



The Neutral Pion Form Factor at the NA62 Experiment

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On behalf of the NA62 collaboration

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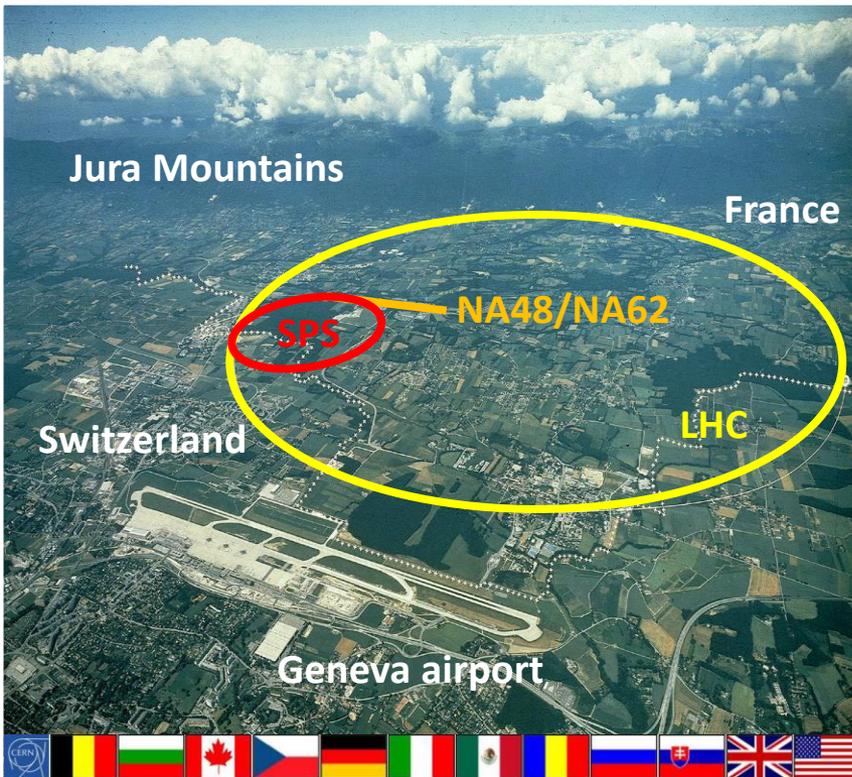
July 25-30 2016, Kyoto, Japan

Kaon Decay-in-Flight Experiments at CERN



Kaon Physics at CERN:

- Fixed target experiments at CERN SPS
- Kaon decay-in-flight
- Neutral Kaons: NA31, NA48, NA48/1
- Charged Kaons: NA48/2, **NA62**



| Experiments' history | | |
|----------------------|-------------------------------|---|
| 1980s | NA31 (K_L/K_S) | First evidence of direct CPV |
| 1997-2001 | NA48 (K_L/K_S) | $Re(\epsilon'/\epsilon)$ Discovery of direct CPV |
| 2002 | NA48/1 (K_S , hyperons) | Rare decay studies |
| 2003-2004 | NA48/2 (K^+/K^-) | Direct CPV, Rare K^+/K^- decays |
| 2007-2008 | NA62 (K^+/K^-) | Lepton universality: $K_{e2}/K_{\mu2}$ |
| 2015 | NA62 (K^+) | $K^+ \rightarrow \pi^+ \nu \bar{\nu}$, Rare K^+ decays and more... |

NA62:
currently ~200 participants,
29 institutions from 13 countries

The NA62 Experiment

- **Main goal:** measurement of $BR(K^+ \rightarrow \pi^+ \nu \bar{\nu})$
- Rare decay studies
- LFV, LNV decays
- Search for heavy ν , axions, ...

Early stage (2007): measurement of the ratio $R_K = \Gamma(K_{e2}) / \Gamma(K_{\mu2})$, lepton universality

- improved NA48/2 layout
- physics runs: 2007-2008
- R_K measurement accuracy: 0.4% (**Phys. Lett. B 719, 2013, 326**)

Primary beam from **CERN SPS:**

- 400 GeV/c protons on beryllium target

Secondary beam:

- Unseparated charged beam ($\pi/p/K$)
- $\sim 6\%$ K component



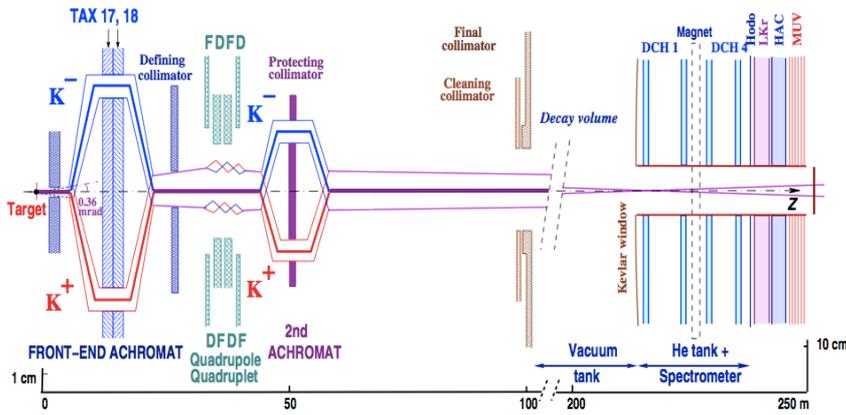
See E. Minucci's talk on NA62
During today's "Fundamental symmetries"
parallel session

π^0 Transition Form Factor in NA62



- **NA62**: a Kaon Factory but also a Pion Factory
 - **Neutral Pions**: lightest mesons → study of **low-energy properties of the strong interaction**
 - Production of a large sample of π^0 mesons from the main K^\pm decay modes
- The π^0 **Transition Form Factor (TFF) slope parameter** enters the differential decay width of the Dalitz decay $\pi^0 \rightarrow \gamma e^+ e^-$ (π_D^0)
- **The NA62 method**: measurement of the π^0 TFF slope parameter from the analysis of the decay $K^\pm \rightarrow \pi^\pm \pi^0$ ($K_{2\pi}$) followed by π_D^0
 - Clean sample of tagged π^0
 - Stringent kinematic constraints
 - Effective background suppression
 - Preliminary results from the 2007 data
- **NA62 data (2007)** $\sim 2 \times 10^{10}$ K^\pm decays in the fiducial region
 - Data taking optimized for the R_K measurement (identification of e^\pm from $K^\pm \rightarrow e^\pm \nu$)
 - Factor 10 reduction of beam intensity wrt NA48/2:
 - Efficient minimum bias trigger configuration
 - Minimum accidental background

The NA62 layout in 2007



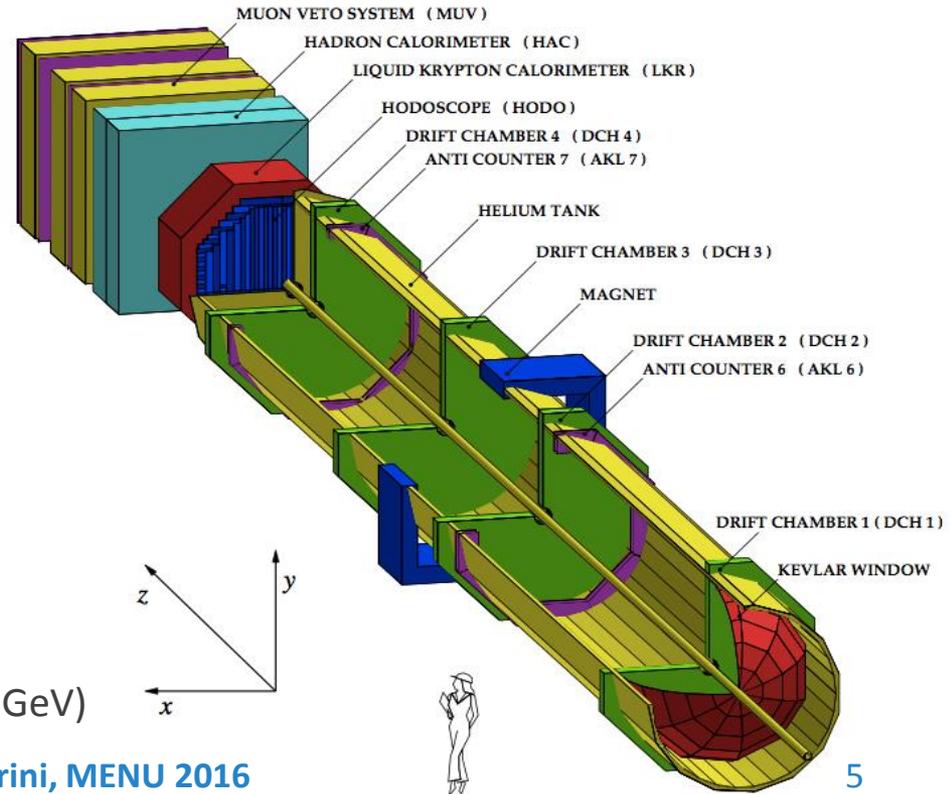
Beam layout:

- Alternate K^\pm beam (NA48/2)
- $p_K = (74 \pm 2) \text{ GeV}/c$

Main trigger: electron from K_{e2}
 \rightarrow Efficient for π_D^0 decays

Principal sub-detectors:

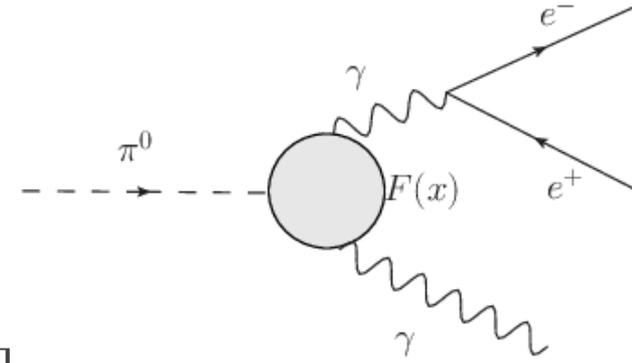
- **Magnetic spectrometer (4 DCHs)**
 - 4 views/DCH \rightarrow high efficiency
 - $\sigma_p/p = 0.48\% \oplus 0.009\% \cdot p [\text{GeV}/c]$
- **Scintillator hodoscope (HOD)**
 - Low-level trigger, time measurement (150 ps)
- **Liquid Krypton EM calorimeter (LKr)**
 - High granularity, quasi-homogeneous
 - $\sigma_E/E = (3.2/\sqrt{E} \oplus 9/E + 0.42)\% [E \text{ in GeV}]$
 - $\sigma_x = \sigma_y = (4.2/\sqrt{E} \oplus 0.6) \text{ mm} (1.5 \text{ mm @ } 10 \text{ GeV})$



The Dalitz Decay $\pi^0 \rightarrow e^+ e^- \gamma$

- Kinematic variables x and y :

$$x = \left(\frac{M_{e^+e^-}}{m_{\pi^0}} \right)^2 = \frac{(p_{e^+} + p_{e^-})^2}{m_{\pi^0}^2}, \quad y = \frac{2p_{\pi^0}(p_{e^+} + p_{e^-})}{m_{\pi^0}^2(1-x)}$$



- Differential decay width: $[r^2 = (2m_e/m_{\pi^0})^2 \equiv x_{min}]$

$$\frac{1}{\Gamma(\pi_{2\gamma}^0)} \frac{d\Gamma(\pi_D^0)}{dx dy} = \frac{\alpha}{4\pi} \frac{(1-x)^3}{x} \left(1 + y^2 + \frac{r^2}{x} \right) (1 + \delta(x, y)) |F(x)|^2$$

Transition Form Factor

Radiative corrections

- Form factor varies slowly:

Approximation $F(x) \approx 1 + ax$, a : TFF slope parameter

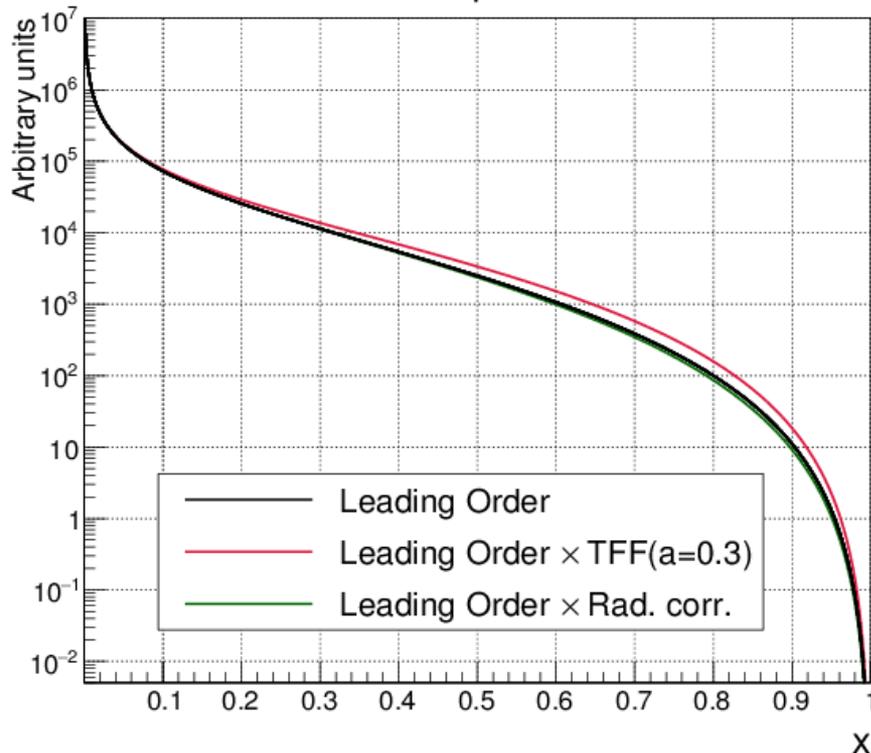
- The π^0 Transition Form Factor (TFF)

- The comparison of TFF slope prediction with model independent measurements is a remarkable test of the theoretical models

$\pi_D^0: d\Gamma/dx$ and Transition Form Factor

$$\frac{1}{\Gamma(\pi_{2\gamma}^0)} \frac{d\Gamma(\pi_D^0)}{dx} = \frac{2\alpha}{4\pi} \frac{(1-x)^3}{x} \left(1 + \frac{r^2}{2x}\right) \sqrt{1 - \frac{r^2}{x}} (1 + \delta(x, y))(1 + ax)^2$$

Dalitz x Spectrum



- π^0 TFF slope from the **Vector Meson Dominance (VMD)** model: $a \approx 0.03$
- The π^0 TFF theoretical models enter the **prediction of important observable quantities**:
 - The rate of the rare decay $\pi^0 \rightarrow e^+e^-$
 - The hadronic light-by-light scattering contribution to $(g - 2)_\mu$
- See recent overview and references in: **A. Nyffeler, arXiv:1602.03398 [hep-ph]**

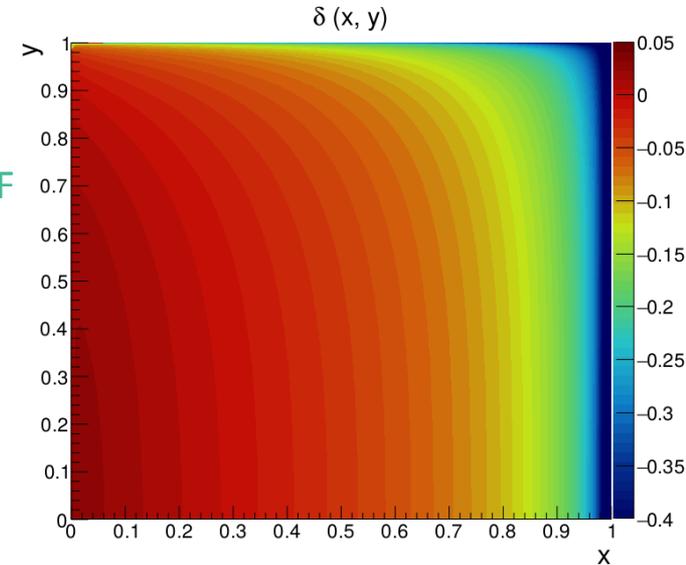
The Radiative Corrections

Radiative correction factor $\delta(x, y)$:

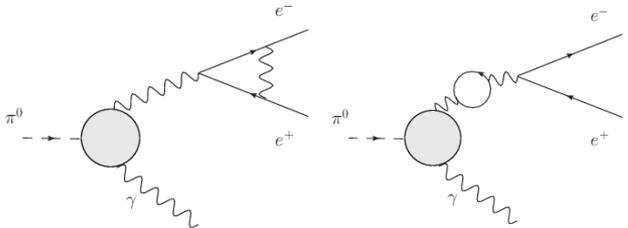
$$\frac{d^2\Gamma}{dxdy} = \left(\frac{d^2\Gamma}{dxdy} \right)_0 (1 + \delta(x, y))$$

Same magnitude as TFF

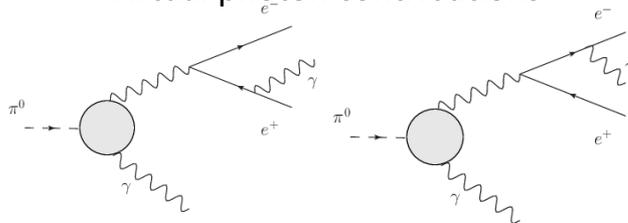
- Essential corrections for the π^0 TFF measurement
- Radiative corrections implemented in the MC π_D^0 event generator, including internal bremsstrahlung photons
- Exploit the Mikaelian and Smith approach revisited by T. Husek et al.



Mikaelian and Smith
[PR D5, 1972, 1763]

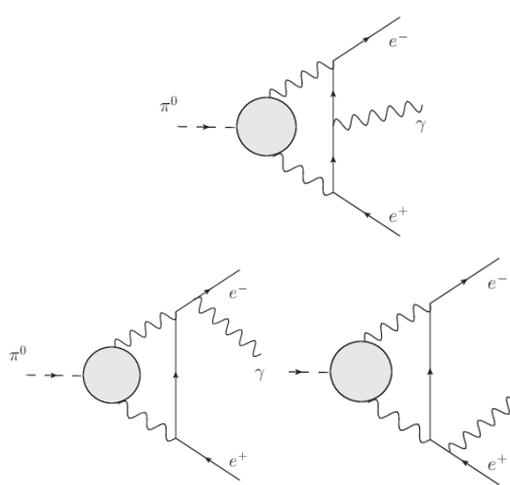


Virtual photon contributions

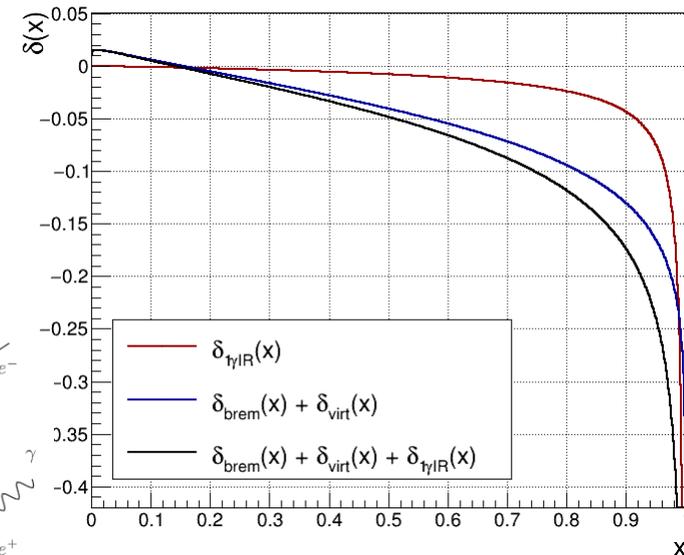


Bremsstrahlung contribution

T. Husek et al.
[PR9 D92, 2015, 054027]



1-loop 1-photon irreducible contributions



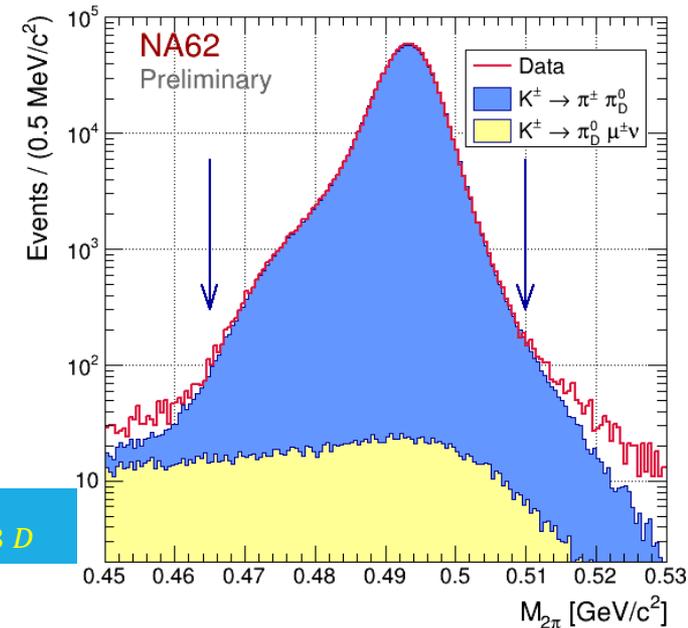
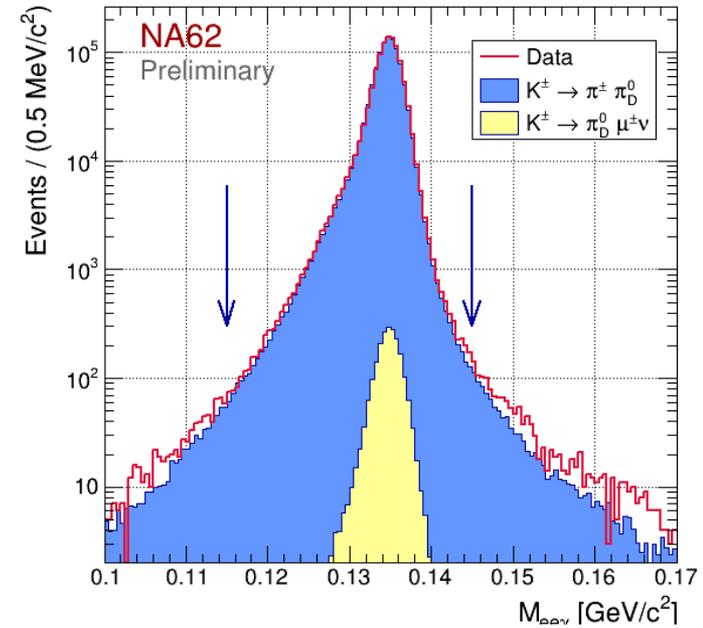
$K^\pm \rightarrow \pi^\pm \pi^0; \pi^0 \rightarrow \gamma e^+ e^-$ selection

The NA62 2007 data sample:

- $\sim 2 \times 10^{10}$ kaon decays in the fiducial region
- $\sim 5 \times 10^9$ boosted π^0 mesons from $K_{2\pi}$
 - Mean free path of π^0 : few μm (negligible)
- $\sim 6 \times 10^7 \pi_D^0$ decays produced

Main selection criteria:

- 3-track vertex topology
- One photon candidate in LKr e.m. calorimeter
- Reconstructed $e^+ e^- \gamma$ invariant mass:
 $115 \text{ MeV}/c^2 < M_{ee\gamma} < 145 \text{ MeV}/c^2$
- Reconstructed $\pi^\pm \pi^0$ invariant mass:
 $465 \text{ MeV} < M_{2\pi} < 510 \text{ MeV}/c^2$
- Reconstructed Dalitz x variable:
 $0.01 < x < 1$
- Missing momentum consistent with the beam size
- 1.05×10^6 fully reconstructed π_D^0 events

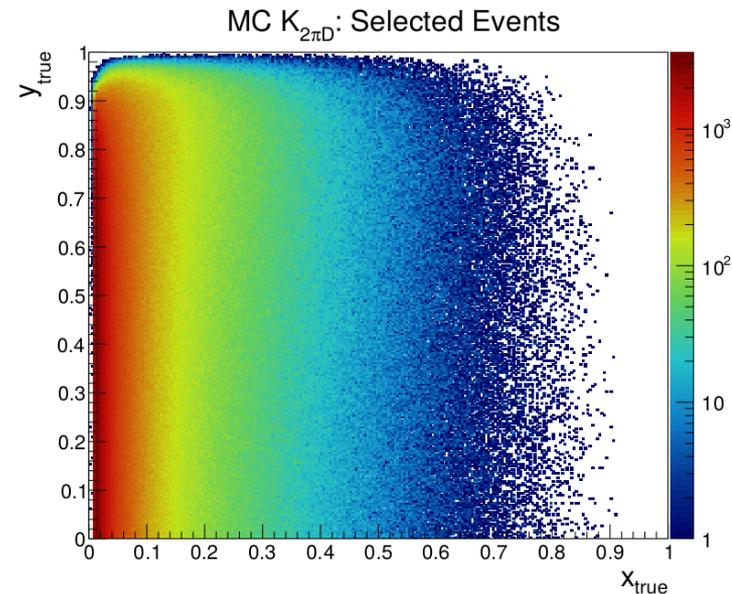
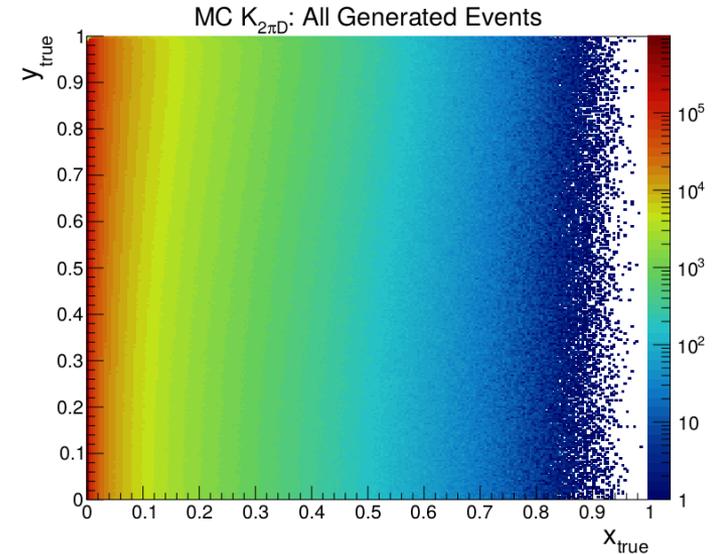
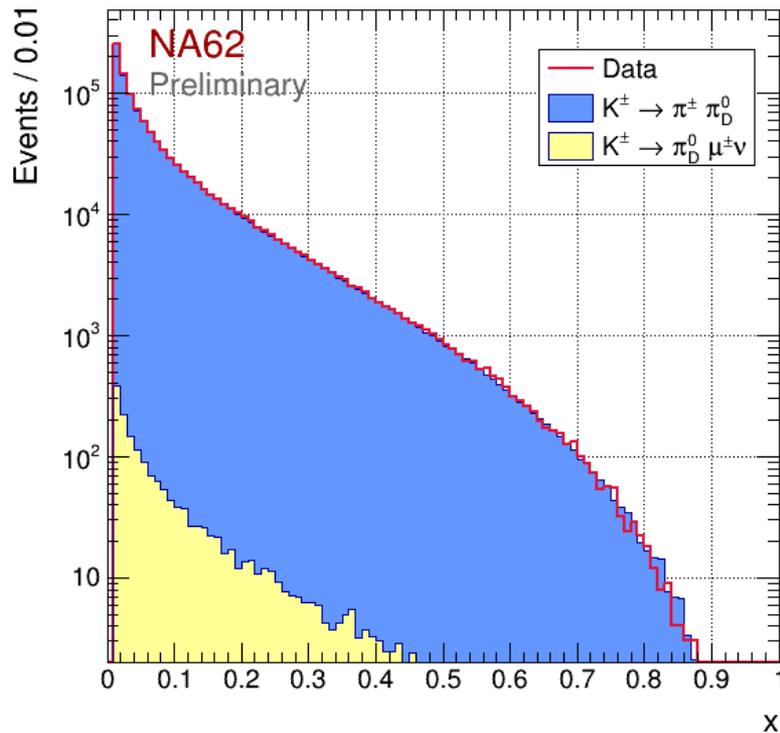


Small contribution from $K_{\mu 3 D}$

π_D^0 Decay Sample

1.05×10^6 fully reconstructed
 π_D^0 events with $x > 0.01$

The TFF slope is obtained by adjusting the simulation to the data x spectrum:
best data/MC agreement from a χ^2 test



The π^0 TFF: preliminary results - I

Fit procedure:

- Split reconstructed Dalitz x data into equal population bins
- Compare data with simulation (constant TFF slope: $a_{sim} = 0.032$)
 - To obtain simulated x distributions, corresponding to different a slope: re-weight simulated events with weight $w(a) = (1 + ax_{true})^2 / (1 + a_{sim}x_{true})^2$
- Minimize $\chi^2(a)$ Data/Simulation comparison wrt a

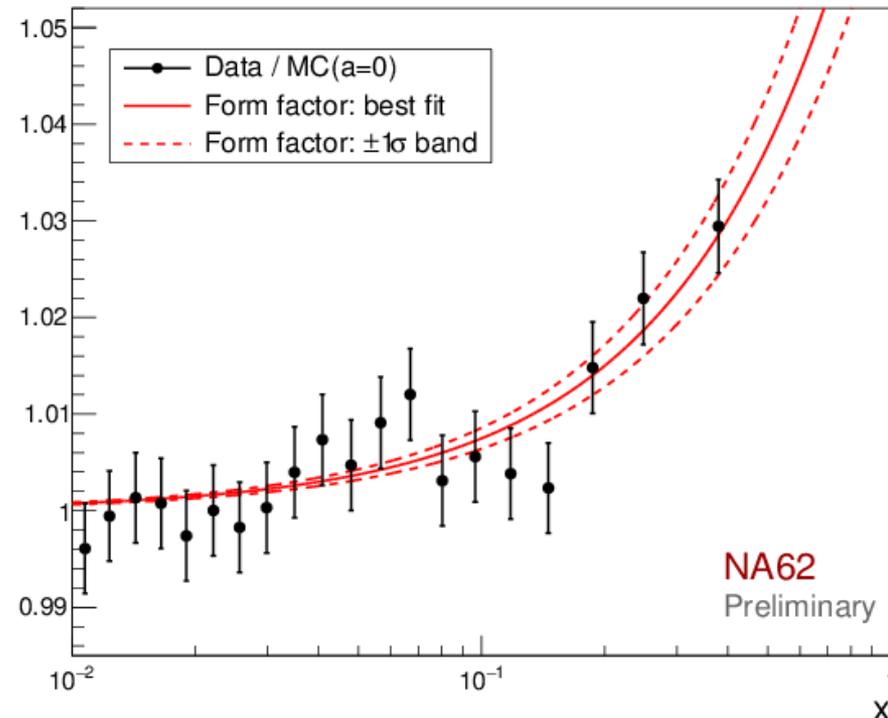
Central PDG value

Fit result:

- $a = (3.70 \pm 0.53_{stat}) \times 10^{-2}$
- ($\chi^2/n.d.f. = 52.5/49$, p-value: 0.34)

Fit result illustration:

- Data/Simulation ($a = 0$) ratio
- 20 equal population bins
- Points are in bin barycenters



The π^0 TFF: preliminary results - II

Systematic Uncertainties

| Source | $\delta a (\times 10^2)$ |
|------------------------------------|--------------------------|
| Statistical – Data | 0.49 |
| Statistical – MC | 0.20 |
| Beam momentum spectrum simulation | 0.30 |
| Spectrometer momentum scale | 0.15 |
| Spectrometer resolution | 0.05 |
| LKr non-linearity and energy scale | 0.04 |
| Particle mis-ID | 0.08 |
| Accidental background | 0.08 |
| Neglected π_D^0 sources in MC | 0.01 |

NA62 preliminary result on π^0 TFF slope parameter:

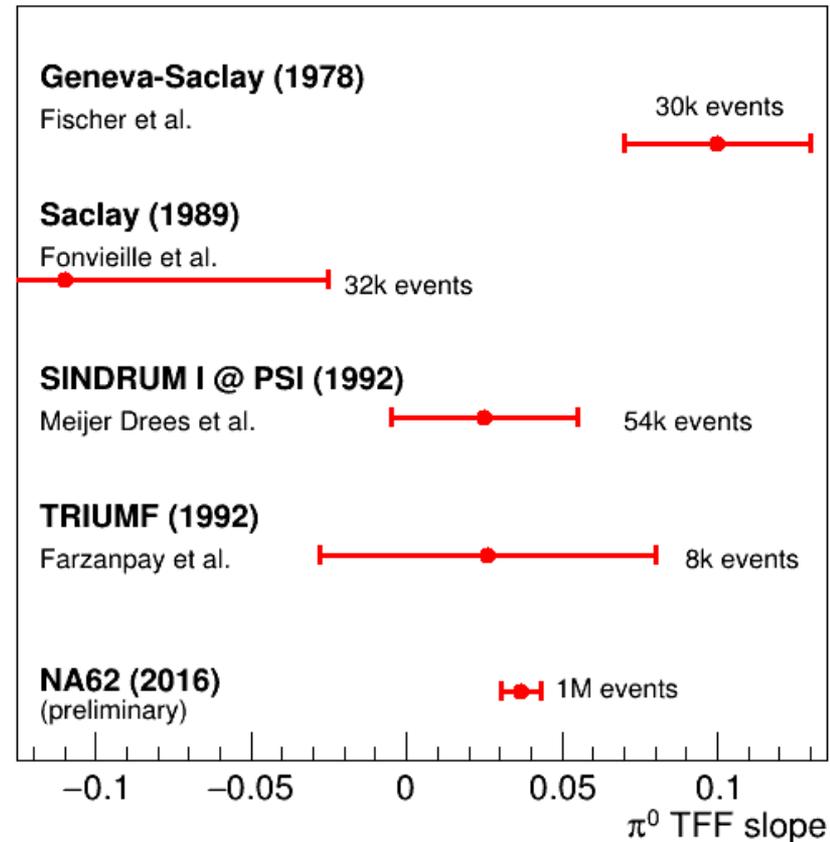
$$a = (3.70 \pm 0.53_{stat} \pm 0.36_{syst}) \times 10^{-2} = (3.70 \pm 0.64) \times 10^{-2}$$

(new preliminary results)

Comparison with world data

- The NA62 results are compared with those of previous experiments using π_D^0 decays to extract the TFF slope from the reconstructed x spectrum.
- Only the measurements which account for radiative corrections are listed.
- The NA62 preliminary measurement, based on 2007 data, is the most precise up-to-date in the time-like region of momentum transfer
- The positive slope value is directly observed with $> 6\sigma$ for the first time

π^0 TFF Slope Measurements from π_D^0



$$a = (3.70 \pm 0.64) \times 10^{-2}$$

And theory expectations

- Chiral perturbation theory:

K. Kampf et al., EPJ C46 (2006), 191.

$$a = (2.90 \pm 0.50) \times 10^{-2}$$

- Dispersion theory:

M. Hoferichter et al., EPJ C74 (2014), 3180.

$$a = (3.07 \pm 0.06) \times 10^{-2}$$

- Two-hadron saturation (THS) model:

T. Husek et al., EPJ C75 (2015) 12, 586.

$$a = (2.92 \pm 0.04) \times 10^{-2}$$

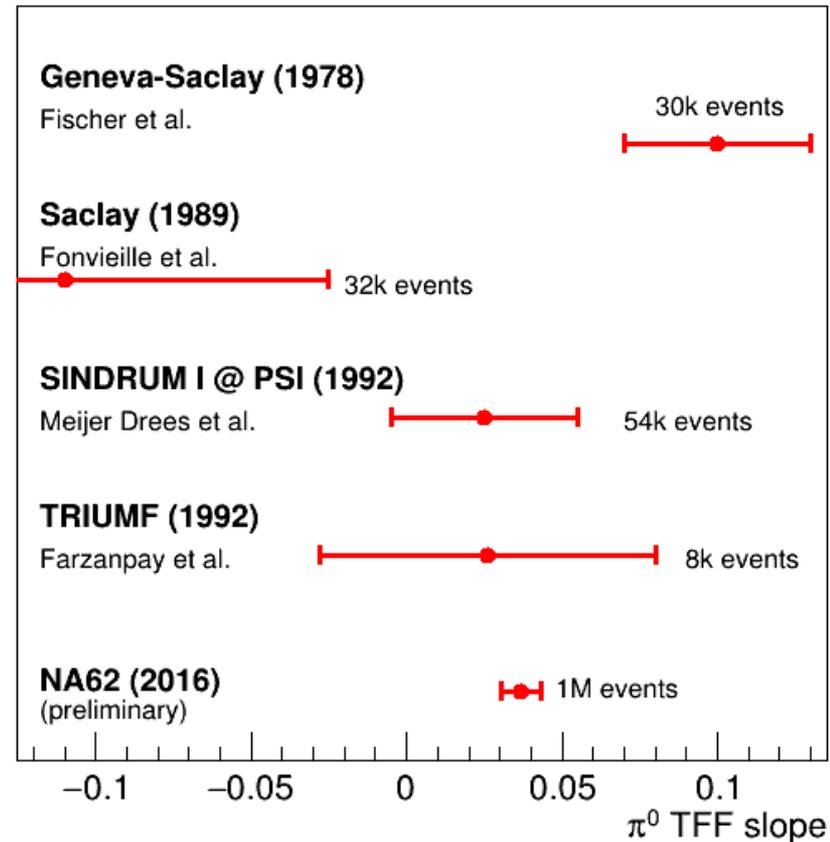
CELLO measurement:

- Extrapolation of space-like momentum region data fit to VMD model:

H. J. Behrend et al., Z. Phys. C49 (1991), 401.

$$a = (3.26 \pm 0.26_{stat}) \times 10^{-2}$$

π^0 TFF Slope Measurements from π_D^0



$$a = (3.70 \pm 0.64) \times 10^{-2}$$

Conclusions

- NA62 has presented **new preliminary results** on the measurement of the π^0 Transition Form Factor slope parameter:

$$a = (3.70 \pm 0.53_{stat} \pm 0.36_{syst}) \times 10^{-2} = (3.70 \pm 0.64) \times 10^{-2}$$

- The result is based on the NA62 **2007 data statistics**
- The selected neutral pions are produced from $K^\pm \rightarrow \pi^\pm \pi^0$ decays
- About **1 million π^0 Dalitz** decays have been fully reconstructed
- The **precision of the TFF measurement has been improved** in the time-like momentum region
- Final result is in preparation:
 - Finalize systematic studies.