Precise measurement of the charged pion polarisability at COMPASS

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Dubna, JINR, 18.03.2015

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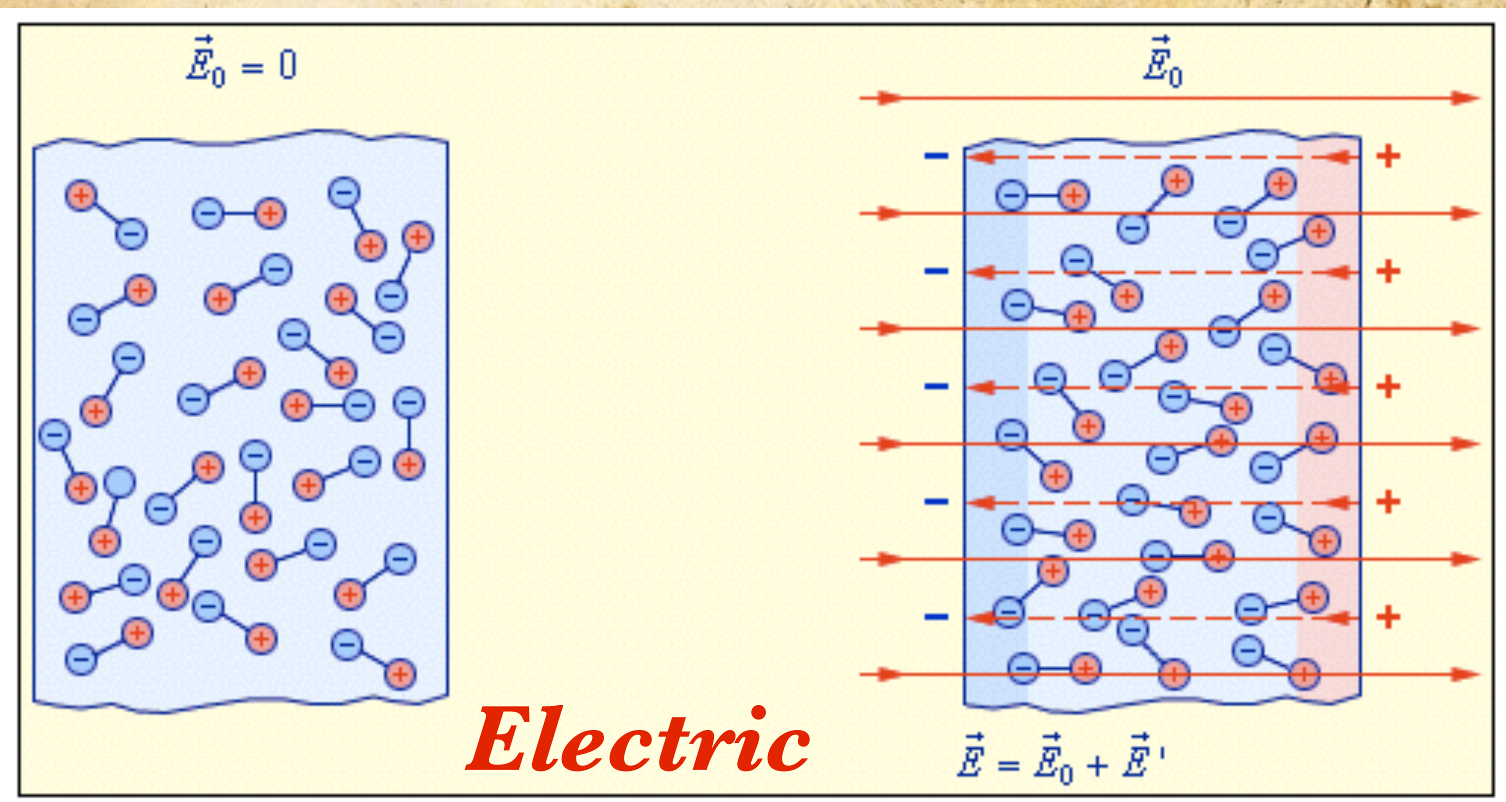
CERN experiment brings precision to a cornerstone of particle physics

11 Feb 2015

Geneva, 11 February 2015. In a paper published yesterday in the journal *Physical Review Letters*, the COMPASS experiment at CERN [1] reports a key measurement on the strong interaction. The strong interaction binds quarks into protons and neutrons, and protons and neutrons into the nuclei of all the elements from which matter is built. Inside those nuclei, particles called pions made up of a quark and an antiquark mediate the interaction. Strong interaction theory makes a precise prediction on the polarisability of pions – the degree to which their shape can be stretched. This polarisability has baffled scientists since the 1980s, when the first measurements appeared to be at odds with the theory. Today's result is in close agreement with theory.

"The theory of the strong interaction is one of the cornerstones of our understanding of nature at the level of the fundamental particles," said Fabienne Kunne and Andrea Bressan, spokespersons of the COMPASS experiment, *"so this result, in perfect agreement with the theory, is a very important one."*

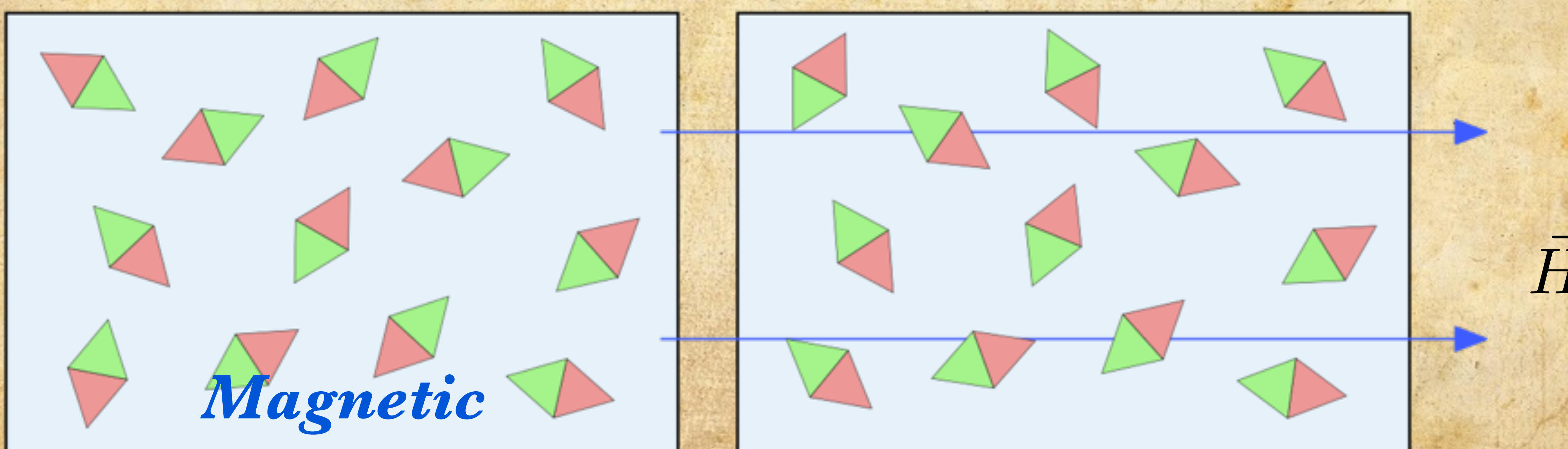
Polarizabilities of a medium



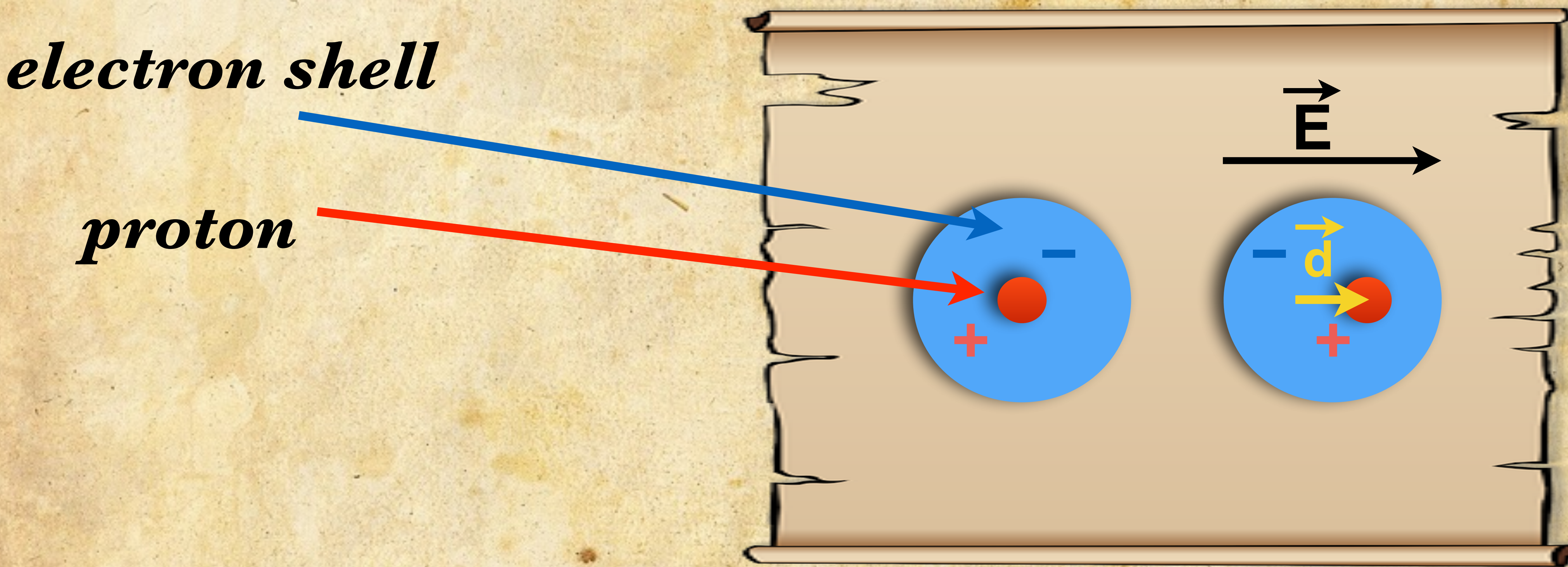
Polarizabilities

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

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



Hydrogen atom
- the simplest QED system



$$\alpha_{\mathrm{H}} = \frac{9}{2}\mathrm{a}^3$$ *, where* **a** *is the Bohr radius*

Polarizabilities of hadrons

Compton amplitude:

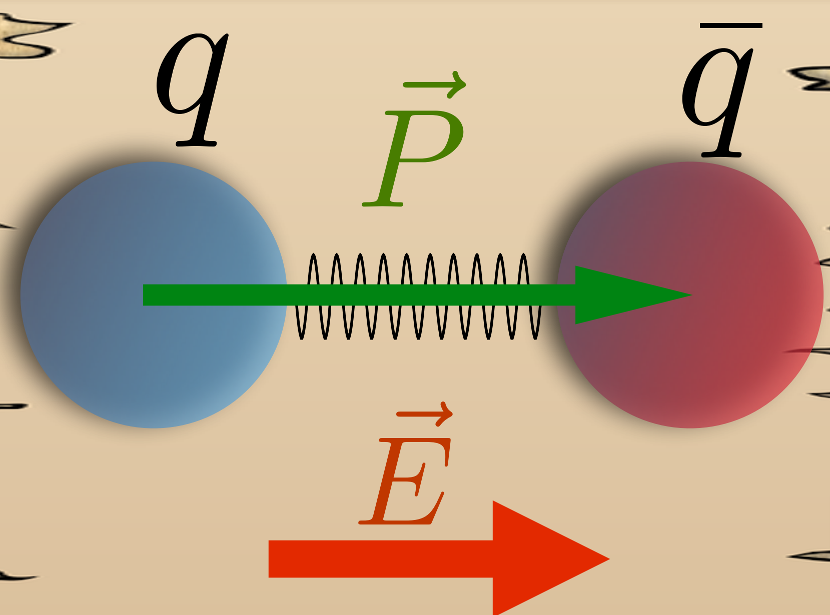
$$A(\gamma X \to \gamma X) =$$

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

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

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

$$H = \dots -(\alpha_X E^2 + \beta_X H^2)/2$$



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

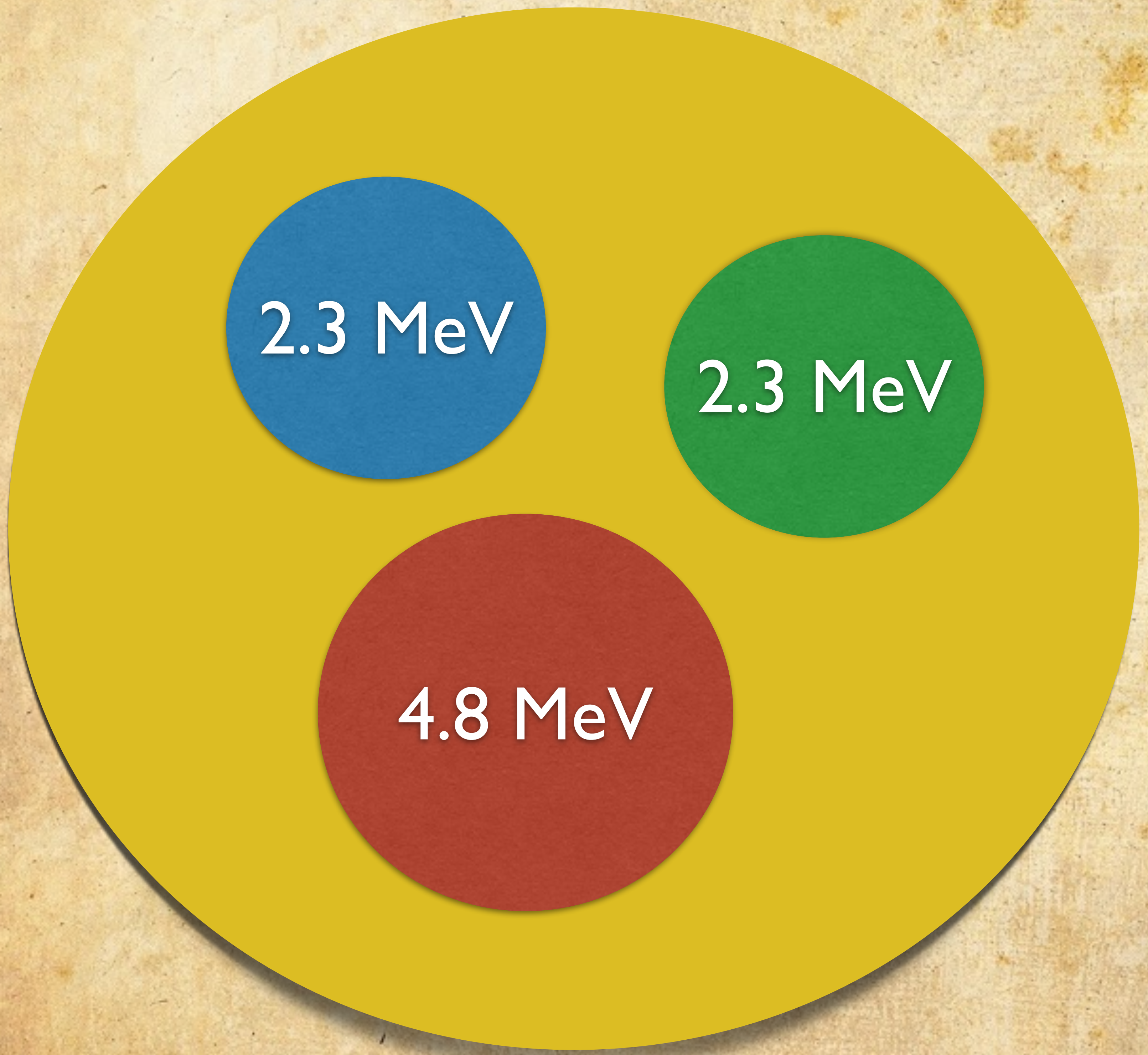
$$\vec{\mu} = \beta_X \vec{H}$$

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 ?

Mass: Higgs boson vs. QCD

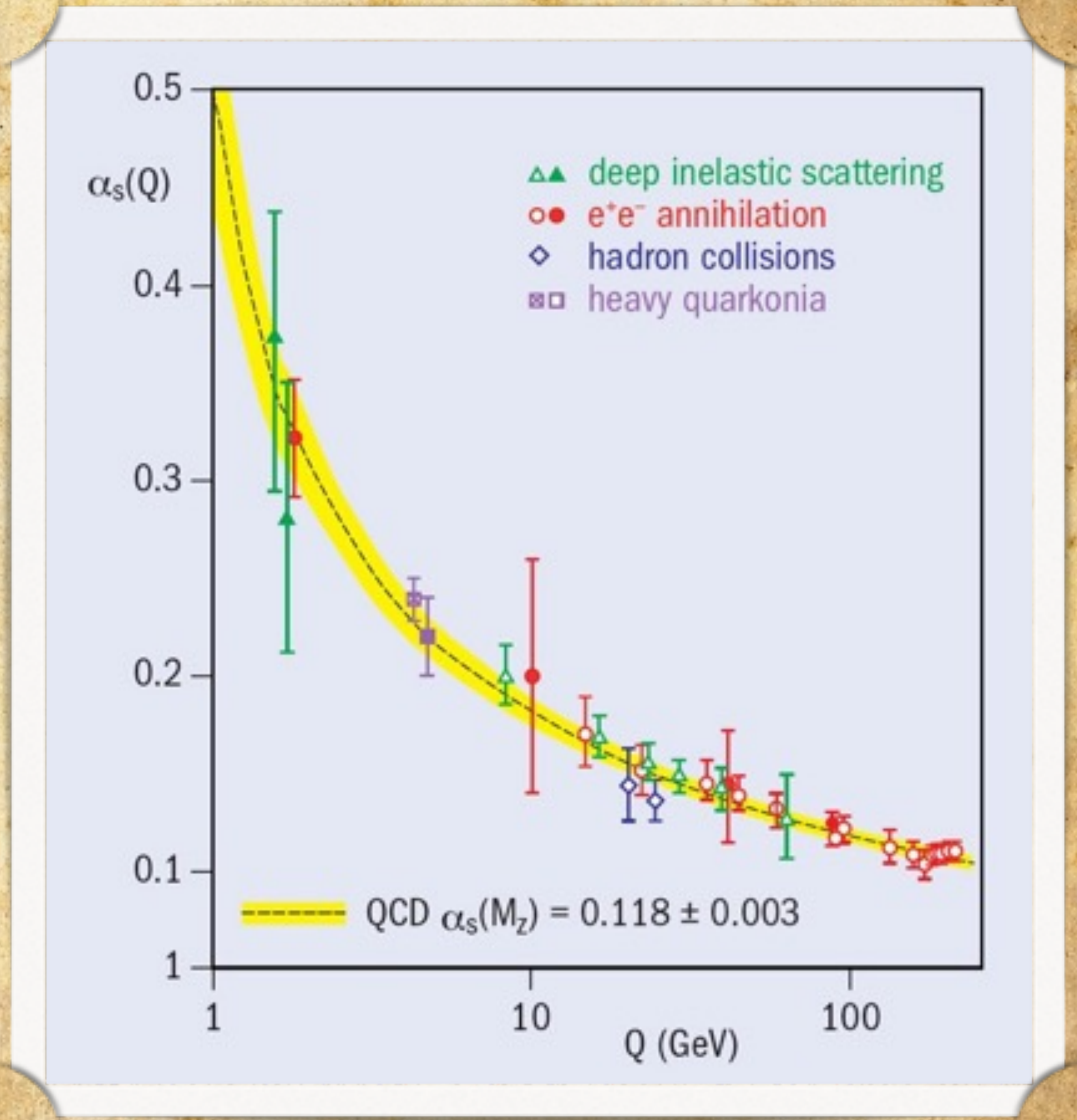


= *938 MeV*

?

QCD - true theory of strong interactions, but…

Since the constant of strong interactions $\alpha_S \sim 1$ at small energies, exact QCD formalism cannot make predictions with reasonable accuracy. Effective phenomenological models are needed



Chiral perturbation theory

Mass of light quarks (m,d) is much smaller than the typical scale M≈1 GeV

$$\mathcal{L}_{QCD} = \mathcal{L}^0 + \mathcal{L}_m$$

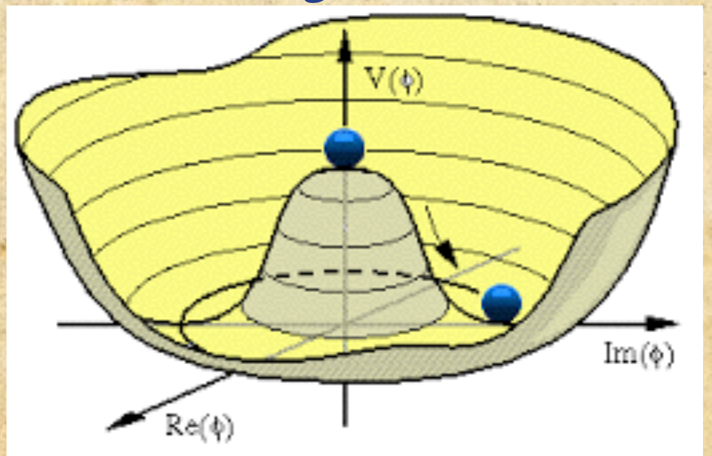
mass term - a small perturbation

Chiral symmetric term

m_q/M , p/M - small parameters in expansion

Approximate chiral symmetry is in lagrangian but not in the mass spectrum of hadrons!

Pions are pseudo-Goldstone bosons in chiral theory.

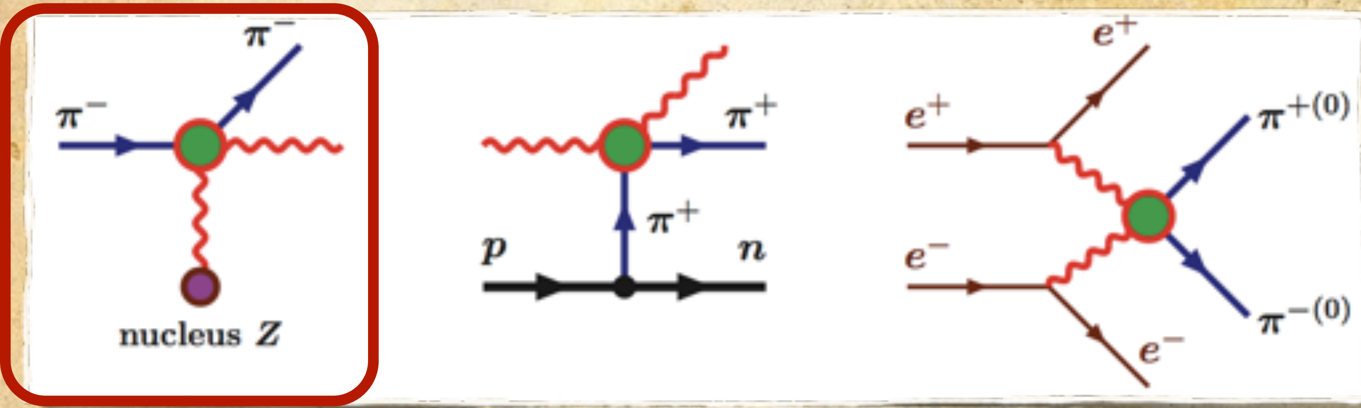


Pion polarizabilities: prediction

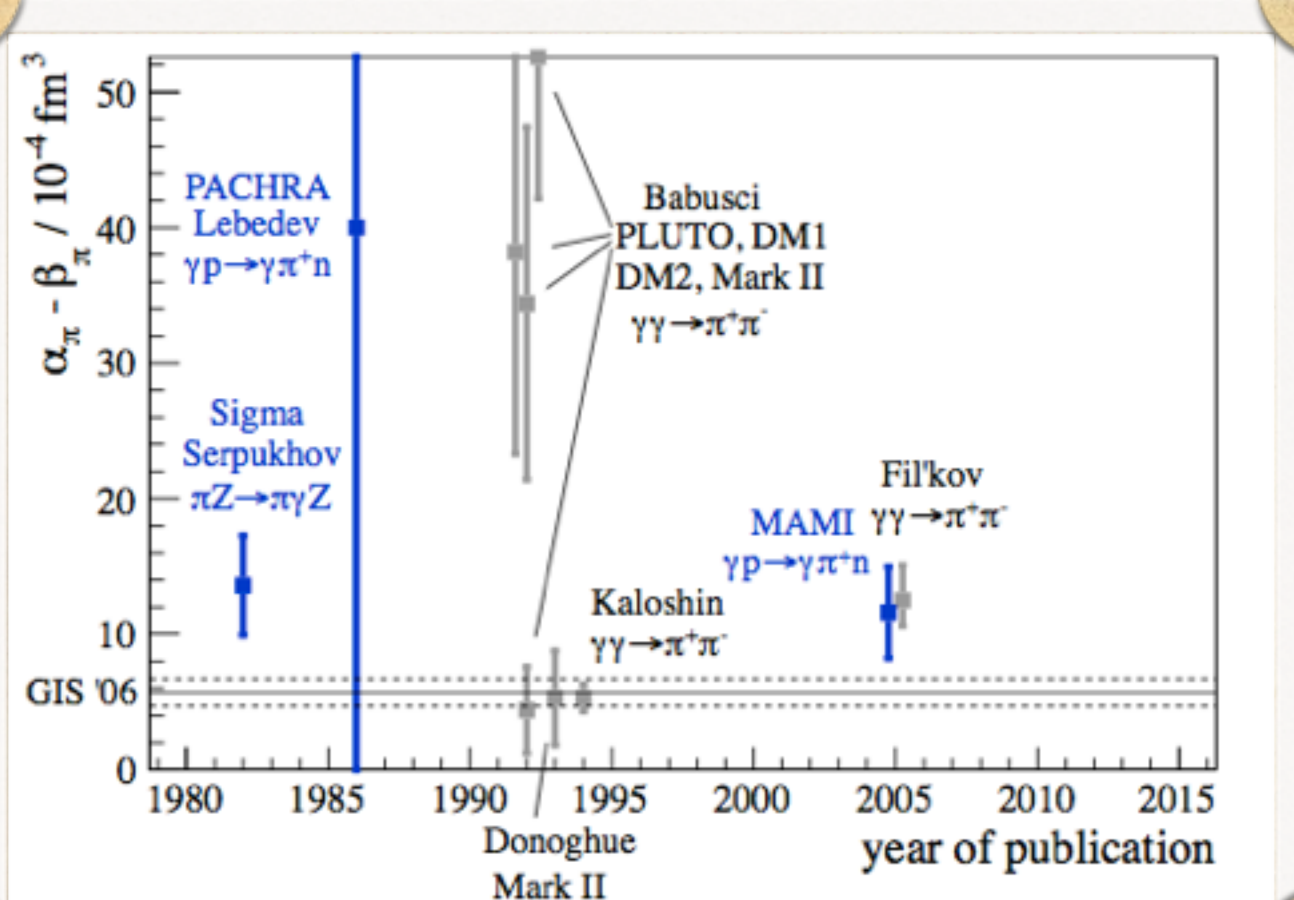
Model	Parameter	10^{-4} fm^3
χPT (1-loop)	$\alpha_\pi-\beta_\pi$	5.4±0.8
	$\alpha_\pi+\beta_\pi$	0
χPT (2-loops)	$\alpha_\pi-\beta_\pi$	5.7±1.0
	$\alpha_\pi+\beta_\pi$	0.16
Nambu-Nona-Lasinio model	$\alpha_\pi-\beta_\pi$	9.8
Quark confinement model	$\alpha_\pi-\beta_\pi$	7.05
	$\alpha_\pi+\beta_\pi$	0.23
QCD sum rules	$\alpha_\pi-\beta_\pi$	11.2±1.0
Dispersion sum rules	$\alpha_\pi-\beta_\pi$	13.6±2.15
	$\alpha_\pi+\beta_\pi$	0.166±0.024

The most of theoretical models are in agreement that $\alpha_\pi-\beta_\pi \gg \alpha_\pi+\beta_\pi \approx 0.2\times10^{-4}\ fm^3$. As for value $\alpha_\pi-\beta_\pi$, predictions are quite different

Experimental results for α_π, β_π



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



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

Primakoff reactions

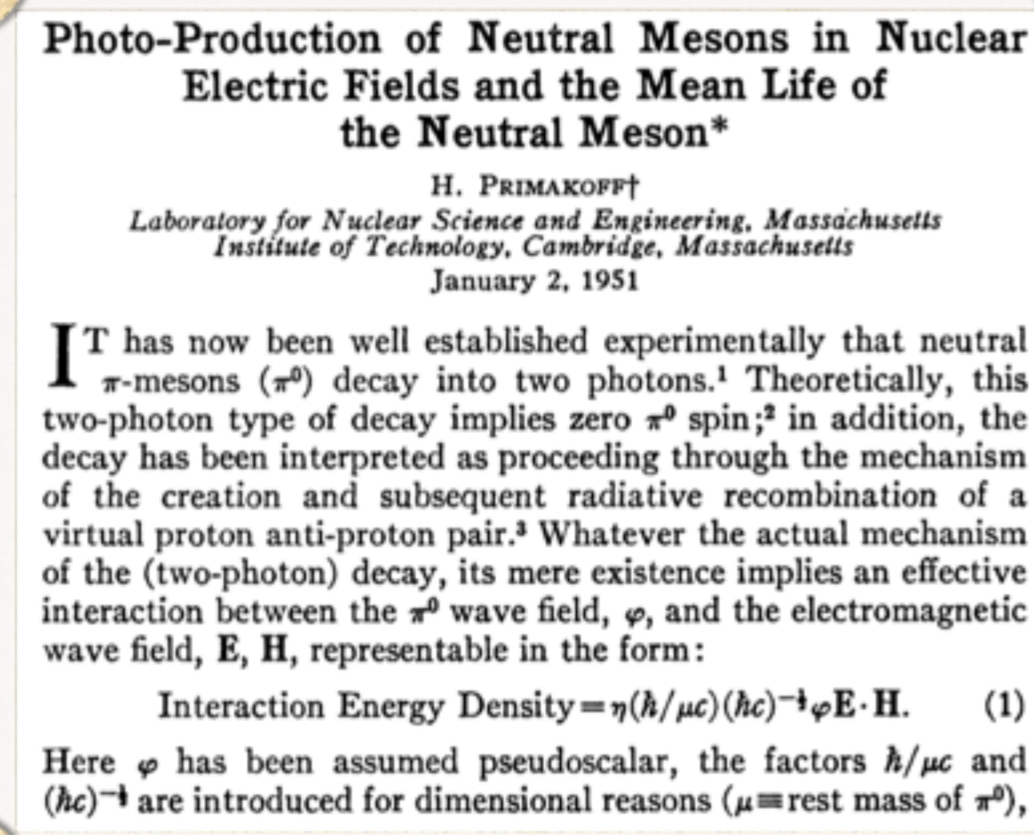


Photo-Production of Neutral Mesons in Nuclear Electric Fields and the Mean Life of the Neutral Meson*

H. PRIMAKOFF†

Laboratory for Nuclear Science and Engineering, Massachusetts Institute of Technology, Cambridge, Massachusetts

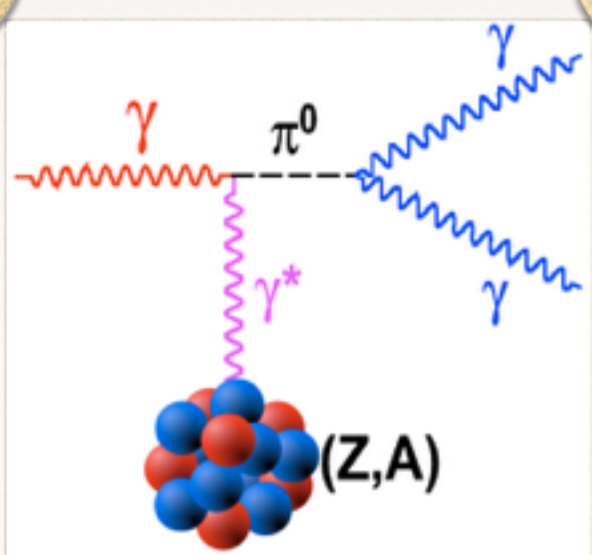
January 2, 1951

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:

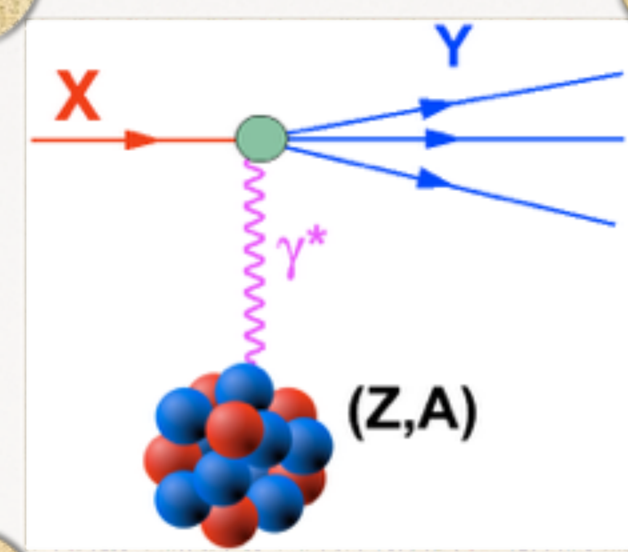
$$\text{Interaction Energy Density} = \eta(\hbar/\mu c)(\hbar c)^{-\frac{1}{2}}\varphi\mathbf{E}\cdot\mathbf{H}. \qquad (1)$$

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 a nucleus can be used as photon target

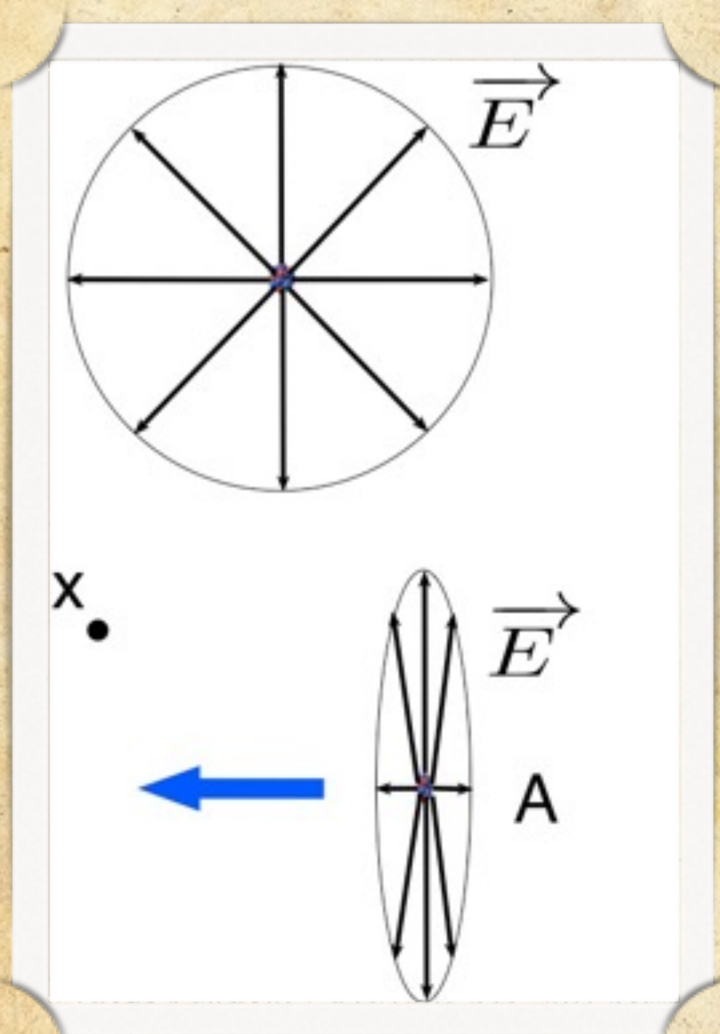


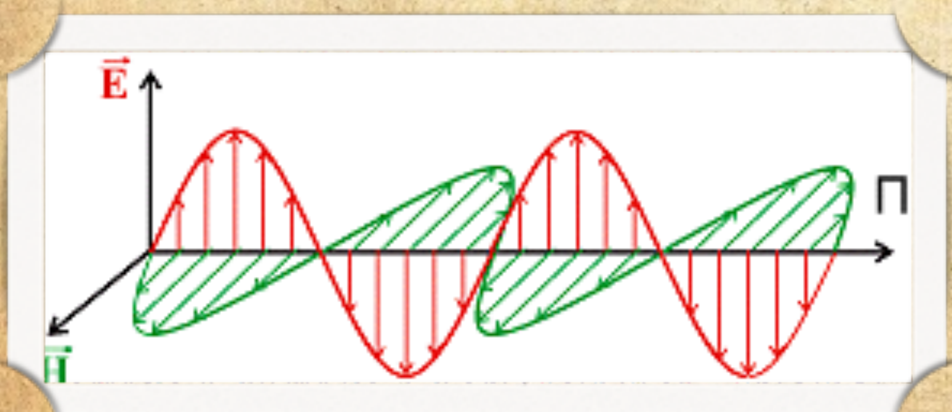
From Primakoff effect to Primakoff reactions



Equivalent photons approach

(Weizsaecker-Williams approximation)





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

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

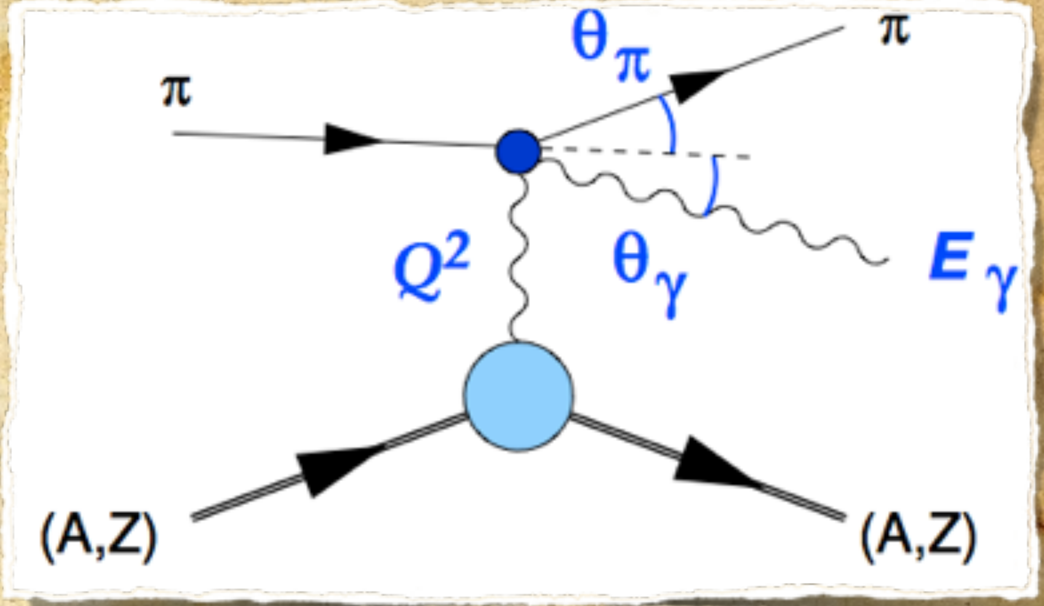
$$d\sigma_{xZ} = \int n_\gamma(\omega)\, d\sigma_{x\gamma}(\omega)\, d\omega$$

density of equivalent photons

Pion polarizabilities and Primakoff cross section

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

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



Compton cross section:

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

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

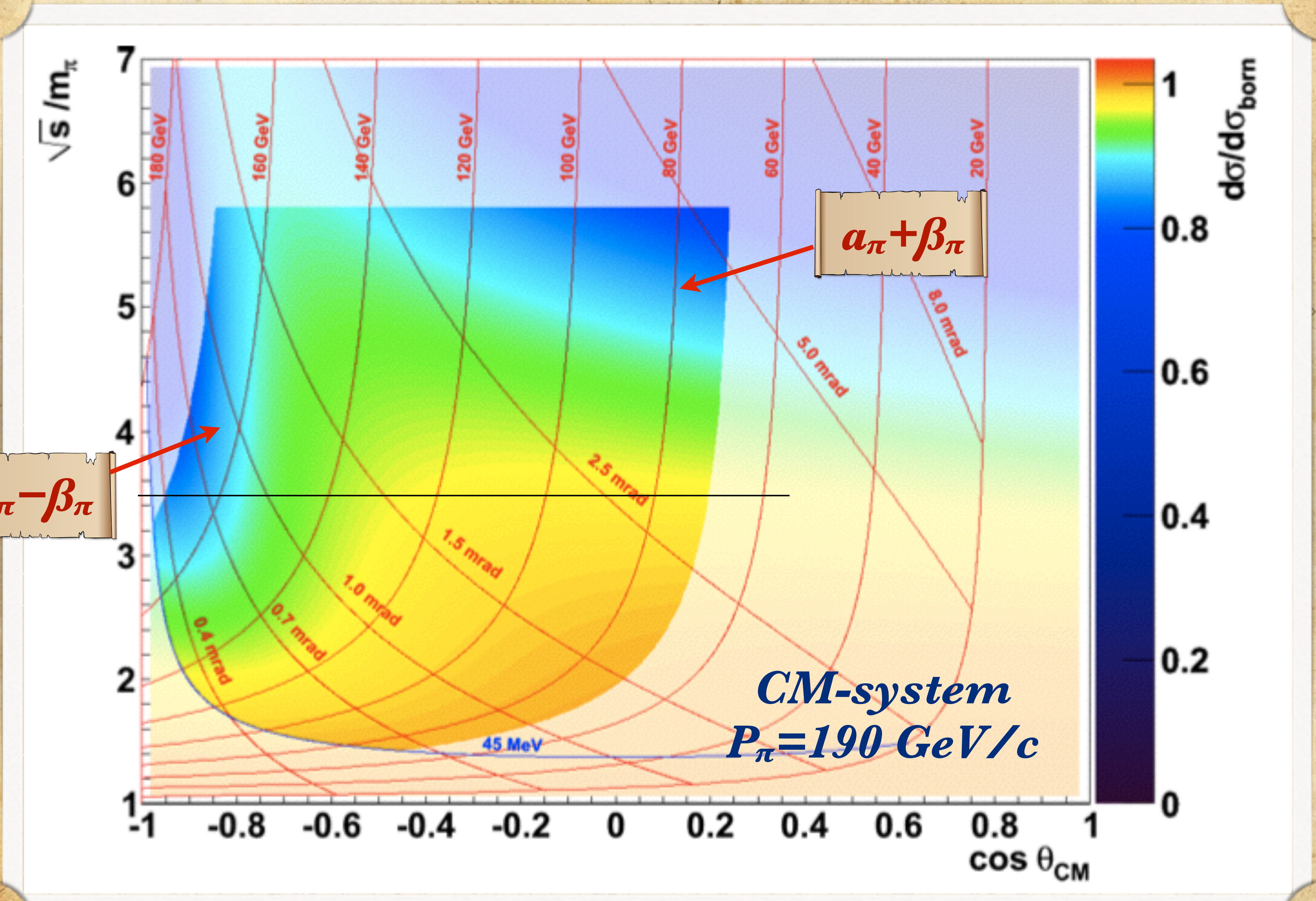
$$\mathcal{P} = z_-^2(\alpha_\pi-\beta_\pi) + \frac{s^2}{m_\pi^4} z_+^2(\alpha_\pi+\beta_\pi)$$

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

$\sigma \sim Z^2$

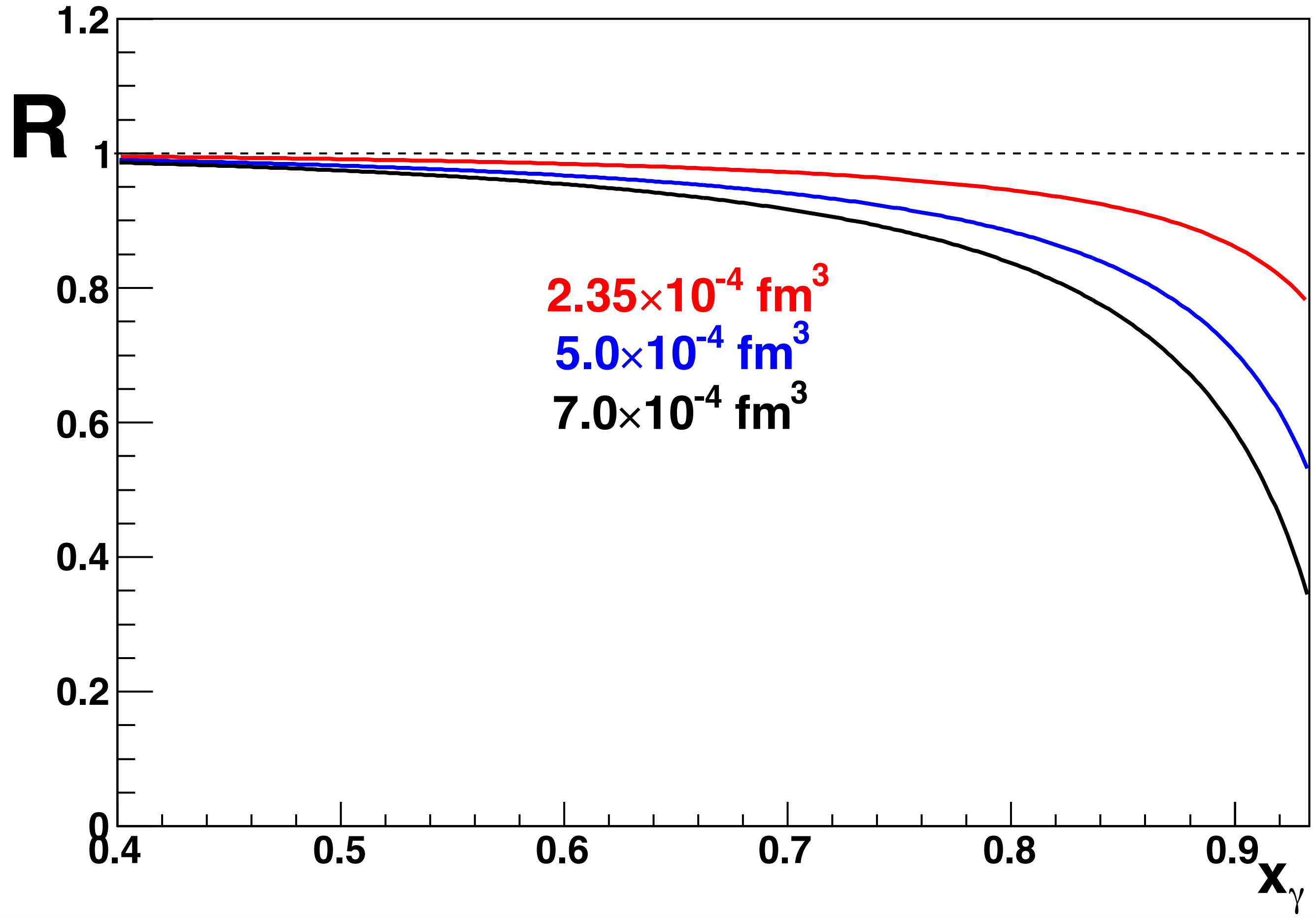
α_π and β_π can be extracted separately from the measurement of the differential cross section

Polarizability effects



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

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



x_γ - relative energy of emitted photon in Lab system

Pion polarizability and JINR

Retrospective review

Original proposal to measure pion polarizability via Primakoff reaction

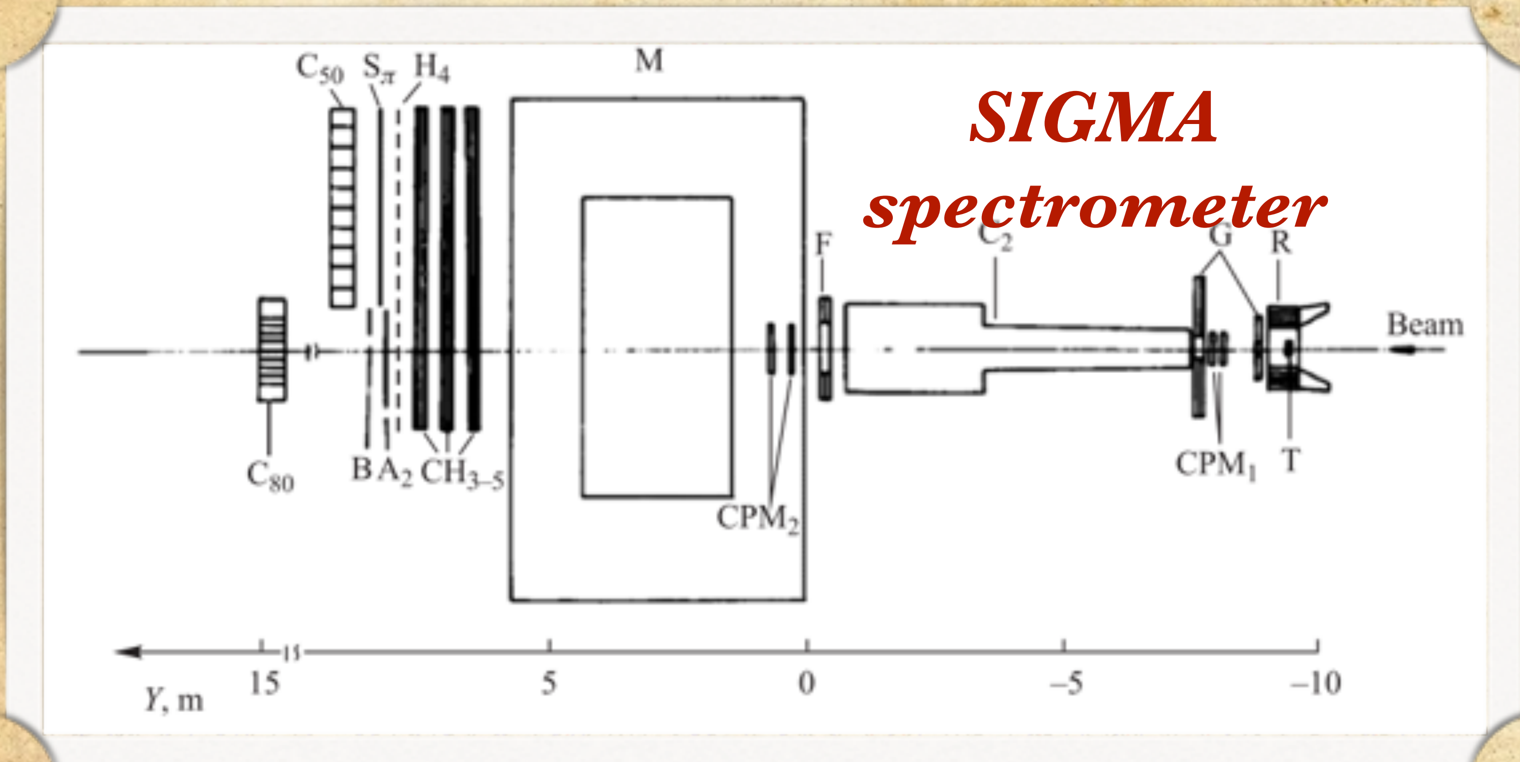
A.G.Galperin, G.V.Mitselmakher, A.G.Olshevski and V.N.Pervushin. Yad.Fiz. 32 (1980) 1053

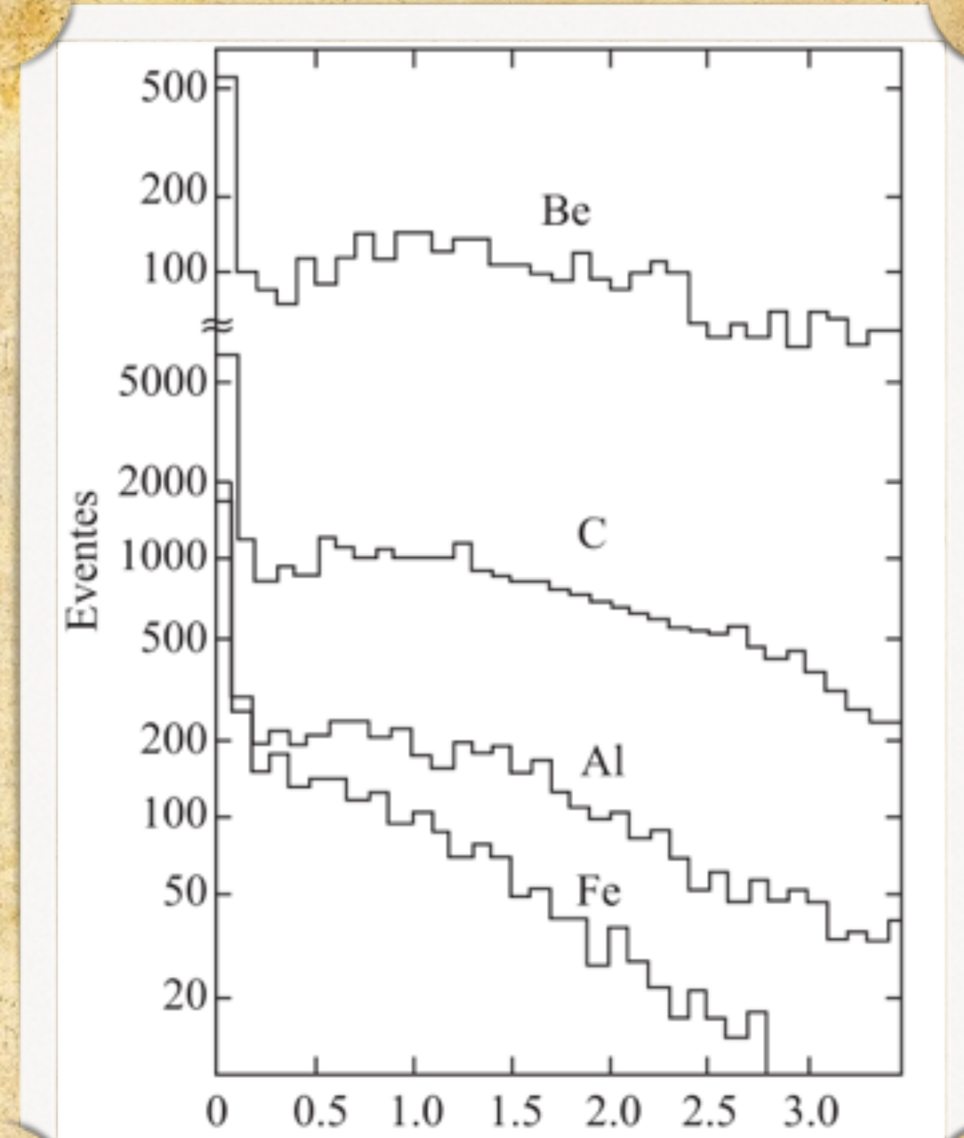
The first observation of the Compton scattering off pion at SIGMA spectrometer

The first measurement of pion polarizabilities

Dubna group brought their experience to the COMPASS experiment

Measurement at the SIGMA setup
(Protvino, IHEP-JINR collaboration)





$Q^2 \times 10^2$, GeV^2/c^2

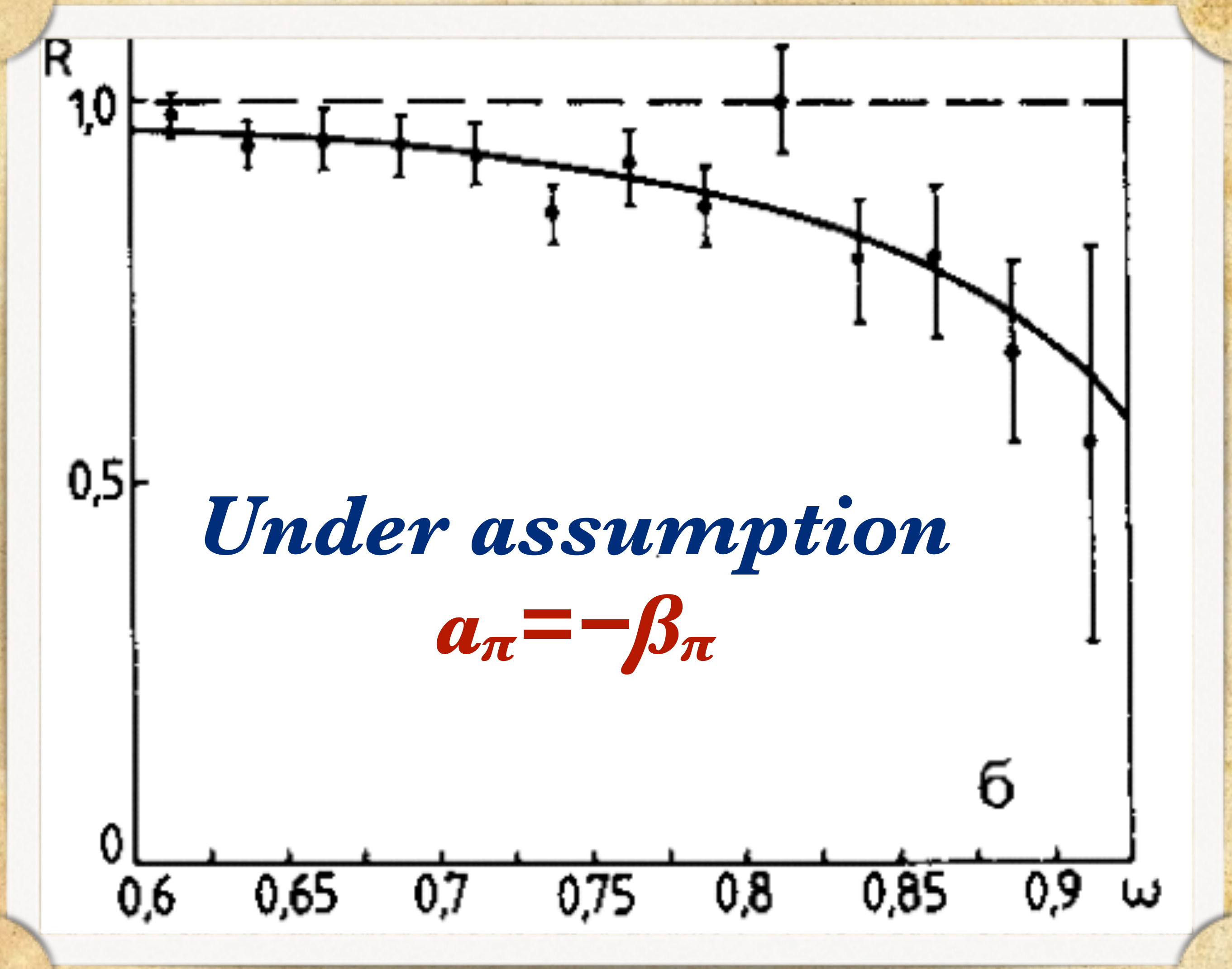
Beam: π^- , P=40 GeV/c

Target: C (0.25 X_0)

(also Be, Al, Fe, Cu,Pb)

Statistics: ~7 000 events with $x_\gamma > 0.5$

Measurement at the SIGMA setup
(Protvino, IHEP-JINR collaboration)



1985

Phys. Lett., B121, 445 (1983)
Z.Phys. C26 (1985) 495

$$a_\pi = -\beta_\pi = (6.8 \pm 1.4_{stat} \pm 1.2_{syst}) \times 10^{-4}\ fm^3$$

$$a_\pi + \beta_\pi = (1.4 \pm 3.1_{stat} \pm 2.8_{syst}) \times 10^{-4}\ fm^3$$
$$a_\pi = (7.8 \pm 2.8_{stat} \pm 1.8_{syst}) \times 10^{-4}\ fm^3$$

The COMPASS experiment

COMPASS (COmmon Muon Proton Apparatus for Structure and Spectroscopy)

is the fixed target experiment on the secondary beam of Super Proton Synchrotron at CERN

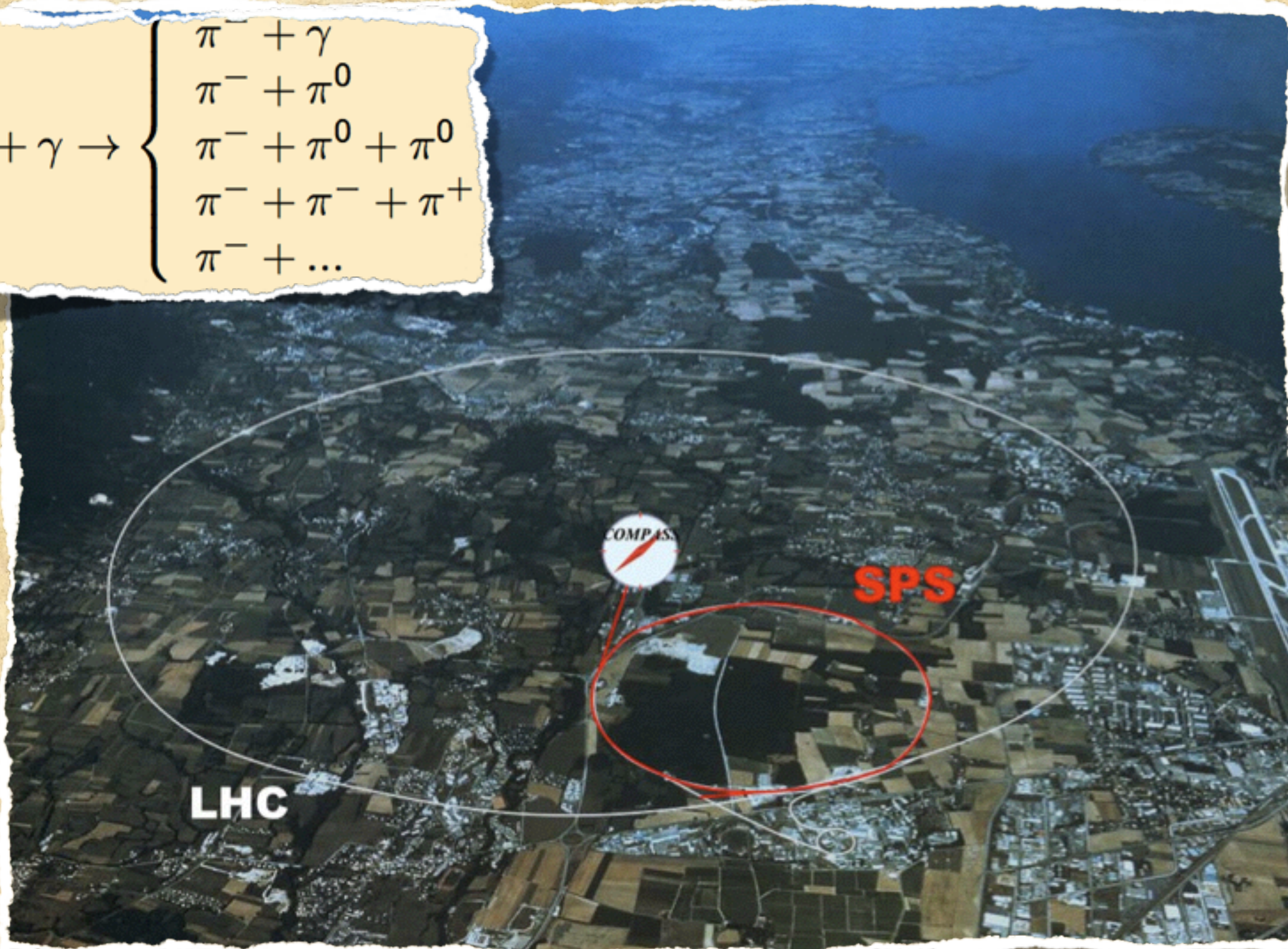
The purpose of this experiment is the study of hadron structure and hadron spectroscopy with high intensity muon and hadron beams.

1996 - Proposal
2002-2011 - Physical data taking

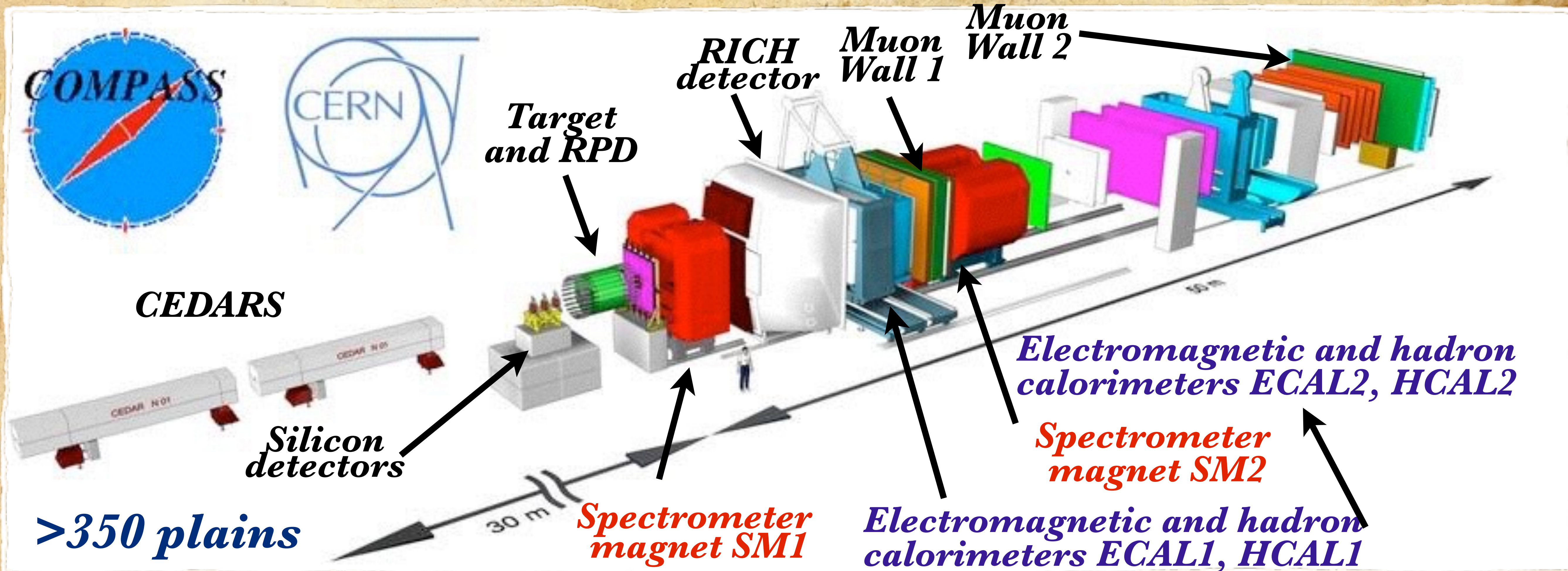
11 countries,
28 institutions,
~240 physicists

COMPASS at CERN

$$\pi^- + \gamma \to \begin{cases} \pi^- + \gamma \\ \pi^- + \pi^0 \\ \pi^- + \pi^0 + \pi^0 \\ \pi^- + \pi^- + \pi^+ \\ \pi^- + \ldots \end{cases}$$



The COMPASS setup



- *CEDAR detectors for beam particle identification*
- *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*

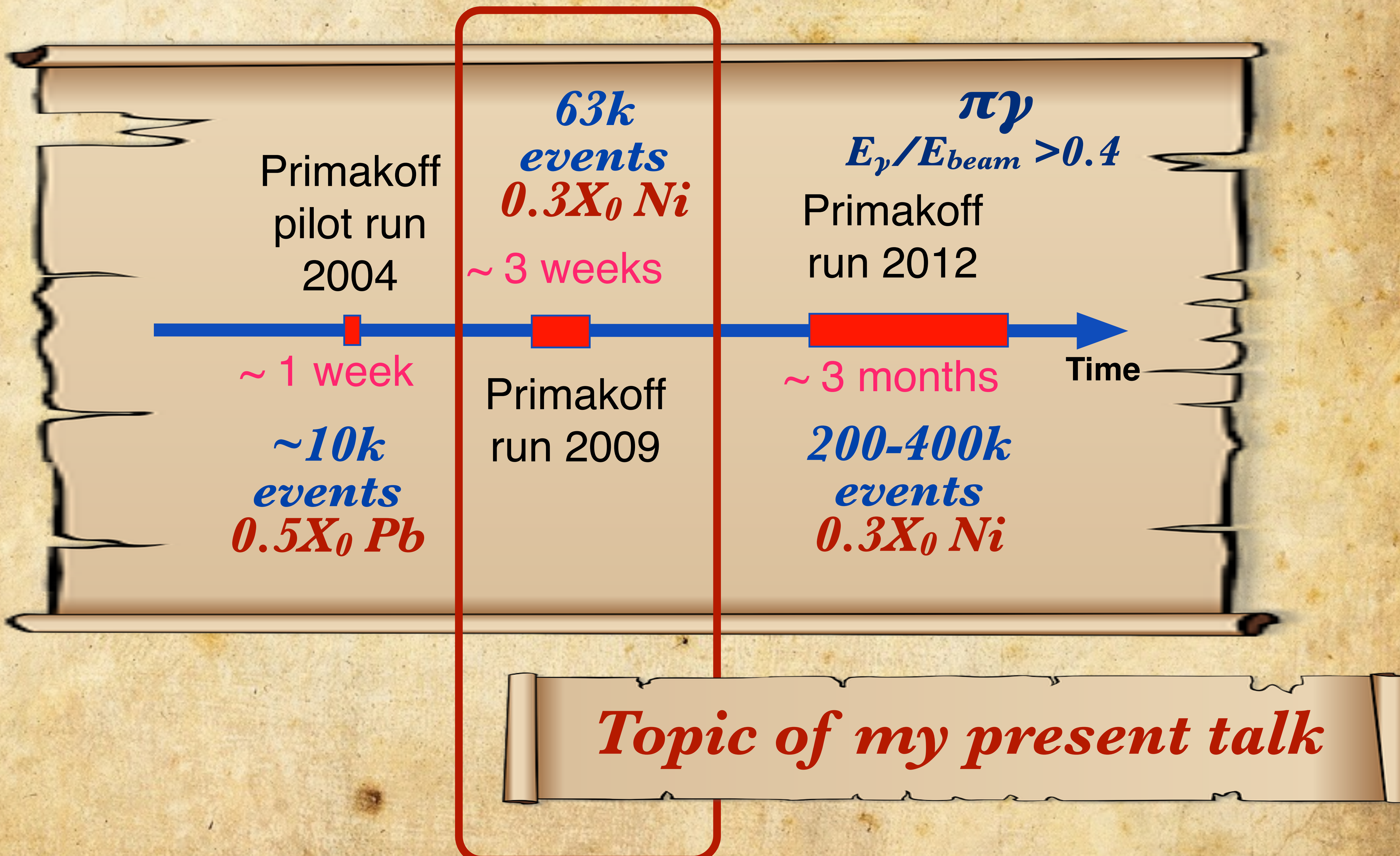
Main advantage of COMPASS

We can use pion and muon beams of the same momentum with the same setup configuration.

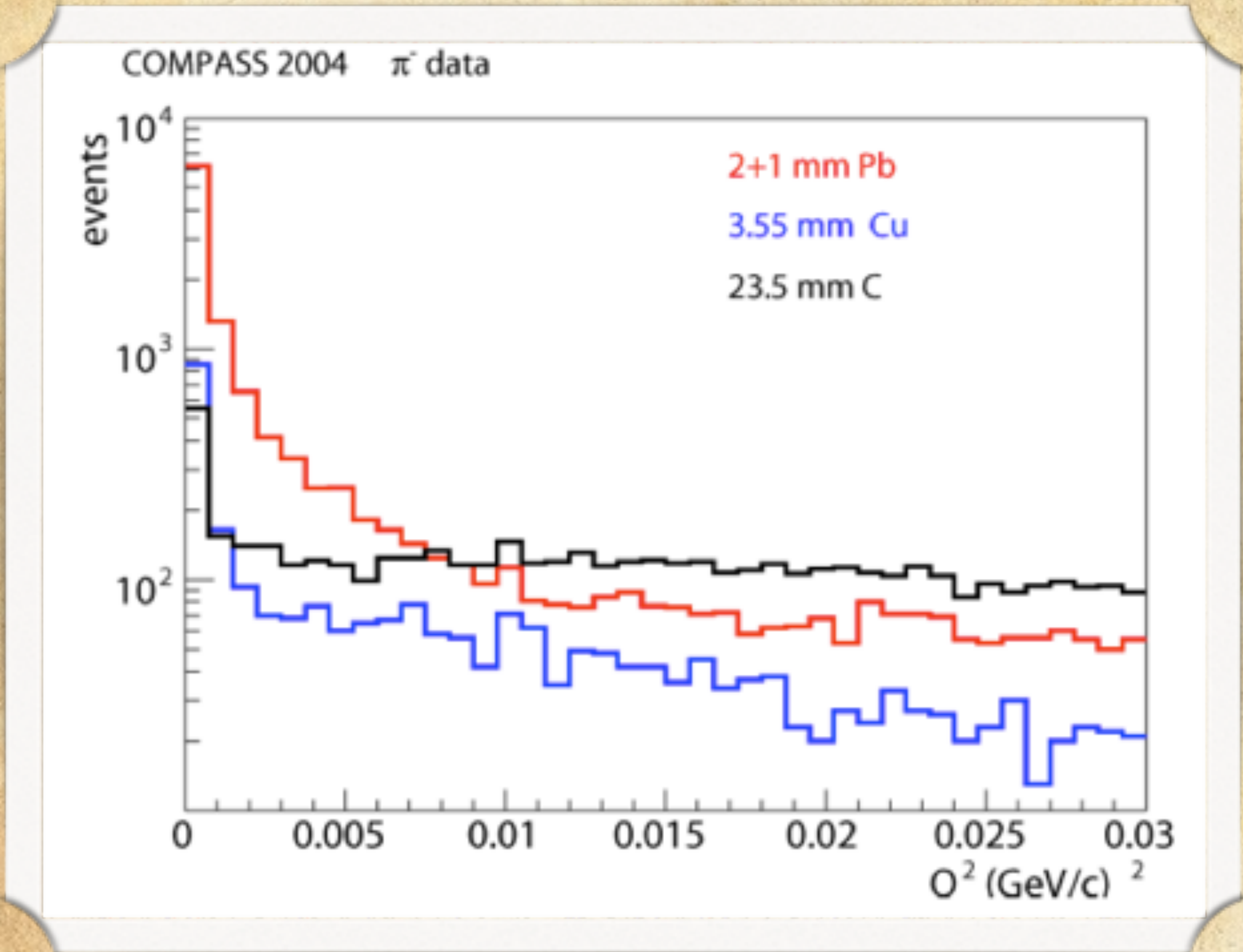
$$\pi^- (A,Z) \rightarrow \pi^- (A,Z)\, \gamma$$
$$\mu^- (A,Z) \rightarrow \mu^- (A,Z)\, \gamma$$

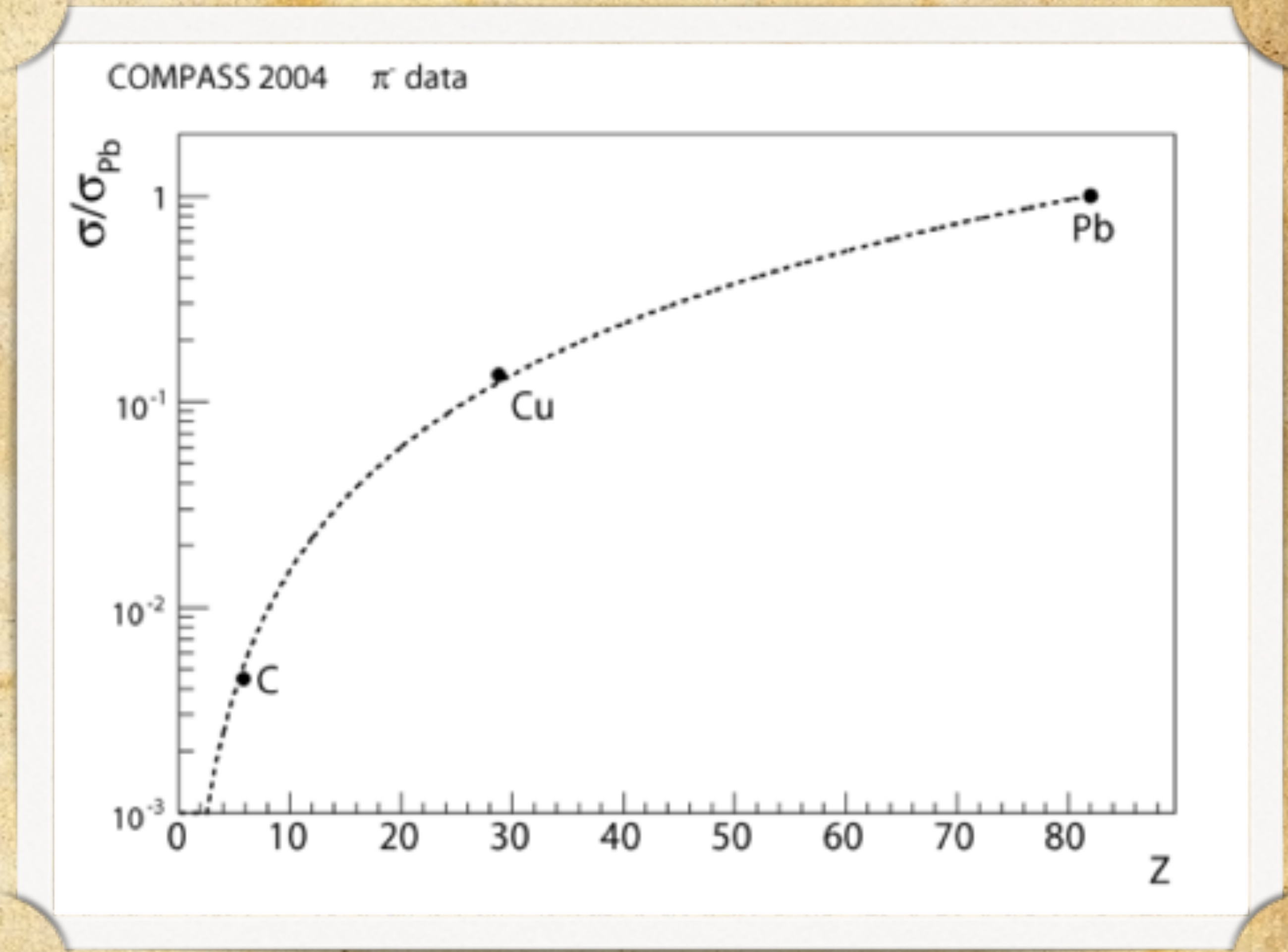
Muon is the point-like particle and corresponding cross section for muon is known with high precision. So, muon data can be used as reference to control our systematics.

Primakoff runs at COMPASS



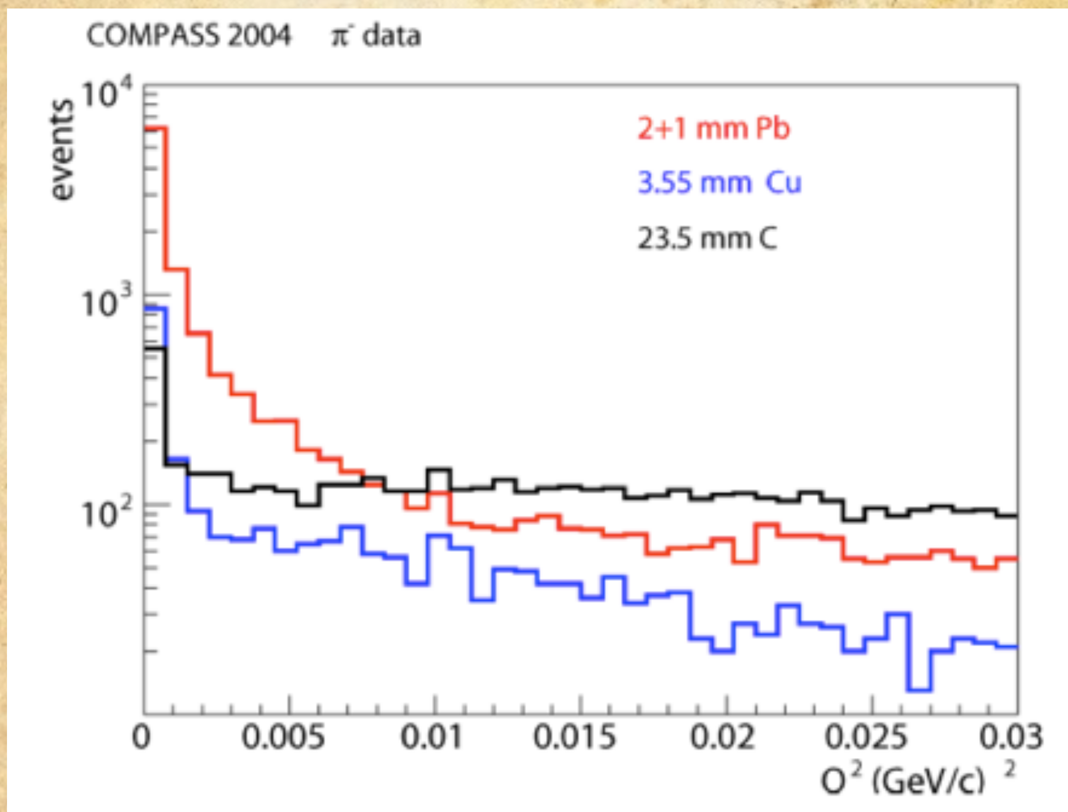
Pilot data taking in 2004



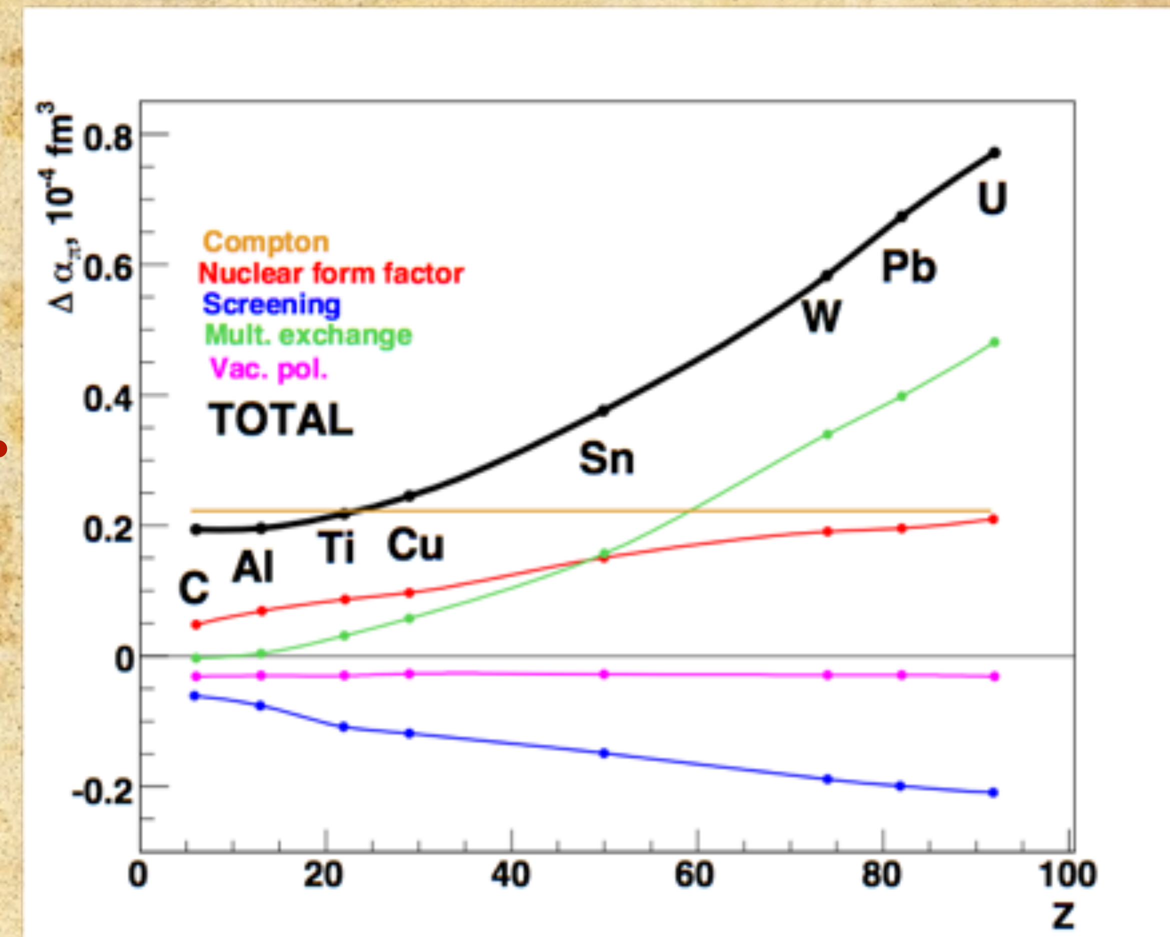


Pion radiative scattering was observed, some preliminary studies were performed

Target: C→Pb→Ni



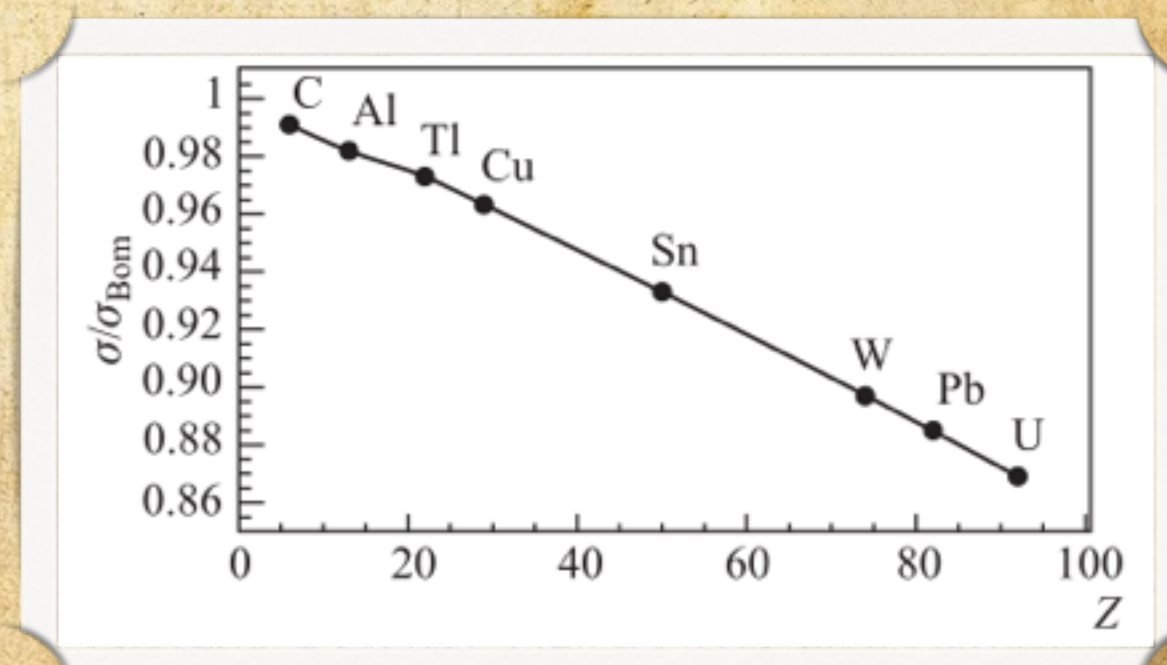
but…



For high Z nuclei:

we have better electromagnetic signal to nuclear background ratio but…

we much stronger depends on calculation of numerous corrections

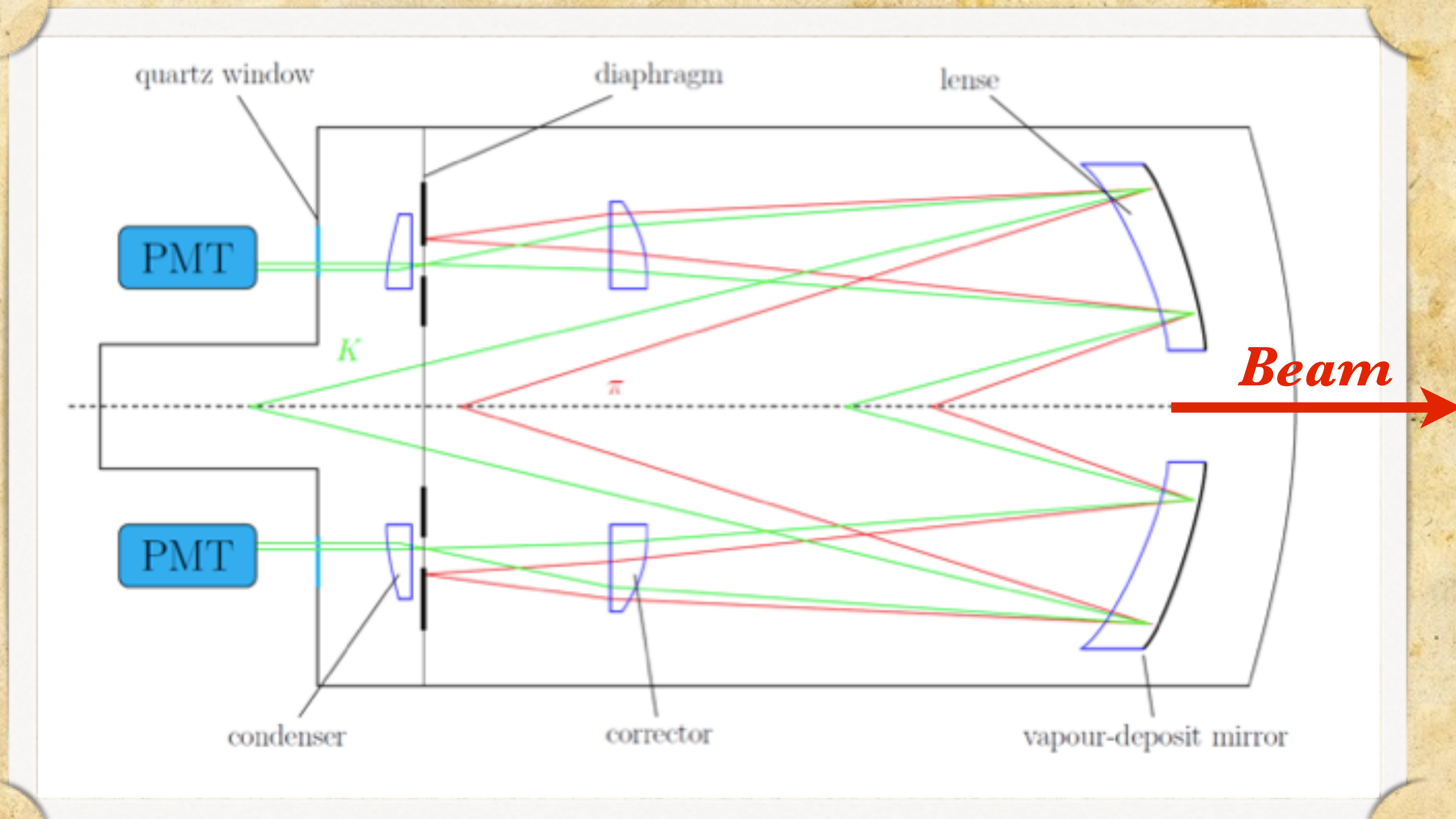


Hadron and muon beams

	Hadron	Muon
P, GeV/c	190	190
dP/P	1%	4%
σ the target, cm	0.5	0.8
Divergence, mrad	0.1	0.4
Intensity, 10^7/9.6 s spill	4	4
Composition	π^- 96% K^- 2.4% p^- 0.8% μ^- ~1% e^- <0.01%	μ^- ~100%

CEDAR detectors

2 differential Cherenkov counters upstream the target

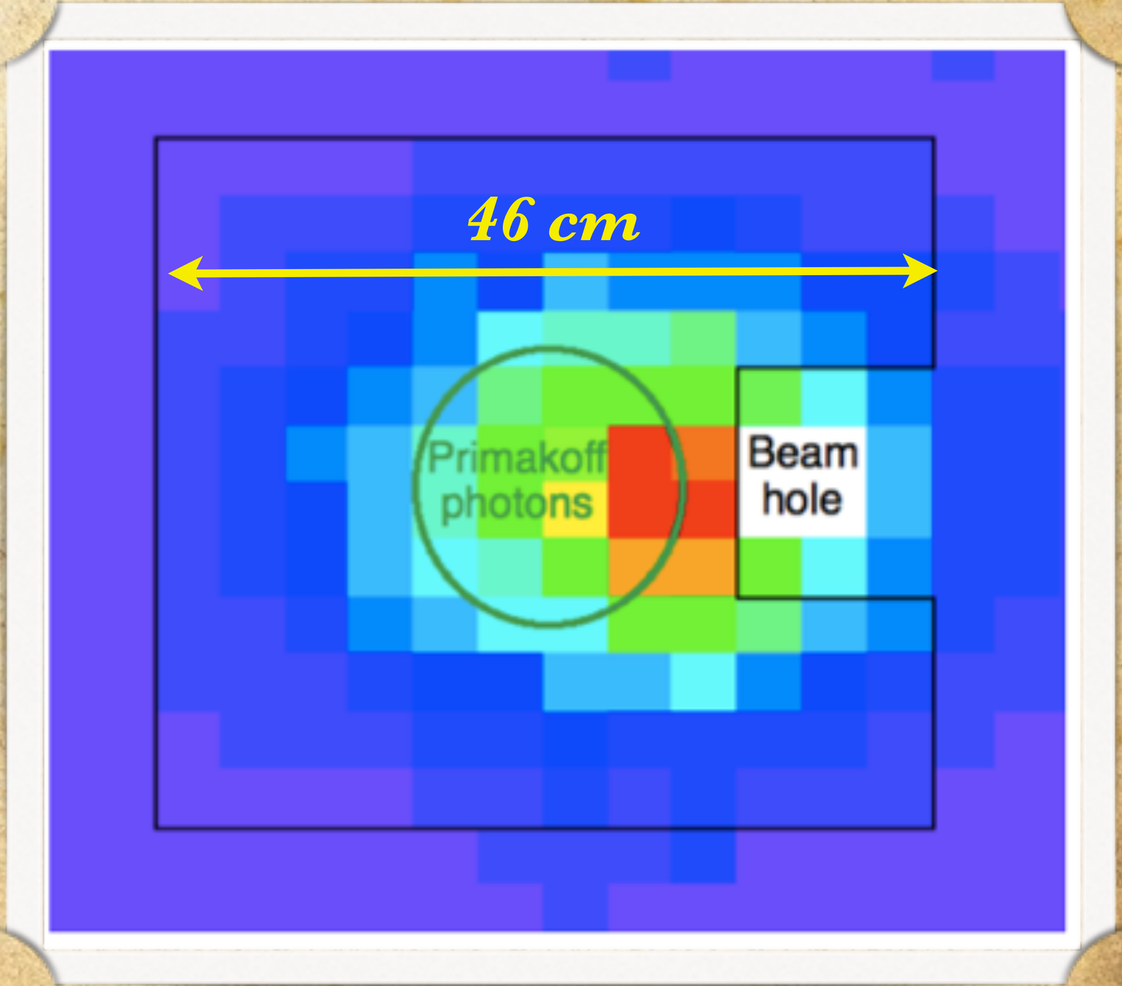


kaon rejection efficiency: ~95% for parallel beam

Trigger

TRIGGER = (BC & ECAL2) !SW !BK1 !BK2

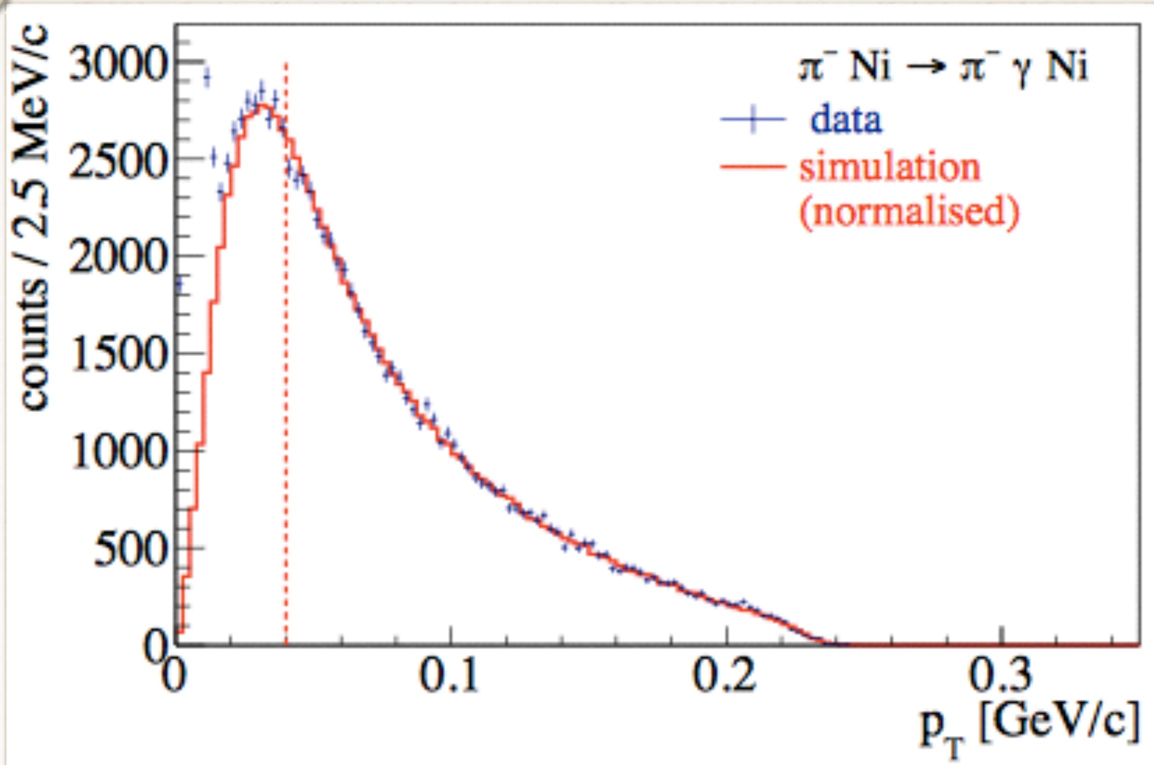
Trigger name	ECAL2 threshold, GeV	Scale factor	Rate, kHz
Primakoff 1	~40	2	~20
Primakoff 2	~60	1	



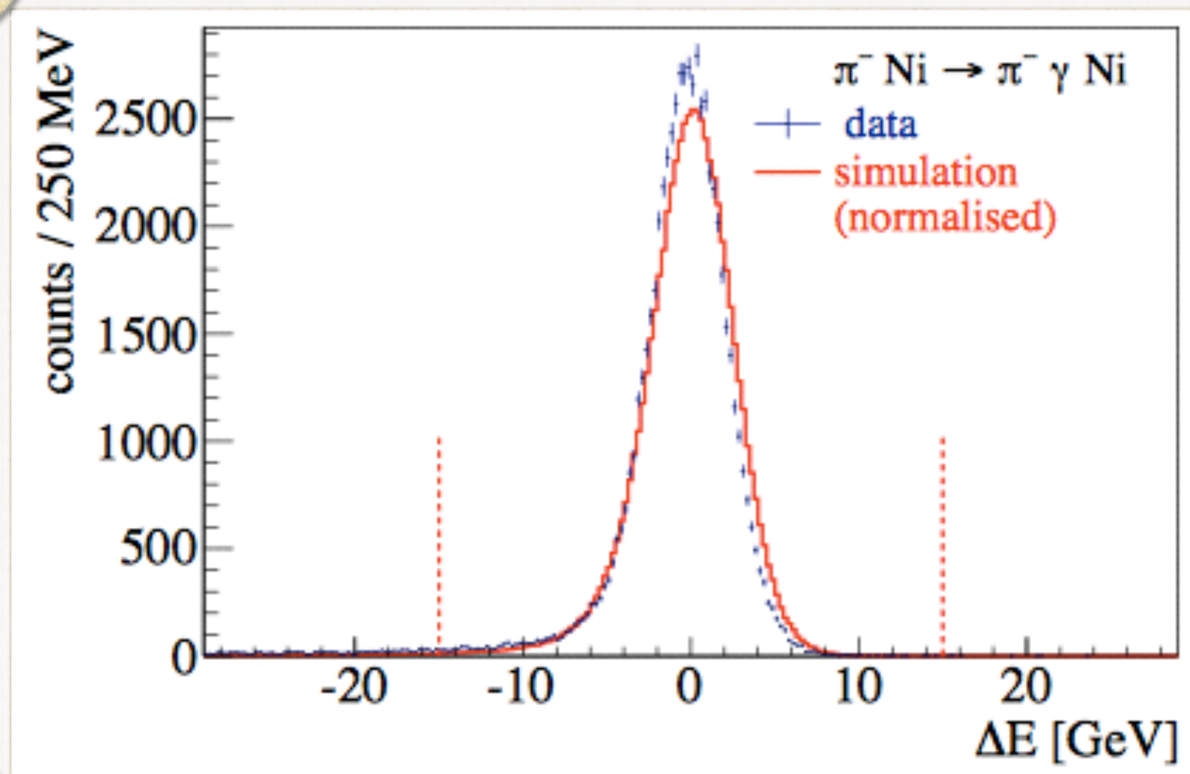
Event selection

- Primakoff1, Primakoff2 triggers
- 1 vertex with 1 outgoing negative track
- No other tracks*
- Beam track is parallel to the nominal beam axis
- Scattered track is not muon
- No activity in RPD
- Exactly 1 neutral cluster in ECAL2 (E>2 GeV)*
- Beam particle is pion (CEDAR)

Kinematic cuts

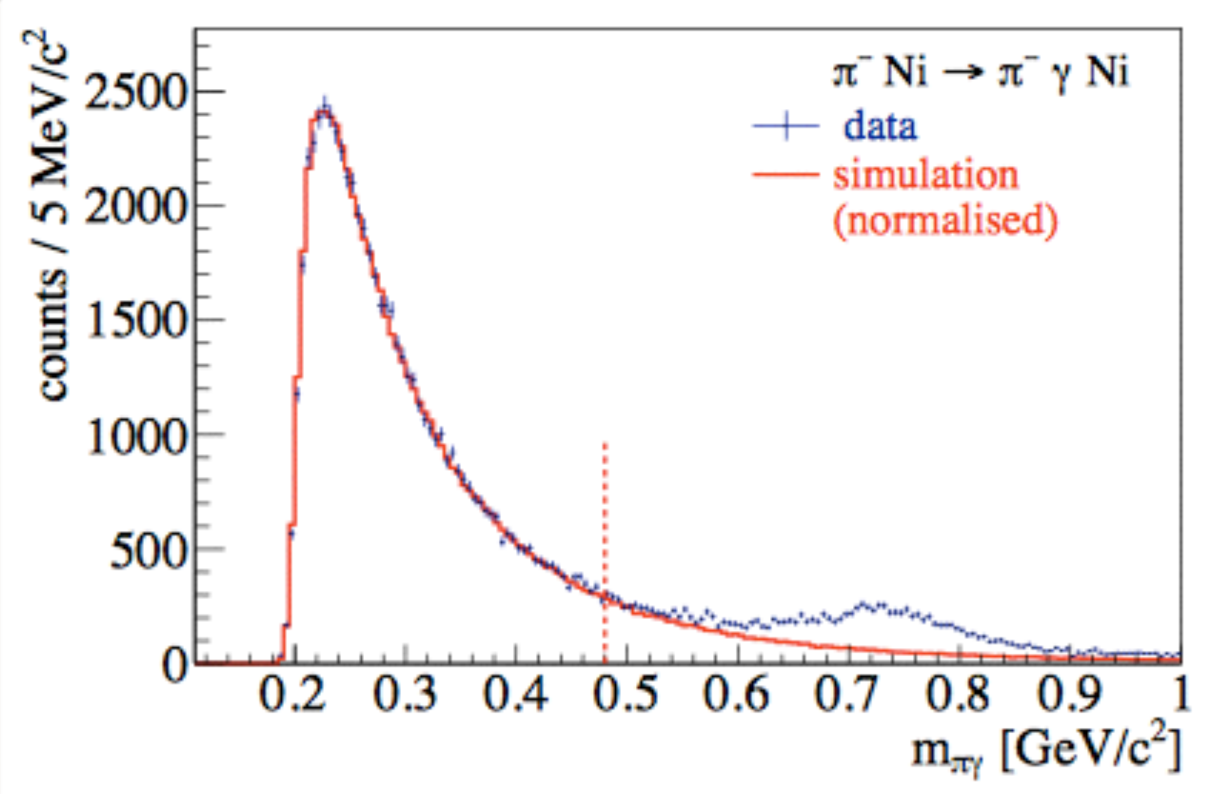


***p_T-cut* to reject low p_T region related with multiple scattering in the material**



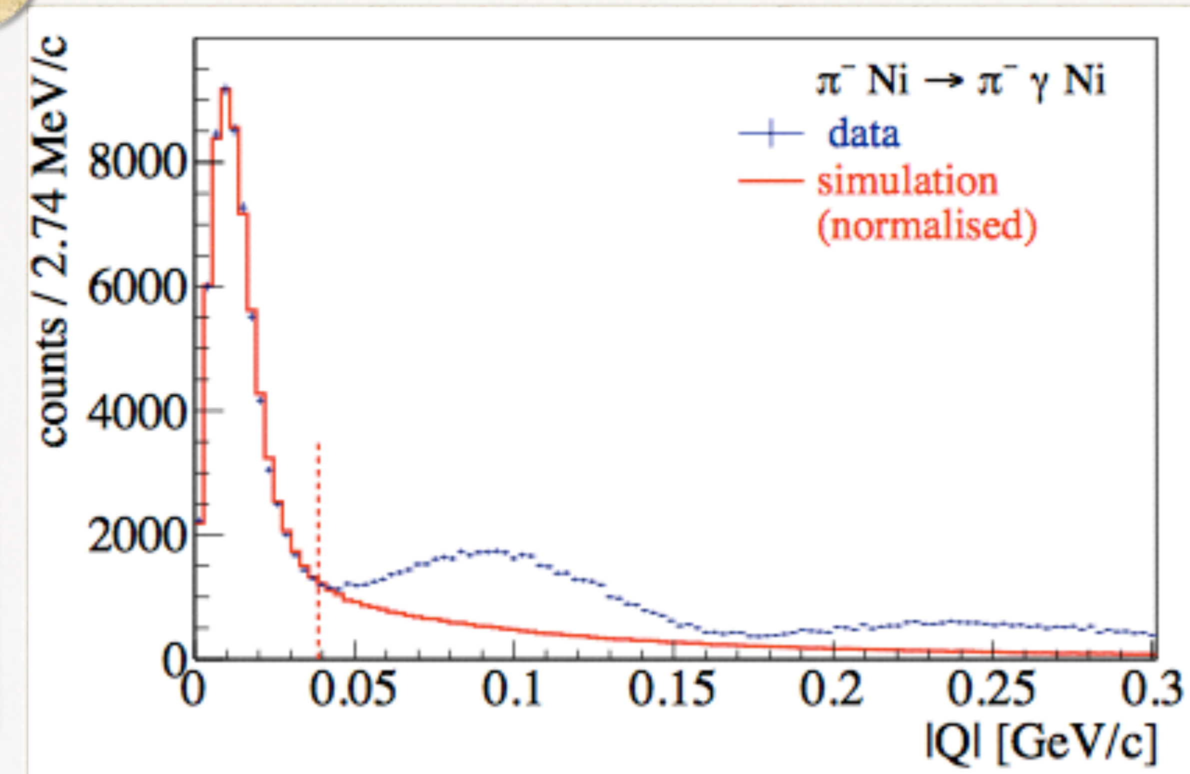
***Exclusivity cut* on the level ±15 GeV to reject events with missed particles in the final state**

Kinematic cuts



$M_{\pi\gamma} < 3.5\, m_\pi$ to avoid ρ-meson production and decay to $\pi\pi^0$

$Q^2 < 1.5\times10^{-3}\,(GeV/c)^2$ to reject πγ state production via strong interaction



π^0 background

$\pi^- Ni \rightarrow \pi^- Ni\, \pi^0 \rightarrow \pi^- Ni\, \gamma\gamma$

single cluster in ECAL2

1γ lost

The same selection criteria were applied for this channel

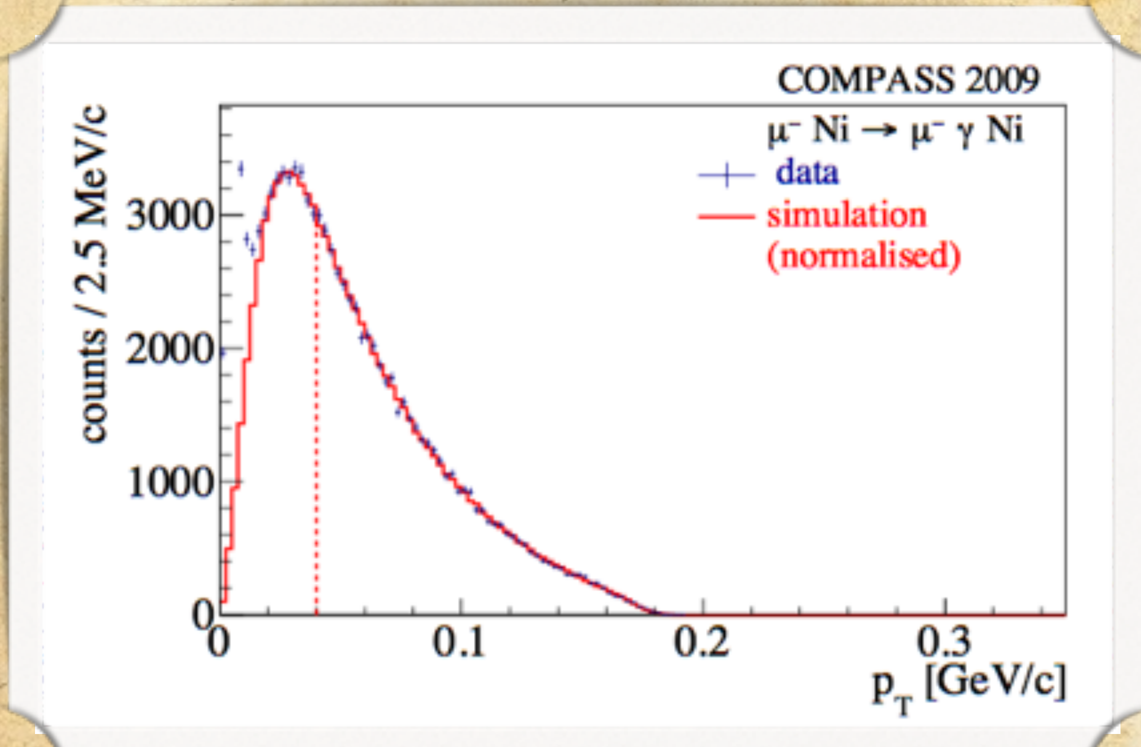
fraction of mis-reconstructed $\pi^-\pi^0$ events in $\pi^-\gamma$ sample

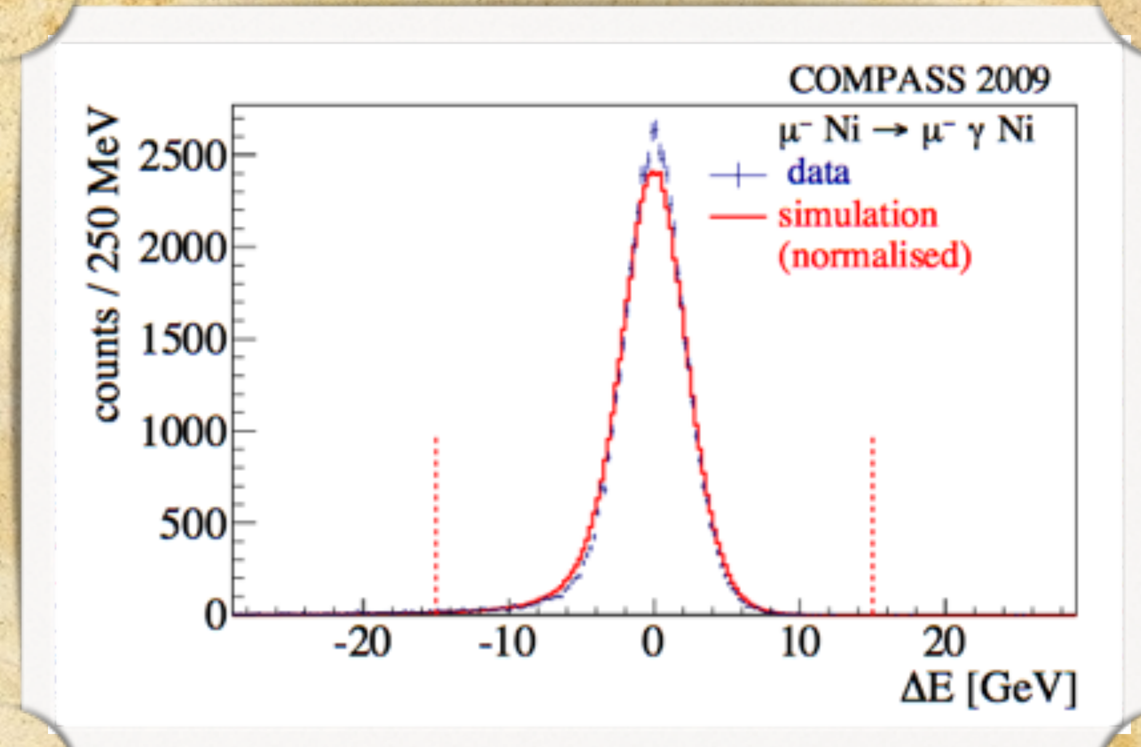
Kaon decay $K^- \rightarrow \pi^-\pi^0$ out of the target is the reference process

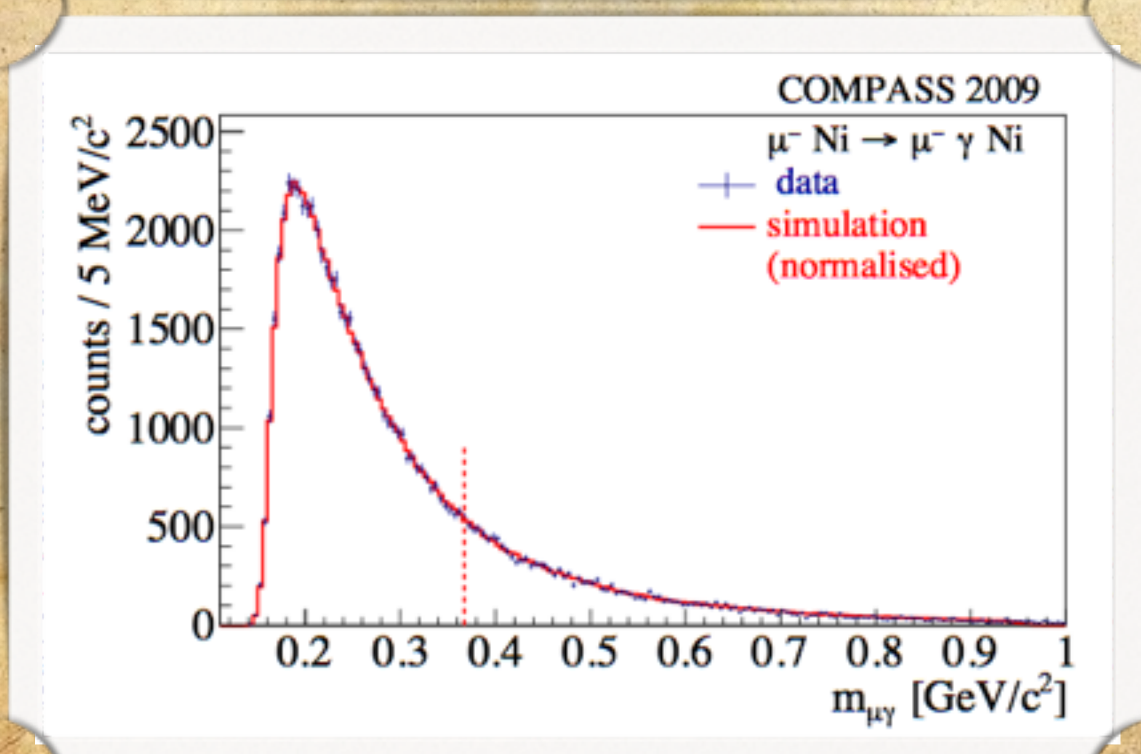
probability to mis-identify $\pi^-\pi^0$ state as $\pi^-\gamma$

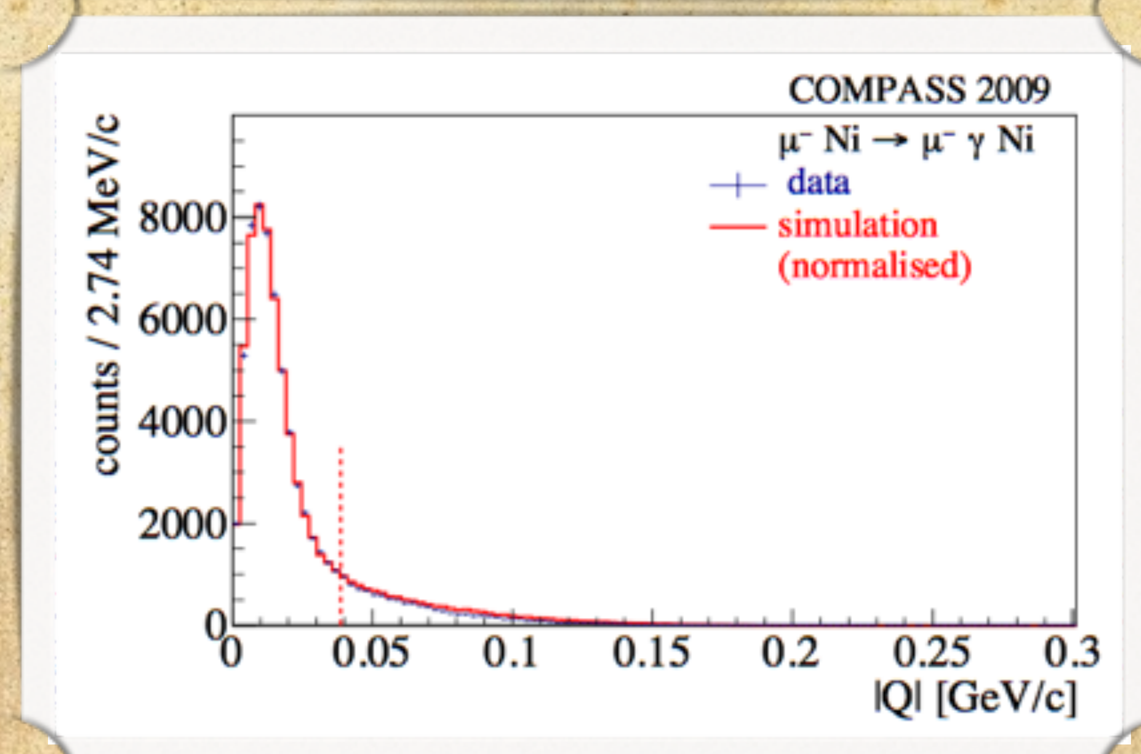
Muon data

The same selection + muon beam momentum measurement

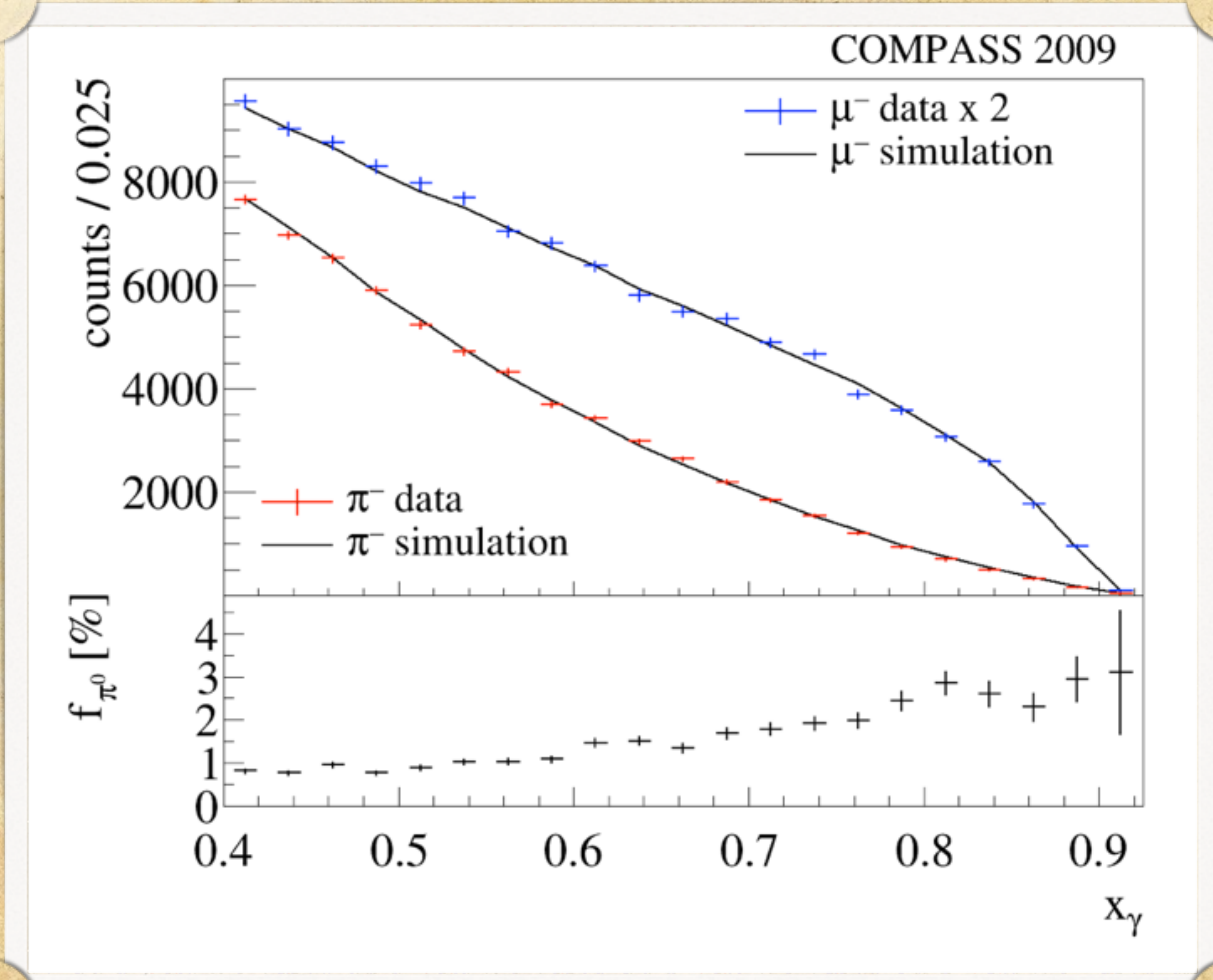




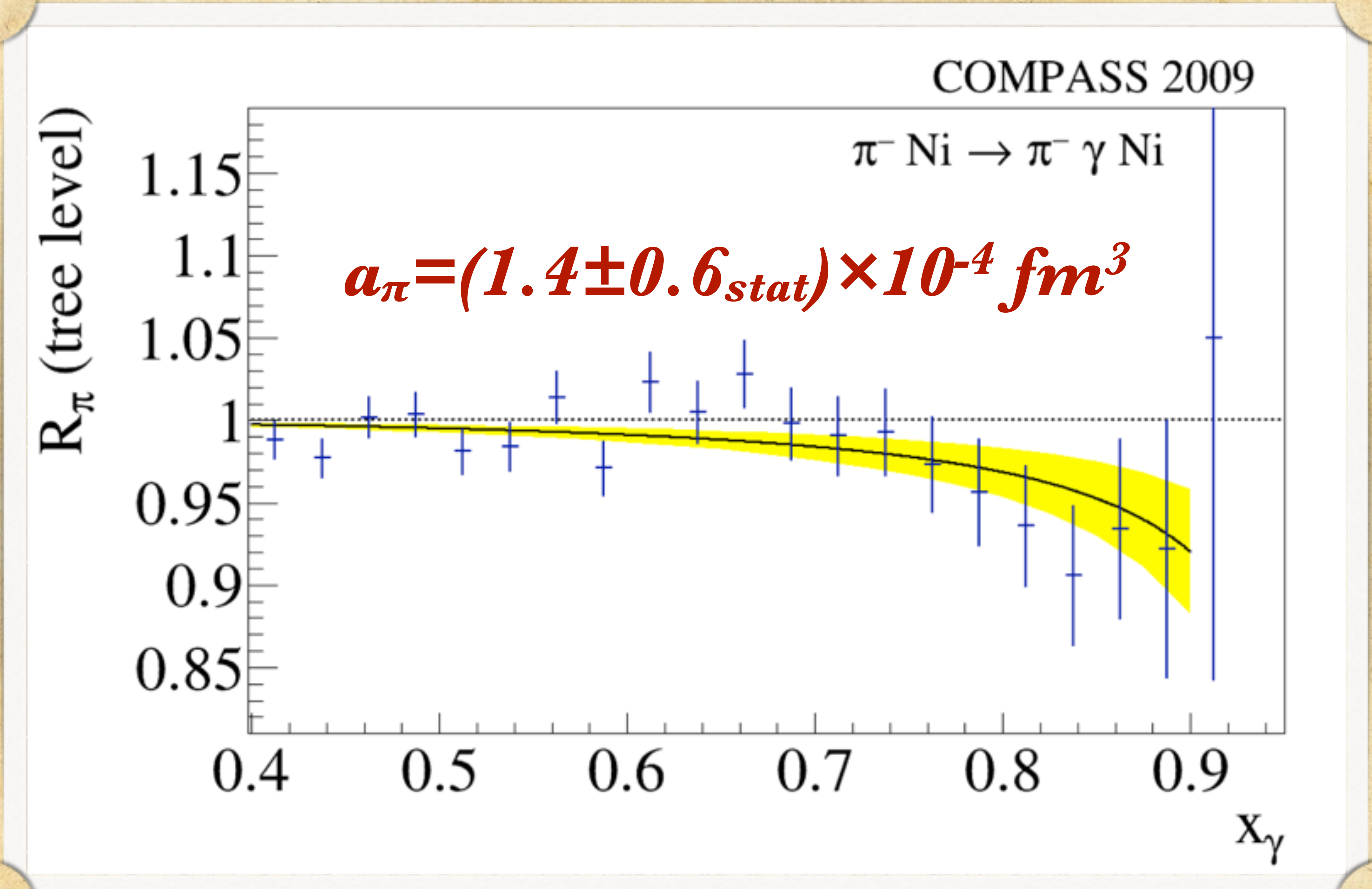




The measured x_γ distributions



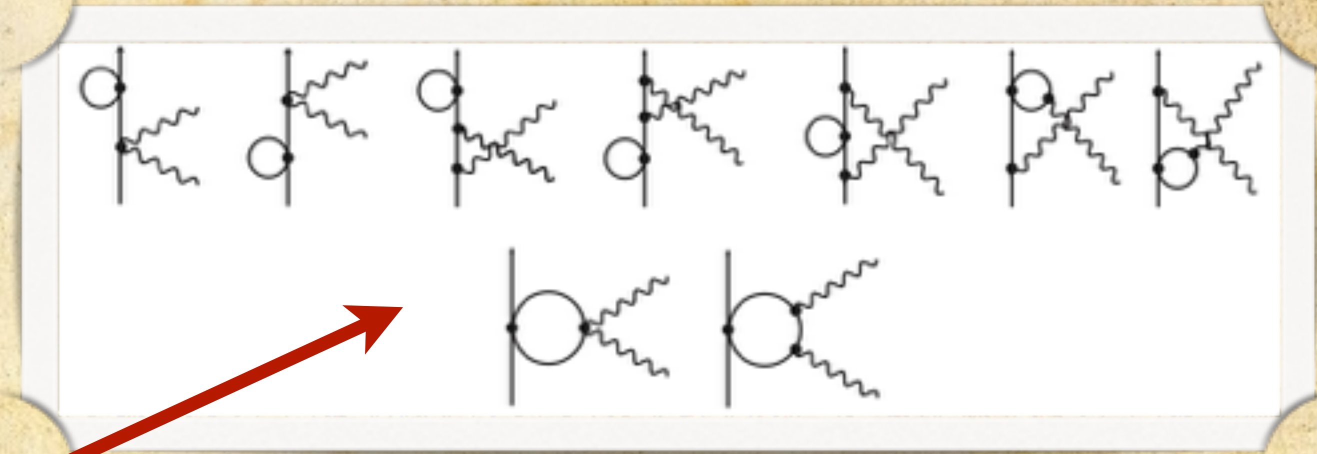
The result?

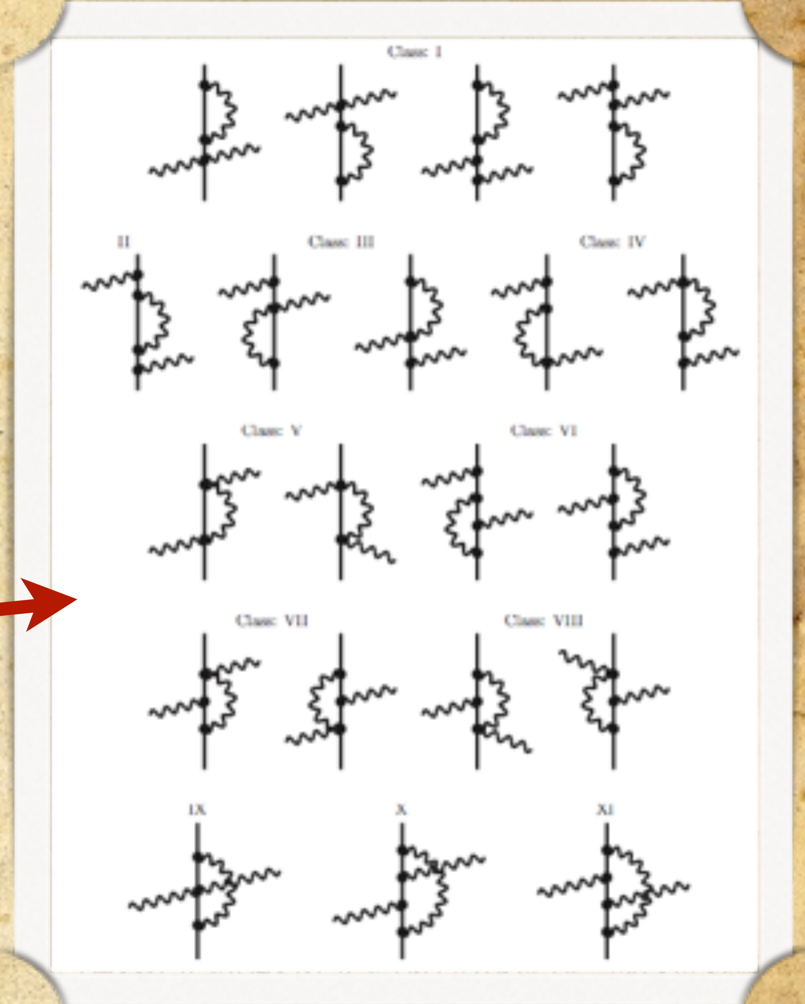


$$a_\pi=(1.4\pm0.6_{stat})\times10^{-4}\ fm^3$$

Not yet!

Corrections

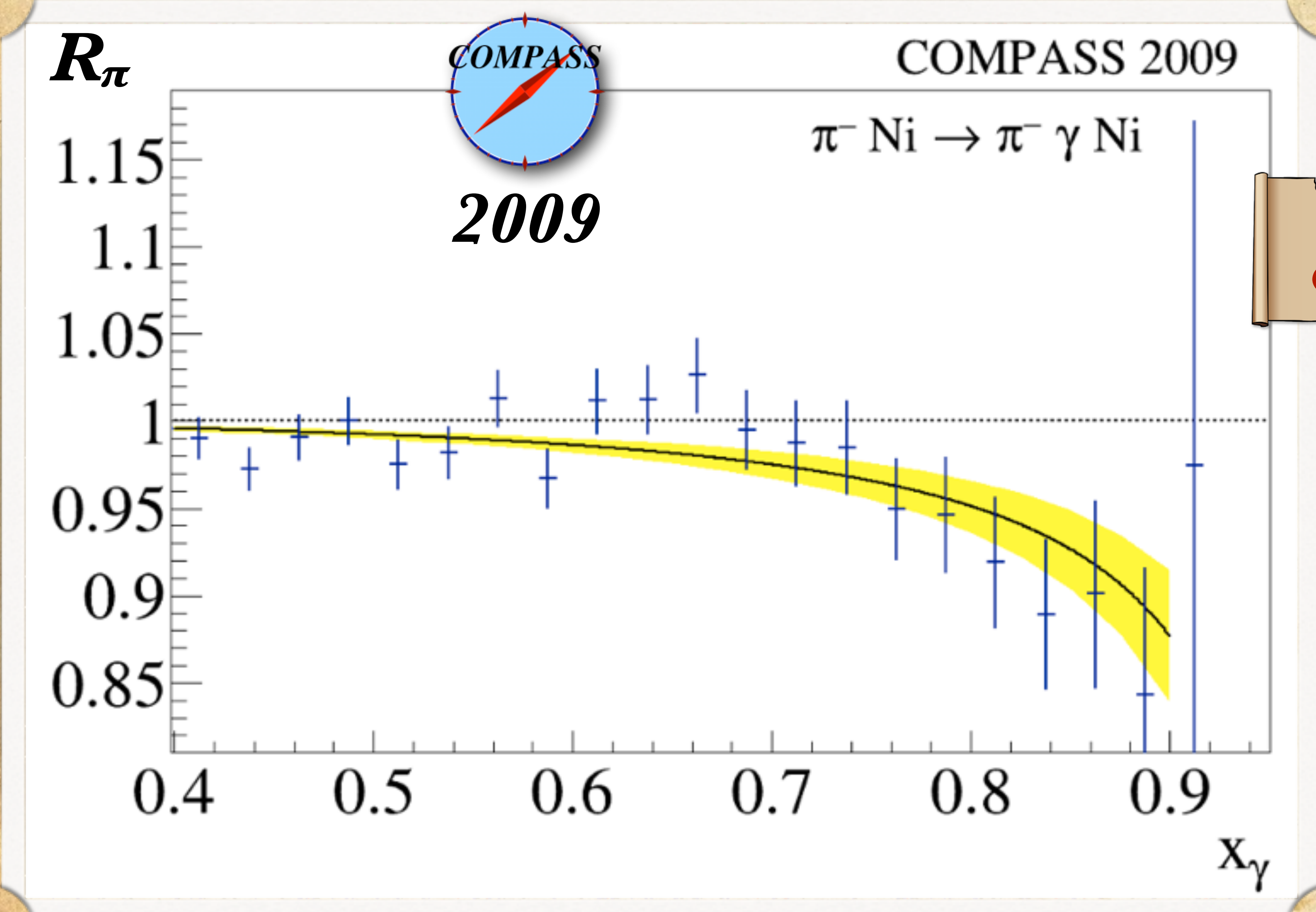




- *pion rescattering*
- *radiative corrections (Compton vertex)*
- *form factor of the Ni nucleus*

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

Pion polarizabilities at COMPASS



with corrections

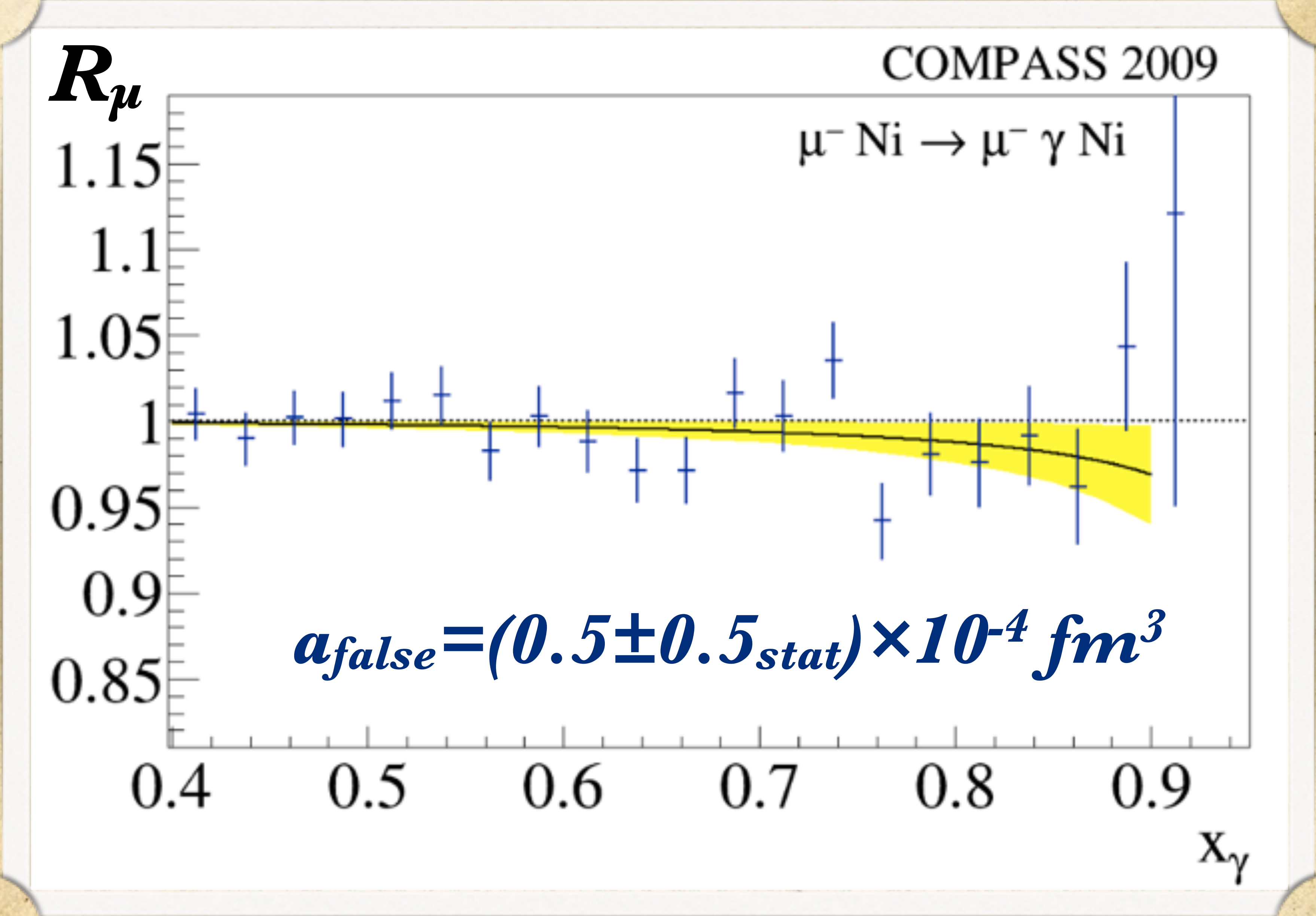
$a_\pi=(2.0\pm0.6_{stat})\times10^{-4}\ fm^3$

Systematic effects

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

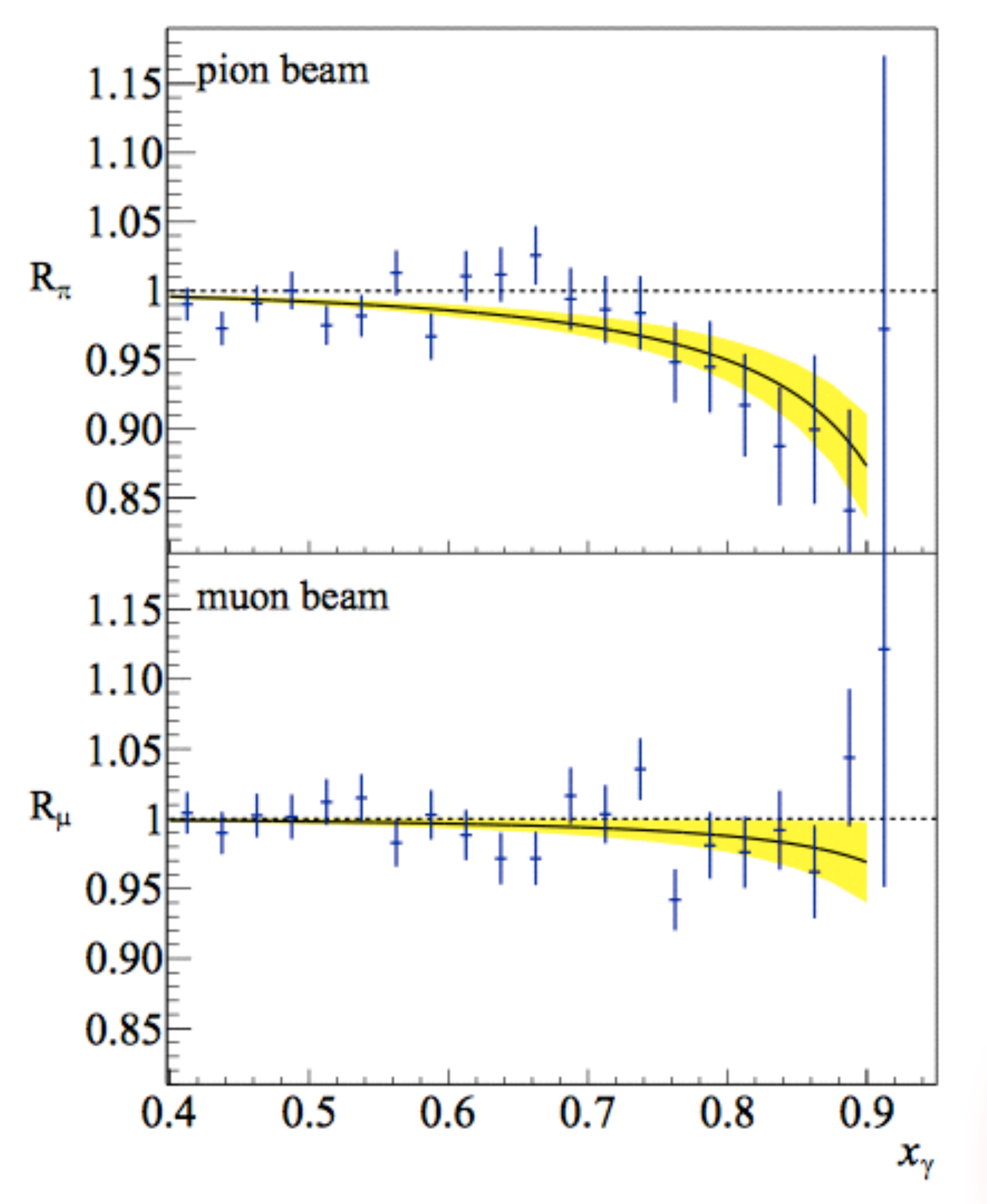
$$a_\pi=(2.0\pm0.6_{stat}\pm0.7_{syst})\times10^{-4}\,fm^3$$

Ratio for muons



False polarizability for muon is consistent with zero within the error

The COMPASS result



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

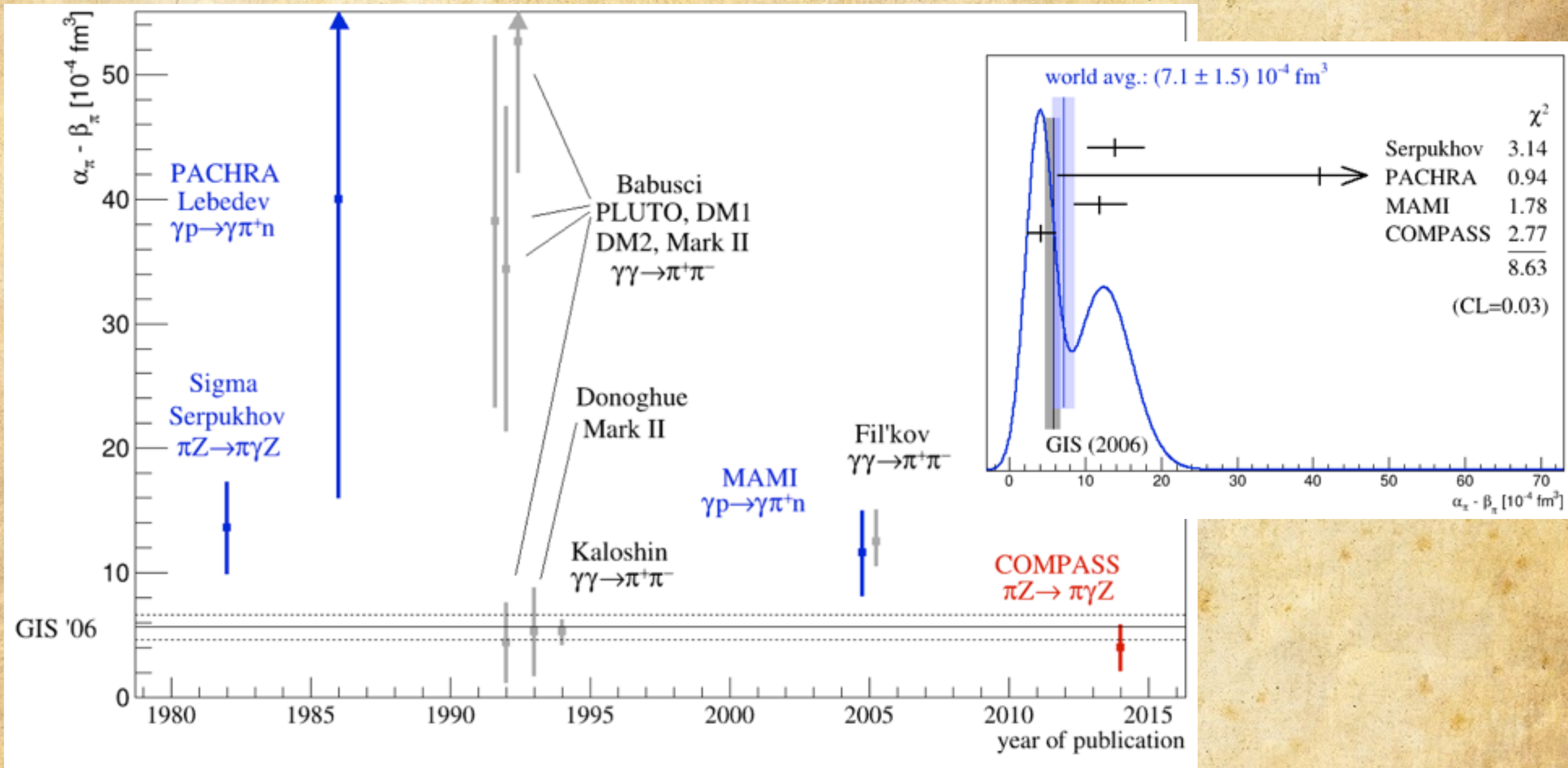
Under assumption $\alpha_\pi=-\beta_\pi$:

$\alpha_\pi=(2.0\pm0.6_{stat}\pm0.7_{syst})\times10^{-4}\ fm^3$

Phys. Rev. Lett. 114 (2015) 06002

Protvino: $\alpha_\pi=-\beta_\pi=(6.8\pm1.4_{stat}\pm1.2_{syst})\times10^{-4}\ fm^3$, χPT: $\alpha_\pi\approx2.8\times10^{-4}\ fm^3$

Pion polarizabilities and COMPASS

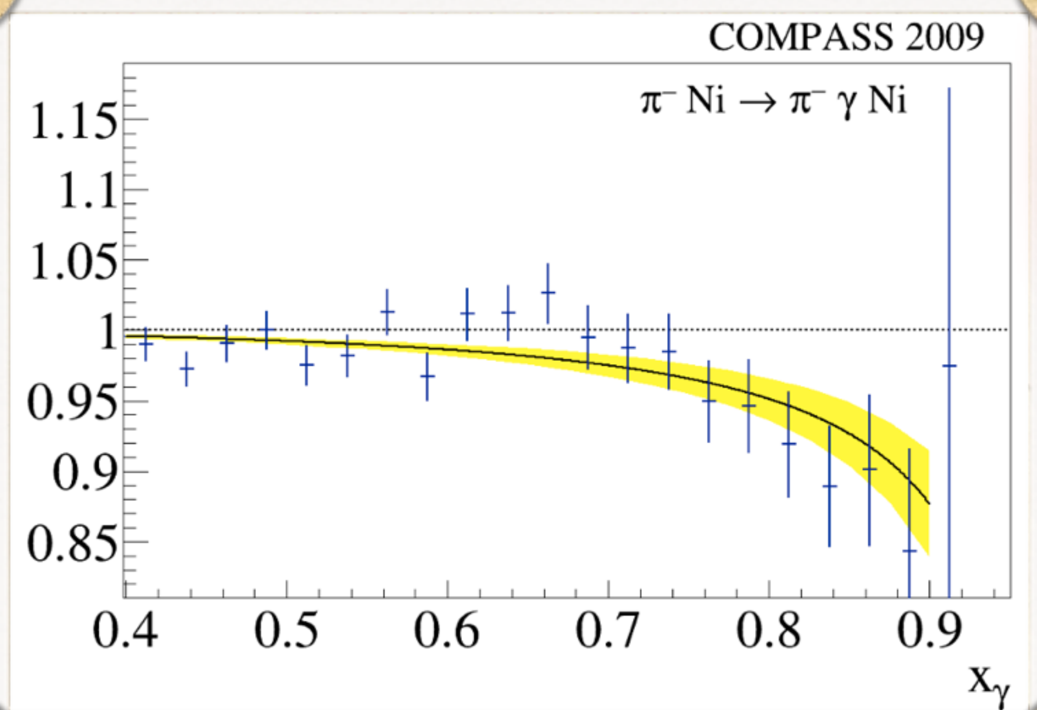


COMPASS

2009

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

Is a_π really a constant in our kinematic range?



Yu. Bystritskiy, A. Guskov, V. Pervushin, M. Volkov Phys. Rev. D 80, 114001 (2009)

$$t=(P_{0\pi}-P_\pi)^2$$

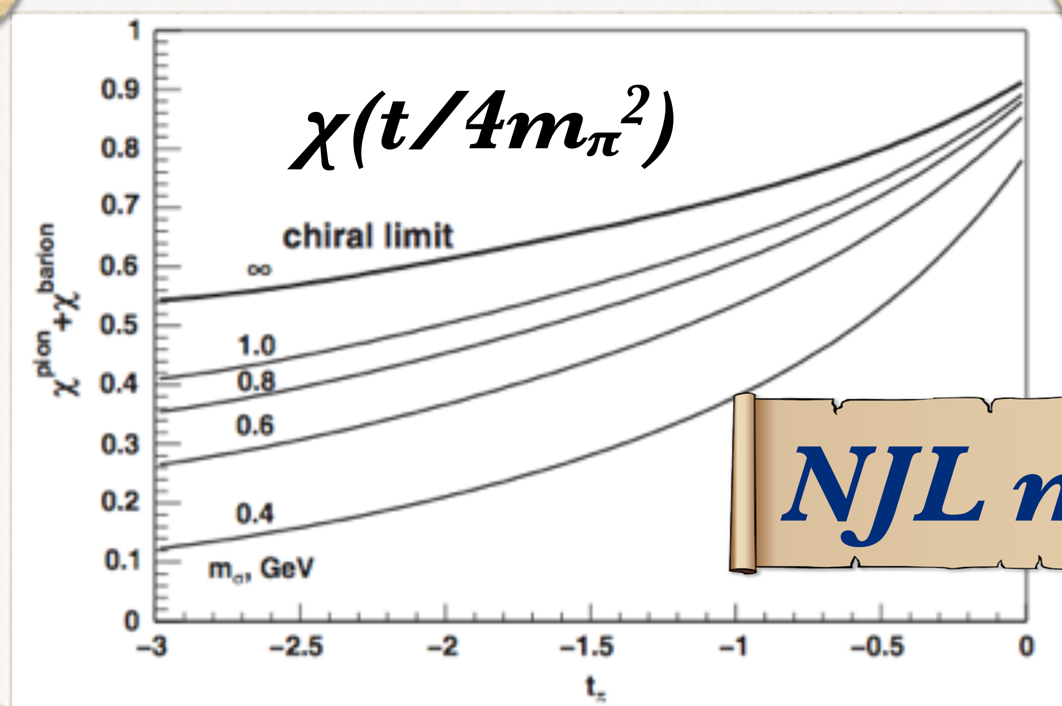
$$a_\pi(t) = a_{\pi\ ch}\,\chi(t)$$

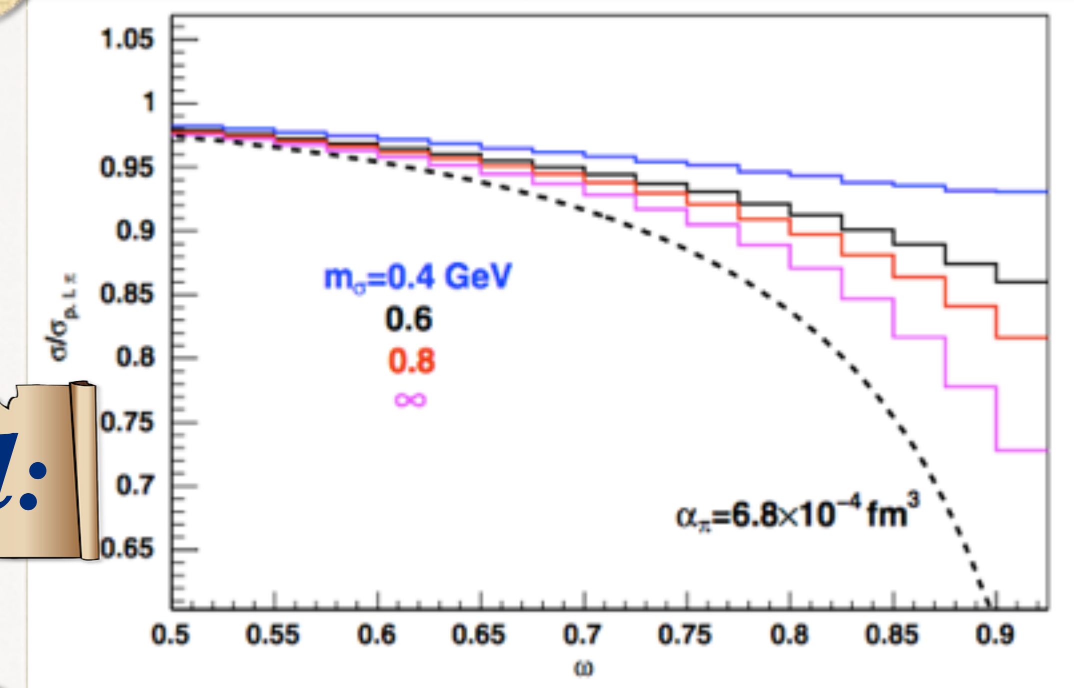
$$a_{\pi\ ch} = 5.8\times10^{-4}\ fm^3$$

m_σ - parameter of the model

$\chi(t/4m_\pi^2)$

NJL model:





Pion polarizabilities at COMPASS

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

COMPASS **2012**

Primakoff data collected in 2012 provide possibility:

- **to reduce uncertainty of α_π measurement to $\sim 0.4\times10^{-4}$ fm^3**
- **to measure $\alpha_\pi+\beta_\pi$ with accuracy $\sim 0.04\times10^{-4}$ fm^3 (χPT: 0.16)**
- **to study dynamics of pion polarizabilities $\alpha_\pi=\alpha_\pi(s,t,\ldots)$**
- **to access quadrupole polarizabilities of pion $\alpha_{\pi2}$ and $\beta_{\pi2}$**

Kaon polarizabilities

Theoretical predictions:

χPT prediction O(p⁴):

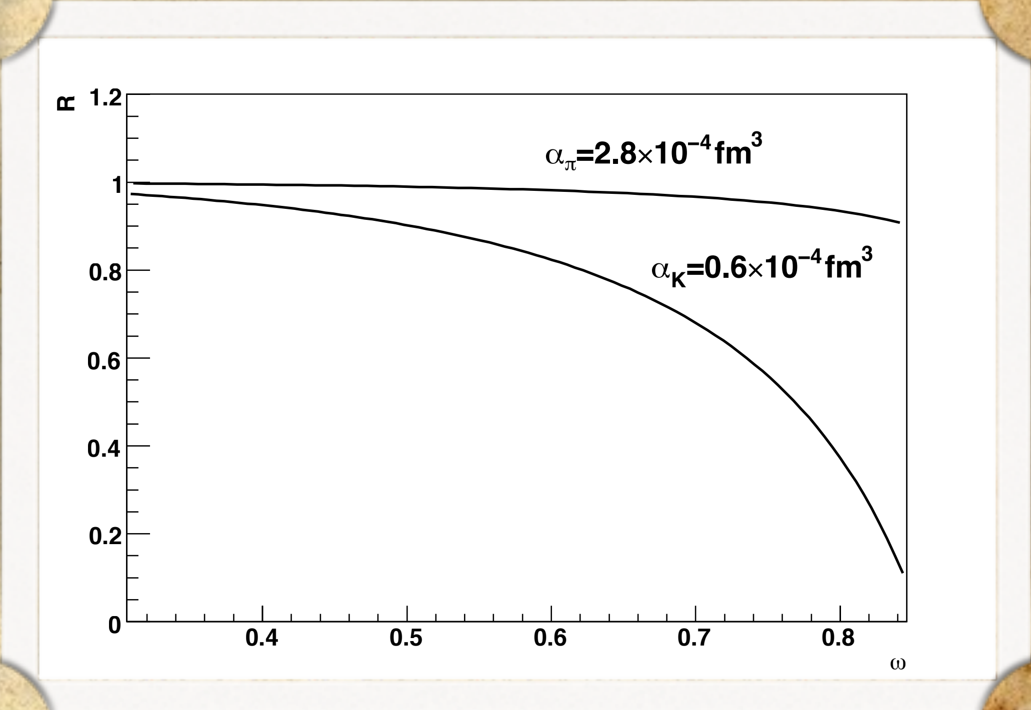
$$\alpha_K + \beta_K = 0$$

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

Quark confinement model:

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

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



Polarization effects

~m^3

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

Experimental results:

a_K=(−4±11)×10^{-4} fm^3

- from kaonic atoms spectra

At COMPASS:

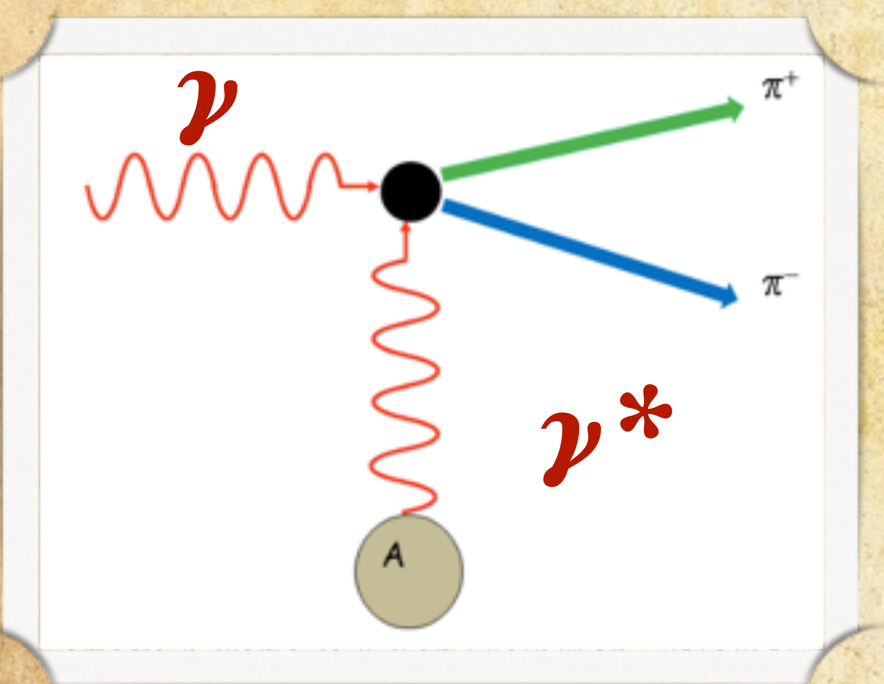
- *~2.4% of kaons in hadron beam*
- *CEDARs for beam kaons identification*

1 Kγ event per 500 πγ

a_π at JLab (proposal)

http://www.jlab.org/exp_prog/proposals/13/PR12-13-008.pdf

Existing detector GlueX at Hall-D



- Polarized photons of ~6 GeV
- 10^7 tagged photons per second
- 0.6 mm ^{106}Sn target
- 20 days of data taking
- Accuracy 0.3×10^{-4} fm^3

Main physical backgrounds:

- pion pair production in strong interaction
- coherent ρ^0 production
- production of lepton pairs

Approved by JLab PAC

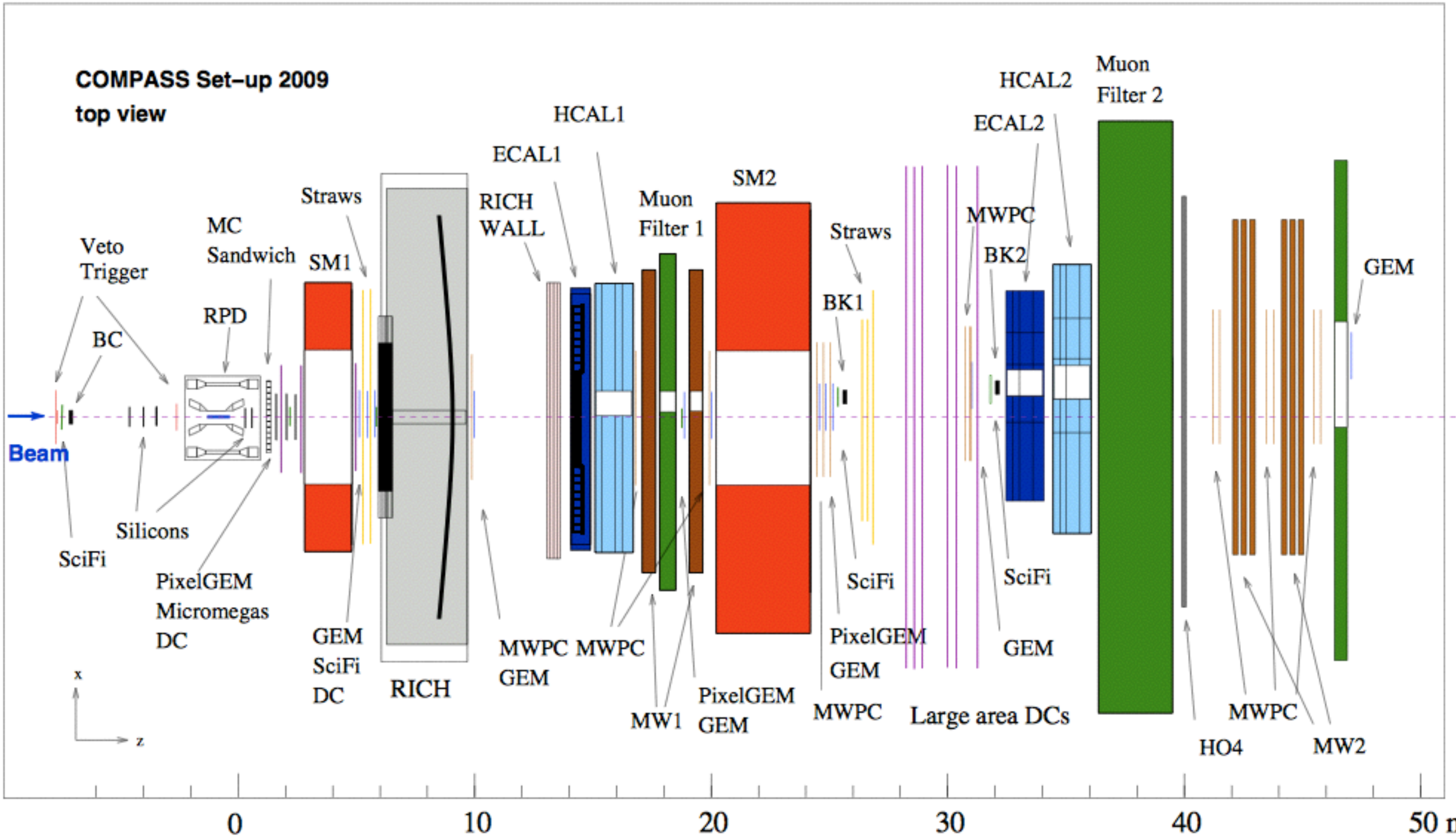
Summary

- ***The COMPASS experiment performed the most precise measurement of pion polarizability α_π under assumption $\alpha_\pi+\beta_\pi=0$ basing on the data of 2009 year.***
- ***The result is:***

$$\alpha_\pi=(2.0\pm0.6_{stat}\pm0.7_{syst})\times10^{-4}\ fm^3$$

- ***This result is published in Physical Review Letters: PRL 114 (2015) 06002***
- ***Contribution of JINR group to this result is determinative at each stage from planning to data taking and analysis***
- ***COMPASS Primakoff data of 2012 still are under analysis and new results for pion (and kaon) polarizabilities are expected***

Backup slides



Backup slides