Measuring the radiative width of the $\rho(770)$ and testing the chiral anomaly at COMPASS

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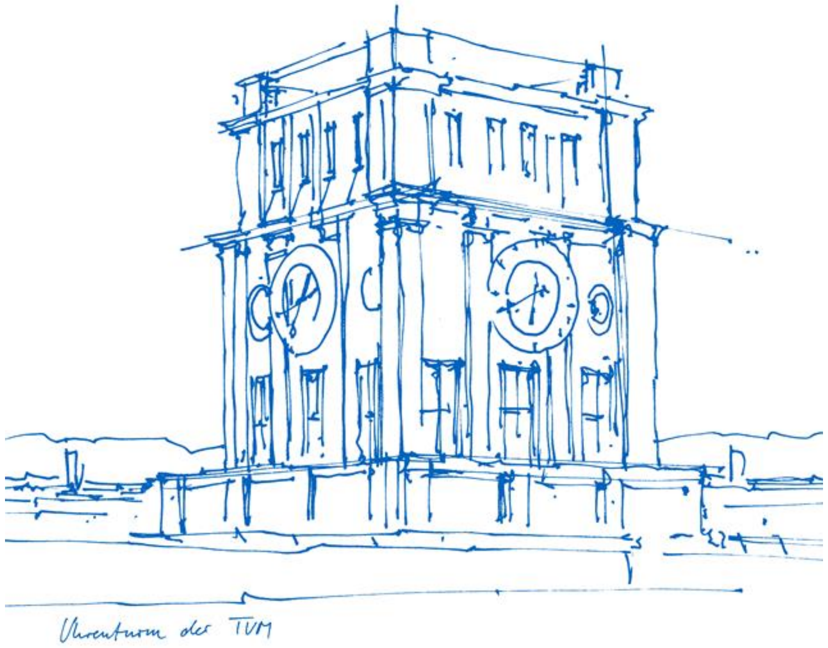
13th workshop on e^+e^- Collisions from Phi to Psi – August 18, 2022



Quantum Chromodynamics

- Quantum Chromodynamics (QCD) as true theory of strong interaction
- Lagrange density of QCD:

$$\mathscr{L}_{QCD} = \sum_{\substack{f=\{u,d,\\ c,s,t,b\}}} \sum_{i,j=1}^{N_c} \overline{\psi}_{f,j}(i\gamma^\mu D^j_{i,\mu} - m_f \delta^j_i)\psi^{f,i} - \frac{1}{4}\sum_{a=1}^{N_c^2-1} G^a_{\mu\nu} G^{\mu\nu}_a$$

- Flavor symmetries?

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Flavor symmetry breaking term ($m_u \neq m_d \neq m_s$)

- Flavor symmetries? -> only approximate symmetries

  - $\boldsymbol{SU(2)}$: $m_u \approx m_d$ -> isospin symmetry
  - $\boldsymbol{SU(3)}$: $m_u \approx m_d \approx m_s$ -> the eightfold way

Chiral symmetry of QCD

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- Approximate flavor symmetries in chiral limit ($m_u = m_d = m_s = 0$):

$SU(3)_R \times SU(3)_L$

- Left- and right-handed fields decouple for massless particles
- Chirality can directly be translated to parity of particle
  → mass-degenerate doublets of states with opposite parity

Chiral symmetry of QCD

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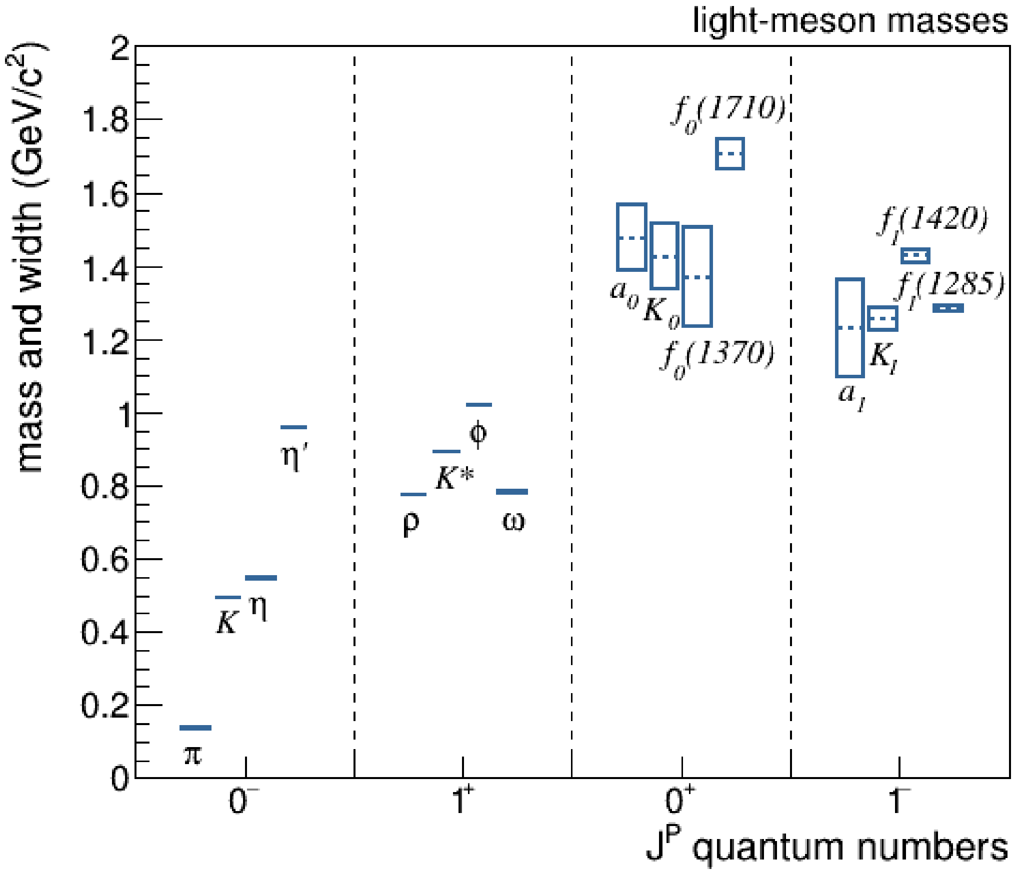
  → mass-degenerate doublets of states with opposite parity
- Why does chiral symmetry not manifest itself in the spectrum (in contrast to isospin and eightful way)?
  → Nambu-Goldstone mechanism for spontaneous/dynamic breakdown of chiral symmetry



Dynamic breaking of chiral symmetry

Spontaneous symmetry breaking

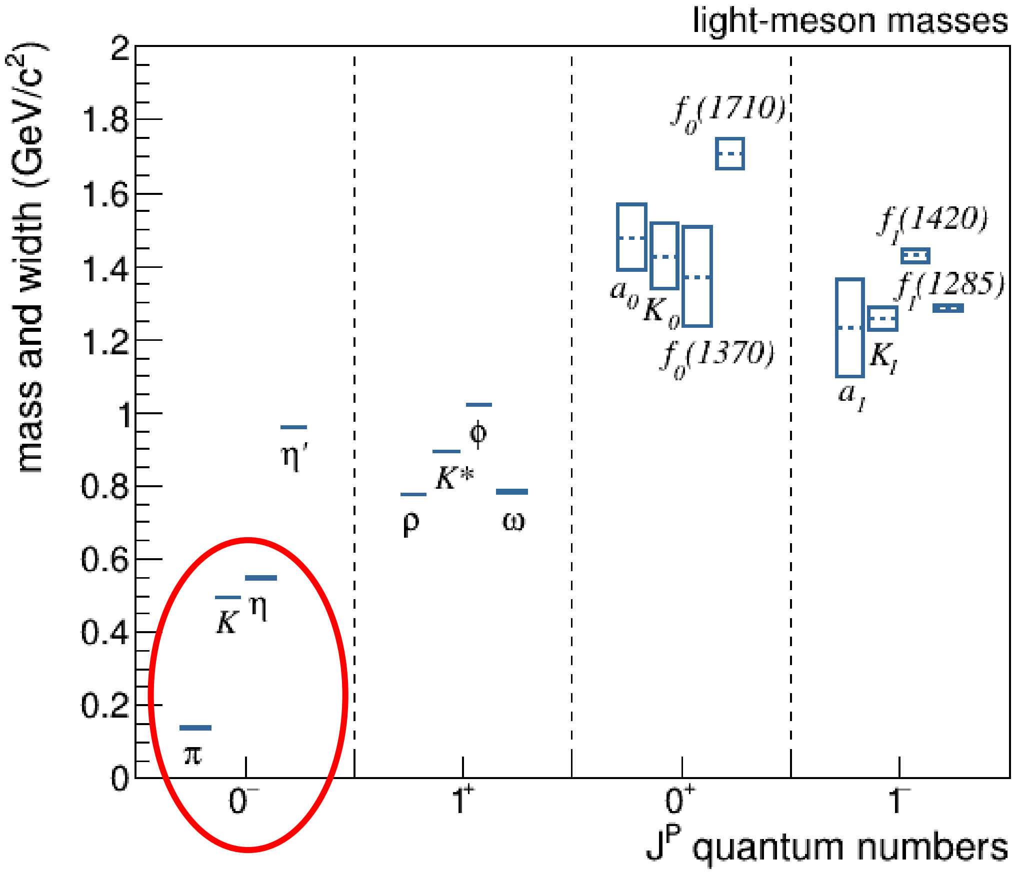
⇒ Eight massless, spinless Goldstone bosons

$$(\pi^{\pm}, \pi^{0}, K^{\pm}, K^{0}, \bar{K}^{0}, \eta)$$

⇒ Explicit breaking of chiral symmetry due to the small quark masses -> Goldstone bosons acquire mass

⇒ $SU(3)_R \times SU(3)_L \rightarrow SU(3)_V$

⇒ Chiral Perturbation Theory: effective Lagrangian with power-counting scheme as low-energy theory for QCD makes use of chiral symmetry



(almost) massless Goldstone bosons

The chiral anomaly

- Lagrange density of QCD:

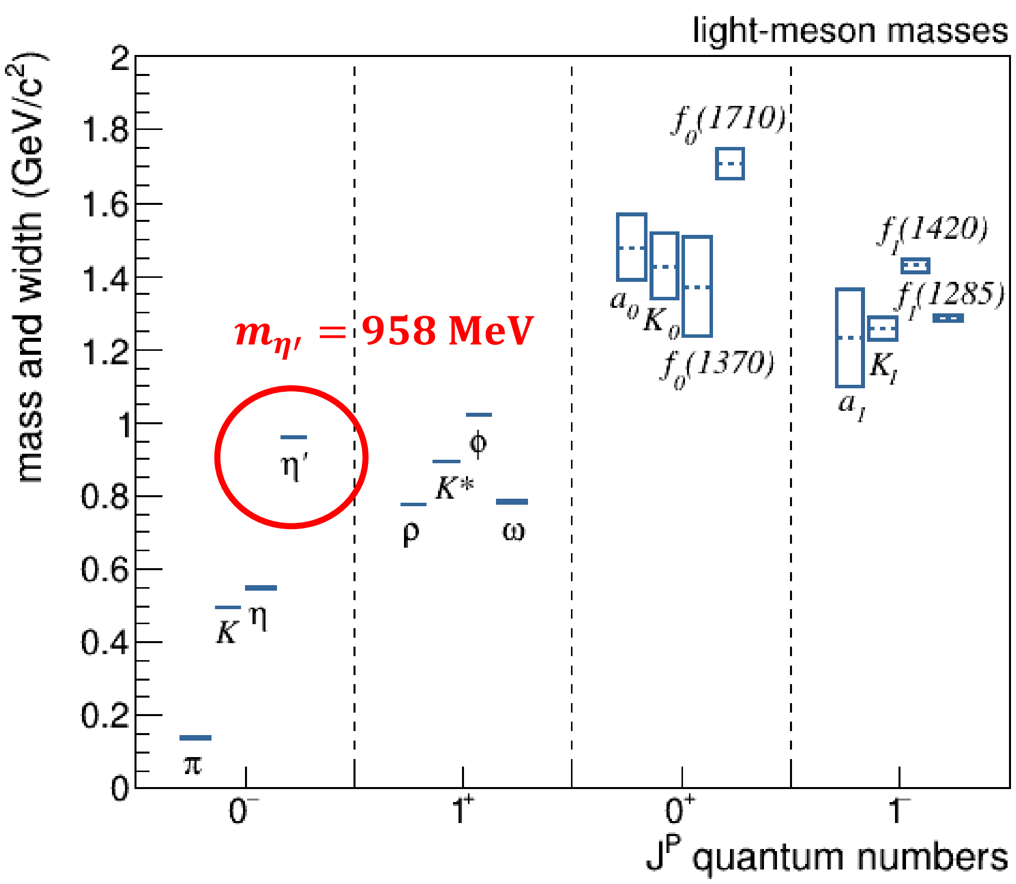
$$\mathcal{L}_{QCD} = \sum_{\substack{f=\{u,d,\\ c,s,t,b\}}} \sum_{i,j=1}^{N_c} \overline{\psi}_{f,j}(i\gamma^{\mu}D^{j}_{i,\mu} - m_f\delta^{j}_{i})\psi^{f,i} - \frac{1}{4}\sum_{a=1}^{N_c^2-1} G^{a}_{\mu\nu}G^{\mu\nu}_{a}$$

- Features *axial* $U(1)$-symmetry in chiral limit:

$$\psi(x) \rightarrow e^{i\theta\gamma_5}\psi(x)$$

- No ninth “unnaturally light” meson

- **Anomalous** symmetry breaking: symmetry of the Lagrangian does not lead to conserved Noether currents
- **Anomaly:** Symmetry of classical Lagrangian violated at quantum level



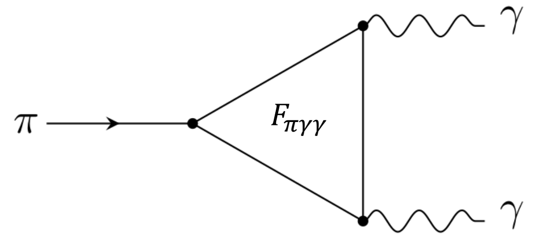
Wess-Zumino-Witten term

- Chiral anomaly in ChPT taken into account by Wess-Zumino-Witten (WZW) term
- Describes coupling of odd number of Goldstone bosons:

$SU(2)$ flavor	$SU(3)$ flavor
$\pi^0 \to \gamma\gamma$	$K^+K^- \to \pi^+\pi^-\pi^0$
$\gamma\pi^- \to \pi^-\pi^0$	$\eta \to \pi^+\pi^-\gamma$
$\pi^+ \to e^+\nu_e\gamma$	$K^+ \to \pi^+\pi^-e^+\nu_e$
etc.	etc.

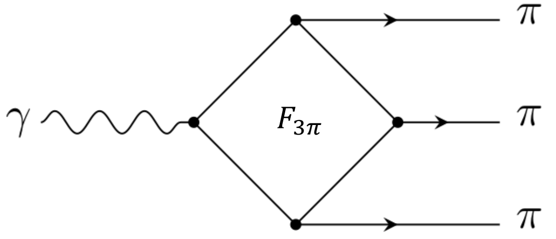
- Effective theory -> pion decay constant measured from leptonic decays of the charged pion $(\pi^\pm \to \mu^\pm + \nu)$

$F_{\pi\gamma\gamma}$



- $F_{\pi\gamma\gamma} = \frac{e^2 N_C}{12\pi^2 F_\pi} = 2.52 \cdot 10^{-2}\mathrm{GeV}^{-1}$

$F_{3\pi}$



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

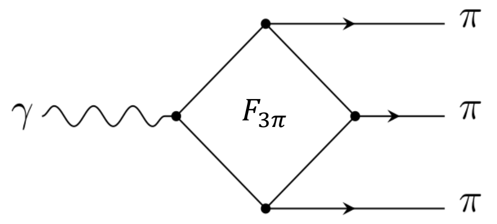
Testing the chiral anomaly - $F_{3\pi}$

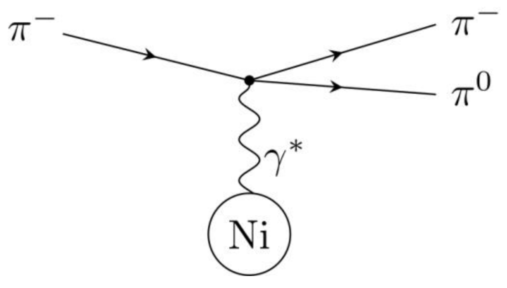
- $F_{3\pi}$: Direct coupling of γ to 3π - process proceeds primarily via the chiral anomaly => one of the most definitive tests of low-energy QCD
- Accessible in Primakoff reactions via: $\pi^-\gamma^* \to \pi^-\pi^0$
- Challenges:

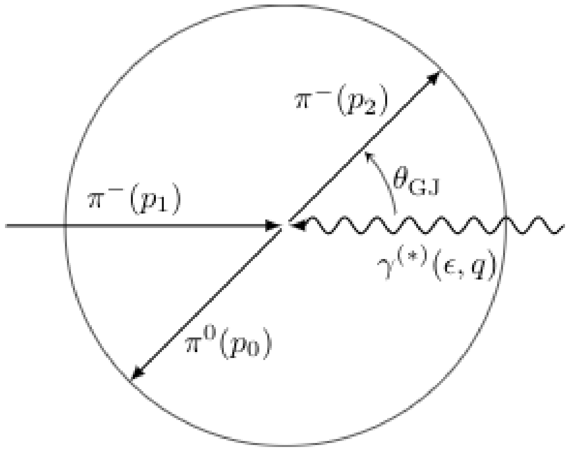
  1. Explicit chiral symmetry breaking:

     $$F_{3\pi} = \frac{eN_C}{12\pi^2 F_\pi^3} = (9.78 \pm 0.05)\mathrm{GeV}^{-3} = F(s = t = u = 0)$$

  2. Coherent background from $\rho(770)$ production

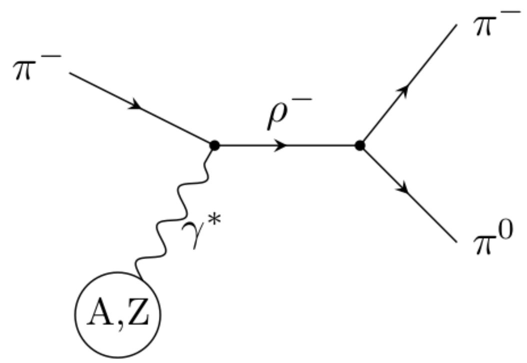


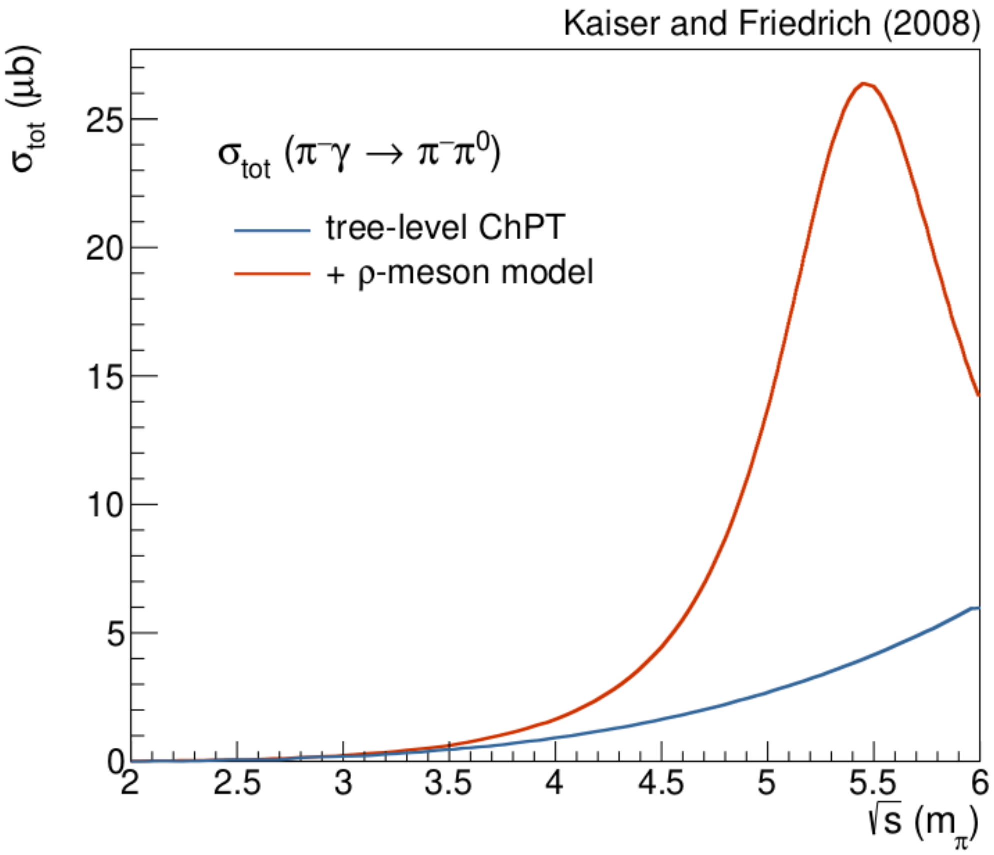




Coherent background from $\rho(770)$ meson

- Background from $\rho(770)$ production (strong and electromagnetic)



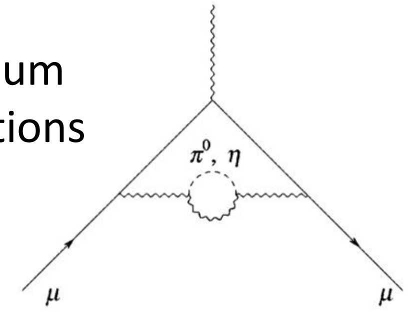


Kaiser, N. and Friedrich, J. M., EPJA 36 no. 2, (2008) 181–188

⇒ possibility of extraction of radiative width of ρ-meson:

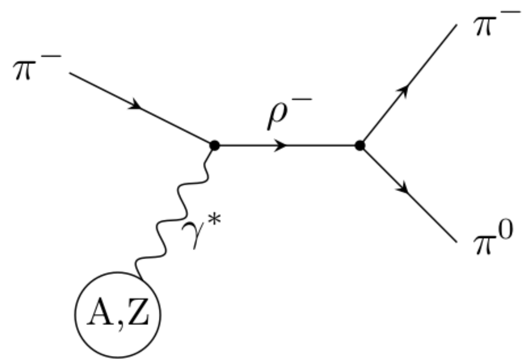
$$\Gamma_{(\rho\to\pi\gamma)}/\Gamma_{\text{tot}} \approx 4.5 \cdot 10^{-4}$$

⇒ contributes to hadronic vacuum polarization terms in calculations of $g-2$ of e and μ



Radiative width of $\rho(770)$ meson

- Background from $\rho(770)$ production (strong and electromagnetic)



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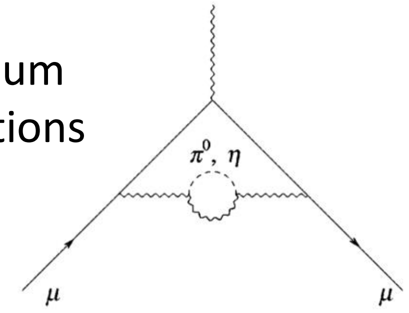
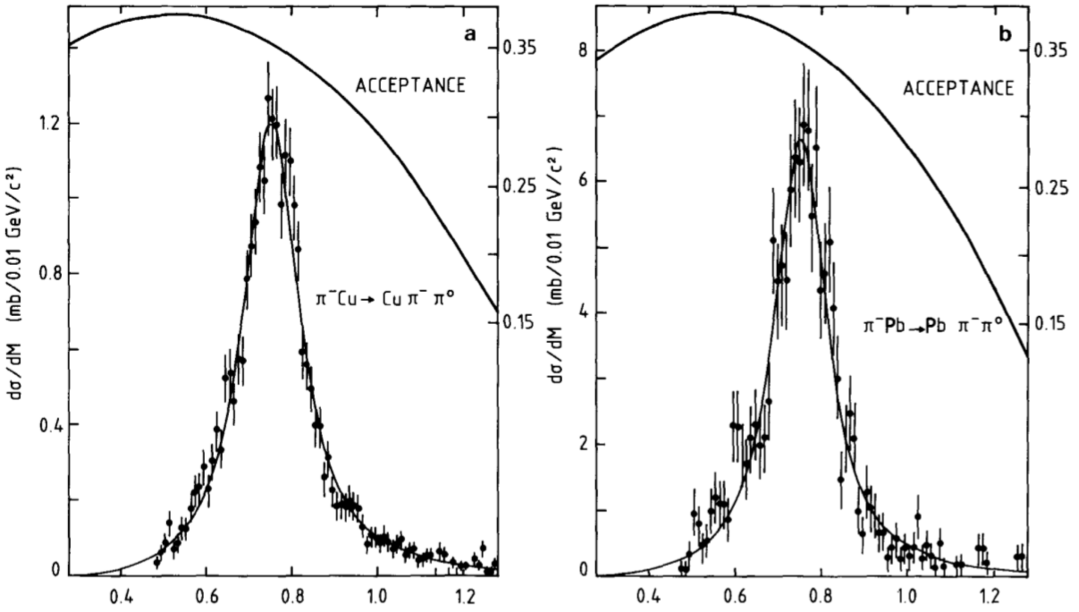


Caprararo, L. *et al.* NPB 288 (1987) 659-680 at CERN (SPS):

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



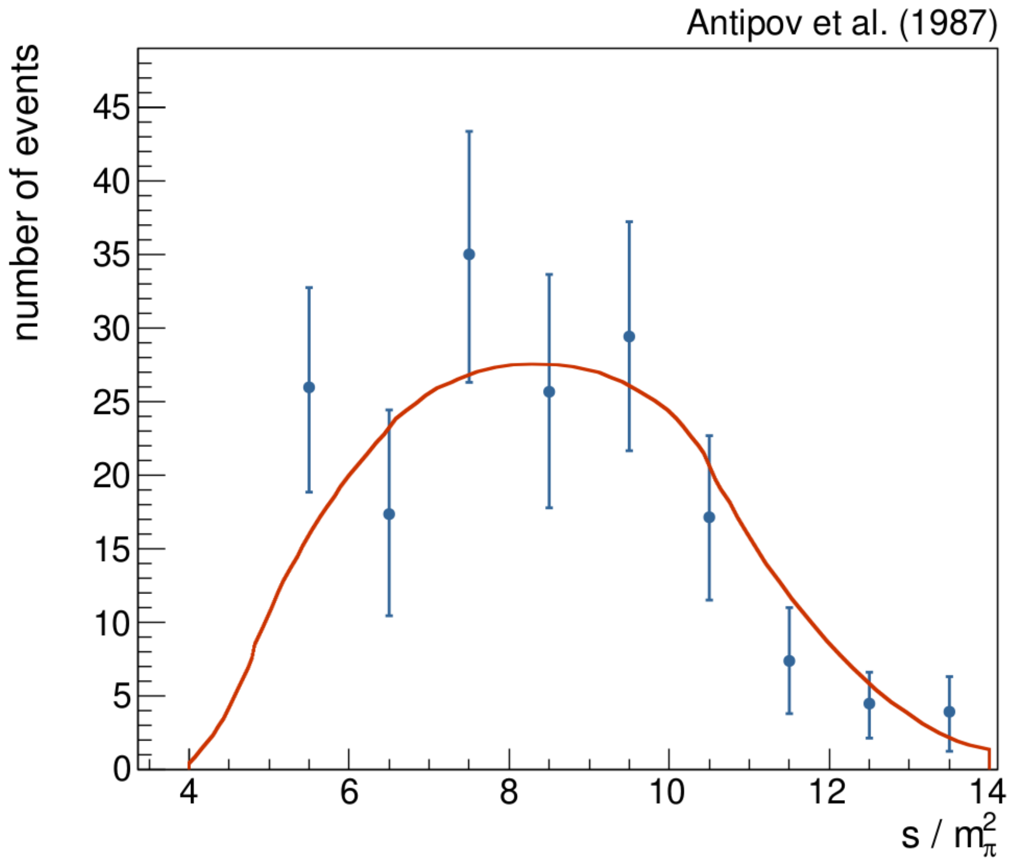
Previous measurement of $F_{3\pi}$

[Antipov, Y. *et al.* PRD 36 (1987) 101103] using data from Serpukhov experiments

Problem of explicit chiral symmetry breaking:

As previously noted, the value $F^{3\pi}$ is supposed to vary slowly with $s,t,q^2 \ll m_\rho{}^2$ so that $F^{3\pi} \simeq F^{3\pi}(0)$.

$\Rightarrow \bar{F}_{3\pi} = (12.9 \pm 0.9 \pm 0.5)\ \mathrm{GeV}^{-3}$



Previous measurement of $F_{3\pi}$ - Reanalysis

Ametller, L. *et al.* PRD 64 (2001) 094009

PHYSICAL REVIEW D, VOLUME 64, 094009

Electromagnetic corrections to $\gamma\pi^{\pm}\rightarrow\pi^{0}\pi^{\pm}$

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(Received 11 July 2001; published 3 October 2001)

The amplitude for the anomalous transitions $\gamma\pi^{\pm}\rightarrow\pi^{0}\pi^{\pm}$ is analyzed within chiral perturbation theory including electromagnetic interactions. The presence of a t-channel one-photon exchange contribution induces sizable $\mathcal{O}(e^2)$ corrections which enhance the cross section in the threshold region and bring the theoretical prediction into agreement with available data. In the case of the crossed reaction $\gamma\pi^{0}\rightarrow\pi^{+}\pi^{-}$, the same contribution appears in the s channel and its effects are small.

DOI: 10.1103/PhysRevD.64.094009 PACS number(s): 12.39.Fe, 11.30.Rd, 13.60.Le, 13.75.−n

Reanalysis of Serpukhov data using chiral expansion:

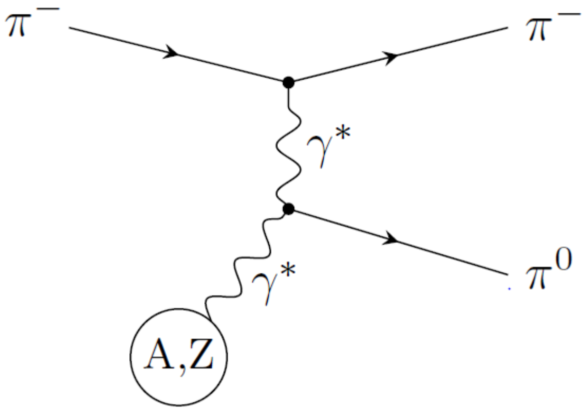
$$F_{3\pi}(s,t,u)=F_{3\pi}\left(f^{(0)}(s,t,u)+f^{(1)}(s,t,u)+f^{(2)}(s,t,u)+\ldots\right)$$

- Extrapolation using one loop and two loop corrections:

$$F_{3\pi}=(11.4\pm 1.3)\ \mathrm{GeV}^{-3}$$

Previous measurement of $F_{3\pi}$ - Reanalysis

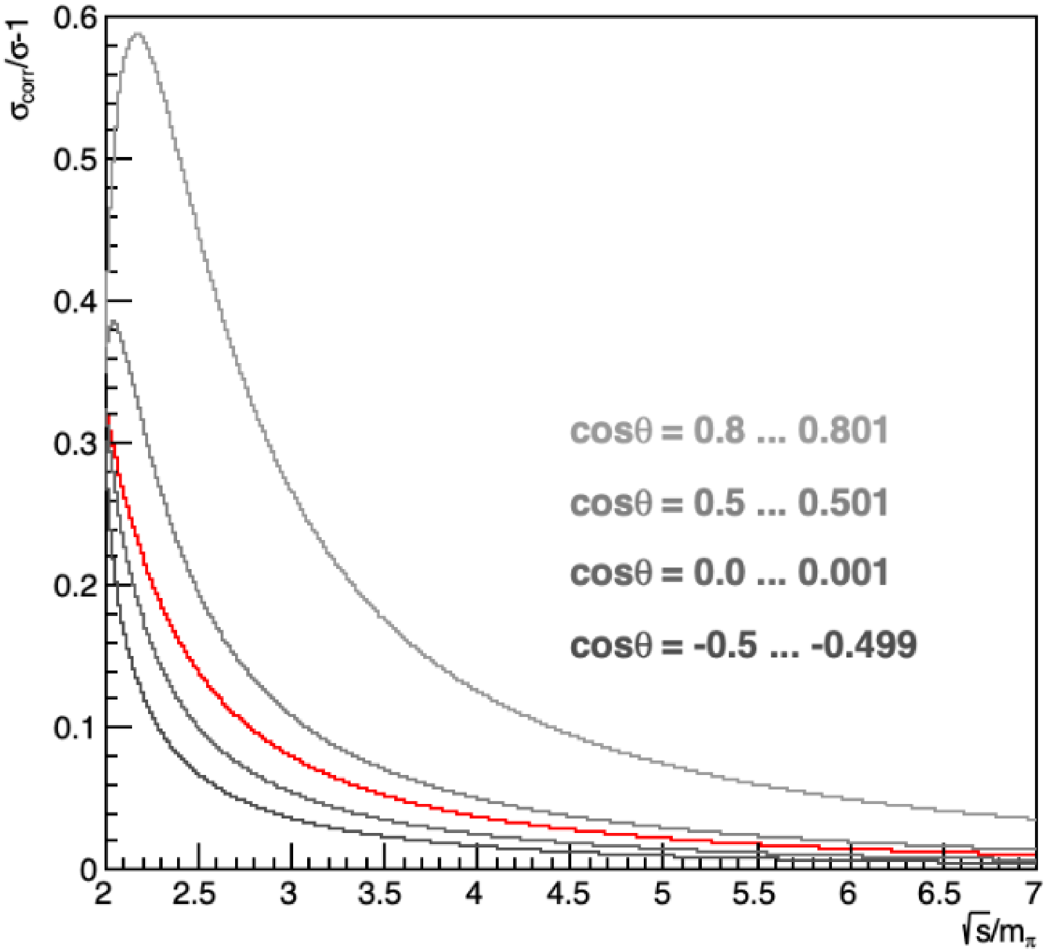
- Electro-magnetic corrections => significant contribution to $f^{(0)}(s,t,u)$ when isospin breaking effect are taken into account.



- Integrated correction amounts to 32% at threshold

$$\Longrightarrow F_{3\pi} = (10.7 \pm 1.2)\ \text{GeV}^{-3}$$

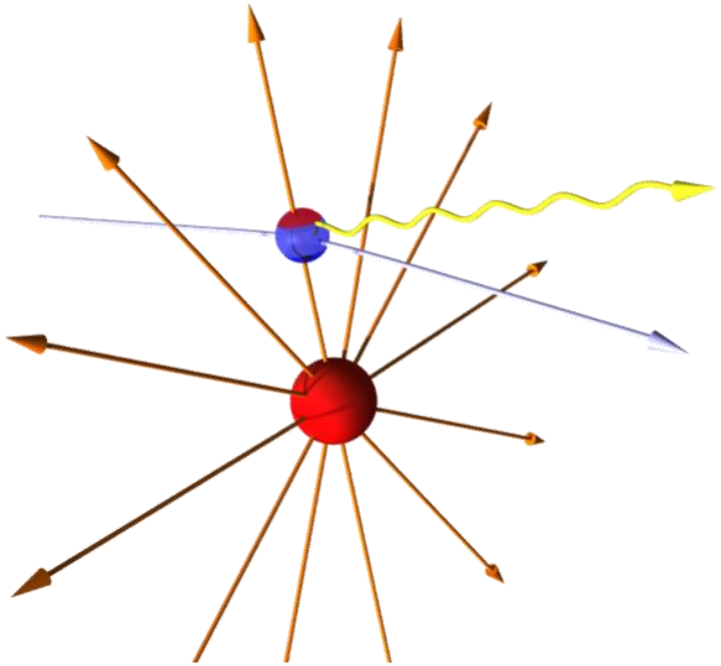
- Precision of previous measurements: $\mathcal{O}(10\%)$
  $\Rightarrow$ More precise experimental determination desirable



Ametller, L. *et al.* PRD 64 (2001) 094009

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 is a source of quasi-real ($P_\gamma^2 \ll m_\pi^2$) photons
- Large impact parameters (ultra-peripheral scattering)



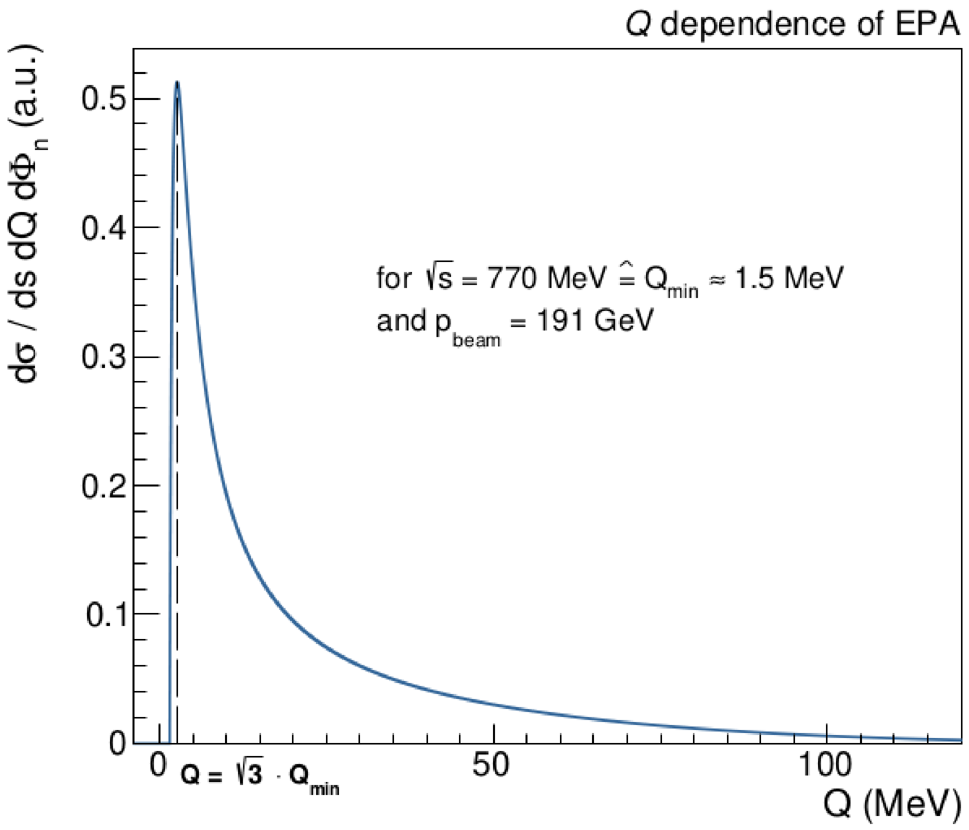
Weizsäcker-Williams approximation

- Coulomb field of relativistic charge ≈ flux of quasi-real photons
  Equivalent **p**hoton **a**pproximation (single-photon exchange)

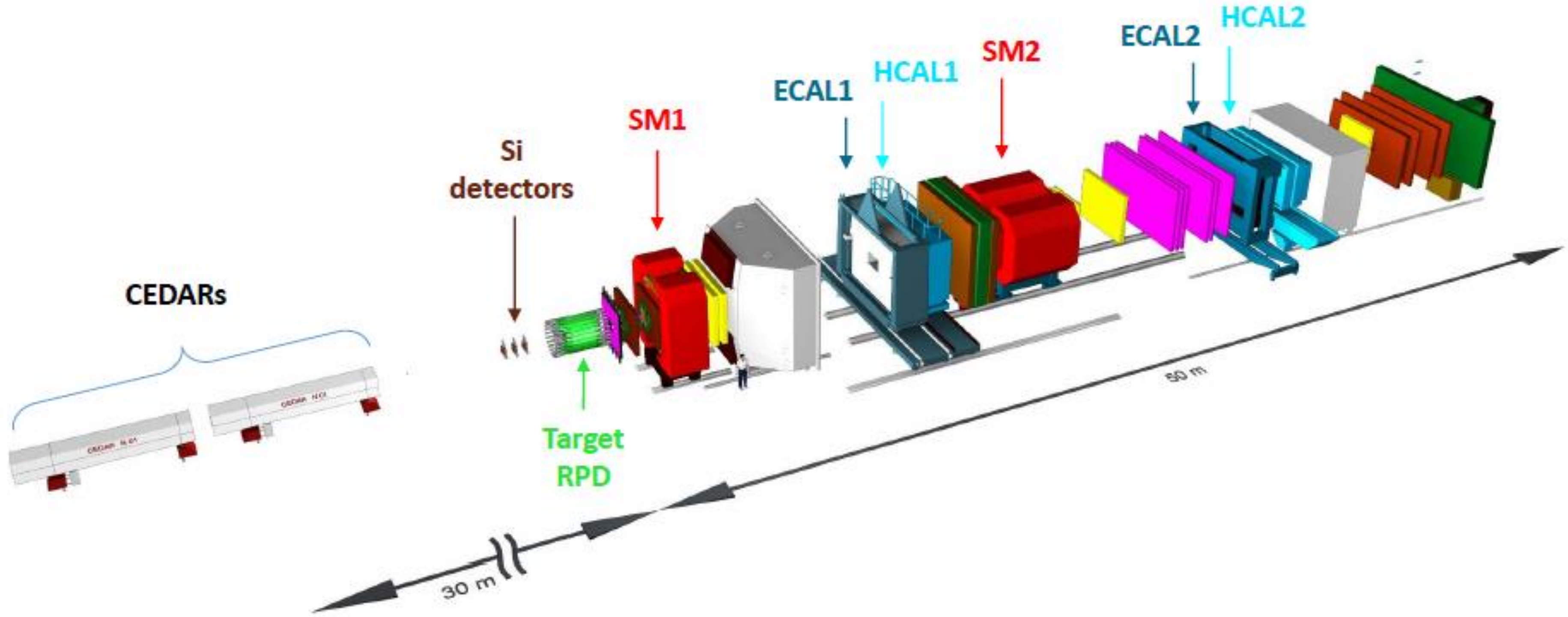
$$\frac{\mathrm{d}\sigma}{\mathrm{d}s\,\mathrm{d}Q^2\,\mathrm{d}\Phi_n} = \underbrace{\frac{Z^2\alpha}{\pi(s-m_\pi^2)}F^2(Q^2)\frac{Q^2-Q^2_{\mathrm{min}}}{Q^4}}_{\text{Flux of quasi-real photons}} \cdot \underbrace{\frac{\mathrm{d}\sigma_{\pi\gamma\to X}}{\mathrm{d}\Phi_n}}_{\pi\gamma \text{ scattering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

- Beam pions scatter off equivalent photons

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



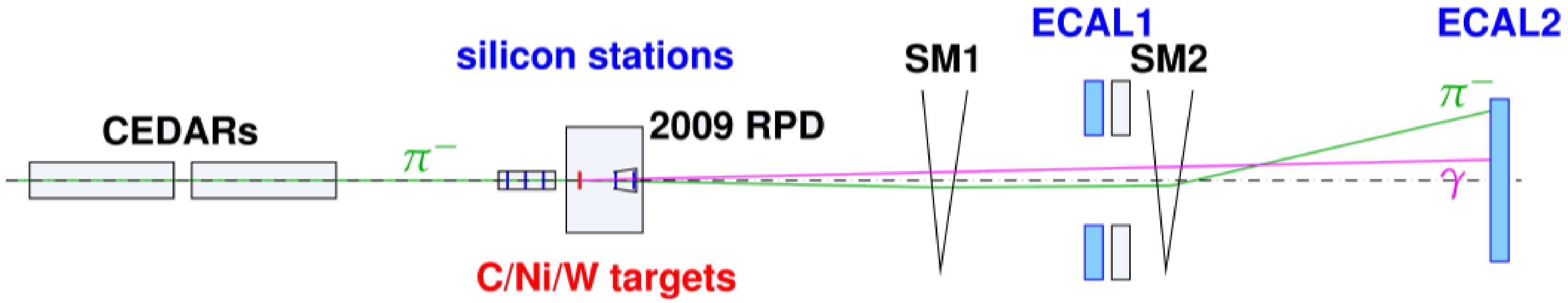
The COMPASS experiment at CERN



Abbon, P. *et al.* NIM A 779 (2014) 69–115

- 190 GeV negative hadron beam
- Beam PID
- Nuclear target(s): Ni and W
- Calorimetric trigger on neutrals
- Two stage spectrometer (LAS and SAS) with tracking and calorimeter

Principle of Measurement



- 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 $(\approx 25\%\ \ X/X_0)$
- 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 determination via free Kaon decays

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

- Dispersive framework to deduce $F_{3\pi}$ from a fit to the $\pi^-\pi^0$ mass distribution up to 1.0 GeV including the $\rho(770)$-resonance:

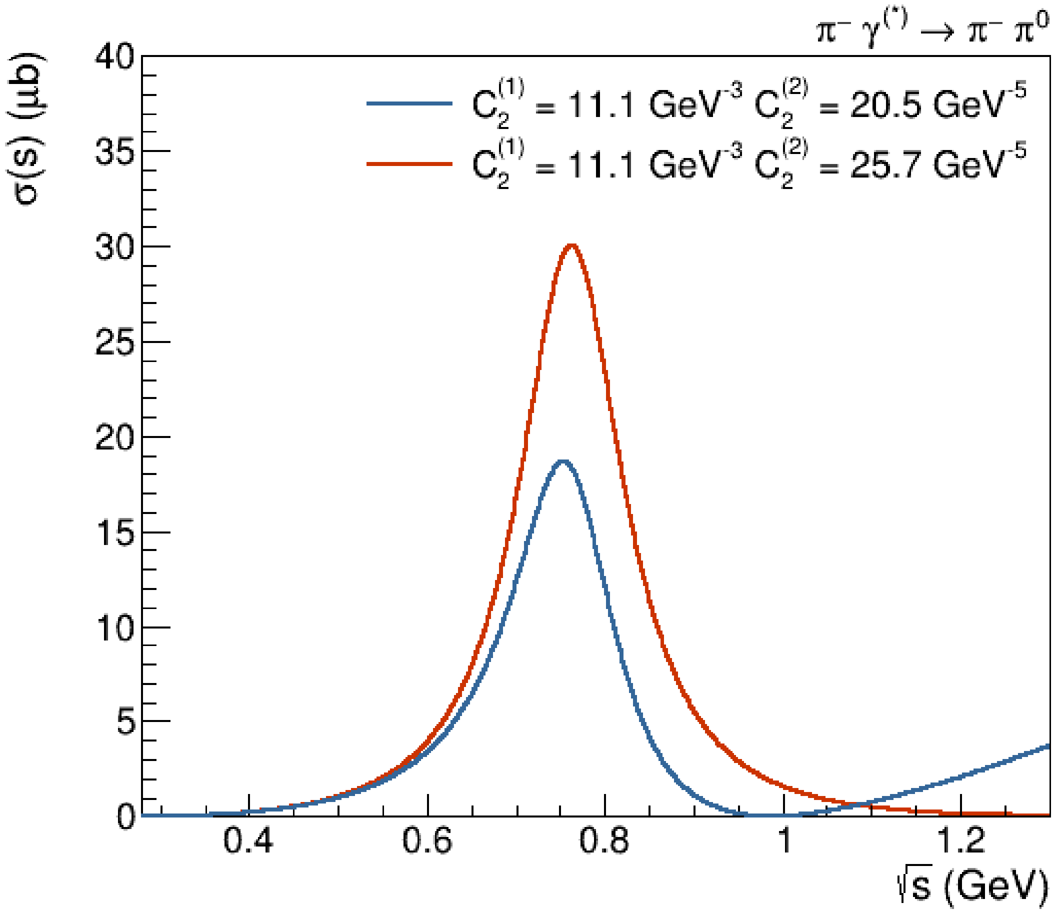
$$\sigma(s) = \frac{(s-4m_\pi^2)^{3/2}(s-m_\pi^2)}{1024\pi\sqrt{s}} \int_{-1}^{1} \mathrm{d}z(1-z^2)|\mathcal{F}(s,t,u)|^2$$

With

$$\mathcal{F}(s,t,u) = C_2^{(1)}\mathcal{F}_2^{(1)}(s,t,u) + C_2^{(2)}\mathcal{F}_2^{(2)}(s,t,u) - \frac{2e^2F_\pi^2F_{3\pi}}{t}$$

$C_2^{(1)}, C_2^{(2)}$: fit parameters

$\mathcal{F}_2^{(1)}(s,t,u)$, $\mathcal{F}_2^{(2)}(s,t,u)$: provided by theory colleagues (Kubis, Hoferichter)



M. Hoferichter, B. Kubis, and D. Sakkas, *PRD* **86** (2012) 116009

Luminosity determination

- Needed for absolute cross section measurement: effective integrated luminosity (DAQ dead time taken into account)

Effective luminosity: $L_{eff} = L \cdot (1 - \epsilon_{DAQ})$

- Luminosity can be determined via free decays of beam kaons in the beam:
  - Use CEDARs to tag kaons
  - Measure free decays where no material
  - Exclusive events with zero momentum transfer

$$N_K = \Phi_\pi \frac{n_K}{n_\pi} BR(K^- \rightarrow \pi^0 \pi^-)(1 - e^{-\frac{L}{\gamma c \tau}})\epsilon_K$$

Number of detected kaon decays (N_K)

Kaon/pion flux ratio ($\frac{n_K}{n_\pi}$)

Probability of kaon decaying in region with length L ($1 - e^{-\frac{L}{\gamma c \tau}}$)

Pion flux (Φ_π)

Branching ratio ($BR(K^- \rightarrow \pi^0 \pi^-)$)

Acceptance for kaon decays for particular final state (ϵ_K)

Kaon decay channels

Decay channel	Γ_i/Γ	Remark
$K^- \to \mu^- \bar{\nu}_\mu$	(63.56 ± 0.11) %	Does not deposit energy in ECAL2 (Primakoff-trigger)
$\boldsymbol{K^- \to \pi^- \pi^0}$	(20.67 ± 0.08) %	Similar systematics as Primakoff $\pi^- \to \pi^- \pi^0$ channel
$K^- \to \pi^- \pi^- \pi^+$	(5.583 ± 0.024) %	Does not deposit energy in ECAL2 (Primakoff-trigger)
$\boldsymbol{K^- \to e^- \pi^0 \bar{\nu}_e}$	(5.07 ± 0.08) %	Non exclusive, missing energy
$\boldsymbol{K^- \to \mu^- \pi^0 \bar{\nu}_\mu}$	(3.352 ± 0.033) %	Non exclusive, missing energy
$\boldsymbol{K^- \to \pi^- \pi^0 \pi^0}$	(1.760 ± 0.023) %	Used to determine $\pi/_K$-ratio in the beam
others	$< 10^{-4}$	No significant contribution to background expected

- Different channels may form background for each other, but give possibility to crosscheck results

Used for luminosity determination

Considered as background process

Effective integrated luminosity

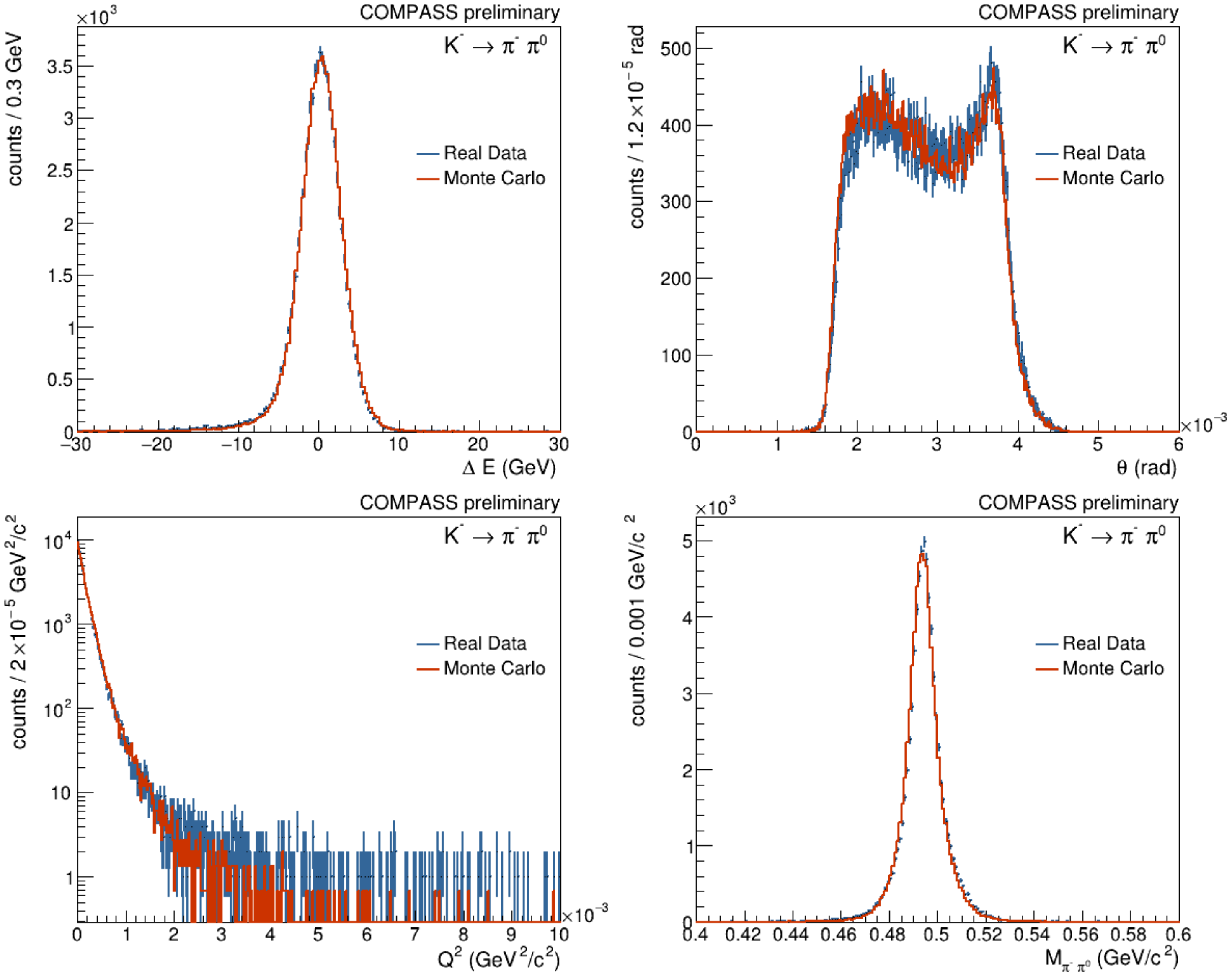
$L_{2\pi,eff} = 5.21 \pm 0.04_{stat}\ nb^{-1}$
$L_{3\pi,eff} = 5.06 \pm 0.12_{stat}\ nb^{-1}$

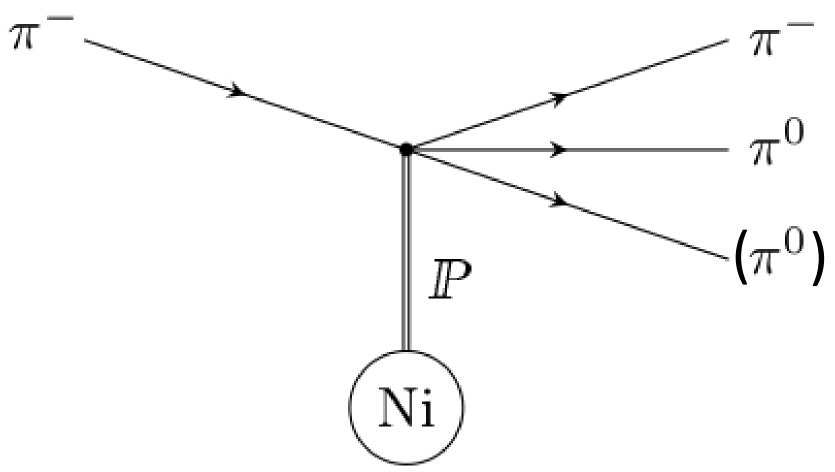
Largest constributions to systematic uncertainty:

- CEDAR tag efficiency: 7%
- ECAL reconstruction: 5%
- kaon/pion beam ratio: 2.5%

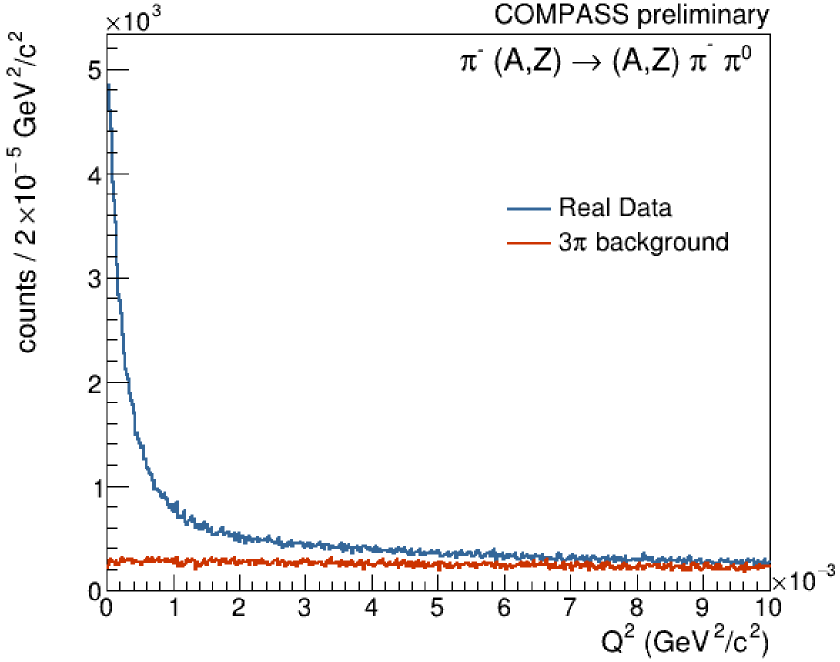
Result:

$L_{eff} = 5.21 \pm 0.48_{syst} \pm 0.04_{stat}$





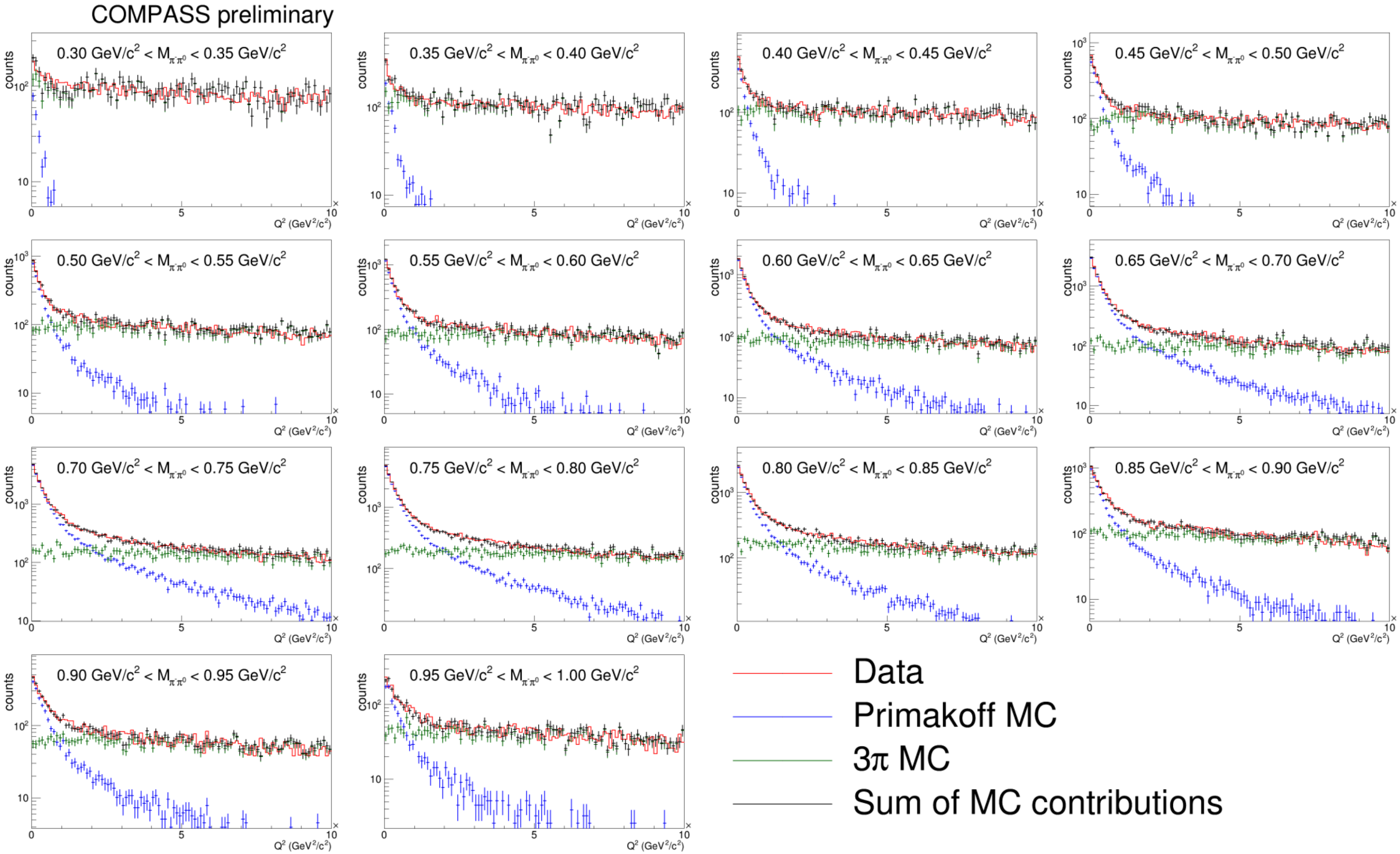
- $\pi^-\pi^0$-final state forbidden by G-parity conservation
- Large cross section for $\pi^-\pi^0\pi^0$ final state $\Longrightarrow$ loss of one (soft) π^0
- Approach: determine leakage from 3pi MC data with 2pi event selection



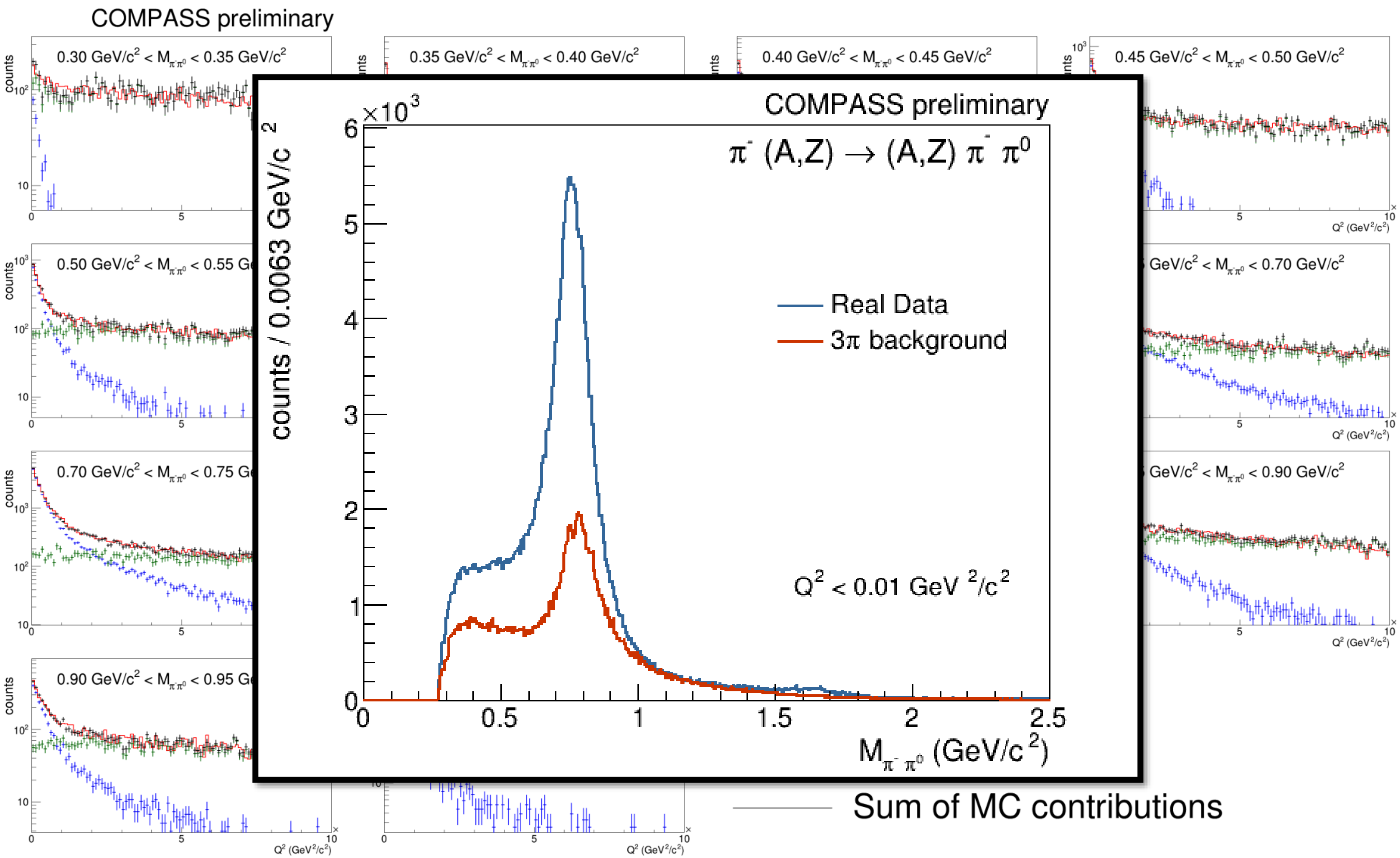
Approach for 3π leakage:

- Select diffractive 3π events
- Develop partial-wave model
- Weight 3π Monte Carlo data set according to model
- Subtract from 2π event sample

Scaling of 3π Monte Carlo background prediction



Scaling of 3π Monte Carlo background prediction



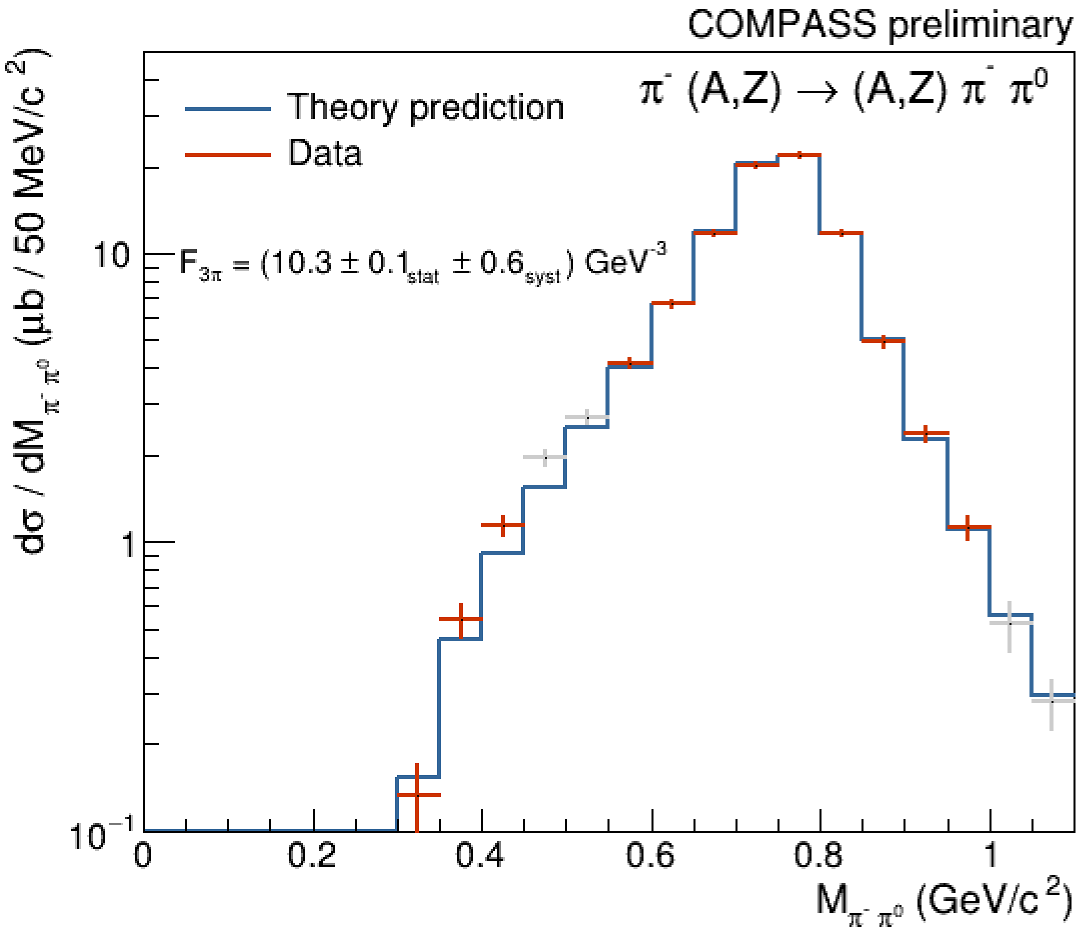
Results of dispersive fits

- Selection: $Q^2 < 1.296 \cdot 10^{-3}\ \mathrm{GeV}^2/c^2$

$$c_2^{(1)} = (10.5 \pm 0.1_{stat} \pm 0.6_{syst})\ \mathrm{GeV}^{-3}$$
$$c_2^{(2)} = (24.5 \pm 0.1_{stat}{}^{+2.9}_{-1.4}{}_{syst})\ \mathrm{GeV}^{-5}$$

$$F_{3\pi} = (10.3 \pm 0.1_{stat} \pm 0.6_{syst})\mathrm{GeV}^{-3}$$
$$\Gamma_{\rho\to\pi\gamma} = \left(76 \pm 1_{stat}{}^{+10}_{-8}{}_{syst}\right)\mathrm{keV}$$

- Preliminary result for $F_{3\pi}$ in agreement with theory prediction from ChPT
- Lower systematics to be expected



Comparison to previous measurements

- COMPASS: First combined measurement of $F_{3\pi}$ and $\Gamma_{\rho\to\pi\gamma}$

$$F_{3\pi} = (10.3 \pm 0.1_{stat} \pm 0.6_{syst})\mathrm{GeV}^{-3}$$
$$\Gamma_{\rho\to\pi\gamma} = \left(76 \pm 1_{stat}{}^{+10}_{-8}{}_{syst}\right)\mathrm{keV}$$

- Intensive test of systematics:
  - Different K^- decay channels
  - Studies on different background contributions (ω and π exchange)

- Accompanied with intensive analysis of $\pi^-\mathrm{Ni} \to \pi^-\pi^0\pi^0\mathrm{Ni}$ for background estimation

Capraro, L. *et al.* NPB 288 (1987) 659-680 at CERN (SPS):

$$\Gamma_{\rho\to\pi\gamma} = (81 \pm 4 \pm 4)\ \mathrm{keV}$$

Obtained by fitting $\mathrm{d}\sigma/\mathrm{d}t$ distribution (separation of nuclear and Coulomb processes)

- Neglecting chiral production of $\pi^-\pi^0$
- Presumably underestimation of systematics (3π leakage, beam composition)

$\Gamma(\pi^{\pm}\gamma)$ **Γ_3**

VALUE (keV)	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
68 ±7 OUR FIT Error includes scale factor of 2.3.					
68 ±7 OUR AVERAGE Error includes scale factor of 2.2. See the ideogram below.					
81 ±4 ±4	CAPRARO	87	SPEC	−	200 $\pi^- A \to \pi^-\pi^0 A$
59.8±4.0	HUSTON	86	SPEC	+	202 $\pi^+ A \to \pi^+\pi^0 A$
71 ±7	JENSEN	83	SPEC	−	156–260 $\pi^- A \to \pi^-\pi^0 A$

Comparison to previous measurements

- COMPASS: First combined measurement of $F_{3\pi}$ and $\Gamma_{\rho\to\pi\gamma}$

$$F_{3\pi} = (10.3 \pm 0.1_{stat} \pm 0.6_{syst})\mathrm{GeV}^{-3}$$
$$\Gamma_{\rho\to\pi\gamma} = \left(76 \pm 1_{stat}{}^{+10}_{-8}{}_{syst}\right)\mathrm{keV}$$

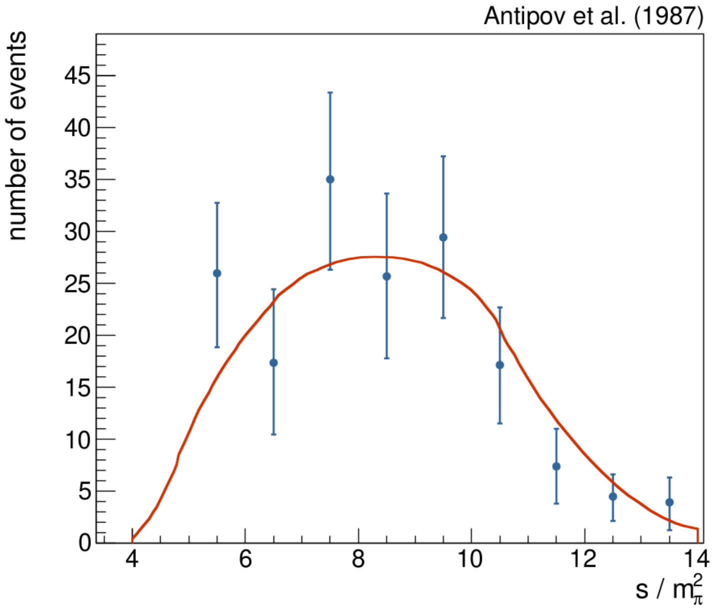
- Intensive test of systematics:
  - Different K^- decay channels
  - Studies on different background contributions (ω and π exchange)

- Accompanied with intensive analysis of $\pi^-\mathrm{Ni} \to \pi^-\pi^0\pi^0\mathrm{Ni}$ for background estimation

Antipov, Y. *et al.* PRD 36 (1987) 101103
and reanalyzed by
Ametller, L. *et al.* PRD 64 (2001) 094009

$$F_{3\pi} = (10.7 \pm 1.2)\ \mathrm{GeV}^{-3}$$

- Neglecting s-channel production of ρ meson
- No proper consideration of systematics



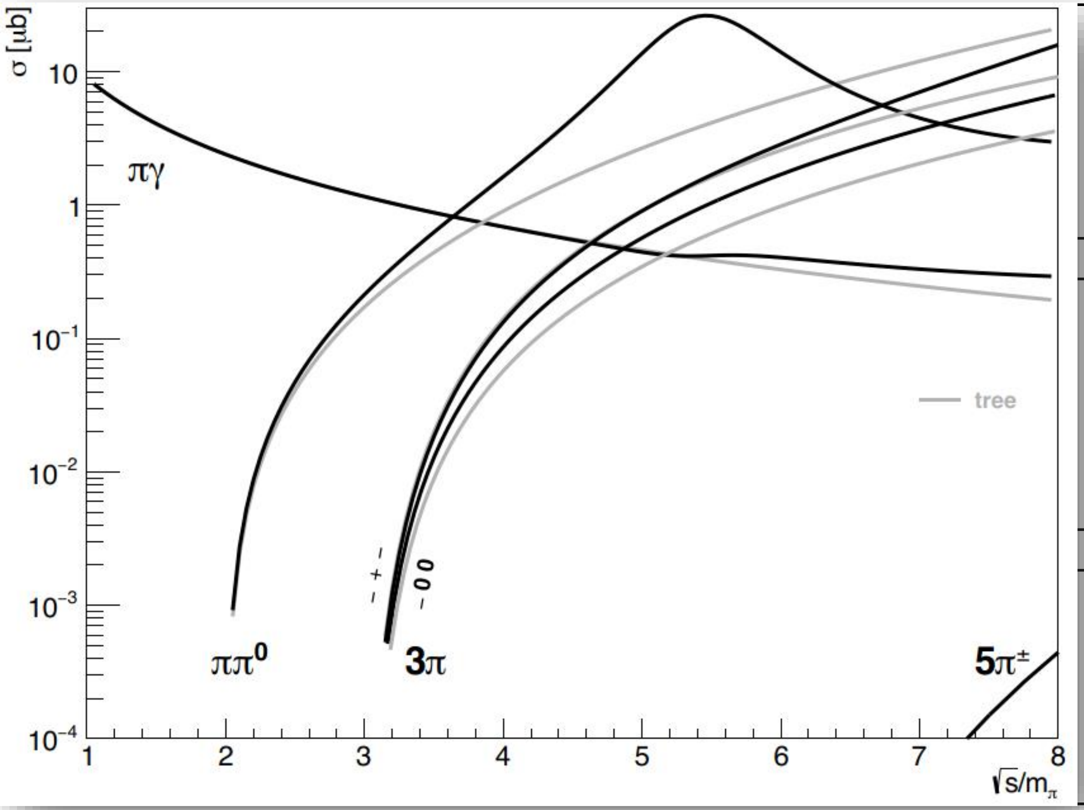
Thank you for your attention

Primakoff data sets at COMPASS

2004	$\pi^+\pi^-\pi^-$: published result →	PRL 108 (2012) 192001
2009	$\pi^-\gamma$: pion polarizabilities →	Phys. Rev. Lett. 114 (2015) 06002
	$\pi^-\pi^0$: chiral anomaly $\pi^-\pi^0\pi^0$: chiral dynamics	Presented in this talk
2012	$\pi^-\gamma$: pion polarizabilities $\pi^-\pi^0$: chiral anomaly $\pi^-\pi^0\pi^0$: chiral dynamics	4x larger data set compared to 2009 No results yet, MC still incomplete

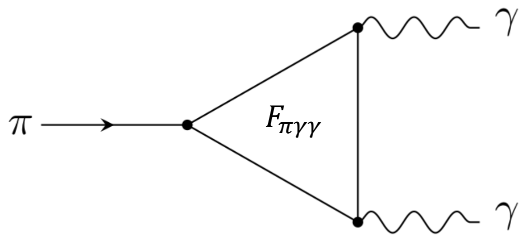
Primakoff data sets at COMPASS

2004	$\pi^+\pi^-\pi^-$: pub
2009	$\pi^-\gamma$: pion pola $\pi^-\pi^0$: chiral ar $\pi^-\pi^0\pi^0$: chira
2012	$\pi^-\gamma$: pion pola $\pi^-\pi^0$: chiral ar $\pi^-\pi^0\pi^0$: chira



- First definitive measurement of π^0-lifetime in 1963:

$$\tau_{\text{exp}}(\pi^0) = (9.5 \pm 1.5) \cdot 10^{-17}\text{s} \neq \tau_{\text{PCAC}}(\pi^0) \approx 10^{-13}\text{s}$$



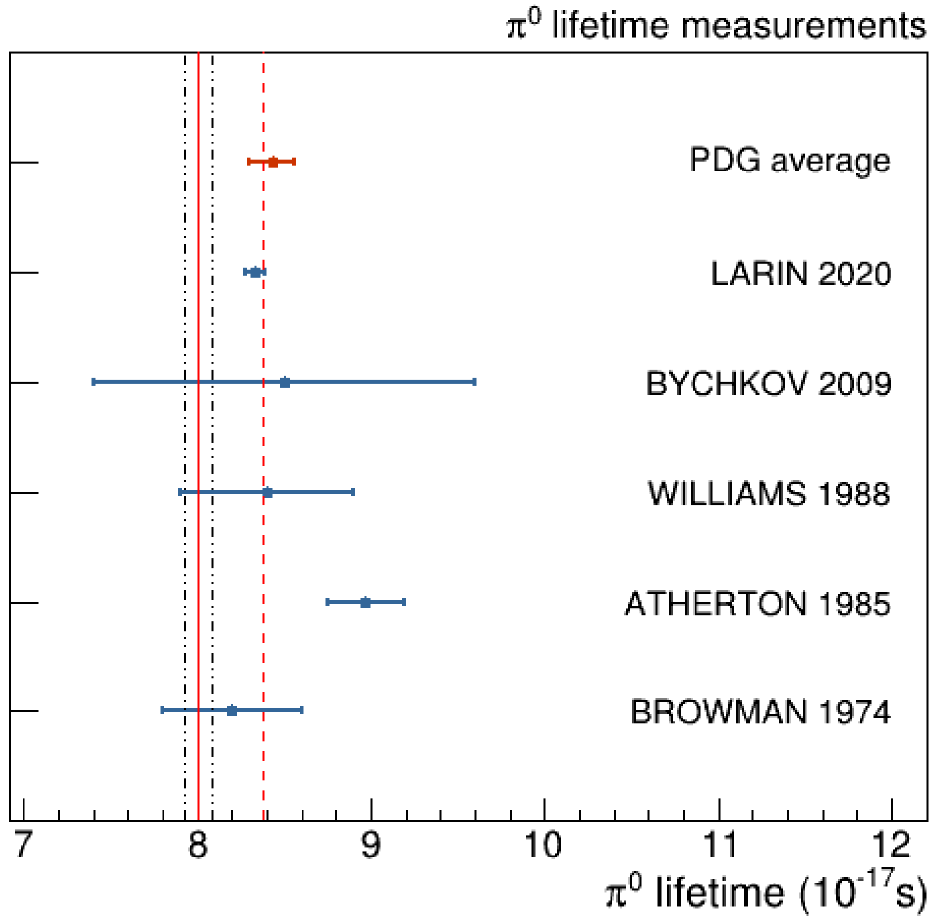
- Adler, Bell, Jackiw, Bardeen 1969: calculation of triangle diagram

$$\Gamma^{\text{anom}}(\pi^0 \to \gamma\gamma) = F^2_{\pi\gamma\gamma} \cdot \frac{m^3_{\pi^0}}{64\pi} = \left(\frac{e^2 N_c}{12\pi^2 F_\pi}\right)^2 \frac{m^3_{\pi^0}}{64\pi} = 7.75\,\text{eV}$$

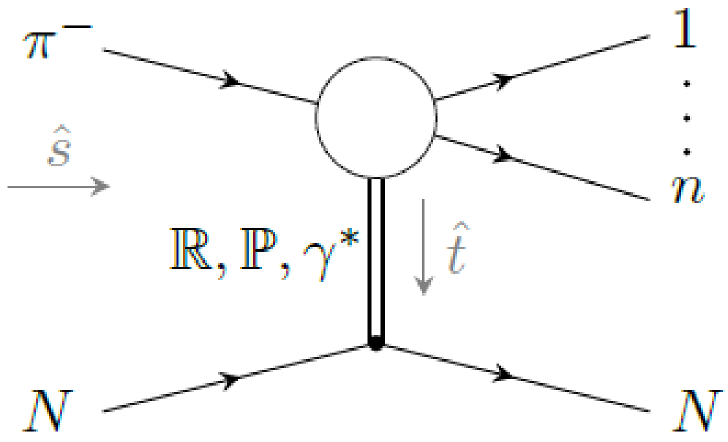
$$\tau(\pi^0) = \text{BR}(\pi^0 \to \gamma\gamma) \cdot \frac{\hbar}{\Gamma^{\text{anom}}(\pi^0 \to \gamma\gamma)} = 8.38 \cdot 10^{-17}\,\text{s}$$

- Moussalam and Kampf 2009: NLO-calculation in chiral perturbation theory

$$\tau_{\text{NLO}}(\pi^0) = (8.04 \pm 0{,}11) \cdot 10^{-17}\text{s}$$



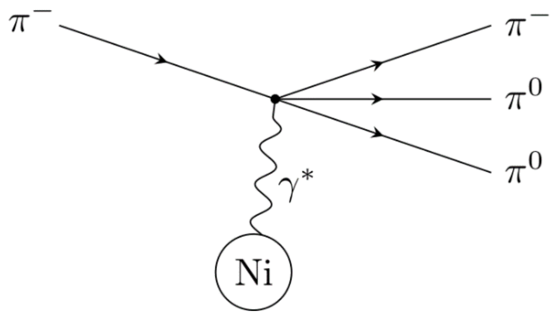
Production mechanisms for mesons at COMPASS

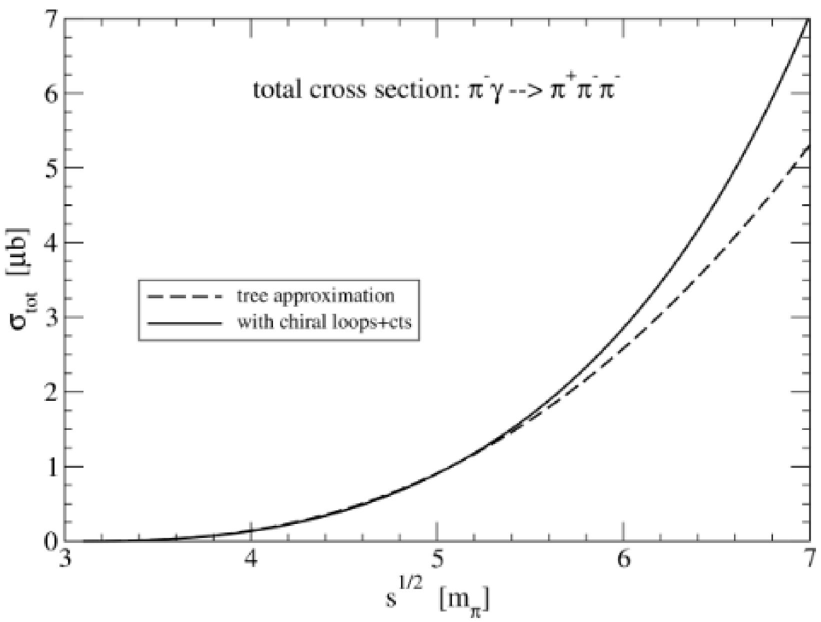


- Strong and electromagnetic production of mesons
- Electromagnetic production via Primakoff effect with sharp Q^2 distribution
- Pomeron exchange: $\pi^-\pi^0$ final state forbidden due to G-parity conservation, but: large cross-section for $\pi^-\pi^0\pi^0$-final state → loss of one (soft) π^0 as main background

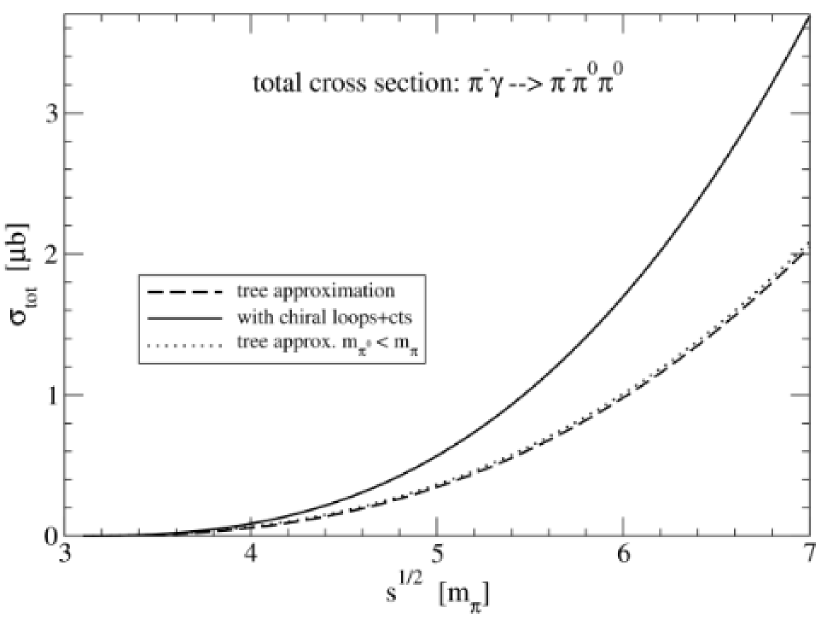
	Primakoff	$\mathbb{P}$ (strong)	$\mathbb{R}$ (strong)
$\sigma(s)$	$\propto \ln(\sqrt{s})$	$\propto$ const.	$\propto 1/\sqrt{s}$
$\sigma(A_{\text{target}})$	$\propto$ const.	$\propto A^{2/3}$	$\propto A^{2/3}$
$\sigma(Z_{\text{target}})$	$\propto Z^2$	$\propto$ const.	$\propto$ const.
$\sigma(t)$	$\propto \frac{Q^2 - Q^2_{\text{min}}}{Q^4} = \frac{\hat{t}'}{\hat{t}^2}$	$\propto e^{-b\hat{t}'}$	$\propto g(\hat{t}) \cdot e^{-b\hat{t}'}$ for small $\hat{t}$

- Direct (point-like) coupling of photon to 4 pions
- Prediction from ChPT at tree- and loop-level available





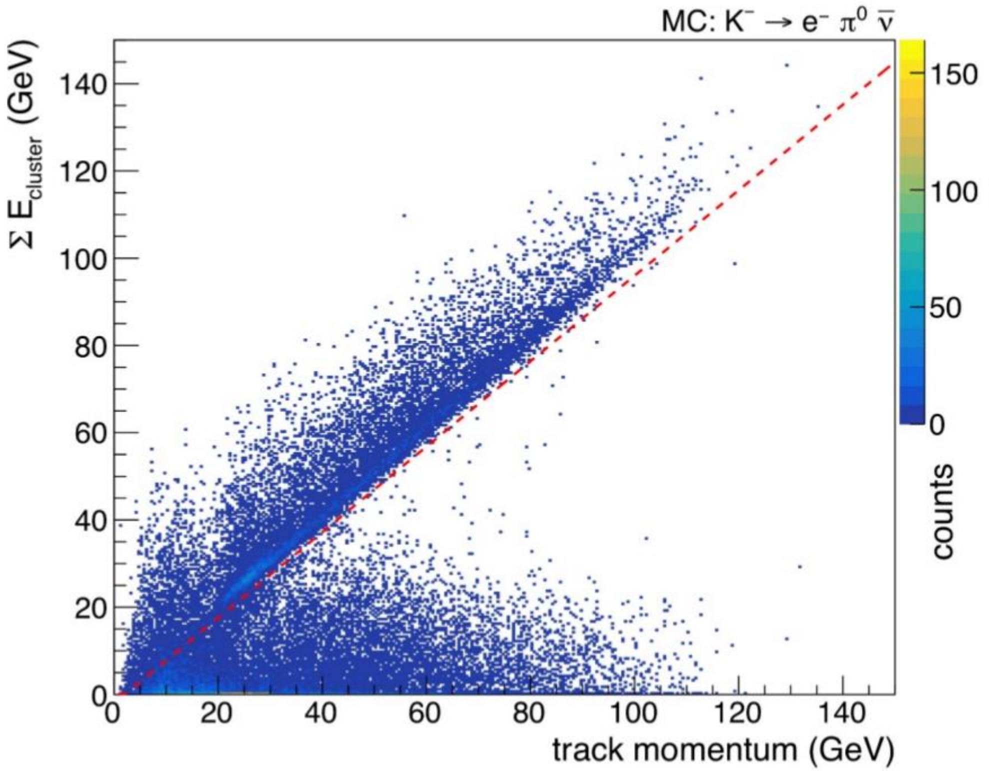
Grabmüller S. (2012). Cryogenic Silicon Detectors and Analysis of Primakoff Contributions to the Reaction $\pi^- Pb \longrightarrow$

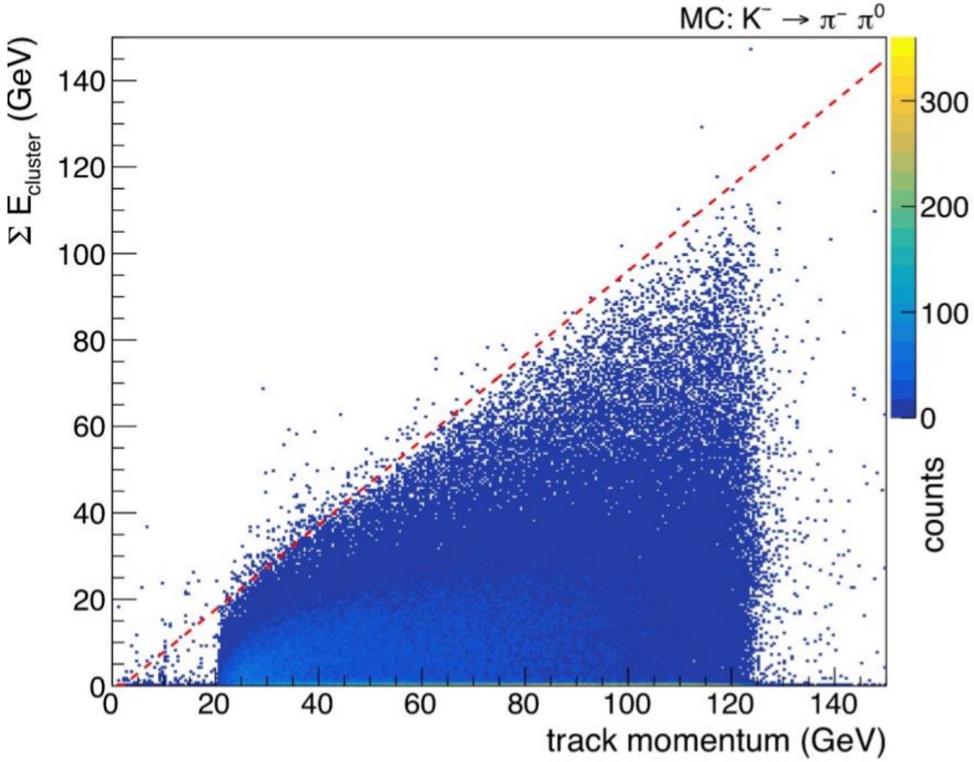


Krämer M. (2016) Evaluation and Optimization of a digital calorimetric trigger and analysis of $\pi^- Ni \longrightarrow$

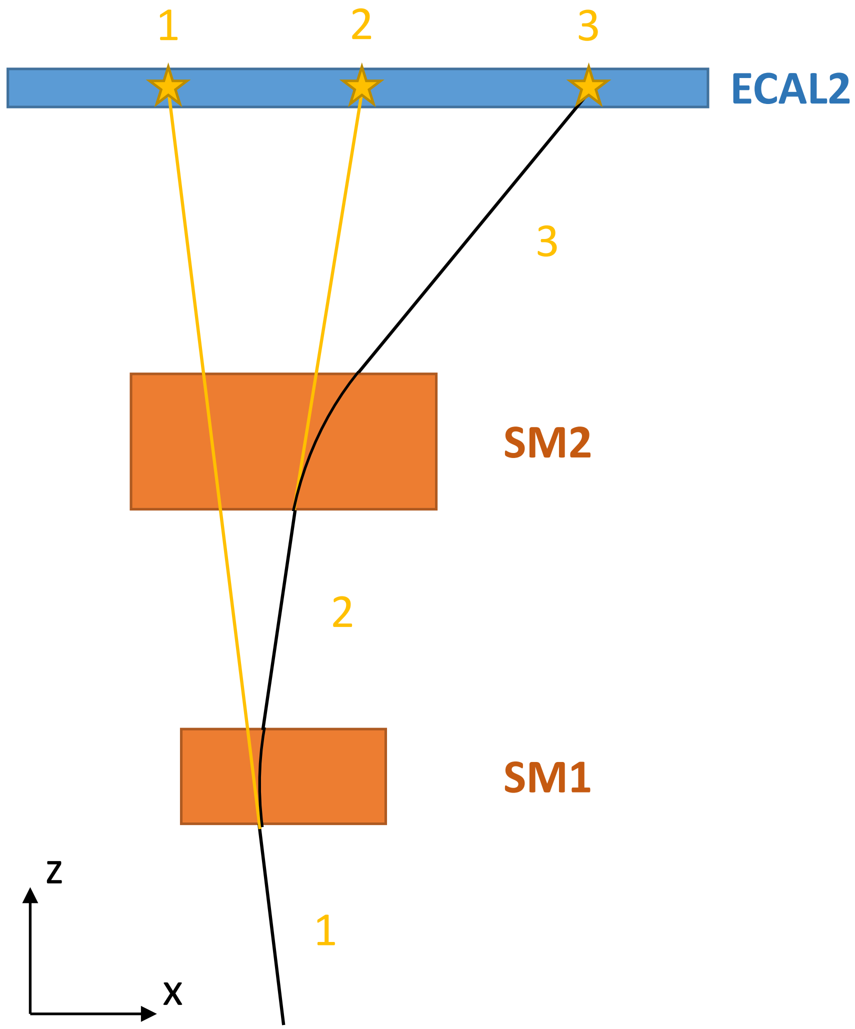
π^- / e^- distinction

- Naive idea: E/p in calorimeter
- Possible discrimination line can be identified
- Still: many electrons deposit less energy than expected
- Reason: energy loss due to Bremsstrahlung in the spectrometer



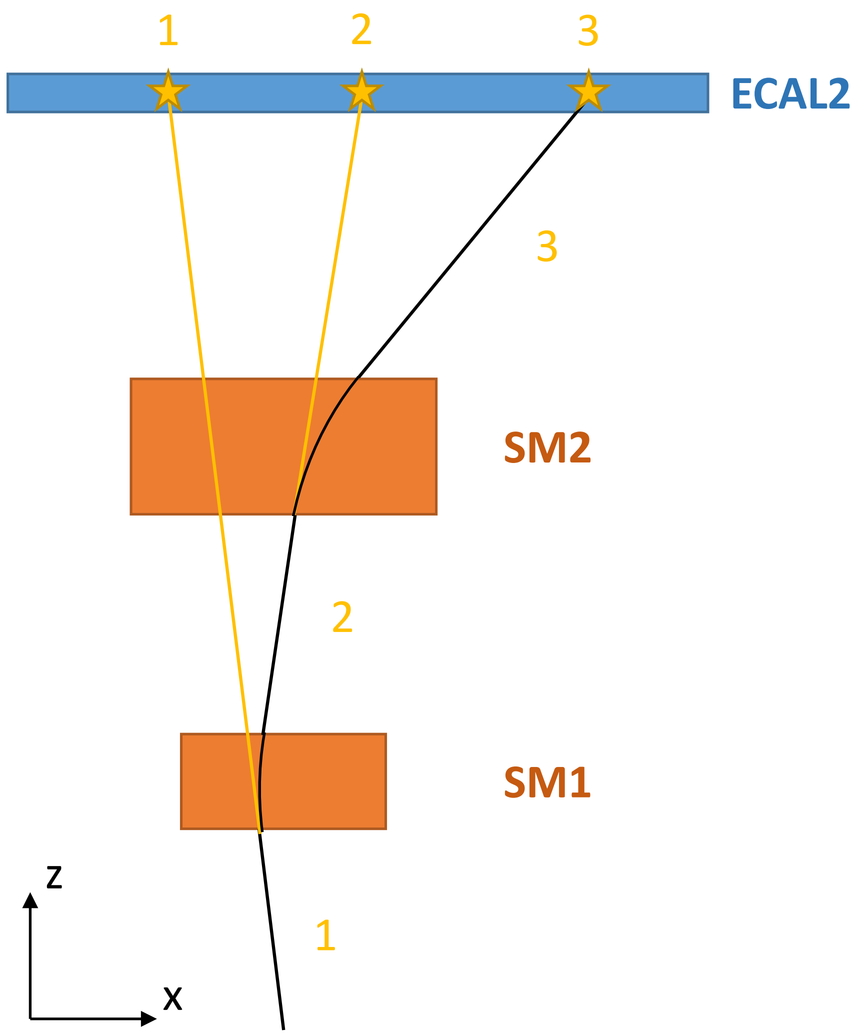


Bremsstrahlung

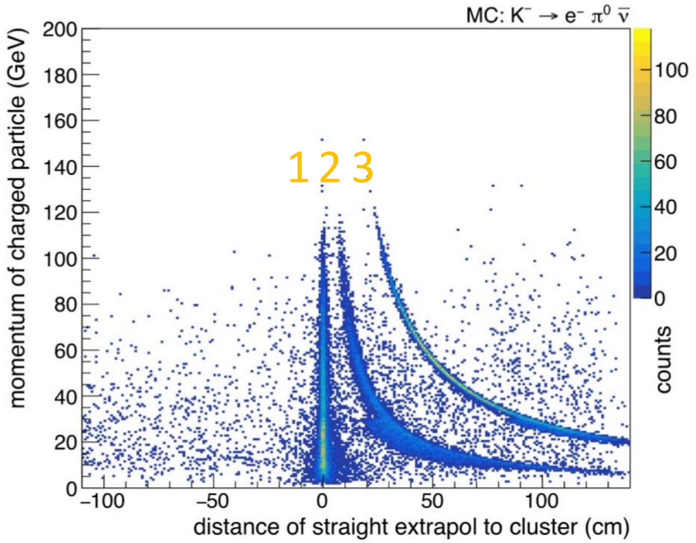


- Charged particle radiates photons while propagating through matter
- Deflection in dipole magnets dependent on momentum of charged track
- 3 distinct regions with increased probability for Bremsstrahlung
- Electrons have higher probability for Bremsstrahlung than pions

Bremsstrahlung

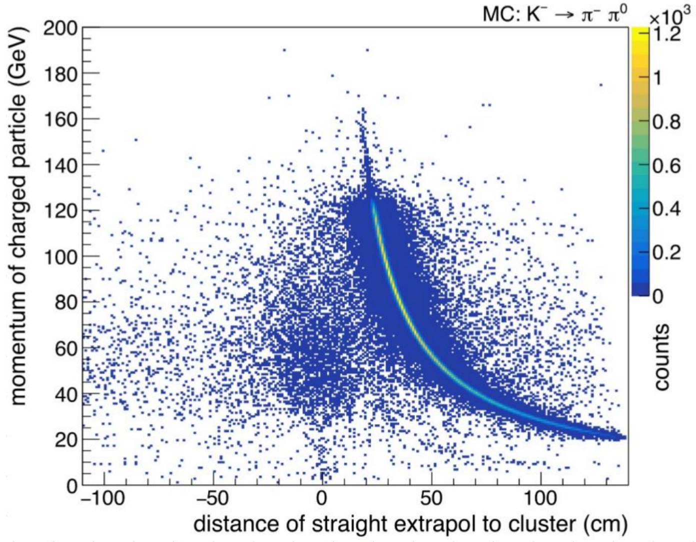


Electrons



vs

pions



Covered kinematic range

- Selection: $Q^2 < 1.296 \cdot 10^{-3}\,\mathrm{GeV}^2/c^2$
- Trigger on energy deposit in central part of electromagnetic calorimeter ($E_{\mathrm{trig}} > 68\,\mathrm{GeV}$)
- Minimum energy of π^0 → maximum scattering angle of π^- in Gottfried-Jackson frame