Search for dark photon at NA48/2, and measurement of $\pi^0$ form factor

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On behalf of the NA48/2 collaboration

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Outline

- NA48/2 experiments at CERN SPS
- Search for the dark photon in $\pi^0$ decays
- Measurement of $\pi^0$ form factor
- Conclusion and prospects
The NA48/2 and NA62 experiments @ SPS

NA48/2 collaboration: 15 institutes from 8 countries:
NA62-RK collaboration: 30 institutes from 13 countries
**NA48/2 data taking**: 4 months in 2003-04 \((K^\pm)\) 60 GeV Simultaneous \(K^\pm\) beam

**NA62-RK data taking**: 4 months in 2007 \((K^+)\) 74 GeV mostly \(K^+\) only beam

**Magnetic Spectrometer**
- 4 drift chambers and a dipole magnet

\[
\frac{(p)}{p} = (1.02 \pm 0.044p)\% \quad p \text{ in GeV/c}
\]

**Liquid Krypton EM calorimeter (LKr)**
- High granularity (13248 cells of 2x2 cm²)
- Quasi-homogeneous, 7m³ liquid Kr \((27X_0)\)

\[
\frac{\sigma(E)}{E} = \frac{3.2\%}{\sqrt{E}} \oplus \frac{9\%}{E} \oplus 0.4\% \quad E \text{ in GeV}
\]
The $\pi^0_D$ decay form factor $|F(x)|$

$\pi^0_D: \pi^0 \rightarrow e^+ e^- \gamma$ differential decay rate:

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

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

First order Form Factor $F(x)$:

- $|F(x)| \sim 1 + ax \quad a = \text{FF slope parameter}$
- Need sample with unbiased $\pi^0$ Dalitz decays.

A clean and large sample of $\pi^0_D$ can be obtained at NA62-RK:

- Source: $K^\pm \rightarrow \pi^\pm \pi^0$ tagged neutral pion ($\sim 10^9 \pi^0 \rightarrow \pi^0_D \sim 10^7$ decays).
- Avoid any trigger bias on the data sample (minimum bias trigger).
- NA62-RK lower statistic but much better trigger conditions wrt to NA48/2.
Measuring $\pi^0_D$ transition FF slope

- Fit the differential decay width as function of $x$:

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

- Theoretical expectation: $a \sim 0.03$ VMD models.

- FF is a tiny effect:
  - Need very precise measurement of $x$
  - Proper radiative corrections $\delta(x, y)$

- Relevant measurement to improve precision calculation of light by light scattering contribution to muon $g-2$. 

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Computing $\pi^0_D$ radiative correction $\delta(x,y)$

Original paper by Mikaelian and Smith: 
Phys. Rev. D5(1972) 1763

Recent improvement Husek, Kampf and Novotny 

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

Husek, Kampf and Novotny 
Parameterization introduced in MC to improve agreement with data.

Simulation includes emission of radiative photons
**NA62-RK \( \pi^0_D \) selection**

- **Source** \( K^\pm \rightarrow \pi^\pm \pi^0 \) and \( K^\pm \rightarrow \pi^0 \mu^\pm \)
  - Tag the \( \pi^0 \) and select its Dalitz decay

- **Main selection cuts:**
  - Three good track candidates
  - One good gamma candidate
  - Reconstructed \( e^+e^-\gamma \) invariant mass region: 
    \( 115 \text{MeV}/c^2 < M_{ee\gamma} < 145 \text{MeV}/c^2 \)
  - Reconstructed \( \pi^+\pi^- \pi^0 \) invariant mass region: 
    \( 465 \text{MeV}/c^2 < M_{\pi^+\pi^-\pi^0} < 510 \text{MeV}/c^2 \)
  - Reconstructed Dalitz variable : \( 0.01 < x < 1 \)

- **Selected data sample NA62-RK 2007:**
  - \( 1.05 \times 10^6 \pi^0_D \) candidates
FF slope fit measurement

- Split the reconstructed Dalitz x data into 20 equi-populated bins
- Compare data with MC TFF slope $a = 0.032$
- Re-weight MC events to get simulated distributions with different values of $a$:
  \[ w(a) = \frac{(1 + a x_{tr})^2}{(1 + a_{sim} x_{tr})^2}, \]
- Perform $\chi^2$ test to extract best $a$

**NA62-RK preliminary fit result:**

\[ a = (3.70 \pm 0.53_{\text{stat}} \pm 0.36_{\text{syst}}) \times 10^{-2} \]

\[ \chi^2 / \text{d.o.f} = 52.5 / 49 \]
The NA62 preliminary measurement is the most precise FF measurement to-date.

Final result and paper to come soon!
What is the universe made of?

- Standard model only includes <20% of the matter in the universe
  - We only know dark matter interacts gravitationally
- Many open questions
  - What is dark Matter made of?
  - How dark matter interact, if it does, with SM particles?
  - Does one or more new dark force exist?
  - How complex is the dark sector spectrum?
The simplest hidden sector model just introduces one extra U(1) gauge symmetry and a corresponding gauge boson: the “dark photon” or $A'$ boson.

The coupling constant and the charges can be generated effectively through the kinetic mixing between the QED and the new U(1) gauge bosons.

$$\mathcal{L}_{\text{mix}} = -\frac{\epsilon}{2} F_{\mu\nu}^{\text{QED}} F_{\mu\nu}^{\text{dark}}$$

In this case the new coupling constant $= \epsilon e$ is just proportional to electric charge and it is equal for both quarks and leptons.

As in QED, this will generate new interactions with SM fermions of type:

$$\mathcal{L} \sim g' q_f \bar{\psi}_f \gamma^\mu \psi_f U'_\mu$$

Not all the SM particles need to be charged under this new symmetry.

In the most general case $q_f$ is different in between leptons and quarks and can even be 0 for quarks. P. Fayet, Phys. Lett. B 675, 267 (2009)
Dark photon and \( g-2_\mu \)

**g-2 in the standard model**

About 3\( \sigma \) discrepancy between theory and experiment. Could be due to hadronic uncertainties on the Light by Light scattering?

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**g-2 and A’**

Additional diagram with dark photon exchange can fix the discrepancy! (with sub GeV A’ masses 😊)

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M. Pospelov
Dark photon searches status

- Visible decays: $A' \rightarrow ee, \mu\mu, \pi\pi$
  - Kinetic mixed dark photons simplest model

- Favored parameters values explaining muon $g-2$ (green band)
  - $A'$-boson light 10-100 MeV

- Status of dark photon searches
  - Beam dump experiments (grey)
  - Fixed target (Apex, A1)
  - Mesons decays (Babar, KLOE, Wasa)

- Theoretical exclusion from $g_e-2$ $g_\mu-2$
  - Tight limit form $\alpha_{EM}$ (red filled area) [PhysRevD.86.095029]

- Much less constraints on "Invisible" decay mode
  - If $M_\chi < M_{A'}/2$, $A' \rightarrow \chi\chi$, $\varepsilon^2$ suppression to all visible modes
  - No assumption on $\alpha_D$ and no kinetic mixing
Dark photon in $\pi^0$ decays

Production (kinetic mixing)

$\pi^0 \rightarrow u, s$

Decay (if no light dark sector)

$(A' \rightarrow e^+ e^-) = \frac{1}{3} \frac{2M_{A'}}{M_{A'^2}} \sqrt{1 + \frac{4m_e^2}{M_{A'^2}^2}} \left(1 + \frac{2m_e^2}{M_{A'^2}^2}\right)$

$BR(p^0 \rightarrow gA') \approx 2 \frac{BR(p^0 \rightarrow A')}{BR(p^0 \rightarrow \gamma \gamma)} \approx 2 \left| F(M_{A'^2}) \right|^2 \left(1 + \frac{M_{A'^2}^2}{M^2}\right)^3$

$BR(\pi^0 \rightarrow \gamma A') / BR(\pi^0 \rightarrow \gamma \gamma) \text{ vs } M_{A'}$

valid for $\varepsilon^2 \ll 1$

$M_{A'} < M_{\pi^0}$ and no lighter wrt A' dark sector particles exist $BR(A' \rightarrow e^+ e^-) = 1$

Batell, Pospelov and Ritz, PHYS. REV. D 80, 095024 (2009)
Number of kaon decays in NA48/2 ('03/'04): \( N_K \approx 2 \cdot 10^{11} \)
- \( 5 \cdot 10^{10} \pi^0 \) tagged decays from \( K^\pm \to \pi^\pm \pi^0 \) and \( K^\pm \to \pi^0 \mu^+ \nu \) decays

Exclusive search for the decay chain \( \pi^0 \to \gamma A', A' \to e^+e^- \)
- Search for a narrow peak in the \( e^+e^- \) invariant mass.
- High efficiency trigger chain for 3-track vertices throughout all the data taking
- Very good spectrometer mass resolution: \( \sigma_{M_{ee}} \approx 0.012 \times M_{ee} \)

DP final state \( \pi^0 \to \gamma A', A' \to e^+e^- \) identical to \( \pi^0_D \to \gamma e^+e^- \);
- Main background is \( K^\pm \to \pi^\pm \pi^0_D \) : \( \text{BR}(K_{2pD}) = 2.4 \times 10^{-3} \)
- Sensitivity is limited by the irreducible \( K_{2pD} \) background.

Signal acceptance:
- depending on \( M_{A'} \) from 4.5% down to 0.5% for high values \( M_{A'} \).

A total of \(~1.7 \times 10^7\) candidates collected during 2003-04 data taking
Data sample: $K_{2\pi D} + K_{\mu 3D}$ selection

**$K^{\pm} \rightarrow \pi^{\pm} \pi^0_D$ selection**
- $|M_{ee\gamma} - M_{\pi^0}| < 8 \text{ MeV/c}^2$
- $|M_{\pi ee\gamma} - M_K| < 20 \text{ MeV/c}^2$
- No missing $P_T$: $< 5 \cdot 10^{-4} \text{GeV}^2/c^2$

$K^{\pm} \rightarrow \pi^{\pm} \pi^0_D$: $1.38 \cdot 10^7 \text{ evt}$

**$K^{\pm} \rightarrow \mu^{\pm} \pi^0_D$ selection**
- $|M_{ee\gamma} - M_{\pi^0}| < 8 \text{ MeV/c}^2$
- $M^2_{miss} < 0.01 \text{GeV}^2/c^4$
- Missing $P_T$ due to neutrino: $5 \cdot 10^{-4} < P_T < 0.04 \text{ GeV}^2/c^2$

$K^{\pm} \rightarrow \mu^{\pm} \pi^0_D$: $3.1 \cdot 10^6 \text{ evt}$

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Statistical significance

- Scanned DP mass range: 9 MeV/c²<M_{DP}<120 MeV/c².
  - Variable DP mass step: 1.5(M_{A'})
  - DP search window: 0.5(M_{A'})
  - 404 DP mass hypothesis tested

- Confidence intervals for N_{A'} are computed from:
  - N_{exp}, N_{obs} and \delta N_{exp}, \delta N_{obs} in the signal mass window
  - Frequentist confidence intervals Rolke-Lopez method.

- Local significance never exceeds 3 \sigma: no dark Photon signal observed
Improvement of the existing limits in the range 9-70 MeV/c^2.

If DP couples to SM through kinetic mixing and decays only to SM fermions, it is ruled out as the explanation for anomalous \((g-2)_\mu\).

Sensitivity limited by irreducible \(D^0\) background: upper limit on \(\epsilon^2\) scales as \(\sim (1/N_K)^{1/2}\), modest improvement with larger data samples.
Favored region \((g-2)\mu\) still available in the low mass region.
Impact of NA48/2 measurement

Favored region \((g-2)\mu\) completely excluded by NA48/2 measurement!

Final result: **PLB746 (2015) 178**
The Be$^8$ anomaly and the proto-phobic fifth force

PRL 116, 042501 (2016)

$\pi^0$-phobia = $\rho^+$-phobia
To avoid NA48/2, prohibit $\pi^0$ decay to $X\gamma$

FROM QUARK CONTENT

$Q_u Q'_u - Q_d Q'_d = 0 \quad Q'_d = -2Q'_u$
ProtoPhobic coupling

NA48/2 it’s not a dark photon!
Conclusions

- **NA62-RK** performed the most precise measurement of the $\pi^0$ TFF
  - $a = (3.70 \pm 0.53_{\text{stat}} \pm 0.36_{\text{syst}}) \times 10^{-2}$ \text{PRELIMINARY}
  - Can be used to reduce uncertainties in the light by light scattering contribution to the $(g-2)_\mu$
  - Final results and paper in preparation

- **NA48/2** set a limit on the dark photon searches (PLB746 (2015) 178)
  - Improvement of the existing limits for visible decays in the range 9-70 MeV/c$^2$. 
  - Allowed value of $\varepsilon^2$ has been pushed well below $10^{-6}$ at 90% CL
  - Assuming kinetic mixing and dark photon decaying to lepton pairs only the whole favored by $(g-2)_\mu$ region has been excluded
  - Several new physics models constrained by the NA48/2 measurement