Latest Physics Results from KLOE

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on behalf of the KLOE-2 Collaboration

47th Scientific Committee – LNF, 14 November 2013

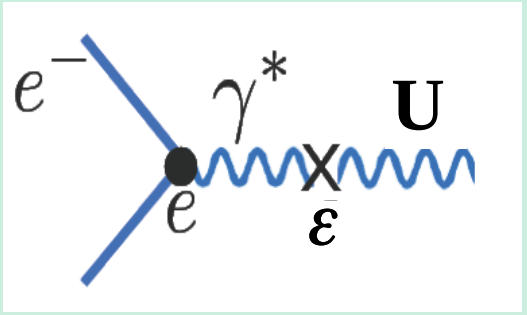
Analysis progresses since last SC

UL($K_S \to \pi^0\pi^0\pi^0$)	PLB 723 (2013) 54-60
$\phi \to K_S K_L \to \pi^+\pi^-\pi^+\pi^-$: CPT and Lorentz invariance	Draft under review of the collaboration
UL($e^+e^- \to U\gamma$)	Final result
UL($e^+e^- \to Uh'$)	New U.L. with MC background events
$\phi \to \eta e^+e^-$	BR and transition form factor
$\phi \to \pi^0 e^+e^-$	Towards transition form factor
$\eta \to \pi^+\pi^-\pi^0$	Fit to the Dalitz plot distribution

Search for dark forces @ KLOE

Hypothesis: existence of a hidden gauge sector weakly coupled with SM through a mixing mechanism of a new gauge boson, U, with the photon:

♦ M_U = 1 MeV - few GeV ♦ $\varepsilon \leq 10^{-3}$



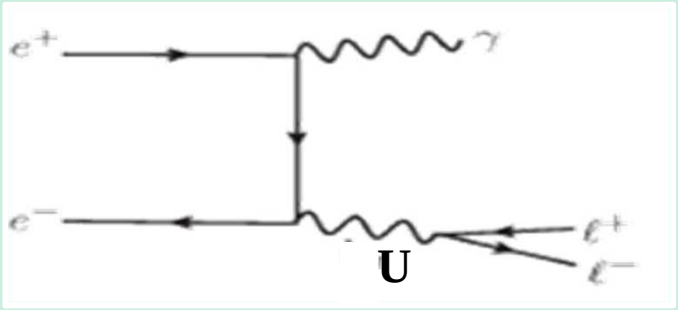
- **Meson decays**: $\phi \to \eta U$, $\eta/\pi^0 \to U\gamma$ ...

  Peculiar of a light meson factory

KLOE-2, PLB 706 (2012) 251
KLOE-2, PLB 720 (2013) 111

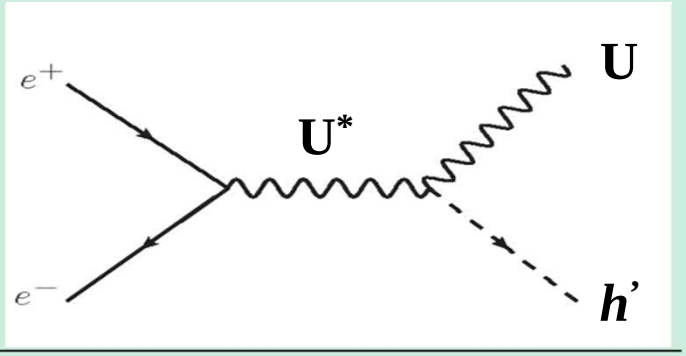
- ***e*⁺*e*⁻ collisions**: $e^+e^- \to U\gamma \to \ell^+\ell^-\gamma$

  x-sec ∝ 1/s : 100 times higher at DAΦNE w.r.t. b-factories, compensate lower luminosities



- ***h*'-strahlung**: $e^+e^- \to U^* \to Uh'$

  Assuming the existence of a higgs' boson, this process can be observed at DAΦNE if $M_U + M_h < M_\phi$

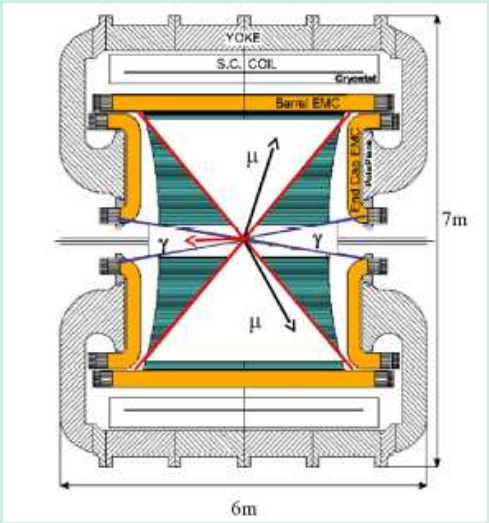


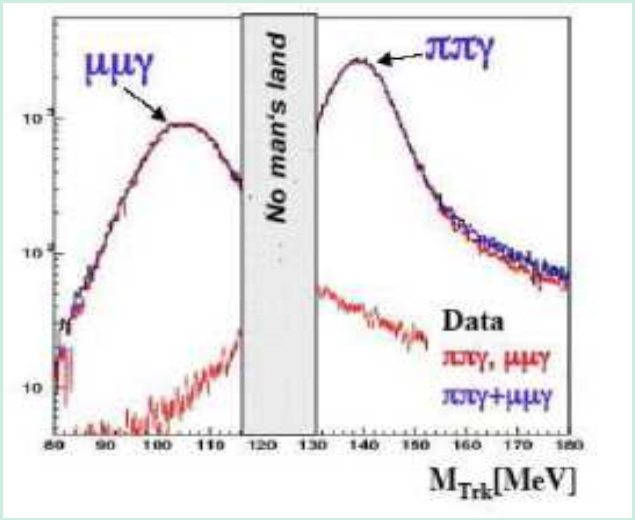
Search for U boson @ KLOE: $e^+e^- \to \mu^+\mu^-\gamma$

Same selection used for the $\sigma(\pi^+\pi^-\gamma)/\sigma(\mu^+\mu^-\gamma)$ analysis [KLOE-2, PLB 720 (2013) 336]

- L_{int} = 240 pb^{-1} @ M_ϕ
- Two charged tracks in the central calorimeter (50° < θ < 130°)
- Undetected small angle photon (θ < 15°, θ >165°):
  $p_\gamma \sim p_{miss(\phi\mu\mu)}$
- PID cut to reject electrons
- π/μ separation using M_{TRK} variable:

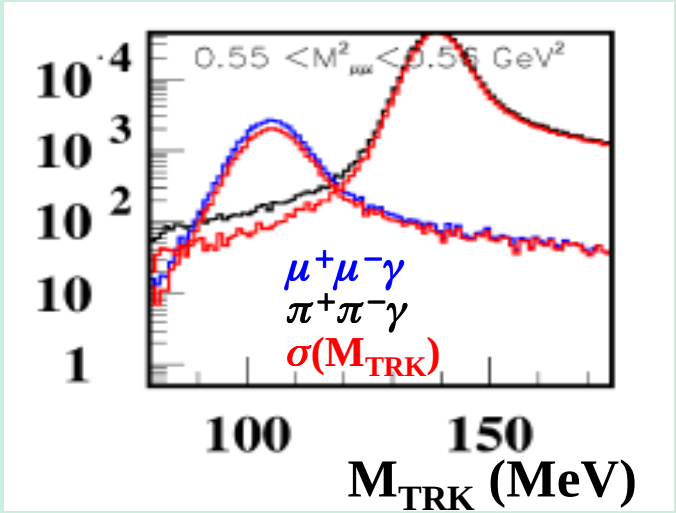
$$\left(\sqrt{s}-\sqrt{|p_+|^2+M_{TRK}^2}-\sqrt{|p_-|^2+M_{TRK}^2}\right)^2-(p_++p_-)^2=0$$





μ: M_{TRK} < 115 MeV
π: M_{TRK} > 130 MeV

$\sigma(M_{TRK})$ < 3 MeV

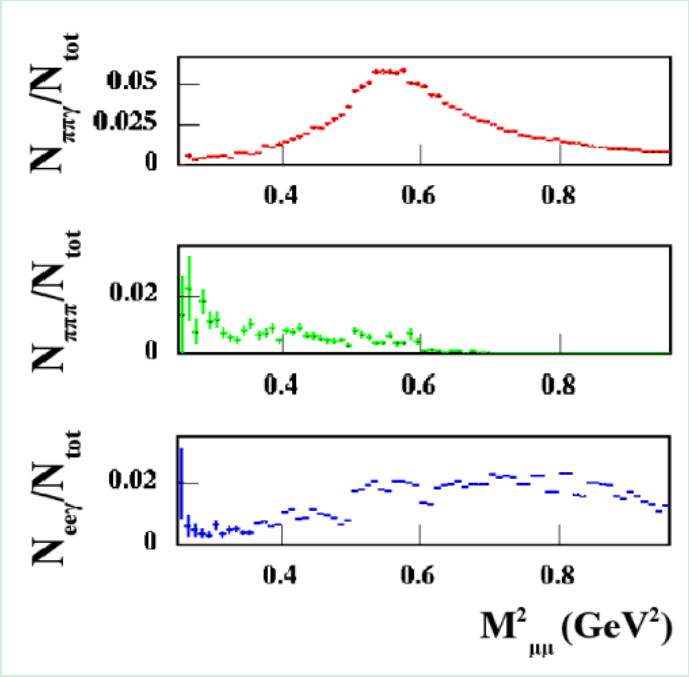


$e^+e^- \to \mu^+\mu^-\gamma$: backgrounds

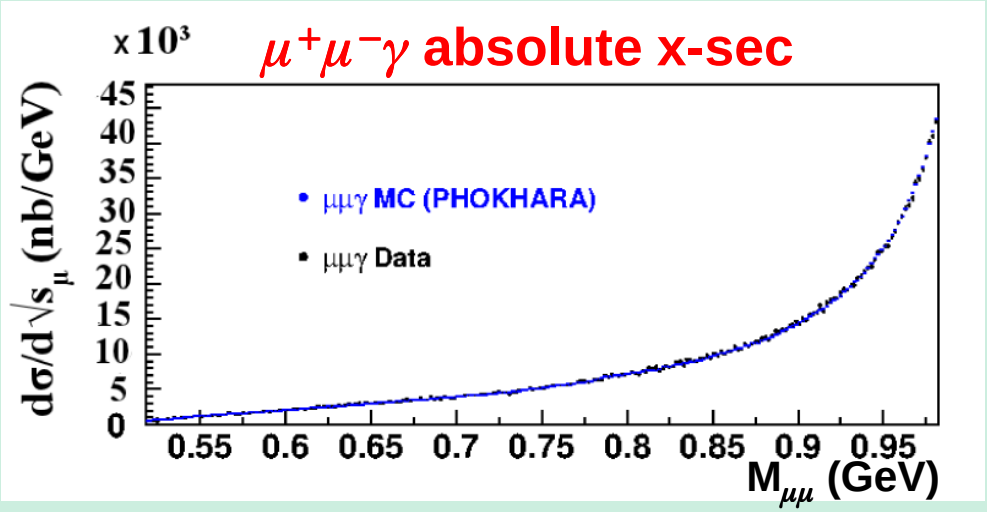
Residual background components:

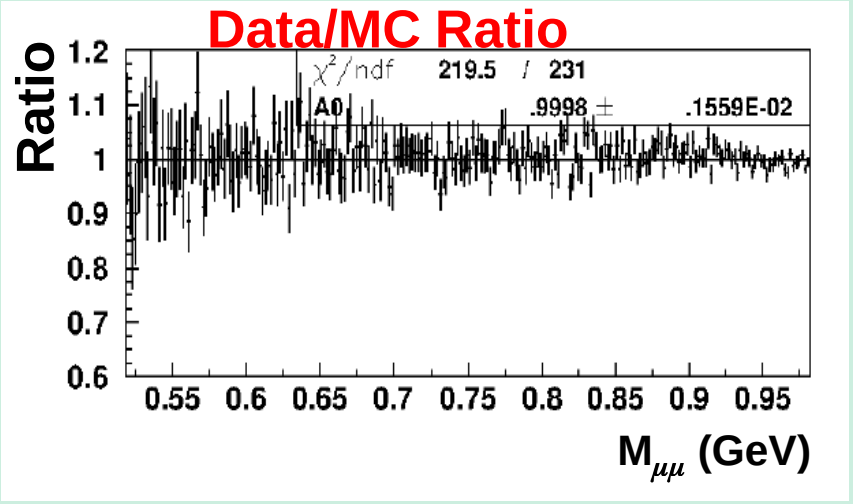
- $e^+e^- \to \pi^+\pi^-\gamma(\gamma)$
- $e^+e^- \to \pi^+\pi^-\pi^0$
- $e^+e^- \to e^+e^-\gamma(\gamma)$

Estimated by fitting the M_{TRK} distribution for 35 $M^2_{\mu\mu}$ slices of 0.02 GeV^2 between 0.26 and 0.96 GeV^2



Background subtraction → absolute $\mu^+\mu^-\gamma$ x-sec compared to MC (PHOKHARA, NLO QED)

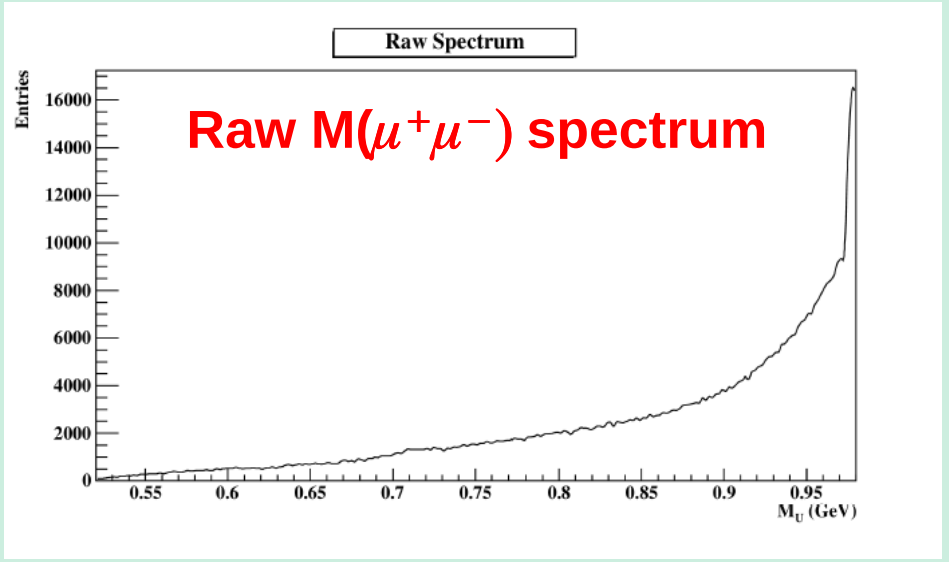


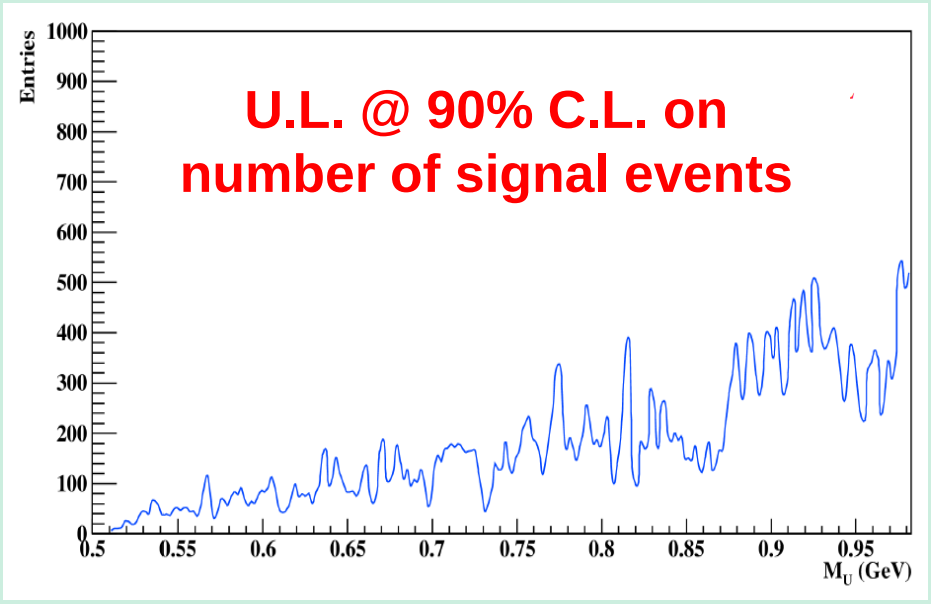


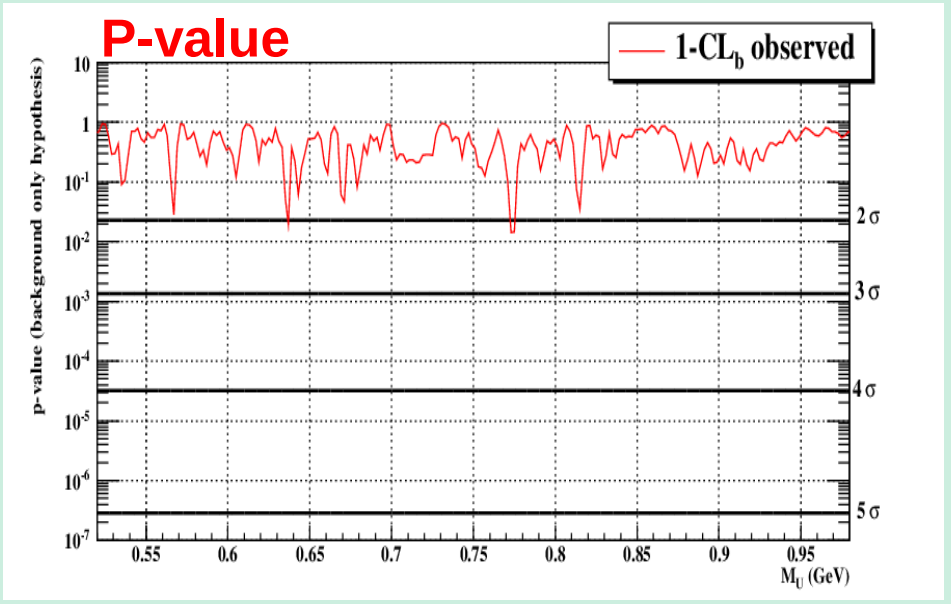
$e^+e^- \to \mu^+\mu^-\gamma$: U.L. on signal events

U.L. extraction @ 90% C.L. using the CLS technique. Inputs:

- Observed $M_{\mu\mu}$ spectrum
- MC signal ($\sigma_{M\mu\mu}$ = 1.3-1.9 MeV)
- Bckg: QED NLO MC prediction
- Systematics on background included bin-by-bin (1.8-1.3%)







$e^+e^- \to \mu^+\mu^-\gamma$: U.L. on ε parameter

$$\varepsilon^2 = \frac{N_{CLS}/(\varepsilon_{eff} \times L)}{H \times I}$$

N_{CLS}= U.L. on signal events

ε_{eff}= analysis efficiency

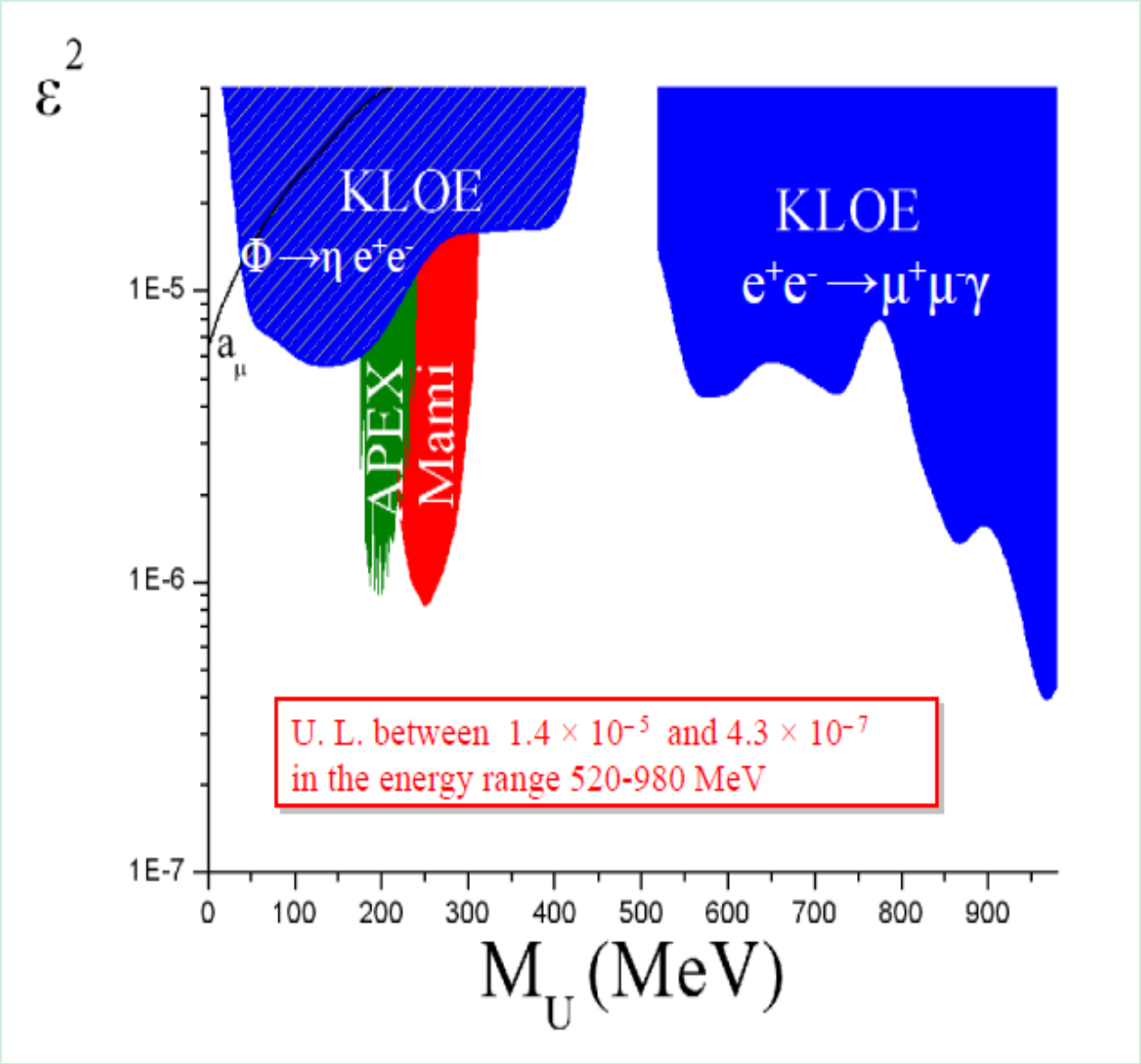
$$H = \frac{d\sigma_{\mu\mu\gamma}/ds_\mu}{\sigma(e^+e^- \to \mu^+\mu^-, s)}$$

$L = 239.29\ pb^{-1}$

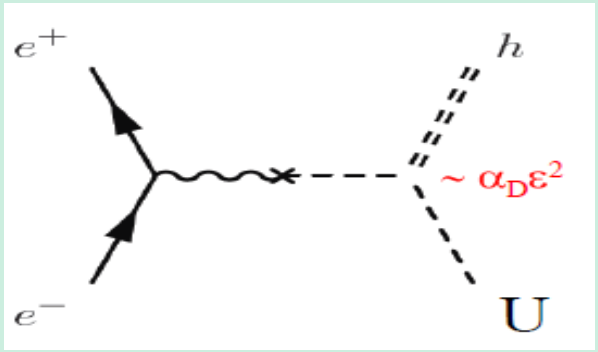
$I = \int \sigma_U^{\mu\mu}\, ds_i \quad s = M_U^2$

s_i=bin

$\sigma_U^{\mu\mu} = \sigma(e^+e^- \to U \to \mu^+\mu^-)$



Search for U boson @ KLOE: *h'*-strahlung



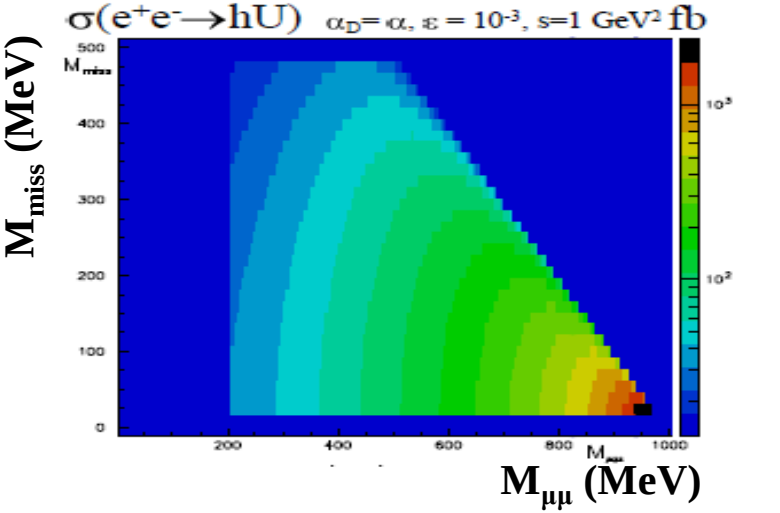
$e^+e^- \rightarrow U\,h'$ (dominant if $m_h < m_U$)

$$\sigma \approx 20\,fb \times \left(\frac{\alpha_D}{\alpha}\right)\left(\frac{\varepsilon^2}{10^{-4}}\right)\frac{10^2\,GeV^2}{s}$$

[B. Batell, M. Pospelov, A. Ritz: PRD79 (2009) 115008]

$m_h > m_U$: $h' \rightarrow UU \rightarrow 4l$

$m_h < m_U$: ***h'*** → **"invisible"**
U→*ll*



Selected channel

$\varepsilon = 10^{-3}$
$\alpha_D = \alpha$
$m_{U,h} \sim 100$ MeV

$\tau_h \sim 5\,\mu s$

L_h > 100 m, increasing with decreasing ε

Higgs invisible up to $\varepsilon \sim 10^{-2} - 10^{-1}$, depending on m_h

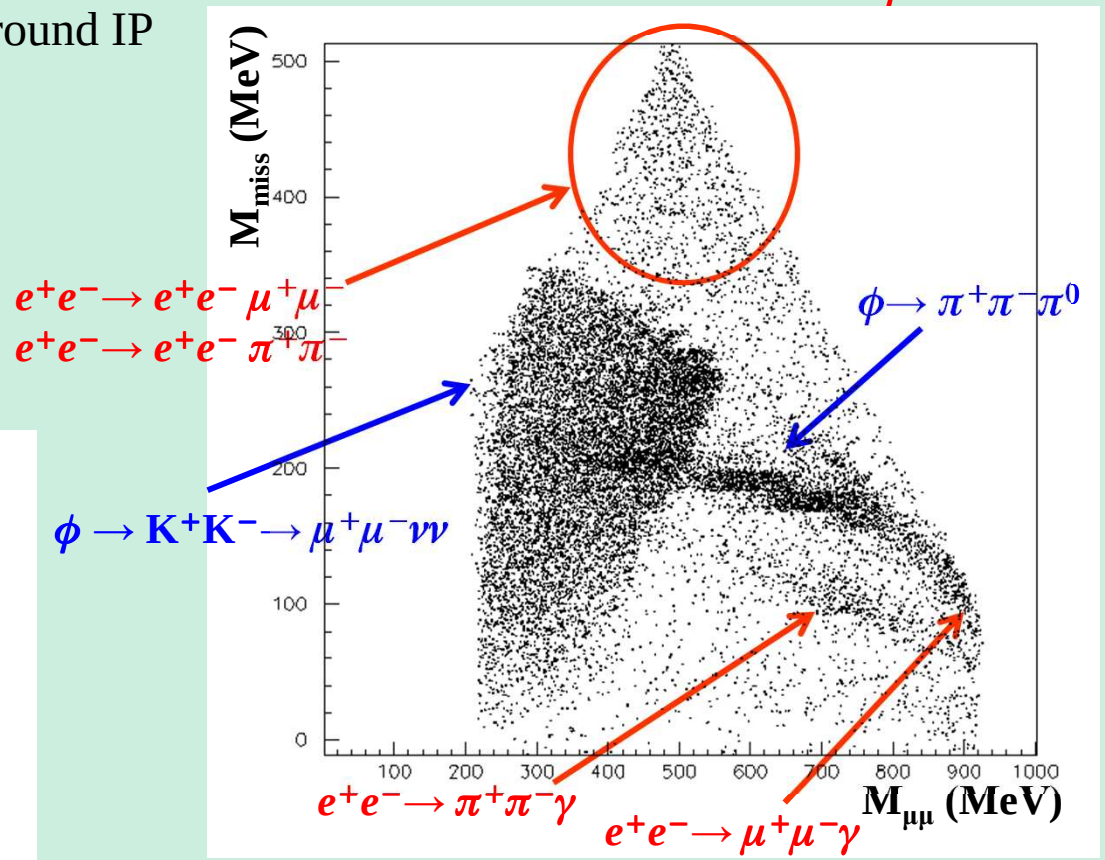
Signature:

a pair of leptons + missing energy

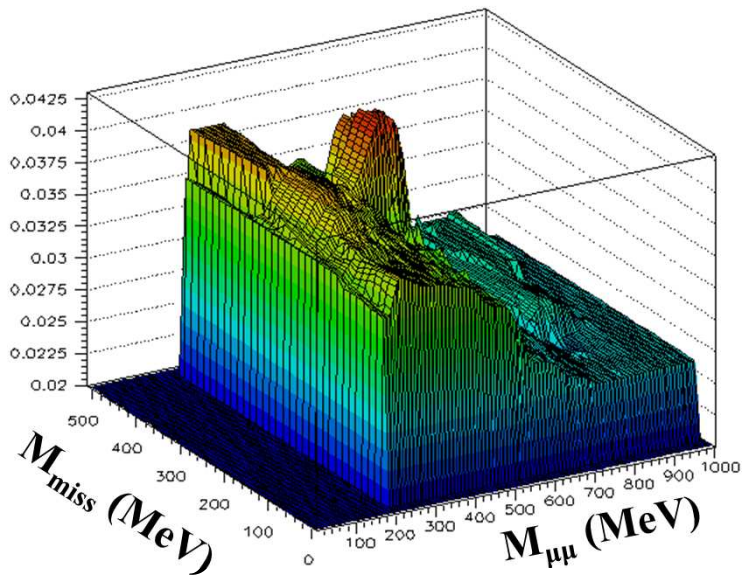
$e^+e^- \to Uh'$, $U \to \mu^+\mu^-$: sample selection

- Two charged tracks, $q_1+q_2=0$
- Vtx in a 8(ρ) × 30(z) cm cylinder around IP
- $p_{1,2} < 460$ MeV
- $\cos\theta_{1,2} < 0.8$, $\cos\theta_{miss} < 0.75$
- $p_1 + p_2 > 450$ MeV , $p_{miss} > 40$ MeV
- Calorimeter veto
- PID: two muons
- Vtx – IP cut ($\phi \to K^+K^-$ veto)

L=1.65 fb^{-1} @ M_ϕ

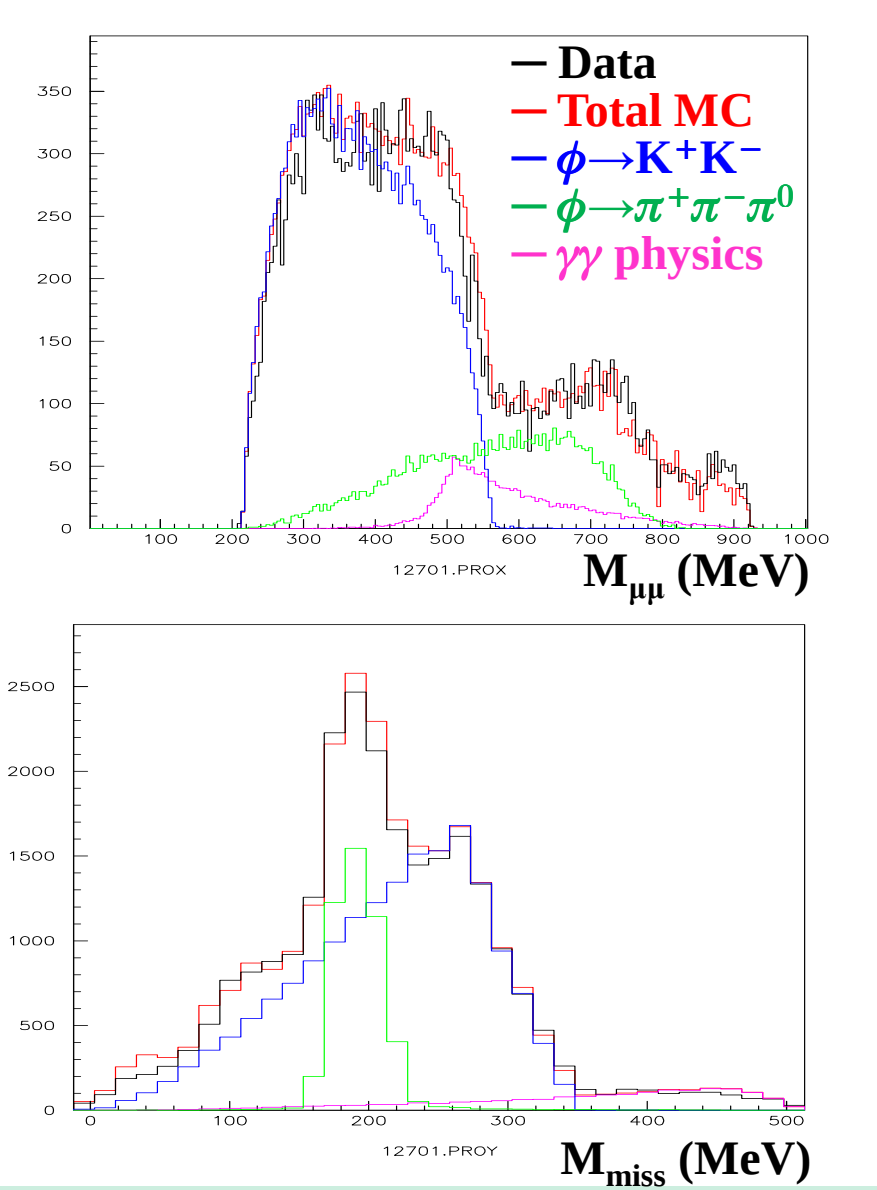


Analysis efficiency



Systematics: 2-4 %
Small impact on final results

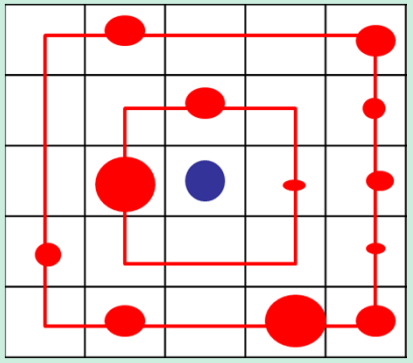
$e^+e^- \to Uh'$, $U \to \mu^+\mu^-$: data-MC comparison



Millions of $\gamma\gamma$ MC events produced at generator level only, with the same conditions of KLOE data. Smearing according to our momentum resolution.

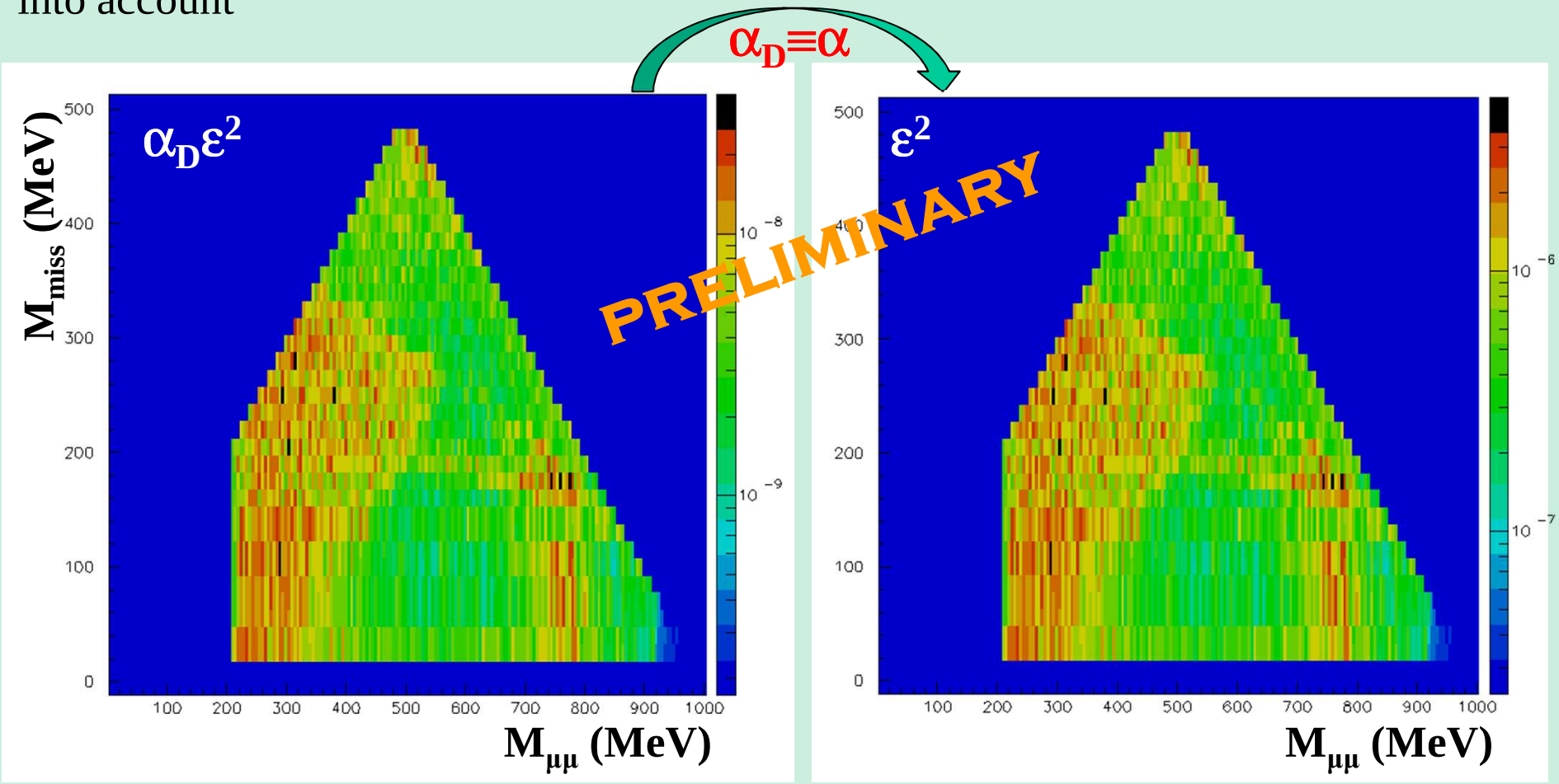
The $M_{\mu\mu}$-M_{miss} plane is then constructed, with a binning size such as 90-95% of the signal is in one single bin.

To extract the U.L., a 5×5 bin matrix is considered. The signal is searched in the central one, the other 24 bins are used to estimate the background, extracting a data-MC scale factor.



$e^+e^- \to Uh'$, $U \to \mu^+\mu^-$: 90% C.L. limits

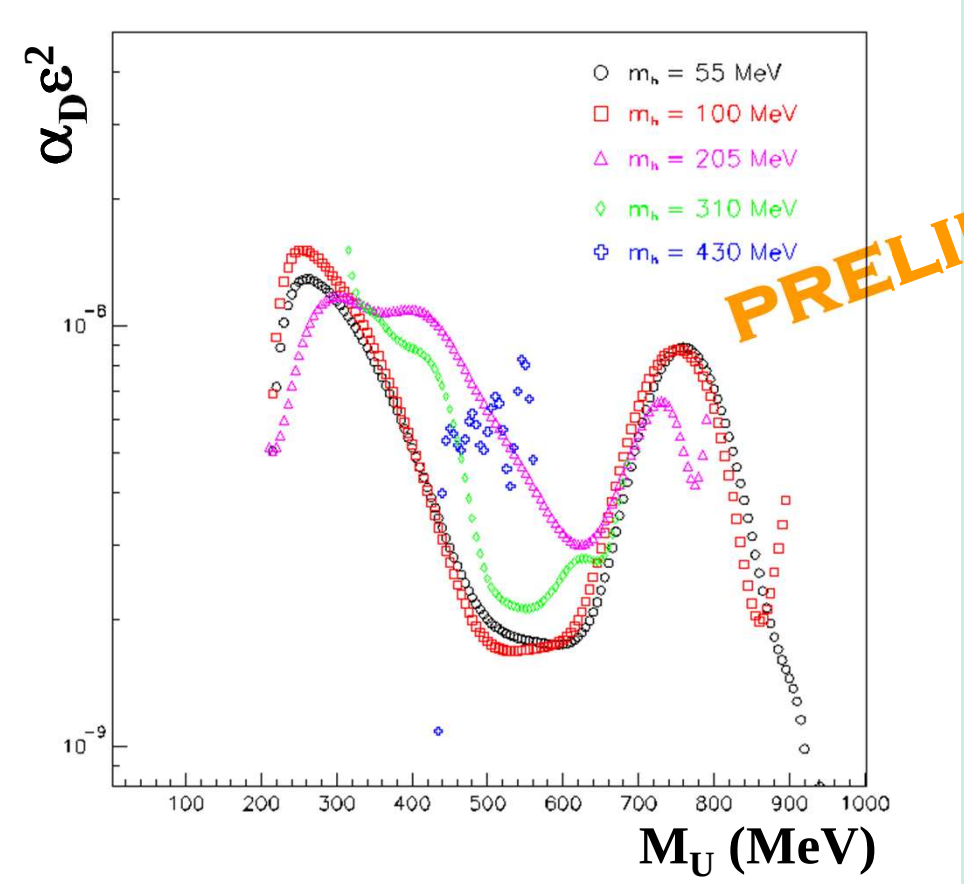
Bayesian approach: statistical fluctuations and systematic uncertainties fully kept into account

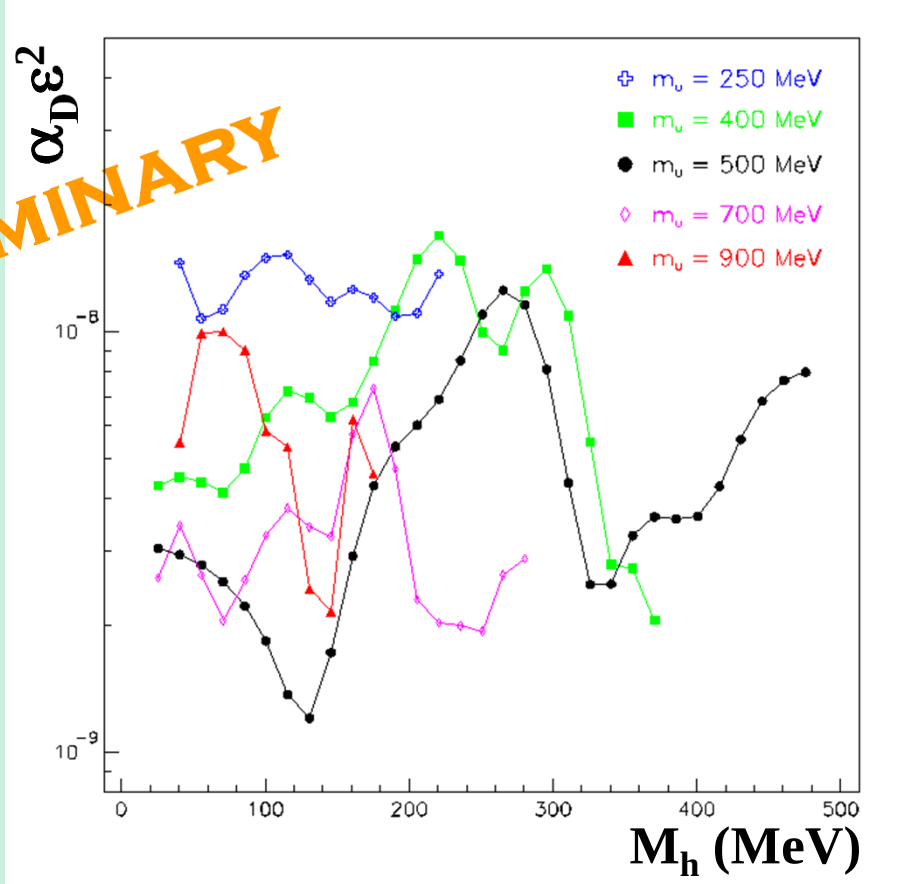


Work is in progress to extract the U.L. also from the 0.2 fb^{-1} off-peak sample

$e^+e^- \to Uh'$, $U \to \mu^+\mu^-$: U.L. projections

Smoothed results





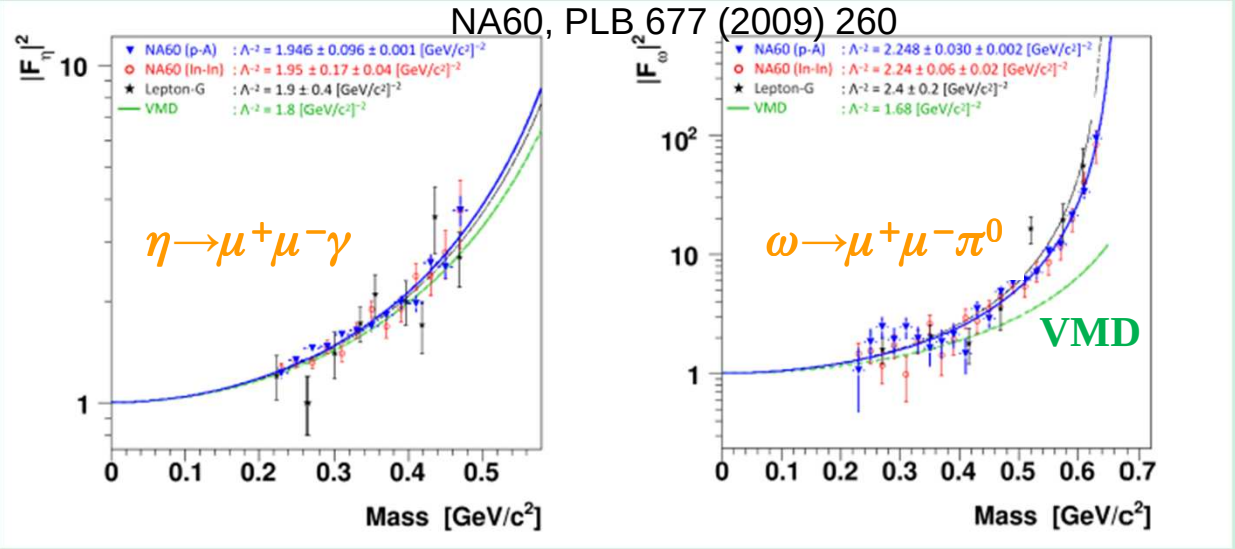
U.L. ~ $10^{-3} \div$ some 10^{-4} in ε if $\alpha_D = \alpha$

Search complementary with BaBar/Belle ones: different final state and phase space

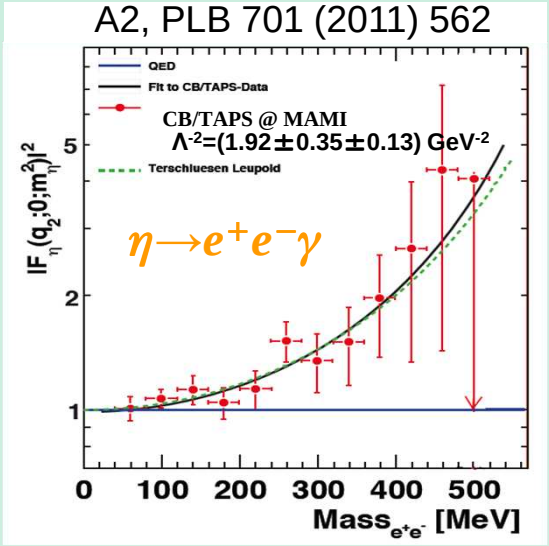
TFF from Dalitz decays

Naive VMD approach well describes $\eta \to \gamma \ell^+ \ell^-$, but fails for $\omega \to \pi^0 \ell^+ \ell^-$

NA60, PLB 677 (2009) 260



A2, PLB 701 (2011) 562



$$F(q^2) = \frac{1}{1 - q^2/\Lambda^2} \qquad (q^2 = M^2_{\ell^+\ell^-})$$

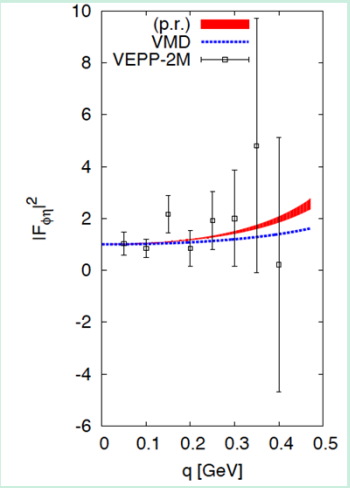
Needed: 1. New measurement of $\omega \to \pi^0 \ell^+ \ell^-$ TFF
2. Study of other V→Pγ^* transitions

The only existing measurement is from $\phi \to \eta e^+ e^-$ (213 events):

$$b_{\phi\eta} = \Lambda_{\phi\eta}{}^{-2} = (\,3.8 \pm 1.8\,)\ \mathrm{GeV}^{-2}$$

[SND, PLB 504 (2001) 275]

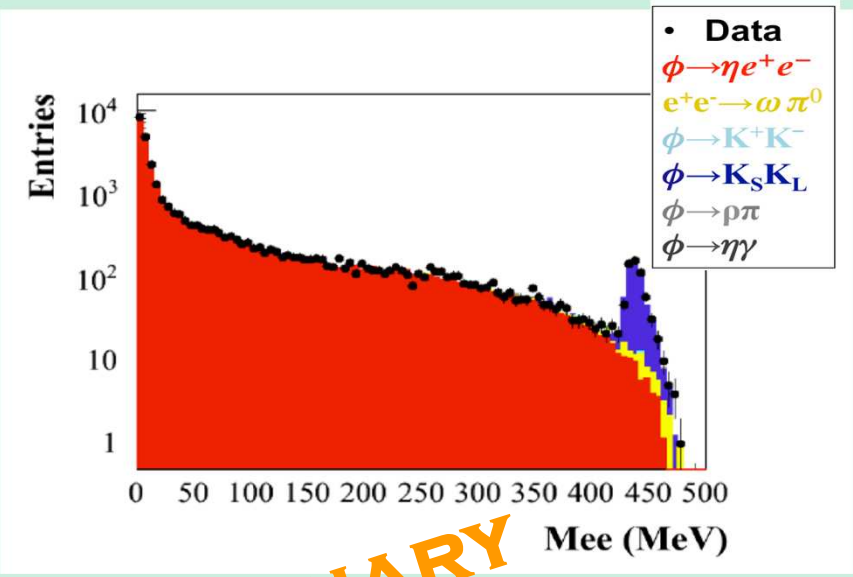
VMD: $b_{\phi\eta} \sim M_\phi{}^2 \sim 1\ \mathrm{GeV}^{-2}$

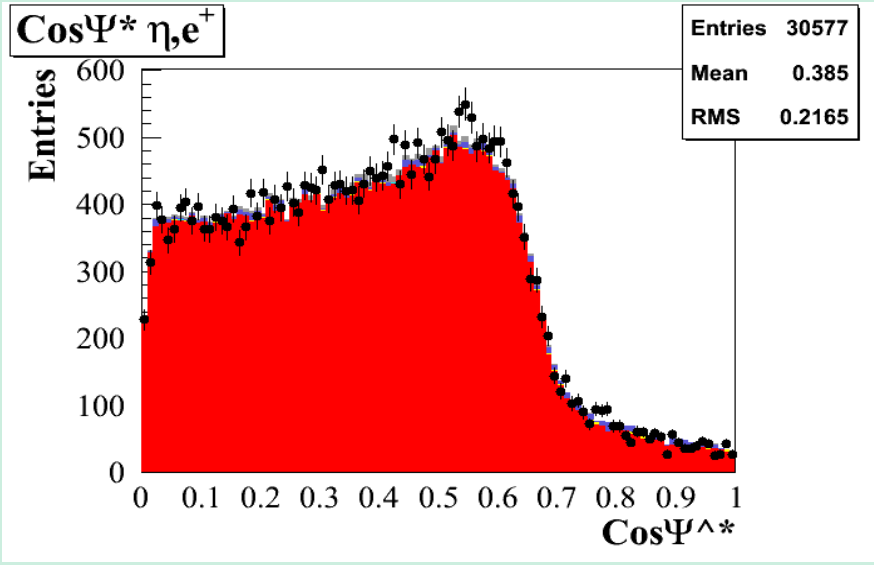


$\phi \to \eta e^+ e^-, \eta \to \pi^0\pi^0\pi^0$

Same selection used for the U boson search with $\phi \to \eta U$ [KLOE-2, PLB 720 (2013) 111]

- L_{int} = 1.7 fb^{-1}
- After all analysis cuts: ~15% global efficiency
  ~ 30000 signal events
  small background contribution (<3%)





Ψ^*: angle between the η and the e^+ in the e^+e^- rest frame

$$BR(\phi \to \eta e^+ e^-) = (1.131 \pm 0.032\ ^{+0.011}_{-0.006}) \times 10^{-4}$$

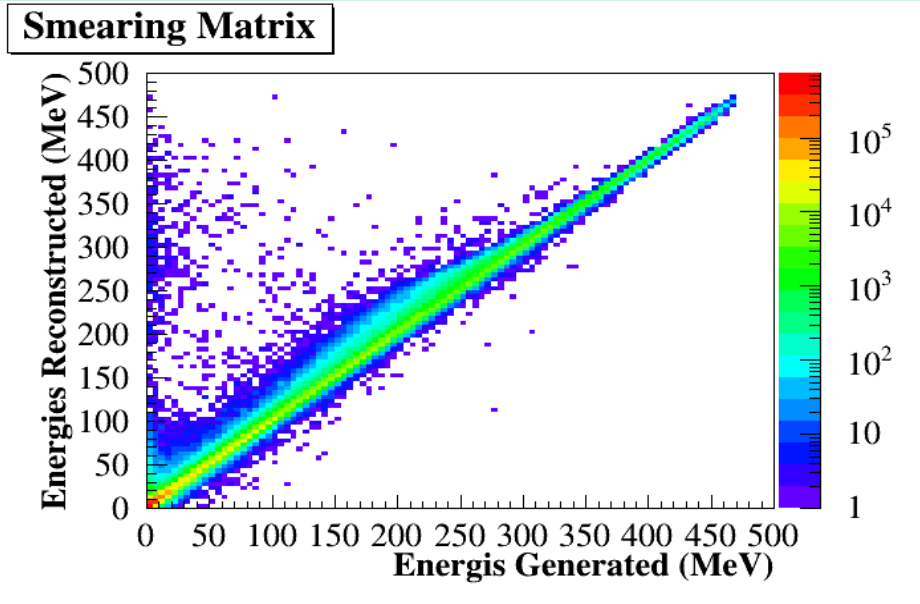
- VMD: 1.1
- SND: $(1.19 \pm 0.31) \times 10^{-4}$ [PLB 504 (2001) 275]
- CMD-2: $(1.14 \pm 0.16) \times 10^{-4}$ [PLB 501 (2001) 191]

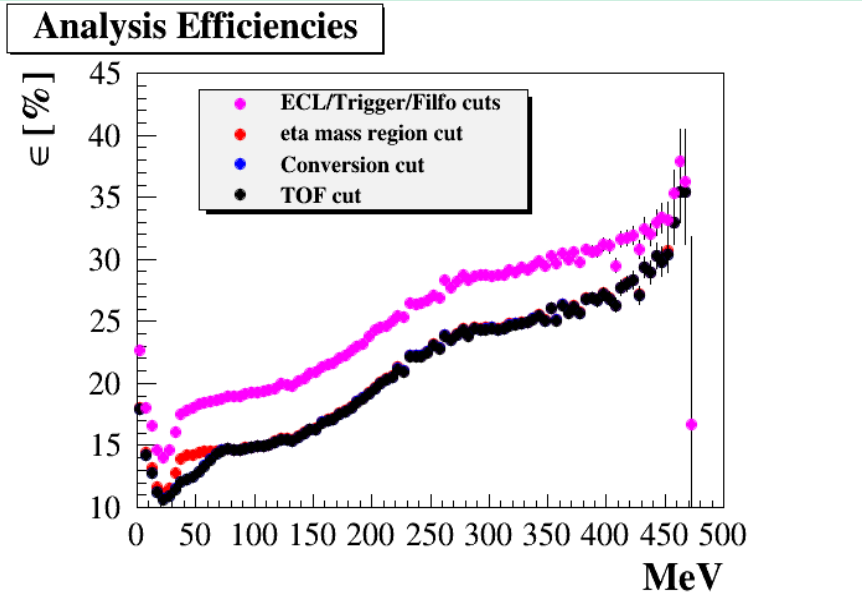
$\phi \to \eta e^+ e^-$: fit to the di-lepton inv. mass

Fit to M_{ee} distribution with decay parametrization from PR128 (1985) 301, to extract transition form factor

$$\frac{d}{dq^2}\frac{\Gamma(\phi \to \eta e^+ e^-)}{\Gamma(\phi \to \eta\gamma)} = \frac{\alpha}{3\pi}\frac{|F_{\phi\eta}(q^2)|^2}{q^2}\sqrt{1-\frac{4m^2}{q^2}}\times\left(1+\frac{2m^2}{q^2}\right)\times\left[\left(1+\frac{q^2}{m_\phi^2-m_\eta^2}\right)^2-\frac{4m_\phi^2 q^2}{(m_\phi^2-m_\eta^2)^2}\right]^{3/2}$$

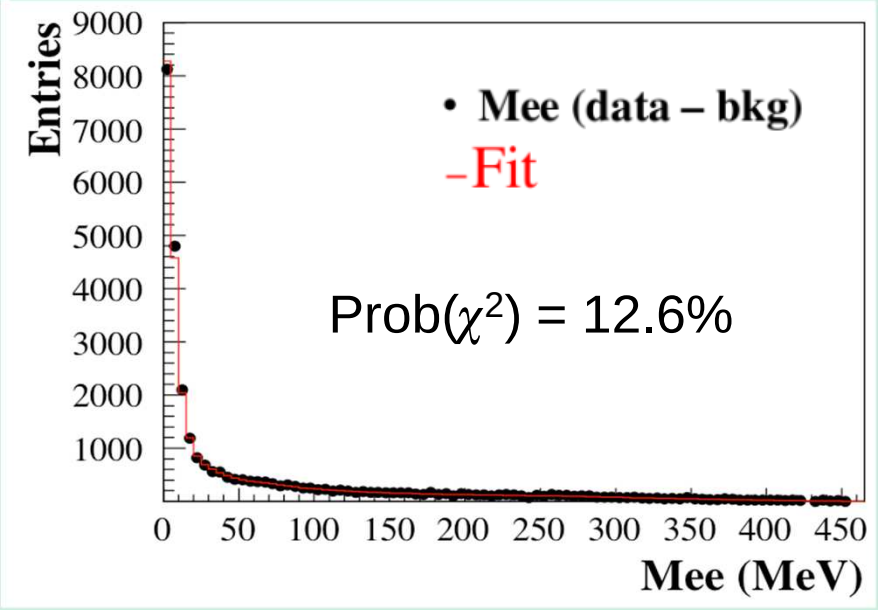
Smearing matrix, bin-by-bin analysis efficiency properly taken into account

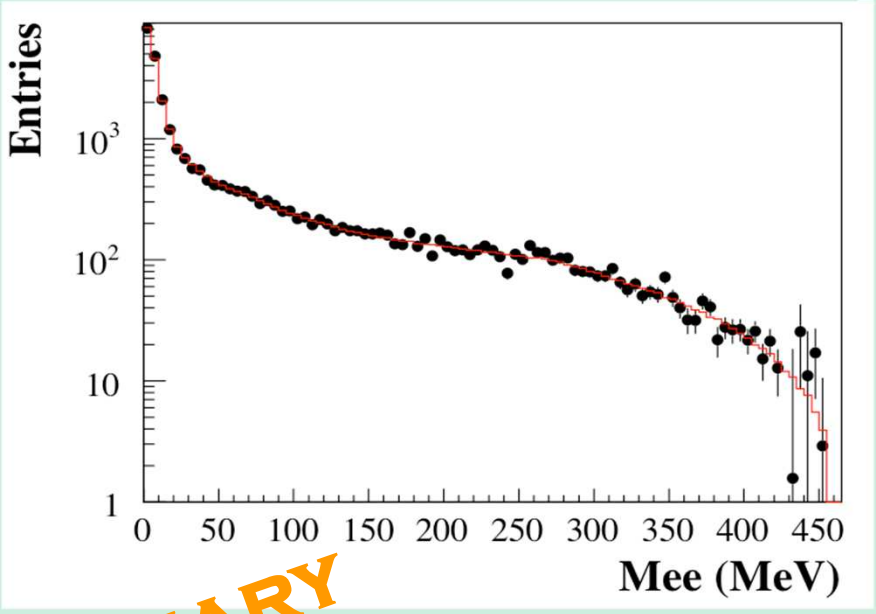




Photons from FSR included in the event generator

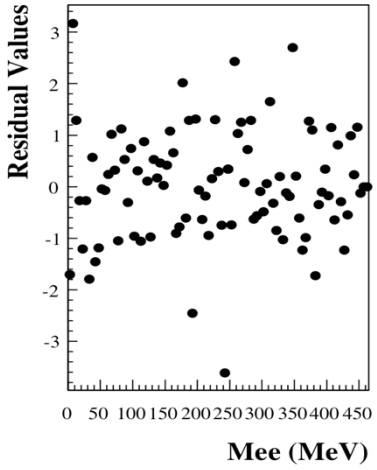
$\phi \to \eta e^+ e^-$: transition form factor

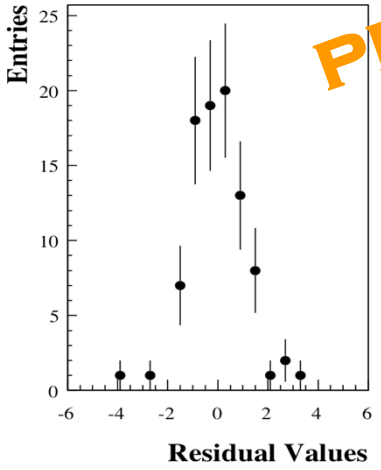




PRELIMINARY

Fit residuals





$$b_{\phi\eta} = (1.17 \pm 0.11\ ^{+0.09}_{-0.08})\ \text{GeV}^{-2}$$

- VMD: ~ 1.0 GeV^{-2}
- SND: (3.8 ± 1.8) GeV^{-2} [PLB 504 (2001) 275]

FF extraction in progress

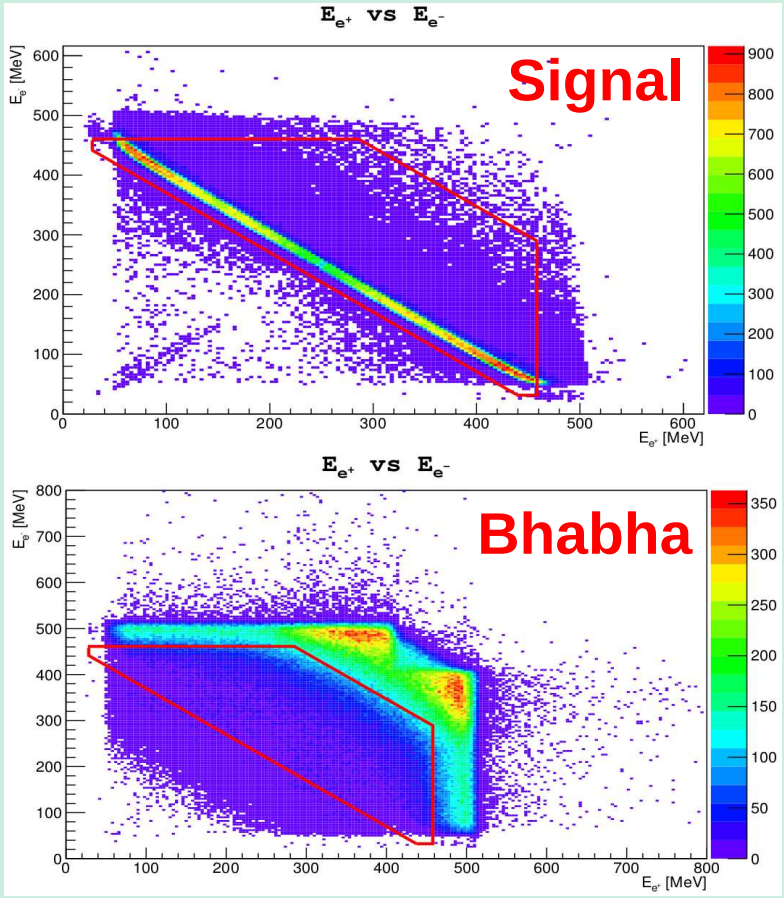
$\phi \to \pi^0 e^+ e^-$

- No data available for $F_{\phi\pi}(q^2)$
- 30-40% error on BR

- SND: $(1.01 \pm 0.40) \times 10^{-5}$ [JETP 75 (2002) 449]
- CMD-2: $(1.22 \pm 0.40) \times 10^{-5}$ [PLB 503 (2001) 237]

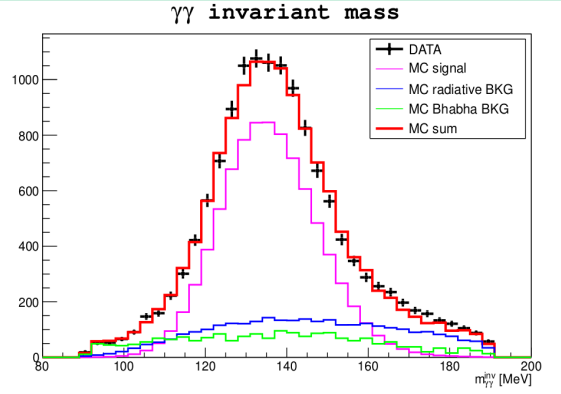
- Background from radiative Bhabha scattering events and $V \to P\gamma$: several orders of magnitude larger

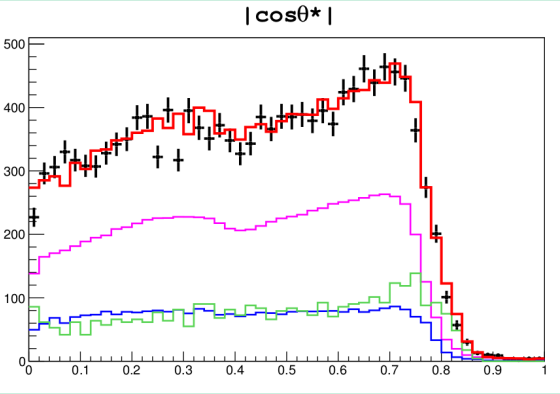
- Selection cuts:
  - $E_e < 460$ MeV
  - $470 < E_{e+} + E_{e-} < 750$ MeV
  - $300 < E_{\gamma 1} + E_{\gamma 2} < 670$ MeV
  - $\theta_{open}(ee) < 145^o$, $27^o < \theta_{open}(\gamma\gamma) < 57^o$
  - $90 < M_{2\gamma} < 190$ MeV
  - $80 < M_{miss}(ee) < 180$ MeV
  - Cut to reject γ conversions

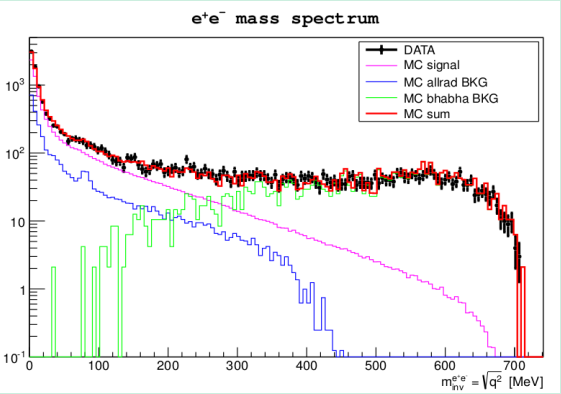


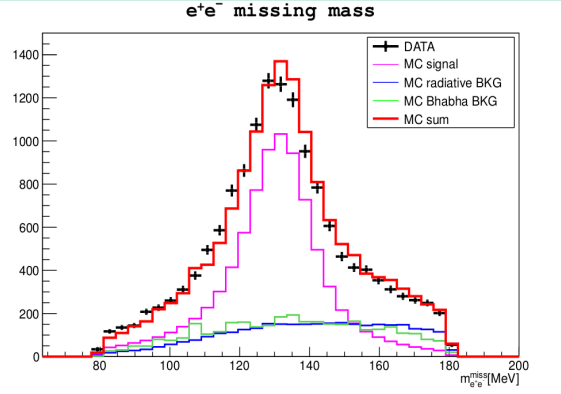
$\phi \rightarrow \pi^0 e^+ e^-$

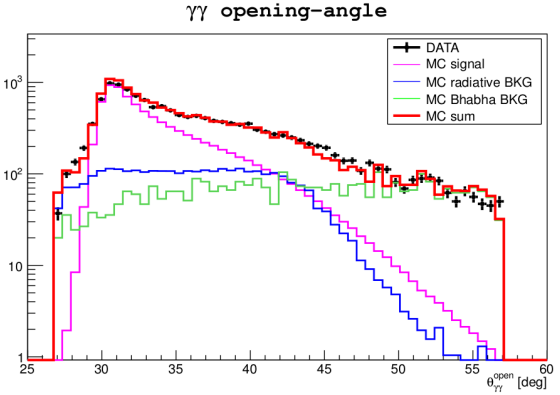
- L_{int} = 1.7 fb^{-1}
- 8777 events selected
- Global efficiency from 15% at low M_{ee} to 2% at 0.6 GeV

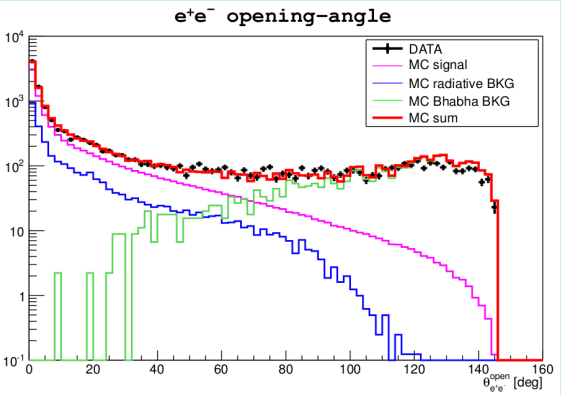








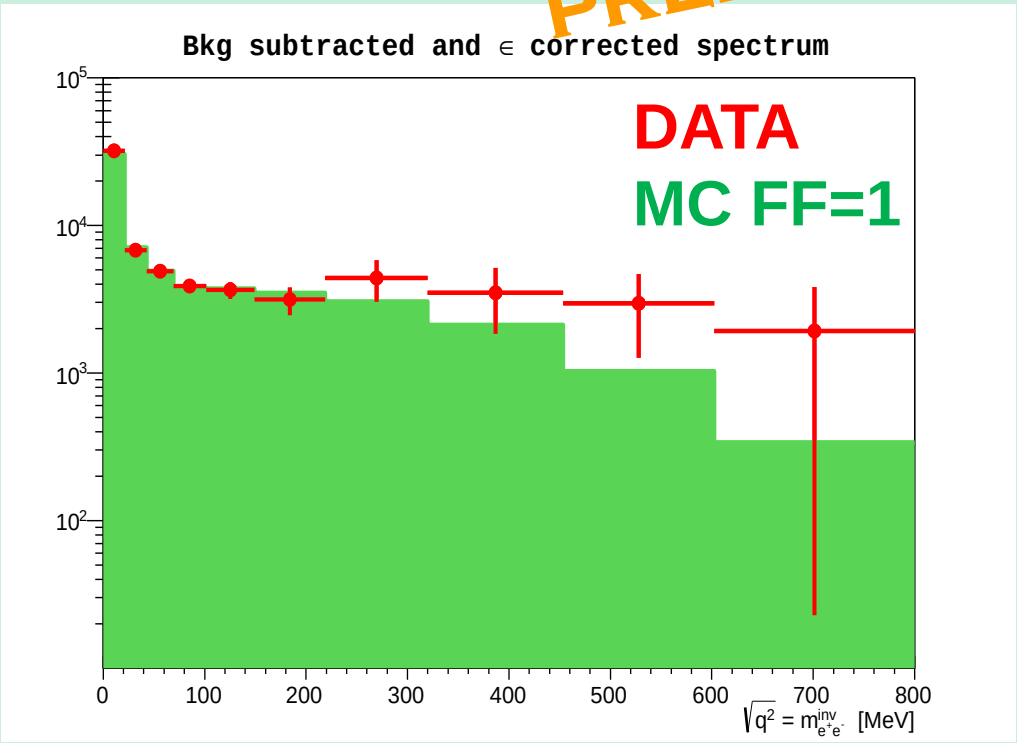


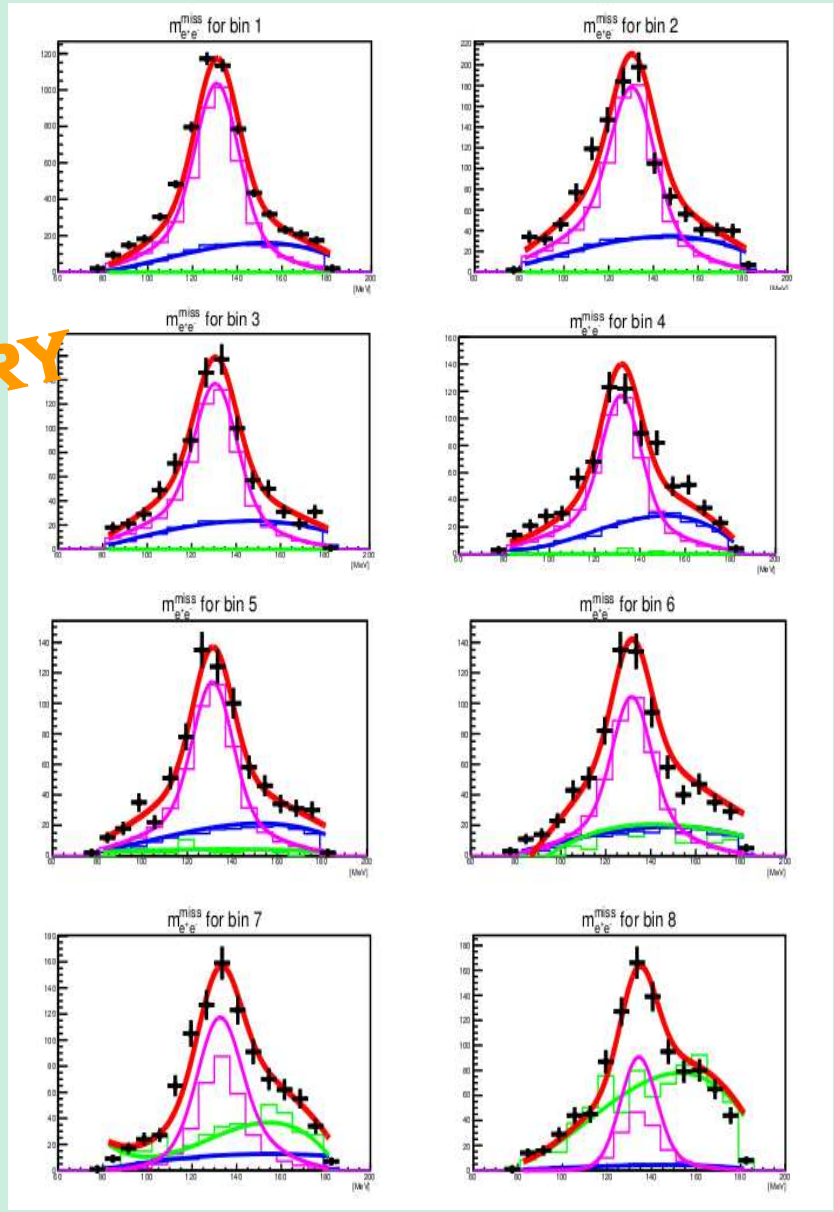


$\phi \to \pi^0 e^+ e^-$: transition form factor

- Bckg subtraction still in progress, evaluated for each M_{ee} value with a fit to the e^+e^- missing mass
- Fit systematics currently limited by Bhabha MC statistics

PRELIMINARY





The $\eta \to \pi^+\pi^-\pi^0$ decay

Isospin violating decay, sensitive to light quark mass difference.

From ChPT:

$$\Gamma = \left(\frac{Q_D}{Q}\right)^4 \overline{\Gamma} \qquad \text{with} \qquad Q^2 \equiv \frac{m_s^2 - \hat{m}^2}{m_d^2 - m_u^2}$$

$$Q_D = 24.2$$

$\overline{\Gamma}$: decay width evaluated in the Dashen limit

A very accurate determination of Q can be obtained:

1. **Measure Γ** 2. **Test $\eta \to \pi\pi\pi$ dynamics** 3. **Calculate $\overline{\Gamma}$**

Largest statistics measurement: KLOE08 (450 pb^{-1}, 1.34×10^6 events)

Dalitz plot density parametrized as polynomial expansion around X=Y=0:

$$|A(X,Y)^2| \propto 1 + aY + bY^2 + cX + dX^2 + eXY + fY^3 \ldots$$

$$X = \frac{\sqrt{3}}{Q}(T_{\pi^+} - T_{\pi^-}), \qquad Y = \frac{3T_{\pi^0}}{Q} - 1$$

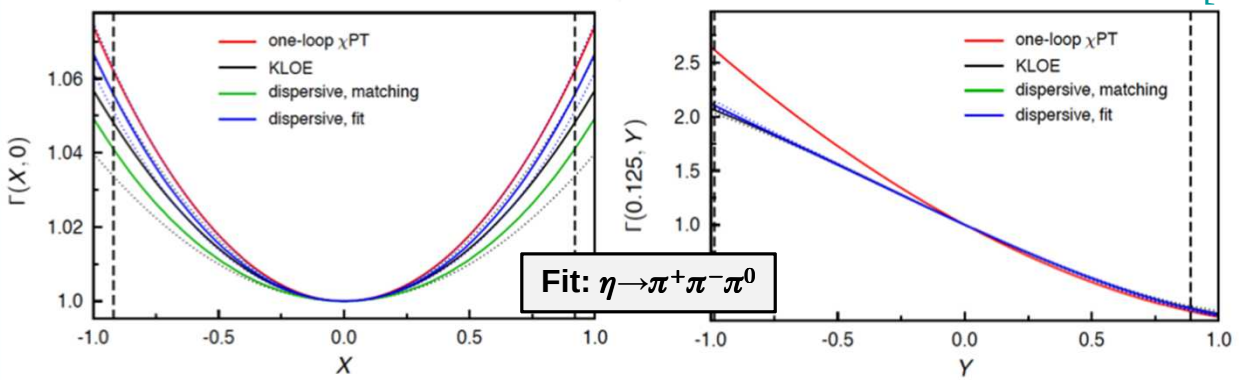
a	$-1.090 \pm 0.005\ ^{+0.008}_{-0.019}$
b	$0.124 \pm 0.006 \pm 0.010$
c	$0.002 \pm 0.003 \pm 0.001$
d	$0.057 \pm 0.006\ ^{+0.007}_{-0.016}$
e	$-0.006 \pm 0.007\ ^{+0.005}_{-0.003}$
f	$0.14 \pm 0.01 \pm 0.02$
$P(\chi^2)$	73%

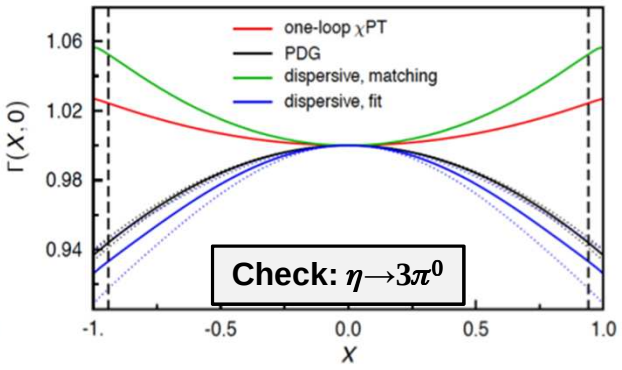
JHEP05 (2008) 006

Q mass ratio constraints from KLOE data

Dispersive analyses of $\eta \to 3\pi$ based on fits to KLOE measurement:

[Colangelo et al. PoS(EPS-HEP2011) 304]





$$Q = 21.3 \pm 0.6$$

using $\hat{m}$ and m_S from lattice QCD:

$$m_u = (2.02 \pm 0.14) MeV$$
$$m_d = (4.91 \pm 0.11) MeV$$

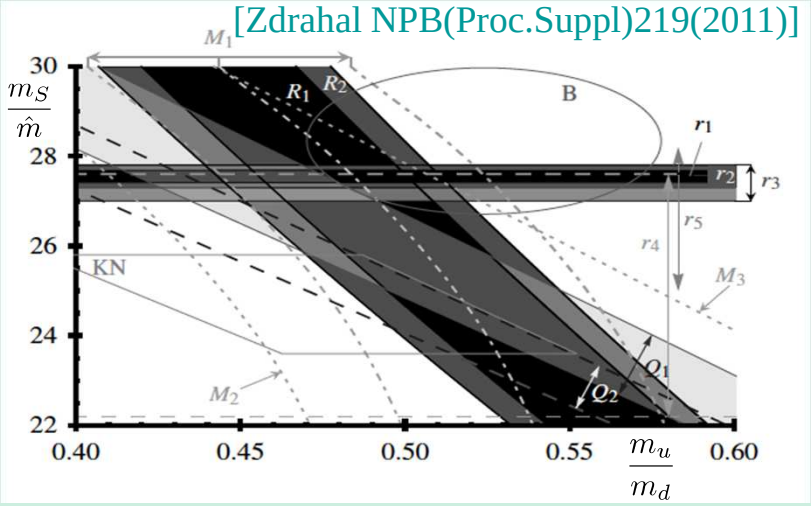
$$R = \frac{m_S - \hat{m}}{m_d - m_u} = 37.7 \pm 3.3$$

[Kampf et al., PRD84(2011)114015]

using $\hat{m}$ and m_S from lattice QCD:

$$m_u = (2.23 \pm 0.14) MeV$$
$$m_d = (4.63 \pm 0.14) MeV$$

[Zdrahal NPB(Proc.Suppl)219(2011)]



$\eta \to \pi^+\pi^-\pi^0$ with full KLOE data set

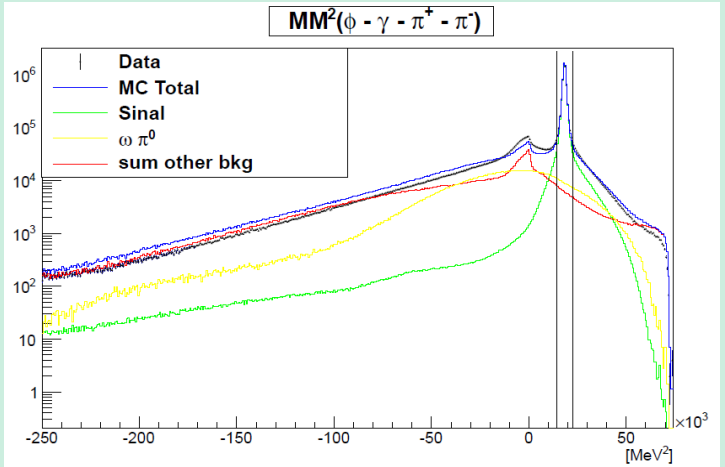
New analysis of full KLOE data set in progress:

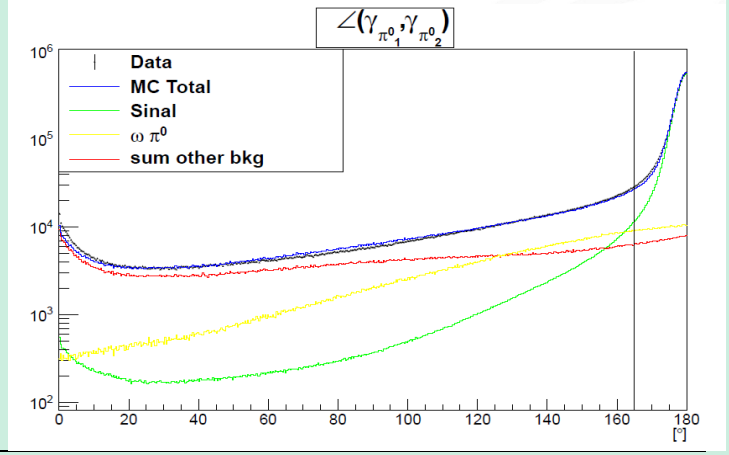
- Larger data set (1.7 fb^{-1}, ~ 4 times KLOE08)
- New analysis scheme
- Improved MC simulation

> Reduce systematics

Analysis steps:

- >= 3 prompt photons
- Most energetic photon (E>250 MeV) assumed primary
- 2 tracks selected by PCA method, assumed pions
- Primary photon energy from 2-body kinematics
- η from ϕ decay, π^0 from η decay
- Photons from π^0 decay selected by opening angle
- Bhabha events rejected with PID + kinematics
- $|MM(\phi - \gamma_{rad} - \pi^+ - \pi^-) - m(\pi^0)| < 15$ MeV
- $\gamma\gamma$ opening angle in the π^0 rest frame > 165°





- **Background scaling factors from fit**
- **Signal efficiency 37.6%**
- **Residual background contamination 0.96%**

$\eta \to \pi^+\pi^-\pi^0$ with full KLOE data set

Fit to the data-bckg ditribution with:

$$N_{theory} = \int N\left(1 + aY + bY^2 + cX + dX^2 + eXY + fY^3 + gX^2Y\right) dPh(X,Y)$$

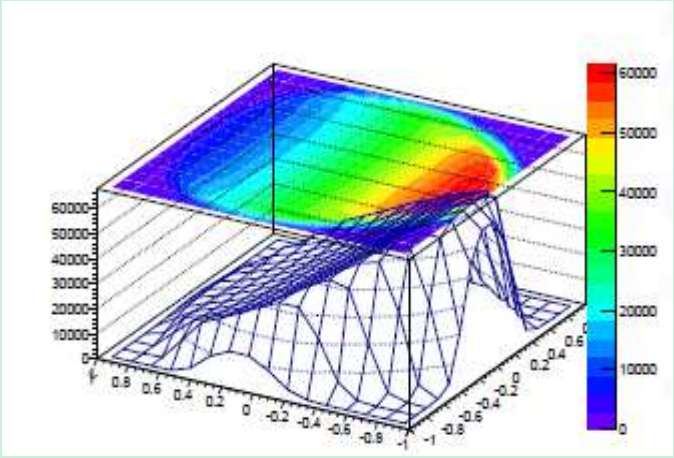
folded with smearing matrix and analysis efficiency

PRELIMINARY

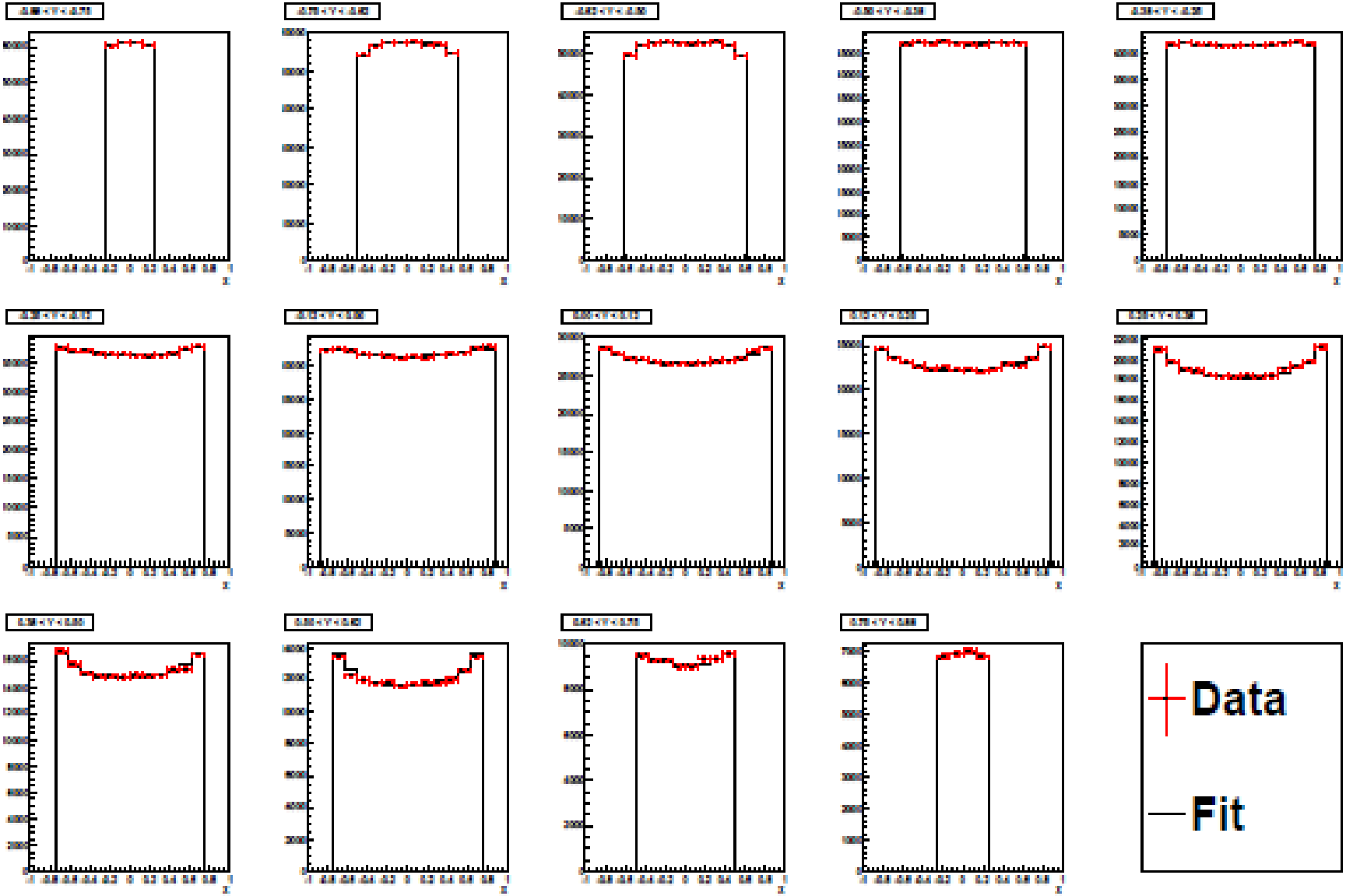
	$-a$	b	d	f
KLOE08	$1.090(5)(^{+8}_{-19})$	0.124(6)(10)	$0.057(6)(^{+7}_{-16})$	0.14(1)(2)
KLOE new	1.104(3)	0.144(3)	0.073(3)	0.155(6)

$\chi^2/N_{dof} = 1.15$

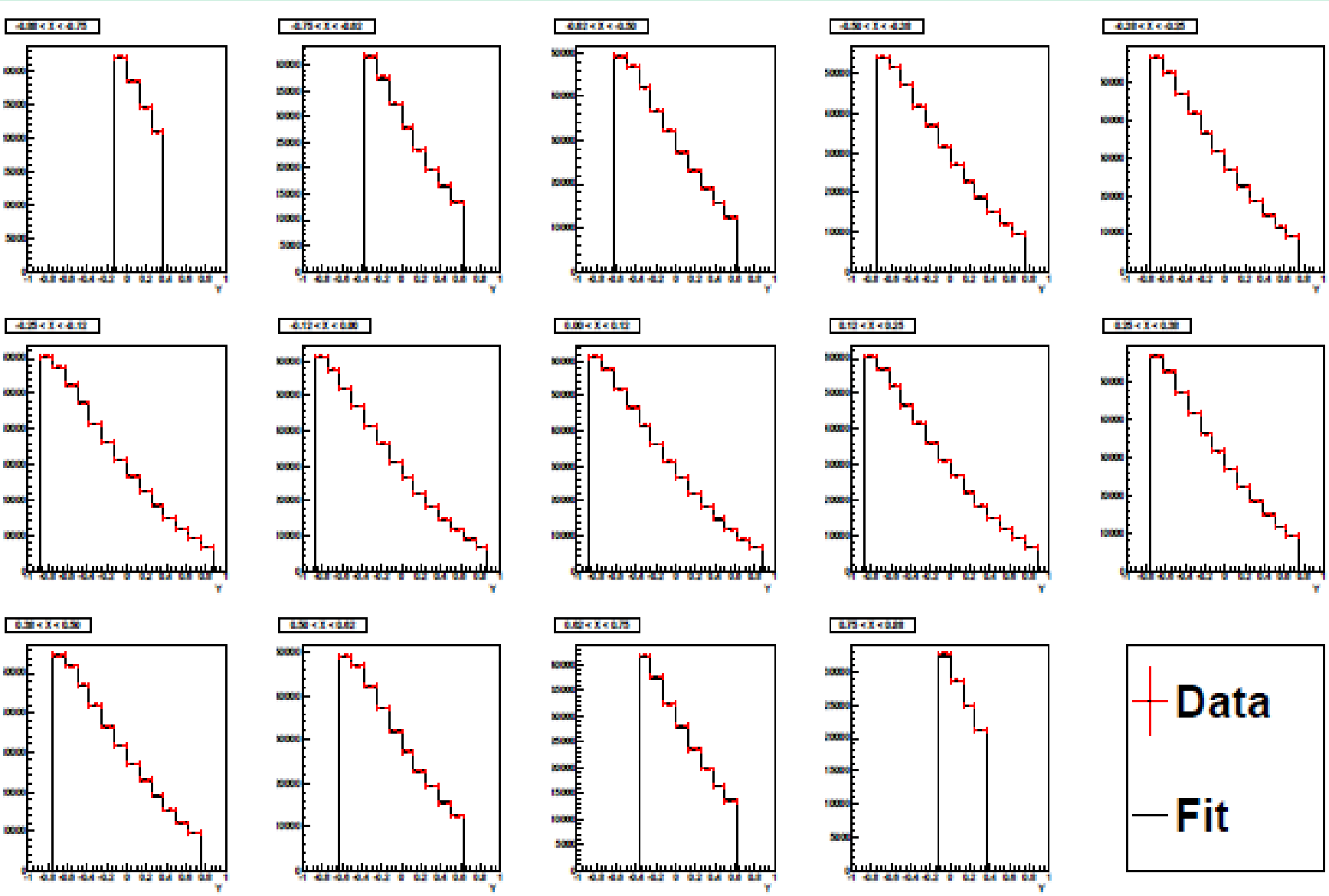
- In agreement with previous KLOE result
- c and e consistent with 0 (C-invariance condition) when used as free fit parameters
- Evaluation of systematics in progress



$\eta \to \pi^+\pi^-\pi^0$: Dalitz plot slices in Y



$\eta \to \pi^+\pi^-\pi^0$: Dalitz plot slices in X



Conclusions

Still harvesting results from KLOE data:

- Dark forces
  - The analysis of $e^+e^- \to \mu^+\mu^-\gamma$ provides the best limit for the U boson search for $520 < M_U < 980$ MeV
  - For the Higgs-strahlung channel, U.L. for $\alpha_D \varepsilon^2 \sim 10^{-8} - 10^{-9}$
- Transition form factor
  - $\phi \to \eta e^+e^-$ in agreement with VMD predictions
  - Analysis scheme finalized for $\phi \to \pi^0 e^+e^-$, fit in progress
- Preliminary results of the Dalitz plot density for $\eta \to \pi^+\pi^-\pi^0$ in agreement with our previous result, with better stat. errors