Exclusive low-t measurements with hadron beams at COMPASS

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on behalf of the COMPASS collaboration

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Outline

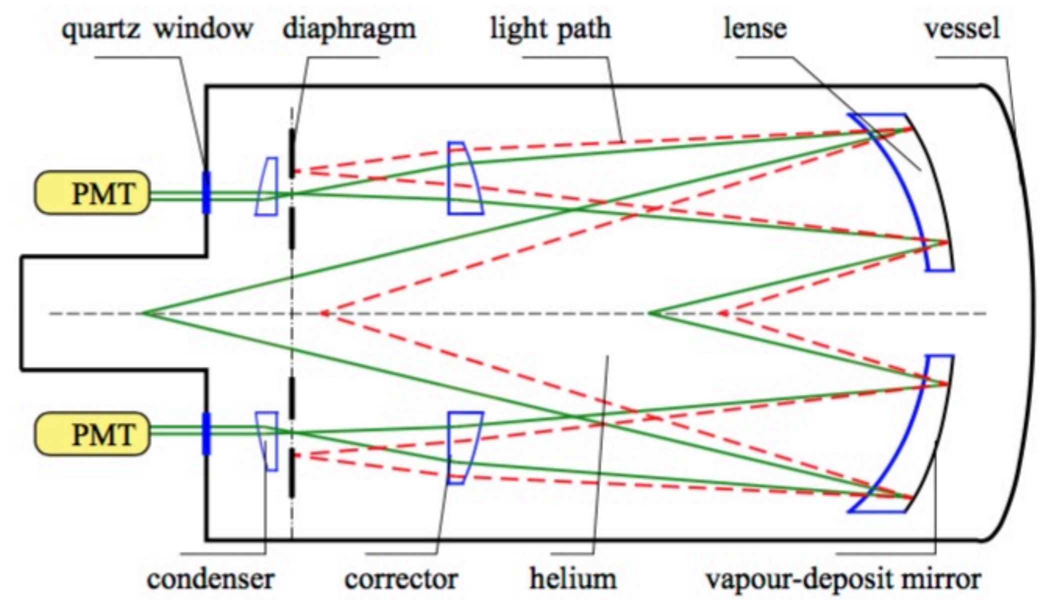
- COMPASS hadron beams
- General remarks
- Pion and kaon polarizabilities
- Chiral anomaly
- Chiral dynamics near threshold
- Radiative widths
- Possible future tasks
- Summary

COMPASS hadron beams

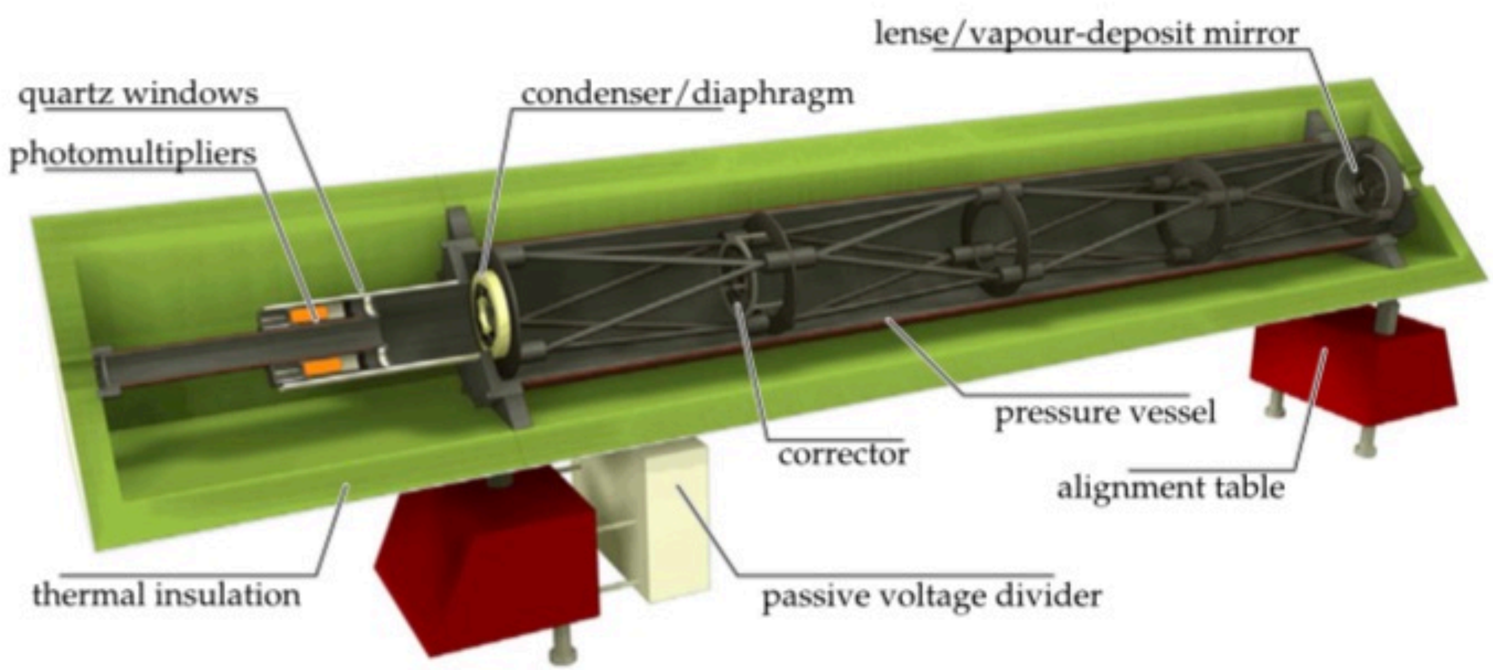
Composition of the beams

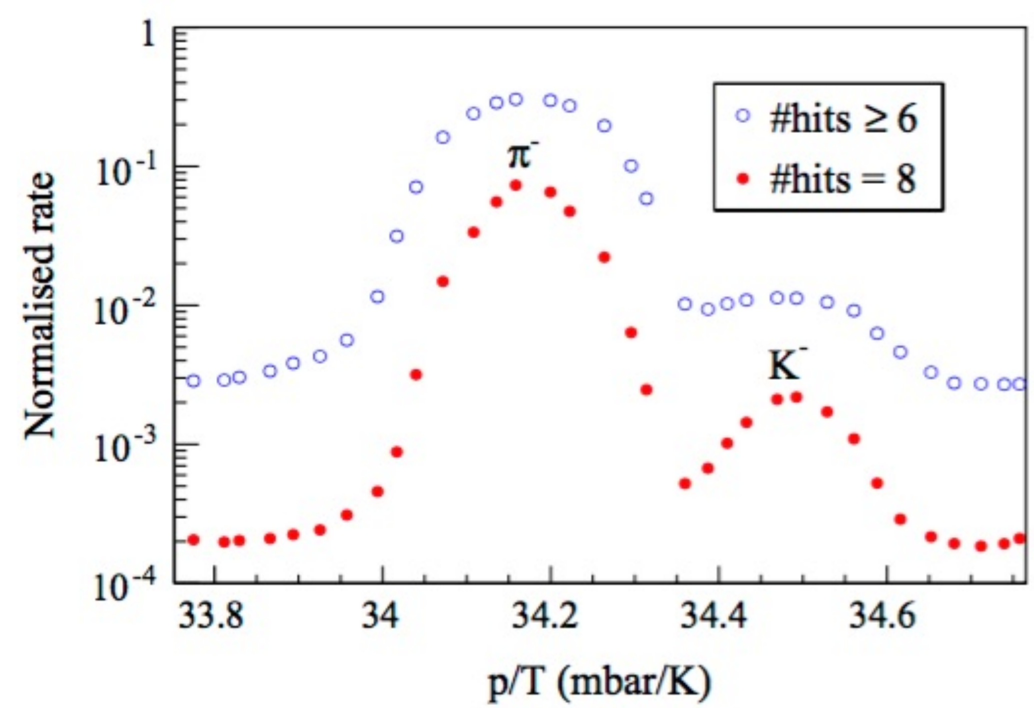
Momentum (GeV/c)	Positive beams			Negative beams		
	π^+	K^+	p	π^-	K^-	$\bar{p}$
100	0.618	0.015	0.367	0.958	0.018	0.024
160	0.360	0.017	0.623	0.966	0.023	0.011
190	0.240	0.014	0.746	0.968	0.024	0.008
200	0.205	0.012	0.783	0.969	0.024	0.007

+ some contamination of muons and electrons

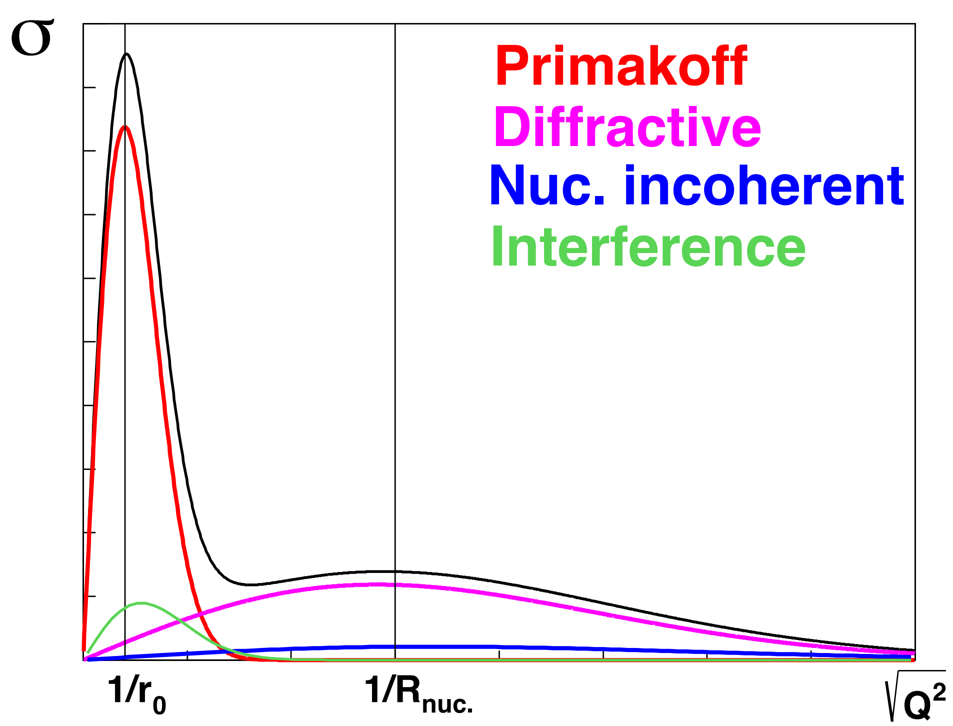


Two Cherenkov detectors (CEDARs) for π/K separation





Low-t ?

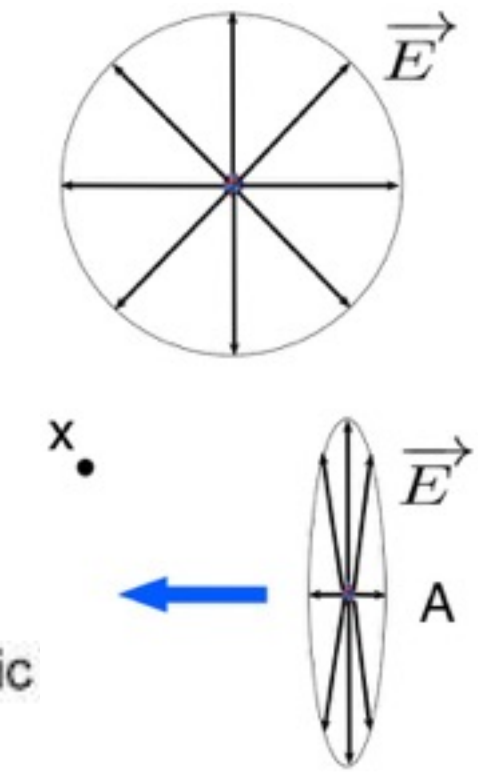


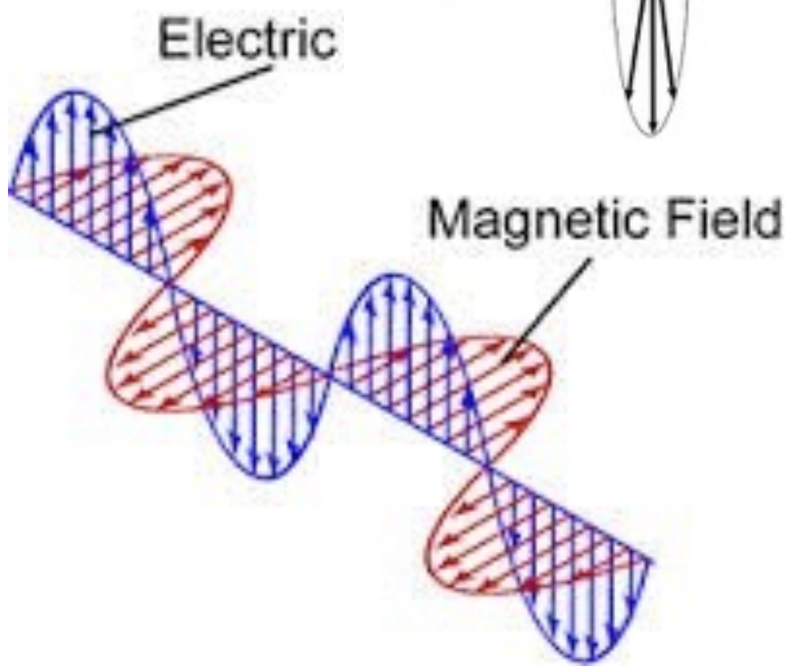
Electromagnetic field of fast charged particle is similar to a field of electromagnetic wave

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

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

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





density of equivalent photons:

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

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

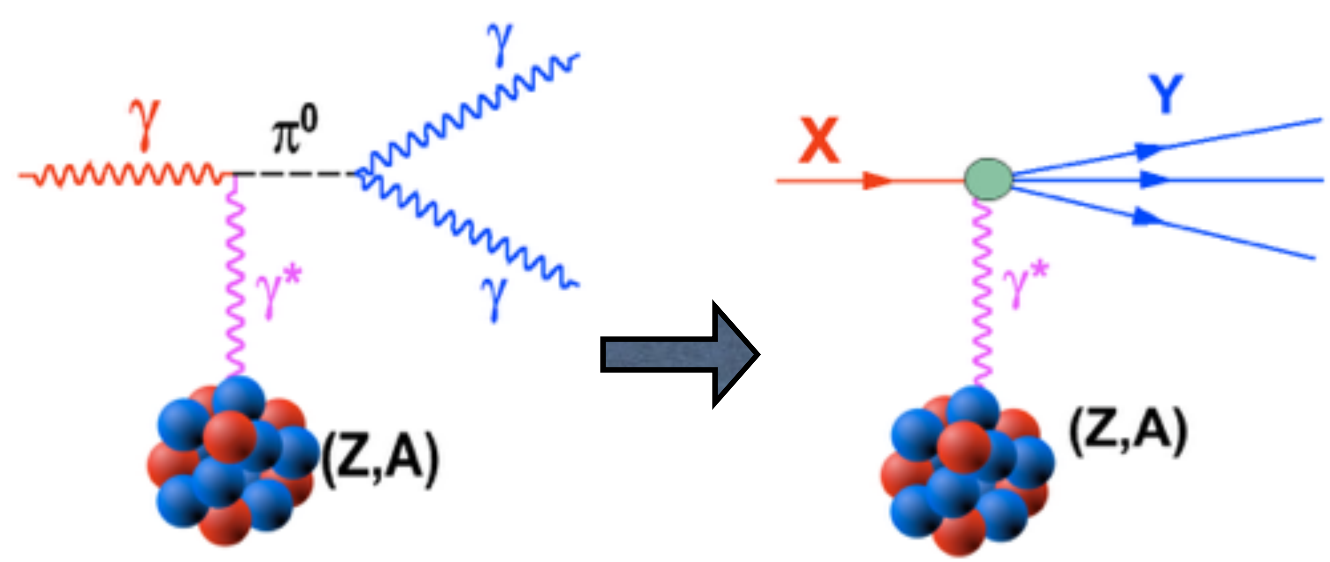
January 2, 1951

IT has now been well established experimentally that neutral π-mesons (π^0) decay into two photons.[1] Theoretically, this two-photon type of decay implies zero π^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 π^0 wave field, φ, and the electromagnetic wave field, **E**, **H**, representable in the form:

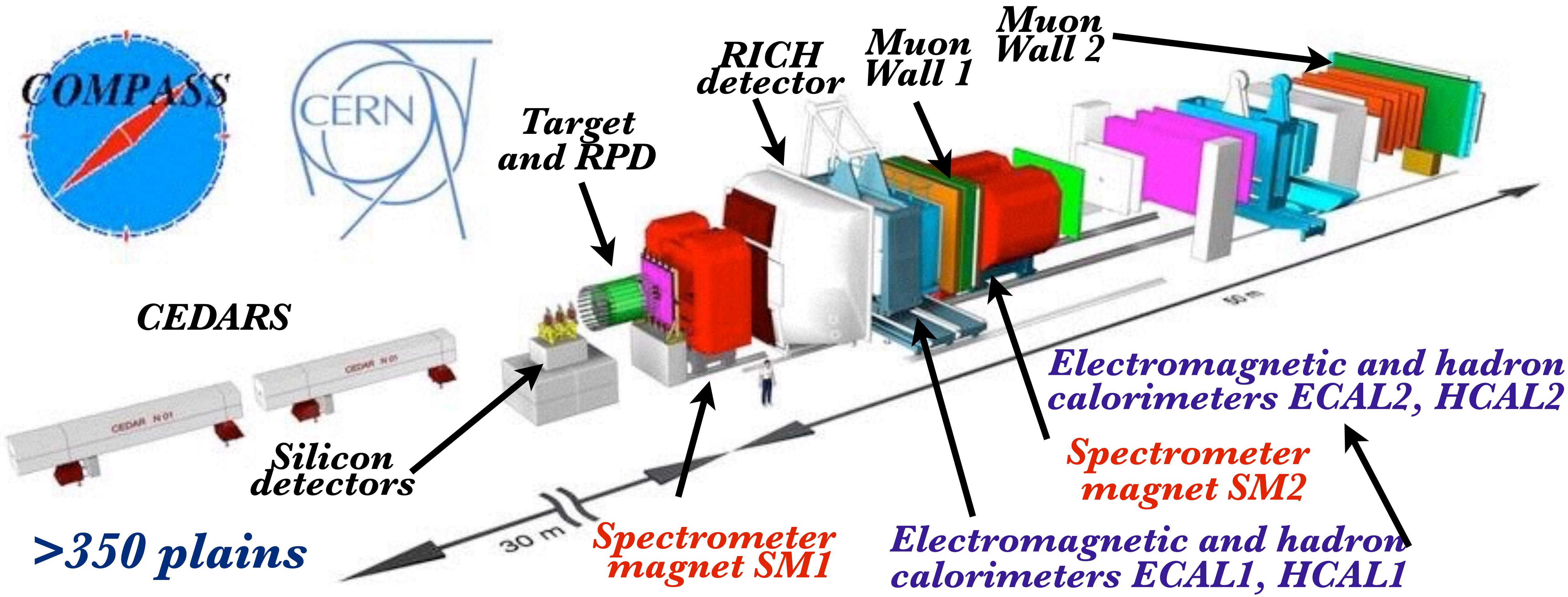
$$\text{Interaction Energy Density} = \eta(\hbar/\mu c)(\hbar c)^{-\frac{1}{2}}\varphi\mathbf{E}\cdot\mathbf{H}. \quad (1)$$

Here φ 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 π^0),

Coulomb field of nucleus can be used as photon target!



The COMPASS setup



- *CEDAR detectors for beam particle identification*
- *Set of nuclear targets (from H to Pb)*
- *Precise silicon detectors to measure small scattering angles*
- *Magnetic spectrometer for pion momentum measurement*
- *Electromagnetic calorimeter with good energy and spacial resolution for photon detection*
- *Muon identification system*
- *Muon beam*

Polarizabilities of hadrons

Compton amplitude:

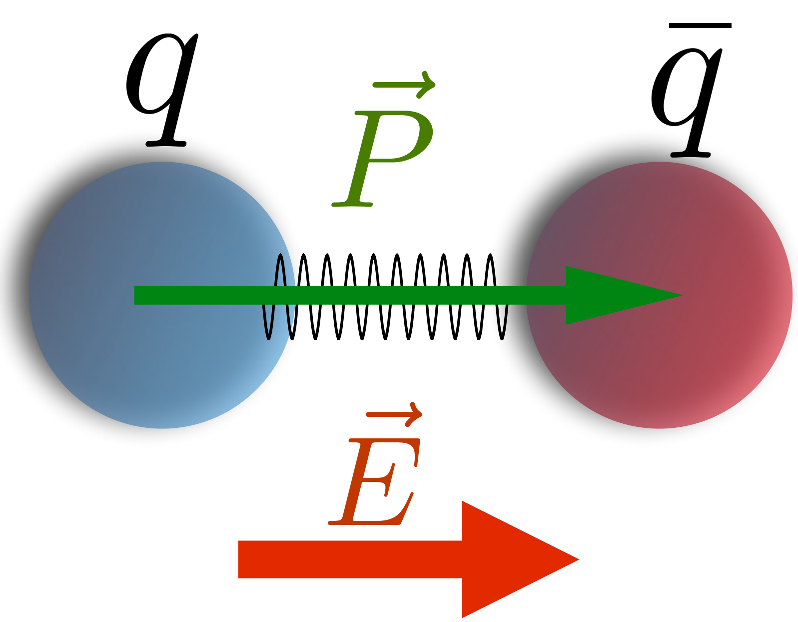
$$A(\gamma X \to \gamma X) =$$

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

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

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

$$\mathbf{H} = \ldots -(\alpha_X E^2 + \beta_X H^2)/2$$



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

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

PDG data:

	α_X, 10^{-4} fm^3	β_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 ?

Pion polarizability (theory)

Chiral theory 2-loop approximation ($O(p^6)$):

$$\alpha_\pi - \beta_\pi = (5.7 \pm 1.0) \times 10^{-4} fm^3$$

$$\alpha_\pi + \beta_\pi = (0.16 \pm 0.1) \times 10^{-4} fm^3$$

Partially conserved axial current (PCAC) approach:

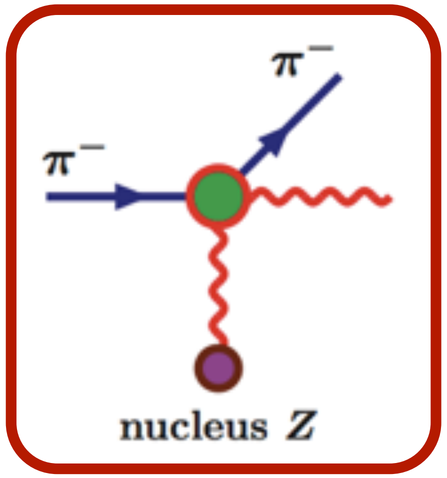
$$\alpha_\pi = -\beta_\pi \propto \frac{F_A}{F_V} = \frac{1}{6}(l_6 - l_5)$$

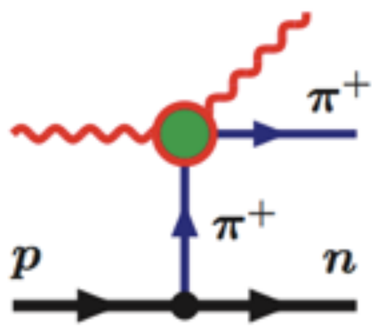
$\alpha_\pi = -\beta_\pi = (2.78 \pm 0.1) \times 10^{-4} fm^3$ **- basing on PIBETA results for F_A/F_V**

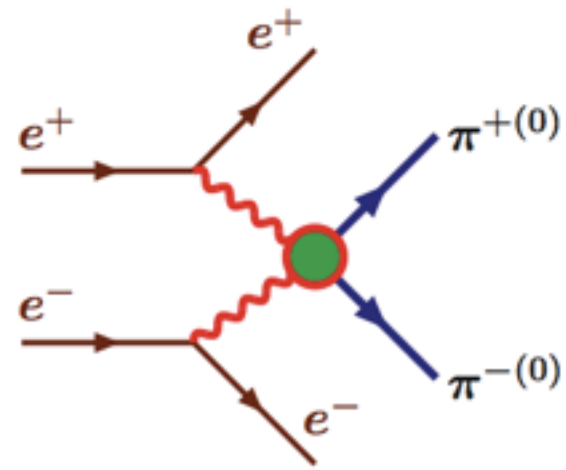
The most of other models like quark confinement model, QCD sum rules, dispersion relations etc. gives:

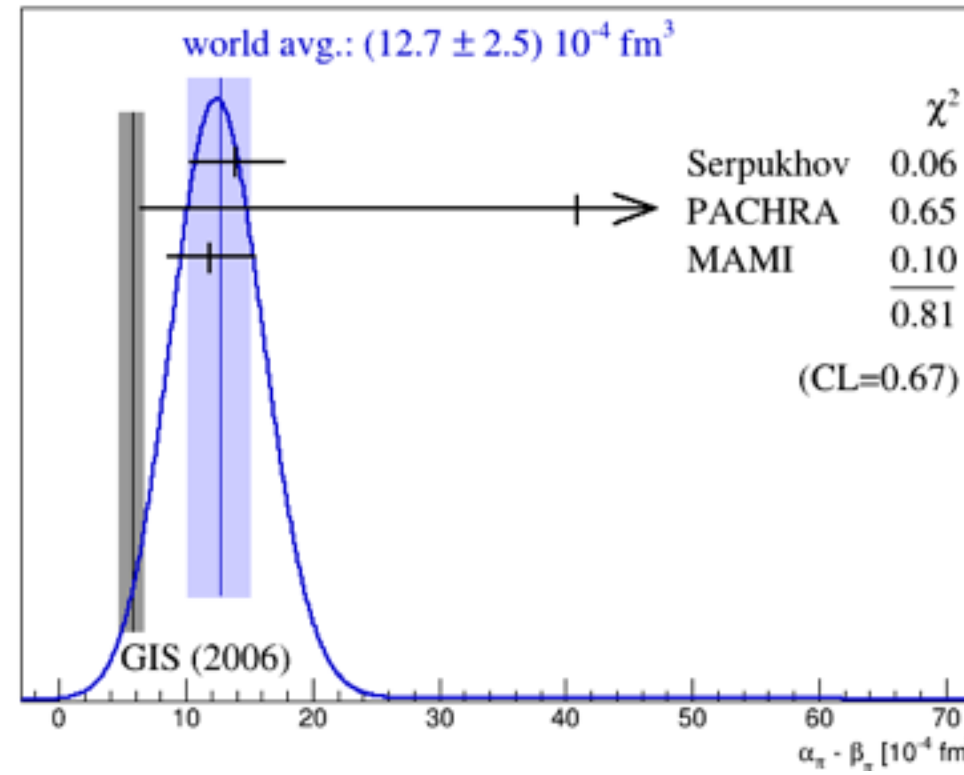
$$8 \times 10^{-4} fm^3 \leq \alpha_\pi - \beta_\pi \leq 14 \times 10^{-4} fm^3$$

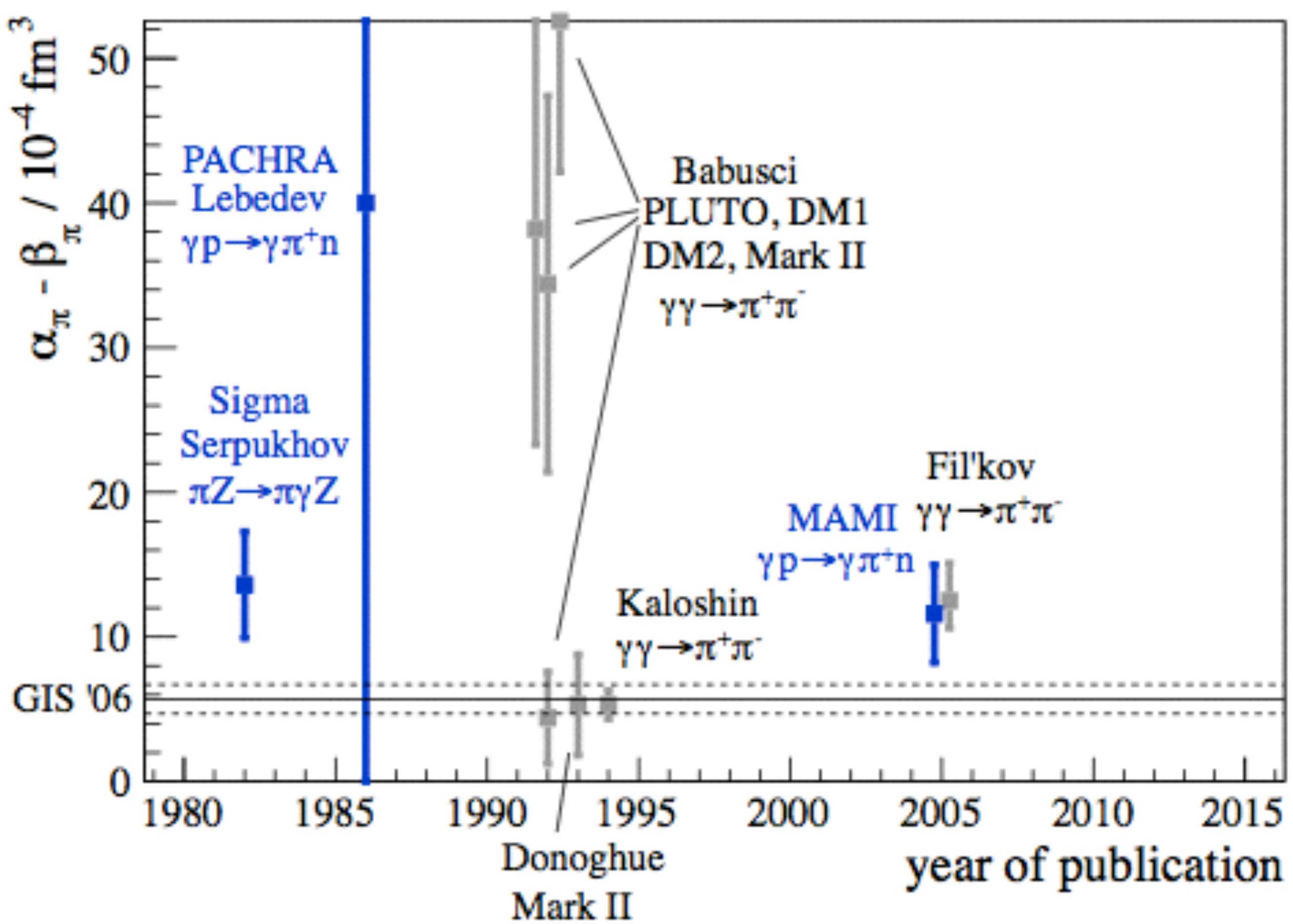
Pion polarizability: experiment









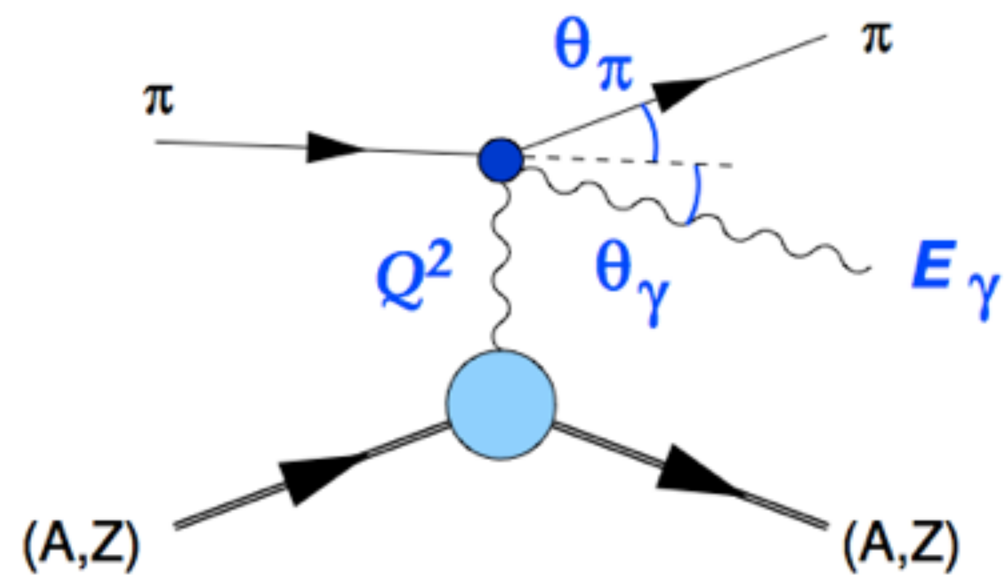


Data	Reaction	Paramater	$[10^{-4} fm^3]$
Serpukhov ($\alpha_\pi + \beta_\pi = 0$)	$\pi Z \to \pi Z \gamma$	α_π	6.8±1.4±1.2
Serpukhov ($\alpha_\pi + \beta_\pi \neq 0$)		$\alpha_\pi + \beta_\pi$ β_π	1.4±3.1±2.8 $-7.1 \pm 2.8 \pm 1.8$
Lebedev	$\gamma N \to \gamma N \pi$	α_π	20±12
Mami A2	$\gamma p \to \gamma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

Polarizabilities and cross section

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

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



Compton cross section:

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

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

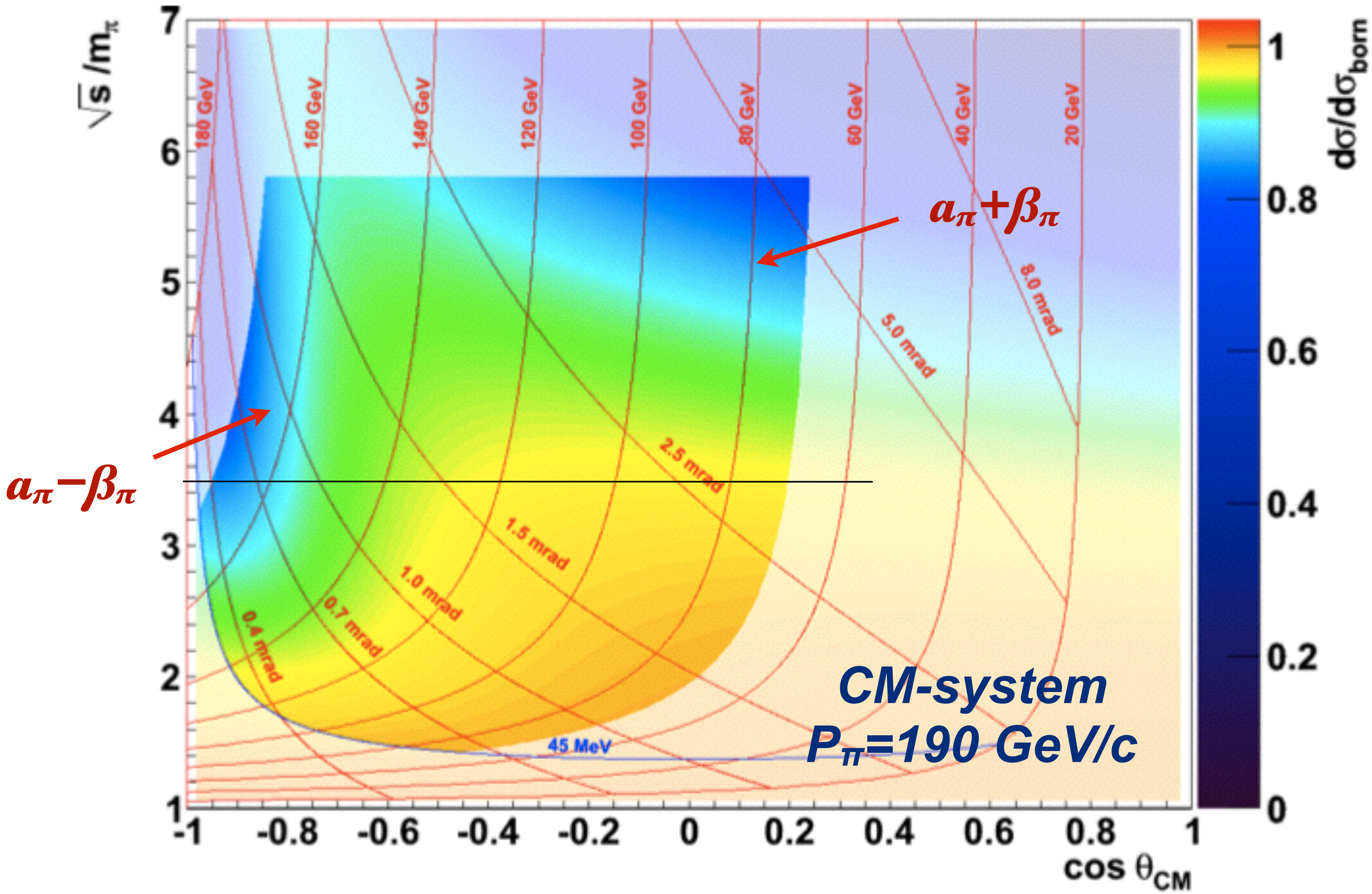
$$\mathcal{P} = z_-^2(\alpha_\pi - \beta_\pi) + \frac{s^2}{m_\pi^4} z_+^2(\alpha_\pi + \beta_\pi)$$

$Q^2 \ll m_\pi^2$

$\sigma \sim Z^2$

α_π and β_π can be extracted separately from the measurement of the differential cross section

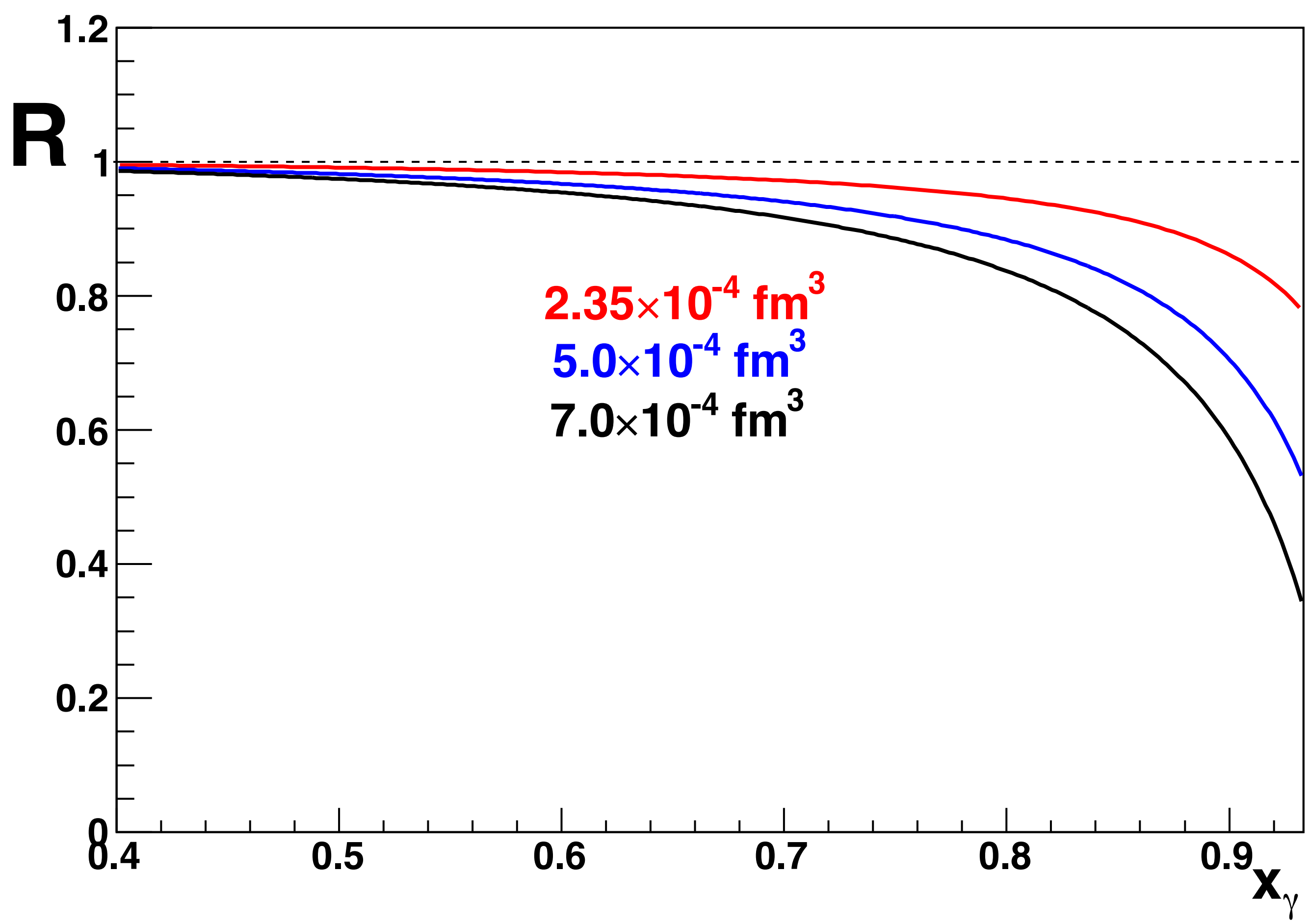
Polarizability effects



Simple case: $\alpha_\pi = -\beta_\pi$

For the case $\alpha_\pi + \beta_\pi = 0$ **=0**

$$R = \frac{\sigma}{\sigma_{p.l.}} \approx 1 - \frac{3}{2} \cdot \frac{x_\gamma^2}{1 - x_\gamma} \cdot \frac{m_\pi^3}{\alpha} \cdot \alpha_\pi$$



***x_γ* - relative energy of emitted photon in Lab system**

Pion polarizabilities at COMPASS

$\pi\gamma$: $x_\gamma > 0.4$

Primakoff pilot run 2004

~ 1 week

~10k events

$0.5X_0$ Pb

~60k events

$0.3X_0$ Ni

~ 3 weeks

Primakoff run 2009

Published result

Primakoff run 2012

~ 3 months

~200k events

$0.3X_0$ Ni

Time

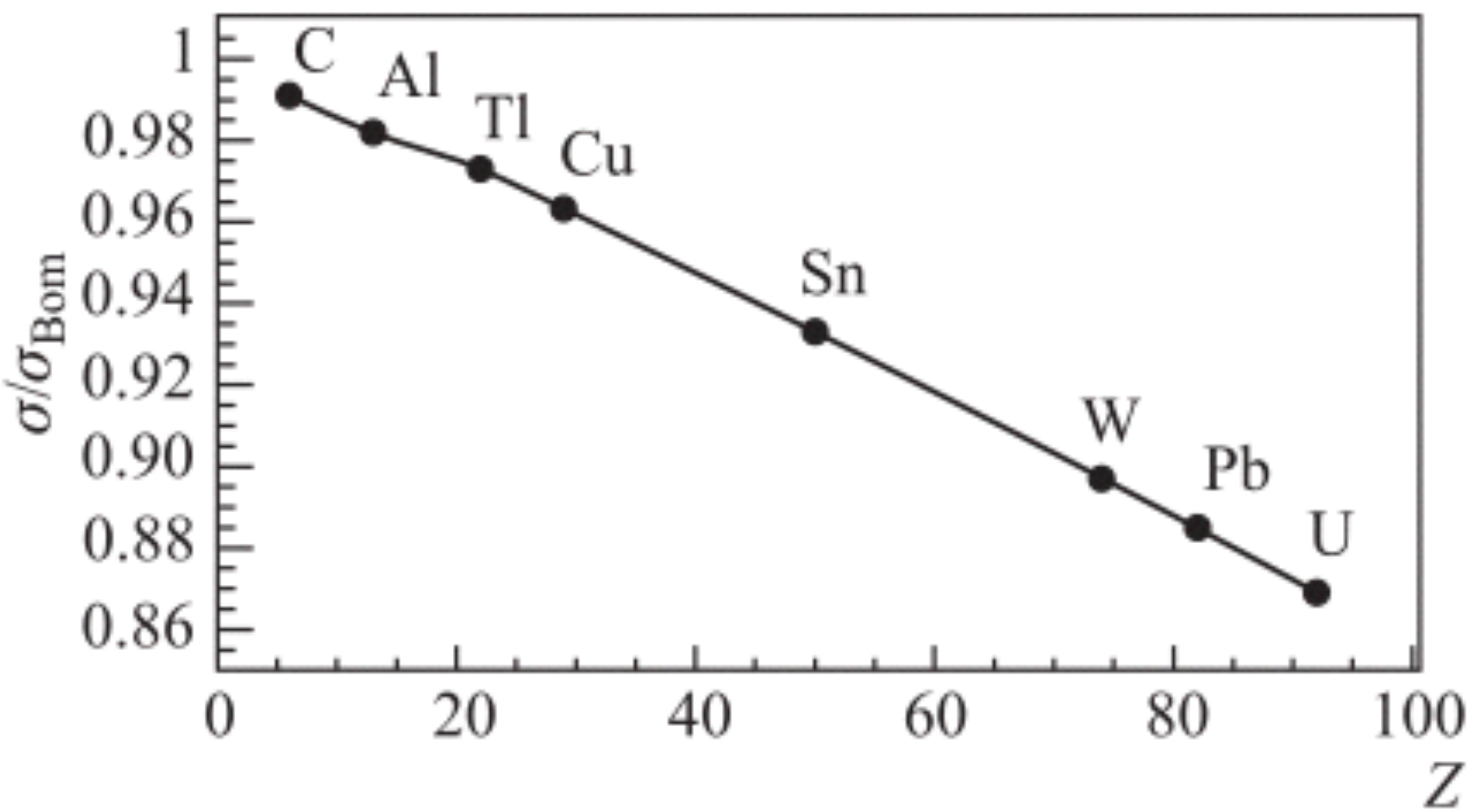
Under analysis

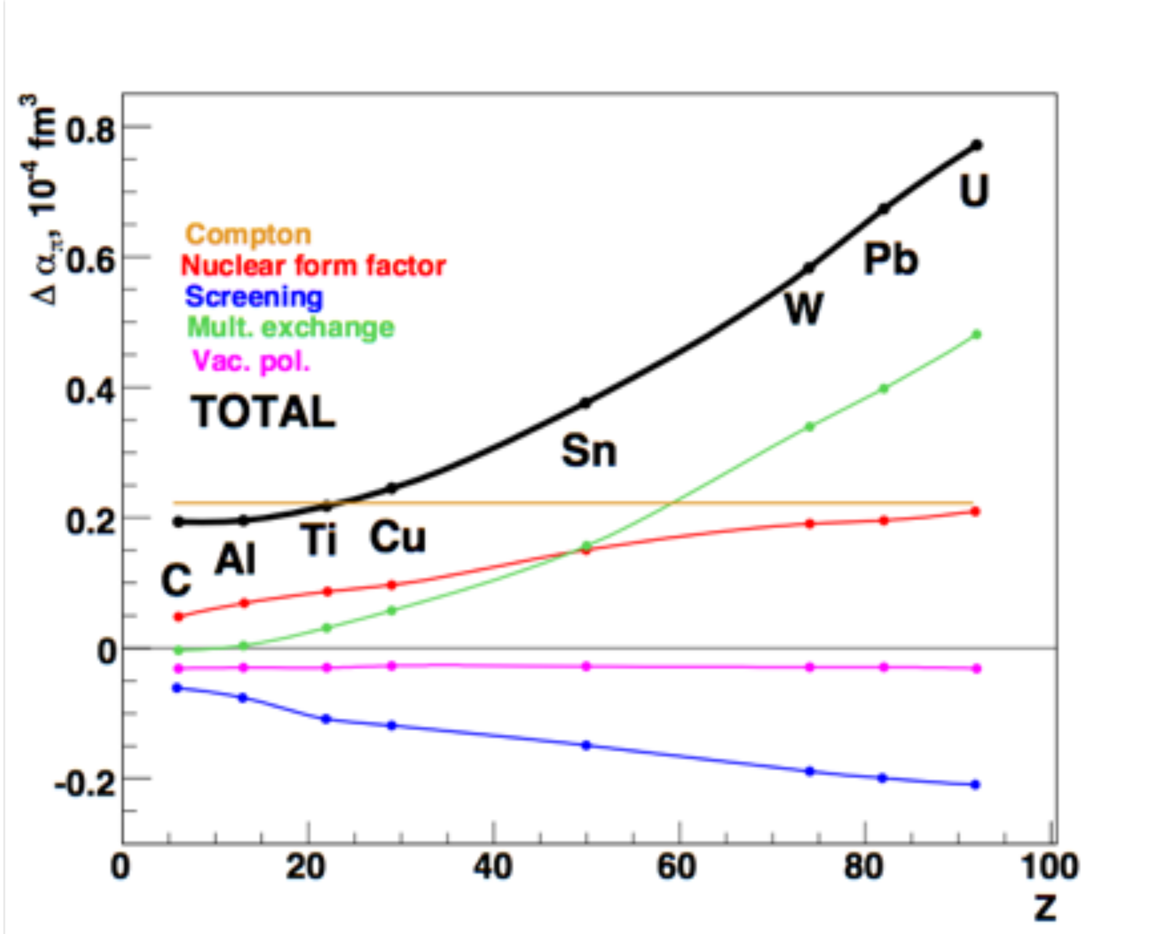
Choice of the target material

$$\sigma_{Born} \sim Z^2$$

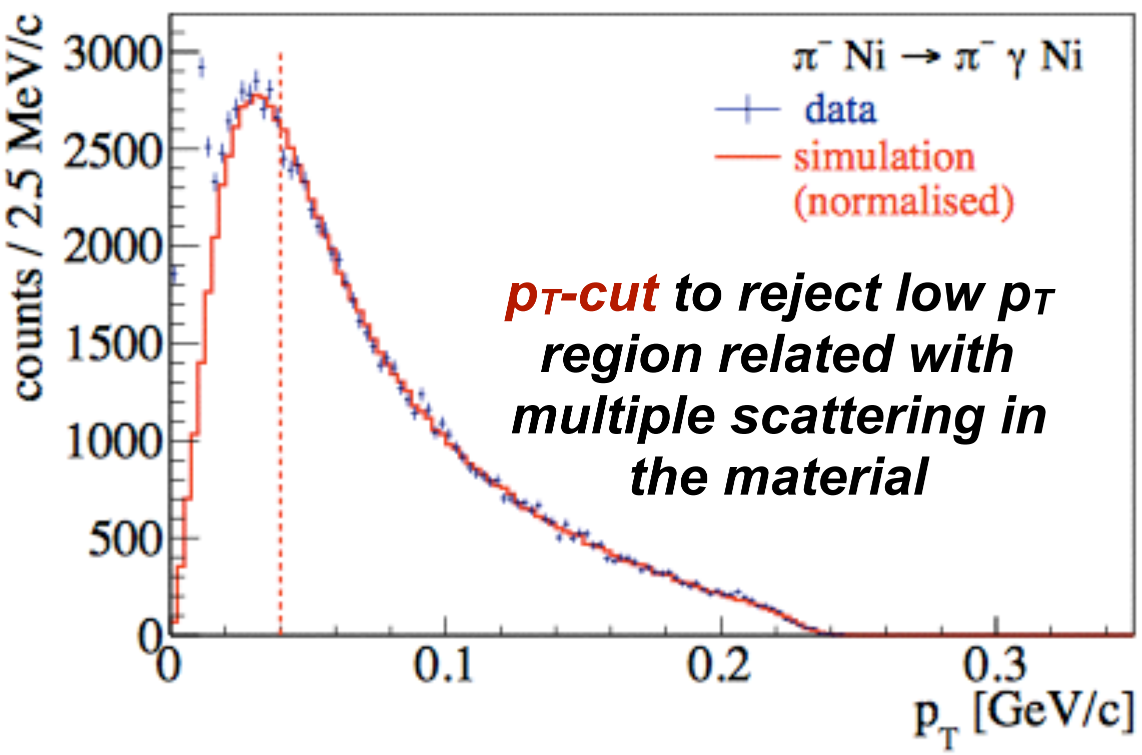
Serpukhov — **COMPASS 2004** — **COMPASS 2009, 2012**

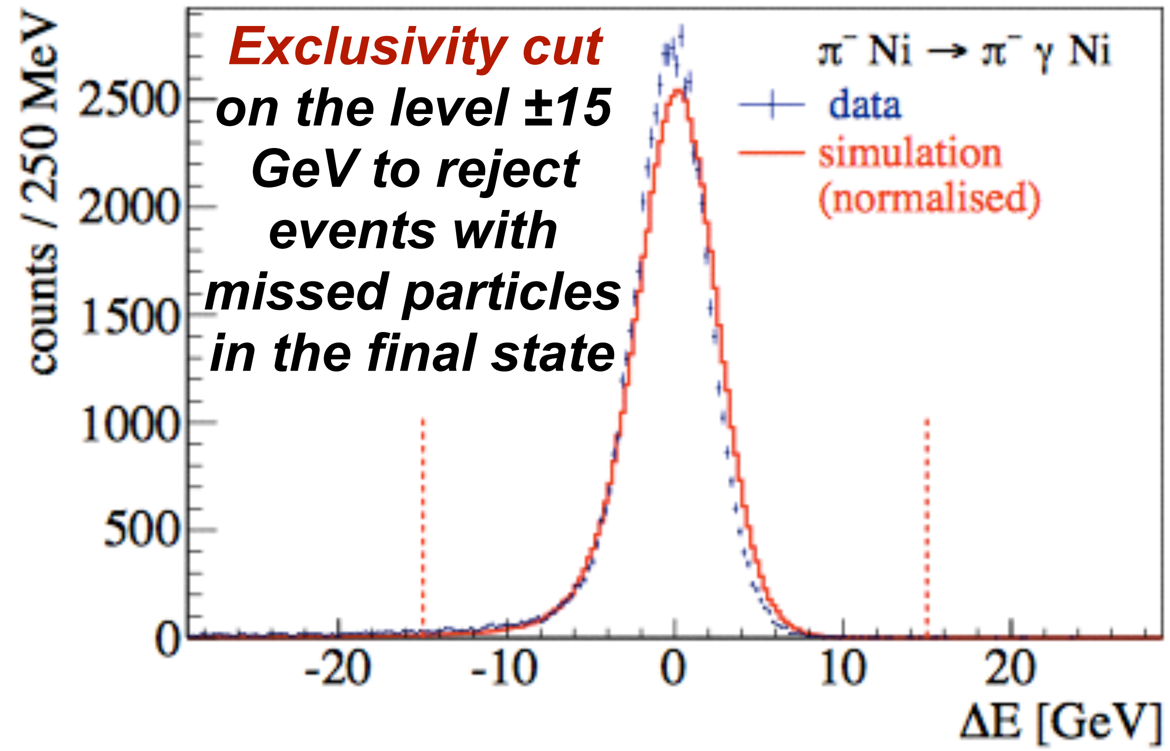
C → Pb → Ni

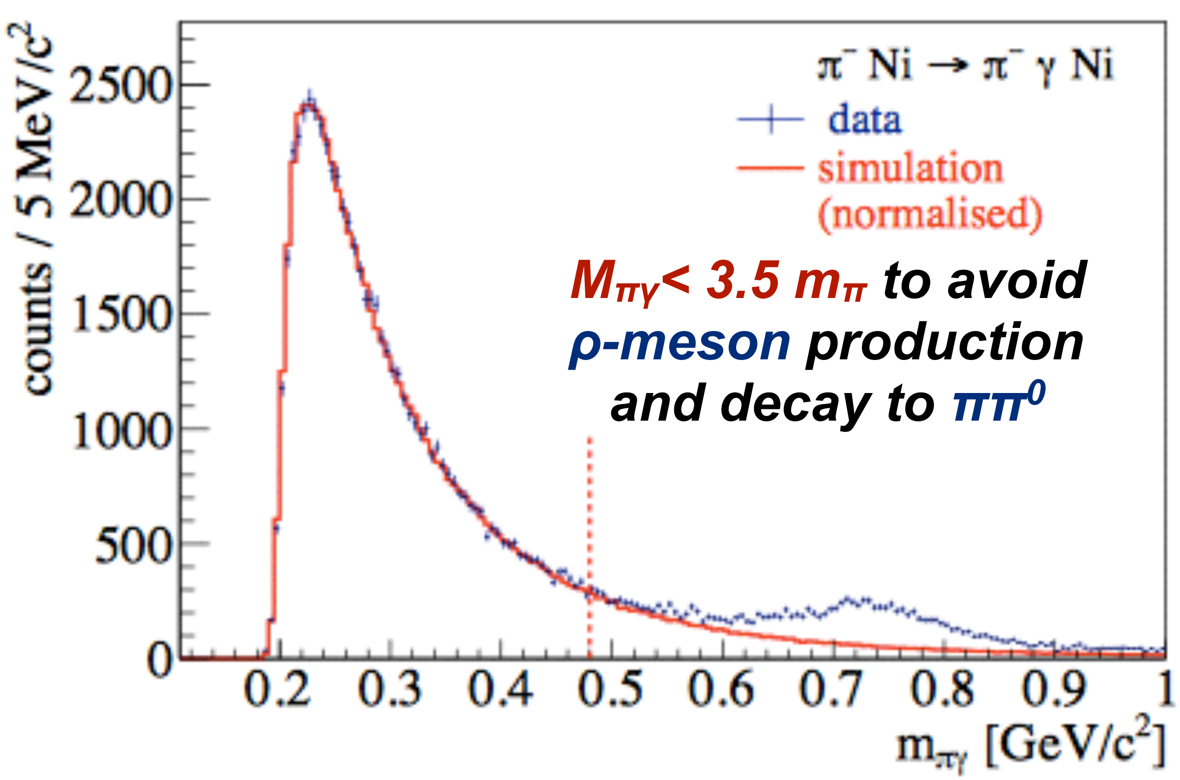


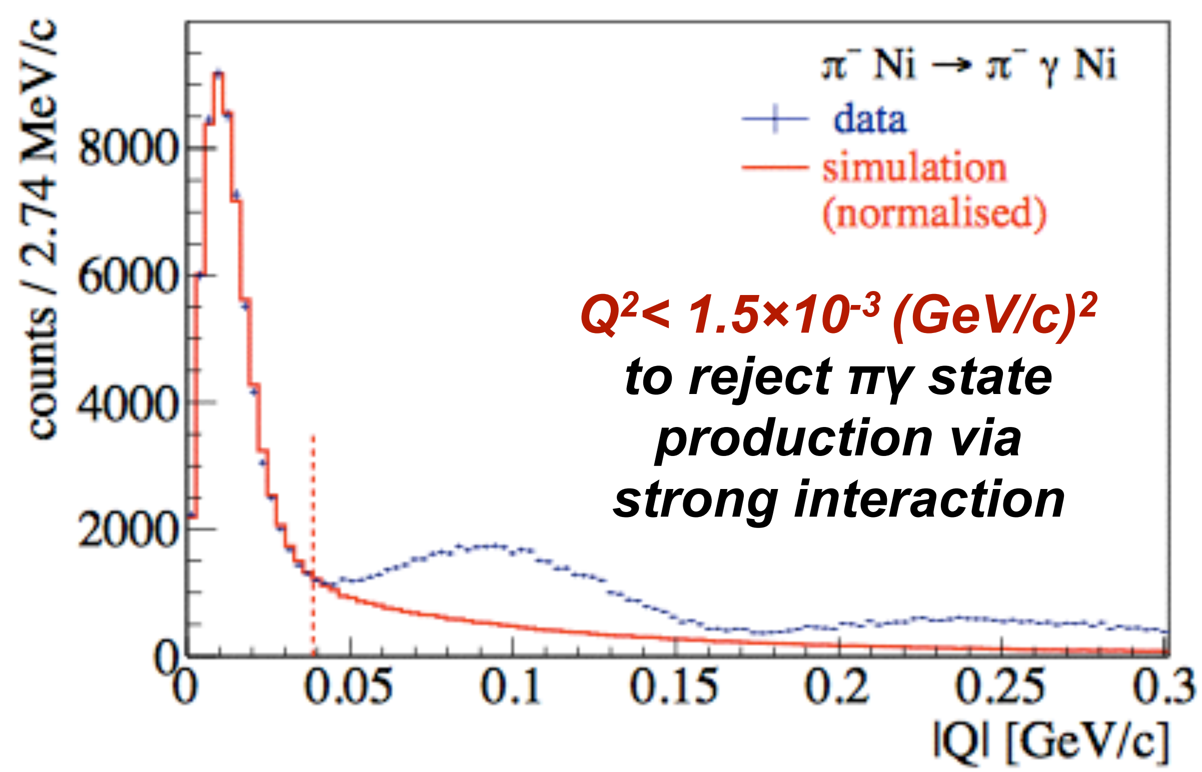


Kinematic cuts



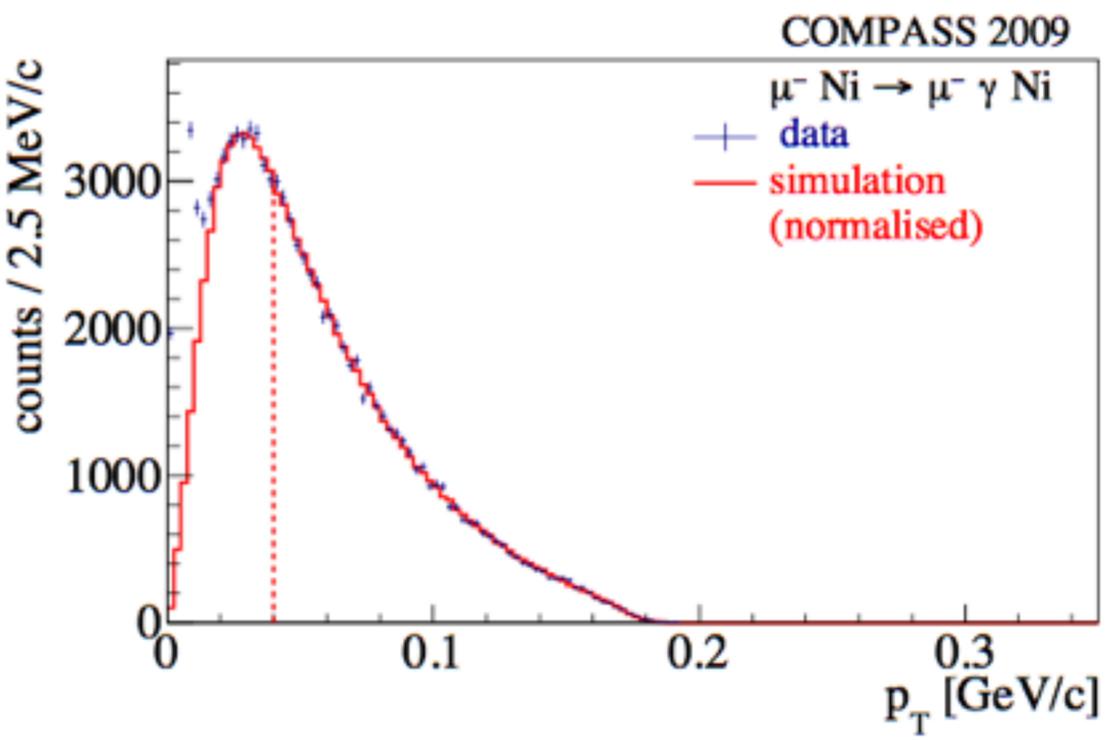


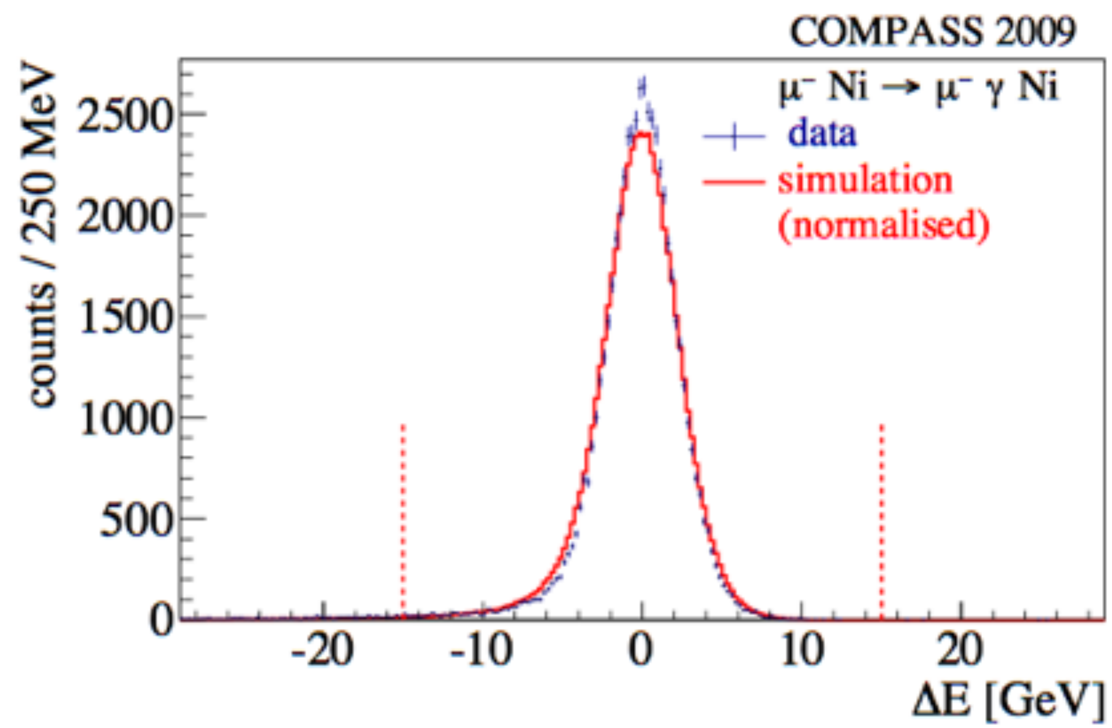


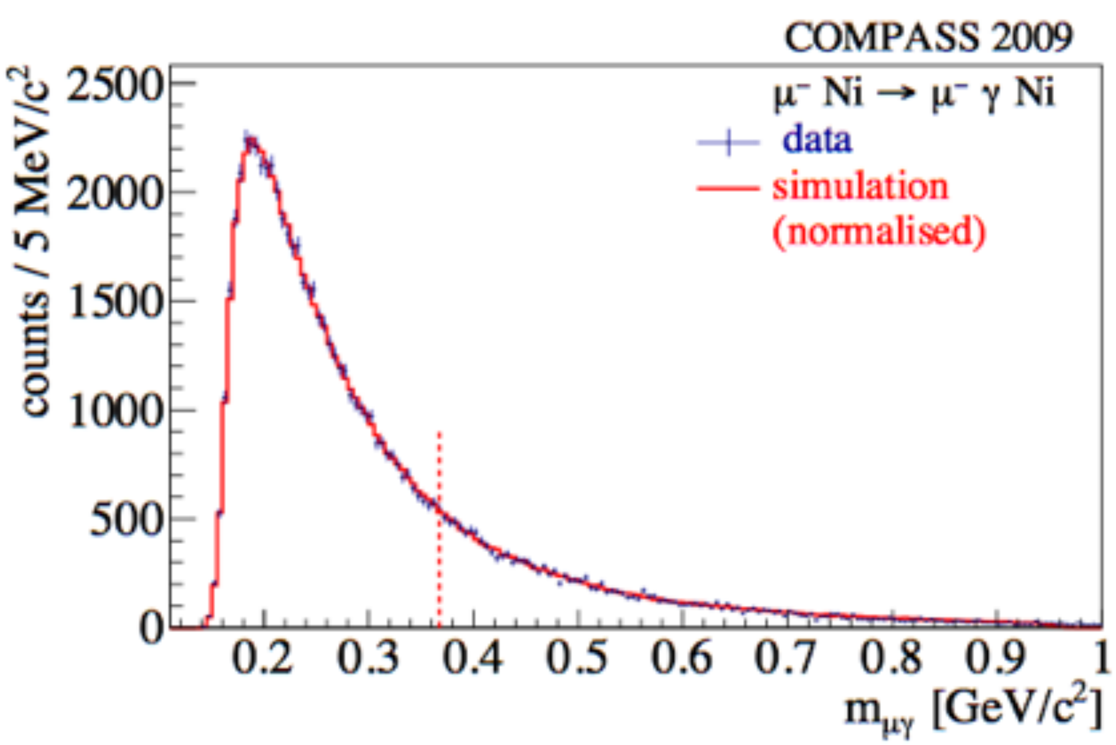


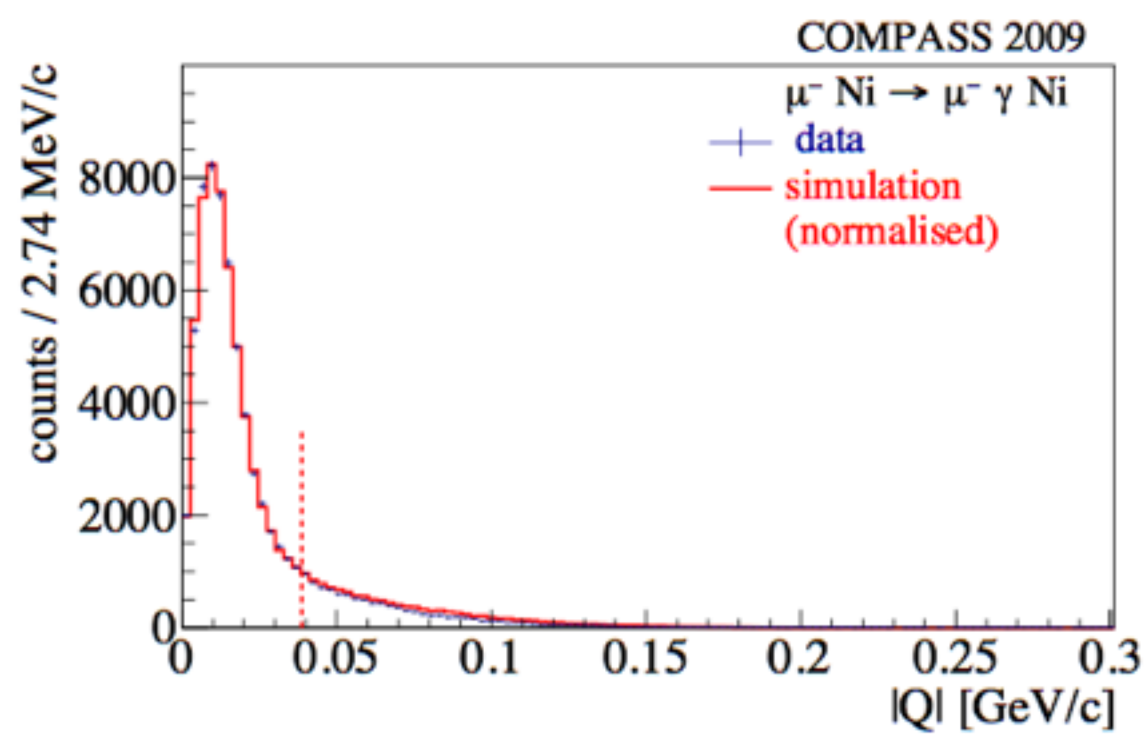
Muon data

The same selection + muon beam momentum measurement

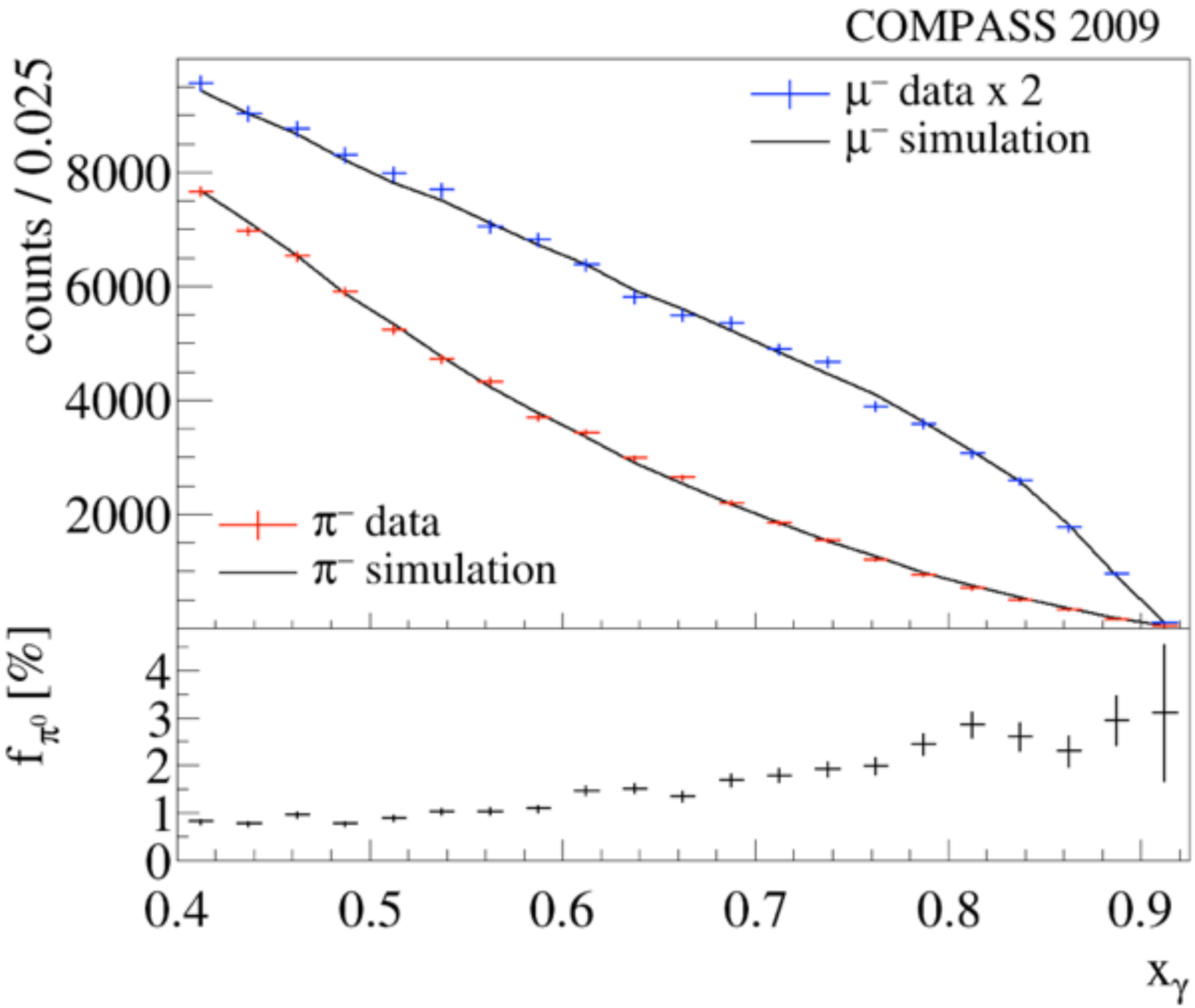






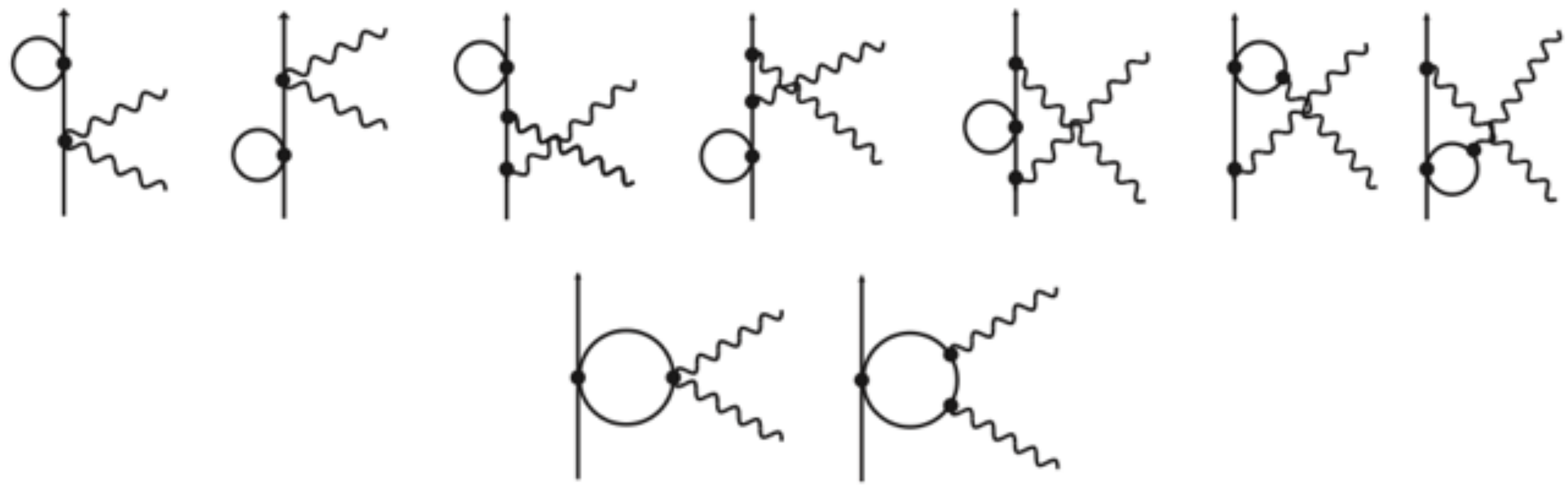


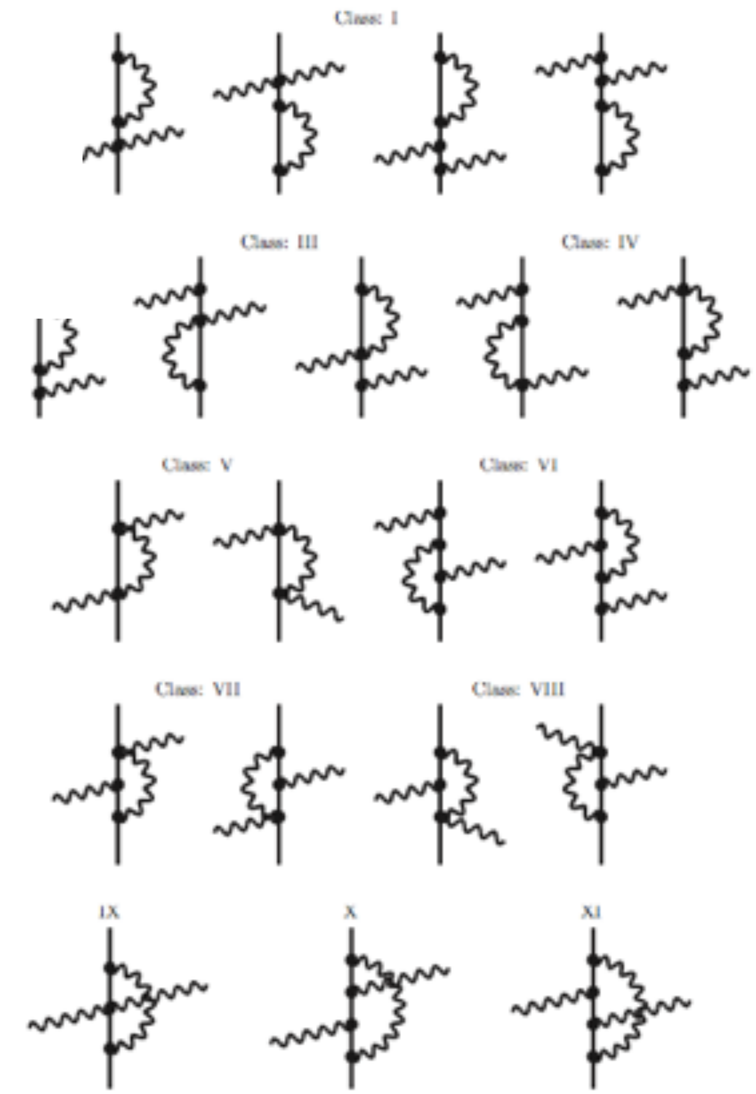
The measured x_γ-distributions



Background from the reaction
$\pi^- Ni \rightarrow \pi^- Ni\ \pi^0$ is subtracted

Corrections



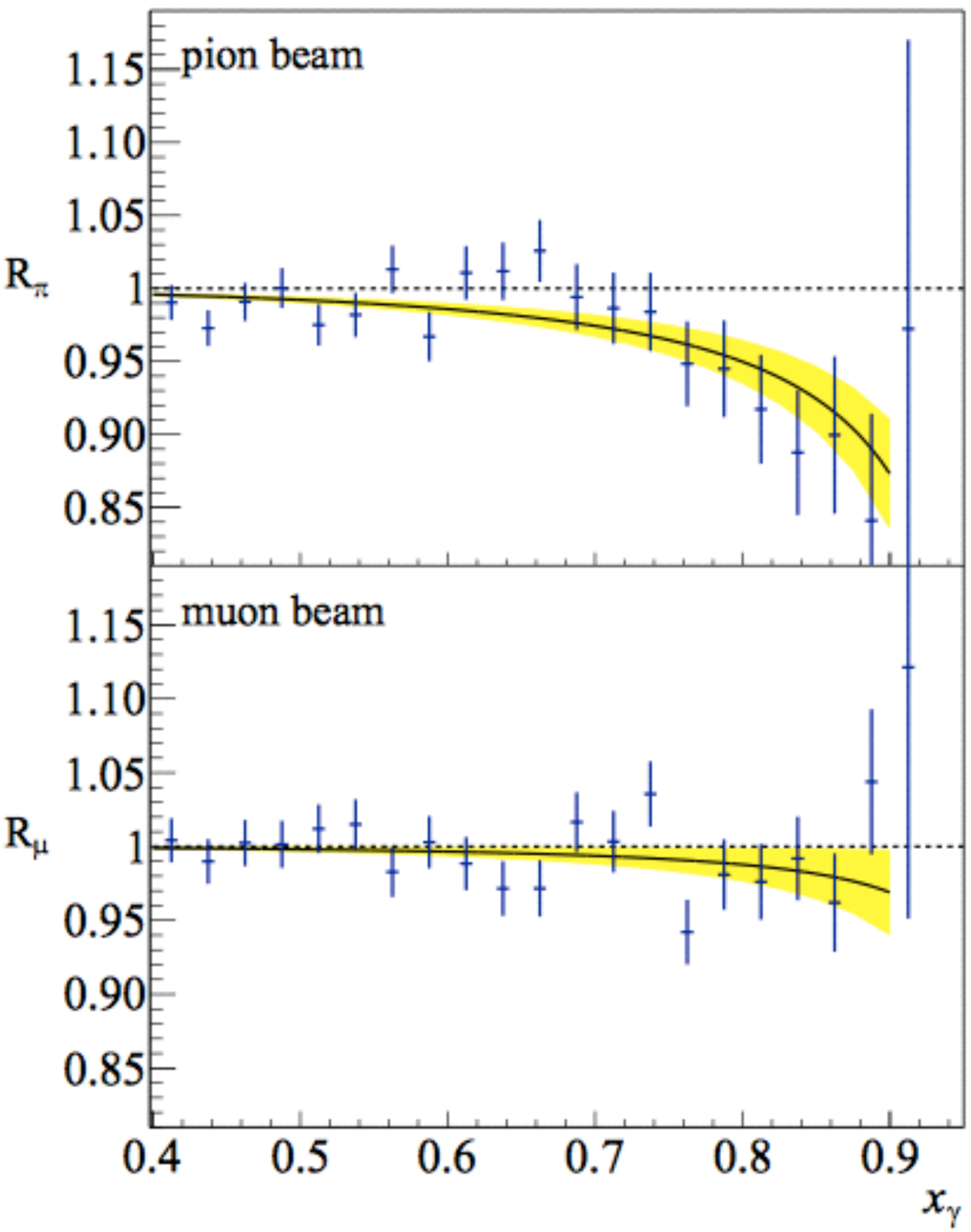


- *pion rescattering*
- *radiative corrections (Compton vertex)*
- *form factor of the Ni nucleus*

- *High Z effects (Zα=0.2)*
- *Nuclear charge screening by atomic electrons*

The COMPASS result

COMPASS **2009**



Source of uncertainty	Estimated magnitude $[10^{-4}\,\mathrm{fm}^3]$
Determination of tracking detector efficiency	0.5
Treatment of radiative corrections	0.3
Subtraction of π^0 background	0.2
Strong interaction background	0.2
Pion-electron elastic scattering	0.2
Contribution of muons in the beam	0.05
Quadratic sum	0.7

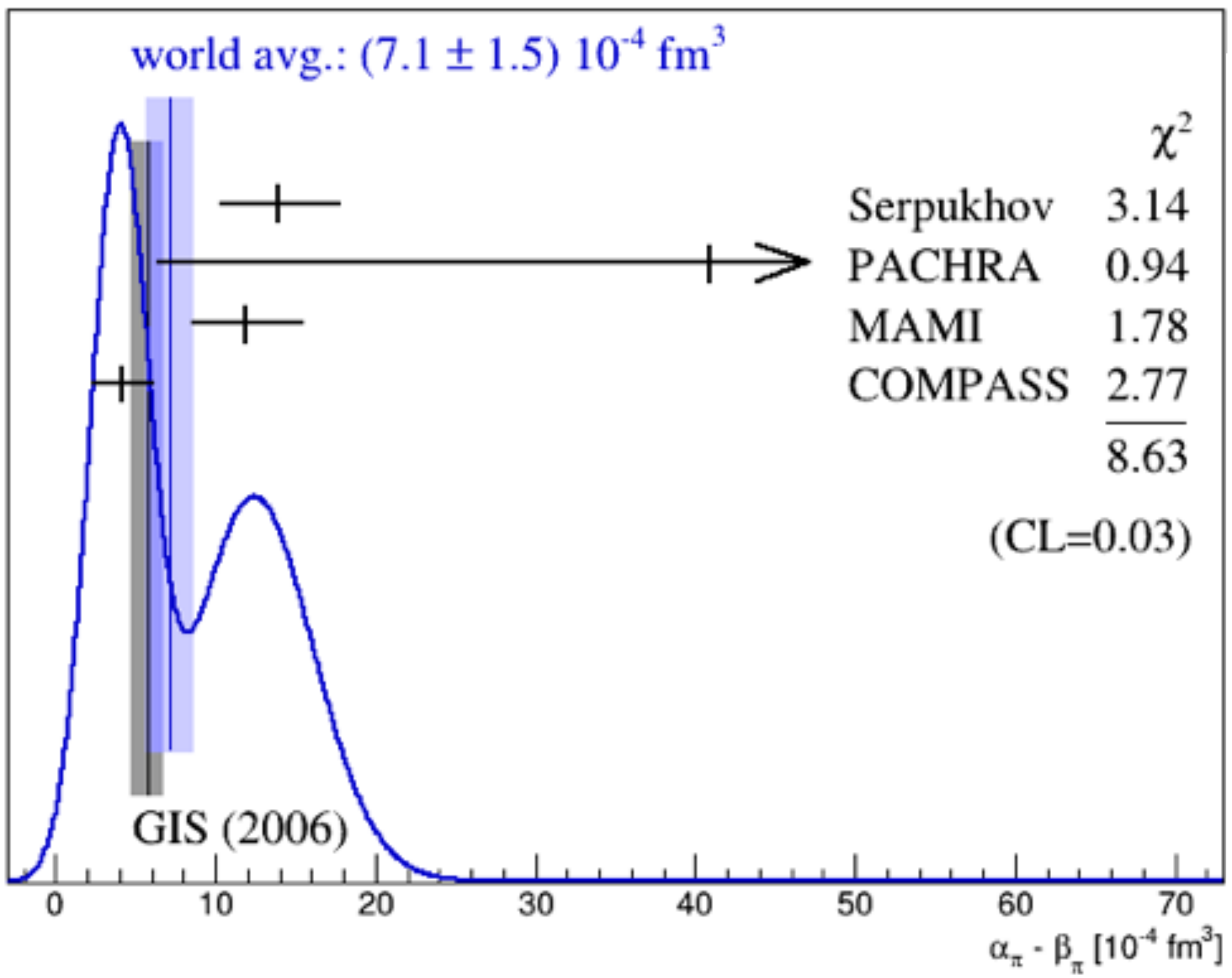
Under assumption $\alpha_\pi = -\beta_\pi$:

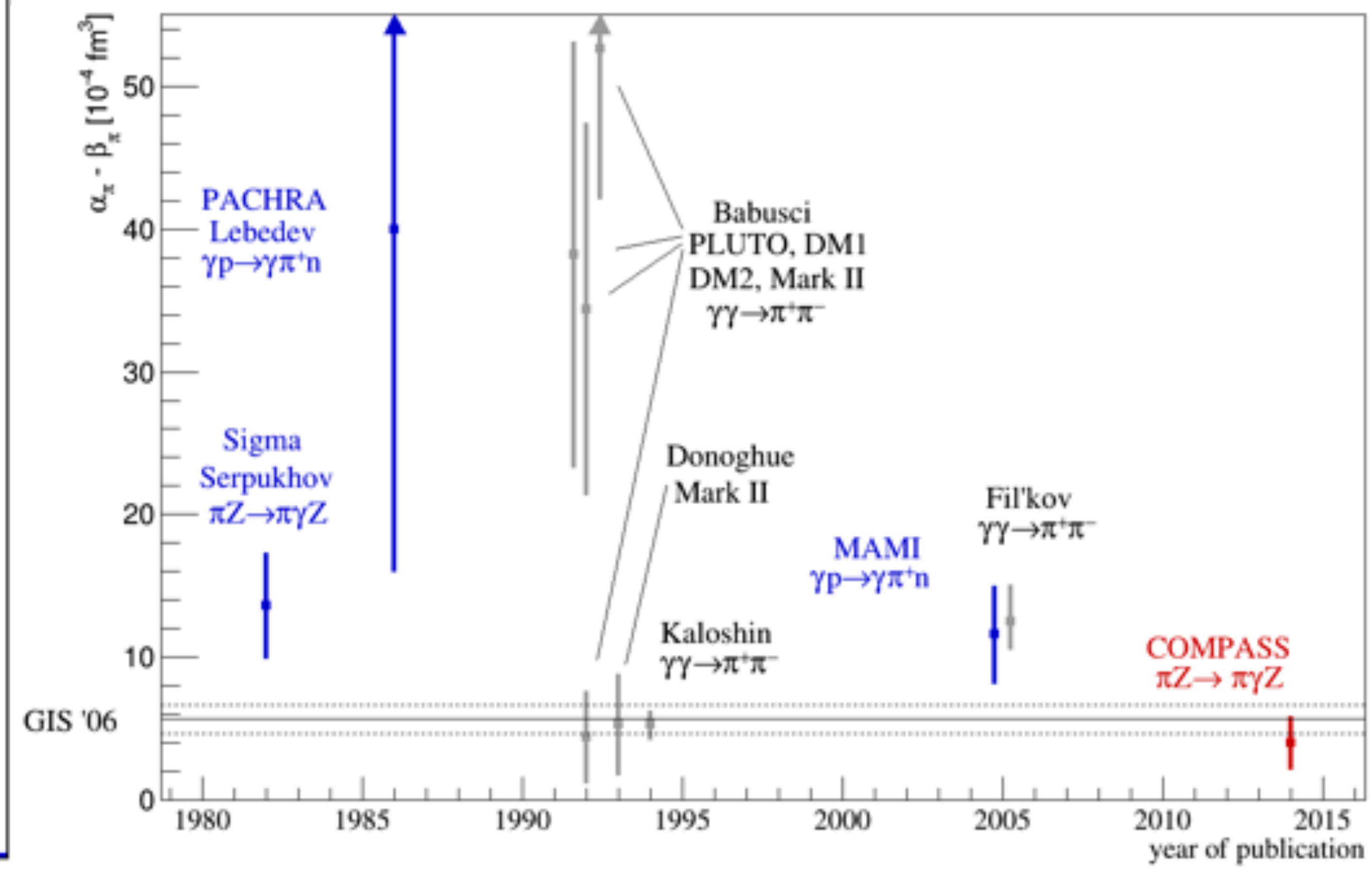
$$\alpha_\pi = (2.0 \pm 0.6_{stat} \pm 0.7_{syst}) \times 10^{-4}\ \mathrm{fm}^3$$

Phys. Rev. Lett. 114 (2015) 06002

Protvino: $\alpha_\pi = -\beta_\pi = (6.8 \pm 1.4_{stat} \pm 1.2_{syst}) \times 10^{-4}\ \mathrm{fm}^3$, χPT: $\alpha_\pi \approx 2.8 \times 10^{-4}\ \mathrm{fm}^3$

The COMPASS result





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

Pion polarizabilities at COMPASS

COMPASS 2012

>200k of $\pi\gamma$ events with x_γ>0.4

Primakoff data collected in 2012 provide possibility:

- to reduce uncertainty of α_π measurement to ~0.3×10^{-4} fm^3 (χPT: 5.7)
- to measure $\alpha_\pi+\beta_\pi$ with accuracy ~0.03×10^{-4} fm^3 (χPT: 0.16)
- to access quadrupole polarizabilities of pion $\alpha_{\pi2}$ and $\beta_{\pi2}$
- to study dynamics of pion polarizabilities $\alpha_\pi=\alpha_\pi(s,t,...)$

Kaon polarizabilities

Theoretical predictions:

$_\chi$PT prediction $O(p^4)$:

$$\alpha_K + \beta_K = 0$$

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

Quark confinement model:

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

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

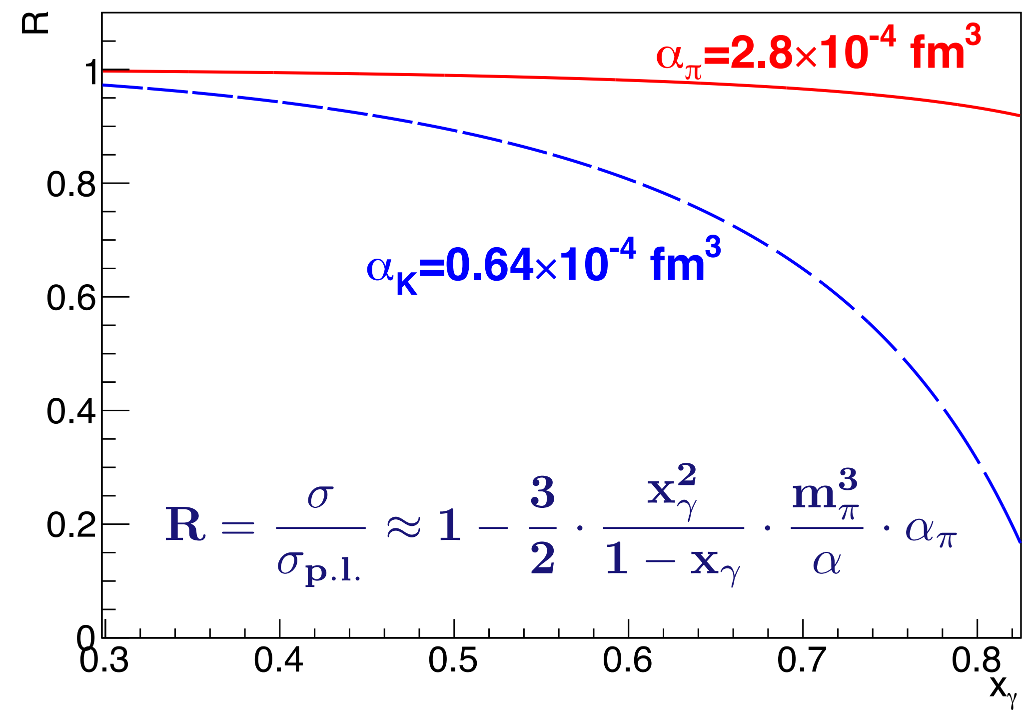
Experimental results:

$\alpha_K < 200 \times 10^{-4}$ fm^3 (1973)

- from kaonic atoms spectra

At COMPASS:

- **~2.4% of kaons in hadron beam**
- **CEDARs for beam kaons identification**



Polarization effects ~m^3

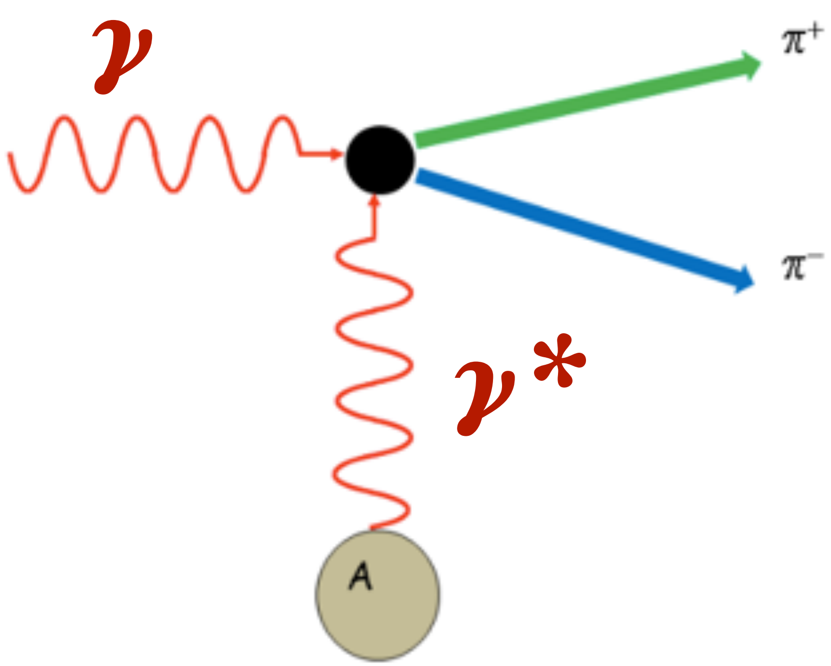
$$\sigma_{Prim} \sim \frac{1}{m^2}$$

1 Kγ event per 500 πγ

Pion polarizability at JLab (plans)

Existing detector GlueX at Hall-D

A. Aleksejevs at. al, Measuring the Charged Pion Polarizability in the $\gamma\gamma \rightarrow \pi^+\pi^-$ Reaction
(A proposal to the 40th Jefferson Lab Program Advisory Committee)



- *Polarized photons of 6 GeV*
- *10^7 tagged photons per second*
- *^{116}Sn target of 0.6 mm*
- *Rate: up to 400 events per hour for $M_{\pi\pi}$<500 MeV*
- *accuracy for $\alpha_\pi - \beta_\pi = \pm 0.6 \times 10^{-4}$ fm^3*

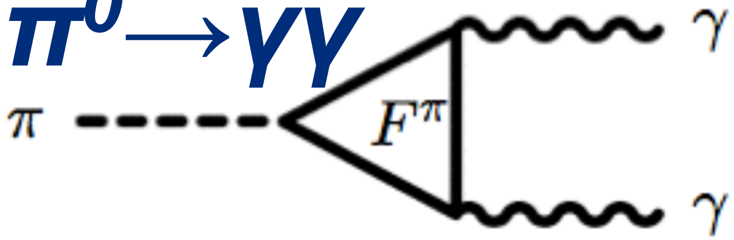
Main physical backgrounds:

- ***pion pair production in strong interaction***
- ***coherent ρ^0 production***

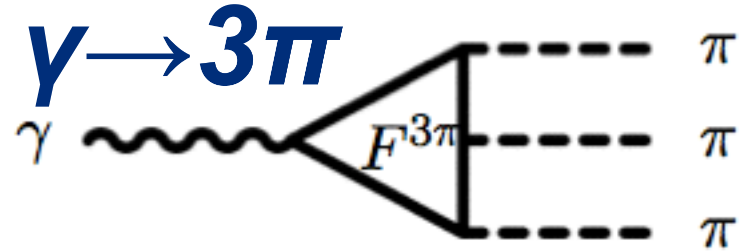
QCD chiral anomaly

Chiral anomaly: chiral symmetry on the level of the lagrangian but non conservation of chiral current

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



$\gamma \rightarrow 3\pi$



For $\pi^- \gamma \rightarrow \pi^- \pi^0$:

$$F_{3\pi}(0,0,0) = \frac{F_\pi(0,0,0)}{ef^2}$$

Low-energy theorem:

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

For $\pi^- \gamma \rightarrow \pi^- \eta$:

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

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

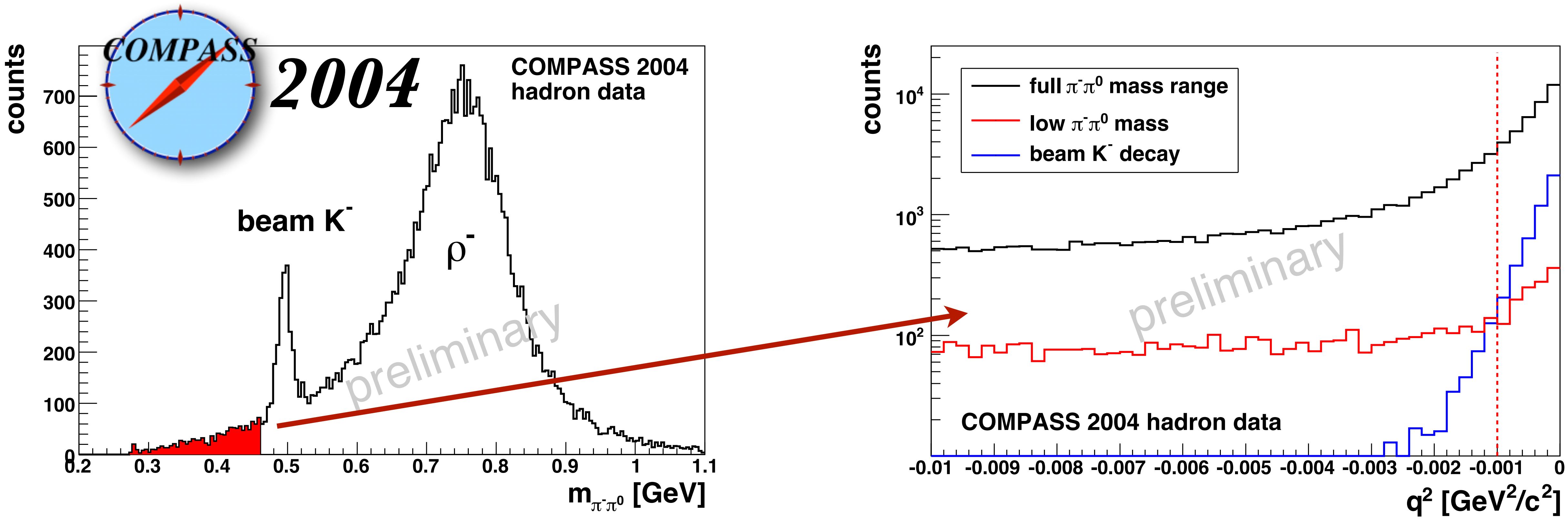
QCD chiral anomaly

Experiment	Year	Reaction	Cross section, nb	$F_{3\pi}$, GeV^{-3}
FRAMM (CERN)	1985	$\pi^- e \to \pi^- e \pi^0$	$\sigma=2.11\pm0.47$	9.6 ± 1.1
SIGMA (Protvino)	1987	$\pi^-(A,Z) \to \pi^-(A,Z)\ \pi^0$	$\sigma/Z^2=1.63 \pm0.23_{stat}\pm0.16_{sys}$	10.7 ± 1.2
E94-015 (JLab)	1994	$\gamma p \to n\pi^-\pi^0$	Proposal	
For π^0:			Low-energy theorem	9.78 ± 0.05

Experiment	Year	Reaction	Cross section, nb	$F_{3\pi}$, GeV^{-3}
VES (Protvino)	1998	$\pi^- Be \to \pi^- Be\ \eta$	$\sigma=135\pm34$	6.9 ± 0.7
For η:			Low-energy theorem	6.5 ± 0.3

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

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:

$\pi^- Z \to \pi^- Z \eta$

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

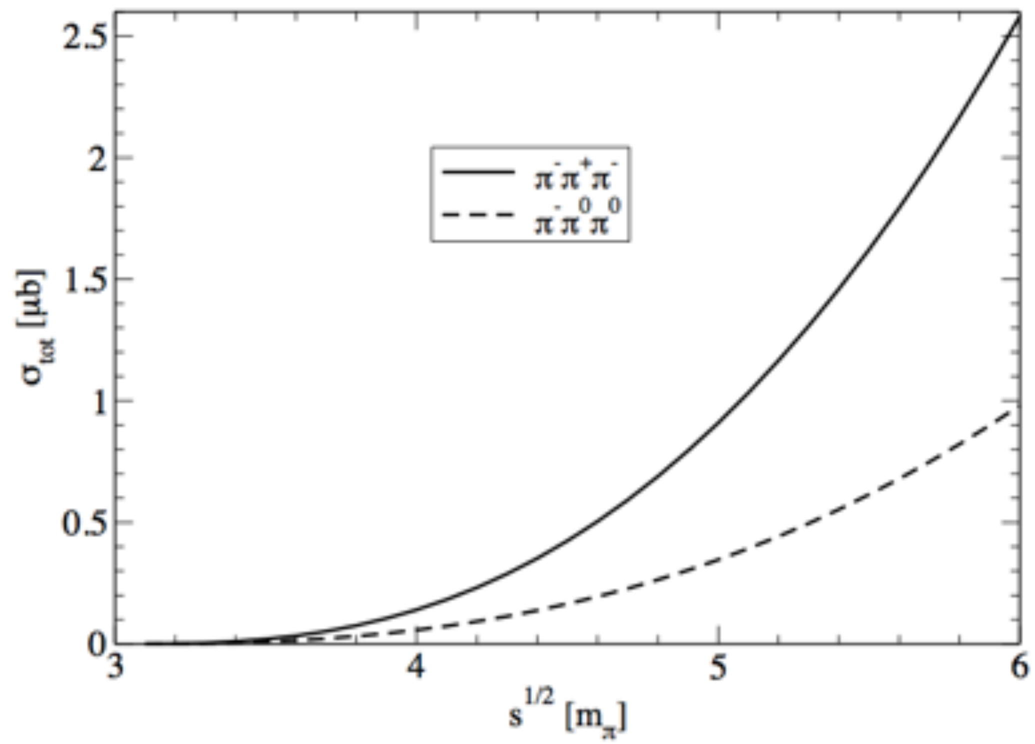
$K^- Z \to K^- Z \eta$

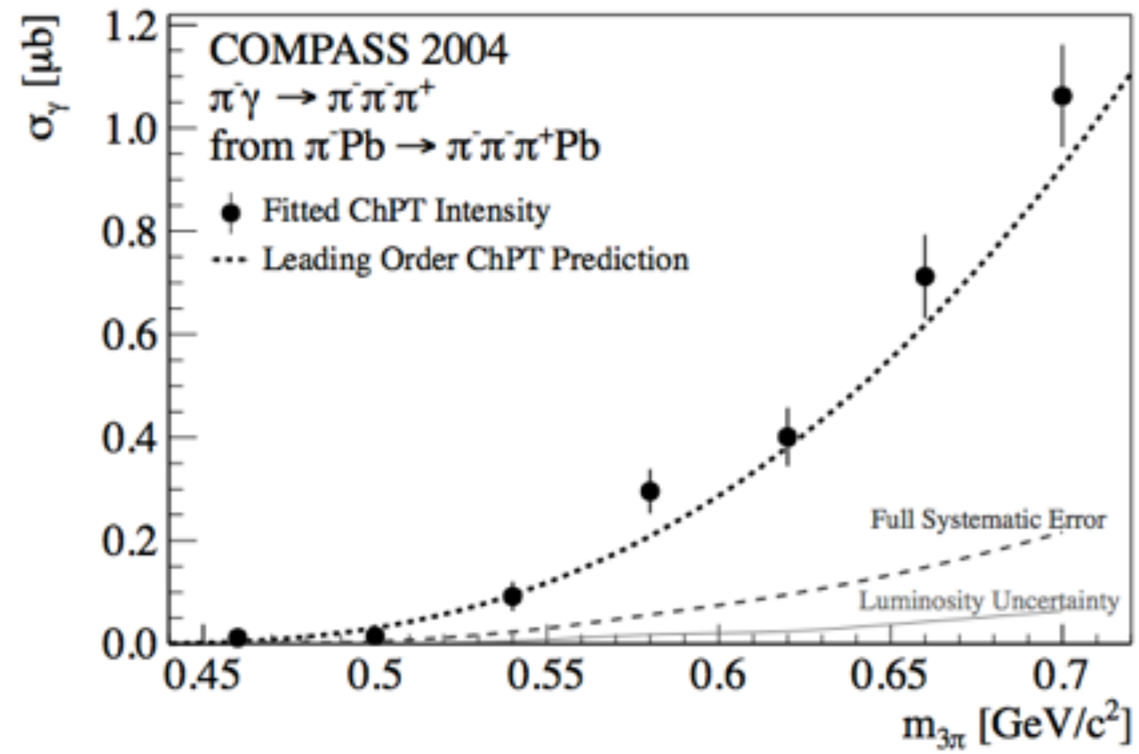
$K^- Z \to K^0 Z \pi^-$

is also possible

πγ cross sections near threshold: $\pi^- \rightarrow \pi^- \pi^+ \pi^-$

Eur.Phys.J. A36 181 (2008)





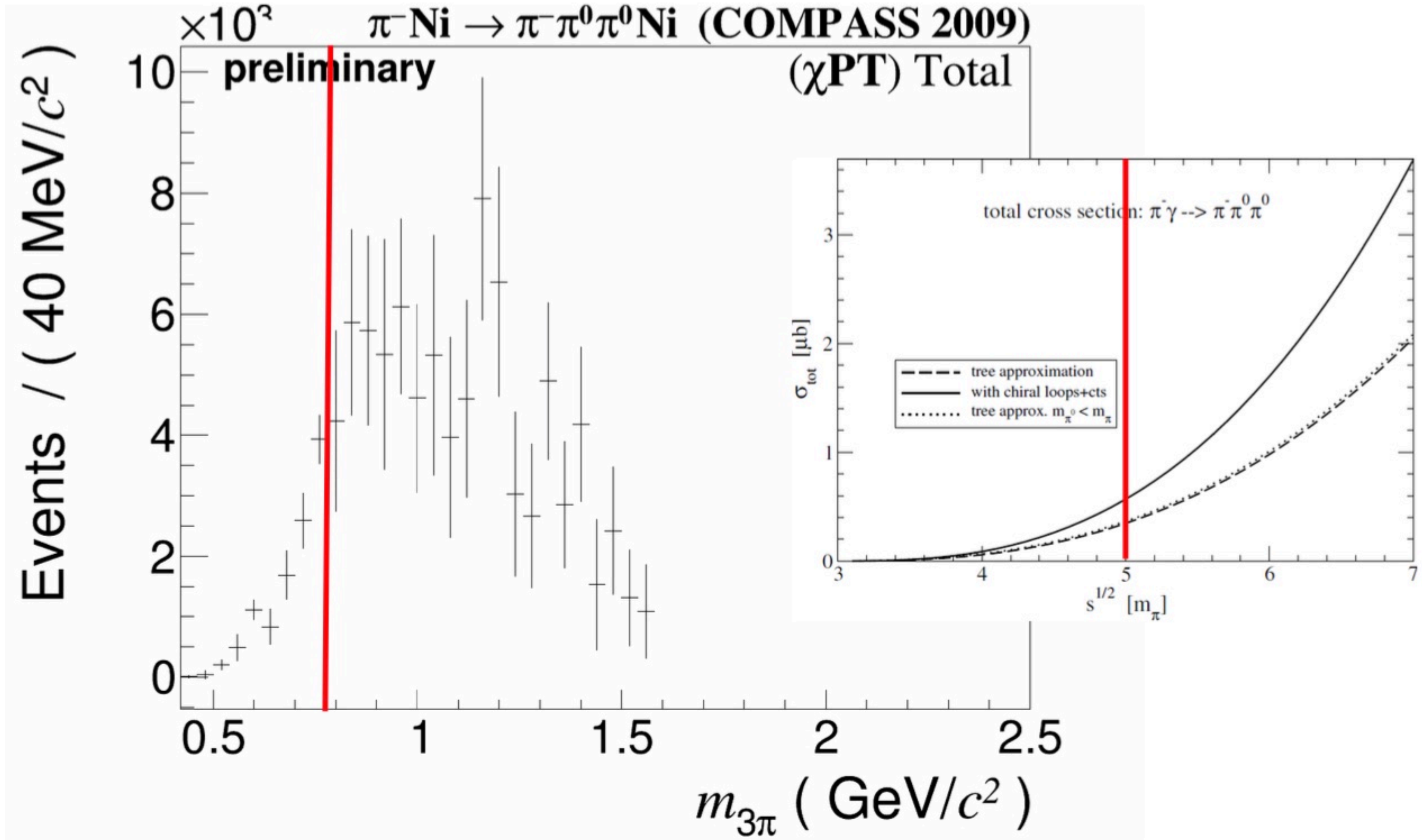
COMPASS already published the result for the cross section of $\pi^-\gamma\rightarrow\pi^-\pi^+\pi^-$ reaction near threshold.

2004

PRL 108, 192001 (2012)

$\pi\gamma$ cross sections near threshold: $\pi^- \rightarrow \pi^- \pi^0 \pi^0$

Reaction $\pi^-\gamma\rightarrow\pi^-\pi^0\pi^0$ is under analysis



Dynamics for reactions with more pions (4+) in the final state can also be investigated

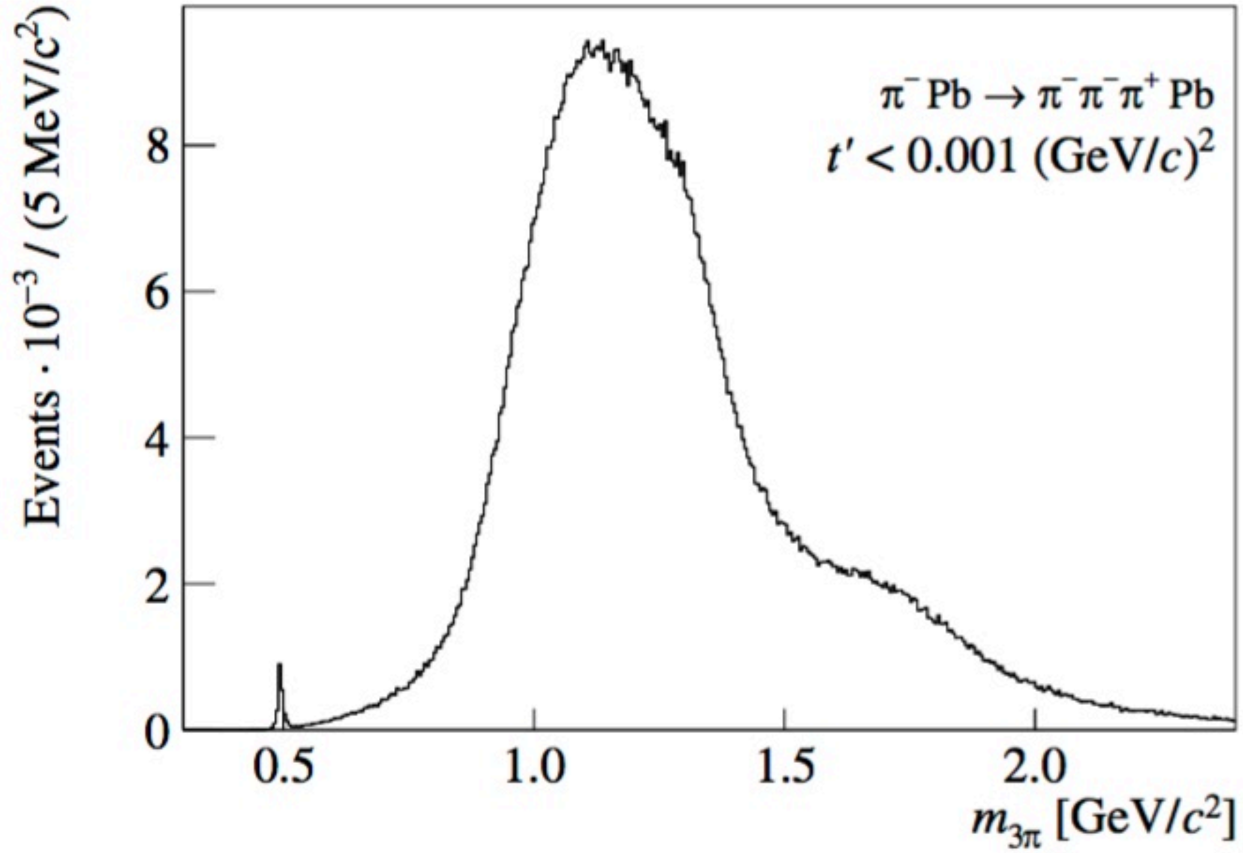
Radiative widths of mesons

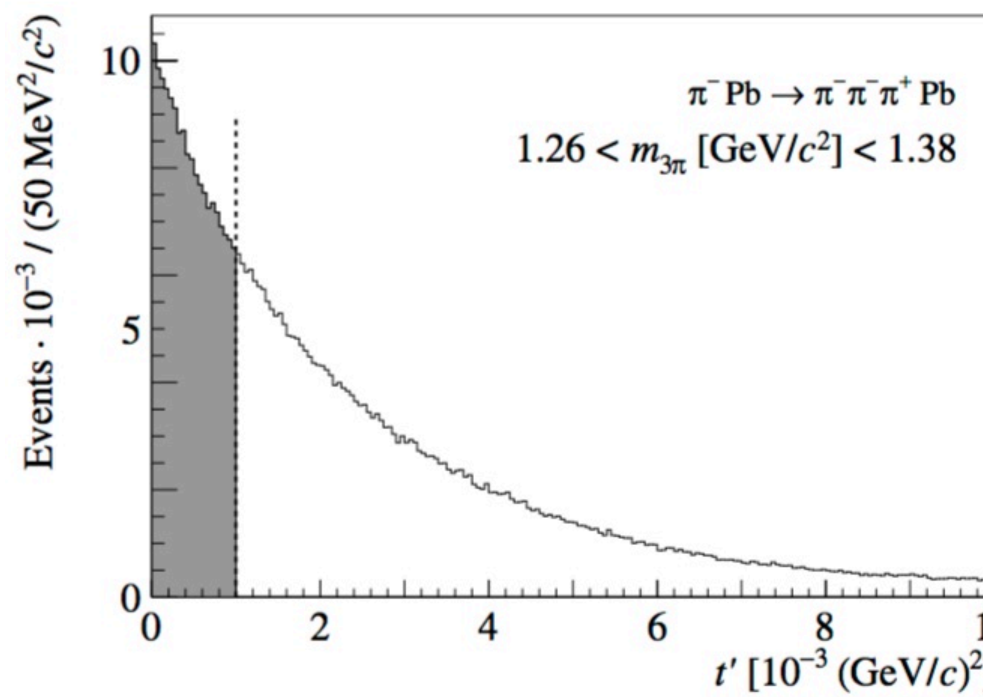
$$\frac{d\sigma}{dm dt'} = 16\alpha Z^2(2J+1)\left(\frac{m}{m^2-m_\pi^2}\right)^3$$
$$\times \frac{m_0^2\,\Gamma_{\pi\gamma}(m)\,\Gamma_{\text{final}}(m)}{(m^2-m_0^2)^2+m_0^2\Gamma_{\text{total}}^2(m)} \times \frac{t'}{(t'+t_{\min})^2}\, F_{\text{eff}}^2(t').$$

$$\sigma_{\text{Primakoff},X} = \int_{m_1}^{m_2}\int_0^{t'_{\max}} \frac{d\sigma}{dm\,dt'}\,dt'\,dm$$
$$= \Gamma_0(X\to\pi\gamma)C_X.$$

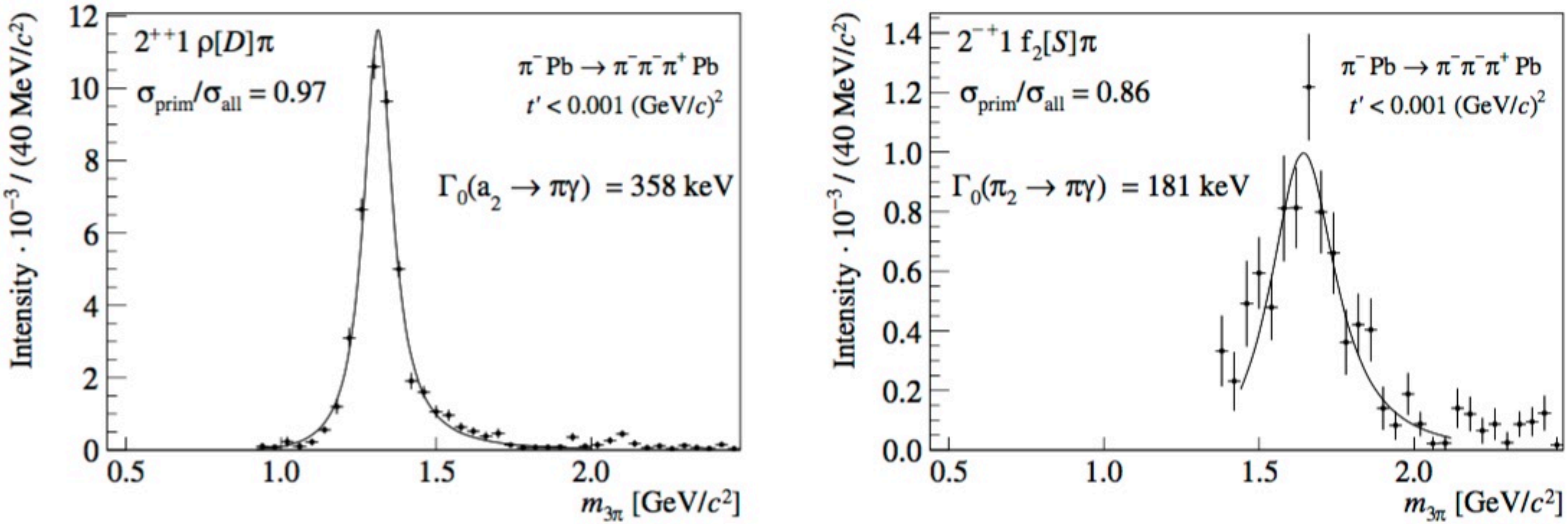
$$\Gamma_{\text{final}}(m) = f_{\text{final}}^{\text{dyn}}(m)\Gamma_0(m_0)\ \text{CG BR}$$

$$\Gamma_0(X\to\pi\gamma) = \frac{N_{X,\text{prim}}/\epsilon_X}{C_X\ L\ \text{CG BR}\ \epsilon_{\text{resol}}}$$





Radiative widths of mesons



	$a_2(1320)$	$\pi_2(1670)$
This measurement	$(358 \pm 6 \pm 42)$ keV	$(181 \pm 11 \pm 27)$ keV $\cdot$ $(0.56/BR_{f_2\pi})$
SELEX [21]	$(284 \pm 25 \pm 25)$ keV	
S. Cihangir *et al.* [24]	(295 ± 60) keV	
E.N. May *et al.* [25]	(0.46 ± 0.11) MeV	
VMD model [1]	(375 ± 50) keV	
Relativ. Quark model [2]	324 keV	
Cov. Osc. Quark model [3]	235 keV	
Cov. Osc. Quark model [4]	237 keV	2 values: 335 keV and 521 keV

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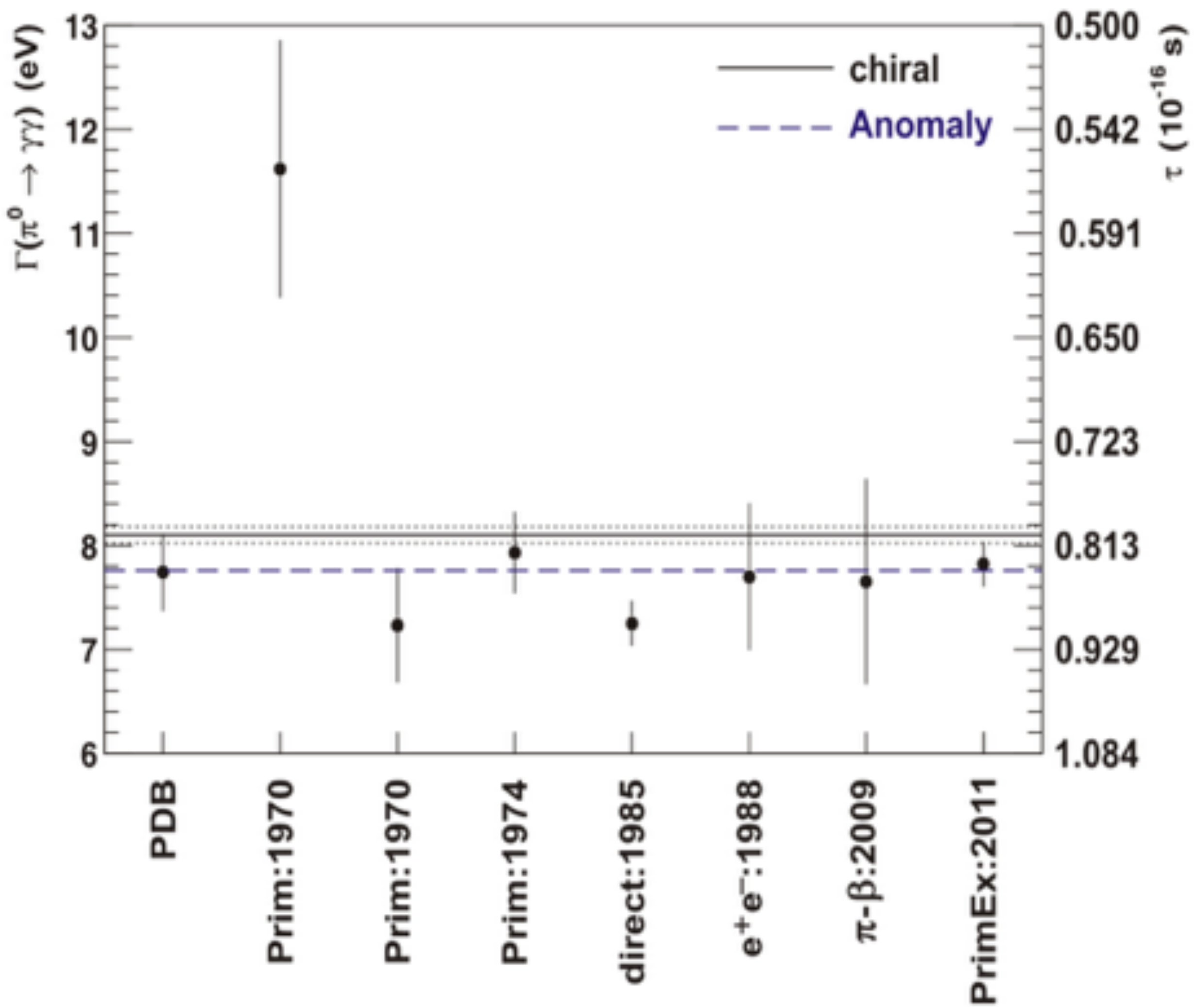
What about kaons?

Particle	BR(→Kγ)	Full width, MeV
$K^*(892)^-$	$(9.9\pm0.9)\times10^{-4}$	50
$K_2^*(1430)^-$	$(2.4\pm0.5)\times10^{-3}$	100
...		

It would be nice to have high statistics with kaons

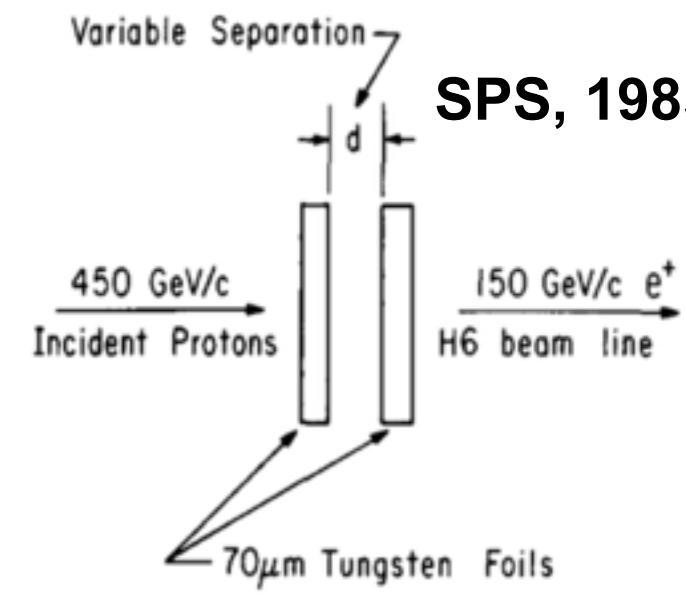
π^0 lifetime



This basic constant of chiral theory is known with accuracy worse than **2%** (**0.02%** for charged pion)

(Exclusive) production off thin foils with precisely variating distance between them.

SPS, 1985



Direct measurement is competitive!

VALUE (10^{-17} s)	EVTS	DOCUMENT ID		TECN	COMMENT
8.52±0.18 OUR AVERAGE	Error includes scale factor of 1.2.				
8.32±0.15±0.18		[1] LARIN	11	PRMX	Primakoff effect
8.5 ±1.1		[2] BYCHKOV	09	PIBE	$\pi^+ \to e^+ \nu \gamma$ at rest
8.4 ±0.5 ±0.5	1182	[3] WILLIAMS	88	CBAL	$e^+ e^- \to e^+ e^- \pi^0$
8.97±0.22±0.17		ATHERTON	85	CNTR	Direct measurement
8.2 ±0.4		[4] BROWMAN	74	CNTR	Primakoff effect

Form factors of $\pi^{\pm}$ and $K^{\pm}$

$$F(q^2) \approx 1 - \frac{q^2 < r^2 >}{6\hbar^2}$$

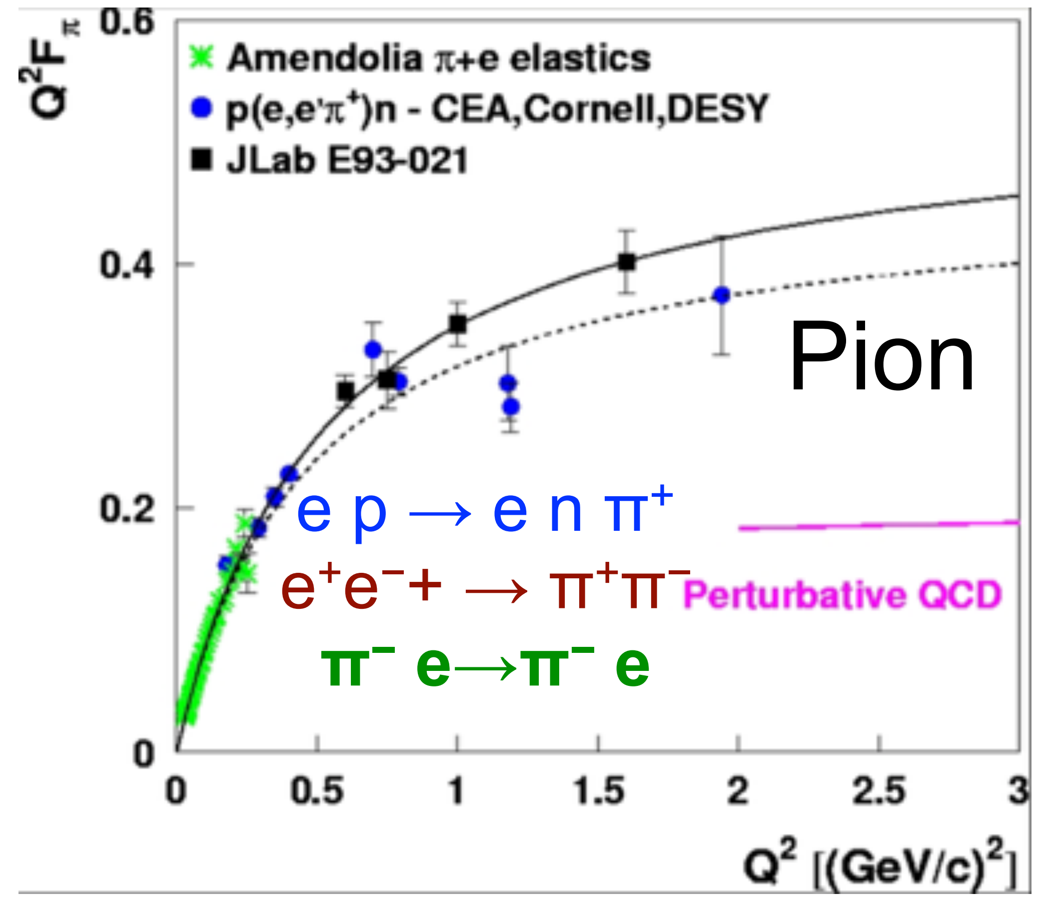
$\pi^{\pm}$ CHARGE RADIUS **0.642±0.008 fm**

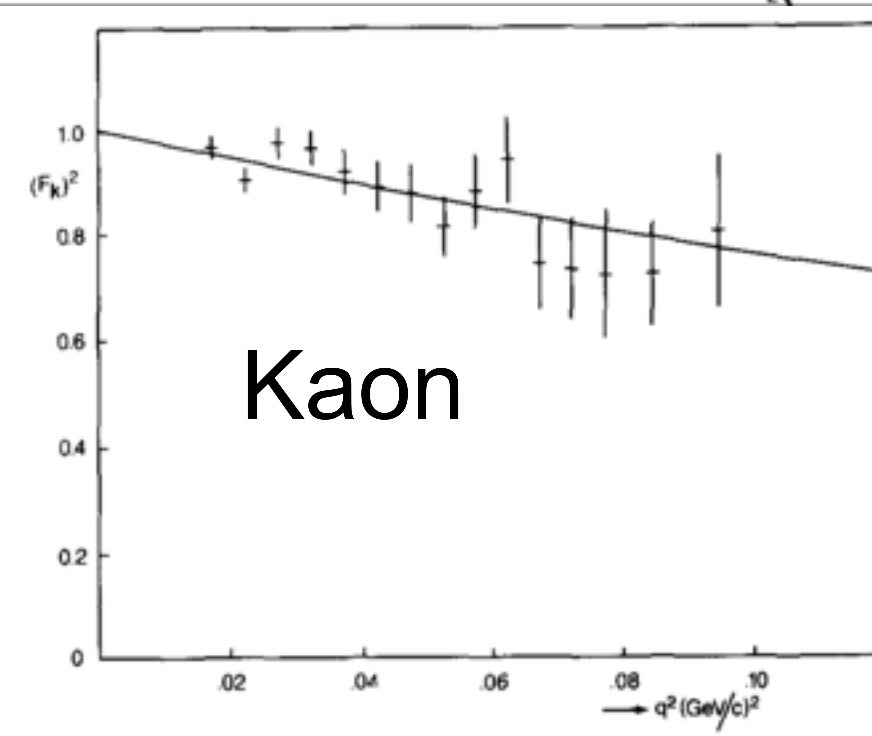
$K^{\pm}$ CHARGE RADIUS **0.560±0.031 fm**

πe→πe ($E_{\pi\ lab} \approx$ 700 MeV)

Ke→Ke ($E_{K\ lab} \approx$ 200 MeV)

Q^2 up to 0.3 GeV^2/c^2





Muons as the reference!

SUMMARY

- ***Low-t reactions provide unique possibility to study processes induced by photons. Study of such reactions is one of the main goals of the COMPASS experiment.***
- ***Main directions of low-t studies at COMPASS are:***
  - ***pion and kaon polarizabilities;***
  - ***chiral anomaly study;***
  - ***meson radiative width;***
  - ***$\sigma_{\pi\gamma}$ dynamics for ChPT tests.***
- ***Ongoing results at COMPASS:***
  - ***the most precise measurement of α_π (published result);***
  - ***measurement of $\pi^-\gamma\rightarrow\pi^-\pi^+\pi^-$ cross section near the threshold (published result);***
  - ***measurement of $\pi^-\gamma\rightarrow\pi^-\pi^0\pi^0$ cross section near the threshold (preliminary result);***
  - ***the most precise measurement of a_2 radiative width (published result);***
  - ***the first measurement of π_2 radiative width (published result).***
- ***More results are expected from existing data but we already thinking about future. If you have any ideas - welcome!***