Constraints on light scalars from PS191 results

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Introduction

$$\mathscr{L}_{SH} = \mu H^\dagger H \phi + \frac{\beta}{2} H^\dagger H \phi^2 \,. \tag{1}$$

Light scalar can be:

- fully determined by its mass m_ϕ and mixing angle θ;
- produced by the SM particles via mixing and can decay into the SM particles through the same mixing;
- a natural part of the extended Higgs sector;
- messenger to the dark matter;
- playing a role of inflaton.

PS191 experiment

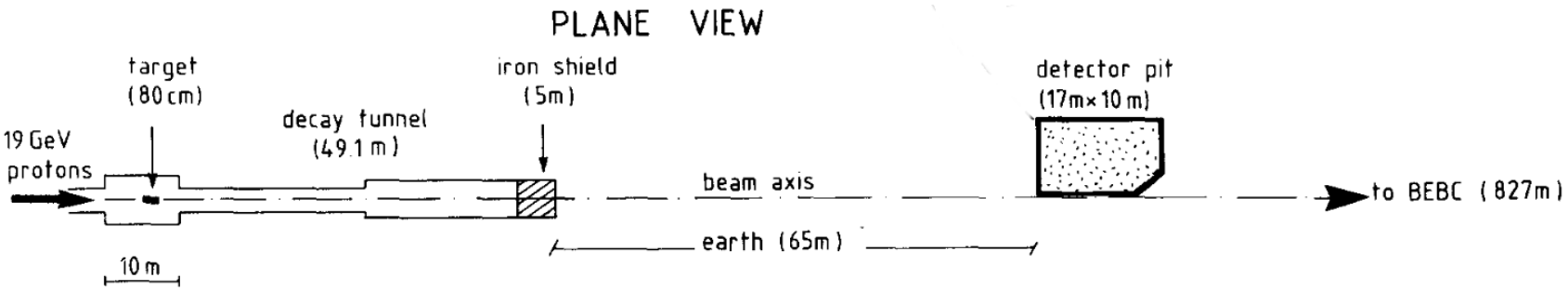


Figure 1: Layout of the PS191 experiment at CERN.

General idea:

$$N_\phi = N_{POT} \times \sum_{K=K^+,K^-,K_L} \frac{N_K}{N_{sim}} \cdot Br(K \to \pi\phi) \cdot \xi_K \cdot P\,. \qquad (2)$$

Kaon production and decay

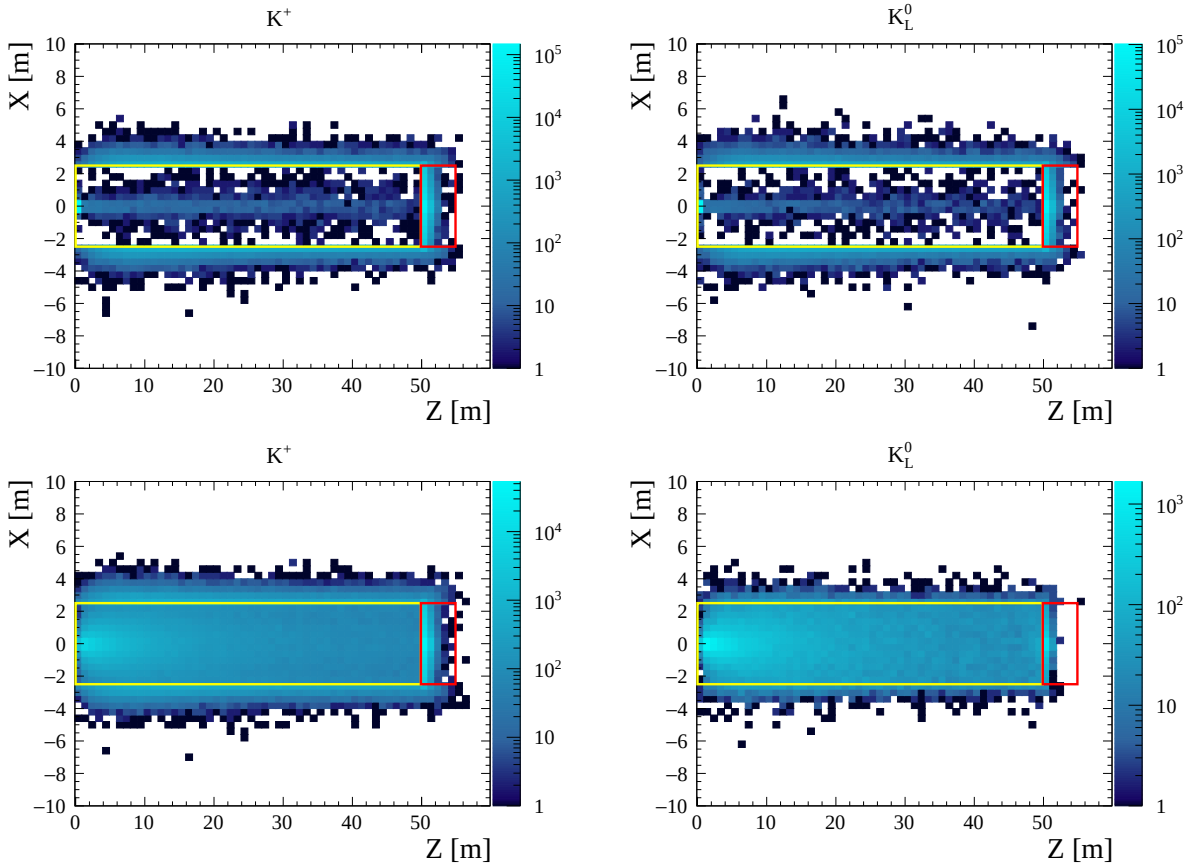


Figure 2: Charged (left) and neutral (right) kaon production (upper row) and decay (lower row) points constrained in the Y direction within the decay volume.

Light scalar production

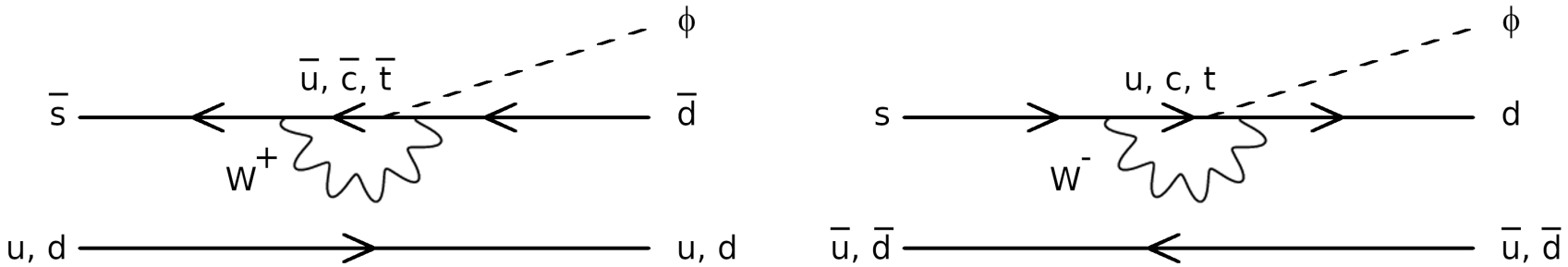


Figure 3: Feynman diagrams for kaon decays into scalar ϕ.

$$\mathrm{Br}\left(K^{\pm} \to \pi^{\pm}\phi\right) = \frac{1}{\Gamma_{K^{\pm}}} \frac{2p_{\phi_{CM}}}{m_{K^{\pm}}} \frac{|\mathscr{M}|^2}{16\pi m_{K^{\pm}}} \approx 1.6 \times 10^{-3} \frac{2p_{\phi_{CM}}}{m_{K^{\pm}}} \theta^2, \quad (3)$$

$$\mathrm{Br}\left(K_L \to \pi^0\phi\right) = \frac{1}{\Gamma_{K_L}} \frac{2p_{\phi_{CM}}}{m_{K_L}} \frac{|\mathrm{Re}\left[\mathscr{M}\right]|^2}{16\pi m_{K_L}} \approx 5.7 \times 10^{-3} \frac{2p_{\phi_{CM}}}{m_{K_L}} \theta^2, \quad (4)$$

$$p_{\phi_{CM}} = \frac{M_K}{2} \sqrt{\left(1 - \frac{\left(m_\phi + m_\pi\right)^2}{m_K^2}\right)\left(1 - \frac{\left(m_\phi - m_\pi\right)^2}{m_K^2}\right)}.$$

Light scalar production

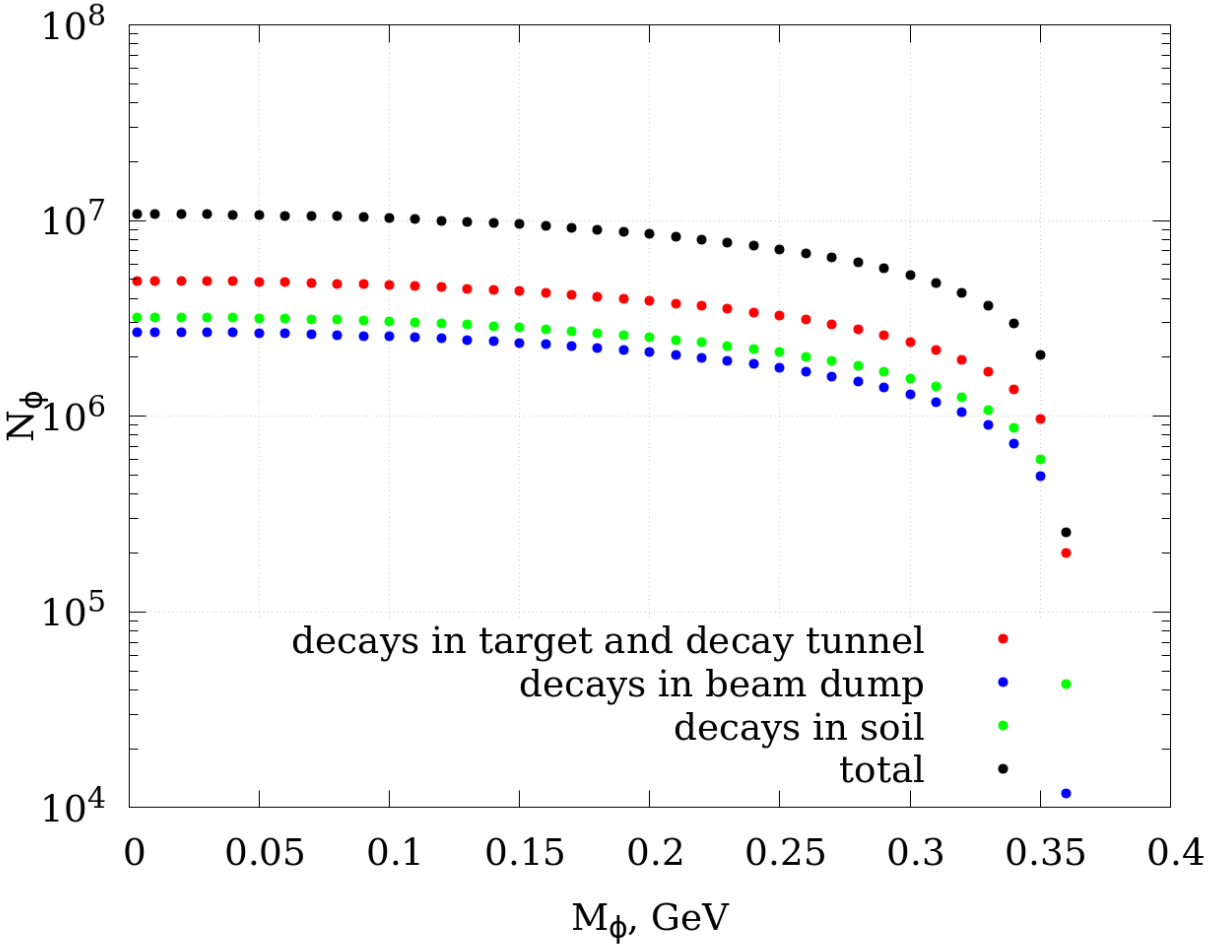
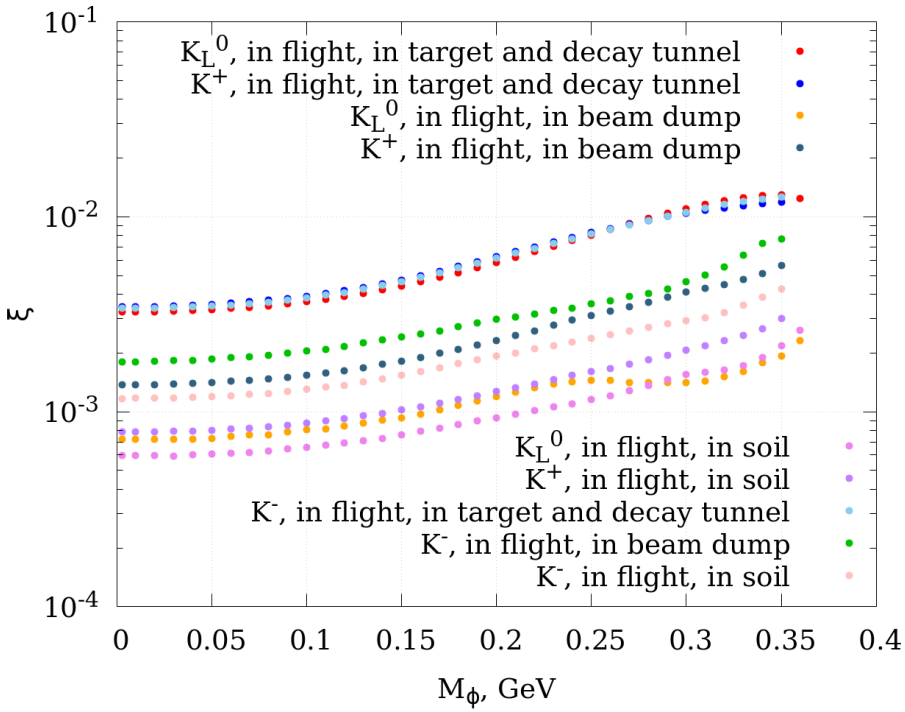


Figure 4: A total number of the light scalars expected to be produced in kaon decays for $\theta^2 = 10^{-8}$. Note that $> 95\%$ of K^+ that reach the dump and $> 80\%$ of K^+ that enter the soil lose all of their momentum before decaying. There are no stopped K^- and K_L^0 decays since these kaons are captured by the nuclei.

Geometrical factor



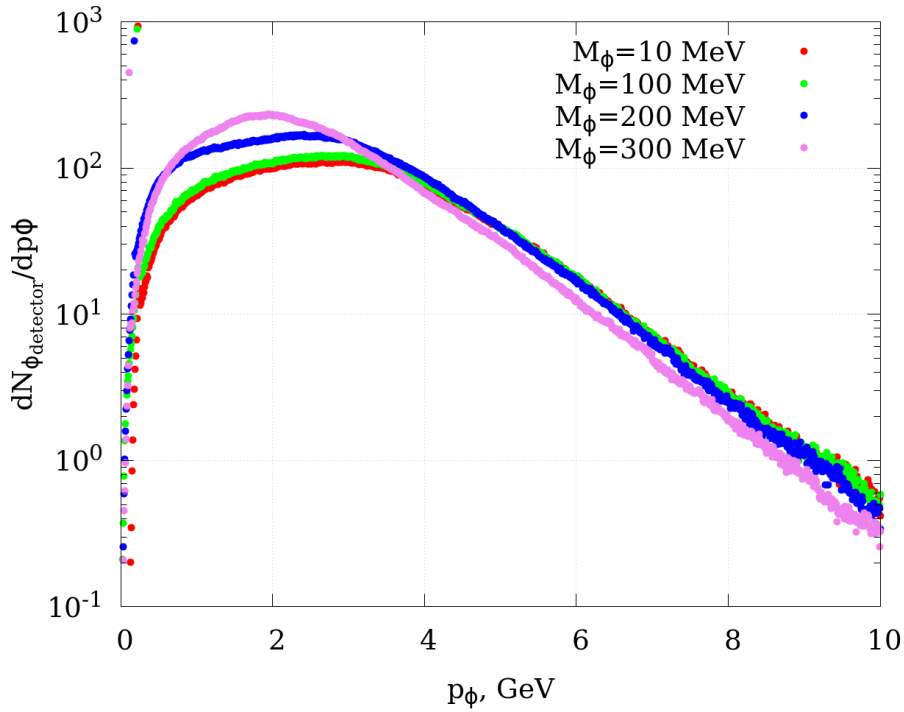


Figure 5: *Left panel:* the geometrical factor ξ for the light scalars as a function of its mass for light scalars produced in neutral and charged kaon decays. *Right panel:* spectra of the light scalars that reach the detector for a set of masses and $\theta^2 = 10^{-8}$.

Light scalar decay

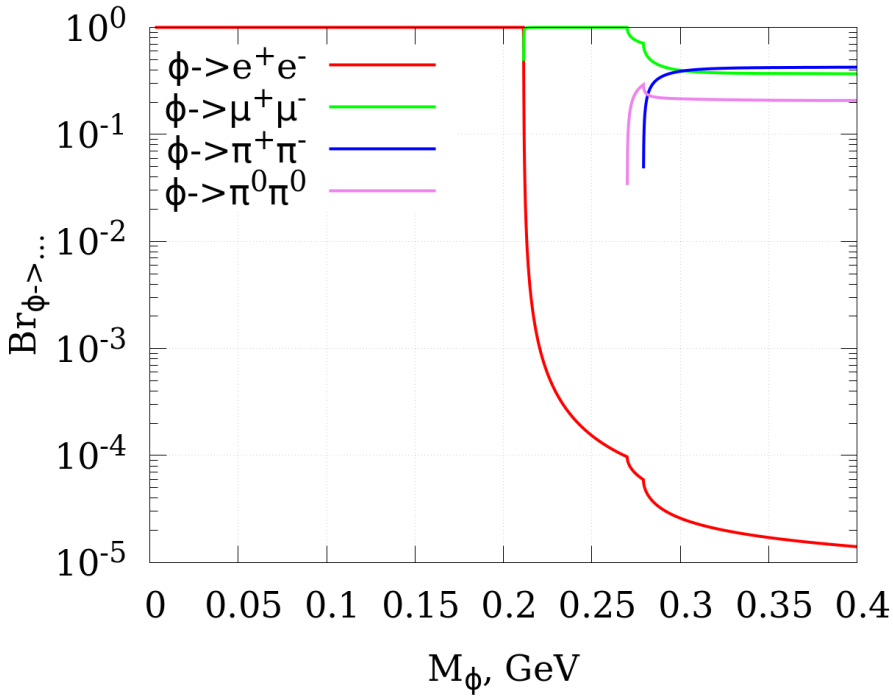
$$\Gamma(\phi \to l^+ l^-) = \frac{G_F m_l^2 m_\phi}{4\sqrt{2}\pi}\left(1-\frac{4m_l^2}{m_\phi^2}\right)^{\frac{3}{2}}\theta^2, \quad (5)$$

$$\Gamma(\phi \to \pi^+\pi^-) = 2\Gamma(\phi \to \pi^0\pi^0) =$$

$$= \frac{G_F m_\phi^3}{8\sqrt{2}\pi}\left(\frac{2}{9}+\frac{11}{9}\frac{m_\pi^2}{m_\phi^2}\right)^2\left(1-\frac{4m_\pi^2}{m_\phi^2}\right)^{\frac{1}{2}}\theta^2, \quad (6)$$

$$P = \left(1-\exp\left(-\Gamma_{visible}\,\Delta l\, M_\phi/p_\phi\right)\right)\exp\left(-\Gamma_{tot}\, d\, M_\phi/p_\phi\right),$$
$$\Gamma_{tot} = \sum\Gamma(\phi \to ...).$$

Light scalar decay



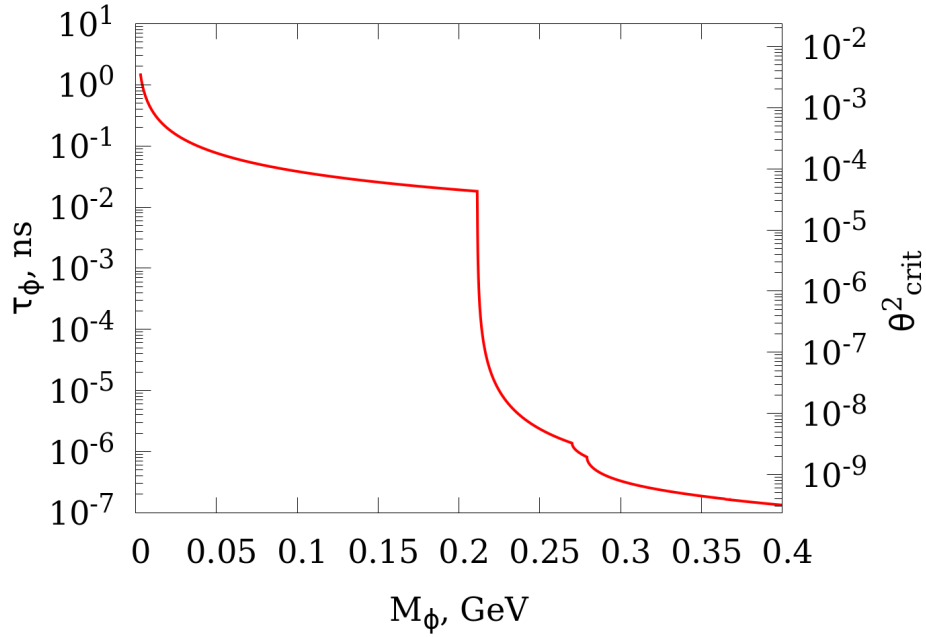
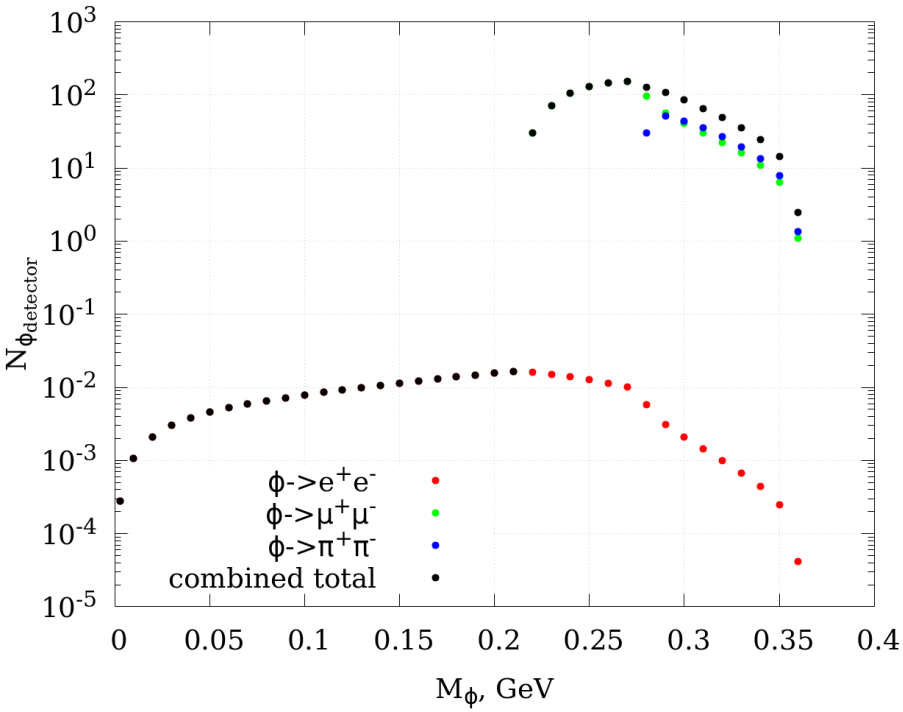


Figure 6: *Left panel:* scalar branching ratios. *Right panel:* scalar lifetime τ_ϕ for $\theta = 1$ and critical mixing θ_{crit} (for a weaker mixing the scalar reaches the PS191 detector).

Light scalar detection



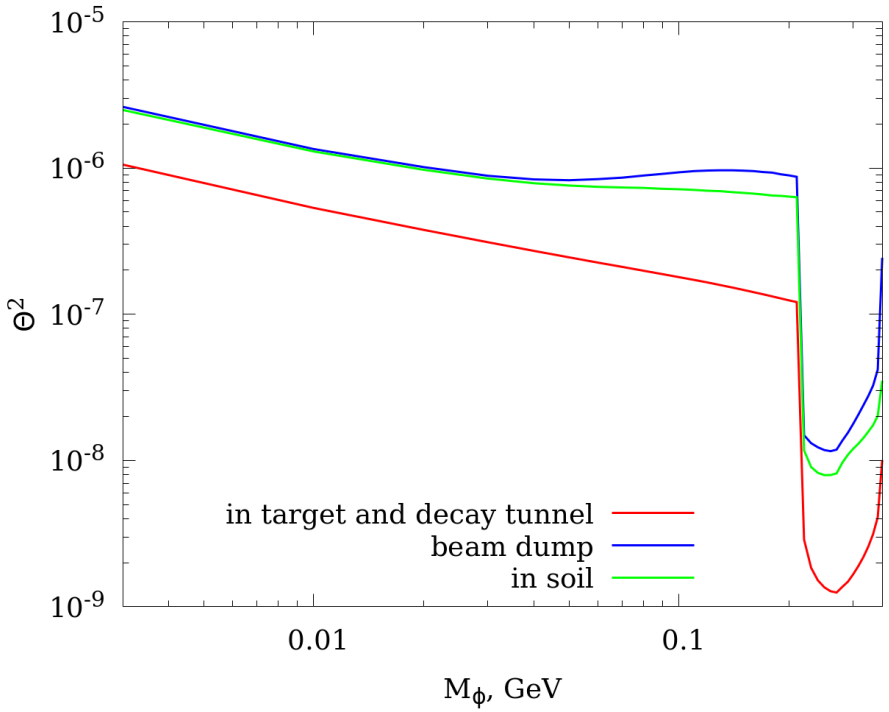


Figure 7: *Left panel:* the simulated number of light scalar decays in the detector volume in various decay modes, $\theta^2 = 10^{-8}$. *Right panel:* contribution of the different initial kaon decay points to the final exclusion: the region above the solid line is excluded at 90% CL from negative searches at PS191, $N_{POT} = 0.3 \times 10^{19}$.

Final estimation

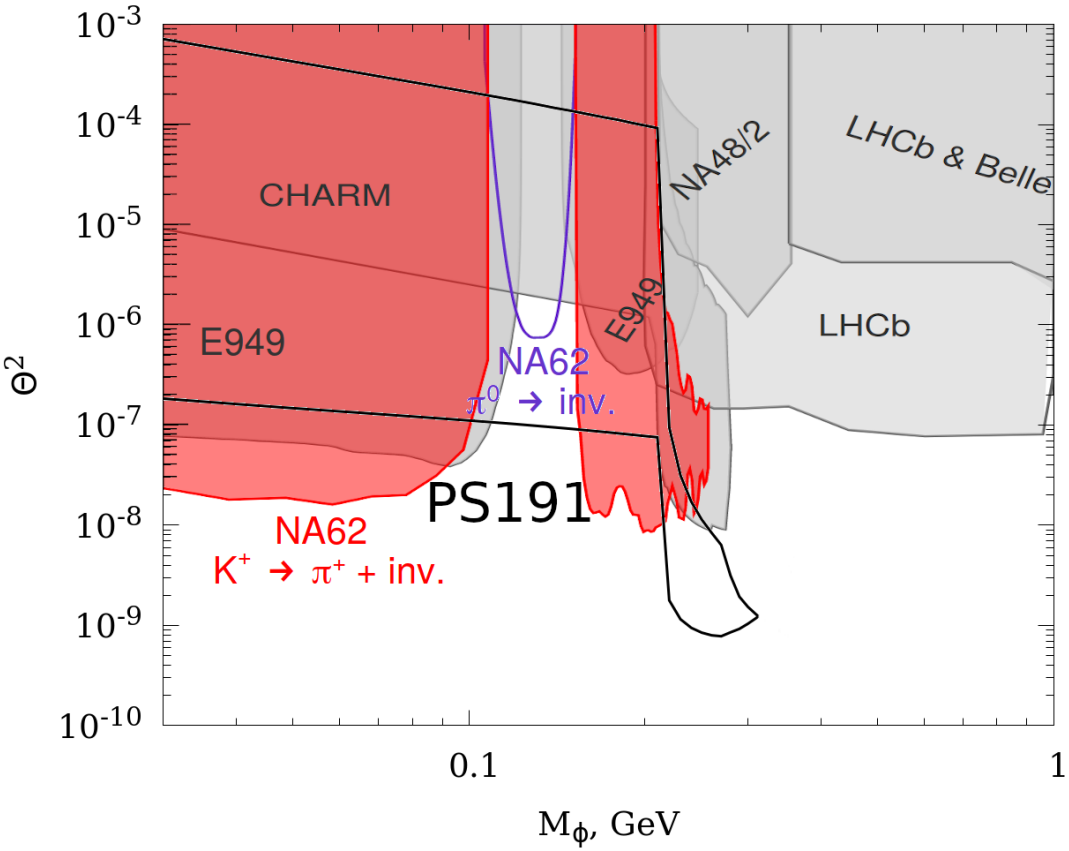


Figure 8: The region outlined by the solid line is excluded at 90% CL from negative searches at PS191.

Conclusion

- In the parameter space of mixing angle and scalar mass, (θ, M_ϕ) our study closes previously viable regions of masses 100-150 MeV and $\theta^2 \sim 10^{-7} - 10^{-6}$, and $M_\phi \sim 200 - 300$ MeV, $\theta^2 \sim 10^{-9} - 10^{-8}$.
- Our analysis can be extended straightforwardly to models with other patterns of scalar couplings to SM particles.
- Our results may be further refined.

Thank you for your attention!

Backup slides

	in target and decay tunnel	in the beam dump	in soil outside decay tunnel
K^+ produced	83833	117493	133535
K^- produced	37439	899	6984
K_L^0 produced	19646	1824	11186
K^+ decayed in flight	92048	4572	18268
K^+ decayed stopped	446	113028	106499
K^- decayed in flight	40580	886	3856
K_L^0 decayed (in flight)	25606	1571	5479

Table 1: Decayed kaon budget for a total simulated statistics of $N_{POT} = 2 \times 10^6$.

Backup slides

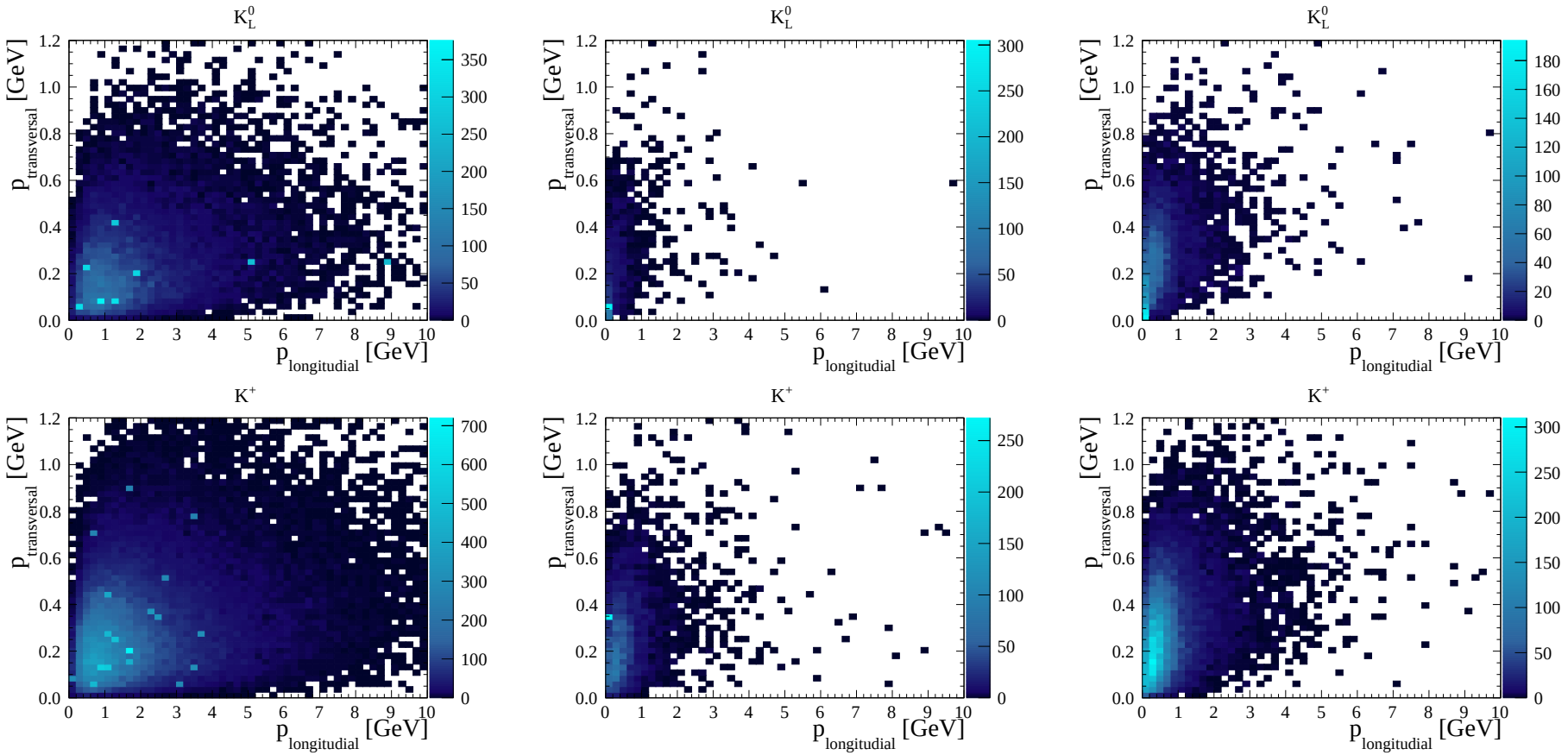


Figure 9: Kinematic distributions of the neutral (top plots) and charged (bottom plots) kaons decayed in the decay volume, beam dump, and sand (from left to right).