LHC Lifetime Frontier and Visible Decay Searches in Composite Asymmetric Dark Matter Models

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in collaborations with
A. Kamada (2112.01202, JHEP 03 (2022) 176)

Dark Sector and Lifetime Frontier

SM Sector

Dark Sector

Unification of forces?

Top partners (SUSY, composite)?

Electroweak Theory

QCD confinement

Low-energy spectrum

Baryons, Leptons, photons

Portal interaction

- dark photon
- dark higgs
- …

requirement for

e.g.) thermalization;

entropy dilution, etc

indirect/direct searches

Lifetime Frontier

Low-energy spectrum

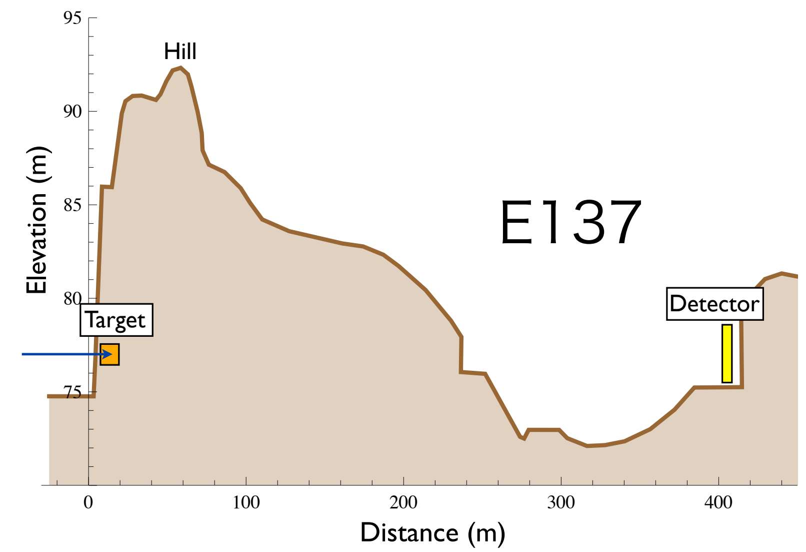
Dark Matter

Associated dark particles

Portal interactions are keys to searching for Dark Sector

Long-lived Particles Searches: Fixed-target Experiments

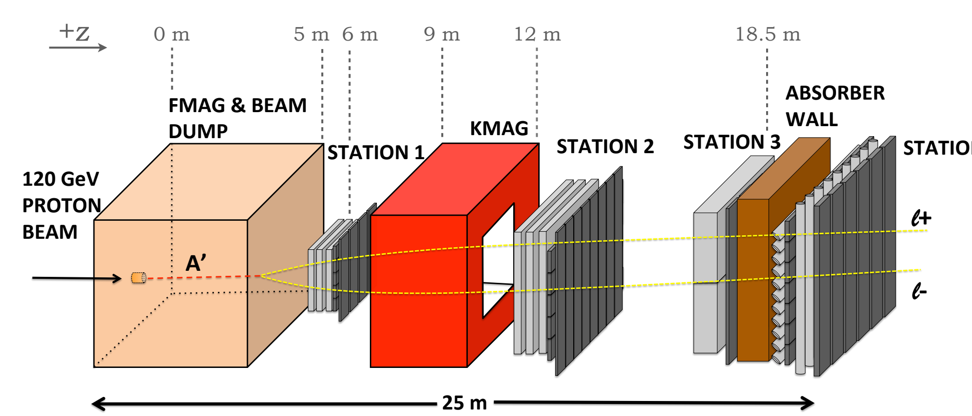
Decay lengths of O(1) cm - O(1) m



- constraints from existing data (E137, CHARM, etc)
- parasitic experiments
  - DarkQuest: designed to study sea quark content of proton

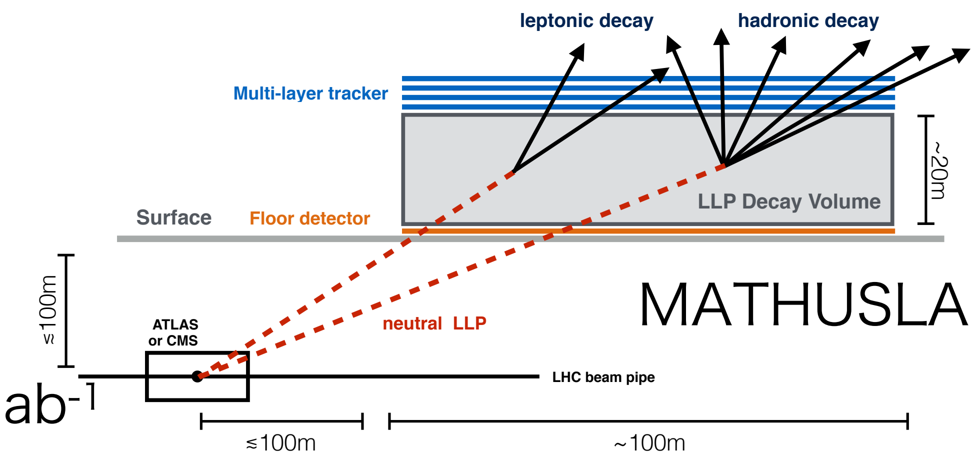
- background-free/small background from SM particles
  - Absorbed by shielding/veto system

DarkQuest (SeaQuest)



Long-lived Particles Searches: LHC lifetime frontier

Decay lengths of O(1)-O(10^2) m



MATHUSLA

- Far-detector experiments at LHC: HL-LHC (2027~) 3 ab^{-1}
- almost background-free (shielded by infrastructure/charged particle trigger)
- Off-axis detector (MATHUSLA, $\theta_{\rm det} \simeq 0.5$; CODEX-b, $\theta_{\rm det} \simeq 1$)

less boosted particle ($\beta\gamma \sim p/p_T \sim \theta_{\rm det}^{-1} \sim O(1)$)

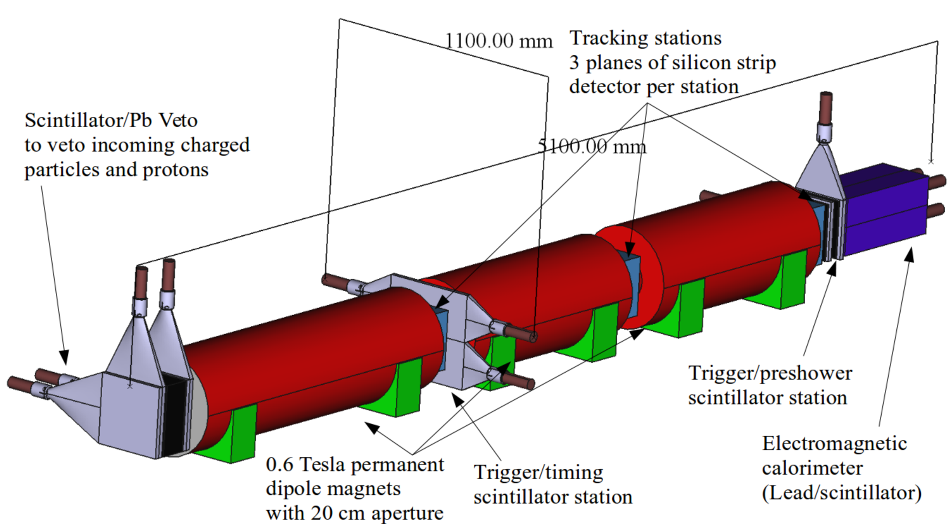
cτ ~ O(10^2) m/ preferred heavy LLPs

- Forward detector (FASER(2), $\theta_{\rm det} \simeq 2 \times 10^{-3}$; FACET, $\theta_{\rm det} \simeq 10^{-3}$)

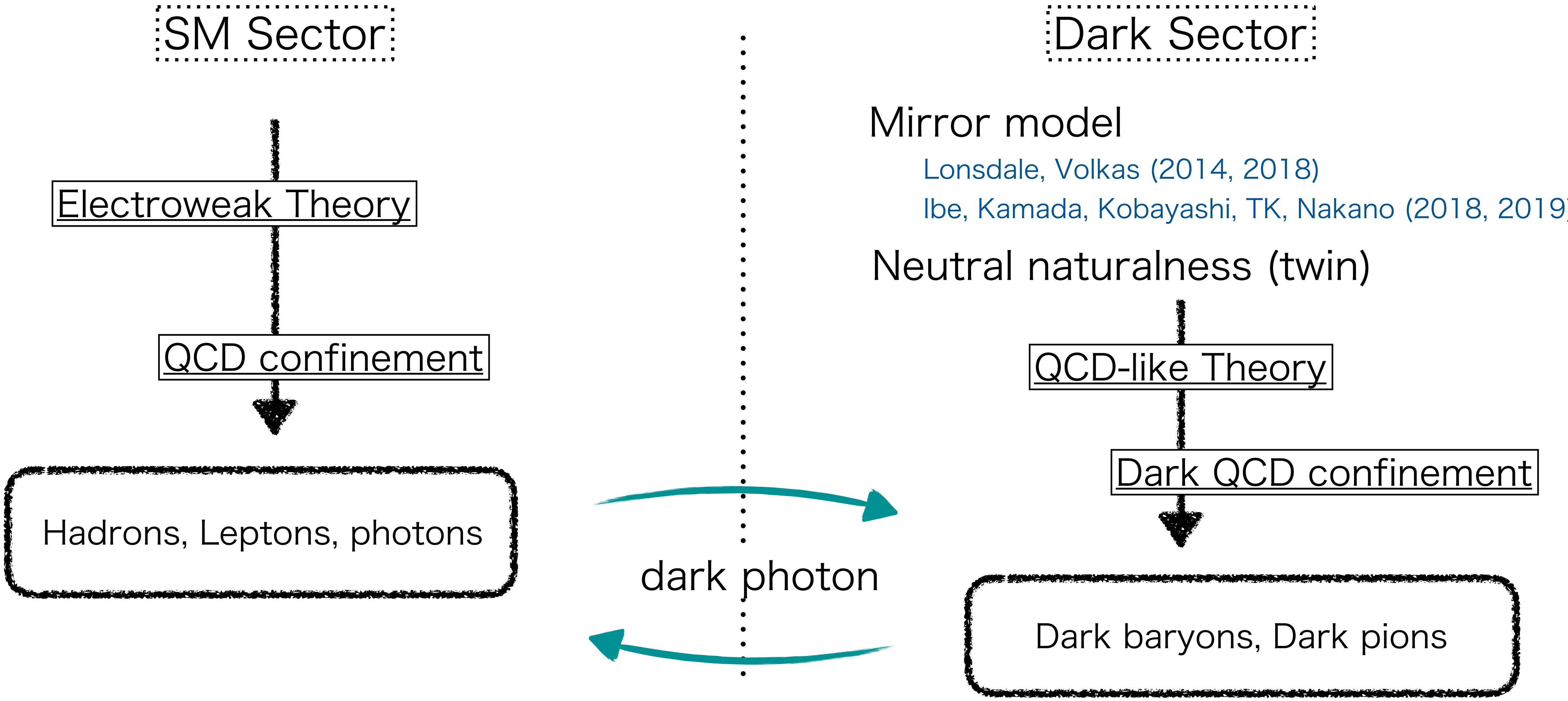
FASER(2)

quite boosted particle ($\beta\gamma \sim \theta_{\rm det}^{-1} \sim O(10^3)$)

cτ ~ O(1) m/ preferred light LLPs



Dark Sector with Confining dynamics



- Similar confinement scale $\Lambda'_{\rm QCD} \sim 1\,{\rm GeV}$ is expected in models with the SM copy
- Dark hadron DM
  - dark pions (SIMP) Hochberg, Kuflik, Murayama, Volansky, Wacker (2015)
  - dark baryons (composite asymmetric DM)

Ibe, Kamada, Kobayashi, Nakano (2018)

To be specific, we consider SU(N_c=3) 2-flavor $\text{QCD}_{\text{dark}} \times \text{QED}_{\text{dark}}$

Composite Asymmetric DM Scenario

SM Sector

Dark Sector

intermediate-scale Portal interaction

$$\frac{1}{\Lambda^n}\mathcal{O}_{\rm SM}\mathcal{O}_{\rm DM}$$

B-L asymmetry

DM asymmetry

(thermal) leptogenesis
$\overline{N}_R \to L + H$

B-L converted into DM number

e.g.) $O_{\rm SM} = LH\,, \quad O_{\rm DS} = \overline{D}'\overline{D}'\overline{U}'$

$$T_D \sim \Lambda\left(\frac{\Lambda}{M_{\rm Pl}}\right)^{\frac{1}{2n-1}}$$

asymmetries separately conserved for $T < T_D$

confinement/dark confinement

deplete symmetric component via $N^{(\prime)}\overline{N}^{(\prime)} \to \pi^{(\prime)}\pi^{(\prime)}$

Observed Baryon Asymmetry

$$\frac{\Omega_{\rm DM}}{\Omega_B} = \frac{m_{\rm DM}\,\eta_{\rm DM}}{m_B\,\eta_B} \sim 5$$

Observed DM density

dark mesons

$$m_{\rm DM} \simeq O(1)\,{\rm GeV}$$

Dark Photon Portal for entropy release

Composite Asymmetric DM Scenario

SM Sector

Dark Sector

intermediate-scale Portal interaction

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Dark Photon Portal for entropy release

Visible Decay/Transition of Dark Hadrons

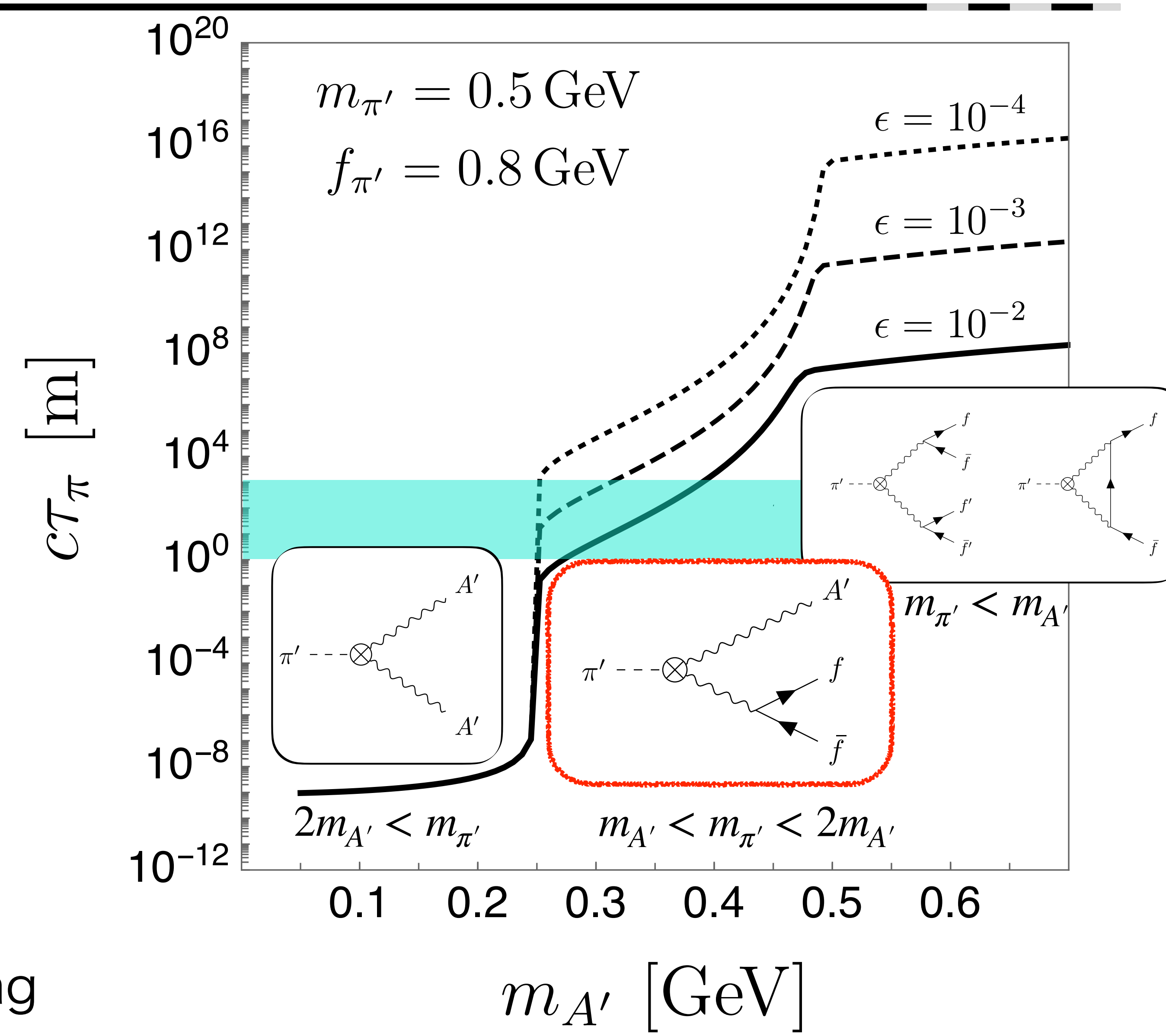
dark pion decay

- pion anomalous decays

$$\mathcal{L}_{\rm eff.} \supset -\frac{N_C \alpha'}{24\pi f_{\pi'}} \pi' F'^{\mu\nu} \tilde{F}'_{\mu\nu}$$

- semi-SM decay: ~ O(1) m

$$c\tau_\pi(\pi'^3 \to A' + f\bar{f})$$
$$\simeq 0.3\,\mathrm{m} \left(\frac{1.0\ \mathrm{GeV}}{m_{A'}}\right)^3 \left(\frac{f_{\pi'}}{0.8\ \mathrm{GeV}}\right)^2 \left(\frac{10^{-3}}{\epsilon}\right)^2 \left(\frac{0.1}{\alpha'}\right)^2$$



dark nucleon transition

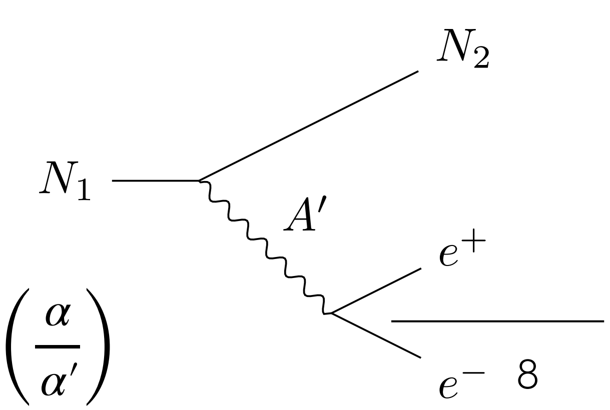
- dark nucleon mixing via U(1)D breaking

off-shell dark photon when $\Delta_N m_{N_2} < m_{A'}$

$$\Gamma(N_1 \to N_2 + f\bar{f}) \simeq \frac{\epsilon^2 \alpha' \alpha Q_f^2}{15\pi} \sin^2 2\theta_V \frac{m_{N_2}^5 \Delta_N^5}{m_{A'}^4}$$

$m_f = 0$ limit

$$c\tau(N_1 \to N_2 + f\bar{f}) \simeq 3\,\mathrm{m} \left(\frac{0.1}{\Delta_N}\right)^5 \left(\frac{8.5\ \mathrm{GeV}}{m_{N_2}}\right)^5 \left(\frac{m_{A'}}{3\ \mathrm{GeV}}\right)^4 \left(\frac{10^{-2}}{\sin 2\theta_V}\right)^2 \left(\frac{5\times 10^{-3}}{\epsilon}\right)^2 \left(\frac{\alpha}{\alpha'}\right)$$

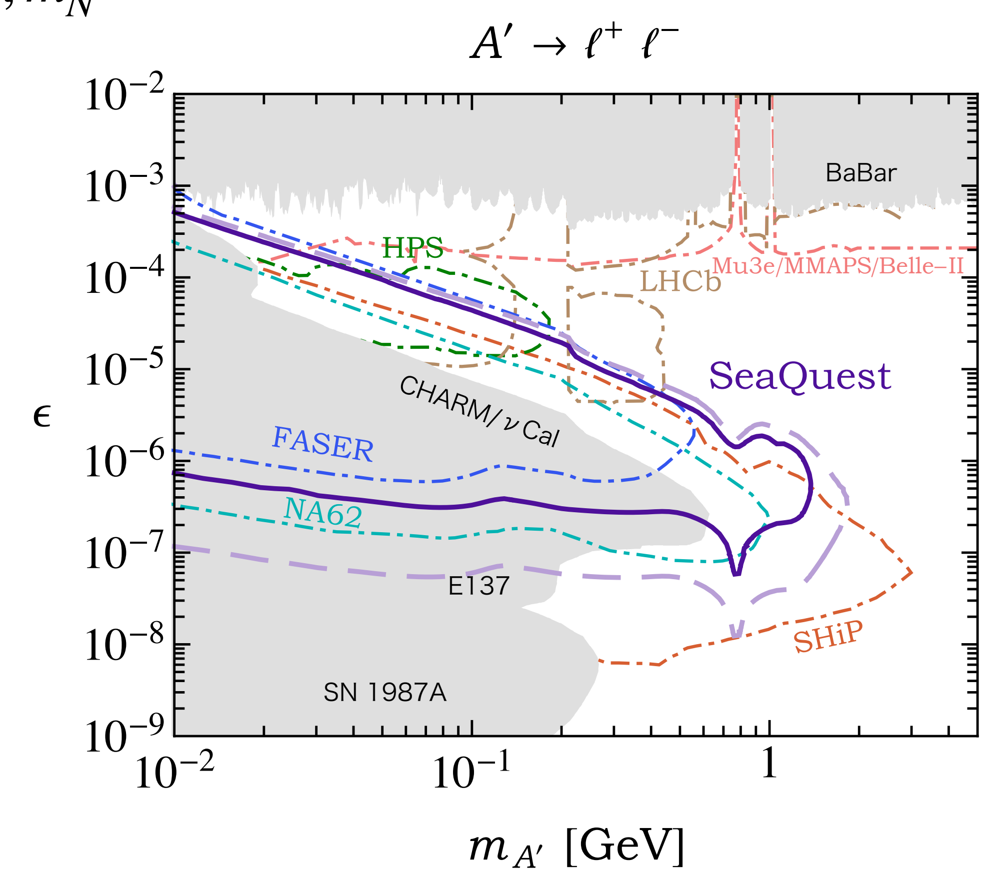


Dark Photon Decay

dark photon is lightest in the dark sector: $m_{A'} < m_{\pi'}, m_{N'}$

- Br(A'→SM)=1
- visible decay signals from A'

$$\Gamma(A' \to \ell^+\ell^-) = \frac{1}{3}\alpha\epsilon^2 m_{A'}\sqrt{1-\frac{4m_\ell^2}{m_{A'}^2}}\left(1+\frac{2m_\ell^2}{m_{A'}^2}\right)$$



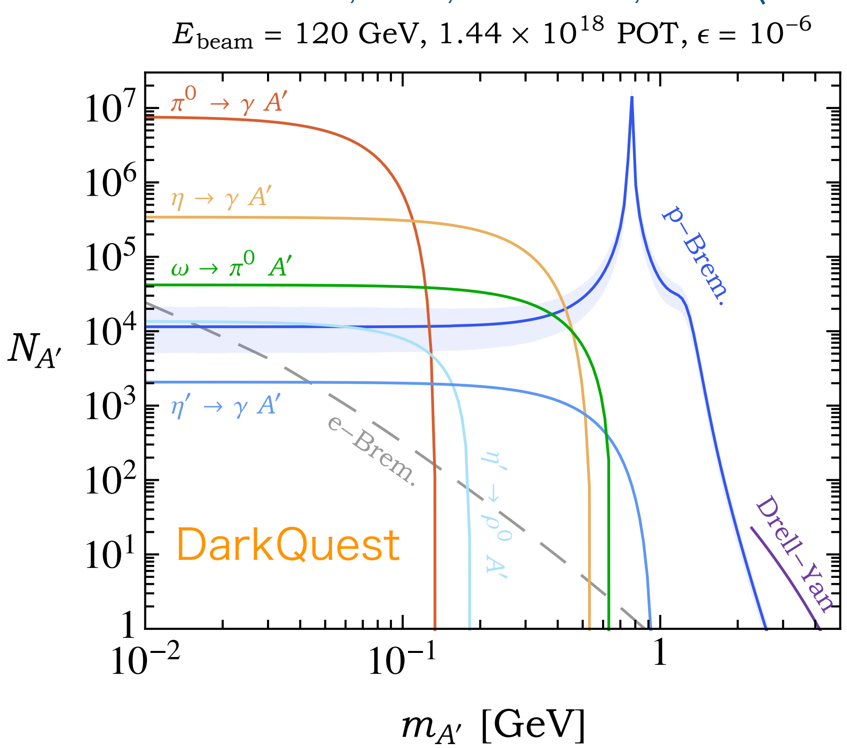
Berlin, Gori, Schuster, Toro (2018)

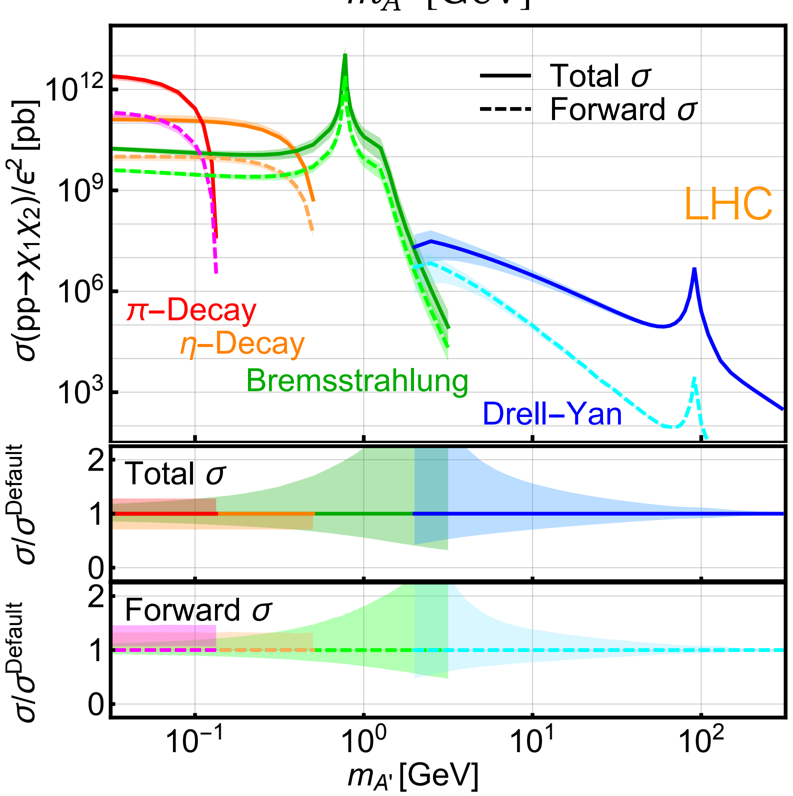
Existing constraints

- Prompt decay: BaBar, KLOE, LHCb, ...
- LLP @ Fixed-target: E137, CHARM, ν Cal, ...

Dark Hadron Production

Berlin, Gori, Schuster, Toro (2018)





Berlin, Kling (2018)

via off-shell dark photon

approximate cross section

$$\frac{d\sigma}{dm_{A'}^{*2}dx} = \frac{d\sigma_{A'}(m_{A'}^*)}{dx} \times \frac{1}{\pi} \frac{m_{A'}^*\Gamma_{A'}(A' \to \text{dark hadrons})}{(m_{A'}^{*2} - m_{A'}^2)^2 + (m_{A'}^*\Gamma_{A'})^2}$$

off-shell A' production

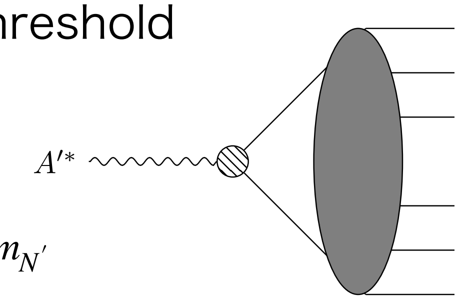
Produced number of dark hadrons

$$N \simeq \int dm_{A'}^{*2} \frac{1}{\pi} \frac{m_{A'}^*\Gamma_{A'}(m_{A'} = m_{A'}^*)}{m_{A'}^{*4}} N_{A'} \Big|_{m_{A'}=m_{A'}^*}$$

Dark Nucleon Production

hadronization just above nucleon-pair prod. threshold

$$N_{N_1} \simeq \frac{n_{N'}\alpha'}{\pi} (\sum Q_{q'}^2) N_{A'} \Big|_{m_{A'}^* = \sqrt{10} m_{N'}}$$



hadron multiplicity $n_{N'} \simeq 0.08$ SM value @ J/psi threshold

DASP Collab. (1979)

Dark Pion Production

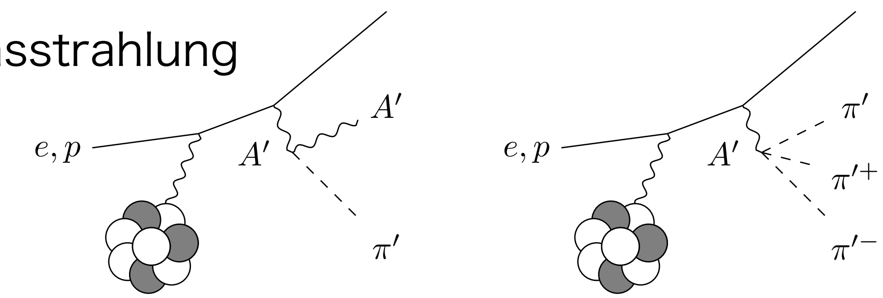
Our interest: dark-neutral pions

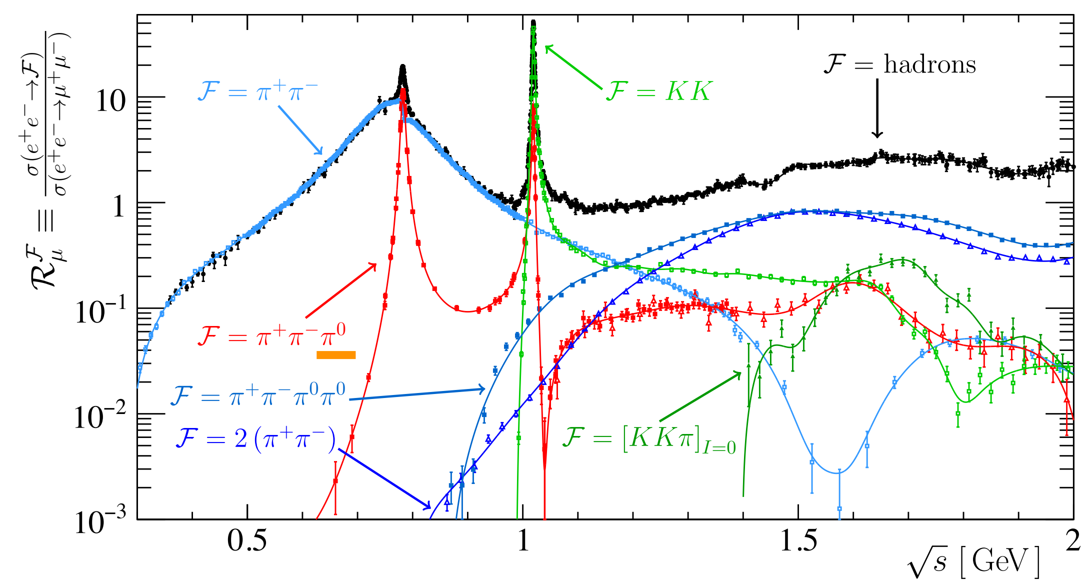
$$\mathcal{L}_{\text{eff.}} \supset -\frac{N_C \alpha'}{24\pi f_{\pi'}} \pi' F'^{\mu\nu} \tilde{F}'_{\mu\nu} - \frac{i N_C e'}{12\pi^2 f^3_{\pi'}} \epsilon^{\mu\nu\rho\sigma} A'_\mu \partial_\nu \pi'^+ \partial_\rho \pi'^- \partial_\sigma \pi'$$

- energy injection $m^*_{A'}$ below $\Lambda'_{\rm QCD}$

  via effective interactions

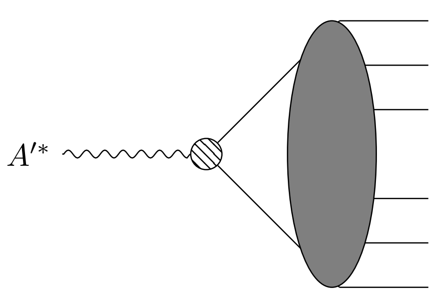
  e.g.) bremsstrahlung





Ilten, Soreq, Williams, Xue (2018)
PDG data

- energy injection $m^*_{A'}$ above $\Lambda'_{\rm QCD}$



$$N_{\pi'} \simeq \frac{n_{\pi'}\alpha'}{\pi}\left(\sum Q^2_{q'}\right) N_{A'}\Big|_{m^*_{A'}=m_{N'}}$$

hadron multiplicity $n_{\pi'} \simeq 2.0$

SM value @ J/psi threshold
DASP Collab. (1979)

* neutral pion produced above ω-resonance in SM

Visible Decay Searches for Dark Pions

Kamada, TK (2021)

$$m_{A'} < m_{\pi'} < 2m_{A'}$$

decay constant: $f_{\pi'} \simeq f_{\pi}\left(\frac{m_{N'}}{m_p}\right)$

visibly-decay dark photon

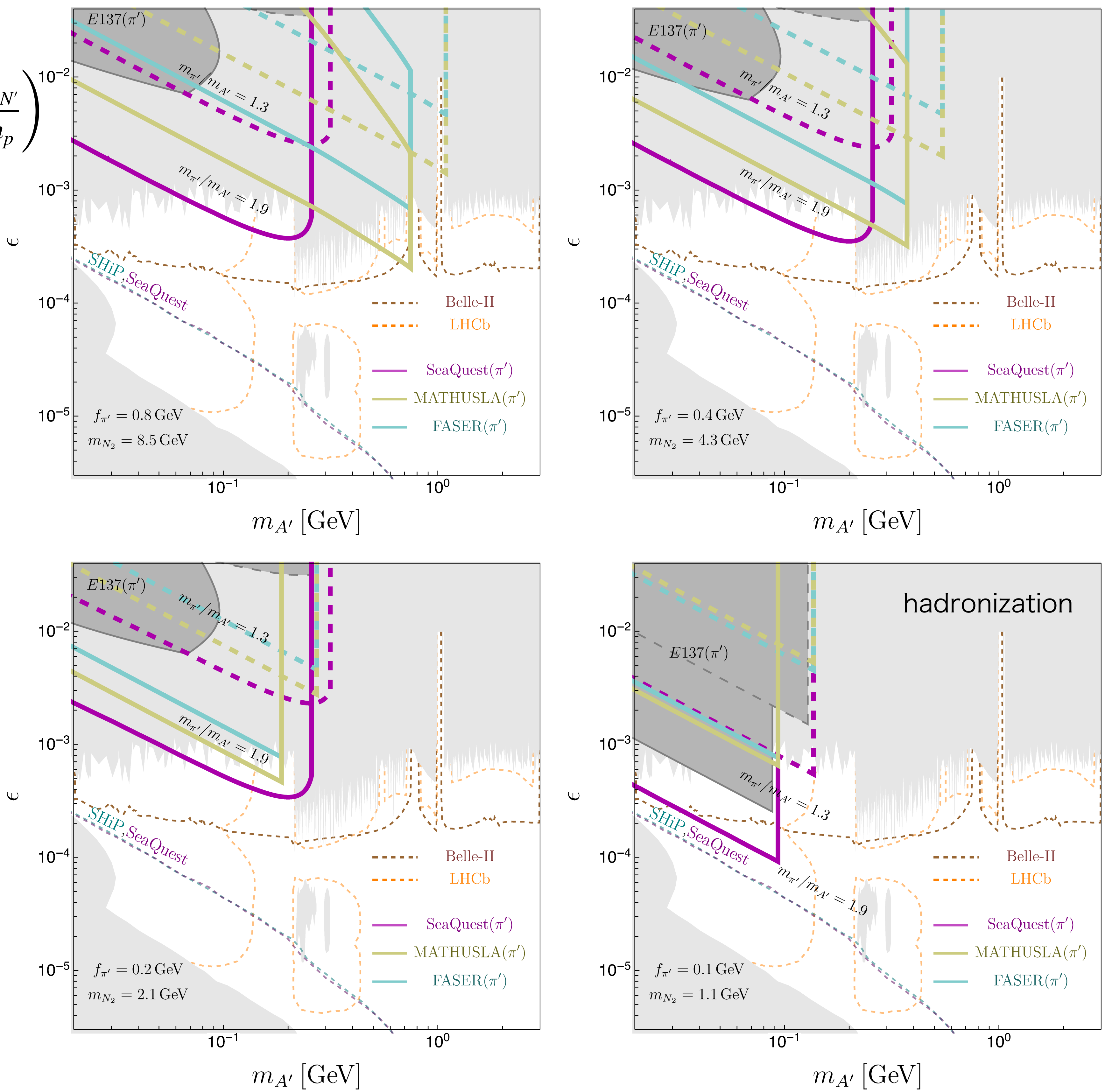
Belle-II, LHC-b (Prompt decay)
SHiP, DarkQuest (Fixed-target)

Existing Constraints:
BaBar/KLOE/LHC-b (Prompt decay)
E137/CHARM/νCal (Fixed-target)

dark pion decay

hadronization
LHC/DarkQuest for $m_{N'} \simeq m_\rho$

Sharp cuts:
hadronization (LHC) $6m_{\pi'} \simeq m_{N'}$
p bremsstrahlung $m_{\pi'} + m_{A'} \simeq m_\rho$



Visible Decay Searches for Dark Pions

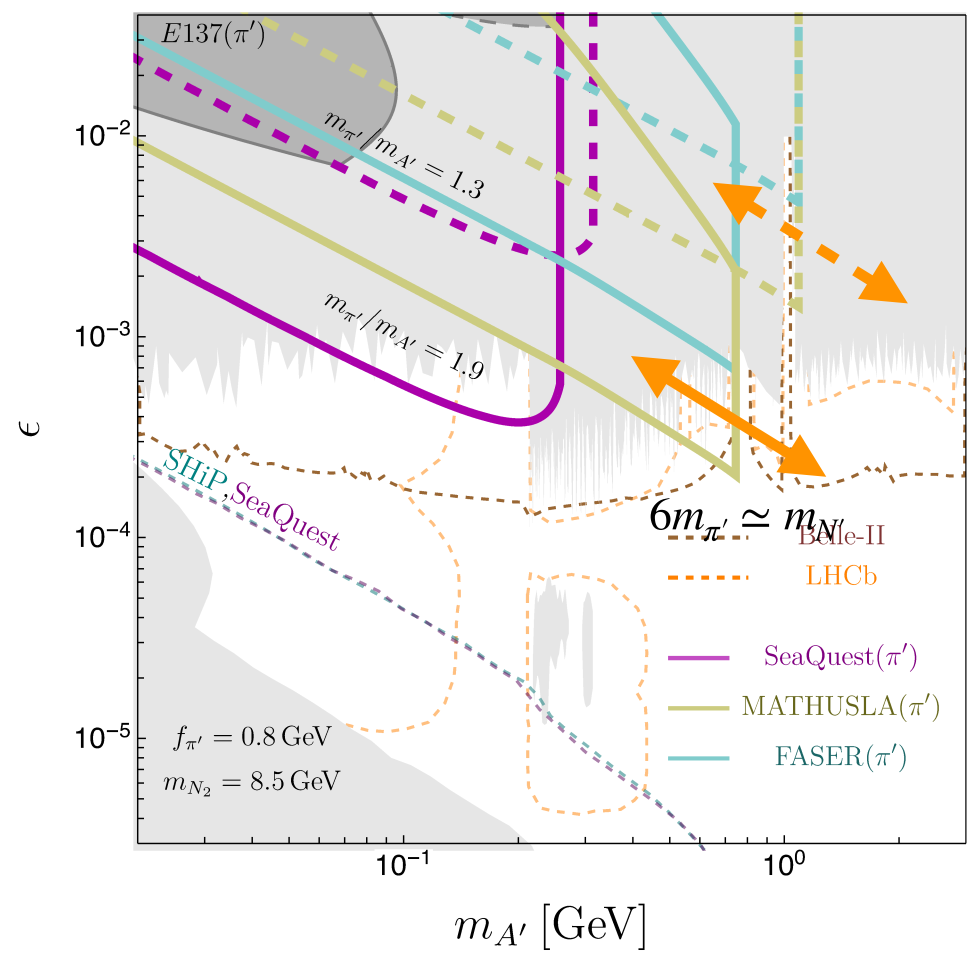
Kamada, TK (2021)

$m_{A'} < m_{\pi'} < 2m_{A'}$

Hadronization Production

$$N_{\pi'} \simeq \frac{n_{\pi'}\alpha'}{\pi}\frac{5}{3}N_{A'}\Big|_{m^*_{A'}=m_{N'}}$$

hadron multiplicity $n_{\pi'} \simeq 2.0$

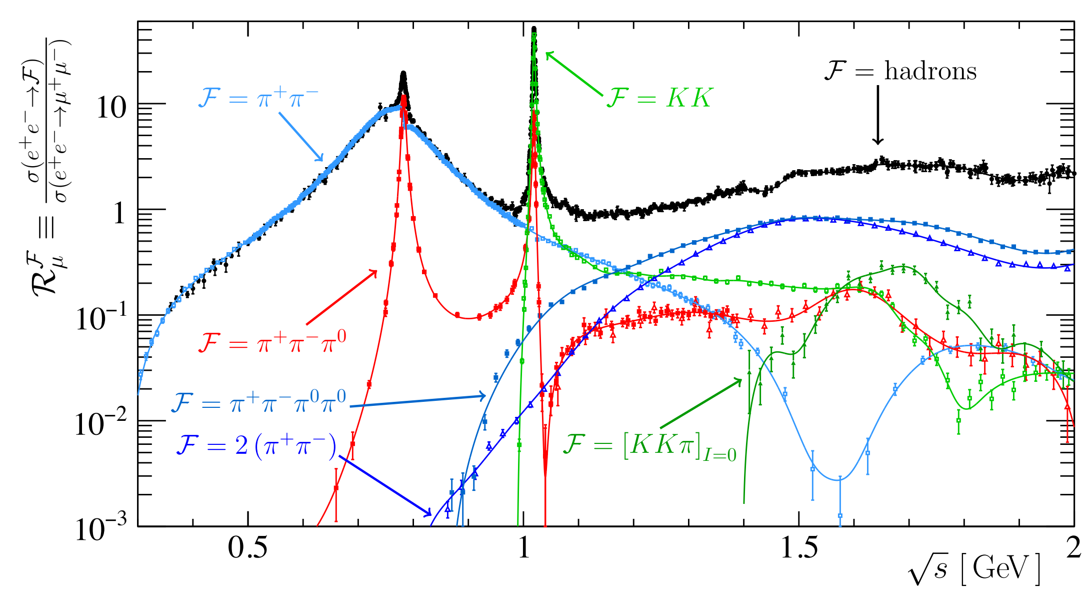


six dark pions ($2\pi'$,$2\pi'^{\pm}$) in one dark hadronization

due to isospin (among π', $\pi'^{\pm}$)

enhanced production
@ ρ, ω-like resonance in the dark sector

further investigation is worthwhile



Visible Decay Searches for Dark Nucleons

Kamada, TK (2021)

dark n-like nucleon = DM

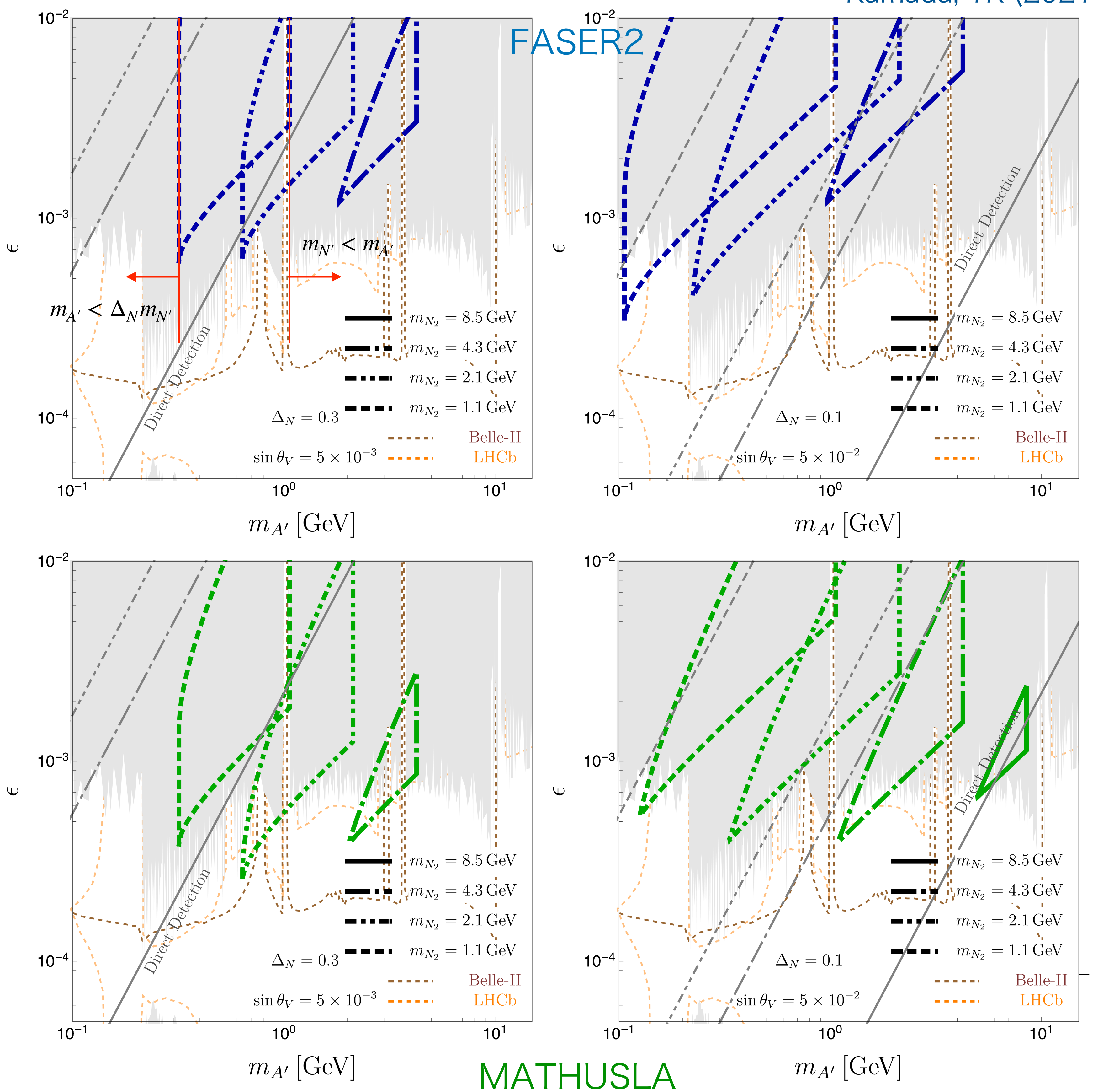
DM-SM scattering

- kinetic mixing
- n'-p' mixing / U(1)$_D$ violation

Direct detection

PandaX-II (2018,2021)
DarkSide-50 (2018)
CRESST-III (2019)

FASER	MATHUSLA
$p/p_T \simeq 10^3$	$p/p_T \simeq 10^0$
short lifetime	long lifetime



Summary and Discussions

Dark Sector searches with Lifetime frontier

- visible decay via a portal mediator (dark photon)
- most of studies: minimal model/its variations

Composite ADM with dark photon @ LLP searches

✓ FASER & MATHUSLA → N' & π'

✓ Fixed-target (DarkQuest) → π'

✓ A' visible decay searches (LHCb, Belle-II)

Discussions

- Specific spectrum: dark pion with $m_{A'} < m_{\pi'} < 2m_{A'}$
- Other models with light dark hadrons
  vector mesons with degenerated spectrum (puffy DM/SIMP)
- modeling/understanding "dark" hadronization is worthwhile for investigating

Cao, TK, Yuan in preparation

Backup Slides

Asymmetries

If the asymmetry is fully shared b/w dark and visible sectors

$$m_{\rm DM} = \frac{\Omega_{\rm DM}}{\Omega_B} m_B \frac{\eta_B}{\eta_{\rm DM}} \simeq 5{\rm GeV}\frac{\eta_B}{\eta_{\rm DM}}$$

- chemical equilibrium
- conservation of charges (B-L, Q)
- rapid sphaleron & top decoupled before EWSB

$$\frac{\eta_B}{\eta_{\rm SM}} = \frac{30}{97}, \qquad \frac{\eta_{\rm SM}}{\eta_{\rm DM}} = \frac{237}{44 n_{g'}}$$

Weinberg, **Cosmology**
Ibe, Matsumoto, Yanagida (2011)
Fukuda, Matsumoto, Mukhopadhyay (2015)

$n_{g'}$: # of generations, $U', \overline{U}', D', \overline{D}'$

the ADM mass

$$\boxed{m_{\rm DM} \simeq \frac{8.5}{n_{g'}}{\rm GeV}}$$

LLP Constraints/Sensitivities

The number of signals

$$N_{\text{signal}} \simeq N_{\text{LLP}} \times (\text{effic.})\,,$$

$$(\text{effic.}) \simeq \frac{1}{N_{\text{event}}} \sum_{\text{event}} (e^{-\underline{\frac{r_{\min}}{d}}} - e^{-\underline{\frac{r_{\max}}{d}}})\underline{A}\,.$$

geometric efficiency
energy threshold

decay length $d = c\tau\beta\gamma$

We formulate approximate sensitivity curves instead of generating events by MC from existing sensitivity curves (A', iDM, ...) Kamada, TK (2021)

Upper bound on decay rate

decay before detector: ($d \ll r_{\min}$)

$$\frac{c\tau_{\text{LLP}} p_{\max} m_{\text{LLP}}^{-1}}{r_{\min}} \ln \frac{N_{\text{LLP}} A}{N_{\text{signal}}} \simeq 1 \qquad \boxed{\frac{d_0}{r_{\min}} \ln \frac{N_\chi^0 A_0}{N_{\text{signal}}} \simeq 1}$$

reference

$$\ln \frac{N_{\text{LLP}} A}{N_\chi^0 A_0} + \frac{r_{\min}}{d_0} = \frac{r_{\min}}{c\tau_{\text{LLP}} p_{\max} m_{\text{LLP}}^{-1}}$$

Lower bound on decay rate

rarely decays inside detector: ($d \gg r_{\max}$)

$$\frac{r_{\max} - r_{\min}}{c\tau_{\text{LLP}} p_{\min} m_{\text{LLP}}^{-1}} \frac{N_{\text{LLP}}}{N_{\text{signal}}} A \simeq 1 \qquad \boxed{\frac{r_{\max} - r_{\min}}{d_0} \frac{N_\chi^0}{N_{\text{signal}}} A_0 \simeq 1}$$

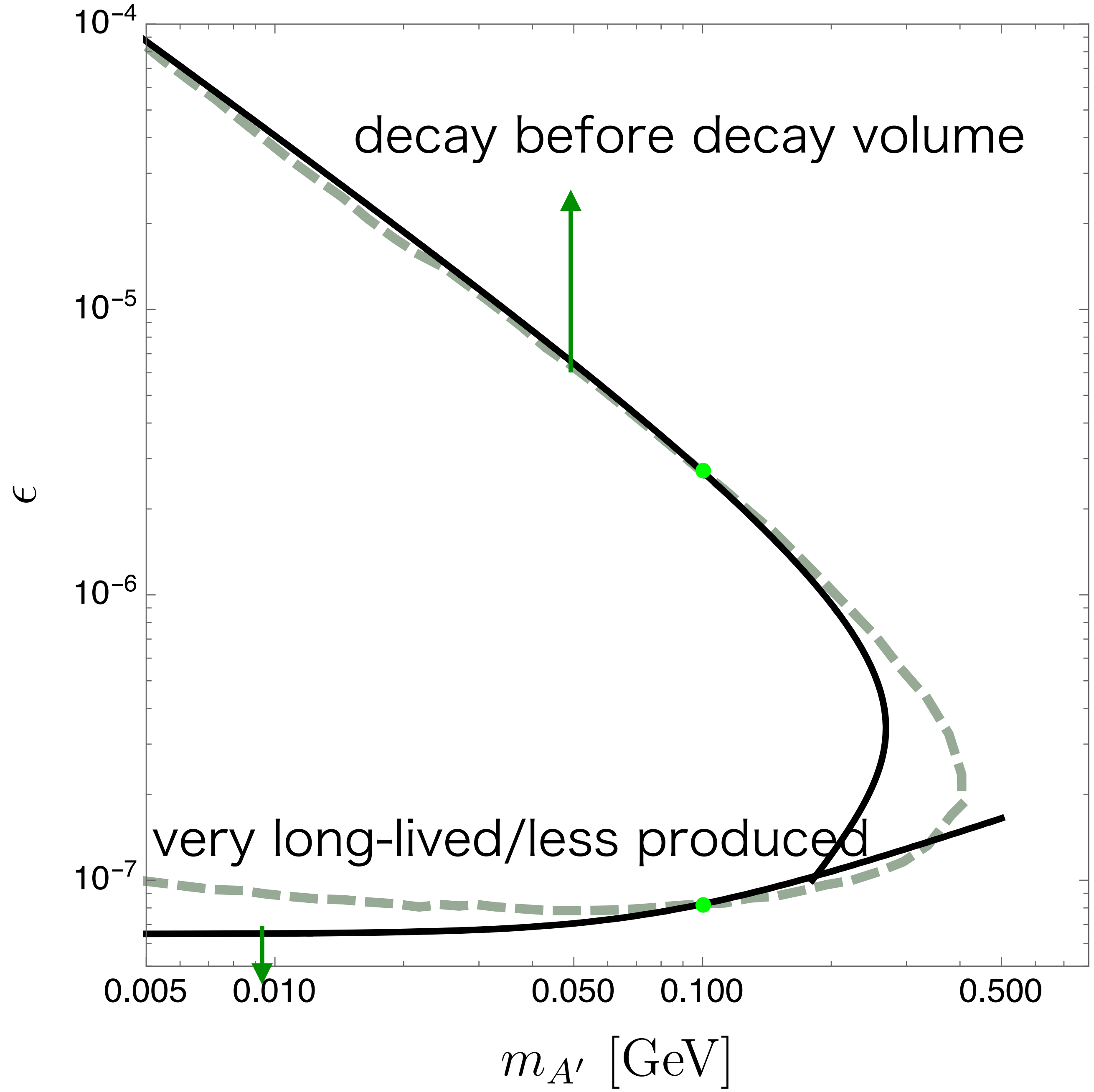
reference

$$\frac{r_{\max} - r_{\min}}{c\tau_{\text{LLP}} p_{N_1:\min} m_{\text{LLP}}^{-1}} \frac{N_{\text{LLP}}}{N_\chi^0} \frac{A}{A_0} = \frac{r_{\max} - r_{\min}}{d_0}$$

Validity of Fitting approx. functions

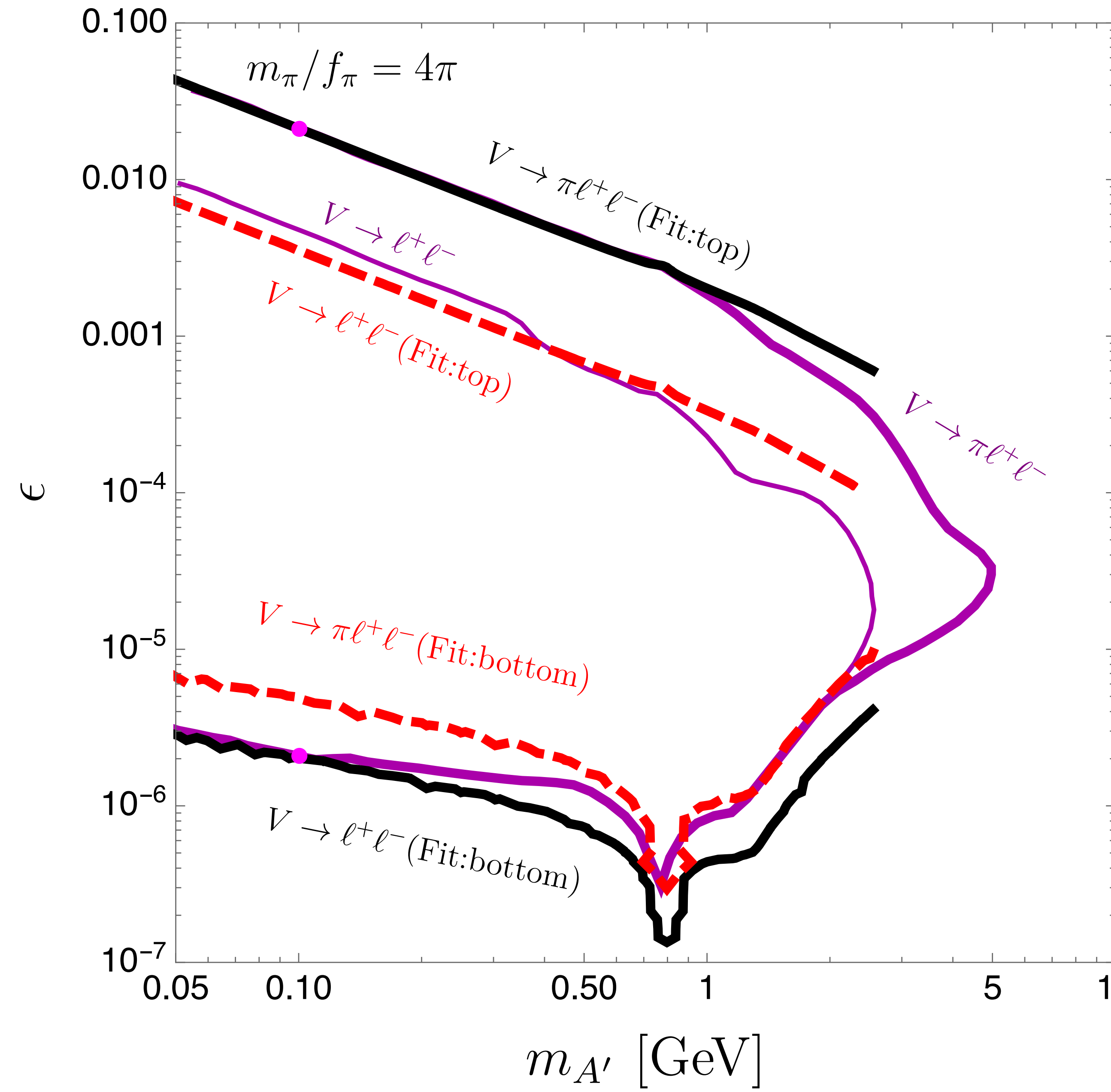
E137 dark photon searches

Bjorken, Essig, Schuster, Toro (2009)



SeaQuest dark rho meson searches

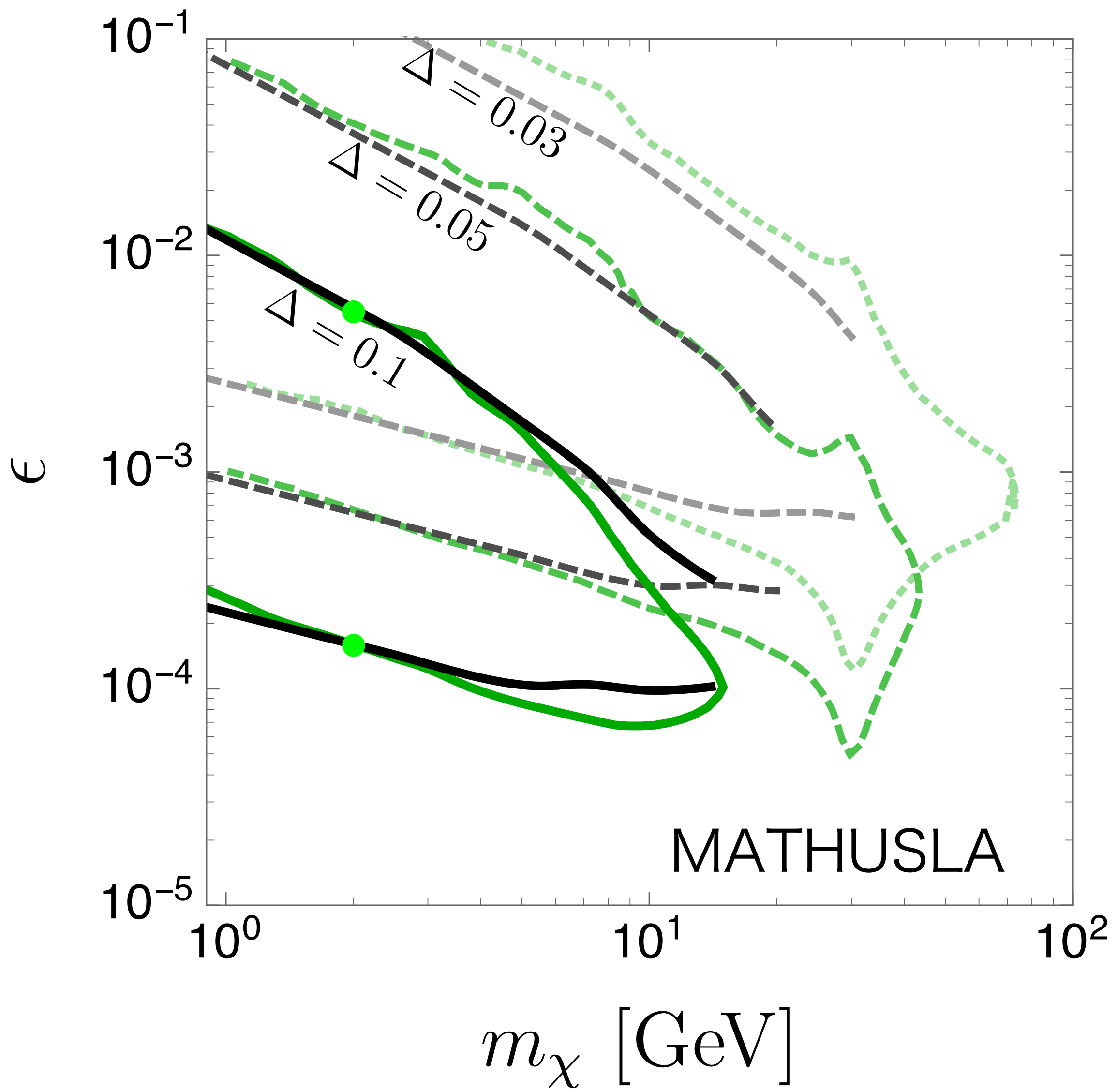
Berlin, Blinov, Gori, Schuster, Toro (2018)

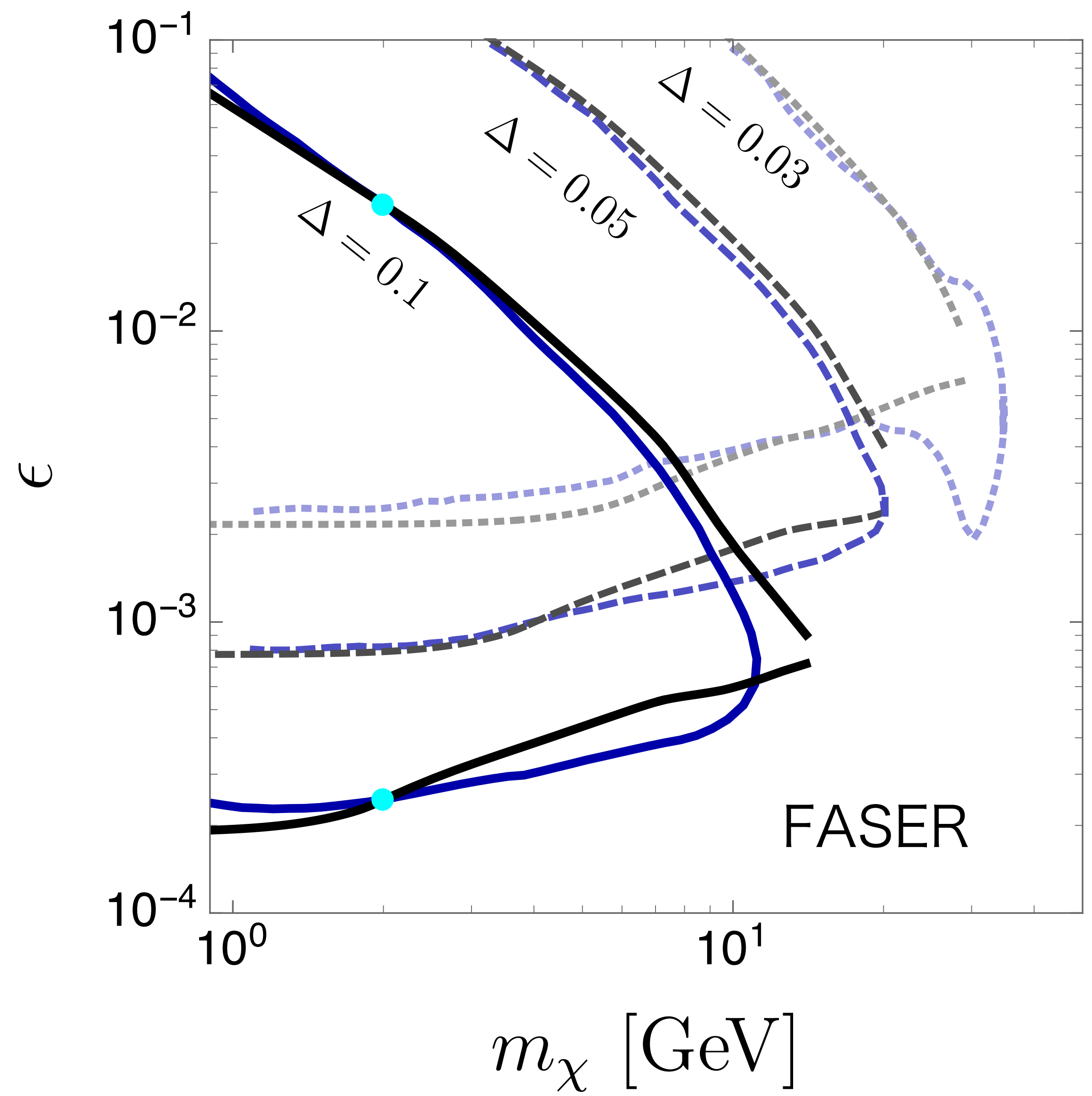


Validity of Fitting approx. functions

iDM searches at LHC frontier

Berlin, Kling (2018)





Intermediate-scale Portal interactions

$\overline{N}_R$ (SM singlet) couples to dark sector

$$\mathcal{L} = \frac{1}{M'^2}\overline{U}'\overline{D}'\overline{D}'\overline{N}_R + y_N LH\overline{N}_R + \frac{1}{2}M_R\overline{N}_R\overline{N}_R + \text{h.c.}$$

$$\to \frac{y_N^2}{M_R^2}(LH)^2 + \text{h.c.}$$ neutrino mass

$$+ \frac{y_N}{M'^2 M_R}\overline{U}'\overline{D}'\overline{D}'(LH) + \text{h.c.}$$ portal interaction

$$+ \frac{1}{2M'^4 M_R}(\overline{U}'\overline{D}'\overline{D}')^2 + \text{h.c.}$$ DM oscillation

- The portal interaction connects two sectors until $T \sim T_D \sim M'\left(M'/M_{\text{Pl}}\right)^{\frac{1}{3}}$.
- DM decays through the portal interaction: SK constraint on $\bar{\nu}$ signal

  -> $M' \gtrsim 10^{8.5}$ GeV   Fukuda, Matsumoto, Mukhopadhyay (2014)

- Majorana mass for dark neutron: leads DM oscillation

  indirect detection constraint

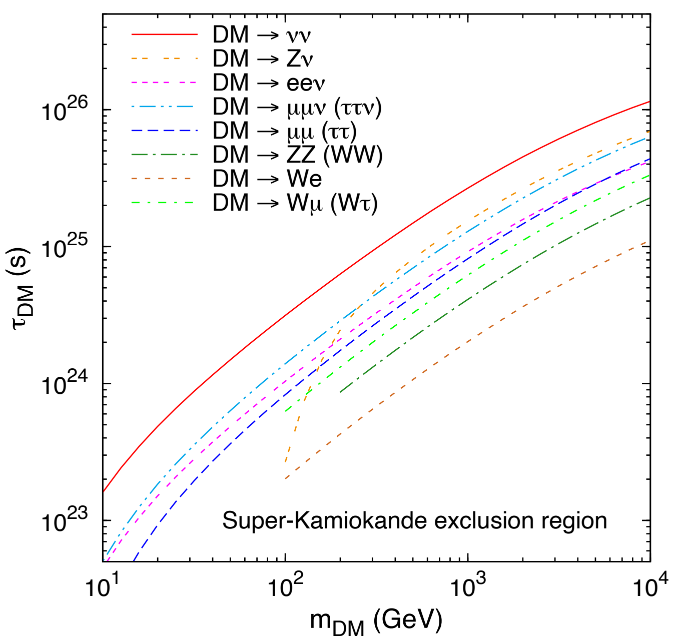
  Buckley, Profumo (2011)
  Ibe, Kobayashi, Nagai, Nakano (2019)

Signals from Intermediate-scale Portal

indirect constraints on M_R

Covi, Grefe, Ibarra, Tran (2010)
Feldstein, Fitzpatrick (2010)
Fukuda, Matsumoto, Mukhopadhyay (2014)

- $\bar{\nu}$ Signal from DM Decay: $n' \to \bar{\nu} + \pi'^0$



$$\frac{y_N}{M'^2 M_R}\overline{U}'\overline{D}'\overline{D}'(LH) + \text{h.c.}$$

$$\tau_{n'} \simeq 10^{17}\text{years}\left(\frac{(M'^2 M_R)^{1/3}}{10^9\ \text{GeV}}\right)^6\left(\frac{10\ \text{GeV}}{m_{n'}}\right)^5$$

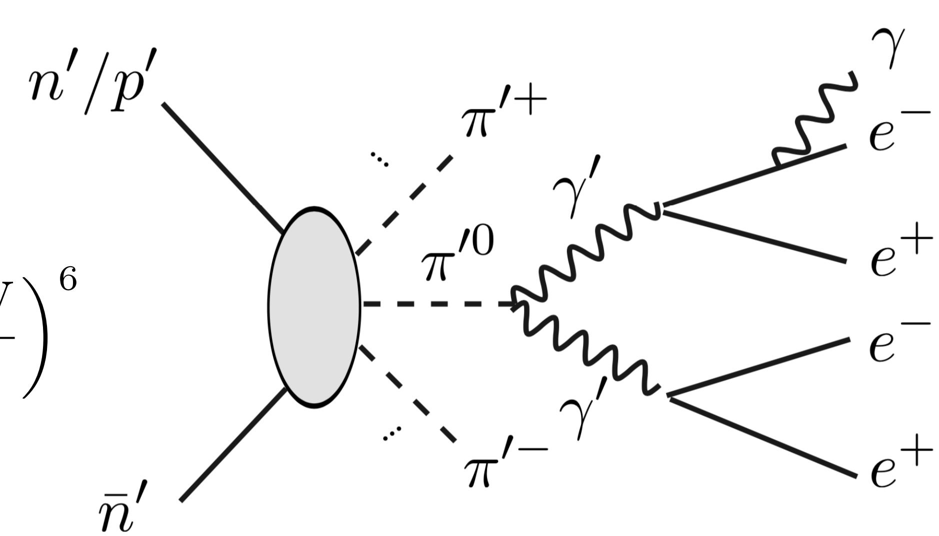
from SK ν-flux measurement: $(M'^2 M_R)^{1/3} \gtrsim 10^{8.5}\ \text{GeV}$

- DM-$\overline{\text{DM}}$ annihilation

Ibe, Kobayashi, Nagai, Nakano (2019)

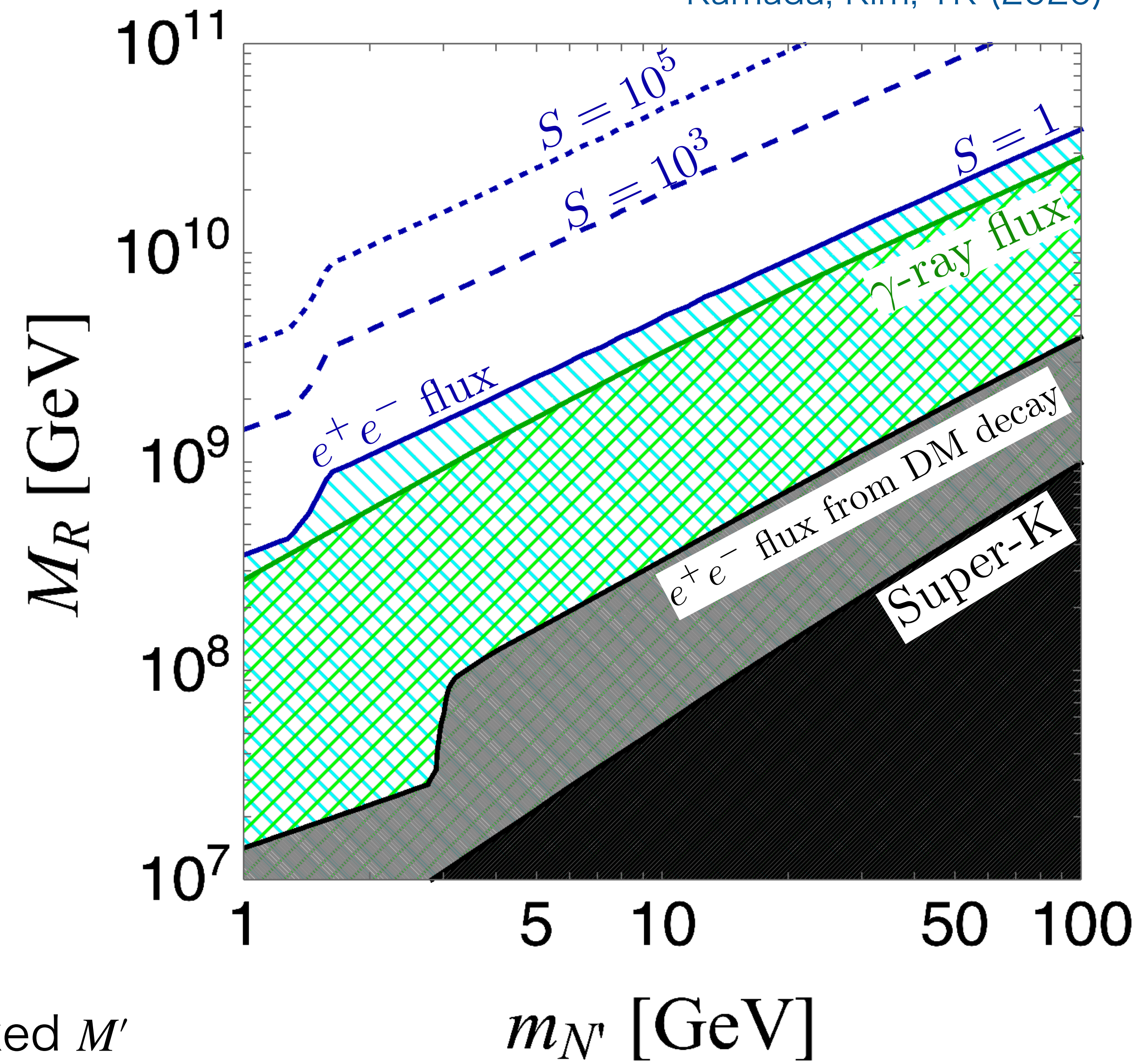
$$\frac{1}{2M'^4 M_R}(\overline{U}'\overline{D}'\overline{D}')^2 + \text{h.c.}$$

$$\tau_{n'\text{-}\bar{n}'} \simeq 10^{14}\text{years}\left(\frac{M_R}{10^9\ \text{GeV}}\right)\left(\frac{M'}{3\times 10^9\ \text{GeV}}\right)^4\left(\frac{10\ \text{GeV}}{m_{n'}}\right)^6$$



Bounds on M_R

Kamada, Kim, TK (2020)



Fixed M'

S : Sommerfeld factor

γ-ray flux from MW's dSphs

Fermi-LAT Collab., PRL (2015)

$\bar{\nu}$-flux measurement (super-K)

e^+-e^- flux (annihilation $\langle \sigma v \rangle$)

$m_{N'} \gtrsim 1.5$ GeV @ AMS-02

$m_{N'} \lesssim 1.5$ GeV @ Voyager-1

Stone, et al, Sience (2013)
AMS Collab., PRL (2014)

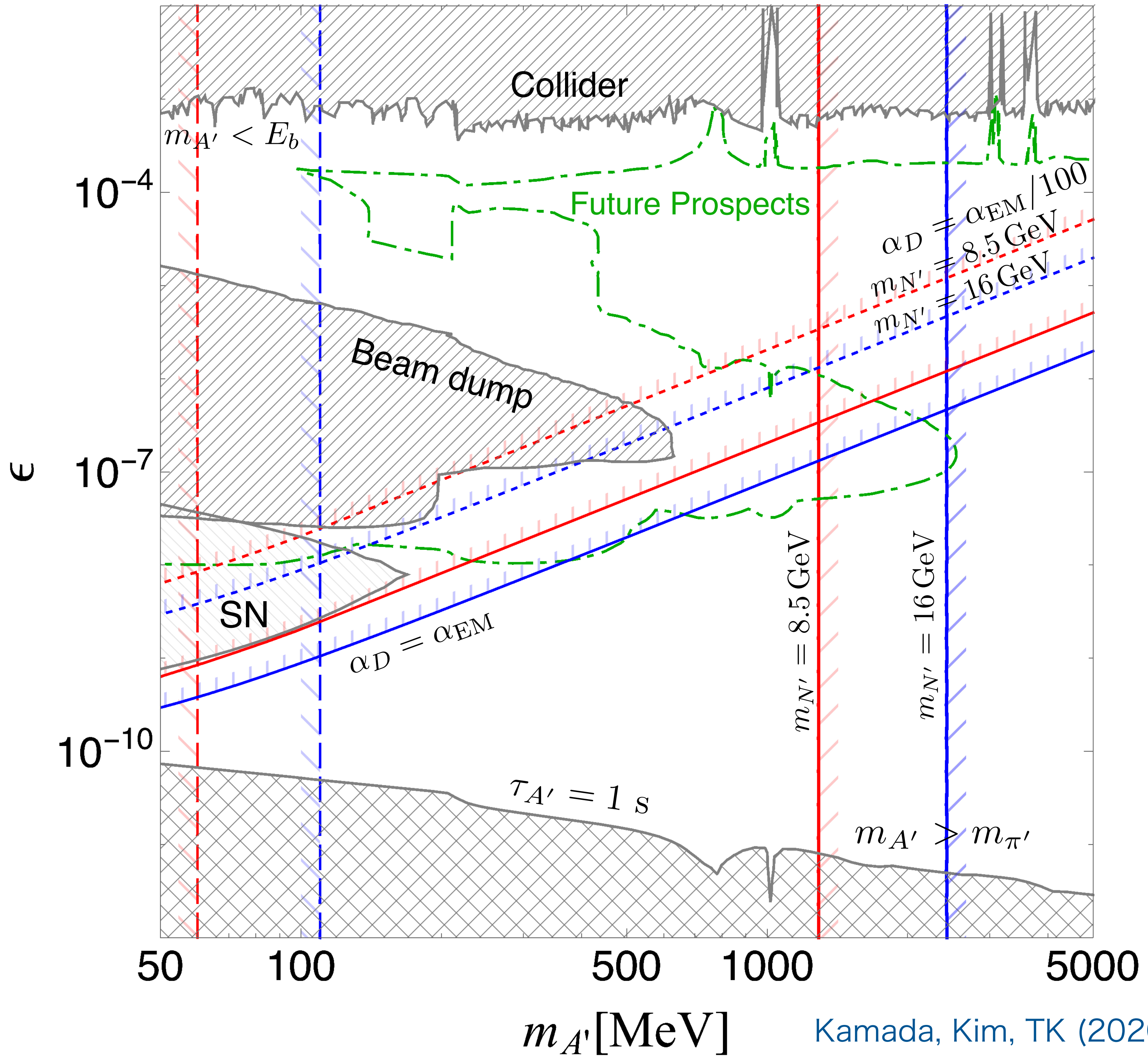
e^+-e^- flux from dark meson ($\tau_{\rm DM}$)

$m_{N'} \gtrsim 3.0$ GeV @ AMS-02

$m_{N'} \lesssim 3.0$ GeV @ Voyager-1

Boudaud, Lavalle, Salati (2016)

Bounds on Dark Photon Parameters



Kamada, Kim, TK (2020)

direct detection experiment

Panda-X (54 ton×day)

$\sigma > 10^{-44}\ \mathrm{cm}^2$ 1802.06912

DM ratio $p' : n' = 1 : 1$

Dark photon:

- lightest in dark sector
- Collider&Beam-dump
- Supernova 1987A

A' recoupling after ν decoupling

reheats only γ, e^+, e^-

- change T_ν / T_γ i.e. N_{eff}

roughly $\tau_{A'} \lesssim 1$ s