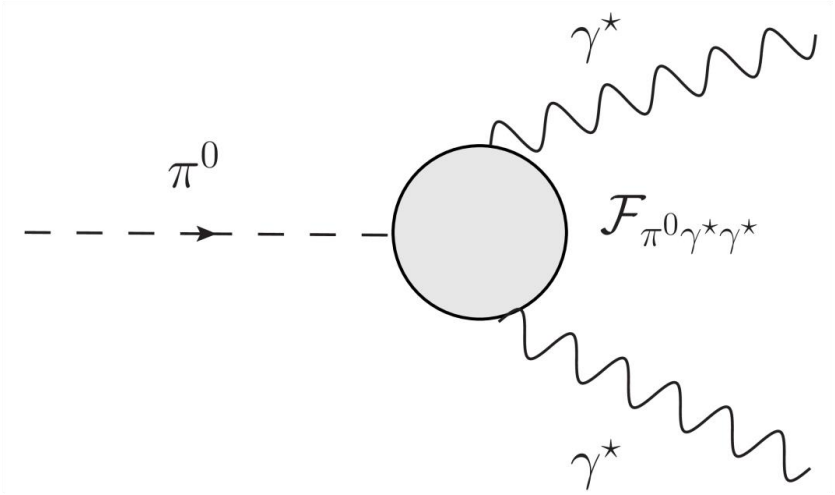
FACULTY
OF MATHEMATICS
AND PHYSICS
Charles University

Neutral Pion Studies at NA62



Michal Koval

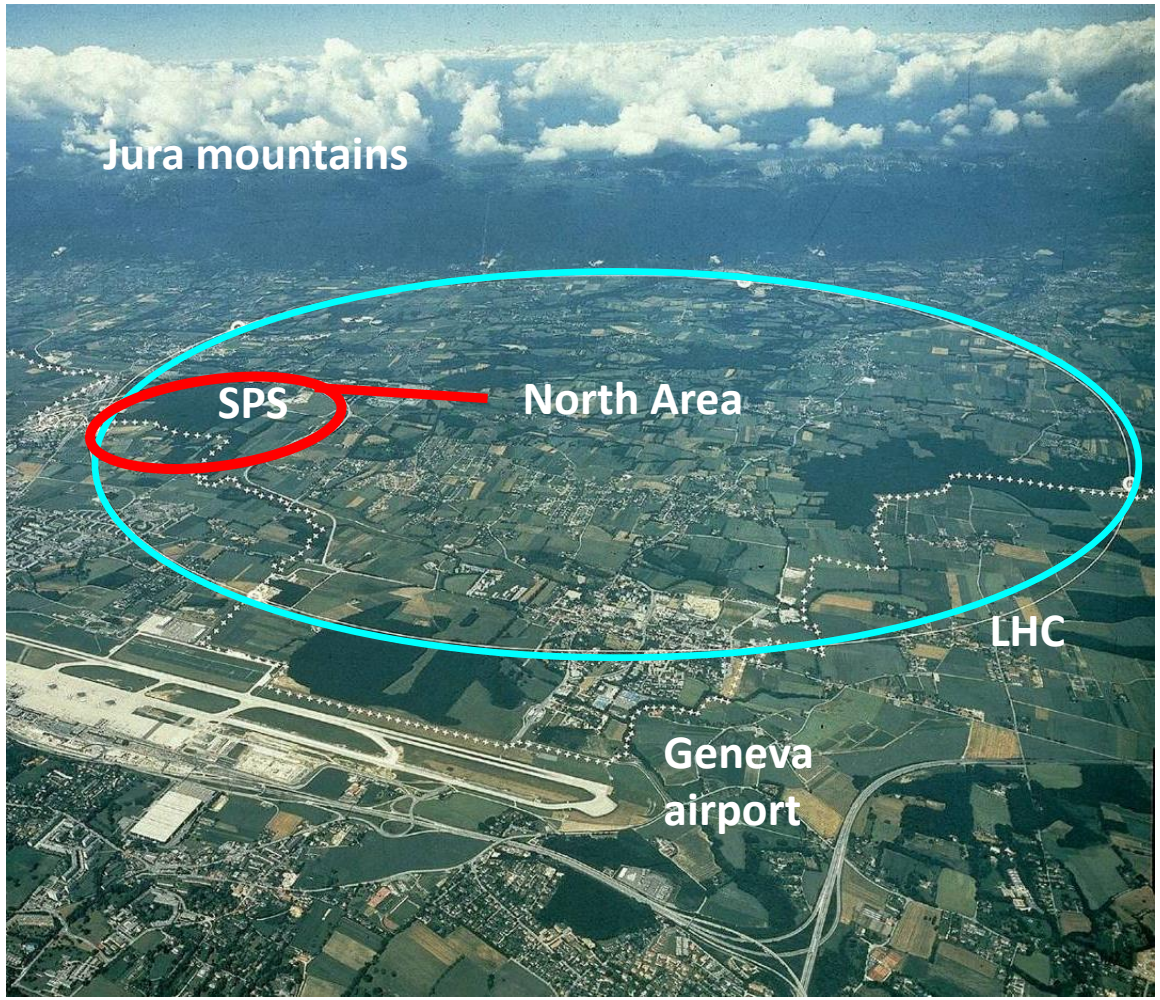
IPNP @ Malá Skála
14 April 2023

Outline

1. NA62: brief introduction (reminder)
   - What type of experiment is it?
   - How can π^0 decays be studied at NA62?

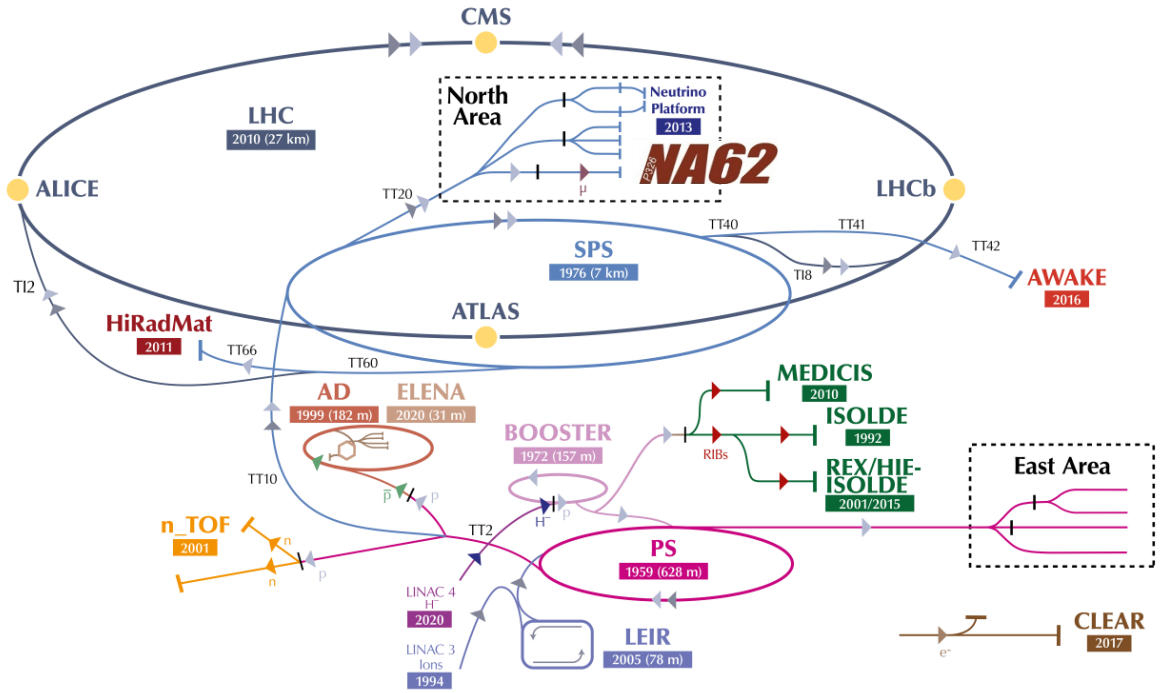
2. Neutral pion decays
   - What is common to various π^0 decays?
   - How are π^0 decays related to (g-2)?

3. Studies of neutral pion at NA62
   - Which π^0 measurements can be done?
   - What are the experimental challenges?



NA62 Experiment

- Fixed target experiment studying charged kaons at CERN Super Proton Synchrotron (SPS)



SPS beam:

- 400 GeV/c protons
  - Target: beryllium
  - Coming in 3.5s long spills
  - $2 \cdot 10^{12}$ protons / spill

Secondary hadron beam:

- Momentum: 75 GeV/c
- Mix of $K^+(6\%)$/ $\pi^+(70\%)$/p^+ (24%)

- The main goal: measurement of the ultra-rare ($B \sim 10^{-10}$) decay $K^+ \to \pi^+ \nu \bar{\nu}$

NA62 Experiment

Charged kaon K^+ in the beam:

- Mass: 493.7 MeV
- Mean lifetime: 1.2×10^{-8}s
- Momentum: 75 GeV

Experimental layout of NA62:

- Kaon decays in flight
  - Mean free path ≈560 meters
- Decay products: $\pi^{\pm}, \mu^{\pm}, e^{\pm}, \pi^0, \gamma, \nu$ with small transverse momenta

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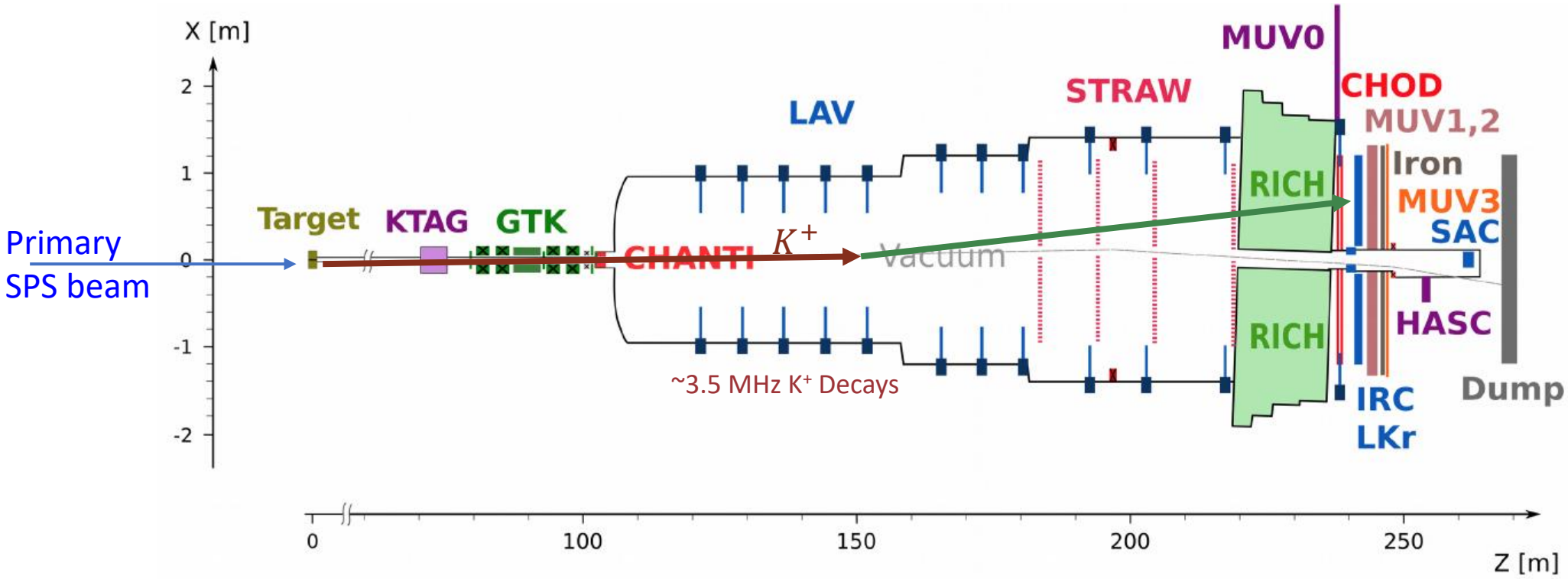
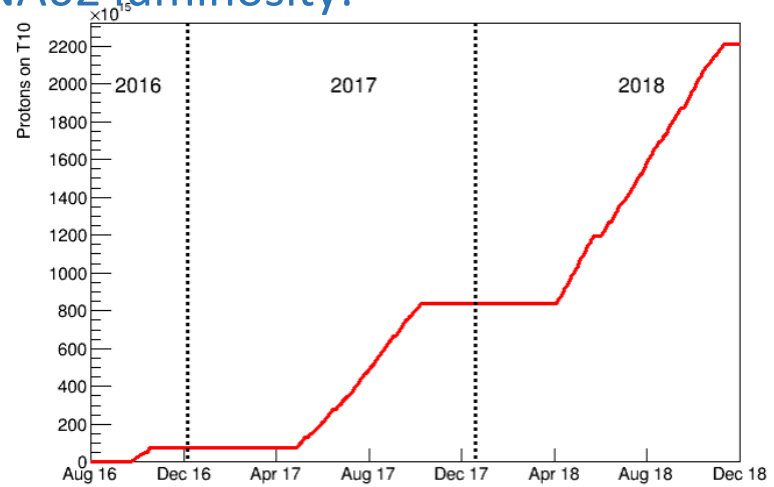


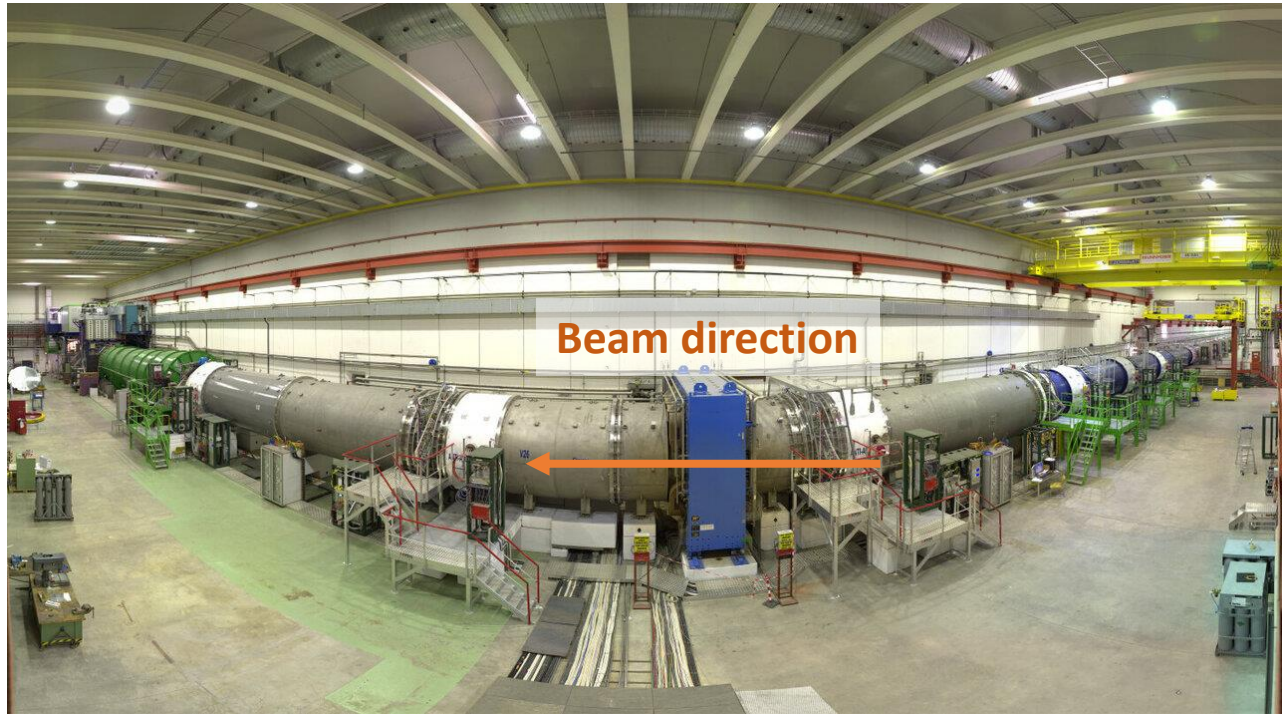
NA62 Experiment

NA62 timeline:

- 2008 – 2014
  Detector R&D
  and installation
- 2014 Pilot run
- 2015 Commissioning
- 2016 – 2018 NA62 Run 1
- 2021 – 2025 NA62 Run 2

NA62 luminosity:





NA62 Experiment: neutral pion production

- Six main decay modes of charged kaon:
- NA62 can be viewed also as a π^0 factory
  - Ideal decay mode for π^0 studies: $K^+ \rightarrow \pi^+\pi^0$

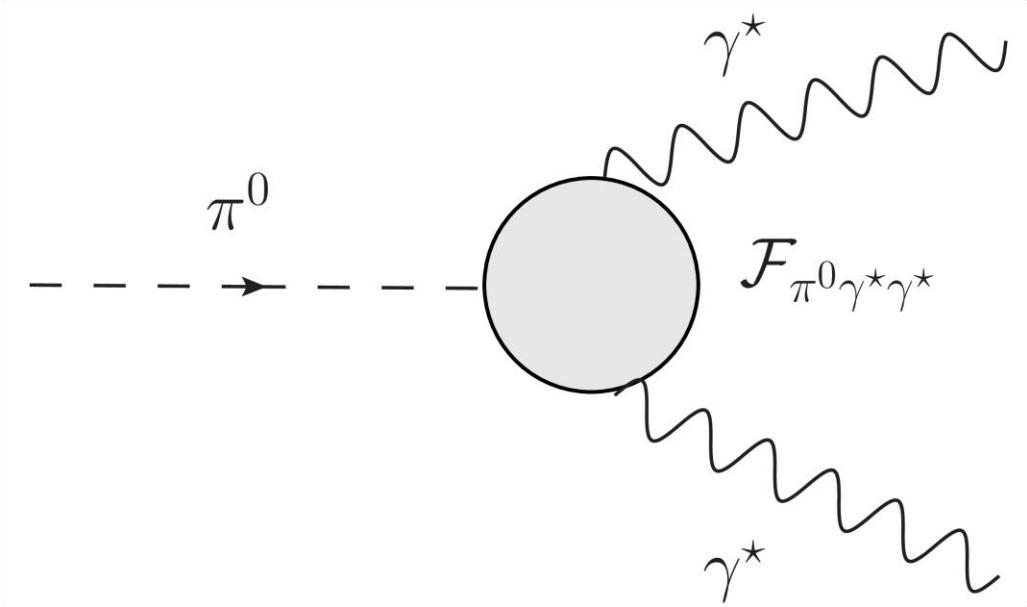
Decay	Branching ratio [%]
$K^+ \rightarrow \mu^+\nu_\mu$	63.6
$K^+ \rightarrow \pi^+\pi^0$	20.7
$K^+ \rightarrow \pi^+\pi^+\pi^-$	5.6
$K^+ \rightarrow \pi^0 e^+\nu_e$	5.0
$K^+ \rightarrow \pi^0\mu^+\nu_\mu$	3.3
$K^+ \rightarrow \pi^+\pi^0\pi^0$	1.7

- π^0 properties at NA62
  - Mass: 135 MeV
  - Mean lifetime: 8.4×10^{-17}s
  - Momentum: ~(5-70) GeV
  - Mean free path: few micrometers

→ Neutral pion decays (almost) at the same vertex position as K^+

Neutral pion decays

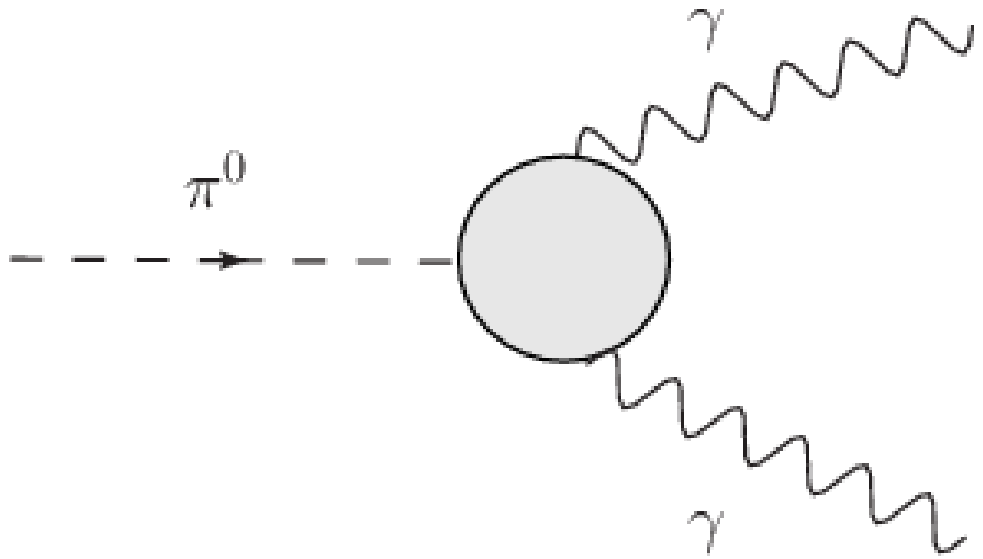
- π^0 decays proceed via the same vertex:



- The electromagnetic interaction described by the formfactor
  $F_{\pi^0\gamma^\star\gamma^\star}(p^2, q^2)$ p, q: 4-momenta of the 2 photons
- The formfactor not known a priori, various models exist (VMD, LMD, THS, …)

Neutral pion decays, $\pi^0 \to \gamma\gamma$

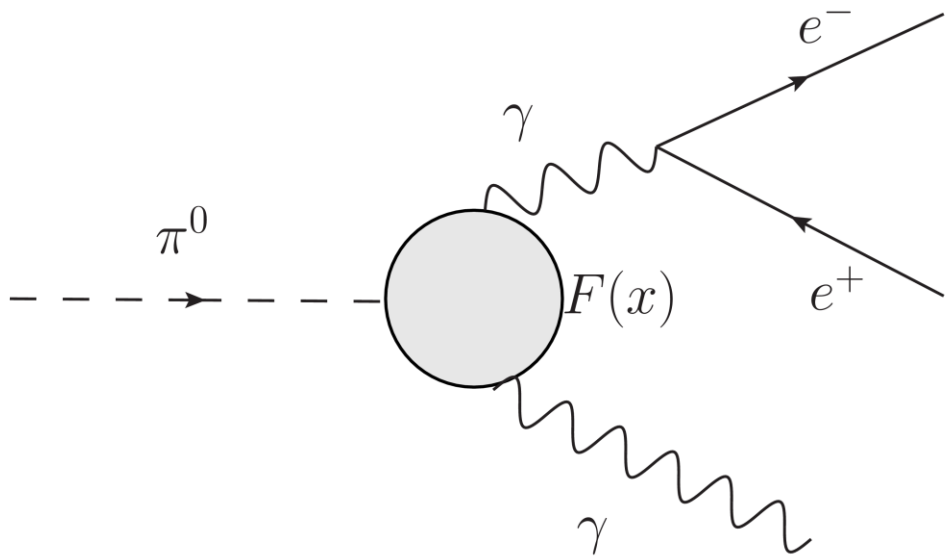
- The main decay mode: $\pi^0 \to \gamma\gamma$ ($B \sim 99\%$)



- Both photons are on shell: formfactor → constant $F_{\pi^0\gamma^\star\gamma^\star}(0,0)$

Neutral pion decays, $\pi^0 \to \gamma e^+ e^-$

- The second mode, the Dalitz decay: $\pi^0 \to \gamma e^+ e^-$ ($B \sim 1\%$)



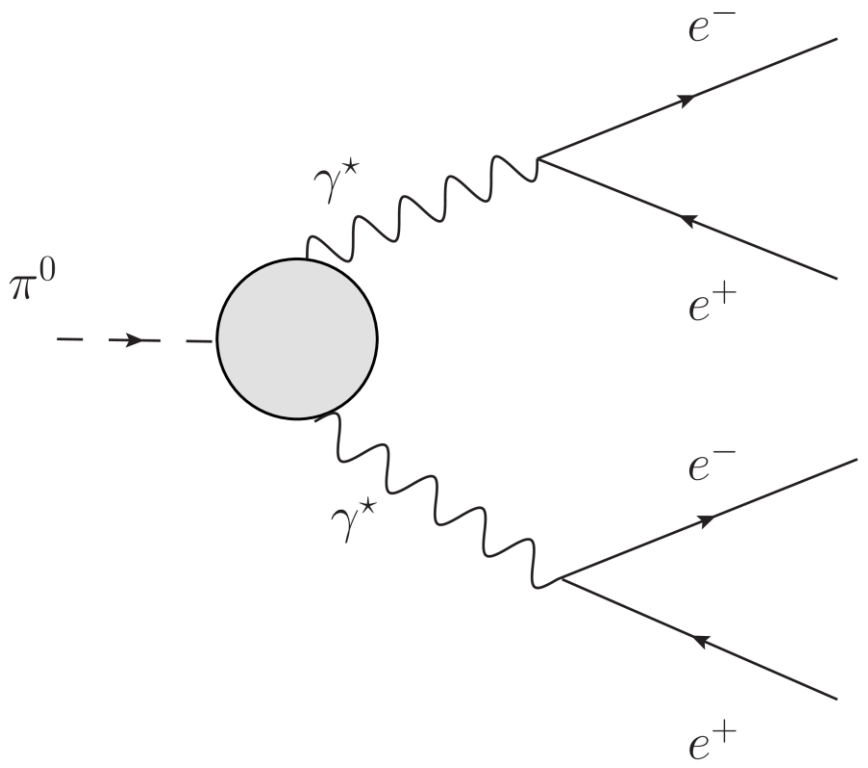
- One γ on shell, one γ off shell: formfactor → 1D function $F_{\pi^0\gamma^\star\gamma^\star}(0, q^2)$
- The function varies slowly in the allowed range of q^2 → linear approximation

$$F(x) = \frac{F_{\pi^0\gamma^\star\gamma^\star}(0,q^2)}{F_{\pi^0\gamma^\star\gamma^\star}(0,0)} = 1 + a\,x \qquad x = q^2/M_{\pi^0}^2$$

Slope parameter of interest for experiment / theory comparison

Neutral pion decays, $\pi^0 \rightarrow e^+e^-e^+e^-$

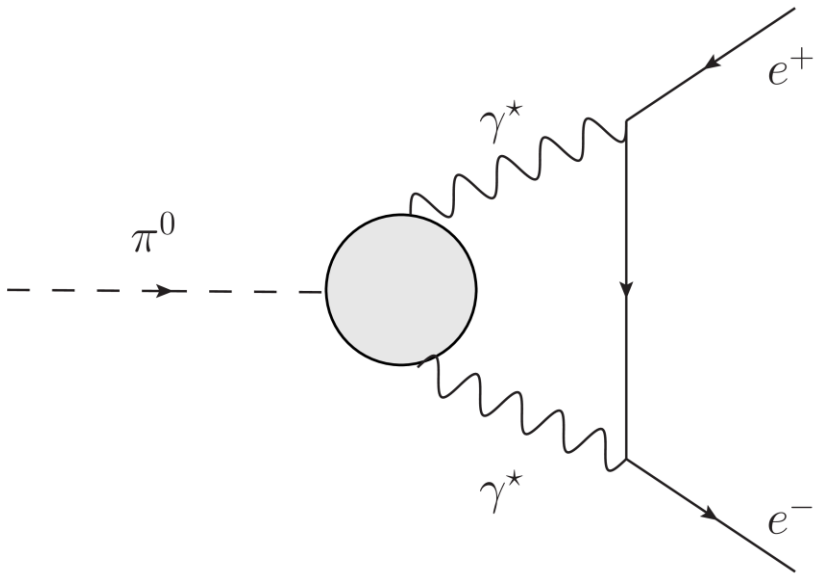
- Rare decay mode, the double Dalitz decay: $\pi^0 \rightarrow e^+e^-e^+e^-$ ($B \sim 3 \times 10^{-5}$)



- Two γ off shell: formfactor remains a 2D function

Neutral pion decays, $\pi^0 \rightarrow e^+e^-$

- Very rare decay mode: $\pi^0 \rightarrow e^+e^-$ ($B \sim 6 \times 10^{-8}$)



- Formfactor model → branching ratio prediction

Neutral pion decays, $\pi^0 \to e^+e^-$, KTeV discrepancy

- Measurement by KTeV E799-II experiment (~ 800 observed events)
  - At first, apparent large (3σ) discrepancy with the Standard Model was claimed

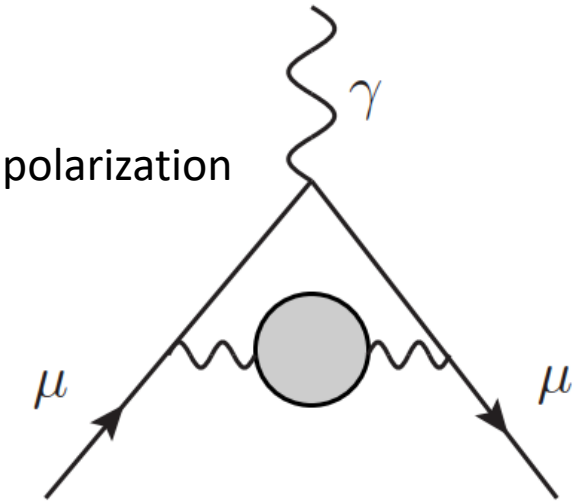
- Main complication for theory / experiment comparison:
  radiative corrections and radiative tail presence $\pi^0 \to e^+e^- + rad.\gamma$ vs. $\pi^0 \to \gamma e^+e^-$

- After new computations of radiative corrections by our colleagues from IPNP
  the discrepancy decreased to $\sim 2\sigma$
  - $\mathrm{B}(\pi^0 \to e^+e^-)_{KTeV} = 6.85(27)(23) \times 10^{-8}$
  - $\mathrm{B}(\pi^0 \to e^+e^-)_{SM} = 6.25(3) \times 10^{-8}$

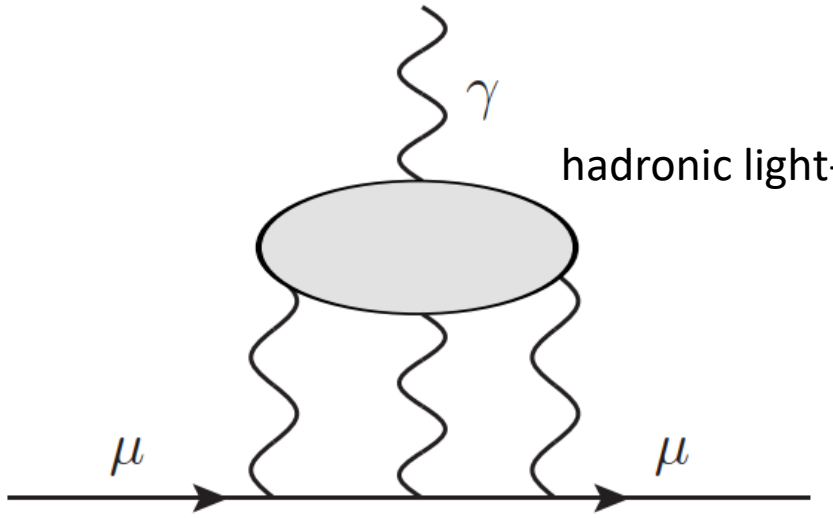
Neutral pion relation to (g-2)

- Important contributions to the (muon) anomalous magnetic moment:

hadronic vacuum polarization



hadronic light-by-light scattering



- Hadronic light-by-light contribution relies on hadronic models (such as $F_{\pi^0\gamma^\star\gamma^\star}(p^2, q^2)$)

Studies of π^0 decays at NA62

Common goal:

Precision measurements of branching ratios and formfactor using:

- $\pi^0 \to \gamma\, e^+e^-$
- $\pi^0 \to e^+e^-e^+e^-$
- $\pi^0 \to e^+e^-$

What is needed:

- Statistics:
  - Large data sample with e^+e^- in the final state
- Systematics (precision):
  - High efficiency of trigger and detectors
  - Precise treatment of radiative corrections in NA62 simlations

Previous most-precise results obtained mostly by KTeV

Studies of π^0 decays at NA62

Data samples:

- **2007 data**: recorded using old experimental setup from NA48/2
  - Low beam intensity → smaller data sample than NA62
  - Simple and fully efficient trigger for $e^{\pm}$

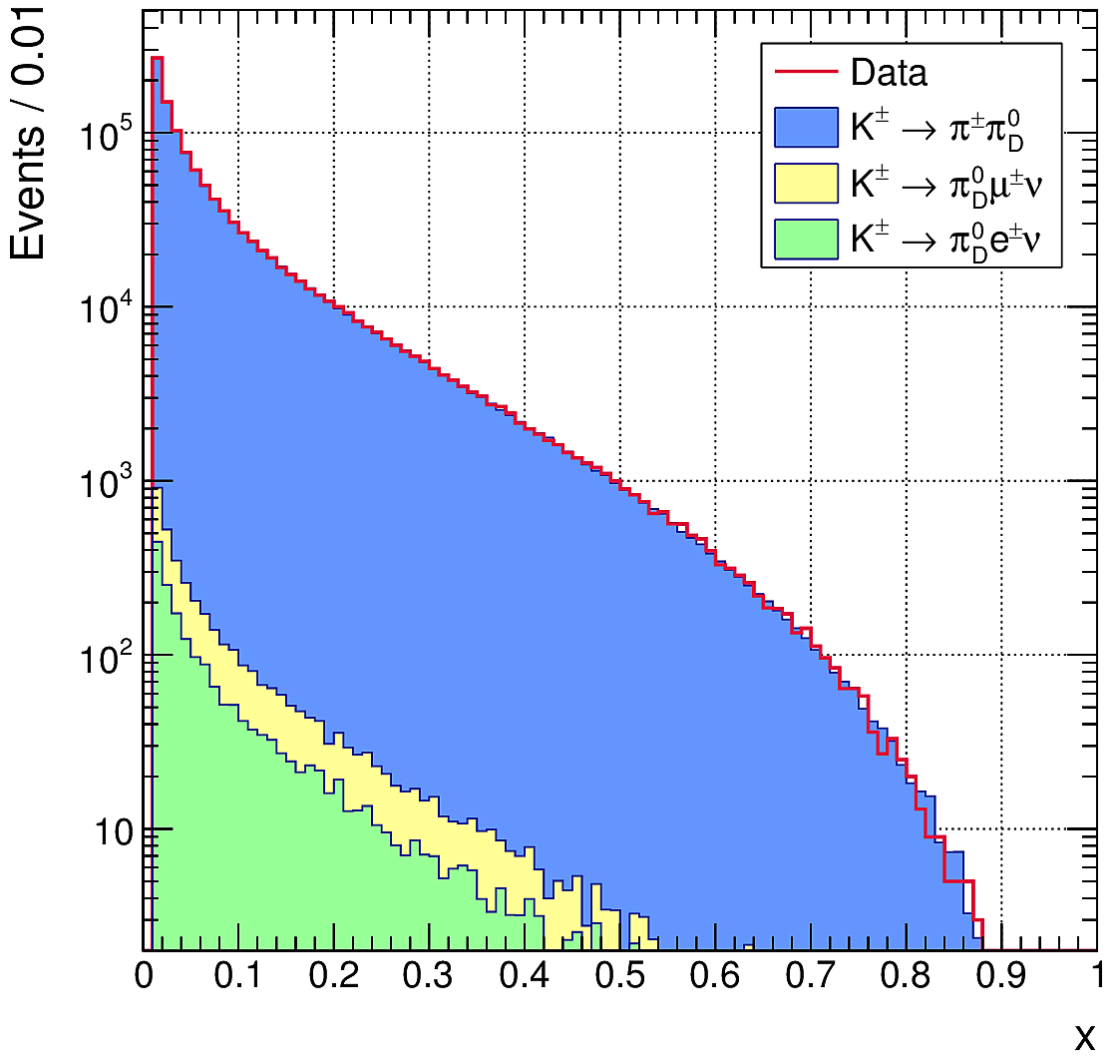
- **NA62 Run 1 data (2016-2018)**:
  - High beam intensity (70% of NA62 nominal)
  - Trigger line for e^+e^-:
    - Running in parallel to the main one ($K^+ \to \pi^+\nu\bar{\nu}$)
    - Conditions not optimized; had to be downscaled by a **factor 8**
  - The π^0 data sample size slightly smaller than KTeV

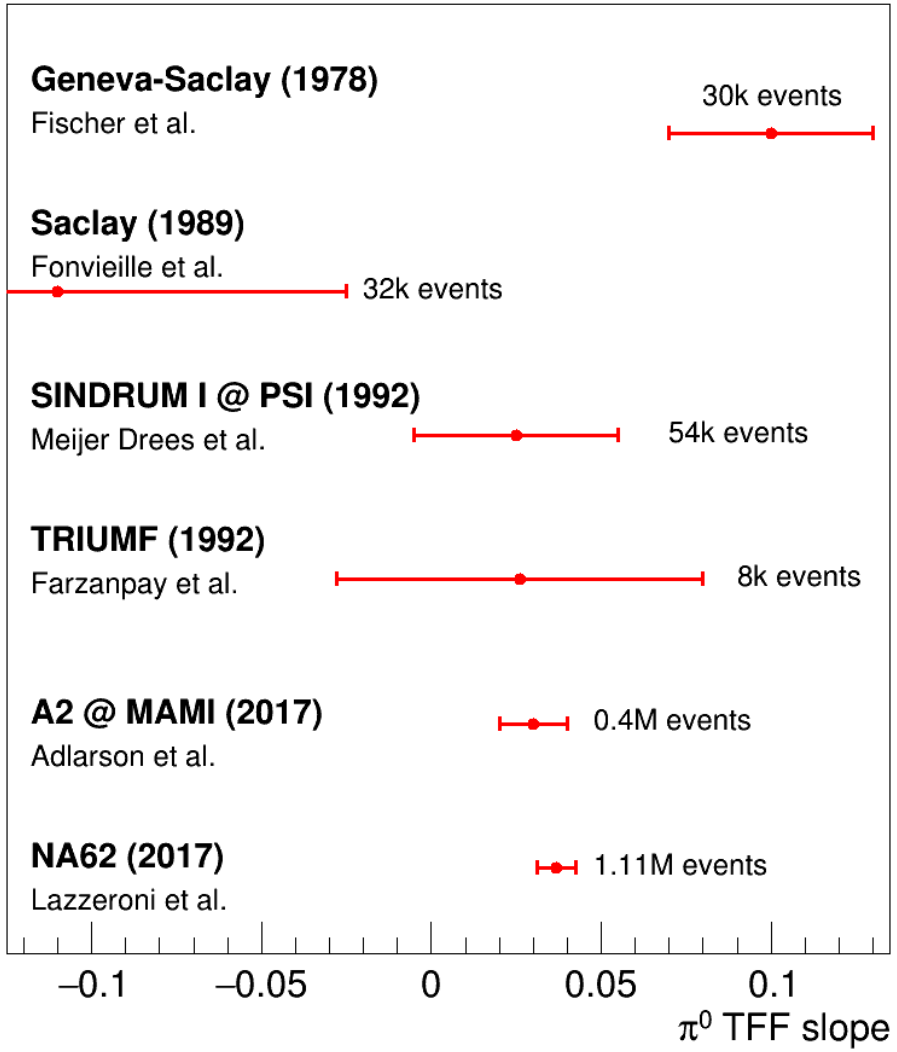
- **NA62 Run 2 data (2021-2025):**
  - Nominal beam intensity
  - Trigger line for e^+e^-:
    - Running in parallel to the main one ($K^+ \to \pi^+\nu\bar{\nu}$)
    - Conditions **optimized**; downscaling reduced to **factor 2**
  - The π^0 sample size is already the world-largest

π^0 Dalitz formfactor slope measurement

$$x = \frac{m_{ee}^2}{M_{\pi^0}^2}$$

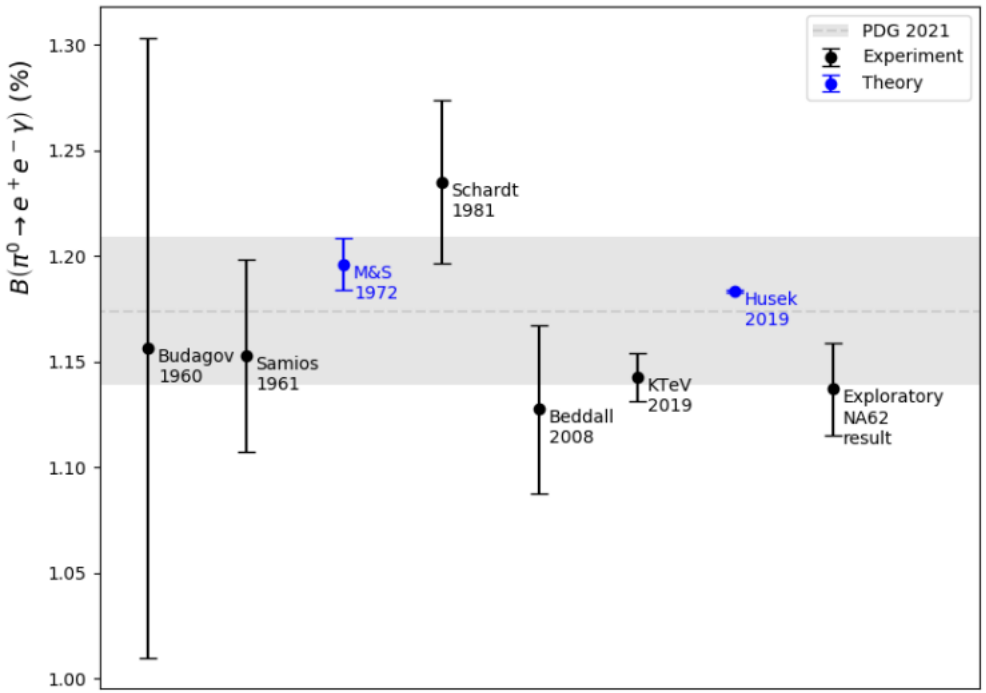
- Using the 2007 data sample to measure the slope in: $F(x) = 1 + a\,x$





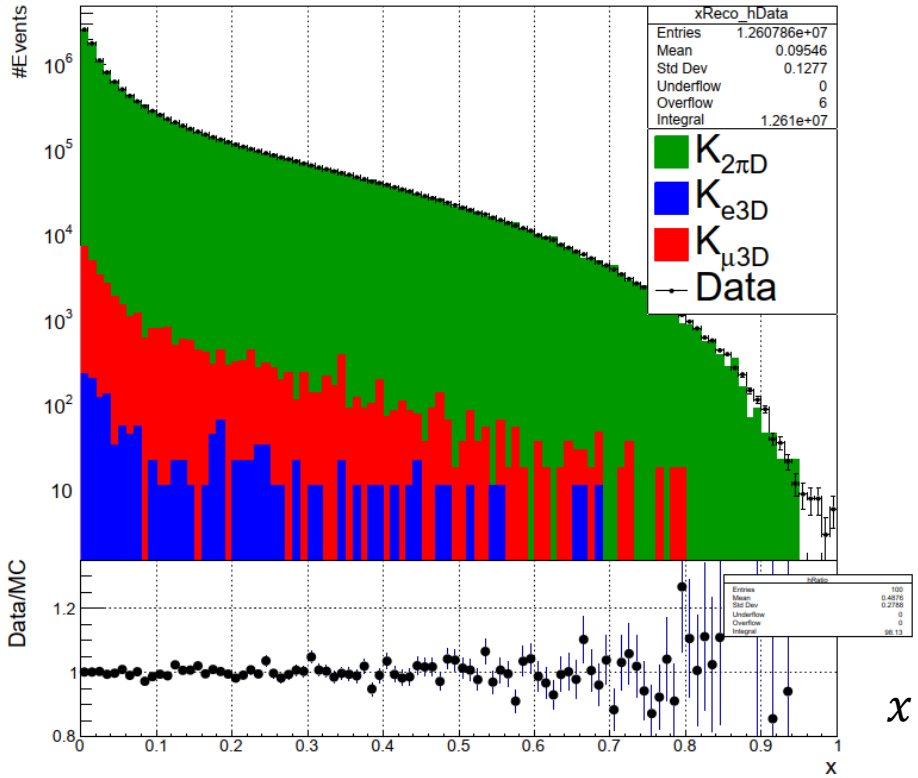
π^0 Dalitz: new data measurements

Branching ratio measurement
NA62 Run 1 data, PhD thesis, unpublished



Limited by various systematic uncertainties
→ New approach to the measurement needed

Form factor slope measurement
NA62 Run 1 data, PhD thesis, unpublished



$$x = \frac{m_{ee}^2}{M_{\pi^0}^2}$$

Data sample larger by factor 10 than 2007 data
→ Precision limited by systematics
Can be improved, manpower needed

π^0 double Dalitz: prospects

- New measurement to be started by Michal Lelak
  - See his poster tomorrow

- Run 1 + Run 2 data should give
  the most precise measurement of the branching ratio and formfactor fits

Summary

1. NA62 experiment
   - Fixed target experiment at CERN SPS, designed to study rare kaon decays ($K^+ \to \pi^+ \nu\bar{\nu}$)
   - Neutral pion (π^0) produced in K^+ decays, decays practically instantaneously

2. Neutral pion decays
   - π^0 decays via electromagnetic interaction with two photons, described by a formfactor
   - The formfactor enters computation of (g-2) in hadronic light-by-light scattering

3. Studies of neutral pion at NA62
   - Ongoing measurements of $\pi^0 \to \gamma\, e^+e^-,\ \pi^0 \to e^+e^-e^+e^-, \pi^0 \to e^+e^-$
   - Large decay samples already recorded
   - Main challenge: keep various effects under control (trigger, backgrounds, …)