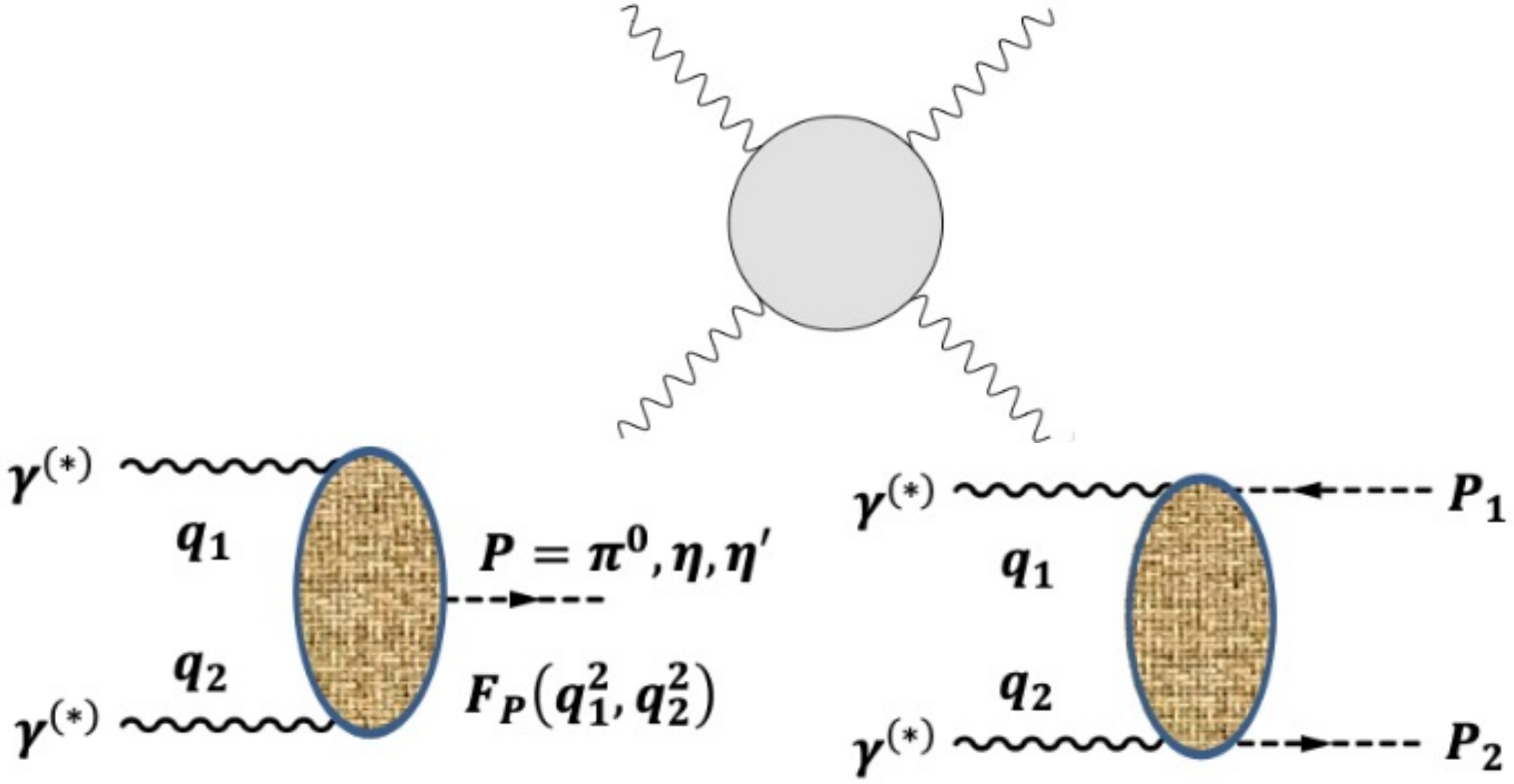
UPPSALA UNIVERSITET

Lecture 7:Experimental input to HLbL

Andrzej Kupsc



NCBJ ŚWIERK

Content of this lecture

- Introduction
- $\gamma^*\gamma^* \to X$
- Transition Form Factors $\gamma^*\gamma^* P = \pi^0, \eta, \ \eta'$
- $\gamma^*\gamma^* \to \pi^0\pi^0, \pi^+\pi^-, \pi^0\eta, \ldots$
- Related processes VVP

Lecture is based on:

- White Book: Phys. Rept. 887, 1 (2020)
- Prog. Part. Nucl. Phys. 107, 20 (2019)
- Phys. Rept. 128, 301 (1985)
- Eur. Phys. J. A 38, 331 (2008)
- Prog.Part. Nucl. Phys. 120, 103884 (2021)
- Phys. Rept. 477, 1 (2009
- *Phys.Rept.* 146, 1 (1987)
- *Phys.Rept.* 945, 1 (2022)

Hadronic contribution

$$a_\mu^{\mathrm{exp}} = 116\,592\,059 \pm 22) \times 10^{-11}$$

$a_\mu^{exp} - a_\mu^{SM} = (250 \pm 48) \cdot 10^{-11}$ (5σ)

hadronic vacuum polarization (HVP)

$a_\mu^{HVP} = (6845 \pm 40) \cdot 10^{-11}$

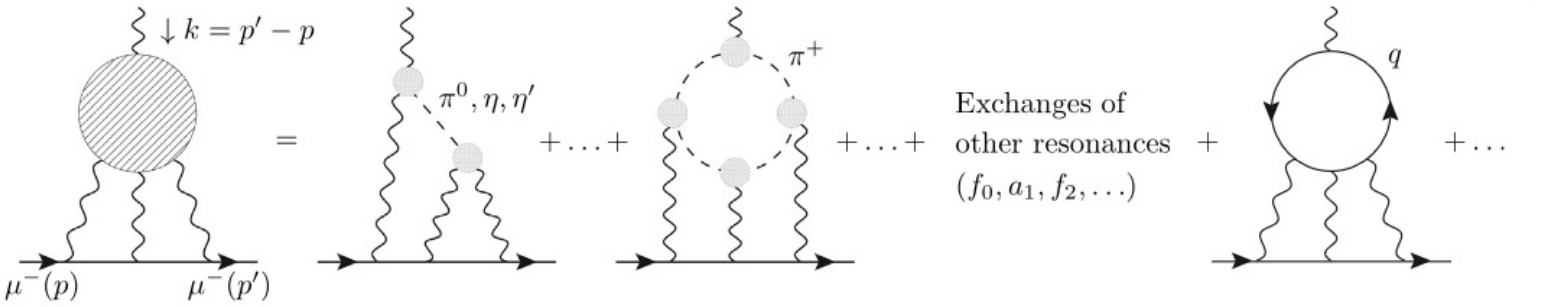
$a_\mu^{exp} - a_\mu^{SM}$: 4% HVP

hadronic light-by-light scattering (HLbL)

$a_\mu^{HLbL} = (92 \pm 19) \cdot 10^{-11}$

418% HLbL
(1% of leptonic LbL)

Hadronic Light by Light



π^0, η,η' exchange

$\pi^{\pm}$-box

hql+SD

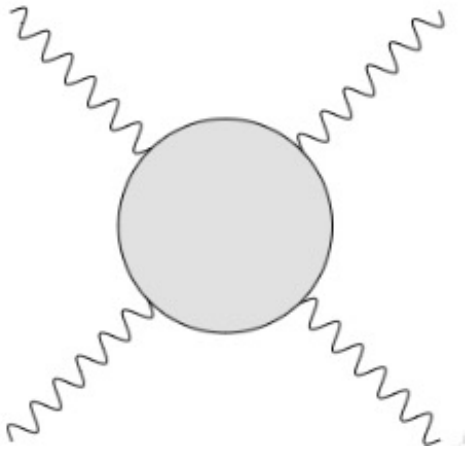
+92(19)= +93.8(4) −15.9(2) +8(1) +18(10) +...

pseudoscalar poles	$a_\mu^{\text{PS-poles}}$	=	$93.8^{+4.0}_{-3.6}$
pion box	$a_\mu^{\pi\text{-box}}$	=	−15.9(2)
S-wave $\pi\pi$ rescattering	$a_{\mu,J=0}^{\pi\pi,\pi\text{-pole LHC}}$	=	8(1)
kaon box	$a_\mu^{K\text{-box}}$	=	− 0.5(1)
scalars and tensors with $M_R \gtrsim 1$ GeV	$a_\mu^{\text{scalars+tensors}}$	~	− 1(3)
axial vectors	a_μ^{axials}	~	6(6)
short-distance contribution	$\Delta a_\mu^{\text{SDC}}$	~	15(10)
charm and other heavy-quark contribution	a_μ^{c}	~	3(1)
Total	$a_\mu^{\text{HLbL,LO}}$	~	92(19)

White Book

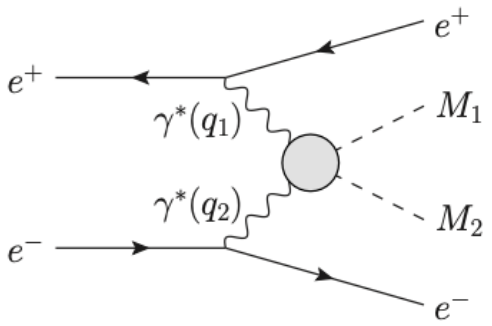
Light by Light scattering tensor

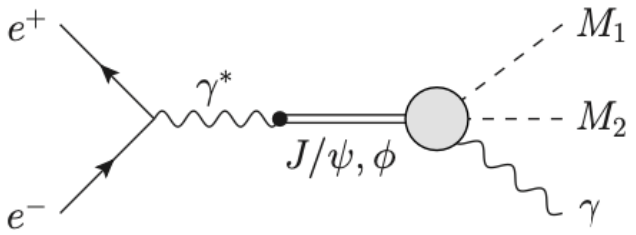
$$\gamma^{(*)}\gamma^{(*)} \to \gamma^{(*)}\gamma^{(*)}$$

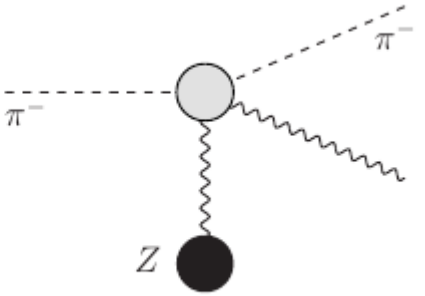


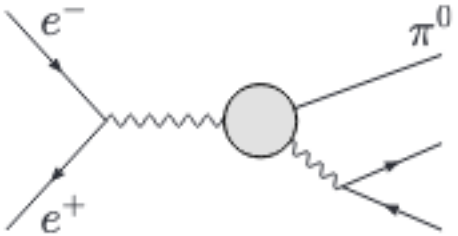
138 Lorentz structures and 43 independent independent scalar functions

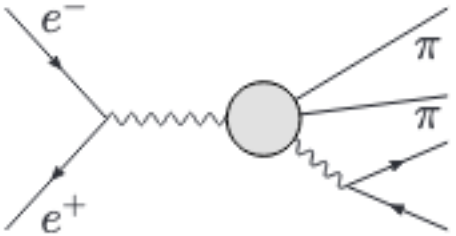
Can one measure $\gamma^{(*)}\gamma^{(*)} \to$ hadrons?

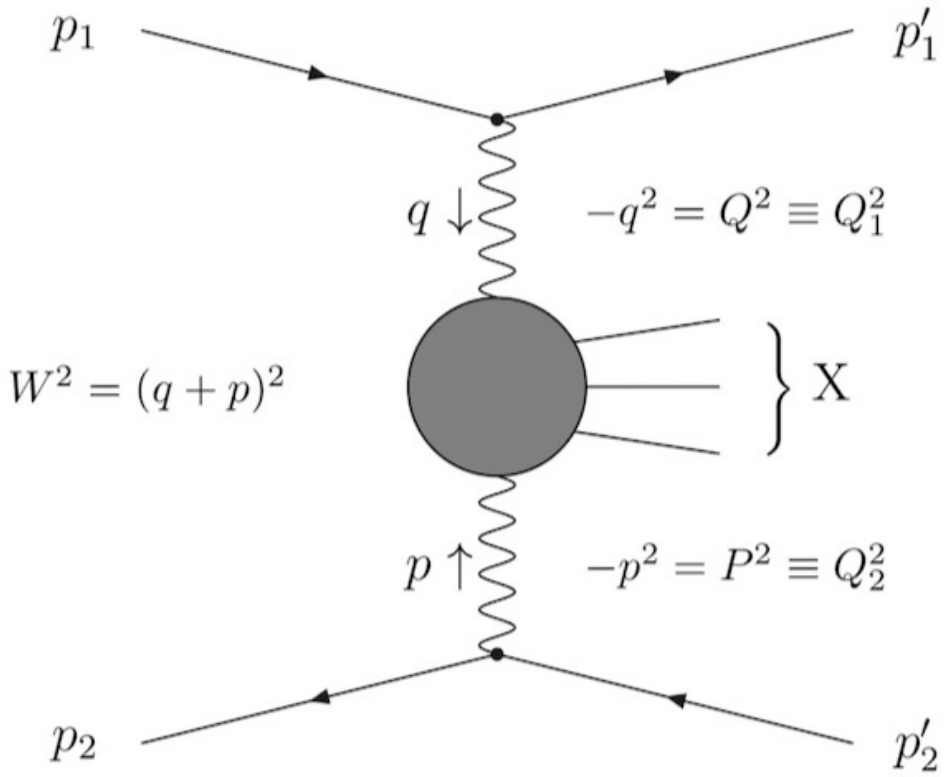

e^+
e^+
$\gamma^*(q_1)$
M_1
$\gamma^*(q_2)$
M_2
e^-
e^-


e^+
γ^*
M_1
M_2
$J/\psi, \phi$
e^-
γ


π^-
π^-
Z


e^-
π^0
e^+

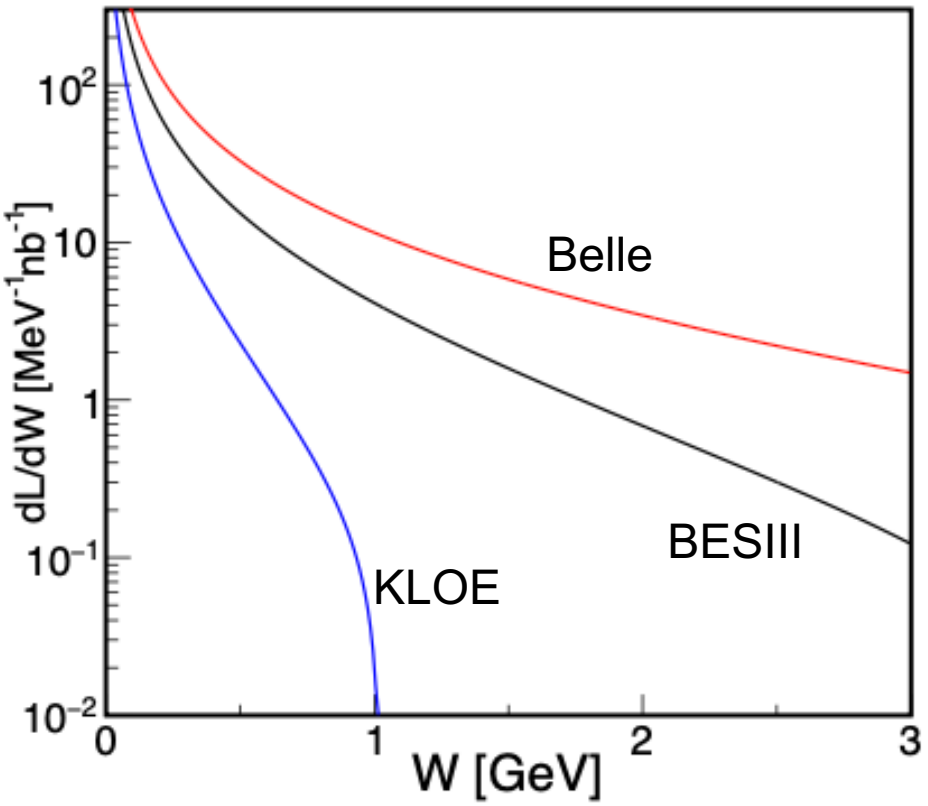

e^-
π
π
e^+

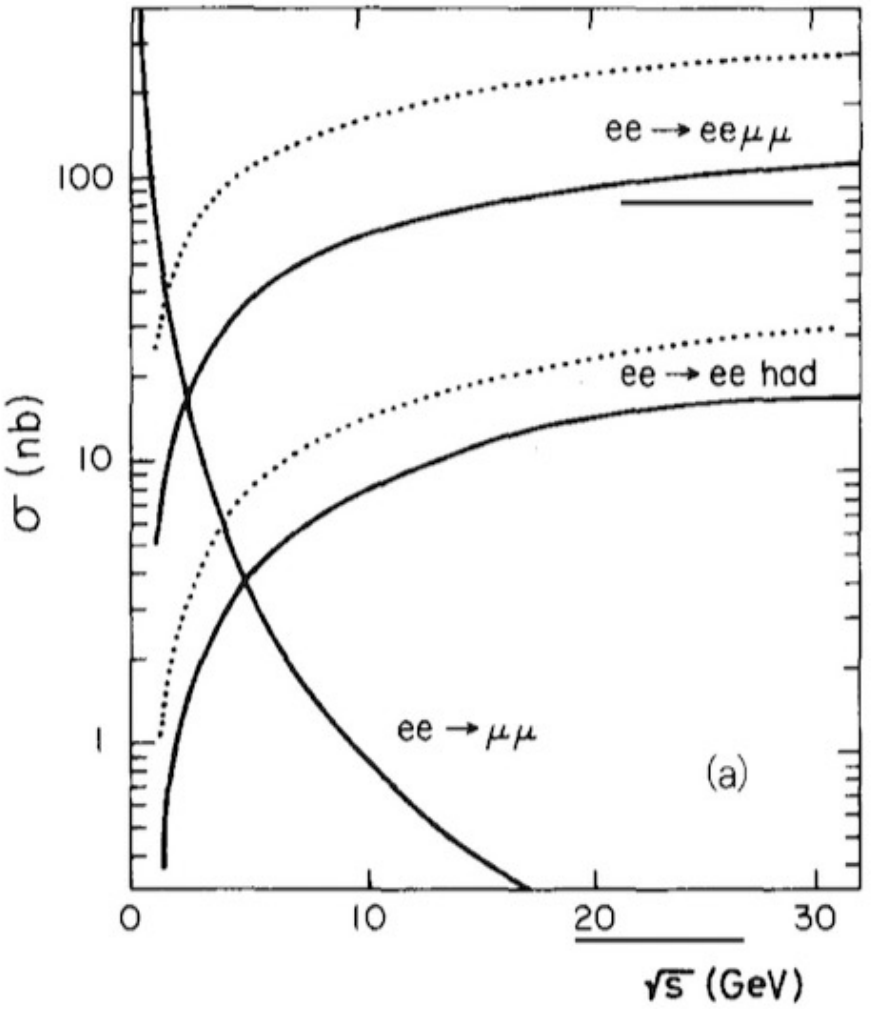


$$Q^2 \approx 4E_b E' \sin^2\left(\frac{\theta}{2}\right)$$

$$T = \frac{e^2}{q_1^2 q_2^2}\, j_\mu j_\alpha R^{\mu\alpha}$$

$$R_{\lambda_1\lambda_2} = \varepsilon_\mu(\lambda_1)\, \varepsilon_\alpha(\lambda_2) R^{\mu\alpha}$$



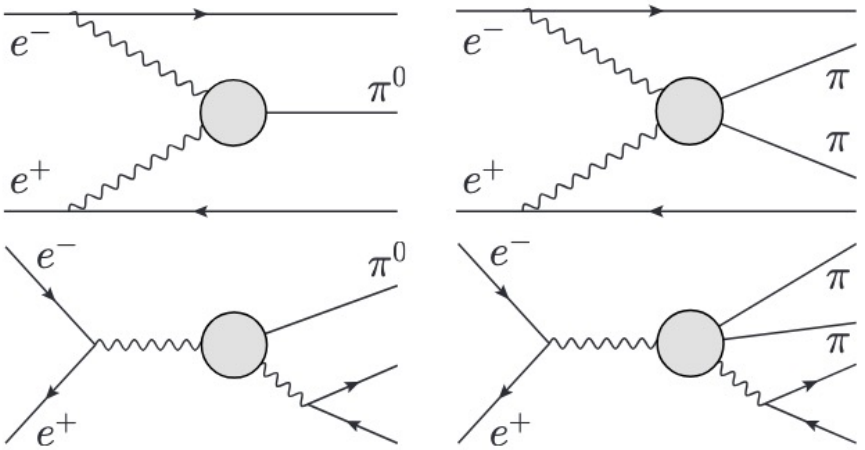


$$N_{eeX} = \mathcal{L} \int \frac{\mathrm{d}F}{\mathrm{d}W} \sigma_{\gamma\gamma \to X}(W)\, \mathrm{d}W$$

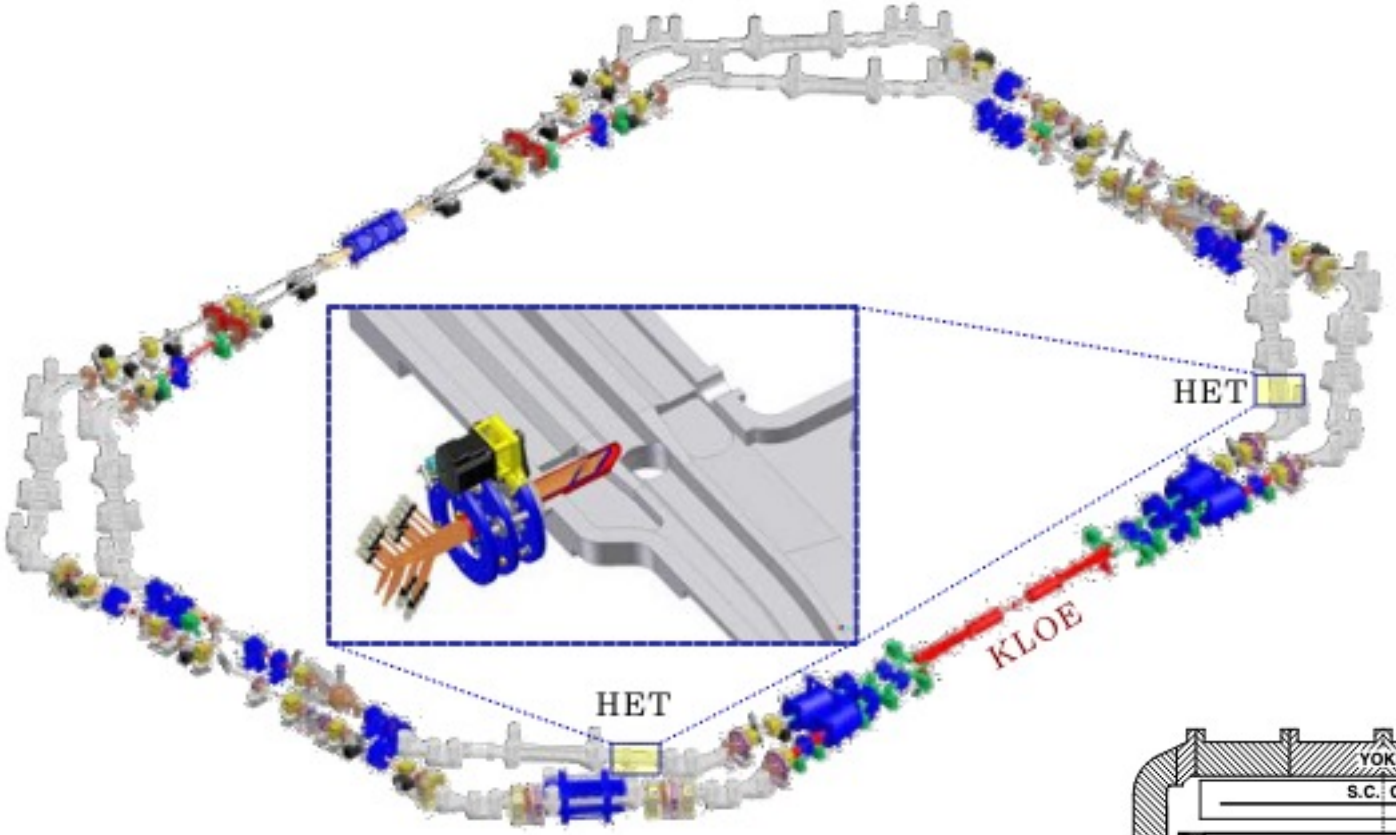
•*Phys.Rept.* 146 (1987) 1-134

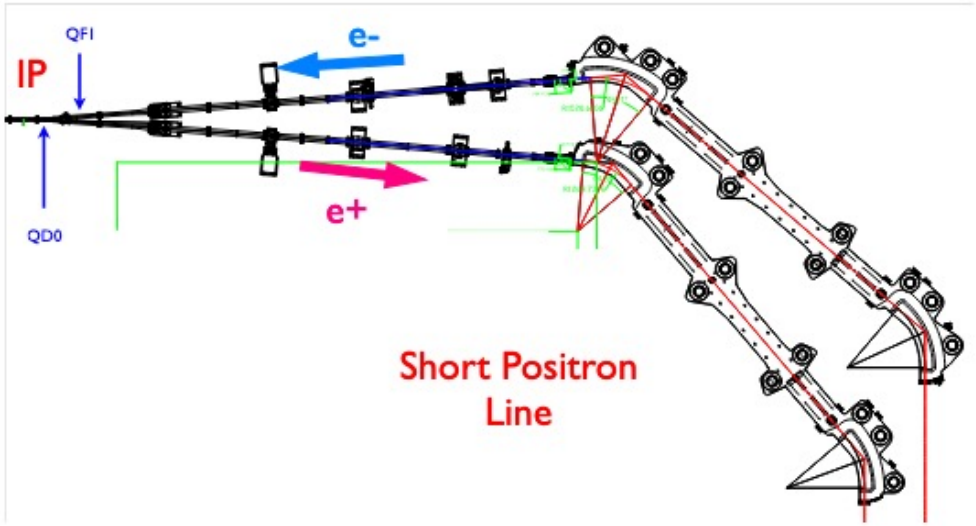
Two photon hadroproduction – experimental considerations

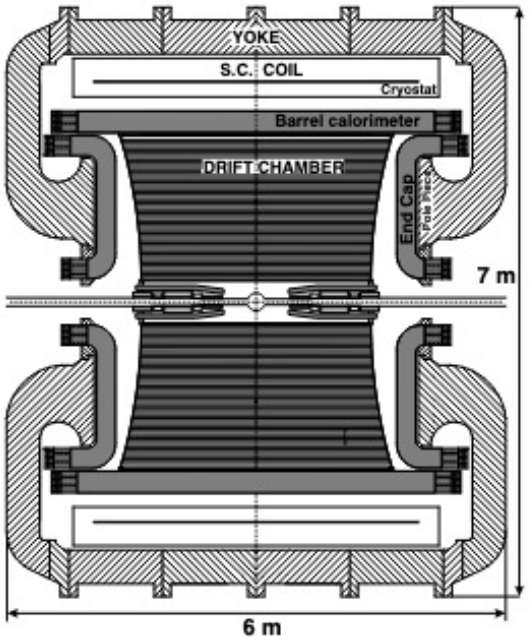
- Dominated by $Q^2 \approx 0,\ \theta \approx 0)$
- Tagging modes
- C=-1 background for $\pi^+\pi^-$
- $W < 0.5\sqrt{s}$



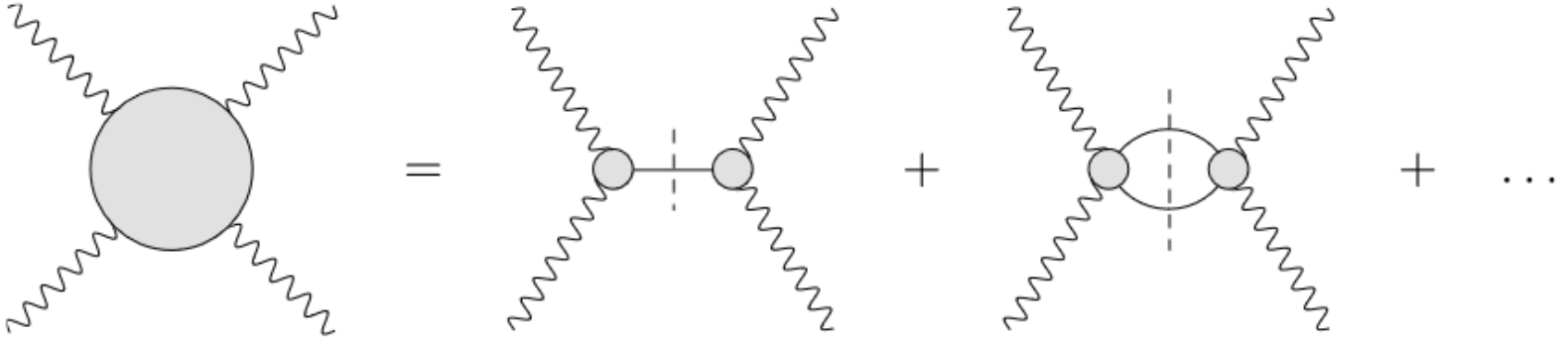
Two photon physics: zero tagging

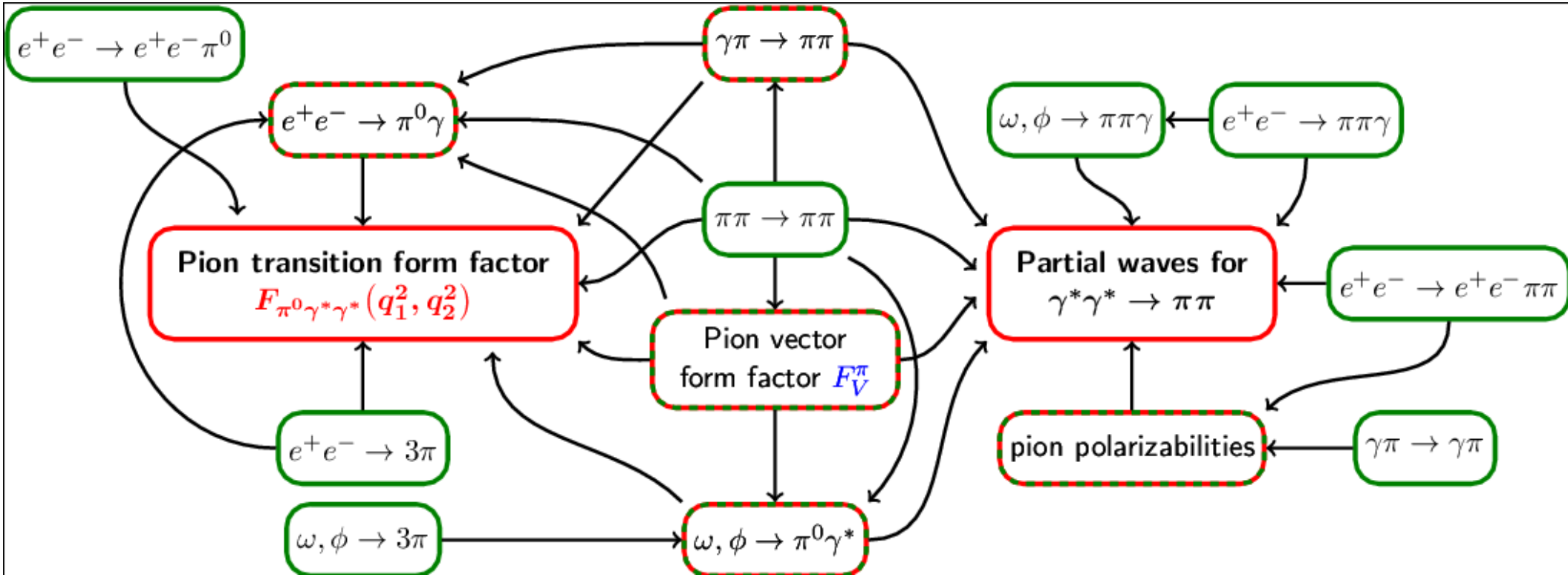






Data driven dispersive HLbL



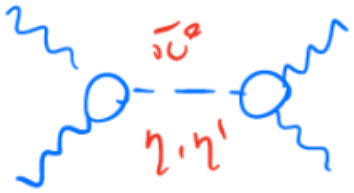


JHEP 1409 (2014) 091

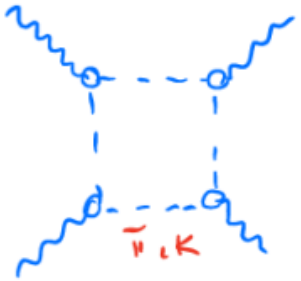
G. Colangelo, M. Hoferichter, M. Procura and P. Stoffer

Artwork M. Hoferichter

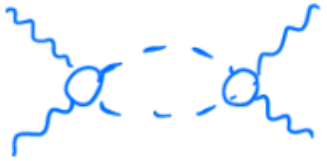
Data sources for dispersive HLbL

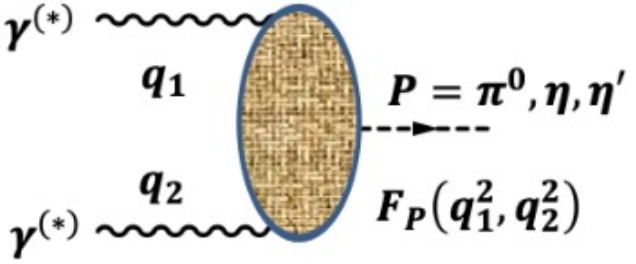


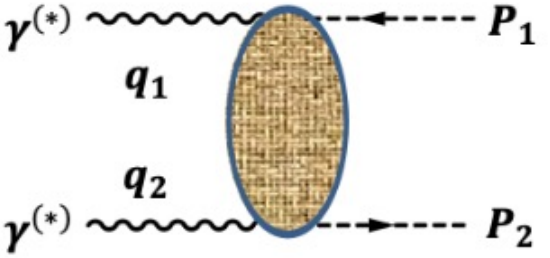
F_{π^0}
$F_\eta, F_{\eta'}$



F_V
F_K

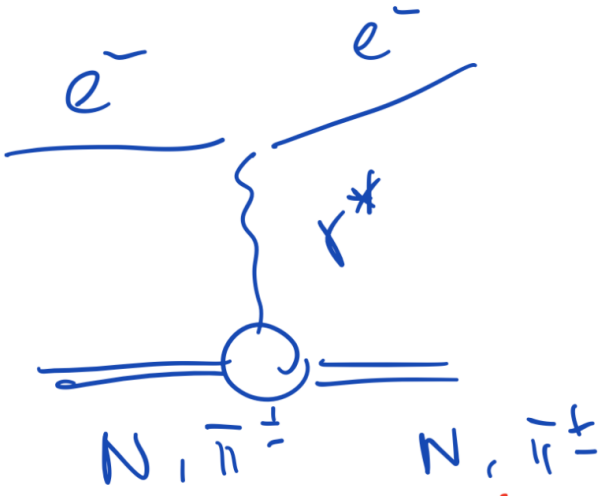


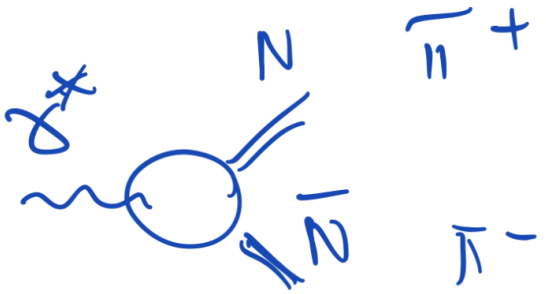




Electromagnetic Form factors (FFs)

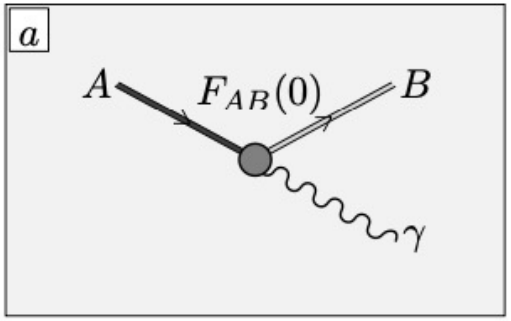
Elastic FFs



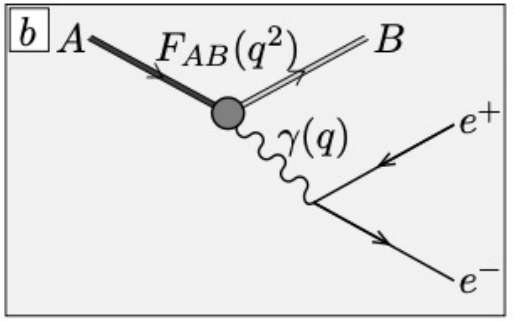


Transition FFs…

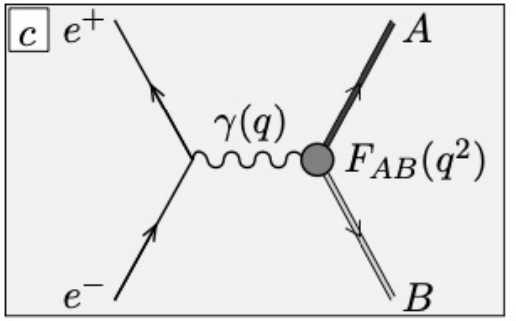
Transition form factors (TFFs)



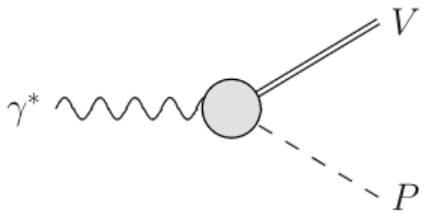
$q^2 = 0$

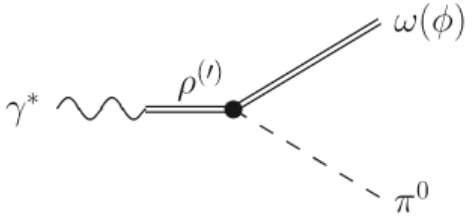


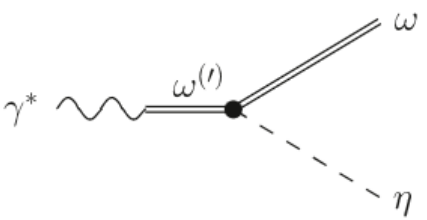
$(2m_e)^2 < q^2 < (M_A - M_B)^2$

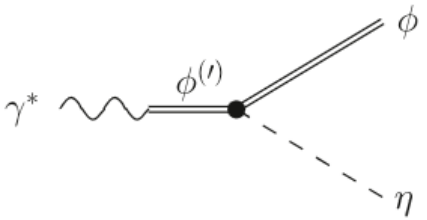


$q^2 > (M_A + M_B)^2$





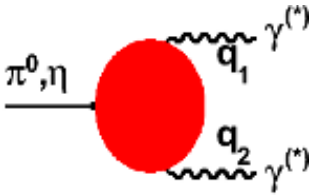




$$\Gamma(V \to P\gamma) = \frac{\alpha}{3} E_\gamma^3 |F_{VP}(0)|^2 , \qquad \Gamma(P \to V\gamma) = \alpha E_\gamma^3 |F_{VP}(0)|^2 ,$$

$$\sigma(e^+e^- \to VP) = \frac{4\pi\alpha^2}{3s^{3/2}} |F_{VP}(s)|^2 P_f(s)$$

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



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

Landsberg Phys. Rep., 128 (1985) 301
Pacetti Eur.Phys.J.A 38 (2008) 331

Radiative widths of η,π^0

η: 5×10^{-19} s; Γ=1.3 keV	$\eta \to \gamma\gamma$
π^0: 8×10^{-17} s; $c\tau$=25 nm	$\pi^0 \to \gamma\gamma$

Two exp. techniques:

$\gamma A \to \eta,\pi^0 A$

PrimEx(II) Science 368,506 (2020)

$\Gamma(\pi^0\to\gamma\gamma)$ = 7.802 (117)eV

$$\Gamma(\pi^0 \to \gamma\gamma) = \frac{\alpha^2 M_{\pi^0}^3}{64\pi^3 F_\pi^2} = 7.750(16)\,\text{eV}$$

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

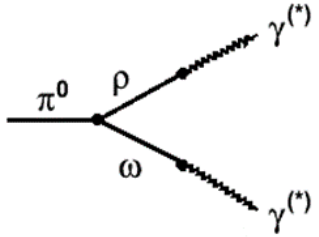
KLOE JHEP 01 (2013) 119

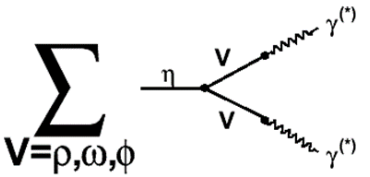
$\Gamma(\eta\to\gamma\gamma)$ = 520(20)(13) eV

$$\Gamma(\pi^0 \to \gamma\gamma) = 7.11 \pm 0.44_{\text{stat}} \pm 0.21_{\text{syst}}\ \text{eV}$$
$$\Gamma(\eta \to \gamma\gamma) = 338 \pm 94_{\text{stat}} \pm 35_{\text{syst}}\ \text{eV}$$
$$\Gamma(\eta' \to \gamma\gamma) = 3.4 \pm 1.0_{\text{stat}} \pm 0.4_{\text{syst}}\ \text{keV}\,.$$

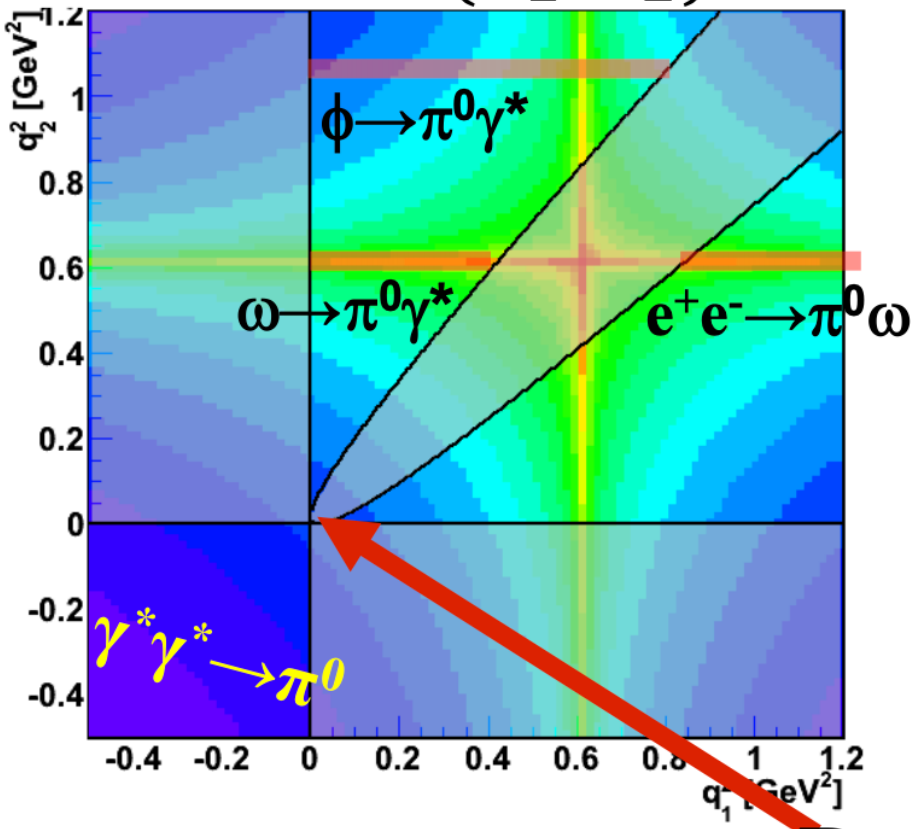
→LQCD: 2305.04570

π^0,η Transition Form Factors

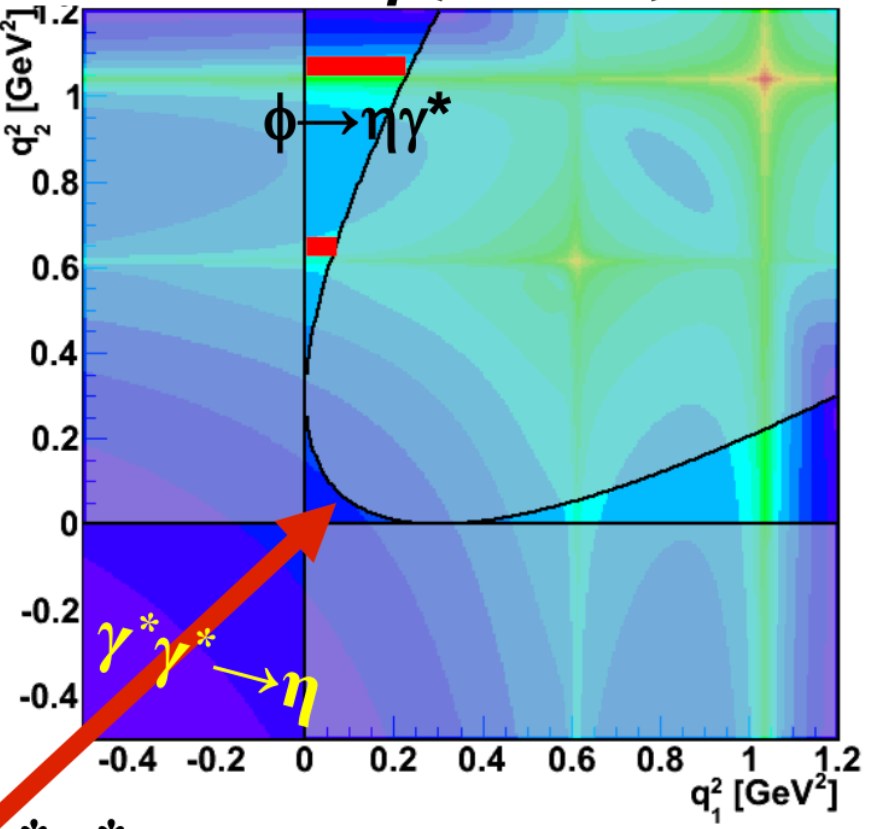




$|F_\pi(q_1^2, q_2^2)|^2$

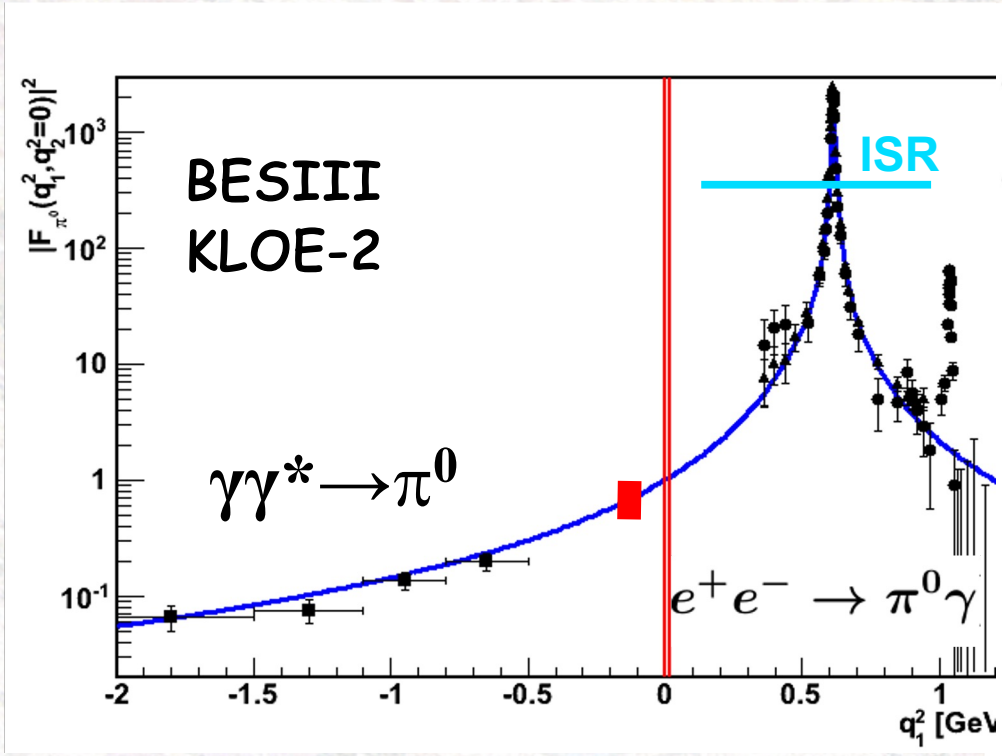


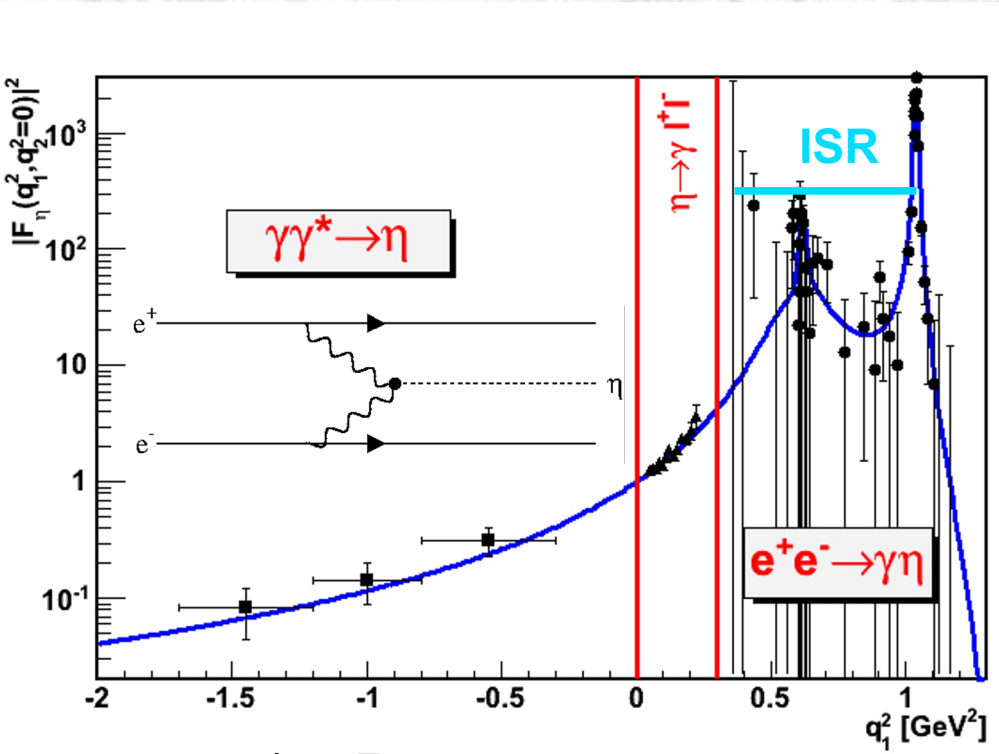
$|F_\eta(q_1^2, q_2^2)|^2$

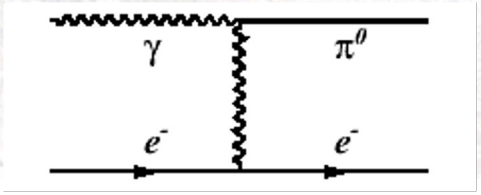


$P \to \gamma^*\gamma^*$

η,π^0 single off shell TFF







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

P→γ*γ

Dalitz decays:

KLOE, WASA,CBall,BESIII

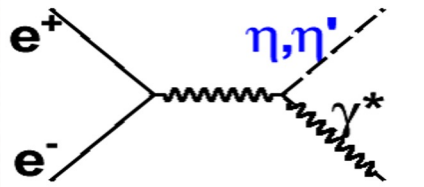
CLAS,NA48

γ*→Pγ

VEPP 2000 0.3-2GeV

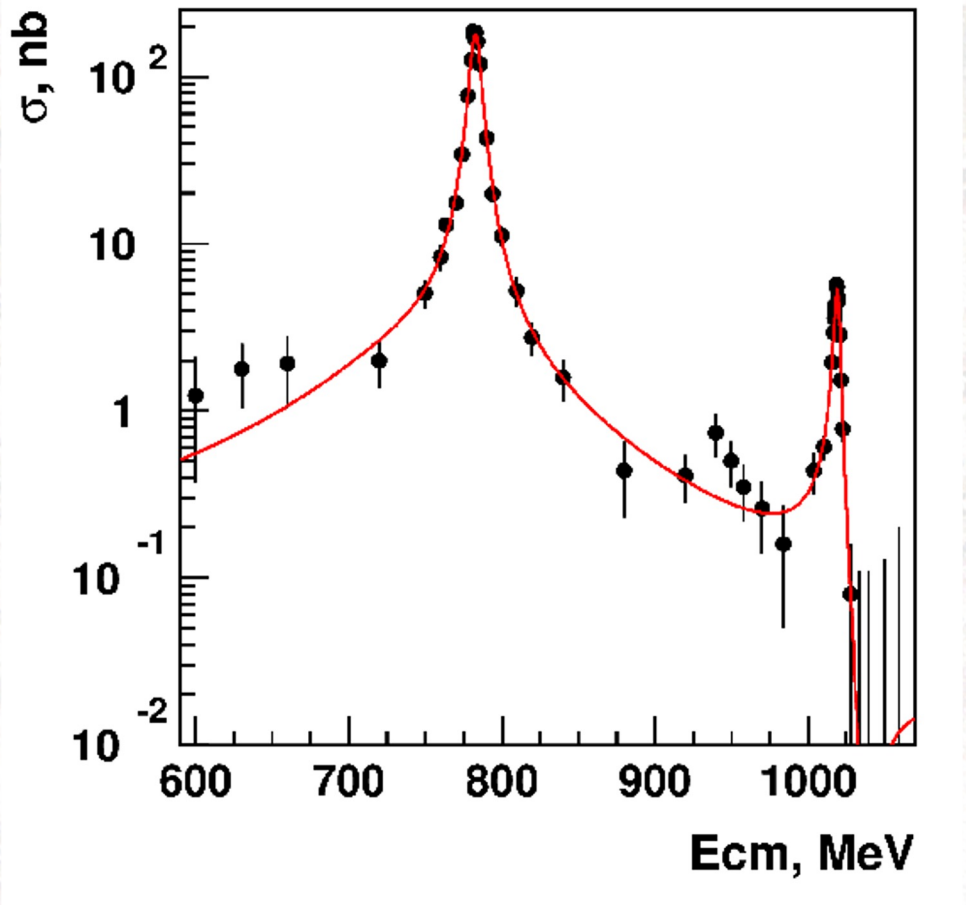
KLOE-2 ISR, BESIII

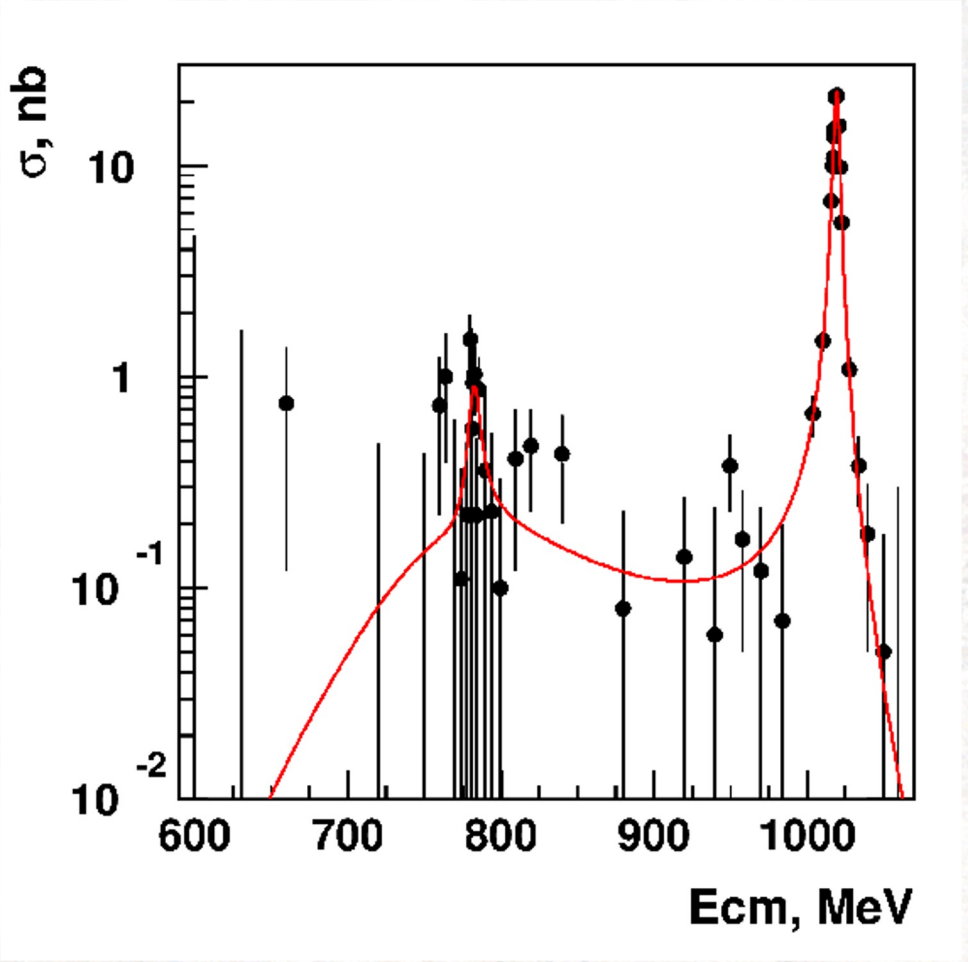
$$\sigma(e^+e^-\to P\gamma)=\frac{8}{3}\pi\alpha\,\Gamma_{\gamma\gamma}|F_P(s,0)|^2\left(\frac{s-m_P^2}{sm_P}\right)^3$$

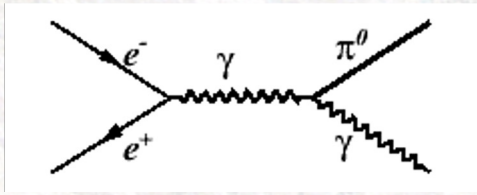


Data:CELLO,NA60,CB-MAMI,CMD-2,SND

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



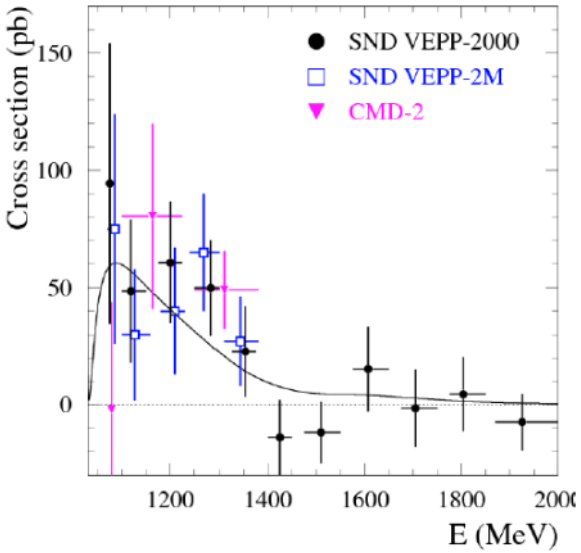




$$\sigma(e^+e^- \to P\gamma) = \frac{8}{3}\pi\alpha\,\Gamma_{\gamma\gamma}|F_P(s,0)|^2\left(\frac{s-m_P^2}{sm_P}\right)^3$$

Data: CMD-2,SND

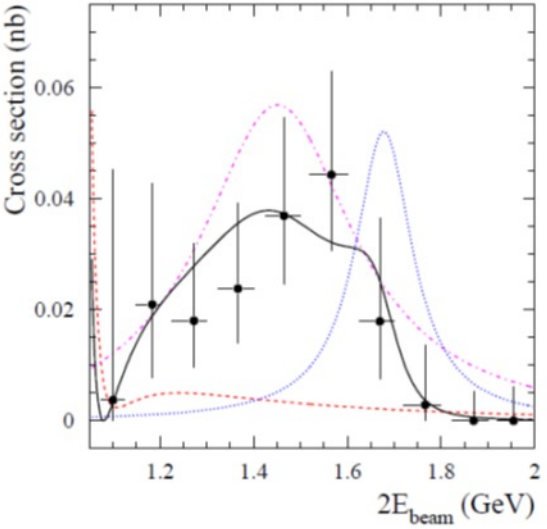
$e^+e^- \to \pi^0\gamma$ at SND



The first search above 1.4 GeV, preliminary

No signal above the background

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



The first measurement above 1.4 GeV, Phys. Rev. D90 (2014) 032002

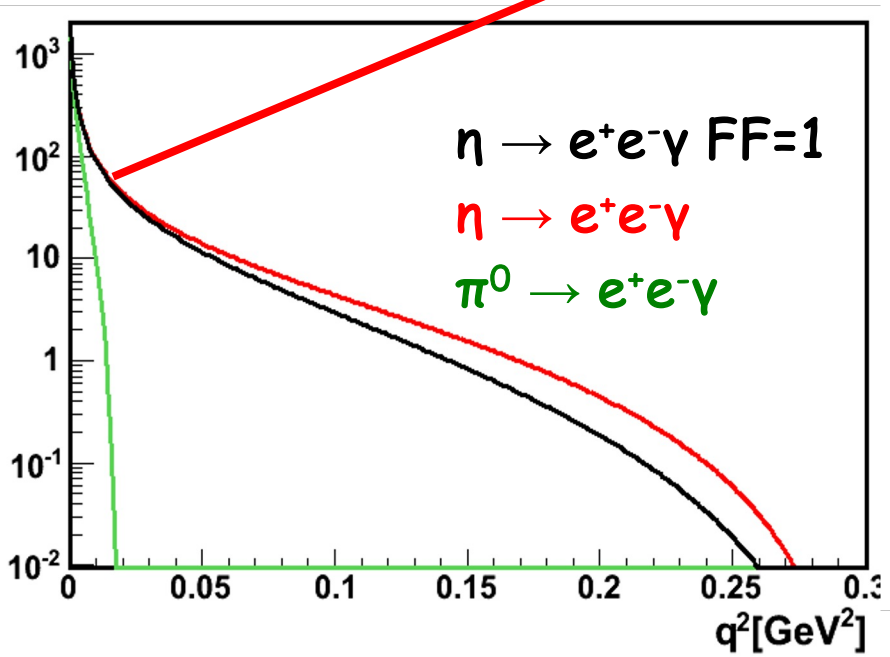
Dominated by the $\rho(1450)$ and $\phi(1680)$ mesons

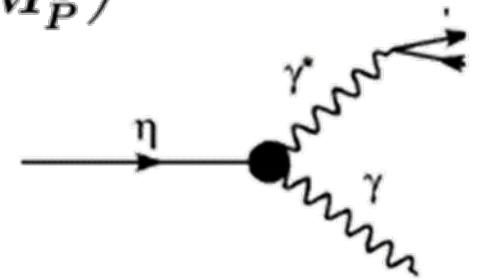
Slide from Simon Eidelman

Dalitz decays

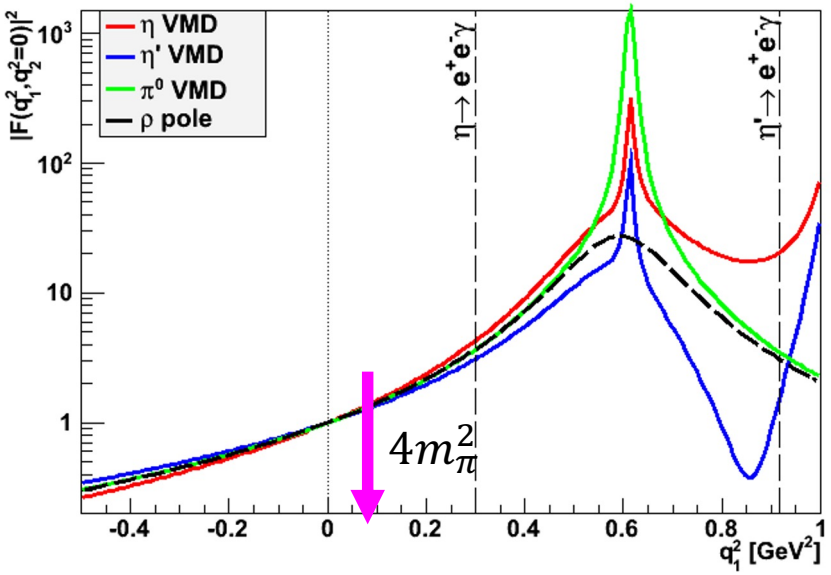
Single Dalitz decays

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

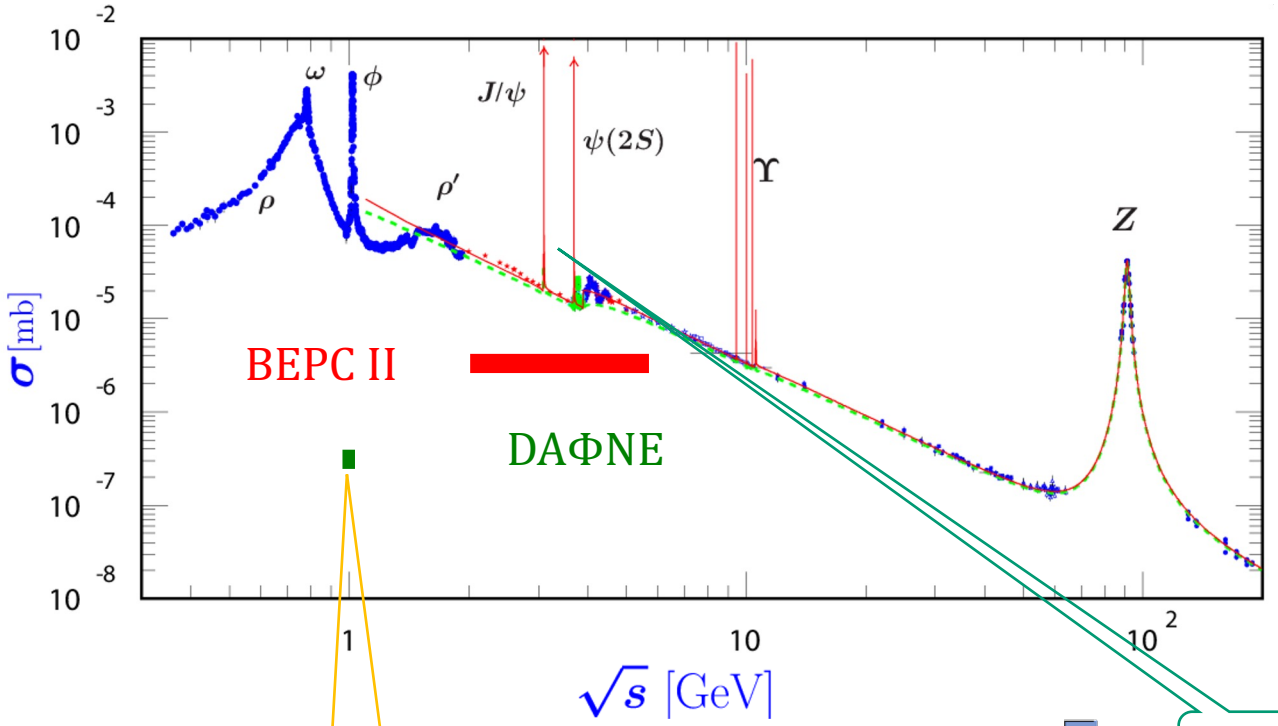


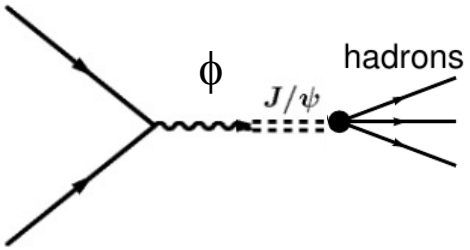


$$b_P = \left.\frac{d\ln|F_P(q^2)|}{dq^2}\right|_{q^2=0}$$



Studies of η and η' decays at e^+e^- colliders

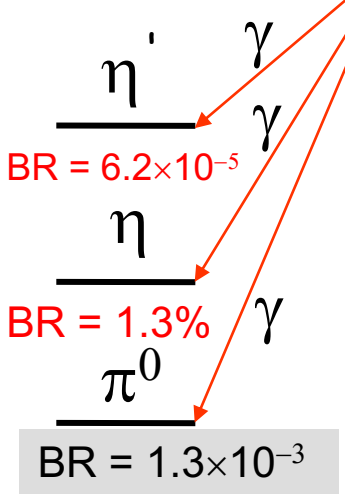


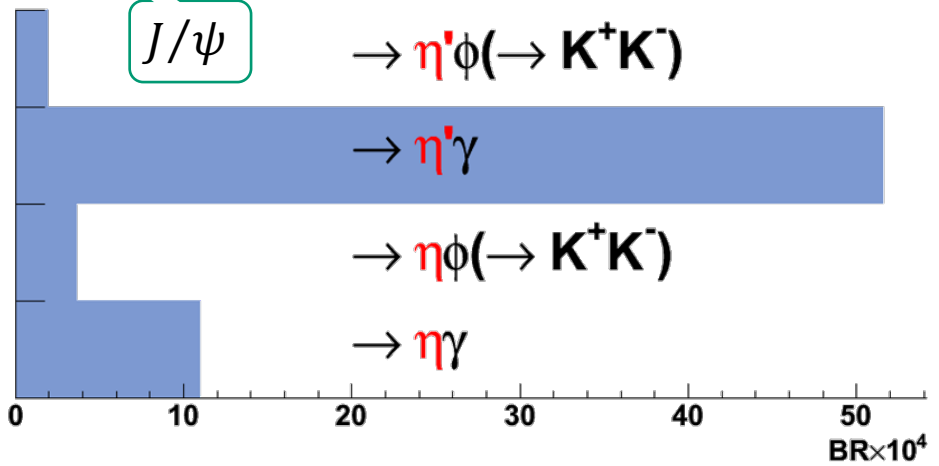


$\phi(1020)$

K^+K^-	BR = 49.2%
$K_L^0K_S^0$	BR = 34.0%

$3\times10^{10}\,\phi$



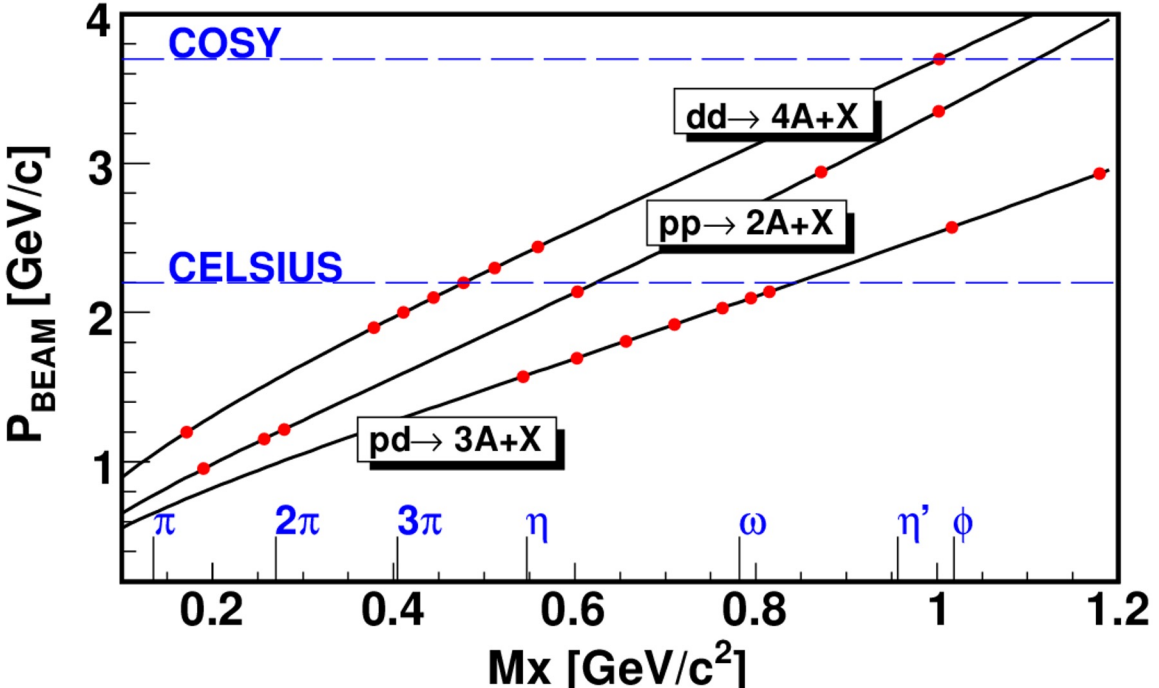


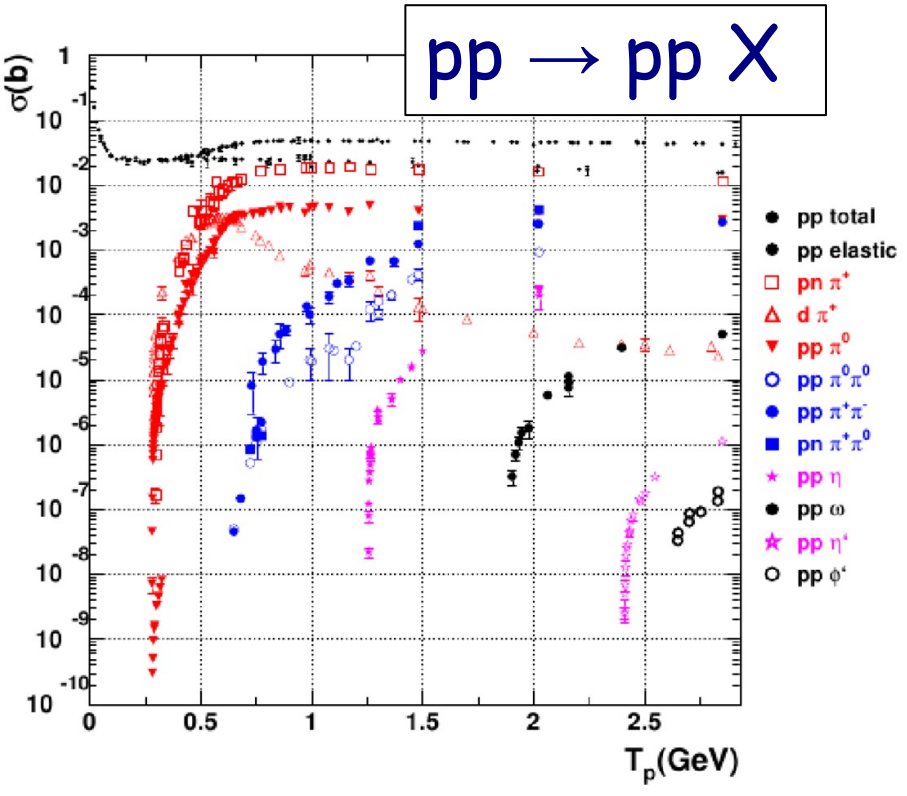
$5\times10^9\,J/\psi$

Hadro-production

	π^0	η	ω	η'
$pd \rightarrow 3HeX$	$O(\mu b)$	$0.4\mu b$	$85nb$	$0.6nb$
$pp \rightarrow pp\ X$	$1\ mb$	$10\mu b$	$10\mu b$	$300nb$

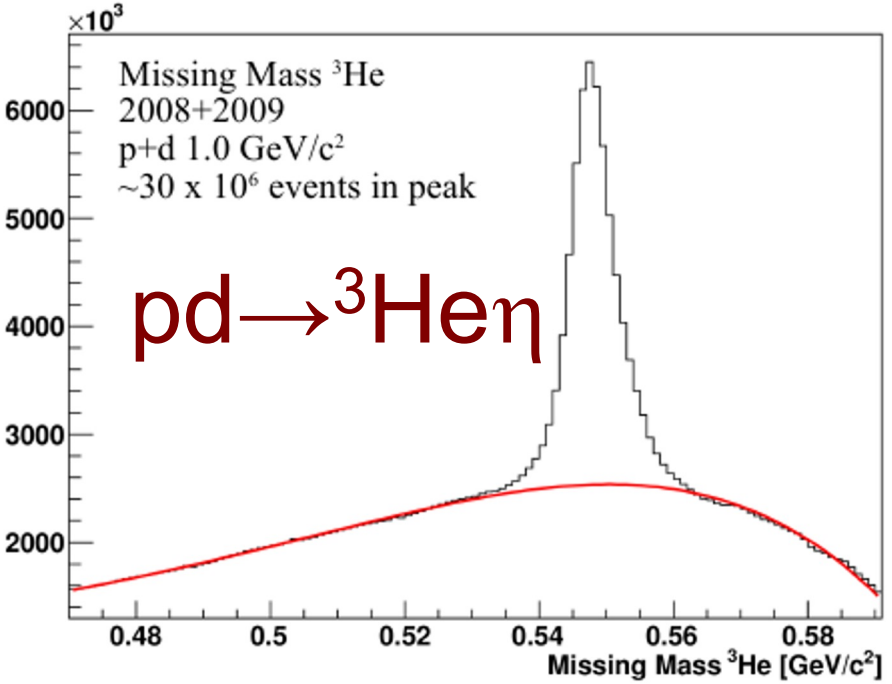
$L < 10^{32} cm^{-2} s^{-1} = 0.1\ nb/s$



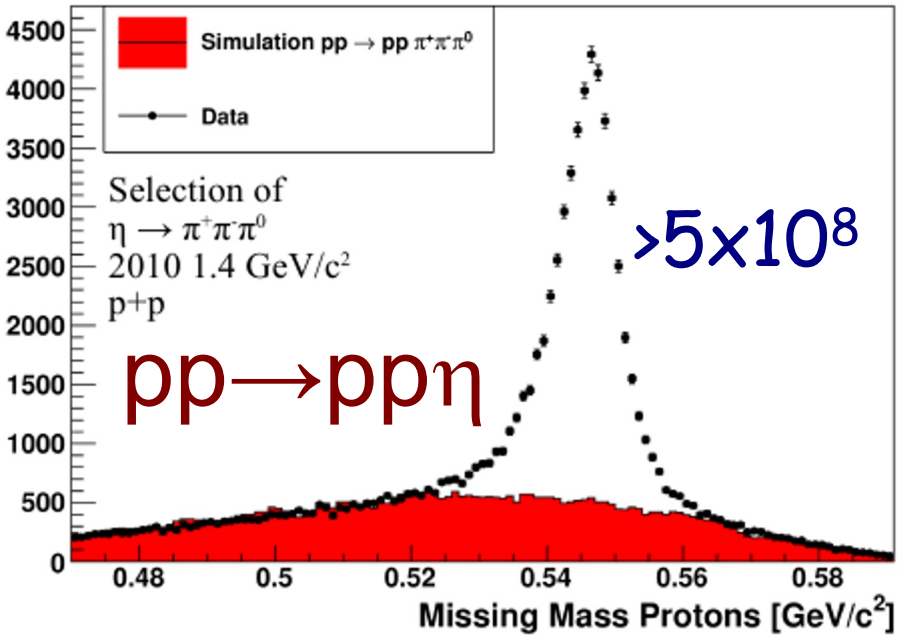


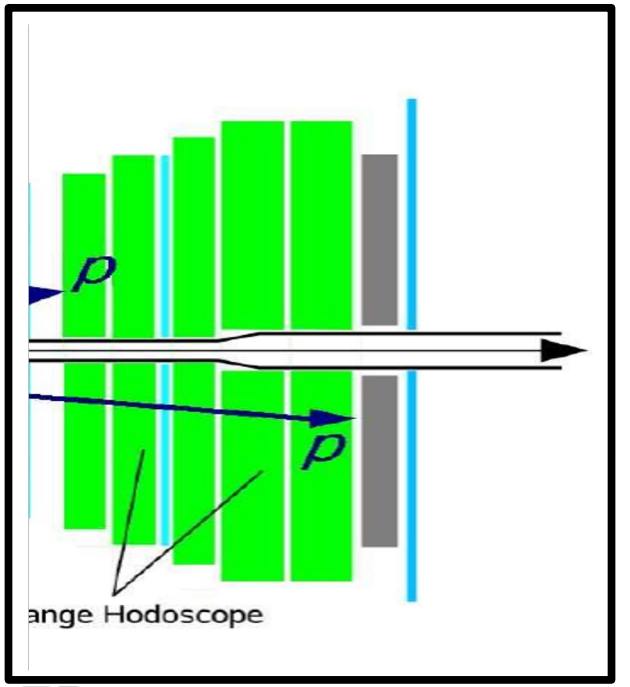
UPPSALA UNIVERSITET

Meson tagging

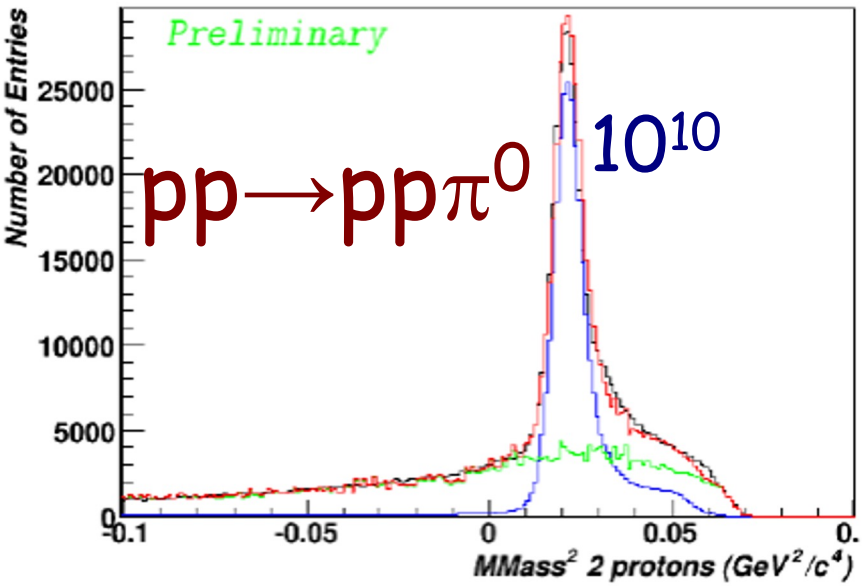


$$Missing\ Mass = \sqrt{(E_{in} - E_{out})^2 - (P_{in} - P_{out})^2}$$





2 FD protons



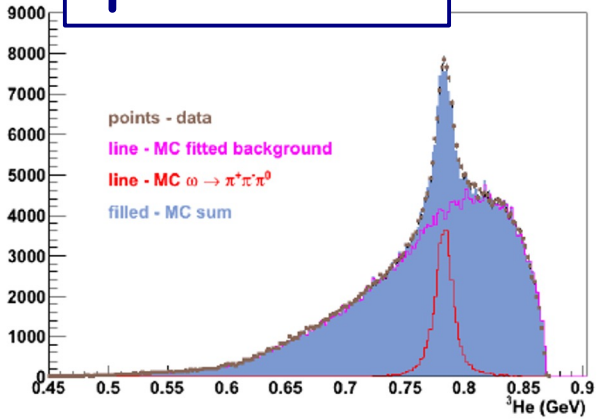
UPPSALA UNIVERSITET

p+ d, ∼ 2 weeks,
P_{beam} 2.25 & 2.19 GeV/c

p +p, pilot run,
P_{beam} 2.851 & 3.350GeV/c

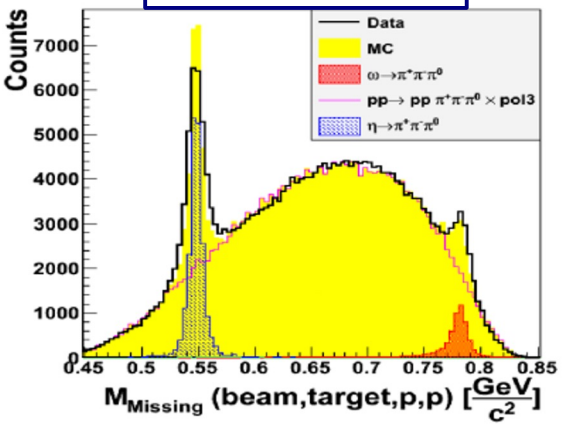
A glance at $\omega \rightarrow \pi^+\pi^-\pi^0$

pd→^{3}Hew



Cut based selection: 72 000 signal events

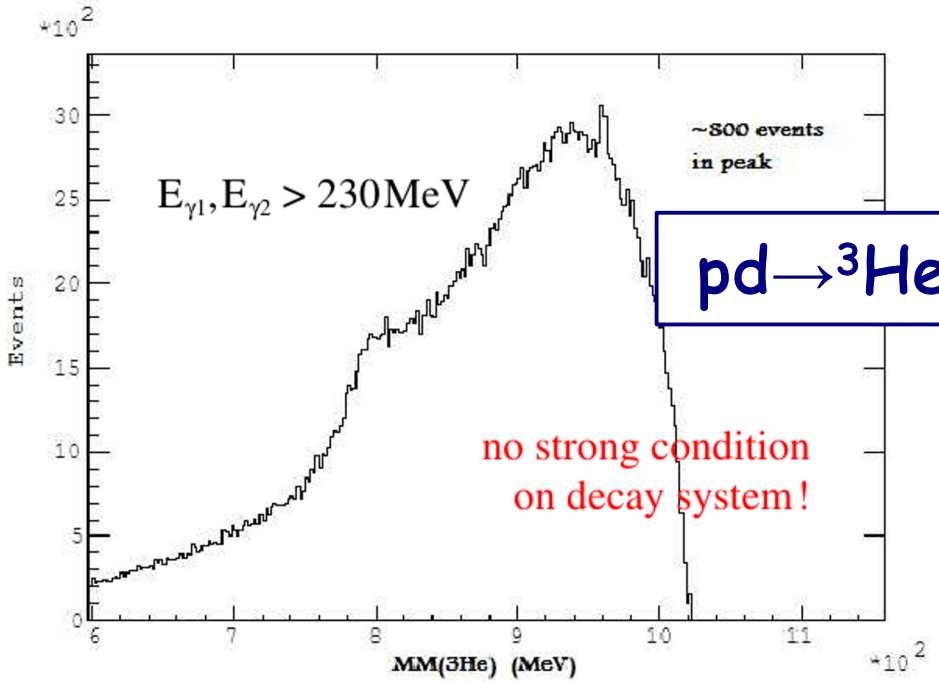
pp→ppω



With kinematical fit: 5600 signal events
(1/3 of collected data)

L.Heijkenskjöld,S.Sawant,F.Anjum Khan

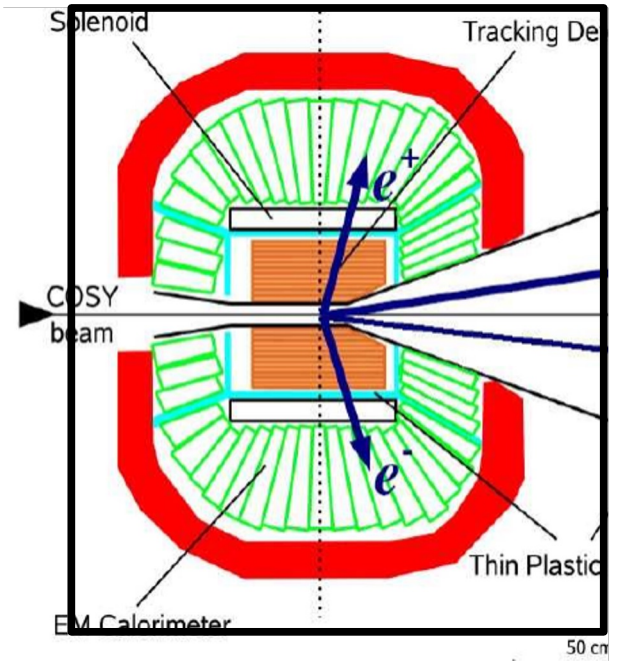
pd→^{3}Hen'

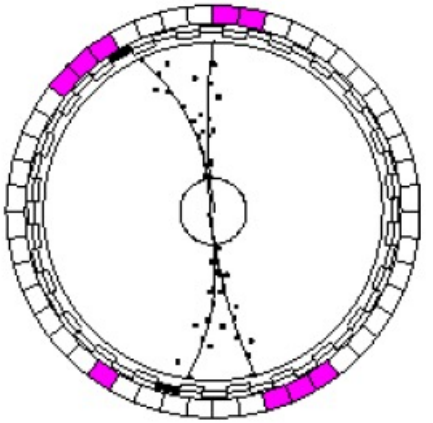


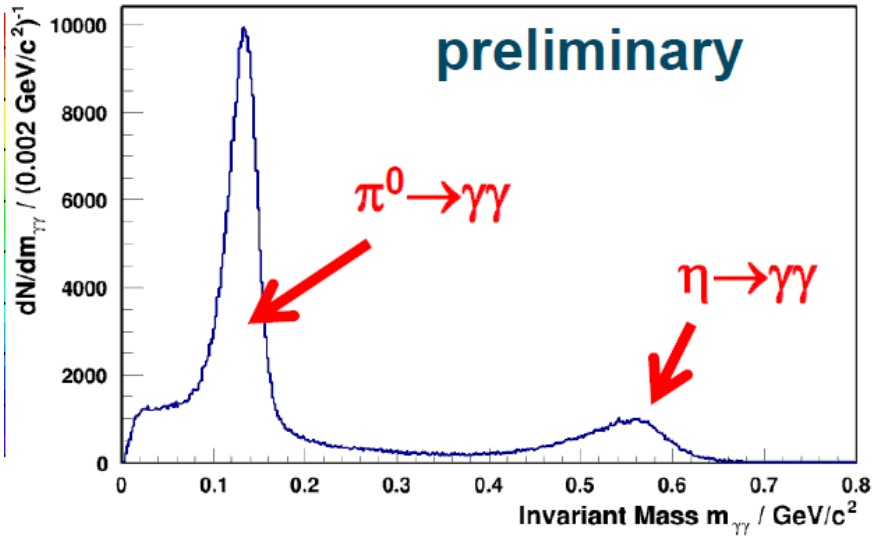
J.Zlomanczuk

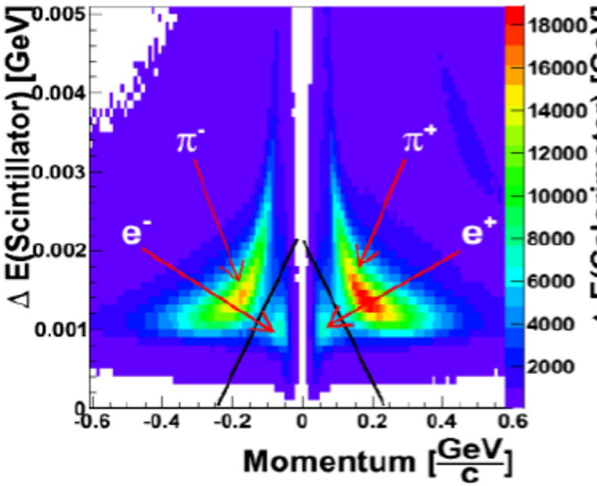
UPPSALA UNIVERSITET

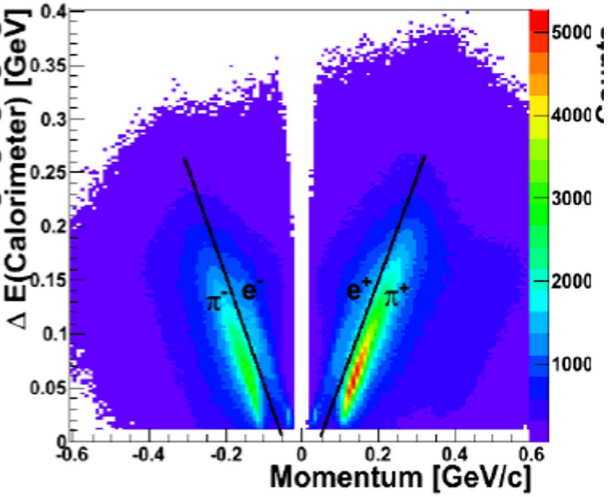
Decay products





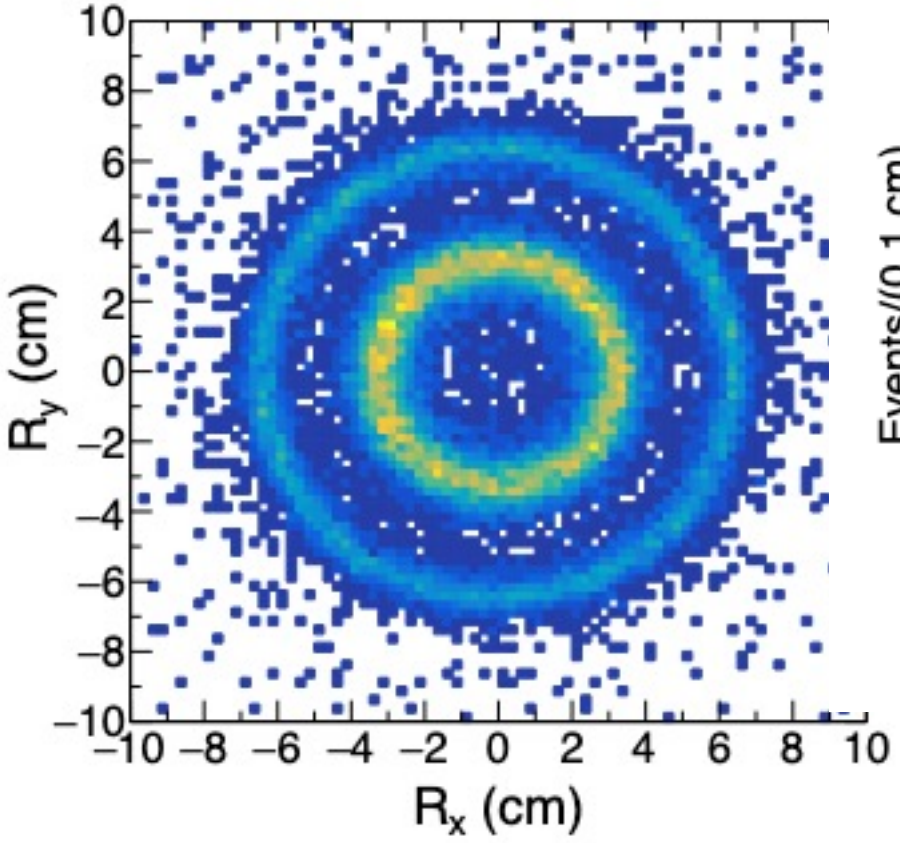


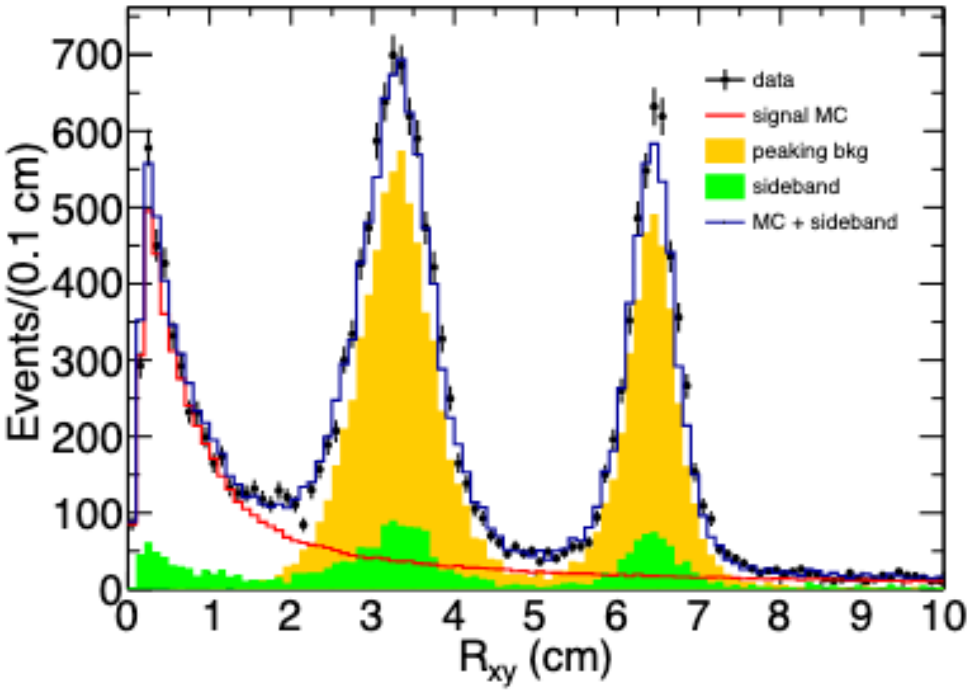




Electron conversion

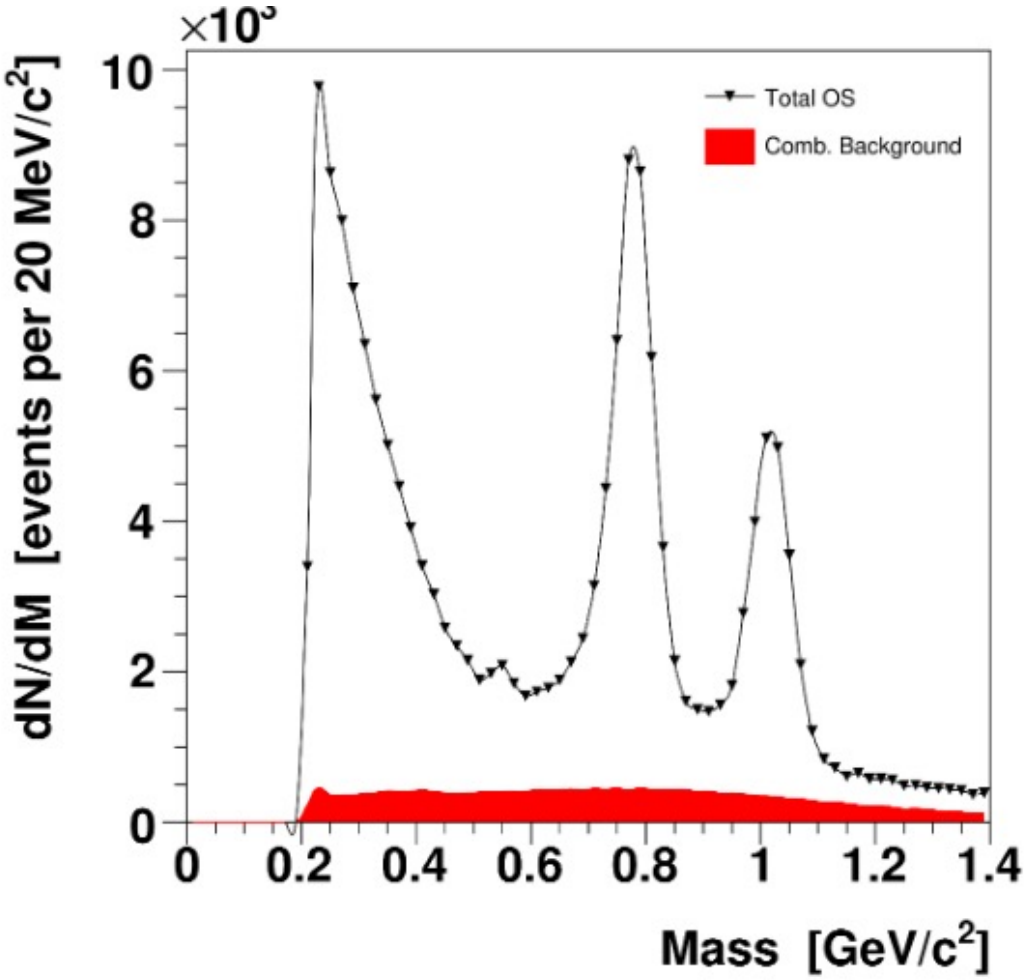
$\eta' \to e^+e^-\gamma$

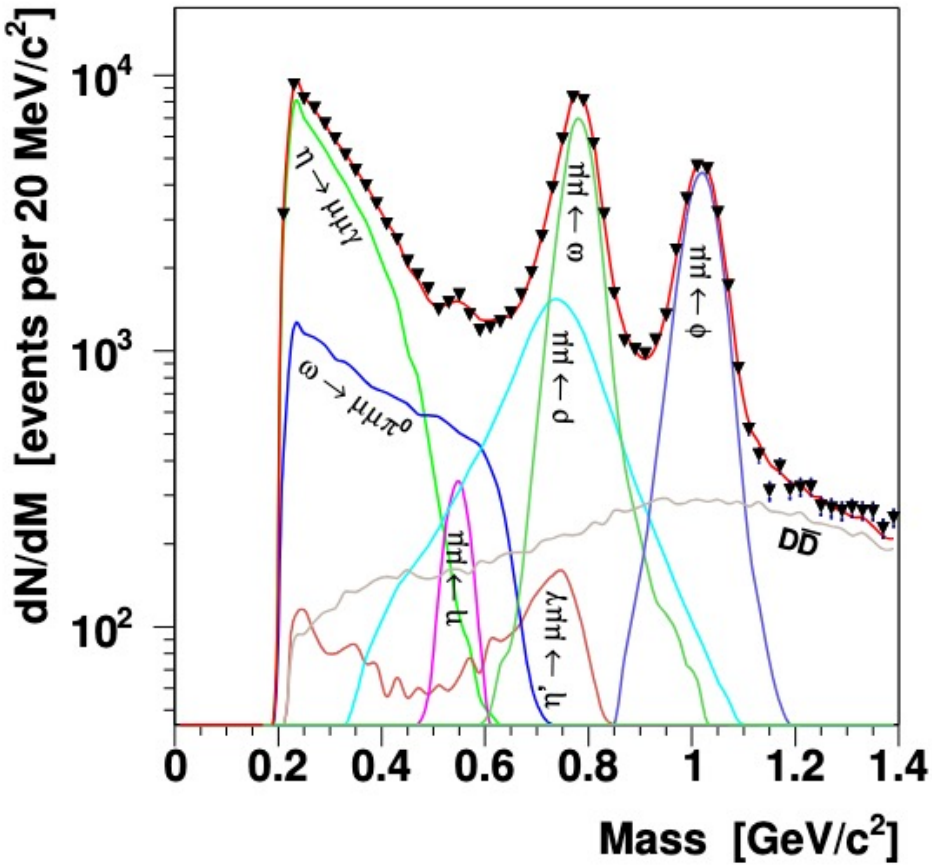




BESIII

NA60

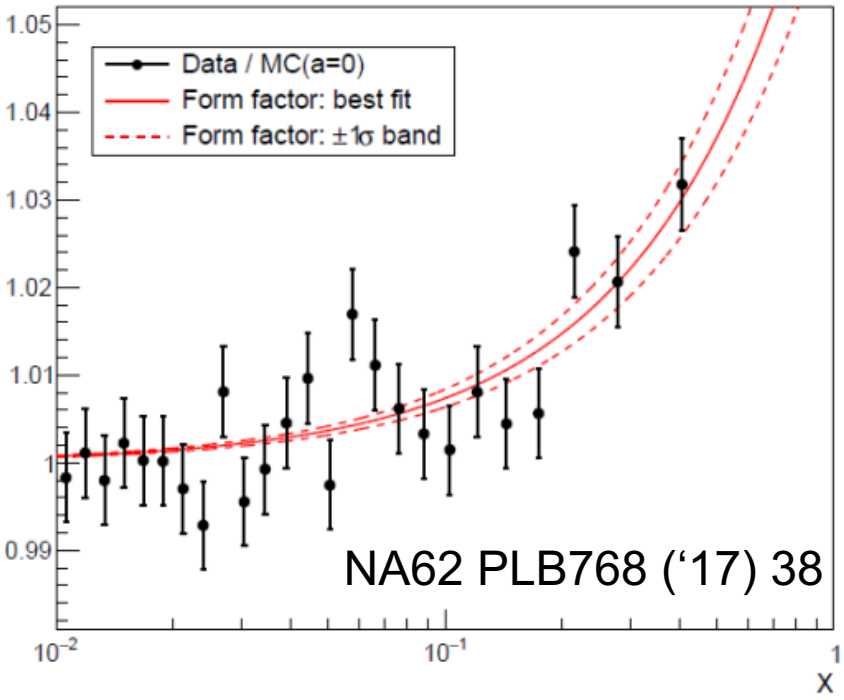




NA60 and CMS: inclusive $\mu^+\mu^-$spectra

NA60 Phys. Lett. B 677, 260 (2009), Phys. Lett. B 757, 437 (2016)

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



$a_\pi=(3.68\pm0.57)\times10^{-2}$

$a_\pi=(3.0 \pm 1.0)\times10^{-2}$ A2 PRC 95 ('17) 025202

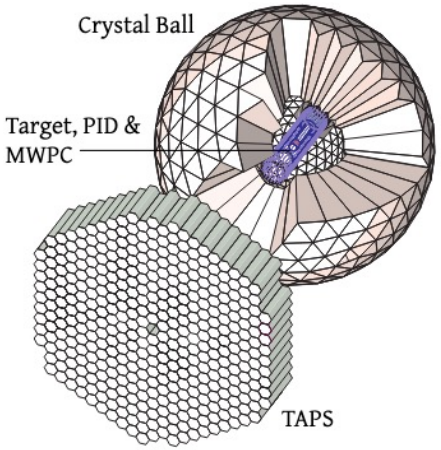
PDG_{AVG} $a_\pi=(3.35 \pm 0.31)\times10^{-2}$

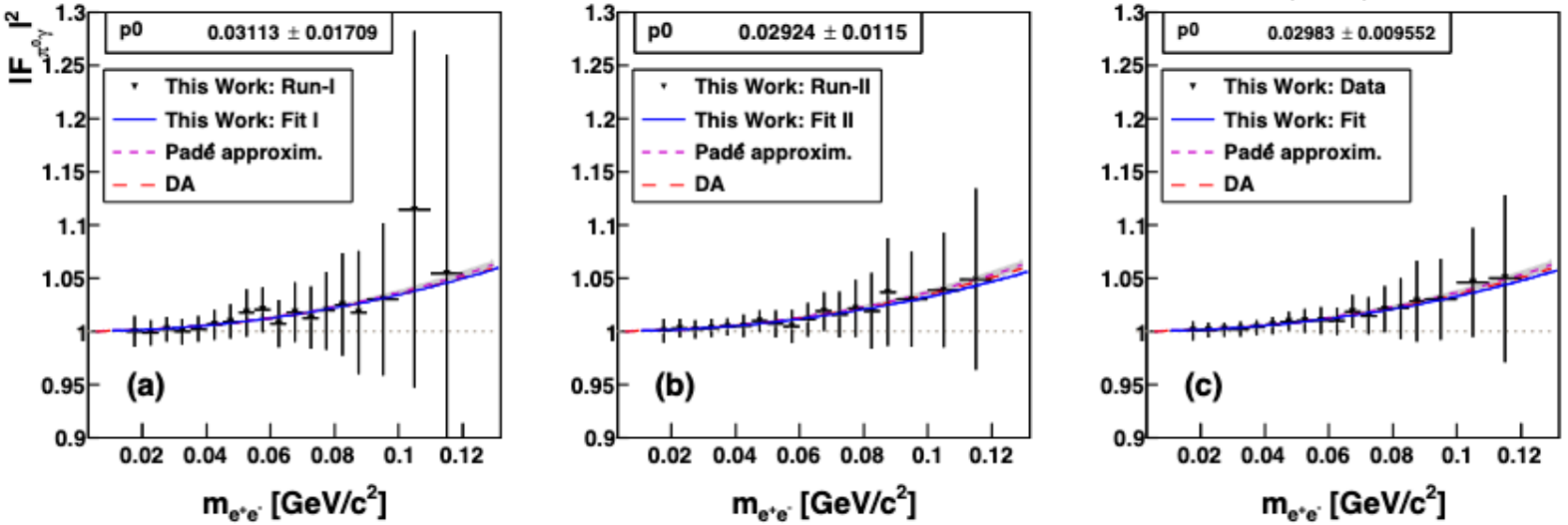
DR: $a_\pi=(3.15 \pm 0.09)\times10^{-2}$ *JHEP* 10 (2018) 141

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

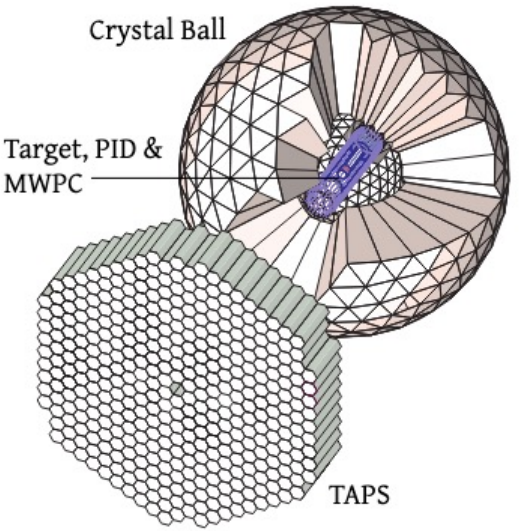
$\gamma p \to p\pi^0$

A2 PRC 95 ('17) 025202



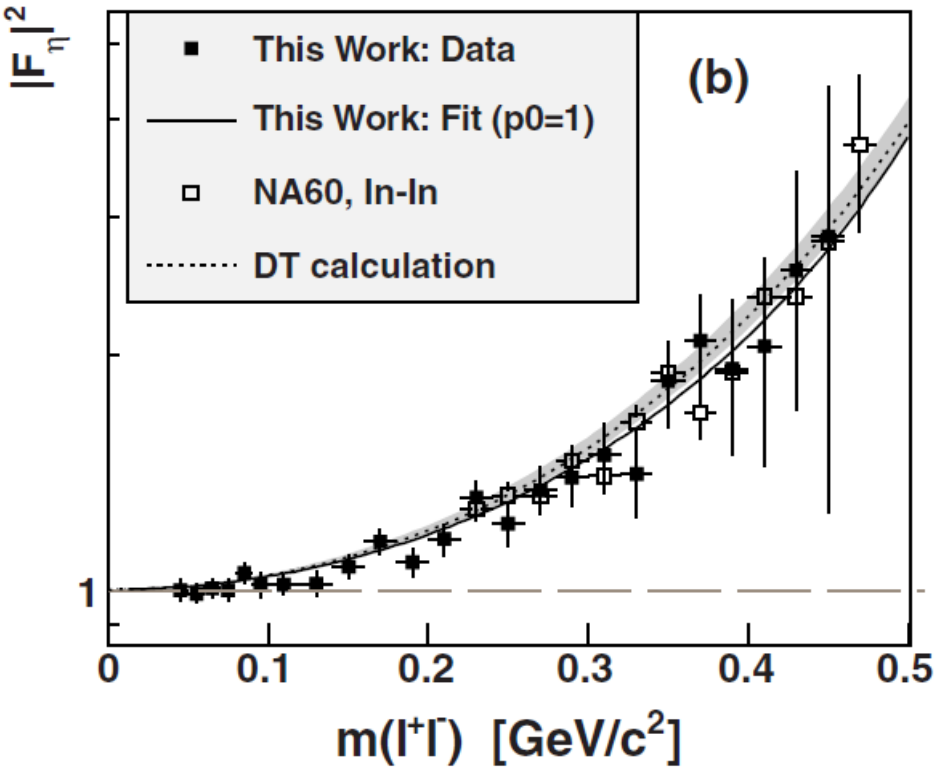


$$\eta \to e^+e^-\gamma$$

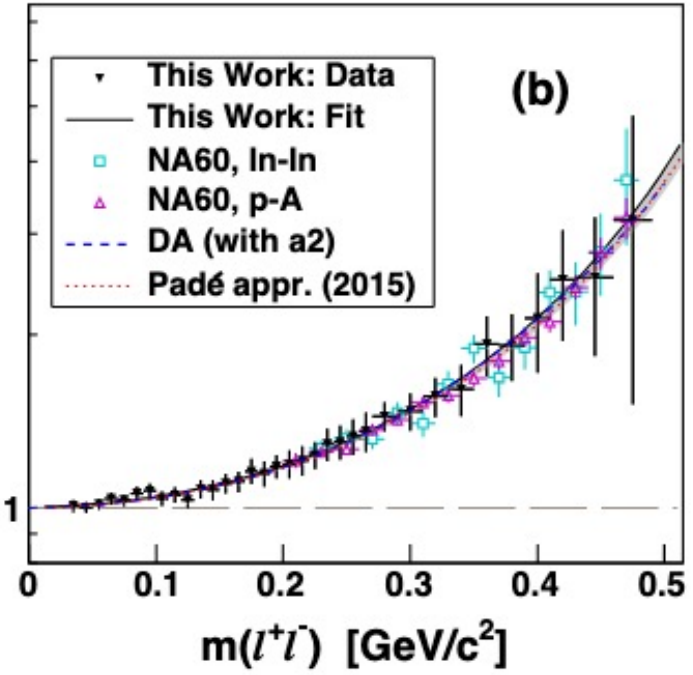


$$\gamma p \to \eta p$$

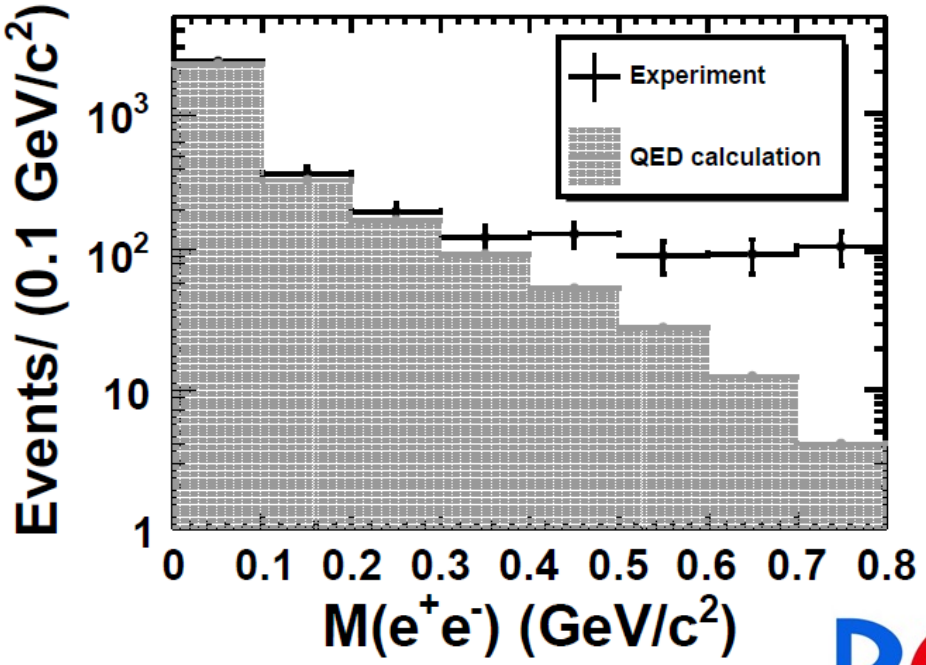
CB/TAPS: PRC89, 044608 (2014)

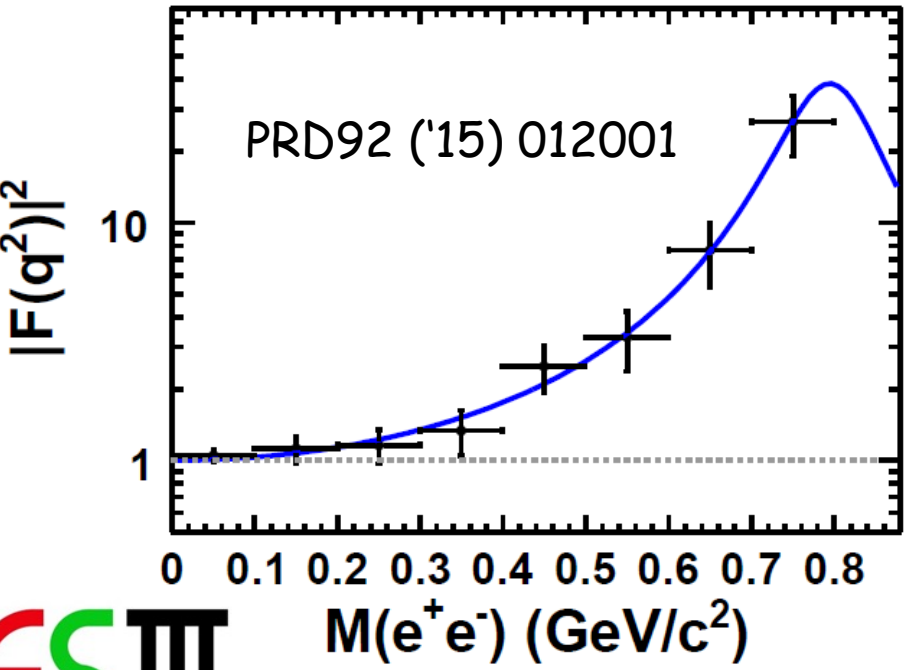


A2 Phys.Rev. C95 (2017) 025202



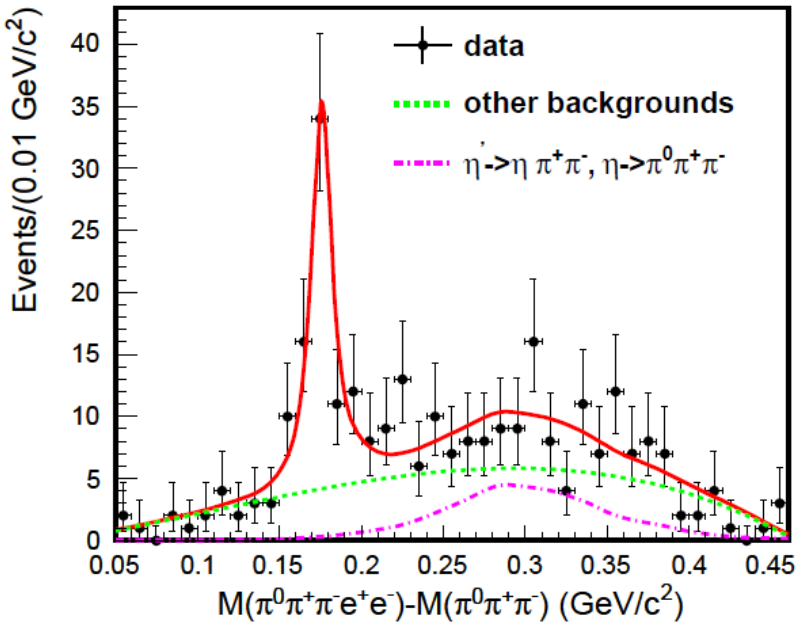
Transition form factor η′→γe+e-





BESIII

Observation of η′→ωe+e-

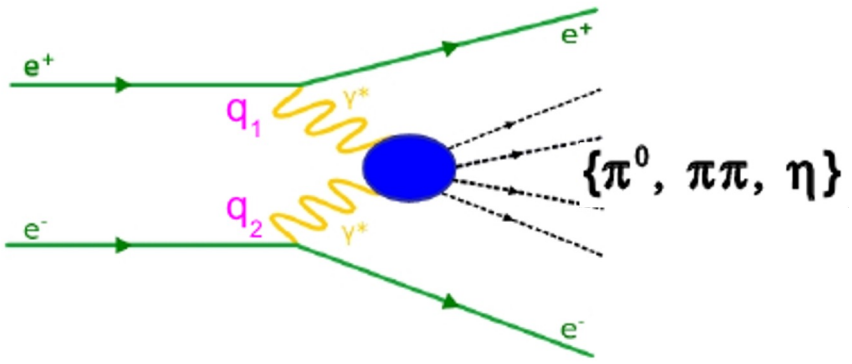


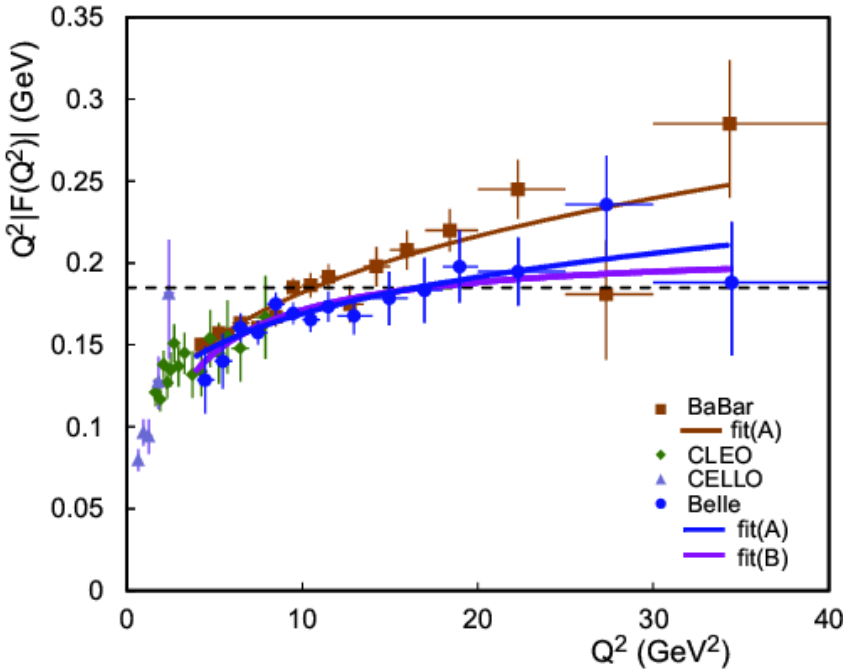
$\Gamma(\eta' \to \omega e^+e^-)/\Gamma(\eta' \to \omega\gamma) = (7.71 \pm 1.34_{stat} \pm 0.54_{syst}) \times 10^{-3}$

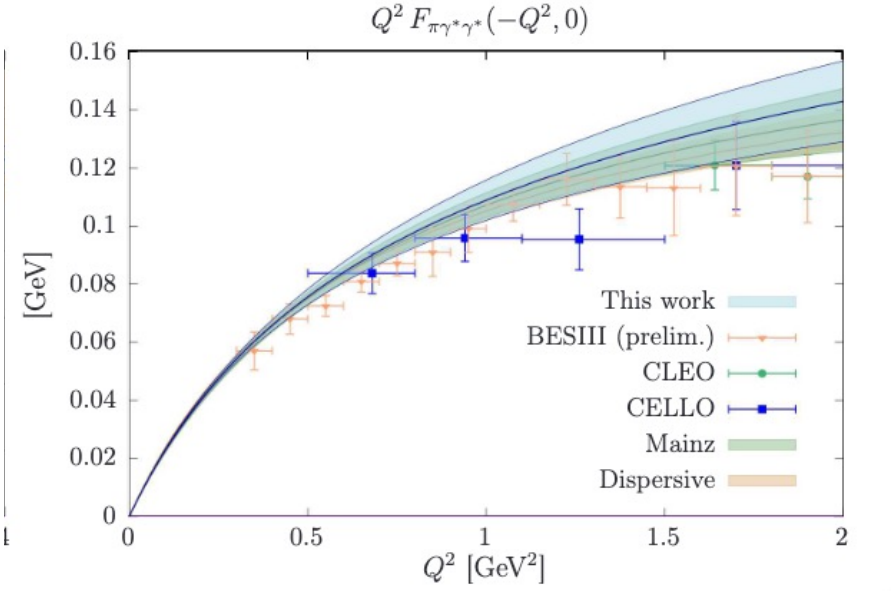
TFF=1: 6.8×10^{-3}

PRD92 ('15) 051101

$\gamma\gamma^* \rightarrow \pi^0$

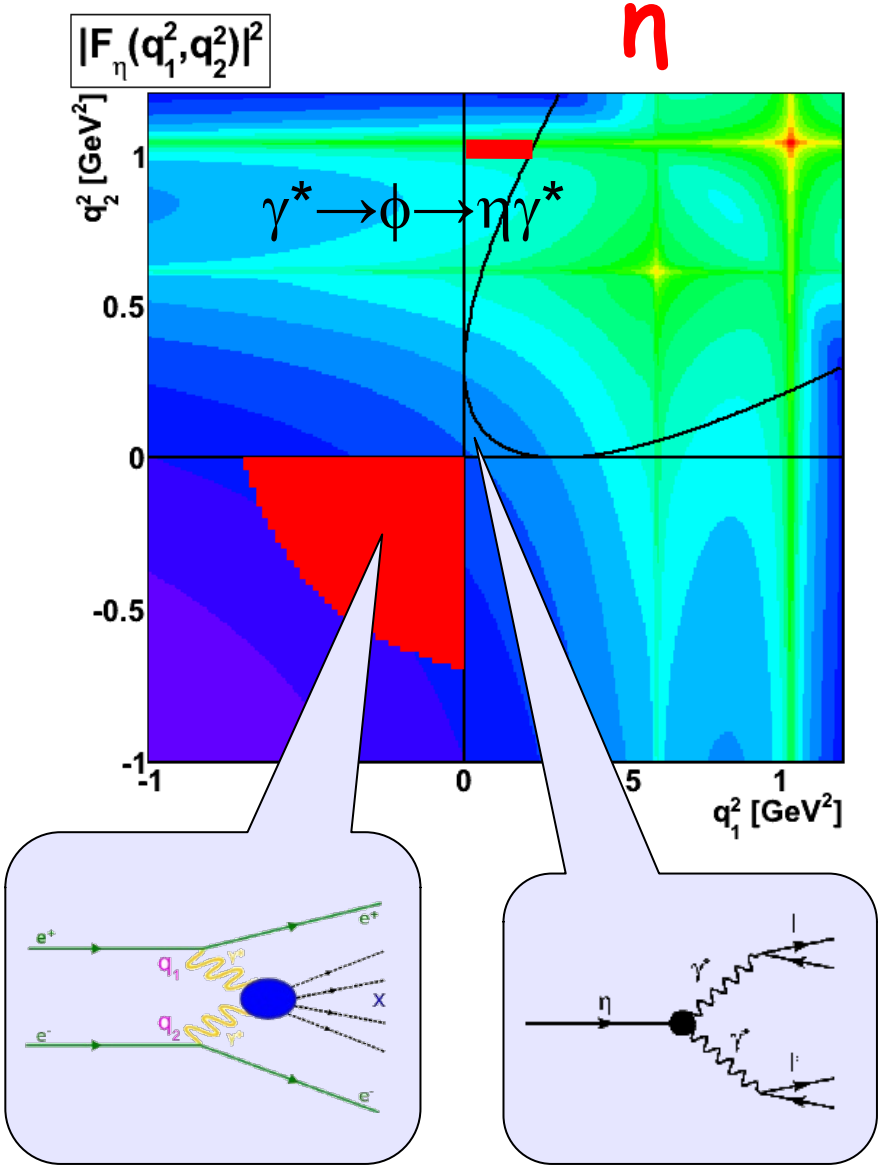




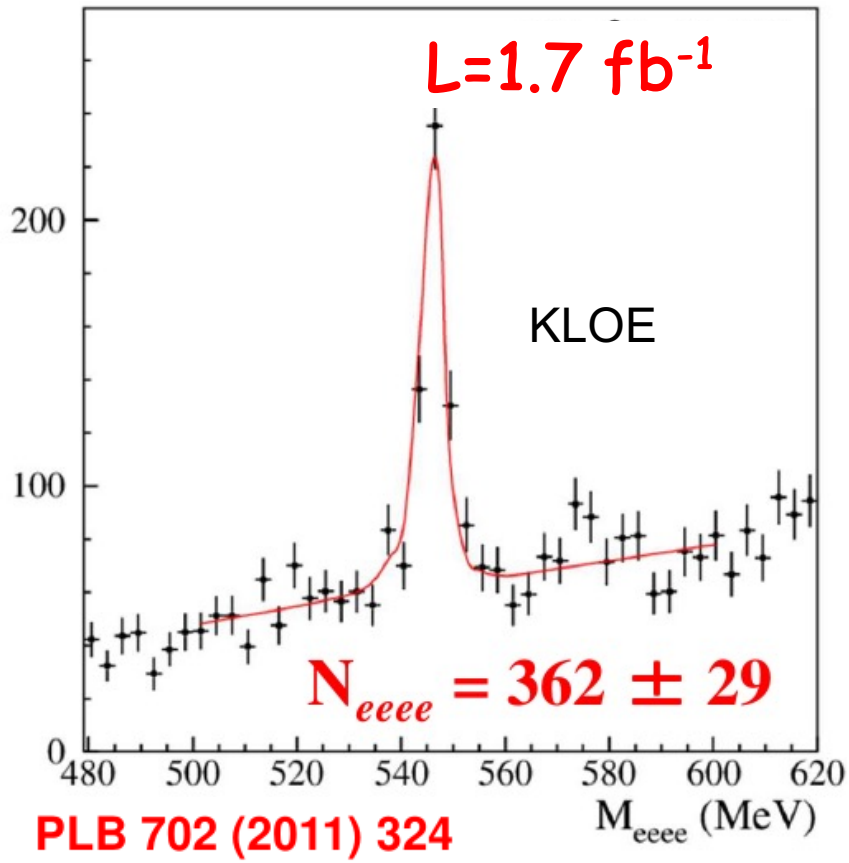


Lattice calculation of the π0, η and η′ transition form factors 2305.04570

Double off shell TFF



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

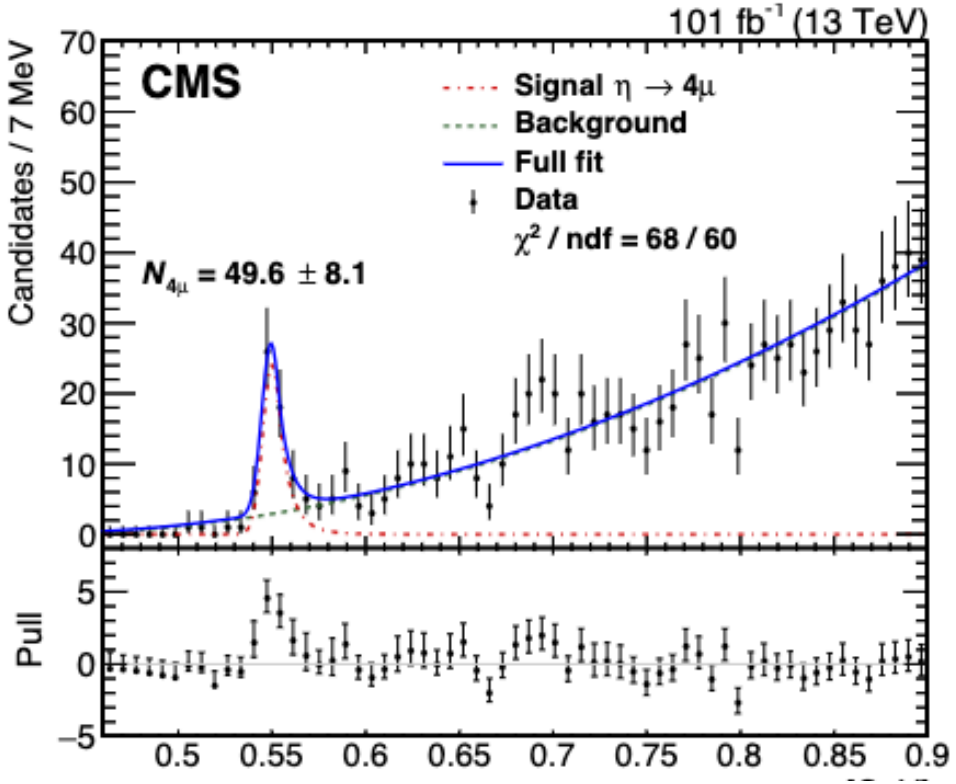


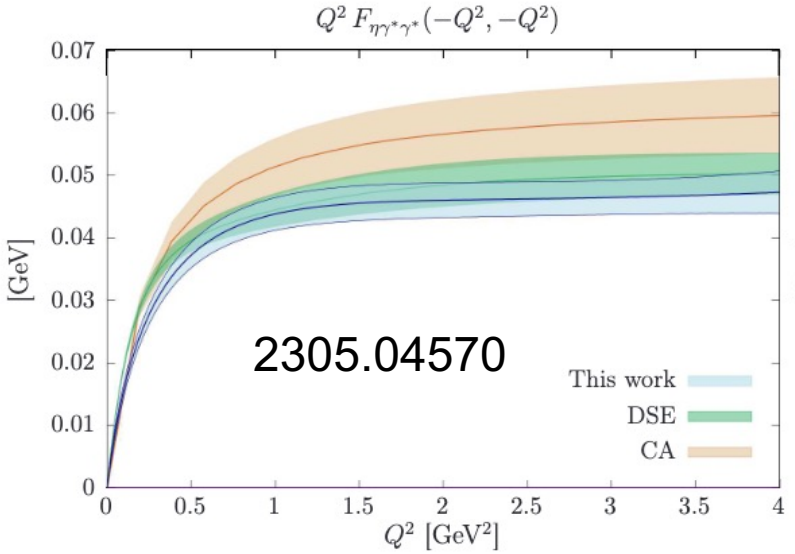
$BR(\eta\to e^+e^-e^+e^-(\gamma))= (2.4 \pm 0.2_{stat} \pm 0.1_{syst}) \times 10^{-5}$

BESIII, PRD 105 (2022) 112010

$$\mathcal{B}(\eta' \to e^+e^-e^+e^-) = (4.5 \pm 1.0(\text{stat.}) \pm 0.5(\text{sys.})) \times 10^{-6}$$

$\eta \to \mu^+\mu^-\mu^+\mu^-$





$$\frac{\mathcal{B}_{4\mu}}{\mathcal{B}_{2\mu}} = (0.86 \pm 0.14\,(\text{stat}) \pm 0.12\,(\text{syst})) \times 10^{-3}$$

CMS arXiv:2305.04904

$\Gamma(\eta \to \mu^+\mu^-\mu^+\mu^-)/\Gamma_{\gamma\gamma}(10^{-9})$	FF=1 6.5	mVMD 9.7(1)
$\Gamma(\eta \to \mu^+\mu^-)/\Gamma_{\gamma\gamma}(10^{-6})$	mVMD 13(1)	Exp. 15(2)

T.Petri arxiv:1010.2378

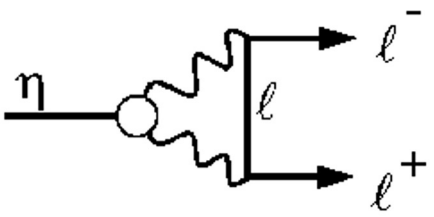
$e^+e^- \to \eta, \eta', f_1 \ldots (C-\text{even})$

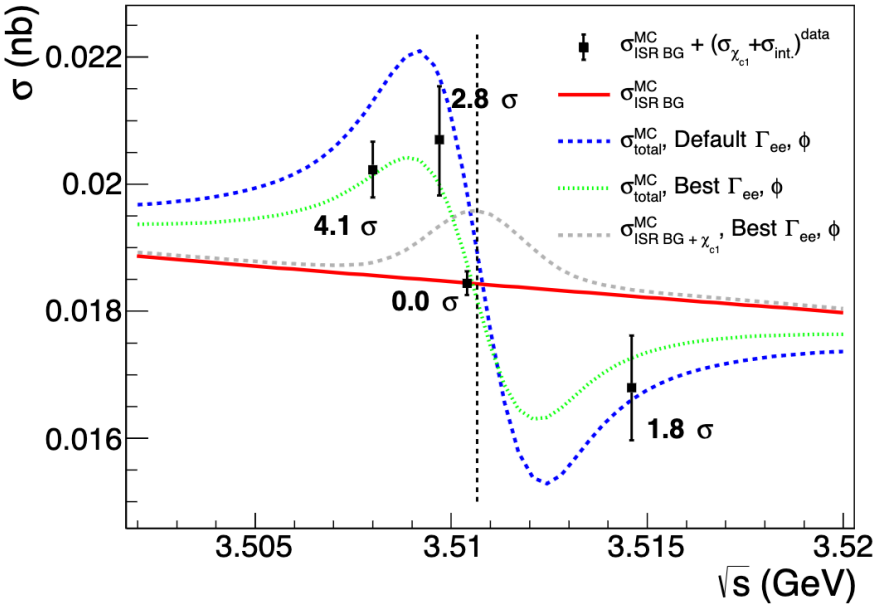
CMD-3 Phys.Lett.B 740 (2015) 273
SND, Phys.Rev.D 91 (2015) 092010

$B(\eta' \to e^+e^-) < 5.6\times10^{-9}$ 90% CL

SND Phys.Rev.D 98 (2018) 5, 052007

$B(\eta \to e^+e^-) < 7.7\times10^{-7}$ 90% CL

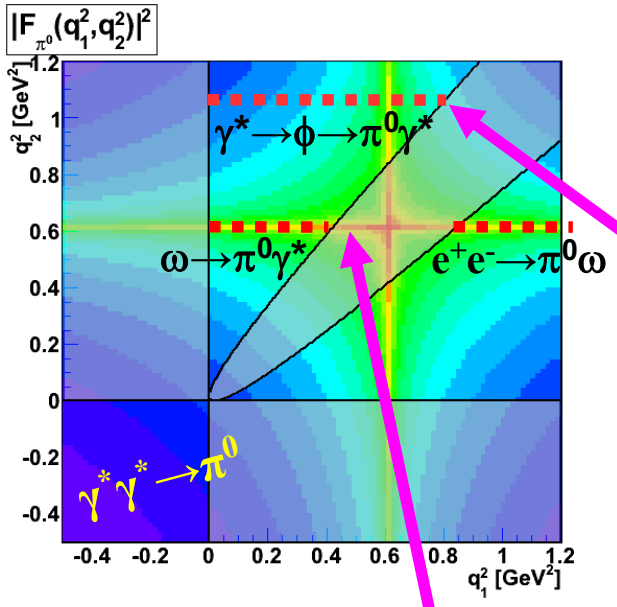


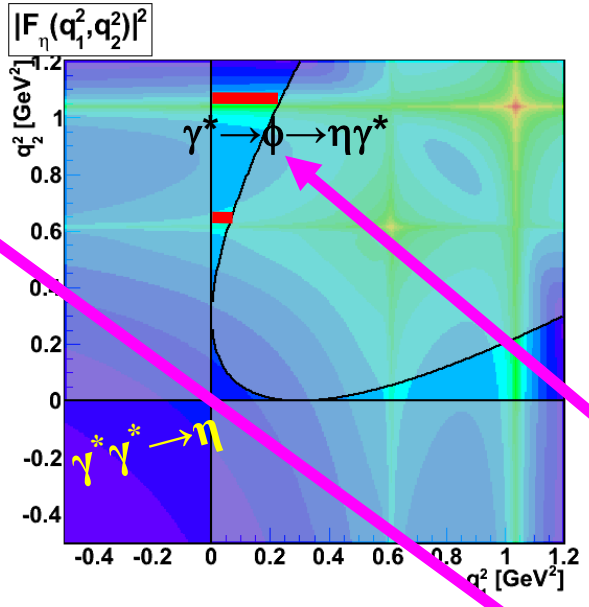


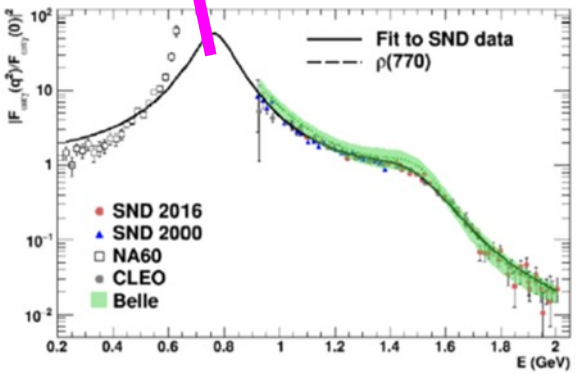
BESIII Phys.Rev.Lett. 129 (2022) 12

Interference $e^+e^- \to J/\psi\,\gamma \to \gamma\mu^+\mu^-$ *and* $e^+e^- \to \chi_{c1}$

$V \to P\gamma^*$ and $e^+e^- \to PV$ processes







In addition to SND and NA60, other data on $\mathcal{F}(\gamma\omega\pi)$ exist:
CLEO ($\tau^- \to \omega\pi^-\nu_\tau$), K.W. Edwards et al., Phys. Rev. D61 (2000) 072003

$$F_{\omega\pi}(s) = \frac{g_{\rho\omega\pi}}{g_\rho}\left(\mathrm{BW}_\rho^{GS}(s) + c_1\mathrm{BW}_{\rho'}(s) + c_2\mathrm{BW}_{\rho''}(s) + \cdots\right)$$

from Simon Eidelman

KLOE

result $b\eta(m^2_\phi)$
$\phi\to\eta\gamma^*$ BR 10^{-4}

Phys.Lett. B742 (2015) 1-6

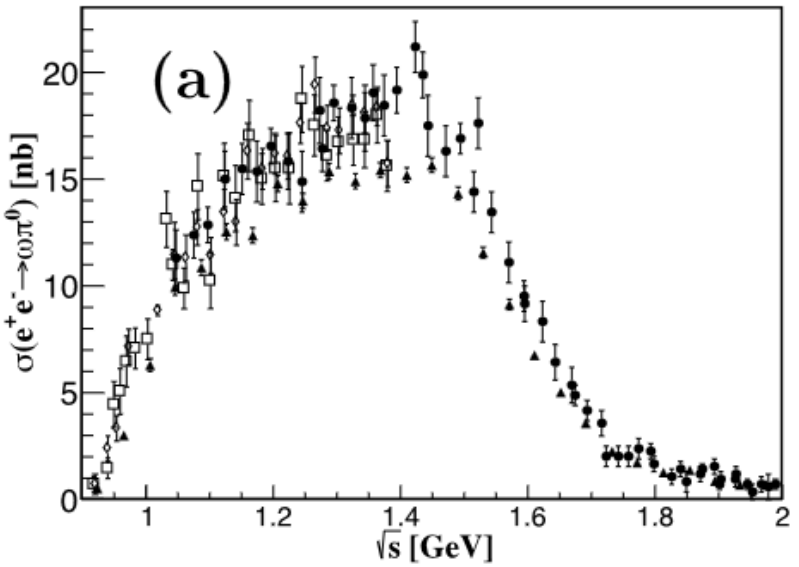
$b_{\varphi\eta} = (1.17 \pm 0.10^{+0.07}_{-0.11})\,\mathrm{GeV}^{-2}$

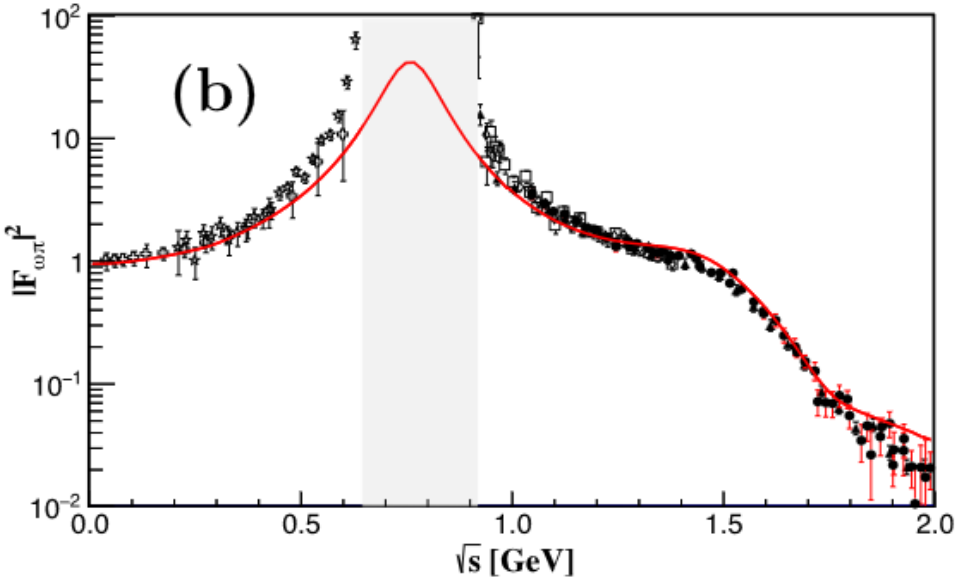
$b\pi^0(m^2_\phi)$ $\phi\to\pi^0\gamma^*$ BR 10^{-5}

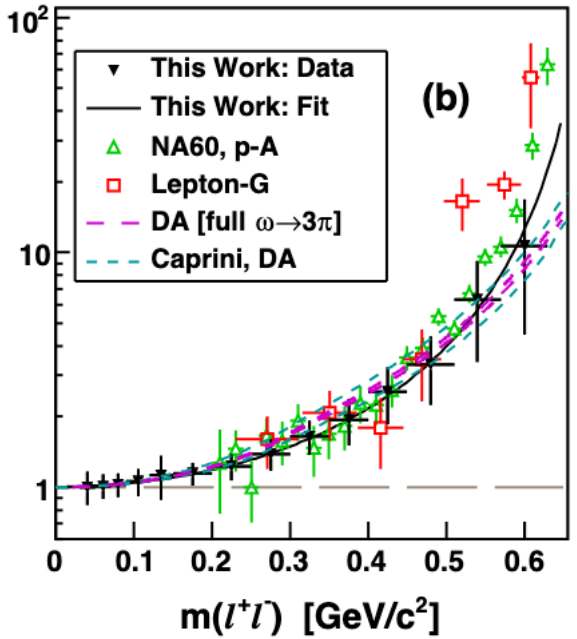
Phys.Lett. B757 (2016) 362-367

$b\varphi\pi^0 = (2.02\pm0.11)\ \mathrm{GeV}^{-2}$

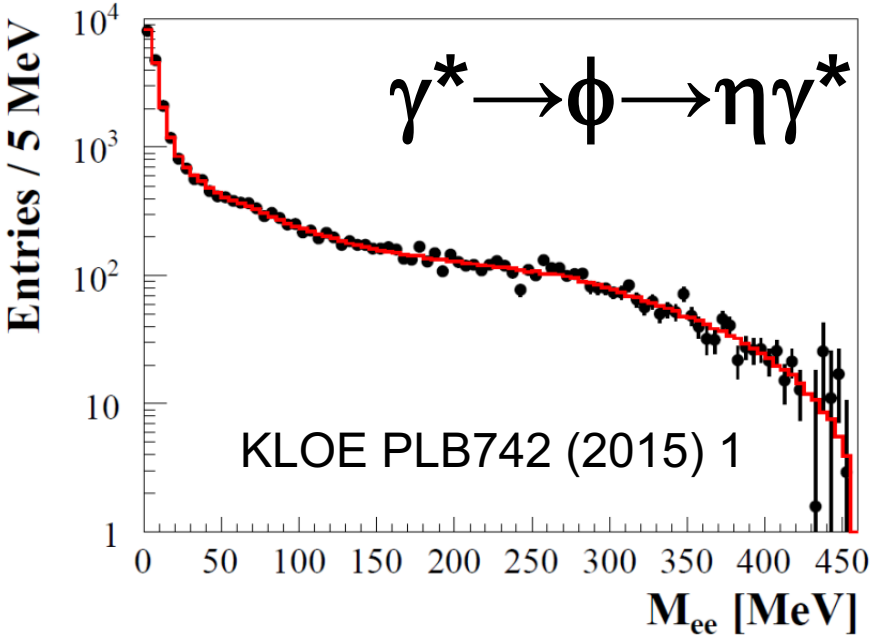
$\omega \rightarrow \pi^0 \gamma^*$ and $\gamma^* \rightarrow \omega \pi^0$

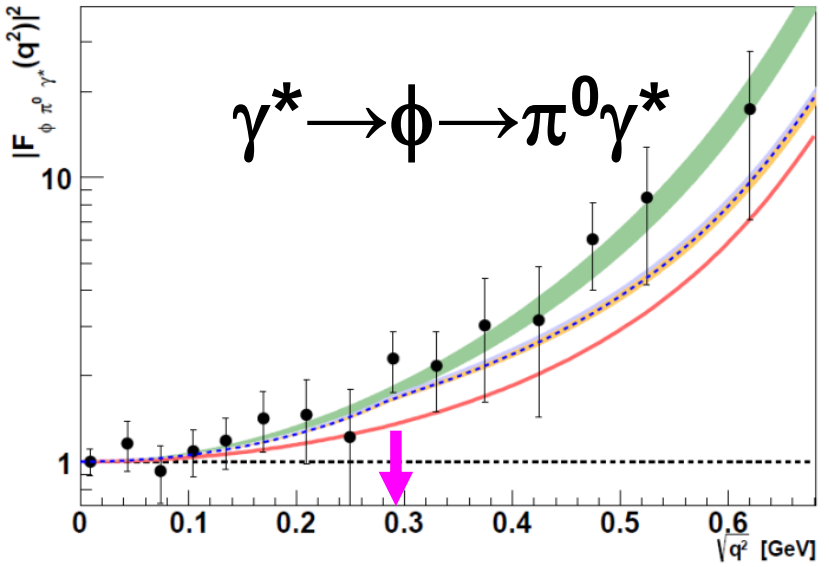






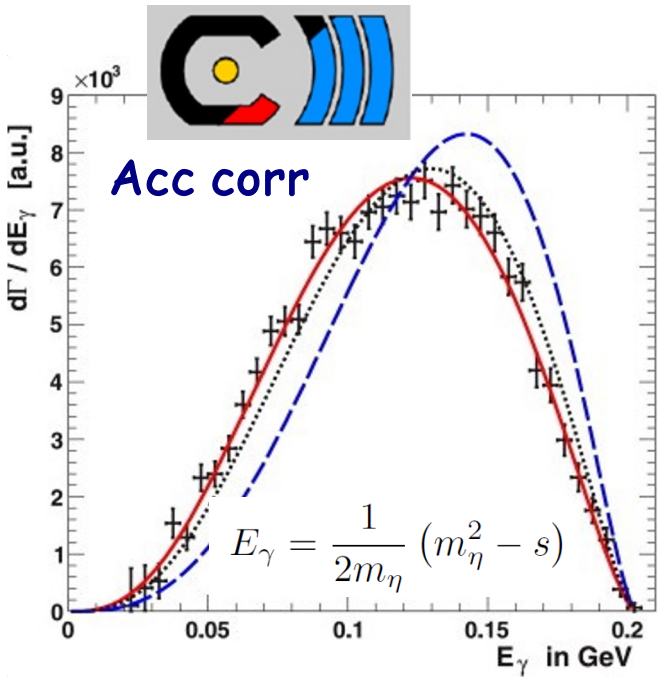
A2 Phys.Rev. C95 (2017) 025202



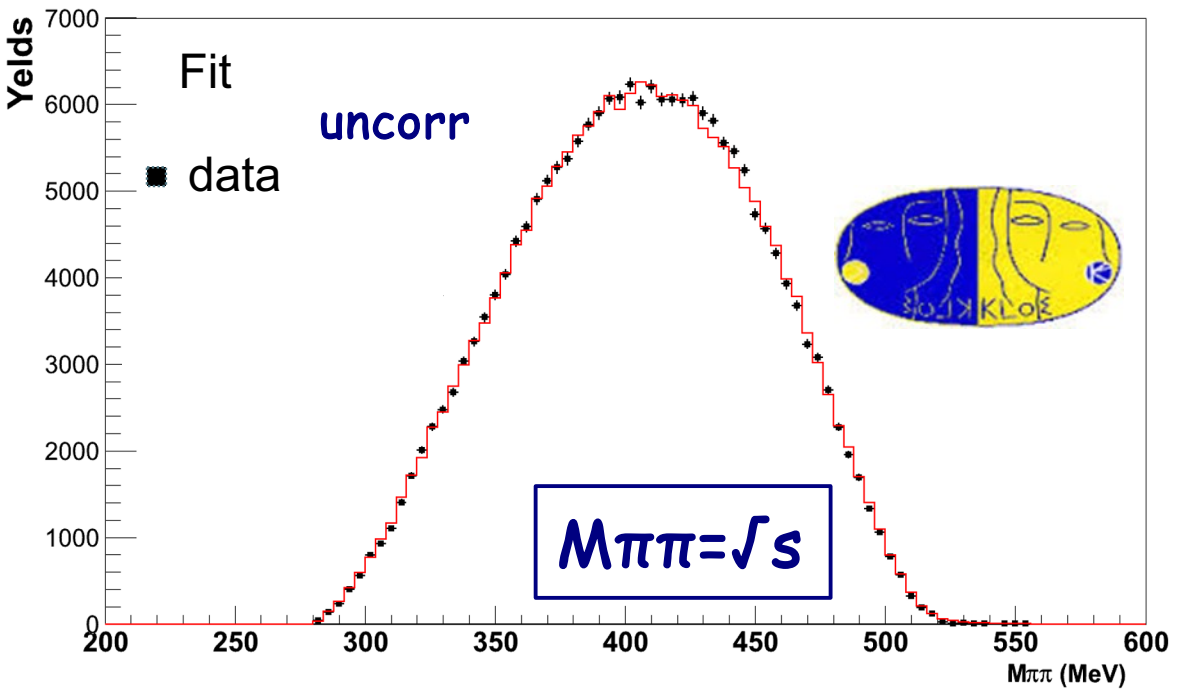


KLOE PLB757 (2016) 362

TFF from radiative processes (ex $\eta \to \pi^+\pi^-\gamma$)



WASA PLB707 (2012) 243



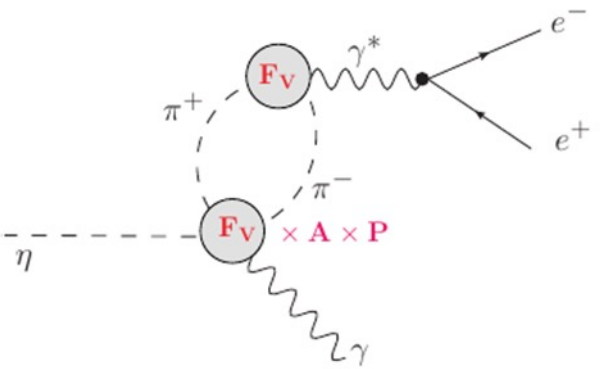
KLOE PLB718 (2013) 910

Model independent parametrization:

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

PLB707 (2012) 184

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



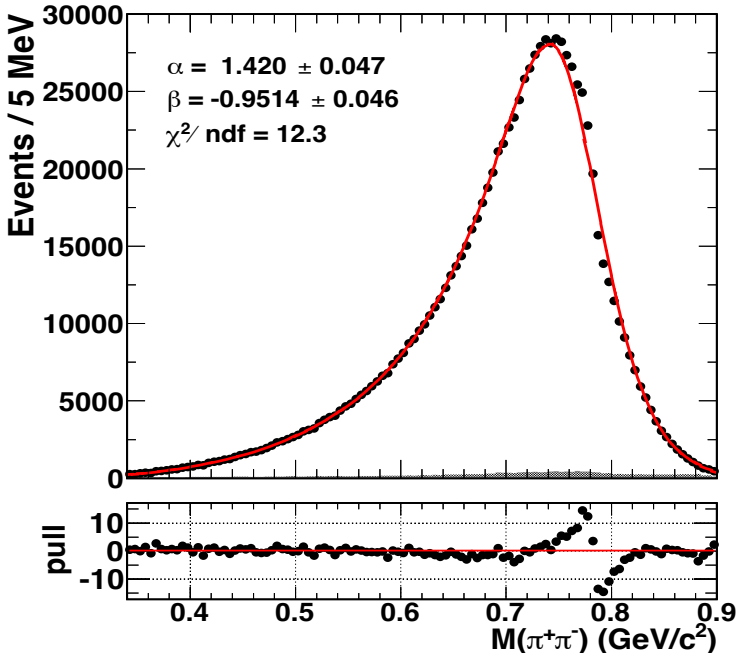
$a=1.89\pm0.25_{stat}\pm0.59_{syst}$ GeV^{-2}

$a=1.31\pm0.08_{stat}\pm0.40_{syst}$ GeV^{-2}

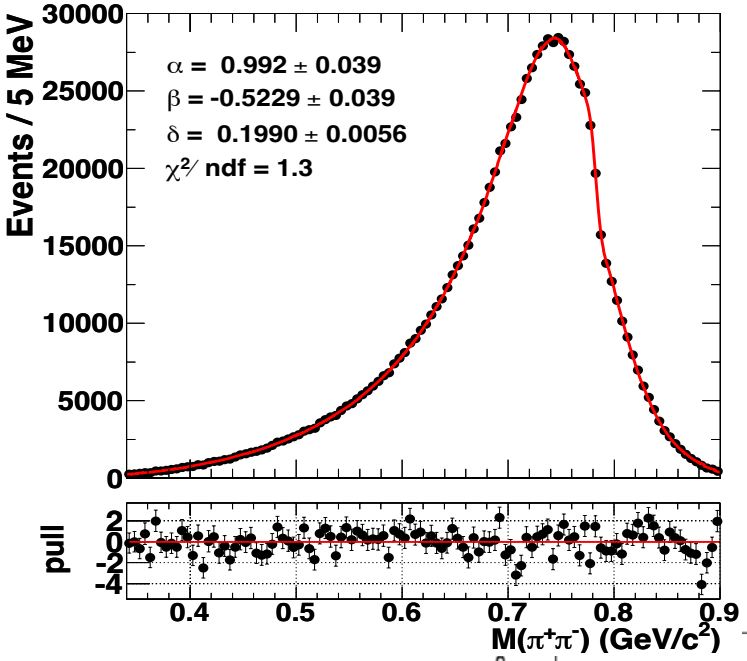
Analysis based on 0.9 x 10^6 η′ → π+π-γ

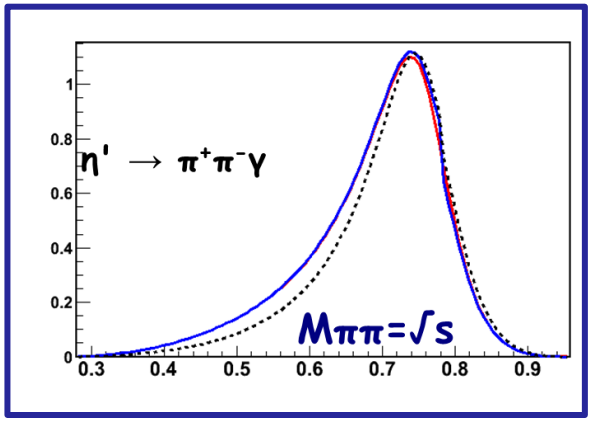
$$\frac{d\Gamma}{ds_{\pi\pi}} = \left|AP(s_{\pi\pi})F_V(s_{\pi\pi})\right|^2 \Gamma_0(s_{\pi\pi})$$

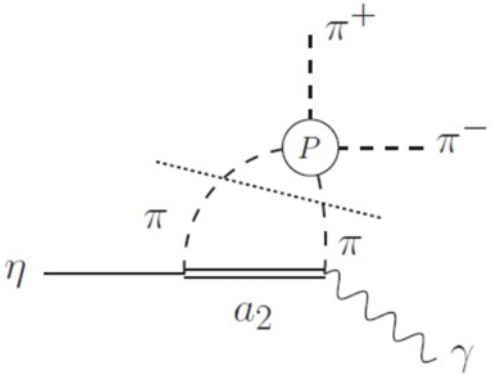
$P(s_{\pi\pi}) = 1 + \alpha\, s_{\pi\pi} + \beta\, s^2_{\pi\pi}$



$P(s_{\pi\pi}) = 1 + \alpha\, s_{\pi\pi} + \beta\, s^2_{\pi\pi} + \delta\, BW_\omega$



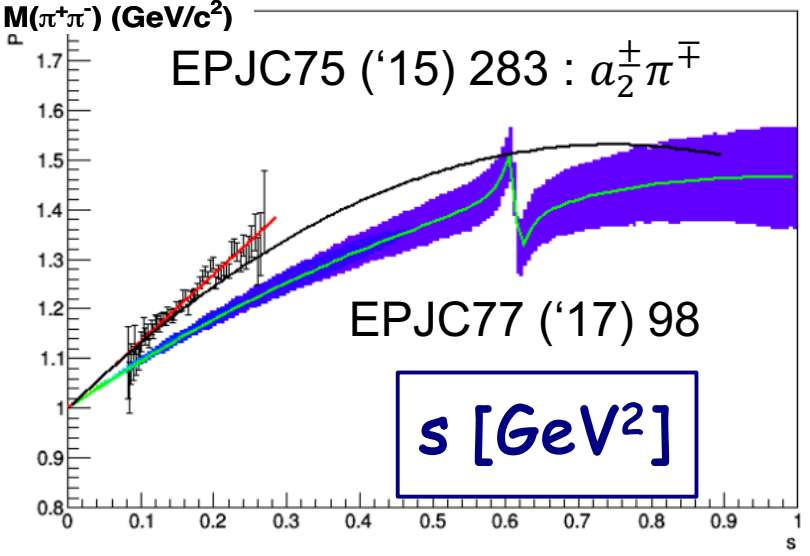




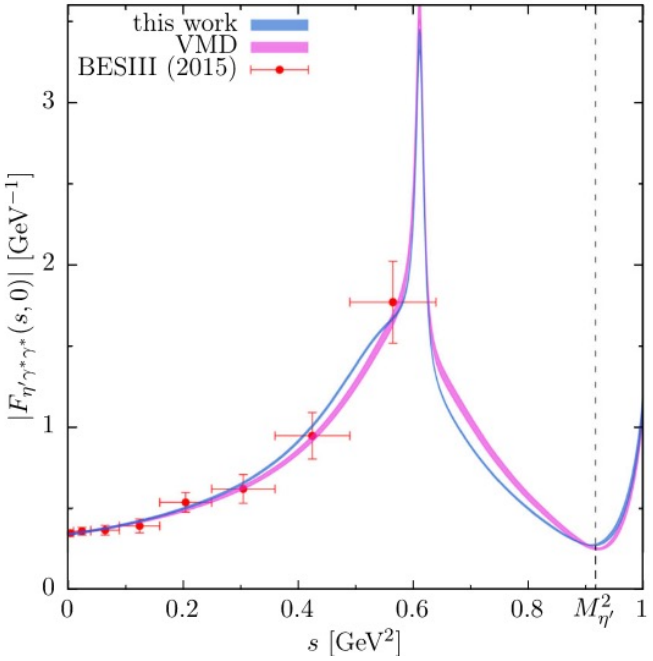
ω contribution necessary

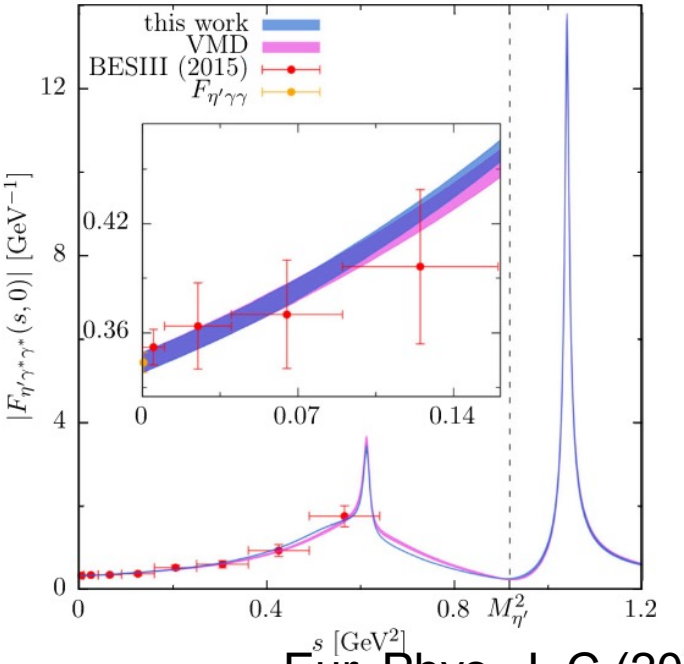
Linear polynomial is insufficient...

Phys.Rev.Lett. 120 (2018) 242003

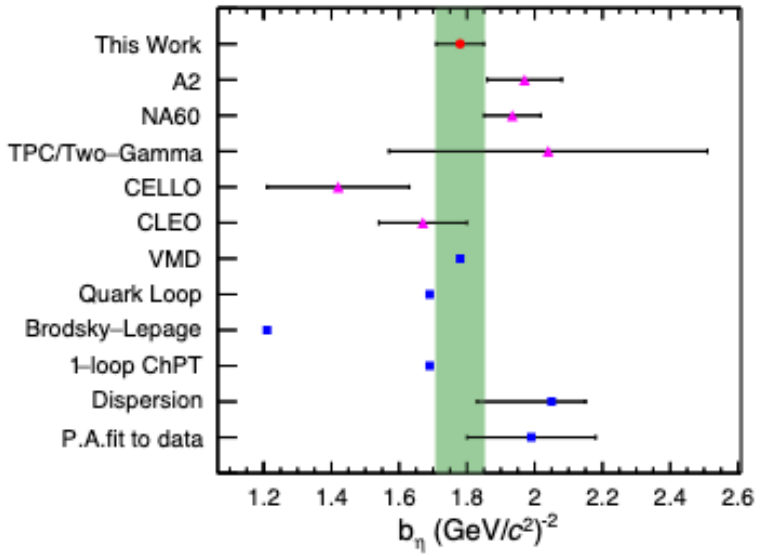


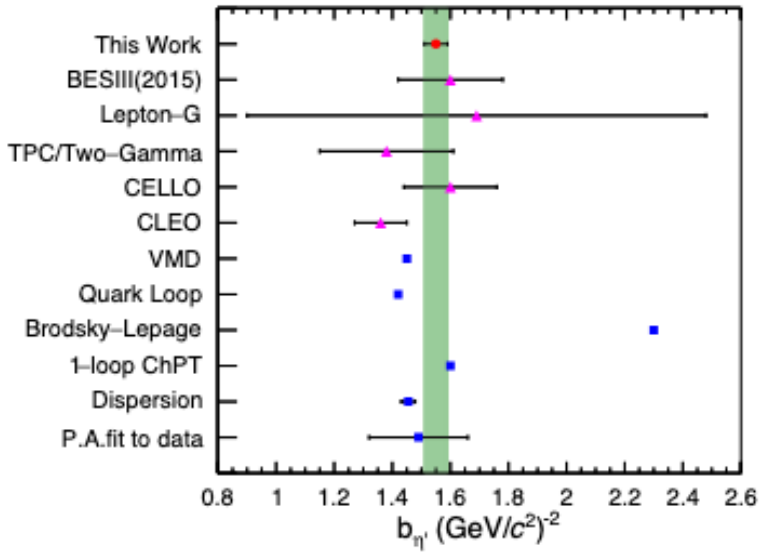
$\eta' \to e^+e^-\gamma$



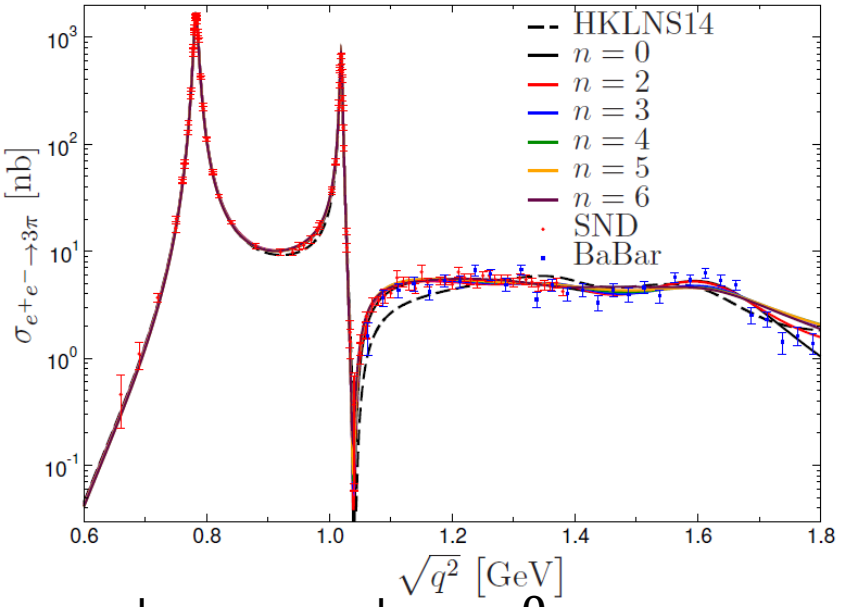


Eur. Phys. J. C (2022) 82:434

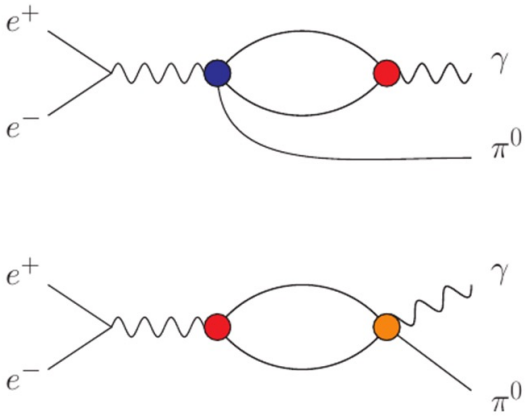




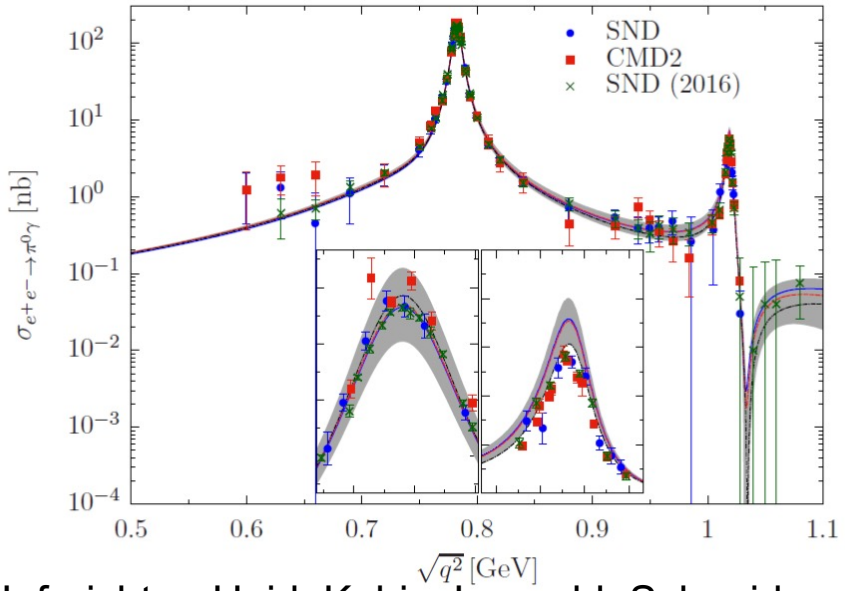
DR for π^0 TFF



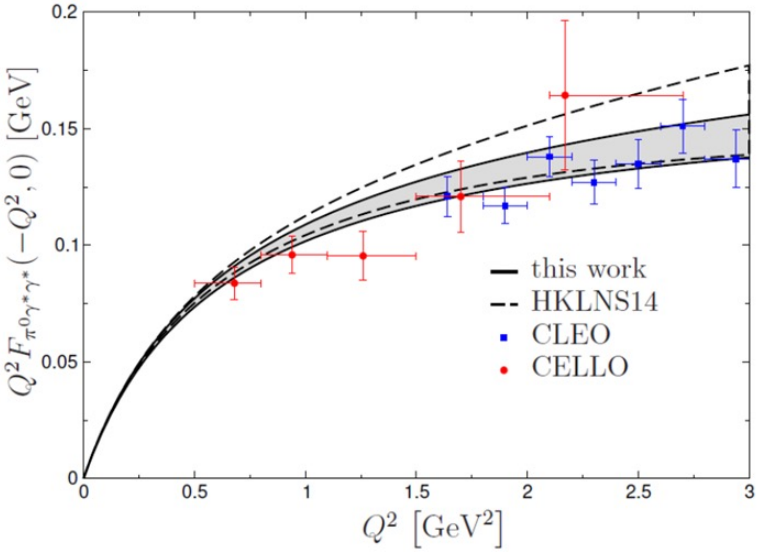
$e^+e^- \to \pi^+\pi^-\pi^0$



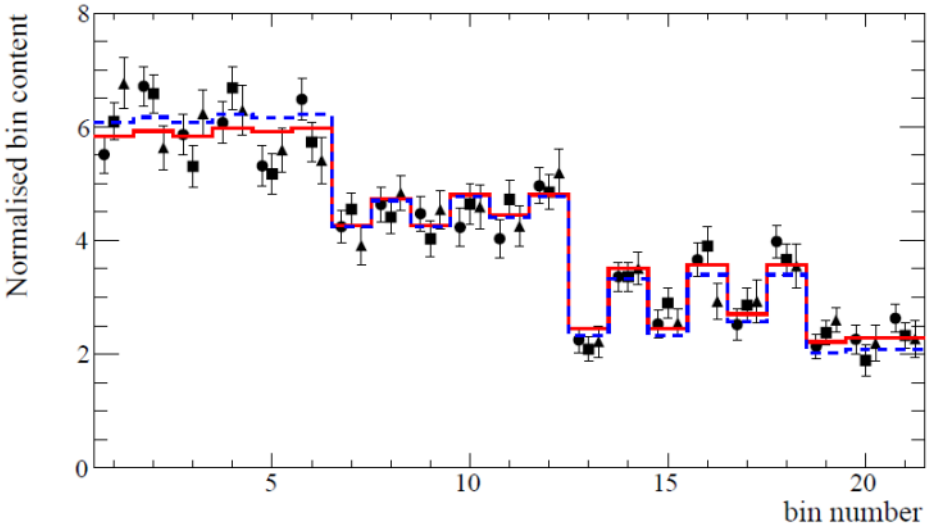
ππ phase shifts + e+e- → 3 π data
Eur.Phys.J. C74 (2014) 3180



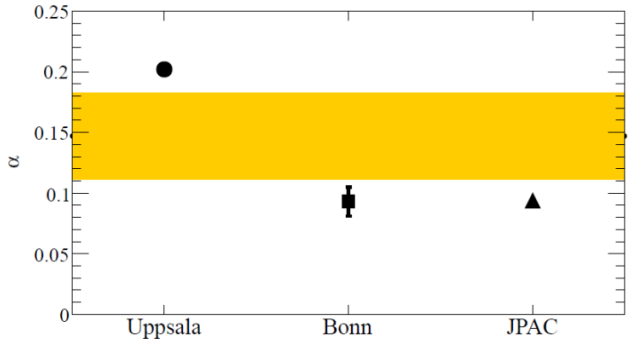
Hoferichter, Hoid, Kubis, Leupold, Schneider
JHEP 10 (2018) 141



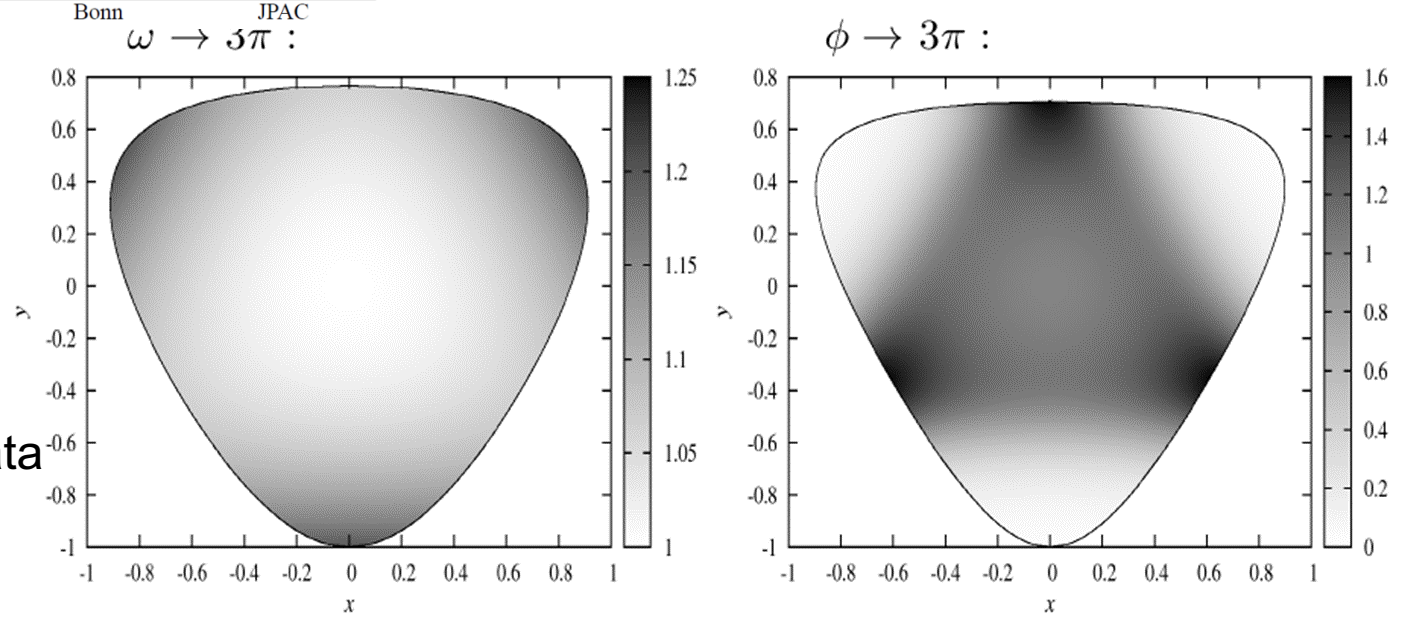
$$\omega/\phi \to \pi^+\pi^-\pi^0$$



WASA PLB770 (2017) 418



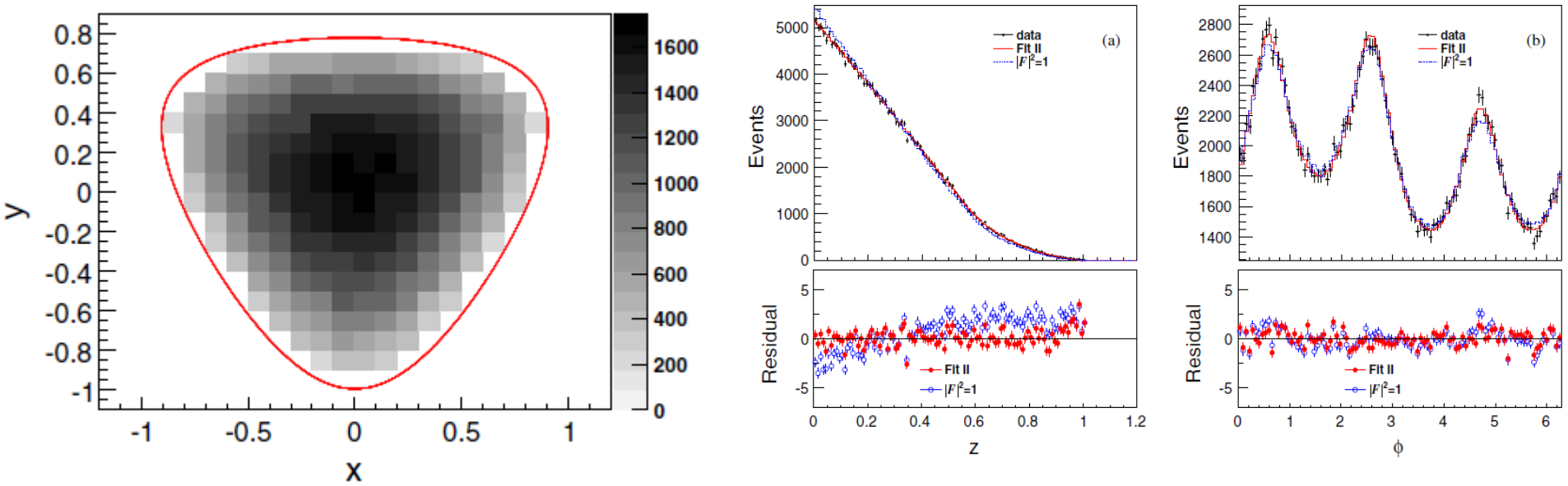
BESIII



for ϕ precise data from CMD2 and KLOE

Eur.Phys.J. C72 (2012) 2014

Slide: Bastian Kubis

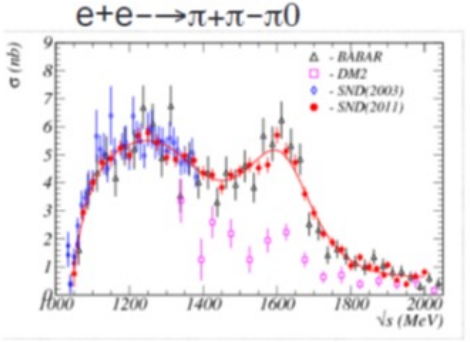


BESIII: PRD98, 112007(2018)

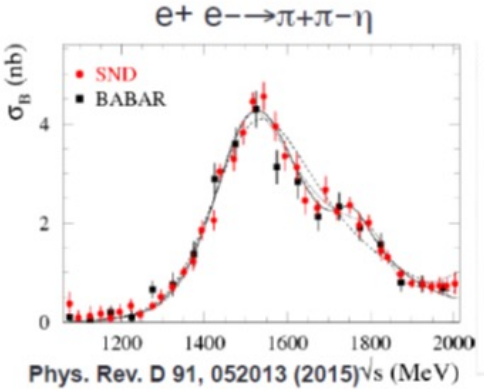
TABLE III. Predictions and fit results for the $\mathcal{F}$ parametrizations. The predictions are from Danilkin *et al.* [4], Niecknig *et al.* [5], and Terschlüsen *et al.* [19]. Theoretical predictions without incorporating crossed-channel effects are indicated by w/o and those with crossed-channel effects by w.

		Theoretical predictions					Experiment
		Ref. [4]		Ref. [5]			
	Para. $\times 10^3$	w/o	w	w/o	w	Ref. [19]	BESIII
Fit I	α	136	94	(137,148)	(84,96)	202	$132.1 \pm 6.7 \pm 4.6$
Fit II	α	125	84	(125,135)	(74,84)	190	$120.2 \pm 7.1 \pm 3.8$
	β	30	28	(29,33)	(24,28)	54	$29.5 \pm 8.0 \pm 5.3$

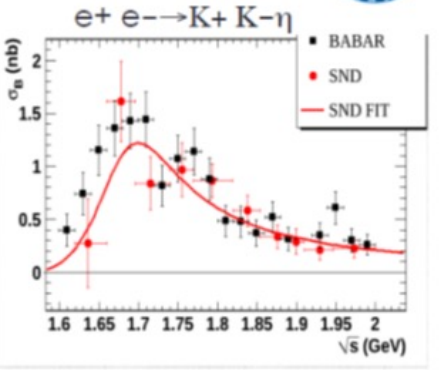
Some SND results overview



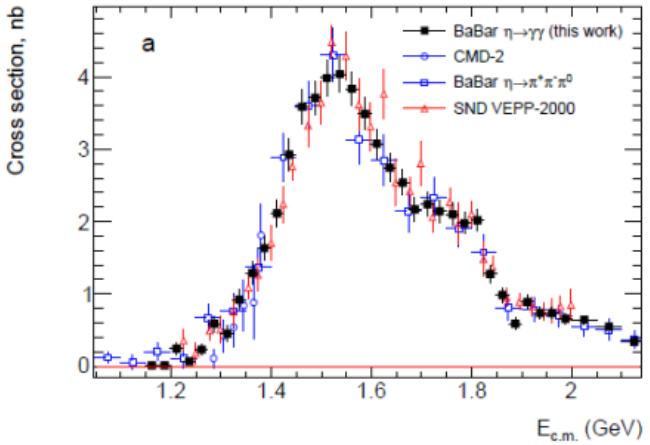
J.Exp.Theor.Phys. 121 (2015) 1.

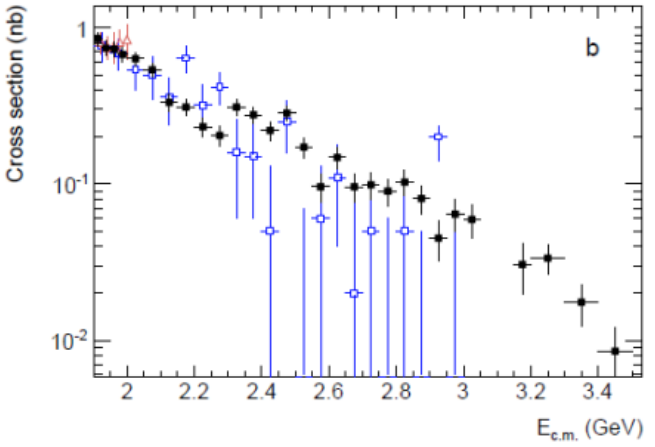


Phys. Rev. D 91, 052013 (2015)



$e^+e^- \to \eta\pi^+\pi^-$ at BaBar





More precise result ⇒ first observation of the $\rho(1700)$ in $\eta\pi^+\pi^-$

J.P. Lees et al., Phys. Rev. D97 (2018) 052007

Slide from Simon Eidelman

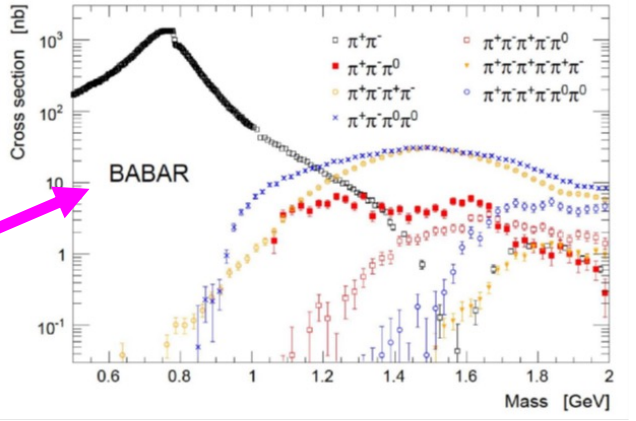
Data for dispersive HLbL

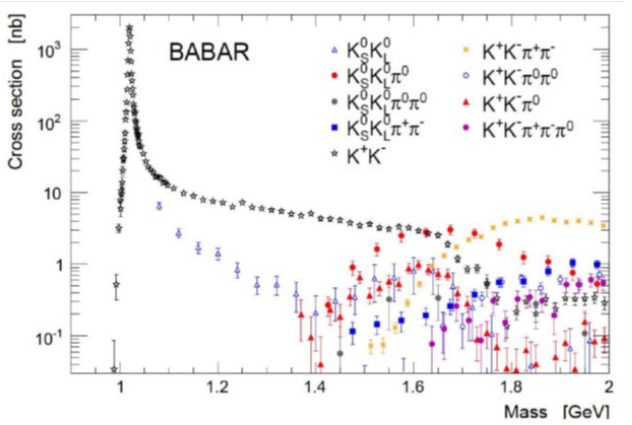
F_{π^0}

F_η, $F_{\eta'}$

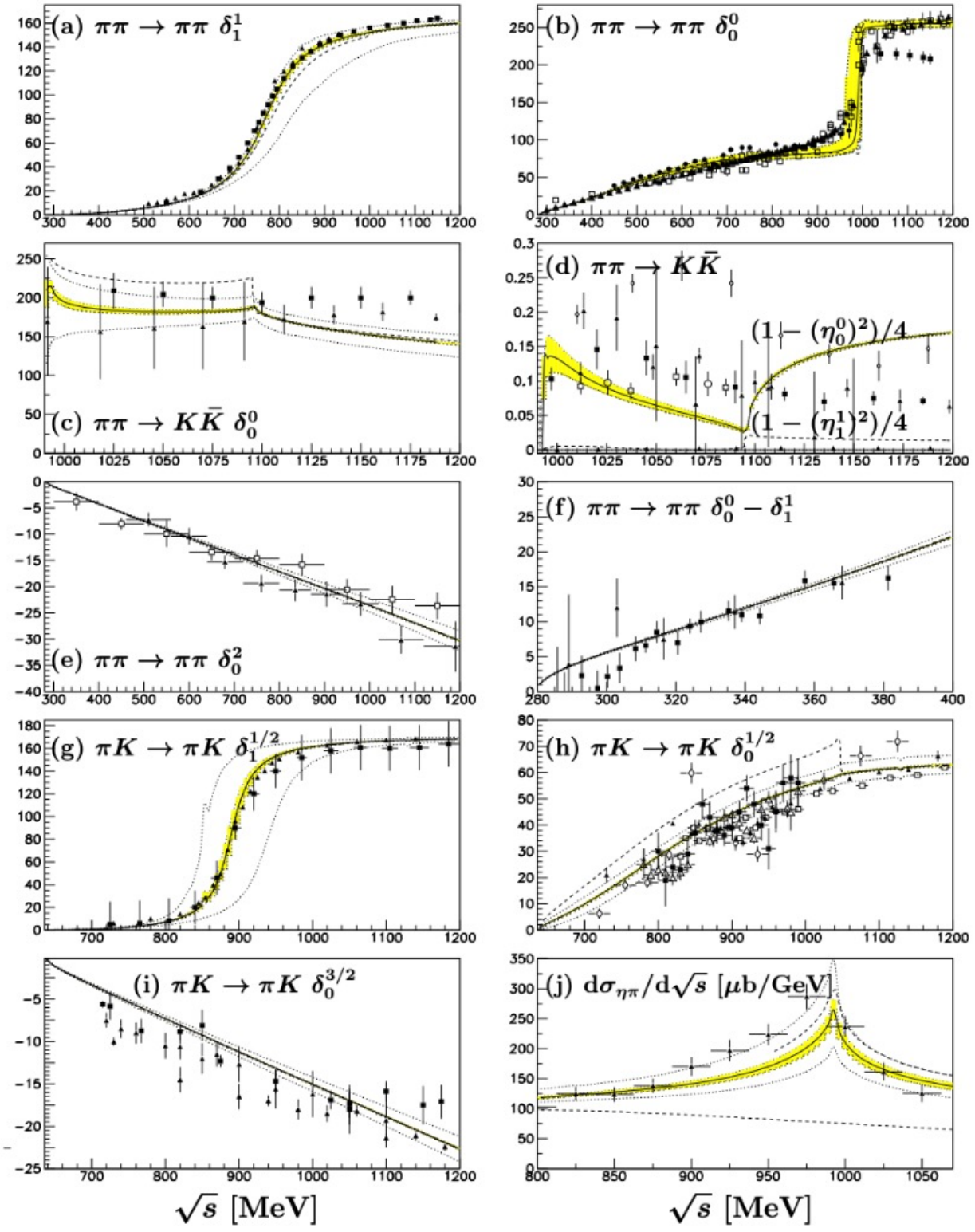
F_V

F_K

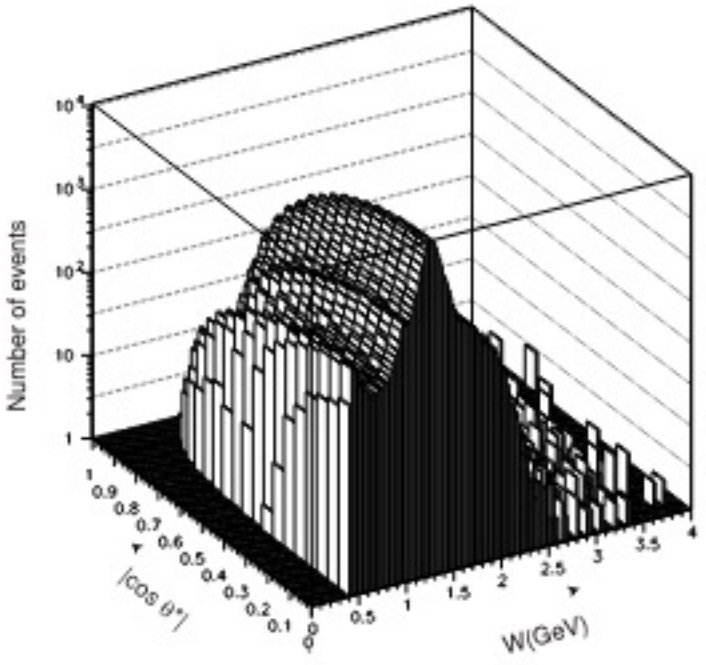


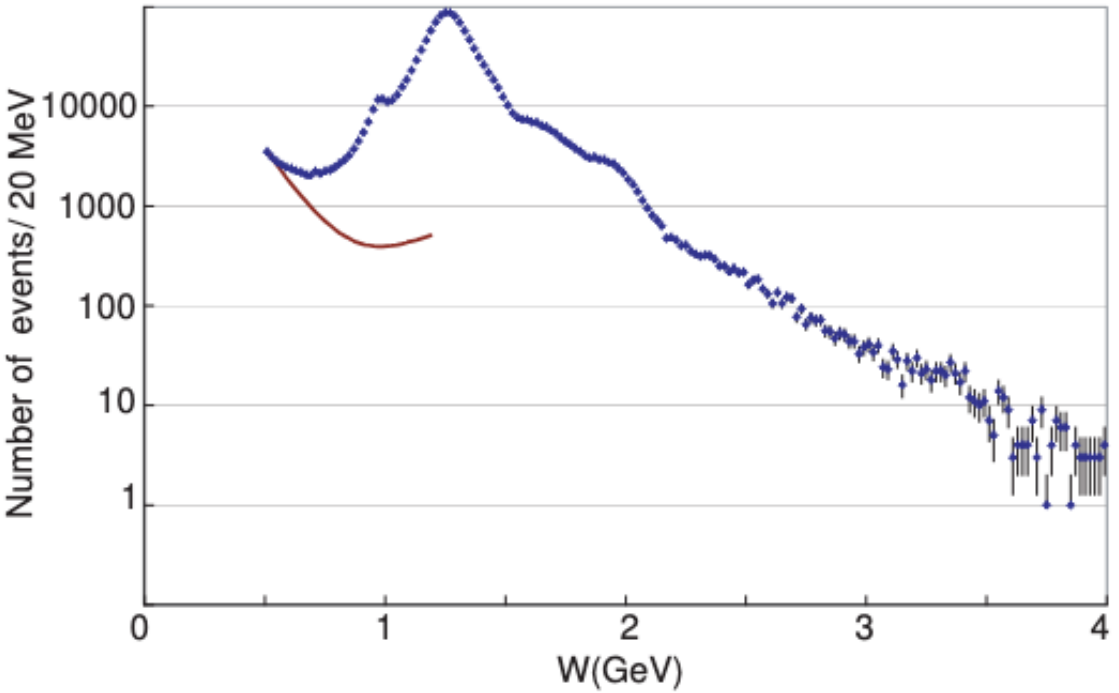


ππ, πK, ηπ, KK phase shifts

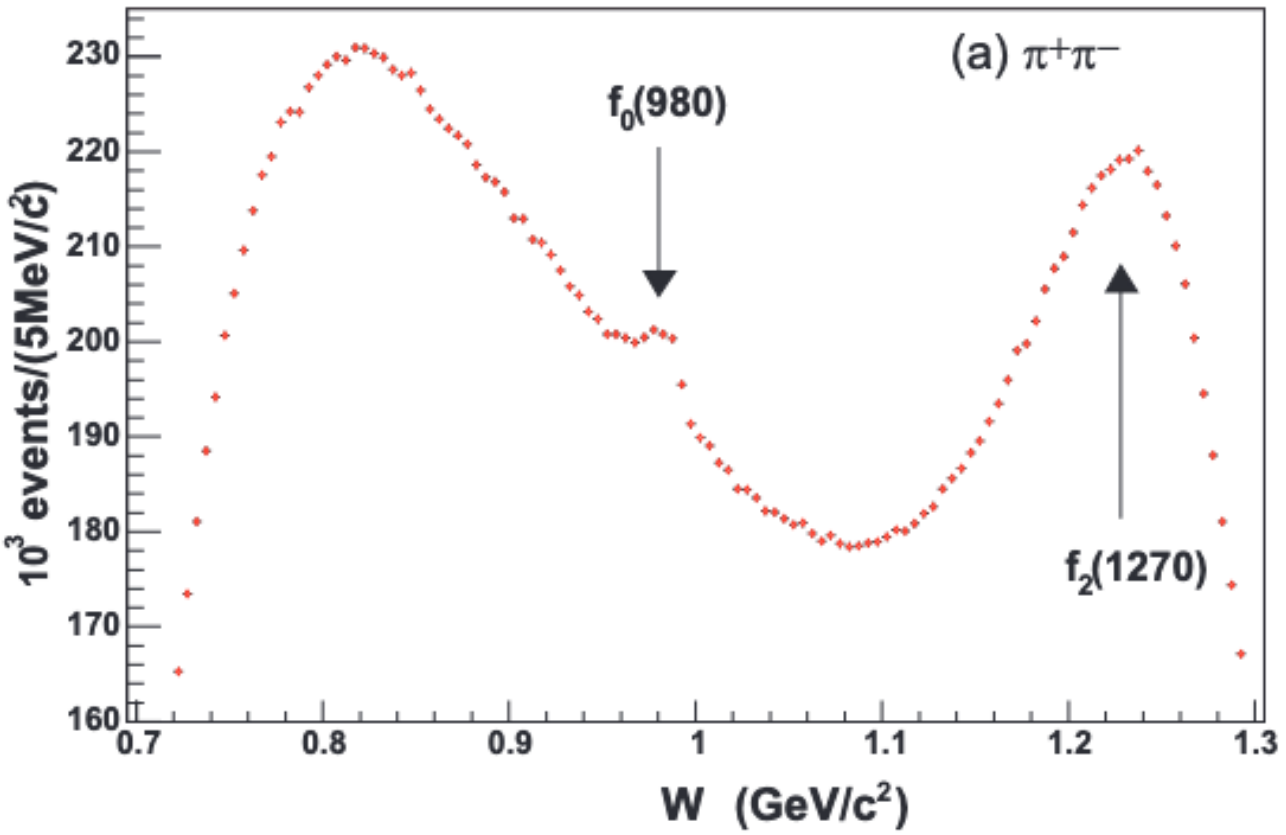

(a) $\pi\pi \to \pi\pi$ δ_1^1
(b) $\pi\pi \to \pi\pi$ δ_0^0
(c) $\pi\pi \to K\bar{K}$ δ_0^0
(d) $\pi\pi \to K\bar{K}$
$(1-(\eta_0^0)^2)/4$
$(1-(\eta_1^1)^2)/4$
(e) $\pi\pi \to \pi\pi$ δ_0^2
(f) $\pi\pi \to \pi\pi$ $\delta_0^0 - \delta_1^1$
(g) $\pi K \to \pi K$ $\delta_1^{1/2}$
(h) $\pi K \to \pi K$ $\delta_0^{1/2}$
(i) $\pi K \to \pi K$ $\delta_0^{3/2}$
(j) $d\sigma_{\eta\pi}/d\sqrt{s}$ [μb/GeV]
$\sqrt{s}$ [MeV]
$\sqrt{s}$ [MeV]

$\gamma\gamma \to \pi\pi\pi$



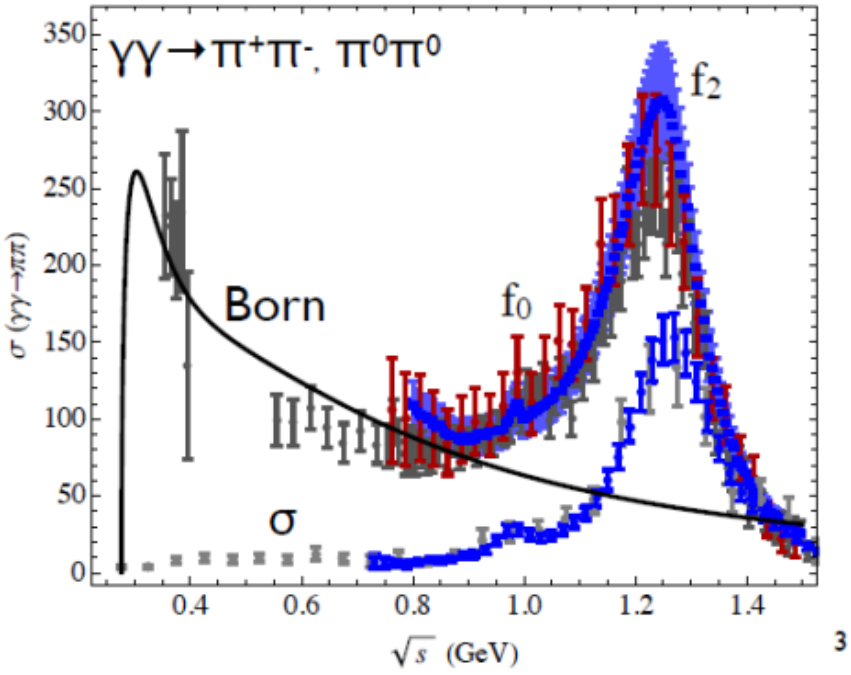


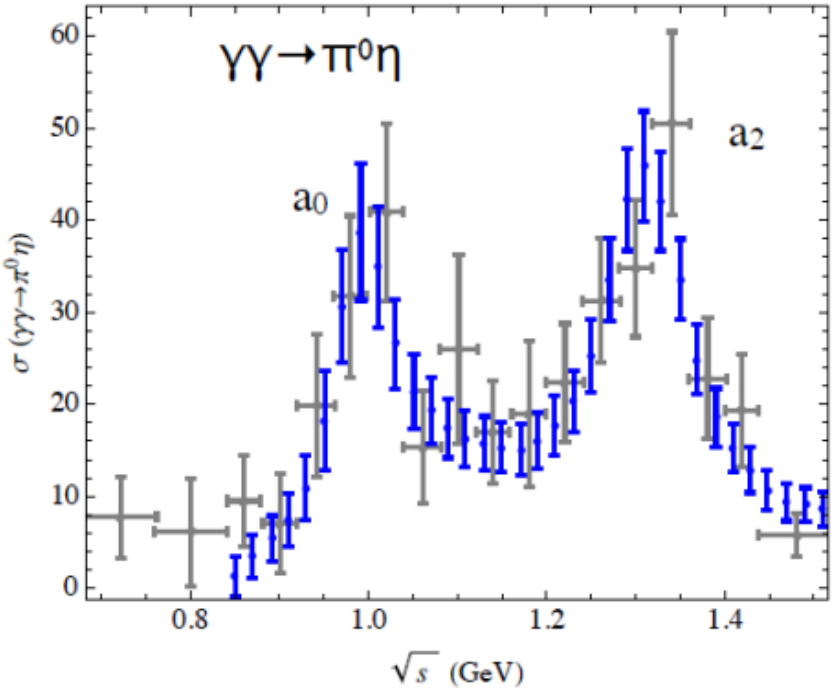
$|\cos\theta^*| \leq 0.8$


(a) $\pi^+\pi^-$
$f_0(980)$
$f_2(1270)$
10^3 events/(5MeV/c^2)
W (GeV/c^2)
230
220
210
200
190
180
170
160
0.7
0.8
0.9
1
1.1
1.2
1.3

Belle

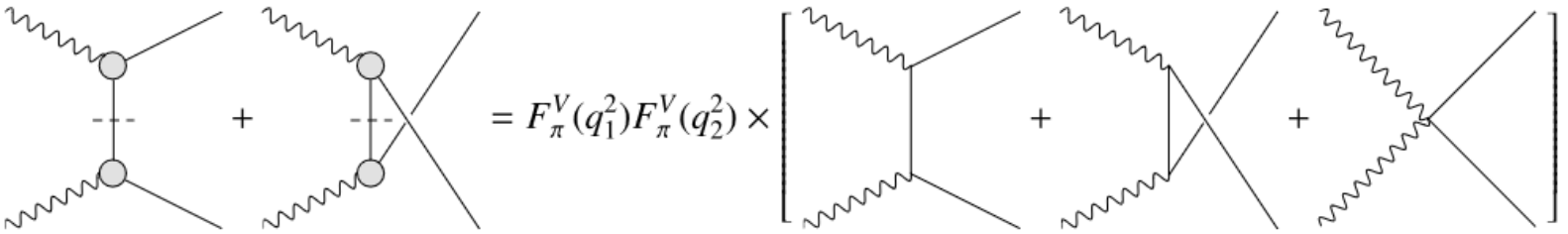
γ γ → ππ; ηπ experiment

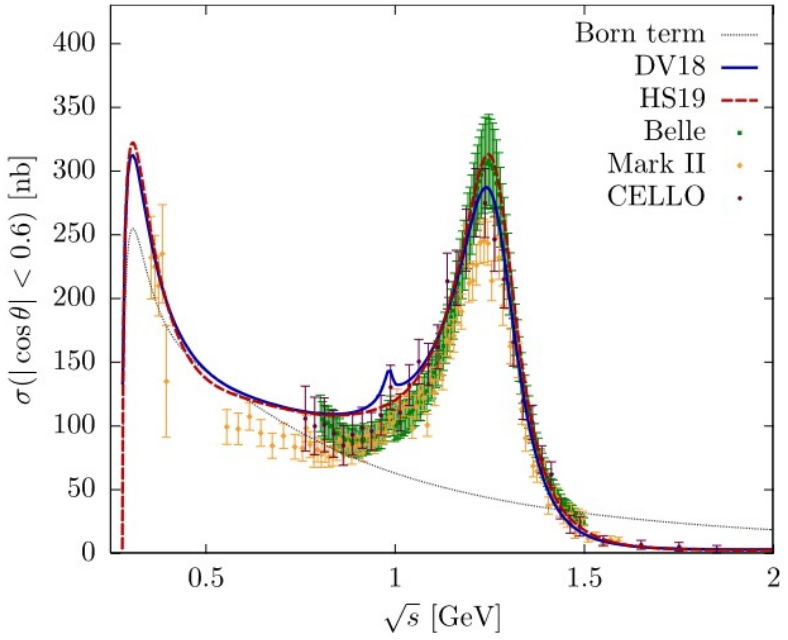


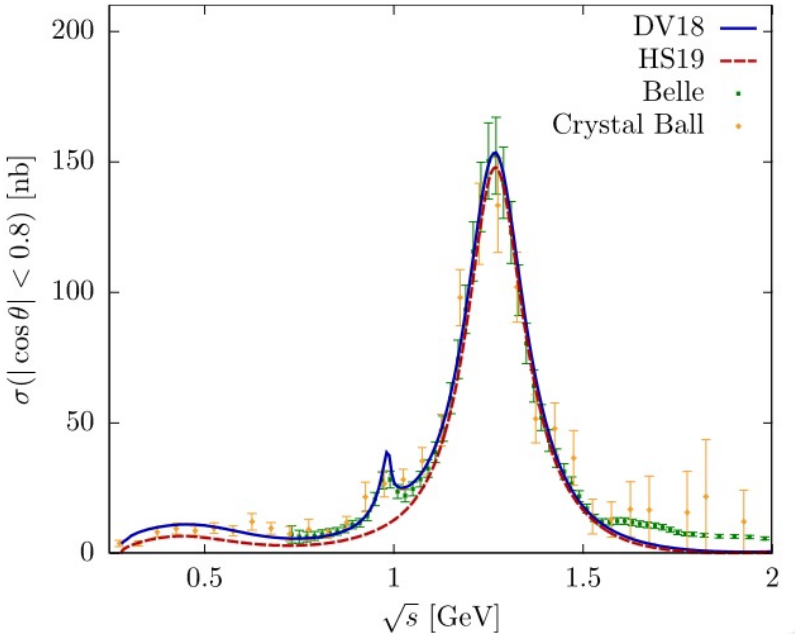


γγ→ππ, KK, ηη, πη (Belle: 07,08, 09,10, ..)
γγ*→ππ, πη (BESIII in progress)

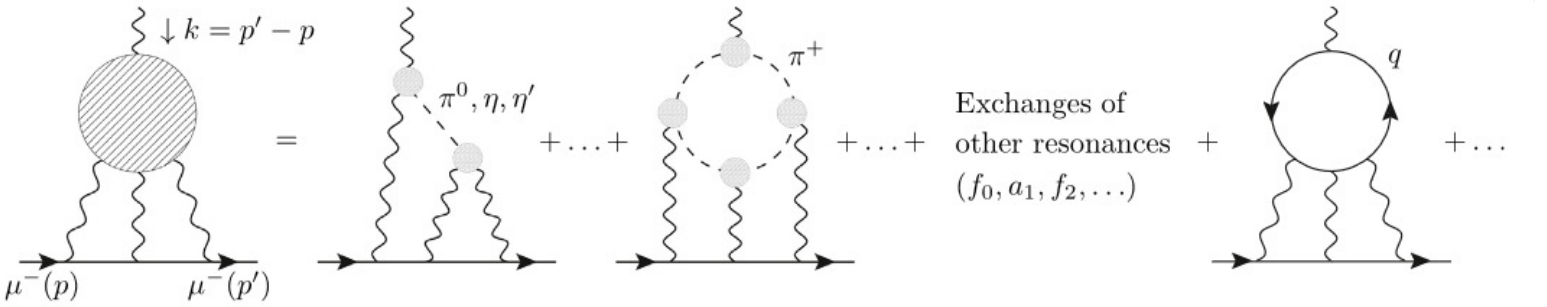
γ γ → ππ - dispersive







Hadronic Light by Light



π^0, η,η' exchange

$\pi^{\pm}$-box

hql+SD

+92(19)= +93.8(4) −15.9(2) +8(1) +18(10) +...

pseudoscalar poles	$a_\mu^{\text{PS-poles}}$	=	$93.8^{+4.0}_{-3.6}$
pion box	$a_\mu^{\pi\text{-box}}$	=	−15.9(2)
S-wave $\pi\pi$ rescattering	$a_{\mu,J=0}^{\pi\pi,\pi\text{-pole LHC}}$	=	8(1)
kaon box	$a_\mu^{K\text{-box}}$	=	− 0.5(1)
scalars and tensors with $M_R \gtrsim 1$ GeV	$a_\mu^{\text{scalars+tensors}}$	~	− 1(3)
axial vectors	a_μ^{axials}	~	6(6)
short-distance contribution	$\Delta a_\mu^{\text{SDC}}$	~	15(10)
charm and other heavy-quark contribution	a_μ^{c}	~	3(1)
Total	$a_\mu^{\text{HLbL,LO}}$	~	92(19)

White Book

Priorities for new experimental input

issue	experimental input [I] or cross-checks [C]
axials, tensors, higher pseudoscalars	$\gamma^{(*)}\gamma^* \to 3\pi,\ 4\pi,\ K\bar{K}\pi,\ \eta\pi\pi,\ \eta'\pi\pi$ [I]
missing states	inclusive $\gamma^{(*)}\gamma^* \to$ hadrons at 1–3 GeV [I]
dispersive analysis of $\eta^{(\prime)}$ TFFs	$e^+e^- \to \eta\pi^+\pi^-$ [I]
	$\eta' \to \pi^+\pi^-\pi^+\pi^-$ [I]
	$\eta' \to \pi^+\pi^- e^+e^-$ [I]
	$\gamma\pi^- \to \pi^-\eta$ [C]
dispersive analysis of π^0 TFF	$\gamma\pi \to \pi\pi$ [I]
	high accuracy Dalitz plot $\omega \to \pi^+\pi^-\pi^0$ [C]
	$e^+e^- \to \pi^+\pi^-\pi^0$ [C]
	$\omega, \phi \to \pi^0 l^+ l^-$ [C]
pseudoscalar TFF	$\gamma^{(*)}\gamma^* \to \pi^0, \eta, \eta'$ at arbitrary virtualities [I,C]
pion, kaon, $\pi\eta$ loops (including scalars and tensors)	$\gamma^{(*)}\gamma^* \to \pi\pi,\ K\bar{K},\ \pi\eta$ at arbitrary virtualities, partial waves [I,C]