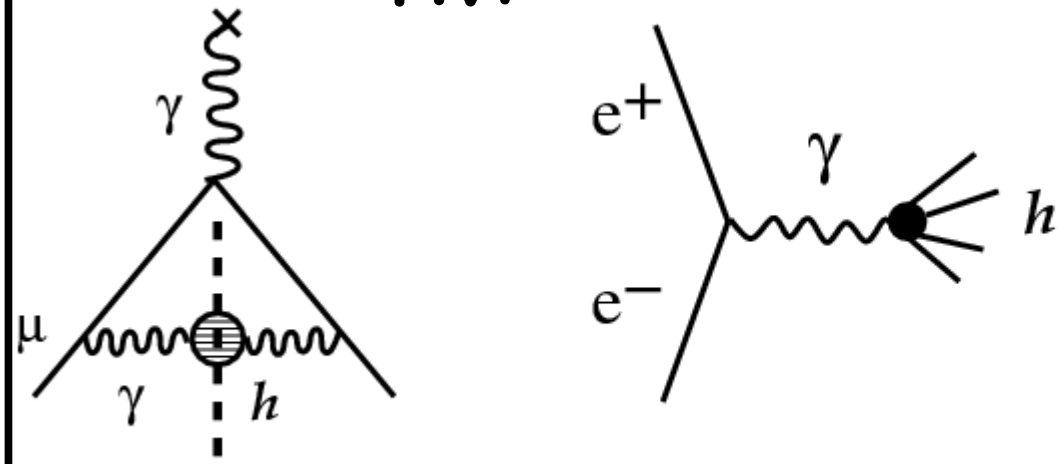
UPPSALA
UNIVERSITET

"g-2 Quo vadis?", Mainz, April 9th, 2014

- Data driven HLbL determination?
- Transition Form Factors of π^0,η,η'
  - → Kinematic regions/data sources
  - → Anomalous processes PVV, PPPV
  - → Dispersive approach to TFF
- $\gamma^{(*)}\gamma^{(*)} \to \pi\pi, \ldots$
- Strategy for experiment?

Hadronic contribution to g-2

HVP



e+e- → γ* → h

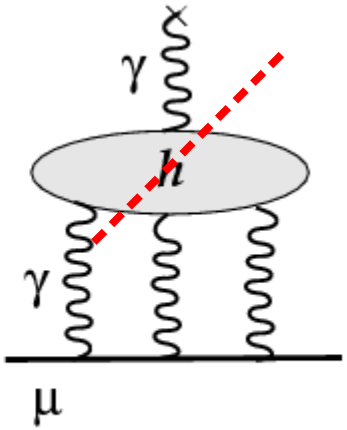
KLOE-2

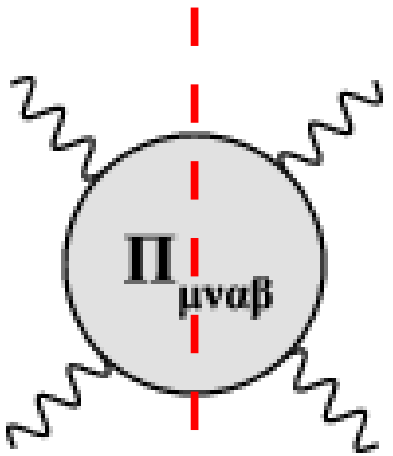
CMD3/SND

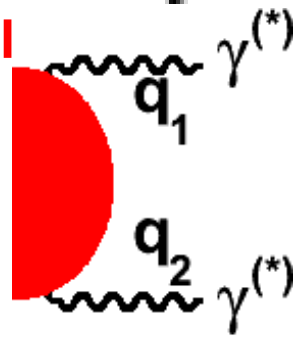
BESIII

BelleII

HLbL







Hadrons

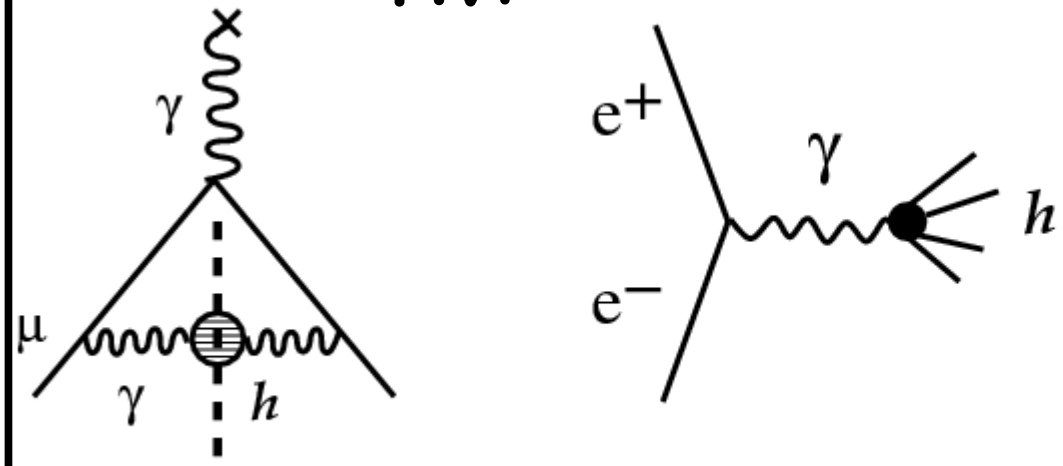
γ(*)γ(*) ↔h

γ(*)→hγ(*)

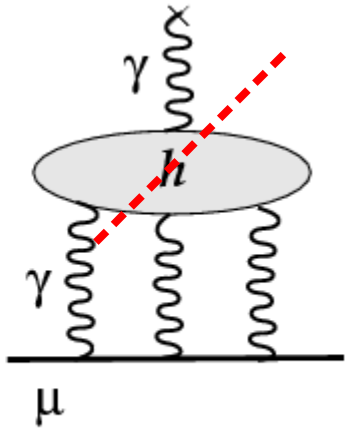
mh<1-2 GeV

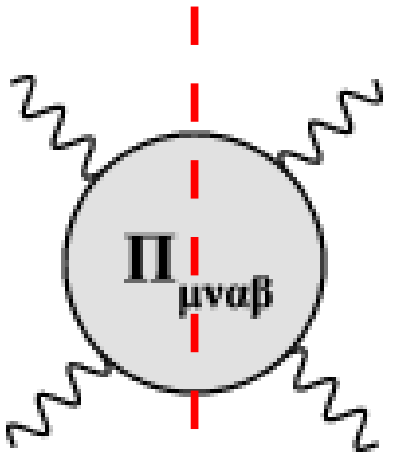
Hadronic contribution to g-2

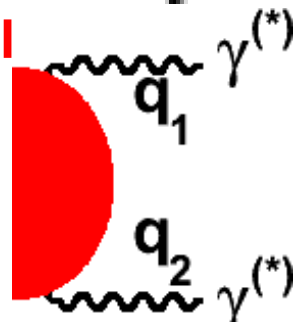
HVP



HLbL







Hadrons

e+e- → γ* → h

KLOE-2

CMD3/SND

BESIII

BelleII

γ(*)γ(*) ↔h

γ(*)→hγ(*), hγ(*)→hγ(*)

+ hadro- photo-production exp

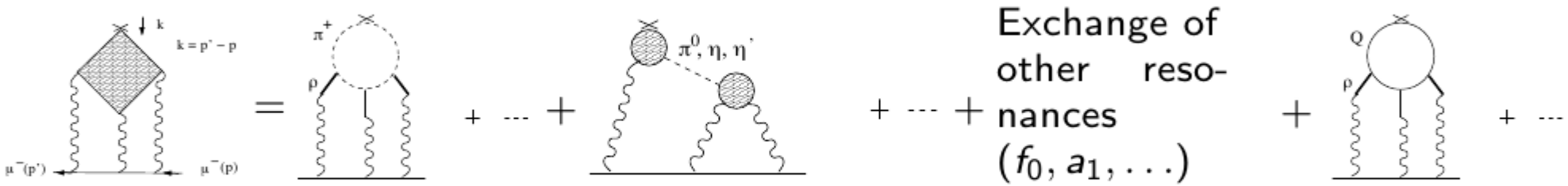
mh<1-2 GeV

Hadronic Light by Light

New g-2 experiment at Fermilab with error

$$\sim 1.6 \cdot 10^{-10}$$

$$a_\mu^{\mathrm{HLbL}} = 10.5(2.6) \times 10^{-10}$$



Chiral counting:	p^4	p^6	p^8	p^8
N_C-counting:	1	N_C	N_C	N_C
	$\pi^\pm$,K-loop	π^0, η,η' exchange		quark-loop
PdRV	$(-1.9\pm1.9)\cdot10^{-10}$	$(11.4\pm1.3)\cdot10^{-10}$	$(0.8\pm1.1)\cdot10^{-10}$	$0.23\cdot10^{-10}$

E. de Rafael, "Hadronic contributions to the muon g-2 and low-energy QCD," Phys. Lett. **B322** (1994) 239-246. [hep-ph/9311316].

Slide: Johan Bijnens,Pere Masjuan

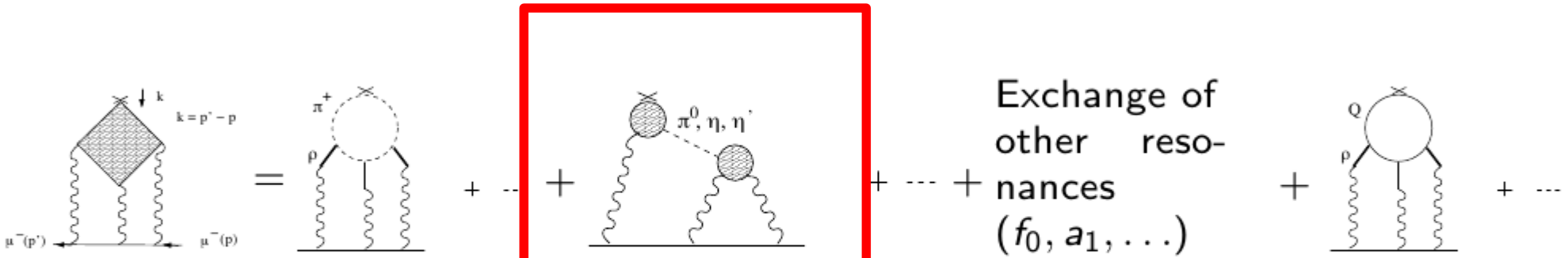
Hadronic Light by Light

New g-2 experiment at Fermilab with error

$$\sim 1.6 \cdot 10^{-10}$$

$$a_\mu^{\mathrm{HLbL}} = 10.5(2.6) \times 10^{-10}$$

Chiral Perturbation Theory counting (p^2)+large-Nc counting



Chiral counting:	p^4	p^6	p^8	p^8
N_C-counting:	1	N_C	N_C	N_C

$$\pi^0 \rightarrow \sim 7 \cdot 10^{-10}$$

$$\eta \rightarrow \sim 1.5 \cdot 10^{-10}$$

$$\eta' \rightarrow \sim 1.5 \cdot 10^{-10}$$

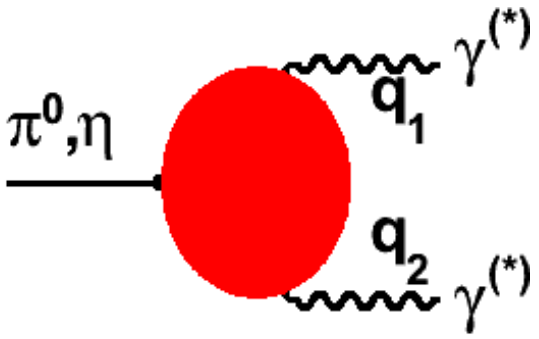
Pseudoscalar Transition Form Factors (TFF)

Structure of light mesons

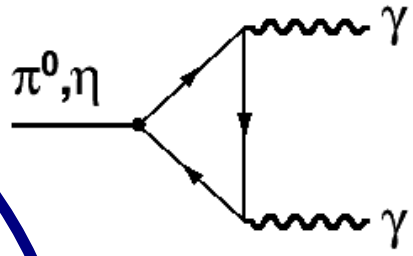
L/H energy QDC LAB

l^+l^- spectra in HIon

$\Gamma(P \to \gamma\gamma)$



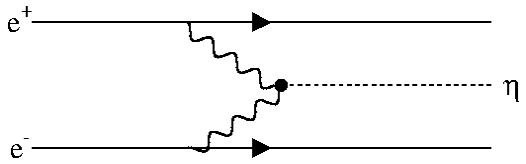
$F_P(q_1^2, q_2^2)$

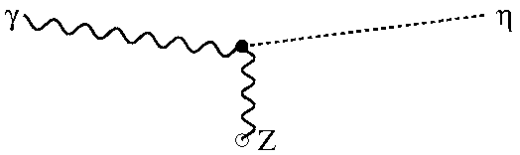


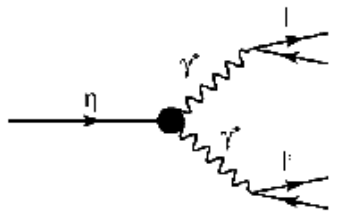
η: Γγγ

m_u/m_d

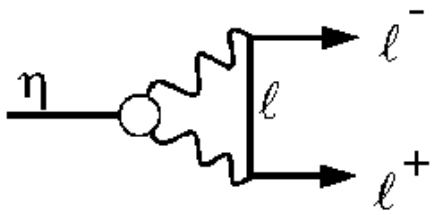
$F\pi^0$ $q^2 \to \infty$ puzzle

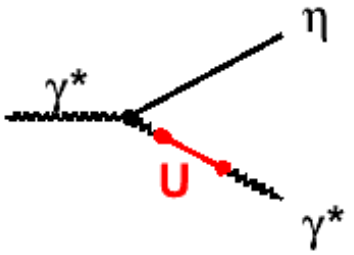




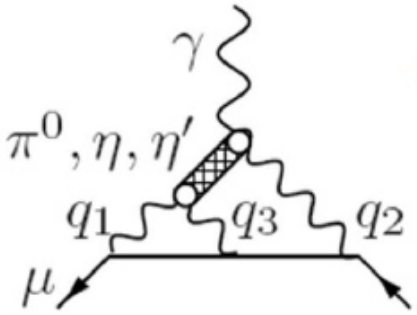


$P \to l^+l^-$





Dark photon



g-2 HLbL

Radiative widths of η, π^0

η, π^0 : narrow and short lived

=> $\Gamma_{tot}=\Gamma_{\gamma\gamma}/BR_{\gamma\gamma}$

η: 5×10^{-19} s; Γ=1.3 keV $\quad \eta \to \gamma\gamma$

π^0: 8×10^{-17} s; $c\tau$=25 nm $\quad \pi^0 \to \gamma\gamma$

Two exp. techniques:

$\gamma Z \to \eta, \pi^0$ Primakoff

$\delta\Gamma(\pi^0\to\gamma\gamma)$ ~2.8%

PrimEx PRL 106,162303(2011)

$\delta\Gamma(\eta\to\gamma\gamma)$ ~5%

VALUE (keV)	EVTS	DOCUMENT ID		TECN	COMMENT
0.510 ± 0.026	**OUR FIT**				
0.510 ± 0.026	**OUR AVERAGE**				
0.51 ± 0.12 ± 0.05	36	BARU	90	MD1	$e^+e^-\to e^+e^-\eta$
0.490 ± 0.010 ± 0.048	2287	ROE	90	ASP	$e^+e^-\to e^+e^-\eta$
0.514 ± 0.017 ± 0.035	1295	WILLIAMS	88	CBAL	$e^+e^-\to e^+e^-\eta$
0.53 ± 0.04 ± 0.04		BARTEL	85E	JADE	$e^+e^-\to e^+e^-\eta$
* * * We do not use the following data for averages, fits, limits, *etc.* * * *					
0.476 ± 0.062	[1]	RODRIGUES	08	CNTR	Reanalysis
0.64 ± 0.14 ± 0.13		AIHARA	86	TPC	$e^+e^-\to e^+e^-\eta$
0.56 ± 0.16	56	WEINSTEIN	83	CBAL	$e^+e^-\to e^+e^-\eta$
0.324 ± 0.046		BROWMAN	74B	CNTR	Primakoff effect
1.00 ± 0.22	[2]	BEMPORAD	67	CNTR	Primakoff effect

e^+e^-: $\gamma\gamma \to \eta, \pi^0$

KLOE-2 Taggers

$5fb^{-1}$ => $\delta\Gamma(\pi^0\to\gamma\gamma)$ ~1%

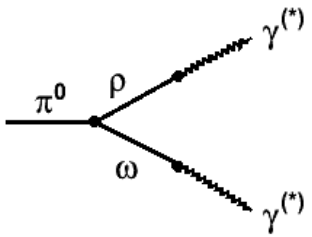
Details: [EPJC 72, 1917 (2012)]

$\sigma(e^+e^- \to e^+e^-\eta, \sqrt{s}=1GeV)$

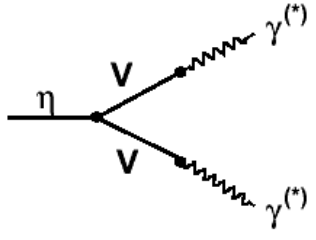
$\Gamma_{\gamma\gamma}=520\pm20_{stat}\pm13_{syst}$ eV

[KLOE JHEP1301 (2013) 119]

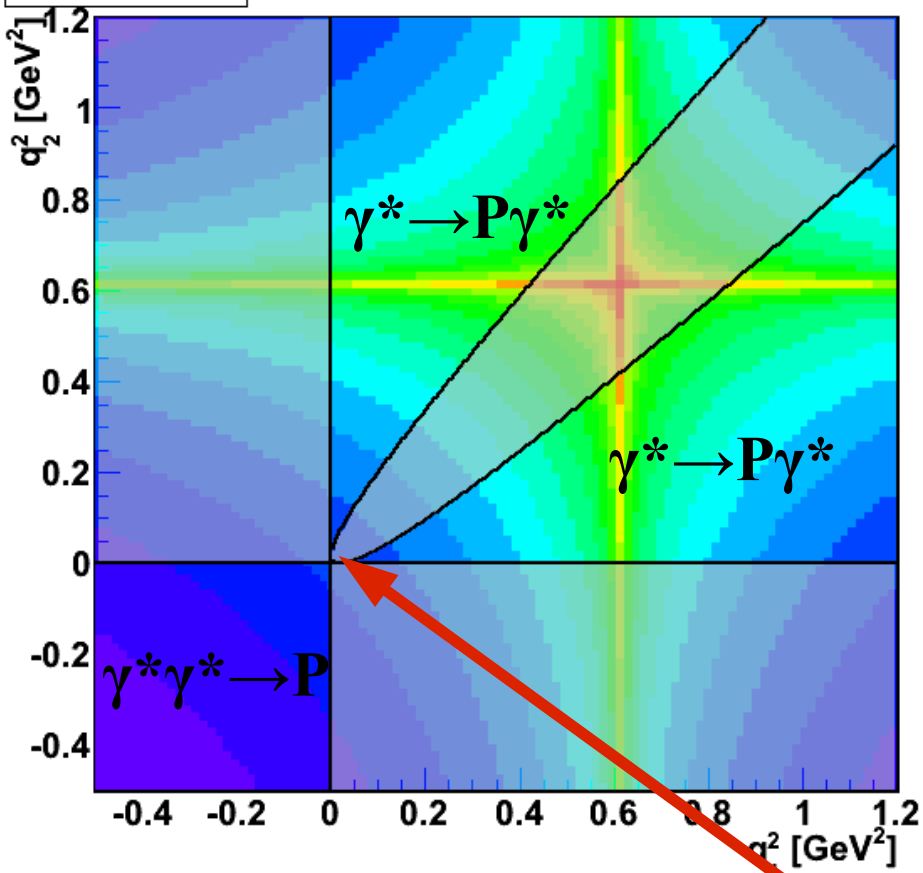
TFF kinematic regions: π^0,η



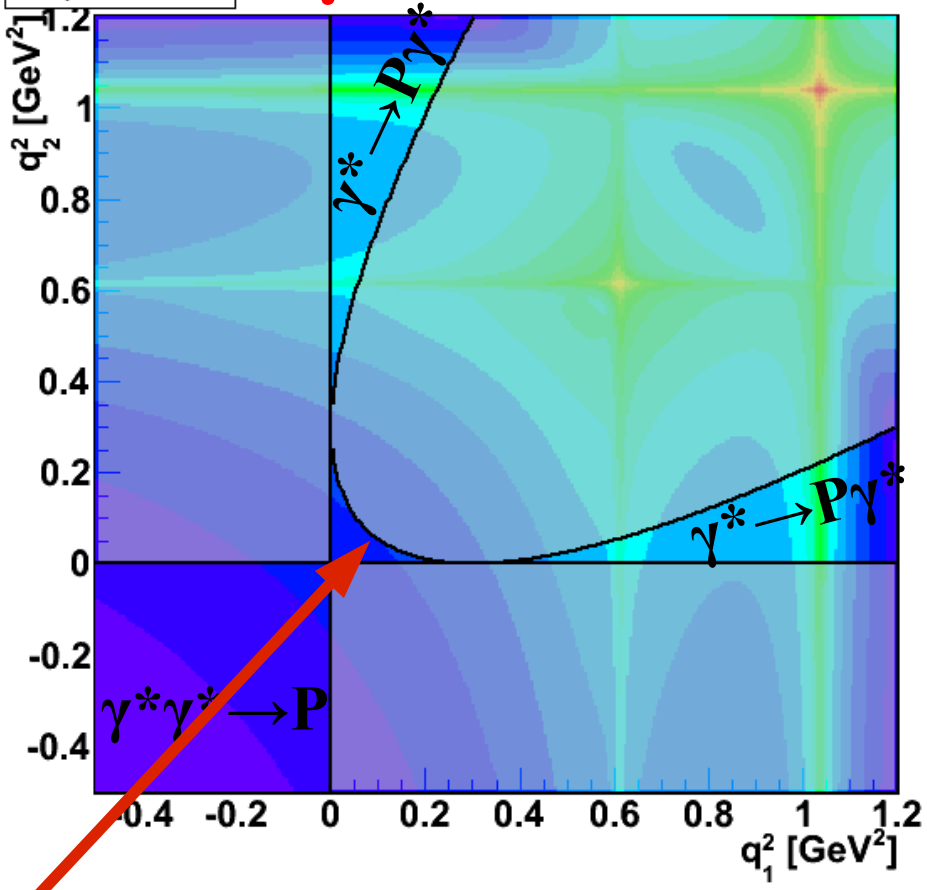
$$\sum_{V=\rho,\omega,\phi}$$



$|F_{\pi^0}(q_1^2,q_2^2)|^2$ **π^0**

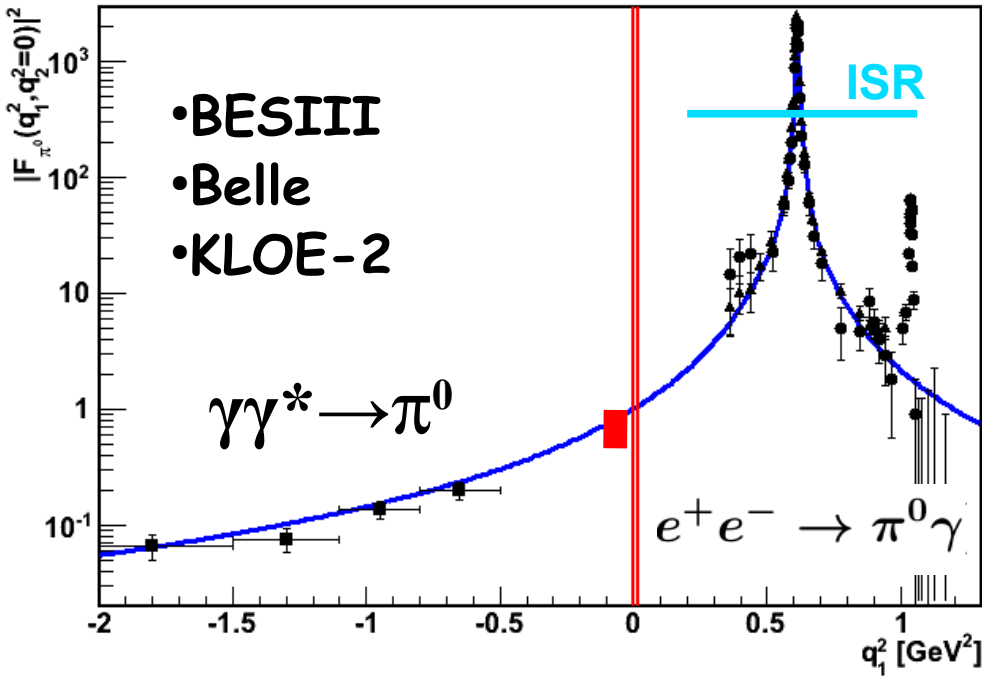


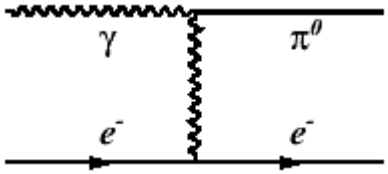
$|F_{\eta}(q_1^2,q_2^2)|^2$ **η**



$P \rightarrow \gamma^*\gamma^*$

η,π^0 single off shell TFF





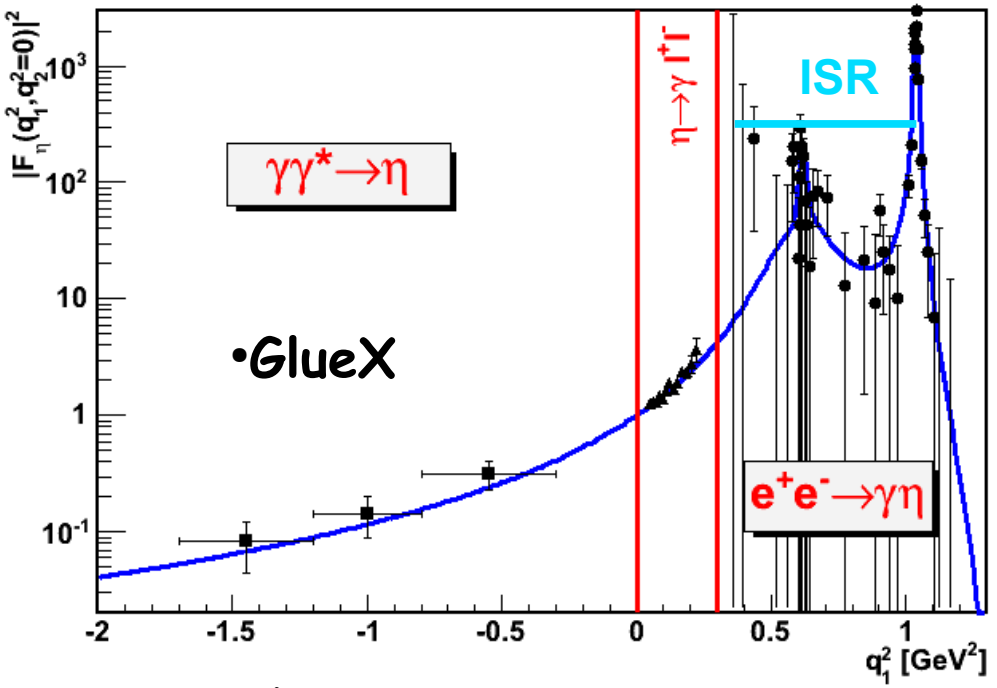
$$\frac{d\sigma}{dt}(e^-\gamma \to e^- P) = \frac{16}{3}\frac{\pi\alpha}{s m_P^3}\,\Gamma_{\gamma\gamma}|F_P(t,0)|^2\,\frac{s-m_P^2+t}{t}$$

P→γ*γ

Dalitz decays:

KLOE, WASA,CBall,BESIII

CLAS,NA48

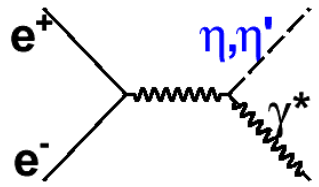


γ*→Pγ

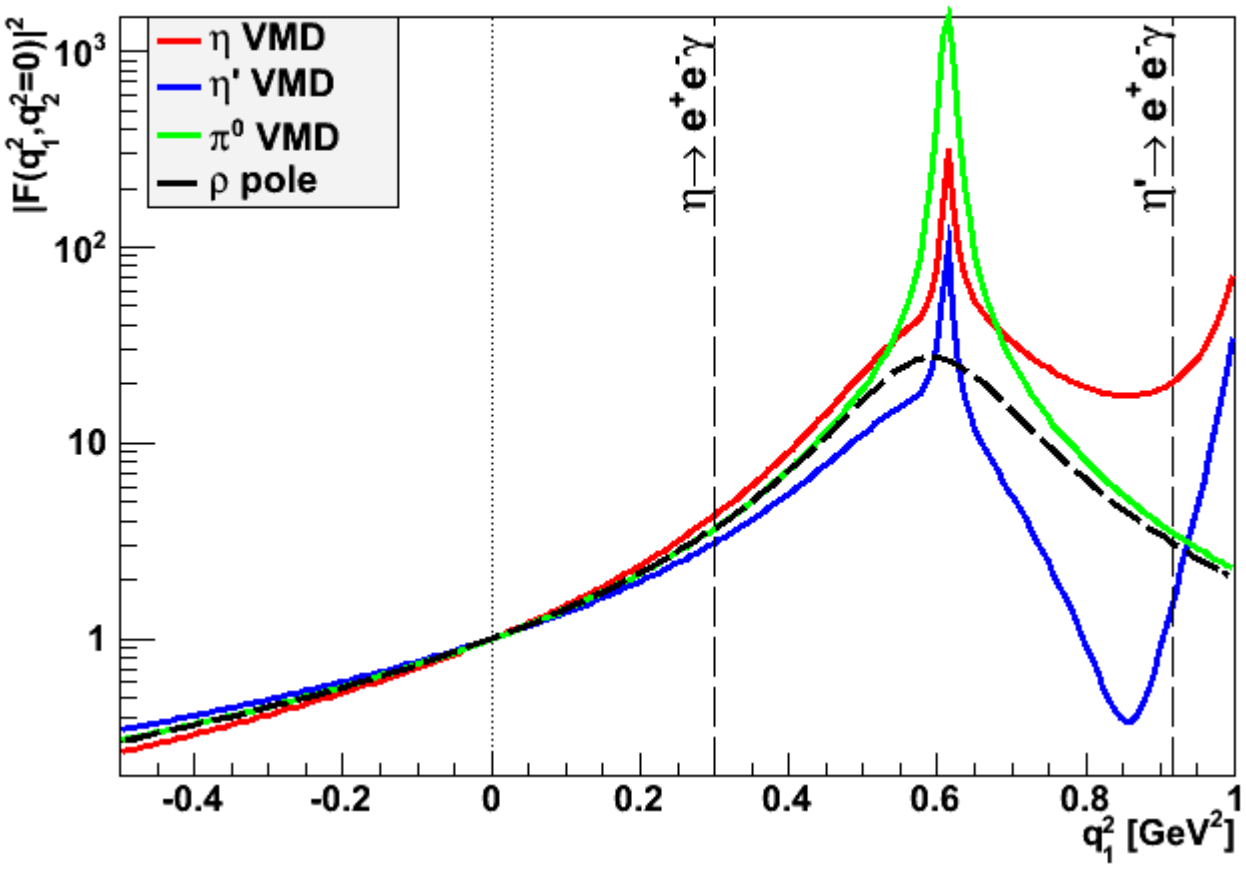
VEPP 2000 0.3-2GeV

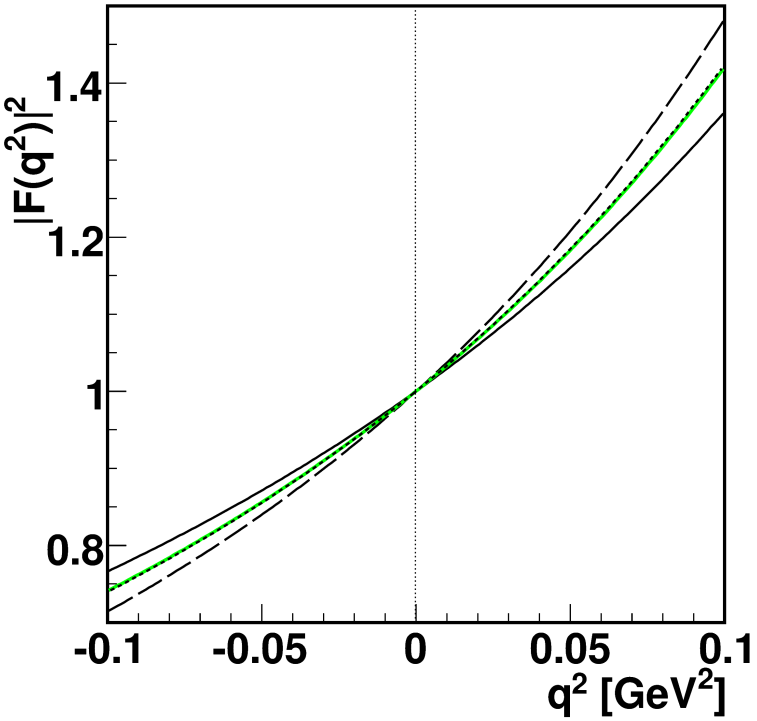
KLOE-2 ISR, BESIII

$$\sigma(e^+e^- \to P\gamma) = \frac{8}{3}\pi\alpha\,\Gamma_{\gamma\gamma}|F_P(s,0)|^2\left(\frac{s-m_P^2}{s m_P}\right)^3$$



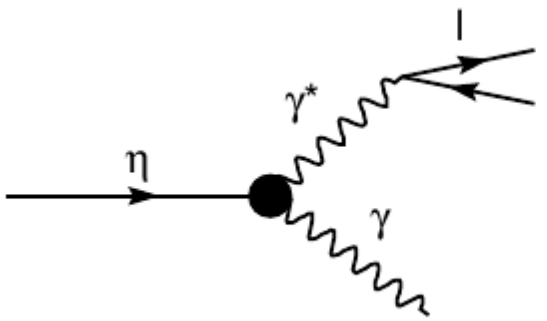
Data:CELLO,NA60,CB-MAMI,CMD-2,SND


η VMD
η' VMD
π⁰ VMD
ρ pole
η→e⁺e⁻γ
η'→e⁺e⁻γ
|F(q₁², q₂²=0)|²
10³
10²
10
1
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1
q₁² [GeV²]

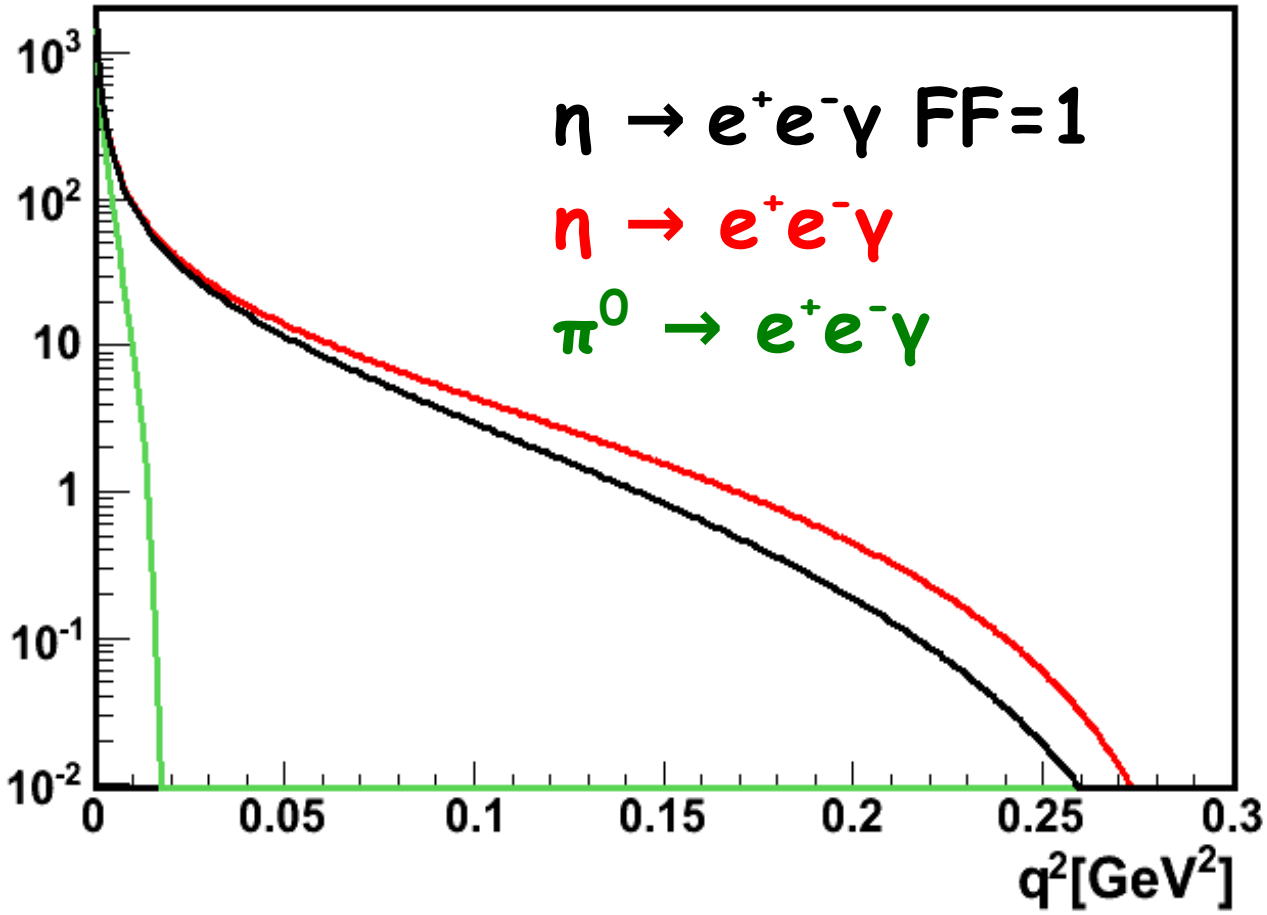

|F(q²)|²
1.4
1.2
1
0.8
-0.1
-0.05
0
0.05
0.1
q² [GeV²]

Dalitz decays

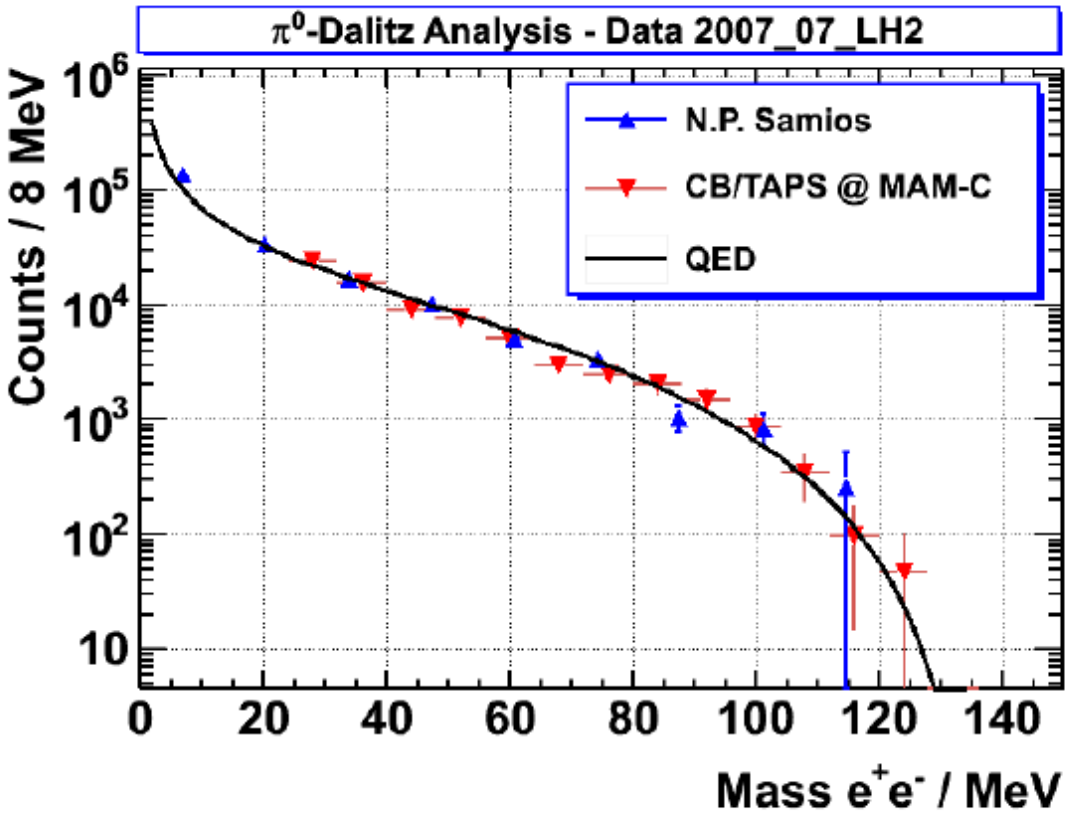
$$\frac{d\Gamma(P \to \ell^+\ell^-\gamma)}{dq^2\Gamma_{\gamma\gamma}} = \frac{2\alpha}{3\pi}\frac{1}{q^2}\sqrt{1-\frac{4m_\ell^2}{q^2}}\left(1+\frac{2m_\ell^2}{q^2}\right)\left(1-\frac{q^2}{M_P^2}\right)^3 |F_P(q^2,0)|^2$$



-



TFF Programme at A2



N.P. Samios et al. (BNL), Phys. Rev. 121 (1961) 275-281.

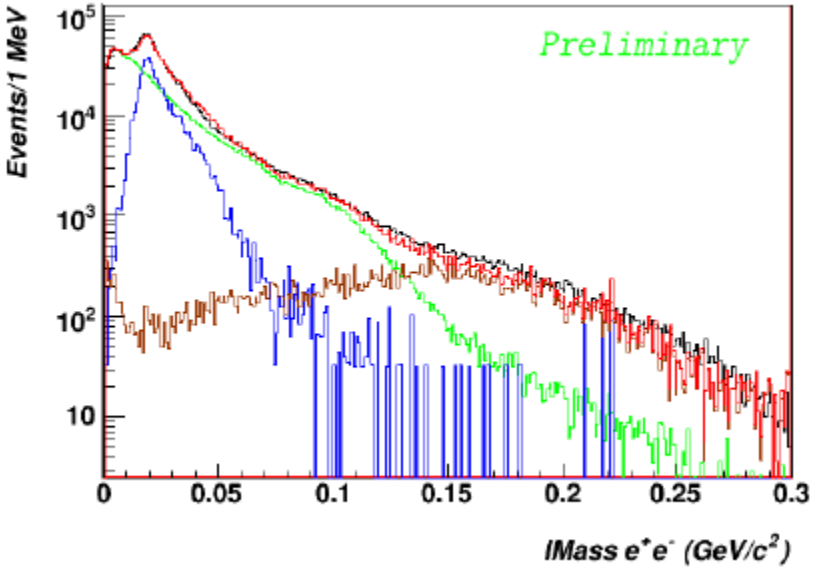
H. Berghäuser, PhD Thesis, University Gießen, Germany, 2010.

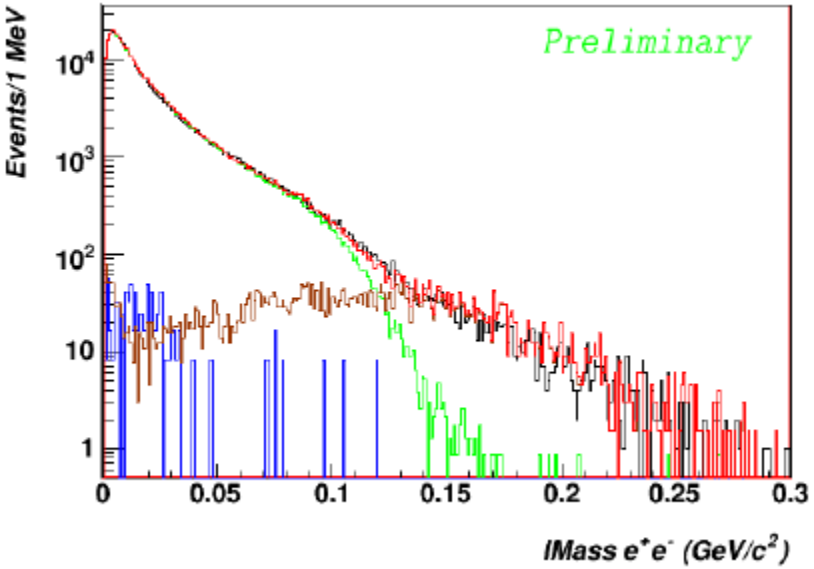
W. Gradl, M. Unverzagt, Jennifer Wettig (University Mainz), G. Ron (Jerusalem)

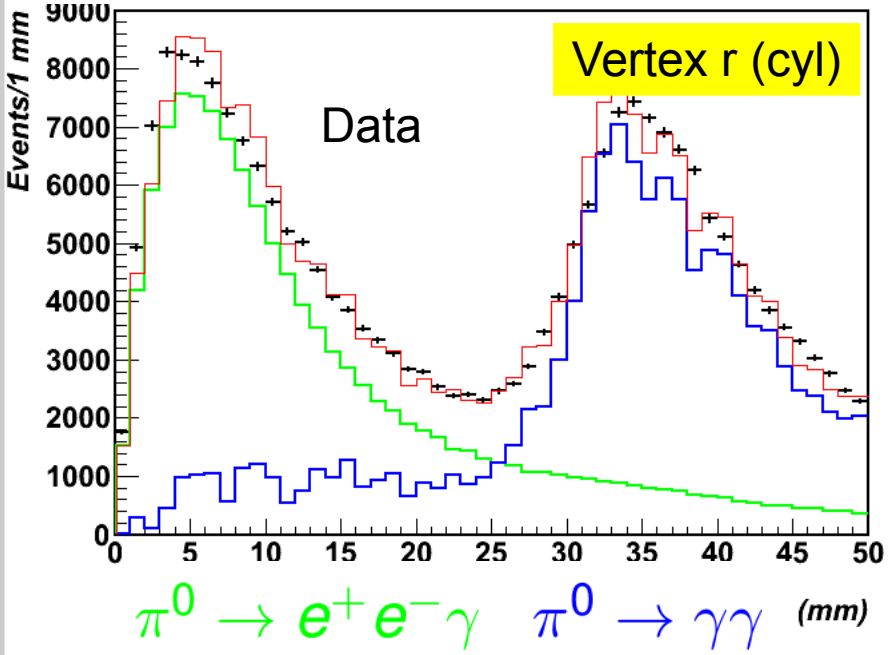
UPPSALA UNIVERSITET

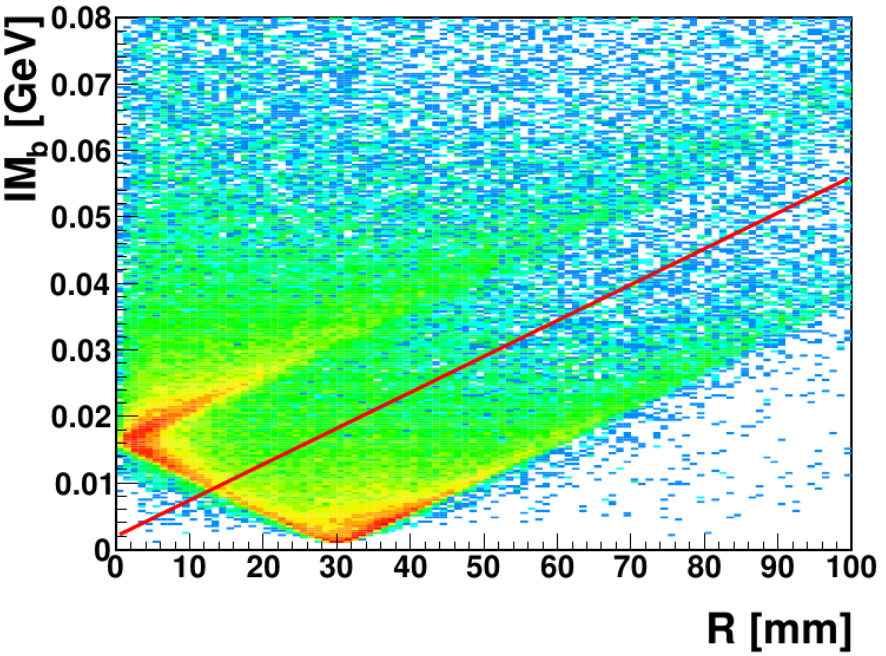
Analysis: $\pi^0 \rightarrow \gamma e^+ e^-$

Vertex r 20 mm + PID



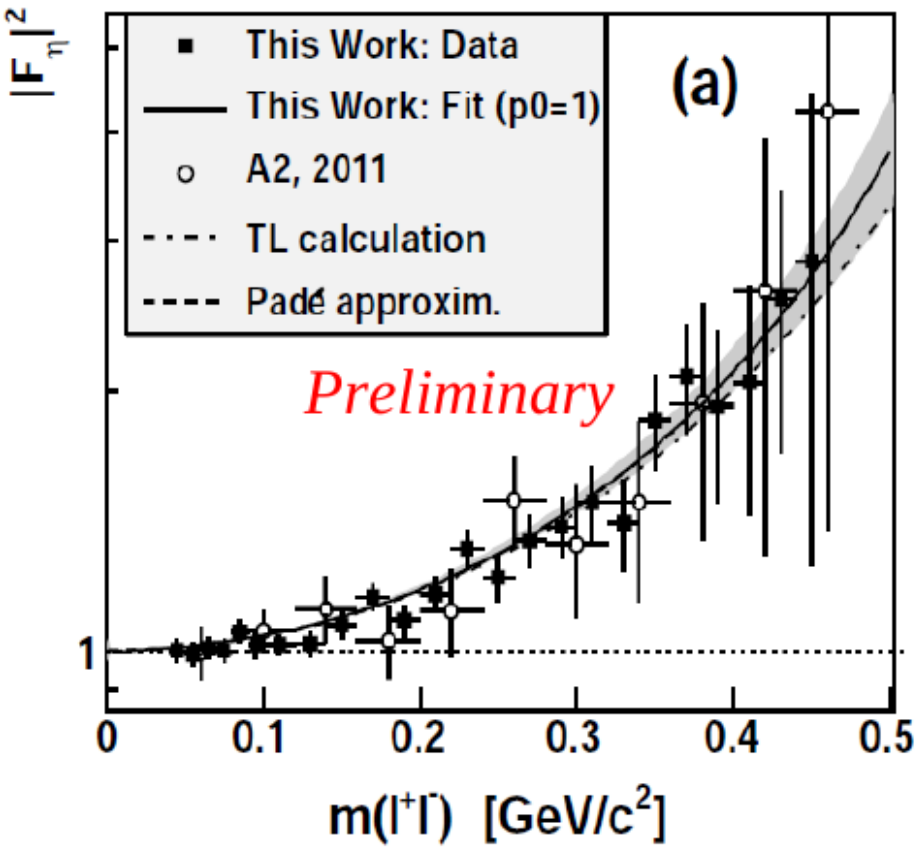


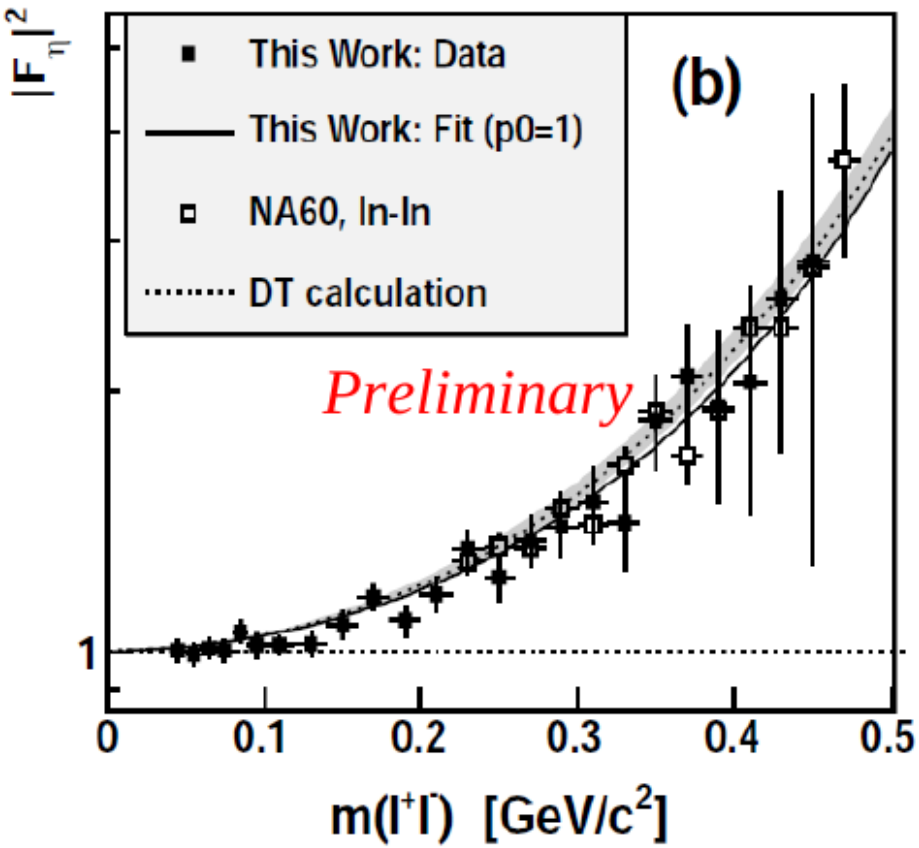




New A2 Result for η TFF

S. Prakhov, M. Unverzagt et al., accepted by Phys. Rev. C, arXiv: 1309.5648 [hep-ex]

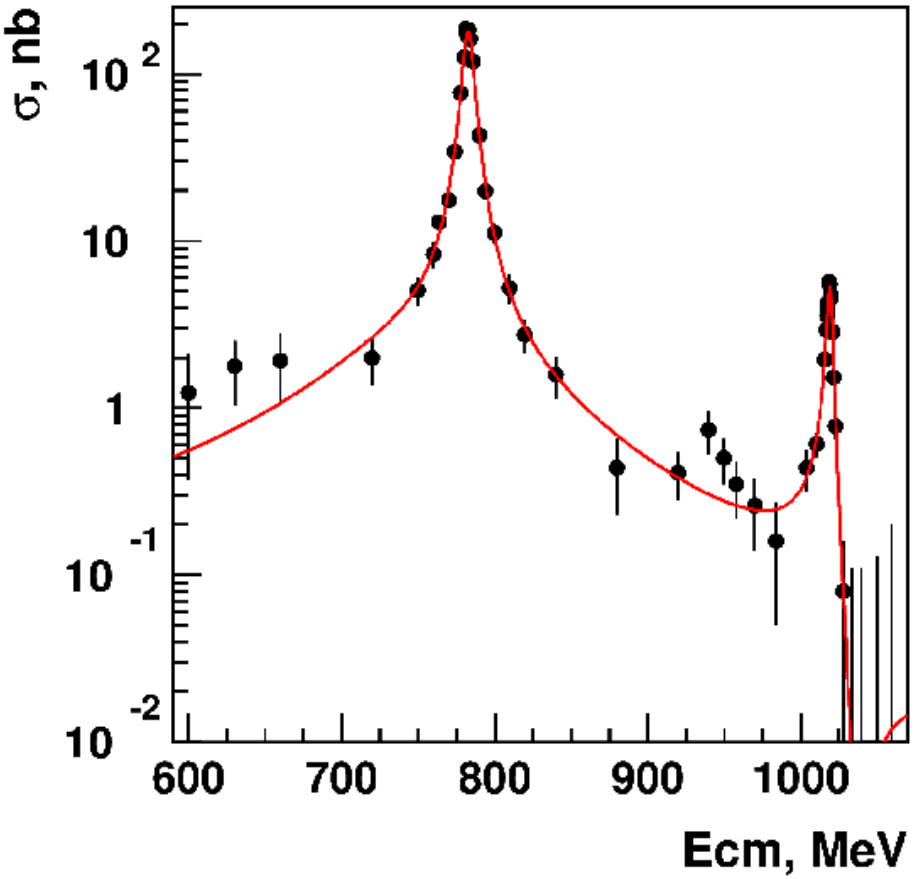


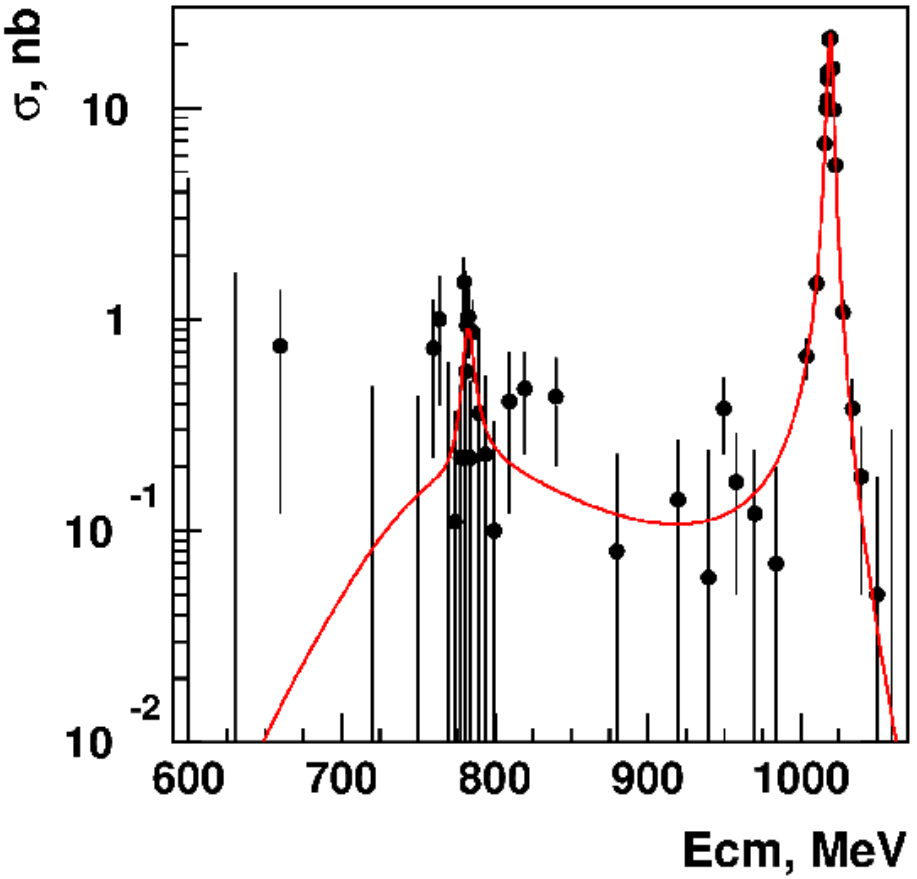


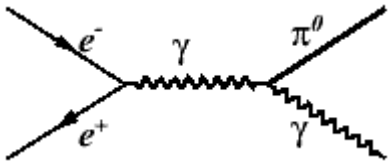
$$\Lambda^{-2} = (1.95 \pm 0.15_{\rm stat} \pm 0.10_{\rm syst})\ {\rm GeV}^{-2} \quad \textit{preliminary}$$

A2, 2011: H. Berghäuser et al., Phys. Rev. B **701** (2011) 562-567.
NA60, In-In: R. Arnaldi et al., Phys. Lett. B **677** (2009) 260.
TL calculation: C. Terschlüsen, Diploma thesis, University Gießen, 2010.
Padé-approximants: R. Escribano, P. Masjuan, P. Sanchez-Puertas, arXiv:1307.2061 [hep-ph].
DT calculation: C. Hahnhart, A. Kupść, U.-G. Meißner, F. Stollenwerk, A. Wirzba, Eur. Phys. J. C73 (2013) 2668.

$\sigma(e^+e^- \to \pi^0\gamma, \eta\gamma)$



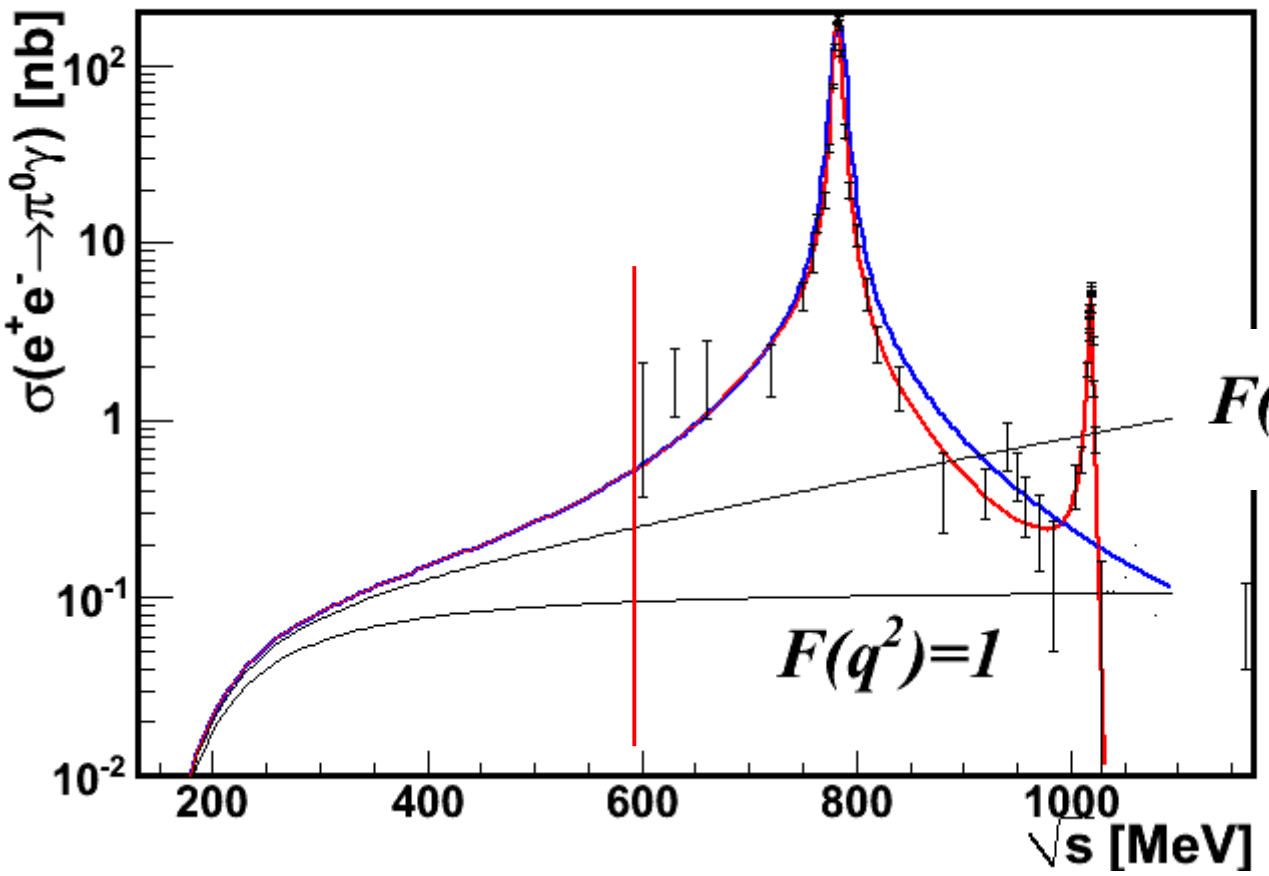




$$\sigma(e^+e^- \to P\gamma) = \frac{8}{3}\pi\alpha\,\Gamma_{\gamma\gamma}|F_P(s,0)|^2\left(\frac{s-m_P^2}{sm_P}\right)^3$$

Data: CMD-2,SND

$\sigma(e^+e^- \to \pi^0\gamma)$

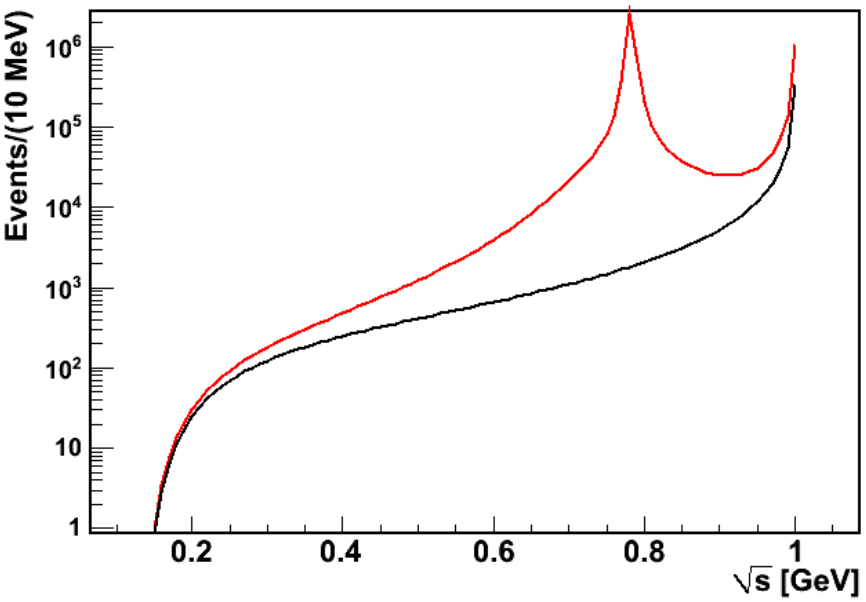


$$F(q^2)=1+a\frac{q^2}{m_\pi^2}$$

Data: CMD-2,SND

$e^+e^- \rightarrow (\pi^0\gamma,\eta\gamma)\gamma_{ISR}$ in Phokhara

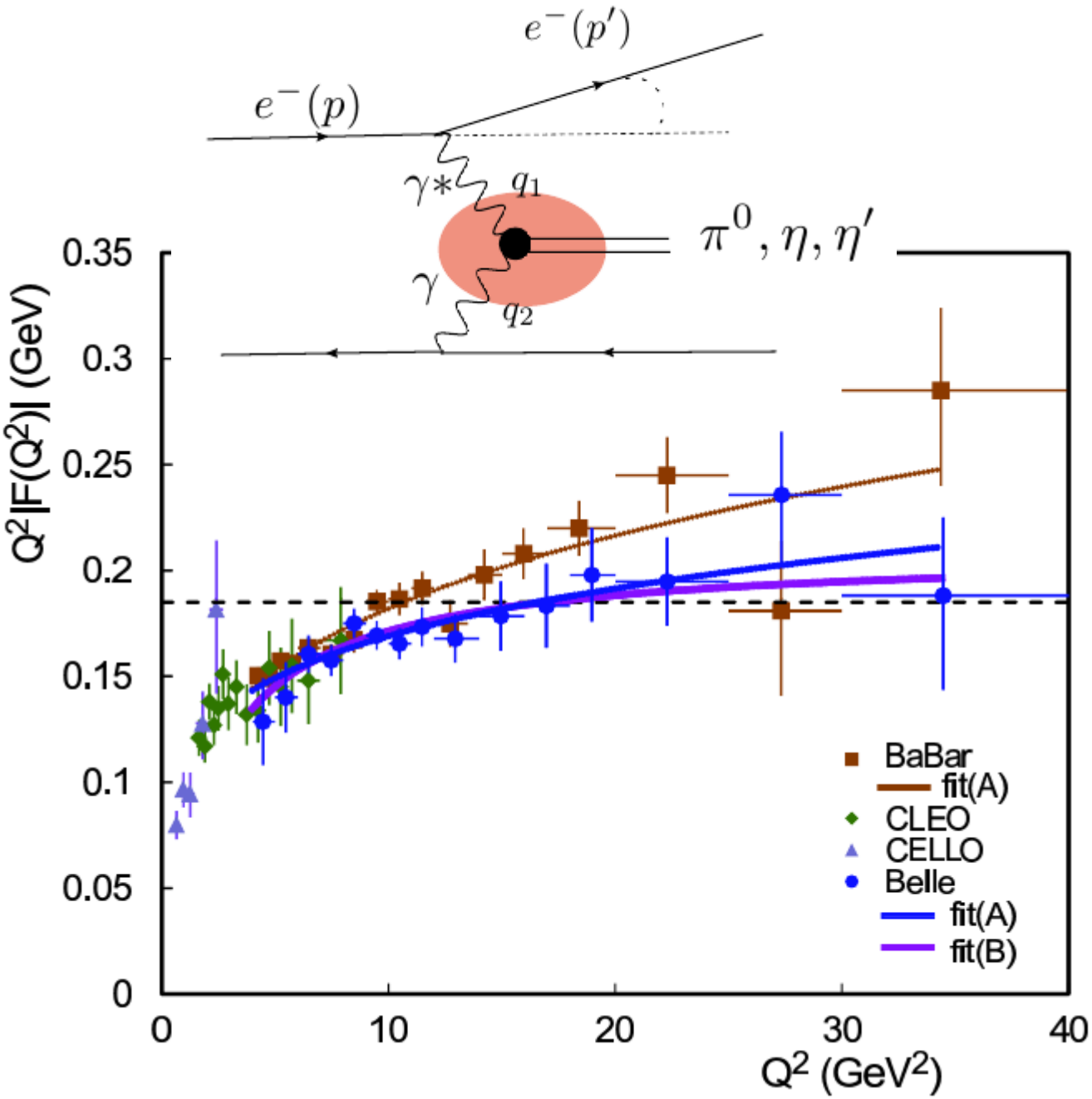
$e^+e^- \rightarrow \pi^0\gamma\gamma_{ISR}$



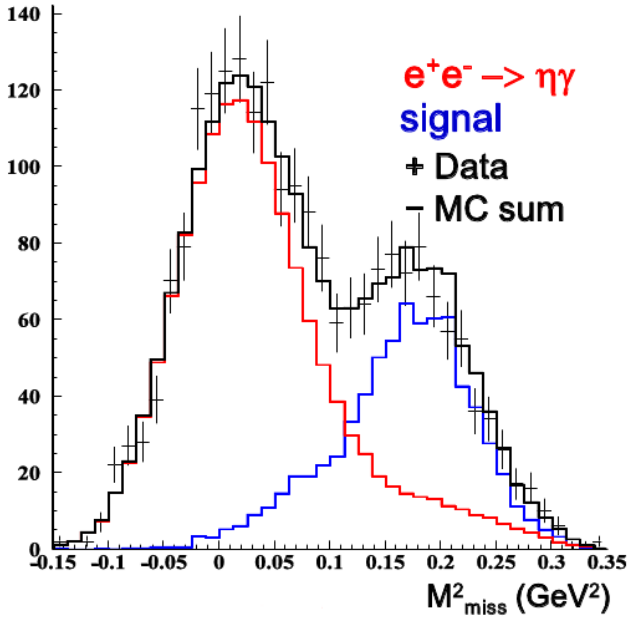
$$\frac{1}{2}\left|\;\pi^0\gamma_1\gamma_2 \;+\; \pi^0\gamma_2\gamma_1\;\right|^2$$

$$d\sigma = K_1|F_P(q_1^2,0)|^2 + K_{12}\mathrm{Re}(F_P(q_1^2,0)F_P^*(q_2^2,0)) + K_2|F_P(q_2^2,0)|^2$$

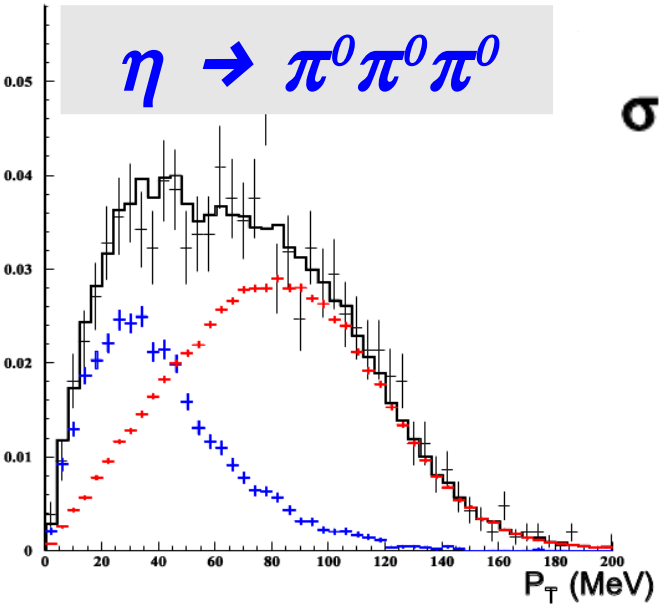
ISR σ	q < 0.7 GeV		T: 30<θ<150		
	L	σU	NU	σT	NT
S: 1.0	: 10 fb^{-1}	6pb	61k	1pb	10k
C: 3.77	: 10 fb^{-1}	280fb	2.8k	60fb	0.3k
B: 10	:0.5 ab^{-1}	44fb	~~22k~~	4fb	2.1k


$e^-(p')$
$e^-(p)$
$\gamma*$
q_1
π^0, η, η'
γ
q_2
$Q^2|F(Q^2)|$ (GeV)
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0
10
20
30
40
Q^2 (GeV^2)
BaBar
fit(A)
CLEO
CELLO
Belle
fit(A)
fit(B)

η meson radiative decay width



$\eta \rightarrow \pi^0\pi^0\pi^0$



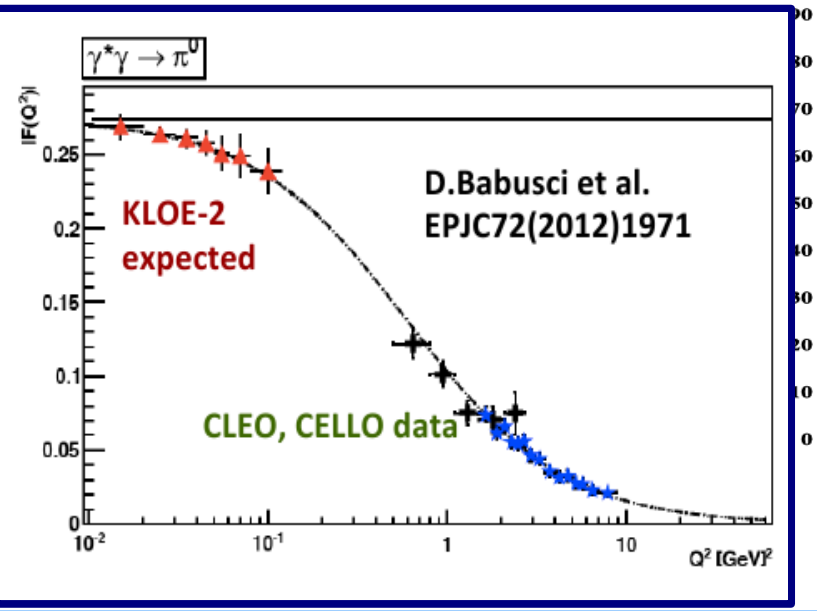
$\sigma(e^+e^- \rightarrow e^+e^-\eta, \sqrt{s}=1GeV)$

$L=240\ pb^{-1}$

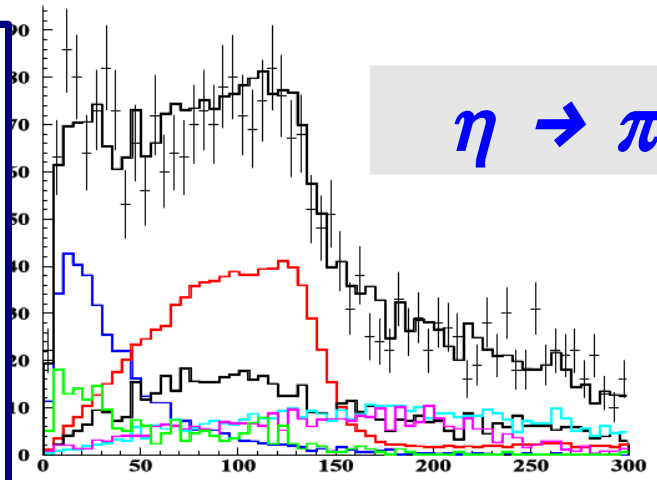
Insensitive to TFF

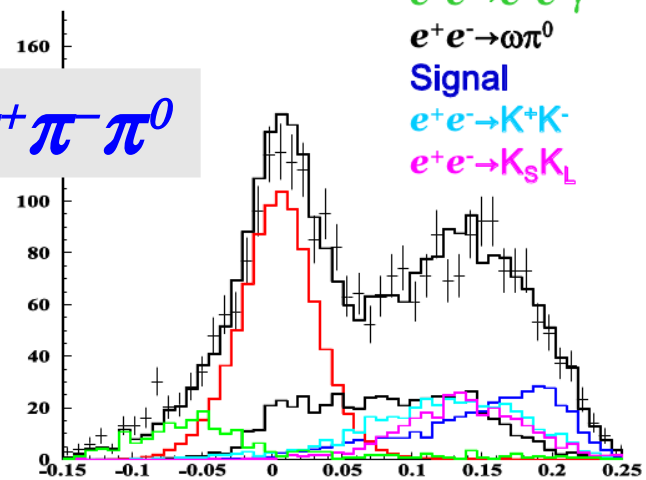
$\Gamma\gamma\gamma=520\pm20\pm13\ eV$

$32.0\pm1.5\pm0.9\ pb$



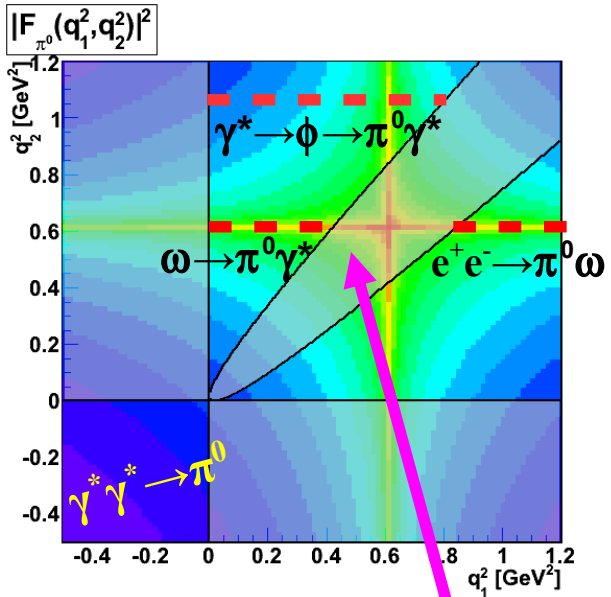
$\eta \rightarrow \pi^+\pi^-\pi^0$

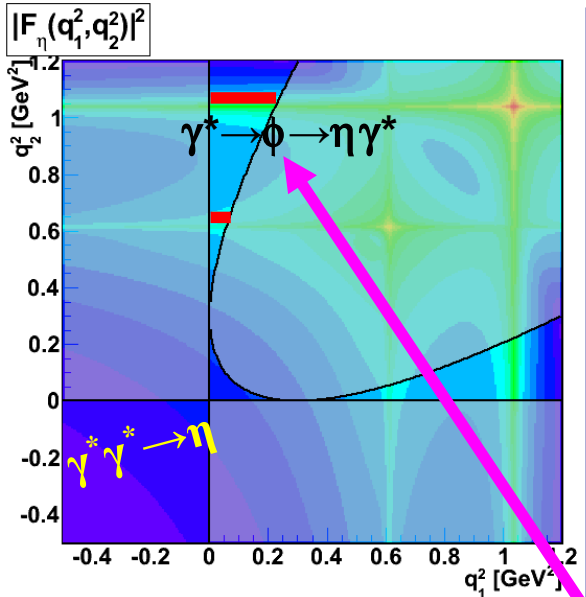


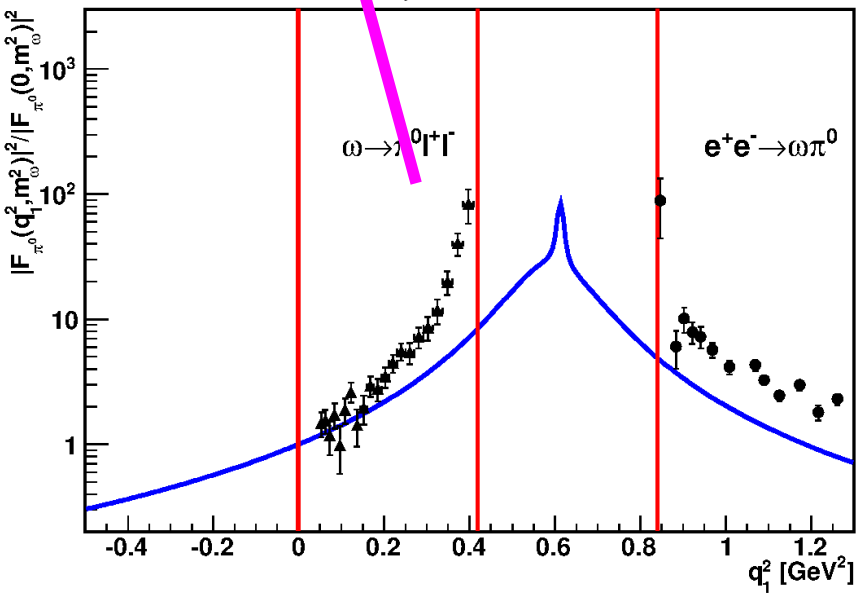


$34.5\pm2.5\pm1.0\ pb$

V → Pγ* and e+e- → PV processes



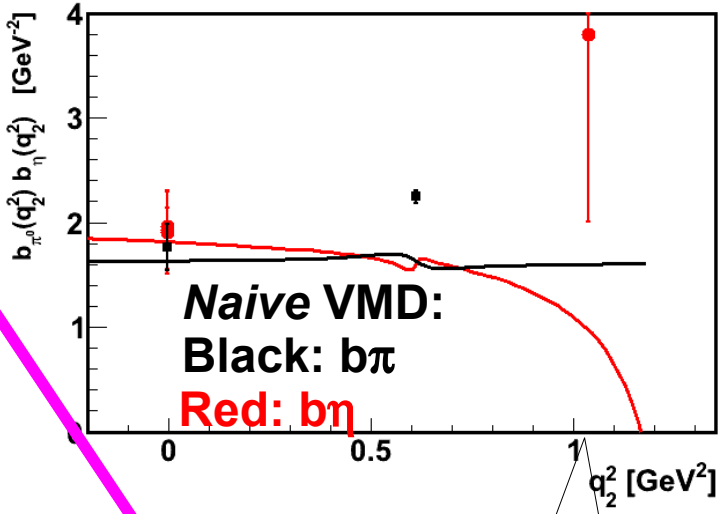




TH: → Bastian talk

slopes bπ, bη

$$b_P(q_2^2) = \left.\frac{\partial \ln |F(q_1^2, q_2^2)|}{\partial q_1^2}\right|_{q_1^2=0}$$



KLOE prel result $b\eta(m^2_\phi)$

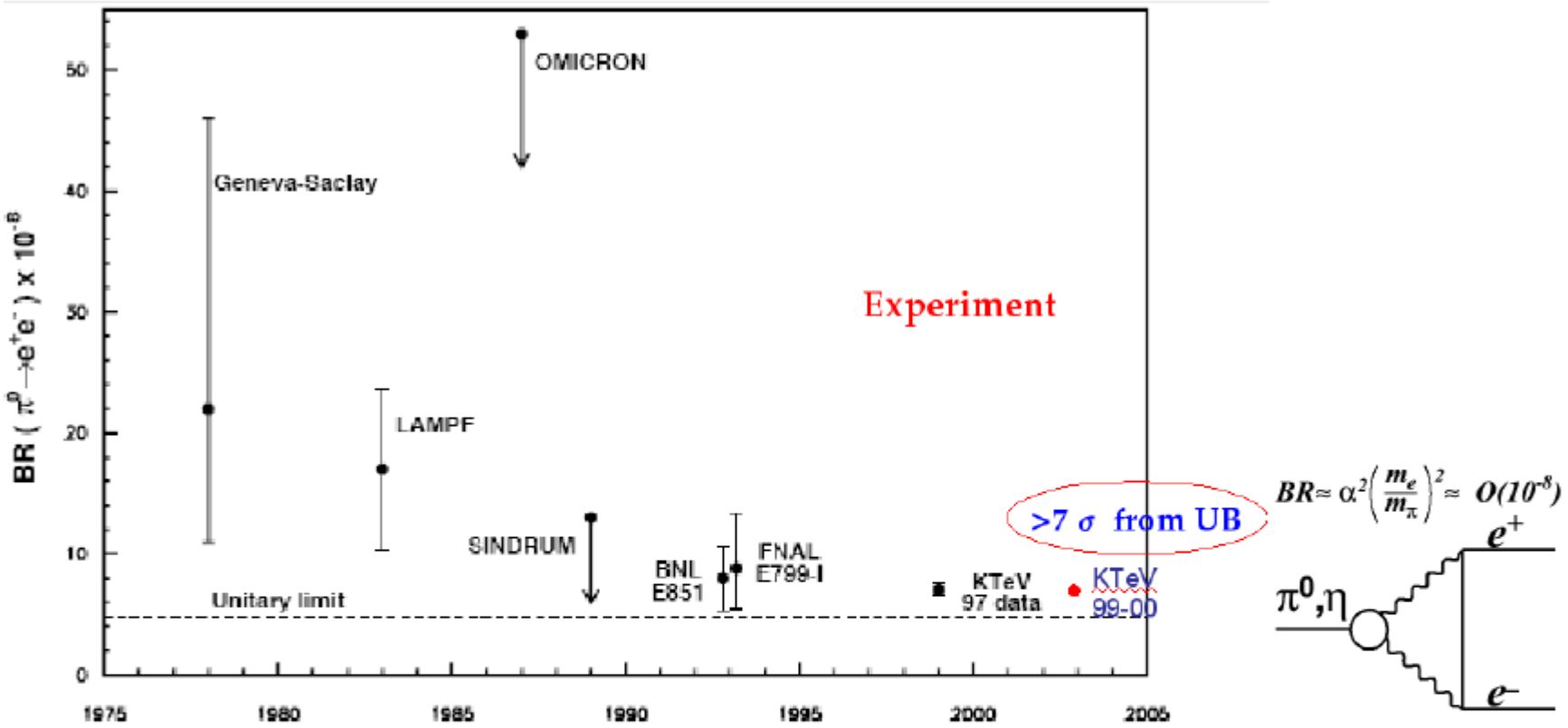
$\phi\to\eta\gamma^*$ BR 10^{-4}

$b\pi^0(m^2_\phi)$ $\phi\to\pi^0\gamma^*$ BR 10^{-5}

Relation to $\omega/\varphi\to\pi^+\pi^-\pi^0$

BESIIIJ/ψ→Pe+e- arXiv:1403.7042

History of $\pi^0 \to e^+e^-$ measurements

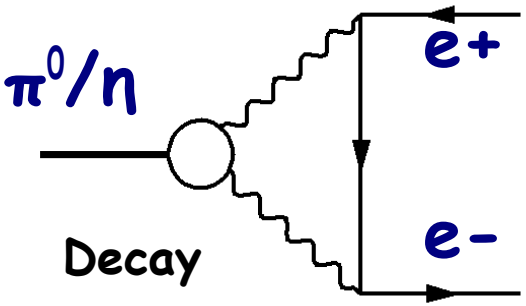


- Unitary bound (model independent) $BR \geq 4.75 \cdot 10^{-8}$
- Experiment: KTeV (794 events from $K_L \to 3\pi^0$):

  $BR(\pi^0 \to e^+e^-) = (6.44 \pm 0.25_{stat} \pm 0.22_{syst}) \times 10^{-8}$

  $BR_{\text{no-rad}}(\pi^0 \to e^+e^-) = (7.48 \pm 0.29_{stat} \pm 0.25_{syst}) \times 10^{-8}$

PRD75:012004(07)

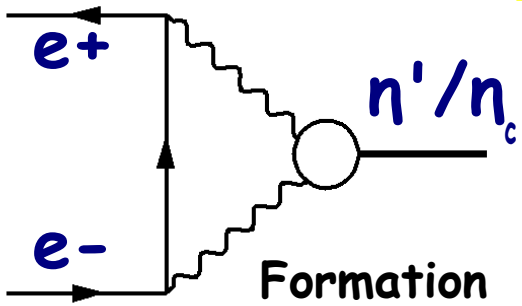


HADES
WASA
CBall
NA48/NA62

	UB	SM	EXP
$\mathcal{B}(\pi^0 \to e^+e^-) \times 10^8$	≥ 4.69	6.23 ± 0.12	7.49 ± 0.38 KTeV2007
$\mathcal{B}(\eta \to e^+e^-) \times 10^9$	≥ 1.78	5.2 ± 0.3	$\leq 5.6 \cdot 10^3$ HADES2012
$\mathcal{B}(\eta' \to e^+e^-) \times 10^{10}$	≥ 0.36	1.9 ± 0.3	$\leq 2.1 \cdot 10^3$ ND1988
$\mathcal{B}(\eta_c \to e^+e^-) \times 10^{14}$	≥ 4.2		

3σ diff

Dorokhov,PLB667,145



Searches using formation:

e+e- → η' , L=0.5pb^{-1}

=> B< $2.1 \cdot 10^{-7}$ 90% CL

Vorobev SJNP 48(1988)273

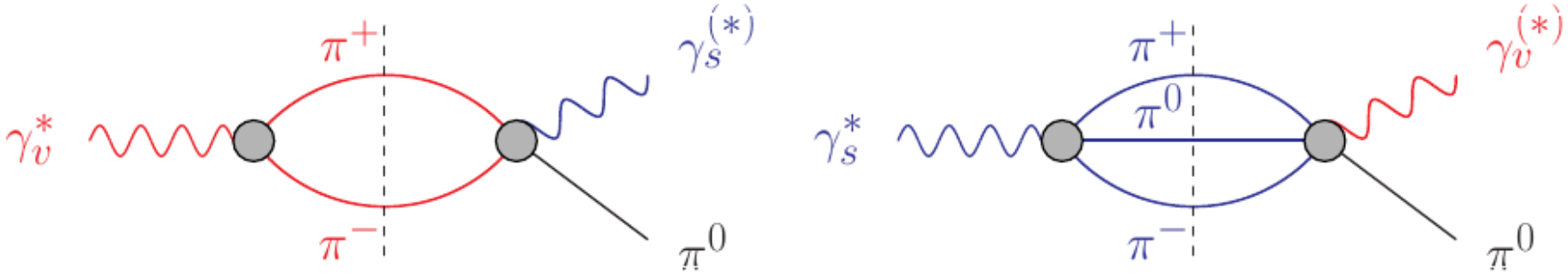
Dispersive analysis of $\pi^0 \to \gamma^*\gamma^*$

- isospin decomposition:

$$F_{\pi^0\gamma^*\gamma^*}(q_1^2, q_2^2) = F_{vs}(q_1^2, q_2^2) + F_{vs}(q_2^2, q_1^2)$$

- analyze the leading hadronic intermediate states:

see also Gorchtein, Guo, Szczepaniak 2012



  - ▷ isovector photon: 2 pions

    $\propto$ pion vector form factor $\times$ $\gamma\pi \to \pi\pi$

    all determined in terms of pion–pion P-wave phase shift

    + Wess–Zumino–Witten anomaly for normalisation
  - ▷ isoscalar photon: 3 pions

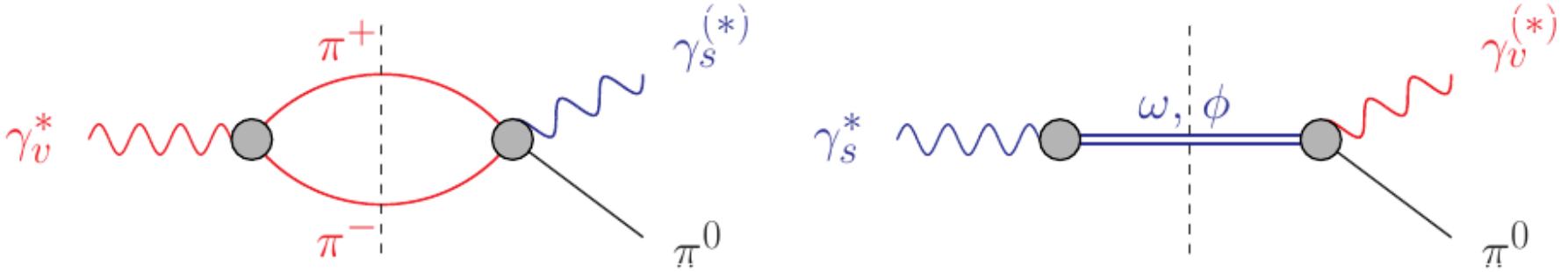
Dispersive analysis of $\pi^0 \to \gamma^*\gamma^*$

- isospin decomposition:

$$F_{\pi^0\gamma^*\gamma^*}(q_1^2, q_2^2) = F_{vs}(q_1^2, q_2^2) + F_{vs}(q_2^2, q_1^2)$$

- analyze the leading hadronic intermediate states:

see also Gorchtein, Guo, Szczepaniak 2012



  - ▷ isovector photon: 2 pions

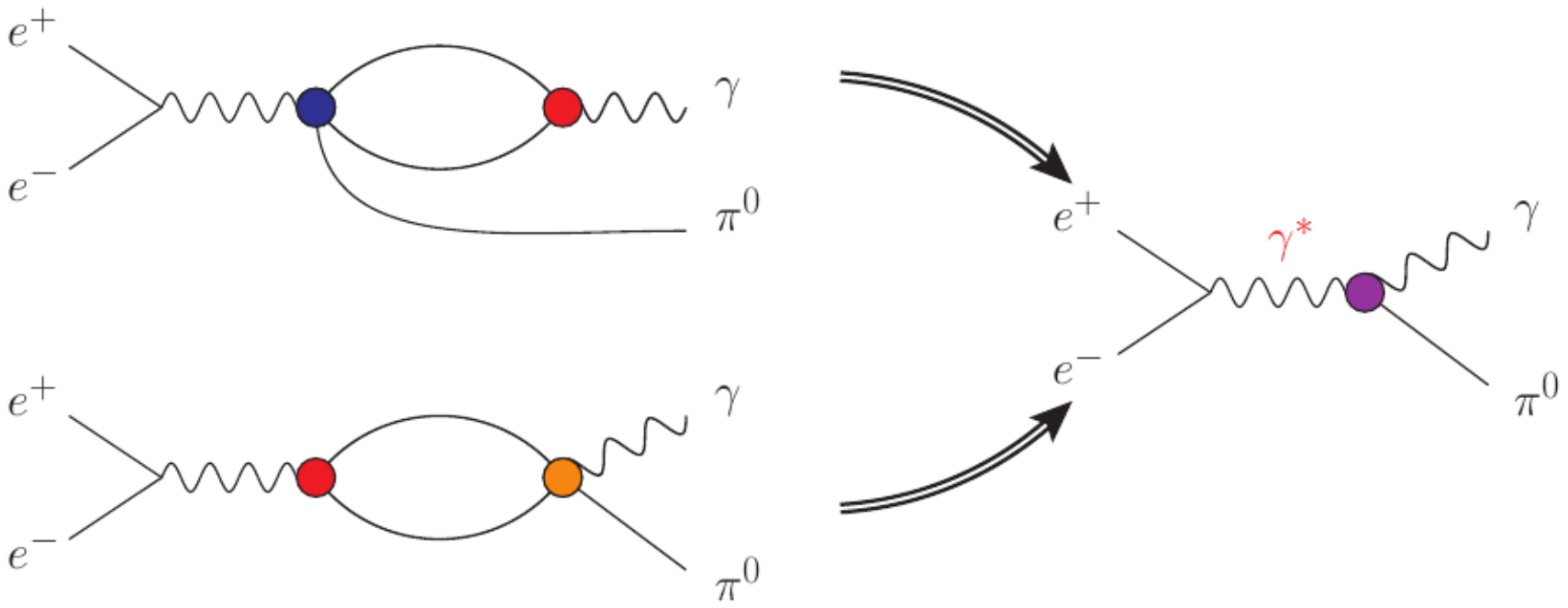
    $\propto$ pion vector form factor $\times$ $\gamma\pi \to \pi\pi$

    all determined in terms of pion–pion P-wave phase shift

    + Wess–Zumino–Witten anomaly for normalisation
  - ▷ isoscalar photon: 3 pions

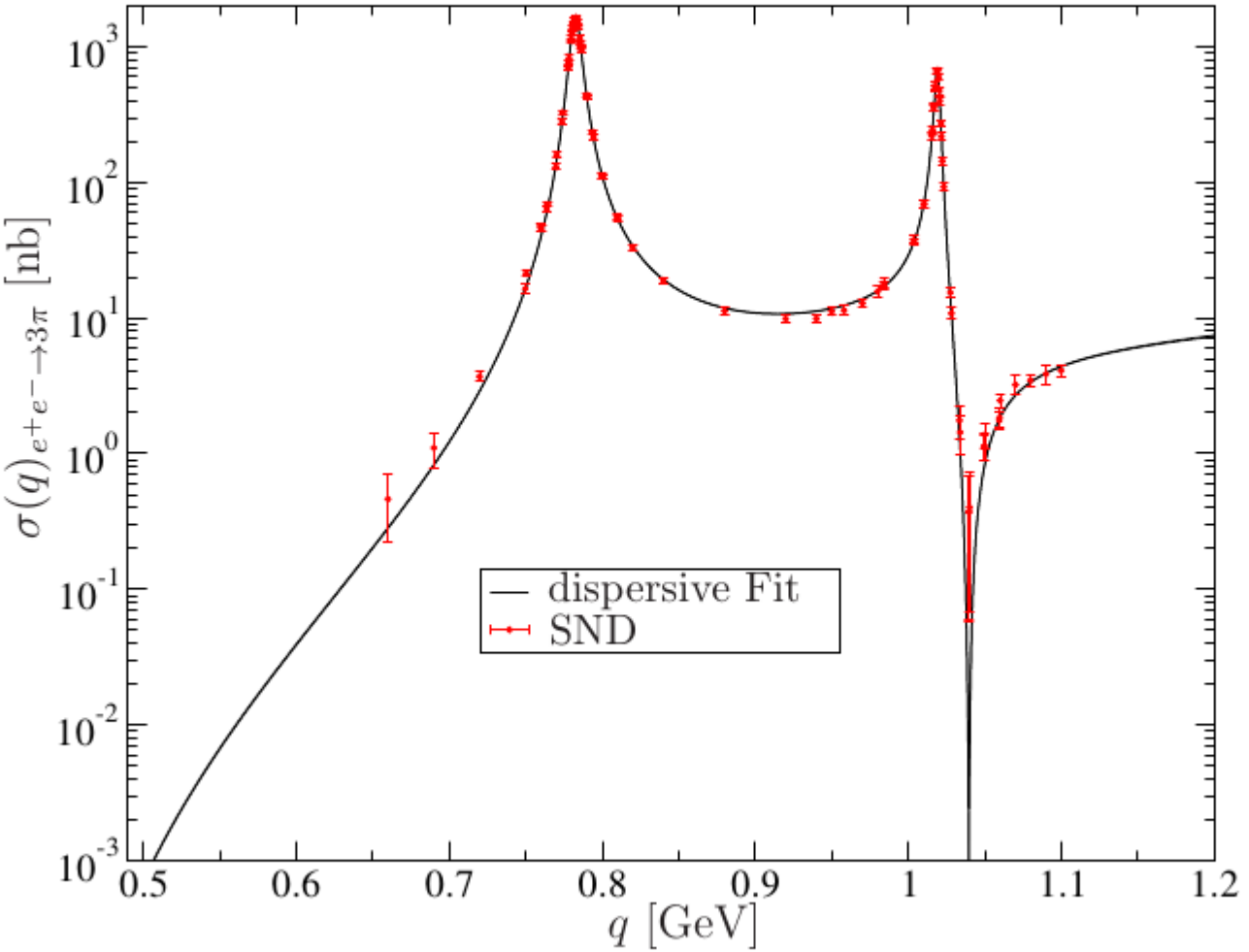
    dominated by narrow resonances ω, ϕ

Towards a dispersive analysis of $e^+e^- \to \pi^0\gamma$



Slide: Bastian Kubis

Fit to $e^+e^- \to 3\pi$ data



Hoferichter, BK, Leupold, Niecknig, Schneider, *preliminary*

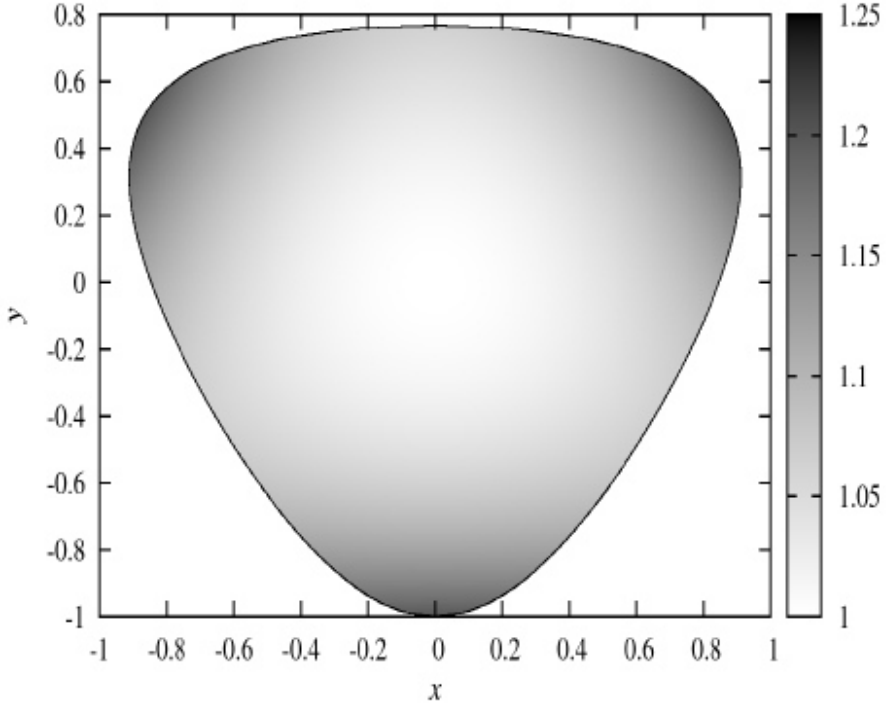
Slide: Bastian Kubis

$\omega/\phi \to 3\pi$ Dalitz plots

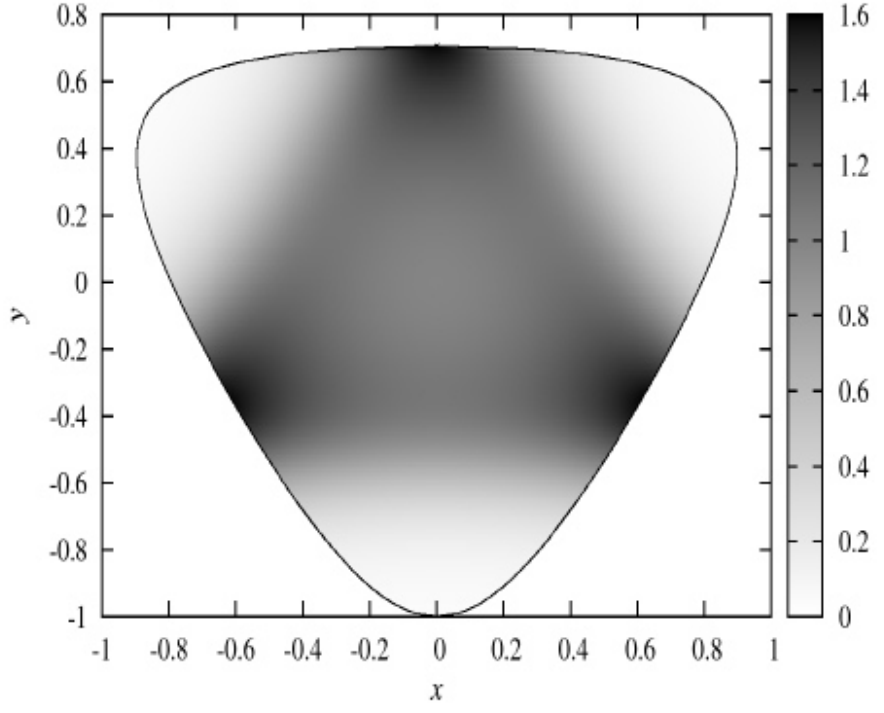
- subtraction constant a fixed to partial width

  $\longrightarrow$ normalised Dalitz plot a prediction

$\omega \to 3\pi$:



$\phi \to 3\pi$:

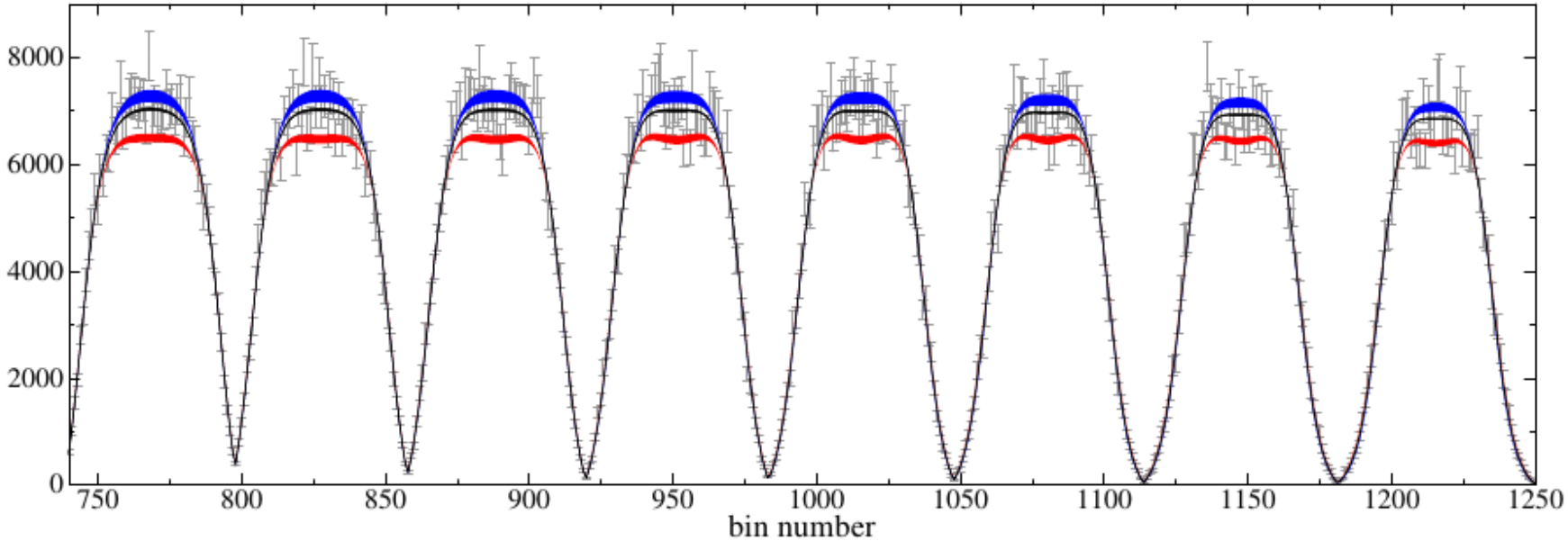


- ω Dalitz plot is relatively smooth
- ϕ Dalitz plot clearly shows ρ resonance bands

Niecknig, BK, Schneider 2012

Experimental comparison to $\phi \to 3\pi$

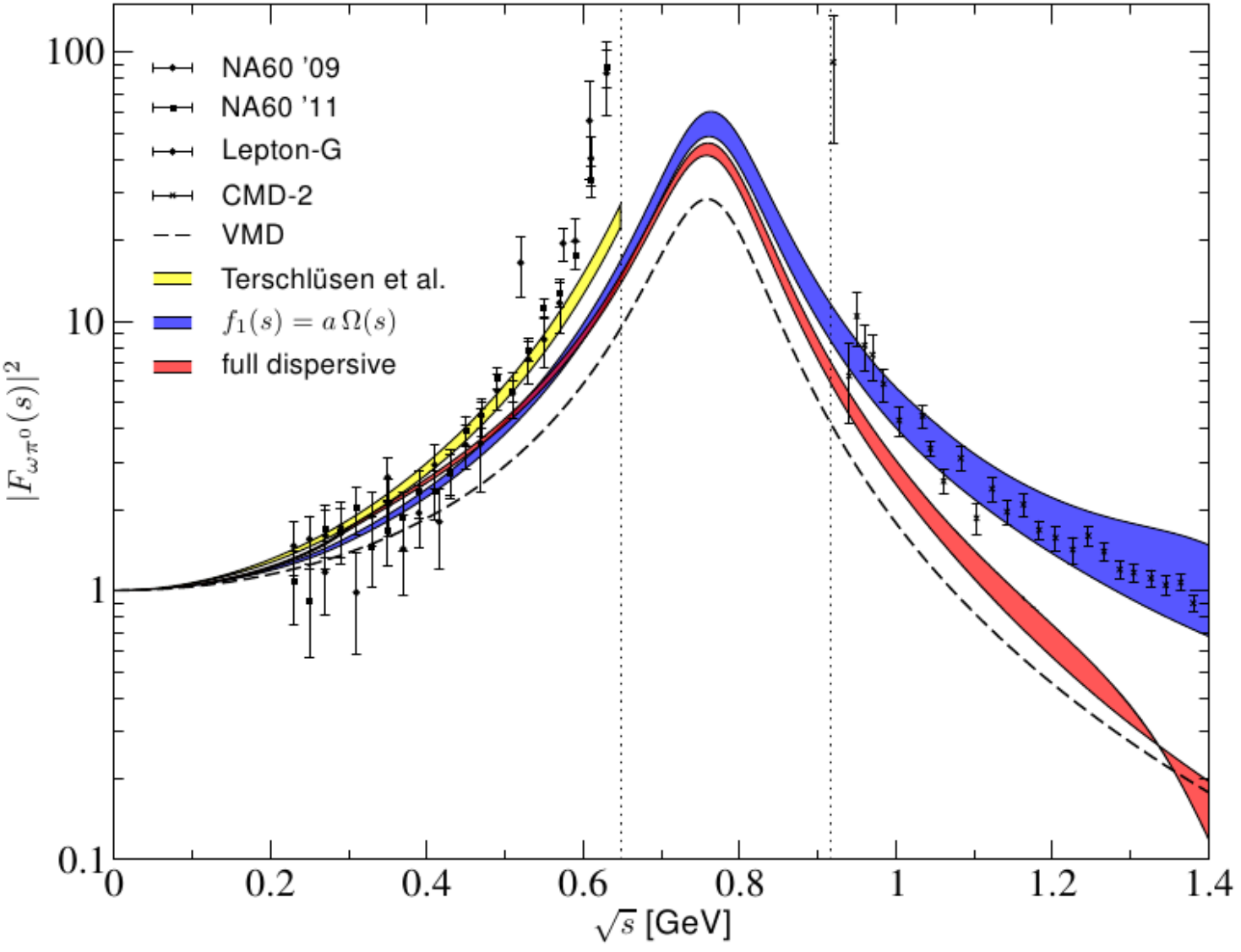
KLOE Dalitz plot: $2 \cdot 10^6$ events, 1834 bins Niecknig, BK, Schneider 2012



	$\hat{\mathcal{F}} = 0$	once-subtracted	twice-subtracted
χ^2/ndof	$1.71 \ldots 2.06$	$1.17 \ldots 1.50$	$1.02 \ldots 1.03$

- perfect fit respecting analyticity and unitarity possible
- contact term emulates neglected rescattering effects
- no need for "background" — inseparable from "resonance"

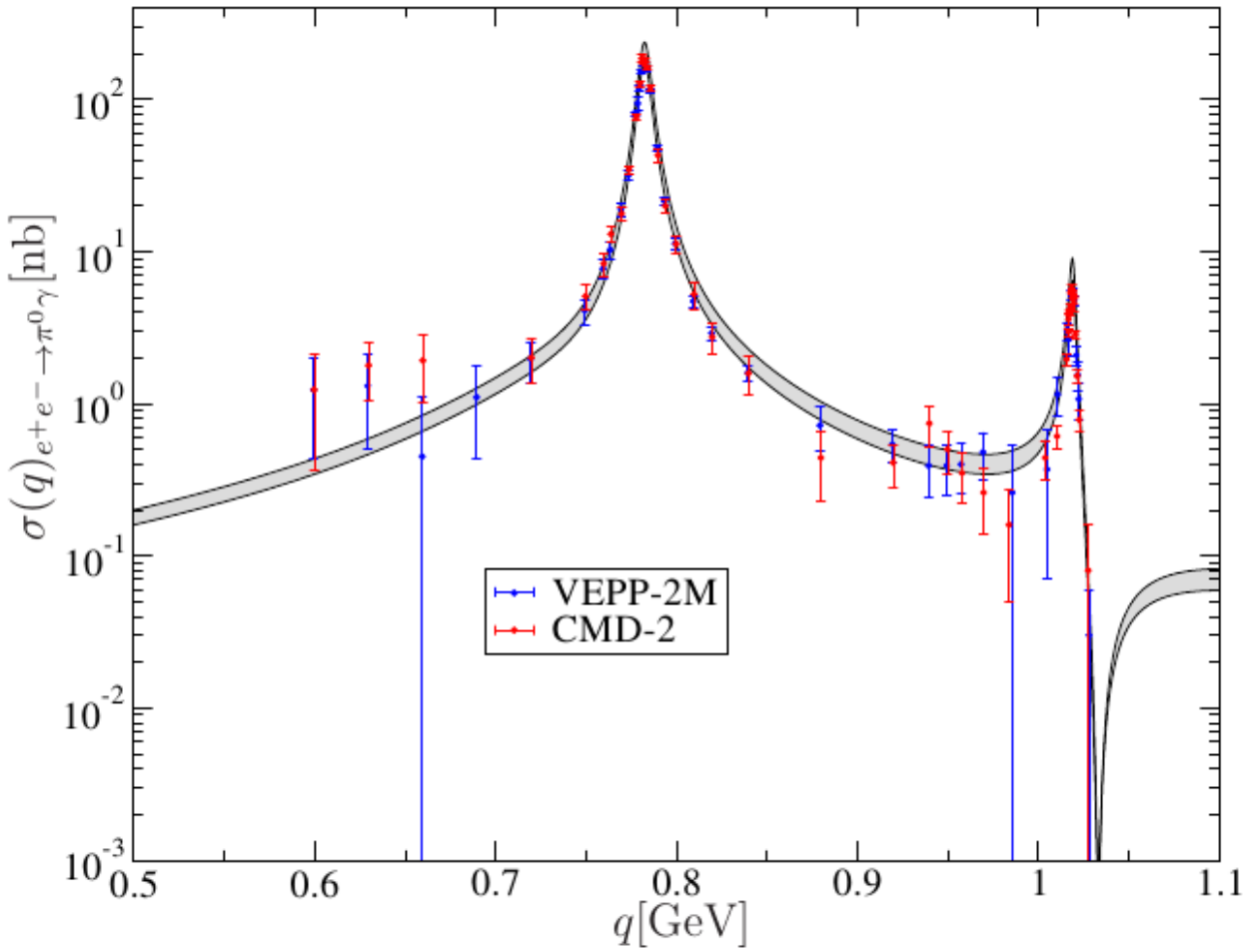
Naive extension to $e^+e^- \to \pi^0\omega$



- full solution above naive VMD, but still too low
- higher intermediate states (4π / $\pi\omega$) more important?

Slide: Bastian Kubis

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

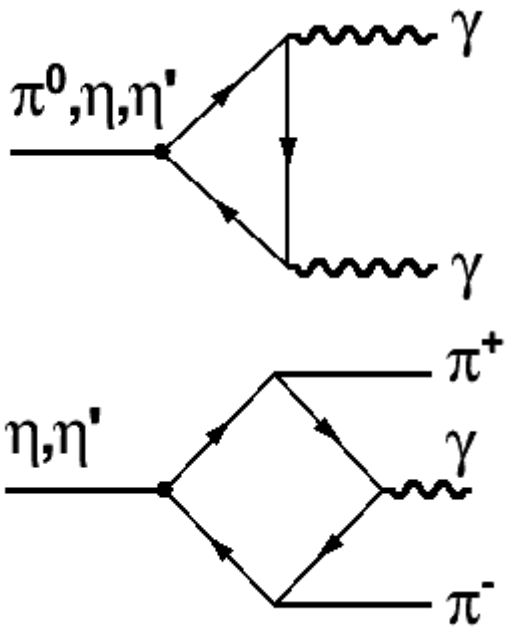


Hoferichter, BK, Leupold, Niecknig, Schneider, *preliminary*

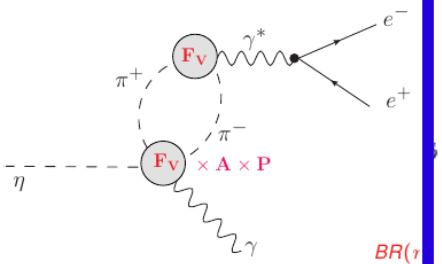
- "prediction"—no further parameters adjusted
- data well reproduced

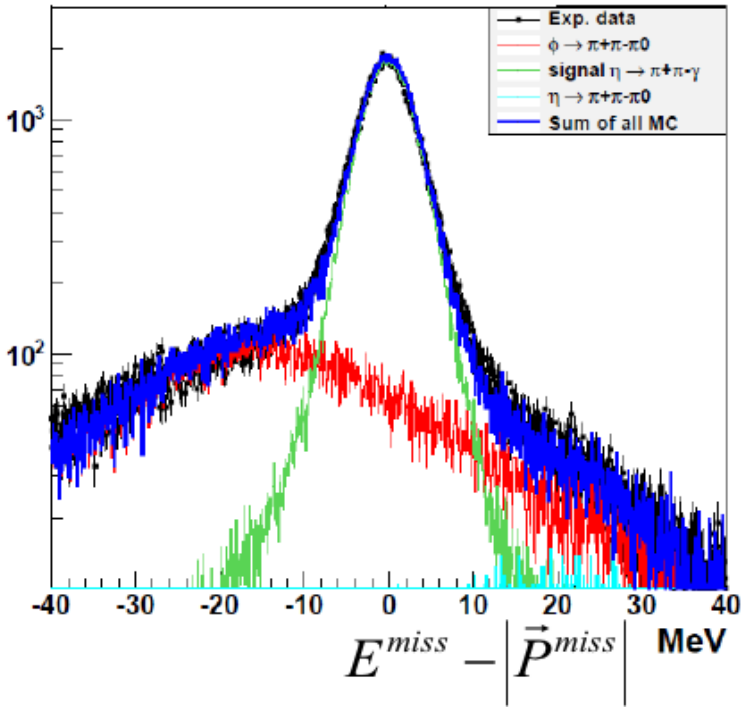
Slide: Bastian Kubis

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



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





- No kin fit:use DC resolution
- Not use EMC Energy

  $\Phi \to \eta\gamma$ L = 558 pb^{-1}

  205 k events

  eff=21%

  S/B=10

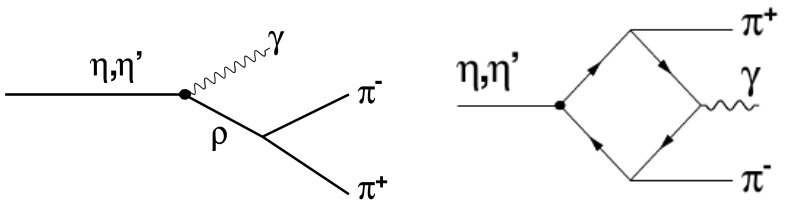
$$\frac{\Gamma(\eta \to \pi^+\pi^-\gamma)}{\Gamma(\eta \to \pi^+\pi^-\pi^0)} = 0.1856 \pm 0.0005 \pm 0.0028$$

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

$\Gamma(\eta \to \pi^+\pi^-\gamma) / \Gamma(\eta \to \pi^+\pi^-\pi^0)$

value	events	author	year
0.203 ± 0.008	PDG average		
0.175 ± 0.007 ± 0.006	859	Lopez	2007
0.209 ± 0.004	18 k	Thaler	1973
0.201 ± 0.006	7250	Gormley	1970

$\eta \rightarrow \pi^+\pi^-\gamma$

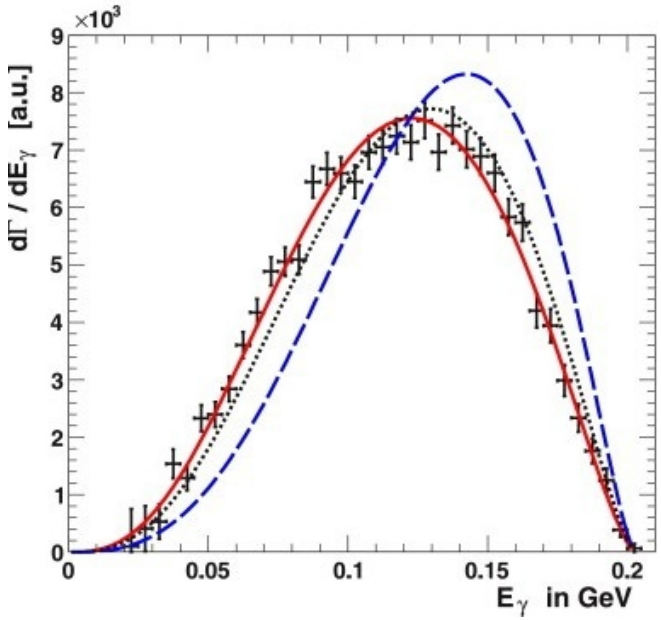


$$\frac{d\Gamma_{\eta(\eta')}}{ds_{\pi\pi}} \propto \left| C + \frac{1}{s_{\pi\pi} - m_\rho^2 - i m_\rho \Gamma_\rho} \right|^2$$

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

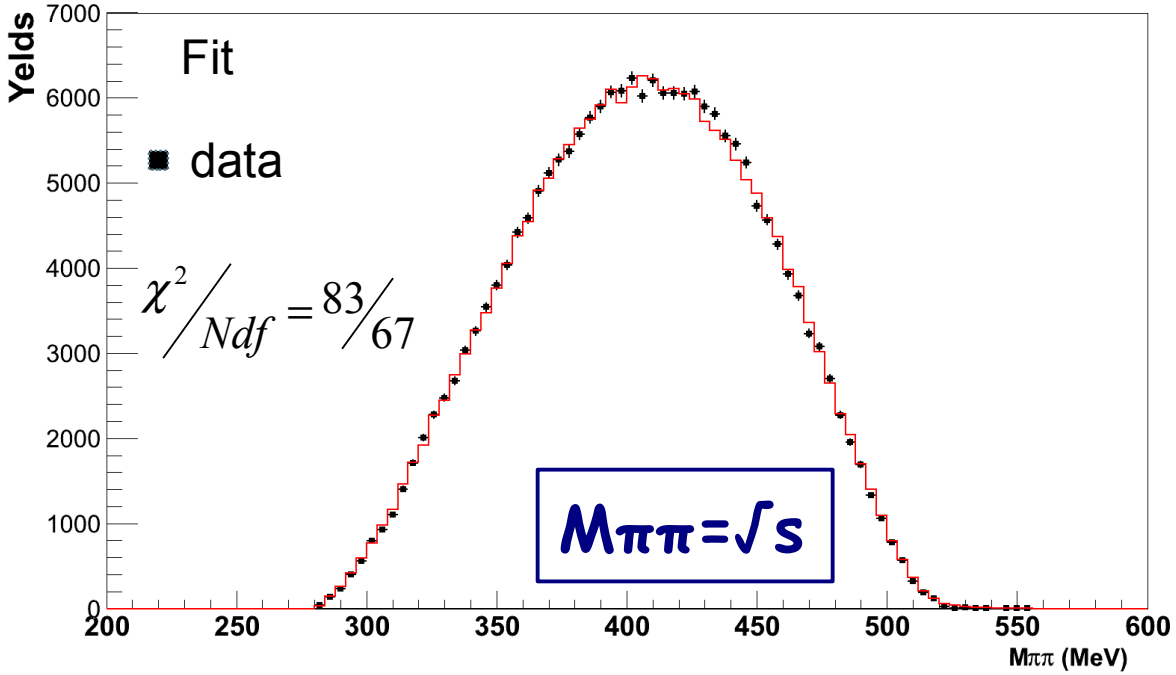
PLB707 (2012) 184

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



$\alpha = 1.89 \pm 0.25_{stat} \pm 0.59_{syst}$ GeV^{-2}

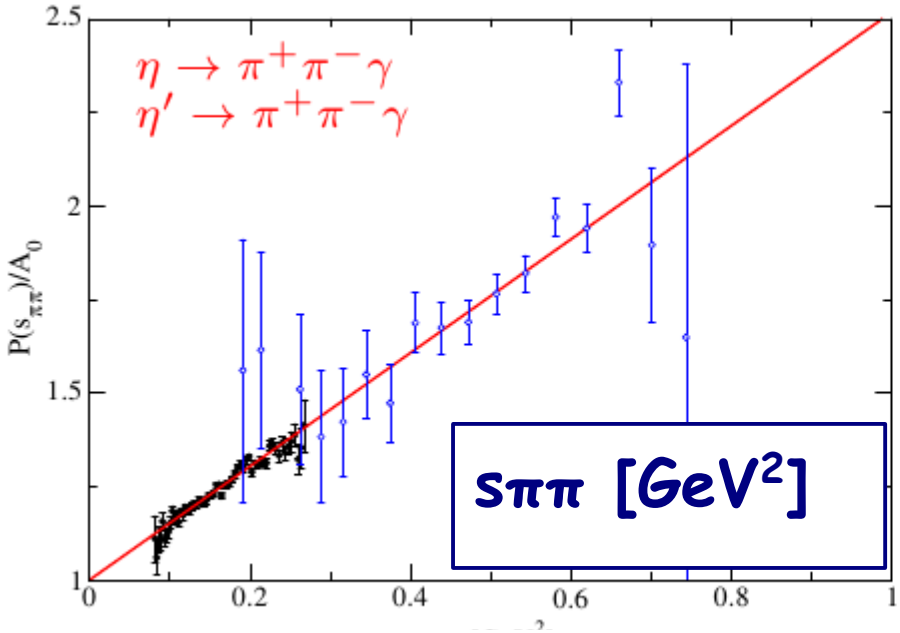
[WASA PLB707 (2012) 243]



$\alpha = 1.31 \pm 0.08_{stat} \pm 0.40_{systv}$ GeV^{-2}

[KLOE PLB718 (2013) 910]

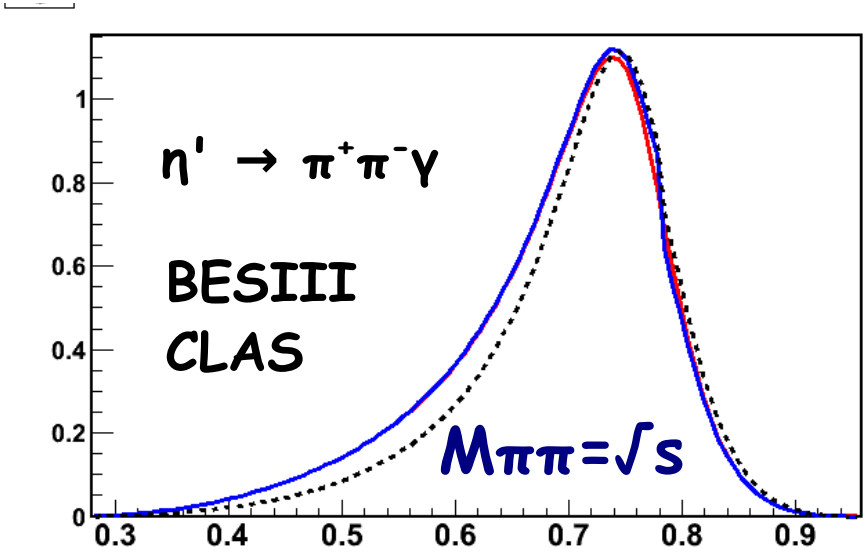
$\eta' \to \pi^+\pi^-\gamma$

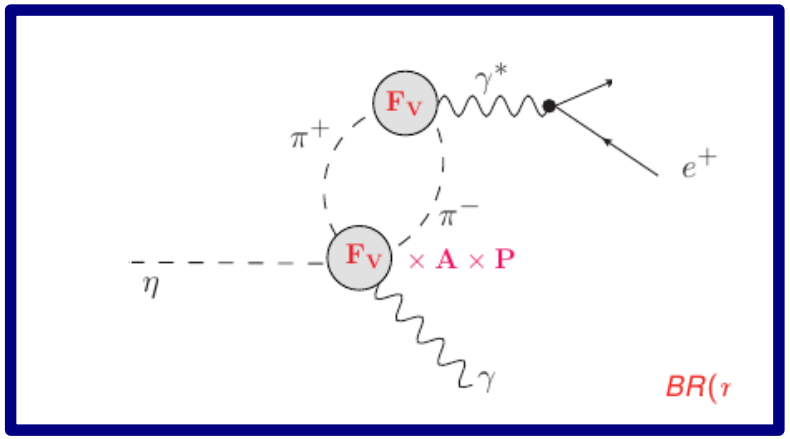


$$P(s_{\pi\pi}) = A_0(1 + \alpha s_{\pi\pi})$$

$\to$ α reaction specific

$\to$ $\alpha[\eta] = \alpha[\eta']$ understood
1-loop ChPT + large N_c



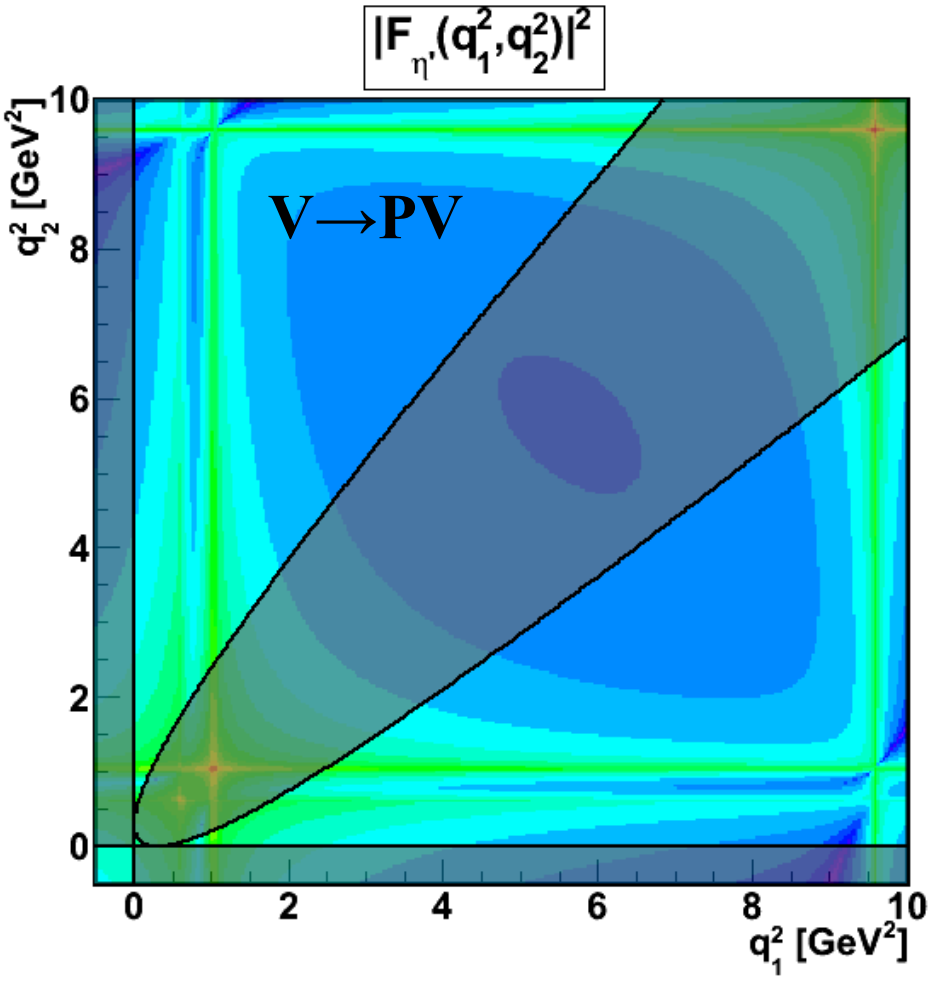


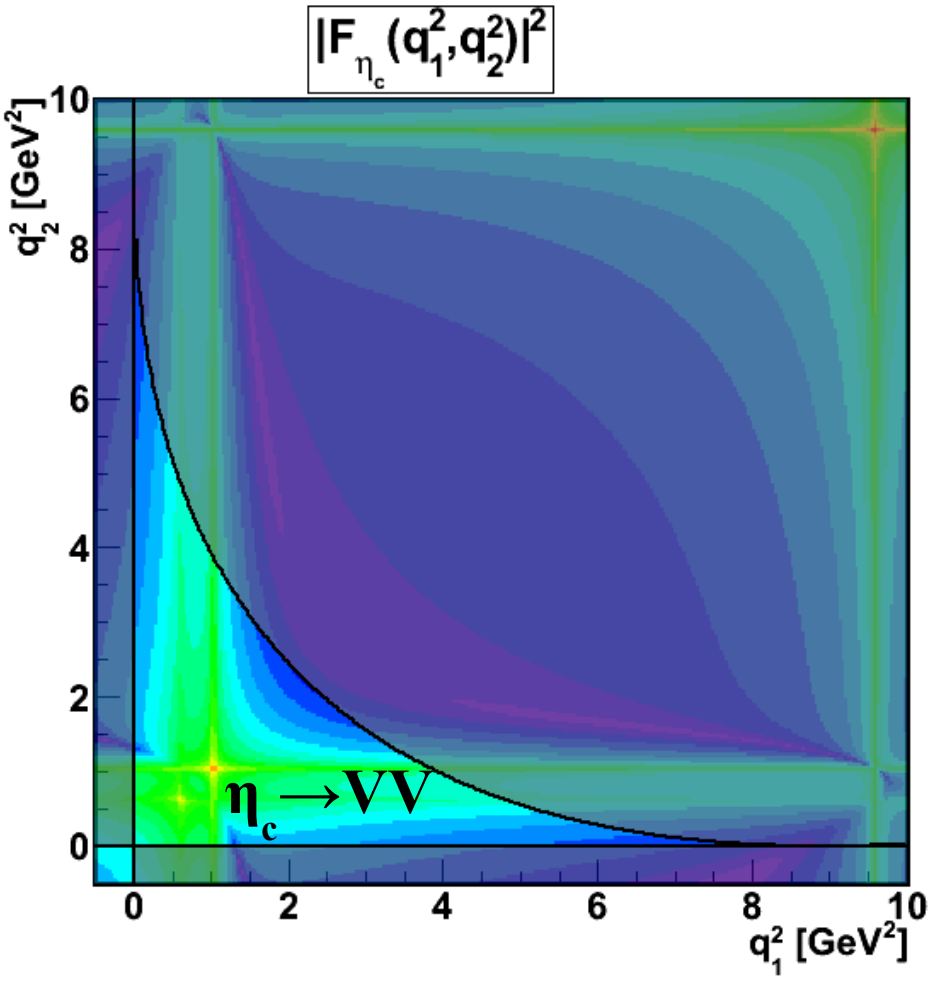
KLOE: A+α => $b_\eta(0) = 2.05^{+0.22}_{-0.10}$ GeV^{-2}

EPJC73(13)2668

DATA: C Barrel PLB 402,195 ('97); KLOE PL B718, 910 ('13)

Outlook η', ηc





η′→π+π−π+π−
η′→π+π−π0π0

arXiv:1404.0096

BESIII:

>5x10^6 η'
17x10^6 η_c

ηc → ρρ 1.8%

ηc → $K^*\overline{K^*}$ 0.7%

ηc → φφ 0.2%

Summary: PS TFF

Transition Form Factors $\pi^0/\eta/\eta'$

Main contribution to a_μ

Dispersive approach for PS TFF

Maybe HLbL,PS is already fixed?

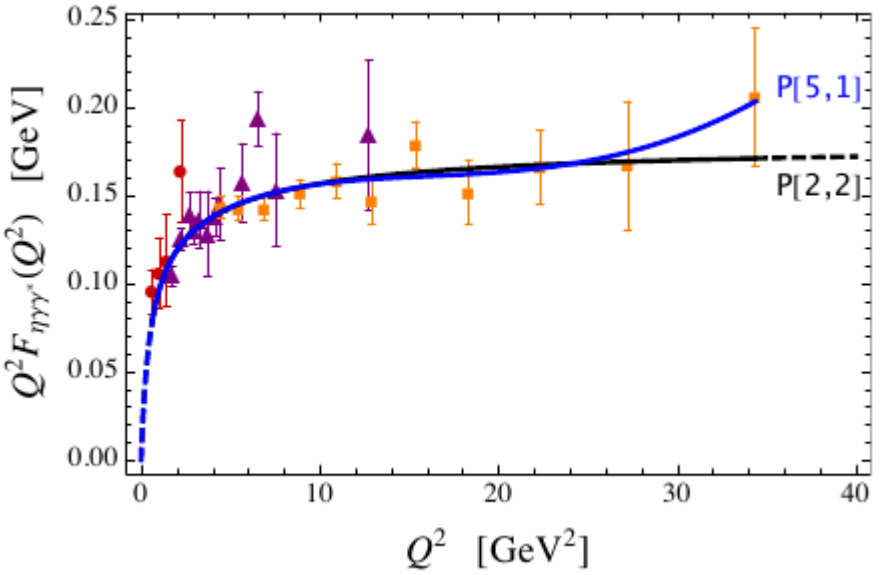
~~Use data from the Transition Form Factor for numerical integral~~

$$F_{P^*\gamma^*\gamma^*}(q_3^2, q_1^2, q_2^2)$$

$$F_{P\gamma^*\gamma^*}(m_P^2, q_1^2, q_2^2)$$

Use data from the Transition Form Factor to constrain your hadronic model

$$F_{P\gamma^*\gamma}(m_P^2, q_1^2, 0)$$



P. Masjuan

P. Sánchez-Puertas: Pade fit to spacelike FP(q2,0)

$$a_\mu^{LbyL;PS} = 8.9(6)(4) \times 10^{-10}$$

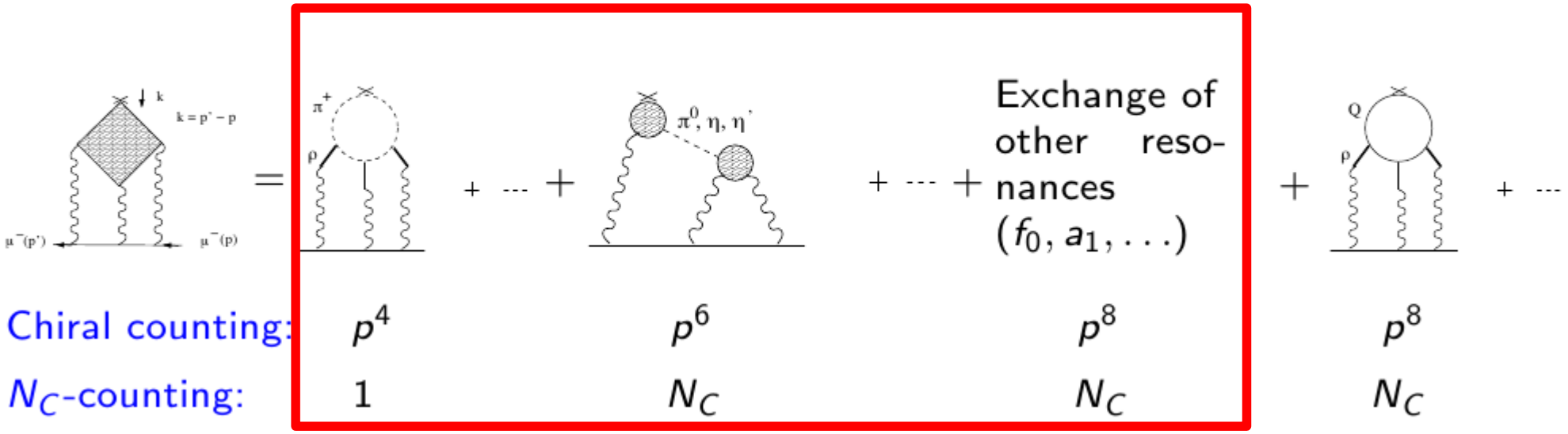
Hadronic Light by Light

New g-2 experiment at Fermilab with error

$$\sim 1.6 \cdot 10^{-10}$$

$$a_\mu^{\mathrm{HLbL}} = 10.5(2.6) \times 10^{-10}$$

Chiral Perturbation Theory counting (p^2)+large-Nc counting



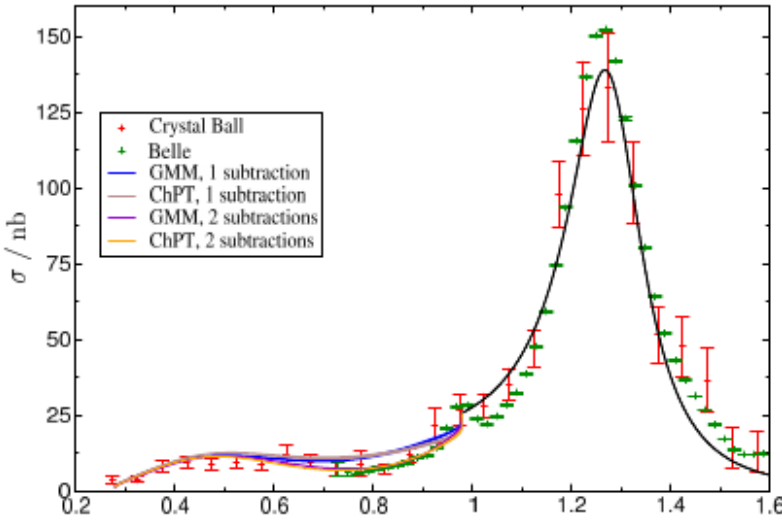
Chiral counting:	p^4	p^6	p^8	p^8
N_C-counting:	1	N_C	N_C	N_C

Dispersive

Dispersion relations for $\gamma^*\gamma^* \to \pi\pi$

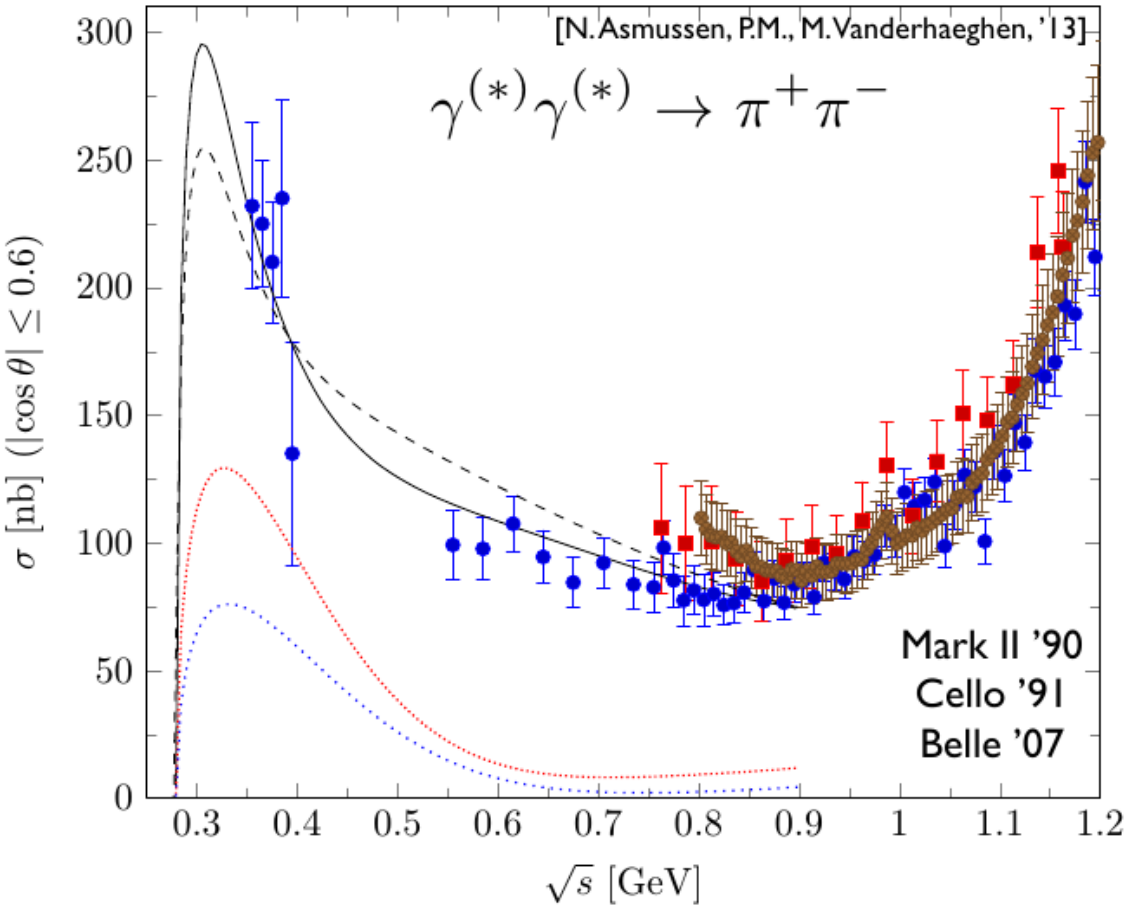
Roy-Steiner eqs. = Dispersion relations + partial-wave expansion + crossing symmetry + unitarity + gauge invariance

- On-shell $\gamma\gamma \to \pi\pi$: prominent D-wave reson. $f_2(1270)$ Moussallam (10) Hoferichter, Phillips, Schat (11)
- $\gamma^*\gamma \to \pi\pi$ Moussallam (13)
- $\gamma^*\gamma^* \to \pi\pi$, new feature: anomalous thresholds Hoferichter, GC, Procura, Stoffer (13)

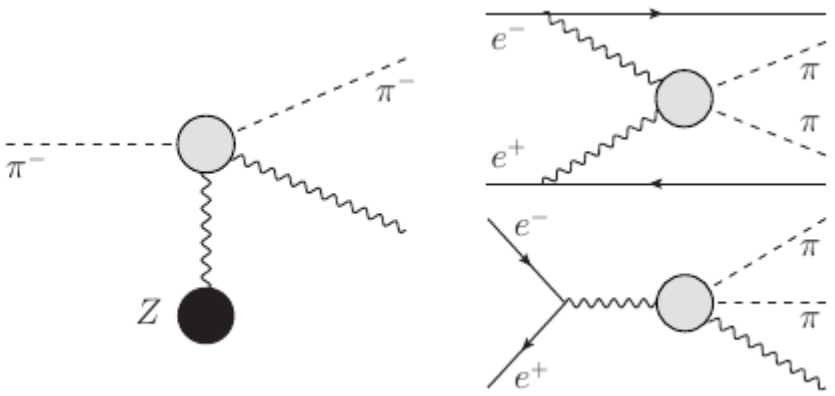


Slide: Gilberto Colangelo

γ(*) γ(*)→ππ; ηπ; KK



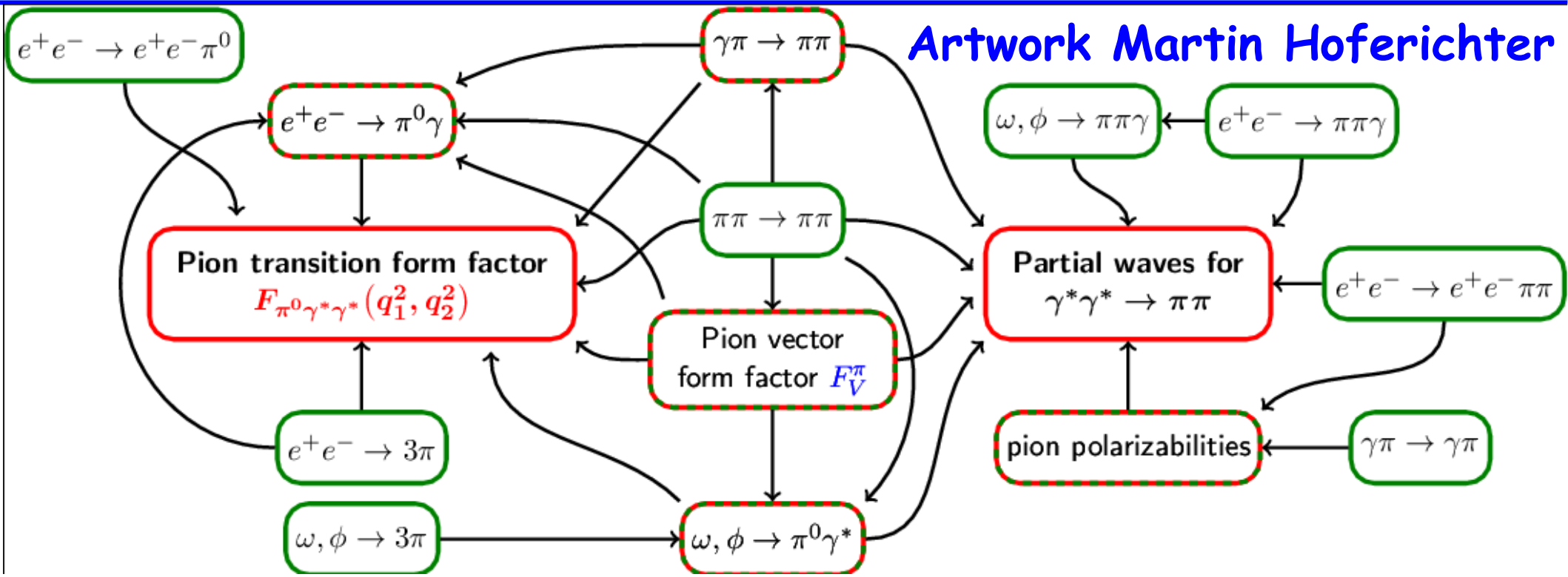
- Low energy: pion polar., ChPT
- Primakoff: $\gamma\pi \to \gamma\pi$ at COMPASS, JLAB
- Scattering: $e^+e^- \to e^+e^-\pi\pi$, $e^+e^- \to \pi\pi\gamma$
- Decays: $\omega, \phi \to \pi\pi\gamma$

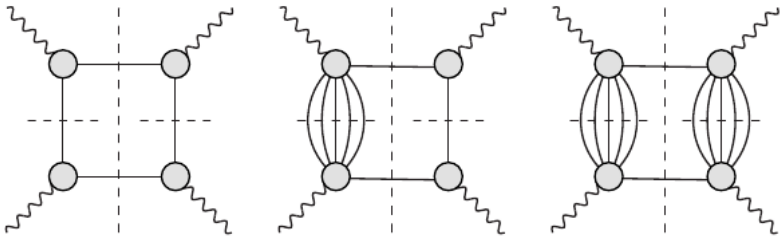


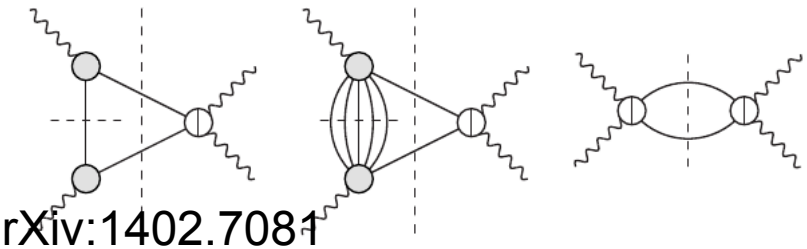
Slide: Gilberto Colangelo & Pere Masjuan

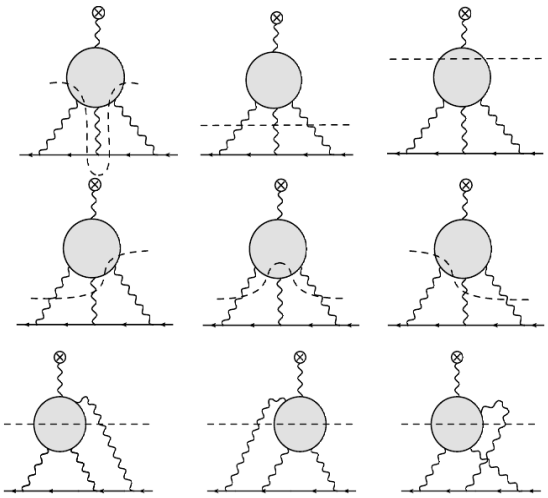
A roadmap for experiment?

Artwork Martin Hoferichter









arXiv:1402.7081
G. Colangelo, M. Hoferichter, M. Procura and P. Stoffer

M. Vanderhaeghen,,V. Pauk