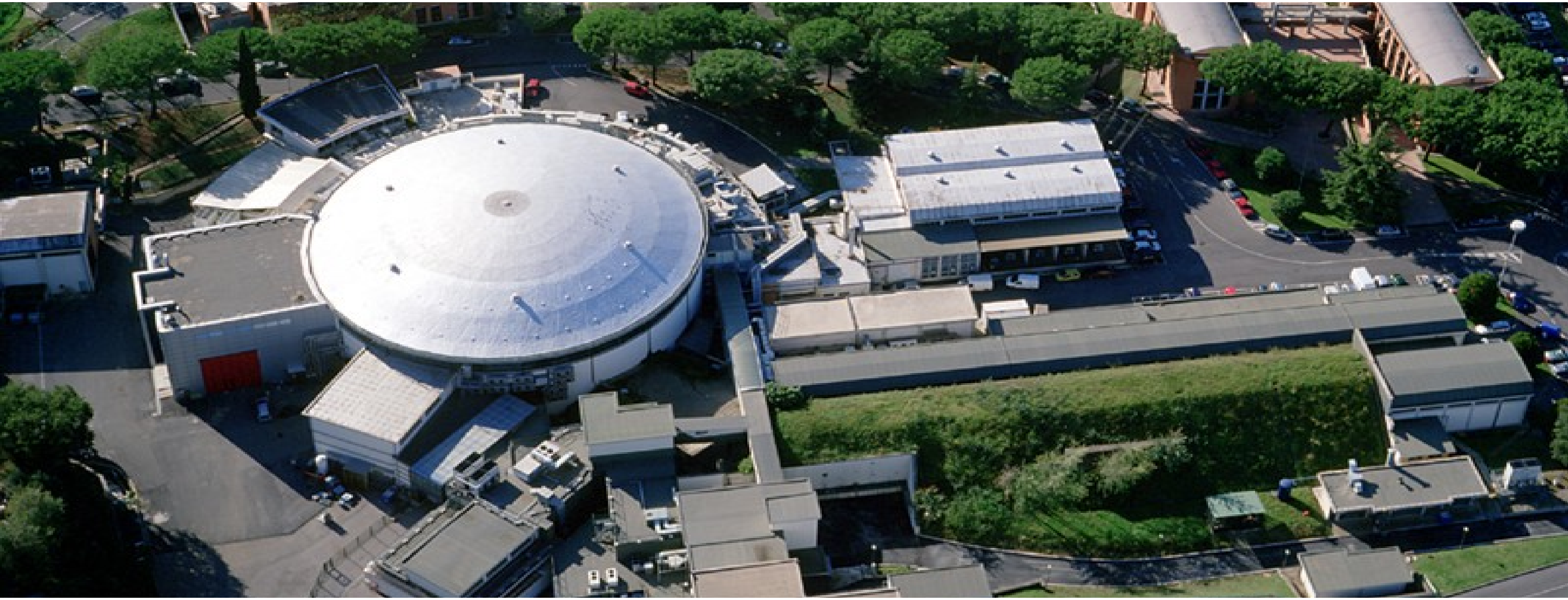


Transition Form Factors (experiment overview - 1)

MATTEO MASCOLO
(on behalf of the KLOE-2 coll.)

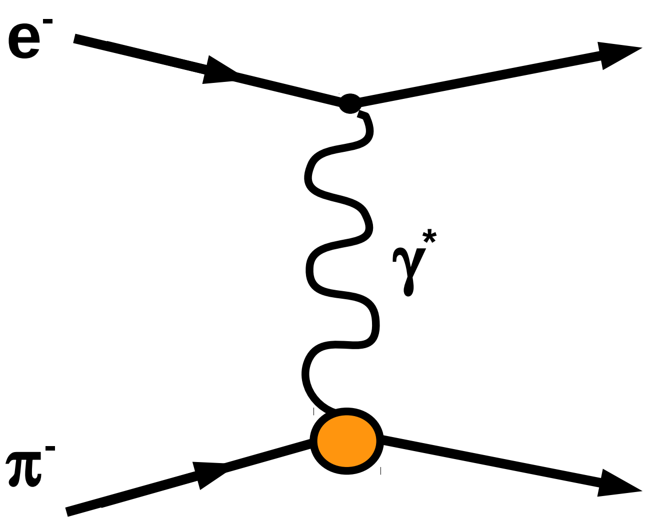
MesonNet 2014 - September 28th – October 1st, 2014 - LNF

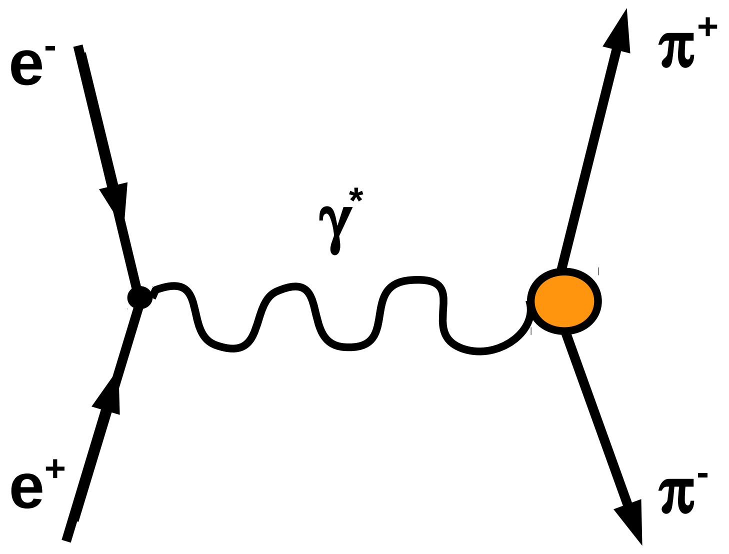
Talk Outline

- ✔ **Introduction: Transition Form Factors**
- ✔ **Physics motivations**
- ✔ **KLOE results ($\phi \rightarrow \eta e^+e^-$)**
- ✔ **KLOE results ($\phi \rightarrow \pi^0 e^+e^-$)**

Form Factors

QED → the electromagnetic interaction between particles is given by the exchange of a virtual photon (γ^*) transferring the squared 4-momentum q^2





Scattering → "space-like" $q^2 < 0$

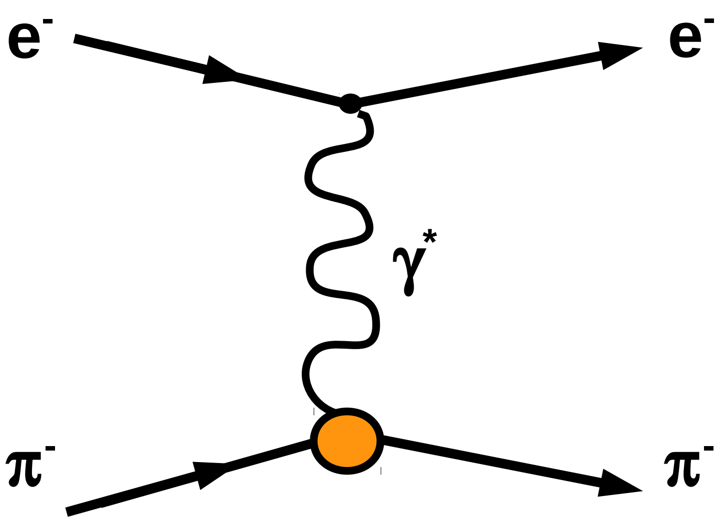
$$q^2 = (p_{e-}^{\,i} - p_{e-}^{\,f})^2 = (\Delta E_{e-})^2 - (\Delta \mathbf{p}_{e-})^2 = -(\Delta \mathbf{p}_{e-})^2 < 0$$

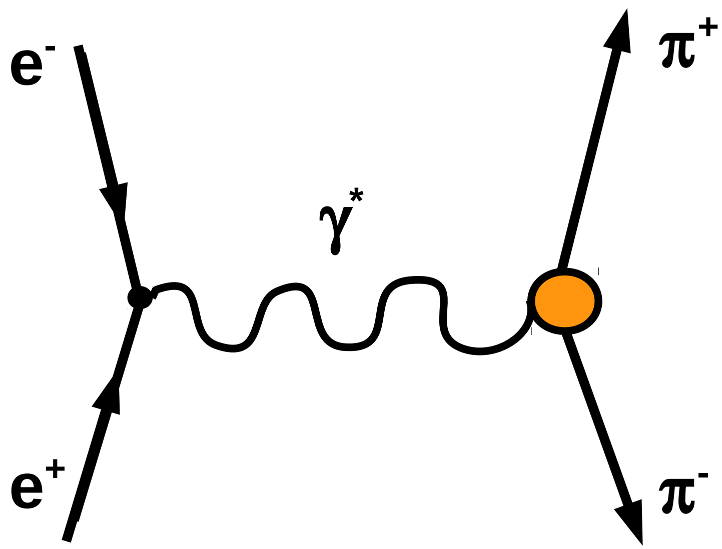
Annihilation → "time-like" $q^2 > 0$

$$q^2 = (p_{e+} + p_{e-})^2 = (2E)^2 - (\mathbf{p} - \mathbf{p})^2 = (2E)^2 > 0$$

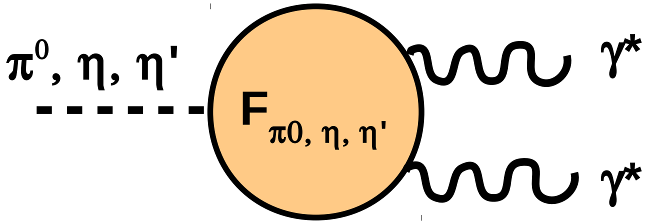
Form Factors

QED → the electromagnetic interaction between particles is given by the exchange of a virtual photon (γ^*) transferring the squared 4-momentum q^2



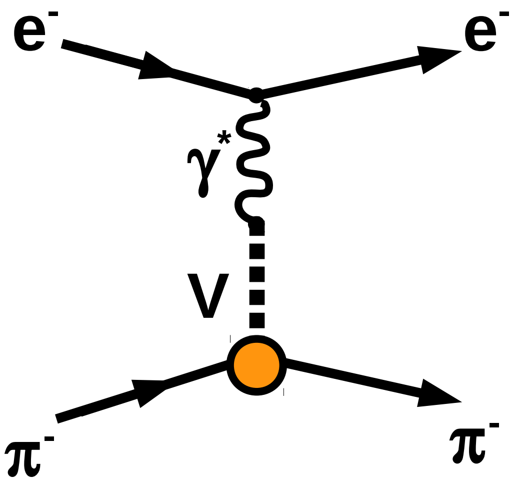


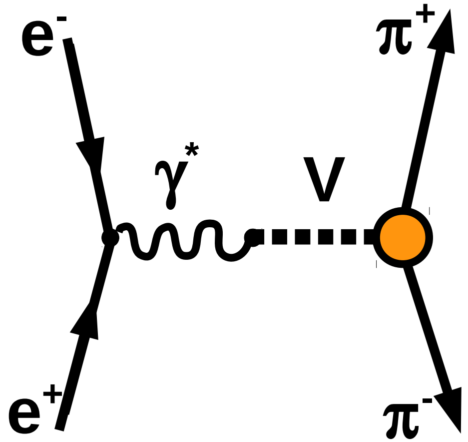
$$\boxed{\frac{d\sigma}{dq^2} = \left[F(q^2)\right]^2 \cdot \left[\frac{d\sigma}{dq^2}\right]_{pointlike}}$$

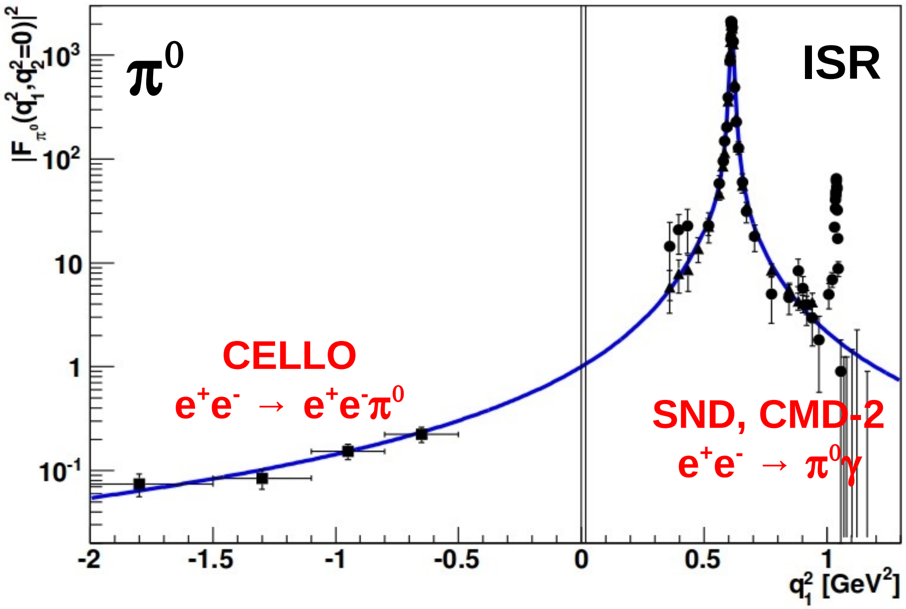


Vector Meson Dominance

- The virtual photon interacts with the hadron through a n intermediate vector meson state with $J^P = 1^-$ (i.e. ρ, ω, ϕ)
- The mechanism is more pronounced in the annihilation process, where q^2 approaches the resonance mass → enhancement of the FF → the V meson decays as a real particle







CMD-2 [Phys. Lett. B 605, 26 (2005)]
SND [Phys. Lett. B 504, 275 (2001)]
CELLO [Z. Phys. C 49, 401 (1991)]

New Meas. → KLOE-2, BES-III

Vector Meson Dominance

- ✔ The virtual photon interacts with the hadron through a n intermediate vector meson state with $J^P = 1^-$ (i.e. ρ, ω, ϕ)
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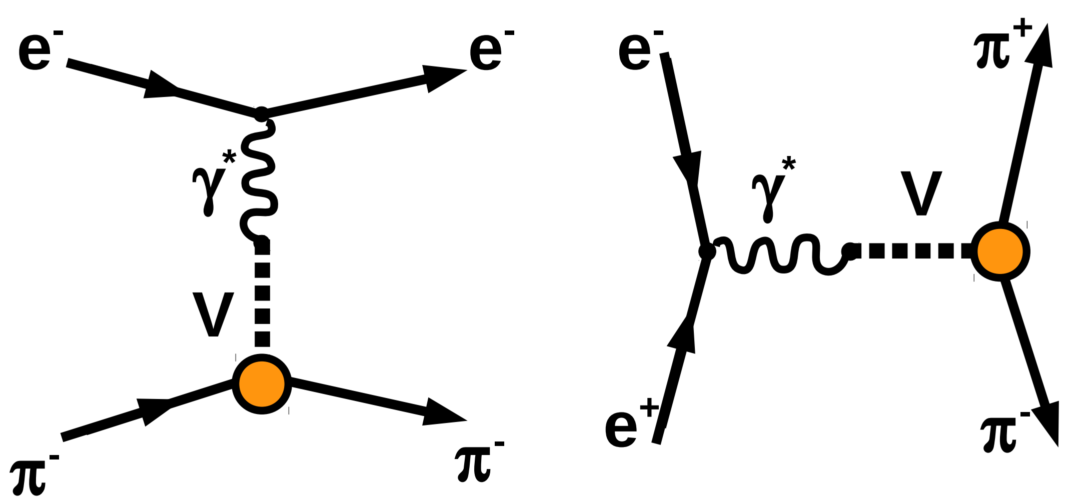
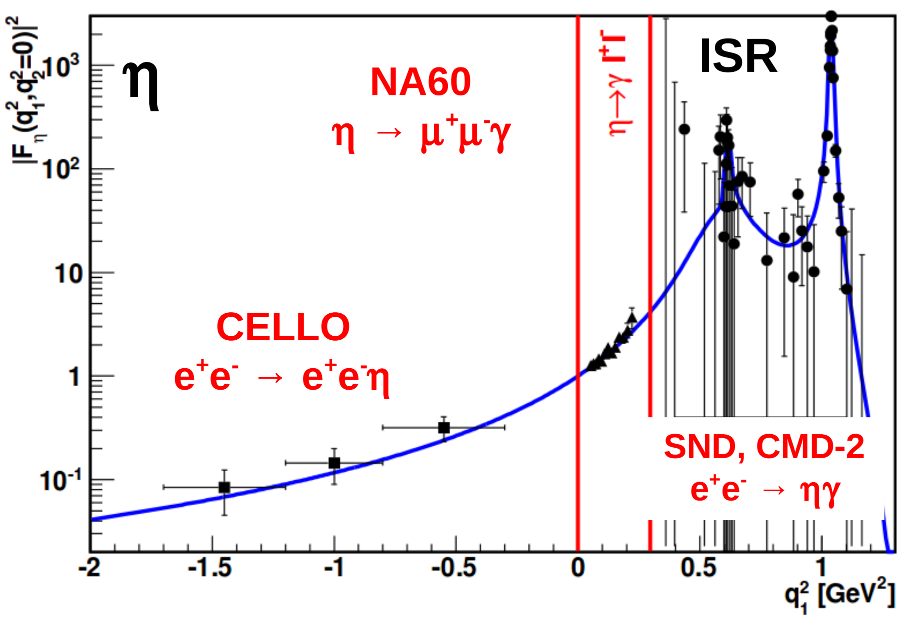




CMD-2 [Phys. Lett. B 605, 26 (2005)]
SND [Phys. Lett. B 504, 275 (2001)]
NA62 [Phys. Lett. B 677, 260 (2009)]

New Meas. → GlueX

Space-like FF: physics motivation (1/3)

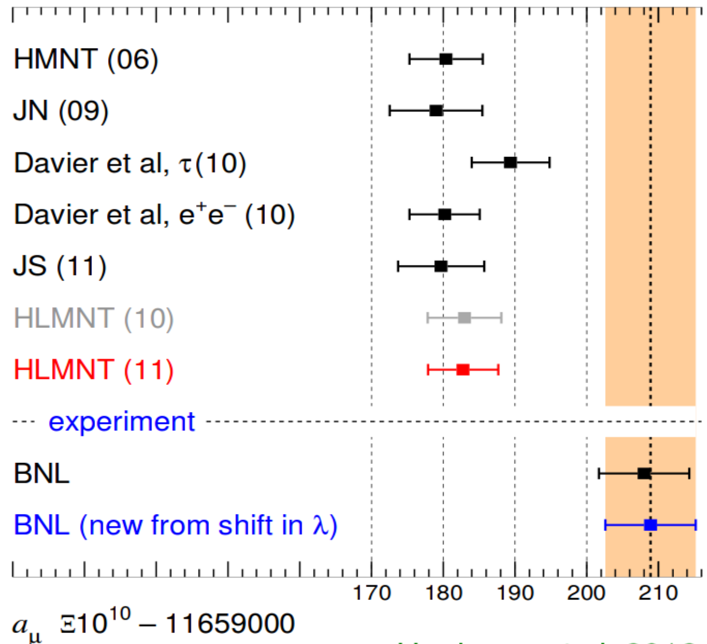
- ✔ **FF is a field of hadronic physics with high precision THEORY and EXPERIMENTS**
- ✔ **The SM prediction of this "deviation", the anomalous magnetic moment a_μ, defined as $a_\mu = (g\text{-}2)/2$, is calculated with high accuracy and measured with extreme precision!**

BUT ...

$$a_\mu^{exp} = 116\,592\,089(54)_{\rm stat}(33)_{\rm syst} \times 10^{-11}$$

$$a_\mu^{SM} = 116\,591\,801(49) \times 10^{-11}$$

$$\boxed{\Delta a_\mu = a_\mu^{exp} - a_\mu^{SM} = 287(80)}$$ **3.6 σ**



Hagiwara et al. 2012

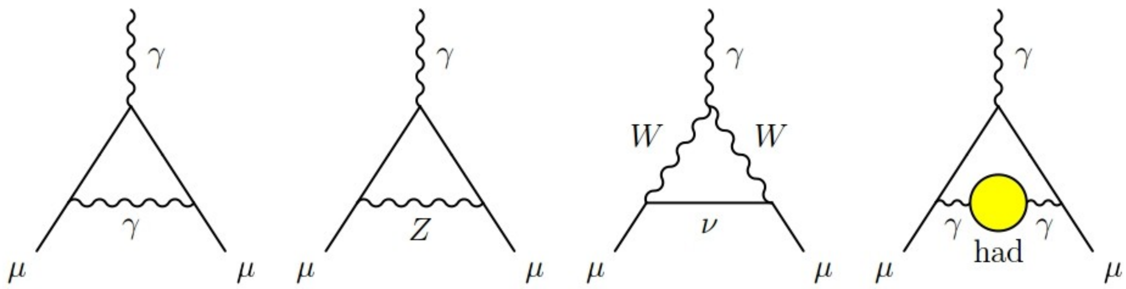
- ✔ **3.6 σ DISCREPANCY BETWEEN THEORY AND EXP.**
- ✔ **New g-2 experiment towards 0.14 ppm (JPARC 0.1 ppm) → Theory improvement !?!**

Space-like FF: physics motivation (2/3)

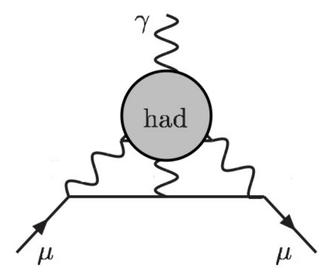
✔ **The SM calculation can be divided into different contributions:**

$$a_\mu^{SM} = 116\,591\,801(49) \times 10^{-11}$$

$$a_\mu^{SM} = a_\mu^{QED} + a_\mu^{EW} + a_\mu^{HAD}$$



✔ **The "Light-by-Light" contribution to the hadronic term is the one which is known with the higher relative uncertainty**



$$a_\mu^{QED} = 116\,584\,718.09(0.15) \times 10^{-11}$$

$$a_\mu^{EW} = 153(1)(1) \times 10^{-11}$$

$$a_\mu^{LO} = 6\,923(42)(3) \times 10^{-11}$$

$$a_\mu^{NLO} = 7(26) \times 10^{-11}$$

$$a_\mu^{HOVP} = -98.4(0.7)$$

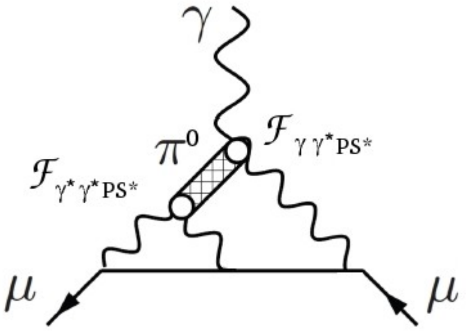
$$a_\mu^{LbL} = 105(26)$$

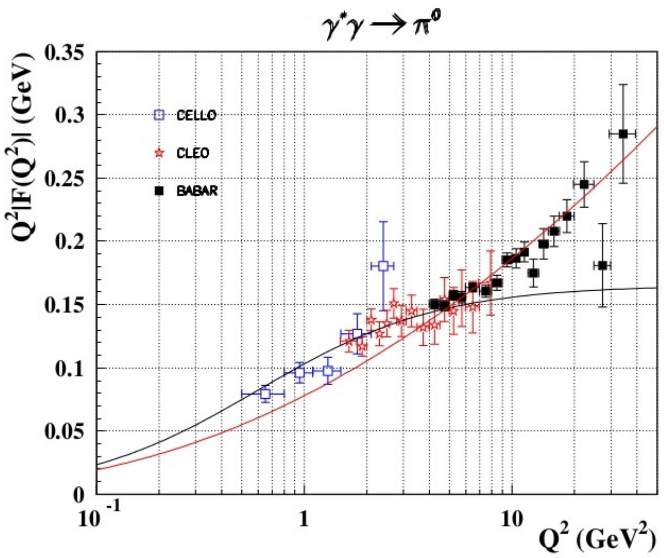
$$a_\mu^{LbL,PS} = 99(16)$$

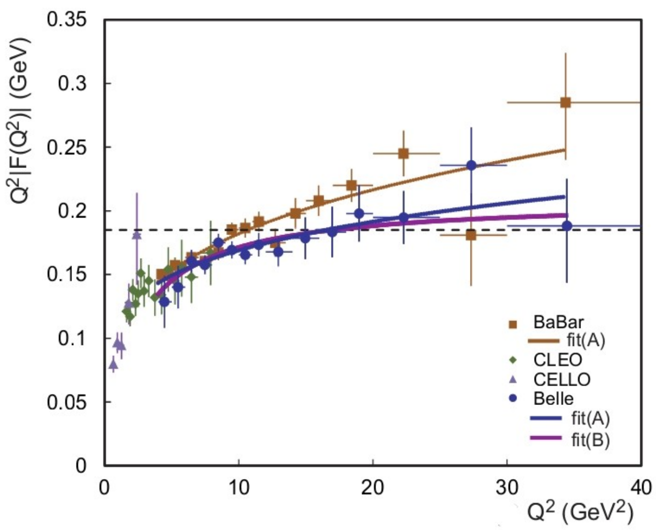
$$\boxed{a_\mu^{LbL,\pi^0} = 72(12)}$$

Space-like FF: physics motivation (3/3)

- **The calculation of the LbL term (of g-2) relies on phenomenological theories, who constrain F(PS*, γ*, γ*) and F(PS*, γ*, γ) with experimental information → i.e. *on-shell* π^0 FFs!**







CELLO → DESY
[Beherend et al., Z. Phys C49 (1991) 401]

CLEO → CESR
[Gronberg et al., Phys. Rev. D57 (1998) 33]

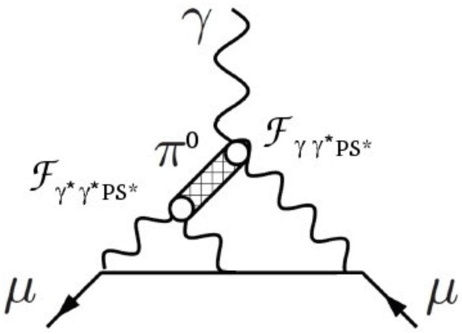
BaBar → SLAC
[Aubert et al., Phys. Rev. D80 (2009) 052002]

Belle → KEK
[Uehara et al., Phys. Rev. D86 (2012) 092007]

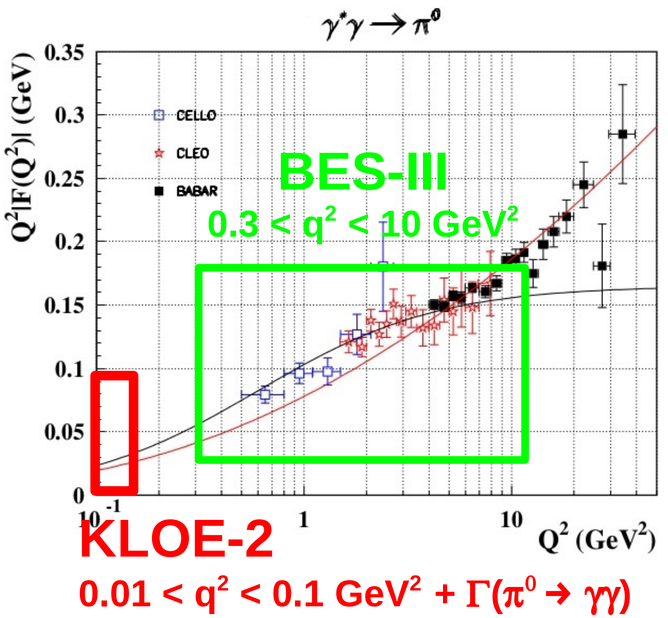
- **γγ processes give access to the single off-shell FF → important to provide new measurements (no data at low q^2) to reduce the model dependence of the LbL (KLOE-2 [EPJC C72 (2012) 1917])**

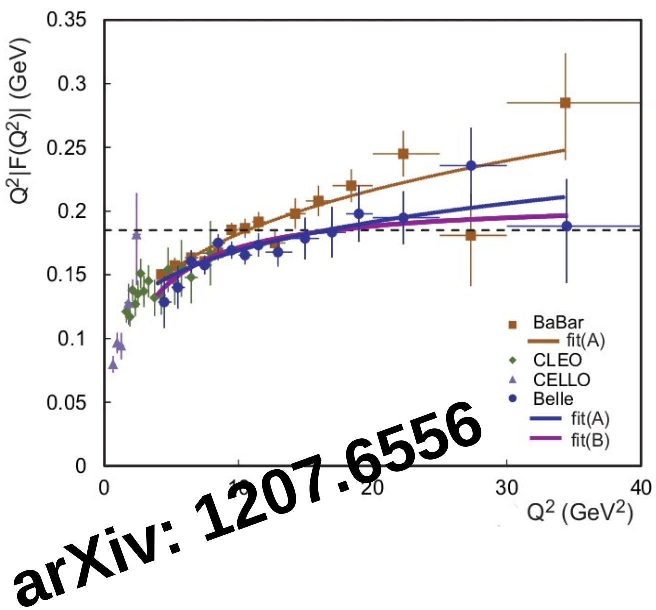
- **The $\Gamma(\pi^0 \to \gamma\gamma)$ decay width is an important ingredient for the FF normalization ($|F(0,0)|^2$) → best measurement up to date is from PrimEx coll. : 2.8%. Strong test of Chiral theory (~ 1%)**

Space-like FF: physics motivation (3/3)



- The calculation of the LbL term (of g-2) relies on phenomenological theories, who constrain F(PS*, γ*, γ*) and F(PS*, γ*, γ) with experimental information → i.e. *on-shell* π^0 TFFs!





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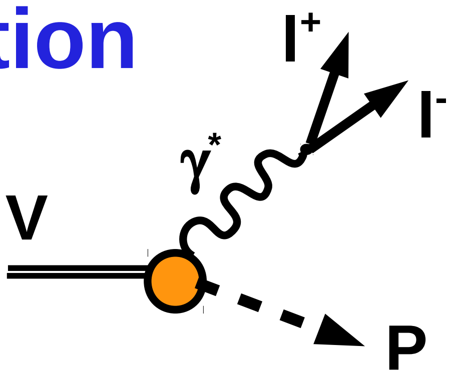
- The $\Gamma(\pi^0 \to \gamma\gamma)$ decay width is an important ingredient for the FF normalization ($|F(0,0)|^2$) → best measurement up to date is from PrimEx coll. : 2.8%. Strong test of Chiral theory (~ 1%)

Time-like (T)FF: physics motivation



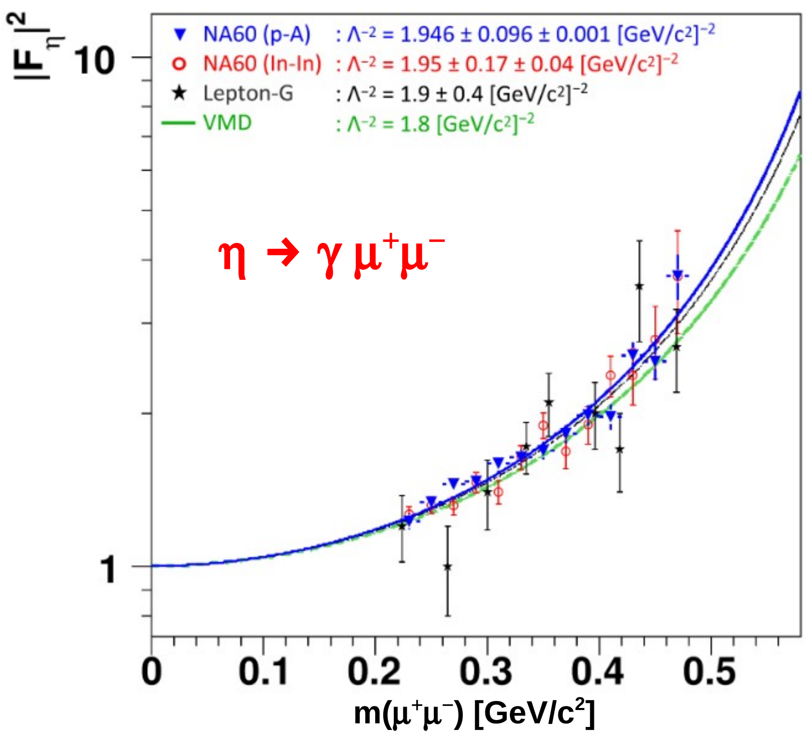
- ✔ **Test the modelings of the TFF: the naïve VMD approach is satisfactory in the description of $\eta \to \gamma \mu^+\mu^-$ but dramatically fails in $\omega \to \pi^0 \mu^+\mu^-$**

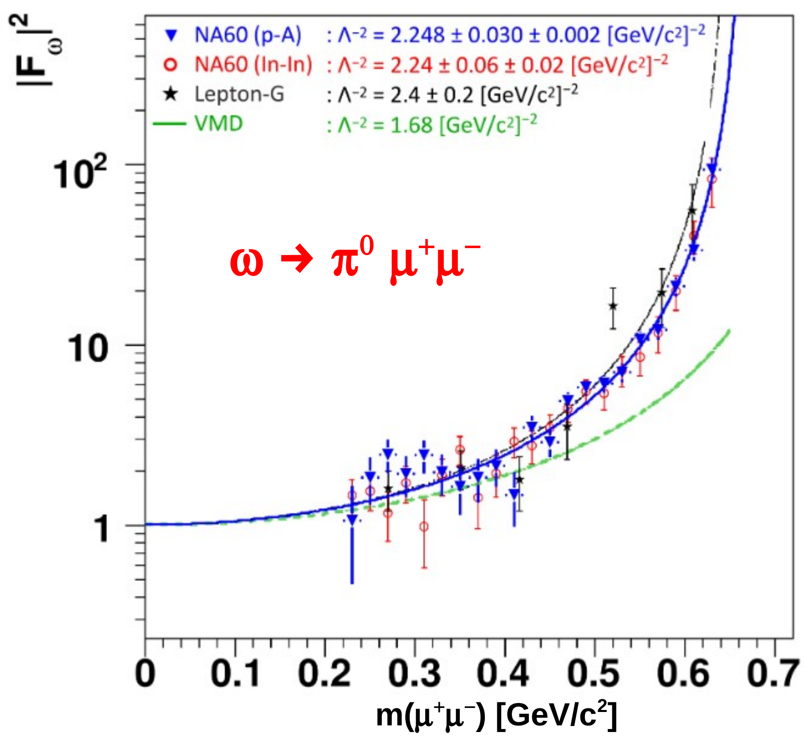
Data

NA60 [In-In] [Phys. Lett. B 677 260-266 (2009)]
NA60 [p-A] [Nucl. Phys. A 855 189-196 (2011)]
Lepton-G [Phys. Lett. B 102 296-298 (1981)]

Theory

Terschlusen and Leupold [Phys. Lett. B 691 191 (2009)]
Ivashyn S. [Prob. Atom. Sci. Tech. 2012N1 179 (2012)]
Schneider, Kubis, Nieking [Phys. Rev. D86 054013 (2012)]





TFF from conversion decays: V → P γ^*

SND @ VEPP-2M
[Phys. Lett. B 504 275-281 (2001)]

$b_{exp} = (3.8 \pm 1.8)\ \mathrm{GeV}^{-2}$

$b_{VMD} \approx 1.0\ \mathrm{GeV}^{-2}$

- **$F_{\phi\eta\gamma^*}$ slope is needed: $b_{\phi\eta} = \Lambda^{-2} = dF(q^2)/dq^2 |_{q^2=0}$**

  $F(q^2,0) \approx 1 + q^2/\Lambda^2$

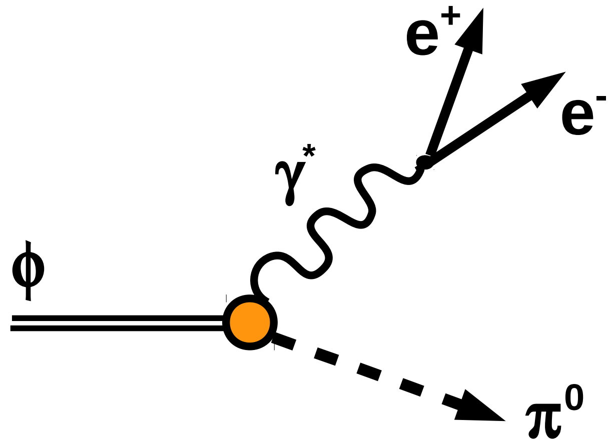
- **NO DATA available for $F_{\phi\pi0\gamma^*}$ TFF (an enhancement due to ρ resonance is expected)**
- **TFFs also useful for $(g\text{-}2)_\mu$ → experimental constraints to the hadronic LbL contribution**
- **Improve the measurement of the B.R. ($\phi \to \pi^0 e^+ e^-$ is a OZI suppressed process)**

BR decay	SND	CMD-2	PDG av.	Tot err.
$\phi \to \eta e^+ e^-$ (10^{-4})	(1.19 ± 0.19 ± 0.12)	(1.14 ± 0.10 ± 0.06)	**(1.15 ± 0.10)**	~ 8.7 %
$\phi \to \pi^0 e^+ e^-$ (10^{-5})	(1.01 ± 0.28 ± 0.29)	(1.22 ± 0.34 ± 0.21)	**(1.12 ± 0.28)**	~ 25 %

[J. Beringer et al. Phys. Rev. D 86 (2012)]

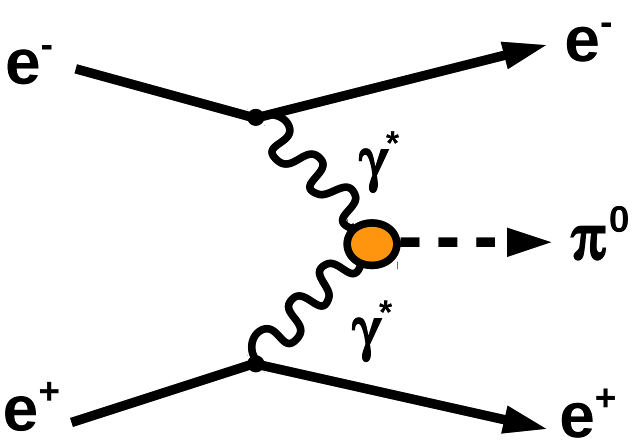
The KLOE/KLOE-2 experiments (π^0 TFF)

Measurement of the π^0 FF in two different kinematical regions of q^2



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

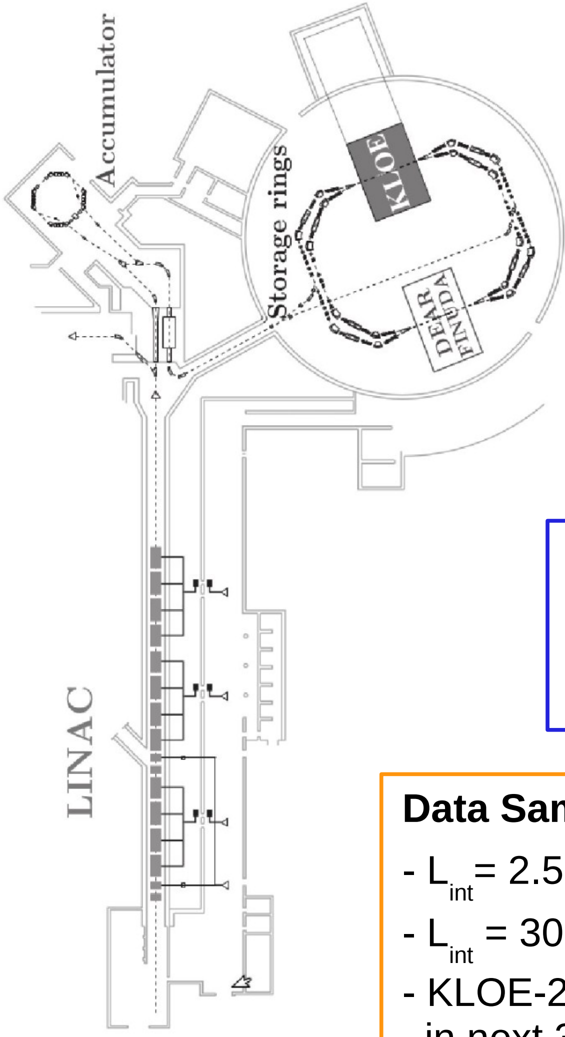
- ✔ $q^2 > 0 \rightarrow F_{\phi\,\pi^0\,\gamma*}(q^2)$
- ✔ **Based on the existent data sample (L_{int} = 1.7 fb^{-1} from 2004/2005 data taking)**



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

- ✔ $q^2 < 0 \rightarrow F_{\pi^0\,\gamma*\,\gamma*}(q_1^2, q_2^2)$
- ✔ **To be measured with the forthcoming KLOE-2 data taking campaign**

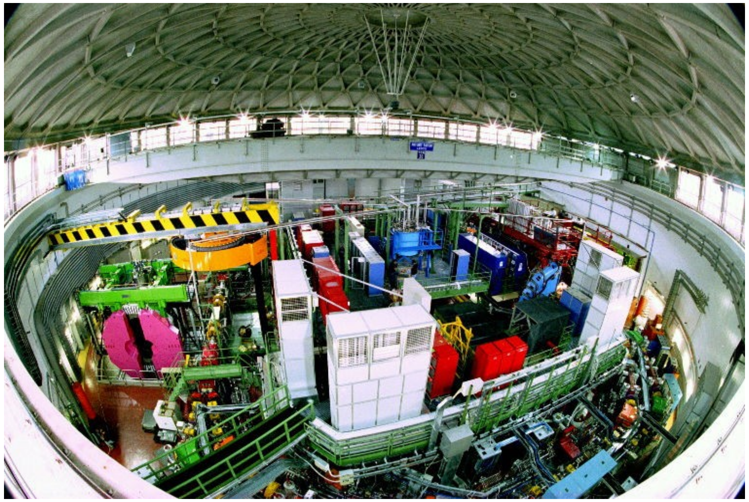
The DAΦNE e^+e^- collider @LNF



Double Anular Φ Factory for Nice Experiments

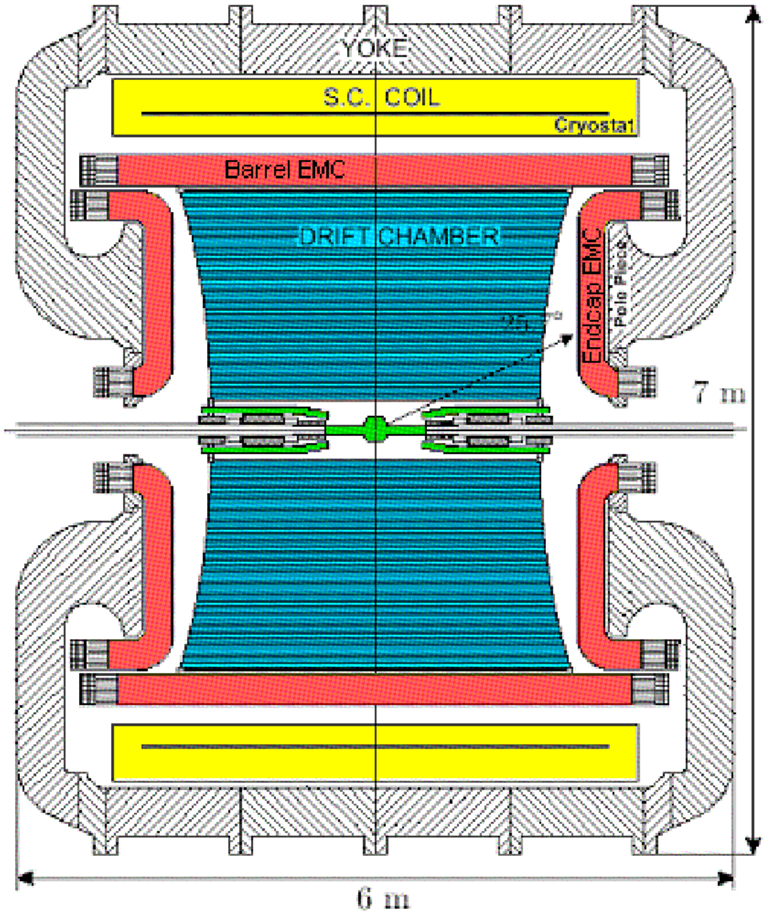
Main features:
- e^+e^- collider @ $\sqrt{s} = 1.02$ GeV
- 97m separate rings for e^+e^-
- Up to 120+120 bunches
- Max collision freq. → 356 MHz
- $T_{bunch} = 2.7$ ns

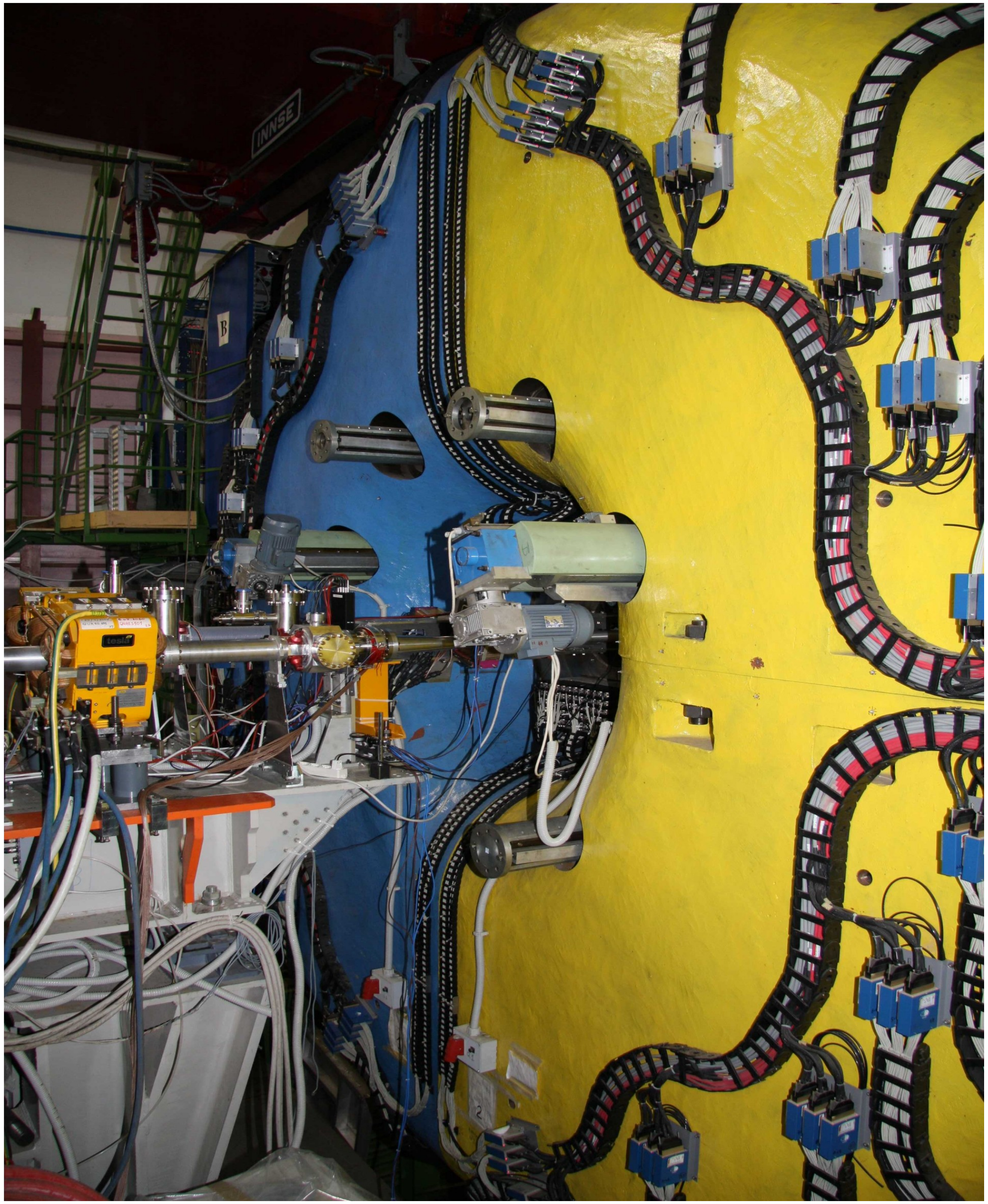
Best performances:
- $L_{peak} = 1.4 \times 10^{32}$ cm^{-2} s^{-1}
- $L_{int} = 8$ pb^{-1}/day



Data Sample:
- $L_{int} = 2.5$ fb^{-1} (until march 2006)
- $L_{int} = 300$ pb^{-1} (collected off the Φ peak)
- KLOE-2 upgrade completed (expected 5 fb^{-1} in next 3 years [Eur. Phys.J. C 68 (2010), 619])

The KLOE detector





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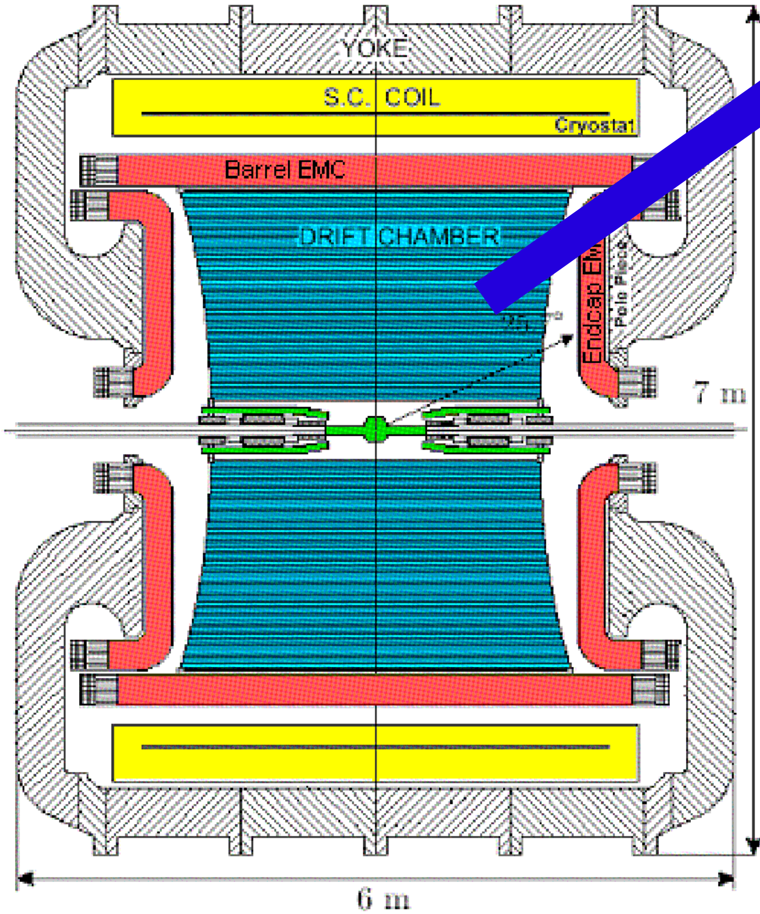
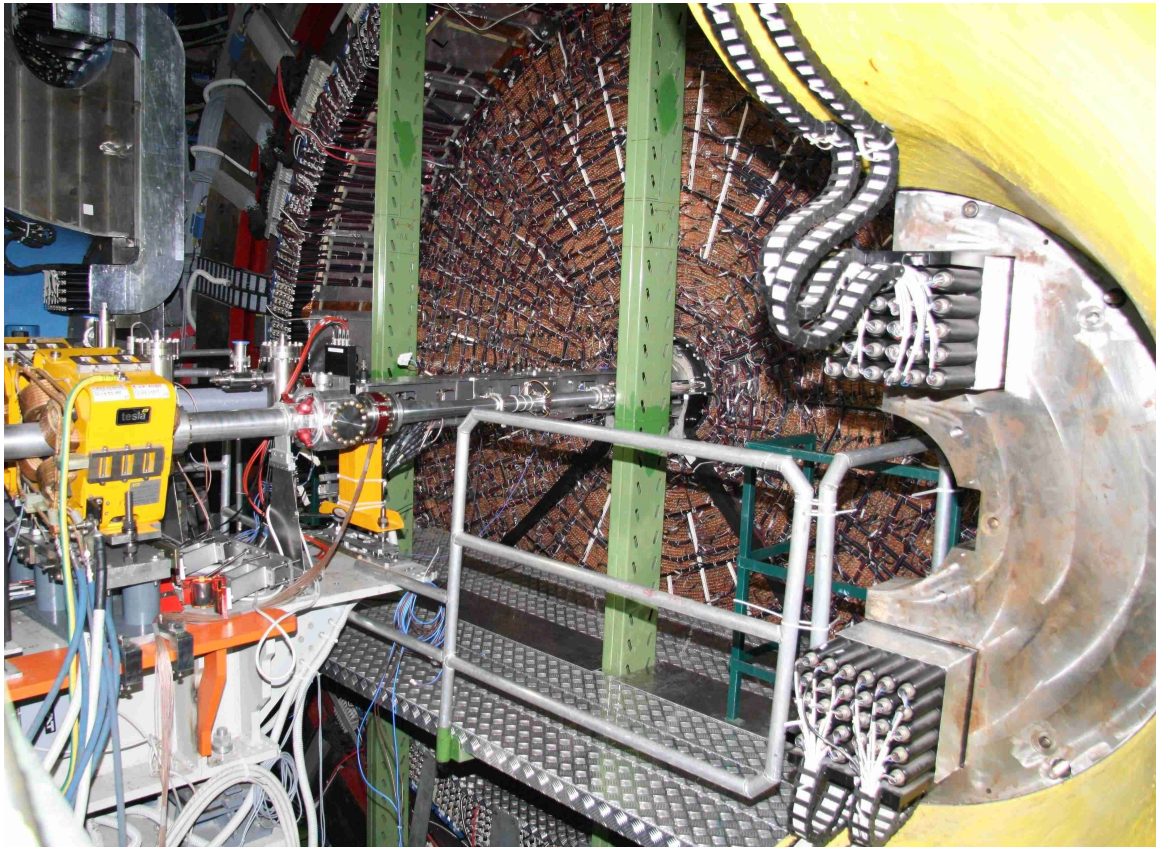
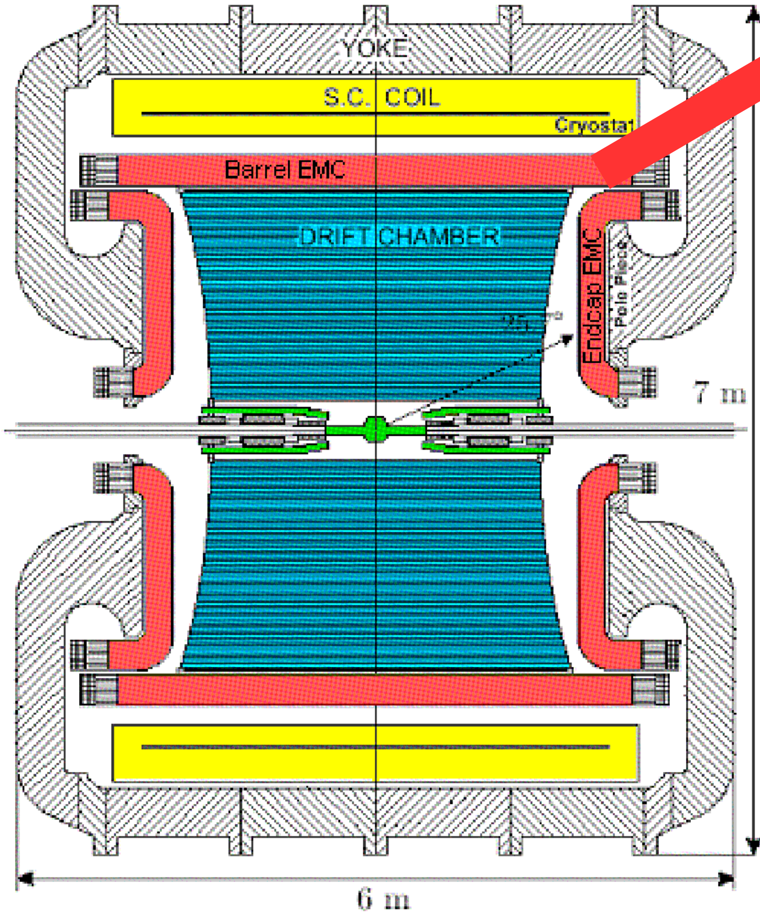


Drift chamber

- Gas mixture (90% He + 10% C_4H_{10})
- $\delta p_t/p_t < 0.4\%$ ($\theta > 45°$)
- $\sigma_{xy} \sim 150\ \mu m$ $\sigma_z \sim 2$ mm

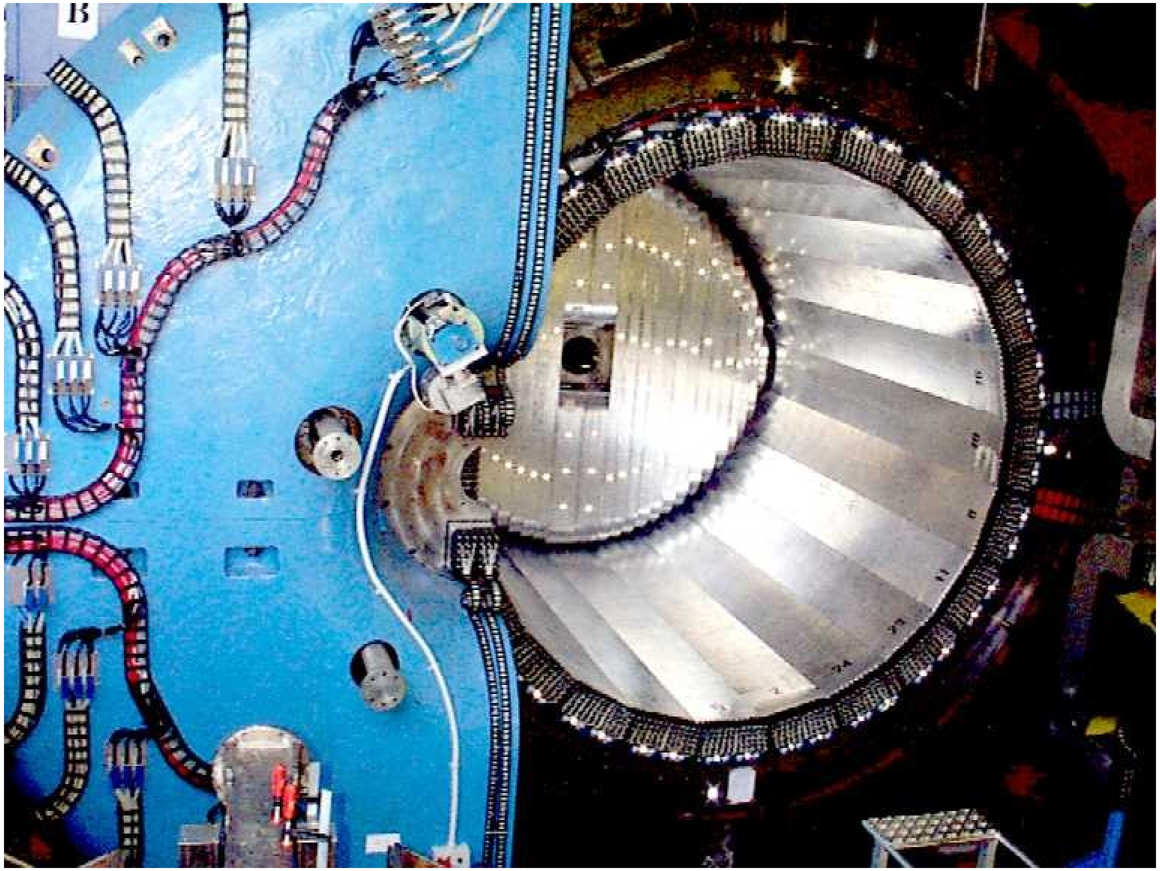


The KLOE detector

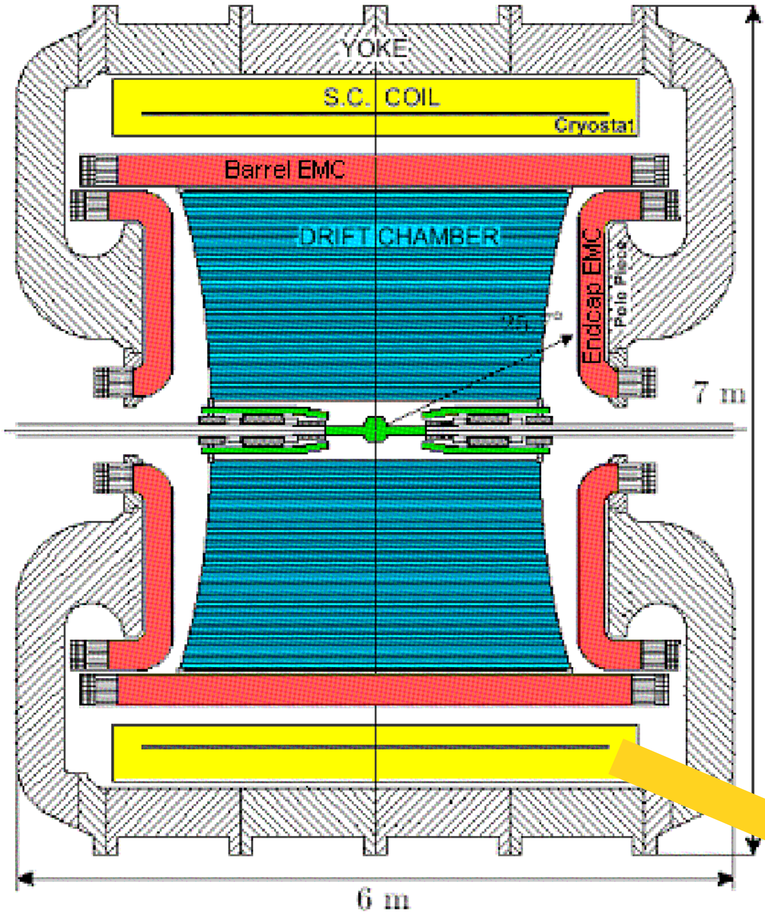


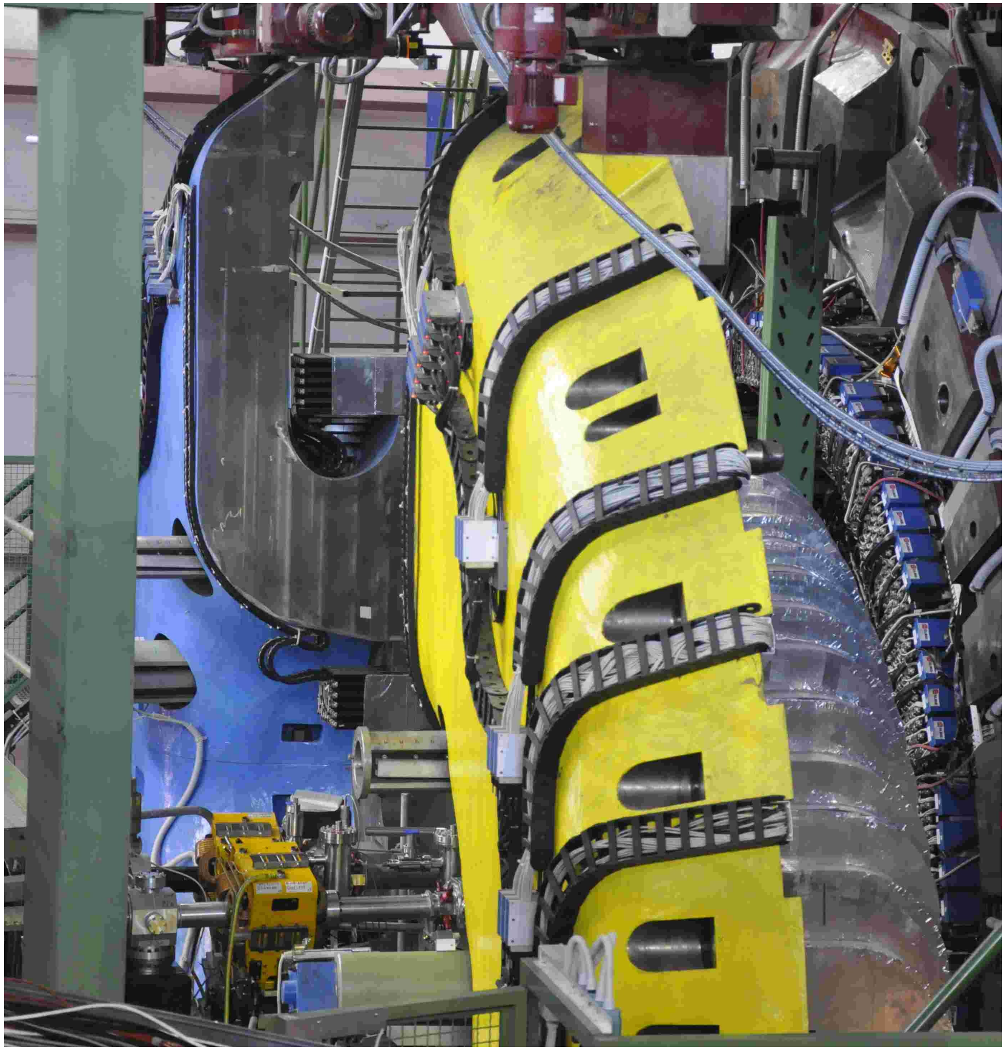
EmC Calorimeter

- Lead/scintillating fibers
- 98% coverage of 4π
- $\delta E/E = 5.7\% / \sqrt{E(\mathrm{GeV})}$
- $\delta t = 57\ \mathrm{ps} / \sqrt{E(\mathrm{GeV})} + 100\ \mathrm{ps}$



The KLOE detector

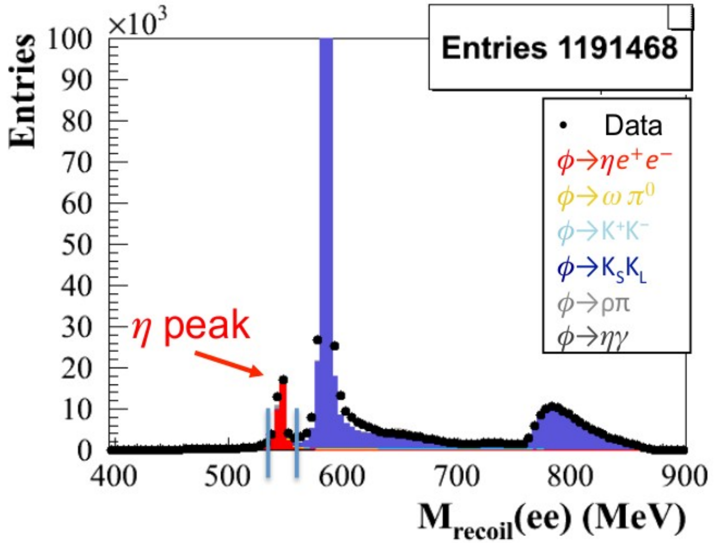


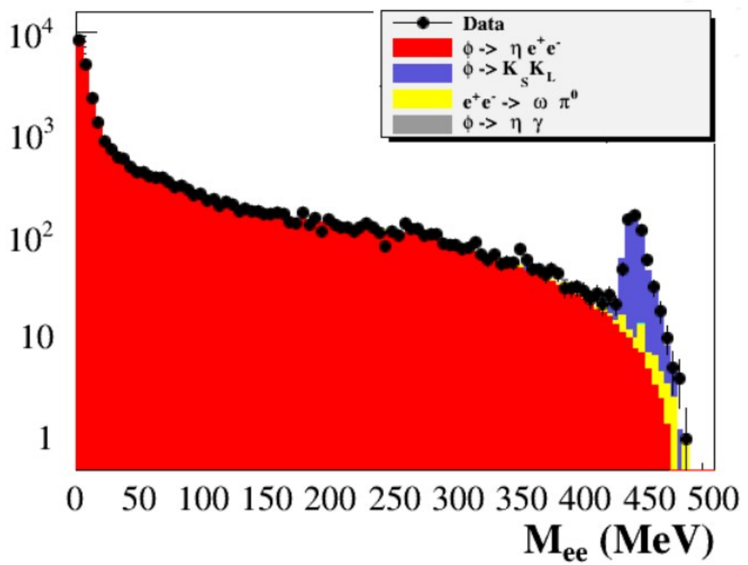


Magnetic field ~0.5 T

The $\phi \to \eta e^+e^-$ analysis

The analysis of $\phi \rightarrow \eta\, e^+e^-$ ($\eta \rightarrow \pi^0\pi^0\pi^0$)





- ✔ The analysis is performed on 1.7 fb^{-1} collected at $\sqrt{s} = M_\phi \approx 1.02$ GeV
- ✔ Pre-selection:
  - 2 tracks of opposite charge from IP
  - 6 photon-clusters candidates from IP
- ✔ Selection:
  - ($400 < M_{6\gamma} < 700$) MeV
  - ($536.5 < M_{miss\text{-}ee} < 554.5$) MeV)
  - Cut to reject γ conversion on BP and DC walls
  - TOF cut for e^+e^- selection
- ✔ ~3 x 10^4 evts selected, ~15% global efficiency (10% low mee to 35% at high mee) < 3% residual bkg contamination

TFF $\phi \to \eta e^+e^-$ ($\eta \to \pi^0\pi^0\pi^0$)

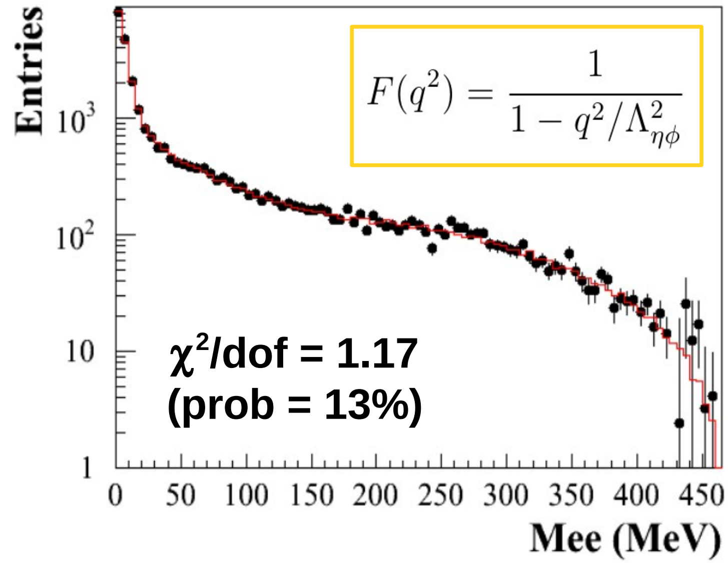
- **Good MC-Data agreement after bkg subtraction (~29600 evts)**
- **$F_{\phi\eta\gamma^*}$ slope is extracted by:**

  - direct fit to the invariant-mass spectrum of the e^+e^- pair to the Landsberg formula [L.G. Landsberg Phys. Rep. 128 301 (1985)]

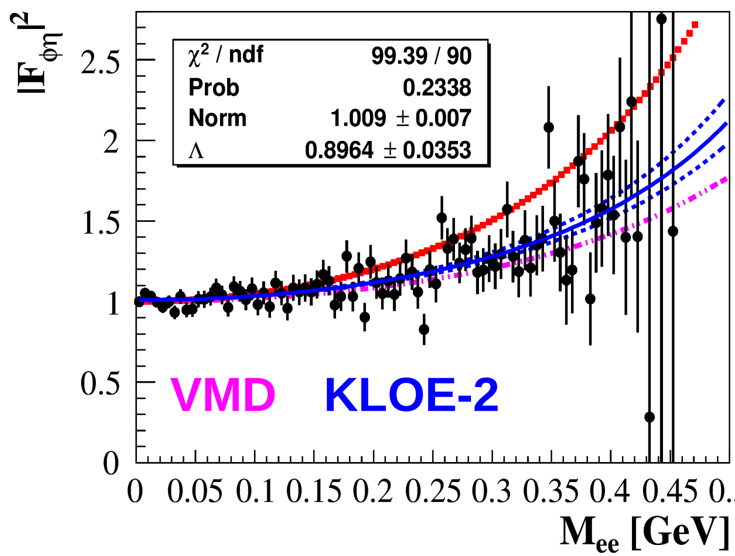
$$\frac{d}{dq^2}\frac{\Gamma(\phi\to\eta e^+e^-)}{\Gamma(\phi\to\eta\gamma)}=\frac{\alpha}{3\pi}\frac{|F_{\phi\eta}(q^2)|^2}{q^2}\sqrt{1-\frac{4m^2}{q^2}}\times\left(1+\frac{2m^2}{q^2}\right)\times\left[\left(1+\frac{q^2}{m_\phi^2-m_\eta^2}\right)^2-\frac{4m_\phi^2q^2}{(m_\phi^2-m_\eta^2)^2}\right]^{3/2}$$

  folded with analysis efficiency and smearing effects

  - fit to the extracted $|F_{\phi\eta\gamma^*}(m_{ee})|^2$



	Previous experiments	**KLOE**
$b_{\phi\eta} = \Lambda_{\phi\eta}$ [GeV^{-2}]	**SND** (3.8 ± 1.8) **[213 evts]**	**$(1.17 \pm 0.10\ ^{+0.07}_{-0.11})$**
BR ($\phi \to \eta e^+e^-$) (10^{-4})	**SND** (1.19 ± 0.22) **CMD-2** (1.14 ± 0.12)	**(1.075 ± 0.039)**
VMD	**B.R. = 1.1 x 10^{-4}**	**$b_{\phi\eta}$ = 1 GeV^{-2}**



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

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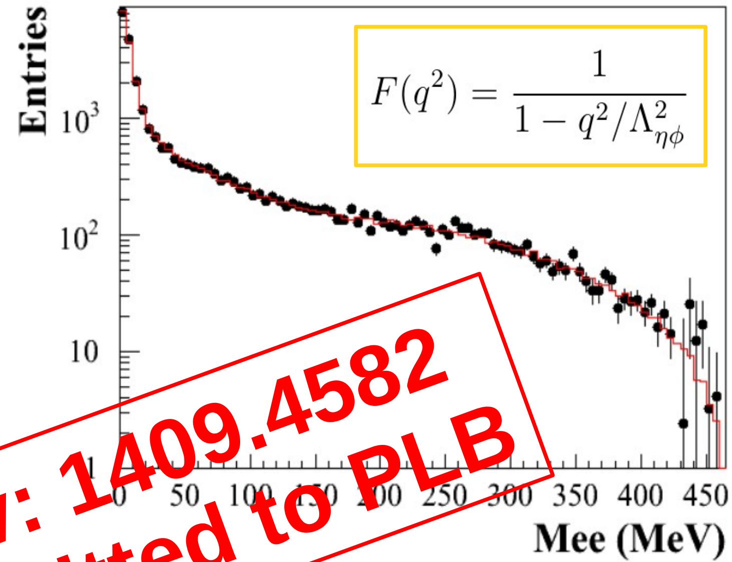
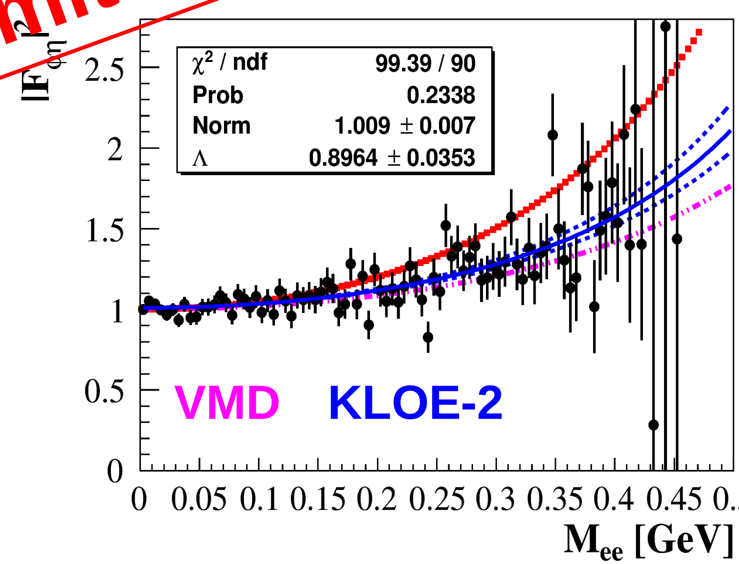
  folded with analysis efficiency and smearing effects

  - fit to the extracted $|F_{\phi\eta\gamma^*}(m_{ee})|^2$



arXiv: 1409.4582 submitted to PLB

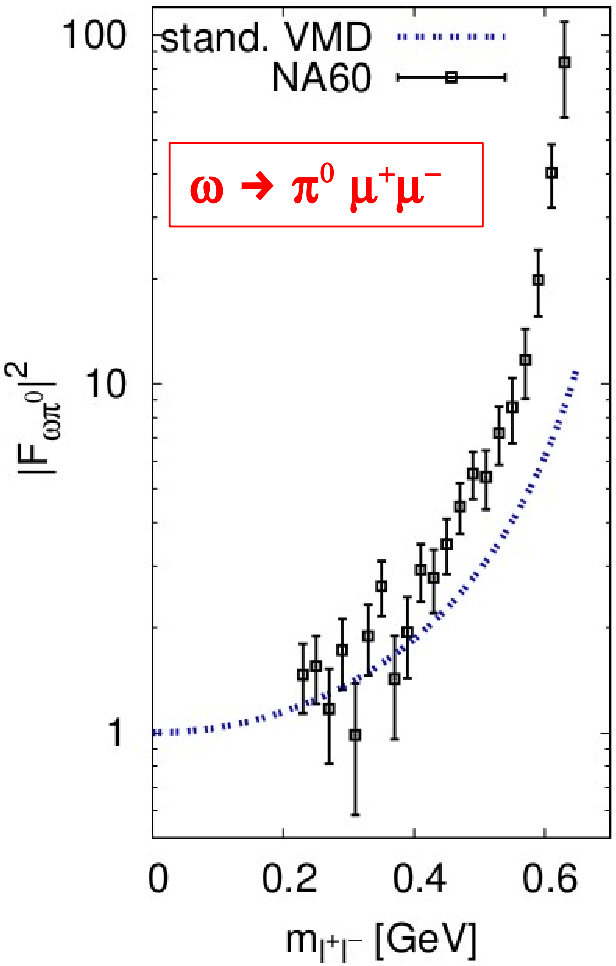
	Previous experiments	KLOE
$b_{\phi\eta} = \Lambda_{\phi\eta}$ [GeV^{-2}]	**SND** (3.8 ± 1.8) **[213 evts]**	**$(1.17 \pm 0.10\ ^{+0.07}_{-0.11})$**
BR ($\phi \to \eta e^+e^-$) (10^{-4})	**SND** (1.19 ± 0.22) **CMD-2** (1.14 ± 0.12)	**(1.075 ± 0.039)**
VMD	**B.R. = 1.1 x 10^{-4}**	**$b_{\phi\eta}$ = 1 GeV^{-2}**

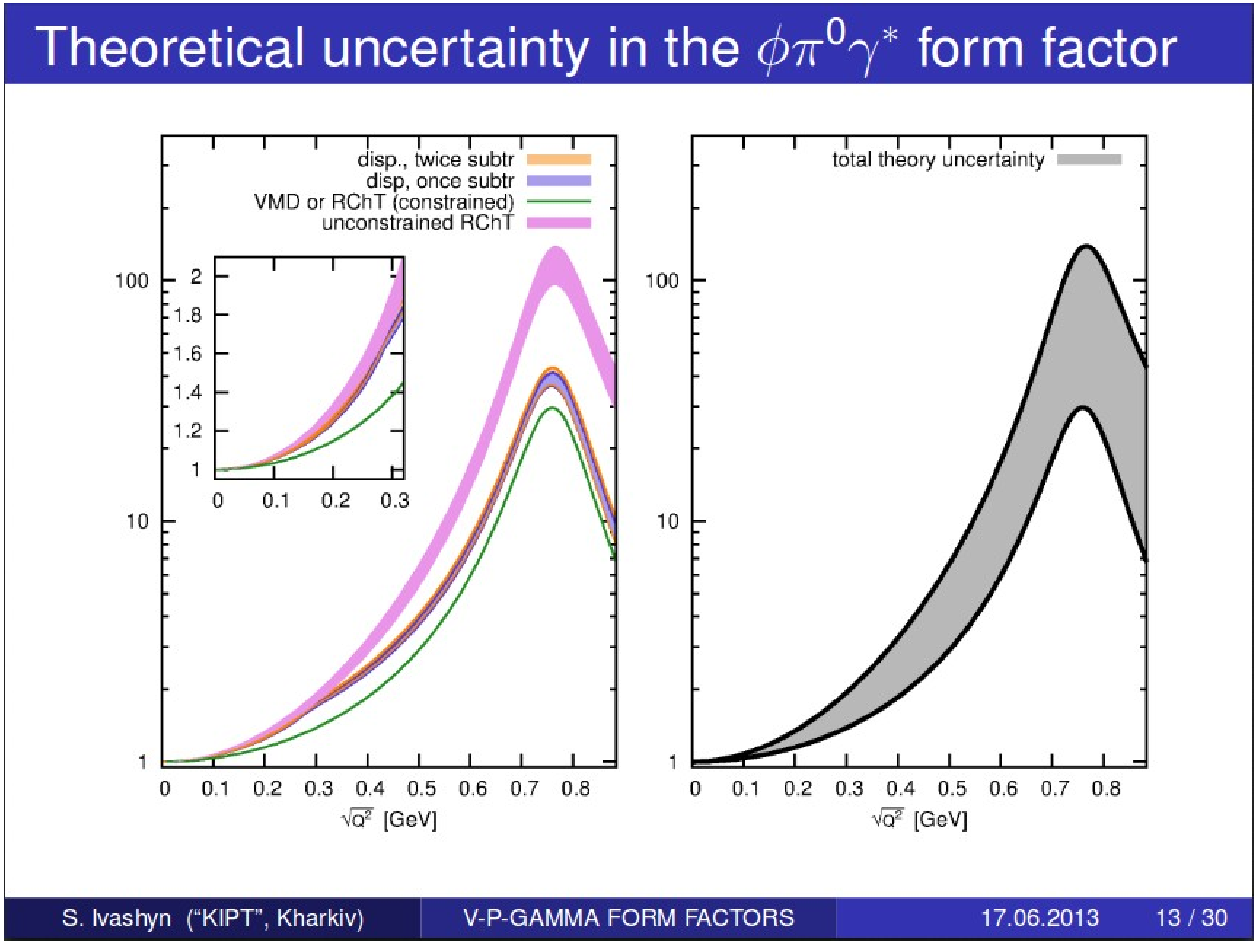


The $\phi \rightarrow \pi^0 e^+e^-$ analysis

$\phi \to \pi^0 e^+e^-$: the actual situation

<u>NO DATA</u> available for $F_{\phi\,\pi 0\,\gamma*}$ TFF → needed to test the theoretical models (ω decay)





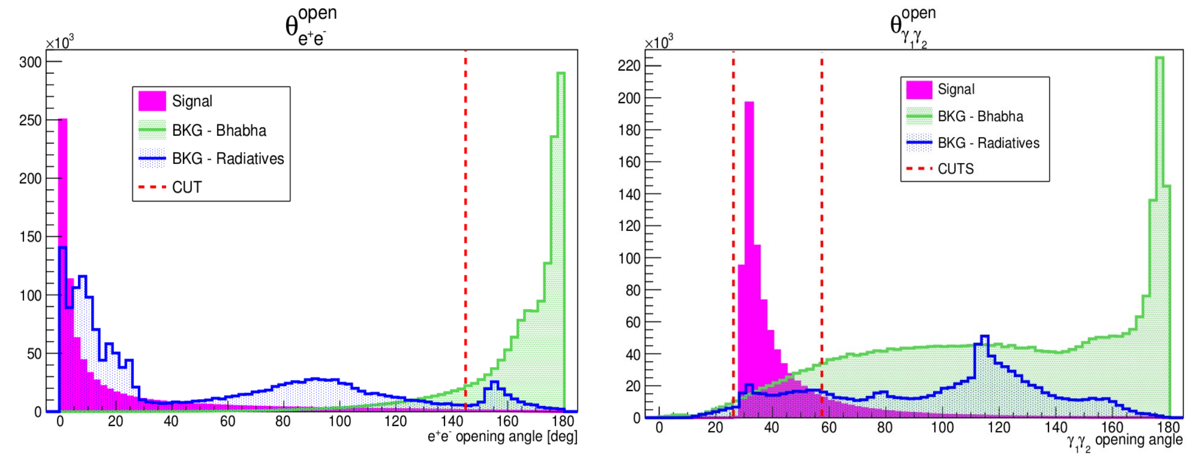
The analysis of $\phi \rightarrow \pi^0 e^+e^-$

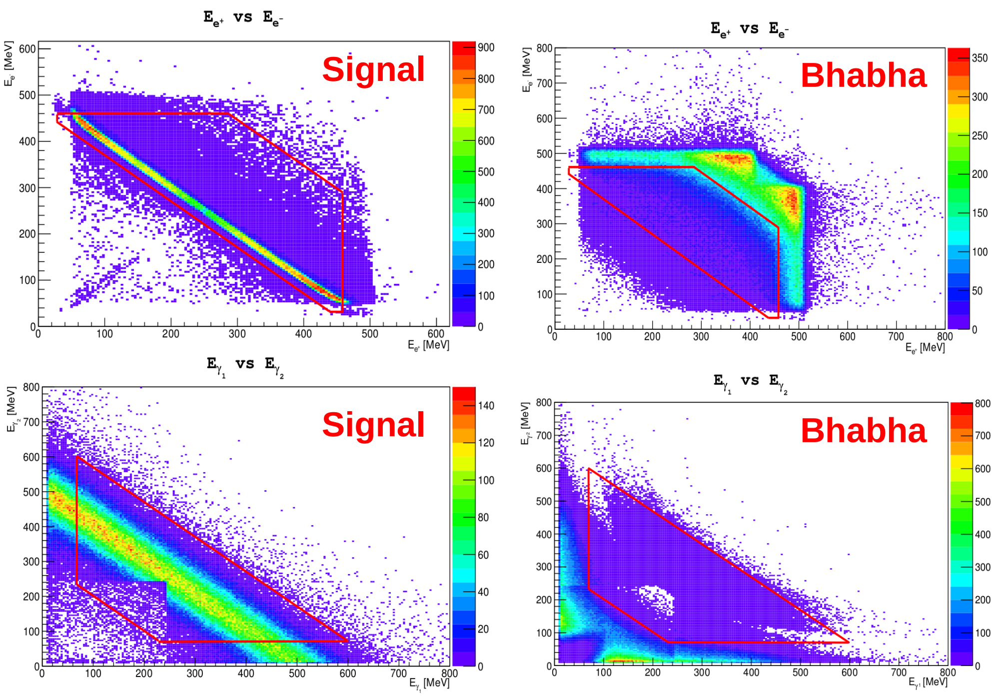
- ✔ Analysis performed on 1.7 fb^{-1} from 2004/2005 collected at $\sqrt{s} \approx 1.02$ GeV
- ✔ Main bkgs: $e^+e^- \rightarrow e^+e^-\gamma\gamma$ and $\phi \rightarrow \pi^0\gamma$ (γ conversion or π^0 to Dalitz)
- ✔ Selection (main):

  - $E_e < 460$ MeV
  - $470 < E_{e+} + E_{e-} < 750$ MeV
  - $300 < E_{\gamma 1} + E_{\gamma 2} < 670$ MeV
  - θ_{open} (ee) < 145° and 27° < θ_{open} ($\gamma\gamma$) < 57°
  - $90 < M_{2\gamma} < 190$ MeV
  - $80 < M_{miss}^{ee} < 180$ MeV
  - Cut to reject γ conv. on BP and DC walls

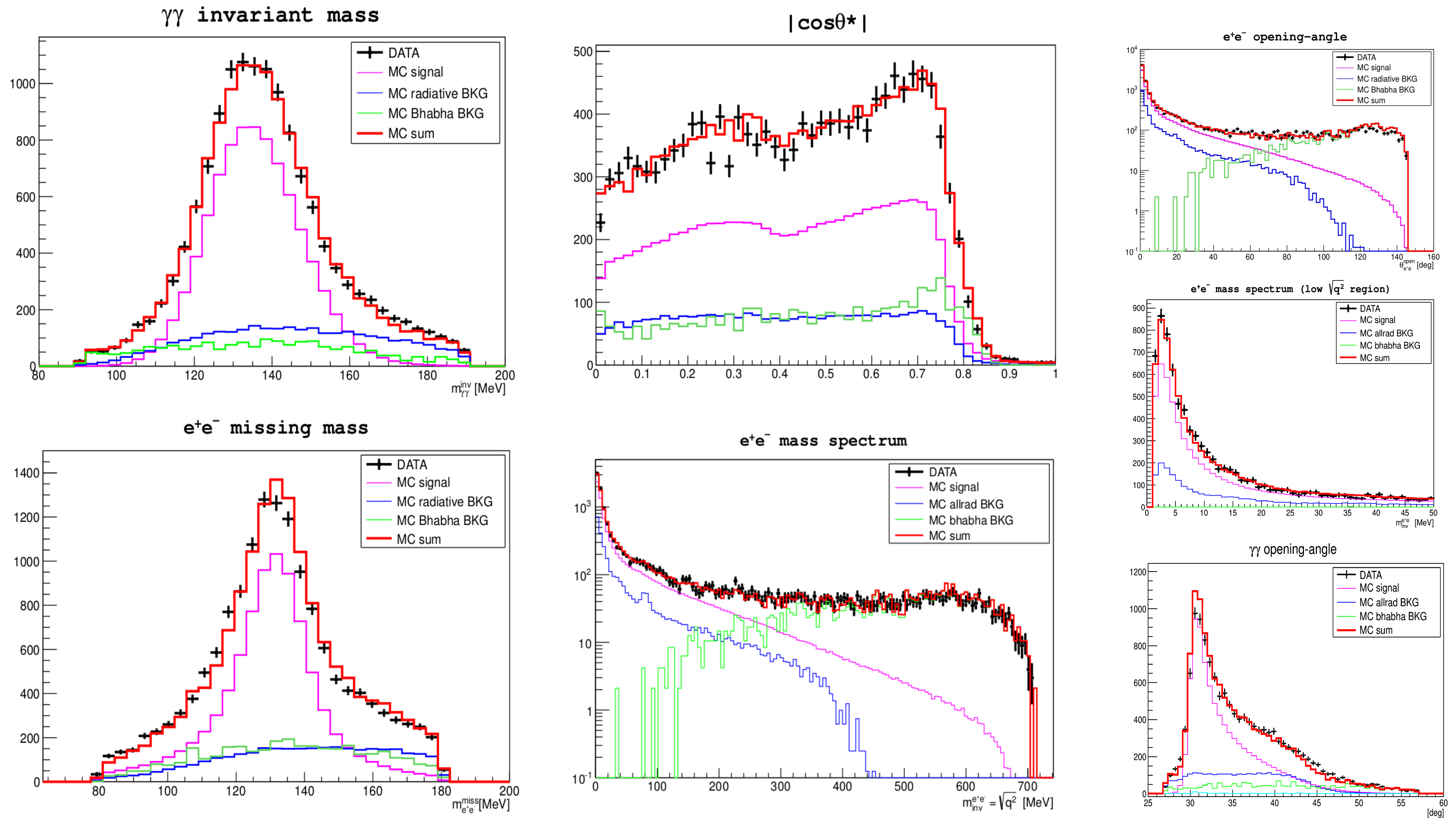
- ✔ ~ 14000 events selected (total bkg cont. ~30% with a global efficiency of ~ 14%)

  [CMD-2 ~70 events for B.R. measurement!]

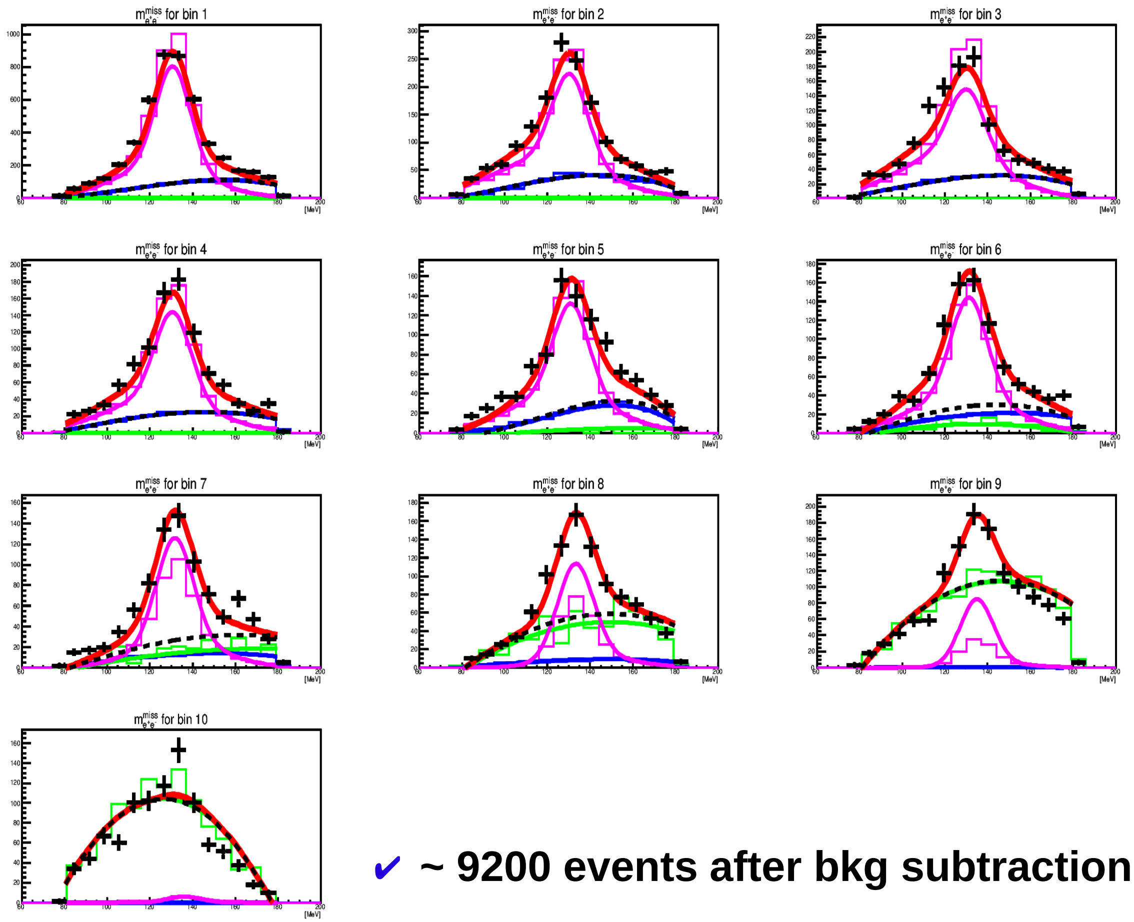


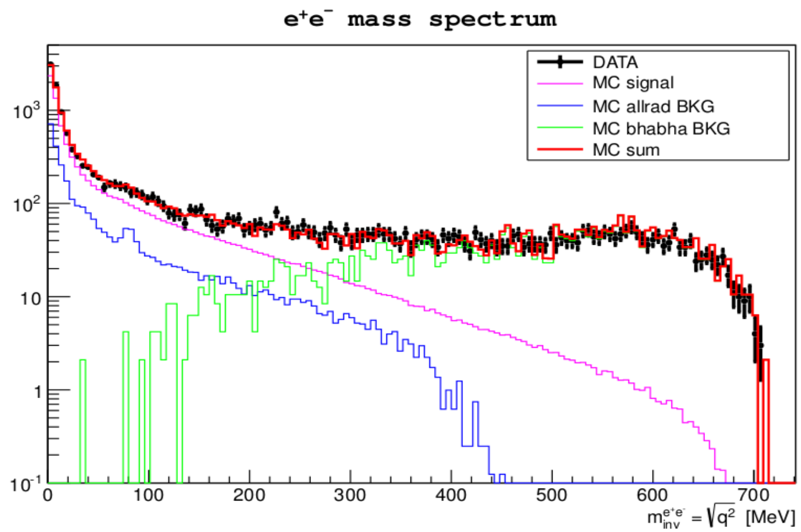


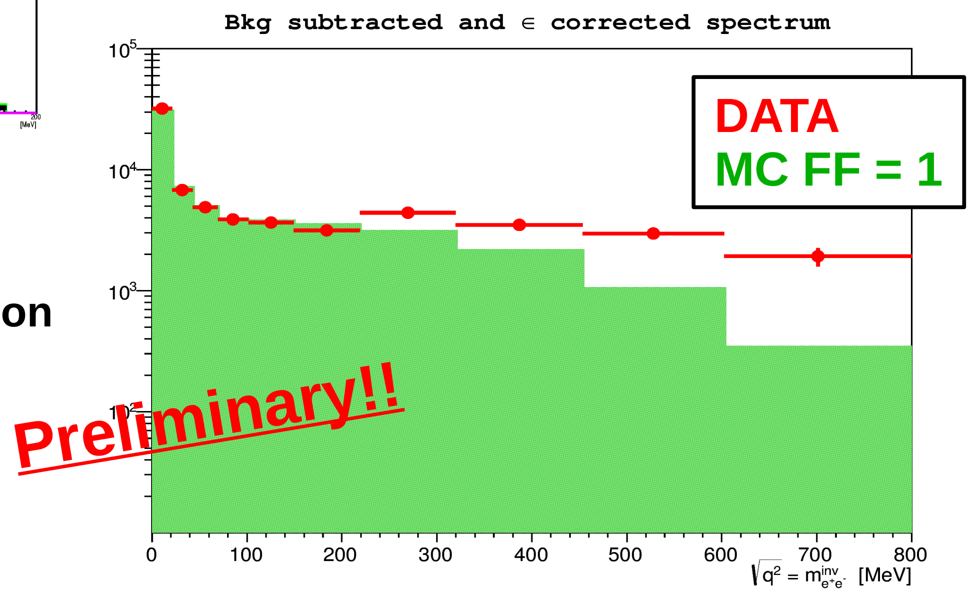
$\phi \rightarrow \pi^0 e^+e^-$: Data-MC agreement



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







- ✔ ~ 9200 events after bkg subtraction
- ✔ B.R. and TFF measurement almost complete (systematic uncertainties are under estimation)

(…more from Patrik in next talk)

Thank you for your attention