Charged pion polarizabilities measurement at the COMPASS experiment

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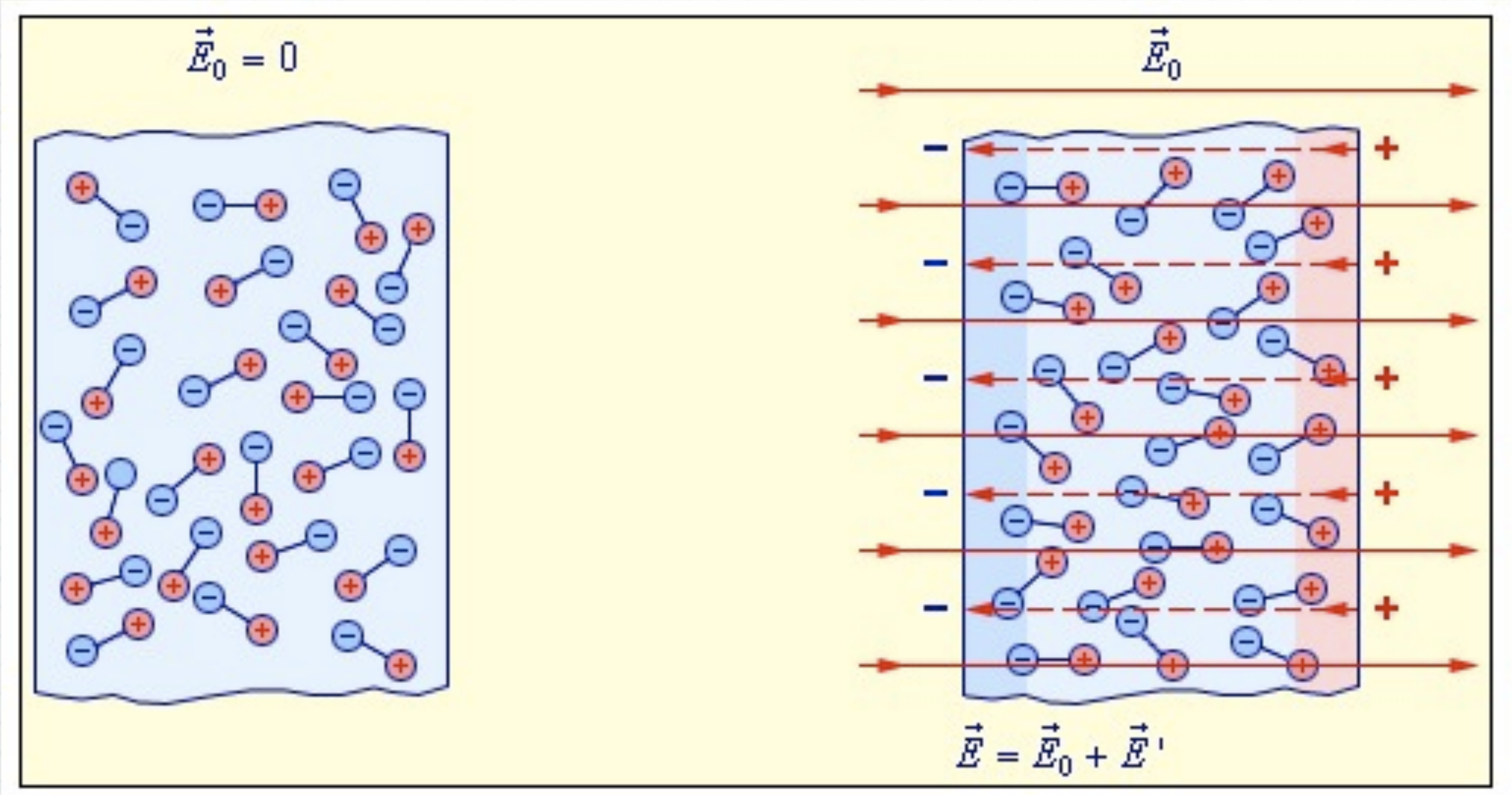
on behalf of the COMPASS collaboration

SPIN-PRAHA 2010

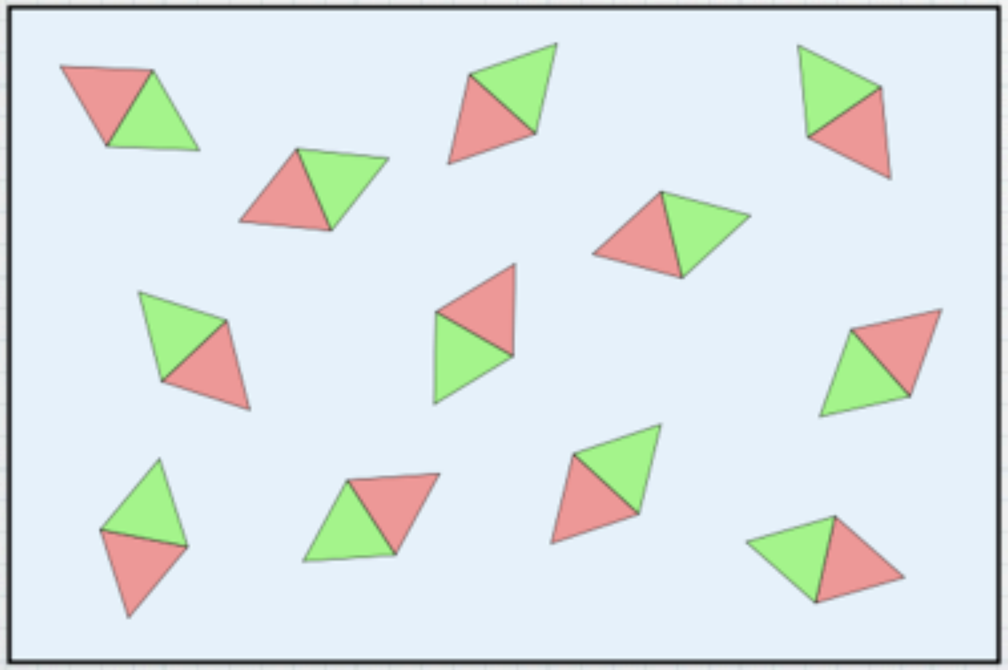
Matter in external fields

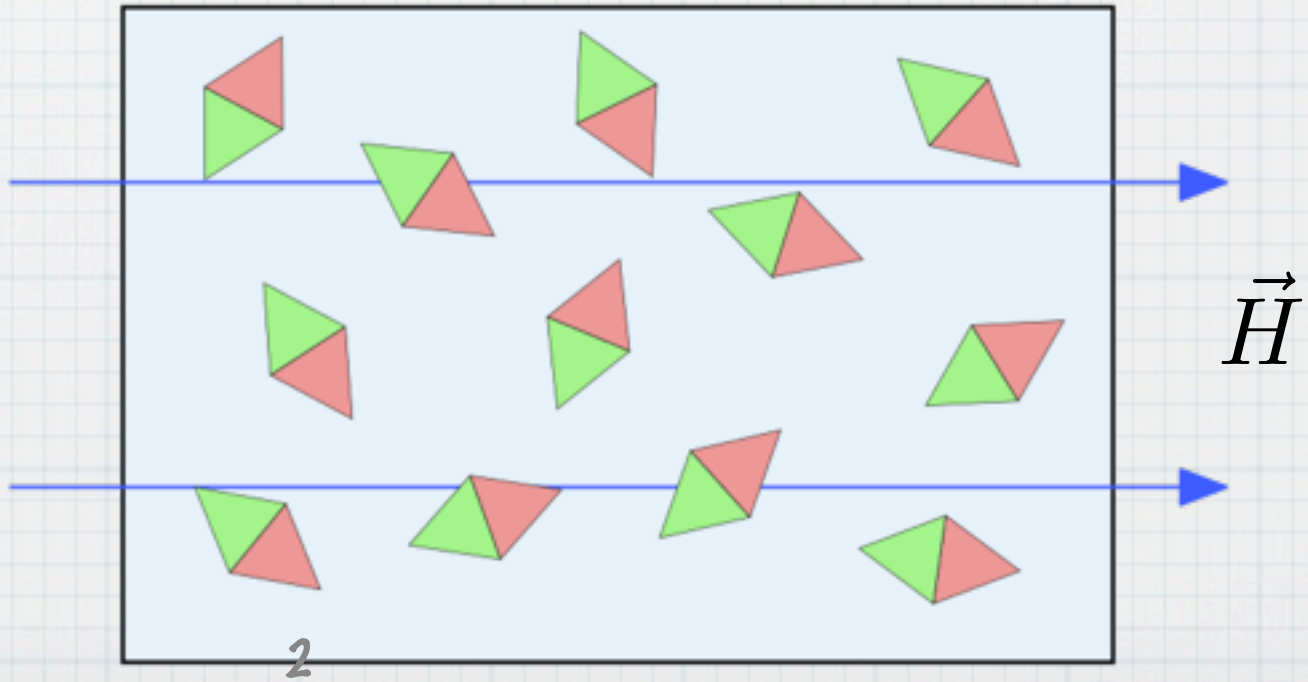


$$\vec{P} = \alpha_\pi \times \vec{E}$$

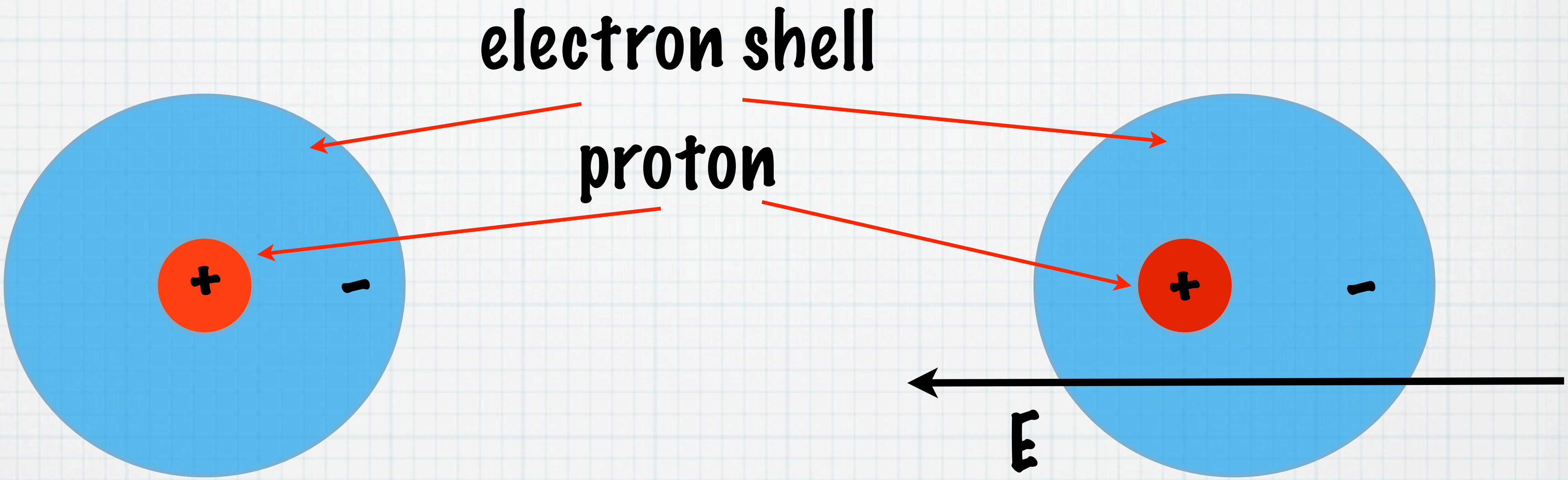
$$\vec{\mu} = \beta_\pi \times \vec{H}$$

Electrical and magnetic polarizabilities of a medium





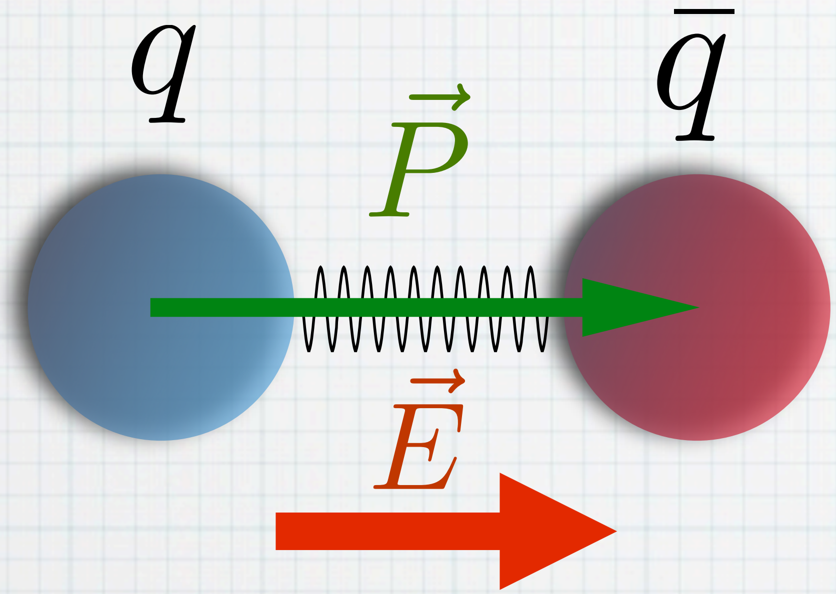
Hydrogen atom - the simplest QED system



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

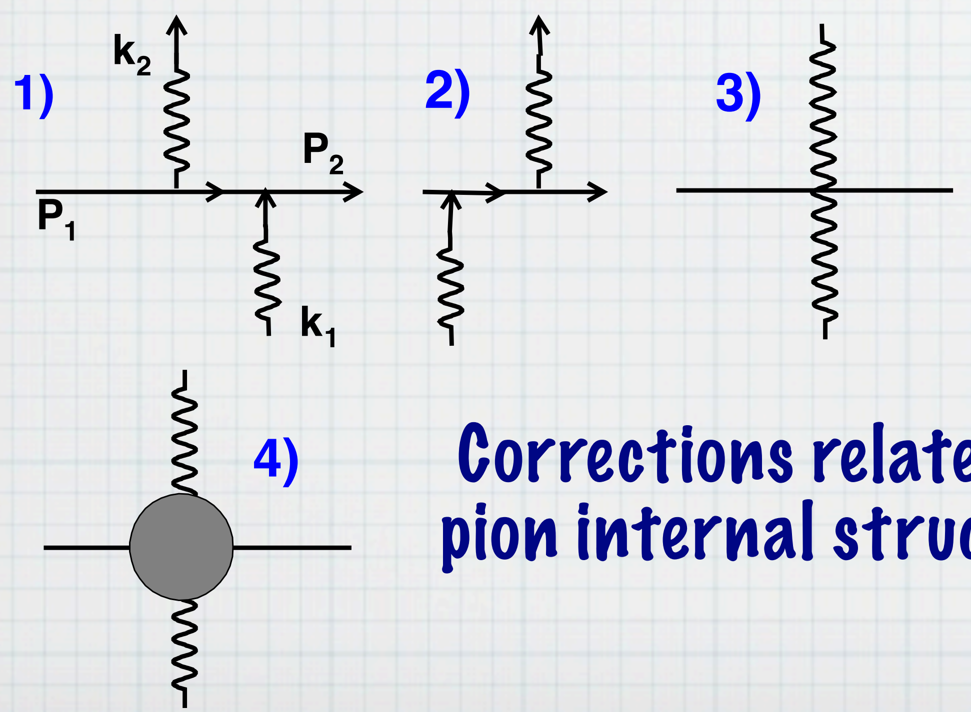
Pion - the "atom" of QCD

$$T(\pi^-\gamma \to \pi^-\gamma) = (-\frac{\alpha}{m_\pi} + \alpha_\pi\omega_1\omega_2)\cdot\hat{\epsilon}_1\hat{\epsilon}_2 + \beta_\pi\omega_1\omega_2(\hat{\epsilon}_1\times\hat{q}_1)\cdot(\hat{\epsilon}_2\times\hat{q}_2) + ...$$



In nonrelativistic approximation the hamiltonian of pion interaction with external electromagnetic field (Compton scattering) corresponding to the 4th diagram can be represented as:

Diagrams of Compton scattering on point-like pion



$$H = -\frac{1}{2}(\alpha_\pi E^2 + \beta_\pi H^2)$$

The electric and magnetic polarizabilities of pion are the quantities characterizing the rigidity of complex QCD system

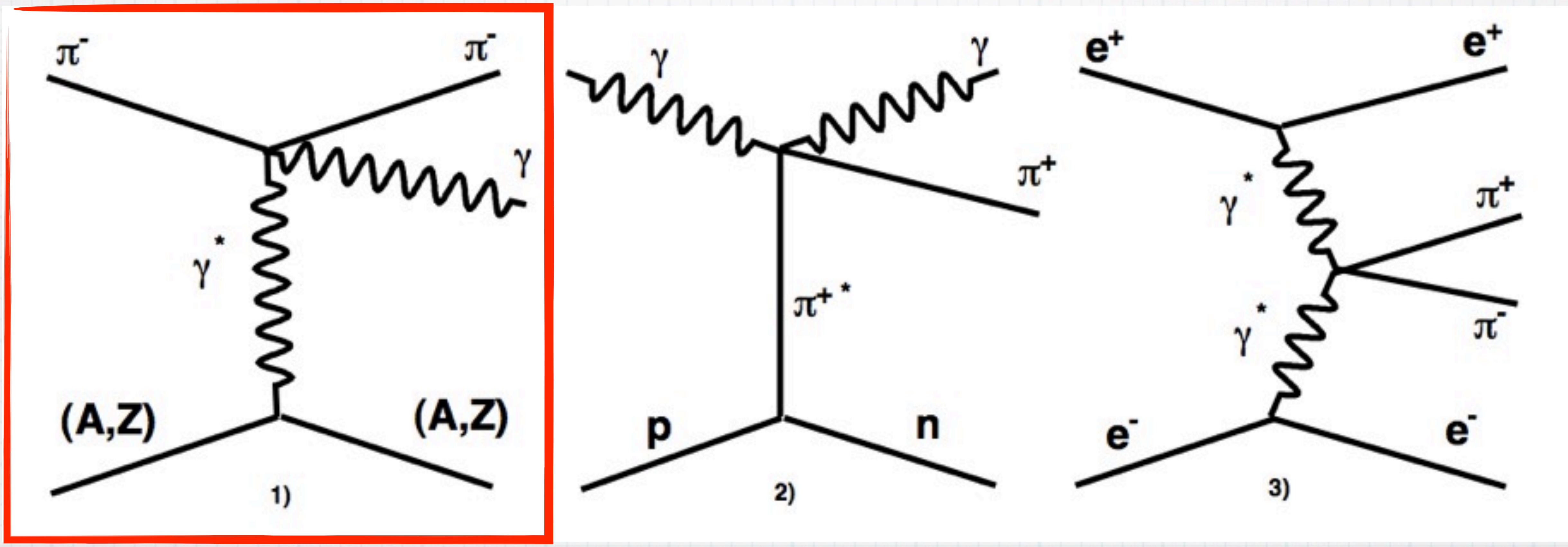
Corrections related to pion internal structure

Theoretical predictions for pion polarizabilities

Model	Parameter	$[10^{-4} fm^3]$
χPT	$\alpha_\pi - \beta_\pi$	5.7 ± 1.0
	$\alpha_\pi + \beta_\pi$	0.16
NJL	$\alpha_\pi - \beta_\pi$	9.8
QCM	$\alpha_\pi - \beta_\pi$	7.05
	$\alpha_\pi + \beta_\pi$	0.23
QCD sum rules	$\alpha_\pi - \beta_\pi$	11.2 ± 1.0
Dispersion sum rules	$\alpha_\pi - \beta_\pi$	13.60 ± 2.15
	$\alpha_\pi + \beta_\pi$	0.166 ± 0.024

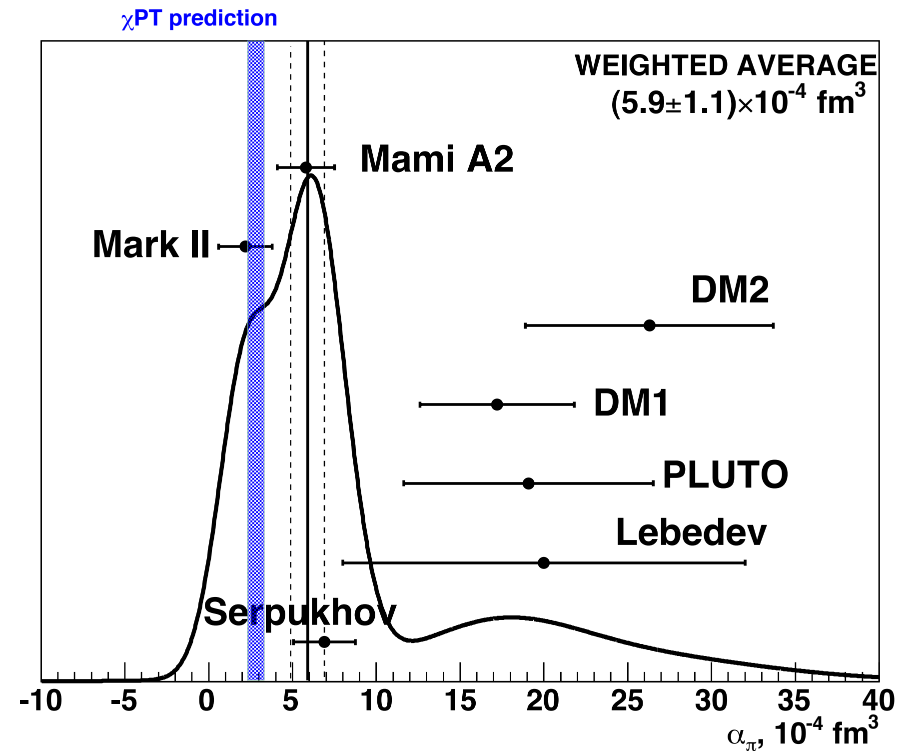
Different theoretical models predict quite different values of pion polarizabilities. An experimental measurement provides a stringent test of theoretical approaches.

Compton scattering on pion? How we can observe it?



- ☑ Radiative scattering of pion on nuclear target with hard photon emission (Primakoff scattering)
- ☑ Radiative pion photoproduction
- ☑ $\pi^+\pi^-$ pair production in e^+e^- collision

Experimental results for α_π and β_π

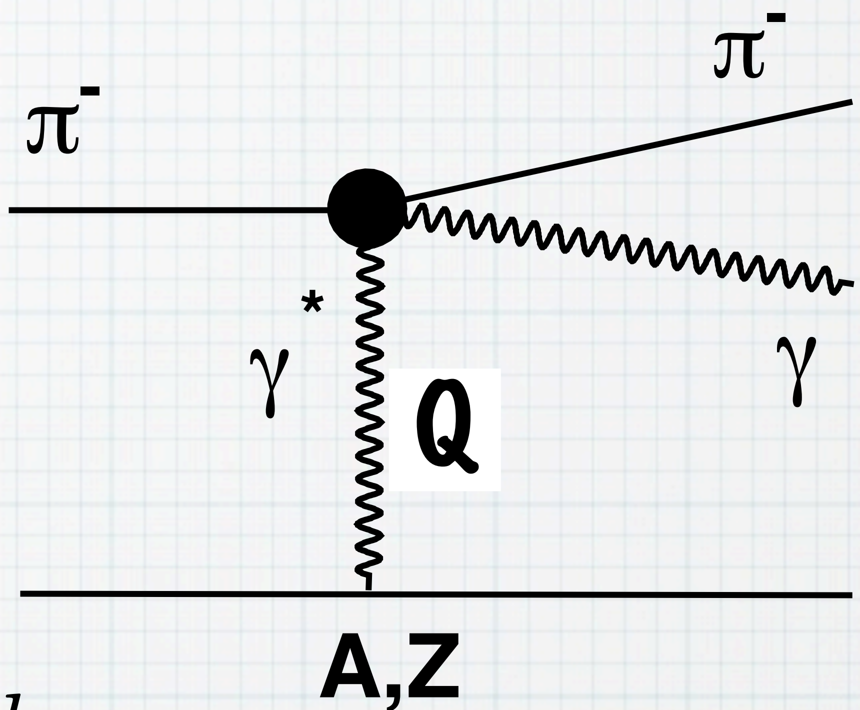


for $\alpha_\pi + \beta_\pi = 0$

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
Global fit: MARK II, VENUS, ALEPH, TPC/2γ, CELLO, BELLE (L. Fil'kov, V. Kashevarov)	$\gamma\gamma \to \pi^+\pi^-$	$\alpha_\pi - \beta_\pi$ $\alpha_\pi + \beta_\pi$	$13.0^{+2.6}_{-1.9}$ $0.18^{+0.11}_{-0.02}$
Global fit: MARK II, Crystal ball (A. Kaloshin, V. Serebryakov)	$\gamma\gamma \to \pi^+\pi^-$	$\alpha_\pi - \beta_\pi$	5.25 ± 0.95

Primakoff reaction

$$\pi^- + (\mathbf{A},\mathbf{Z}) \rightarrow \pi^- + (\mathbf{A},\mathbf{Z}) + \gamma$$



quasi-real photon Compton scattering on π^-

$$d\sigma = \int d\sigma_{Compton} \times n(\omega_0, k_{0\perp}) d\omega_0 dk_{0\perp}$$

where $q = (\omega_0, k_0)$ is 4-vector of virtual photon

$$\sigma_{Compton} = \sigma(\alpha_\pi, \beta_\pi)$$

Main signatures:

$\sigma \sim Z^2$

$Q << m_\pi$

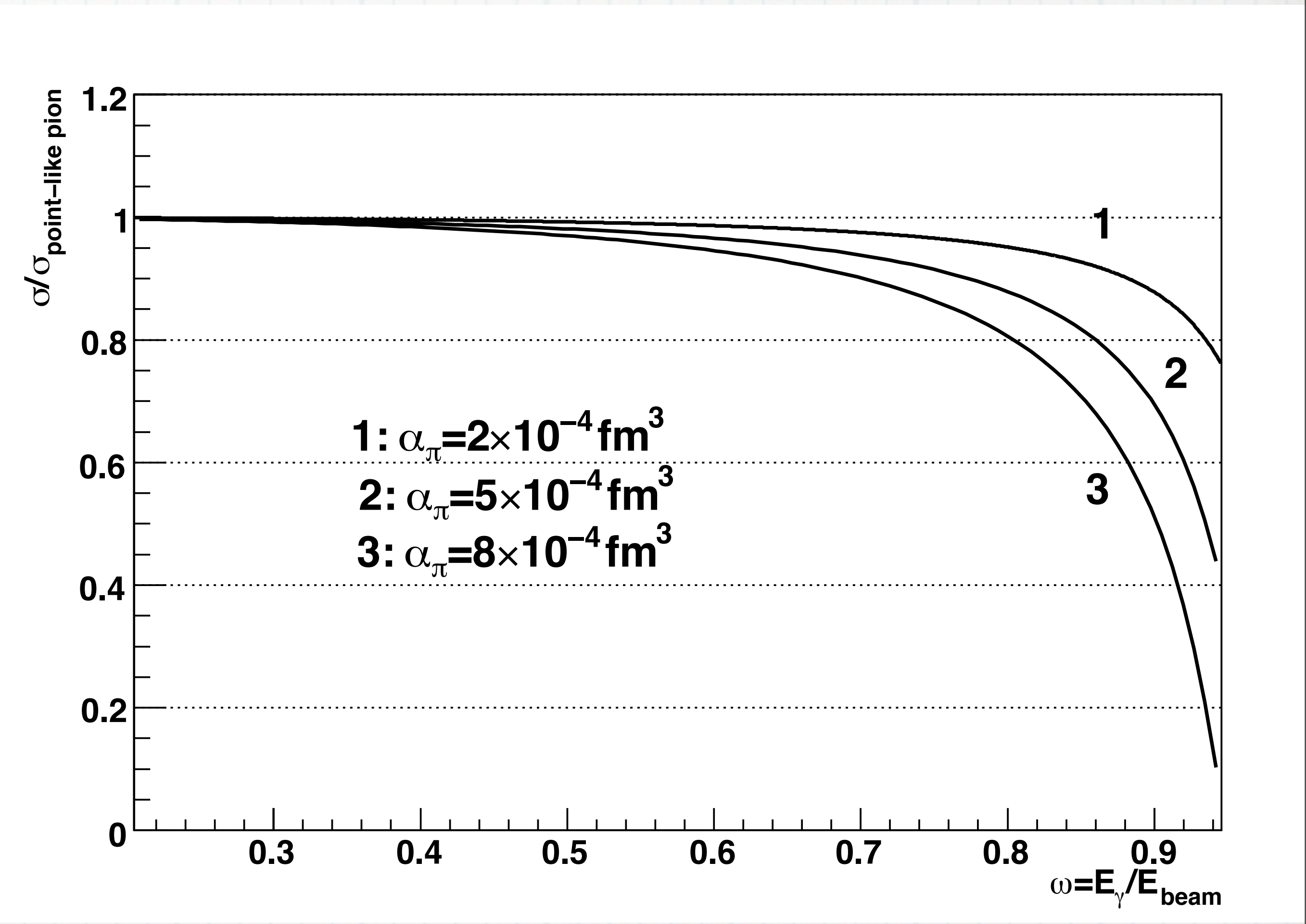
For extraction of pion polarizabilities we compare the measured differential cross section of Primakoff reaction and the theoretically predicted cross section for point like pion

How the polarizabilities can be extracted?

For measurement of α_π and β_π under approximation $\alpha_\pi + \beta_\pi = 0$ we compare differential cross section

$$\frac{d\sigma}{d\omega}, \text{ where } \omega = \frac{E_\gamma}{E_{beam}}$$

measured and theoretically predicted for point like pion



$$\mathbf{R} = \frac{\sigma_{\mathbf{measured}}(\omega)}{\sigma_{\mathbf{point-like}}(\omega)} = \frac{\mathbf{N}_{\mathbf{measured}}(\omega)}{\mathbf{N}_{\mathbf{point-like}}(\omega)}$$

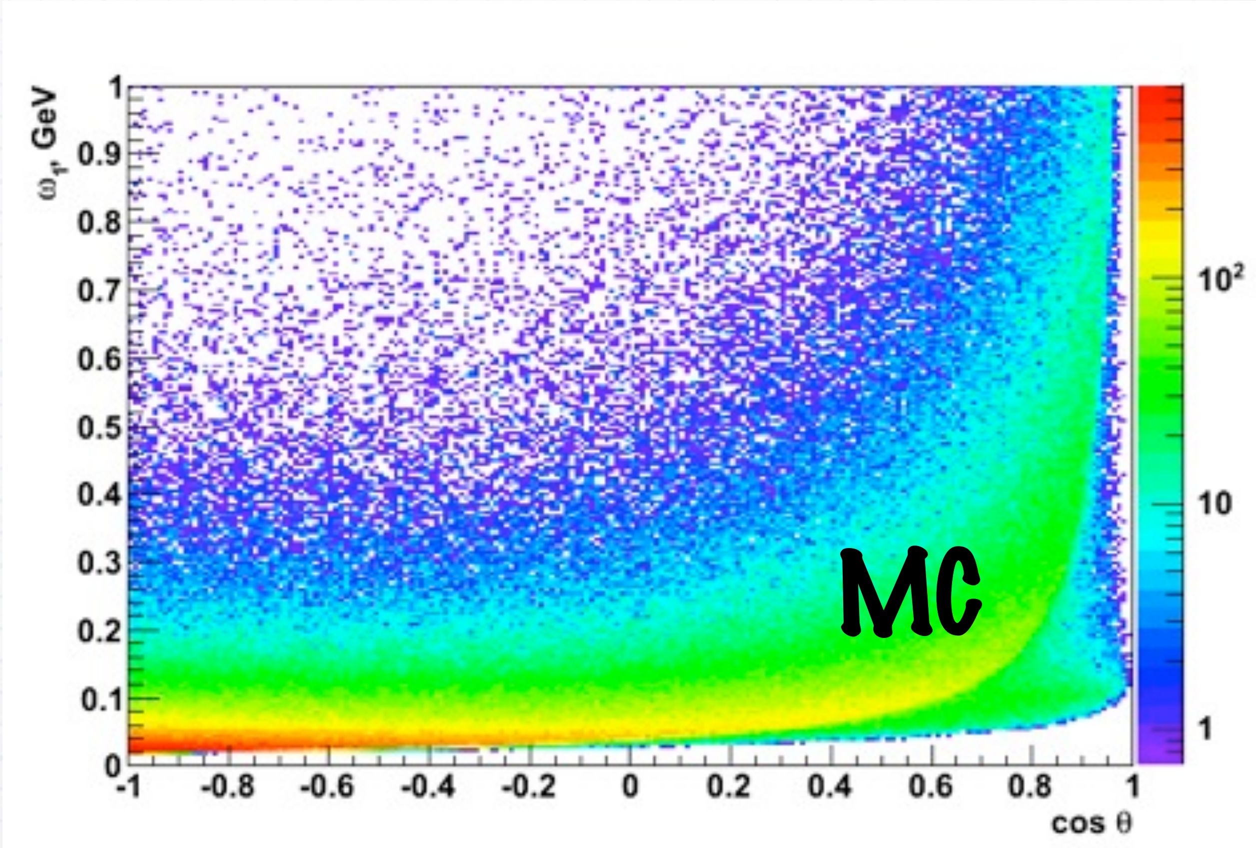
measurement

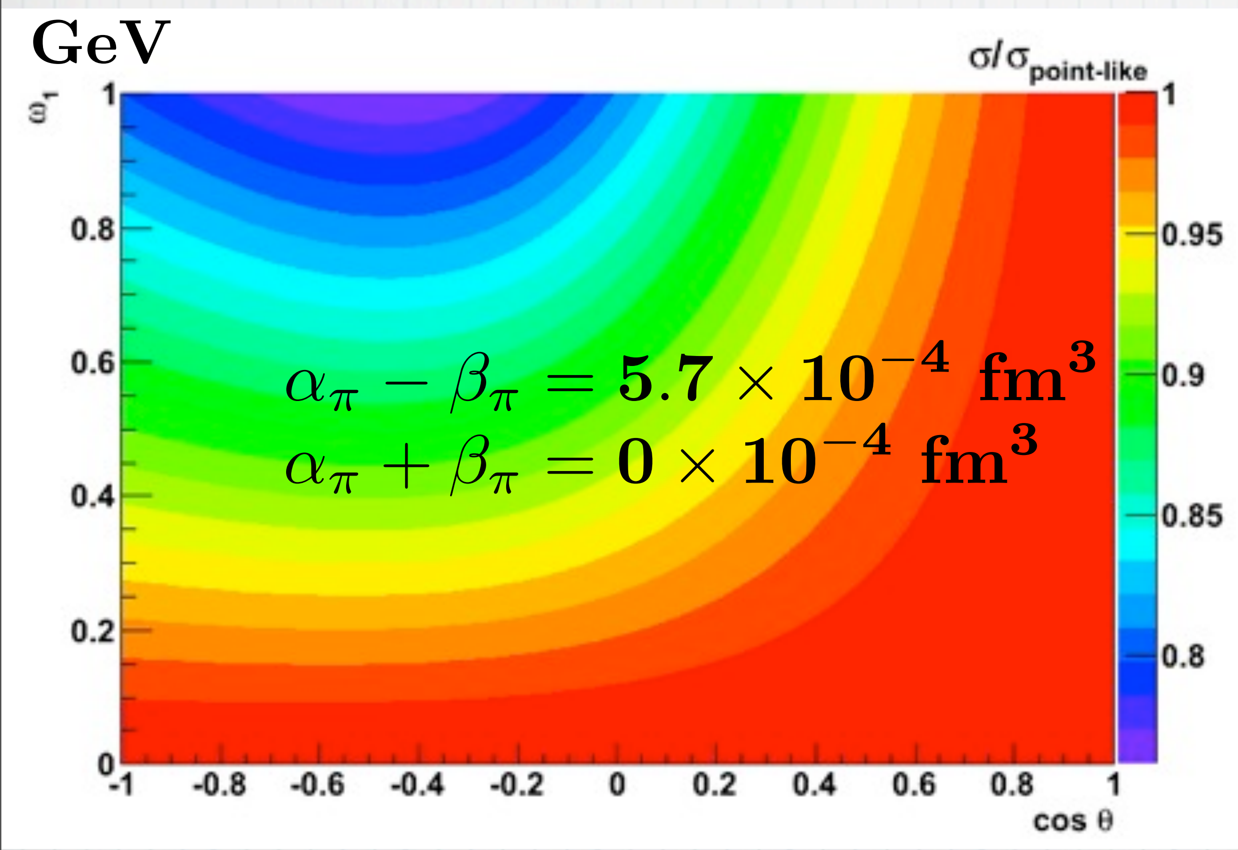
Monte Carlo simulation

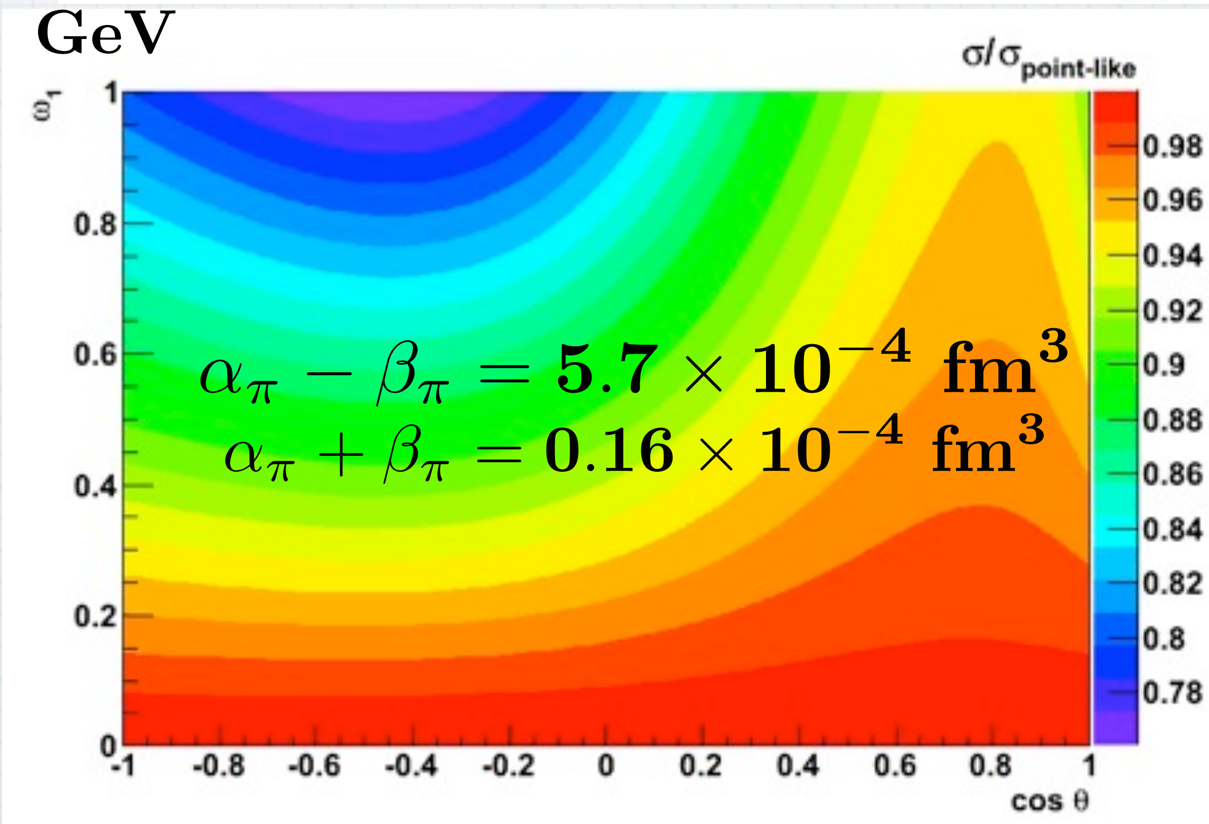
$$\mathbf{R} \approx \mathbf{1} - \frac{\mathbf{3}}{\mathbf{2}} \cdot \frac{\omega^{\mathbf{2}}}{\mathbf{1} - \omega} \cdot \frac{\mathbf{m}_\pi^{\mathbf{3}}}{\alpha} \cdot \alpha_\pi$$

Cross section (pion at rest)

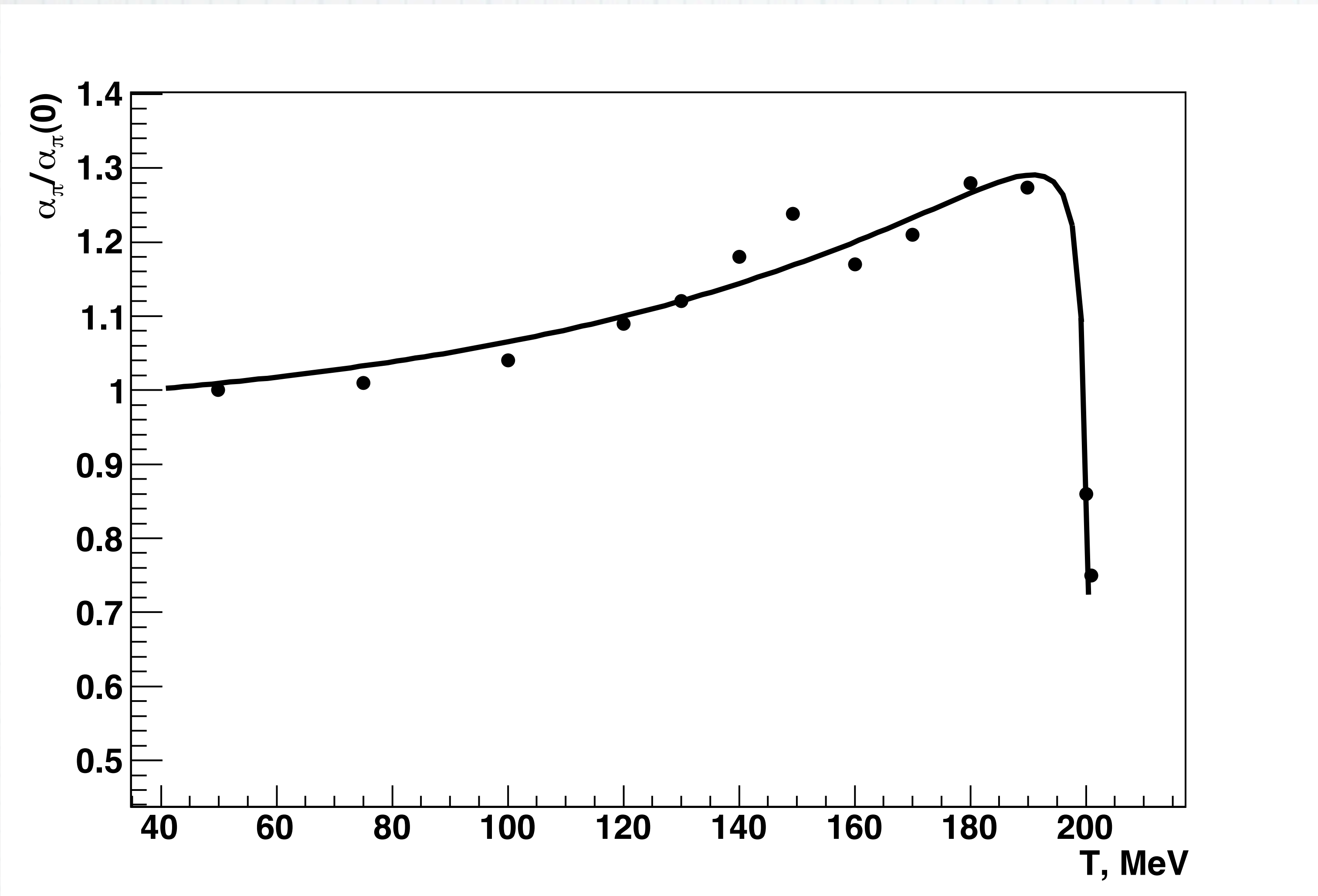
$$\frac{d^3\sigma}{dQ\,d\omega_1\,d(cos\theta)} = \frac{2\alpha^3 Z^2}{m_\pi^2\omega_1} \times \frac{Q^2 - Q^2_{min}}{Q^4}|F_A(Q^2)|^2 \times$$
$$\times\left(F^{Pt}_{\pi\gamma} + \frac{m_\pi\omega_1^2}{\alpha}\cdot\frac{\alpha_\pi(1+cos^2\,\theta)+2\beta_\pi cos\,\theta}{(1+\frac{\omega_1}{m_\pi}(1-cos\,\theta))^3}\right)$$







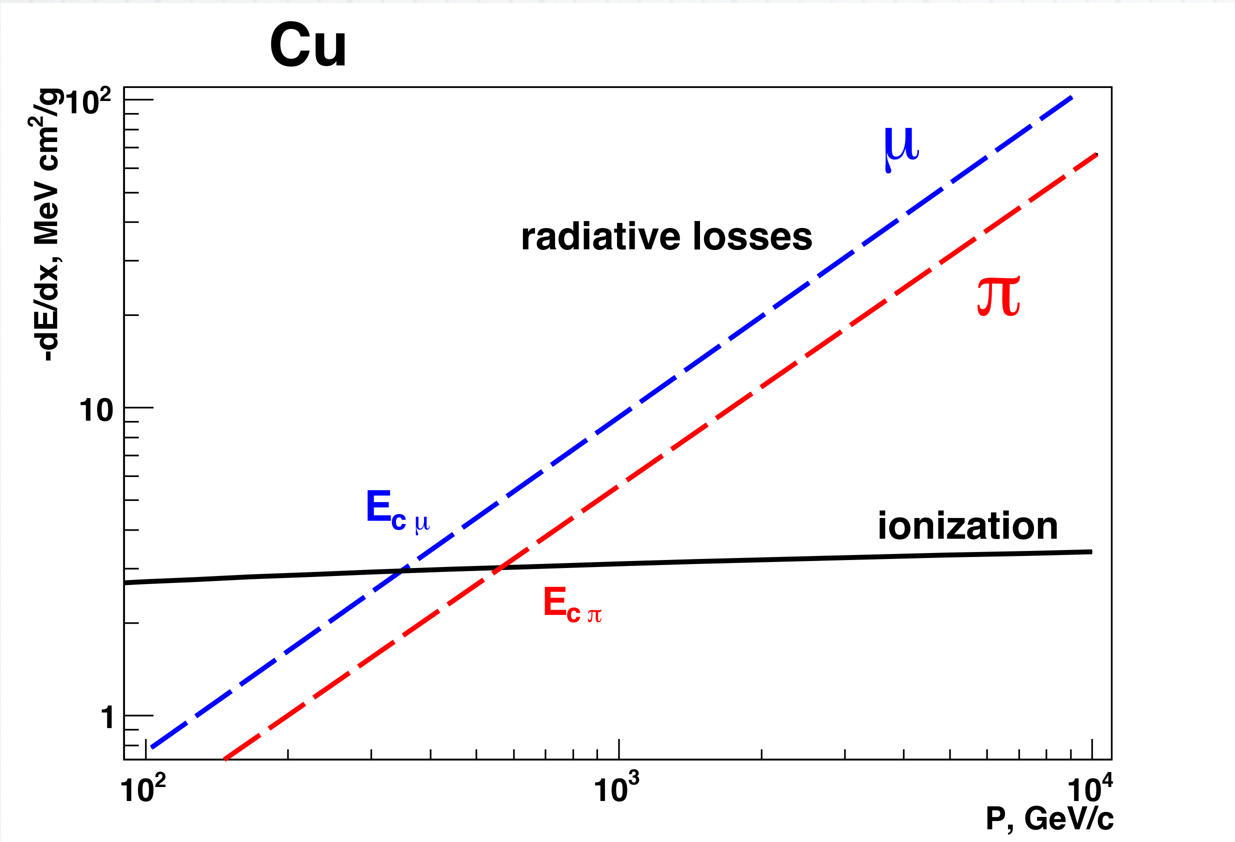
Pion polarizabilities and hot matter

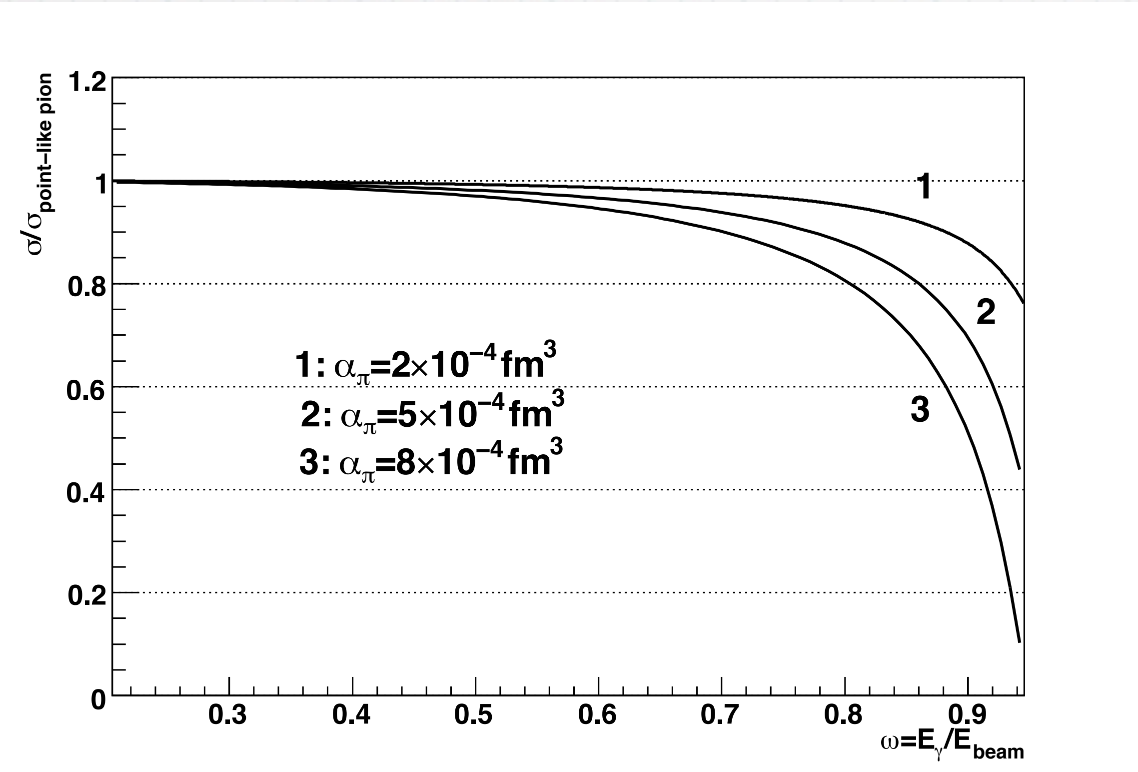


A. E. Dorokhov et. al. Chineze Jornal of Physics, 34 (3-11) 1996

Pion polarizabilities are important parameters of hot hadron matter near the critical point where the chiral symmetry restoration, phase transition and deconfinement of quarks take place.

Pion polarizabilities and calorimetry at LHC





$$\mathbf{E_{c\ \pi}(Z) \sim \frac{1}{Z}}$$

$$\mathbf{E_{c\ \pi}(Cu) \approx 600\ GeV}$$

For pion momenta above ~1 GeV radiation losses dominate over ionization. For precise simulation of calorimeter response (cluster shape) at such energies detailed knowledge about pion bremsstrahlung and pion polarizabilities is needed

COMPASS experiment

The fixed target experiment on SPS at CERN

1996 - COMPASS proposal
1999 - 2001 - construction and installation
2001 - technical run
2002 - 2004, 2006 - 2007 - data taking with muo
beam
October-November 2004 - pilot hadron run
2008 - hadron run
2009 - hadron run

MUON PROGRAM

* $\Delta G/G$
* Structure functions
* Exclusive production of vector mesons
* Λ-physics
* Transversity
* GPD

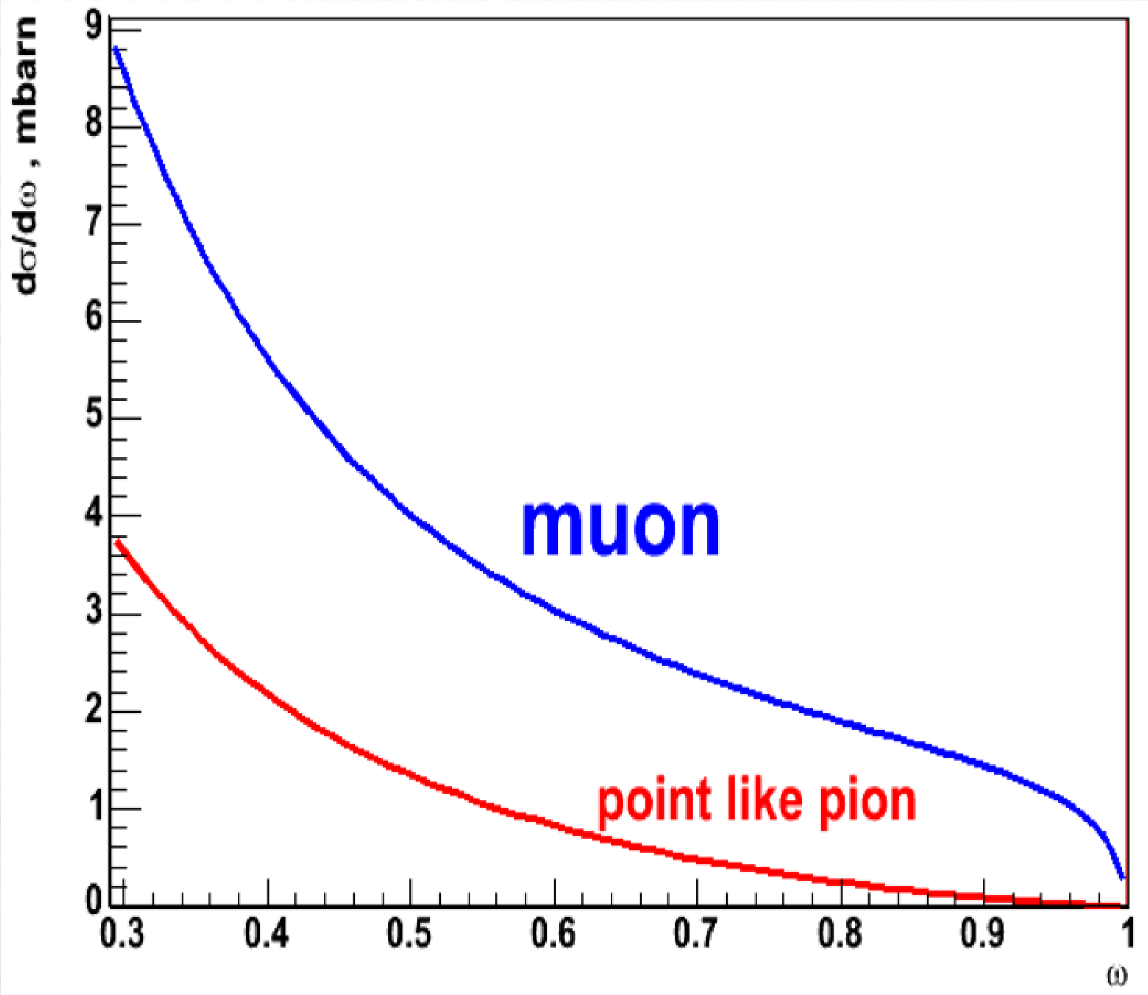
HADRON PROGRAM

* Pion and kaon polarizabilities
* Chiral anomaly
* Charm baryons
* Glueballs and exotic mesons
* Diffractive production
* Drell-Yan

Self-test with muon beam

At COMPASS we have possibility to use pion and muon beams with the same momentum and the same configuration of the setup.

Since muon is the point-like particle, the measured differential Primakoff cross section should exactly correspond to theoretically predicted one.



So the statistics collected with muon beam can be used for study of systematic effects.

COMPASS pilot hadron run 2004

TARGETS:

main

- **Pb 3 mm**
- **Pb 1.6 mm**
- **Pb 2 + 1 mm**
- **C 23,5 mm**
- **Cu 3.55 mm**
- **Empty target**

About 10 days of data taking (pilot run)
Integrated beam flux is 10^{11} pions

Beam:

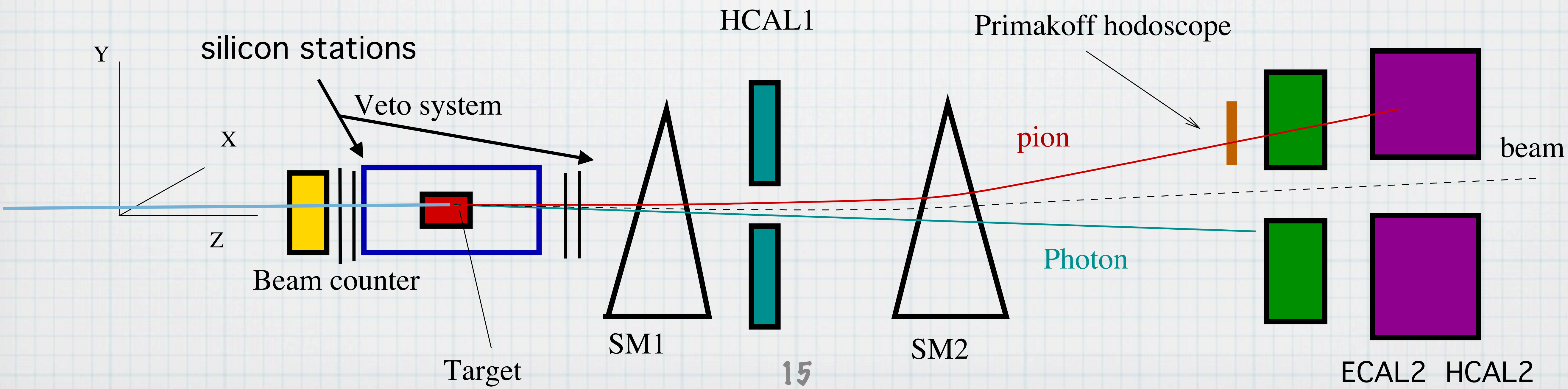
secondaries beam from SPS

π^{-} (190 GeV)

μ^{-} (190 GeV)

Trigger:

>100 GeV in electromagnetic calorimeter



Background processes and corrections

Hadron beam

Particle	Fraction,%
π^-	93.5
K^-	3
μ^-	3
p^-	0.5
e^-	~0.1

$\pi\to\pi\gamma$ (Born) Primakoff

$\pi\to\pi\gamma$ diffractive

Correction to Compton vertex

Vacuum polarization

Nuclear charge screening

Multiple photon exchange

Electromagnetic form factor of nucleus

$e\to e\gamma$

$\mu\to\mu\gamma$

$K\to K\gamma$

$p\to p\gamma$

$\pi\to\rho\to\pi^-\pi^0$

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

$\pi\to\pi^-\pi^0$ Primakoff

$\pi\to\pi^-\pi^0$ diffractive

$\pi\to\pi^-\pi^0\gamma$

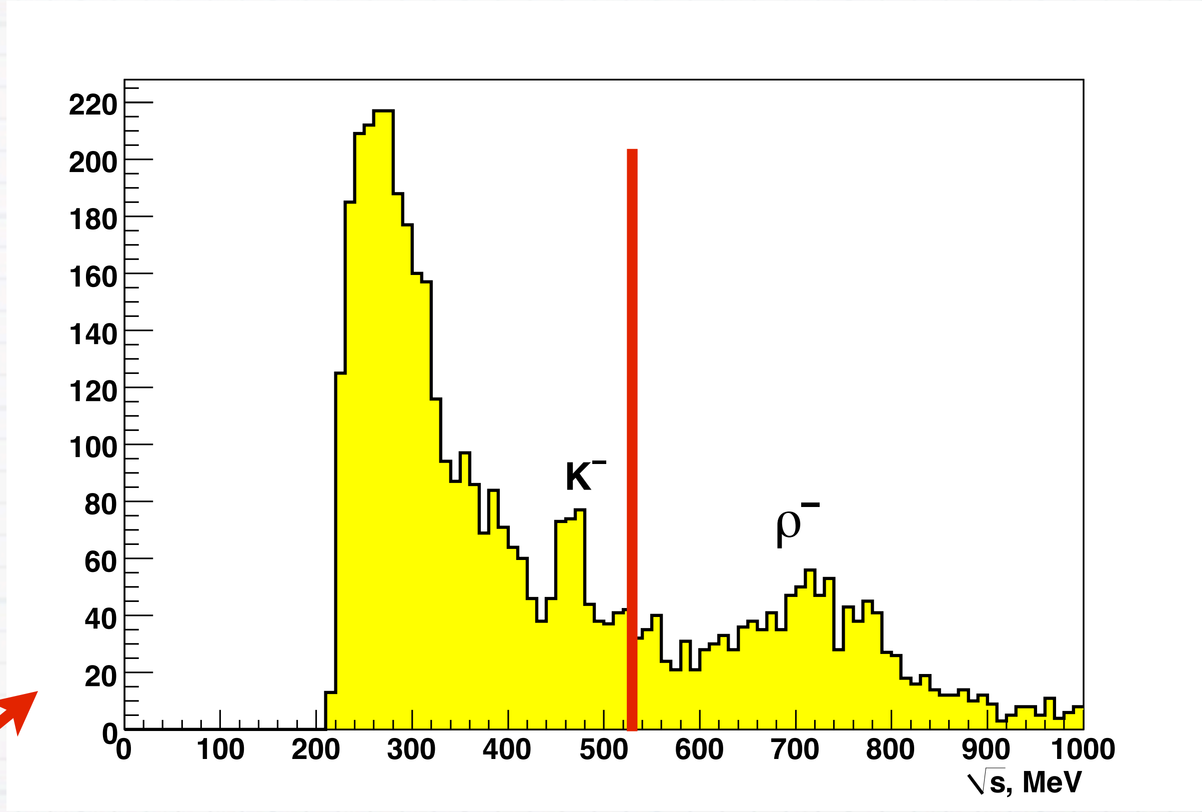
$K\to K^*(892)\to \to K^-\pi^0$

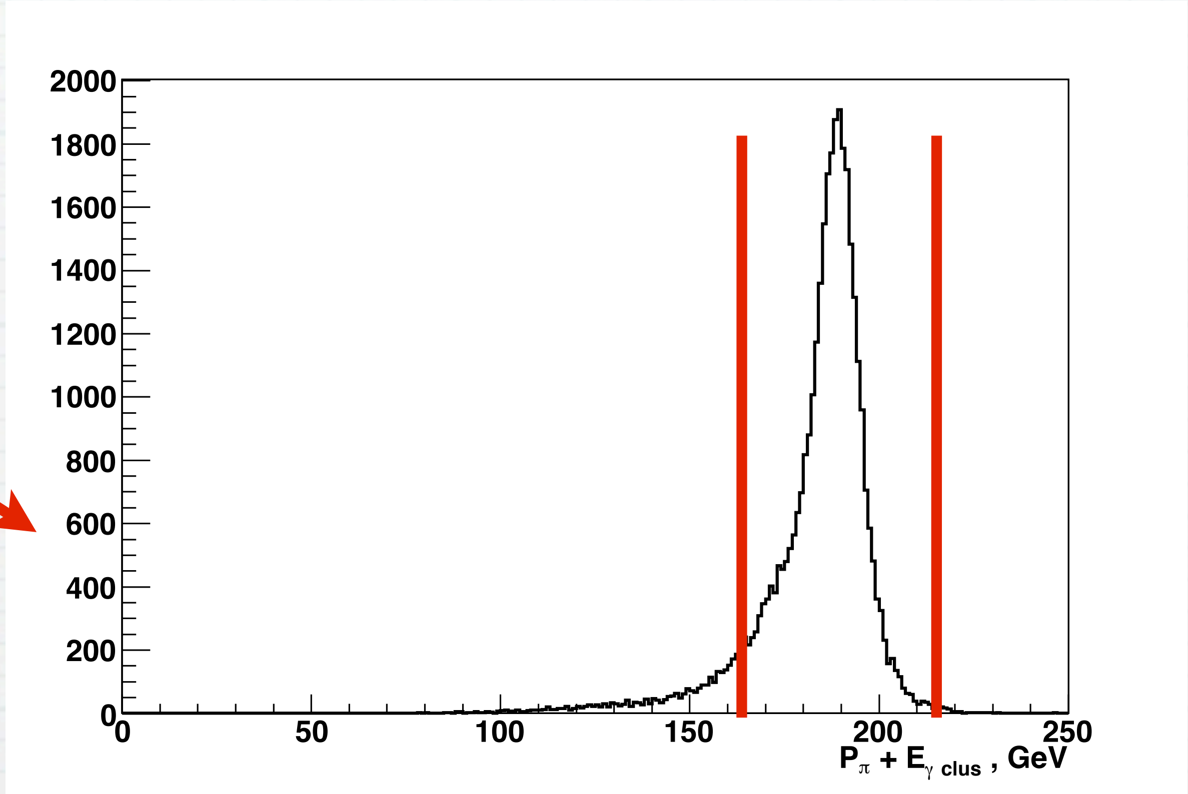
$K\to K_2^*(1430)\to \to K^-\pi^0$

Too many processes correspond to X^- and 1 cluster in the calorimeter the final state !

Event selection

- π + γ in the final state
- no other clusters in ECAL2 with E>7 GeV
- primary vertex near the nominal target position
- invariant mass $M_{\pi\gamma} < 3.75\ M_\pi$
- $|E_\gamma + P_\pi - P_{beam}| < 25$ GeV
- $P_t > 45$ MeV/c
- $0.5 < \omega < 0.9$
- $Q < 2\times10^{-3}\ (GeV/c)^2$

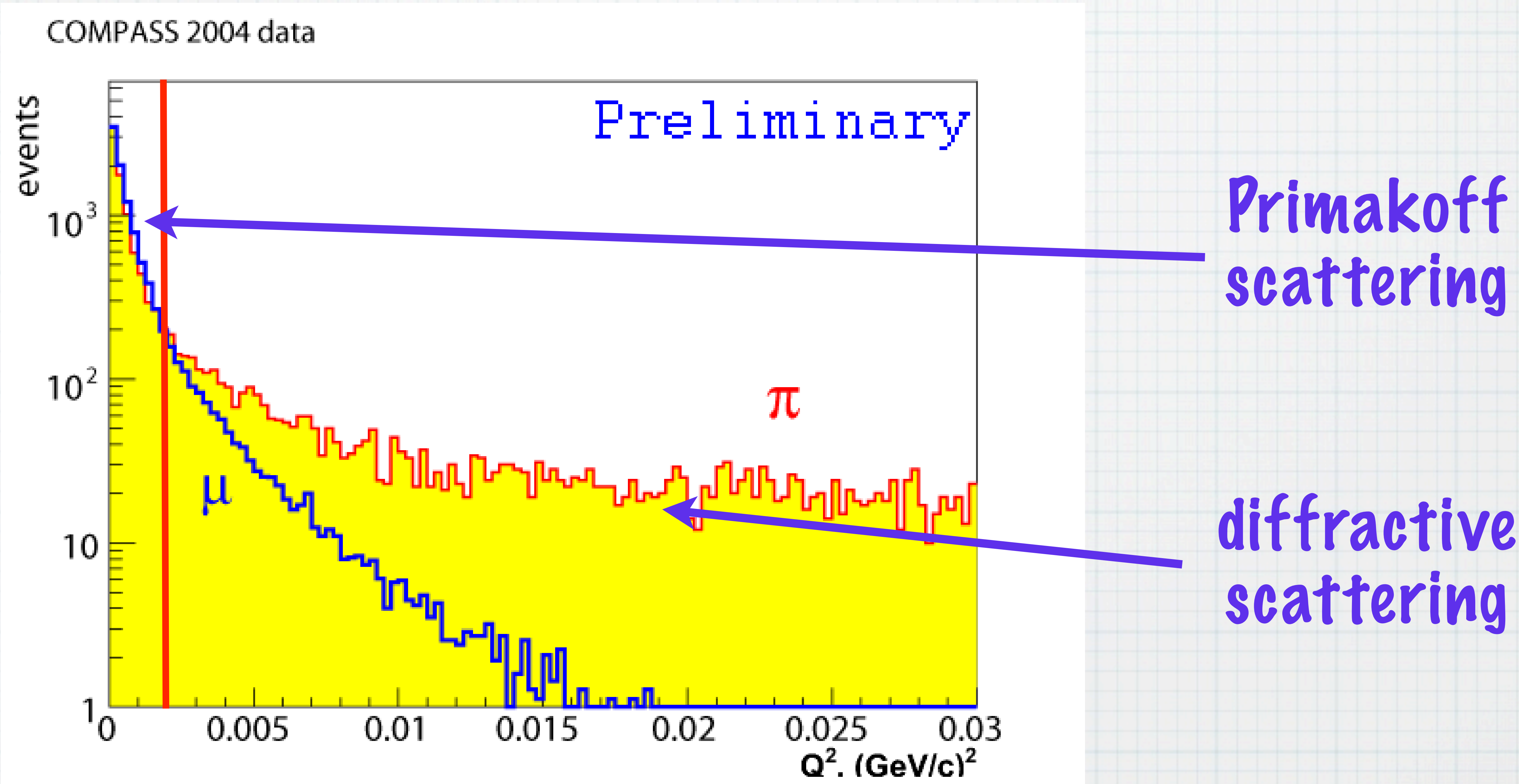




The same selection criteria for pion and muon events

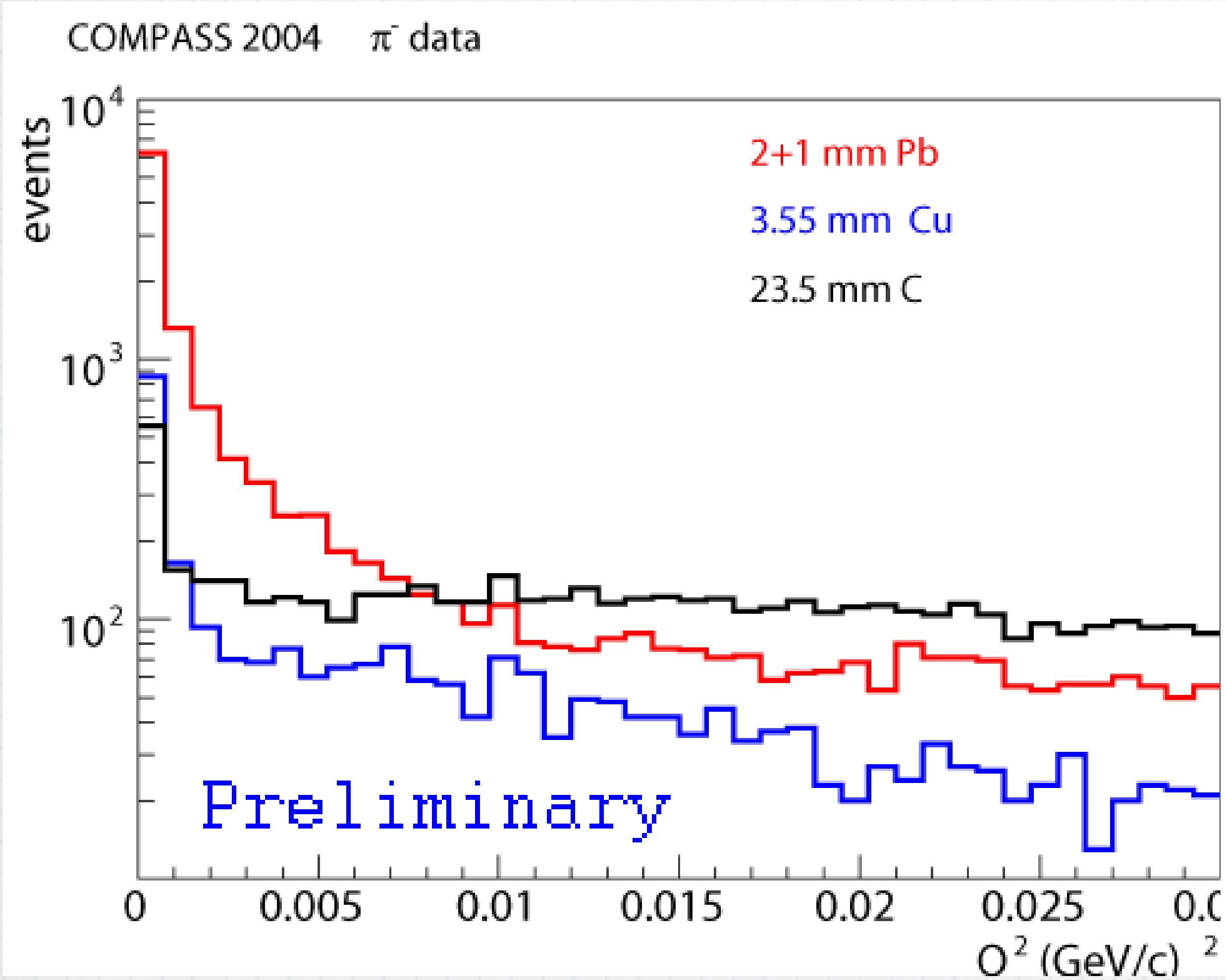
next page

Q2 distribution for πγ and μγ exclusive events

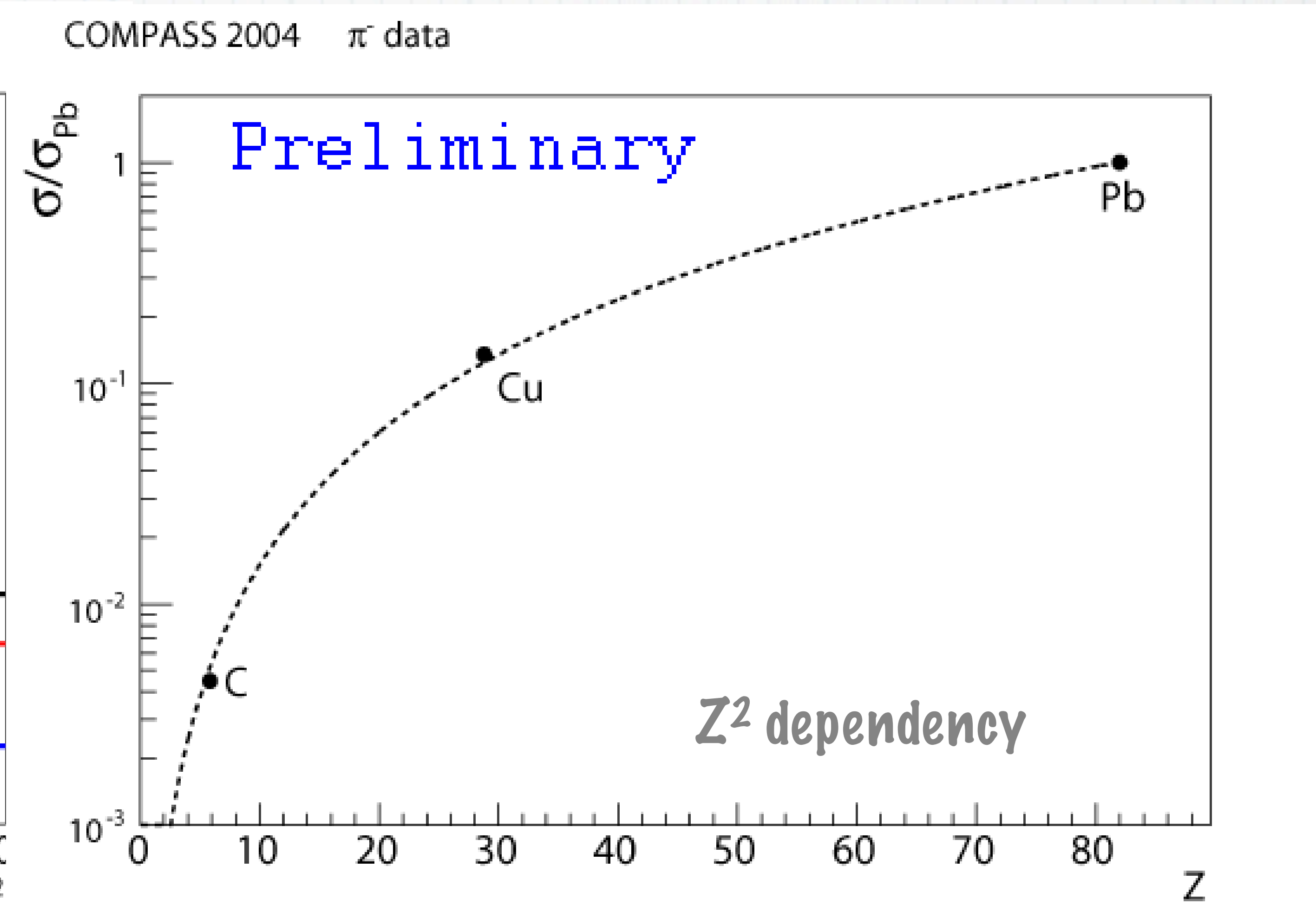


Primakoff scattering on different nuclear targets

Q^2-distribution for different target materials



Z-dependency of the Primakoff cross section



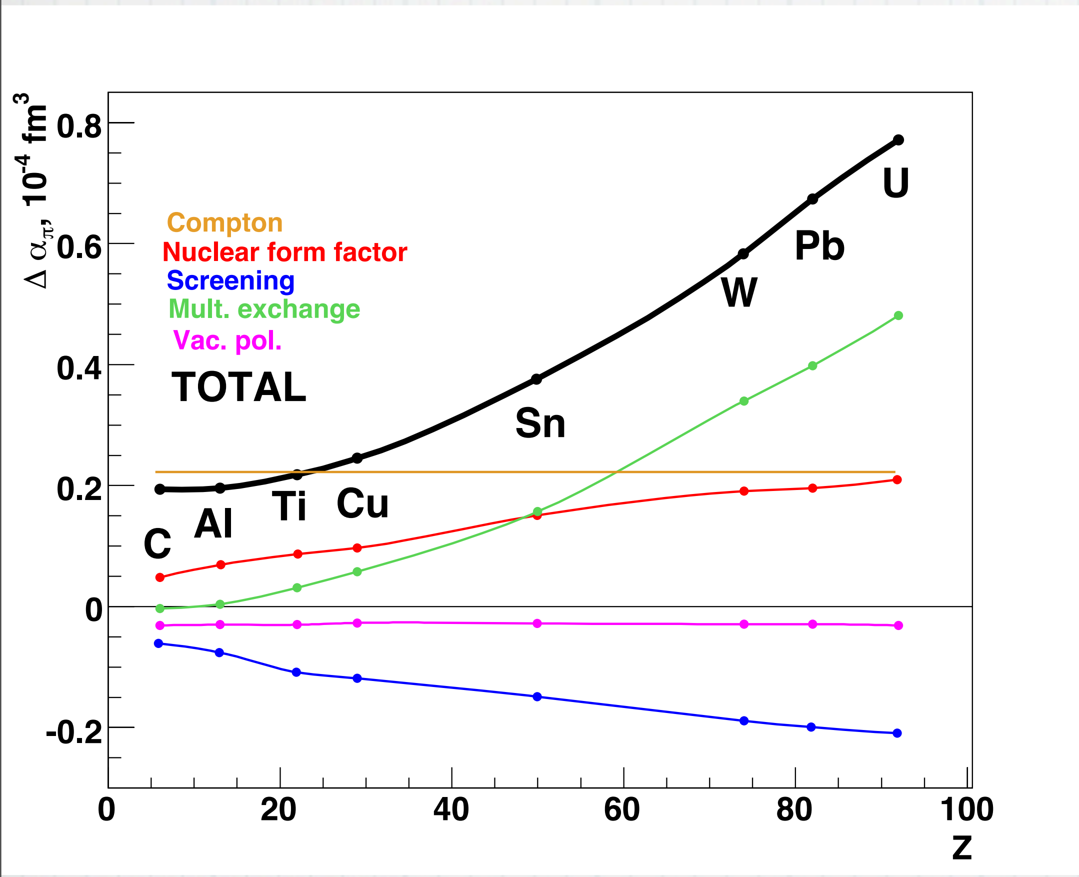
Strong dependence of Primakoff signal (Q=0) to diffractive background (Q>>0.01) ratio on the target material

Good agreement with Z^2-dependency for the Primakoff cross section in the wide Z range

COMPASS hadron run 2009

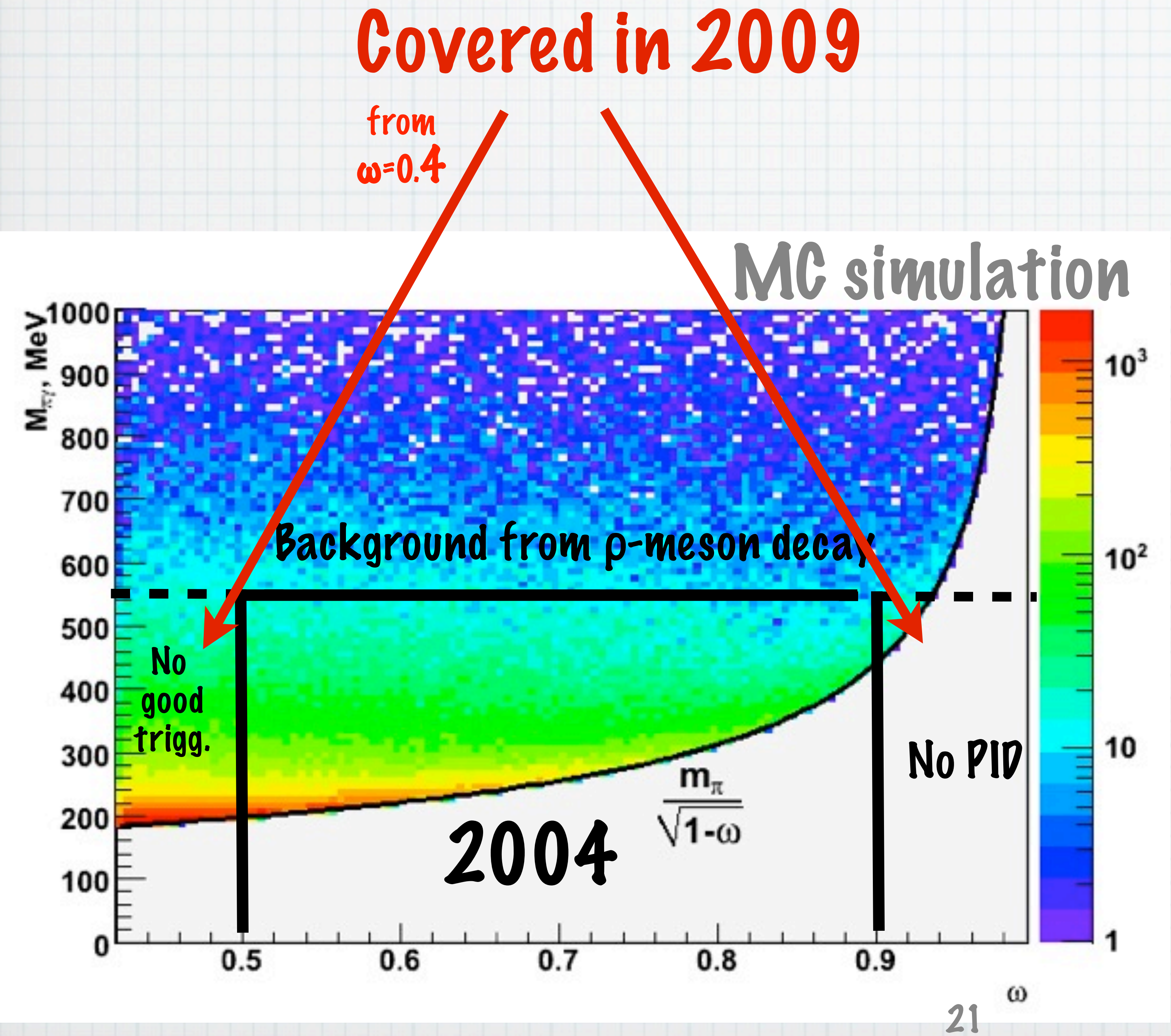
Main changes:	Run 2004	Run 2009
Main target	Pb (0.5 X_0)	Ni (0.3 X_0)
Total beam flux, 10^{11}	1 (π), 0.7 (μ)	3 (π), 1.3 (μ)
Main trigger condition	E_γ>90 GeV	E_γ>65 GeV

New target → smaller radiative corrections, better resolution for Q^2



New digital calorimeter trigger: only the central part of electromagnetic calorimeter was included into the trigger → lower trigger threshold, identical performance during operation with pion and muon beams

COMPASS hadron run 2009: other changes



- CEDAR for beam kaons identification
- Electron converter for electron background suppression
- Beam momentum measurement for muon beam
- Extended identification of secondary particles
- Better performance of electromagnetic calorimeter
- Cluster timing for better pile up rejection
- Stable conditions of data taking

New opportunities

* Precise measurement of α_π and β_π
* $\alpha_\pi(\omega)$, $\alpha_\pi(M)$ - the first measurement
* Estimation of quadrupole polarizabilities $\alpha_{2\pi}$ and $\beta_{2\pi}$
* First observation of Primakoff scattering with kaons and first estimation of kaon polarizabilities

New data taking for Primakoff physics is proposed to be performed in 2012
(see the COMPASS-II proposal at wwwcompass.cern.ch for detailes)

Days	π beam, days	μ beam, days	Flux π, 10^{11}	Flux μ, 10^{11}	$\alpha_\pi - \beta_\pi$ σ_{tot}	$\alpha_\pi + \beta_\pi$ σ_{tot}	$\alpha_2 - \beta_2$ σ_{tot}
120	90	30	59	12	± 0.27	fixed	fixed
					± 0.26	± 0.016	fixed
					± 0.66	± 0.025	± 1.94
					ChPT prediction		
					5.70	0.16	16

Summary

* During the pilot hadron run 2004 the possibility to measure pion polarizabilities at COMPASS was tested. The obtained experience was used for the preparation for the new data taking in 2009.
* In 2009 new data taking for Primakoff study was performed. Setup improvements made since 2004 and stable conditions of data taking permit to expect that pion polarizabilities can be extracted with high precision from the data collected in 2009.
* χPT physics and hadron polarizability measurement remain one of the most important points of future COMPASS physical program.