A search for the dark photon in the OKA experiment

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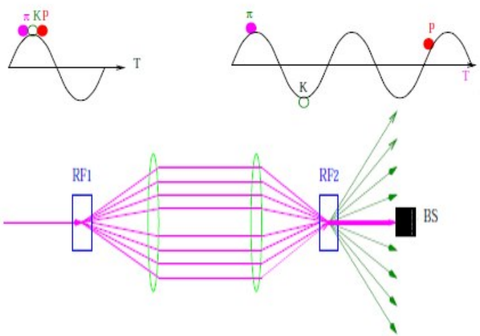
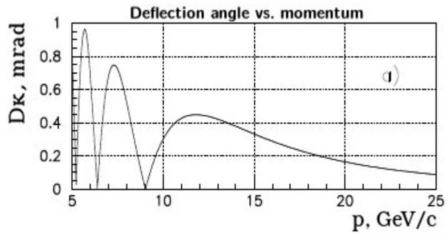
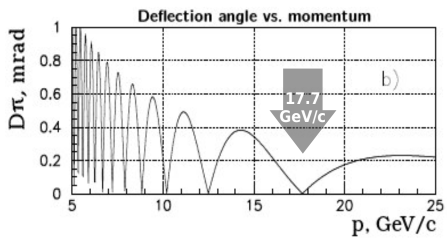
OKA: the experiment with RF-separated high energy $K^{\pm}$ @ U-70

RF separation with Panofsky scheme is realised. It uses two Karlsruhe-CERN SC RF deflectors. Sophisticated cryogenic system, built at IHEP provides superfluid He for cavities cooling.



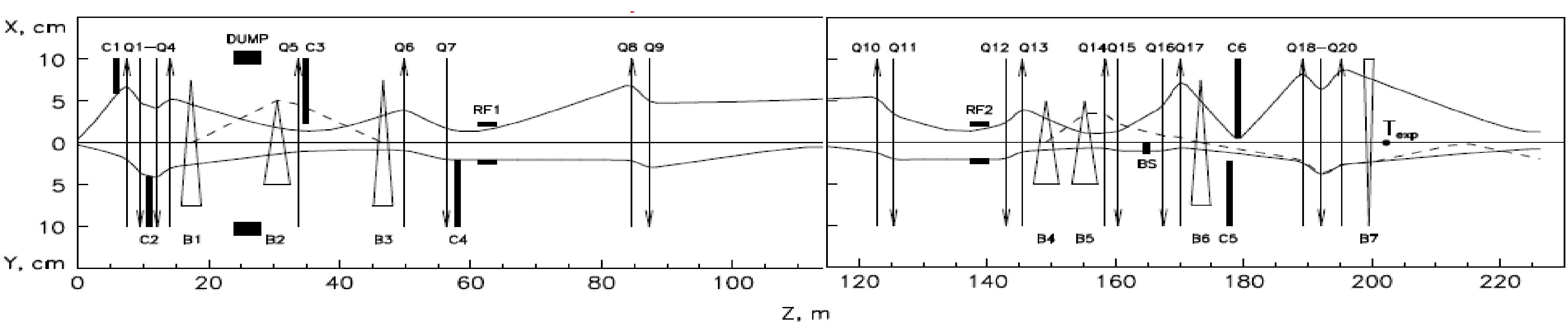




Operating frequency,(S-band)	2865 MHz
Wavelength, λ	~10.5 cm
Effective deflector length	2.74 m
Number of cells/deflector	104
Mean deflecting field	~1(0.6) MV/m
Working temperature	1.8 K

Main beam parameters :

Primary proton beam energy	50 GeV
Primary proton beam intensity	$7 \cdot 10^{12}$ ppp
Secondary beam momentum	17.7 GeV/c
Length of the beam line	~200m
K^+ intensity after RF sep	$0.5 \cdot 10^{6}$
K^+ in the beam	12.5%(up to 20%)



OKA setup at the U-70 accelerator complex

RF deflector in the beam line

Liquid He lines

Tail of the beam line

General view of the OKA setup

Decay volume Veto System

ECAL, matrix hodoscope,
DT, ST chambers (left to right).

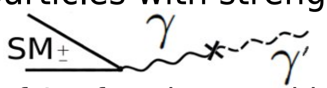
Dark photon

Boson (spin=1) introduced by a new Abelian gauge symmetry, $U(1)_D$
(such as, all the fields of the SM are singlets)

massive ($A' \equiv \gamma'$) /spontaneously broken $U(1)_D$/

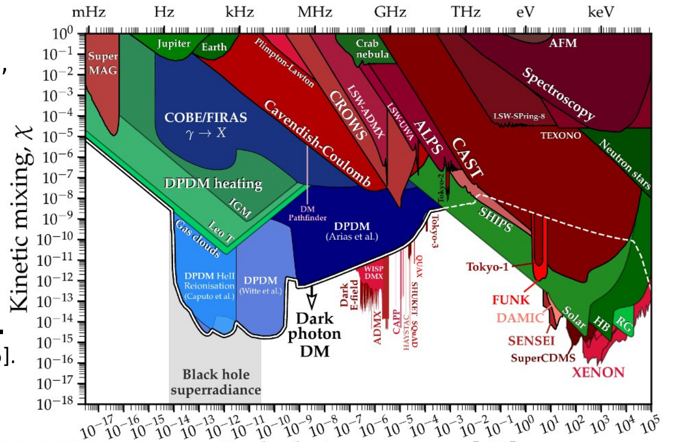
can interact with SM particles through a renormalizable operator, $\chi e A'_\mu J^\mu_{EM}$, which involves
– electromagnetic current J_{EM}
– small parameter χ due to the kinetic mixing between the dark and SM Abelian gauge fields
(A' couples to charged particles with strength χqe).

A' can be produced:



– in decays or scatterings of SM fermions and hadrons
– could decay into (el.)charged fermions and mesons
– could decay into DM particles (invisible)

Numerous experiments (and cosmological, astrophysical considerations) made strict limitations on χ in wide mass range of A'/γ'.
See [axriv:2105.04565].

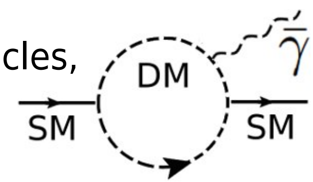


Phys.Rev.D 104 (2021) 9, 095029
arxiv:2105.04565
FIG. 1. Current constraints on the DP's mass, m_X, and kinetic mixing parameter with the SM photon, χ. The general colour-scheme is: cosmological bounds in blue, experimental bounds in red, and astrophysical bounds in green. The thick white line that divides the parameter space in two is the upper limit for which DPs are a viable candidate for 100% of the DM.

massless ($\bar{\gamma}$) /$U(1)_D$ remains unbroken/

– does not interact directly with SM objects
– while it could interact with massive DM particles, which may interact with SM particles

Interaction ($\bar{\gamma} \Longleftrightarrow$ SM) goes only via loops with DM particles, hence different physics from massive case A'.

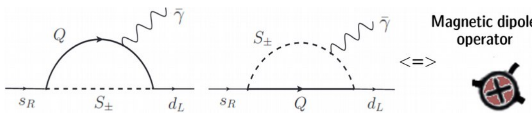


New proposals: to search for $\bar{\gamma}$ assuming minimal extension of SM; consider [$K^+ \to \pi^+ \pi^0 \bar{\gamma}$] as a simplest example (and similar) which can be mediated by FCNC transition of [$s \to d\bar{\gamma}$] caused by dipole -type coupling generated at one loop at dark sector degrees of freedom:

M. Fabbrichesi et.al, [Phys. Rev. Lett. 119, 031801 (2017)], [arxiv:1705.03470];
J.-Y.Su, J.Tandean [Eur.Phys.J.C 80 (2020) 9, 824], [arxiv:2006.05985]

Theoretical estimates for $K^+ \to \pi^+\pi^0\bar{\gamma}$

In [Phys. Rev. Lett. 119, 031801 (2017)] a simplified extension of SM is proposed:



+ new heavy dark fermion Q [singlet in SM, charged under unbroken $U(1)_D$];
+ new heavy messengers (scalar particles) S_L, S_R charged under $U(1)_D$;
SM fermions couple to the dark fermion by means of a Yukawa-like interaction. Messenger fields S± couple to both left- and right- handed SM fermions with a strength of $g_L/\sqrt{2}$ and $g_R/\sqrt{2}$.
Assumed: common mass for the dark fermion and the lightest scalar field, which identified with the new-physics scale **Λ**.

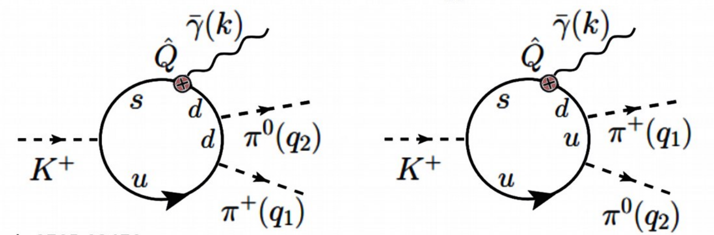
The estimated amplitude and decay rate:

$$\hat{M} \equiv \langle \bar{\gamma}\, \pi^+\pi^0 | \, \mathcal{H}_{eff}^{\Delta S=1} \, | K^+ \rangle$$

$$\frac{d^2\Gamma}{dz_1 dz_2} = \frac{m_K}{(4\pi)^3} |M(z_1,z_2)|^2 \{z_1 z_2 [1-2(z_1+z_2) - r_1^2 - r_2^2] - r_1^2 z_2^2 - r_2^2 z_1^2\}$$

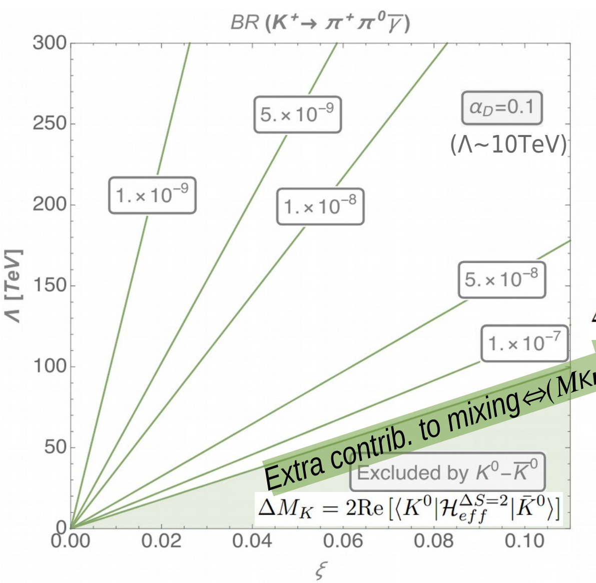
where $z_i = k \cdot q_i / m_K^2$ and $r_i = M_{\pi_i}/m_K$

calculation is performed within chiral quark model, χQM, in which quarks are coupled to hadrons by an effective interaction so that matrix elements can be evaluated by loop diagrams (several free parameters).



arxiv:1705.03470

χQM diagrams for the process $K^+ \to \pi^+\pi^0\tilde{\gamma}$. The ⊕ stands for the insertion of the magnetic dipole operator $\hat{Q}$



$BR(K^+ \to \pi^+\pi^0\bar{\gamma})$ as a function of the effective scale Λ and coupling $\xi = g_L g_R/2$, for a representative choice of the coupling strength $\alpha_D = 0.1$. arxiv.org:1705.03470

$$\mathrm{BR}(K^+ \to \pi^+\pi^0\bar{\gamma}) \sim \alpha_D \frac{\xi^2}{\Lambda^2}$$

$$\Delta M_K = 8.47 \times 10^{-13} \frac{\xi^2}{\Lambda^2}$$

(ξ^2/Λ^2)

$$\mathrm{BR}(K^+ \to \pi^+\pi^0\bar{\gamma}) \lesssim 1.6 \times 10^{-7}$$

Several uncertainties:

- M, the mass of the constituent quarks ~200MeV (err~5%) however an increase in M from 200MeV to 250 MeV => Br=Br*2.5;
- The $O(p^4)$ CHPT corrections expected to be small;
- QCD parametrs and renormalisation at low energy scale;
- dependence on $\alpha_D = (e_D)^2/(4\pi)$ parameter (cosmological relic density put bounds on the ratio α_D/Λ^2)

Theoretical, model-independent restrictions on $K^+\to\pi^+\pi^0\bar{\gamma}$

In [Eur.Phys.J.C 80 (2020) 9, 824] authors revisited FCNC [$s\to d\bar{\gamma}$] approach for [$K^+\to\pi^+\pi^0\bar{\gamma}$]
(they also considered K_L and K_s decays and provided
model independent constraints for $K^+\to\pi^+\pi^0\bar{\gamma}$).

The Lagrangian: $\mathcal{L}_{ds\bar{\gamma}} = -\bar{d}(\mathbb{C}+\gamma_5\mathbb{C}_5)\sigma^{\mu\nu}s\,\bar{F}_{\mu\nu} + \text{H.c.}$

$\bar{F}_{\mu\nu} = \partial_\mu \bar{A}_\nu - \partial_\nu \bar{A}_\mu$ is the field-strength tensor of $\bar{\gamma}$, and $\sigma^{\mu\nu} = i[\gamma^\mu,\gamma^\nu]/2$.

$\mathbb{C}$ and $\mathbb{C}_5$ – constants which have the dimension of inverse mass and can be complex.

The influence of $\mathcal{L}_{ds\bar{\gamma}}$ in for the [$K^+\to\pi^+\pi^0\bar{\gamma}$] decay done in the framework of chiral pertur.theory.:

$$\mathcal{M}_{K^-\to\pi^-\pi^0\bar{\gamma}} = \frac{8a_T}{f}\left[\epsilon_{\alpha\omega\mu\nu}\,\bar{\varepsilon}^{\alpha*}p_-^{\omega}p_0^{\mu}\bar{q}^{\nu}\,\mathbb{C} + i\left(p_-^{\mu}p_0^{\nu} - p_-^{\nu}p_0^{\mu}\right)\bar{\varepsilon}_\mu^*\bar{q}_\nu\,\mathbb{C}_5\right]$$

where: $f=f_\pi$=92MeV,
a_T =0.658(23)/GeV const.from lattice QCD,
$\bar{\varepsilon}$ and $\bar{q}$– polariz.vector and momentum for $\bar{\gamma}$.

We derive: $$\left|\mathcal{M}_{K^-\to\pi^-\pi^0\bar{\gamma}}\right|^2 = -\frac{64a_T^2}{f^2}\left[m_{\pi^-}^2(p_0 p_{\bar{\gamma}})^2 + m_0^2(p_- p_{\bar{\gamma}})^2 - 2(p_- p_0)(p_- p_{\bar{\gamma}})(p_0 p_{\bar{\gamma}})\right]\left(|\mathbb{C}|^2+|\mathbb{C}_5|^2\right)$$

Prediction: $\mathcal{B}(K^-\to\pi^-\pi^0\bar{\gamma}) = 1.12\times10^{10}\left(|\mathbb{C}|^2+|\mathbb{C}_5|^2\right)\text{GeV}^2$

the term $(|\mathbb{C}|^2+|\mathbb{C}_5|^2)$ is estimated using $(1 - \sum_i \mathcal{B}()_i)$: (Observed ch.)

$$\mathcal{B}(\Lambda\to n\bar{\gamma}) = 2.75\times10^{12}\left(|\mathbb{C}|^2+|\mathbb{C}_5|^2\right)\text{GeV}^2,$$
$$\mathcal{B}(\Sigma^+\to p\bar{\gamma}) = 1.54\times10^{11}\left(|\mathbb{C}|^2+|\mathbb{C}_5|^2\right)\text{GeV}^2,$$
$$\mathcal{B}(\Xi^0\to\Lambda\bar{\gamma},\Sigma^0\bar{\gamma}) = 1.61\times10^{12}\left(|\mathbb{C}|^2+|\mathbb{C}_5|^2\right)\text{GeV}^2,$$
$$\mathcal{B}(\Xi^-\to\Sigma^-\bar{\gamma}) = 1.32\times10^{12}\left(|\mathbb{C}|^2+|\mathbb{C}_5|^2\right)\text{GeV}^2,$$
$$\mathcal{B}(\Omega^-\to\Xi^-\bar{\gamma}) = 5.18\times10^{12}\left(|\mathbb{C}|^2+|\mathbb{C}_5|^2\right)\text{GeV}^2.$$

[arXiv:1911.13301]

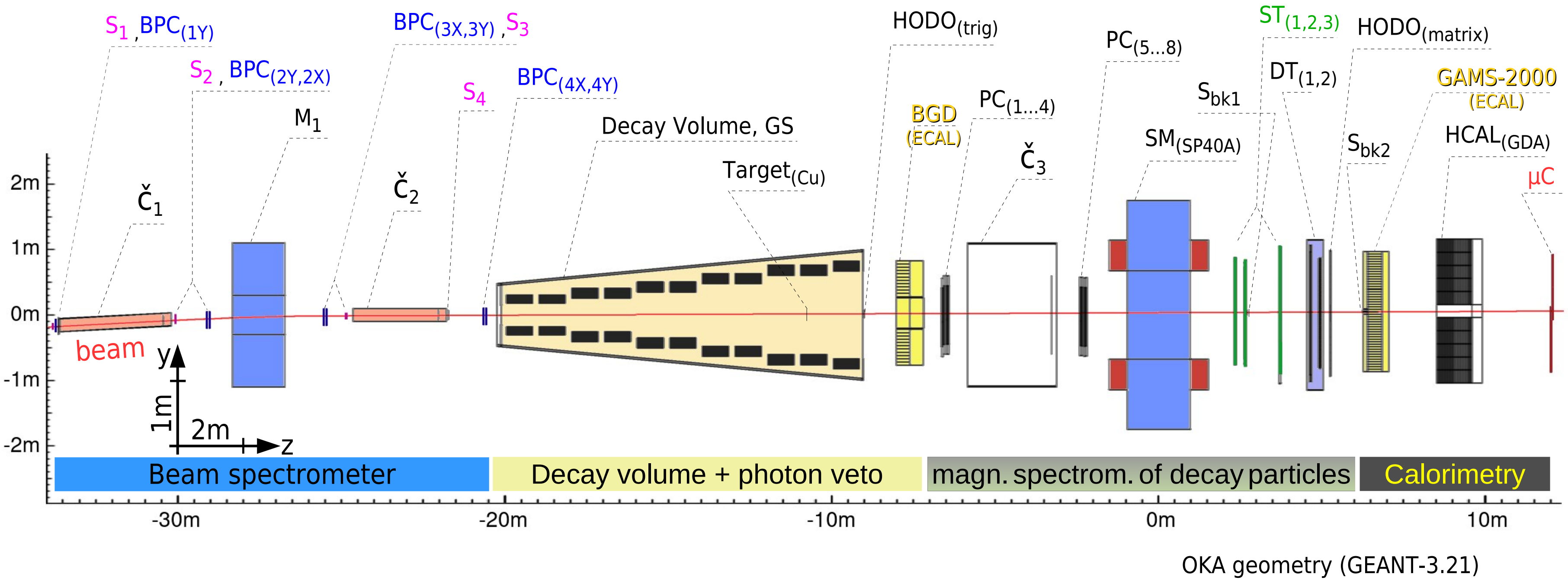
NB: The approximate maxima for branching fractions were ***determined indirectly*** from the data on the observed channels quoted by the PDG. For each of the parent hyperons, the sum of the Br() values subtracted from unity with their errors (increased to 2 sigmas) combined in quadrature.

Most stringent bound is from Ξ^0 ⇒ $|\mathbb{C}|^2+|\mathbb{C}_5|^2 < \dfrac{2.1\times10^{-16}}{\text{GeV}^2}$

Hence, the maximal estimate for branching fraction from (accuracy of) current results in PDG is moderate: $\mathcal{B}(K^-\to\pi^-\pi^0\bar{\gamma}) < 2.4\times10^{-6}$

Can be addressed by the existing OKA data!

The OKA setup



(§) Trigger: 6mm scint. (S_0) & 2mm (S_1,S_2,S_3); beam cherenkov counters ($\check{C}_1$,$\check{C}_2$), beam anti scint.: $Sbk_{1,2}$

(§) Beam spectrometer: y-magnet (M2) & 7 BPCs (1mm pitch ~1500 channels)

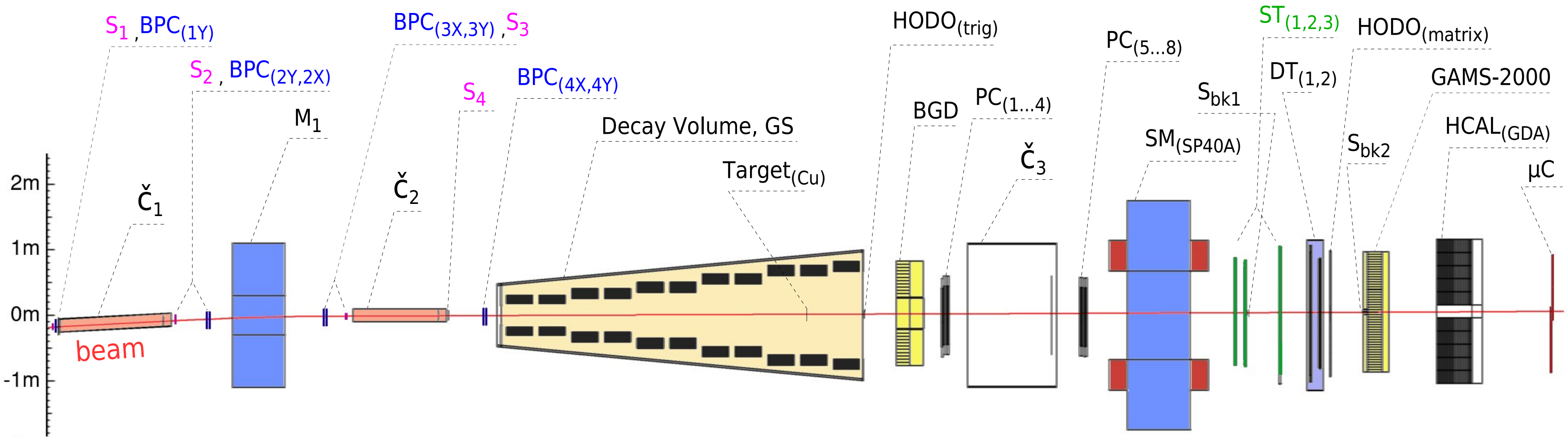
(§) Decay volume (filled with helium) & veto (guard system «GS») 670 Pb-Sc (200 ADC channels)

(§) Decay particles spectrometer: 8 PCs (2mm pitch 5K channels), wide accept. x-magnet (SP40A) 0.6Tm, 200x140cm^2, 3straw (10mm pitch 1K chan.), 2DT (Φ30mm /300 chan.), matrix HODOscope.

(§) EM-calorimeters: lead glass «GAMS-2000» (~2300 chan. 4X4cm^2), «BGD» (~1050 chan. 5x5cm^2)

(§) HCAL «GDA» (120 Fe-Sc 20x20cm^2), 4 muon counters (scint. plates 1x1m^2 (μC)

Data samples (2012 / 2013)



Data taken by OKA and used in this analysis:

– during run14: Pbeam=17.7 GeV/c

Main trigger: $(S_1 \bullet S_2 \bullet S_3 \bullet S_0 \bullet \overline{C}_1 \bullet C_2 \bullet \overline{S}_{bk1,2} \bullet [\Sigma_{GAMS}>Mip])$ ~$2.3 \cdot 10^9$ triggers

Kaon decay trigger: $(S_1 \bullet S_2 \bullet S_3 \bullet S_0 \bullet \overline{C}_1 \bullet C_2 \bullet \overline{S}_{bk1,2})$ – prescaled {1/10}

½ duty time – taken with 2mm-Cu target (placed near the exit of decay volume)

Reconstructed $5 \cdot 10^8$ single track events

– during run15: Pbeam=17.7 GeV/c

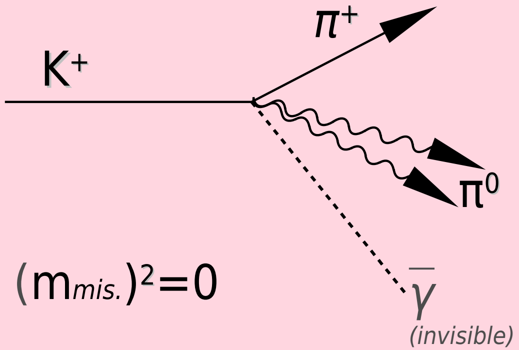
Main trigger: $(S_1 \bullet S_2 \bullet S_3 \bullet S_0 \bullet \overline{C}_1 \bullet C_2 \bullet \overline{S}_{bk1,2} \bullet [\Sigma_{GAMS}>Mip])$ ~$1.35 \cdot 10^9$ triggers

Kaon decay trigger: $(S_1 \bullet S_2 \bullet S_3 \bullet S_0 \bullet \overline{C}_1 \bullet C_2 \bullet \overline{S}_{bk1,2})$ – prescaled {1/10}

Reconstructed $3 \cdot 10^8$ single track events

$K^+ \to \pi^+\pi^0\bar{\gamma}$ and its main backgrounds signatures

Decay of interest: $K^+ \to \pi^+\pi^0\bar{\gamma}$



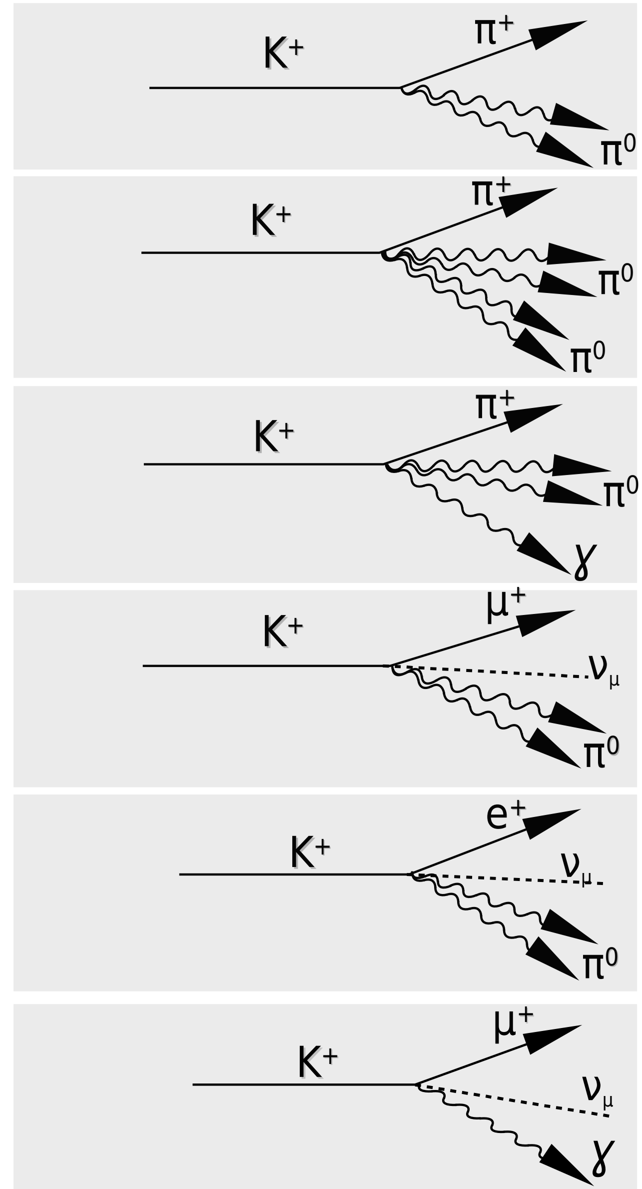
for $(m_{mis.})^2=0$

Main selections

- single track events with good reconstr. vertex from inside the decay volume
- beam momentum ≃ 17.7 GeV/c
- π^+ charged track after kaon decay
- $=2\gamma$ events seen in GAMS/BGD forming π^0
- quality cuts (high track quality, acceptance, etc.)
- γ *in* BGD/GAMS: not near the border;
  γ *in* GAMS: $y_\gamma \neq y_{track}$ (avoid bremstr. from charged track)
- missing energy, (π^+,π^0)-momentum in CMS
- photon veto from Decay Volume+BGD

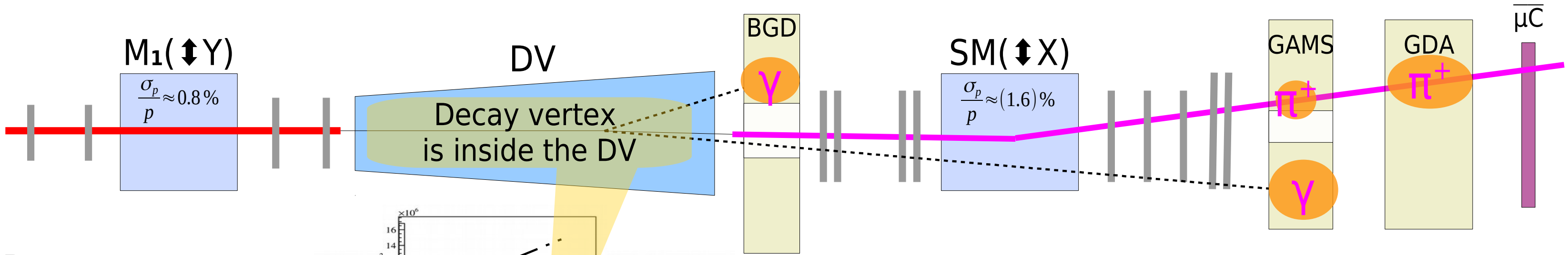
MC simulation for signal [$K^+ \to \pi^+\pi^0\bar{\gamma}$] and main background processes to study acceptance and efficiency (and for background subtraction procedure as well).

Background processes

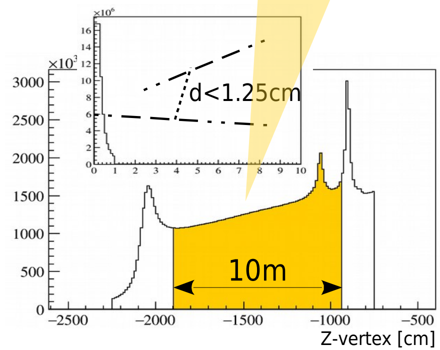


$K^+ \to \pi^+\pi^0$, $K^+ \to \pi^+\pi^0\overline{\gamma}$ selections

1) Reconstructed single (beam) track before DV with proper momentum ~17 GeV/c and (high quality) single track after; in absence of any additional track segments after SM(SP40A).



2) Decay vertex inside DV
(~2σ inside entrance/exit foils).



3) Secondary track matches to hadron clusters (π^+) in GAMS||GDA

(later it is also required an anti-coincidence with the muon counter behind HCAL).

4) Exactly 2 γ-clusters in ECALs:
either [2γ in GAMS] & [veto by the energy deposition in BGD]
or [1γ in GAMS] & [=1γ in BGD, & veto for any other clusters in BGD].

5) Prohibited events with γ clusters from margins of GAMS||BGD (prevent low quality showers).

6) Suppression of possibility for γ irradiated by secondary charged track by rejecting tracks with the same Y-position of photon at GAMS (second magnet SM(SP40) acts in X-direction).

Selections for $K^+ \to \pi^+\pi^0$, $K^+ \to \pi^+\pi^0\gamma$

1) Reconstructed single (beam) track before DV with proper momentum ~17 GeV/c and (high quality) single track after; in absence of any additional track segments after SM(SP40A).

2) Decay vertex is inside DV (~2σ inside entrance/exit foils).

3) Secondary (decayed) track is matching to hadron cluster (π^+) in GAMS||GDA
(later it is also required an anti-coincidence with the muon counter behind HCAL).

4) Exactly 2 γ-clusters in ECALs:
either [2γ in GAMS] & [veto by the energy deposition in BGD]
or [1γ in GAMS] & [=1γ in BGD, & veto for any other clusters in BGD].

5) Prohibited events with γ clusters from margins of GAMS||BGD (prevent low quality showers),

6) Suppression of possibility for γ irradiated by secondary charged track by rejecting tracks with the same Y-position of photon at GAMS (second magnet SM(SP40) acts in X-direction).

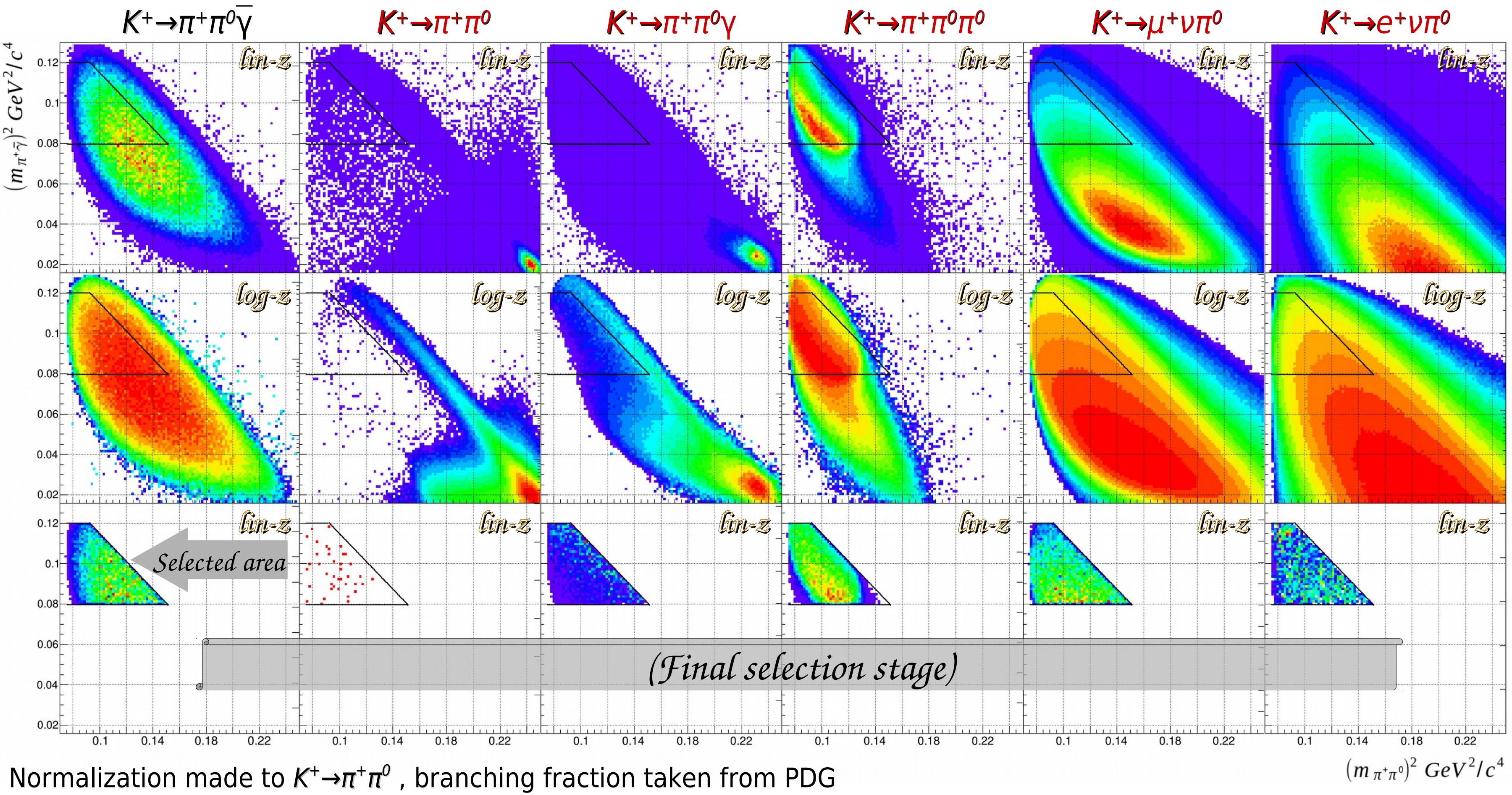
Selection for $K^+ \to \pi^+\pi^0$ candidates:
– single secondary π^+ candidate is selected (tracking, calorimetry)
– π^0 candidate: 2γ with $|m(\gamma\gamma) - m(\pi^0)| < 15$ MeV/c^2 (to build π^0 momentum with $m = m_{\pi^0}$)

Statistics of ~$3 \cdot 10^7$ events with K2π candidates for analysis:
OKA-run14/2012г.: $N(K^+ \to \pi^+\pi^0) = 17.2 \cdot 10^6$
OKA-run15/2013г.: $N(K^+ \to \pi^+\pi^0) = 11.5 \cdot 10^6$

Normalization of MC to EXP is done at this stage!

Background reduction strategy to reduce number of involved backgrounds and their magnitudes (specific for $K^+ \to \pi^+\pi^0\overline{\gamma}$)

The MC results (with matrix elements taken into account) after basic cuts for $K^+ \to \pi^+\pi^0$ candidates. Dalitz plots for the signal and misidentified backgrounds:



Normalization made to $K^+ \to \pi^+\pi^0$, branching fraction taken from PDG (signal described according to [Eur.Phys.J.C 80 (2020) 9, 824]/[arxiv:2006.05985]).

Strong background suppression within [selected area] is possible!

Selection of the $K^+ \to \pi^+ \pi^0 \overline{\gamma}$

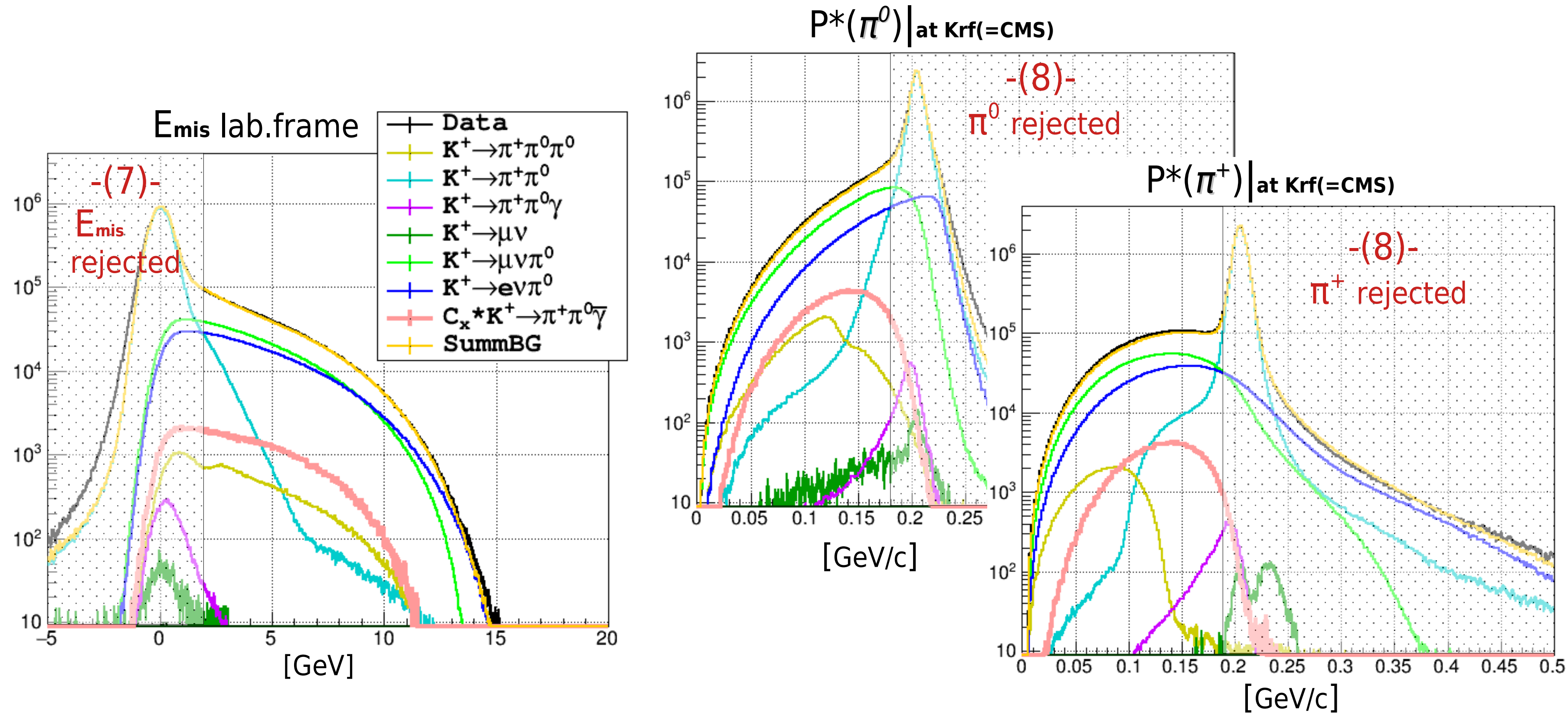
Suppression of the $K^+ \to \pi^+ \pi^0$ and $K^+ \to \pi^+ \pi^0 \pi^0$ (with 2γ lost)

7**) Emis = {E(K^+)-E(π^+)-E(π^0)} >2.3 GeV (part of the signal is also suppressed)

8**) Momenta of the π^0 and π^+ at the kaon rest frame (p)*

$(p_{\pi 0})^* < 0.180$ GeV/c and $(p_{\pi +})^* < 0.189$ GeV/c

*NB: cuts 7**) and 8**) are not used during efficiency calculation of the Kπ2 which is a normalisation process for $K^+ \to \pi^+ \pi^0 \overline{\gamma}$*



Selection of the $K^+\to\pi^+\pi^0\overline{\gamma}$

Suppression of the $K^+\to\pi^+\pi^0$ and $K^+\to\pi^+\pi^0\pi^0$ (with 2γ lost)

7**) E_{mis} = {E(K^+)-E(π^+)-E(π^0)} >2.3 GeV (part of the signal is also suppressed)
8**) Momenta of the π^0 and π^+ at the kaon rest frame (p)*
$(p_{\pi 0})^* < 0.180$ GeV/c and $(p_{\pi+})^* < 0.189$ GeV/c
*NB: cuts 7**) and 8**) are not used during efficiency calculation of the Kπ2 which is a normalisation process for $K^+\to\pi^+\pi^0\overline{\gamma}$*

Suppression of the $K^+\to\mu^+\nu\pi^0$, $K^+\to e^+\nu\pi^0$ by means of calorimetry (matched with charged track)

9^{ECAL}) charged track extrapolation to Z_{GAMS} matches ($\Delta R<8$cm) with cluster:
a) events with e^+ shower (E/p>0.75) in GAMS are rejected
b) events with "early" hadron shower (Ncells>4 or E>1.9 GeV) in GAMS are kept, while showers with poor pion/muon separation are subject for further investigation in HCAL.

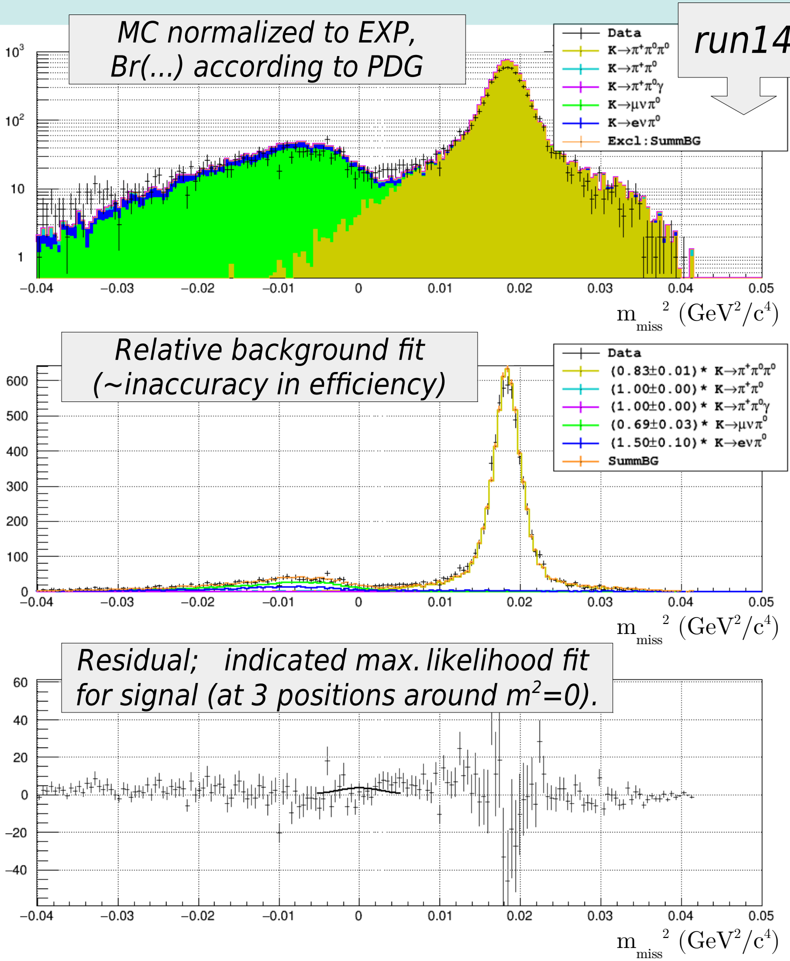
9^{HCAL}) events with poor pion/muon separation in GAMS are checked in GDA(HCAL):
if charged track extrapolation to Z_{GDA} matches ($\Delta R<22$cm) with cluster in GDA
good hadron shower in GDA(HCAL) is required: either (Ncells≥1 & E/p>0.67 & E>4 GeV)
or (Ncells≥4)

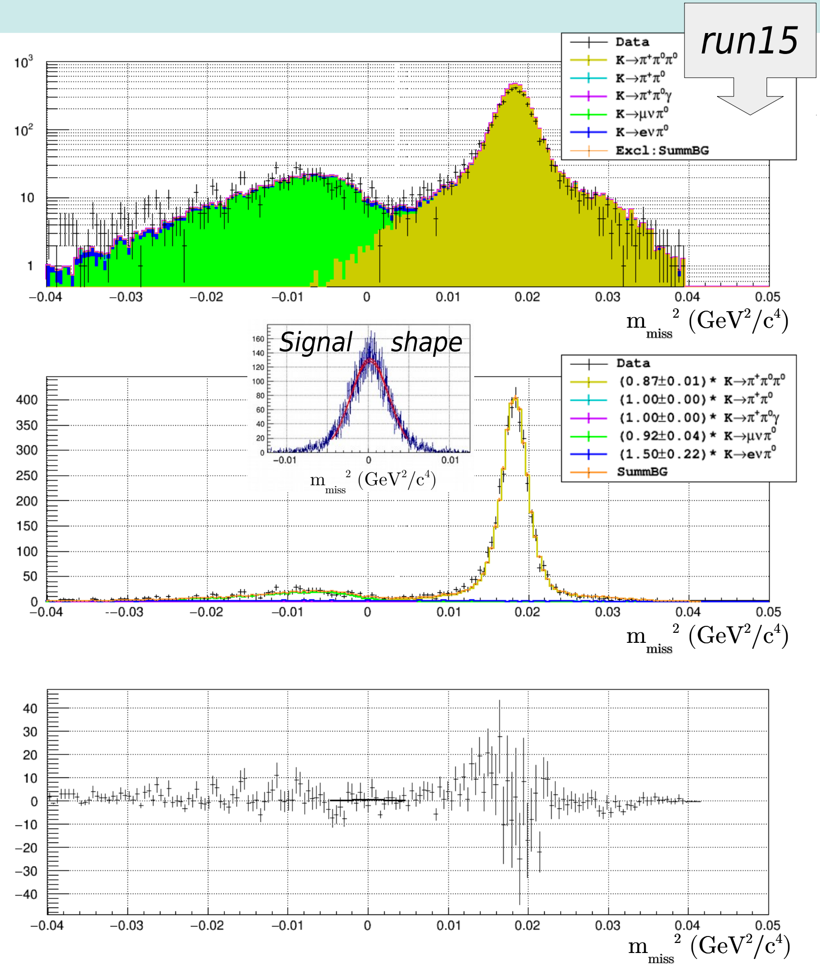
10) Rejecting events in which one of 4x muon counters μC is fired,
matching to the track extrapolation (some acceptance reduction)

11) Direction of missing momentum crosses GAMS acceptance

12) Veto in DV = decay volume hermetisity (events with ΣE>100MeV in DV are rejected)

The 90% CL upper limit estimates



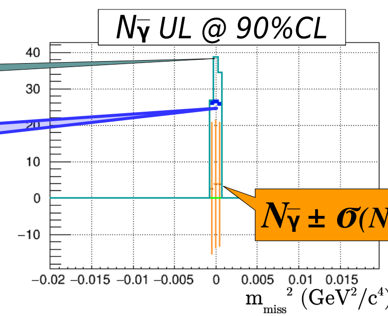


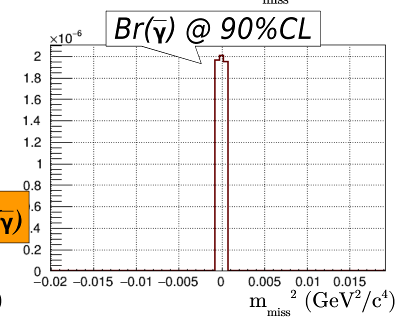
UL 90%CL $N_{\bar\gamma}$ (Feldman-Cousins ±1.2σ window)

UL 90%CL for $N_{\bar\gamma}$ ML-fit with signal shape (±2σ window)

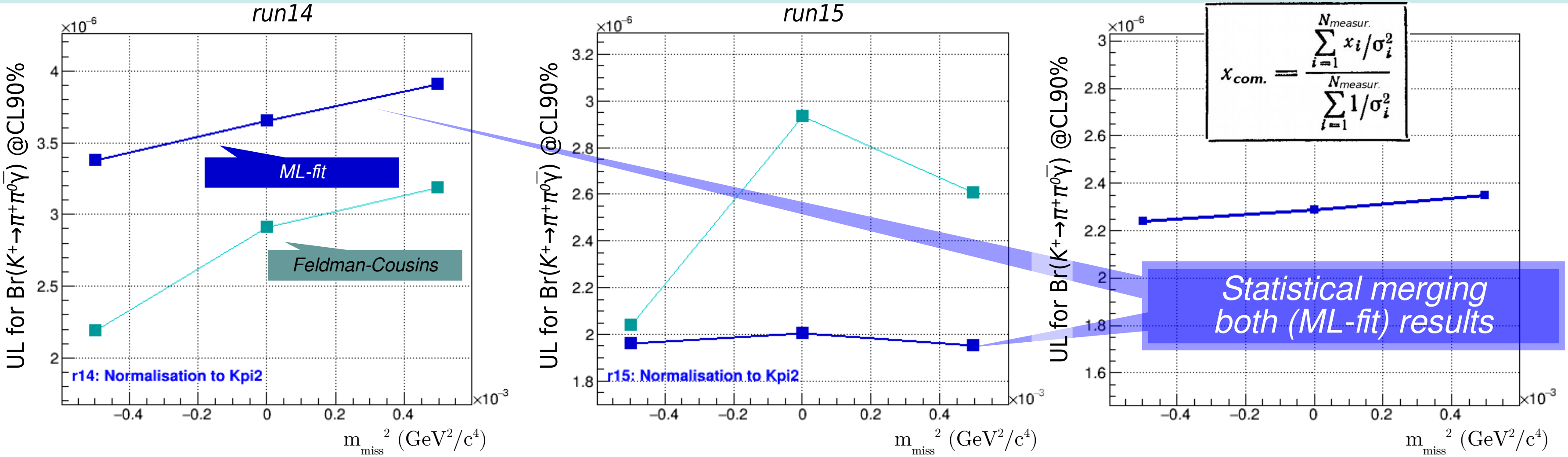
$$N_{\bar\gamma}^{(Upp.Lim\,90\%CL)} = 1.28\,\sigma(N_{\bar\gamma}) + N_{\bar\gamma}^{(fit)}\text{, for } N_{\bar\gamma}^{(fit)} \ge 0$$

$$N_{\bar\gamma}^{(Upp.Lim\,90\%CL)} = 1.28\,\sigma(N_{\bar\gamma})\text{, for } N_{\bar\gamma}^{(fit)} < 0$$





Statistical combination of two experiments (preliminary results)



$$Br(K^+ \to \pi^+ \pi^0 \bar{\gamma}) = Br(K\pi 2) \cdot (N_{\bar{\gamma}}/\varepsilon_{\bar{\gamma}}) \cdot (\varepsilon_{K\pi 2}/N_{K\pi 2})$$

	run14	run15
$\varepsilon_{K\pi 2}$	=0.074	=0.075
$N_{K\pi 2}$	=10M	=6.2M
$\varepsilon_{\bar{\gamma}}$	=0.0108	=0.0103
$\sigma_{\bar{\gamma}}$ [GeV²/c⁴]	$=2.6\cdot 10^{-3}$	$=2.4\cdot 10^{-3}$

(i.e. $\sigma_{\bar{\gamma}} \simeq 50$ MeV/c²; 5% error included in fit)

OKA preliminary result: **$Br(K^+ \to \pi^+ \pi^0 \bar{\gamma}) < 2.3\cdot 10^{-6}$** at 90%CL

corresponds [s→d$\bar{\gamma}$] to : $(|\mathbb{C}|^2 + |\mathbb{C}_5|^2) < 2.05\cdot 10^{-16}$ [1/GeV²]

Some of the systematics:

Syst. err. on ($\varepsilon_{K\pi 2}/N_{K\pi 2}$) ratio is ≈3.5%

Syst. err. ≈ 13% (compar. with an alternative normalization to $K \to \pi^+\pi^0\pi^0$)

Syst. err. ≈ 20% (cuts variation for Emis, $(p_{\pi+})^*$, $(p_{\pi 0})^*$)

Systematics in quadrature ≈ 24% (prelim., more detailed study is ongoing).

Cf.: BESIII result on $Br(\Sigma^+ \to p + \text{invis.}) < 3.2\cdot 10^{-5}$ (90%CL) [PLB 852(2024)138614]

⇒ for [s→d$\bar{\gamma}$]: $(|\mathbb{C}|^2 + |\mathbb{C}_5|^2) < 2.08\cdot 10^{-16}$ [1/GeV²]

We plan to improve this result with new data:
([available: 2018 data] + [future: awaiting new run])

The work is supported by RSCF grant №22-12-00051-П

Thank you for your attention

Massive dark photon /backup/

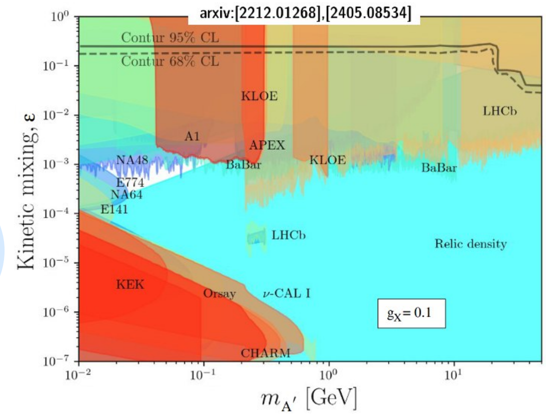
Boson (spin=1) introduced by a new Abelian gauge symmetry, $U(1)_D$
(such as, all the fields of the SM are singlets)

massive (A' ≡ γ') /spontaneously broken $U(1)_D$/

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} - \frac{1}{2}\chi F_{\mu\nu}F'^{\mu\nu} - \frac{1}{2}m^2_{A'}A'_\mu A'^\mu$$

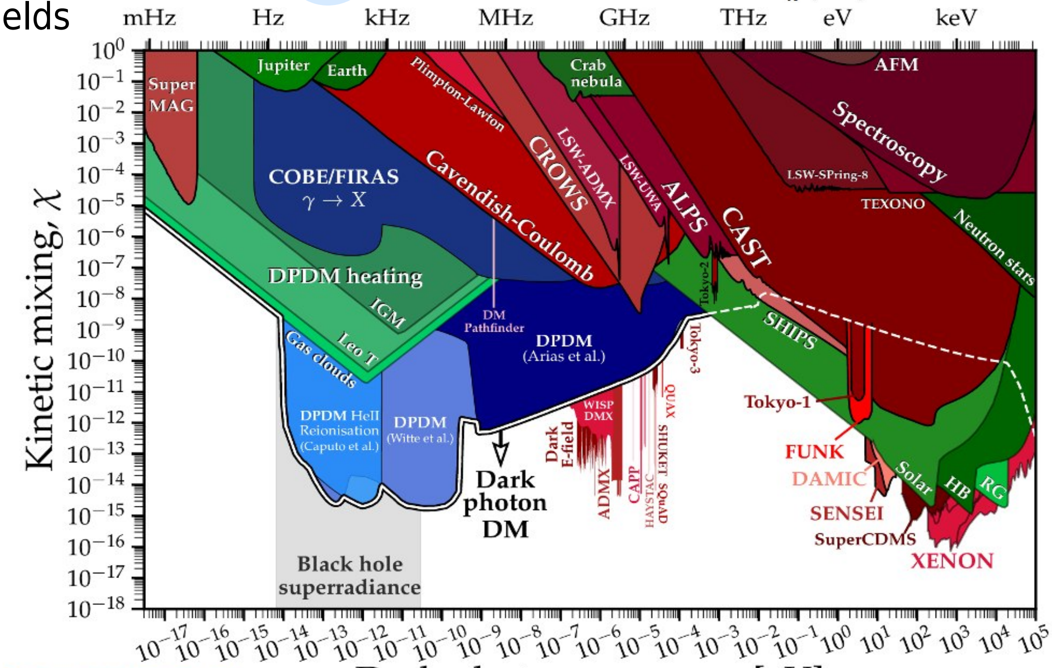
can interact with SM particles through a renormalizable operator, $\chi e A'_\mu J^\mu_{EM}$, which involves
– electromagnetic current J_{EM}
– small parameter χ due to the kinetic mixing between the dark and SM Abelian gauge fields (A' couples to charged particles with strength $\chi q e$).

Backup slide



A' can be produced:
– in decays or scatterings of SM fermions and hadrons
– could decay into (el.)charged fermions and mesons
– could decay into DM particles (invisible)

Numerous experiments (and also) cosmological and astrophysical bounds provide strict limitations on χ in wide mass range of A'/γ'.



Phys.Rev.D 104 (2021) 9, 095029
arxiv:2105.04565

FIG. 1. Current constraints on the DP's mass, m_X, and kinetic mixing parameter with the SM photon, χ. The general colour-scheme is: cosmological bounds in blue, experimental bounds in red, and astrophysical bounds in green. The thick white line that divides the parameter space in two is the upper limit for which DPs are a viable candidate for 100% of the DM.

Motivation /backup/

“Hunting Down Massless Dark Photons in Kaon Physics”

(M. Fabbrichesi et.al) [**Phys. Rev. Lett. 119, 031801** (2017)][arxiv.org:1705.03470]
https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.119.031801
–
If dark photons are massless, they couple to standard-model particles only via higher dimensional operators, while direct (renormalizable) interactions induced by kinetic-mixing, which motivates most of the current experimental searches, are absent. We consider the effect of possible flavor-changing magnetic-dipole couplings of massless dark photons in kaon physics. In particular, we study the branching ratio for the process [$K^+ \to \pi^+ \pi^0 \bar{\gamma}$] with a simplified-model approach, assuming the chiral quark model to evaluate the hadronic matrix element.
We find that branching ratios up to $O(10^{-7})$ are allowed — depending on the dark-sector masses and couplings. Such large branching ratios for [$K^+ \to \pi^+ \pi^0 \bar{\gamma}$] could be of interest for experiments dedicated to rare K+ decays like NA62 at CERN, where $\bar{\gamma}$ can be detected as a massless invisible system.

Backup slide

“Kaon decays shedding light on massless dark photons”

Jhih-Ying Su, Jusak Tandean [**Eur.Phys.J.C 80 (2020) 9, 824**], [arxiv:2006.05985]
–
We explore kaon decays with missing energy carried away by a massless dark photon, $\bar{\gamma}$, assumed to have flavor-changing dipole-type couplings to the d and s quarks. ..., ..., Interestingly, the same interactions give rise to the flavor-changing two-body decays of hyperons with missing energy and are subject to model-independent constraints that can be inferred from the existing hyperon data. ... ... Furthermore, we find that [$K^+ \to \pi^+ \gamma \bar{\gamma}$] and [$K^+ \to \pi^+ \pi^0 \bar{\gamma}$] are allowed to be maximally of order as well, which may be probed by NA62. Complementarily, the hyperon modes can have rates which are potentially accessible by BESIII. Thus, these ongoing experiments could soon be able to offer significant tests on the existence of the massless dark photon.
(See also review: https://arxiv.org/pdf/1607.05928)