IWHSS 2013

# Experimental review of Primakoff reactions

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JINR, Dubna

on behalf of the COMPASS collaboration

Erlangen, 22.7.2013

# Henry Primakoff

**Photo-Production of Neutral Mesons in Nuclear Electric Fields and the Mean Life of the Neutral Meson***

H. PRIMAKOFF†
*Laboratory for Nuclear Science and Engineering, Massachusetts Institute of Technology, Cambridge, Massachusetts*

January 2, 1951

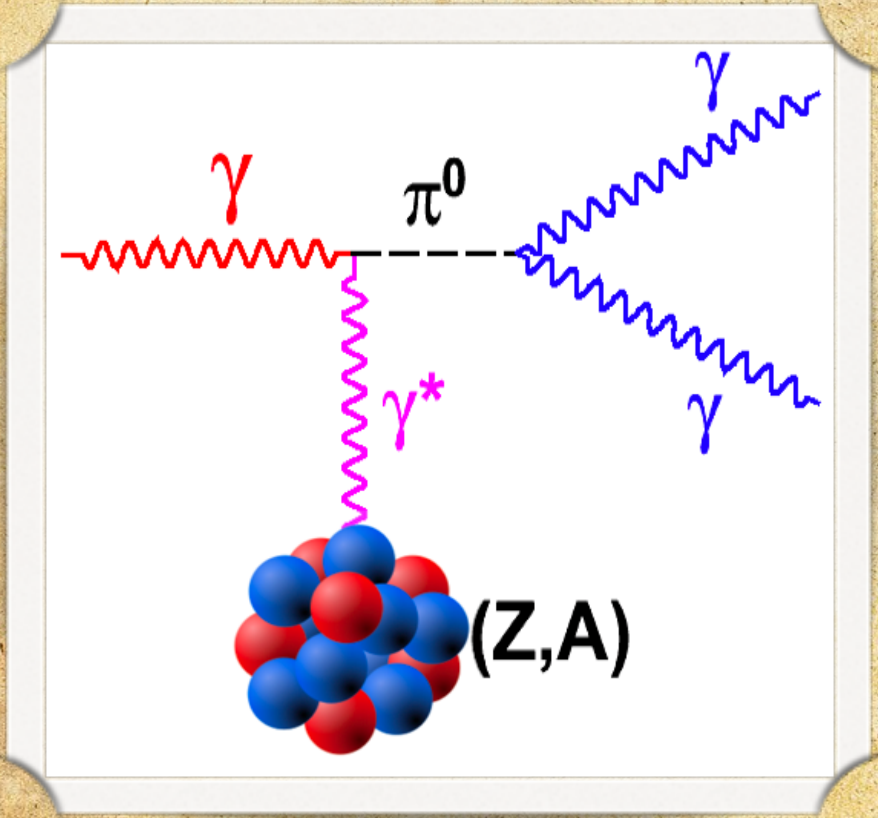
IT has now been well established experimentally that neutral $\pi$-mesons ($\pi^0$) decay into two photons.[1] Theoretically, this two-photon type of decay implies zero $\pi^0$ spin;[2] in addition, the decay has been interpreted as proceeding through the mechanism of the creation and subsequent radiative recombination of a virtual proton anti-proton pair.[3] Whatever the actual mechanism of the (two-photon) decay, its mere existence implies an effective interaction between the $\pi^0$ wave field, $\varphi$, and the electromagnetic wave field, **E**, **H**, representable in the form:

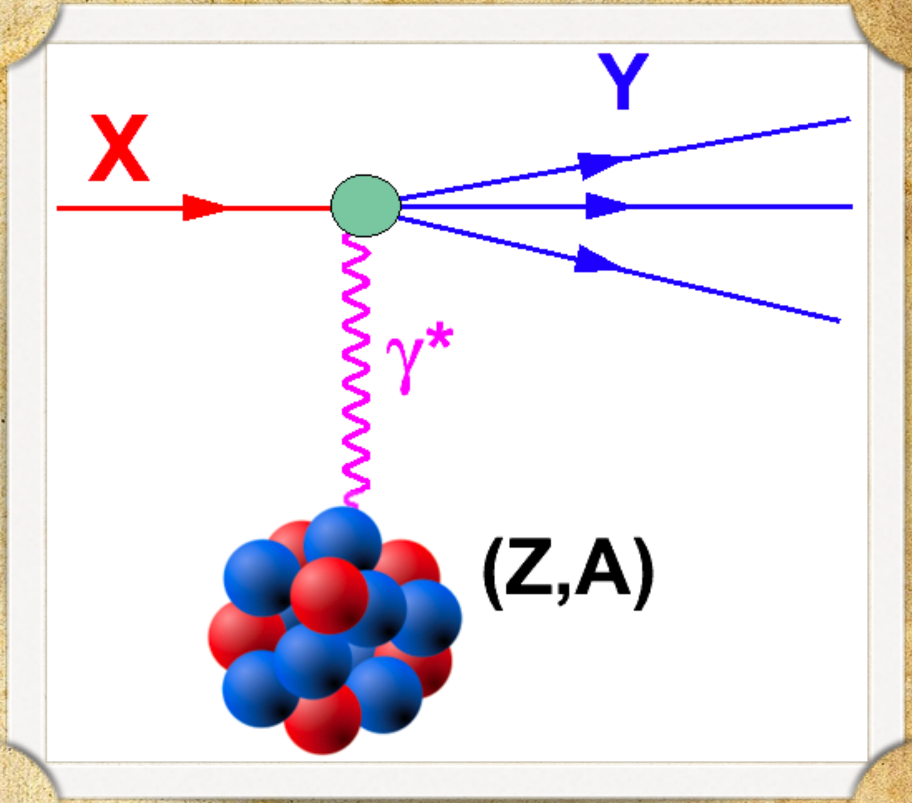
$$\text{Interaction Energy Density} = \eta(\hbar/\mu c)(\hbar c)^{-\frac{1}{2}}\varphi\mathbf{E}\cdot\mathbf{H}. \qquad (1)$$

Here $\varphi$ has been assumed pseudoscalar, the factors $\hbar/\mu c$ and $(\hbar c)^{-\frac{1}{2}}$ are introduced for dimensional reasons ($\mu \equiv$ rest mass of $\pi^0$),

**Coulomb field of nucleus can be used as photon target**

# From Primakoff effect



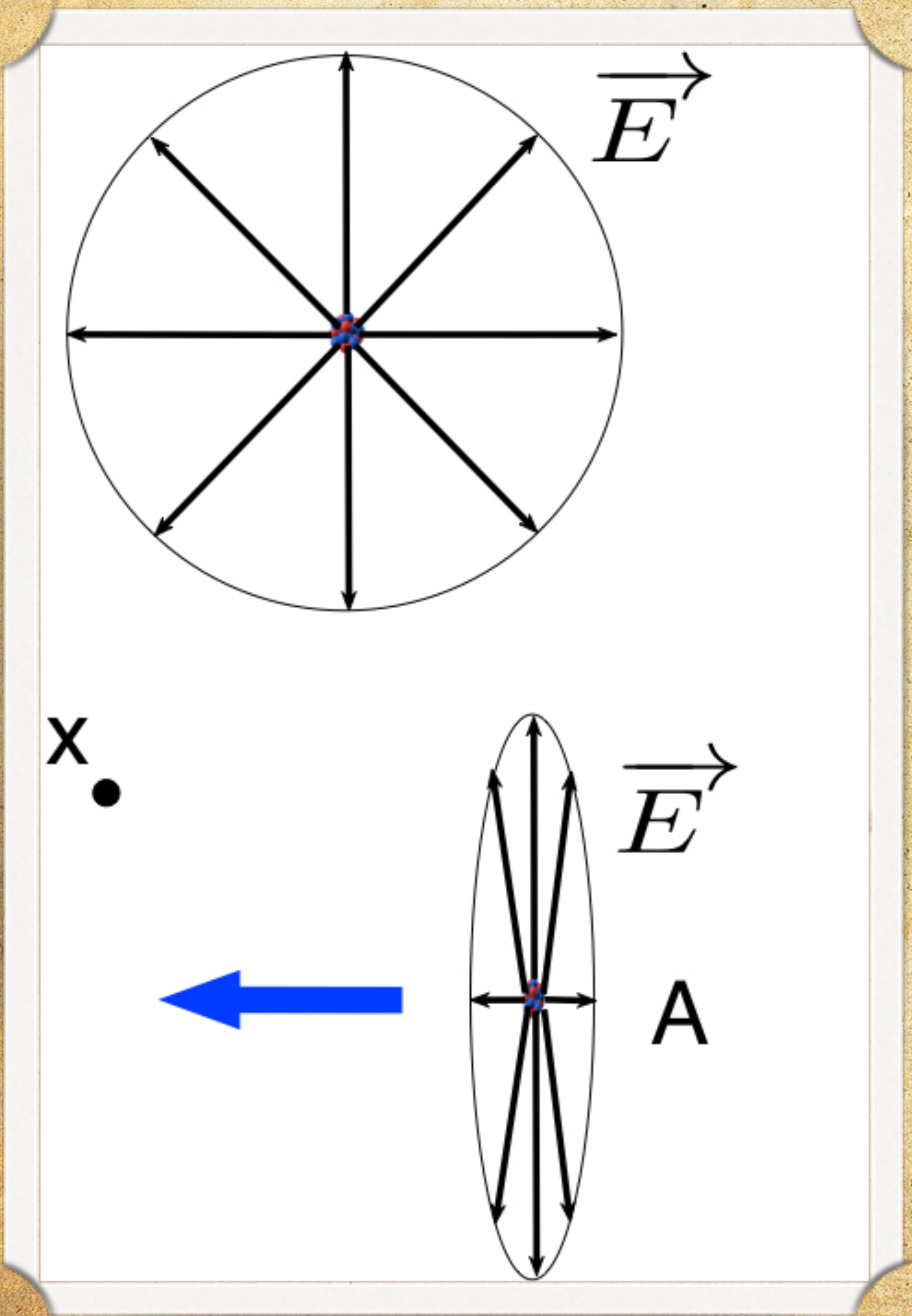

# to Primakoff reactions

# Outline

- General remarks on Primakoff reactions
- Pion and kaon polarizabilities
- Chiral anomaly in QCD
- $3\pi$ production near threshold
- Radiative widths of mesons

# Equivalent photon method

## (Weizsaecker-Williams approximation)




***Electromagnetic field of fast charged particle is similar to a field of electromagnetic wave***

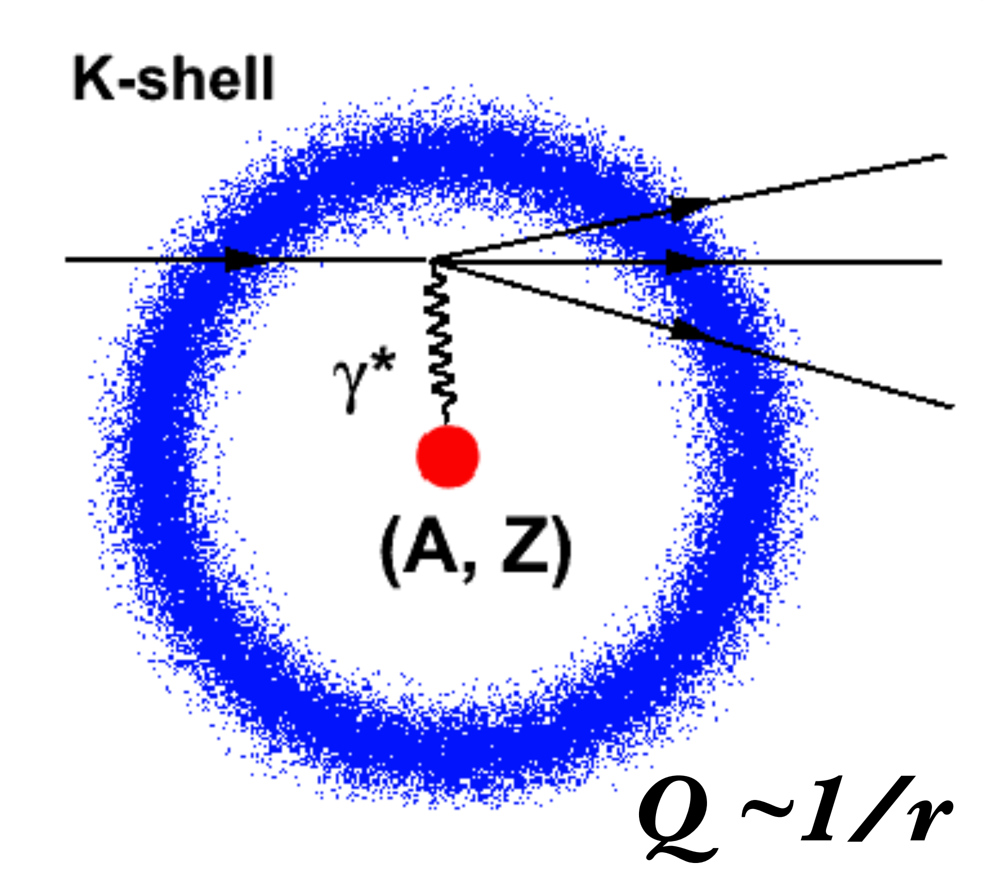
$$\sigma_{x\gamma}(\omega, Q^2) \rightarrow \sigma_{x\gamma}(\omega, 0)$$

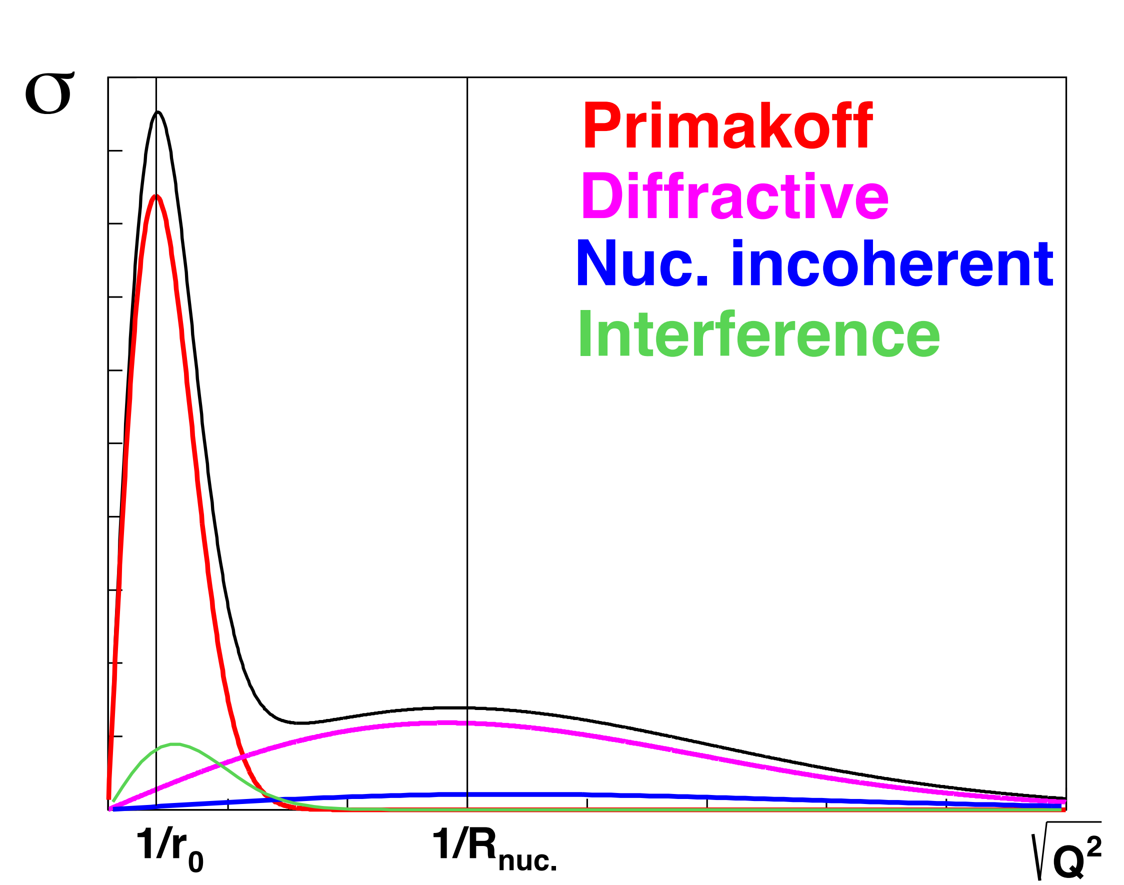
$$d\sigma_{xA} = \int n_\gamma(\omega) d\sigma_{x\gamma}(\omega) d\omega$$

$$n_\gamma(\omega) \sim \frac{Z^2\alpha}{\omega} ln \frac{E}{\omega}$$

***density of equivalent photons***

# General remarks

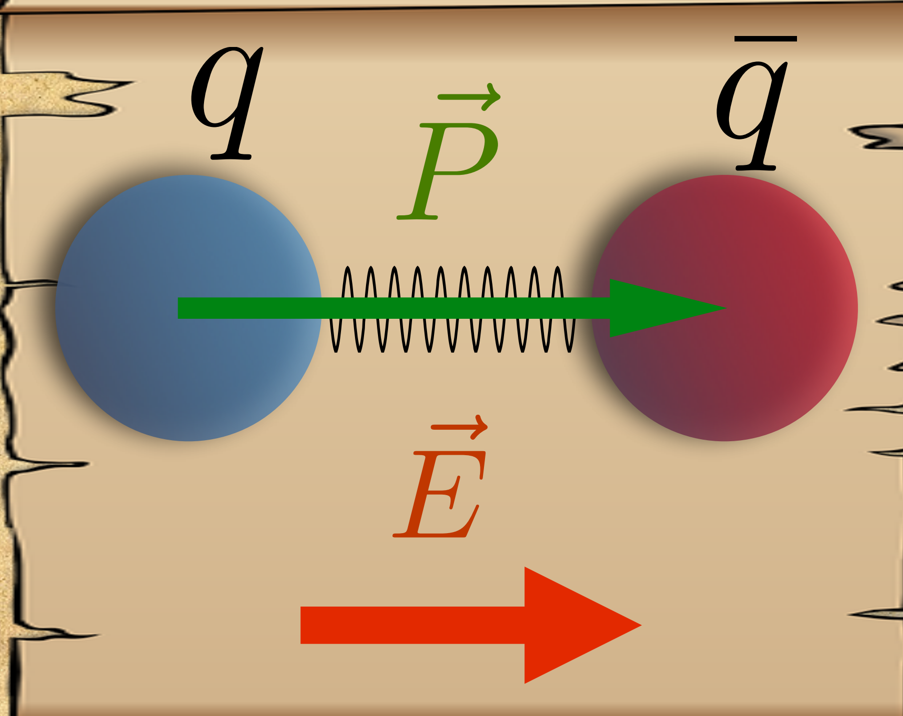



***Nuclear size:***
*40 MeV/c (Ni)*
*33 MeV/c (Pb)*
***K-shell size:***
*0.1 MeV/c (Ni)*
*0.3 MeV/c (Pb)*

$$\sigma = c_1(T_{Prim}+e^{i\phi}T_{Diff})^2+\sigma_{Inc} = \sigma_{Prim} + \sigma_{Diff} + \sigma_{Int} + \sigma_{Inc}$$

# Polarizabilities of particles




$$\vec{P} = \alpha_X \vec{E}$$

$$\vec{\mu} = \beta_X \vec{H}$$

***The electric and magnetic polarizabilities of a particle are the quantities characterizing the rigidity of QCD system***

## Compton amplitude:

$$A(\gamma X \to \gamma X) =$$

$$(-\frac{\alpha}{m}\delta_{o\pm} + \alpha_X \omega_1 \omega_2)\hat{e}_1 \cdot \hat{e}_2 +$$

$$+\beta_X \omega_1 \omega_2 (\hat{e}_1 \times \hat{q}_1)(\hat{e}_2 \times \hat{q}_2) + \ldots$$

**PDG data:**

| | $\alpha_X$, $10^{-4}$ fm$^3$ | $\beta_X$, $10^{-4}$ fm$^3$ |
|---|---|---|
| p | 12.0±0.6 | 1.9∓0.6 |
| n | 12.5±1.7 | 2.7∓1.8 |

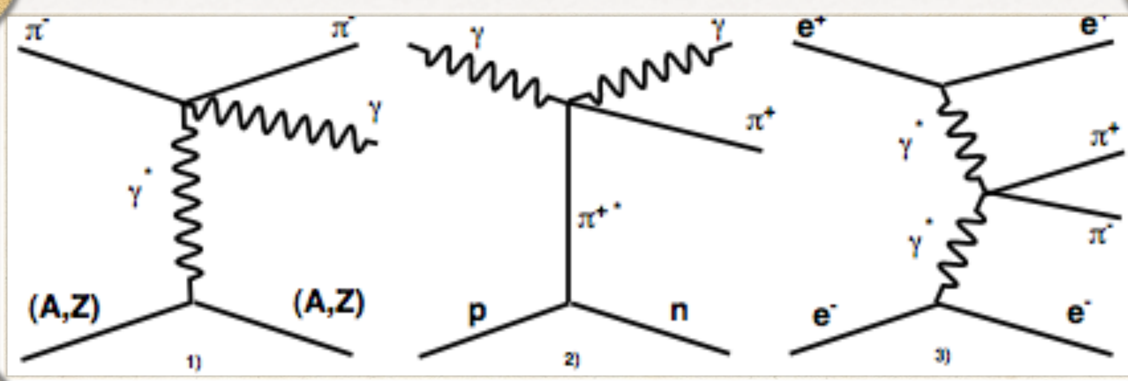
***π, K ?***

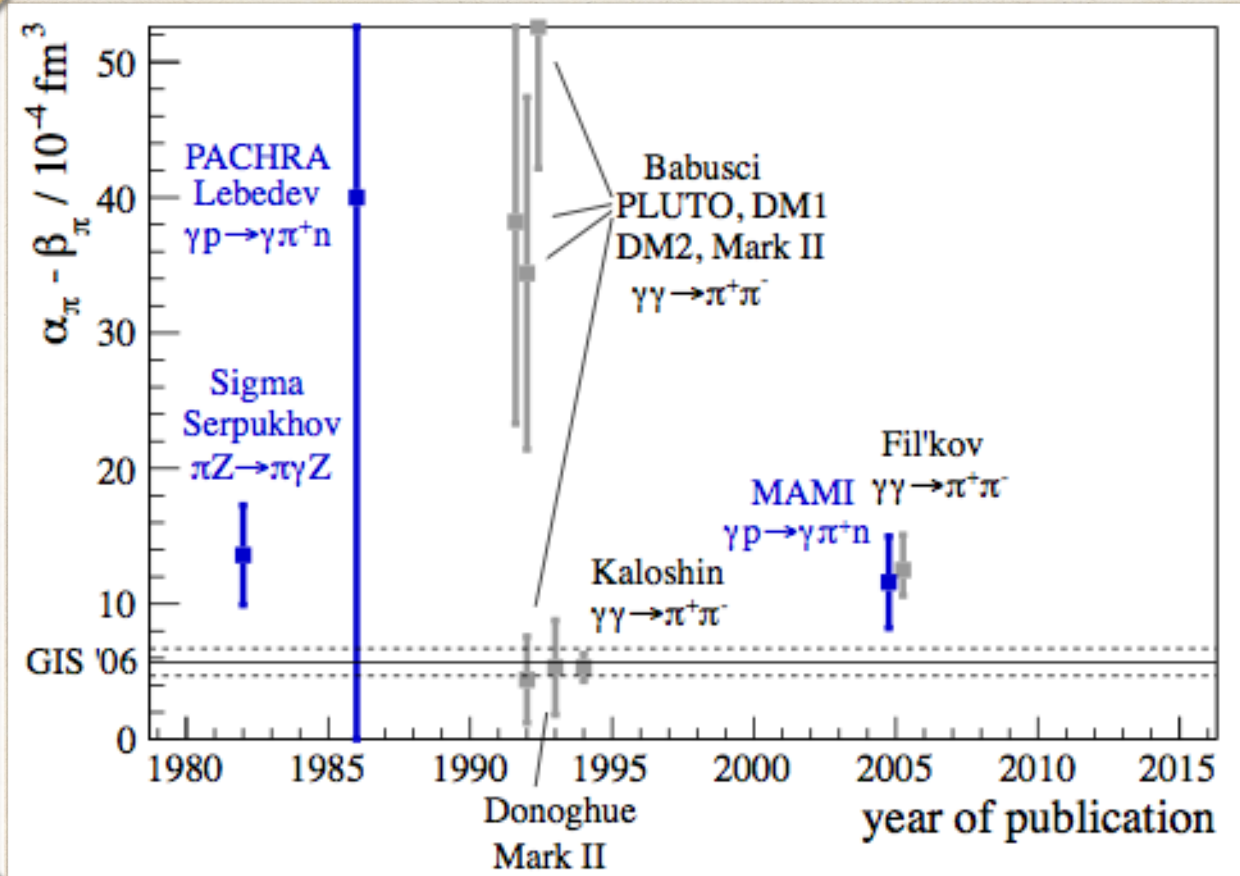
# Theoretical predictions for $\alpha_\pi,\beta_\pi$

| Model | Parameter | $[10^{-4} fm^3]$ |
|---|---|---|
| $\chi$PT (1 loop) | $\alpha_\pi - \beta_\pi$ | $5.4 \pm 0.8$ |
| | $\alpha_\pi + \beta_\pi$ | 0 |
| $\chi$PT (2 loops) | $\alpha_\pi - \beta_\pi$ | $5.7 \pm 1.0$ |
| | $\alpha_\pi + \beta_\pi$ | 0.16 |
| Nambu-Jona-Lasinio model | $\alpha_\pi - \beta_\pi$ | 9.8 |
| Quark confinement model | $\alpha_\pi - \beta_\pi$ | 7.05 |
| | $\alpha_\pi + \beta_\pi$ | 0.23 |
| QCD sum rules | $\alpha_\pi - \beta_\pi$ | $11.2 \pm 1.0$ |
| Dispersion sum rules | $\alpha_\pi - \beta_\pi$ | $13.60 \pm 2.15$ |
| | $\alpha_\pi + \beta_\pi$ | $0.166 \pm 0.024$ |

***The most of theoretical models are in agreement that $\alpha_\pi - \beta_\pi \gg \alpha_\pi + \beta_\pi \approx 0.2 \times 10^{-4} fm^3$. As for value $\alpha_\pi - \beta_\pi$, predictions are quite different***

# Experimental results for $\alpha_\pi, \beta_\pi$




| Data | Reaction | Paramater | $[10^{-4} fm^3]$ |
|---|---|---|---|
| Serpukhov ($\alpha_\pi + \beta_\pi = 0$) | $\pi Z \to \pi Z \gamma$ | $\alpha_\pi$ | 6.8±1.4±1.2 |
| Serpukhov ($\alpha_\pi + \beta_\pi \neq 0$) | | $\alpha_\pi + \beta_\pi$<br>$\beta_\pi$ | 1.4±3.1±2.8<br>$-7.1 \pm 2.8 \pm 1.8$ |
| Lebedev | $\gamma N \to \gamma N \pi$ | $\alpha_\pi$ | 20±12 |
| Mami A2 | $\gamma p \to \gamma \pi^+ n$ | $\alpha_\pi - \beta_\pi$ | 11.6±1.5±3.0±0.5 |
| PLUTO | $\gamma\gamma \to \pi^+\pi^-$ | $\alpha_\pi$ | 19.1±4.8± 5.7 |
| DM1 | $\gamma\gamma \to \pi^+\pi^-$ | $\alpha_\pi$ | 17.2±4.6 |
| DM2 | $\gamma\gamma \to \pi^+\pi^-$ | $\alpha_\pi$ | 26.3±7.4 |
| Mark II | $\gamma\gamma \to \pi^+\pi^-$ | $\alpha_\pi$ | 2.2±1.6 |
| Combined fit: MARK II, VENUS, ALEPH, TPC/2$\gamma$, CELLO, BELLE (L. Fil'kov, V. Kashevarov) | $\gamma\gamma \to \pi^+\pi^-$ | $\alpha_\pi - \beta_\pi$<br>$\alpha_\pi + \beta_\pi$ | $13.0^{+2.6}_{-1.9}$<br>$0.18^{+0.11}_{-0.02}$ |
| Combined fit: MARK II, Crystal Ball (A. Kaloshin, V. Serebryakov) | $\gamma\gamma \to \pi^+\pi^-$ | $\alpha_\pi - \beta_\pi$ | $5.25 \pm 0.95$ |

***At the moment experimental uncertainty for pon polarizabilities is too high. New experiments are needed!***

# Pion polarizabilities and Primakoff cross section

$$\frac{d\sigma}{ds\,dt\,dQ^2} = \frac{\alpha}{\pi(s-m_\pi^2)} \cdot F_{\text{eff}}^2(Q^2) \cdot \frac{Q^2 - Q^2_{\min}}{Q^4} \cdot \frac{d\sigma_{\pi\gamma}}{dt}$$

$$Q_{\min} = (s - m_\pi^2)/2E_{\text{beam}}$$

$$\frac{d\sigma_{\pi\gamma}}{d\Omega_{cm}} = \frac{\alpha^2(s^2 z_+^2 + m_\pi^4 z_-^2)}{s(sz_+ + m_\pi^2 z_-)^2} - \frac{\alpha\, m_\pi^3\,(s-m_\pi^2)^2}{4s^2(sz_+ + m_\pi^2 z_-)} \cdot \mathcal{P}$$

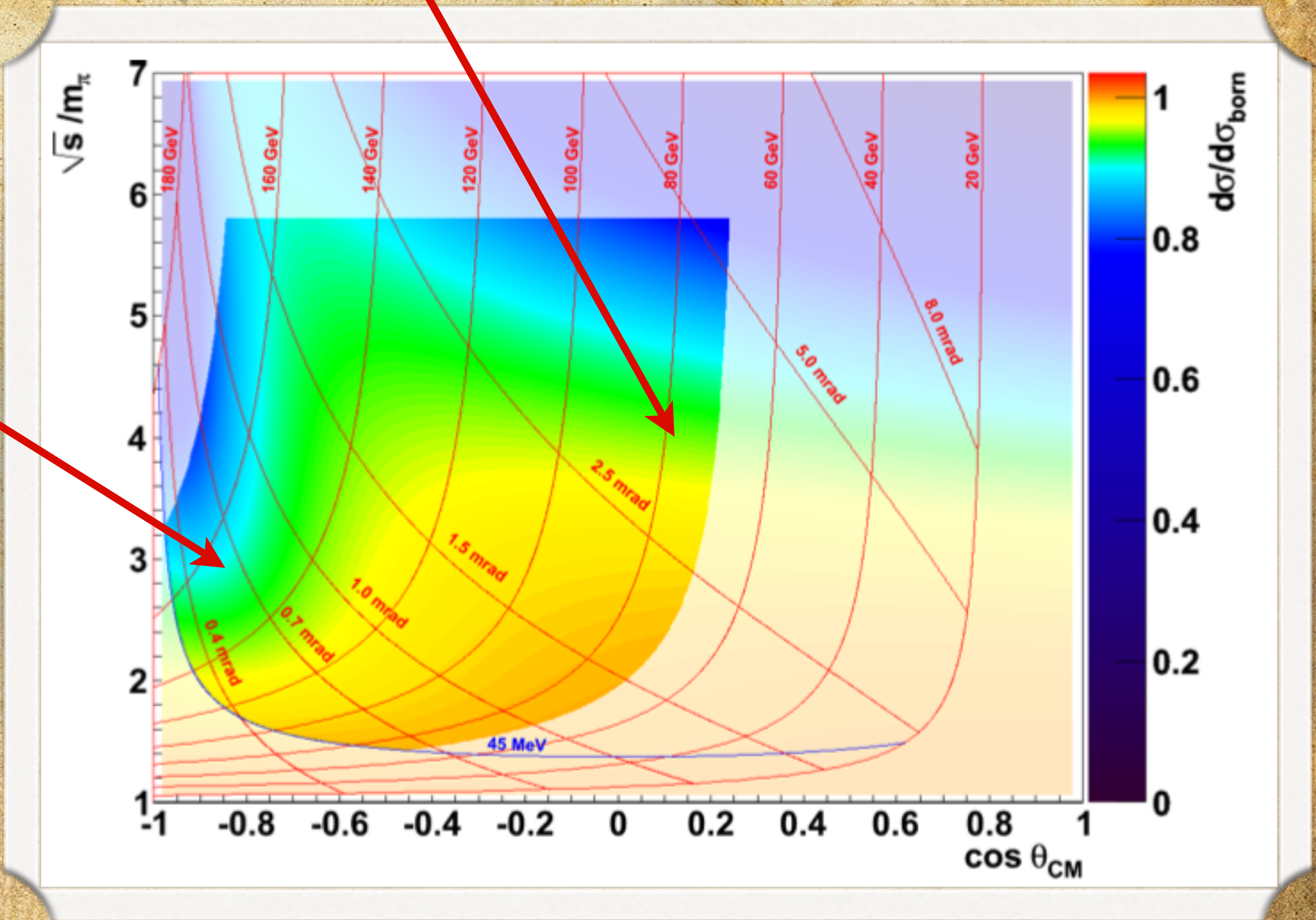
$$z_\pm = 1 \pm \cos\theta_{cm}$$

$$\mathcal{P} = z_-^2(\alpha_\pi - \beta_\pi) + \frac{s^2}{m_\pi^4} z_+^2(\alpha_\pi + \beta_\pi)$$

**CM-system**

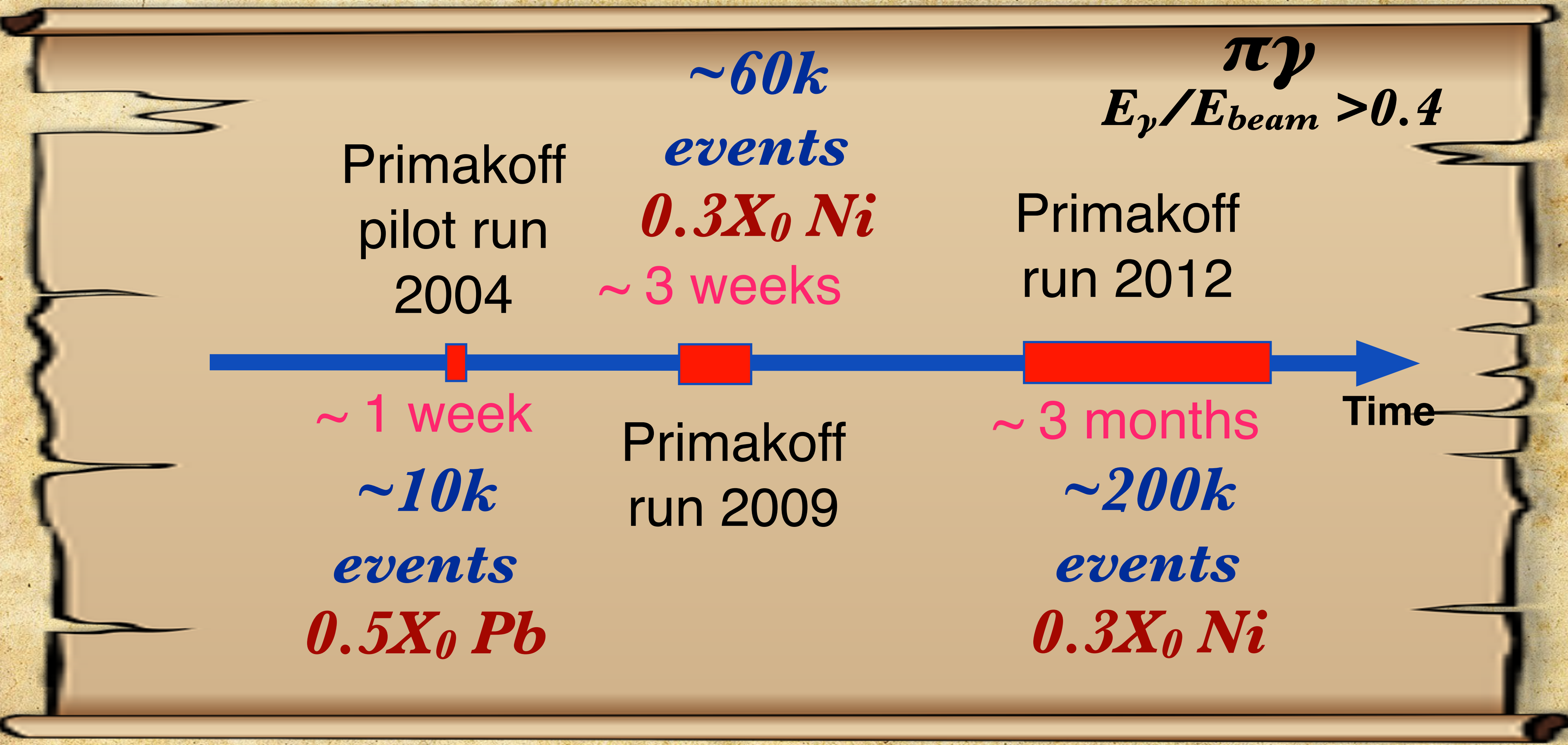
$a_\pi + \beta_\pi$

$a_\pi - \beta_\pi$



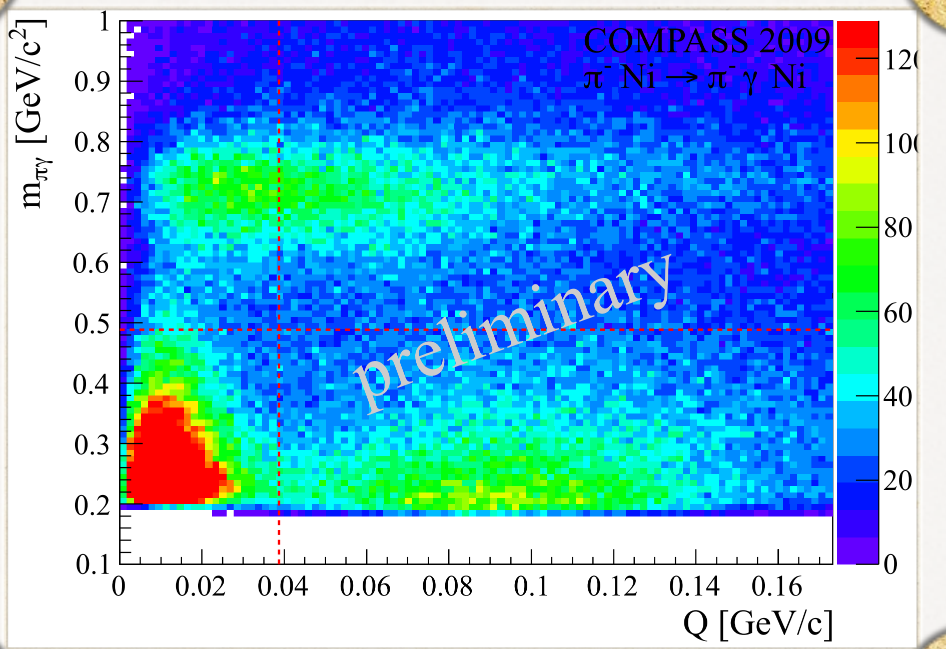

***$a_\pi$ and $\beta_\pi$ can be extracted separately from the measurement of the differential cross section***

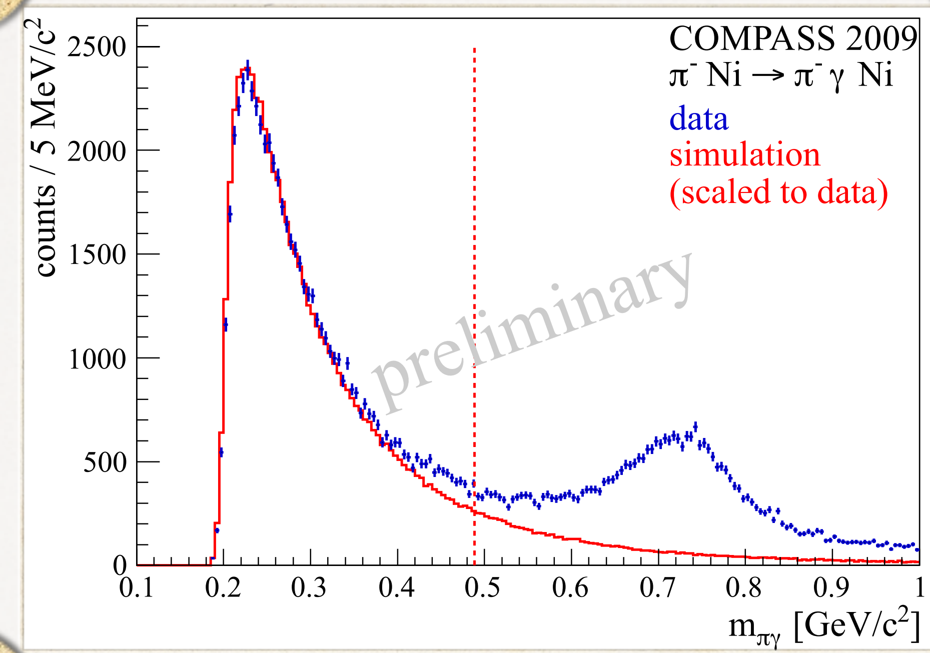
# Pion polarizabilities at COMPASS

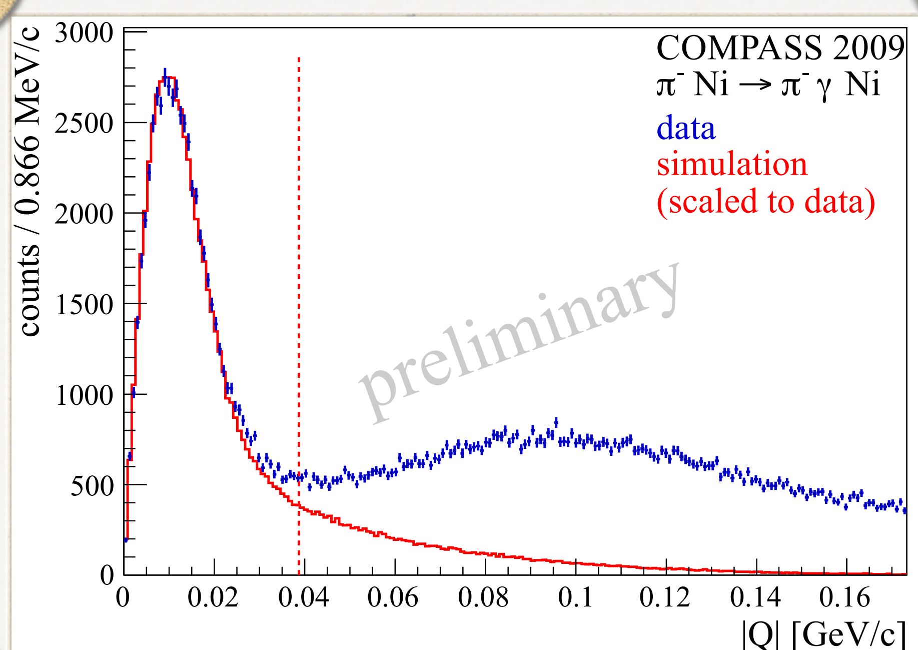


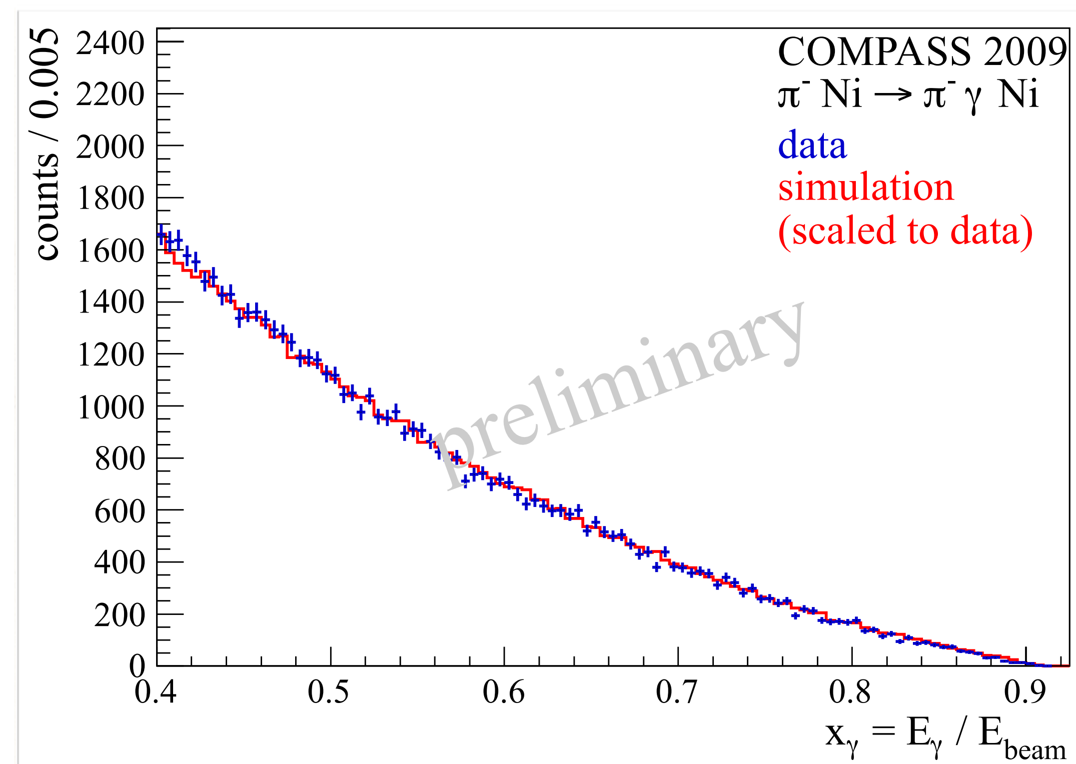

- ***Precise silicon detectors to measure small scattering angles***
- ***Electromagnetic calorimeter with good energy and spacial resolution for photon detection***
- ***Calorimeter-based trigger on hard photon(s) in the final state***
- ***Possibility to use hadron and muon beams with the same momentum 190 GeV/c***

# Pion polarizabilities at COMPASS

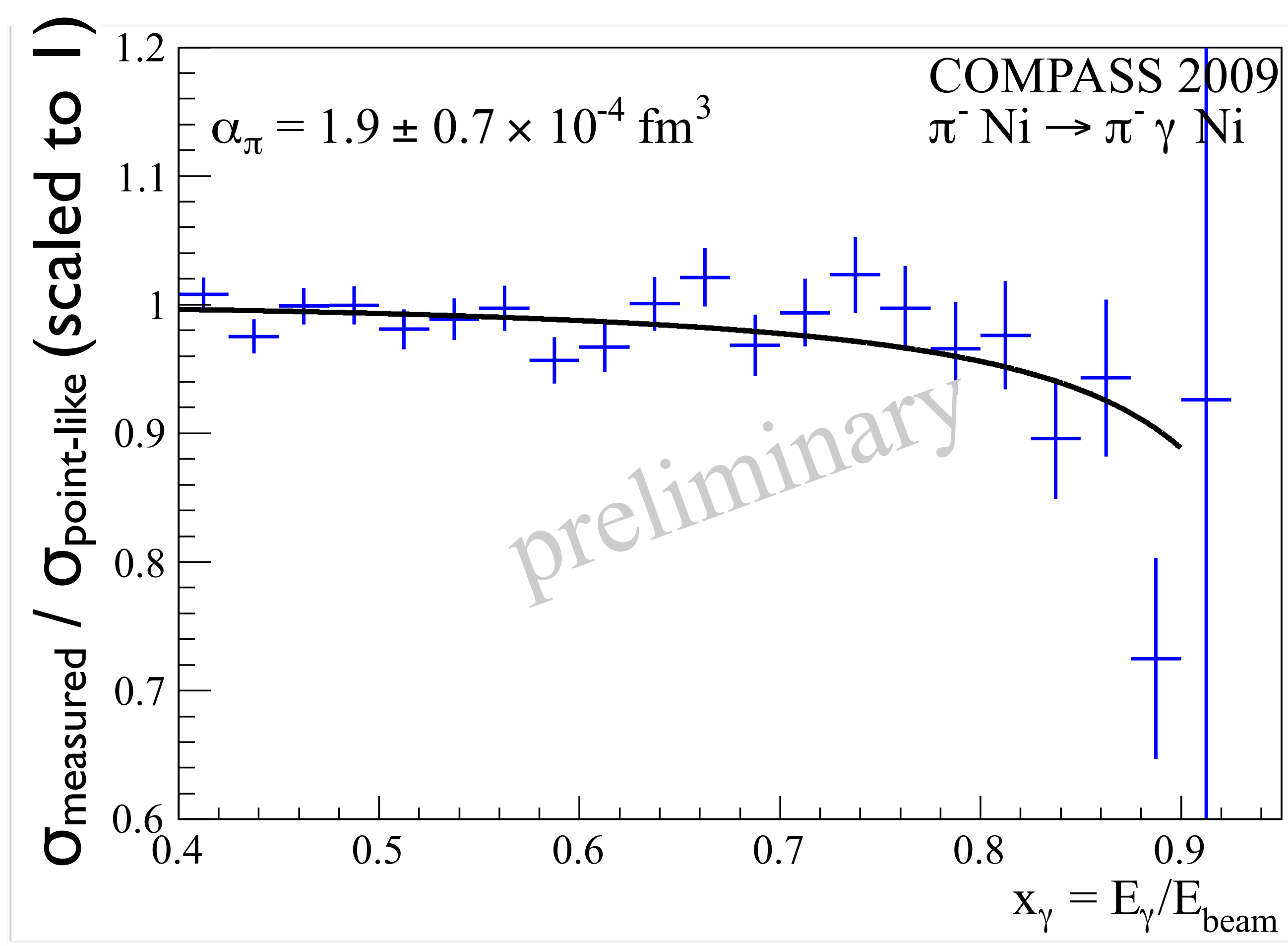


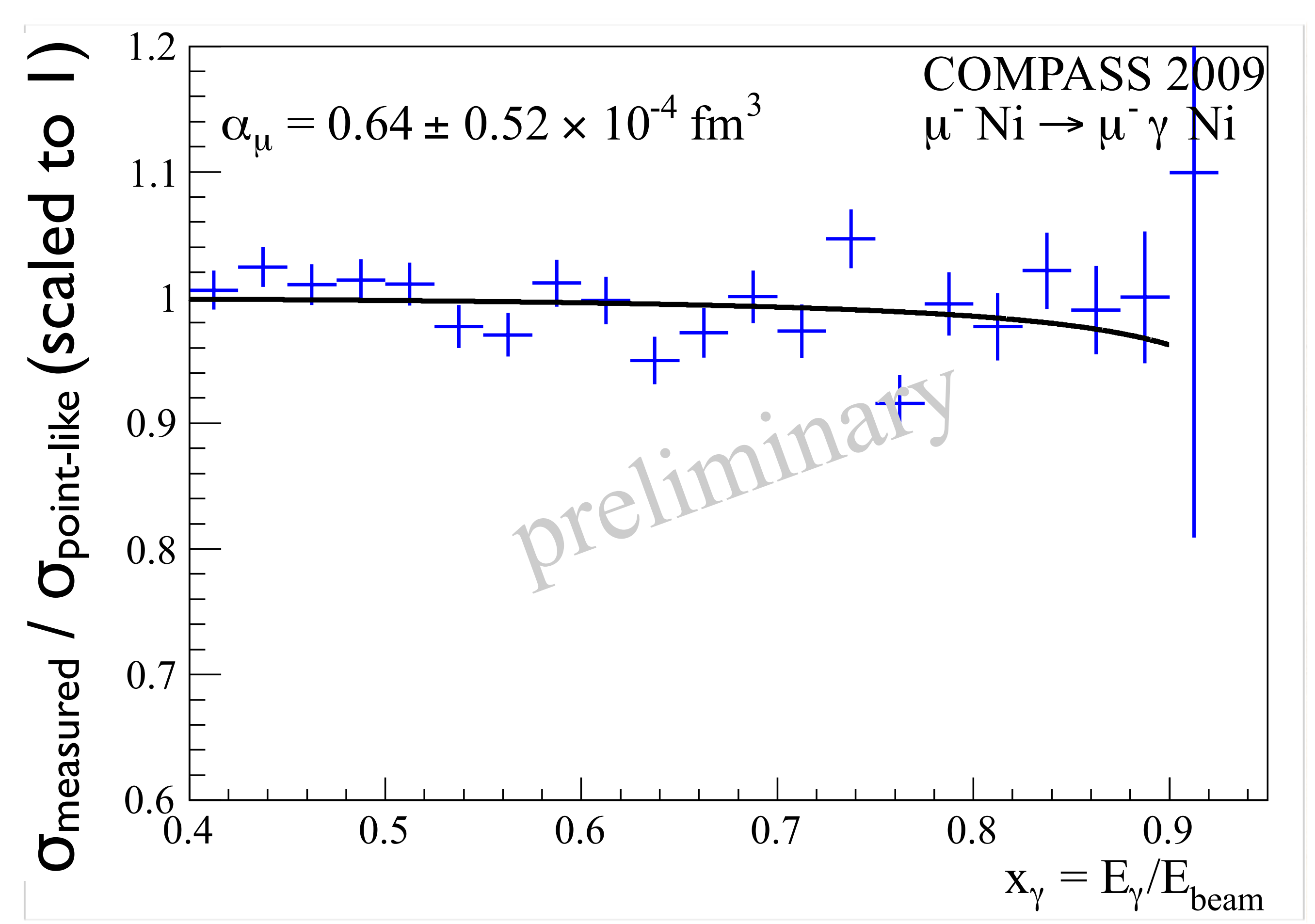



# Pion polarizabilities at COMPASS




***Assumption: $a_\pi + \beta_\pi = 0$***

***Preliminary result:***

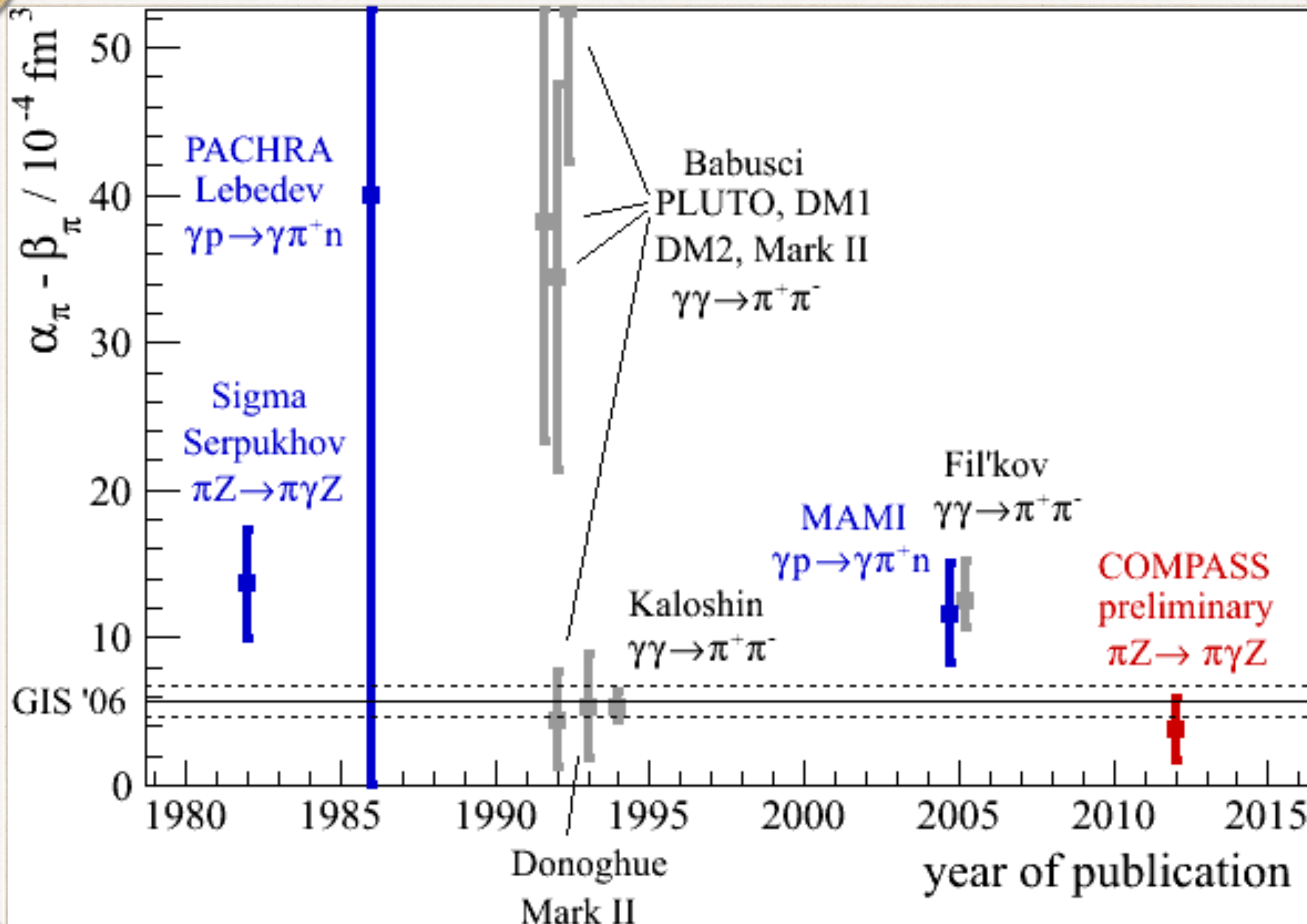
COMPASS

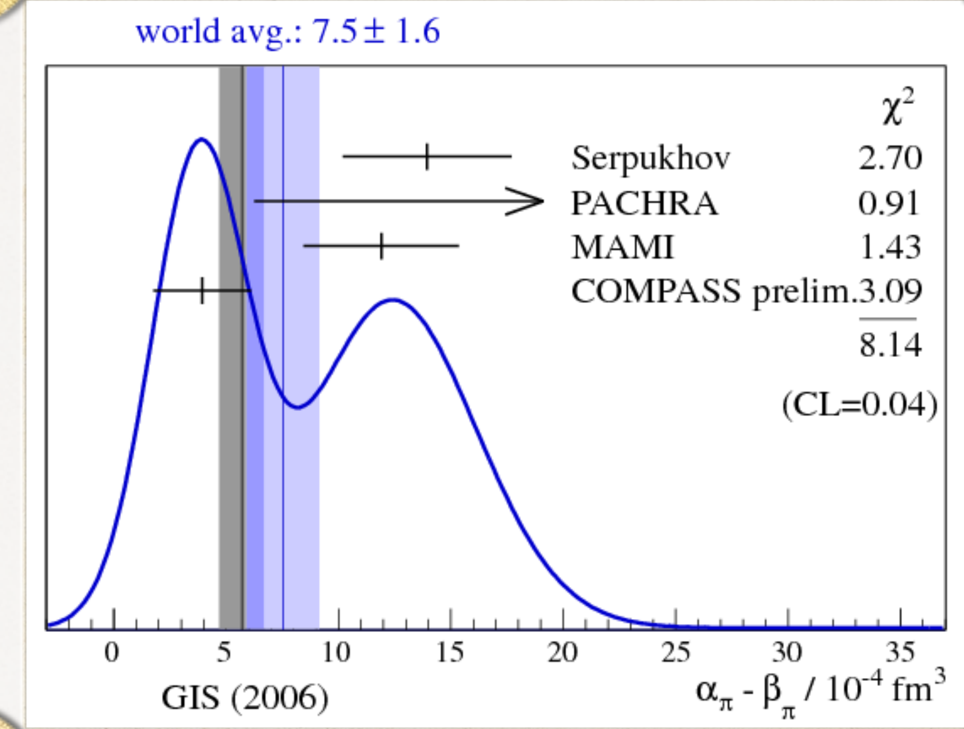
2009

***$a_\pi = (1.9 \pm 0.7_{stat} \pm 0.8_{syst}) \times 10^{-4}$ fm$^3$.***

***Main contribution to systematics coming from reproduction of tracking efficiency in MC***

# Pion polarizabilities at COMPASS




COMPASS
2009

***COMPASS preliminary result for pion polarizability is the most precise among dedicated measurements***

# Pion polarizabilities at COMPASS

**>200k of $\pi\gamma$ events with $E_\gamma/E_{beam}>0.4$**

**2012**

**Primakoff data collected in 2012 provide possibility:**

- **to reduce uncertainty of $\alpha_\pi$ measurement to $\sim 0.3\times10^{-4}\ fm^3$ ($\chi$PT: 5.7)**
- **to measure $\alpha_\pi+\beta_\pi$ with accuracy $\sim 0.03\times10^{-4}\ fm^3$ ($\chi$PT: 0.16)**
- **to access quadrupole polarizabilities of pion $\alpha_{\pi2}$ and $\beta_{\pi2}$**
- **to study dynamics of pion polarizabilities $\alpha_\pi=\alpha_\pi(s,t,\ldots)$**

# Kaon polarizabilities

## Theoretical predictions:

*χPT prediction O(p⁴):*

$$\alpha_K + \beta_K = 0$$

$$\alpha_K = \alpha_\pi \times \frac{m_\pi F_\pi^2}{m_K F_K^2} \approx \frac{\alpha_\pi}{5} \approx 0.6 \times 10^{-4} fm^3$$

***Quark confinement model:***

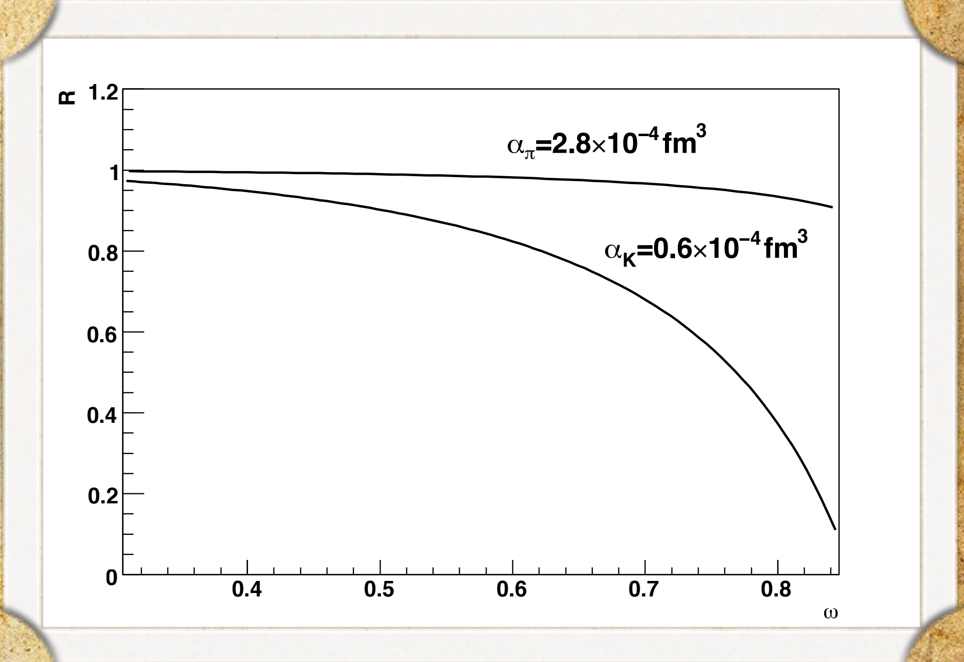
$$\alpha_K + \beta_K = 1.0 \times 10^{-4} fm^3$$

$$\alpha_K = 2.3 \times 10^{-4} fm^3$$

## Experimental results:

$a_K = (-4 \pm 11) \times 10^{-4}\ fm^3$

***- from kaonic atoms spectra***




***Polarization effects ~m³***

$$\sigma_{Prim} \sim \frac{1}{m^2}$$

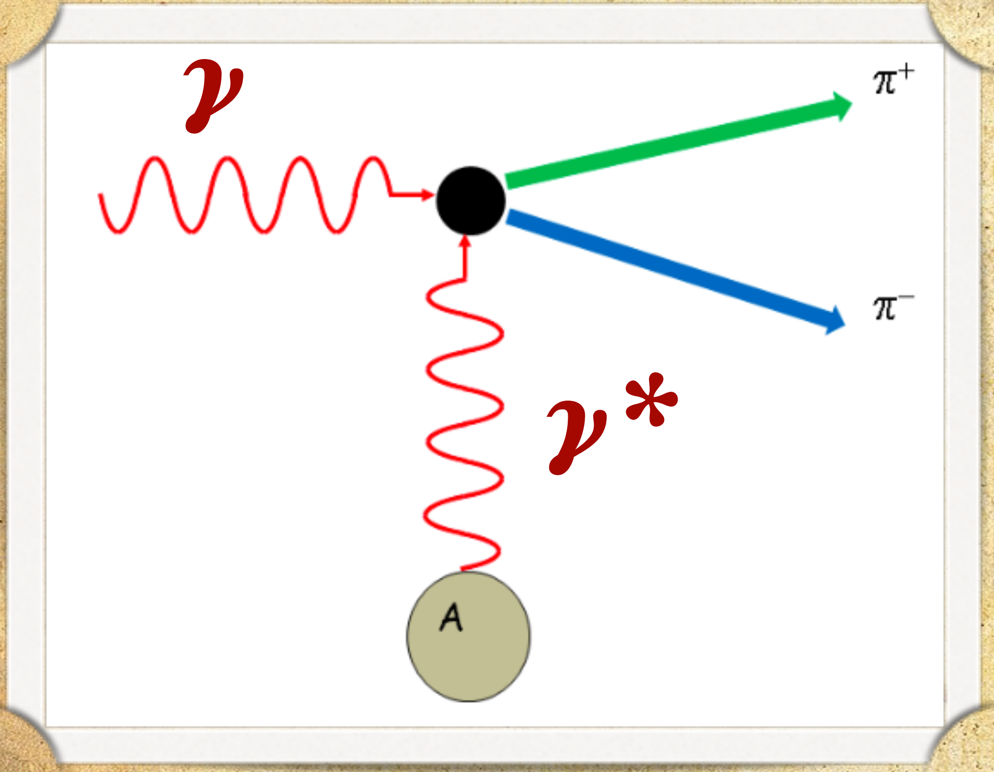
### At COMPASS:

- ~2.6% of kaons in hadron beam
- CEDARs for beam kaons identification

**1 Kγ event per 500 πγ**

# PRIMEX at JLab (plans)

## Existing detector
## GlueX at Hall-D




LoI and D. Lawrence, talk at
Chiral dynamics 2012

- Polarized photons of 8.5 GeV
- $10^7$ tagged photons per second
- 5% $X_0$ Pb target
- 500 hours of running
- ~36 000 Primakoff events

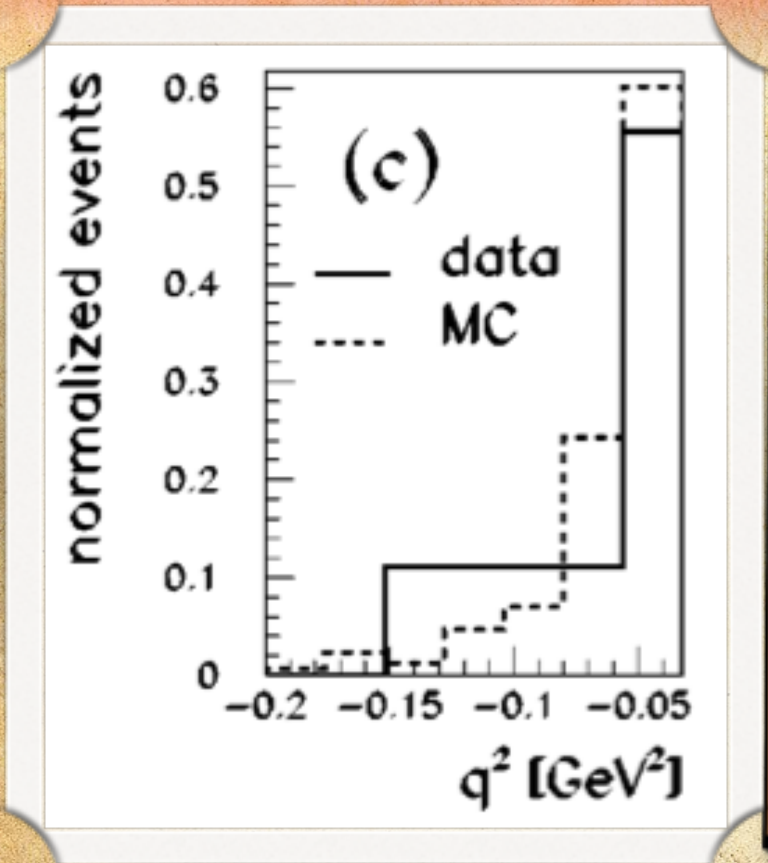
(before detector acceptance)
(vs. 400 events in MARK II)

**Main physical backgrounds:**

- pion pair production in strong interaction
- coherent $\rho^0$ production

# Primakoff scattering off electrons

*Phys. Rev. C66 , 034613 (2002)*




## SELEX collaboration:

**the first observation of $\pi^- e^- \rightarrow \pi^- e^- \gamma$ process**

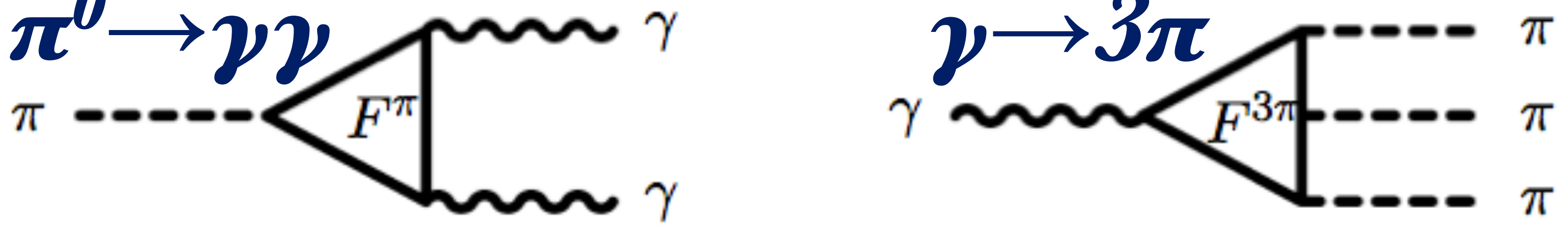
**9±3 events observed (8 expected)**

**There was an idea to measure pion polarizability using this process , but…**

| | Nuclear target | Electron target |
|---|---|---|
| Advantages | Large cross section | No strong interaction |
| Weak points | Diffractive bkg., nuclear and high Z effects | Small cross section |

# QCD chiral anomaly

$\pi^0 \to \gamma\gamma$ $\gamma \to 3\pi$




**For $\pi^0$:**

**Low-energy theorem:**

$$F_{3\pi} = \frac{eN_c}{12\pi^2 F_\pi^3} = (9.78 \pm 0.05)\,\mathrm{GeV}^{-3}$$

**For $\eta$:**

$$F_{\eta\pi\pi\gamma}(0,0,0) = \frac{e}{4\pi^2 f_\pi^3}\left(\frac{f_\pi}{f_8}\frac{cos\theta_p}{\sqrt{3}} - \frac{f_\pi}{f_0}\sqrt{\frac{2}{3}}sin\theta_p\right)$$

$$F_{\eta\pi\pi\gamma}(0,0,0) = 6.5 \pm 0.3\ \mathrm{GeV}^{-3}$$

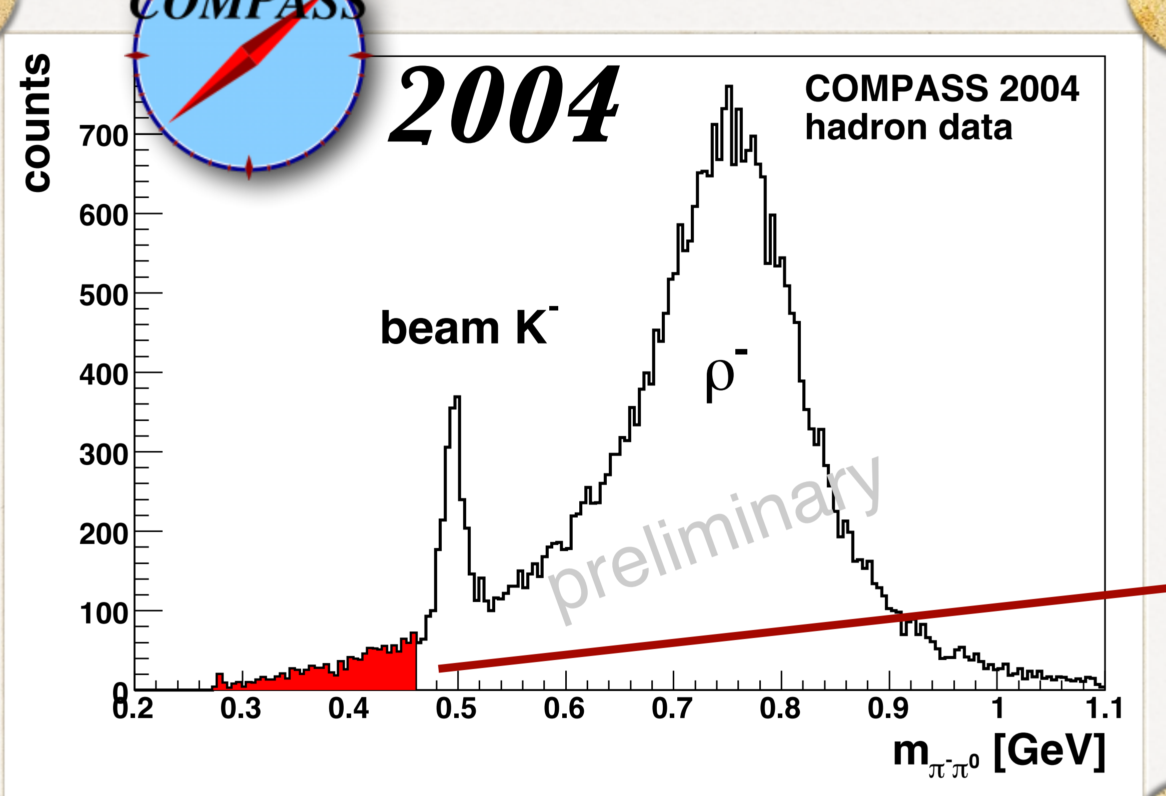
# QCD chiral anomaly

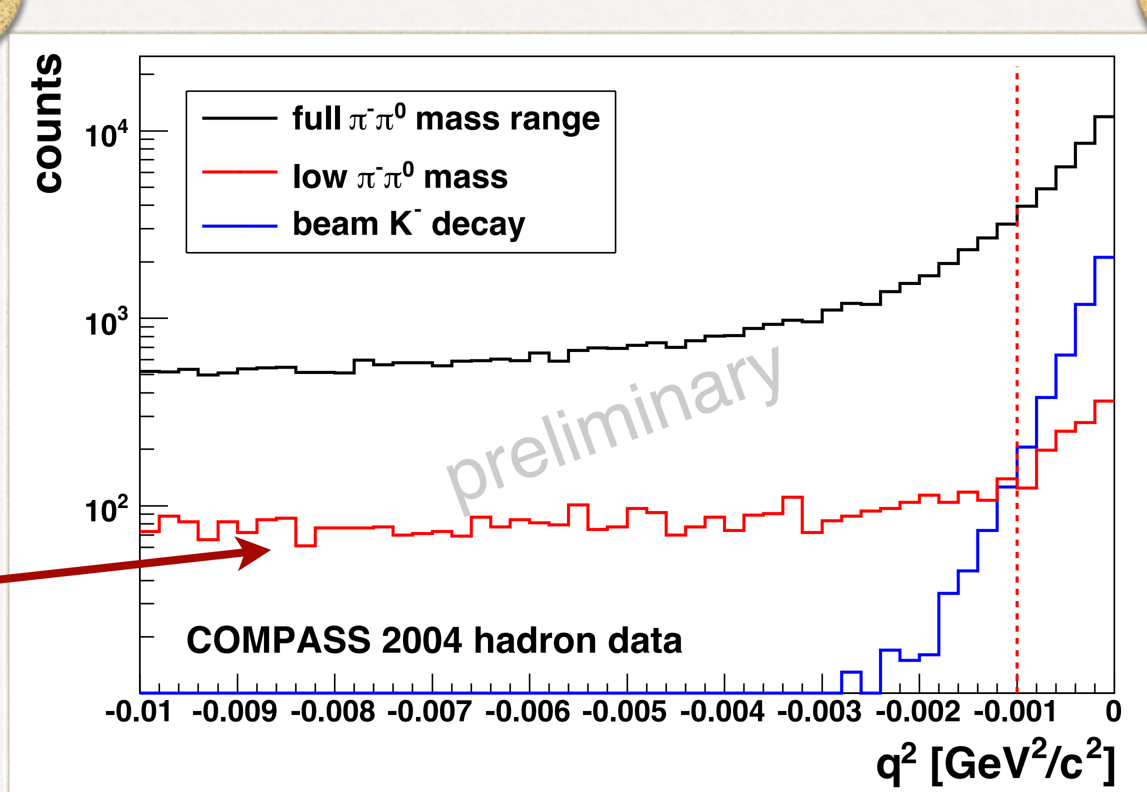
| Experiment | Year | Reaction | Cross section, nb | $F^{3\pi}$, GeV$^{-3}$ |
|---|---|---|---|---|
| FRAMM (CERN) | 1985 | $\pi^- e \rightarrow \pi^- e \pi^0$ | $\sigma = 2.11 \pm 0.47$ | $9.6 \pm 1.1$ |
| SIGMA (Protvino) | 1987 | $\pi^-(A,Z) \rightarrow \pi^-(A,Z)\,\pi^0$ | $\sigma/Z^2 = 1.63 \pm 0.23_{stat} \pm 0.16_{sys}$ | $10.7 \pm 1.2$ |
| E94-015 (JLab) | 1994 | $\gamma p \rightarrow n \pi^- \pi^0$ | Proposal | |
| For $\pi^0$: | | | Low-energy theorem | $9.78 \pm 0.05$ |

| | | | | |
|---|---|---|---|---|
| VES (Protvino) | 1998 | $\pi^- Be \rightarrow \pi^- Be\, \eta$ | $\sigma = 135 \pm 34$ | $6.9 \pm 0.7$ |
| For $\eta$: | | | Low-energy theorem | $6.5 \pm 0.3$ |

Problem of extrapolation to zero: $F(s,t,Q^2) \rightarrow F(0)$

# Chiral anomaly at COMPASS



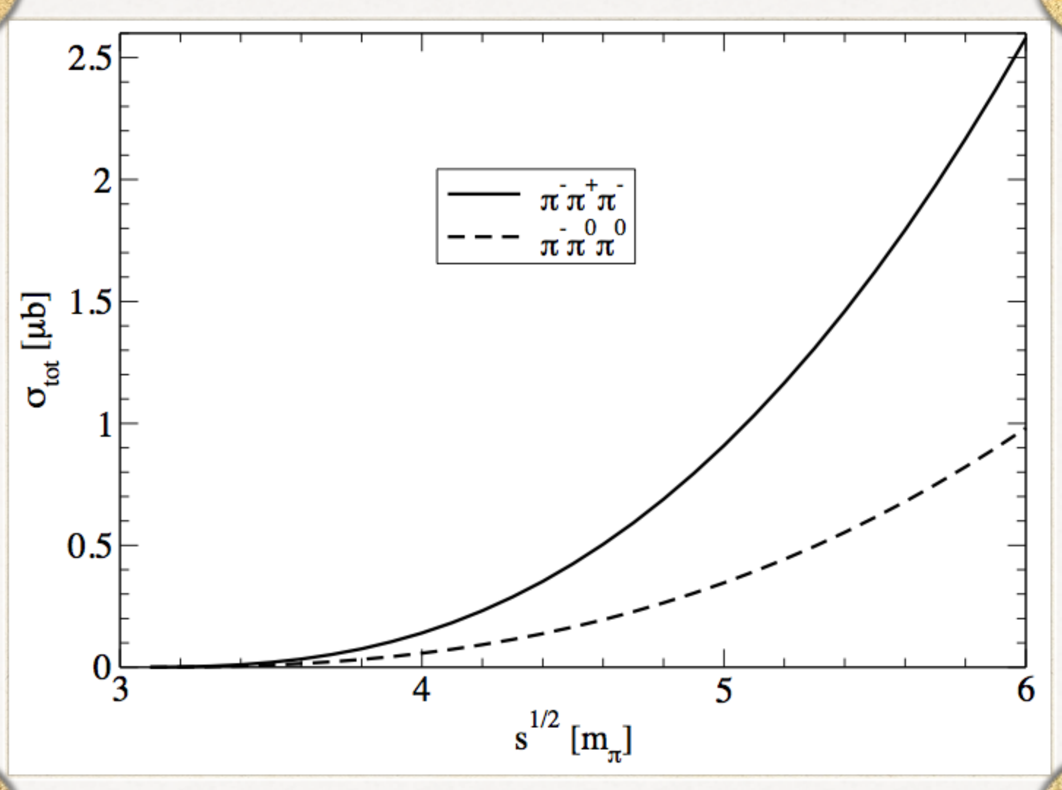

***We have more than 10k $\pi^- Z \to \pi^- Z \pi^0$ events in 2012 run data (600 events in Protvino experiment)***

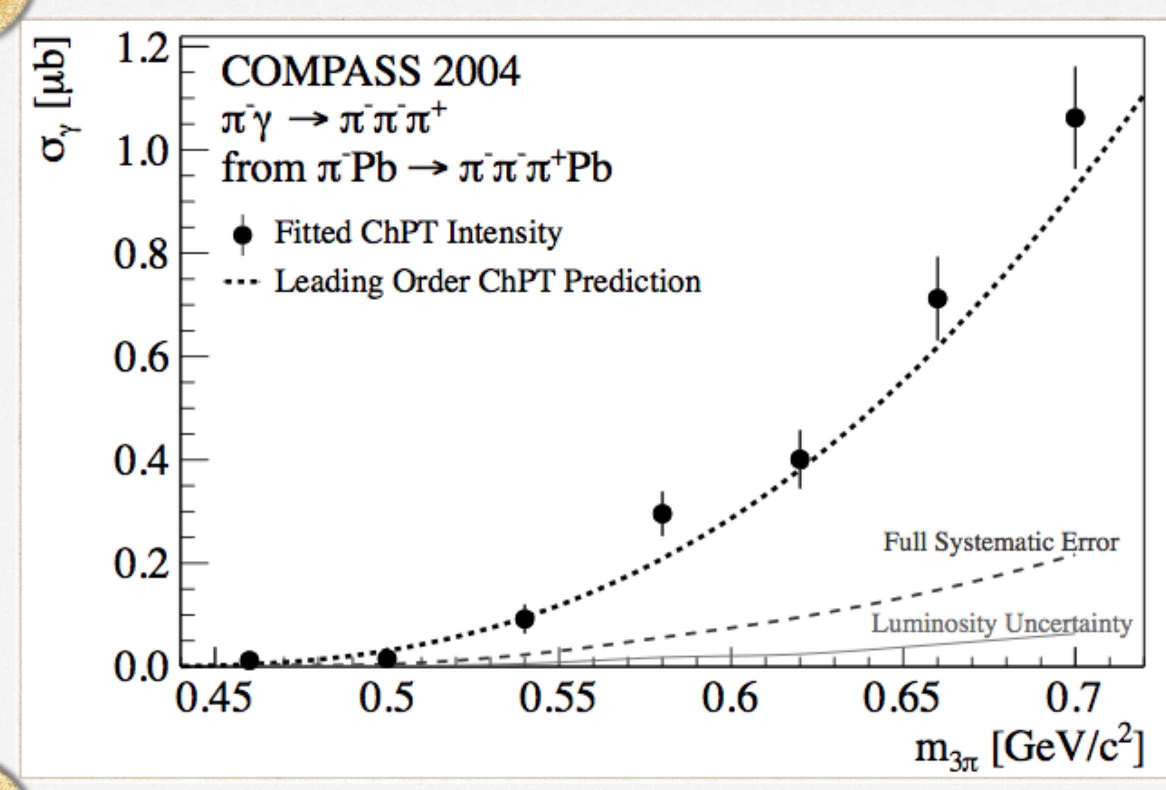
***Study of such processes like:***

***$\pi^- Z \to \pi^- Z \eta$***
***$K^- Z \to K^- Z \pi^0$***
***$K^- Z \to K^- Z \eta$***
***$K^- Z \to K^0 Z \pi^-$***

***is also possible***

# $\pi^-\gamma$ cross sections near threshold




***COMPASS already published the result for the cross section of $\pi^-\gamma\to\pi^-\pi^+\pi^-$ reaction near threshold. Reaction $\pi^-\gamma\to\pi^-\pi^0\pi^0$ is under analysis***

COMPASS **2004**

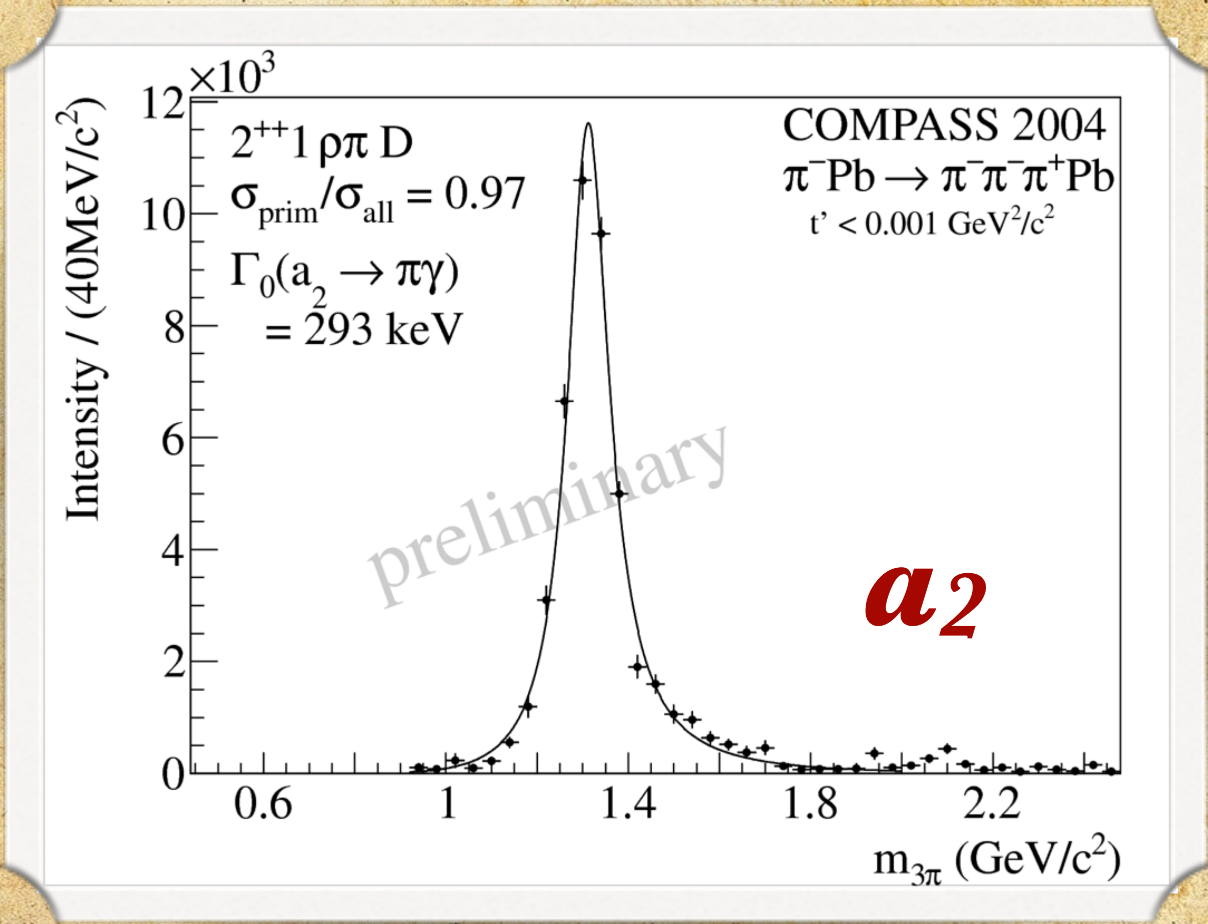
*PRL 108, 192001 (2012)*

# Radiation widths of mesons

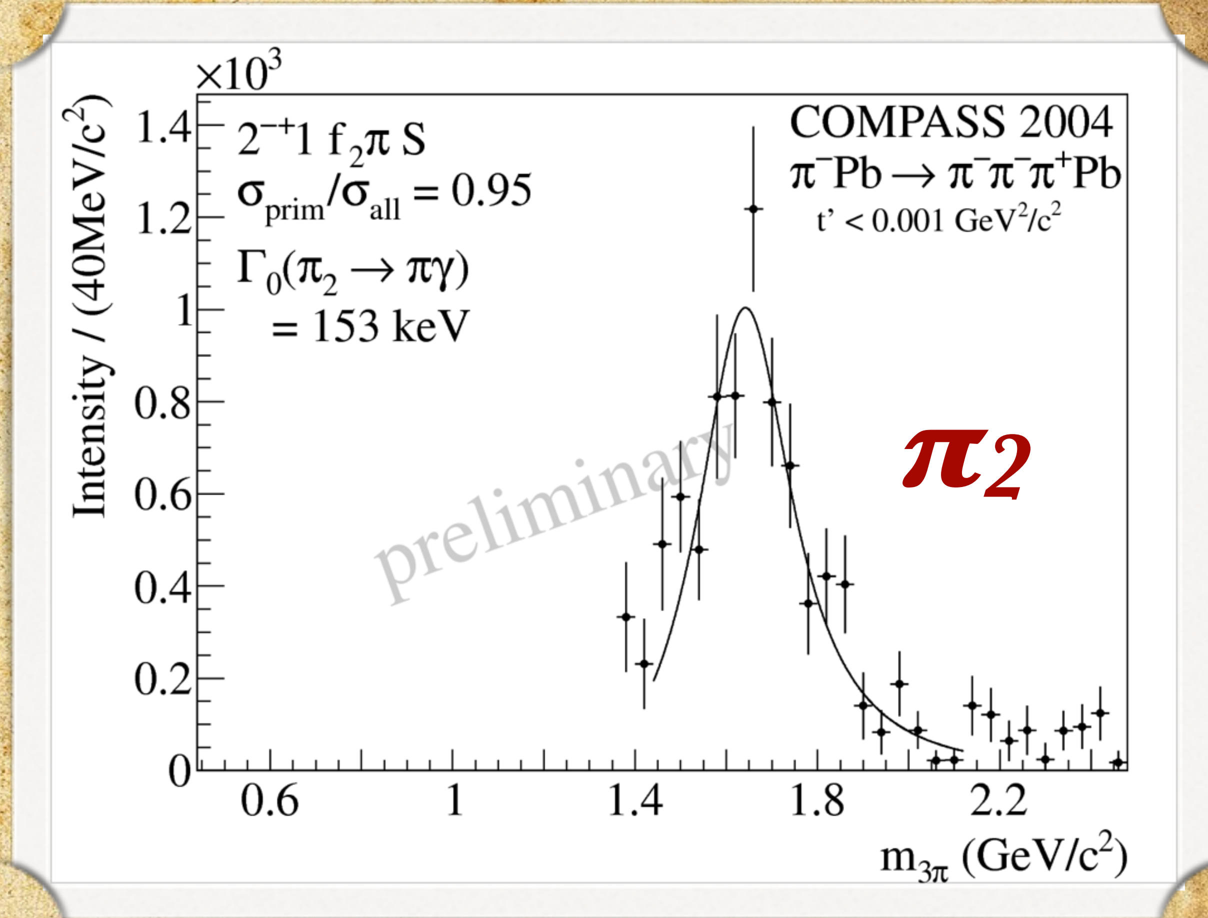
$$\sigma_{\text{Primakoff}} = \int_{m_1}^{m_2} \int_{t_0}^{t_{\max}} \frac{\mathrm{d}\sigma}{\mathrm{d}m\mathrm{d}t}\, \mathrm{d}t\, \mathrm{d}m = \Gamma_0(X \to \pi\gamma) \cdot C$$

| Meson | Full width, MeV | $\pi(K)\gamma$ width, keV |
|---|---|---|
| $\rho^-(770)$ | 149.1 | 68±7 |
| $b_1(1235)$ | 142 | 230±60 |
| $a_1(1260)$ | 367 | seen |
| $a_2(1320)$ | 105 | 287±30 |
| $K^*(892)$ | 50.8 | 50±5 |
| $K^*_2(1430)$ | 98.5 | 241±50 |

# Radiation widths of mesons





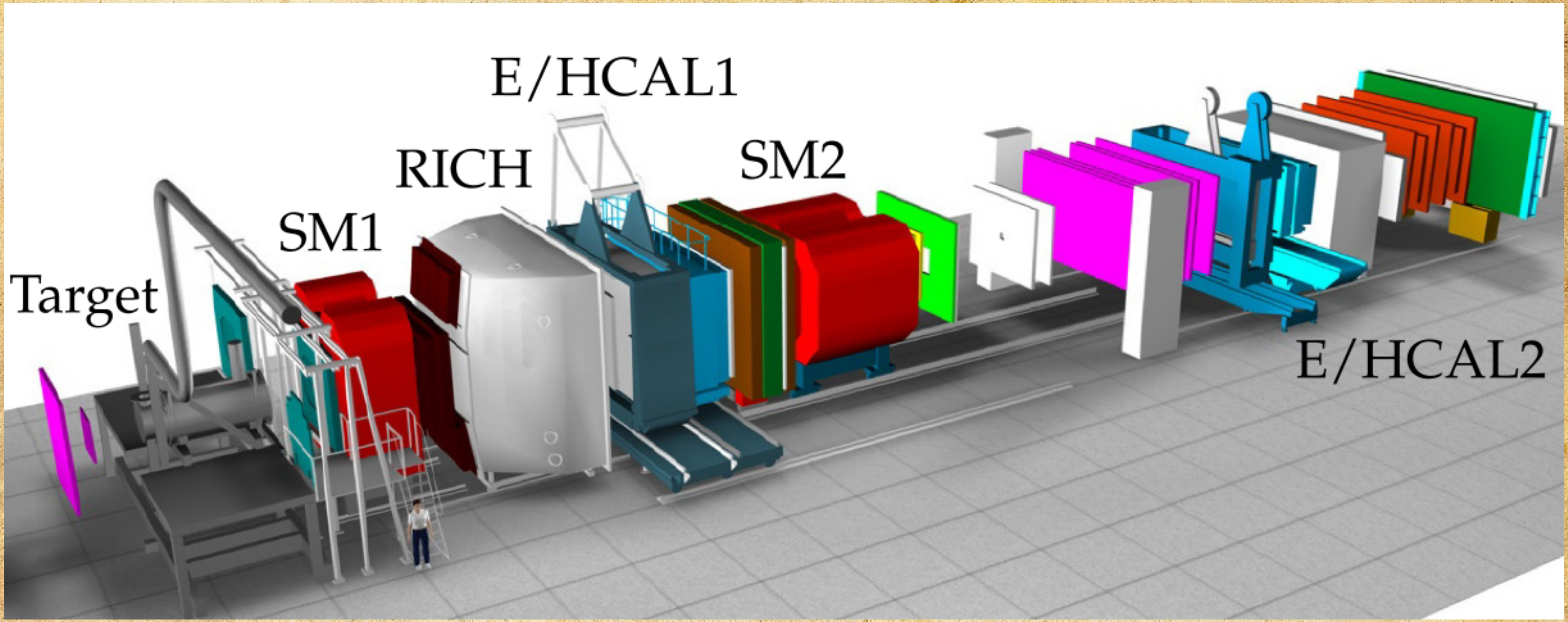



| Γ, keV | $a_2(1320)$ | $\pi_2(1670)$ |
|---|---|---|
| COMPASS | 293±5±26 | $(153\pm10\pm21)\times BR_{model}/BR_{true}$ |
| PDG aver. value | 287±30 | --- |

# Summary

- Primakoff reactions provide unique possibility to study processes induced by photons.
- Study of Primakoff reactions is one of the main goals of the COMPASS experiment.
- Main directions of Primakoff studies at COMPASS are:
  - pion and kaon polarizabilities;
  - chiral anomaly study;
  - meson radiative width;
  - $\sigma_{\pi\gamma}$ dynamics for ChiPT tests.
- Ongoing results at COMPASS:
  - the most precise measurement of $a_\pi$ (prelim. result);
  - measurement of $\pi^-\gamma\to\pi^-\pi^+\pi^-$ cross section near the threshold (published result);
  - the most precise measurement of $a_2$ radiative width (prelim. result);
  - the first measurement of $\pi_2$ radiative width (prelim. result).
- More results are expected.

# Backup slides




# The COMPASS setup