Hunting sub GeV scale dark matter by studying displaced vertices at the colliders.

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Workshop on New Physics with Displaced Vertices

In collaborate with
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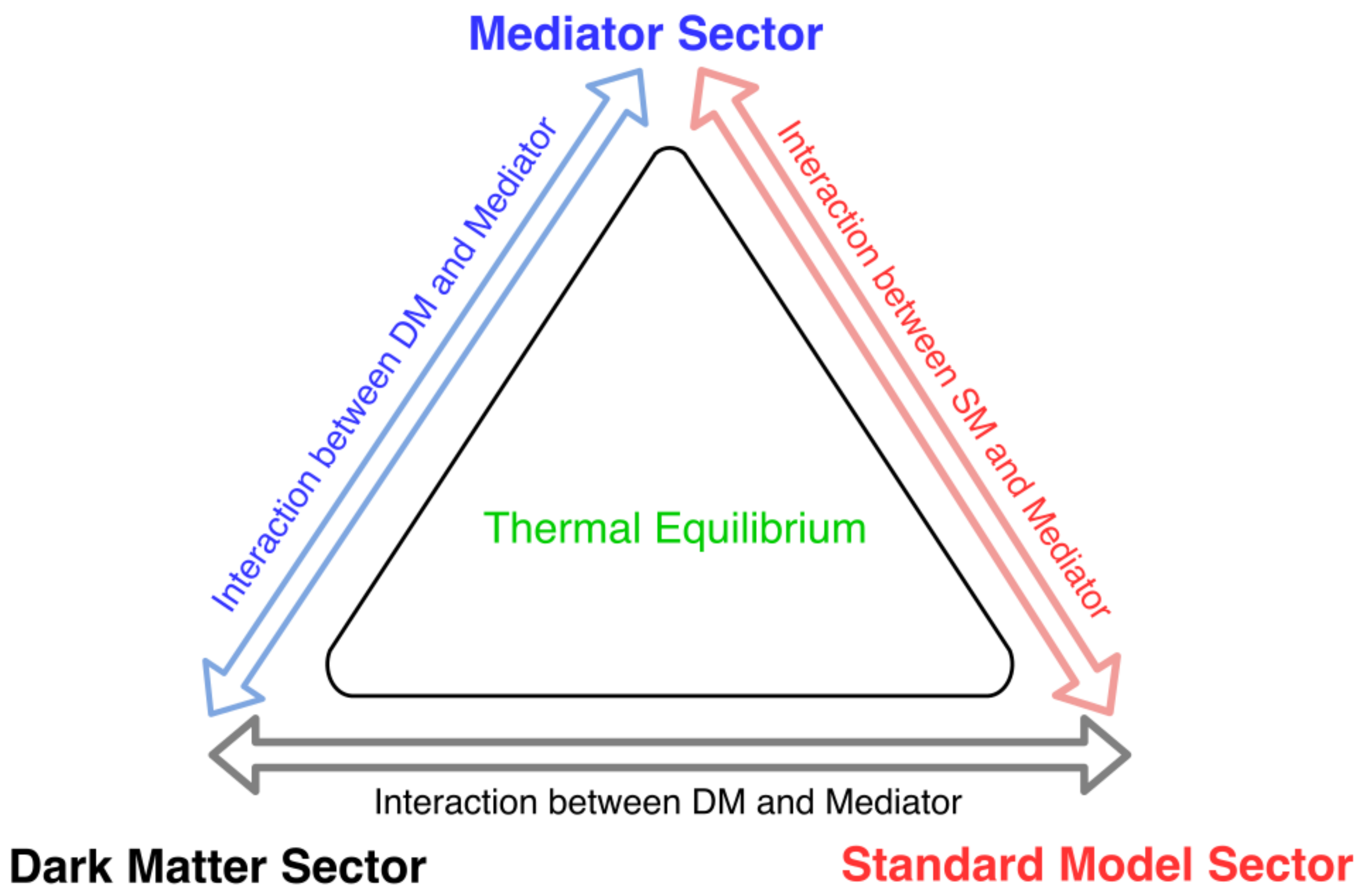
References:
180X.XXXX

Contents

- WIMP DM and its light mediator searching in sub-GeV displaced vertices experiments.
- A simplified model for a Majorana WIMP and scalar mediator.
  - Models
  - Mediator decay
- Detectors and strategies
- Summary

The belief of the WIMP "Miracle"

- Belief 1: DM cannot strongly couple to SM atoms, otherwise we have seen it already.
- Belief 2: The early universe was at very high temperature and thermal equilibrium.
- DM might have interaction with SM particles via mediator, because momentum exchange or temperature transfer are needed to maintain thermal equilibrium in the early universe.
- Even if interaction between DM and SM are very weak, DM-SM TE can still be built via Mediator.

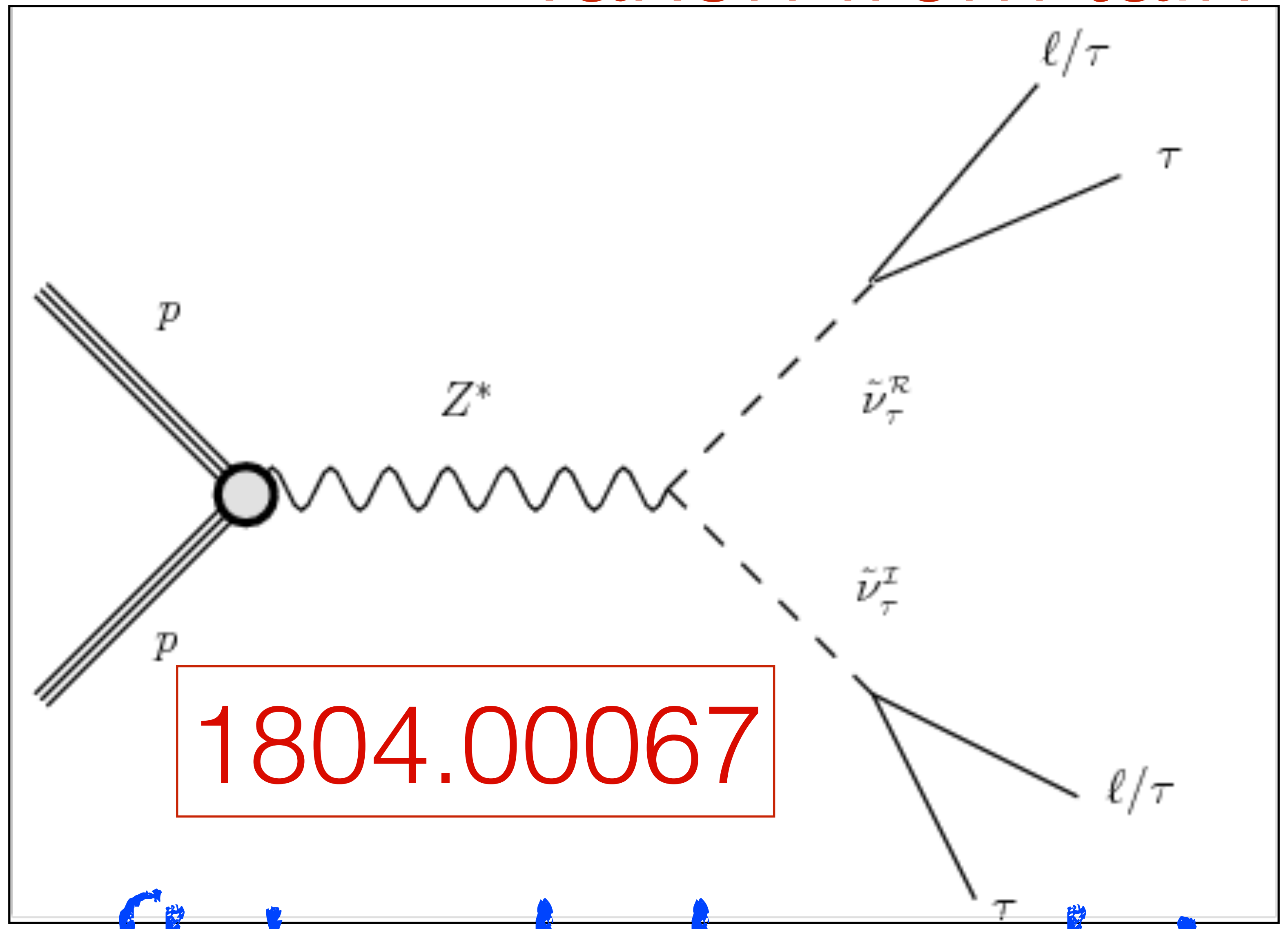


Mediator search

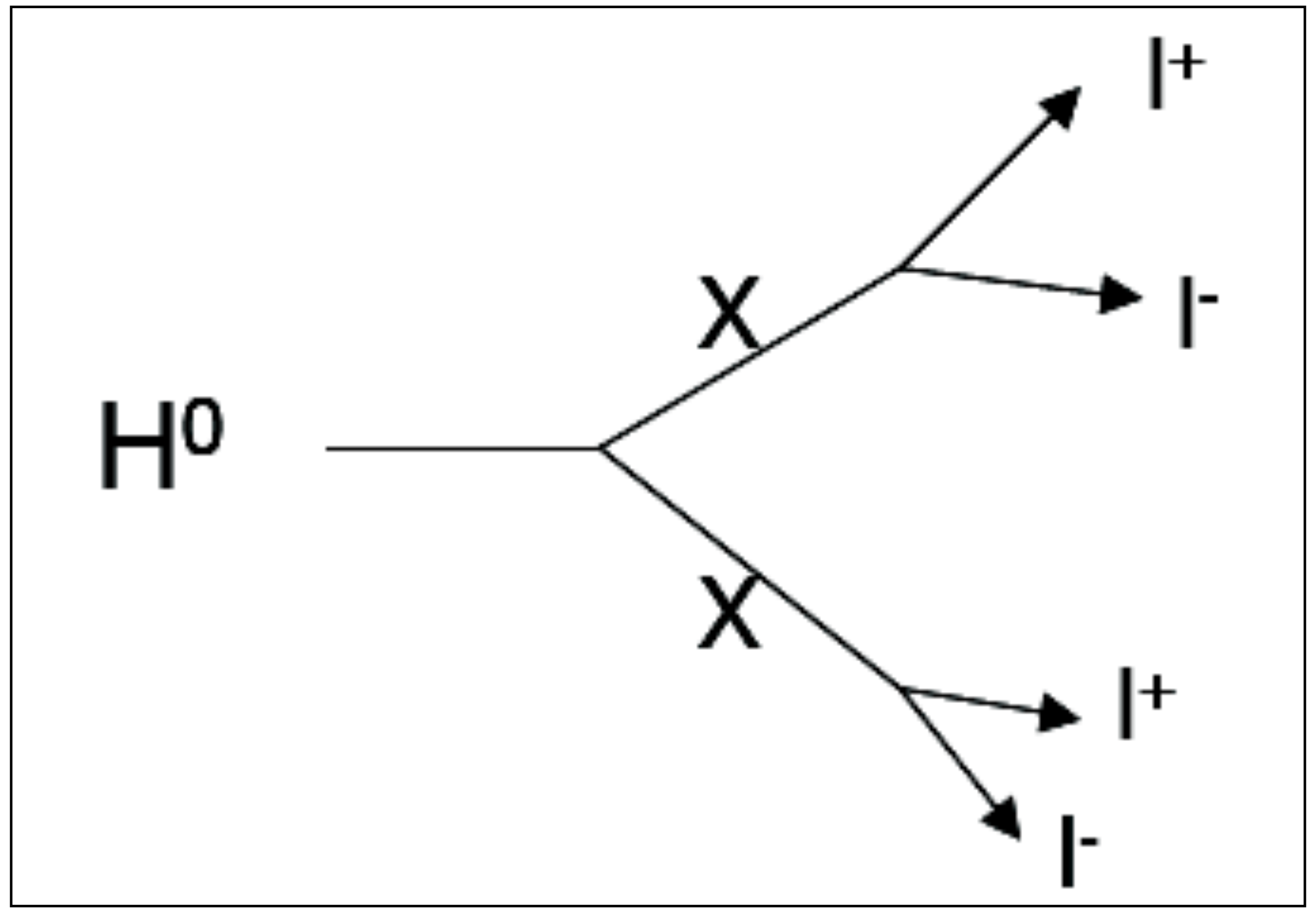
- Neutral
  - ~cm < βγcτ < detector scale: non-prompt decay to
    - displaced leptons
    - displaced photon+X
    - displaced jets, top, W, Z…..
  - βγcτ > detector scale: decay outside detector
    - MET, covered by SUSY/DM searches.
- Charged
  - ~cm < βγcτ < detector scale: kink/fork track
  - βγcτ >detector scale: decay outside detector

The long-live BSM particle decay: displaced vertex search.

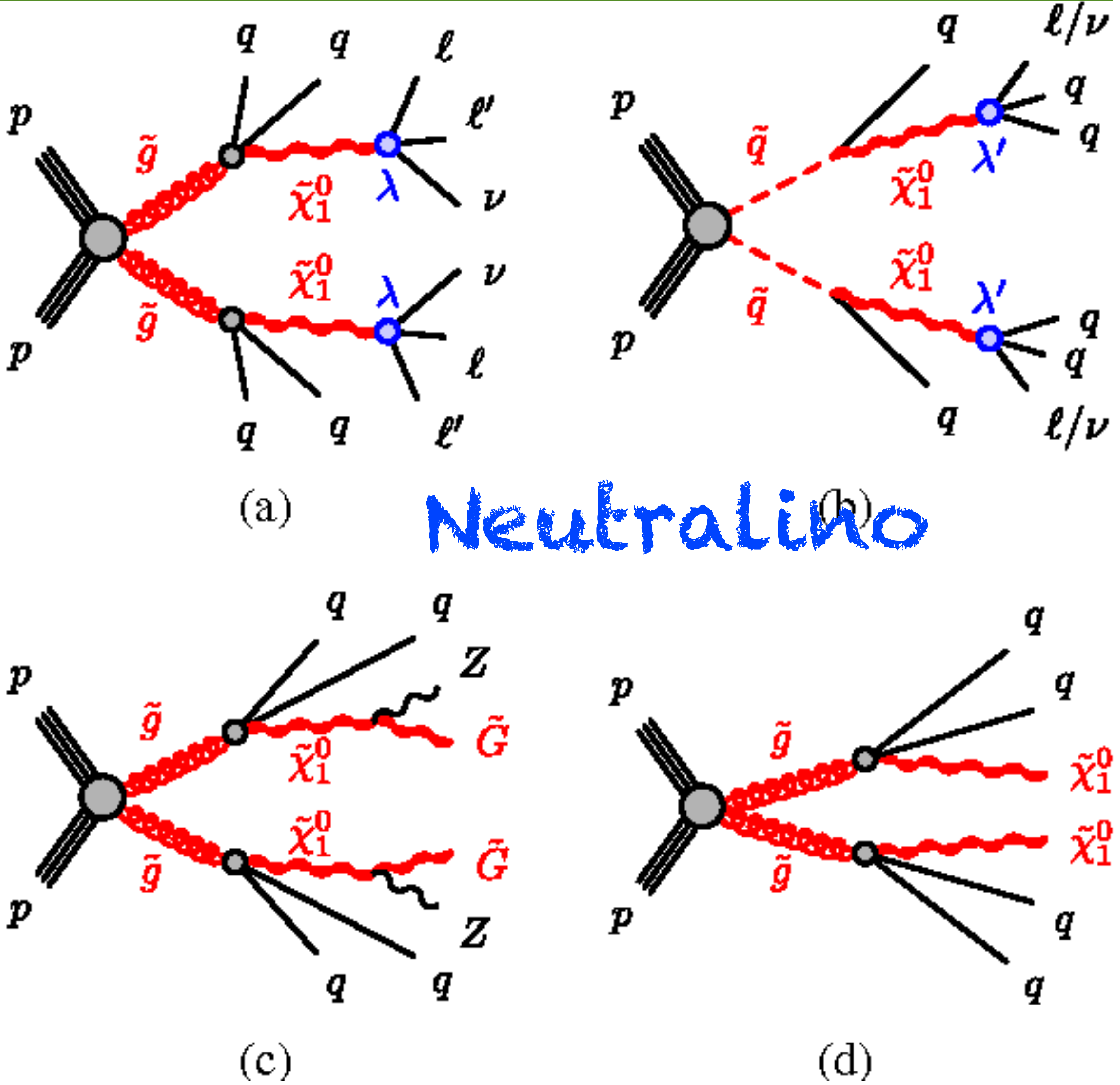
Taken from talk of J. Chen



Left-handed sneutrino



Dark Higgs



Neutralino

Majorana DM and its Higgs mediator

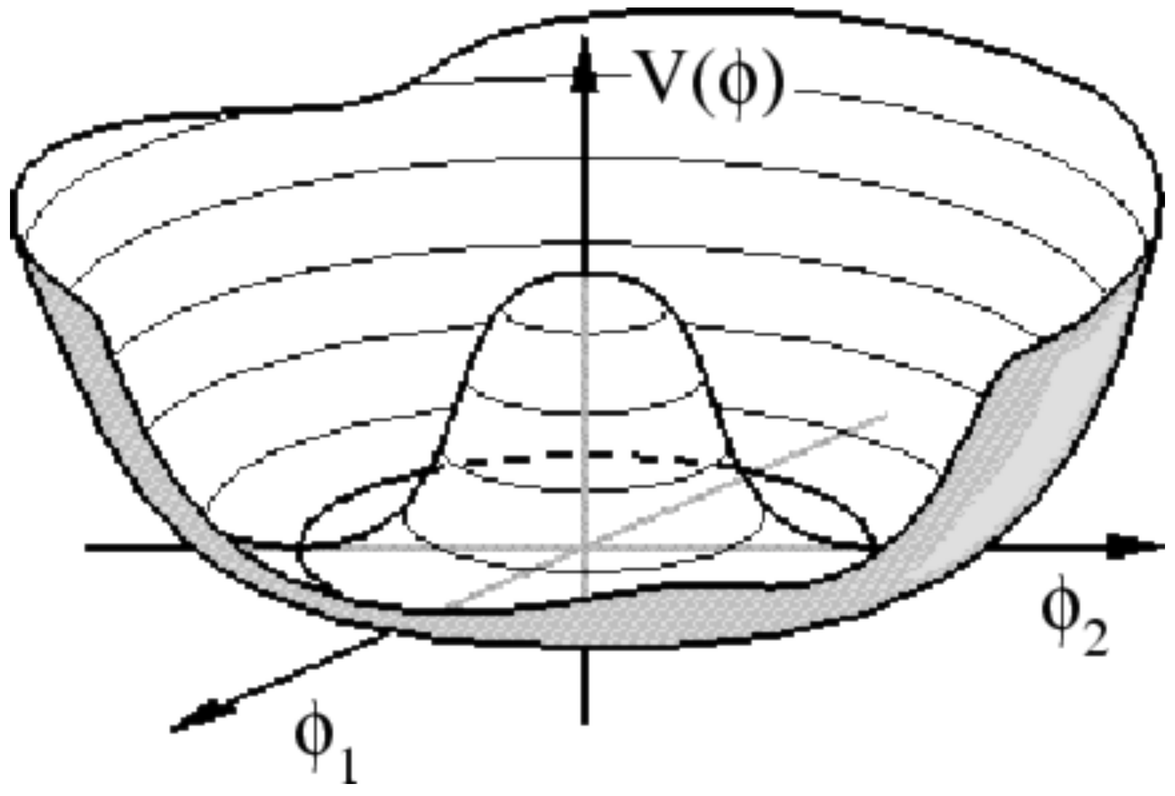
$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{2}\bar{\chi}(i\partial\!\!\!/ - m_\chi)\chi + \frac{1}{2}(\partial\Phi)^2 - \frac{c_s}{2}\Phi\bar{\chi}\chi - \frac{c_p}{2}\Phi\bar{\chi}i\gamma_5\chi - V(\Phi,H),$$

DM: Majorana singlet

phi: real singlet

$$\begin{aligned} V_H(H) &= \mu_H^2 H^\dagger H + \frac{\lambda_H}{2}(H^\dagger H)^2, \\ V_\Phi(\Phi) &= \mu_1^3\Phi + \frac{\mu_\Phi^2}{2}\Phi^2 + \frac{\mu_3}{3!}\Phi^3 + \frac{\lambda_\Phi}{4!}\Phi^4, \\ V_{\Phi H}(\Phi,H) &= A_{\Phi H}\Phi H^\dagger H + \frac{\lambda_{\Phi H}}{2}\Phi^2 H^\dagger H. \end{aligned}$$

$$\begin{aligned} 0 \le & \; m_\chi \le 30\,\mathrm{GeV}, \\ -1 \le & \; c_s \le 1, \\ 0 \le & \; m_\phi \le 1\,\mathrm{TeV}, \\ -\pi/6 \le & \; \theta \le \pi/6, \\ -1\,\mathrm{TeV}^2 \le & \; \mu_\Phi^2 \le 1\,\mathrm{TeV}^2, \\ -\mathrm{TeV} \le & \; \mu_3 \le 1\,\mathrm{TeV}, \\ -1 \le & \; \lambda_\Phi \le 1. \end{aligned}$$



$$\begin{pmatrix} h \\ \phi \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} h' \\ \phi' \end{pmatrix}.$$

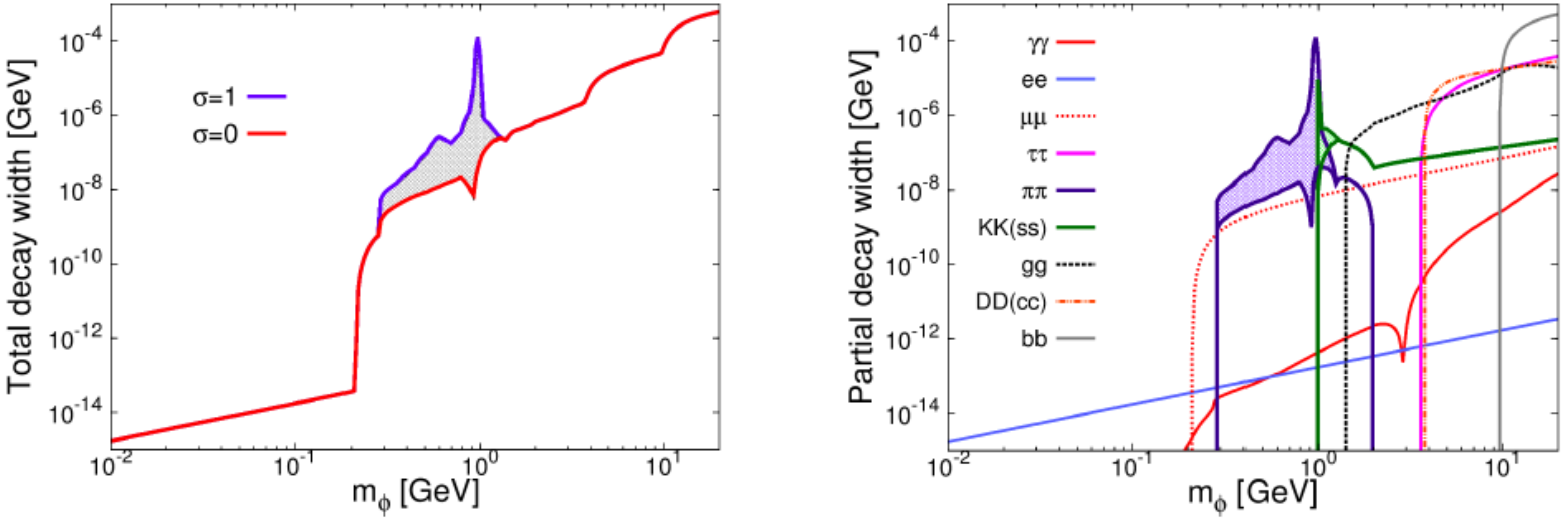
We allowed new physics scale located at the region greater than TeV.

Some features of model

- Relic density is still the dominant constraint.
- To satisfy relic density, the mediator should be as light as (or even lighter) than the dark matter.
- We choose CP-conserved (cp=0), p-wave to escape from CMB constraints.
- The introduction of the bosonic (scalar or vector) mediator is mandatory for a fermionic WIMP (fermionic thermal dark matter) to have a renormalizable interaction between the dark matter and SM particles.

Light Higgs decay

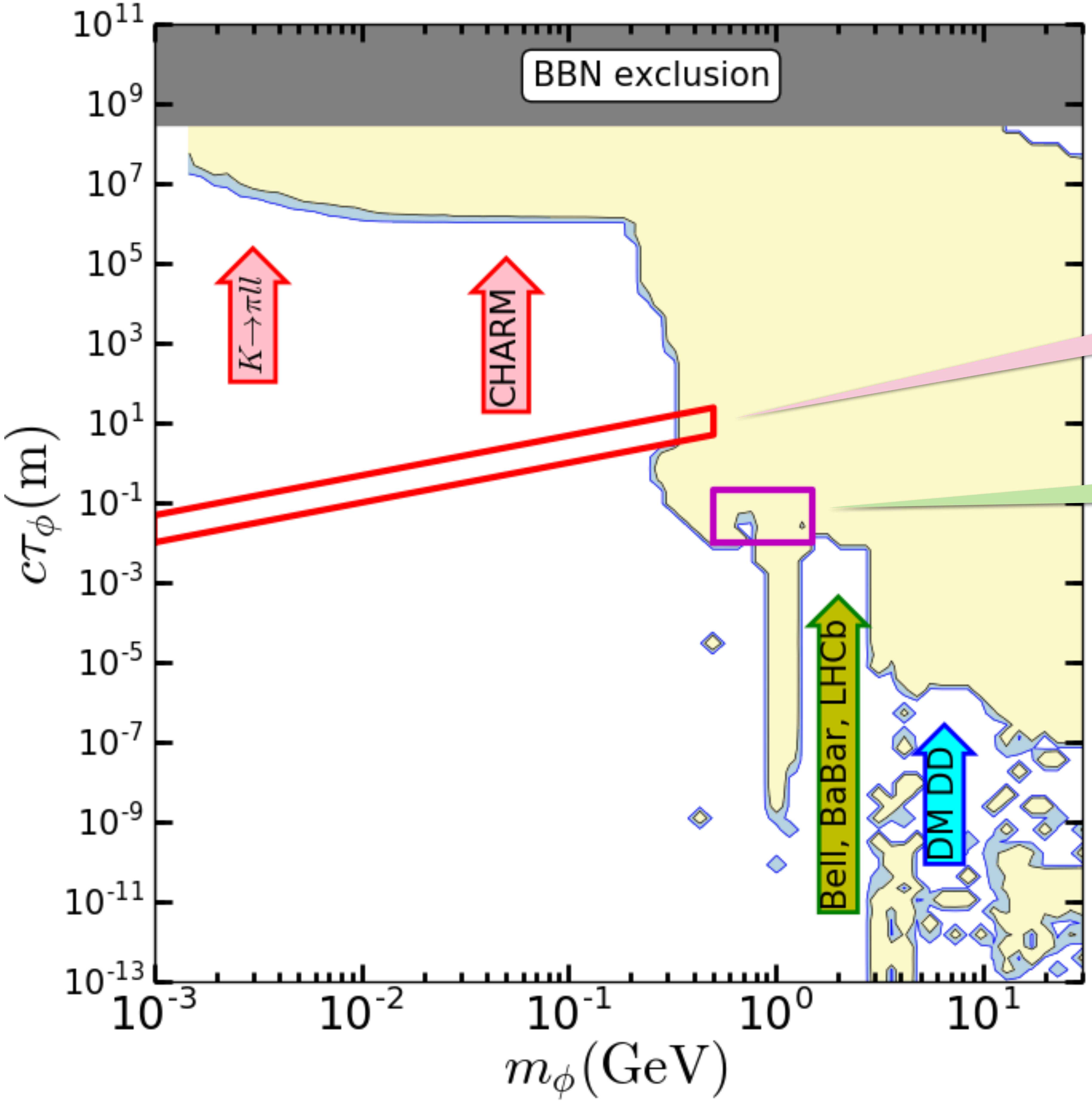
$$\Gamma(\phi \to \text{SMs}) = \sin^2\theta \times \Gamma(h_{\text{SM}} \to \text{SMs})|_{m^2_{h_{\text{SM}}} \to m^2_\phi}.$$



John F. Donoghue, J. Gasser, H. Leutwyler Nucl.Phys. B343 (1990) 341-368

Higgs decays to KK and pi-pi with some QCD uncertainties.

Light Higgs decay



Kaon, CHARM (DV)

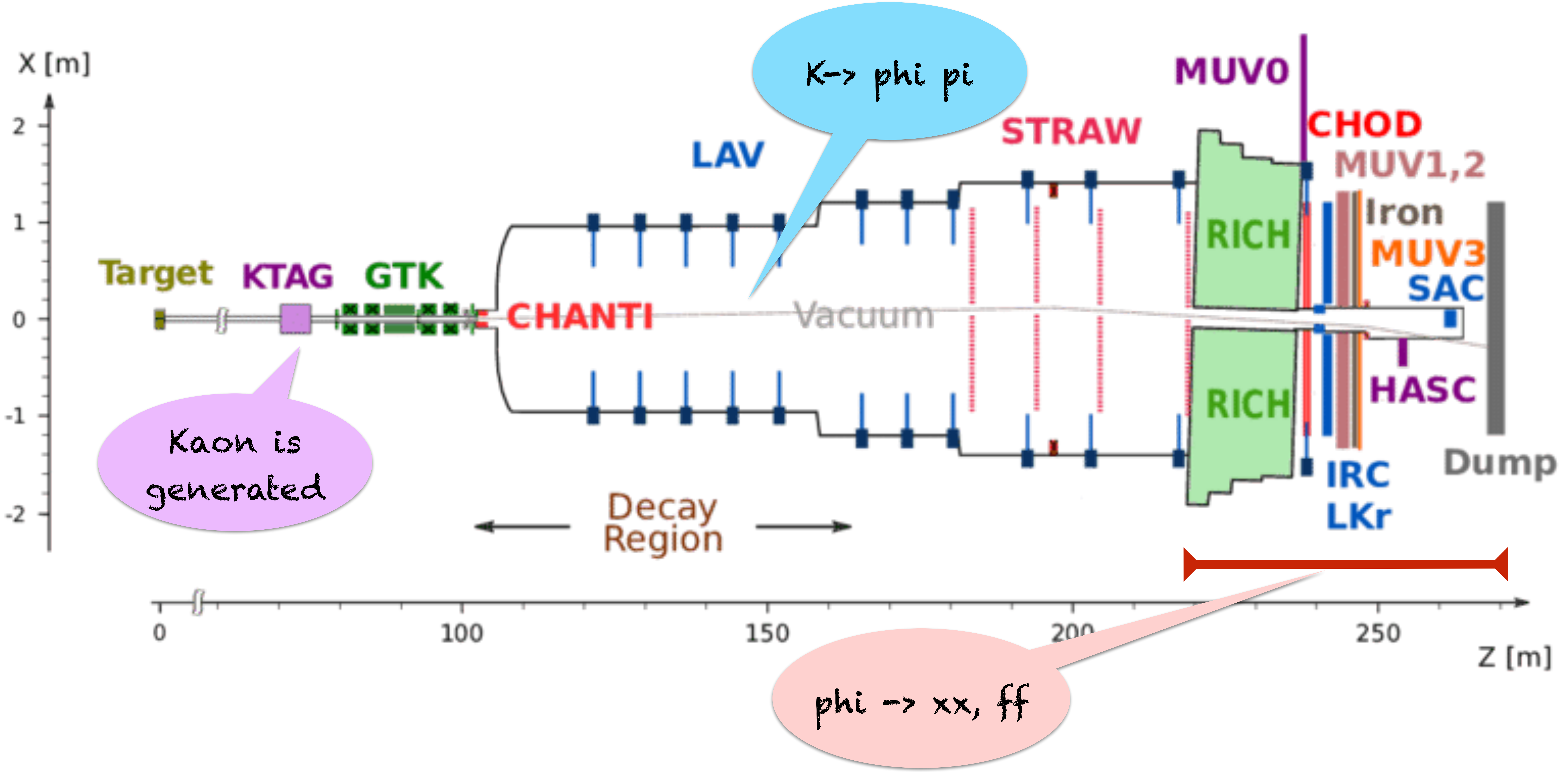
B-meson, BaBar (DV)

$$\Gamma(\phi \to \mathrm{SMs}) = \sin^2\theta \times \Gamma(h_{\mathrm{SM}} \to \mathrm{SMs})|_{m^2_{h_{\mathrm{SM}}} \to m^2_\phi} \,.$$

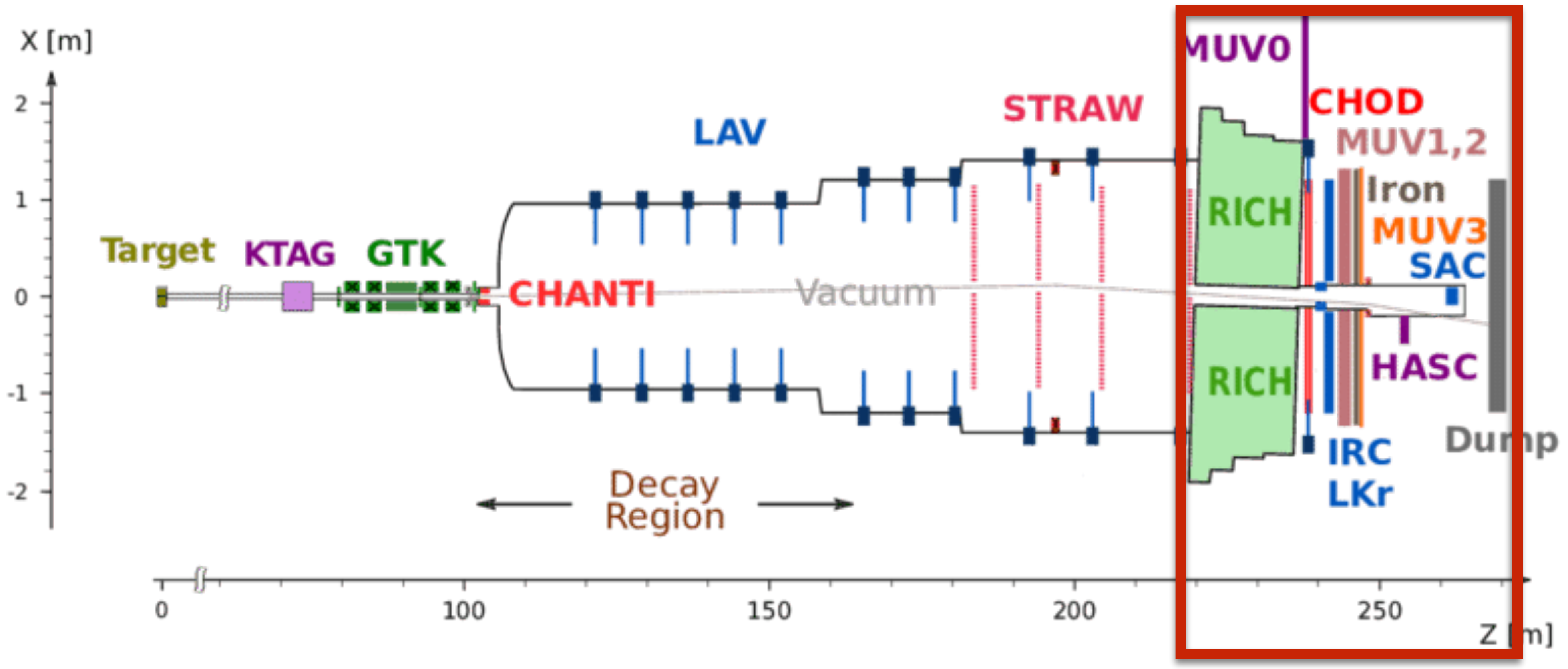
$$\Gamma(\phi \to \chi\chi) = \cos^2\theta \, \frac{m_\phi}{16\pi} \left[c_s^2 \left(1 - \frac{4m_\chi^2}{m_\phi^2}\right)^{3/2} + c_p^2 \left(1 - \frac{4m_\chi^2}{m_\phi^2}\right)^{1/2} \right] .$$

displaced vertex can constrain some parameter space.

Beam Dump experiments: Layout of the NA62 experiment.



Beam Dump experiments



Detector size

P_p is the probability that the mediator decays inside the detector,

$$P_p \equiv \frac{1}{2}\int_0^{\pi} d\theta_\phi \sin\theta_\phi \left(1 - \exp\left[-\frac{l_{xy}}{\sin\theta_\phi}\frac{1}{\gamma\beta c\tau_\phi}\right]\right),$$

the factor P_l being the probability that ϕ decays outside the detector,

$$P_l \equiv \frac{1}{2}\int_0^{\pi} d\theta_\phi \sin\theta_\phi \exp\left[-\frac{l_{xy}}{\sin\theta_\phi}\frac{1}{\gamma\beta c\tau_\phi}\right],$$

- Phi prompt decay: decay length shorter than detector size.
- Very-long lived phi or decay to DM: missing energy.
- Phi decay length~O(100 m) and phi > 2*charge SM: displaced vertex.

	Present	Future
Relic abundance	Planck [15]	– – –
Equilibrium	See the text	– – –
Direct detection	XENON1T [20], CRESST [24], PANDAX [21], NEWS-G [25], SuperCDMS [23]	NEWS-SNOLAB [29, 30], SuperCDMS [28], LZ [26, 27]
DOF ($\Delta N_{\rm eff}$)	PLANCK [31]	CMB-S4 [33]
BBN	See the text	– – –

	Present	Future
Υ decay	CLEO [41], BABAR [42, 43]	Belle II [46]
B decay	Belle [49, 56], LHCb [50, 53, 54], BaBar [45, 48, 57, 58]	Belle II [52, 59], LHCb [55]
K decay	N48/2 [61], KTeV [62, 63], E949 [67], CHARM [64, 65], KEK E391a [68]	SHiP [66], KOTO [71], NA62 [69, 70]

Upsilon decay

- It is b-bbar bound state.
- Detection channel: upsilon(1S,2S,3S) decays to photon and phi and then phi decays to lepton pairs.
- For Phi mass smaller than upsilon mass (9.4 GeV), it allows us to study mu mu or tau tau invariant mass.
- CLEO and Babar can do the job.
- Present constraint is not as strong as Kaon and B-meson.

$$\gamma_\phi \simeq m_\Upsilon/(2m_\phi) \simeq 25.$$

- However, the decay length (gamma*tau*c~O(0.1) mm) which is shorter than the present Barbar sensitivity of displaced vertex searches, O(1) cm.

B-meson decay

- B-meson mass around 5.3 GeV.
- Detection channel: b-quark decays to phi and s-quark (loop-level).
- BaBar : $\mathrm{Br}(B \to X_s \phi)\,\mathrm{Br}(\phi \to e^- e^+, \mu^- \mu^+, \pi^- \pi^+, K^- K^+)$
- LHCb: $B^\pm \to K^\pm + \phi \to K^\pm + \mu^- \mu^+$ and $B^0 \to K^{*0} + \phi \to K^{*0} + \mu^- \mu^+$
- Present constraint bits parameter space of MeV DM.
- Future constraints: Belle II (50 ab-1), LHCb (300 times).

Search for long-lived scalar particles in $B^+ \to K^+\chi(\mu^+\mu^-)$ decays

LHCb,
Phys. Rev. D 95, 071101 (2017)
1612.07818

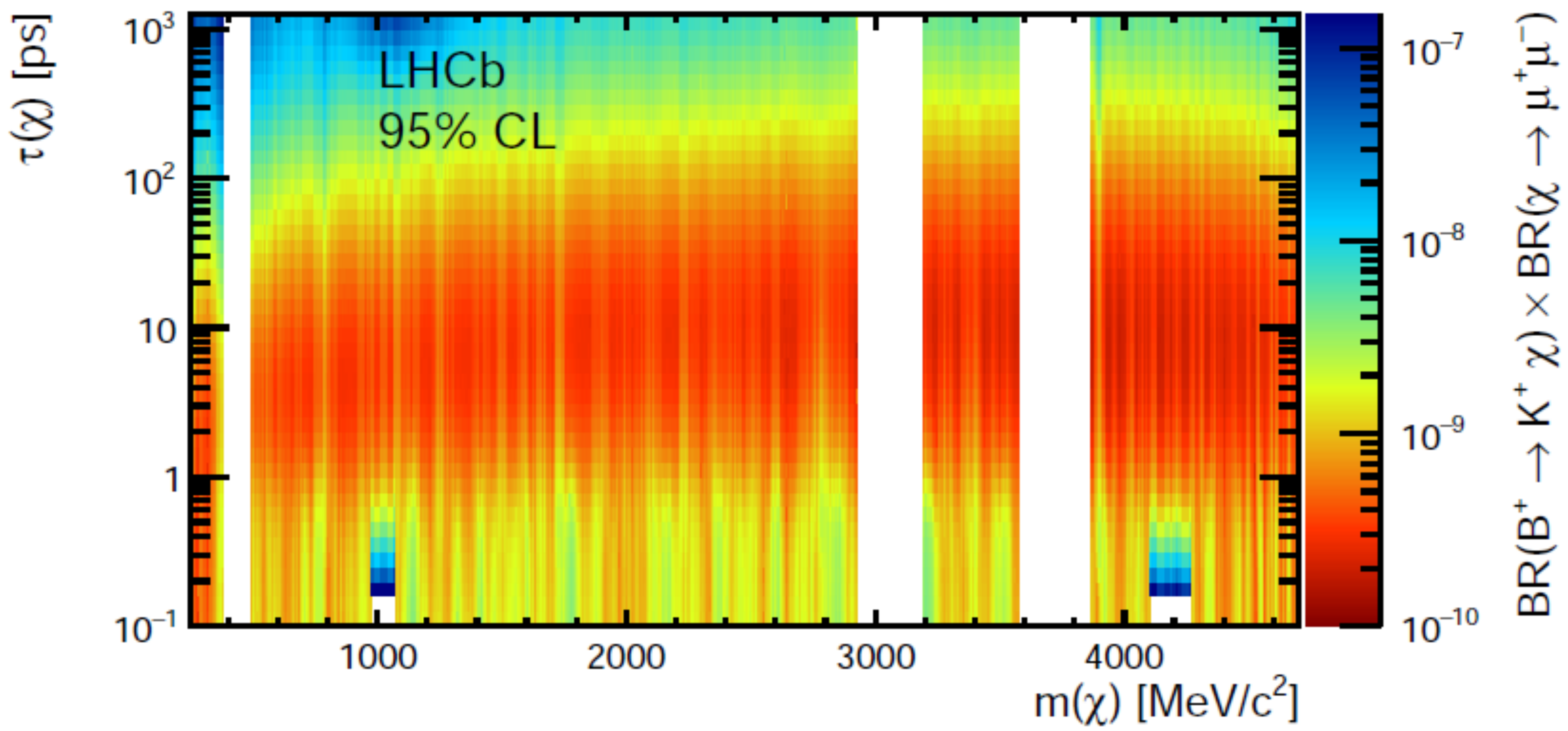
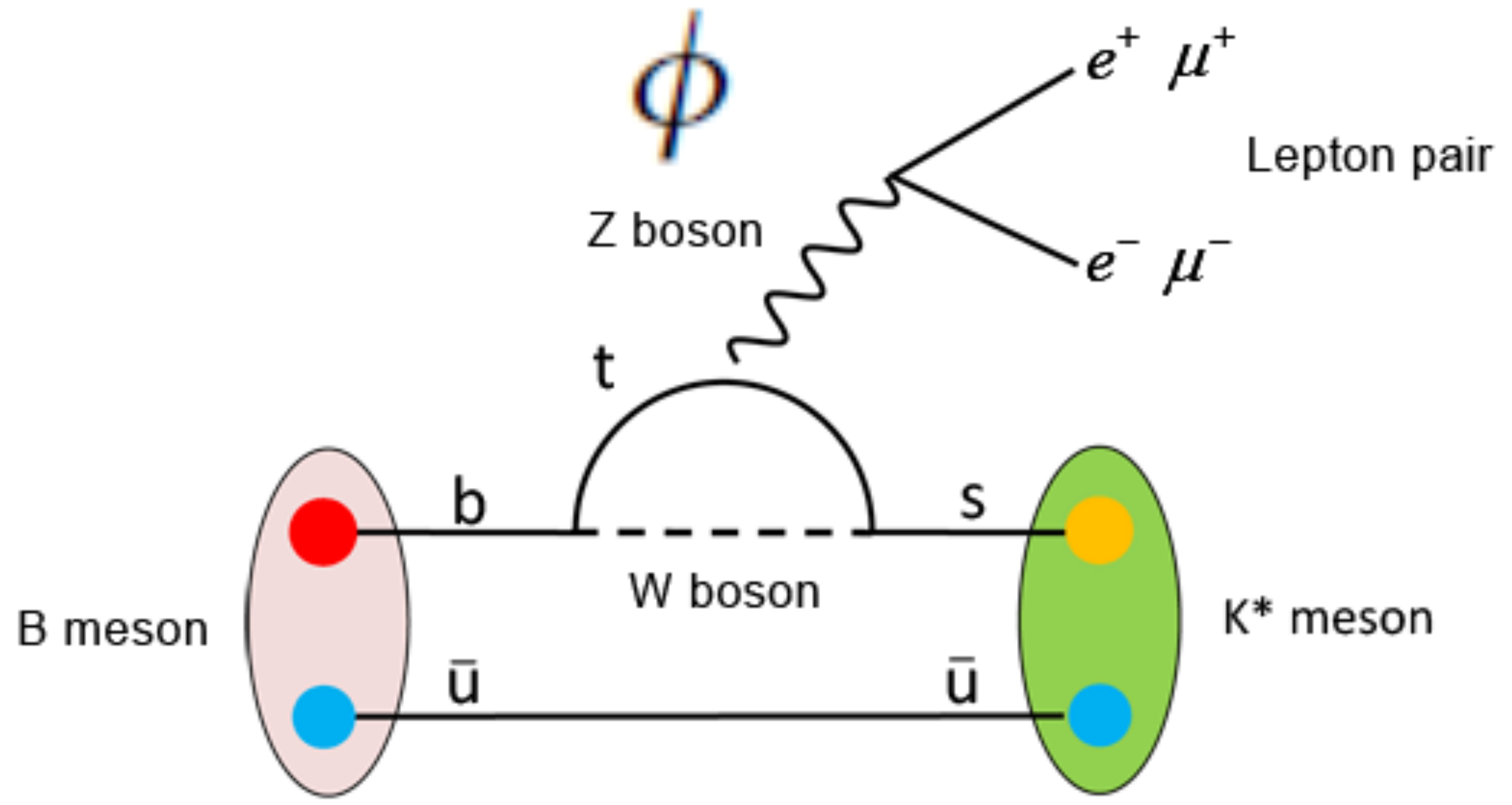


Figure 4: Excluded branching fraction for the $B^+ \to K^+\chi(\mu^+\mu^-)$ decay as a function of $m(\chi)$ and $\tau(\chi)$ at 95% CL. Regions corresponding to the fully-vetoed K^0_S, J/ψ, $\psi(2S)$ and $\psi(3770)$ and to the partially-vetoed ϕ and $\psi(4160)$ are excluded from the figure. All systematic uncertainties are included in the calculation of the upper limit.

$$B^\pm \to K^\pm + \phi \to K^\pm + \mu^-\mu^+$$

$$B^0 \to K^{*0} + \phi \to K^{*0} + \mu^-\mu^+.$$



it gives a stringent constraint in the region of $m_\phi \geq 1.5$ GeV.

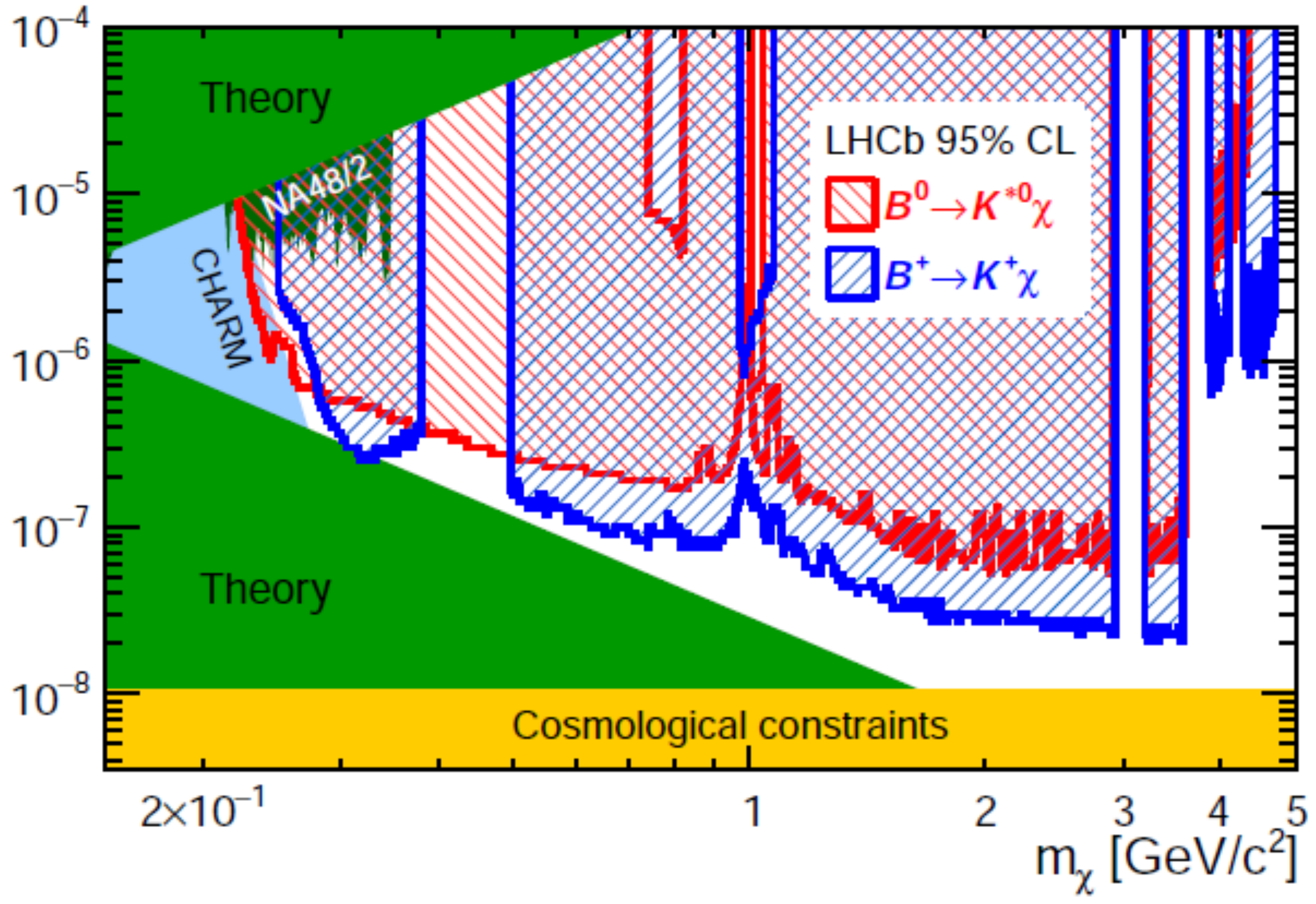


Figure 5: Parameter space of the inflaton model described in Refs. [2–4]. The region excluded at 95% CL by this analysis is shown by the blue hatched area. The region excluded by the search with the $B^0 \to K^{*0}\chi(\mu^+\mu^-)$ decay [8] is indicated by the red hatched area. Direct experimental constraints set by the CHARM experiment [7] and NA48 experiments [7, 28] and regions forbidden by theory or cosmological constraints [4] are also shown.

Kaon decay

$$K^+ : u\bar{s}$$

$$K_L : \frac{d\bar{s} - s\bar{d}}{\sqrt{2}}$$

$$s \to d + \phi$$

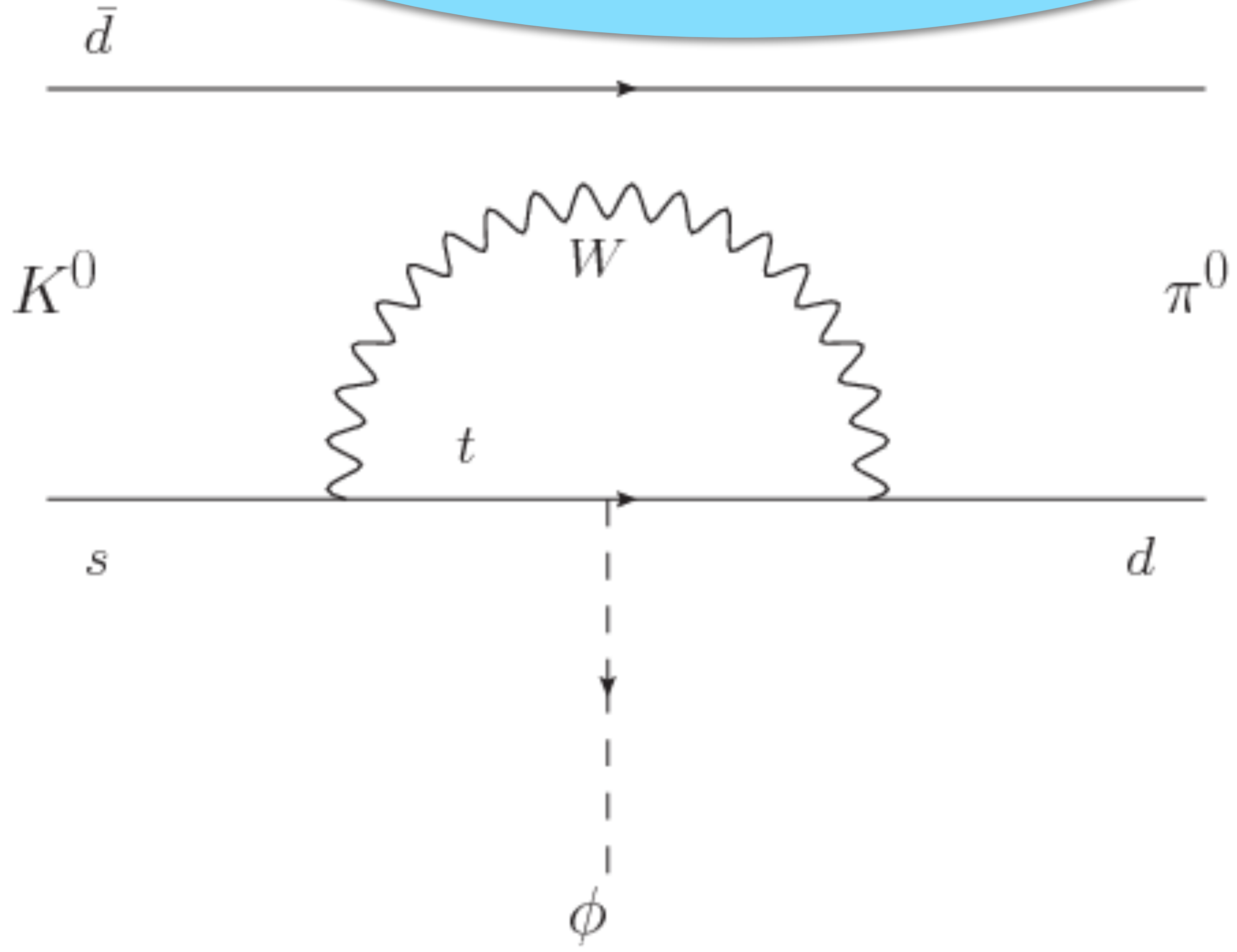
$$N_{\mathrm{TH.}} = 2.9\times 10^{17} \times \frac{\sigma_\phi}{\sigma_\pi} \times \mathcal{P}_{\mathrm{dec}} < 2.3 \text{ @ } 95\%\mathrm{C.L.}$$

$$\frac{\sigma_\phi}{\sigma_{\pi^0}} \simeq 3\left[\frac{\chi_s}{2}\mathrm{Br}(K^\pm \to \pi^\pm \phi) + \frac{\chi_s}{4}\mathrm{Br}(K_L \to \pi^0 \phi) + \chi_b\,\mathrm{Br}(B \to \phi + X_s)\right]$$

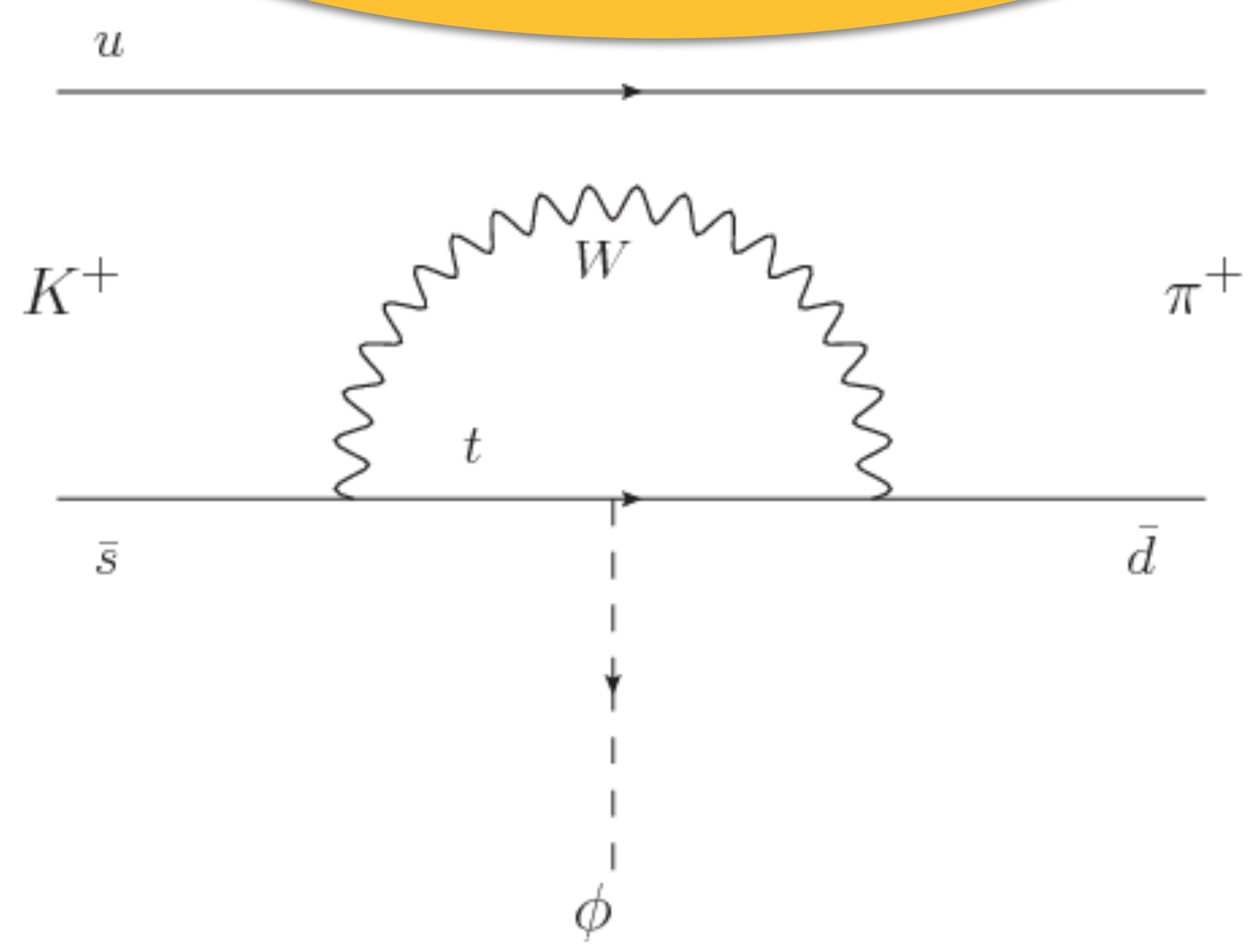
chi_s:
fraction of strange quarks produced by pp.

chi_b:
fraction of bottom quarks produced by pp.

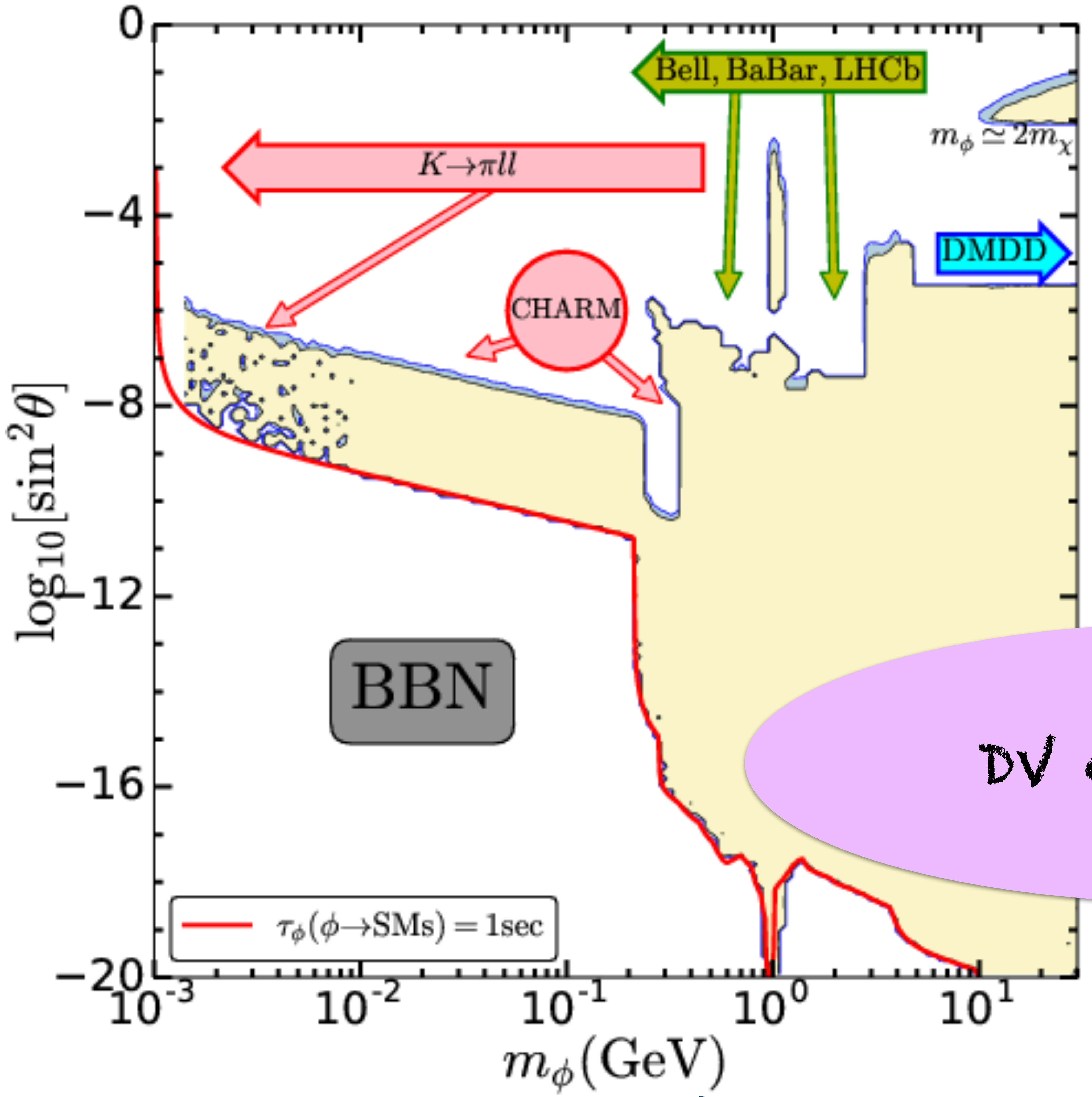
$$P_{\mathrm{dec}} = -\exp\left[-\frac{L_2}{\gamma\beta c\tau_\phi}\right] + \exp\left[-\frac{L_1}{\gamma\beta c\tau_\phi}\right]$$

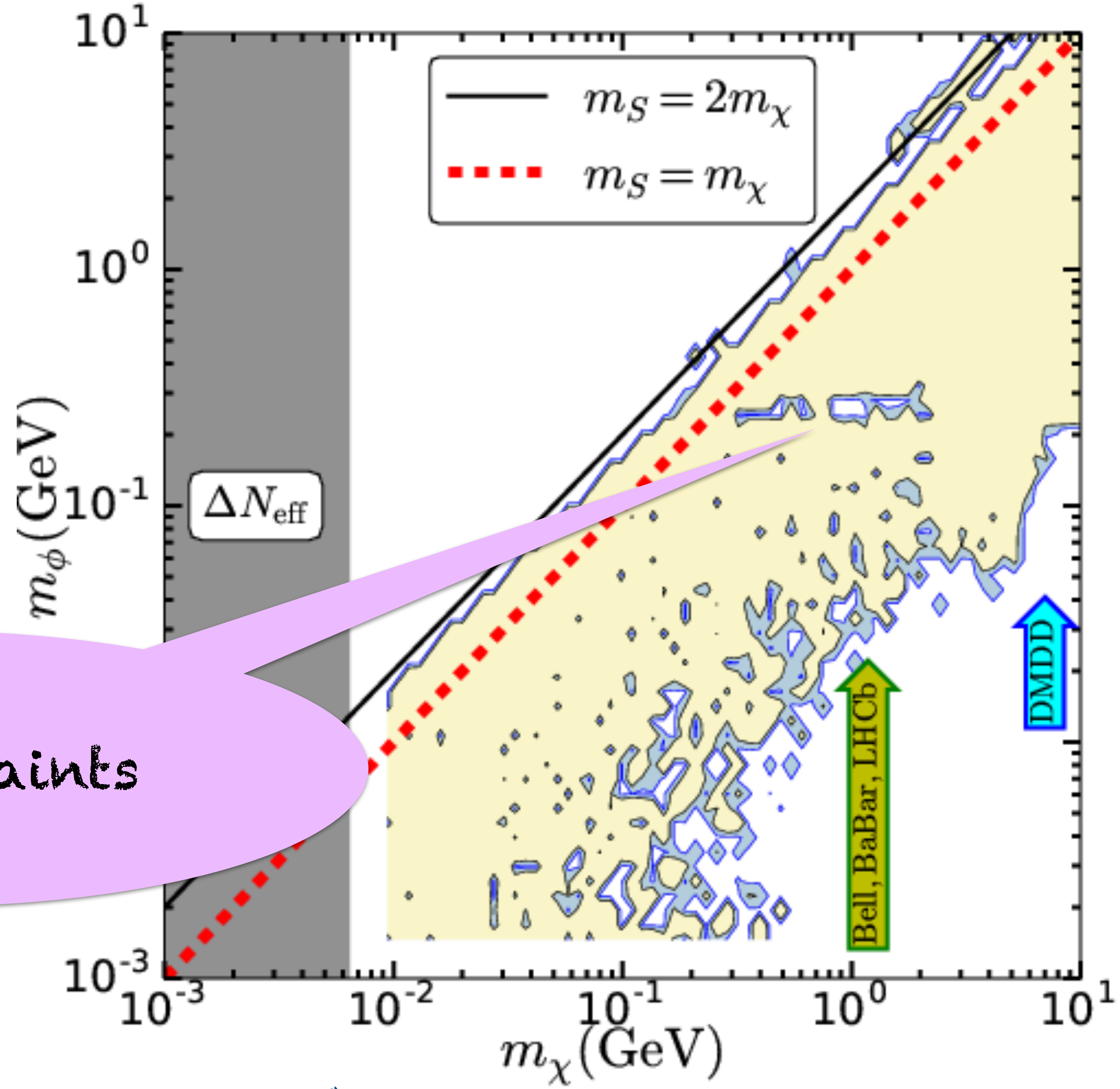


For CHARM:
L1=L2-35 m=480 m
L2: total distance



MeV Mediator (dark Higgs) search





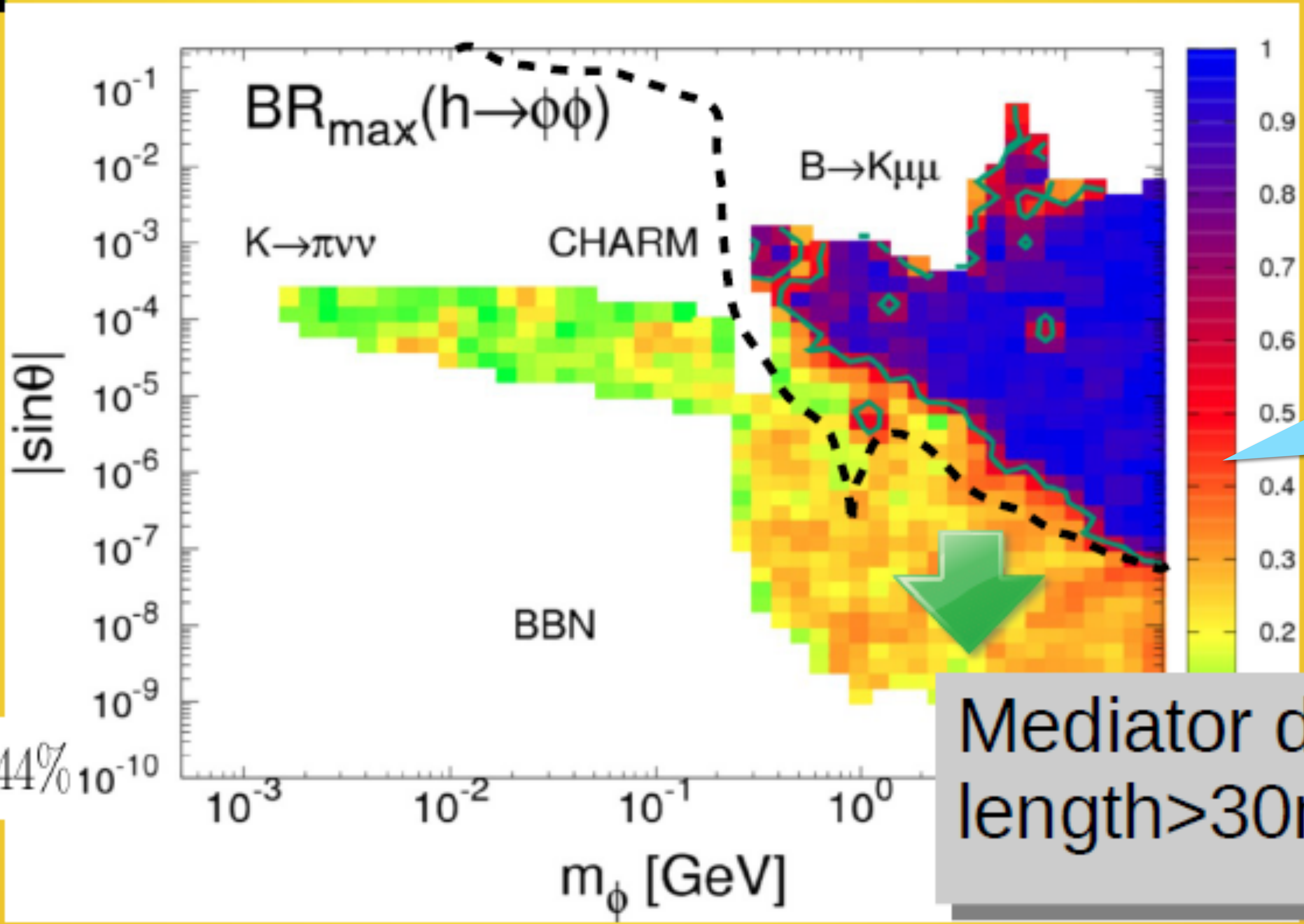
The regions is ready to be tested.

- Current experimental constraints for light mediator

$$C_{\phi\phi h} \simeq \frac{2(m_\phi^2 - \mu_\Phi^2)}{v_H}$$

$$\Gamma(h \to \phi\phi) \simeq \frac{C_{\phi\phi h}^2}{32\pi m_h}$$

$$\Delta BR(h_{125} \to \text{invisible}) \lesssim 0.44\%$$



Branch ratio of Higgs invisible decay

Mediator decay length>30m

H. Baer et. al., ILC: 1306.6352

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Summary

- Dark Matter physics is more and more interesting and important at the post LHC era.
- A small but important region is hidden by other collider search (such as mono-X) but it can be tested by DV search.
- Future sensitive can be improved around 100 times.

The End

Thank you for your attention.

Low mass Mediator search

Experiment	Lab	Production	Detection	Vertex	Mass(MeV)	Mass Res. (MeV)	Beam	Ebeam (GeV)	Ibeam or Lumi	Machine	1st Run	Next Run
APEX	JLab	e-brem	$\ell^+\ell^-$	no	$65-600$	0.5%	e^-	1.1–4.5	150 μA	CEBAF(A)	2010	2018
A1	Mainz	e-brem	e^+e^-	no	$40-300$	?	e^-	0.2–0.9	140 μA	MAMI	2011	–
HPS	JLab	e-brem	e^+e^-	yes	$20-200$	1–2	e^-	1–6	50–500 nA	CEBAF(B)	2015	2018
DarkLight	JLab	e-brem	e^+e^-	no	< 80	?	e^-	0.1	10 mA	LERF	2016	2018
MAGIX	Mainz	e-brem	e^+e^-	no	$10-60$	?	e^-	0.155	1 mA	MESA	2020	–
NA64	CERN	e-brem	e^+e^-	no	$1-50$	?	e^-	100	2×10^{11} EOT/yr	SPS	2017	2022
Super-HPS	SLAC	e-brem	vis	yes	< 500	?	e^-	$4-8$	1 μA	DASEL	?	?
(TBD)	Cornell	e-brem	e^+e^-	?	< 100	?	e^-	0.1-0.3	100 mA	CBETA	?	?
VEPP3	Budker	annih	invis	no	$5-22$	1	e^+	0.500	$10^{33}\,\mathrm{cm^{-2}s^{-1}}$	VEPP3	2019	?
PADME	Frascati	annih	invis	no	$1-24$	$2-5$	e^+	0.550	$\leq 10^{14}\,e^+$OT/y	Linac	2018	?
MMAPS	Cornell	annih	invis	no	$20-78$	$1-6$	e^+	6.0	$10^{34}\,\mathrm{cm^{-2}s^{-1}}$	Synchr	?	?
KLOE 2	Frascati	several	vis/invis	no	< 1.1 GeV	1.5	e^+e^-	0.51	$2\times10^{32}\,\mathrm{cm^{-2}s^{-1}}$	DAϕNE	2014	-
Belle II	KEK	several	vis/invis	no	$\lesssim 10$ GeV	$1-5$	e^+e^-	4×7	$1\sim10\,\mathrm{ab^{-1}}$/y	Super-KEKB	2018	-
SeaQuest	FNAL	several	$\mu^+\mu^-$	yes	$\lesssim 10$ GeV	$3-6\%$	p	120	10^{18} POT/y	MI	2017	2020
SHIP	CERN	several	vis	yes	$\lesssim 10$ GeV	$1-2$	p	400	2×10^{20} POT/5y	SPS	2026	-
LHCb	CERN	several	$\ell^+\ell^-$	yes	$\lesssim 40$ GeV	~ 4	pp	6500	$\sim 10\,\mathrm{fb^{-1}}$/y	LHC	2010	2015

- Dark photon or dark higgs below GeV region can be interesting (and popular?).
- More coming experiments to explore MeV DM.

1608.08632