Precyzyjny pomiar polaryzowalności pionu

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Electromagnetic polarisabilities of the pion

- Magnitude of polarisability of a composite system by an external electromagnetic field
  characterises the „rigidity” of the system

- π meson, quark-antiquark system, lightest object bound by the strong force
  its rigidity reflects the strength of the binding force

- Theory of strong interactions (ChPT) predicts the pion electric and magnetic polarisabilities
  with (present) uncertainties of ≈ 18%

- Expected ‘deformation’ is about $2x10^{-4}$ of the pion volume, tiny effect
  ➡ good control of experimental systematics needed

- To produce such deformation the electric field of 10^{18} V/cm needed

- No trustworthy measurements of pion polarisabilities prior to COMPASS
  ➡ no entry in „Review of Particle Physics” yet

Chiral perturbation theory in a nut-shell

- Chiral symmetry – symmetry of Lagrangian under which left- and right-handed Dirac fields (QCD quarks) transform independently
  - in QCD with mass-less quarks the chiral symmetry is *spontaneously* broken by a quark condensate $\langle \overline{q}_R^a q_L^b \rangle$ formed through nonperturbative action of QCD gluons, with mass-less pion identified as the Goldstone boson
  - due to non-vanishing and differing quark masses, in the real world the chiral symmetry is *explictely* broken, and pions are not massless, they are pseudo-Goldstone bosons
- Chiral perturbative theory (ChPT) is low-energy expansion of QCD with the same symmetries as 'mather' theory, and hadrons as effective degrees of freedom
- Unknown coupling constants in ChPT Lagrangian are determined by fits to experimental data or derived from the underlying theory (QCD)
- ChPT provides a consistent description of low-energy hadronic physics:
  light-meson masses, decays, effective couplings, pion scattering lengths a_0 and a_2
  proton and neutron electric and magnetic polarisabilities etc,

COMPASS result makes ‘an event’ at CERN

- on February 11, 2015 in Physical Review Letters published COMPASS article
  „Measurement of Charged-Pion Polarizability”

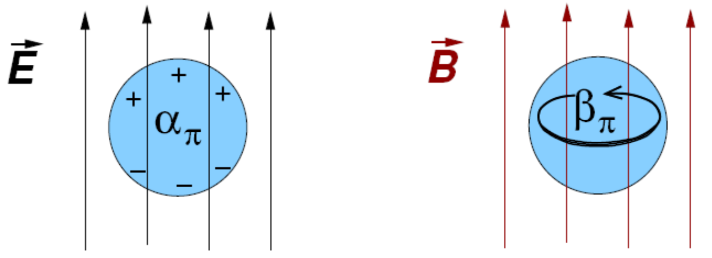
- the same day the result announced at the CERN press release

some citations from the press release

- ” CERN experiment brings precision to a cornerstone of particle physic ”
- ” […] a key measurements on the strong interaction”
- ” This result is admirably complementary to the studies of fundamental interactions performed at the LHC and a testimony to the diversity and strength of CERN’s research program”, *Rolf Heuer, Director General*

- the first page in News of March 2015 issue of the CERN Courrier

Pion polarisabilities – definitions and access



differential cross section for $\pi\,\gamma \longrightarrow \pi\,\gamma$ modified compared to poin-like pion

CMS kinematic variables:
s - total energy squared
θ_{cm} - scattering angle

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

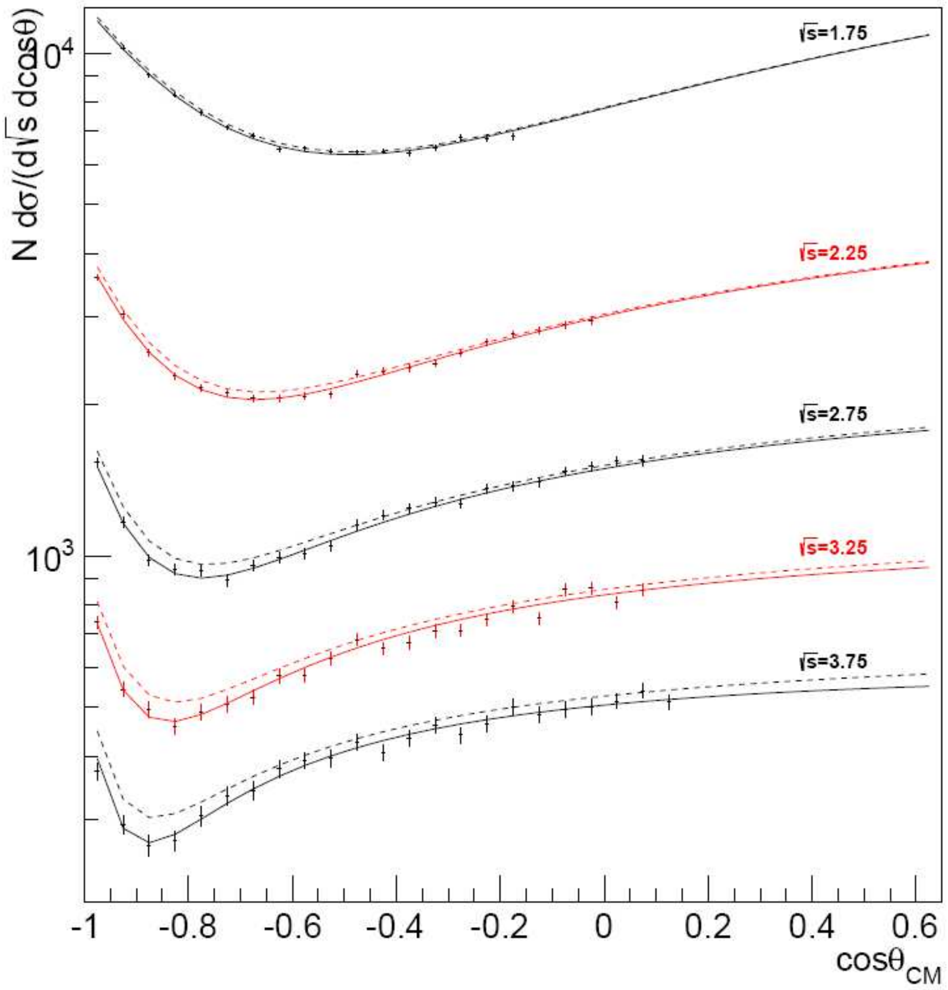
$$\mathcal{P} = z_-^2(\alpha_\pi - \beta_\pi) + \frac{s^2}{m_\pi^4} z_+^2(\alpha_\pi + \beta_\pi) - \frac{(s - m_\pi^2)^2}{24s} z_-^3(\alpha_2 - \beta_2)$$

$z_\pm = 1 \pm \cos\theta_{cm}$ $\quad\alpha = 1/137$ fine structure constant

2-loop ChPT prediction: $\alpha_\pi - \beta_\pi = (5.7 \pm 1.0)\ 10^{-4}\ \mathrm{fm}^3$ $\quad \alpha_\pi + \beta_\pi = (0.2 \pm 0.1)\ 10^{-4}\ \mathrm{fm}^3$

Effect of the pion polarisabilities on measured cross section

$\pi \gamma \rightarrow \pi \gamma$



- - - - - - - - - point-like pion

——— ChPT 2-loop prediction

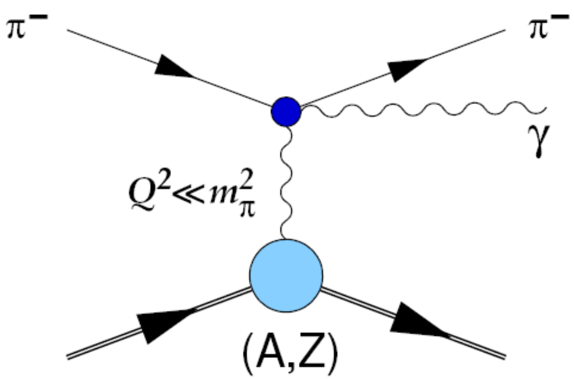
\+ simulation assuming statistics collected in 2012

[s in units of m_π^2]

- $\sigma_{tot}(s)$ weak sensitivity to pion's structure
- up to 20% effect on backward θ_{CM} scattering angles

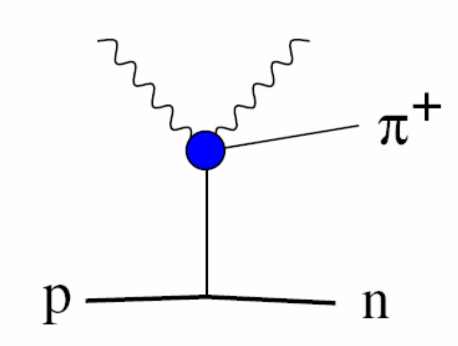
Ways to access $\pi \gamma \to \pi \gamma$ scattering

(A)



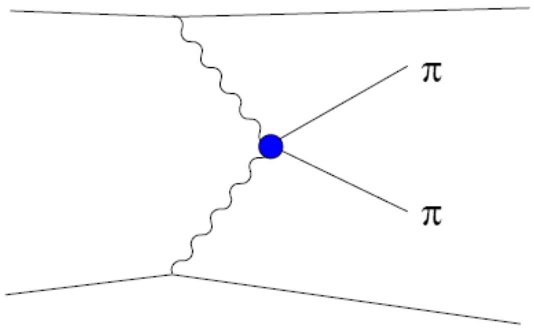
Primakoff process

(B)



radiative pion photoproduction

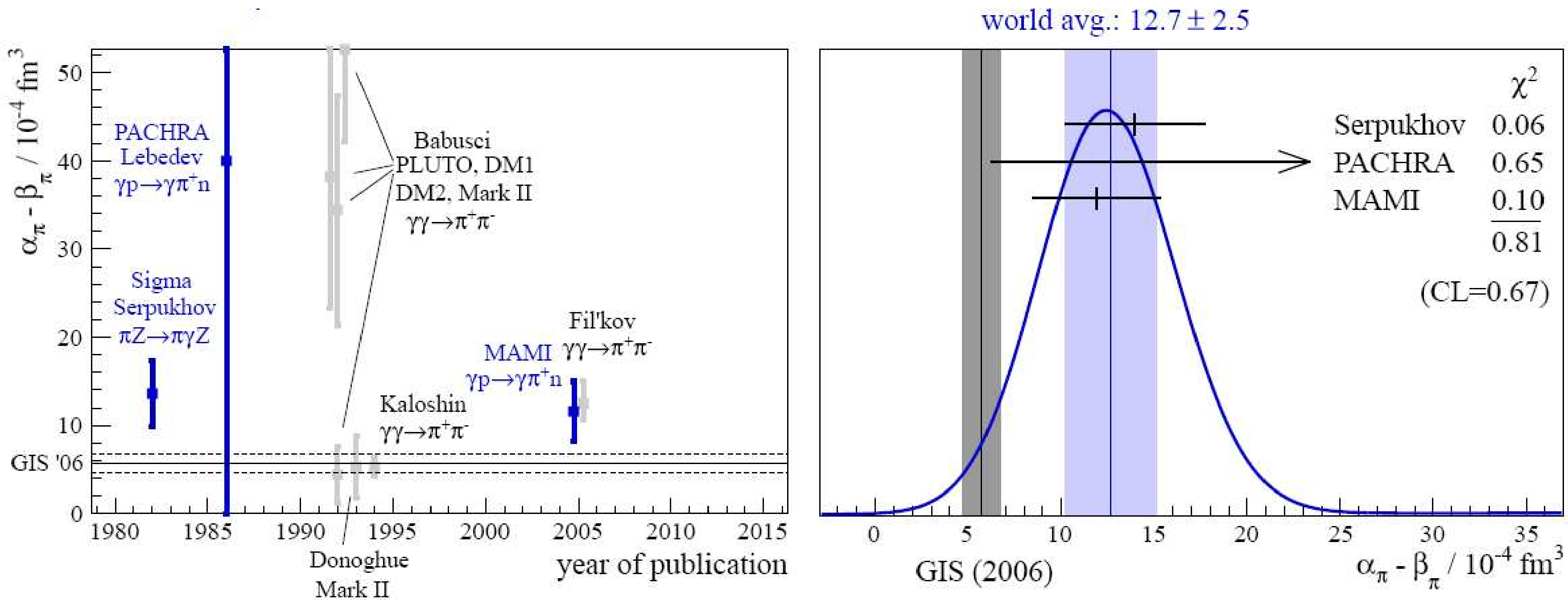
(C)



photon-photon fusion

$Q^2 = - (p^\mu_\pi + p^\mu_\gamma - p^\mu_{beam})^2$

Pion polararisability – world data before COMPASS



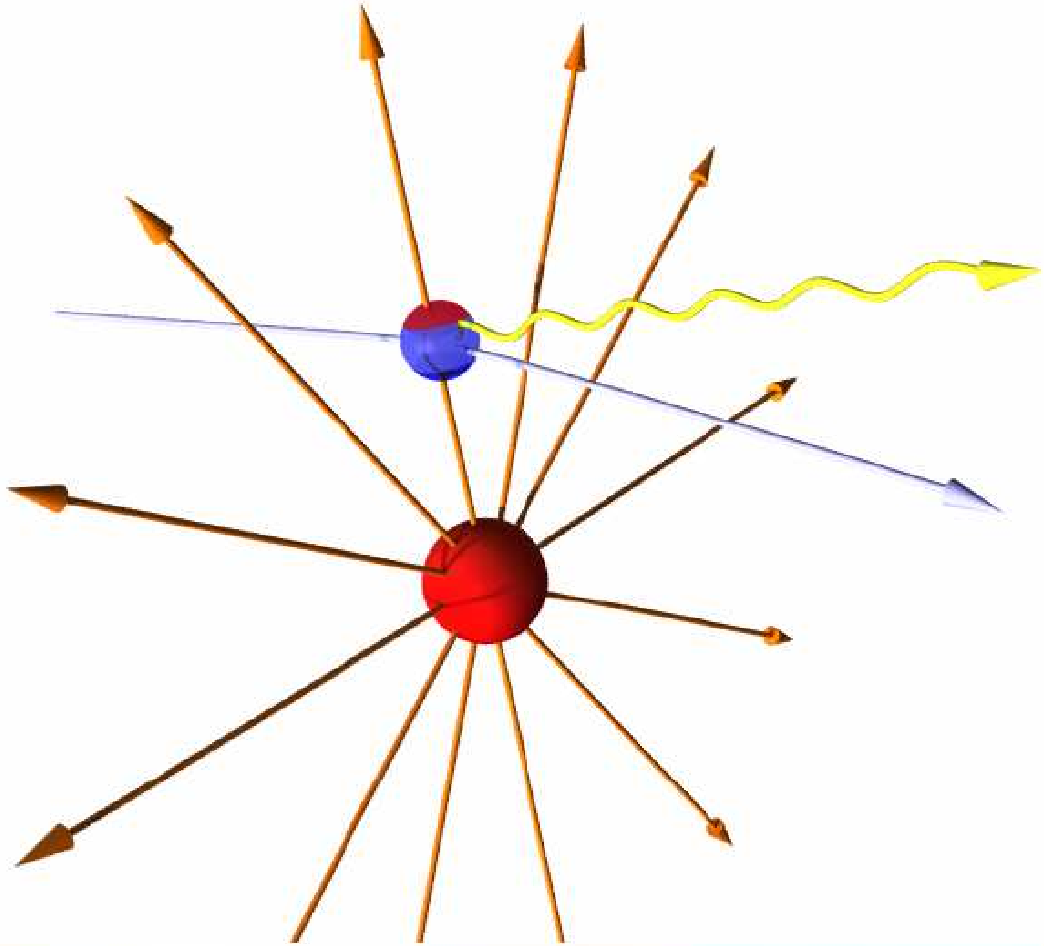
GIS'06: ChPT prediction, Gasser, Ivanov, Sainio, NPB745 (2006)

plots from Thiemo Nagel, PhD thesis, TUM 2012

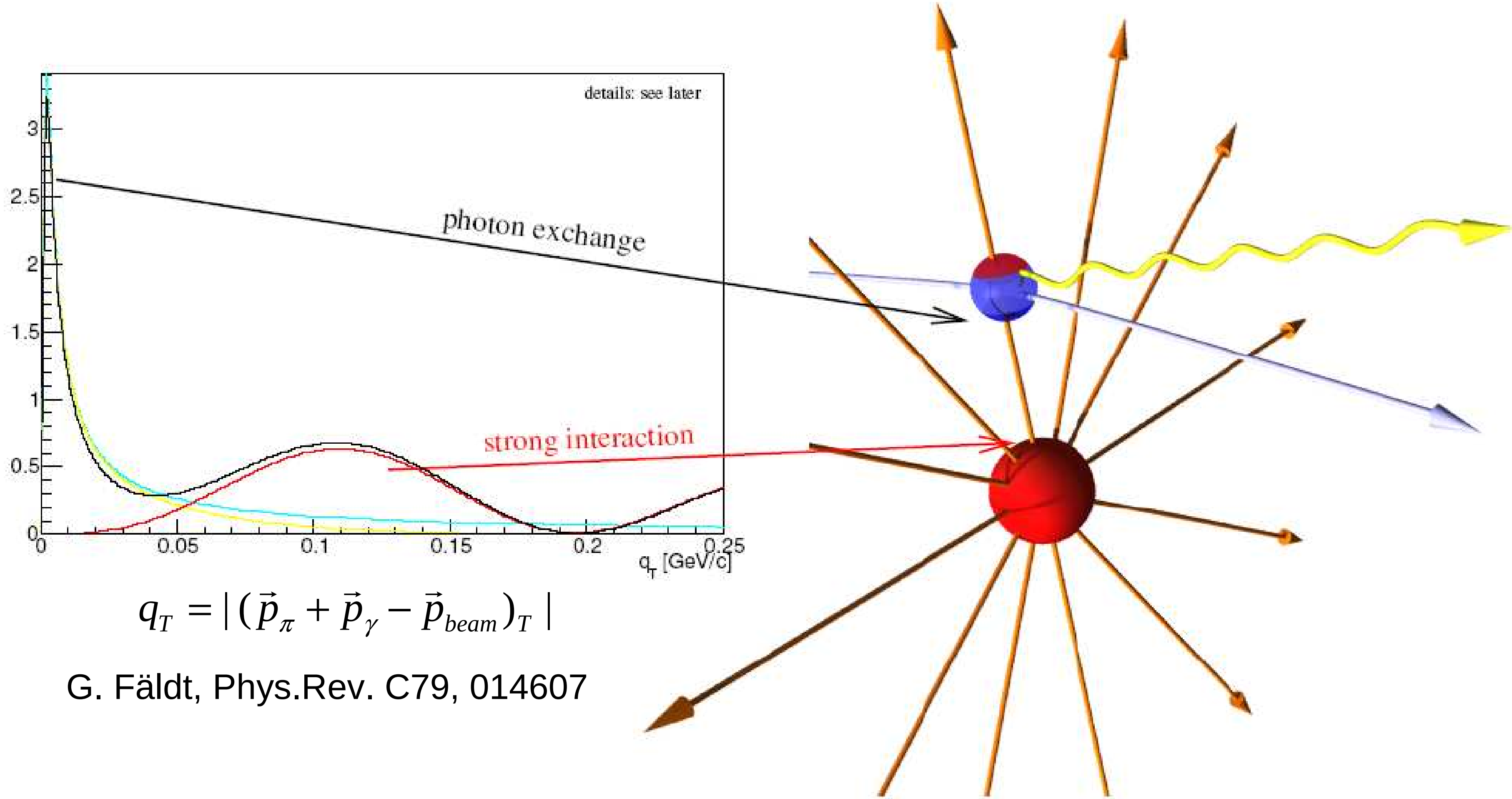
Fil'kov analysis objected by Pasquini, Drechsel, Scherer, PR C81 (2010) 029802

Pion polararisability via Primakoff Compton scattering

- Charged pion traversing the nuclear electric field
  - typical field strength at $r = 5R_{Ni}$: $E \sim 300\,\text{kV/fm}$
- **Bremsstrahlung emission**
  - particle scatters off *equivalent photons*
  - tiny momentum transfer $Q^2 \approx 10^{-5}\,\text{GeV}^2/c^2$
  - pion/muon (quasi-)real Compton scattering
- Polarisability contribution
  - Compton cross-section typically diminished
  - expected charge separation $\sim 10^{-5}\,\text{fm} \cdot e$



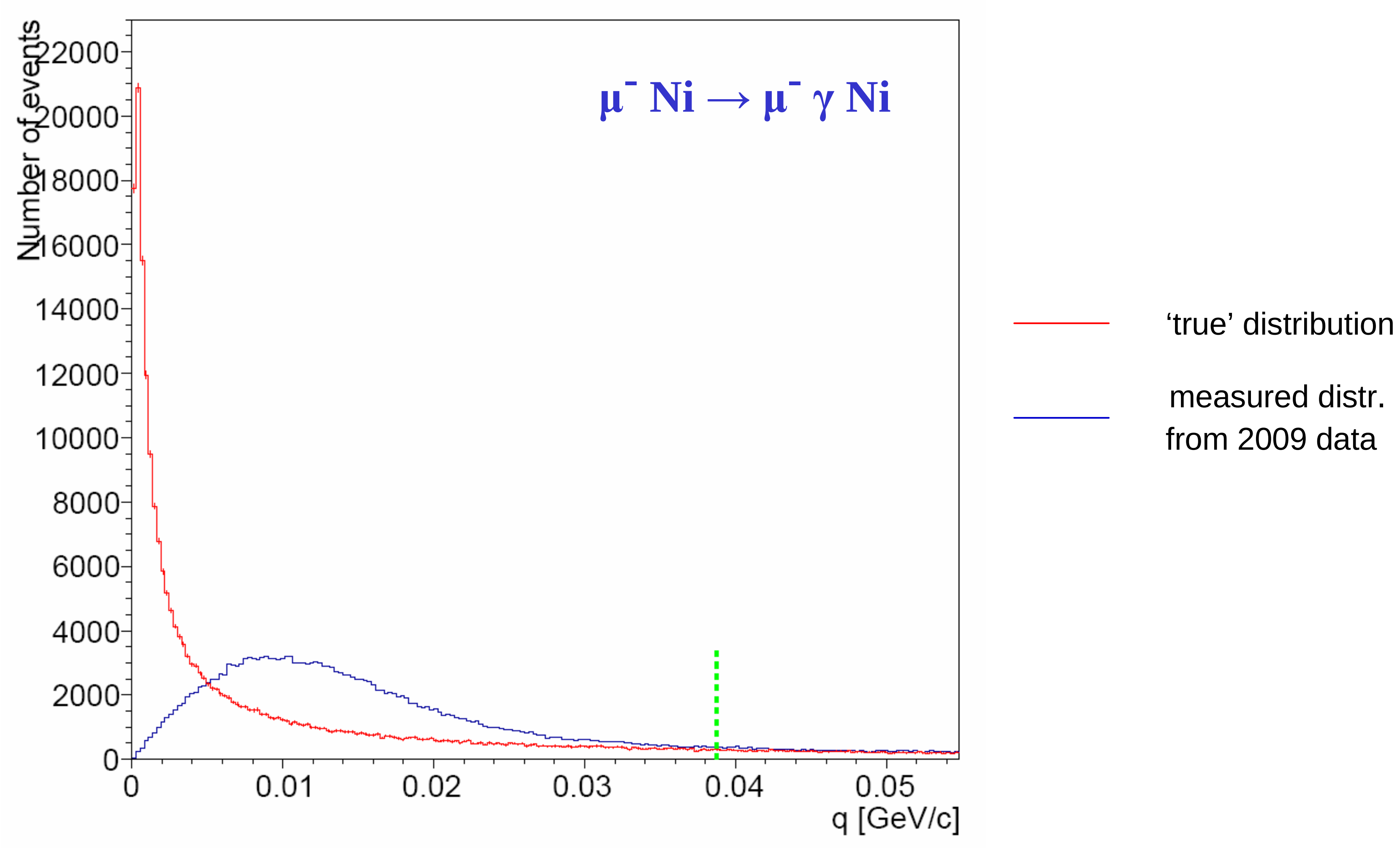
Interplay of electromagnetic and strong interactions



$$q_T = |(\vec{p}_\pi + \vec{p}_\gamma - \vec{p}_{beam})_T|$$

G. Fäldt, Phys.Rev. C79, 014607

Pure Primakoff sample from $\mu^- \, Ni \rightarrow \mu^- \, \gamma \, Ni$



$$q = | \vec{p}_{\pi} + \vec{p}_{\gamma} - \vec{p}_{beam} |$$

achieved resolution 12 MeV/c (10 times larger than the true peak structure)

π-nucleus cross-section connection to πγ cross section

equivalent-photon approximation approach

π (A,Z) → X (A,Z)

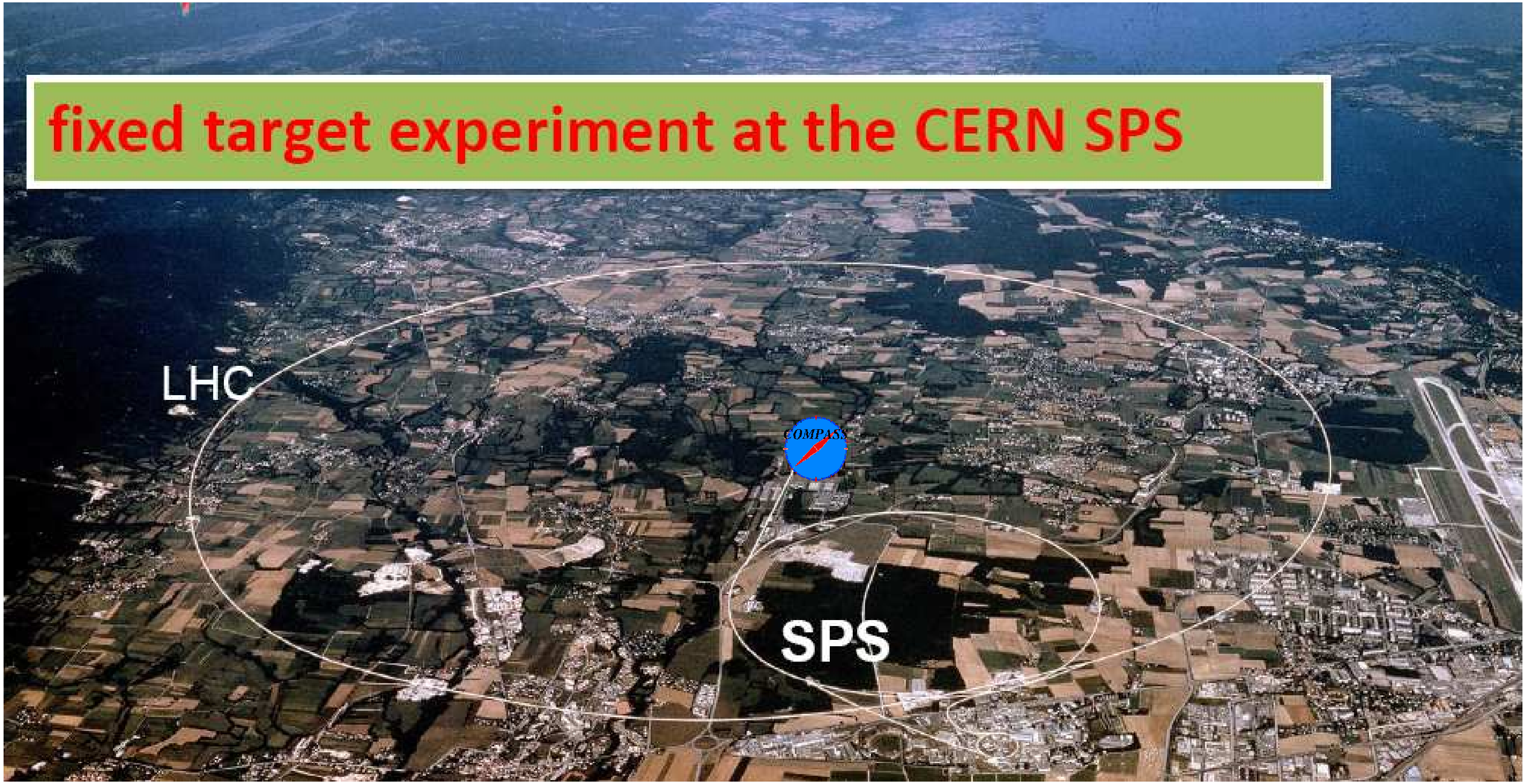
π γ → X

$$\frac{d\sigma^{\mathrm{EPA}}_{(A,Z)}}{ds\,dQ^2\,d\Phi_n} = \frac{Z^2\alpha}{\pi(s-m_\pi^2)} F^2(Q^2) \frac{Q^2-Q^2_{\mathrm{min}}}{Q^4} \frac{d\sigma_{\pi\gamma\to X}}{d\Phi_n}$$

nucleus electromagnetic form factor

phase-space element of final state X

COmmon Muon Proton Apparatus for Structure and Spectroscopy



~ 220 physicists from 24 institutions

- Located at CERN North Area M2 beam line
  - Possible beams: μ^+, μ^-, π^+, π^-, K, p → Several physics programs

- Programs with muon beam
- Programs with hadron beams

COMPASS (2002 – 2011)

Muon beam:

- Spin structure, gluon polarization
- Flavour decomposition
- Transversity
- Transverse Momentum-dependent PDFs

p, d polarised target (L & T)

Hadron beams:

- Pion polarisability
- Diffractive and Central production
- Light meson spectroscopy
- Baryon spectroscopy

small LH_2 or nuclear targets

COMPASS - II (2012 – 2017)

Muon beam:

- DVCS and HEMP
- Unpolarized SIDIS and TMDs

long LH_2 target

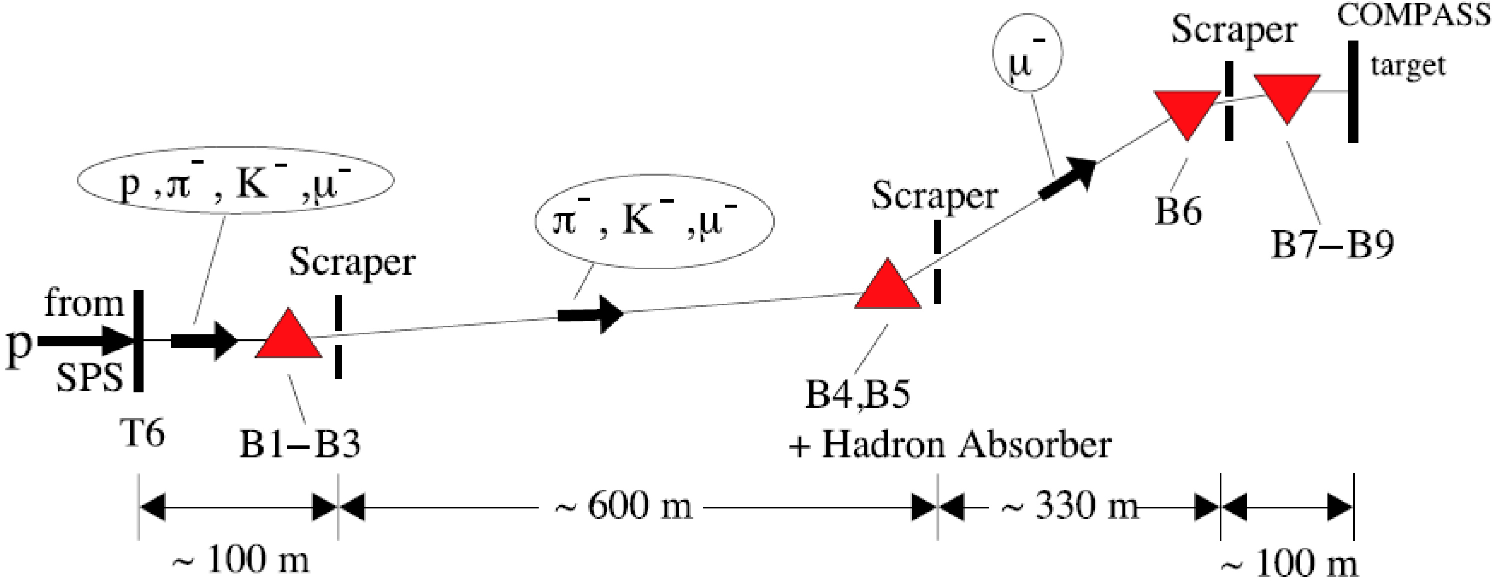
Hadron beams:

- Pion and Kaon polarisabilities
- Drell-Yan process

nuclear targets or polarised p target (T)

Reconfigurable target region - versatile experimental setup!

M2 beam line schematics for ‘muon’ configuration

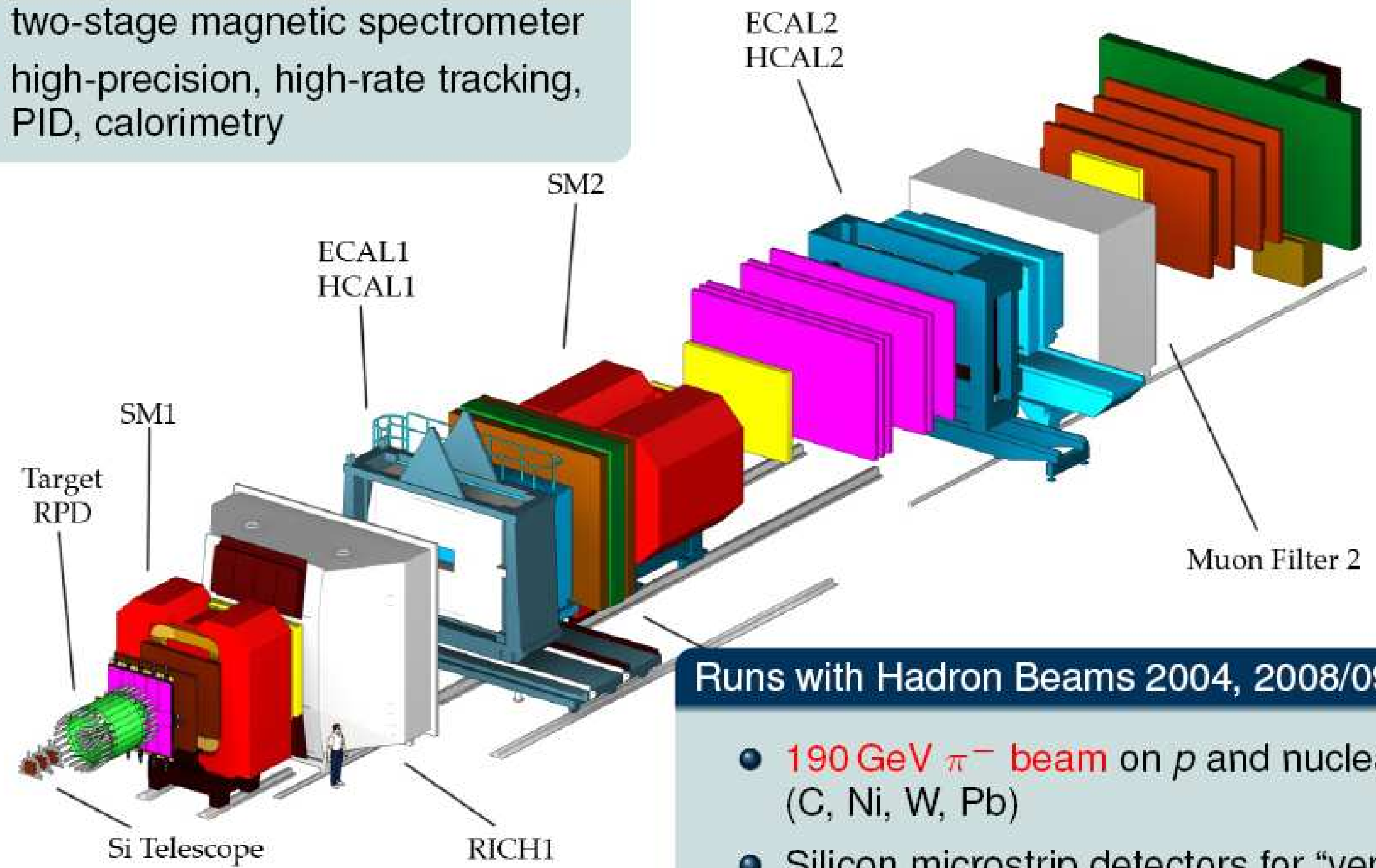


9.9 m long Be absorber (at B4): in for muon beam, out for hadron beam

COMPASS experimental setup

Fixed-target experiment

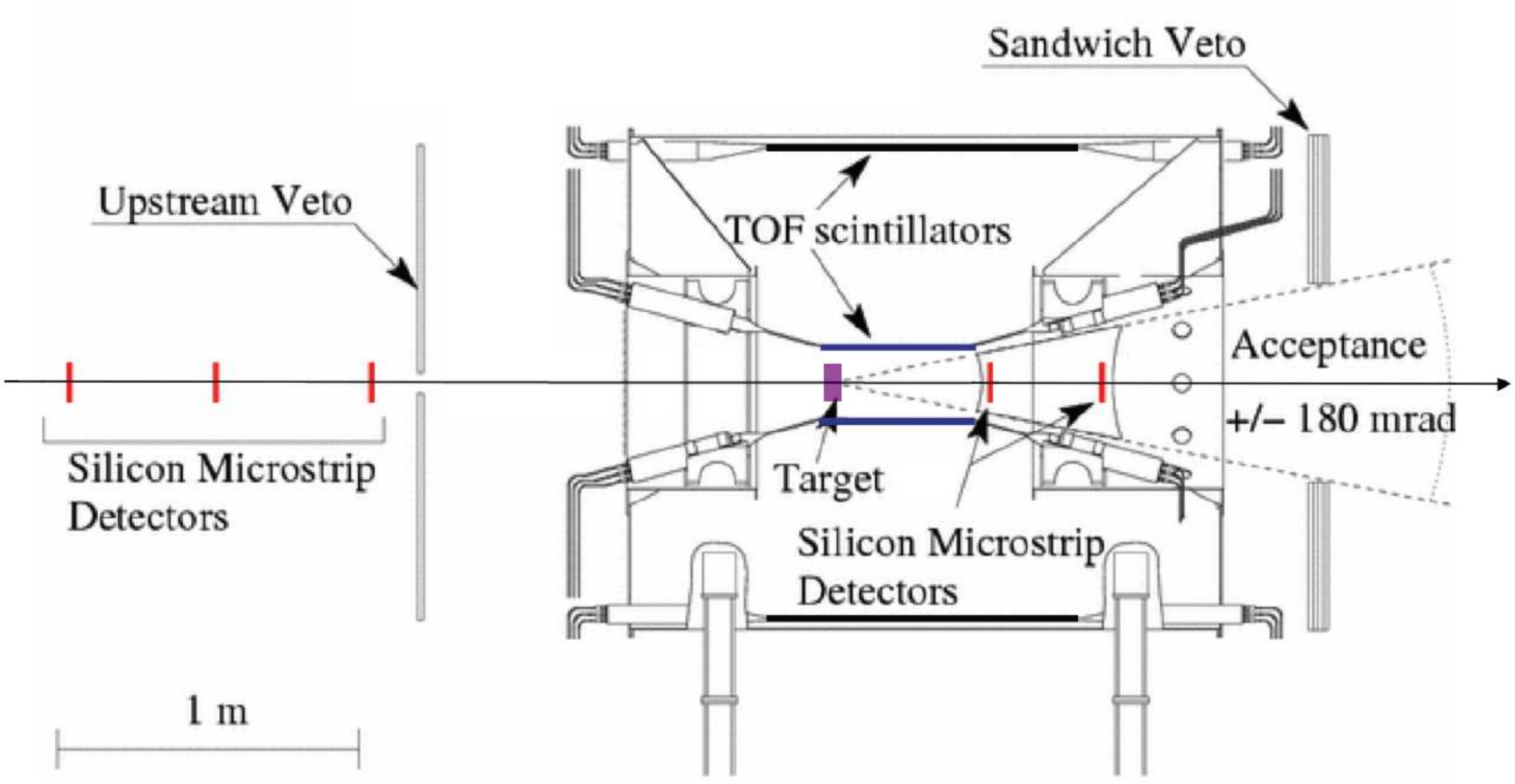
- two-stage magnetic spectrometer
- high-precision, high-rate tracking, PID, calorimetry



Runs with Hadron Beams 2004, 2008/09, 2012

- 190 GeV π^- beam on p and nuclear targets (C, Ni, W, Pb)
- Silicon microstrip detectors for "vertexing"
- recoil and (digital) ECAL triggers

Target region

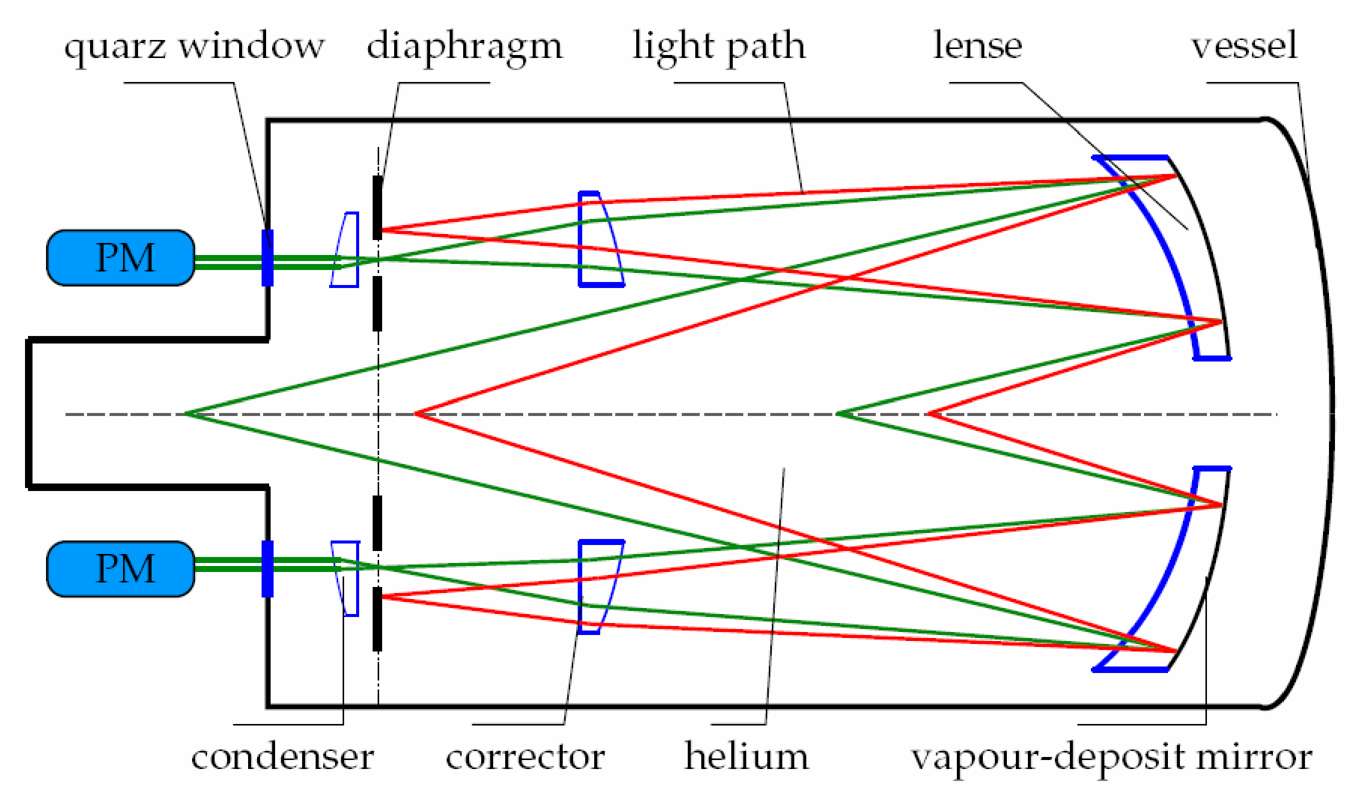


Main target: disc 4.2 mm long and 5 cm Ø of Ni (fraction of spin-0 isotopes 99%)

5 cryogenic silicon micro-strip detector stations, with spacial resolution of 4 – 11 μm
excellent for vertexing and precise determination of momentum transfer to the nucleus

CEDAR – to select beam pions (96.8%)

ChErenkov Differential counter with Achromatic Ring focus

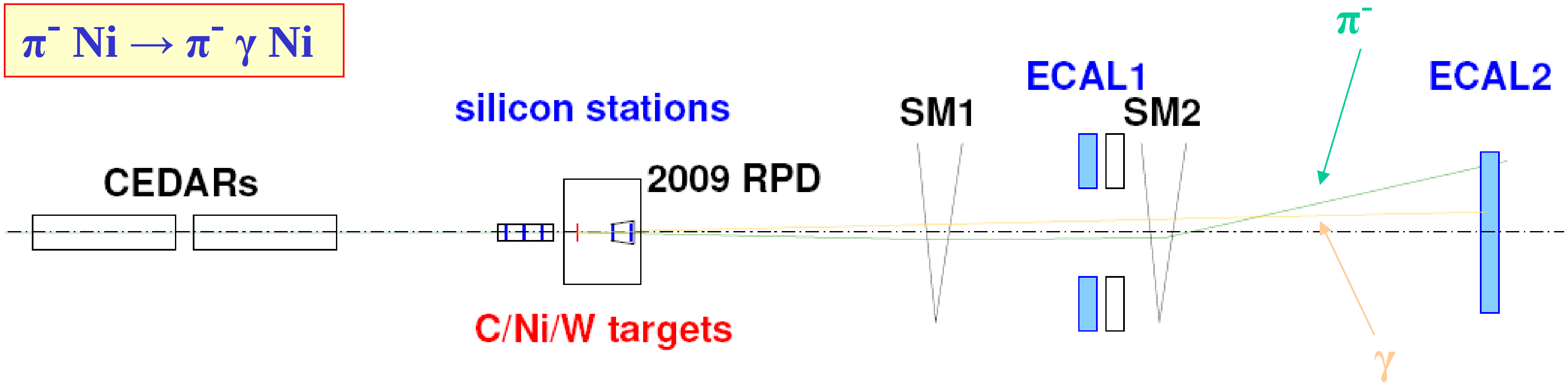


Two CEDAR detectors located about 30 m upstream of the target

In 2009 Primakoff data taking both CEDARs set on kaons
to attain the highest kaon suppression

Principle of measurement and event selection

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

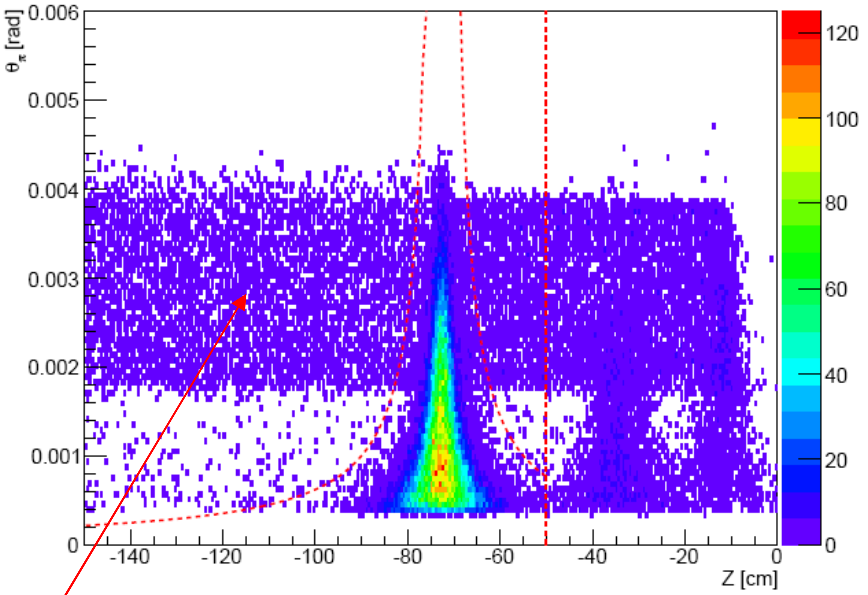


- Two dedicated Primakoff trriggers: incoming beam particle AND energy deposit either > 60 or > 40 GeV in central part of ECAL2
- Topology of event: just one outgouing negatively charged track
  + common vertex of beam and charged tracks within the target
  + just one ECAL2 energy cluster > 2 GeV not attributed to charged track
- Outgoing pion with $p_T > 40$ MeV/c
  to avoid region dominated by multiple scattering of pion in the target
- Exclusivity selection: energy balance must be $|\Delta E| < 15$ GeV
  $$\Delta E = E_\pi + E_\gamma - E_{beam}$$
- Selection of photon exchange (Primakoff process): $Q^2 < 0.0015$ (GeV/c)^2
- Invariant mass $m_{\pi\gamma} < 3.5 m_\pi \approx 0.49$ GeV/c^2
  to suppress backround from $\rho^-(770)$ production with decay into $\pi^- \pi^0$

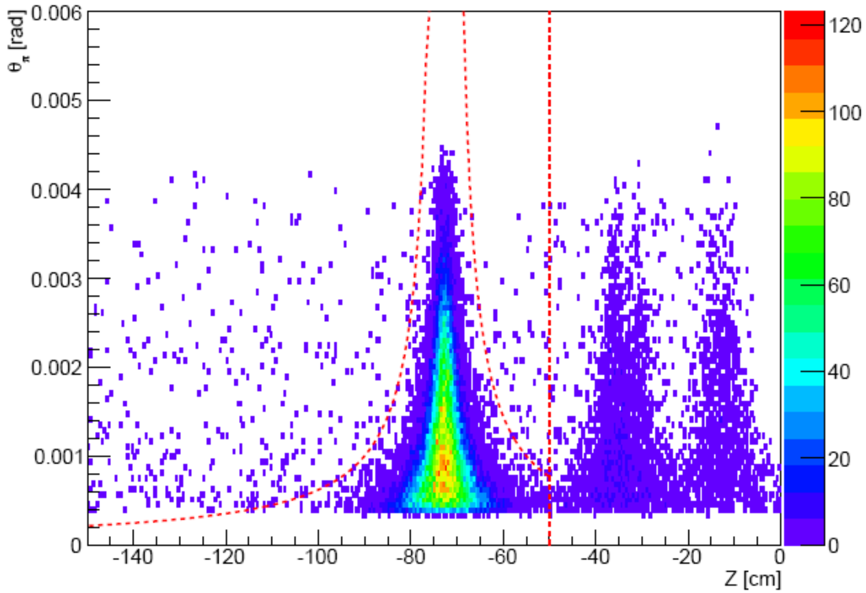
Vertex resolution and suppression of beam kaons (2.4%)

here and in the following slides all ‘Primakoff selections’ applied
except those those shown in a given plot

no PID of beam



kaons suppressed using CEDAR info.



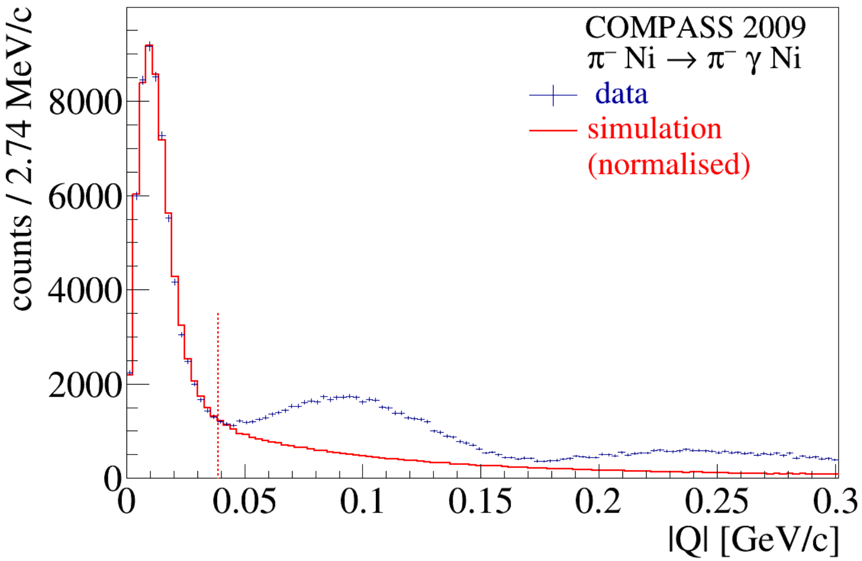
decays of beam kaons: $K^- \to \pi^- \pi^0 \to \pi^- \gamma \not\gamma$

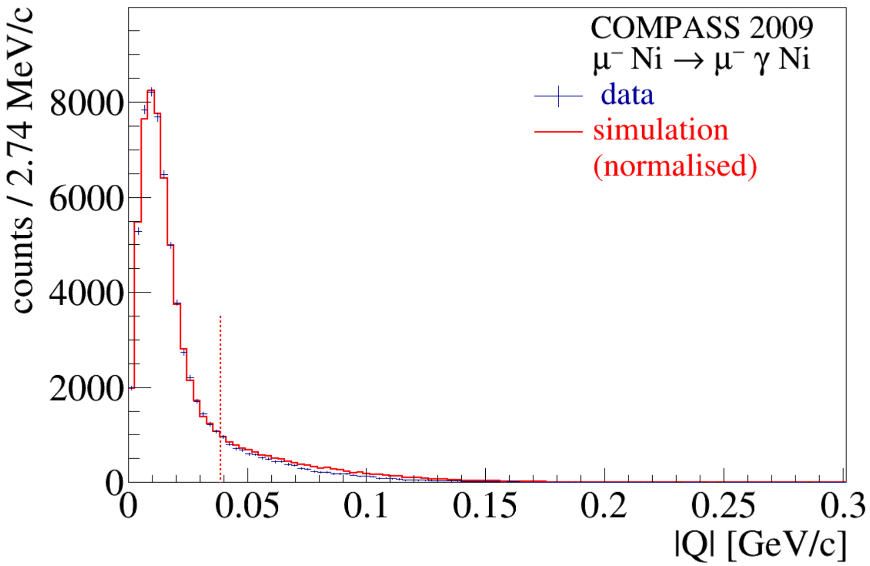
pion scattering angle vs. longitudinal position of the vertex

⬇

θ_π-dependent cut on z to isolate interactions on Ni target (denoted by red lines)

Identifying $\pi\gamma \rightarrow \pi\gamma$ (or $\mu\gamma \rightarrow \mu\gamma$) reaction; selection of photon exchange

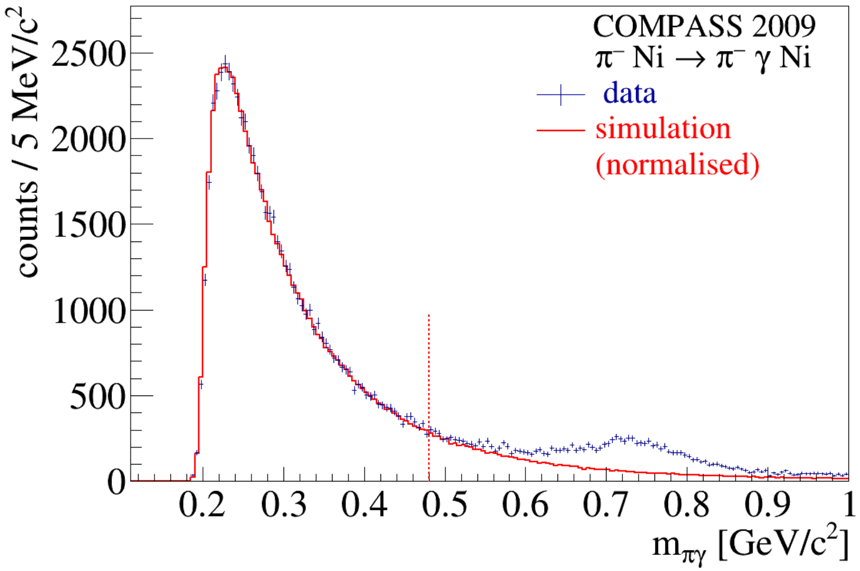


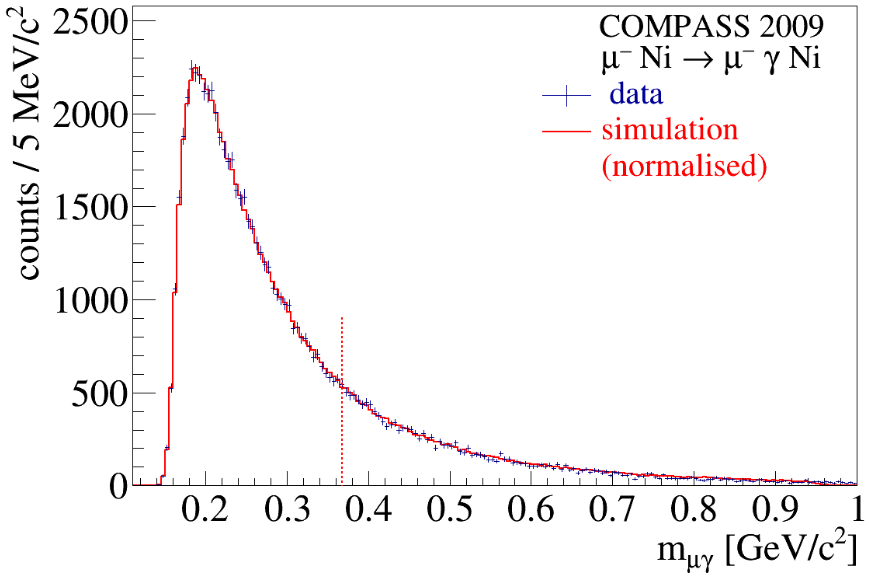


$Q^2 < 0.0015\ (\mathrm{GeV}/c)^2$

$Q^2 = -\,(p^{\mu}_{\pi} + p^{\mu}_{\gamma} - p^{\mu}_{beam})^2$

Mass of the final $\pi\gamma$ (or $\mu\gamma$) system



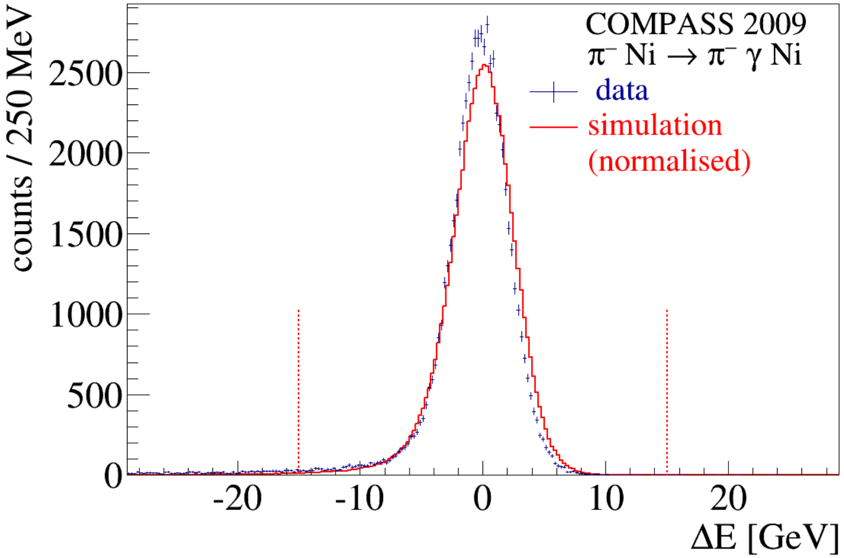


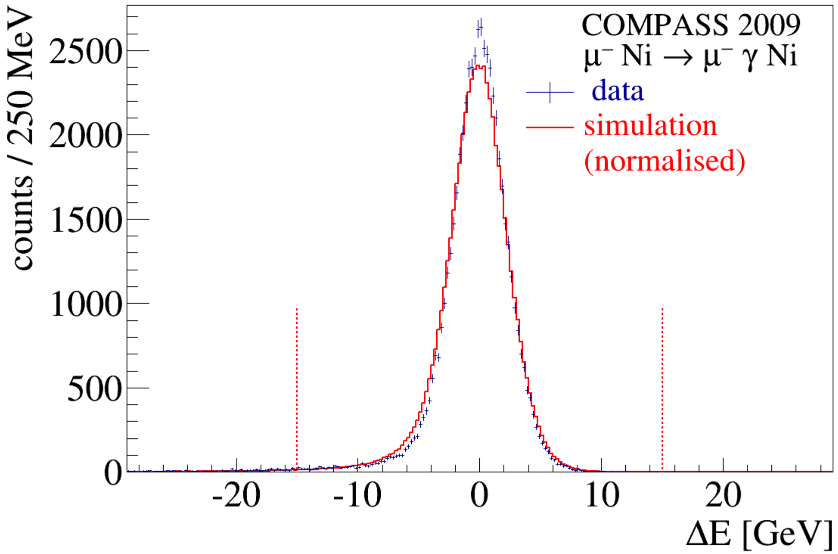
$m_{\pi\gamma} < 3.5 m_\pi \approx 0.49$ GeV/c^2

to suppress backround from $\rho^-(770)$ production

with decay into $\pi^- \pi^0 \rightarrow \pi^- \gamma \not{\gamma}$

Identifying $\pi\gamma \rightarrow \pi\gamma$ (or $\mu\gamma \rightarrow \mu\gamma$) reaction; exclusivity selection





$|\Delta E| < 15$ GeV

$$\Delta E = E_{\pi} + E_{\gamma} - E_{beam}$$

$\sigma \approx 3$ GeV, mainly from ECAL2

for selected range $Q^2 < 0.0015\ (\text{GeV}/c)^2$

kinetic energy of Ni recoil < 8 keV, neglected for ΔE

Extraction of the pion polarisability

- Assuming $\alpha_\pi = -\beta_\pi$, from the cross section for $\pi\,\gamma^*_{\{Ni\}} \rightarrow \pi\,\gamma$

$$R_\pi = \left(\frac{d\sigma_{\pi\gamma}}{dx_\gamma}\right) \Big/ \left(\frac{d\sigma^0_{\pi\gamma}}{dx_\gamma}\right) = 1 - \frac{3}{2}\frac{m_\pi^3}{\alpha}\frac{x_\gamma^2}{1-x_\gamma}\alpha_\pi$$

$x_\gamma = E_\gamma / E_{beam}$

measured cross section

simulated cross section expected for $\alpha_\pi = 0$

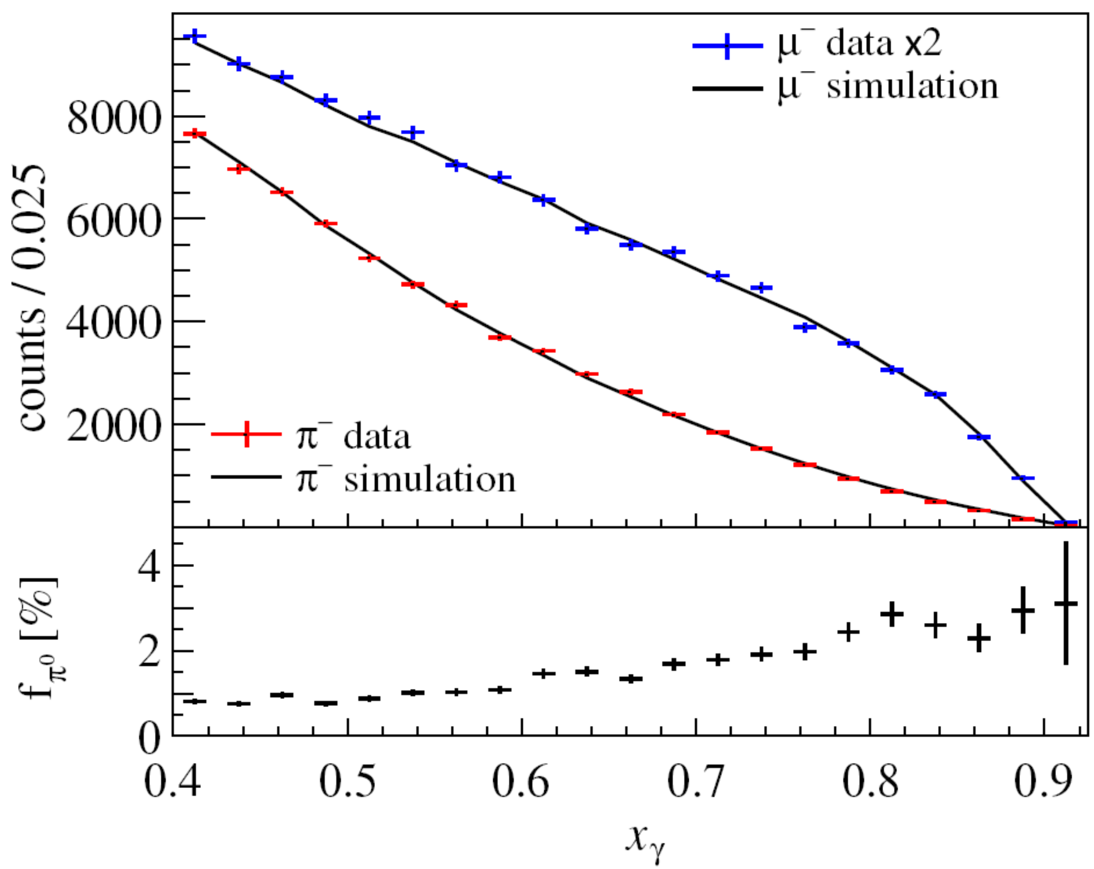
fit to $R_\pi(x_\gamma) \longrightarrow \alpha_\pi$

- Control systematics by
  - $\mu\,\gamma^*_{\{Ni\}} \rightarrow \mu\,\gamma$

  and

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

Photon energy spectra for pion and muon beams



≈ 63 000 Primakoff events (x_γ > 0.4)

(Serpukhov ≈ 7 000 for x_γ > 0.5)

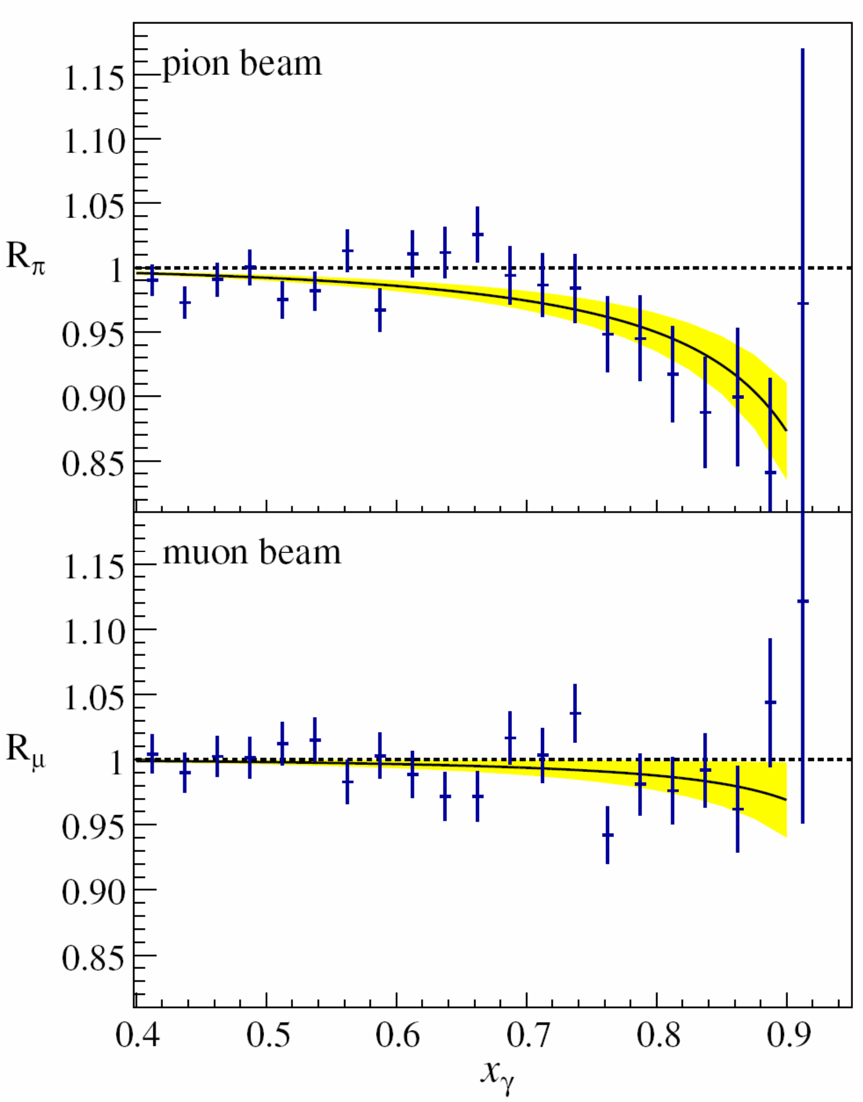
$x_\gamma = E_\gamma / E_{beam}$

fraction f_{π° of π° background from $\pi^- \mathrm{Ni} \rightarrow \pi^- \pi^\circ X \rightarrow \pi^- \gamma \not\gamma X$

subtracted from the pion data

estimated from decays of beam kaons $K^- \rightarrow \pi^- \pi^\circ$ → $\pi^- \gamma \gamma$ / → $\pi^- \gamma \not\gamma$

Pion polarisability – COMPASS result



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

2-loop ChPT prediction $\alpha_\pi = 2.93 \times 10^{-4}\ fm^3$

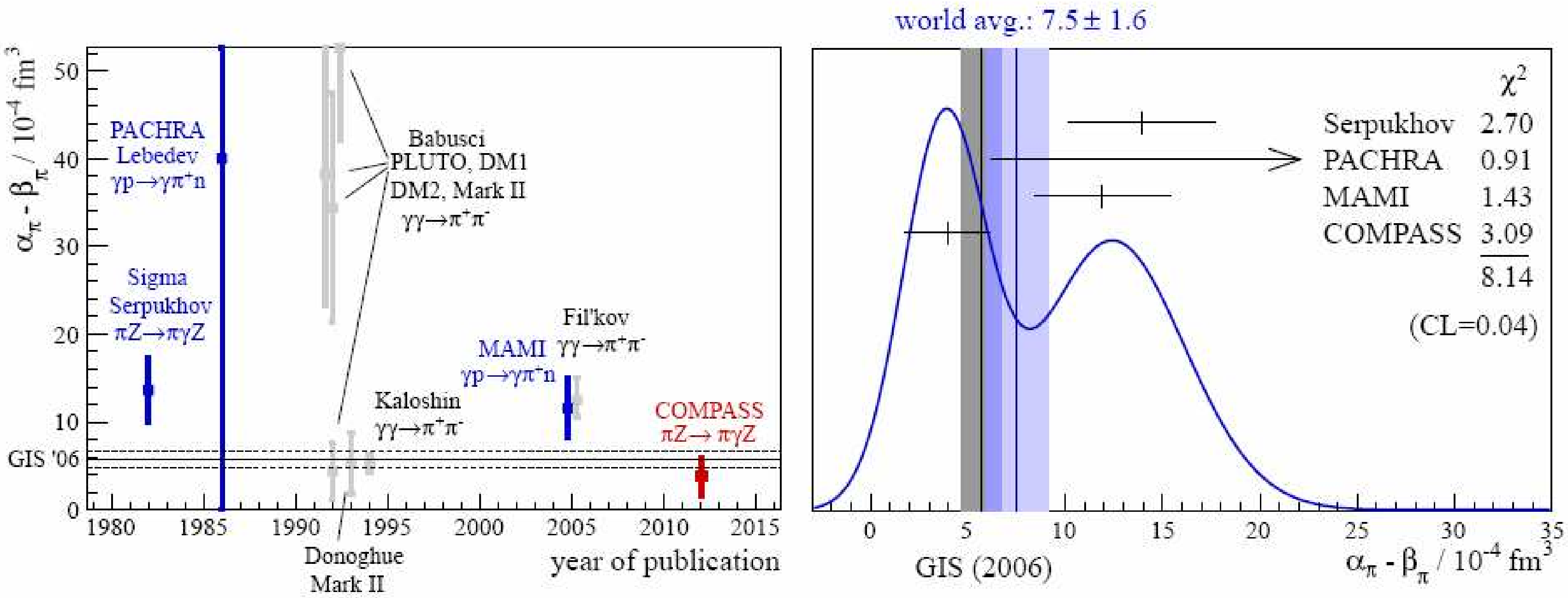
⇨ expectation from ChPT confirmed within the uncertainties

control measurements of ‘false polarisability’ with muon beam

$\alpha_\mu = (0.5 \pm 0.5_{stat})\ 10^{-4}\ fm^3$

⇨ no significant systematic bias

Pion polararisability – world data including COMPASS



- The new COMPASS result is in significant tension with the earlier measurements of the pion polarisability
- The expectation from ChPT is confirmed within the uncertainties

Conclusions and outlook

- measurement of the pion polarisability via the Primakoff reaction (2009 data)

  $\alpha_\pi = (2.0 \pm 0.6_{stat} \pm 0.7_{syst})\ 10^{-4}\ \text{fm}^3$ with assumption $\alpha_\pi = -\beta_\pi$

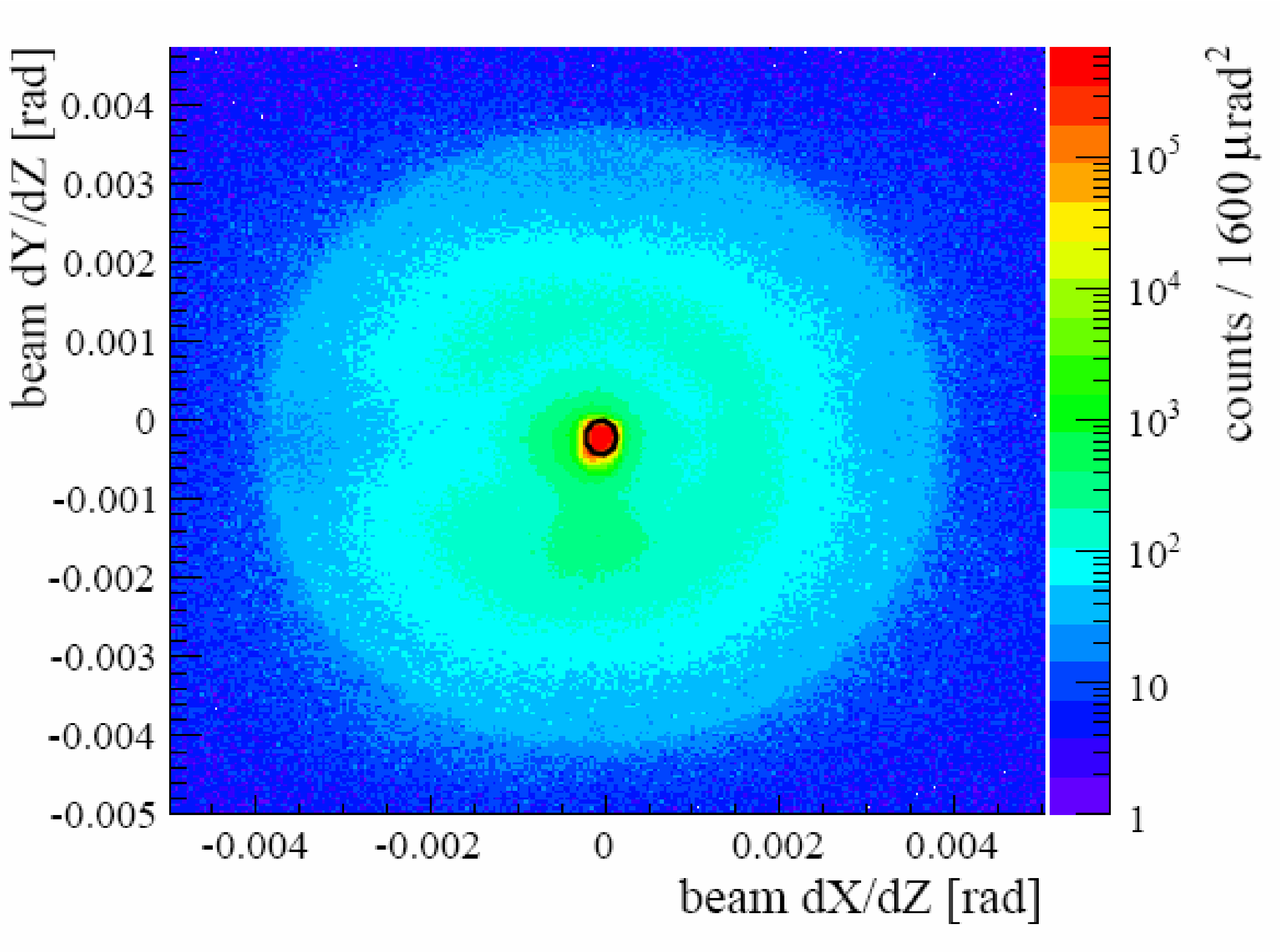
  - new precise experimental determination
  - control of systematics: $\mu\,\gamma \rightarrow \mu\,\gamma$
  - the expectation for ChPT confirmed within the uncertainties
  - the COMPASS results is in tension with the earlier measurements

- high statistics run 2012 (COMPASS-II) (≈ 4 times larger than in 2009)

  - separate determination of α_π and β_π
  - measurement of quadrupole polarisabilities of α_2 and β_2
  - *s*-dependence of polarisabilities
  - first measurement of the kaon polarisability

Backup

Divergence of the hadron beam



beam divergence cut indicated in black

Systematic uncertainties

TABLE I. Estimated systematic uncertainties at 68% confidence level.

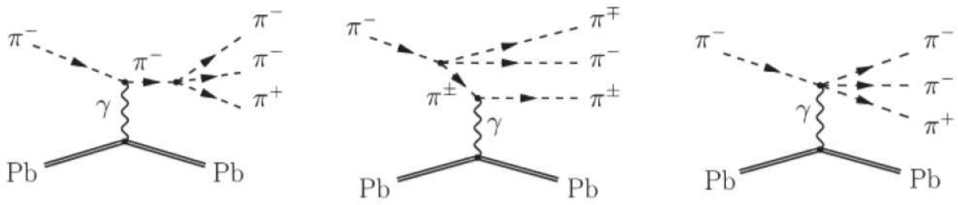
Source of uncertainty	Estimated magnitude $[10^{-4}\ \mathrm{fm}^3]$
Determination of tracking detector efficiency	0.5
Treatment of radiative corrections	0.3
Subtraction of π^0 background	0.2
Strong interaction background	0.2
Pion-electron elastic scattering	0.2
Contribution of muons in the beam	0.05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

Other Primakoff processes

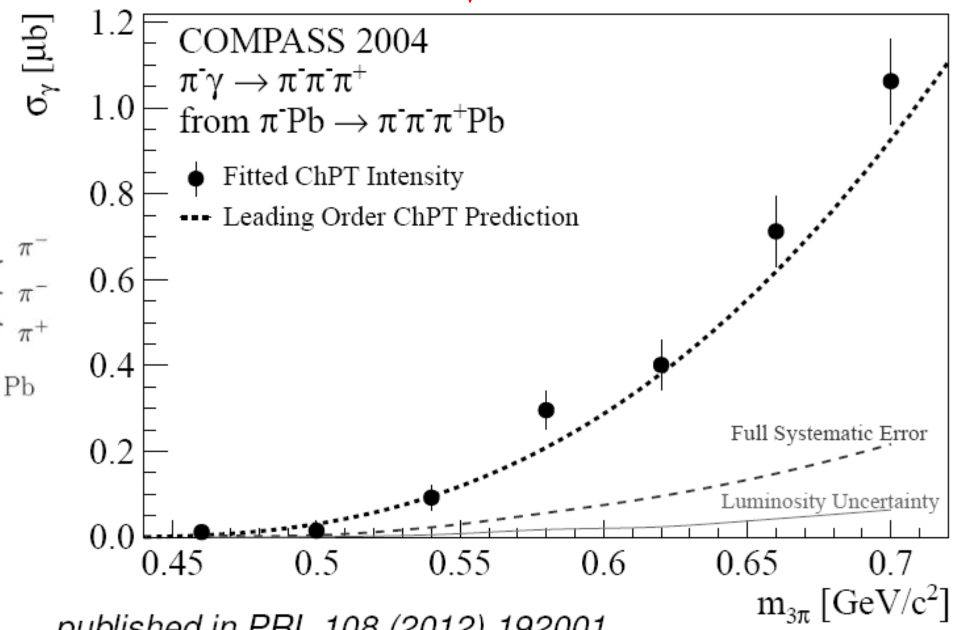
$$\pi^- + \gamma \to \begin{cases} \pi^- + \gamma \\ \pi^- + \pi^0 \; / \; \eta \\ \pi^- + \pi^0 + \pi^0 \\ \pi^- + \pi^- + \pi^+ \\ \pi^- + \pi^- + \pi^+ + \pi^- + \pi^+ \\ \pi^- + \dots \end{cases}$$

$\Leftarrow$ published

analogously: Kaon-induced reactions $K^- + \gamma \to \cdots$



Measured absolute cross-section of $\pi^-\gamma \to \pi^-\pi^-\pi^+$



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