Search for a new light scalar in the $S \to \mu^+\mu^-$ decay

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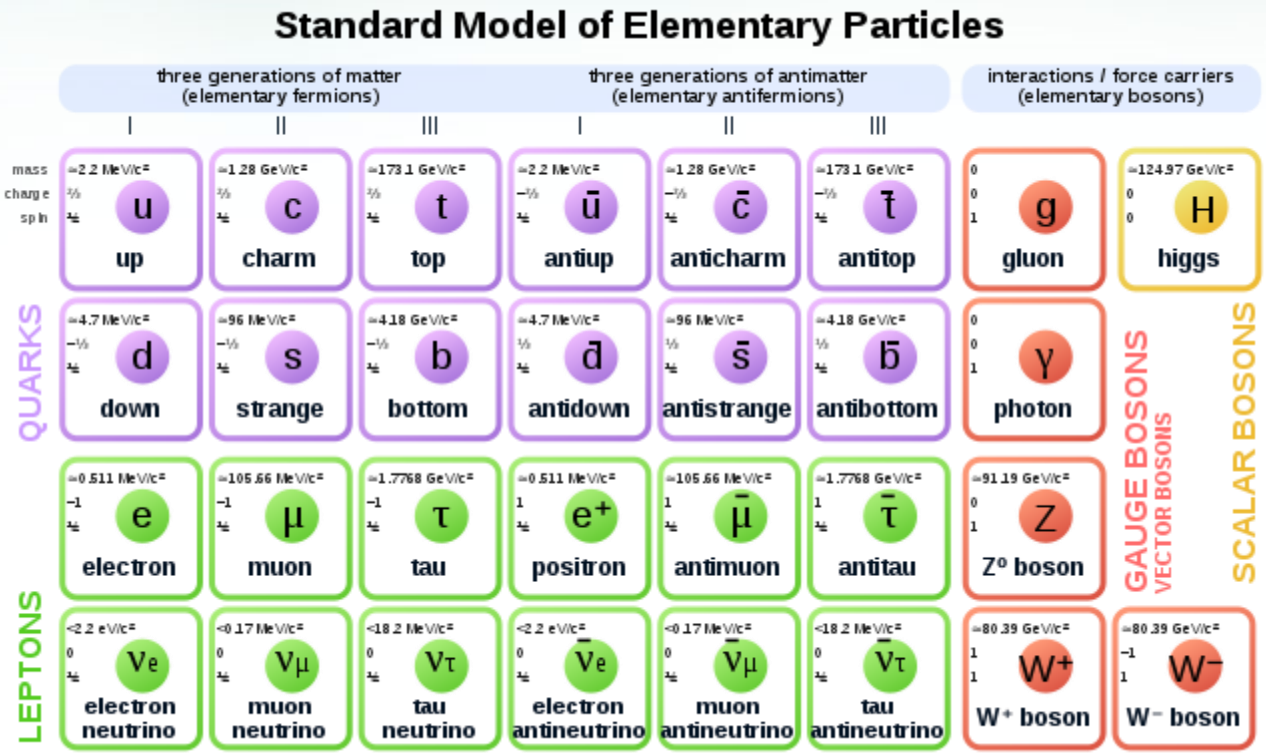
Outline

- Standard Model and beyond
- Models with a light scalar
- Scalar production
- Scalar decay
- Search for a light scalar in $K \to \pi S$, $S \to \mu\mu$
- Search for a light scalar in $B \to KS$, $S \to \mu\mu$
- Conclusions

Standard Model



Phenomena not explained by the Standard Model (SM)

- Neutrino masses/oscillations
- Baryon asymmetry of the Universe
- Dark Matter
- Dark Energy
- Gravity

Intrinsic difficulties

- Hierarchy problem
- Strong CP problem
- …

SM is incomplete

Physics beyond the SM

Simplest model extension

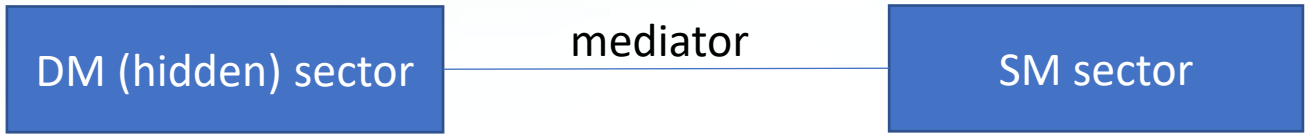
- Add one singlet scalar field
- New scalar couples to the Higgs boson (scalar portal, Higgs portal)
- Mass could be O(GeV)

What could explain:

- Dark Matter
- Inflation
- Hierarchy problem

Dark Matter and a new scalar

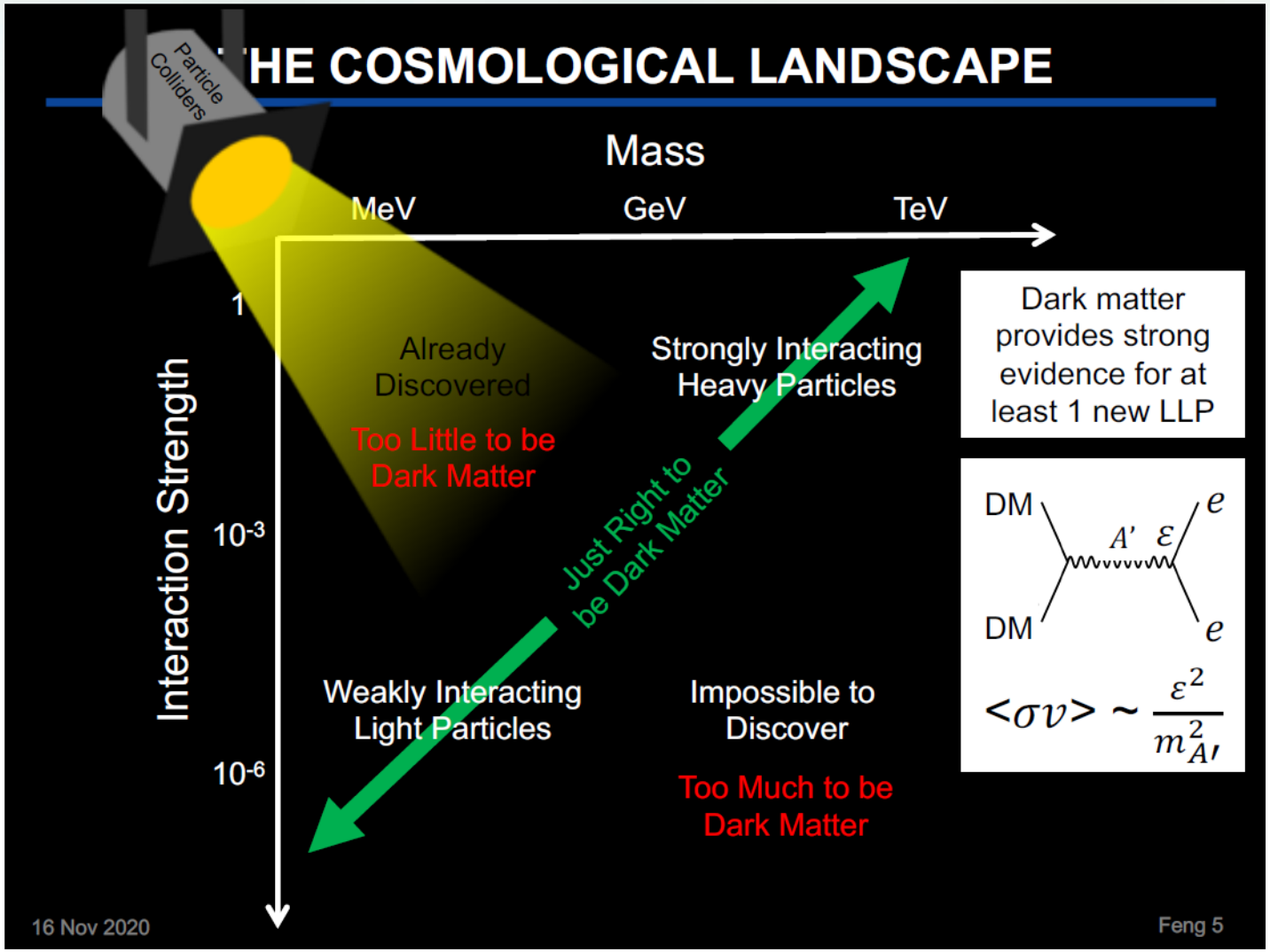
Hidden sector concept



Portal	Coupling
Vector: Dark Photon, A'	$-\frac{\varepsilon}{2\cos\theta_W} F'_{\mu\nu} B^{\mu\nu}$
Scalar: Dark Higgs, S	$(\mu S + \lambda_{\mathrm{HS}} S^2) H^\dagger H$
Fermion: Heavy Neutral Lepton, N	$y_N L H N$
Pseudo-scalar: Axion, a	$\frac{a}{f_a} F_{\mu\nu}\tilde{F}^{\mu\nu}$, $\frac{a}{f_a} G_{i,\mu\nu}\tilde{G}_i^{\mu\nu}$, $\frac{\partial_\mu a}{f_a}\overline{\psi}\gamma^\mu\gamma^5\psi$

Searching for a mediator: portal towards the light DM

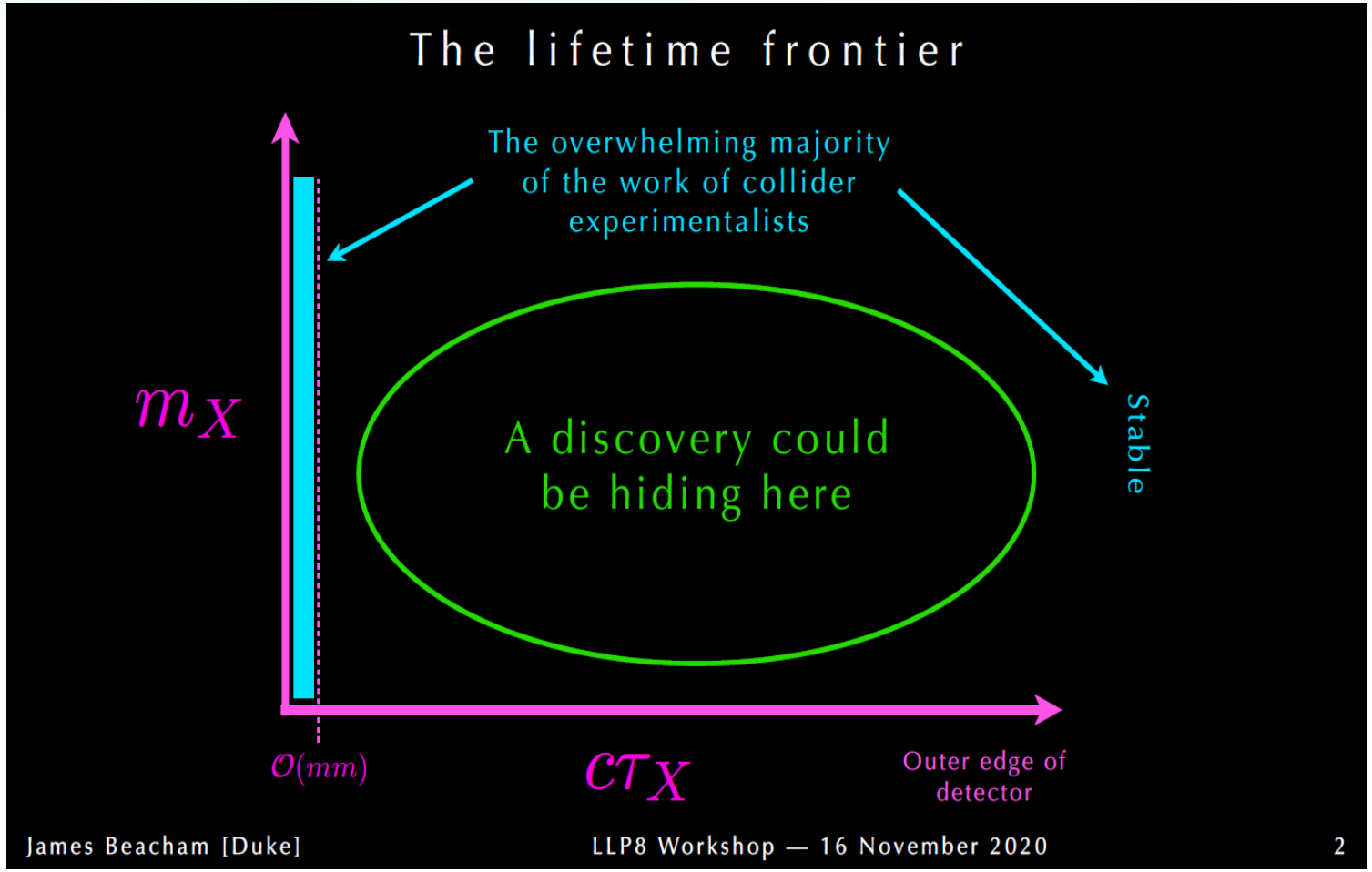
New scalar: mass and lifetime



- M ~O(GeV)
- Interaction strength ~1/τ

Long lived particle (LLP)

New scalar: lifetime



Sensitivity to large τ needed

- Experiments with a long decay volume
- High intensity beams

Hierarchy problem and a new scalar

Hierarchy problem for the Higgs mass:

- Measured mass = bare mass + quantum corrections
- Good model: small quantum corrections
- SM: very big quantum corrections

- Fine tuning of corrections to obtain the measured mass

Other formulation of the same problem:

- Why is the Higgs mass so small compared to the Planck mass?

Possible solution: relaxion mechanism

- Dynamic solution of the hierarchy problem
- Relaxion is a scalar particle
- Evolution of the relaxion field reduces the initially big Higgs mass to the measured value

Inflaton model

Models with a light inflaton

- Light scalar field
- Inflaton feebly coupling to the Higgs boson
- Can explain the inflation
- Can be incorporated into the vMSM model (explains neutrino masses, BAU, DM)
- 2 free parameters (mass and coupling constant θ)
- (m, θ) values limited from the cosmology
- Most sensitive processes: K and B decays

will be used here as the reference model

Model lagrangian

arXiv: 0912.0390

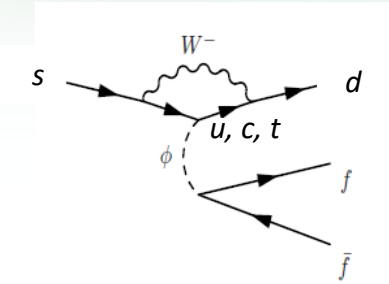
$$\mathcal{L}_{XSM} = \mathcal{L}_{SM} + \mathcal{L}_{XN} \,,$$

$$\mathcal{L}_{XN} = \frac{1}{2}\partial_\mu X \partial^\mu X + \frac{1}{2} m_X^2 X^2 - \frac{\beta}{4} X^4 - \lambda \left(H^\dagger H - \frac{\alpha}{\lambda} X^2 \right)^2$$

Scalar production in K decays

Kaon decay K → π S

- 3 terms in the amplitude
- Dominant contribution from the FCNC d-s transition
- Non-negligible interference with 4-fermion operator contribution



amplitude

$$A\left(K^+ \to \pi^+ \chi\right) \simeq \theta \frac{M_K^2}{v}\left\{\gamma_1 \frac{1-\kappa}{2}\left(1-\frac{m_\chi^2 - M_\pi^2}{M_K^2}\right) - \gamma_2(1-\kappa) + \frac{1}{2}\frac{3G_F\sqrt{2}}{16\pi^2}\sum_{i=c,t} V_{id}^* m_i^2 V_{is}\right\}$$

$$A\left(K_L \to \pi^0 \chi\right) = -A\left(K^+ \to \pi^+ \chi\right)$$

small

negligible

t-quark contribution dominant

Branching ratio

$$\mathrm{Br}\left(K^+ \to \pi^+ \chi\right) = \frac{1}{\Gamma_{\mathrm{total}}(K^+)} \frac{|A(K^+ \to \pi^+ \chi)|^2}{16\pi M_K} \frac{2|\mathbf{p}_\chi|}{M_K} \approx 1.3 \times 10^{-3} \cdot \left(\frac{2|\mathbf{p}_\chi|}{M_K}\right) \theta^2$$

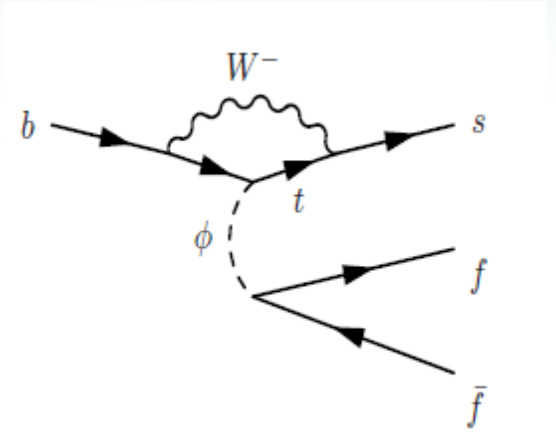
arXiv: 0912.0390

BR(K→π S) proportional to θ^2

Scalar production in B decays

B decays $B^0 \to K^{0*}$ S and $B^+ \to K^+$ S:

- FCNC b-s transition



t-quark dominant contribution

$$\mathcal{L}_{\phi sb} = g_{\phi sb}\phi\,\bar{s}_L b_R + \text{h.c.},$$

$$g_{\phi sb} = \frac{s_\theta\, m_b}{v}\,\frac{3\sqrt{2}\,G_F\, m_t^2\, V_{ts}^* V_{tb}}{16\pi^2}$$

BR(B→K S) proportional to θ^2

Decay width

$$\Gamma_{B\to K^{(*)}\phi} = |g_{\phi sb}|^2 \left|\langle K^{(*)}|\bar{s}_L b_R|B\rangle\right|^2 \frac{\lambda_{B,K^{(*)}\phi}^{1/2}}{16\pi\, m_B}$$

$$|\langle K^*|\bar{s}_L b_R|B\rangle|^2 = \frac{1}{4}\frac{m_B^4\,\lambda_{B,K^{(*)}\phi}}{(m_b+m_s)^2}\,A_{K^*}^2 \longrightarrow A_{K^*} = \frac{1.36}{1-q^2/27.9\,\text{GeV}^2} - \frac{0.99}{1-q^2/36.8\,\text{GeV}^2}$$

$$|\langle K|\bar{s}_L b_R|B\rangle|^2 = \frac{1}{4}\frac{(m_B^2-m_K^2)^2}{(m_b-m_s)^2}\,f_K^2 \longrightarrow f_K = \frac{0.33}{1-q^2/37.5\,\text{GeV}^2}\,.$$

arXiv: 1809.01876

Scalar decay

Decay width to leptons:

$$\Gamma(\phi \to \bar{\ell}\ell) \equiv \Gamma_{\bar{\ell}\ell} = \frac{s_\theta^2 G_F m_\phi}{4\sqrt{2}\pi} m_\ell^2 \beta_\ell^3$$

$$\beta_\ell = \sqrt{1 - 4m_\ell^2/m_\phi^2}$$

Γ(S→ …) proportional to θ^2

S→ee:

- Negligible for m > 2*m_μ wrt muon channel
- Bkg from photon conversion

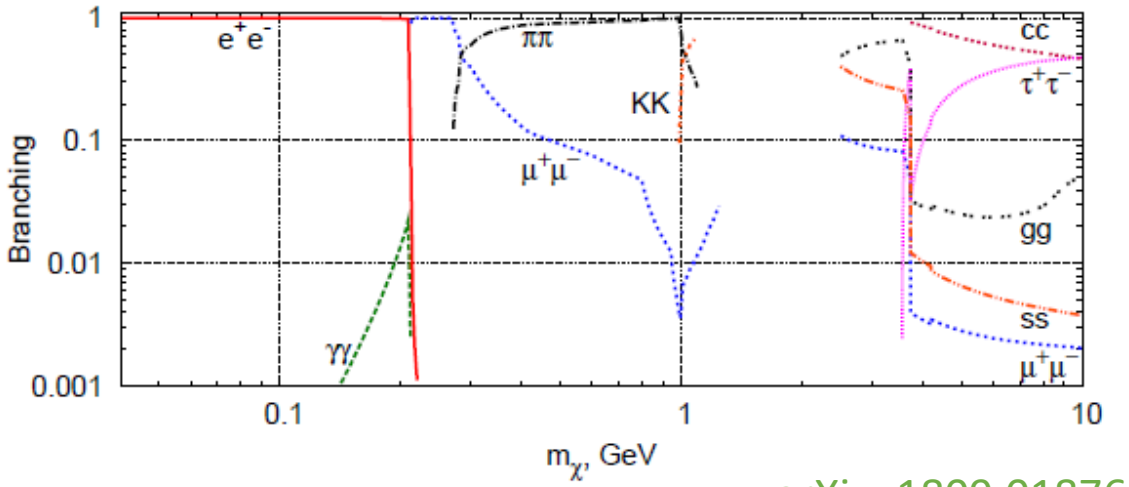
S→μμ

- dominant for m < 2*mπ
- Non-negligible BR for m > 2*m_π

S→γγ

- negligible

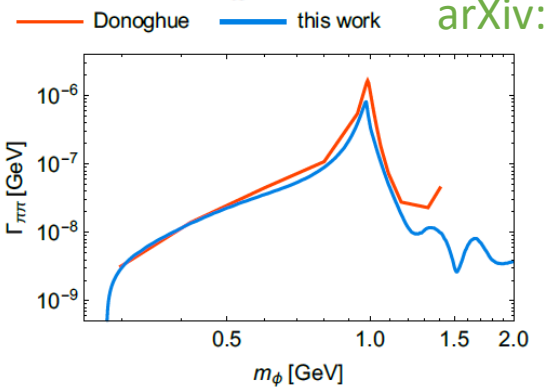
arXiv: 0912.0390



S→π π: non-trivial theoretical calculations

- ChPT for m < 1.3 GeV
- Dispersive analysis for 1.3 < m < 2 GeV
- Perturbative spectator model for m > 2 GeV

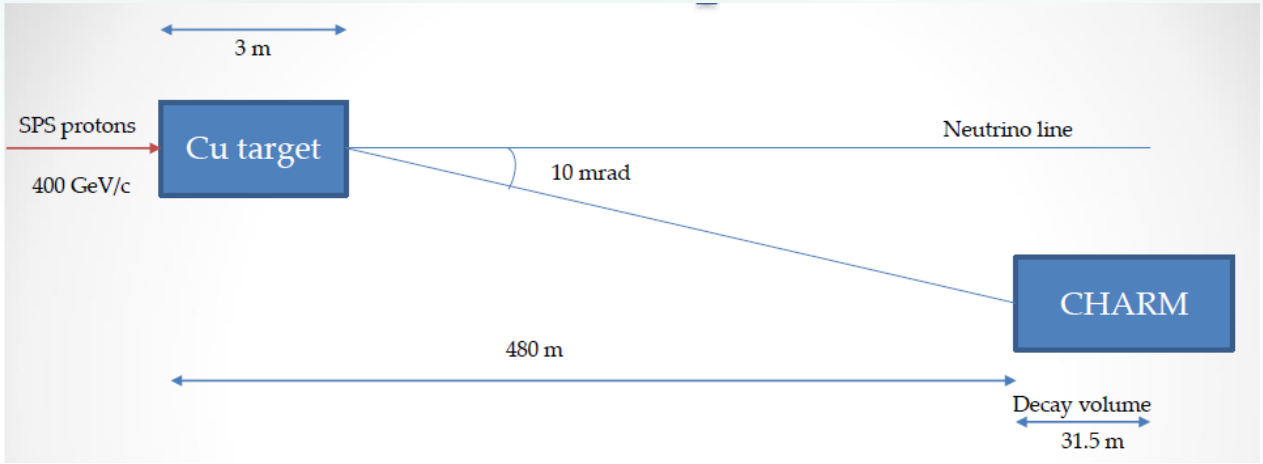
arXiv: 1809.01876



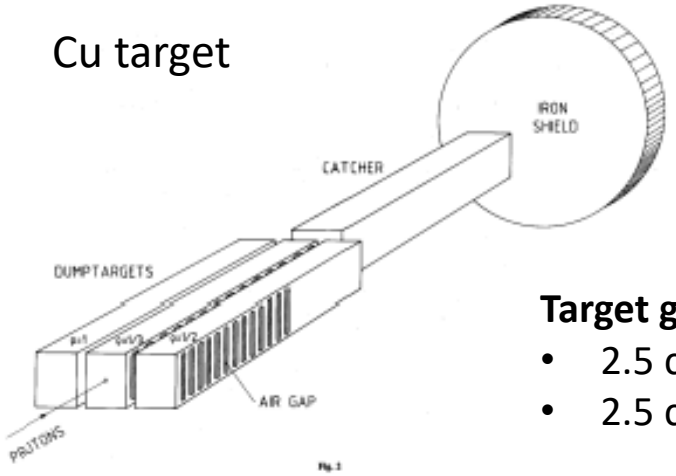
Muon channel seems to be the cleanest

Scalar search in CHARM

CHARM setup



Cu target



Target geometry

- 2.5 cm Cu + 2.5 cm air ($1.7*10^{18}$ POT)
- 2.5 cm Cu + 5 cm air ($0.7*10^{18}$ POT)

Scalar production @ CHARM:

- B decays
- K decays

Kaon absorption:

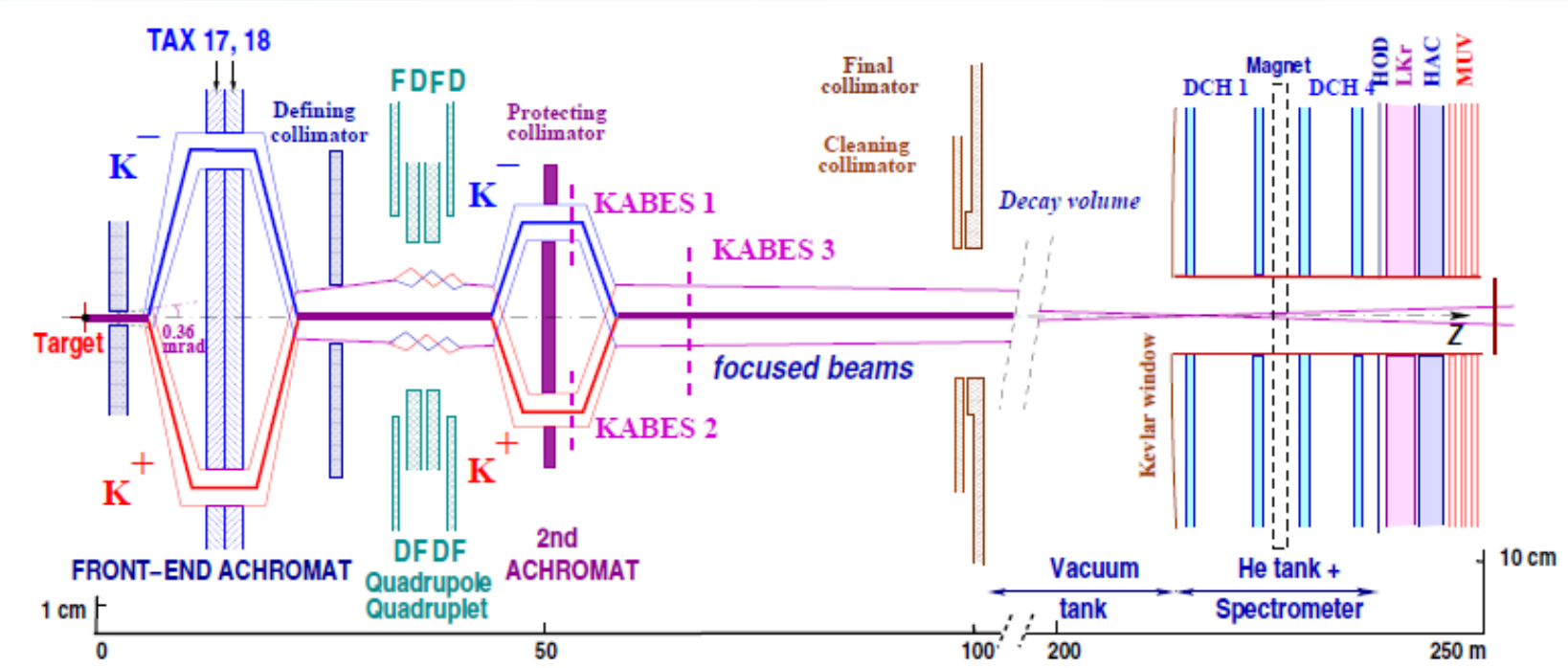
- λ = 13 cm in Cu
- Effective density smaller due to air gaps
- No kaons escape the target but some of them decay

Data collected:

- $2.4*10^{18}$ POT
- Signatures: S→γγ, S→μμ, S→ee
- No signal candidates observed

Scalar search in NA48/2

NA48 setup

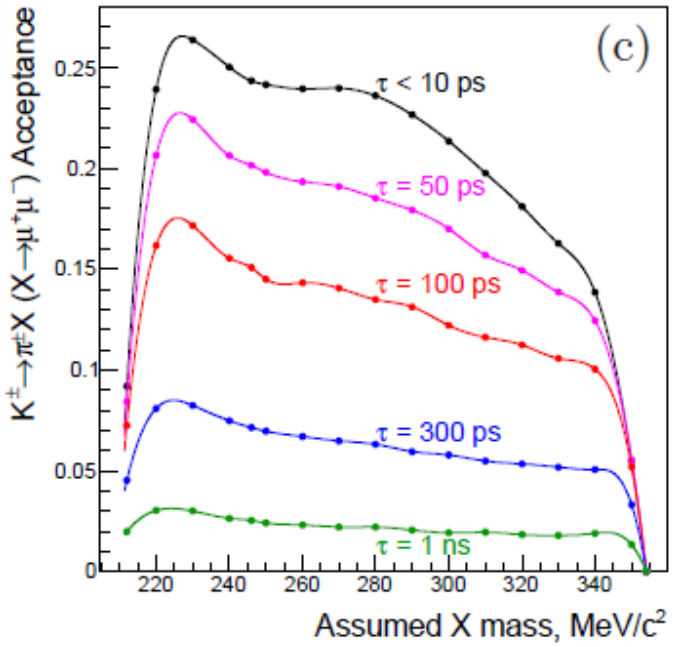


Scalar search in NA48/2

- $K^{\pm} \rightarrow \pi^{\pm} S$, $S \rightarrow \mu^{+}\mu^{-}$
- 2003-2004 data
- Only prompt decays accessible due to the trigger configuration

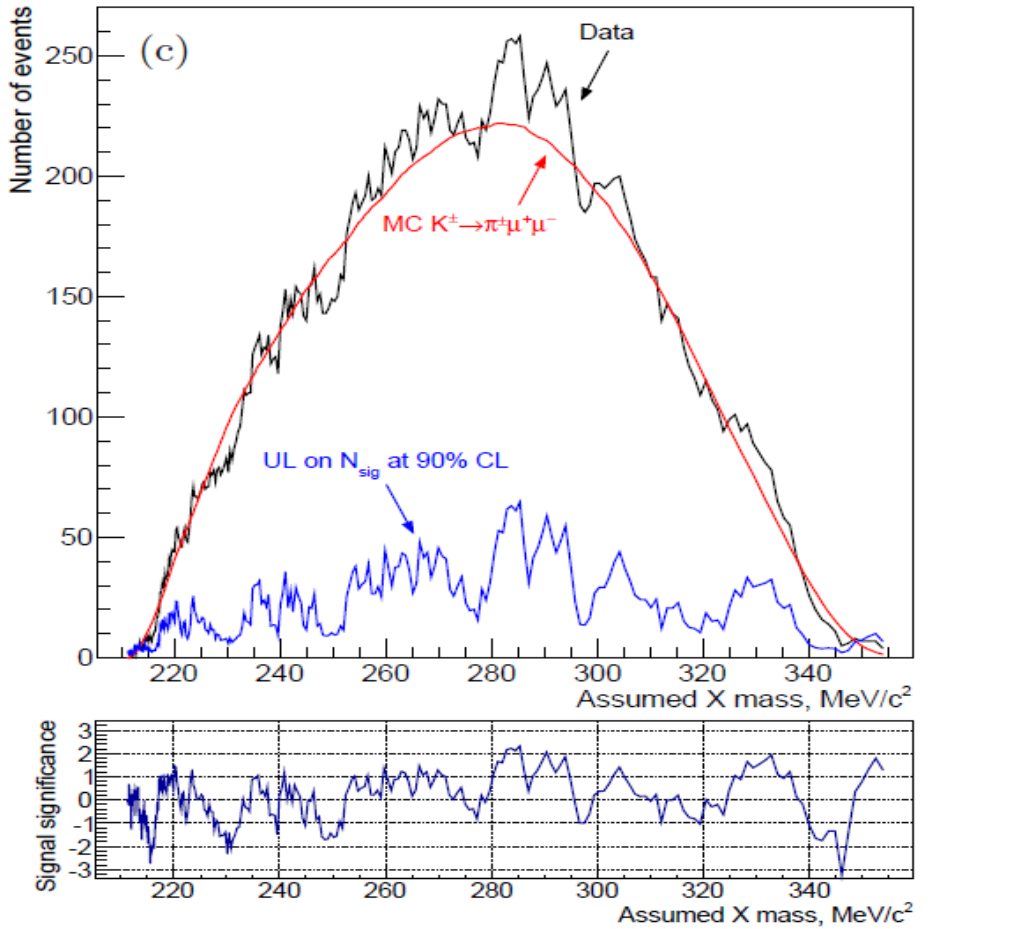
Limits from NA48/2

Signal acceptance



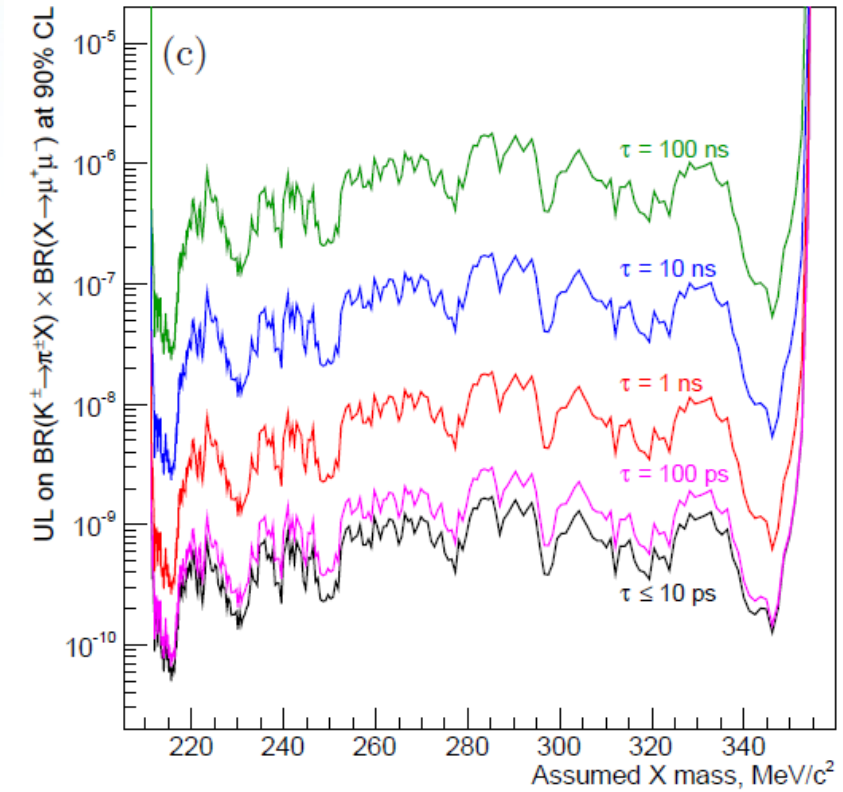
arXiv: 1612.04723

Mass scan

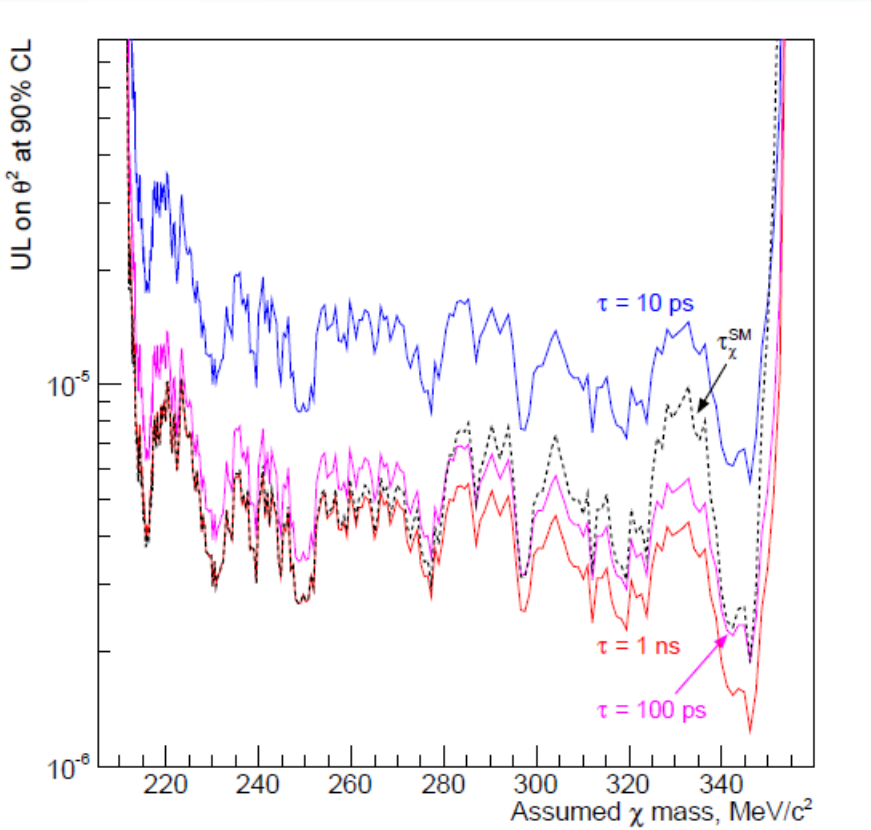


Limits from NA48/2

UL on BR



UL on θ^2



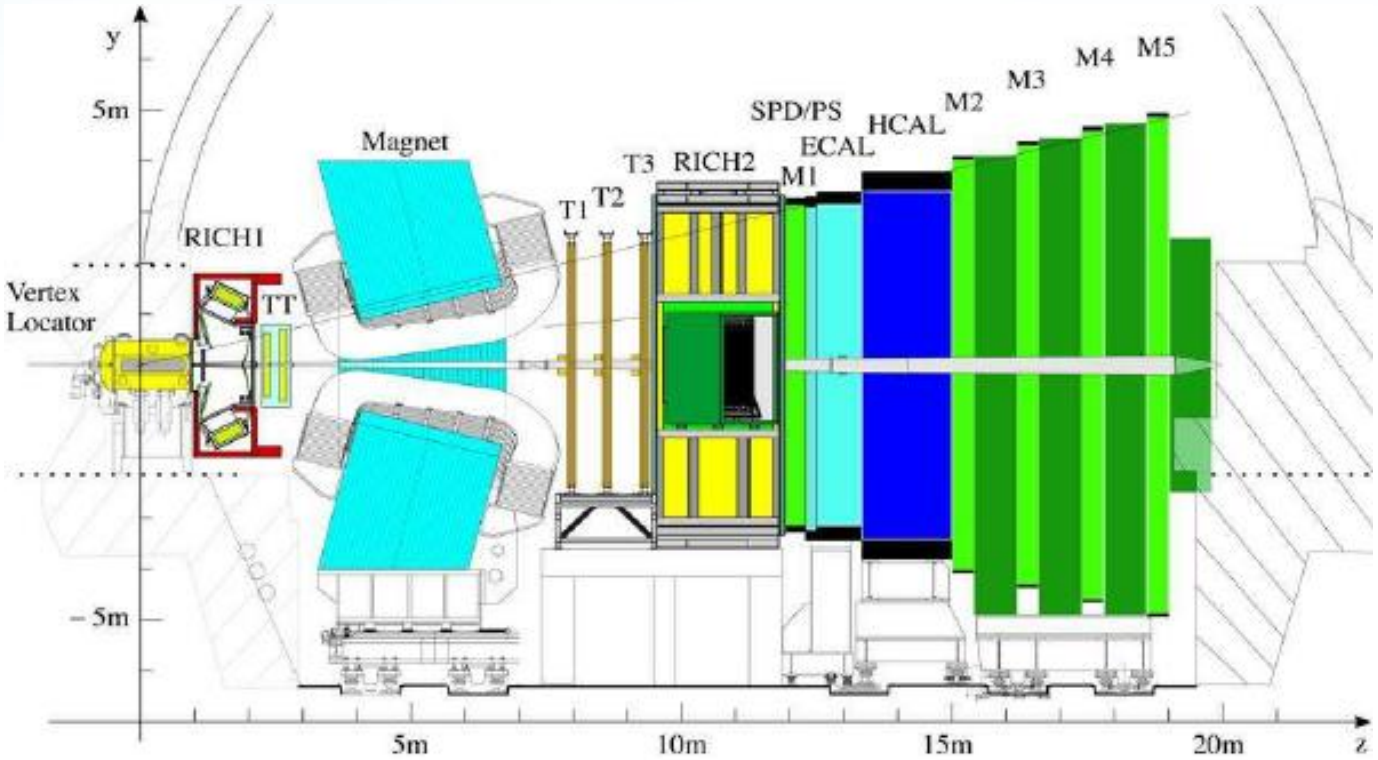
Prompt analysis: loose UL's for large τ

arXiv: 1612.04723

$$\theta^2 = \sqrt{\frac{8\pi\hbar v^2}{\alpha_\chi}} \sqrt{\frac{\mathcal{B}(K^\pm \to \pi^\pm \chi)\mathcal{B}(\chi \to \mu^+\mu^-)}{\tau_\chi M_\chi^3 \lambda^{\frac{1}{2}}(1, r_\pi^2, r_\chi^2)\lambda^{\frac{1}{2}}\left(1, \tilde{\rho}_\mu^2, \tilde{\rho}_\mu^2\right)\tilde{\chi}_{\mu\mu}}}$$

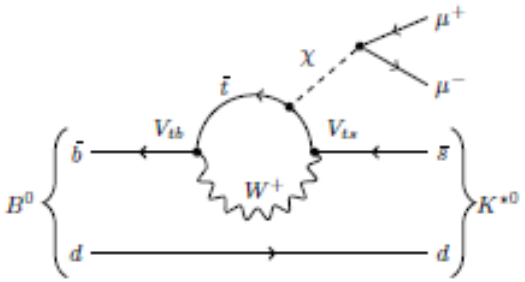
Scalar search in LHCb

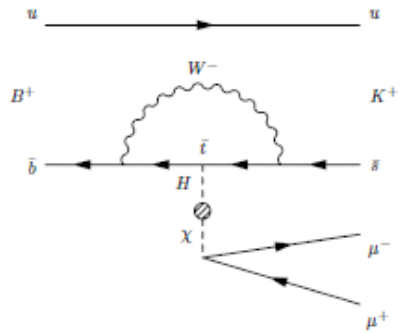
LHCb setup



Scalar search in LHCb

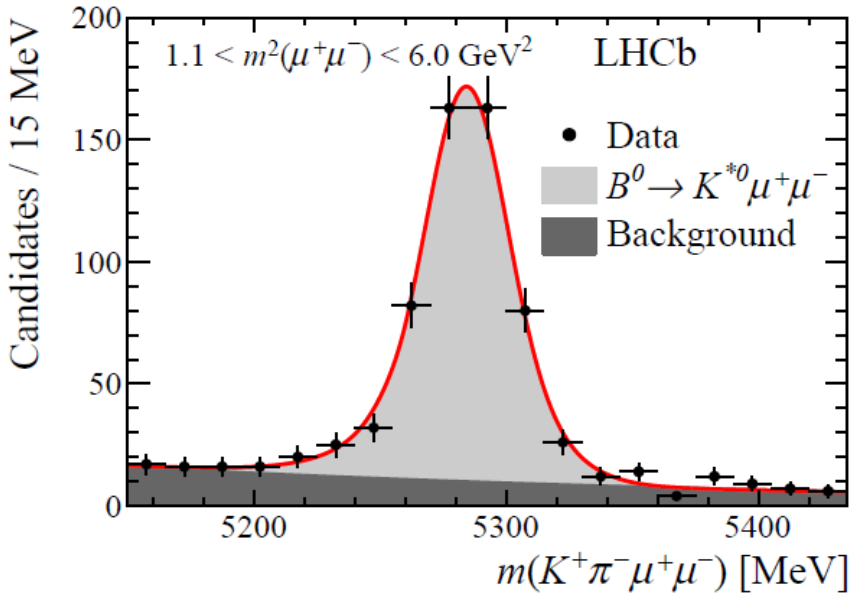
- Run 1 data, 3 fb^{-1}
- $B^0 \rightarrow K^* S$, $S \rightarrow \mu^+ \mu^-$
- $B^+ \rightarrow K^+ S$, $S \rightarrow \mu^+ \mu^-$



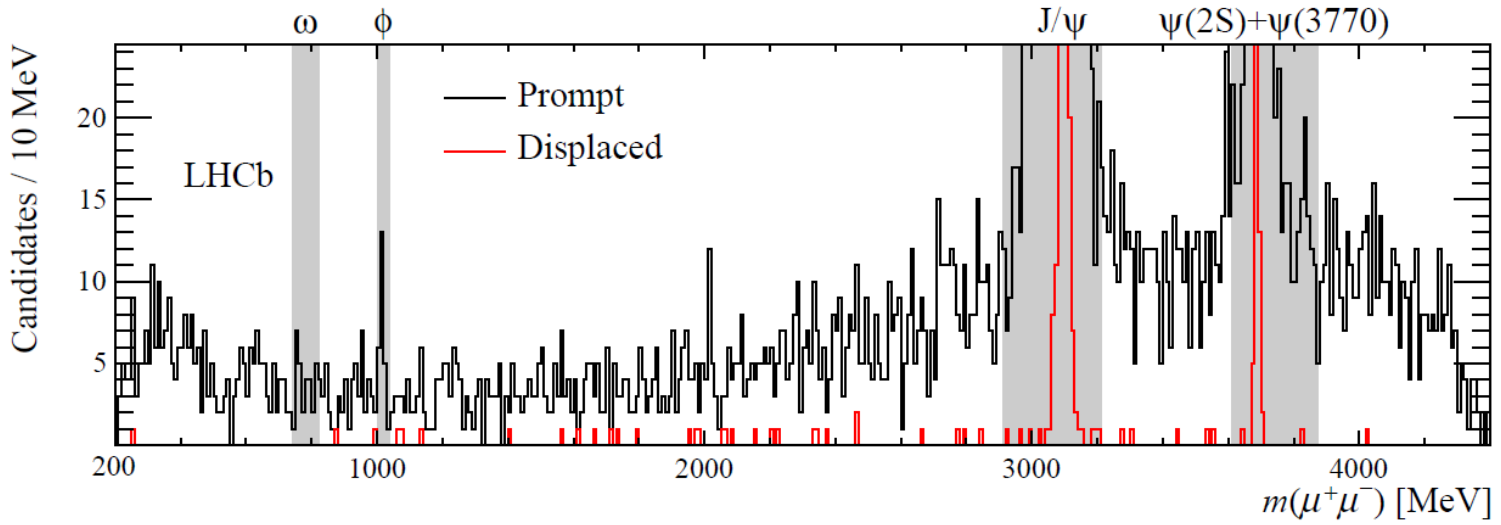


Scalar search in LHCb: B^0

invariant mass for the normalization $B^0 \rightarrow K^{*0} \mu^+ \mu^-$



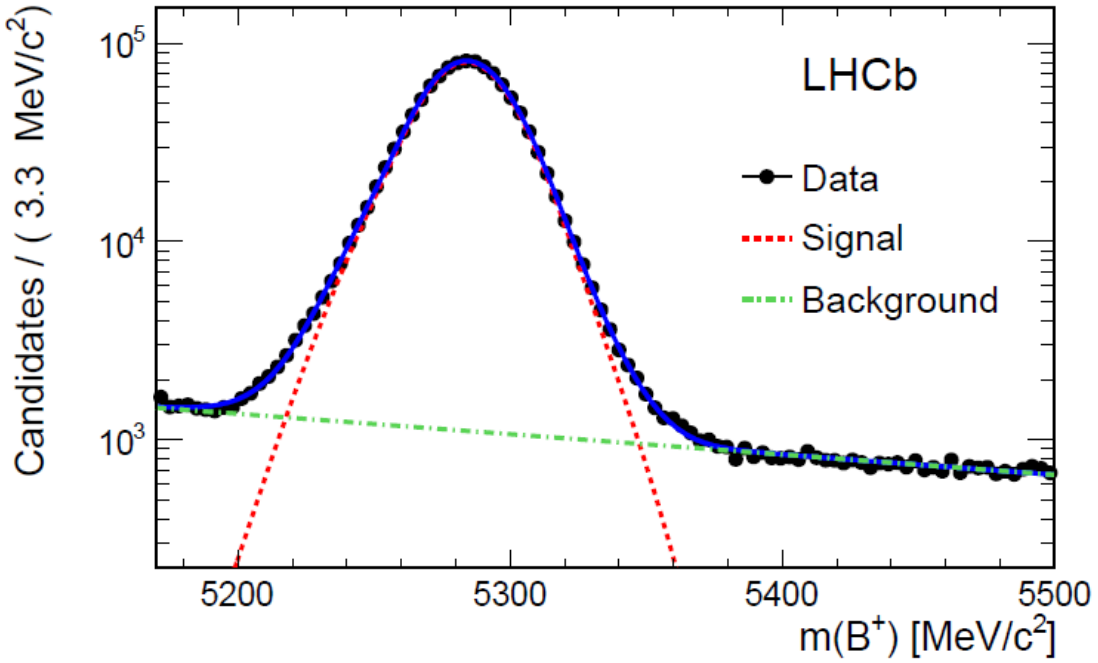
Mass scan



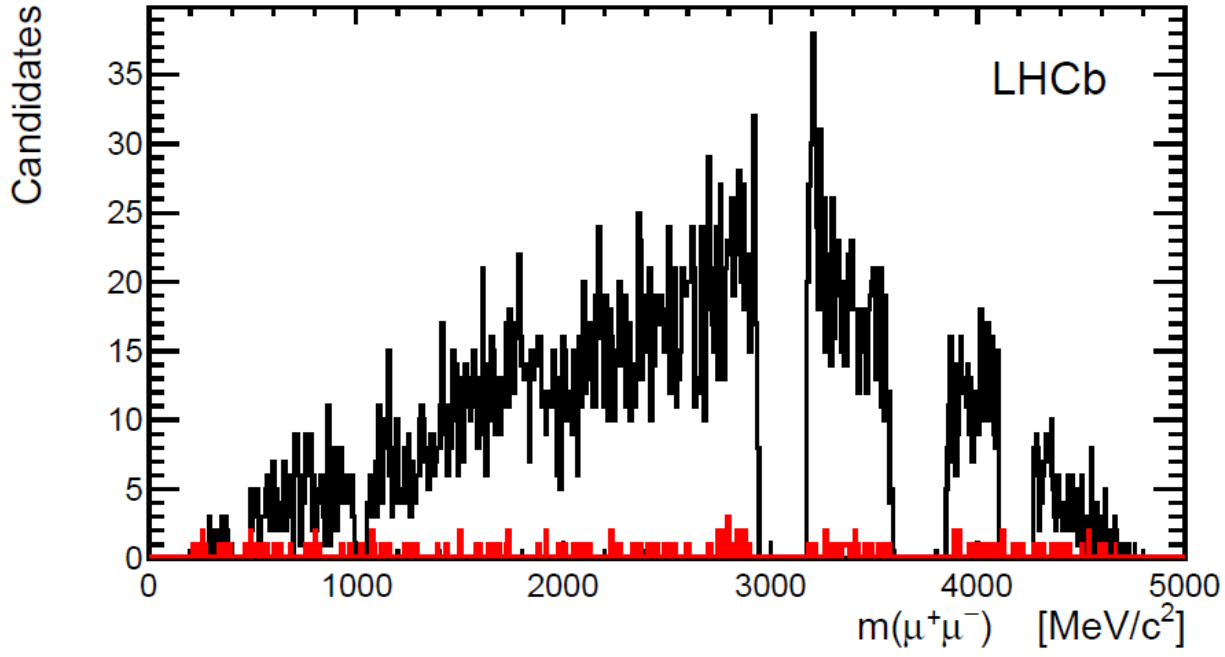
arXiv: 1508.04094

Scalar search in LHCb: B^+

Invariant mass for the normalization $B^+ \to K^+ J/\psi(\mu\,\mu)$



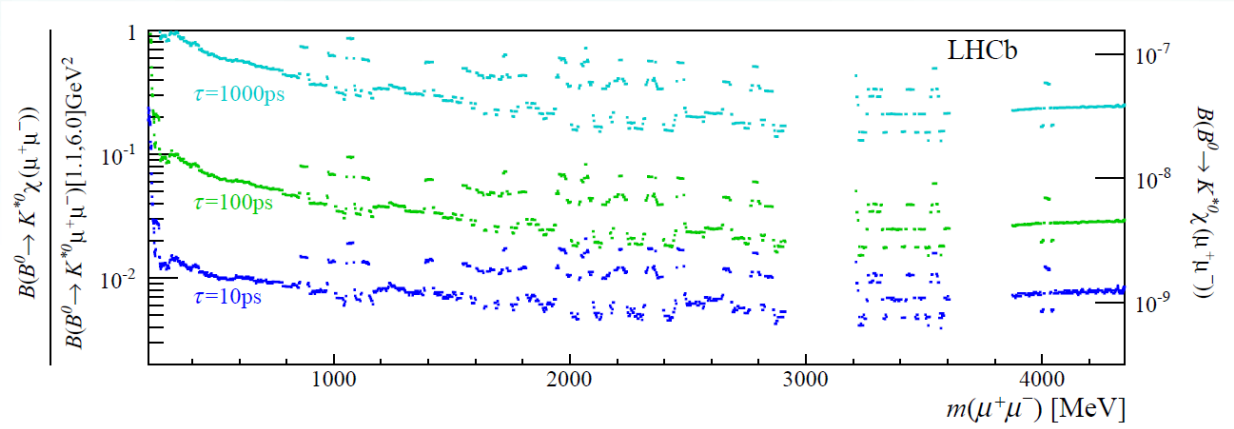
Mass scan

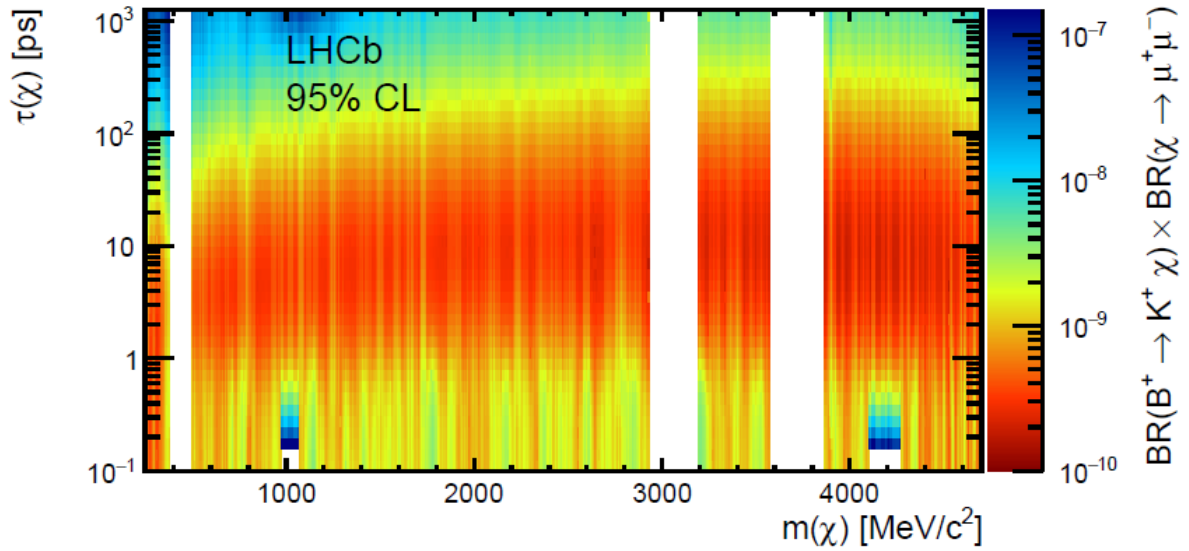


arXiv: 1612.07818

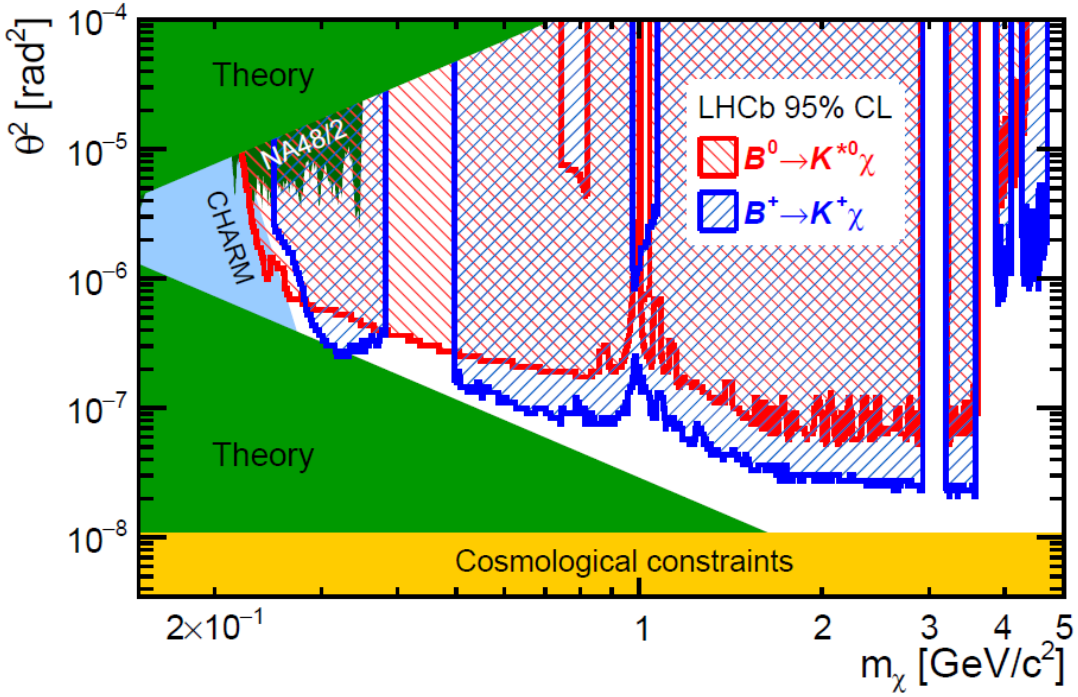
Limits from LHCb

Limits on BR





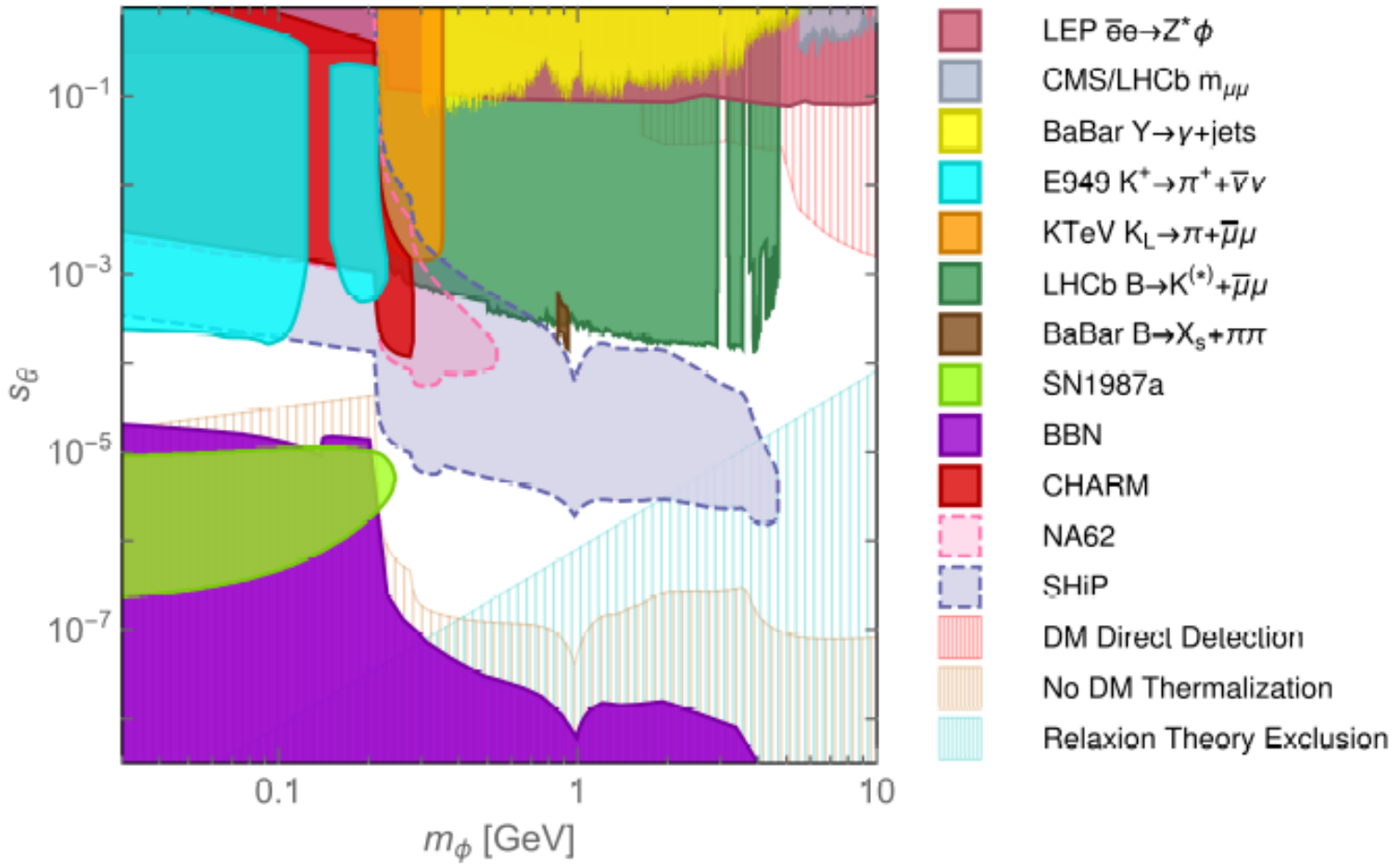
Limits on θ^2



arXiv: 1612.07818

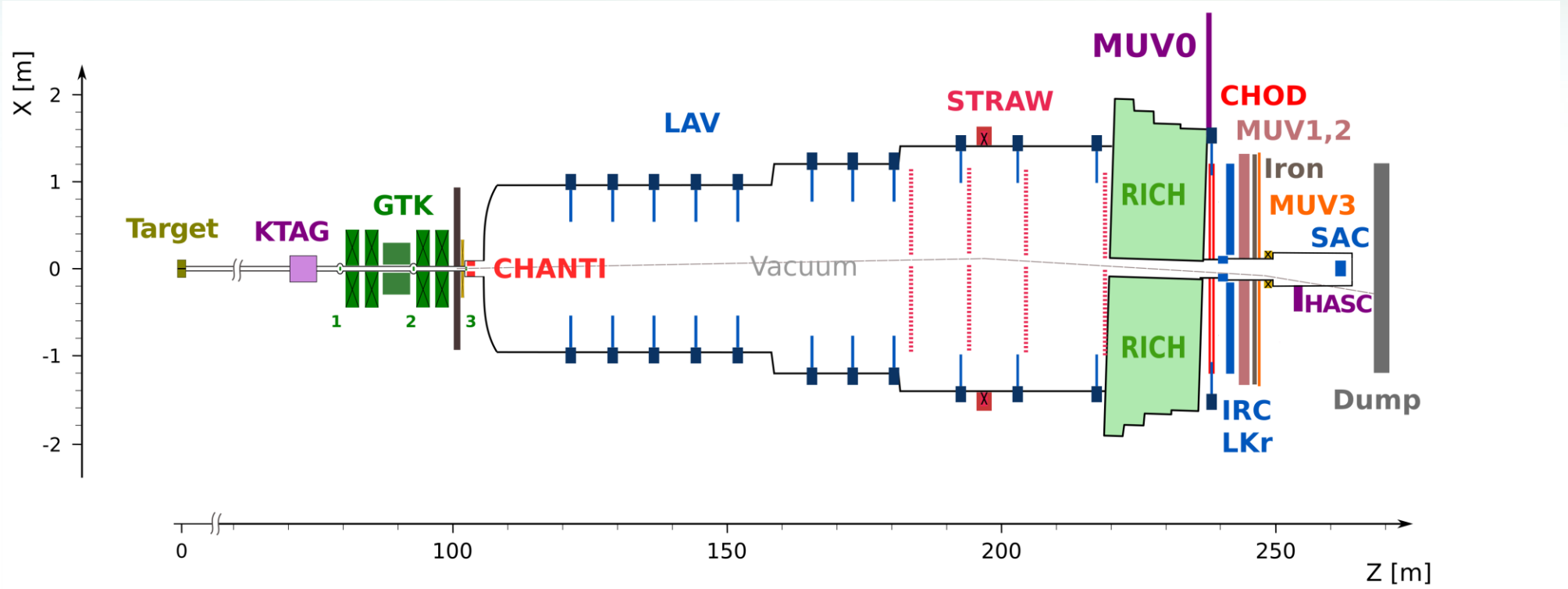
Combined limits

arXiv: 1809.01876



Scalar search in NA62

NA62 setup

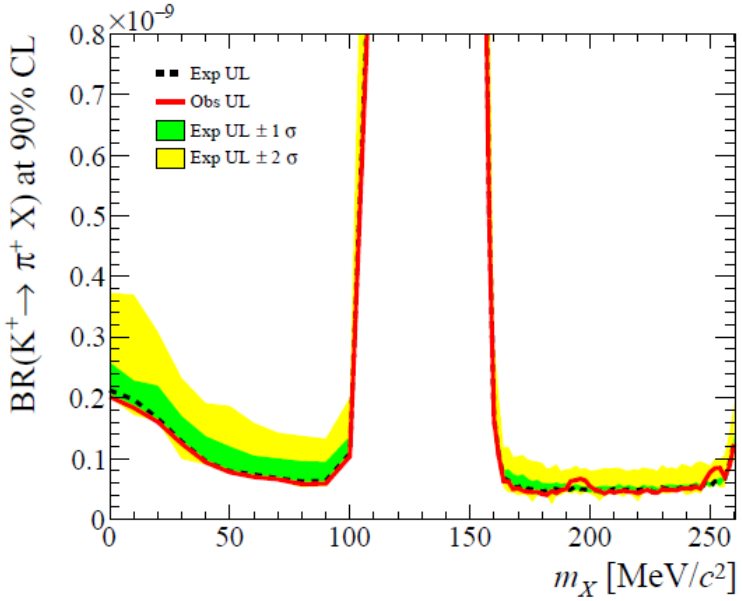


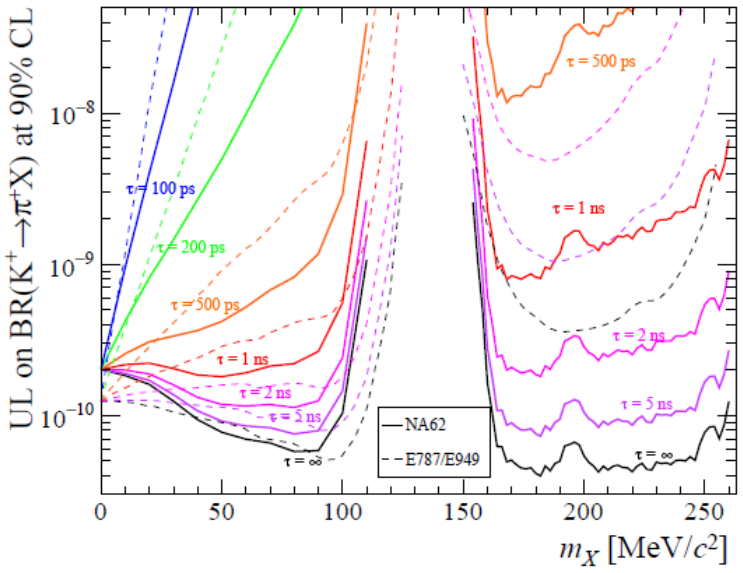
Scalar search in NA62

- Displaced analysis: $K^+ \to \pi^+ S$, $S \to \mu^+ \mu^-$ → Ongoing analysis
- Production: $K^+ \to \pi^+ S$ (byproduct of the PNN analysis) → Published
- Decay: $S \to \mu^+ \mu^-$ (beam dump mode) → Planned for the next run

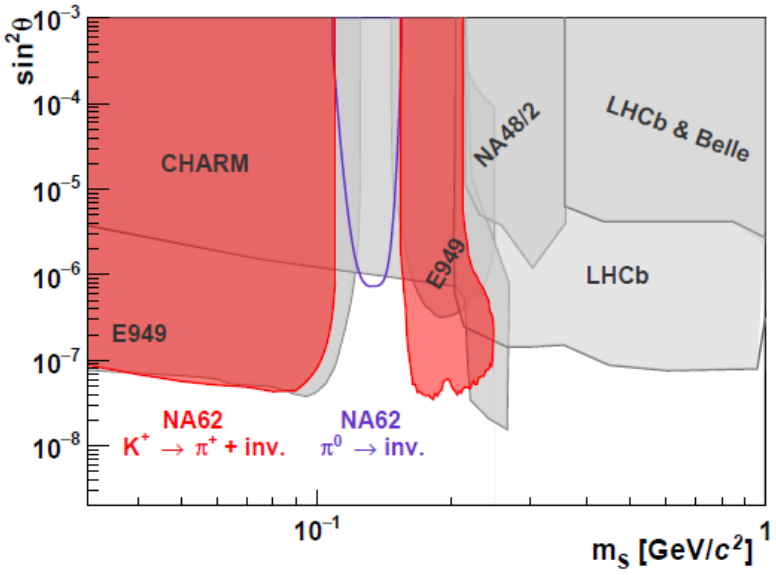
Limits from NA62 on BR(K→πS)

Limits on BR





Limits on θ²



arXiv: 2011.11329

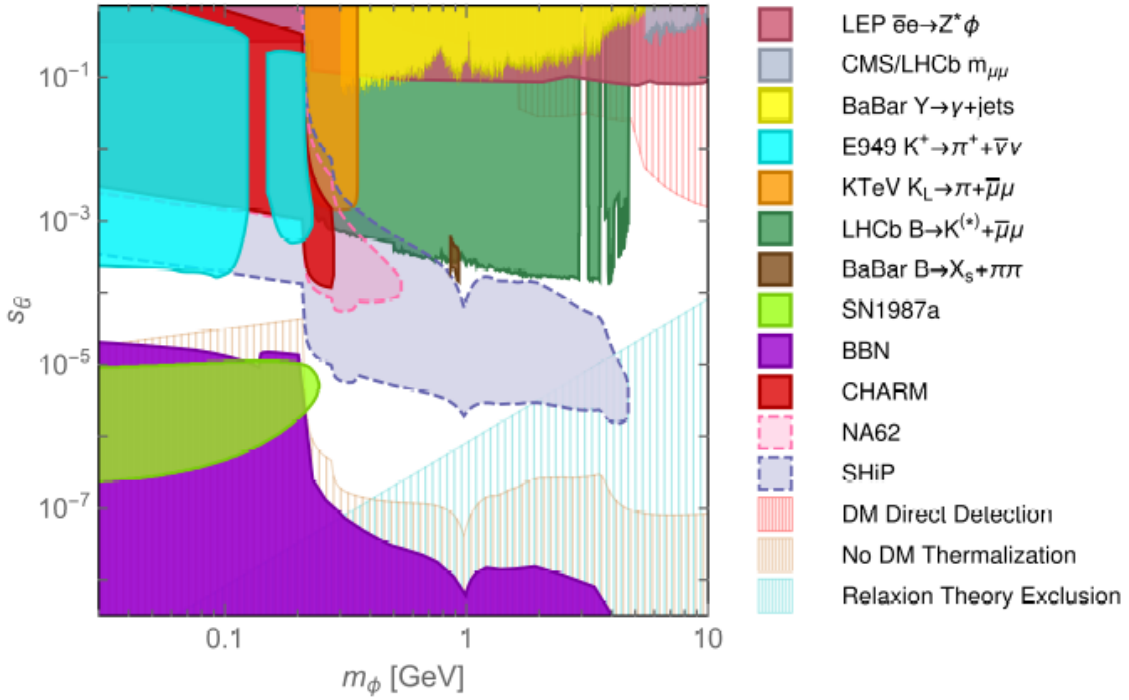
Conclusions

Models with a light scalar

- ❑ possible extension of SM
- ❑ Could explain Dark Matter, hierarchy problem, inflation
- ❑ Inflaton model: 2 parameters m, θ (coupling with Higgs)
- ❑ Best production processes: K and B decays
- ❑ Best decay signature: $S \rightarrow \mu^+ \mu^-$

Experimental searches for the light scalar

- ➢ Beam dump (CHARM, SHIP)
- ➢ K decays (NA48/2, NA62)
- ➢ B decays (LHCb)



Thank you !

Spare