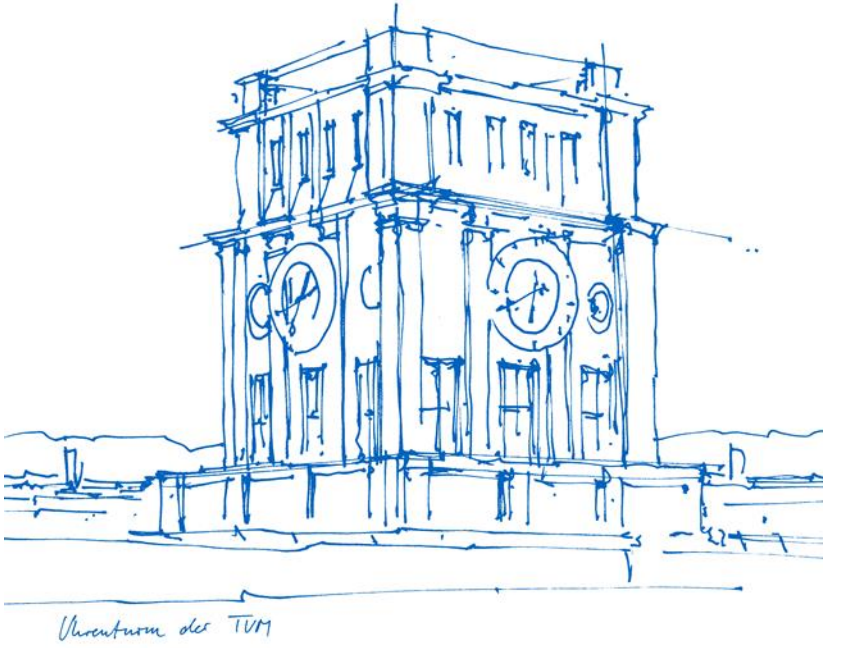
Extracting Chiral Perturbation Theory Parameters from Primakoff Measurements at COMPASS

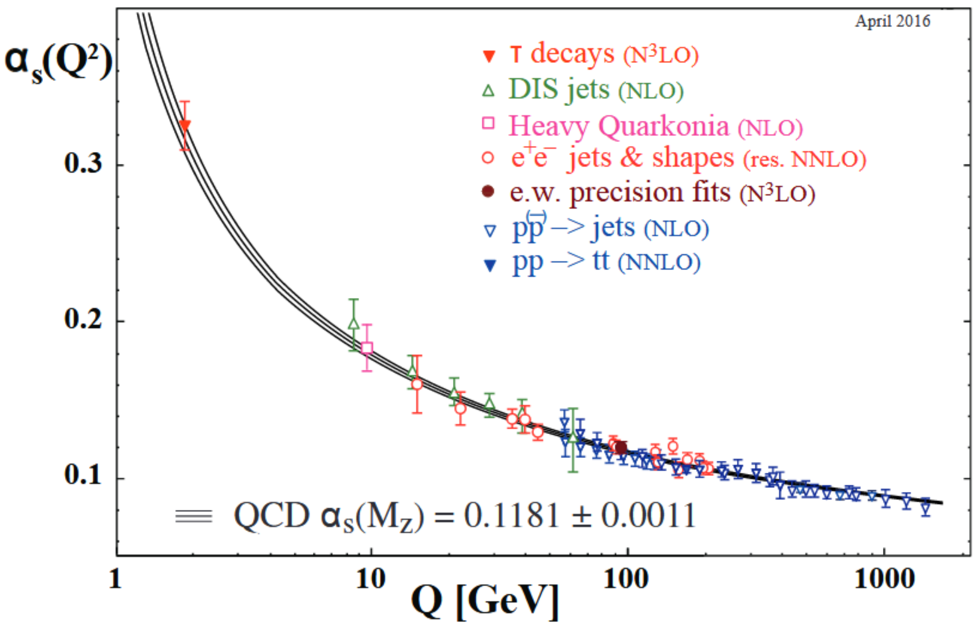
Dominik Steffen

Arbeitstreffen Kernphysik 2020



Chiral Perturbation Theory (ChPT)

- QCD the true theory of strong interaction
- Perturbation theoretical series $f(\alpha_S) = c_0 + c_1\alpha_S + c_2\alpha_S^2 + \cdots$ fails for $\alpha_S \sim 1$.
- Expansion in powers of α_S no longer applicable when $\alpha_S \sim 1$ to obtain predictions => not applicable for bound states => Effective Theory (ChPT)
- At low Q: Effective degrees of freedom π, η, K
- Expansion not in α_S, but in quark masses and momenta of interacting particles
- Systematic way to calculate corrections: loop, 2-loop, etc.
- Basic predictions: interactions and properties of pseudoscalar mesons



M. Tanabashi *et al.* (Particle Data Group), Phys. Rev. D **98**, 030001 (2018).

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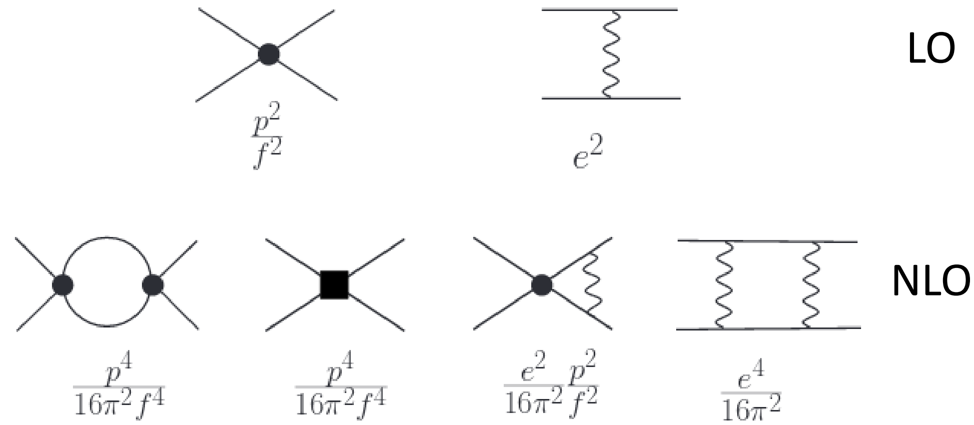
Example: $\pi\pi$-scattering



G. Buchalla, O. Cata, A. Celis, and C. Krause, LMU-ASC-10-16 (2016)

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Dichotomous character of the pion

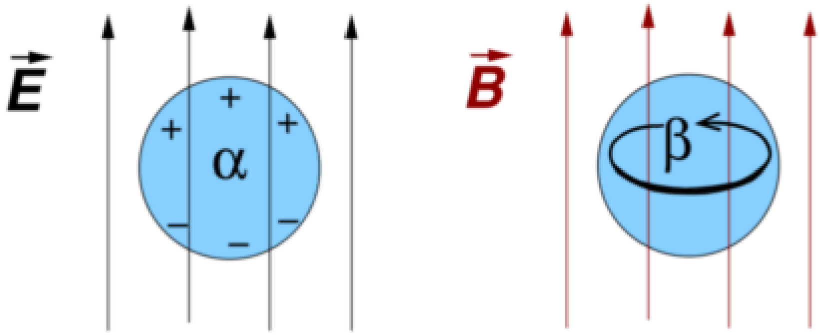
1. Pion as the lightest bound state of $q\bar{q}$ in QCD
2. Pion as Nambu-Goldstone boson of the dynamically broken chiral symmetry (DCSB)

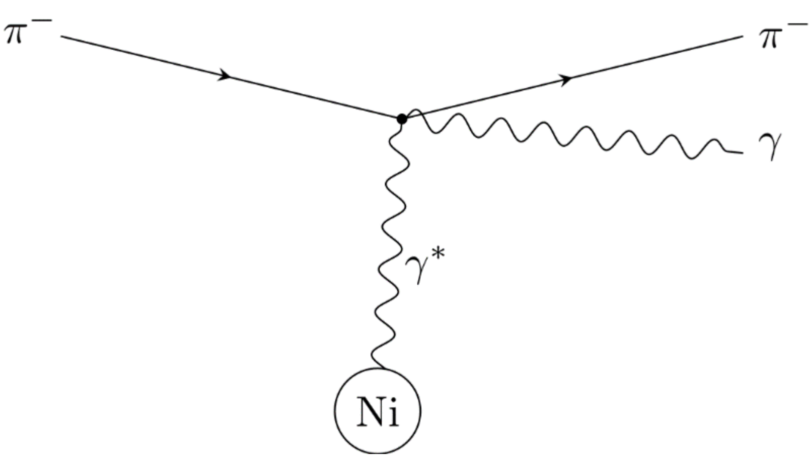
   $\Rightarrow$ DCSB for low mass of pion

Pion polarizability

- Classically: structure-dependent response to electromagnetic field (due to non-point-like)
- Well-known for atoms and molecules
- Measured on 10%-level for nucleons
- At quantum level: correction to Compton cross-section $\gamma\pi \longrightarrow \gamma\pi$
- ChPT (2-loop) prediction:

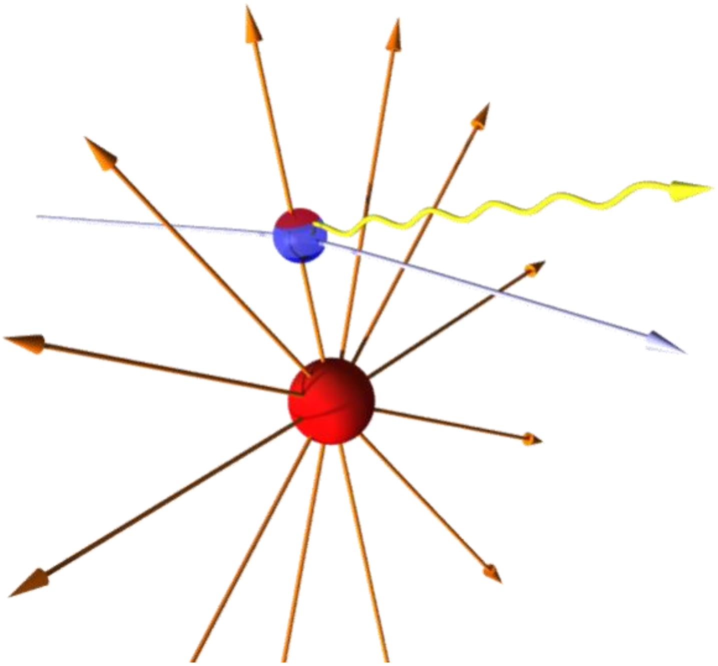
$$\begin{aligned} \alpha_\pi &= 2.93 \pm 0.5 \\ \beta_\pi &= -2.77 \pm 0.5 \end{aligned}$$





Primakoff reactions

- Idea dates back to Henry Primakoff ("photon target")
- Photon is provided by the strong Coulomb field of a nucleus (typical field strength at $d = 5R_{Ni}$: $E \approx 300\ \mathrm{kV/fm}$
- Coulomb field of nucleus as a source of quasi-real ($P_\gamma^2 \ll m_\pi^2$) photons
- Large impact parameters (ultra-peripheral scattering)



Weizsäcker-Williams approximation

- Coulomb field of relativistic charge ≈ flux of quasi-real photons:

Form factor

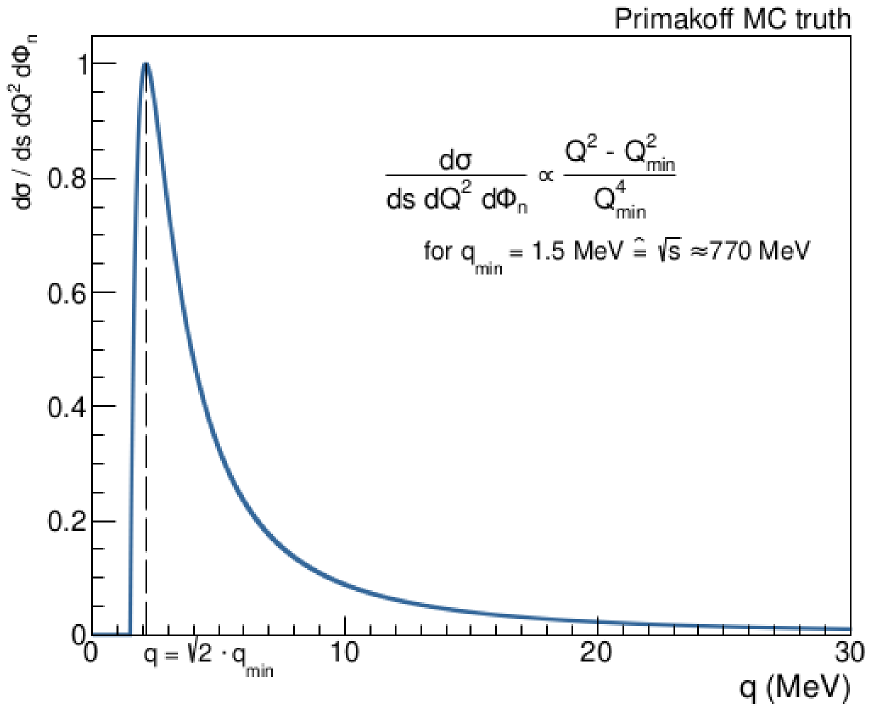
$$\frac{\mathrm{d}\sigma}{\mathrm{d}s\,\mathrm{d}Q^2\,\mathrm{d}\Phi_n} = \underbrace{\frac{Z^2\alpha}{\pi(s-m_\pi^2)} F^2(Q^2) \frac{Q^2 - Q^2_{\mathrm{min}}}{Q^4}}_{\text{Flux of quasi-real photons}} \cdot \underbrace{\frac{\mathrm{d}\sigma_{\pi\gamma\to X}}{\mathrm{d}\Phi_n}}_{\text{Cross-section of reaction}}$$

(assuming 1-photon exchange) Flux of quasi-real photons Cross-section of reaction

Weizsäcker-Williams approximation

- Coulomb field of relativistic charge ≈ flux of quasi-real photons:

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

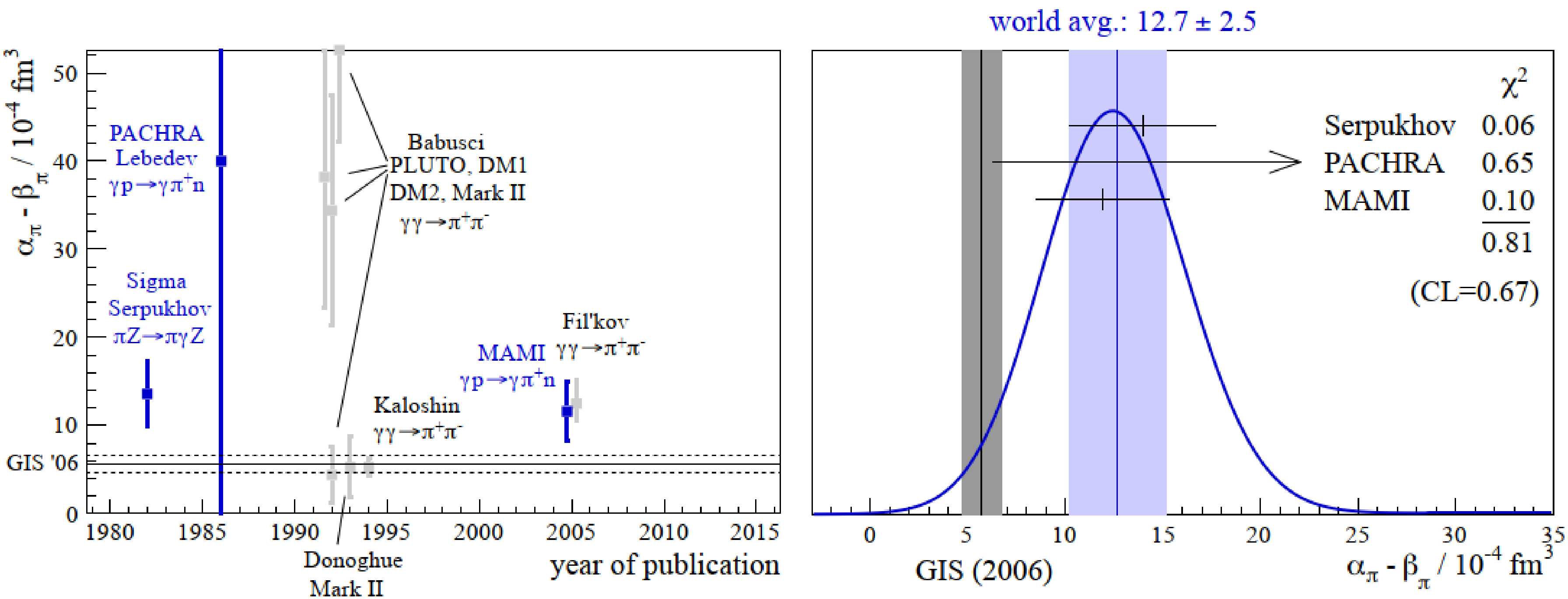


- Particles scatter off equivalent photons
- Peak at tiny momentum transfers $Q^2 \approx 10^{-5}\mathrm{GeV}^2/c^2$

General requirements for Primakoff

- Fixed target setup with nuclear target (Z-dependence of WW approximation)
- Good q^2-resolution to separate Coulomb processes (Primakoff) from other processes (strong processes)
- Neutral particles in final state $\longrightarrow$ calorimetry with good position/energy resolution for good q^2-resolution.
- Beam and final state particle ID
- Selection of target material and beam energy to improve the separation of Primakoff events from background

World data before COMPASS

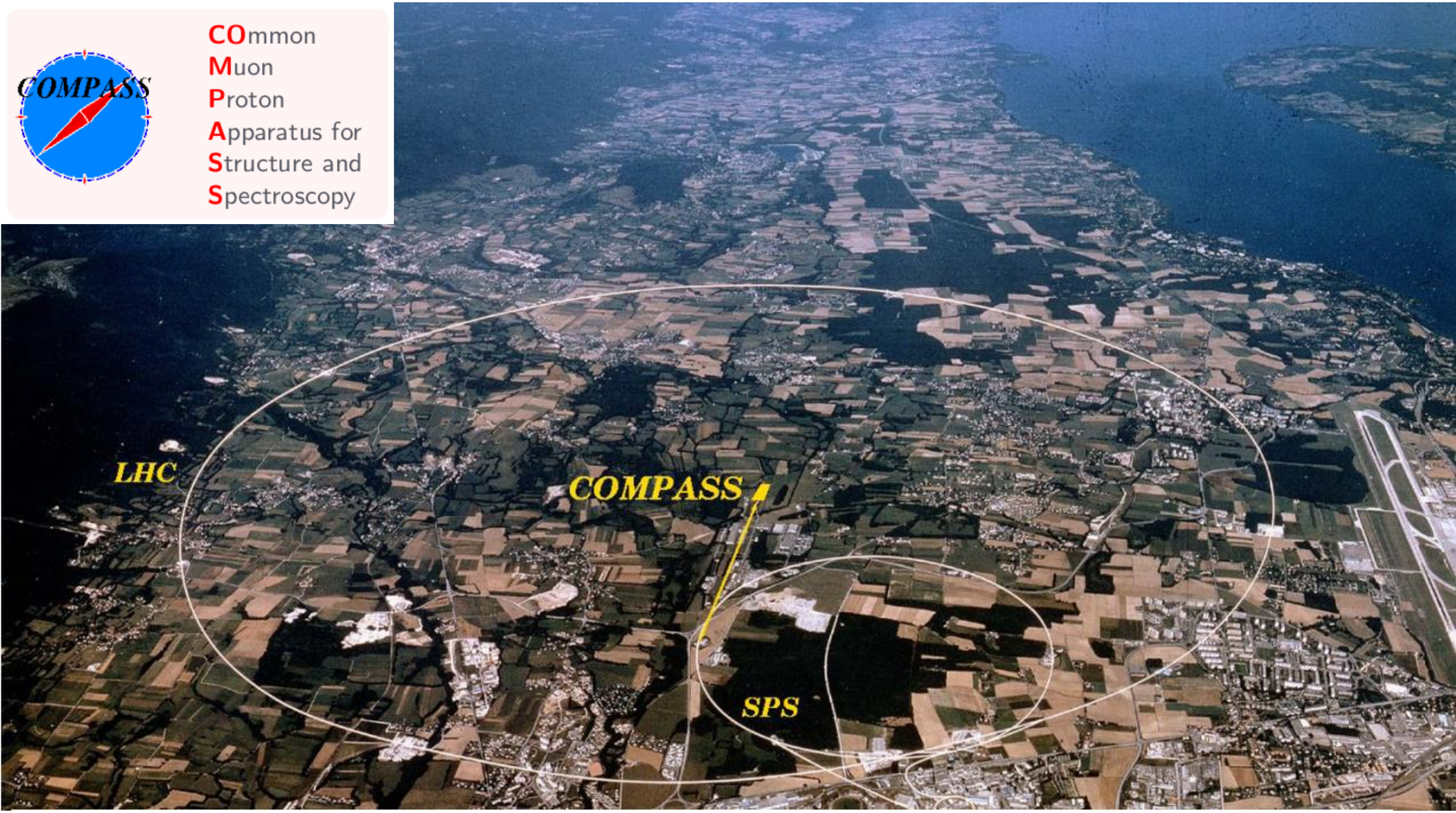


GIS'06: ChPT prediction, Gasser, Ivanov, Sainio, NPB745 (2006), plots: T. Nagel, PhD

Fil'kov analysis objected by Pasquini, Drechsel, Scherer PRC81, 029802 (2010)

COMPASS overview

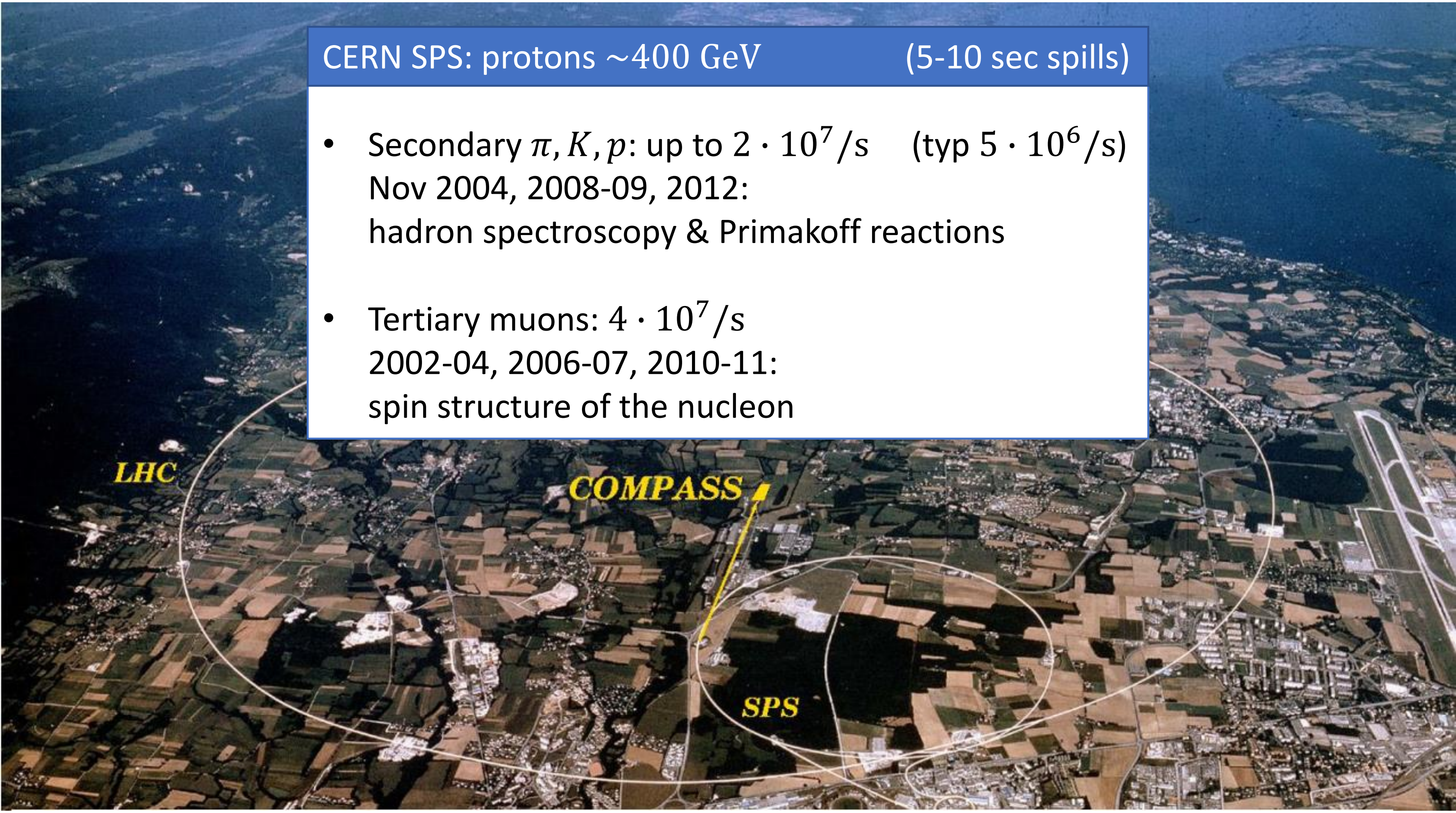
COmmon
Muon
Proton
Apparatus for
Structure and
Spectroscopy



COMPASS overview

CERN SPS: protons ~ 400 GeV (5-10 sec spills)

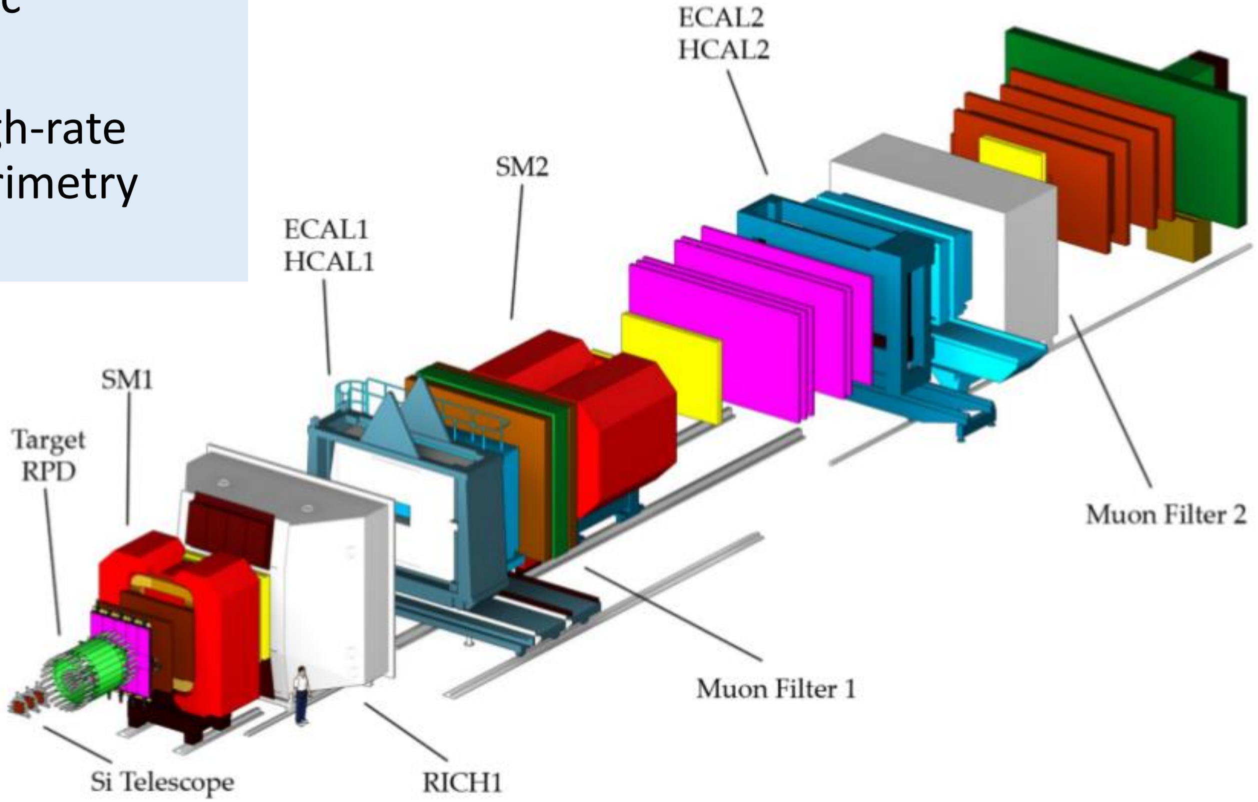
- Secondary π, K, p: up to $2 \cdot 10^7/s$ (typ $5 \cdot 10^6/s$)
  Nov 2004, 2008-09, 2012:
  hadron spectroscopy & Primakoff reactions
- Tertiary muons: $4 \cdot 10^7/s$
  2002-04, 2006-07, 2010-11:
  spin structure of the nucleon



Experimental setup

Fixed target experiment

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



Setup in 2009

Experimental setup

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- two stage magnetic spectrometer
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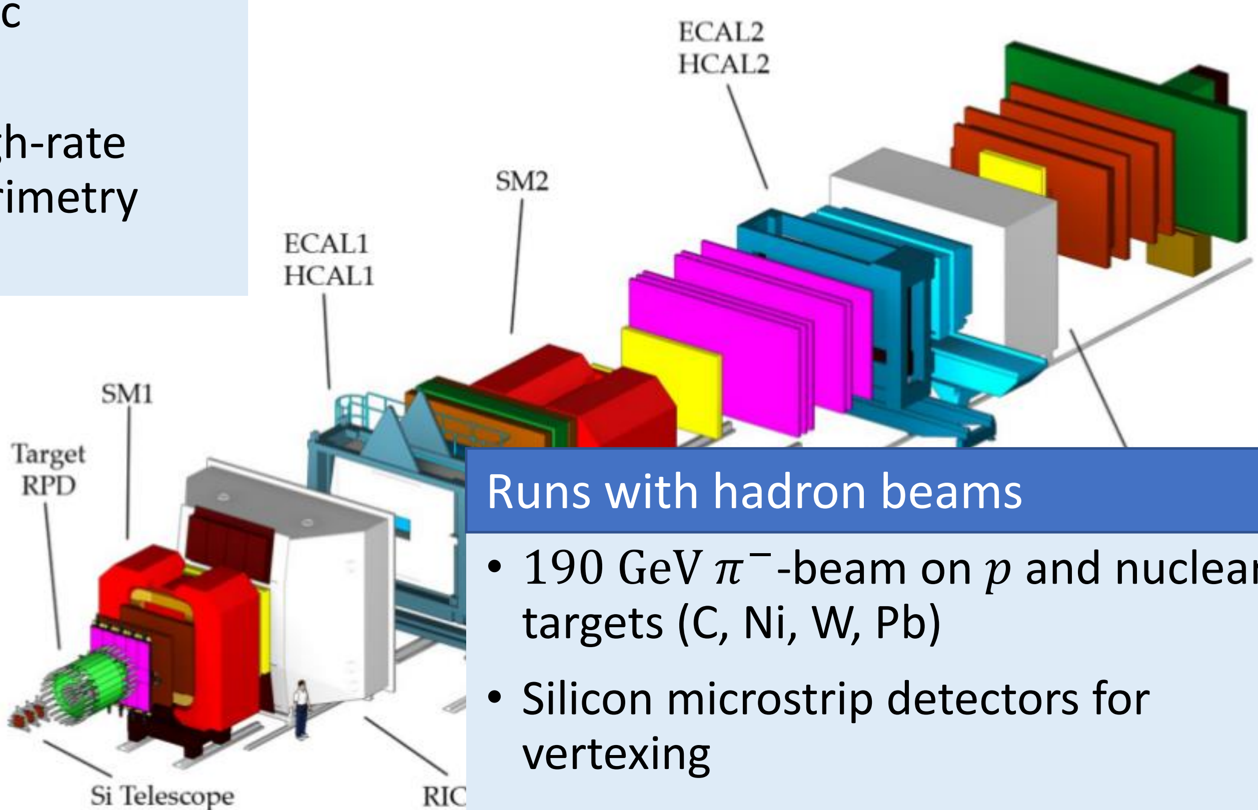


Setup in 2009

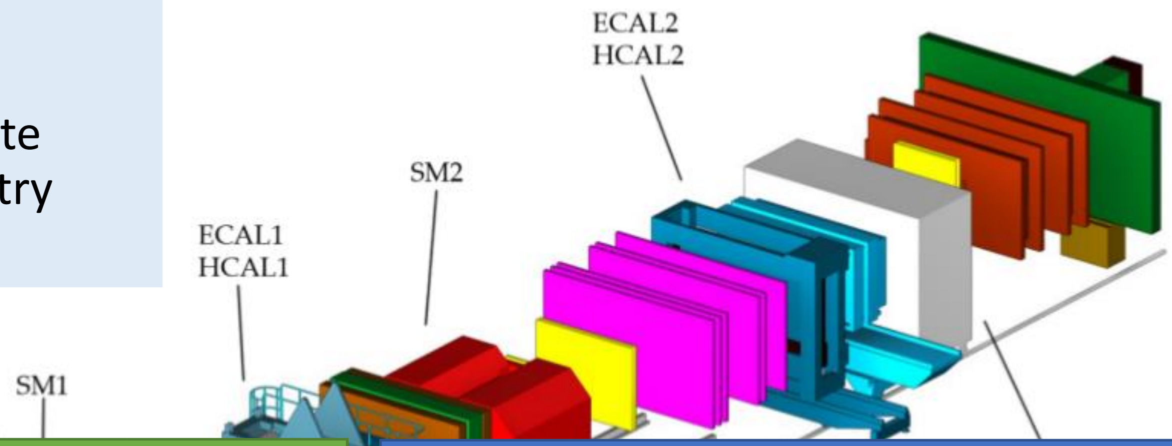
Runs with hadron beams

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

Experimental setup

Fixed target experiment

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



Access to $\pi + \gamma$ reactions:

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

Runs with hadron beams

- 190 GeV π^--beam on p and nuclear targets (C, Ni, W, Pb)
- Silicon microstrip detectors for vertexing
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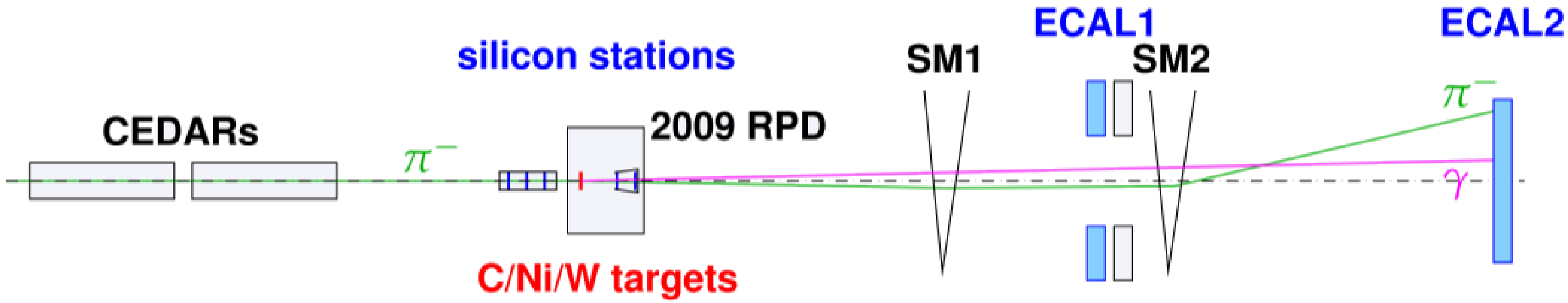
Measurement principle



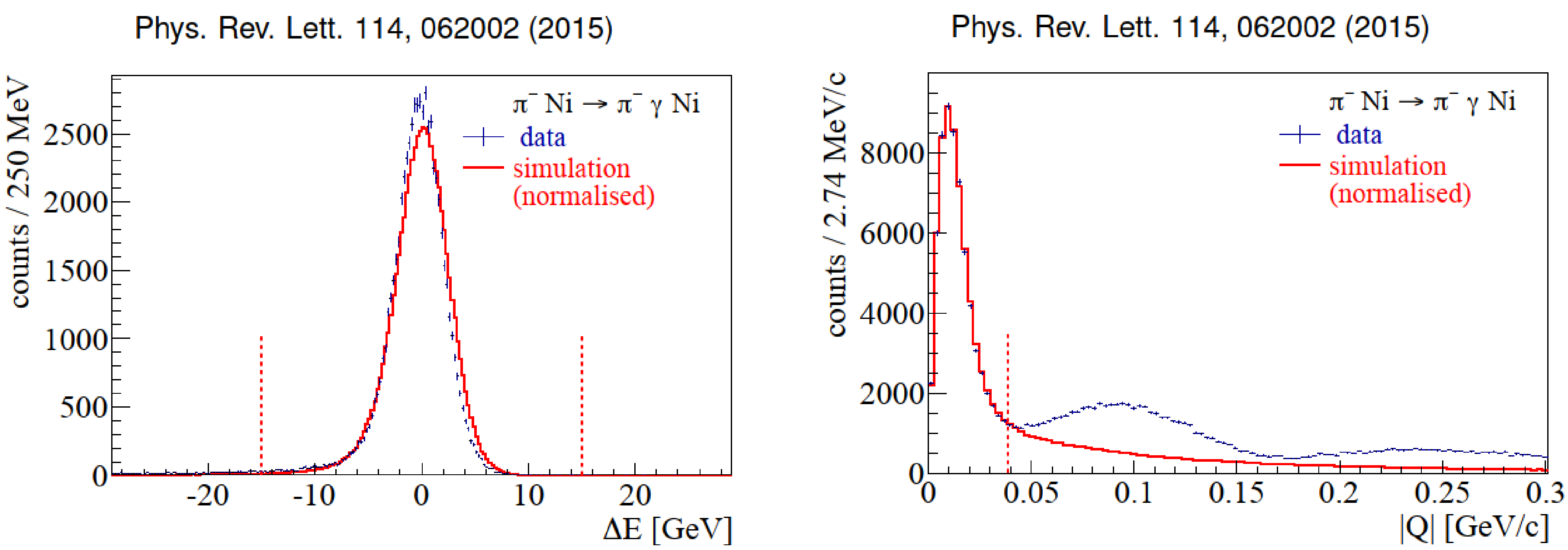
- 190 GeV negative hadron beam: $96.8\%\ \pi^-, 2.4\%\ K^-, 0.8\%\ \bar{p}$
- Beam particle identification by Cherenkov detectors
- 4mm Ni target disk ($\approx 25\%\ X_0$)
- Measure scattered π^- and produced photons (number of photons depends on final state)
- Select exclusive events at very low Q^2
- For absolute cross-section measurements: Luminosity

  Luminosity determination via free Kaon decays

$$(K^- \longrightarrow \pi^-\pi^0 \text{ or } K^- \longrightarrow \pi^-\pi^0\pi^0)$$

Extracting the pion polarizability

- Identify exclusive reactions $\gamma\pi \longrightarrow \gamma\pi$ at smallest momentum transfer $Q^2 < 0.0015\ \mathrm{GeV}^2/c^2$



Extracting the pion polarizability

- Identify exclusive reactions $\gamma\pi \longrightarrow \gamma\pi$ at smallest momentum transfer $Q^2 < 0.001\ \mathrm{GeV}^2/c^2$

- Assuming $\alpha_\pi + \beta_\pi = 0$, from the cross-section

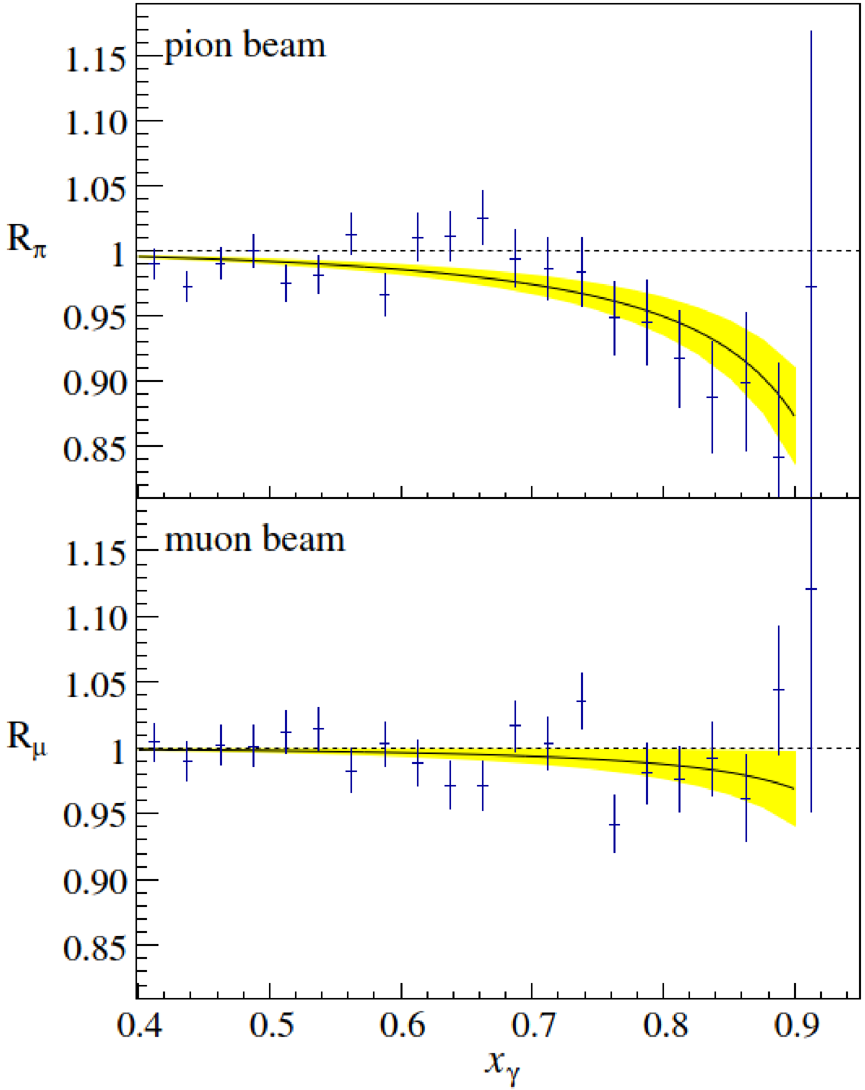
$$R = \frac{\sigma(x_\gamma)}{\sigma_{\alpha_\pi=0}(x_\gamma)} = \frac{N_{meas}(x_\gamma)}{N_{sim}(x_\gamma)} = 1 - \frac{3}{2} \cdot \frac{m_\pi^3}{\alpha} \cdot \frac{x_\gamma^2}{1-x_\gamma} \alpha_\pi$$

  can be derived, depending on $x_\gamma = E_{\gamma(\mathrm{lab})}/E_{\mathrm{beam}}$

- Control systematics by reaction:

$$\mu\gamma \longrightarrow \mu\gamma$$

Result for the pion polarizability



$\boldsymbol{\alpha_\pi} = (\,2.0 \pm 0.6_{\text{stat}}\,) \times 10^{-4}\,\text{fm}^3$

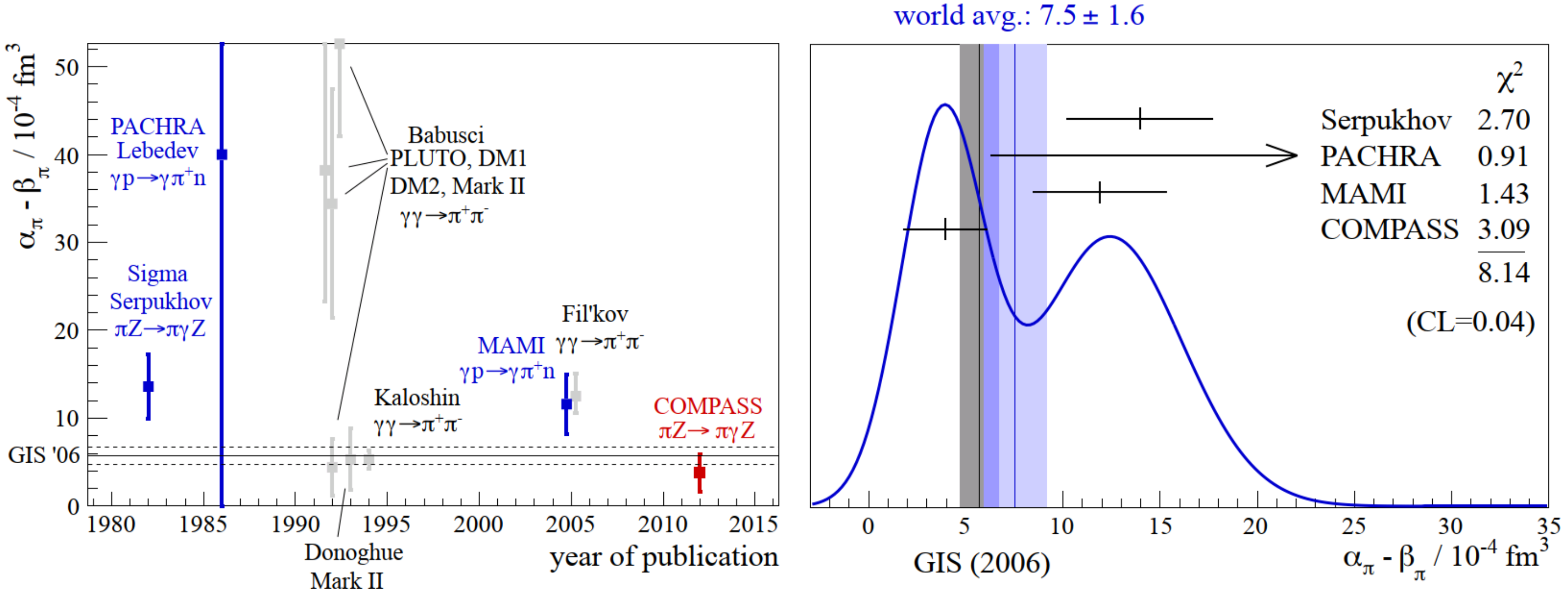
(assuming $\alpha_\pi = -\beta_\pi$)

"false polarisability" from muon data:

$(\,0.5 \pm 0.5_{\text{stat}}\,) \times 10^{-4}\,\text{fm}^3$

Phys. Rev. Lett. 114, 062002 (2015)

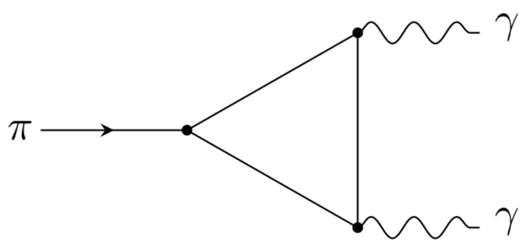
World data including COMPASS



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

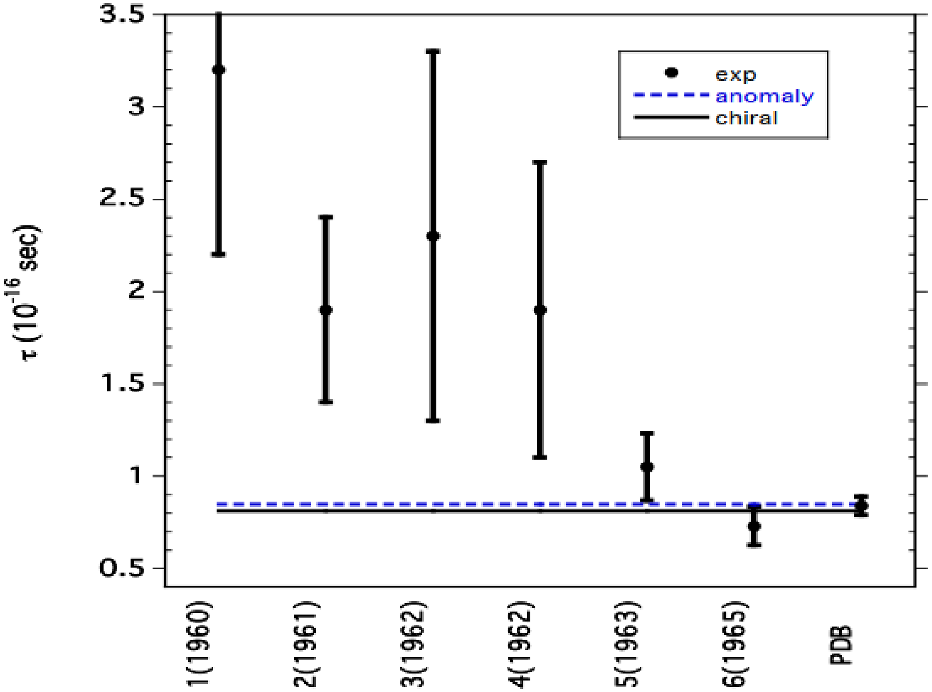
Discovery of the Chiral Anomaly

- Early 60ies: Partially Conserved Axial Current (PCAC): $\tau_{PCAC}(\pi^0) \approx 0.95 \cdot 10^{-13}\text{s}$
- 1960 - 1963: First definitive, high energy measurements of the π^0-lifetime . E.g. with an 18 GeV proton beam at CERN: $\tau(\pi^0) = (0.95 \pm 0.15) \cdot 10^{-16}\text{s}^*$
- Adler, Bell, Jackiw, Bardeen 1969: calculation of triangle diagram



$$\tau_{anom}(\pi^0) \approx 0.838 \cdot 10^{-16}\text{s}$$

$\Rightarrow$ non-conservation of the axial current



A. M. Bernstein and Barry R. Holstein Rev. Mod. Phys. 85, 49 (2013)

* von Dardel, C., et al., 1963, Phys. Lett.4, 51

Chiral Anomaly

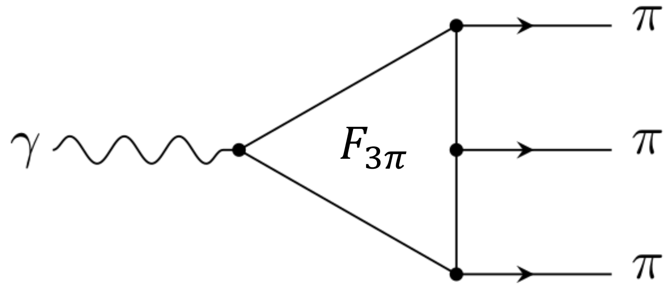
- $F_{3\pi}$: Direct coupling of γ to 3π - process proceeds primarily via the chiral anomaly => one of the most definitive tests of low-energy QCD
- Soft pion limit: $A(\gamma \rightarrow \pi\pi\pi) = 0$ (conservation of angular momentum)
- ChPT prediction in chiral limit:

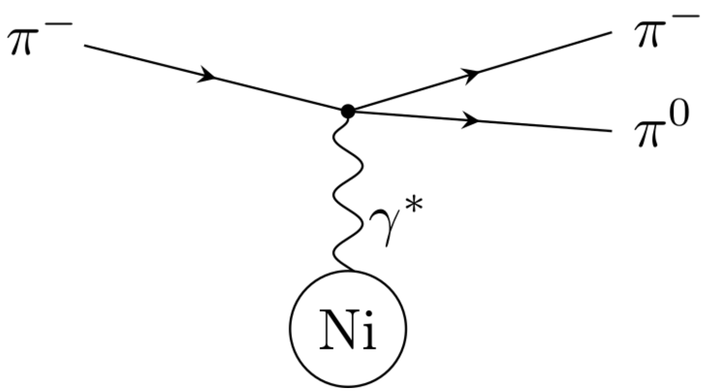
$$F_{3\pi} = \frac{eN_C}{12\pi^2 F_\pi^3} = (9.78 \pm 0.05)\,\mathrm{GeV}^{-3}$$

- ChPT corrections due to small masses of quarks:

$$\rightarrow F_{3\pi} = F_{3\pi}(s,t,u)$$

  (s, t, u-dependence)
- Accessible in Primakoff reactions via: $\pi^-\gamma^* \rightarrow \pi^-\pi^0$





Radiative width of ρ-meson

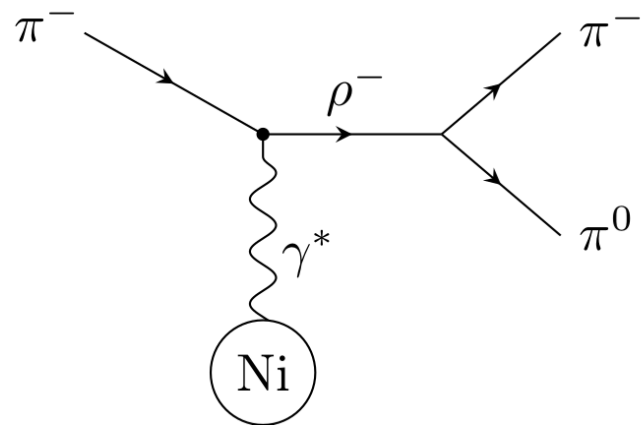
- Pomeron exchange forbidden by g-Parity $\Rightarrow$ clean Primakoff signal (except ω/π-exchange)

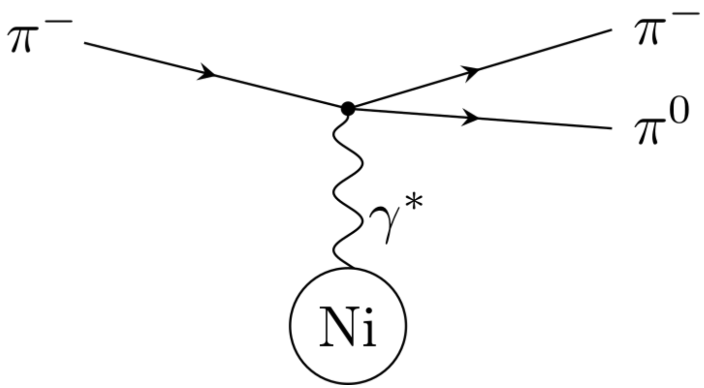
- Coherent background of $\rho(770)$-production (strong and electro-magnetic)

  Interference between Chiral Anomaly and $\rho(770) \Rightarrow$ possibility of extraction of radiative width of ρ-meson $\Gamma_{(\rho\to\pi\gamma)}/\Gamma_{\text{tot}} \approx 4.5 \cdot 10^{-4}$

- $m_{\pi^-\pi^0}$ distribution shows contribution from $\rho(770)$.

  At kinematic threshold: non-resonant behaviour but chiral anomaly





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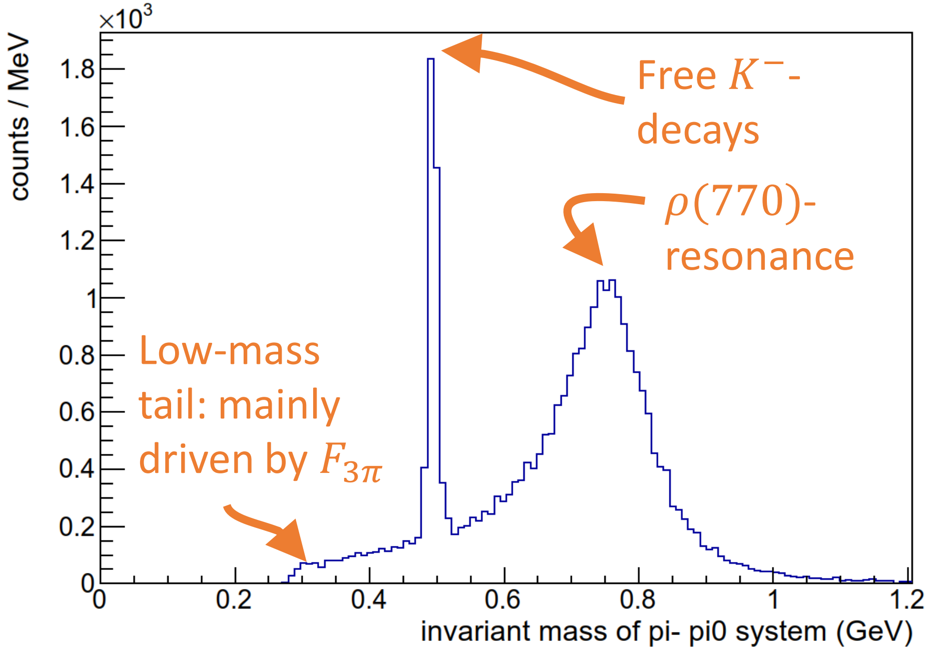


Previous measurements

Chiral Anomaly:

Ametller, L. *et al.* Phys.Rev. D64 (2001) 094009 from Serpukhov experiments:

- Using extrapolation & em corr: $F_{3\pi} = (10.7 \pm 1.2)\ \mathrm{GeV}^{-3}$
- Compare to prediction from ChPT and Chiral Anomaly: $F_{3\pi} = (9.78 \pm 0.05)\ \mathrm{GeV}^{-3}$

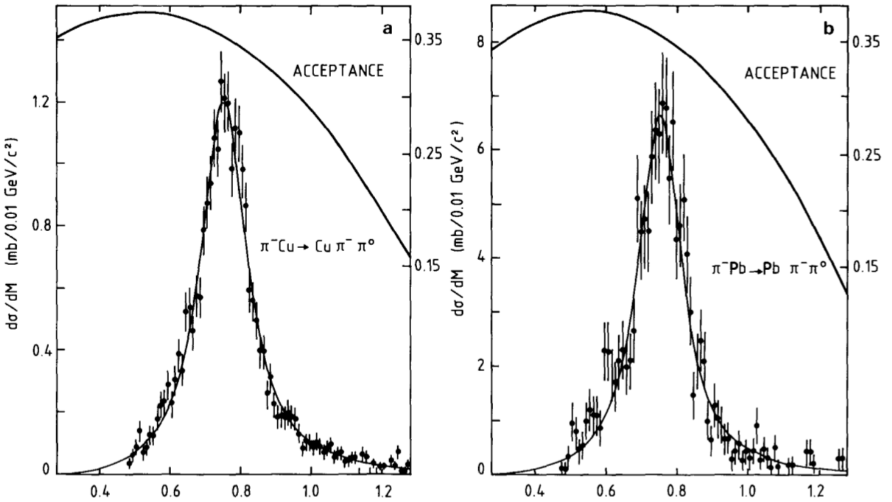
Precision of previous measurements: $\mathcal{O}(10\%)$

$\Rightarrow$ More precise experimental determination desirable

Radiative width of ρ-meson:

Capraro, L. *et al.* Nucl.Phys. B288 (1987) 659-680 at CERN (SPS):

- From fit of $\mathrm{d}\sigma/\mathrm{d}t$ for ρ production: $\Gamma(\rho \to \pi\gamma) = (81 \pm 4 \pm 4)\ \mathrm{keV}$



Final State: $\pi^-\pi^0$

- Dispersive framework to deduce $F_{3\pi}$ from a fit to the full data set up to 1.2 GeV including the $\rho(770)$-resonance:

  Hoferichter, Kubis, and Sakkas
  Phys. Rev. D 86, 116009 (2012)

$$\sigma(s) = \frac{(s-4M_\pi^2)^{\frac{3}{2}}(s-M_\pi^2)}{1024\pi\sqrt{s}} \int_{-1}^{1} \mathrm{d}z\,(1-z^2)|\mathcal{F}(s,t,u)|^2$$

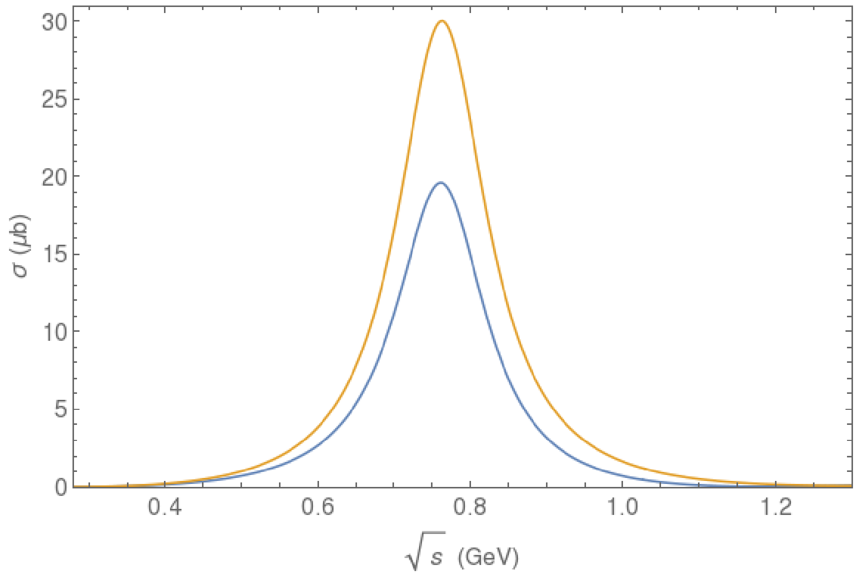
with $\mathcal{F}(s,t,u) = C_2^{(1)}F_2^{(1)}(s,t,u) + C_2^{(2)}F_2^{(2)}(s,t,u)$

Two fit parameters

Determinable iteratively

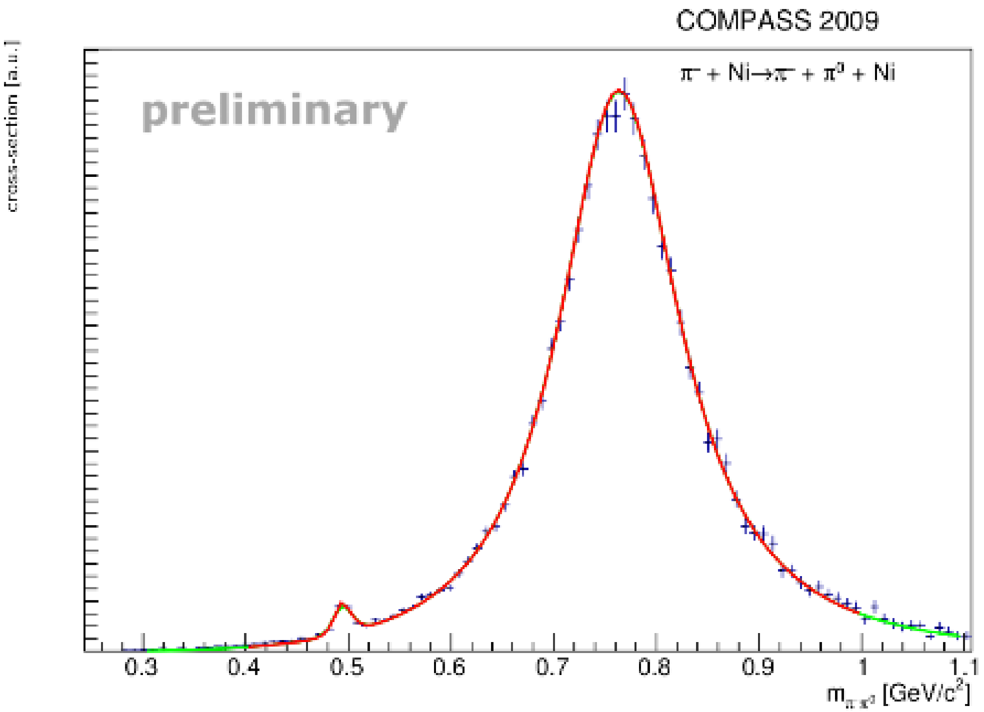
$C_2^{(1)} = 11.1\ \mathrm{GeV}^{-3};\ C_2^{(2)} = 25.5\ \mathrm{GeV}^{-5}$

$C_2^{(1)} = 9.4\ \mathrm{GeV}^{-3};\ C_2^{(2)} = 20.7\ \mathrm{GeV}^{-5}$



Fit to the data

- Fit of the final normalized and acceptance-corrected mass-distribution with subtracted background



- Fit of the theoretical model in good agreement with data
- Statistical uncertainty $\mathcal{O}(1\%)$
- Result to be expected within the next months

Summary and Outlook

- ChPT and DCSB well established in QCD (pion in as Nambu-Goldstone boson)
- Measurement of the pion polarizability at COMPASS
  - Via Primakoff process, COMPASS has determined

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

  - Most precise experimental determination
  - Systematic control via $\mu\gamma \longrightarrow \mu\gamma$
- Measurement of the Chiral Anomaly via $F_{3\pi}$ and the radiative width of the ρ-meson upcoming
  - Using the Primakoff reaction $\pi^-\gamma^* \to \pi^-\pi^0$ and a full fit to the $m_{\pi^-\pi^0}$-spectrum up to 1.2 GeV from a dispersive model
  - Statistical uncertainties expected to be $\mathcal{O}(1\%)$
- Other related channels at COMPASS:

$$\left.\begin{array}{r} \pi^-\gamma^* \to \pi^-\pi^0\pi^0 \\ \pi^-\gamma^* \to \pi^-\pi^-\pi^+ \end{array}\right\} \text{chiral tree and loop predictions available}$$