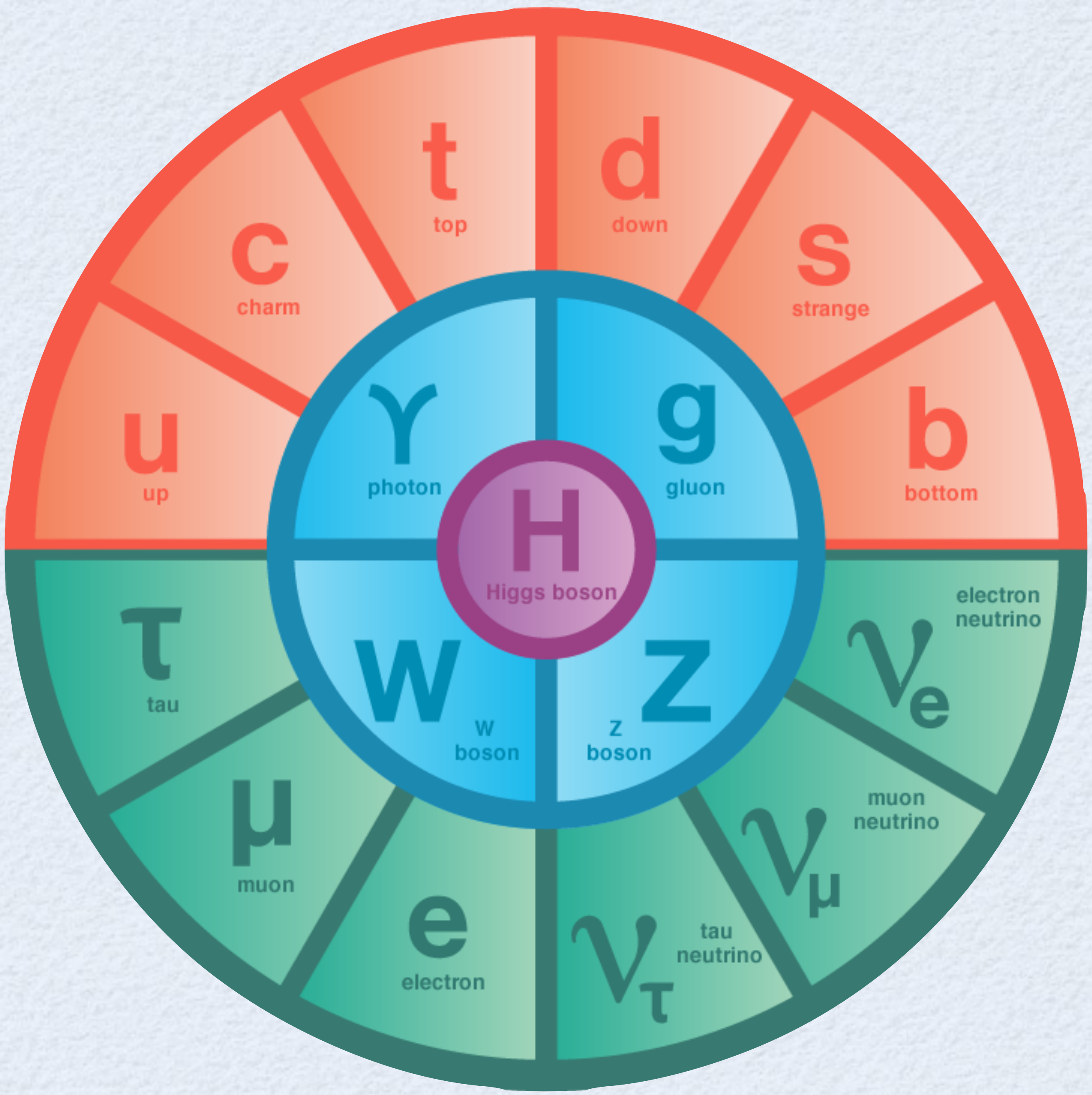
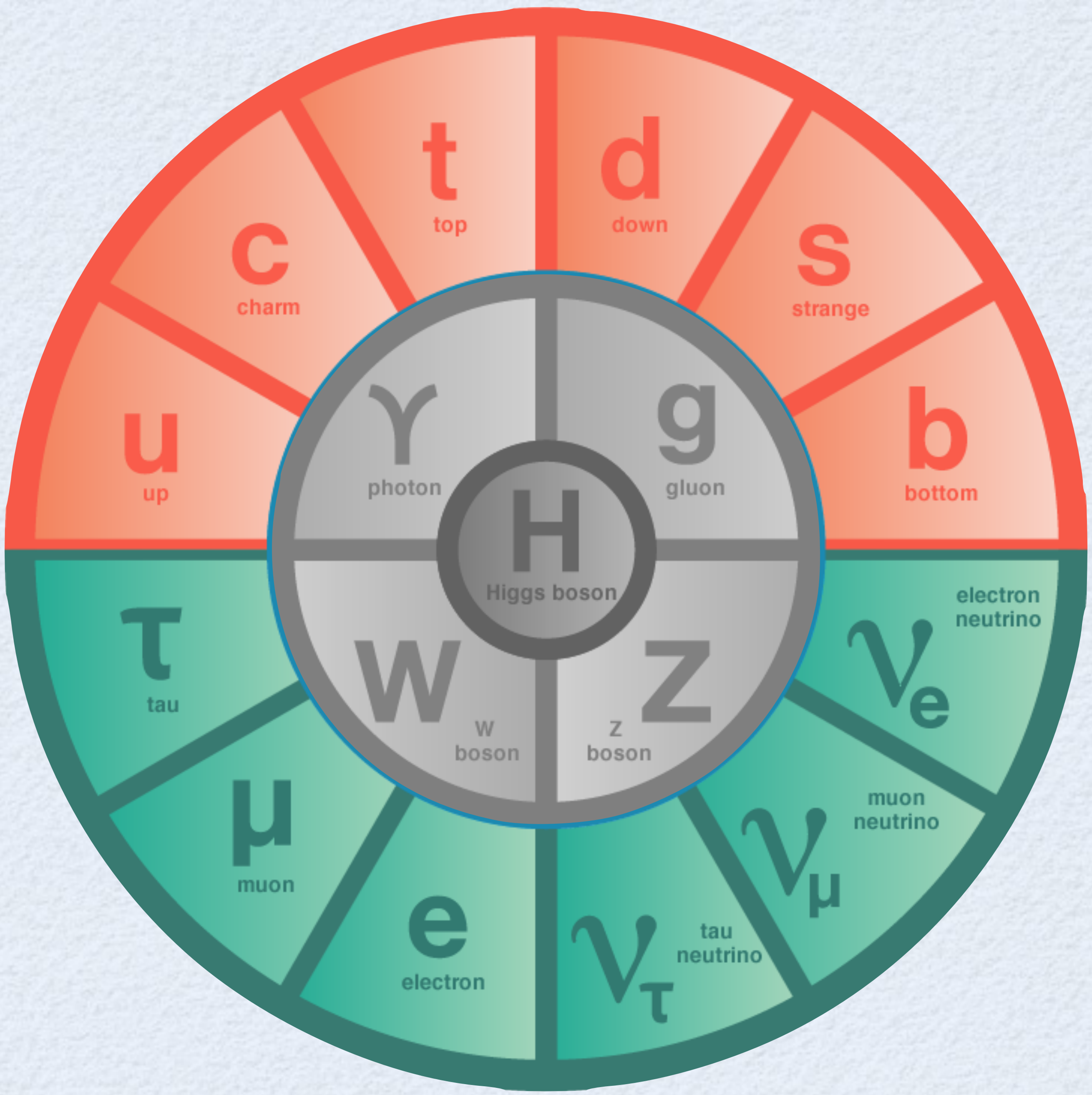
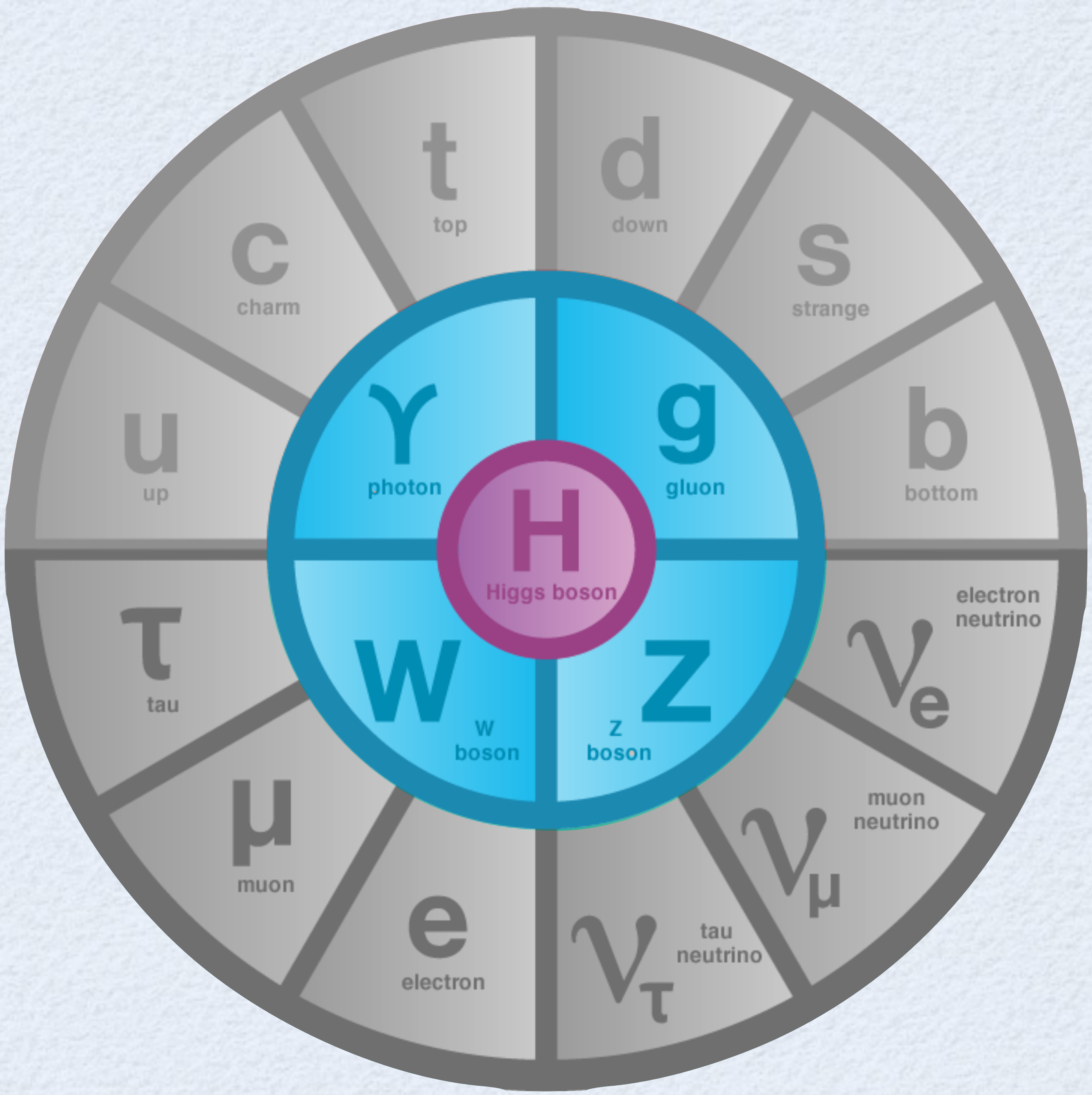
Probing New Physics across Scales

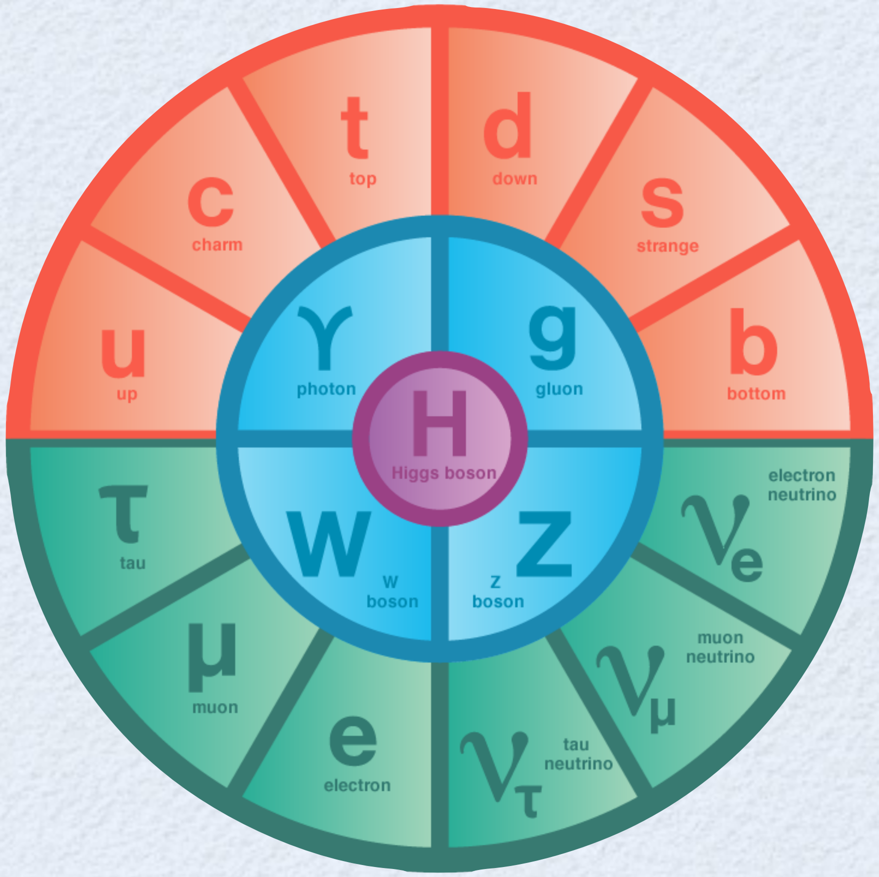
Yotam Soreq

Theoretical Particle Physics Seminar, University of Zurich, Nov. 27, 2018


t
top
d
down
c
charm
s
strange
u
up
b
bottom
γ
photon
g
gluon
H
Higgs boson
W
w
boson
Z
z
boson
τ
tau
electron
neutrino
ν_e
μ
muon
muon
neutrino
ν_μ
e
electron
ν_τ
tau
neutrino


t
top
d
down
c
charm
s
strange
u
up
b
bottom
γ
photon
g
gluon
H
Higgs boson
W
W
boson
Z
Z
boson
τ
tau
electron
neutrino
μ
muon
e
electron
tau
neutrino
muon
neutrino


t
top
d
down
c
charm
s
strange
u
up
b
bottom
γ
photon
g
gluon
H
Higgs boson
W
W boson
Z
Z boson
τ
tau
electron neutrino
ν e
μ
muon
muon neutrino
ν μ
e
electron
tau neutrino
ν τ



if the Standard Model is so successful, why do we look for new physics?

Why New Physics?

experimental evidences:

- Baryogenesis
- ν oscillations
- dark matter

theory issues:

- tuning of the Higgs mass
- the strong CP problem
- the flavor puzzle

the quest for new physics

The Quest for New Physics

The Quest for New Physics

zoom

energy
frontier

The Quest for New Physics

zoom

brightness

energy
frontier

The Quest for New Physics

zoom

brightness

energy
frontier

intensity
frontier

The Quest for New Physics

zoom

brightness

focus

energy frontier

intensity frontier

The Quest for New Physics

zoom

brightness

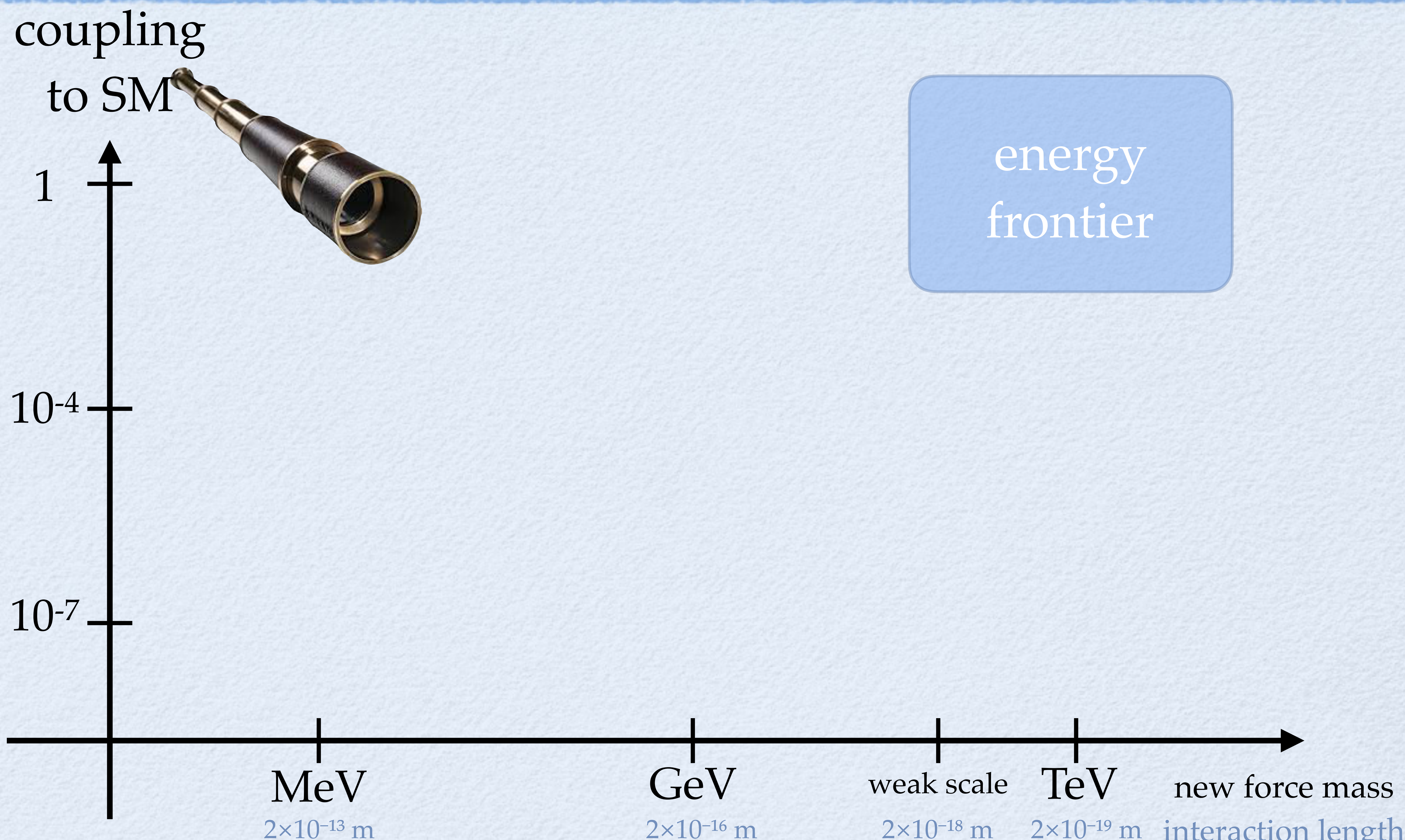
focus

energy frontier

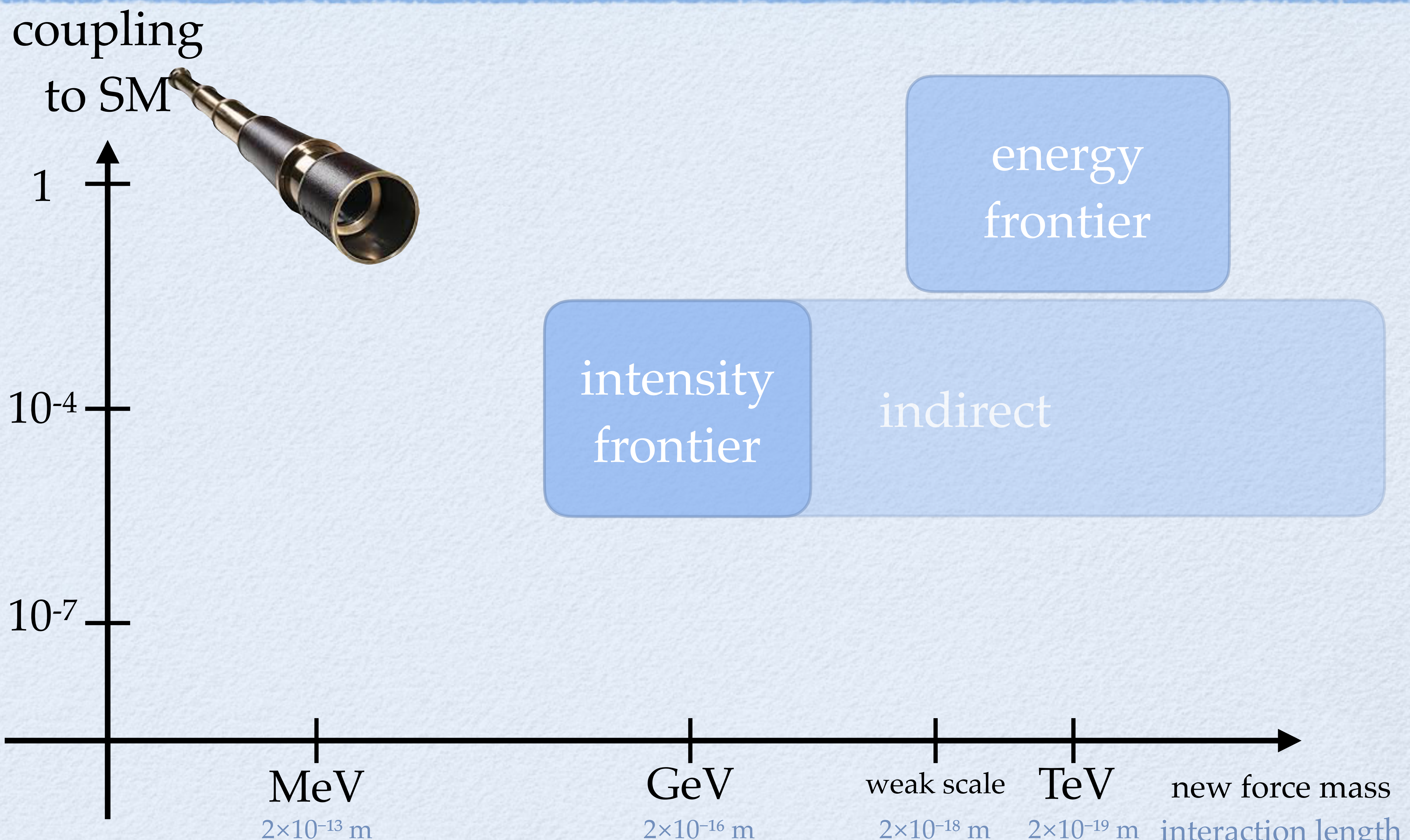
intensity frontier

precision frontier

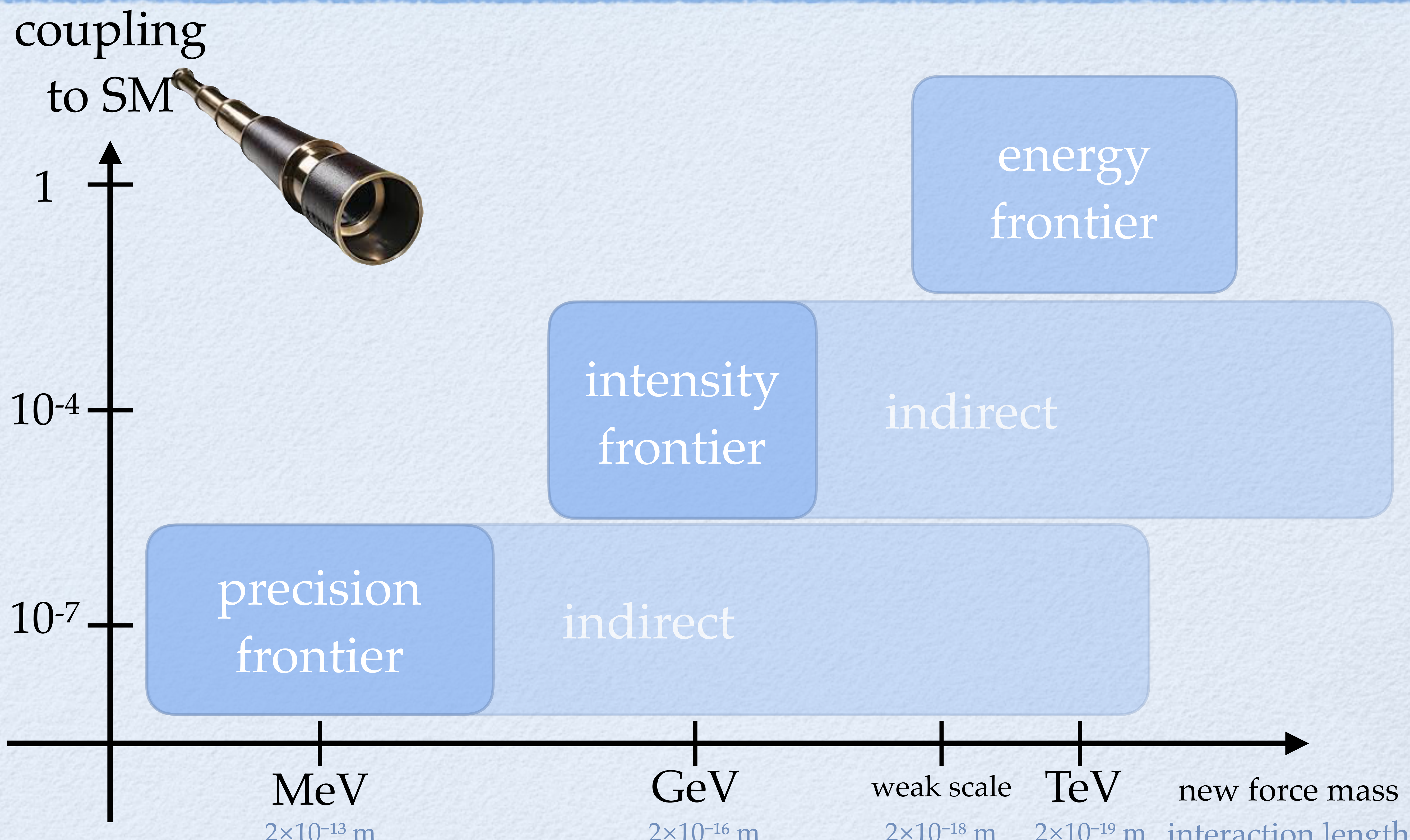
The Quest for New Physics



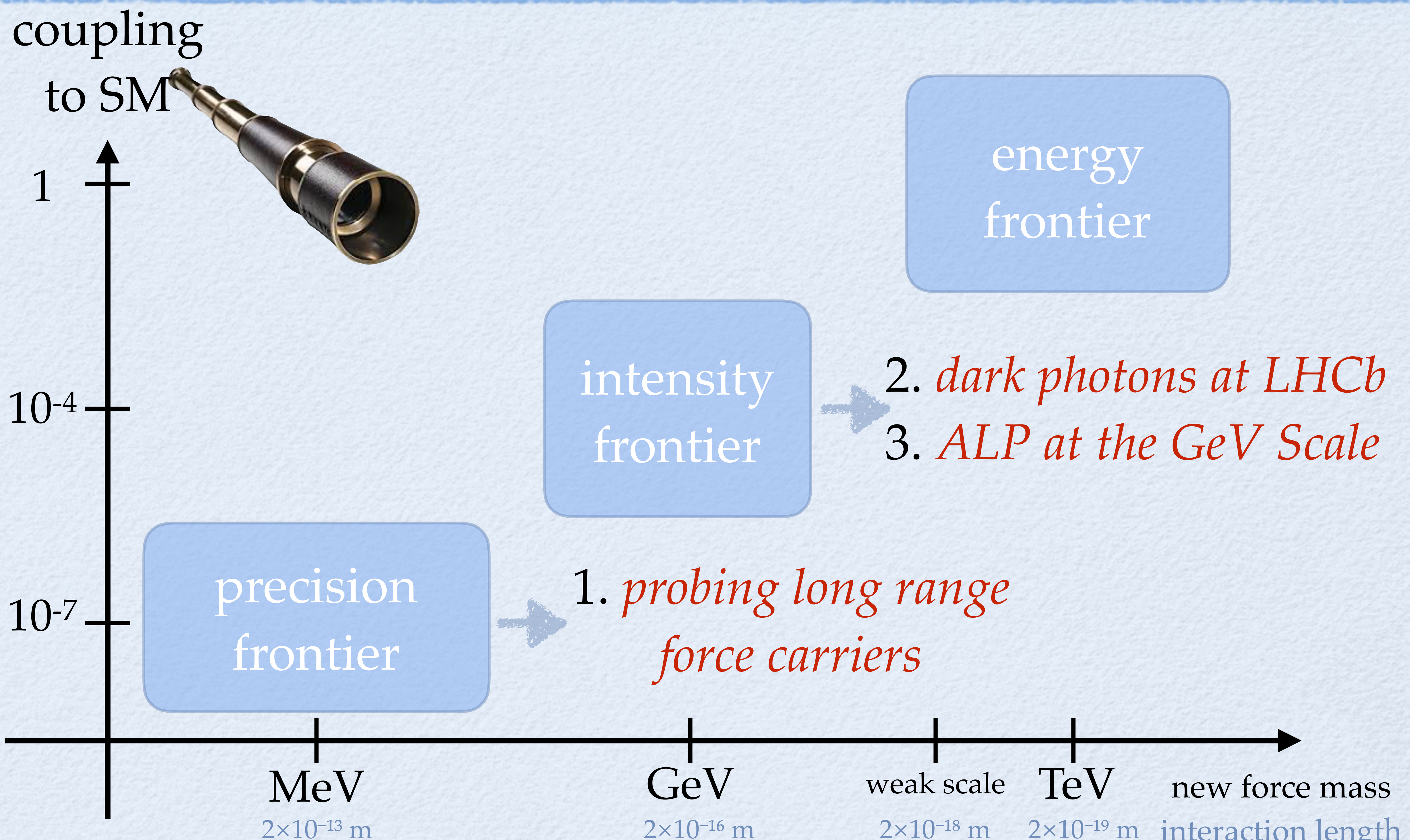
The Quest for New Physics



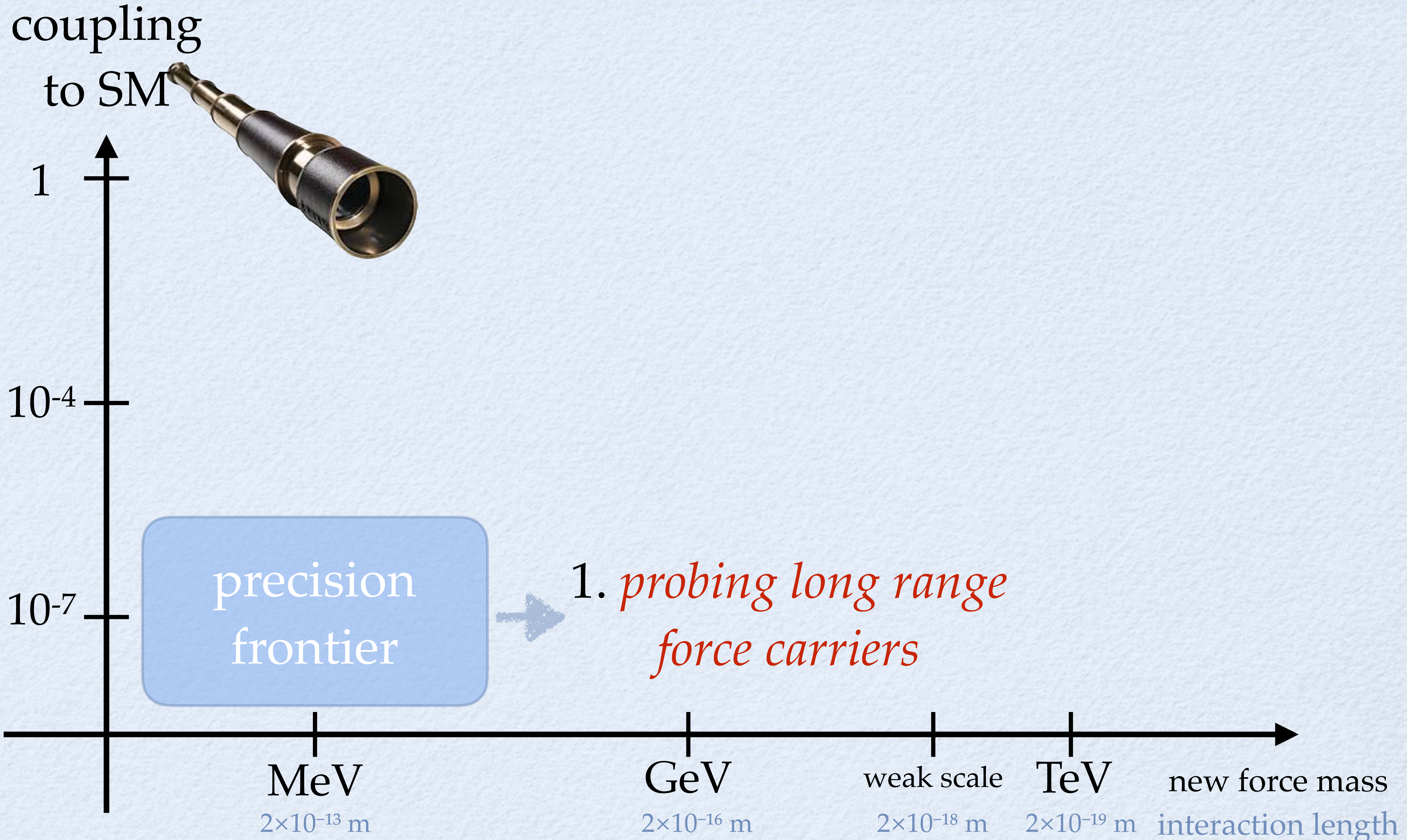
The Quest for New Physics



The Quest for New Physics



The Quest for New Physics



Higgs

Higgs $\xleftrightarrow[\theta]{\text{mixing}}$ light new particles

Higgs ⟷ mixing θ ⟷ light new particles

⇓

new force couples to matter

$$\frac{y_e y_A}{4\pi}\sin\theta\,\frac{e^{-m_\phi r}}{r}$$

Probing new spin independent interactions

ϕ - a new force carrier (spin 0, 1 or 2), mass m_ϕ

at atomic systems ⇒ effective Yukawa like potential

interaction length~$1/m_\phi$

Probing new spin independent interactions

ϕ - a new force carrier (spin 0, 1 or 2), mass m_ϕ

at atomic systems ⇨ effective Yukawa like potential

$$\frac{y_e(y_p Z + (A-Z)y_n)}{4\pi}\frac{e^{-m_\phi r}}{r}$$

electron-nucleus interaction

$$\frac{y_e^2}{4\pi}\frac{e^{-m_\phi r_{12}}}{r_{12}}$$

electron-electron interaction

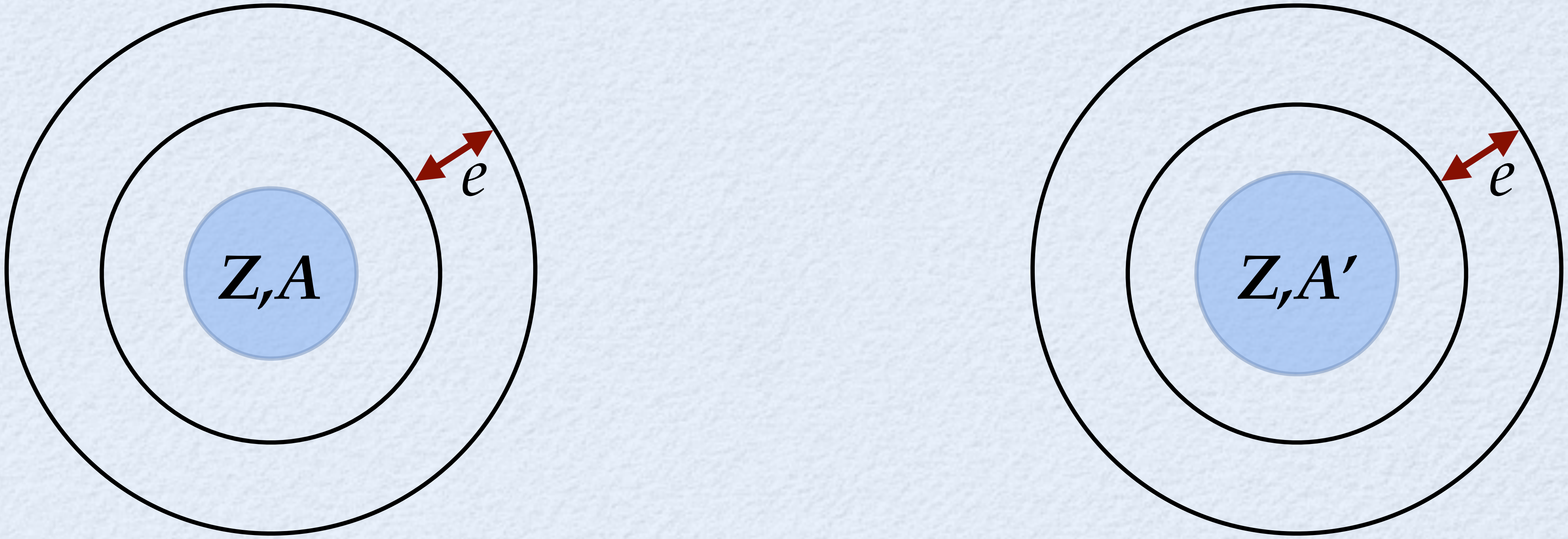
⇨ modify the electronic transition frequencies

interaction length~$1/m_\phi$

Isotope shift

basic idea

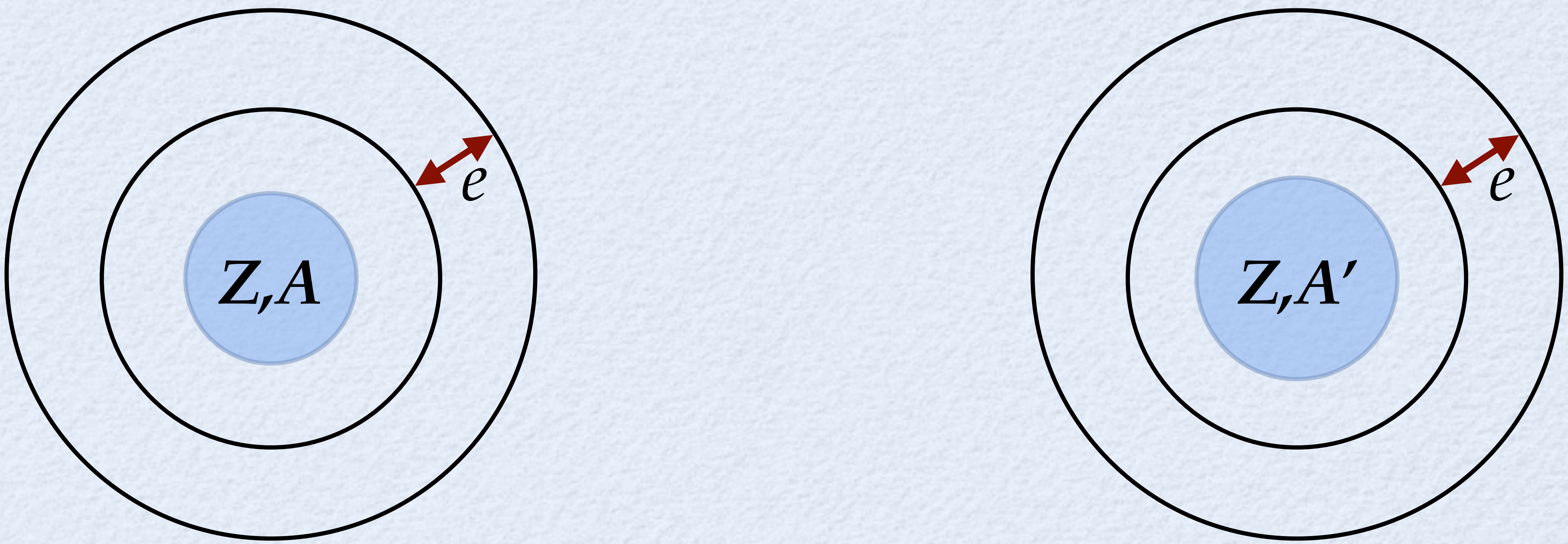
measure the same electronic transition in different isotopes



ISOTOPE SHIFT

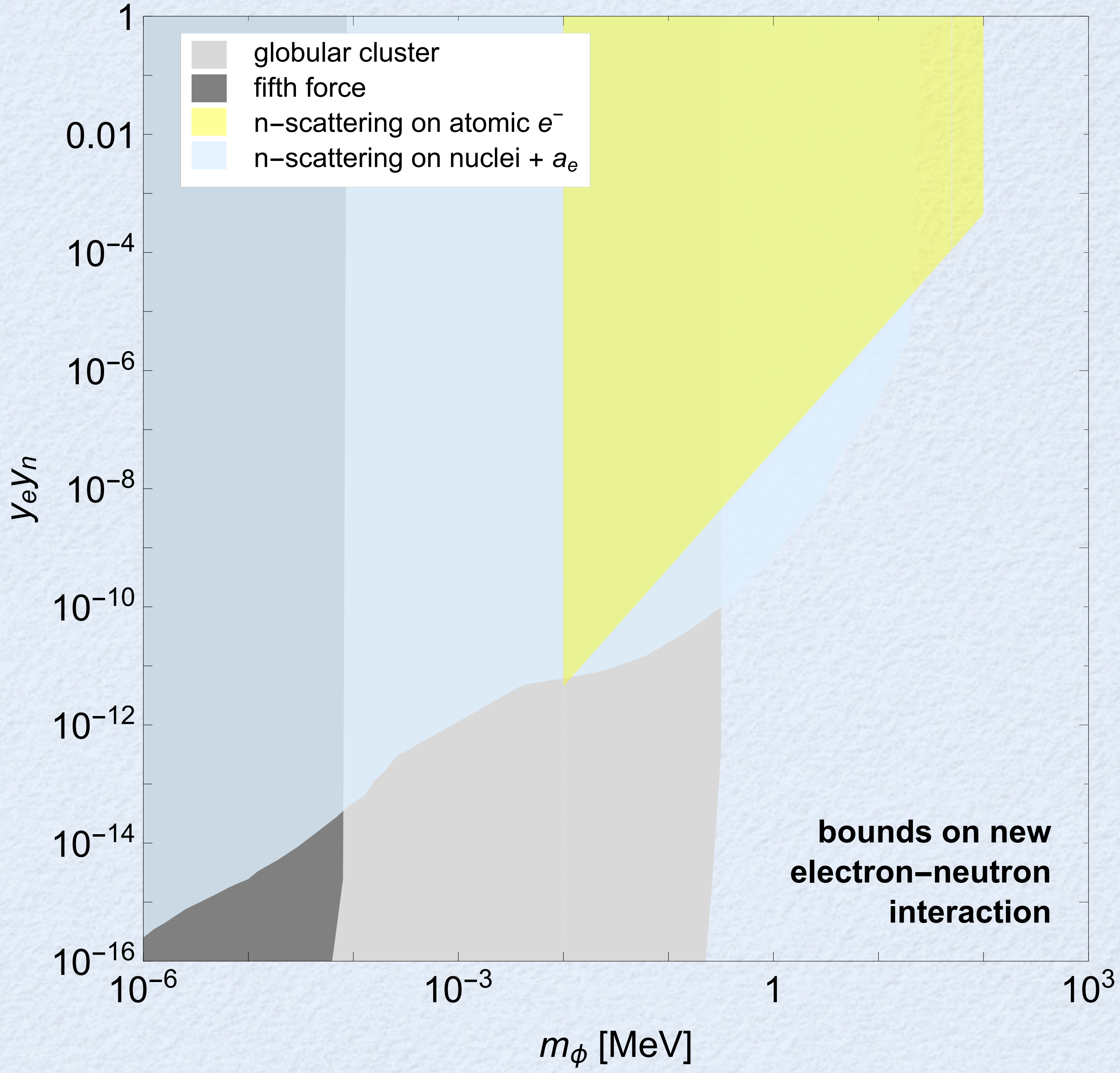
basic idea

measure the same electronic transition in different isotopes



probe the electron-neutron interaction ($y_e y_n$)

Current bounds: e-n interaction



to maximize the sensitivity for new physics

to maximize the sensitivity for new physics

theory uncertainty
smaller than
experimental one

few electrons systems
(hydrogen, helium)

to maximize the sensitivity for new physics

theory uncertainty smaller than experimental one

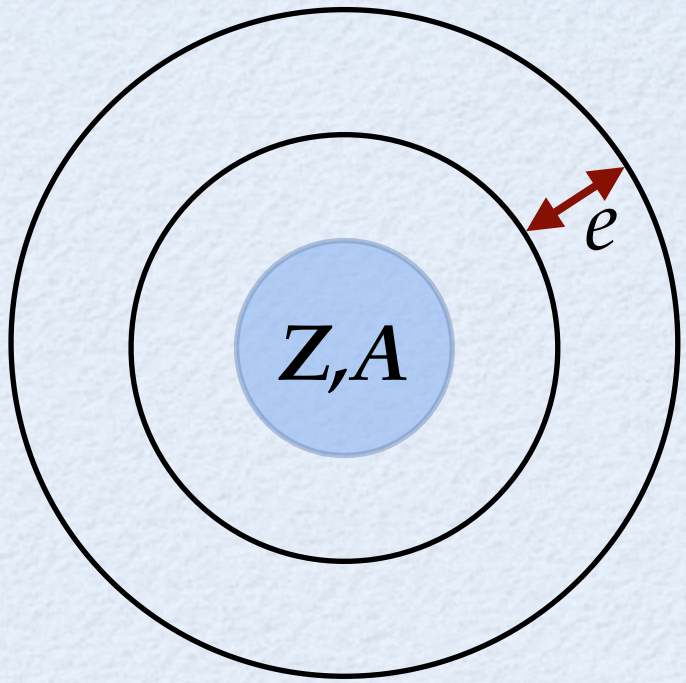
unique observable which are insensitive to theory error

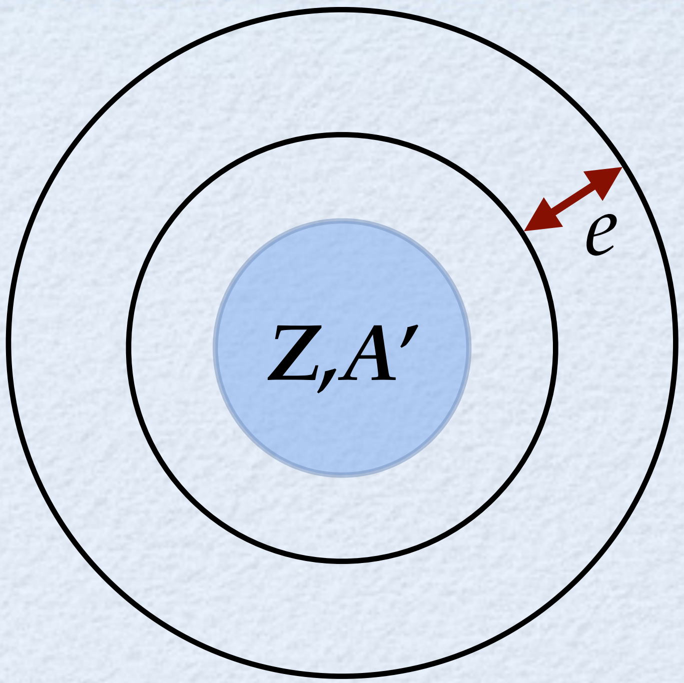
few electrons systems
(hydrogen, helium)

heavy elements
(calcium, strontium, ytterbium)

few electrons systems

Few electrons systems -isotope shift





standard model

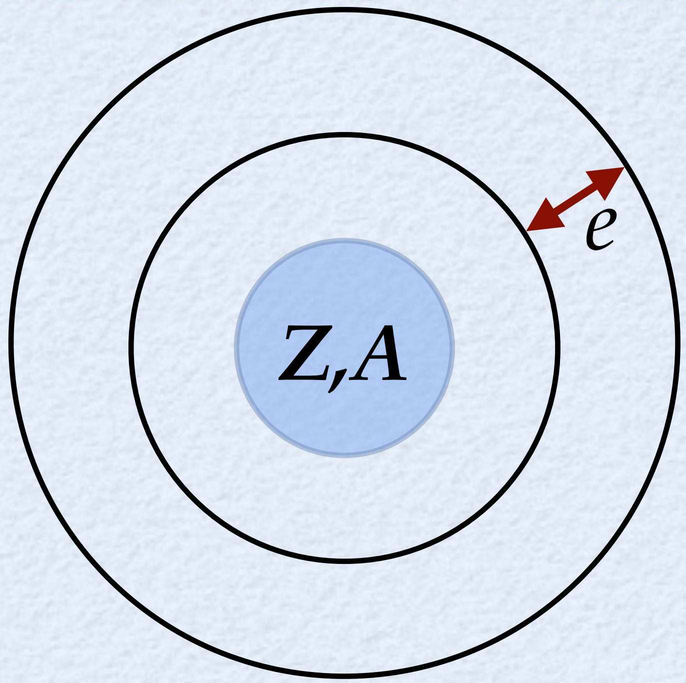
$$\nu_i^{A,A'} = \nu_i^{A} - \nu_i^{A'} = \nu_{i,0}^{A,A'} + F_i \left\langle r^2 \right\rangle_{A,A'}$$

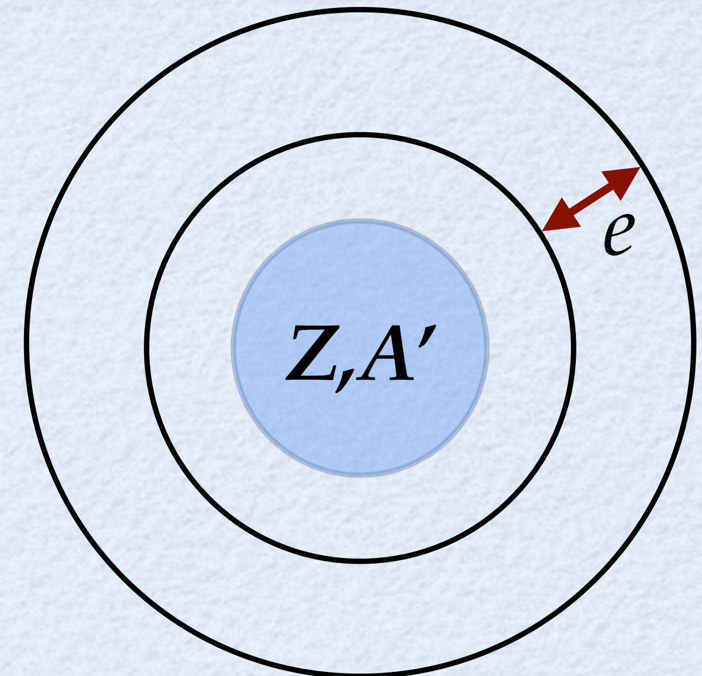
point like　　　finite radius

for theory calculations:
e.g. Pachucki, Patkos, Yerokhin, 1704.06902

Delaunay, Frugiuele, Fuchs, **YS**, PRD 1709.02817

Few electrons systems -isotope shift





standard model | new force

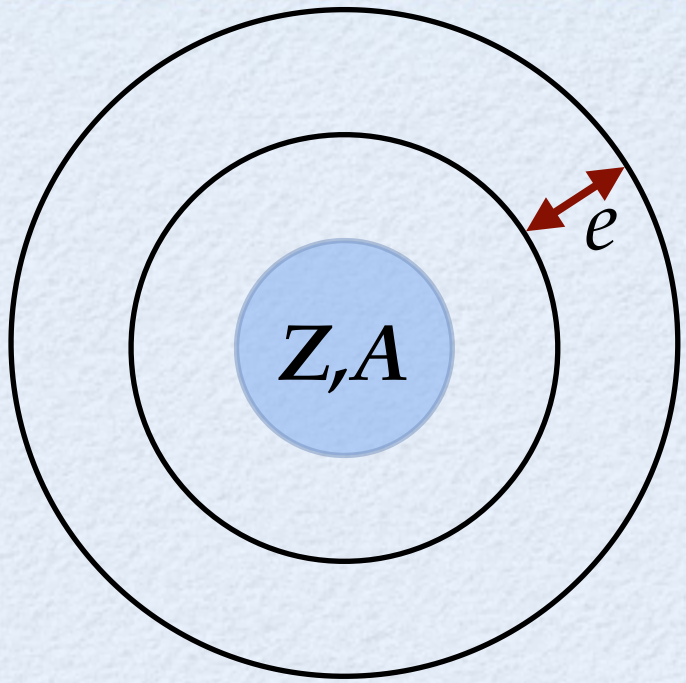
$$\nu_i^{A,A'} = \nu_i^{A} - \nu_i^{A'} = \nu_{i,0}^{A,A'} + F_i \left\langle r^2 \right\rangle_{A,A'} + y_e y_n X_i (A - A')$$

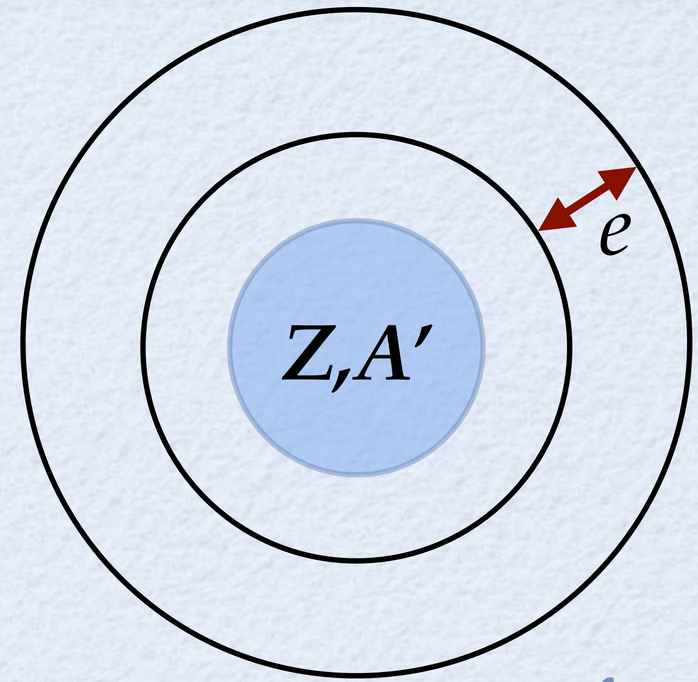
point like | finite radius | *e*-*n* interaction

Delaunay, Frugiuele, Fuchs, **YS**, PRD 1709.02817

for theory calculations:
e.g. Pachucki, Patkos, Yerokhin, 1704.06902

Few electrons systems -isotope shift





standard model — new force

$$\nu_i^{A,A'} = \nu_i^{A} - \nu_i^{A'} = \nu_{i,0}^{A,A'} + F_i \left\langle r^2 \right\rangle_{A,A'} + y_e y_n X_i (A - A')$$

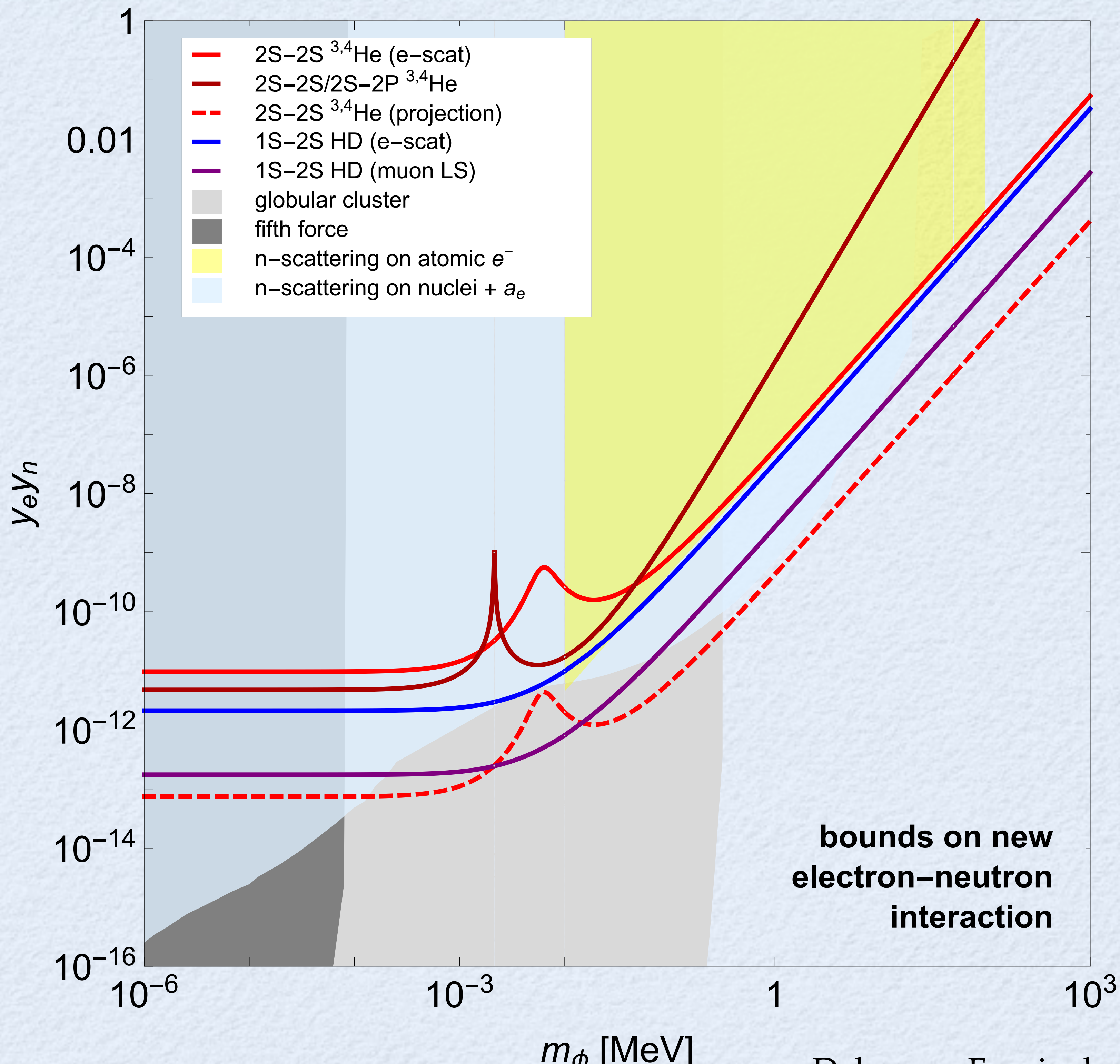
point like — finite radius — *e*-*n* interaction

the charged radius is the dominant error (from *e*-scattering) ⇒ combing **two** transitions ⇒ **no** need for charge radius from scattering

Delaunay, Frugiuele, Fuchs, **YS**, PRD 1709.02817

for theory calculations:
e.g. Pachucki, Patkos, Yerokhin, 1704.06902

Few electrons systems -isotope shift



Delaunay, Frugiuele, Fuchs, **YS**, PRD 1709.02817

heavy elements

Heavy Elements - Isotope Shift

theory error $\gg$ experimental error

$$\nu_i^{AA'} \equiv \nu_i^A - \nu_i^{A'}$$

Heavy elements - isotope shift

theory error $\gg$ experimental error

factorization of **electronic** effects **nucleus** effects

$$\nu_i^{AA'} \equiv \nu_i^{A} - \nu_i^{A'} = K_i \mu_{AA'} + F_i \delta\langle r^2\rangle_{AA'} + \ldots$$

Mass Shift

Field Shift (short distance)

$$\mu_{AA'} \equiv \frac{1}{m_A} - \frac{1}{m_{A'}}$$

King, 63

Heavy elements - isotope shift

theory error $\gg$ experimental error

factorization of **electronic** effects **nucleus** effects

$$\nu_i^{AA'} \equiv \nu_i^A - \nu_i^{A'} = K_i \mu_{AA'} + F_i \delta\langle r^2 \rangle_{AA'} + \ldots$$

Mass Shift

Field Shift (short distance)

$$\mu_{AA'} \equiv \frac{1}{m_A} - \frac{1}{m_{A'}}$$

i=1,2

$$\left(\frac{\nu_2^{AA'}}{\mu_{AA'}}\right) = K_{21} + F_{21}\left(\frac{\nu_1^{AA'}}{\mu_{AA'}}\right)$$

linear relation in the SM

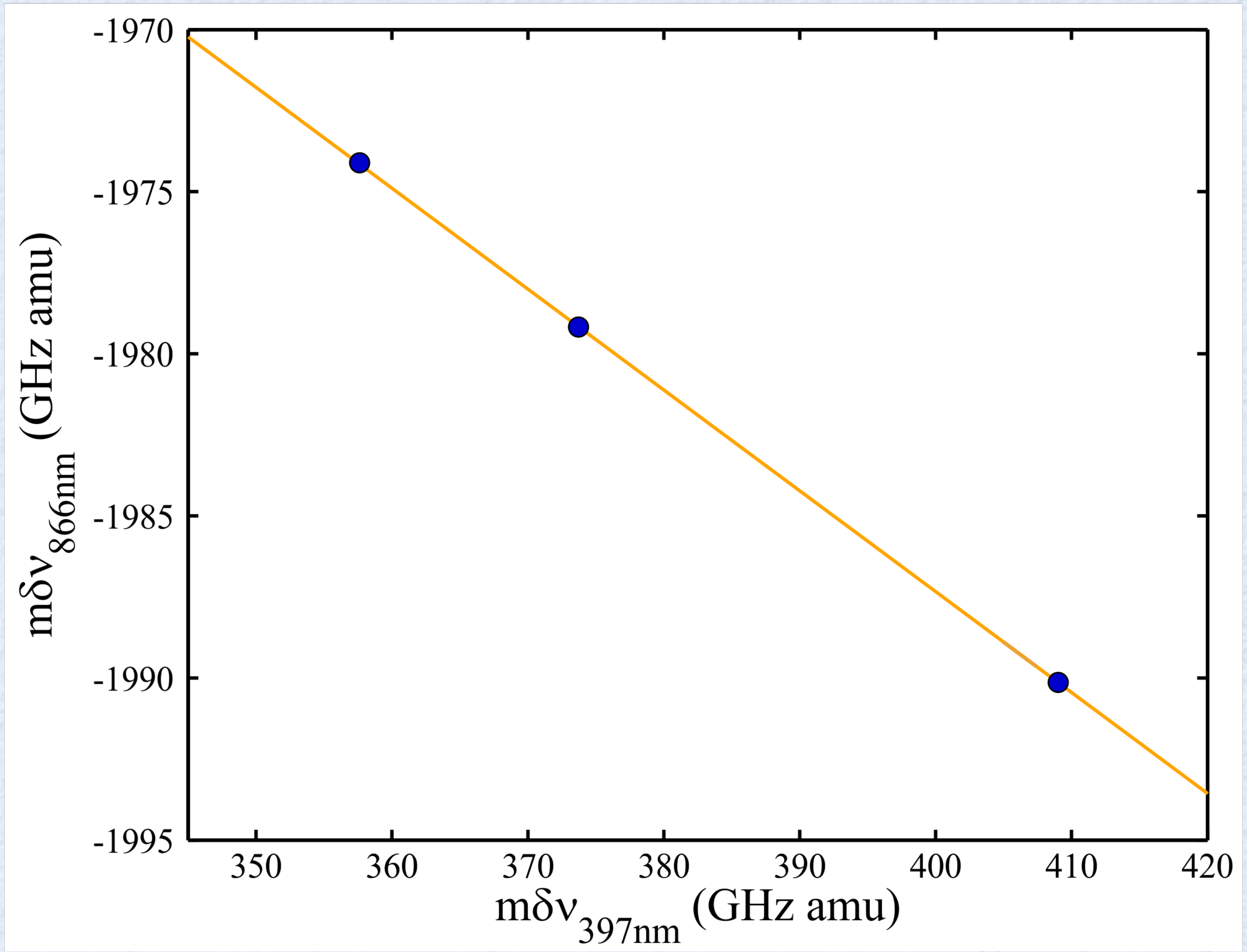
King, 63

$K_{21} \equiv K_2 - F_{21} K_1 \qquad F_{21} \equiv F_2 / F_1$

Heavy elements - isotope shift

isotope shift of Ca^{+}

$4D \rightarrow 4P_{1/2}$



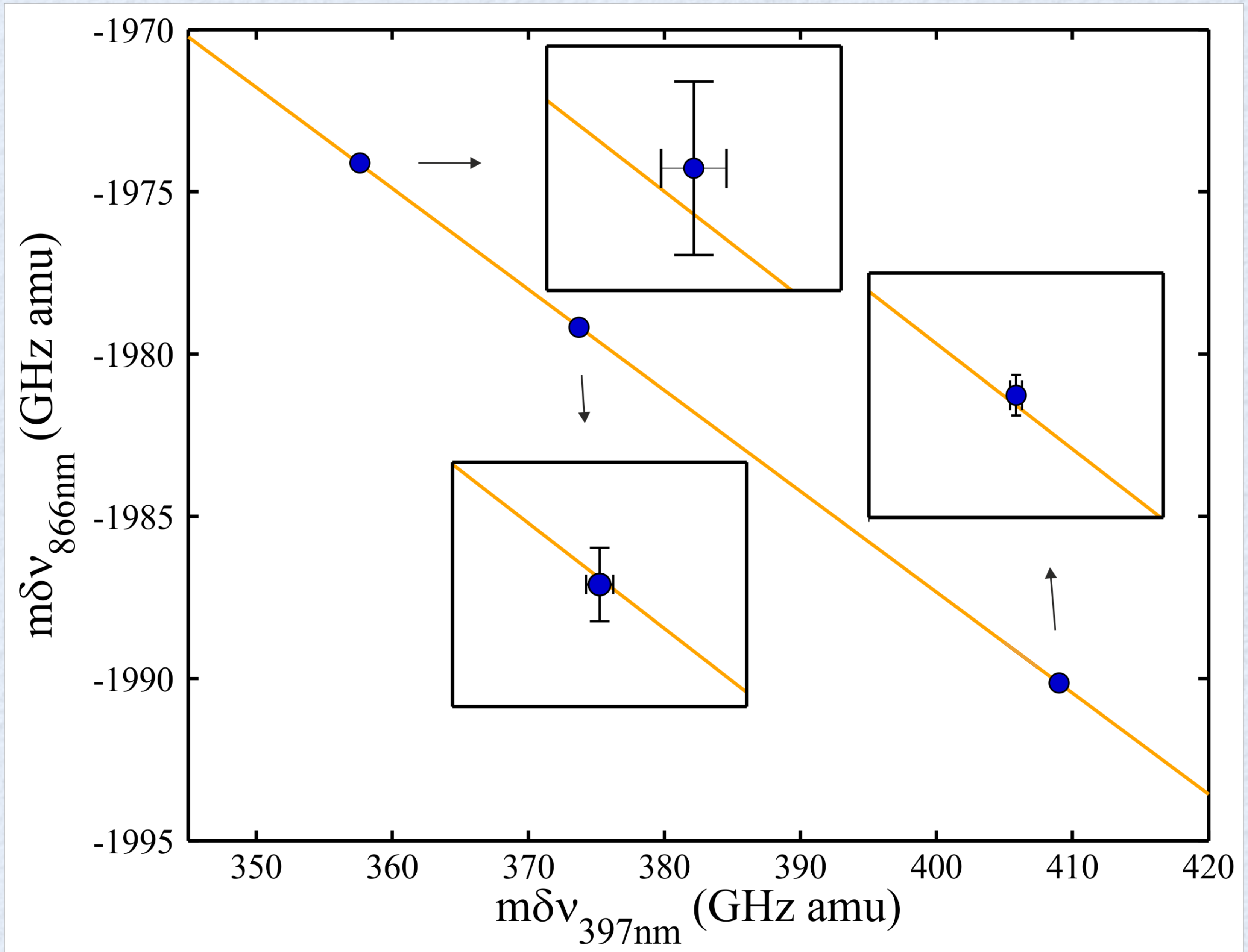
Gebert et al. 2015

$4S \rightarrow 4P_{1/2}$

O(100kHz) error

Heavy elements - isotope shift

isotope shift of Ca^+



Gebert et al. 2015

$4D \to 4P_{1/2}$

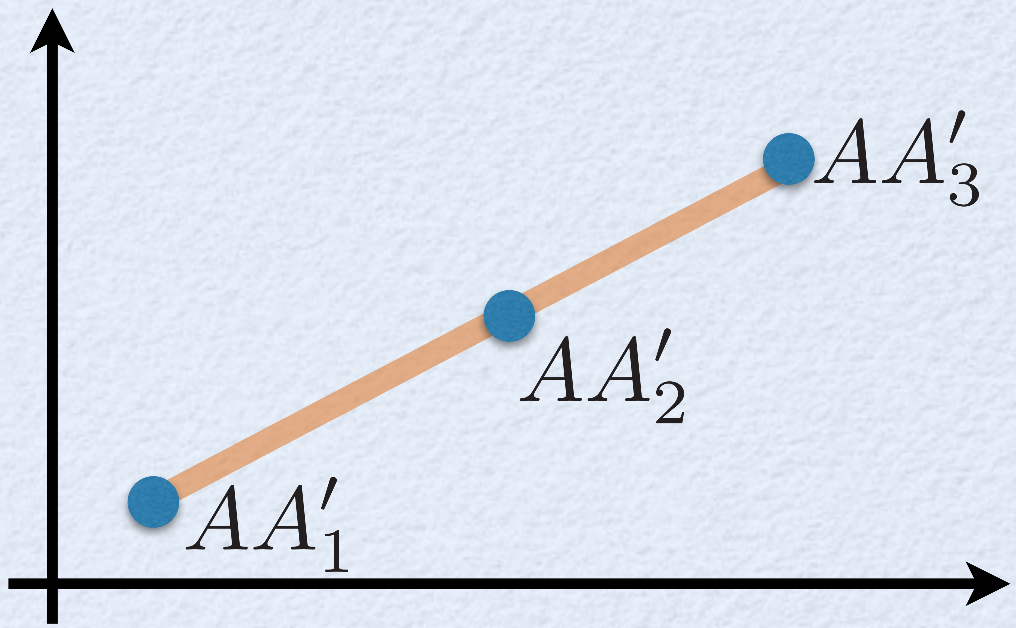
$4S \to 4P_{1/2}$

O(100kHz) error

Heavy Elements - Isotope Shift

$$\nu_i^{AA'} = K_i \mu_{A,A'} + F_i \langle r^2 \rangle_{A,A'} + y_e y_n X_i (A - A')$$

new force
(the *only* theory inputs)



Delaunay, Ozeri, Perez, **YS**, PRD 1601.05087
Berengut, Budker, Delaunay, Flambaum, Frugiuele, Fuchs, Grojean, Harnik, Ozeri, Perez, **YS**, 1704.05068

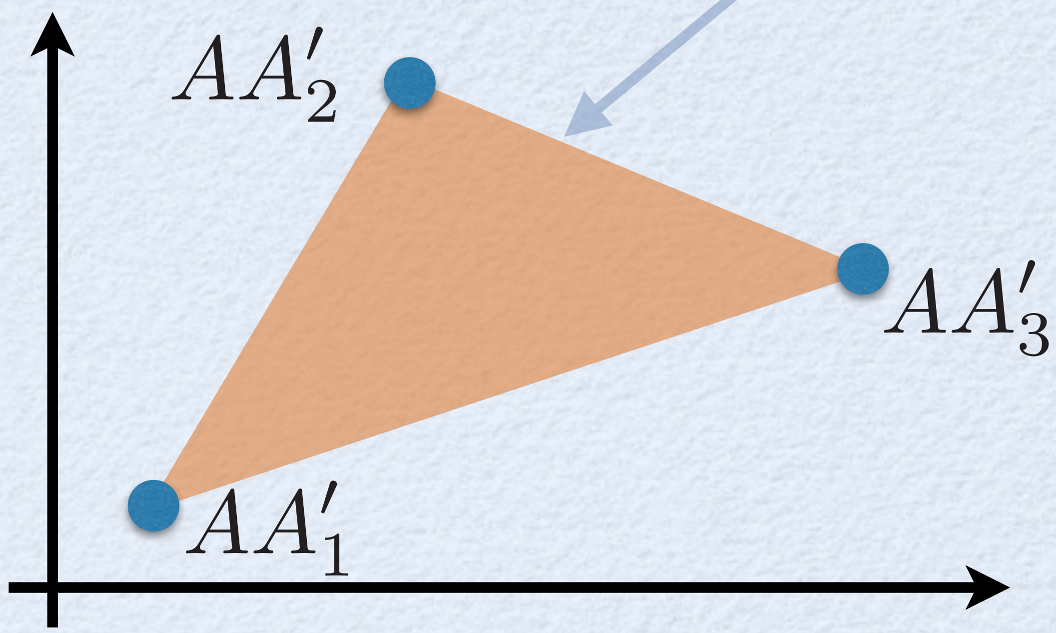
Heavy Elements - Isotope Shift

$$\nu_i^{AA'} = K_i \mu_{A,A'} + F_i \langle r^2 \rangle_{A,A'} + y_e y_n X_i (A - A')$$

new force
(the *only* theory inputs)

- long range new physics
- misalignment between the new physics and the isotope shift

nonlinear King plot from new physics



similar to data driven background estimation at the LHC

Delaunay, Ozeri, Perez, **YS**, PRD 1601.05087
Berengut, Budker, Delaunay, Flambaum, Frugiuele, Fuchs, Grojean, Harnik, Ozeri, Perez, **YS**, 1704.05068

Heavy elements - isotope shift

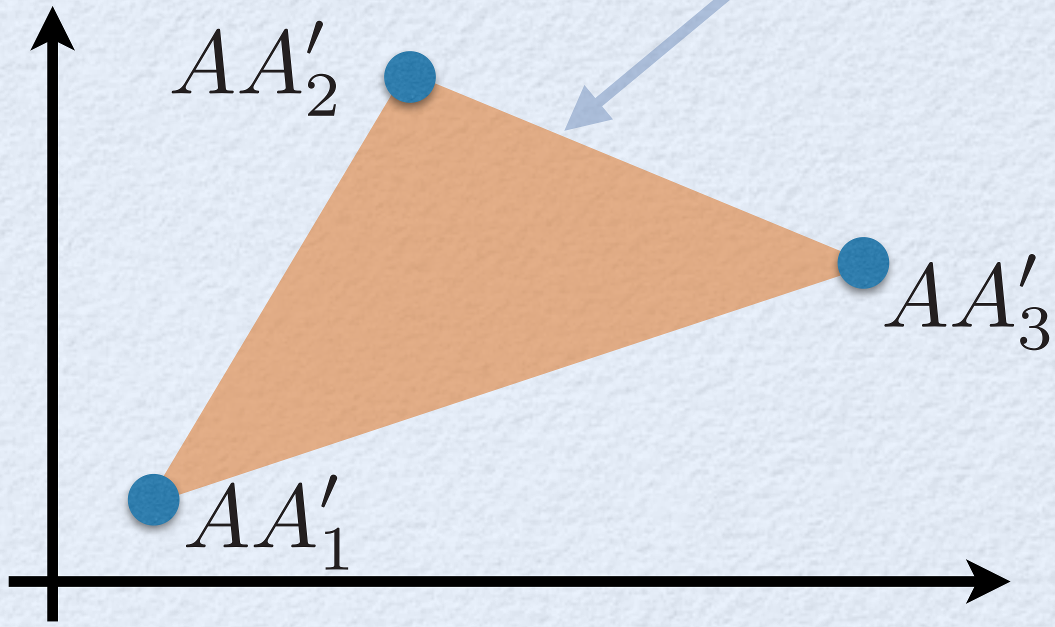
$$\nu_i^{AA'} = K_i \mu_{A,A'} + F_i \langle r^2 \rangle_{A,A'} + y_e y_n X_i (A - A')$$

new force

(the *only* theory inputs)

- long range new physics
- misalignment between the new physics and the isotope shift

nonlinear King plot from new physics



similar to data driven background estimation at the LHC

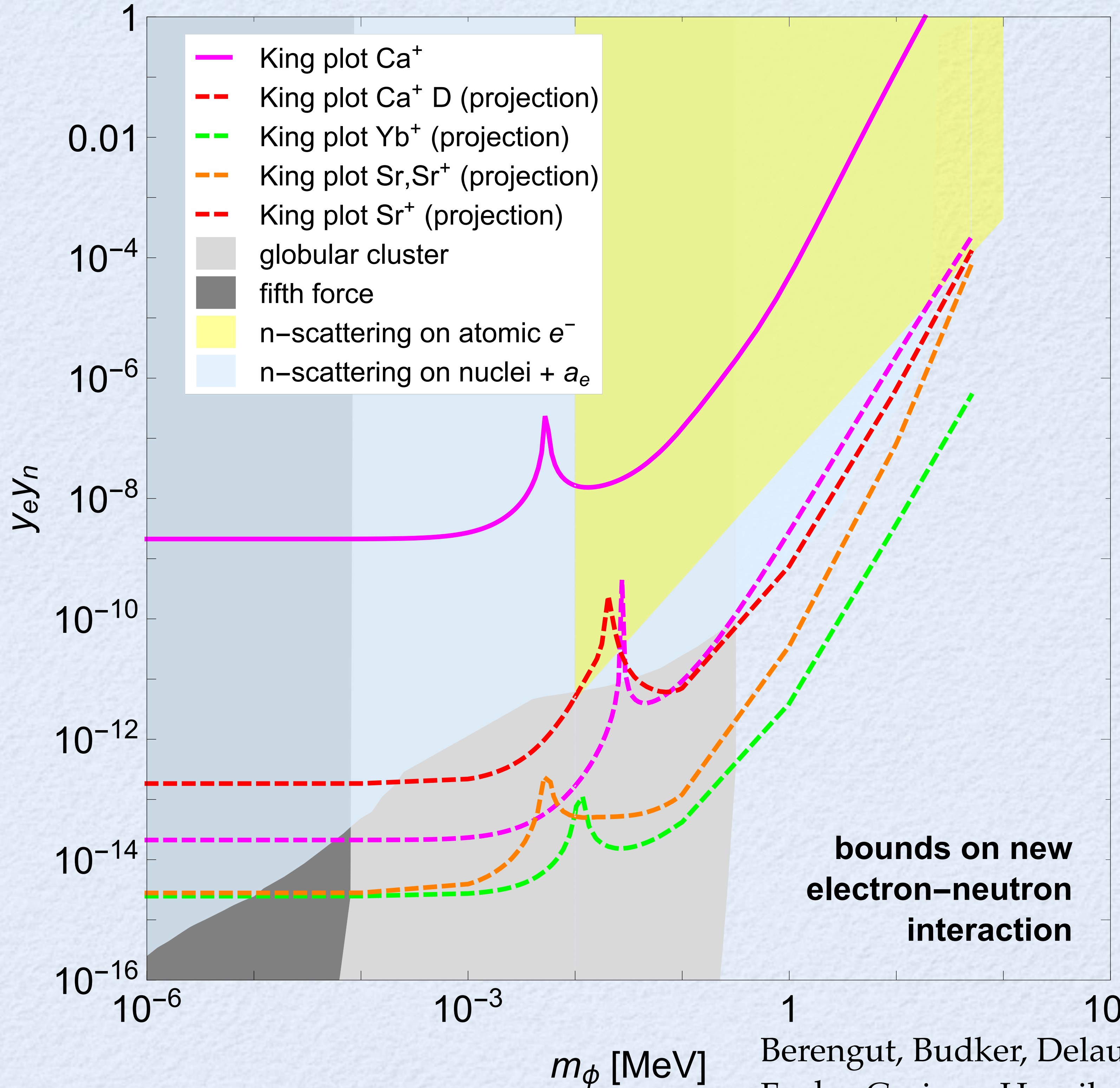
data consistent with linearity → constrain NP

Delaunay, Ozeri, Perez, **YS**, PRD 1601.05087

Berengut, Budker, Delaunay, Flambaum, Frugiuele, Fuchs, Grojean, Harnik, Ozeri, Perez, **YS**, 1704.05068

estimation of SM nonlinearity:
Flambaum, Geddes, Viatkina 1709.00600

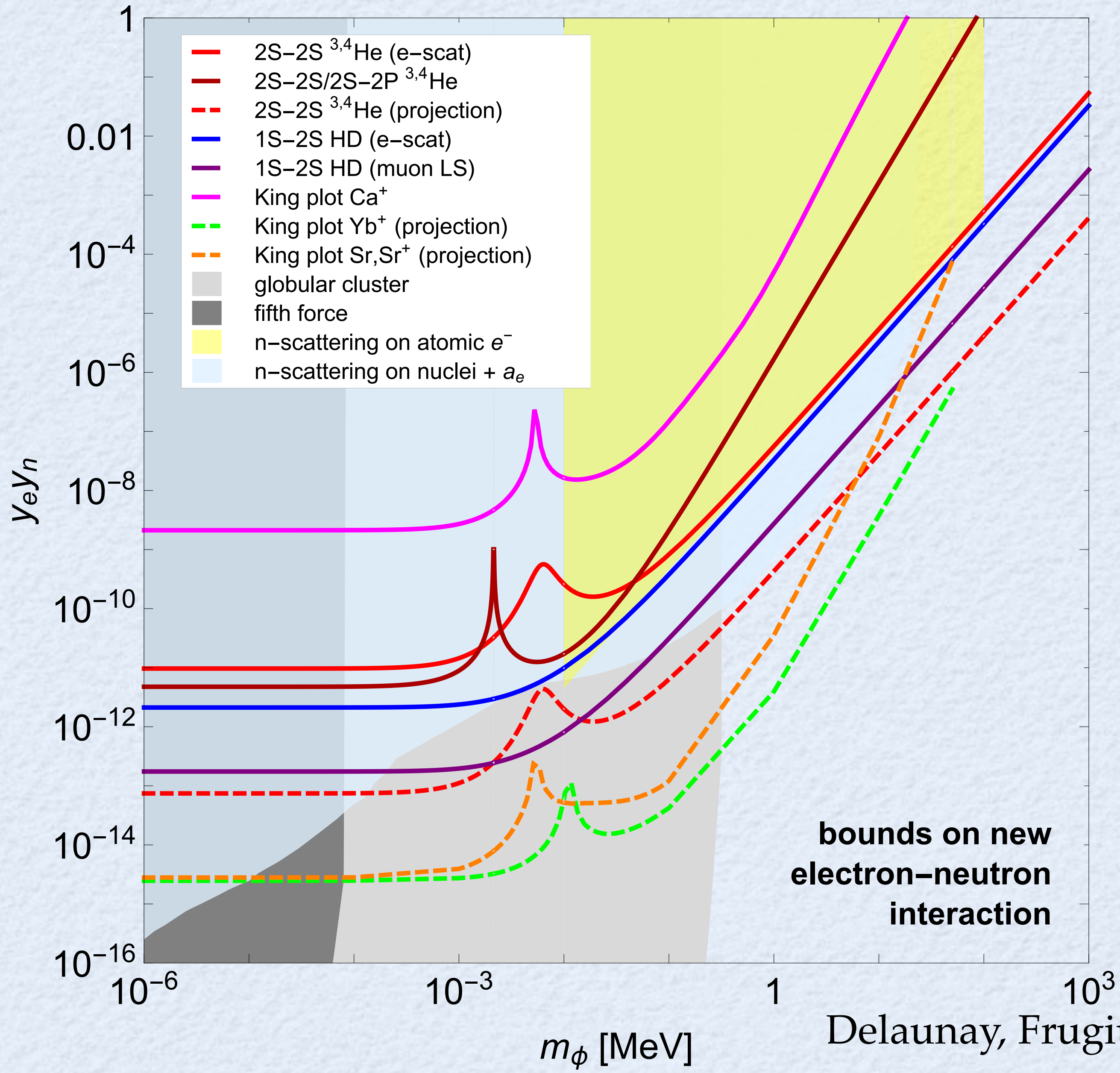
Heavy elements - isotope shift



Berengut, Budker, Delaunay, Flambaum, Frugiuele, Fuchs, Grojean, Harnik, Ozeri, Perez, **YS**, 1704.05068

Isotope shifts: summary

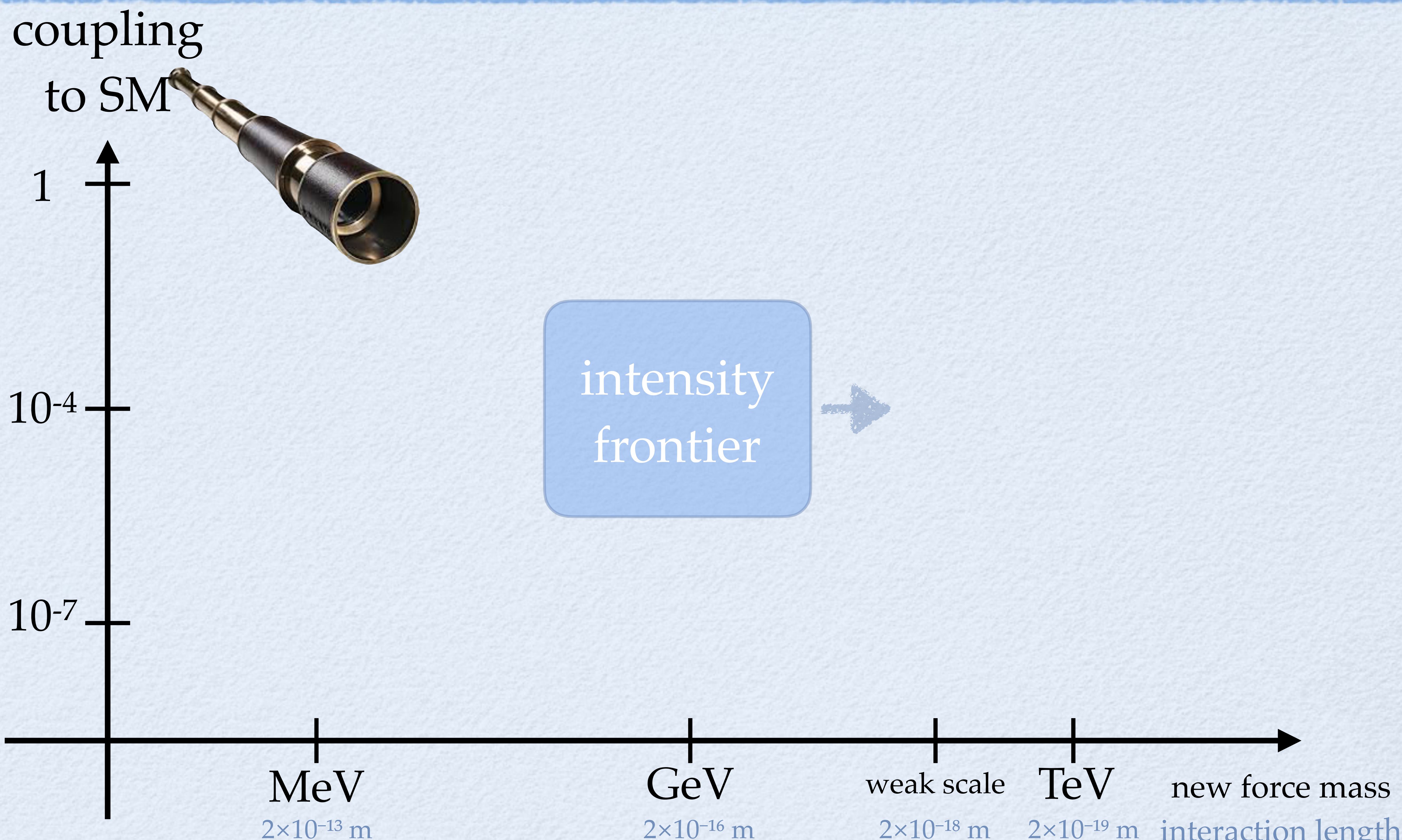
Higgs ⟷ mixing ⟷ light new particles ⇒ new force couples to matter



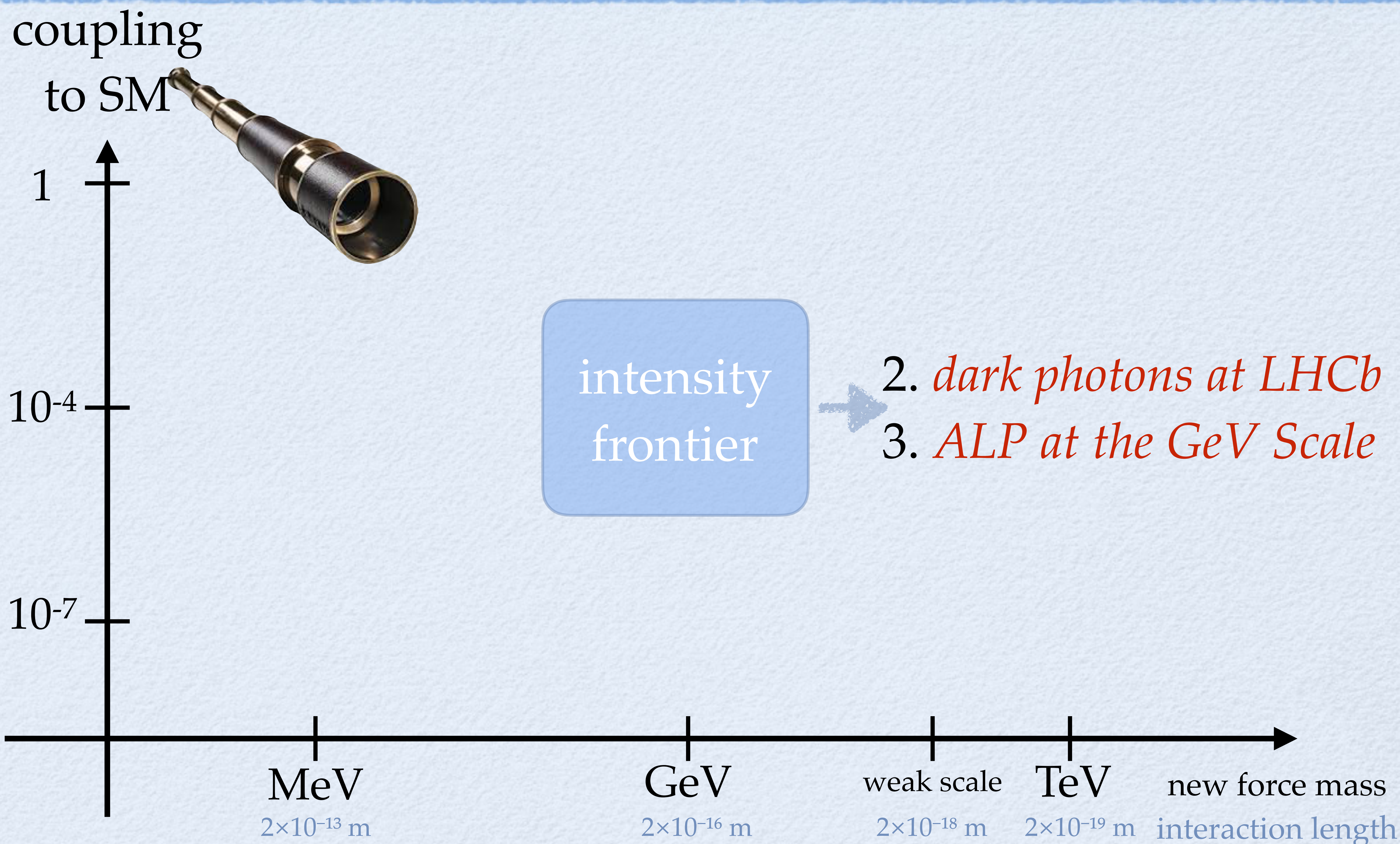
Delaunay, Frugiuele, Fuchs, **YS**, PRD 1709.02817

Berengut, Budker, Delaunay, Flambaum, Frugiuele, Fuchs, Grojean, Harnik, Ozeri, Perez, **YS**, 1704.05068

The Quest for New Physics



The Quest for New Physics



dark matter

standard model ⟷ dark matter

a portal

standard model ⟷ dark matter

↓

a portal

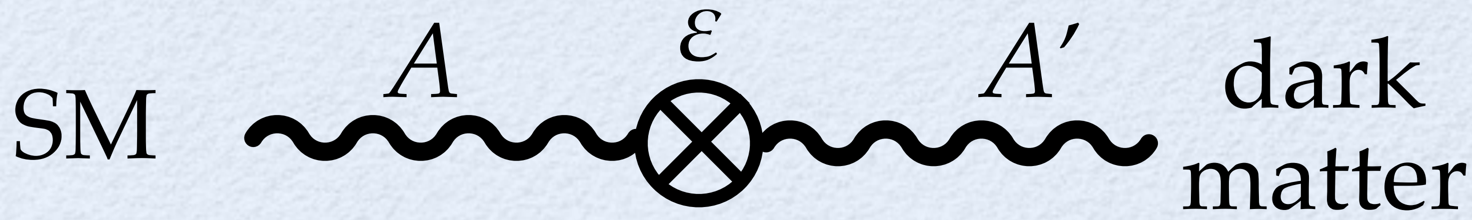
⇩

dark photon - A' / Axion like particles - a

(ALPs)

DARK PHOTON

portal between the standard model and dark matter



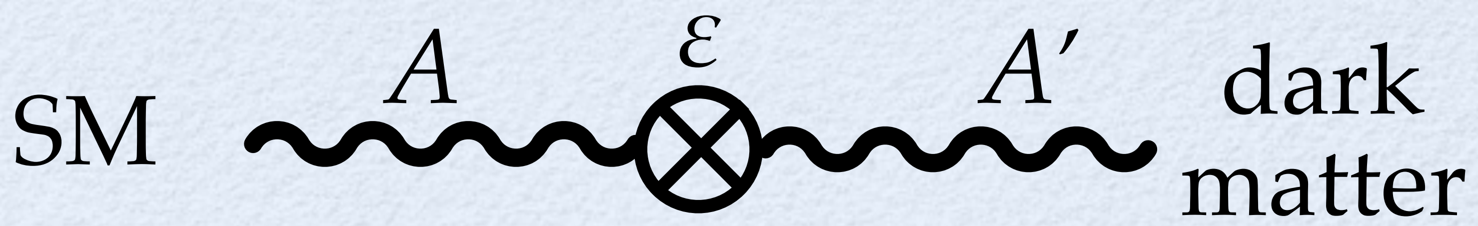
(kinetic mixing)

$m_{A'} \ll m_Z,\ \varepsilon \ll 1$

Holdom, 86′

Dark Photon

portal between the standard model and dark matter

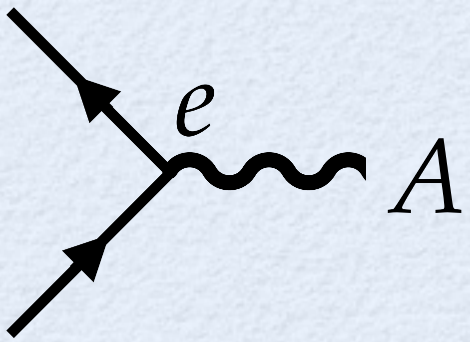


(kinetic mixing)

$m_{A'} \ll m_Z$, $\varepsilon \ll 1$

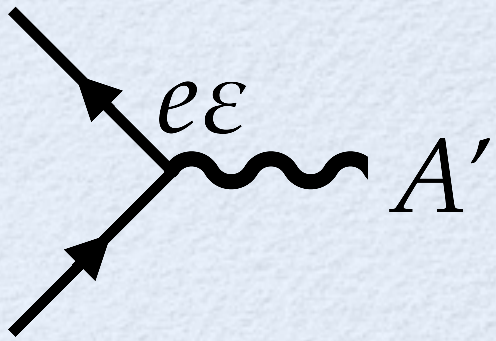
Holdom, 86′

electromagnetic process



$m_A = 0$

dark photon process



+ mass effect

($m_{A'} > 0$)

Dark Photon Signal

differential relation:

$$\frac{d\sigma_{pp\to XA'\to X\mu^+\mu^-}}{d\sigma_{pp\to X\gamma^*\to X\mu^+\mu^-}} = \epsilon^4 \frac{m_{\mu\mu}^4}{(m_{\mu\mu}^2 - m_{A'}^2)^2 + \Gamma_{A'}^2 m_{A'}^2}$$

Bjorken, Essig, Schuster, Toro, 0906.0580

Dark Photon Signal

differential relation:

$$\frac{d\sigma_{pp\to XA'\to X\mu^+\mu^-}}{d\sigma_{pp\to X\gamma^*\to X\mu^+\mu^-}} = \epsilon^4 \frac{m_{\mu\mu}^4}{(m_{\mu\mu}^2 - m_{A'}^2)^2 + \Gamma_{A'}^2 m_{A'}^2}$$

per mass bin:

$$\frac{S}{B_{\rm EM}} \approx \epsilon^4 \frac{\pi}{8} \frac{m_{A'}^2}{\Gamma_{A'}\sigma_{m_{\mu\mu}}} \approx \frac{3\pi}{8} \frac{m_{A'}}{\sigma_{m_{\mu\mu}}} \frac{\epsilon^2}{\alpha_{\rm EM}(N_\ell + \mathcal{R}_\mu)}$$

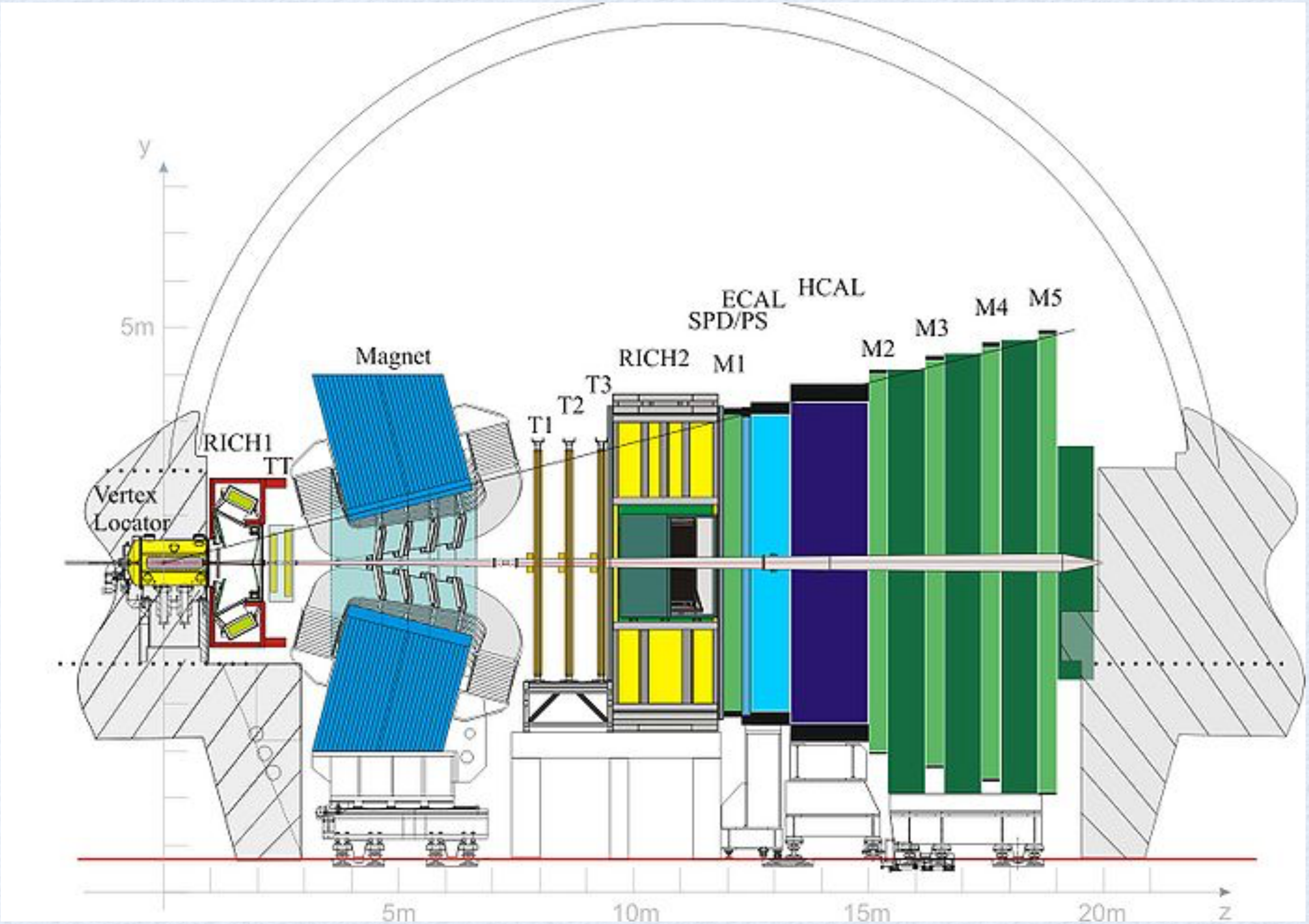
$$\frac{\Gamma_{A'}}{m_{A'}} \approx \frac{\epsilon^2 \alpha_{\rm EM}}{3} (N_\ell + \mathcal{R}_\mu)$$

number of leptons with mass below $m_{A'}/2$

$$\frac{\sigma_{e^+e^-\to \rm hadrons}}{\sigma_{e^+e^-\to\mu^+\mu^-}}$$

Bjorken, Essig, Schuster, Toro, 0906.0580

DARK PHOTON AT LHCB

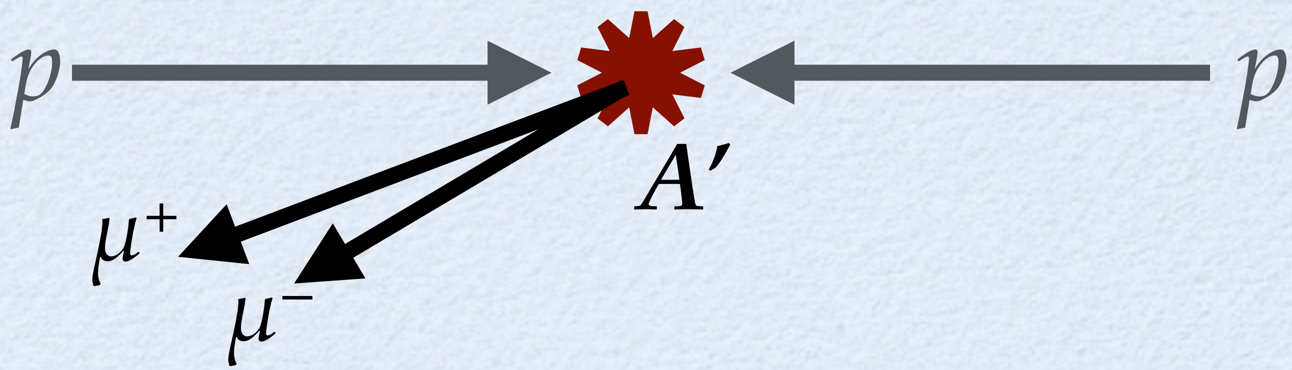


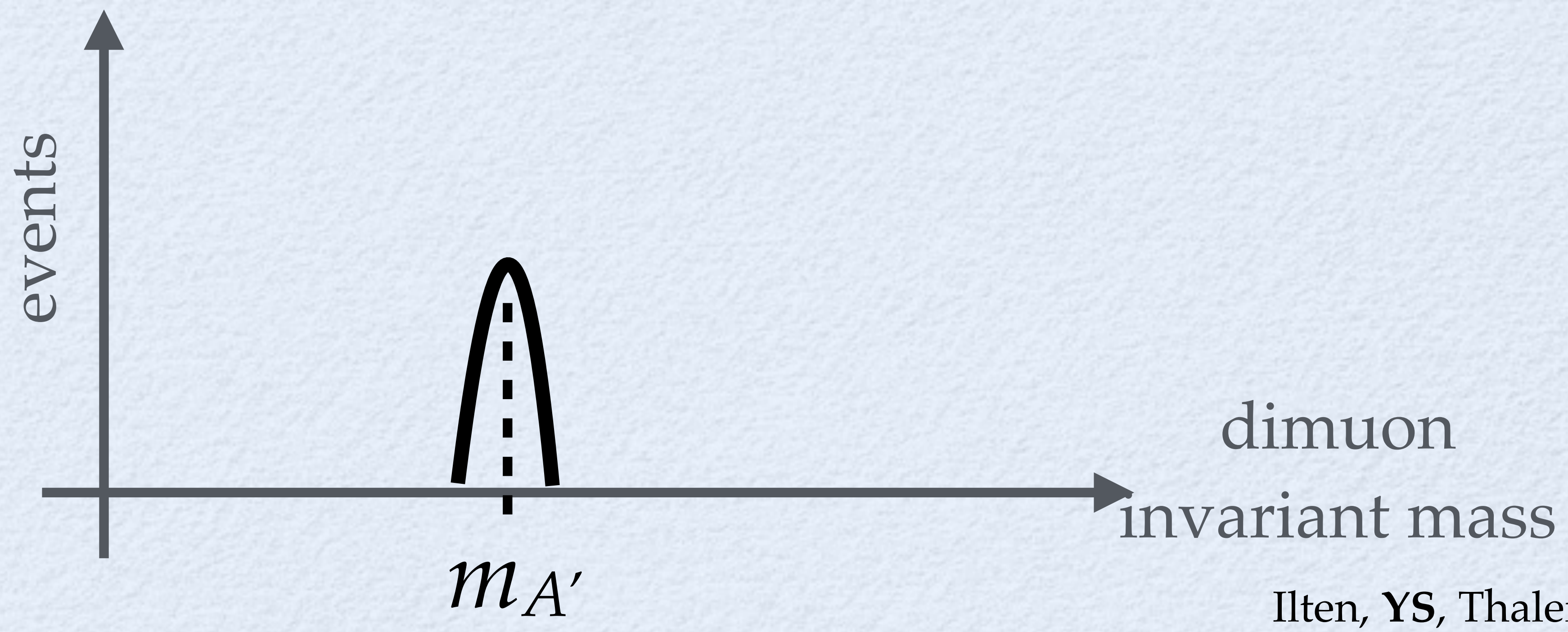
Signal and backgrounds

prompt

short lifetime

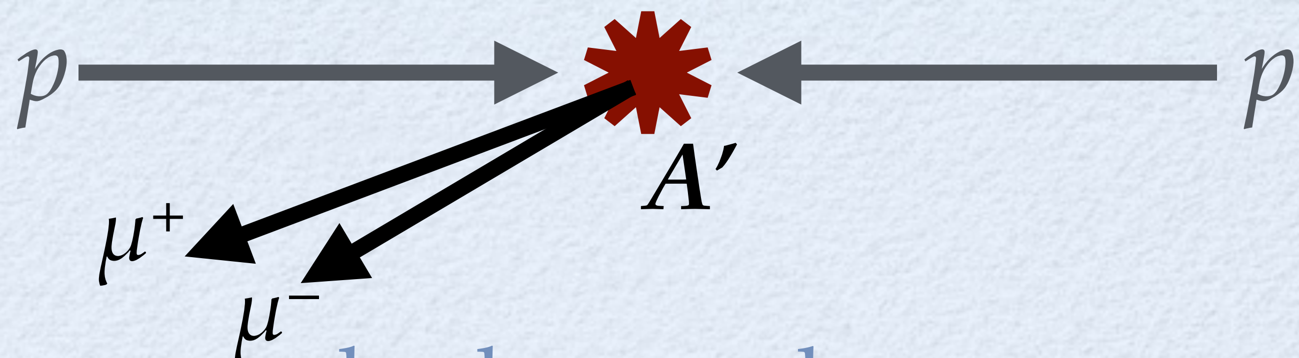
larger ε





Ilten, **YS**, Thaler, Williams, Xue, PRL 1603.08926

Signal and Backgrounds



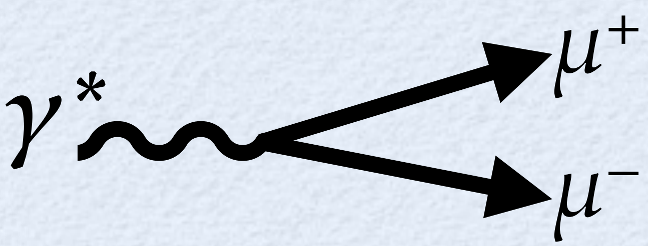
prompt

short lifetime

larger ε

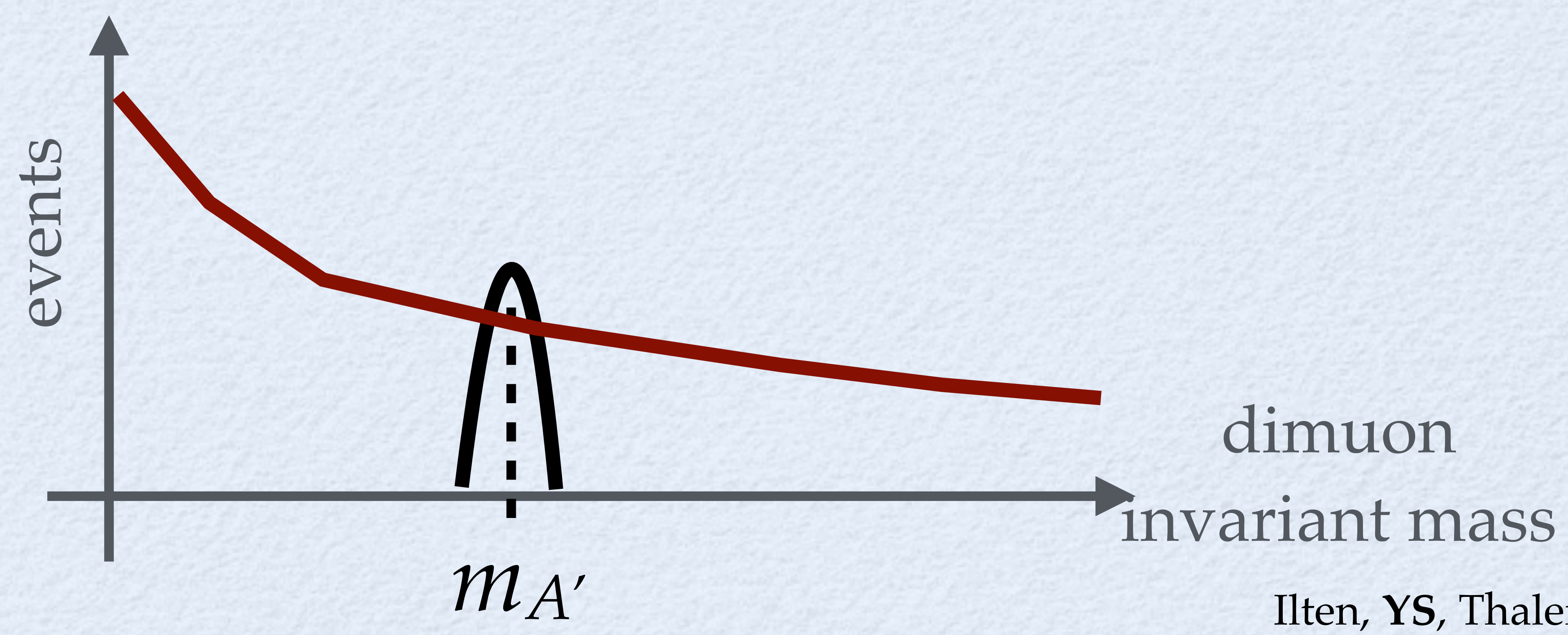
"good" backgrounds

$S_{A'} \propto B_{\text{EM}}$



meson decays

Drell-Yan



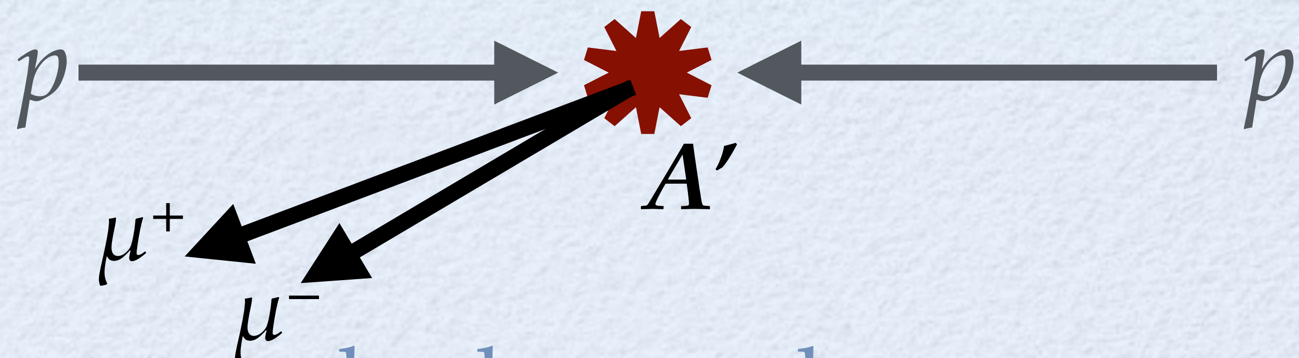
Ilten, **YS**, Thaler, Williams, Xue, PRL 1603.08926

Signal and backgrounds

prompt

short lifetime

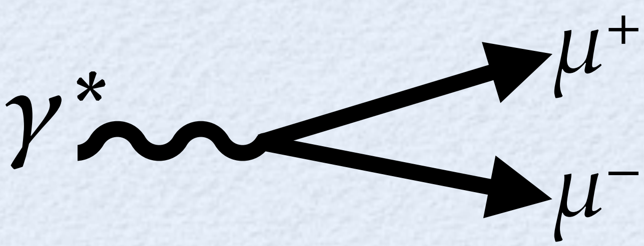
larger ε



backgrounds

"good" | "bad"

$S_{A'} \propto B_{\mathrm{EM}}$ | $S_{A'} \not\propto B_{\mathrm{EM}}$

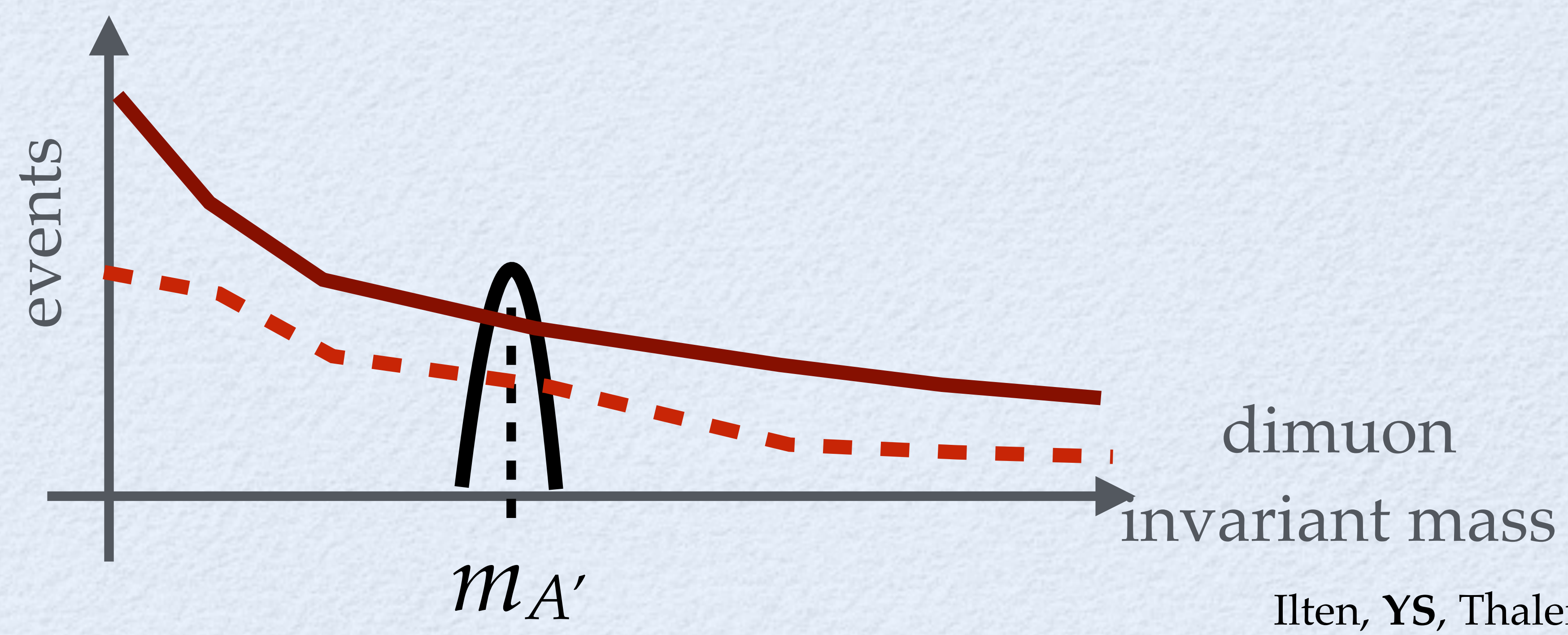


meson decays

Drell-Yan

misidentified hadrons

(pions, kaons)



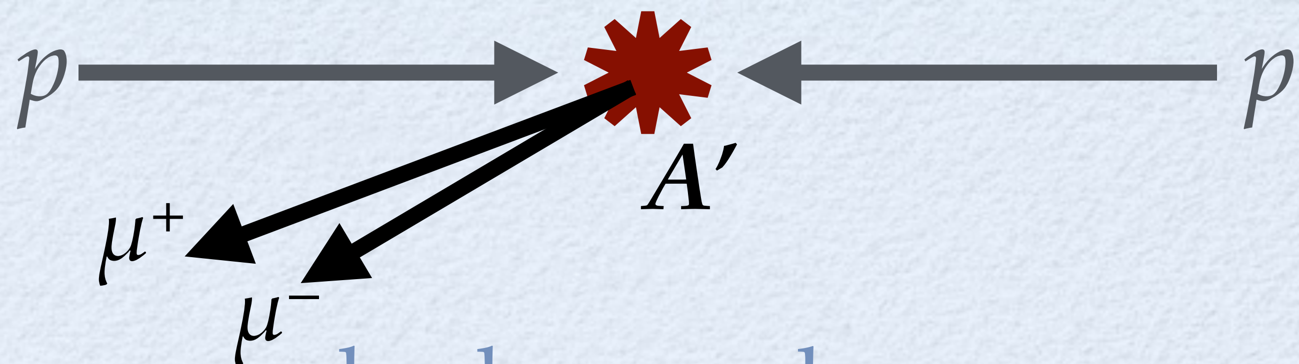
Ilten, **YS**, Thaler, Williams, Xue,
PRL 1603.08926

Signal and Backgrounds

prompt

short lifetime

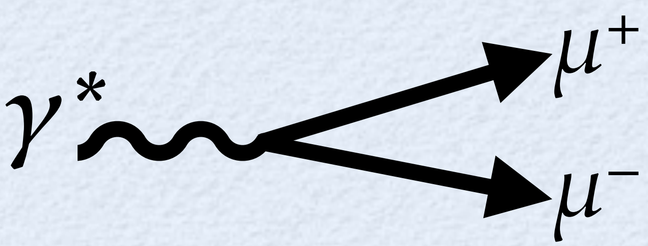
larger ε



backgrounds

"good"

$S_{A'} \propto B_{\mathrm{EM}}$



meson decays

Drell-Yan

"bad"

$S_{A'} \not\propto B_{\mathrm{EM}}$

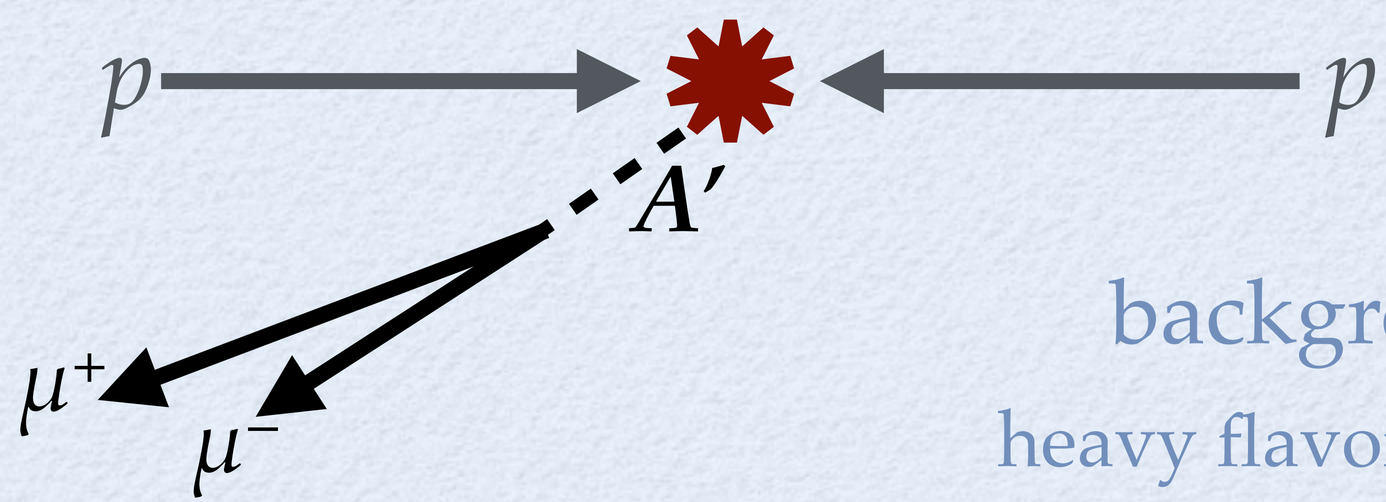
misidentified hadrons

(pions, kaons)

displaced

long lifetime

smaller ε



backgrounds

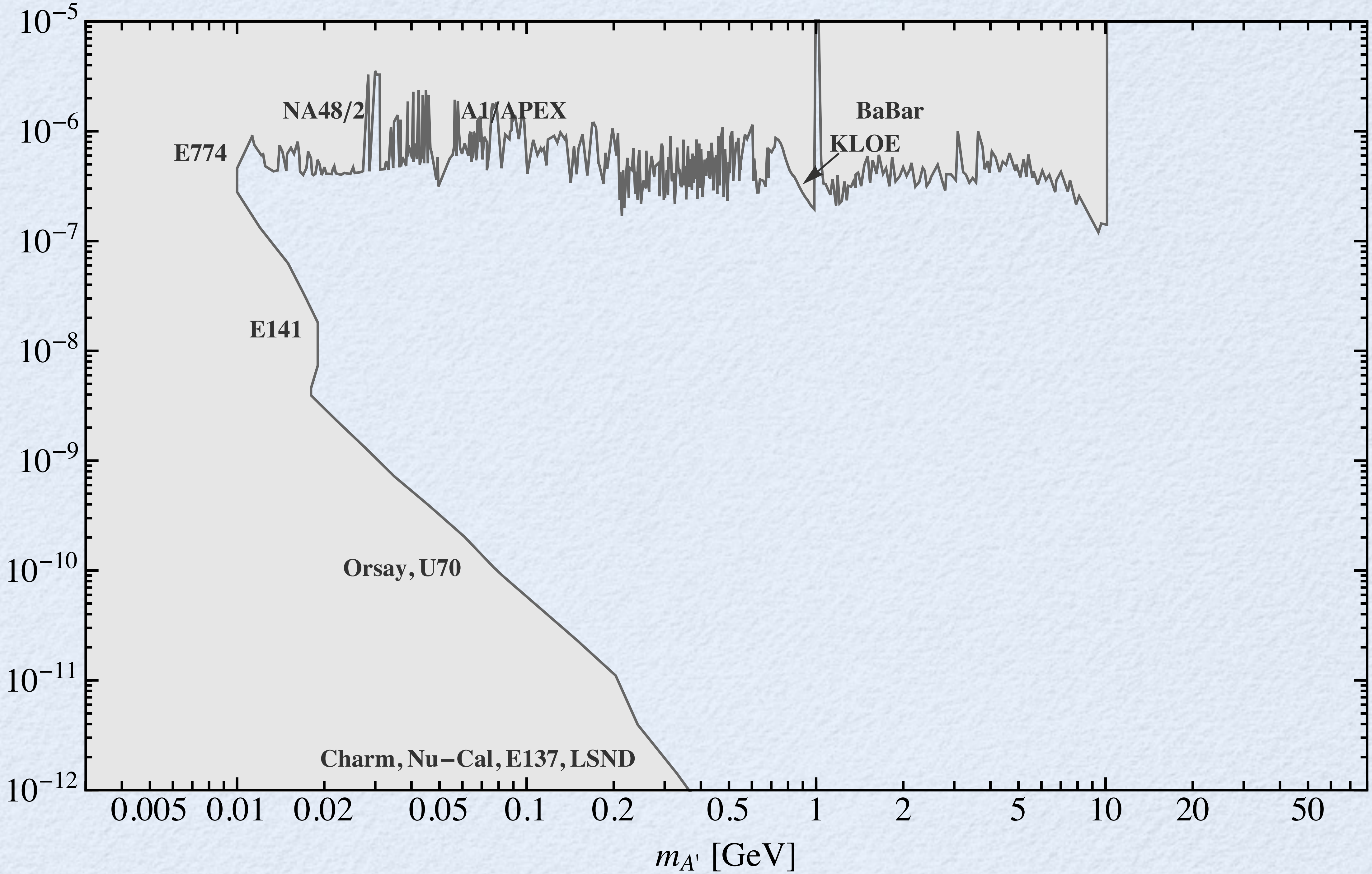
heavy flavor (*b*,*c*) decays

Ilten, **YS**, Thaler, Williams, Xue,
PRL 1603.08926

BOUNDS ON A'

short
lifetime

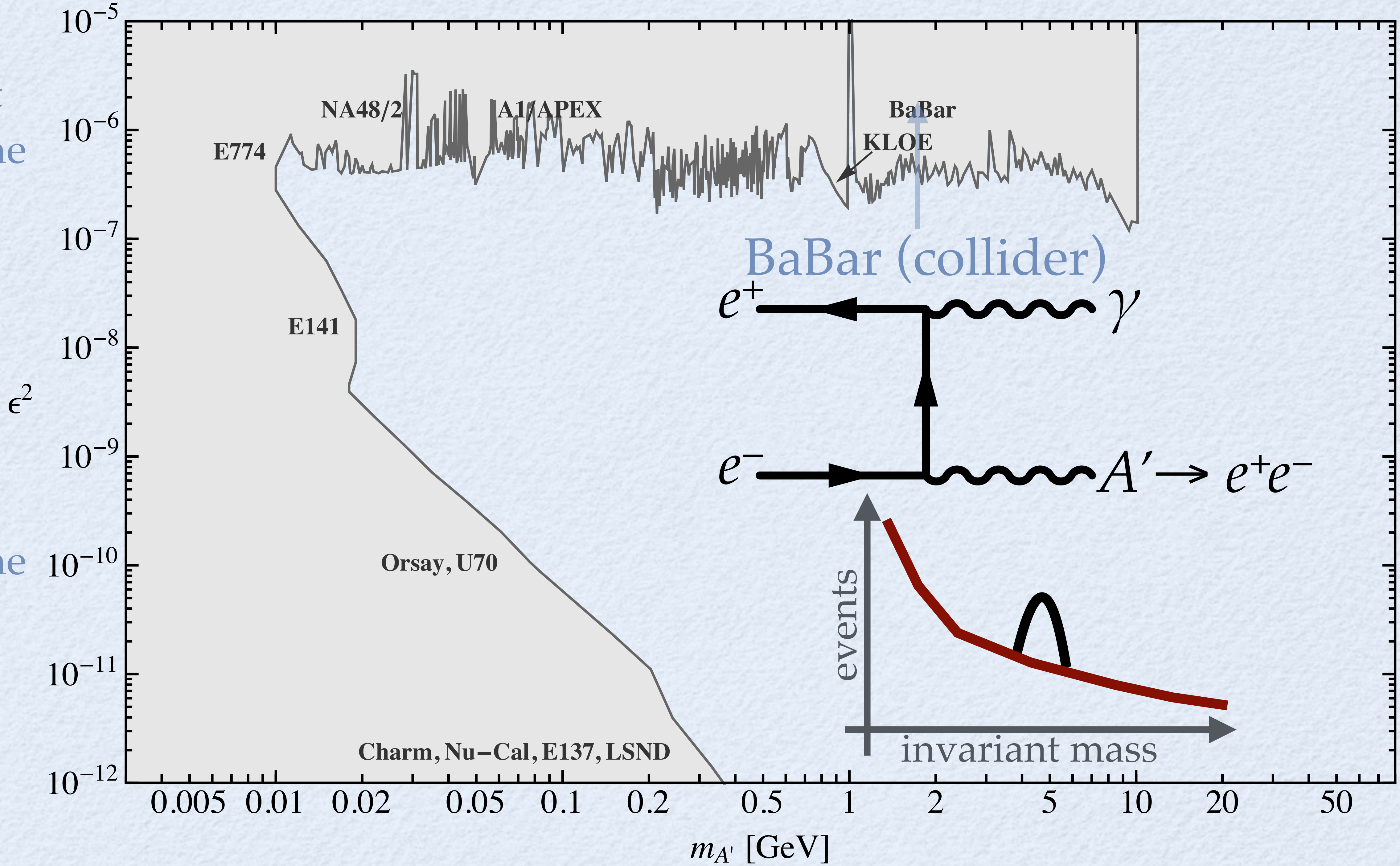
long
lifetime



BOUNDS ON A′

short lifetime

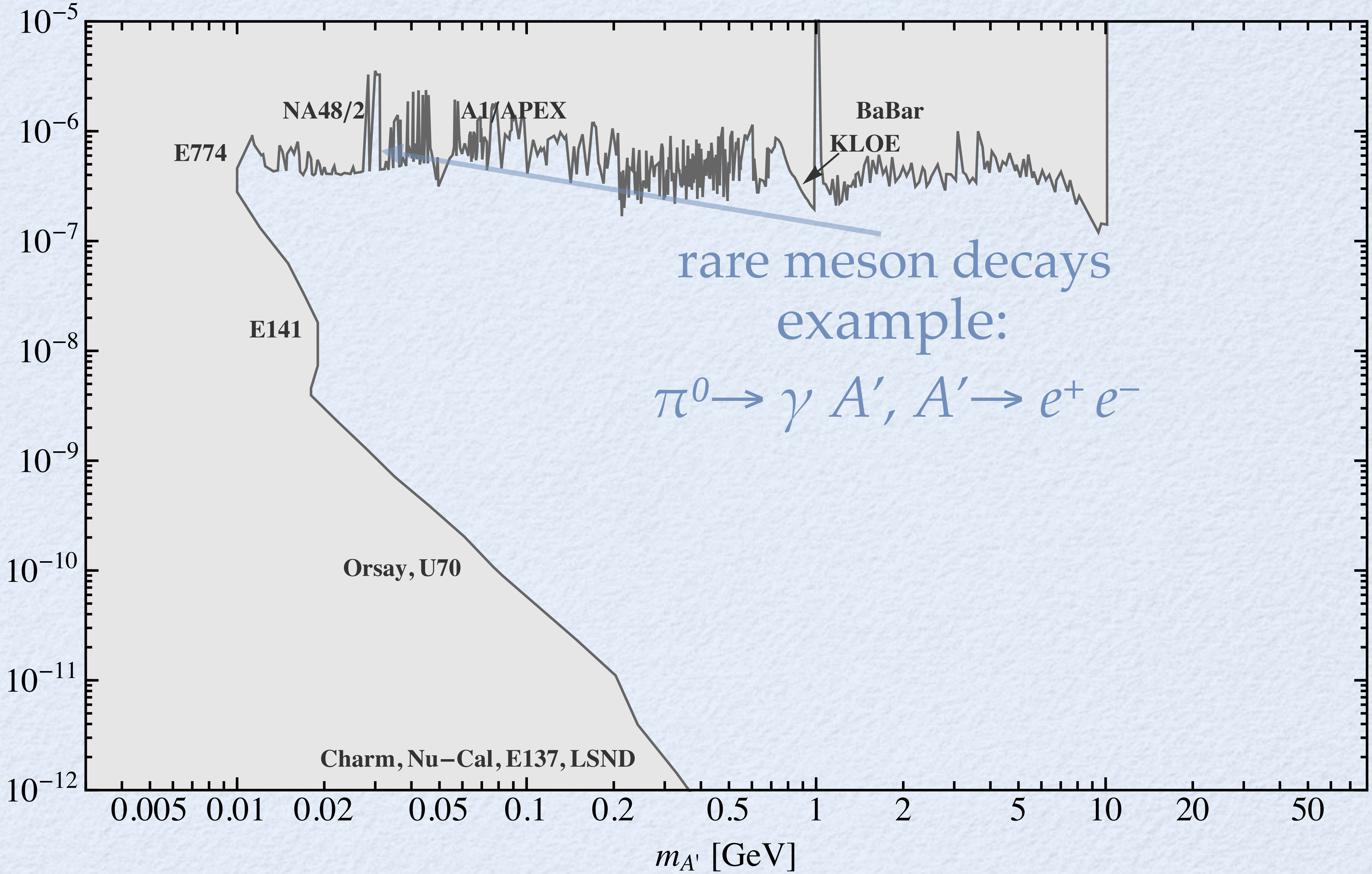
long lifetime



BOUNDS ON A'

short lifetime

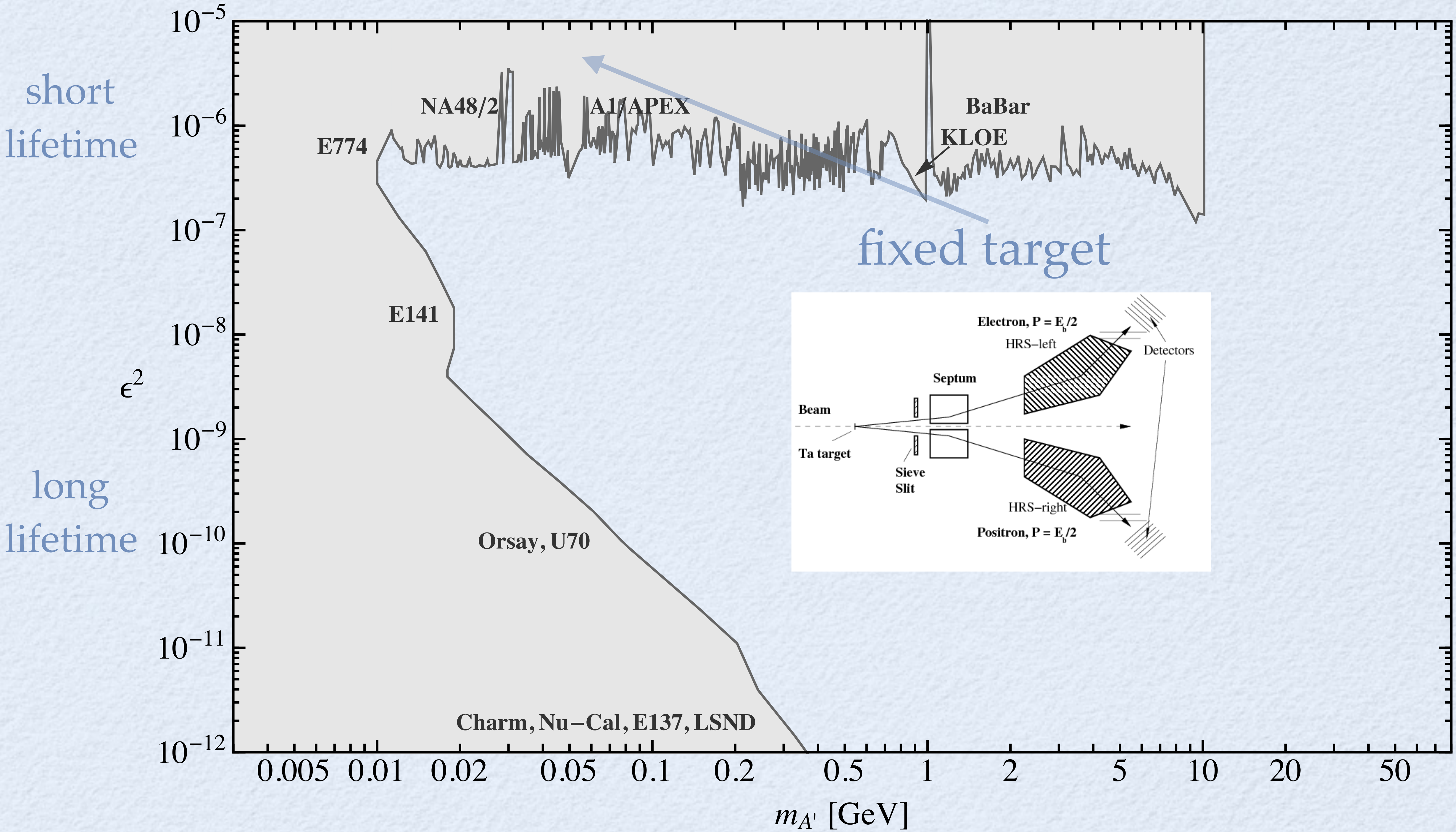
long lifetime



rare meson decays example:

$\pi^0 \to \gamma\, A'$, $A' \to e^+ e^-$

Bounds on A'



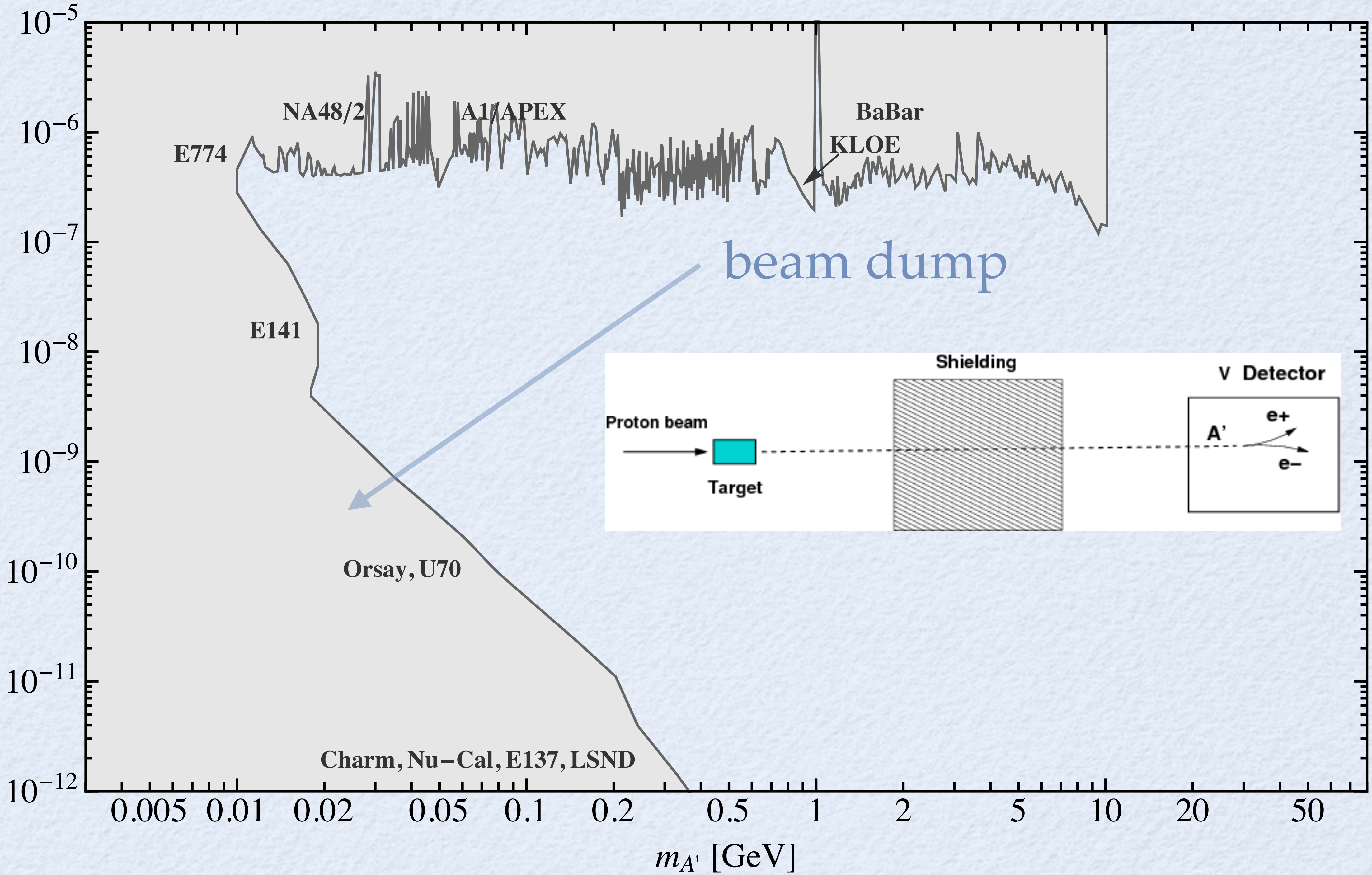
short lifetime
long lifetime
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
ϵ^2
NA48/2
A1/APEX
BaBar
KLOE
E774
E141
Orsay, U70
Charm, Nu−Cal, E137, LSND
fixed target
0.005 0.01 0.02 0.05 0.1 0.2 0.5 1 2 5 10 20 50
$m_{A'}$ [GeV]
Electron, P = $E_b/2$
HRS−left
Detectors
Septum
Beam
Ta target
Sieve
Slit
HRS−right
Positron, P = $E_b/2$

Bounds on A'

short lifetime

long lifetime

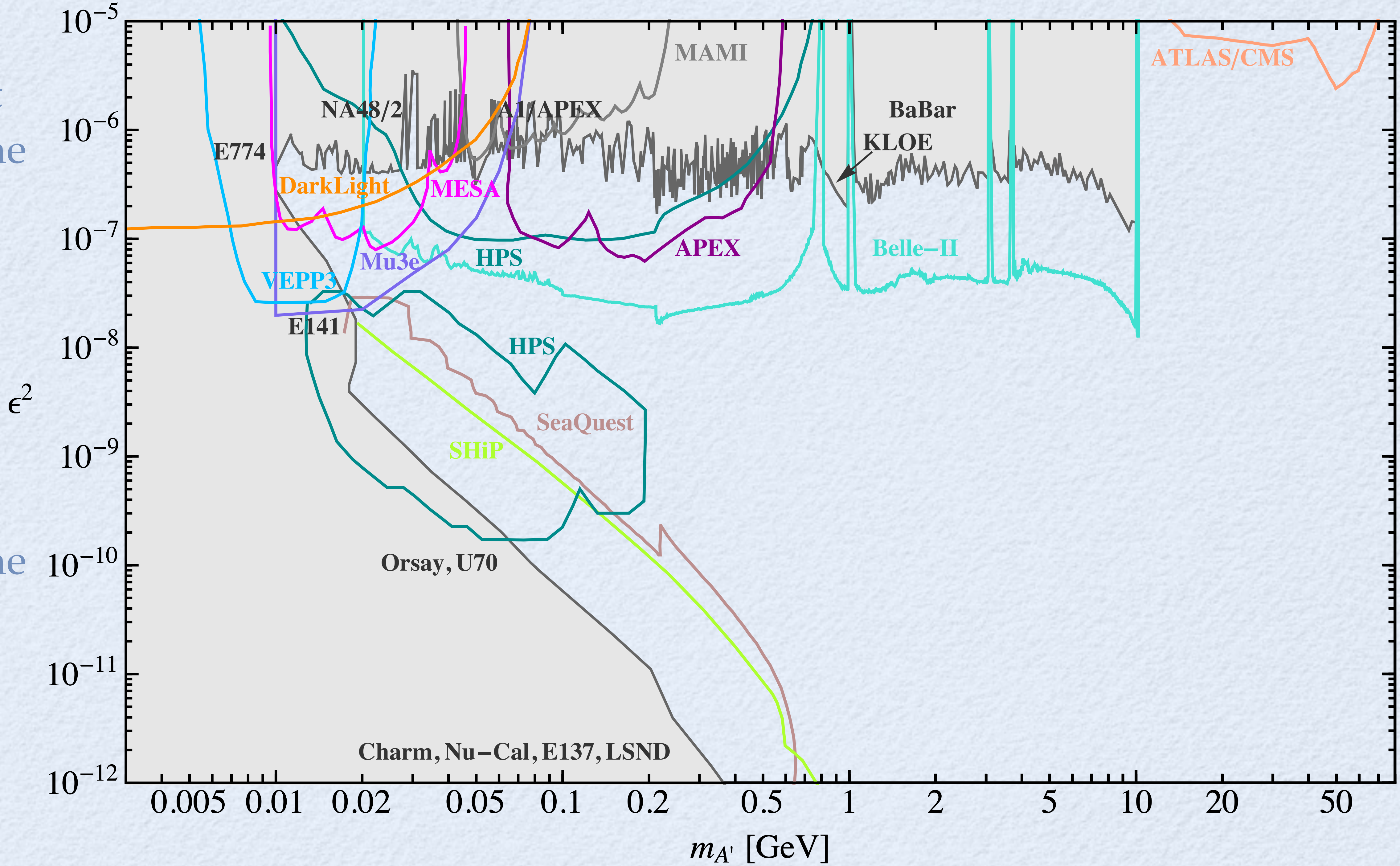
beam dump



BOUNDS ON A'

short lifetime

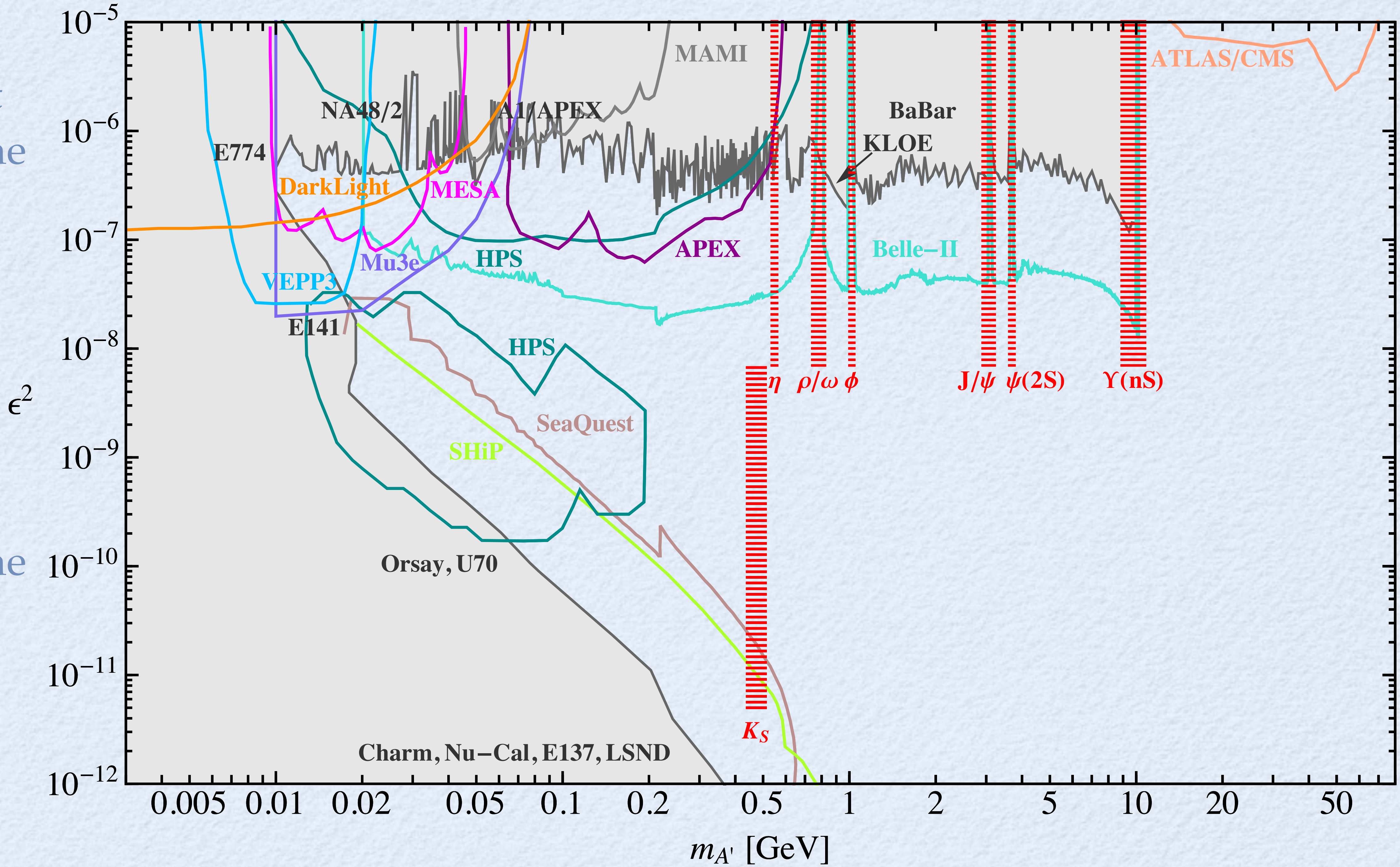
long lifetime



LHCb Dark Photon Reach

short lifetime

long lifetime

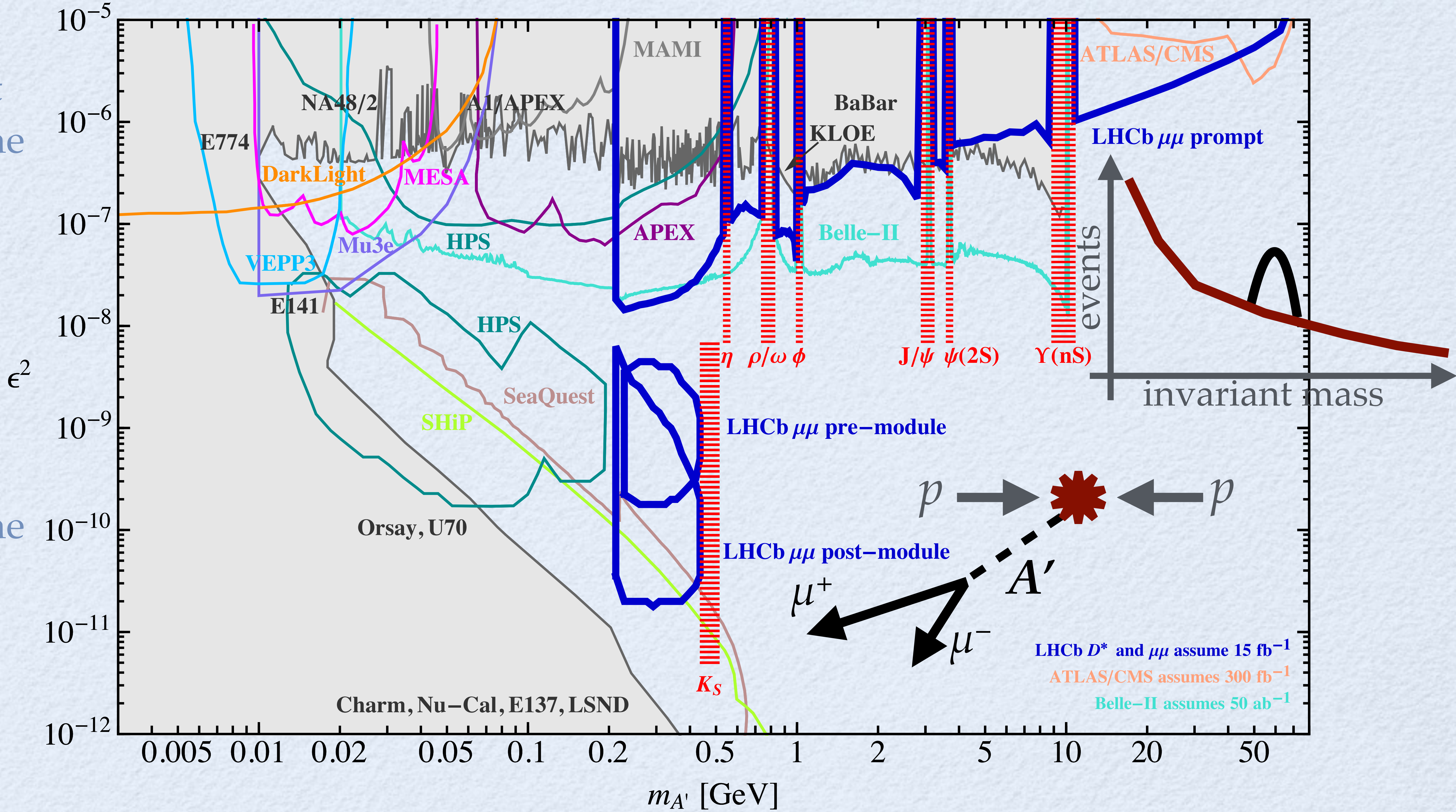


Ilten, **YS**, Thaler, Williams, Xue, PRL 1603.08926

LHCb Dark Photon Reach

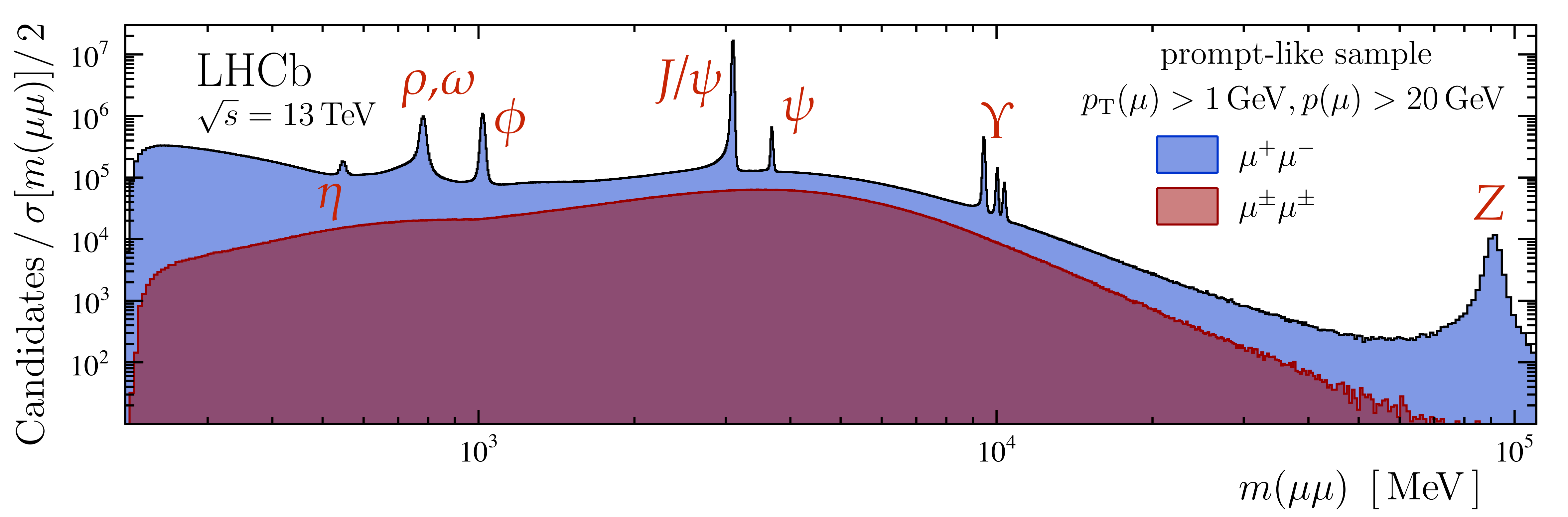
short lifetime

long lifetime



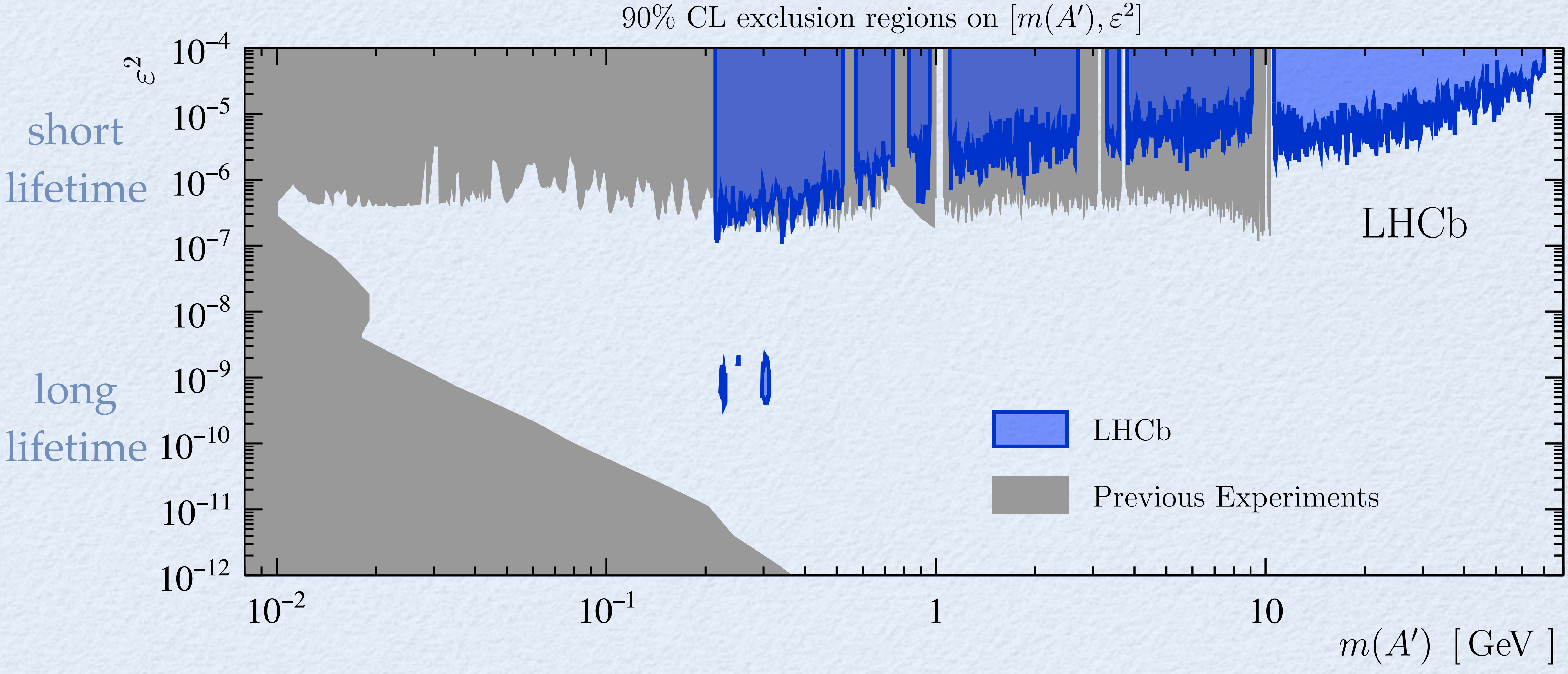
Ilten, **YS**, Thaler, Williams, Xue, PRL 1603.08926

LHCb Result with 2016 Data



LHCb, 1710.02867

LHCb Result with 2016 Data

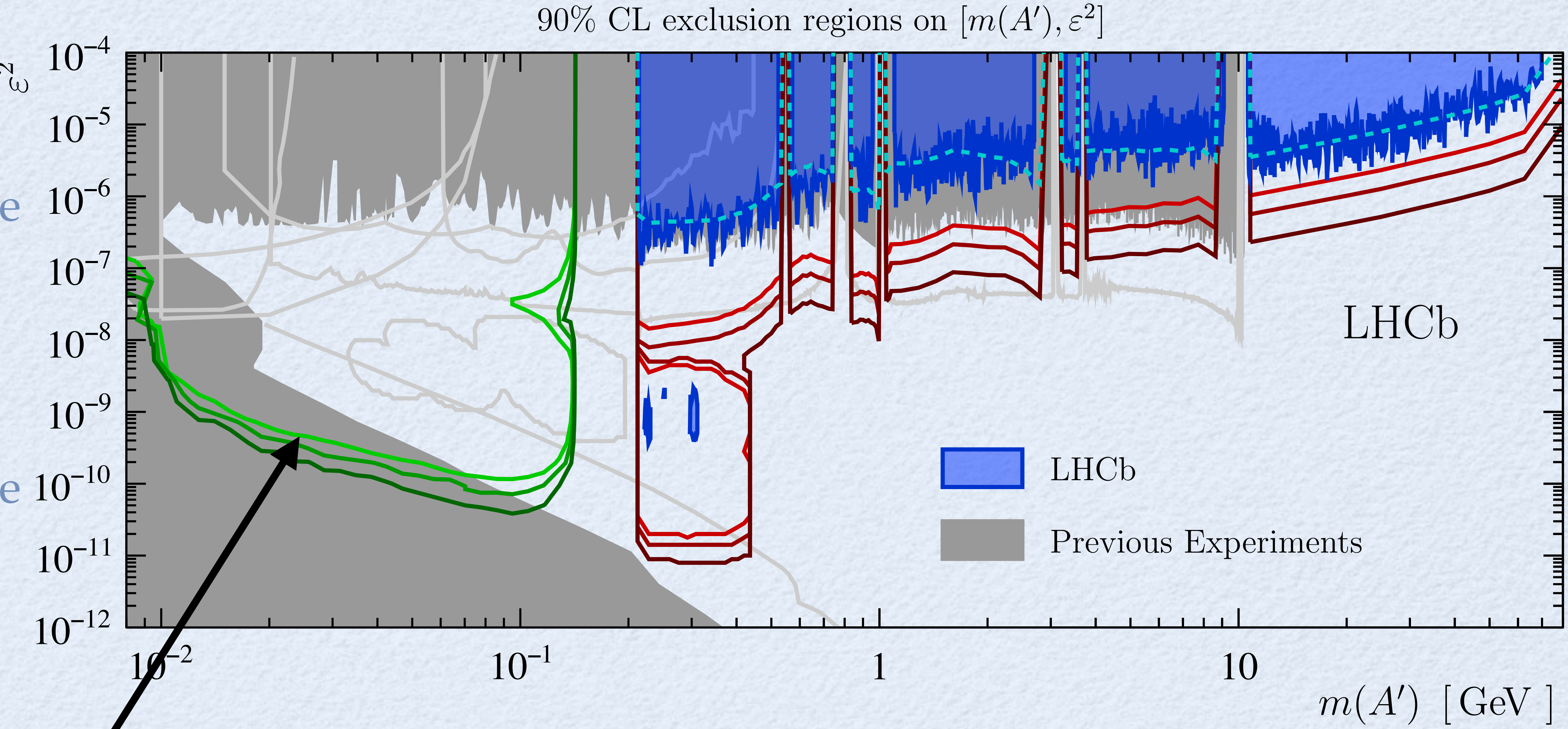


LHCb, 1710.02867

LHCb Result with 2016 Data

short lifetime

long lifetime

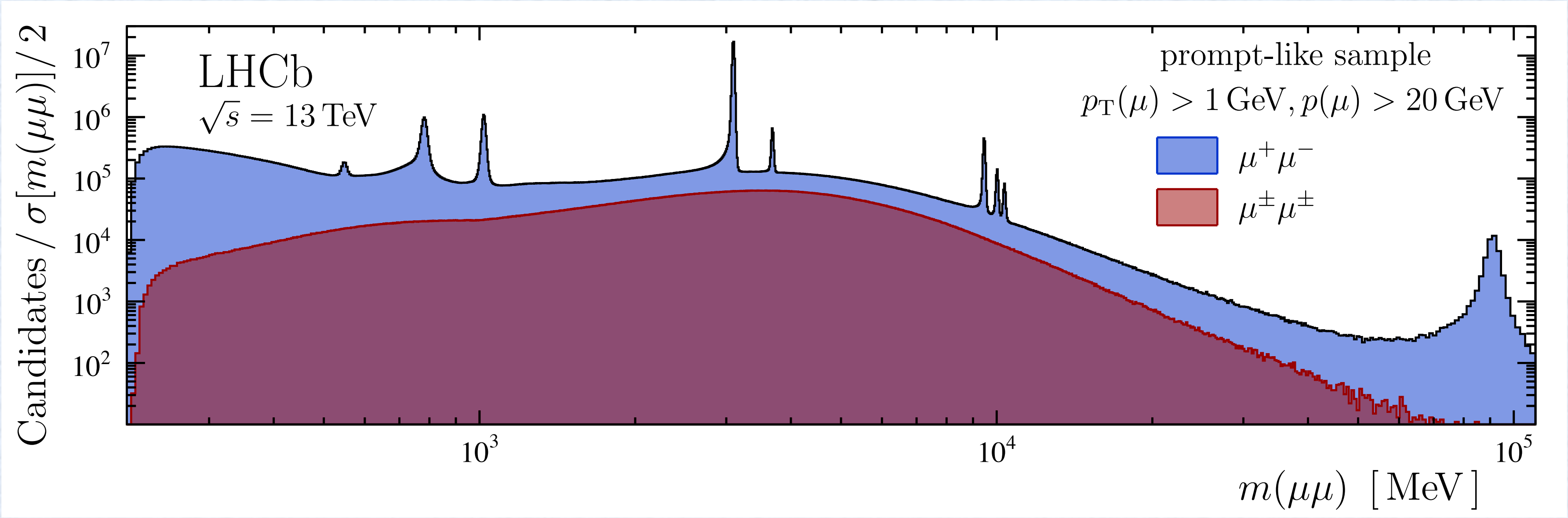


$D^* \to D A'$, $A' \to e^+ e^-$

Ilten, Thaler, Williams, Xue, 1509.06765

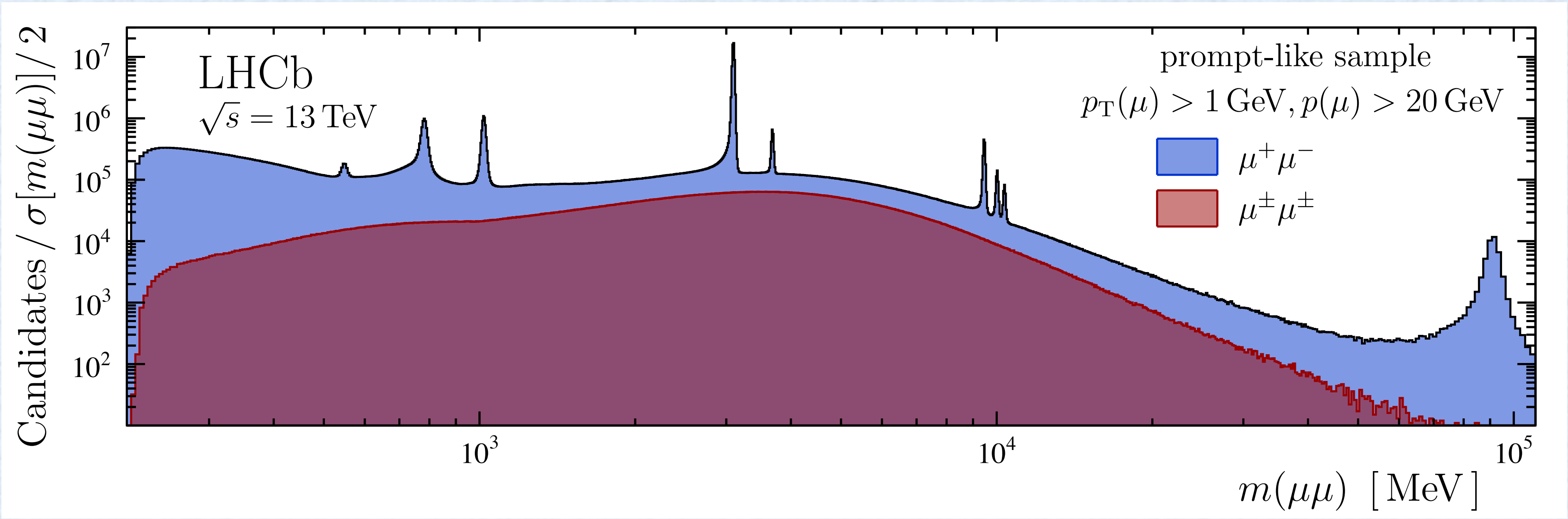
LHCb, 1710.02867

Beyond the Dark Photon Model



LHCb, 1710.02867

Beyond the dark photon model



LHCb, 1710.02867

generic vector resonances

$$\mathcal{L} \subset g_X \sum_f x_f \bar{f}\gamma^\mu f X_\mu + \sum_\chi \mathcal{L}_{X\chi\bar{\chi}}$$

rescaling of the production and branching ratio

$$\sigma_X \mathcal{B}_{X\to\mathcal{F}}\, \epsilon(\tau_X) = \sigma_{A'} \mathcal{B}_{A'\to\mathcal{F}}\, \epsilon(\tau_{A'})$$

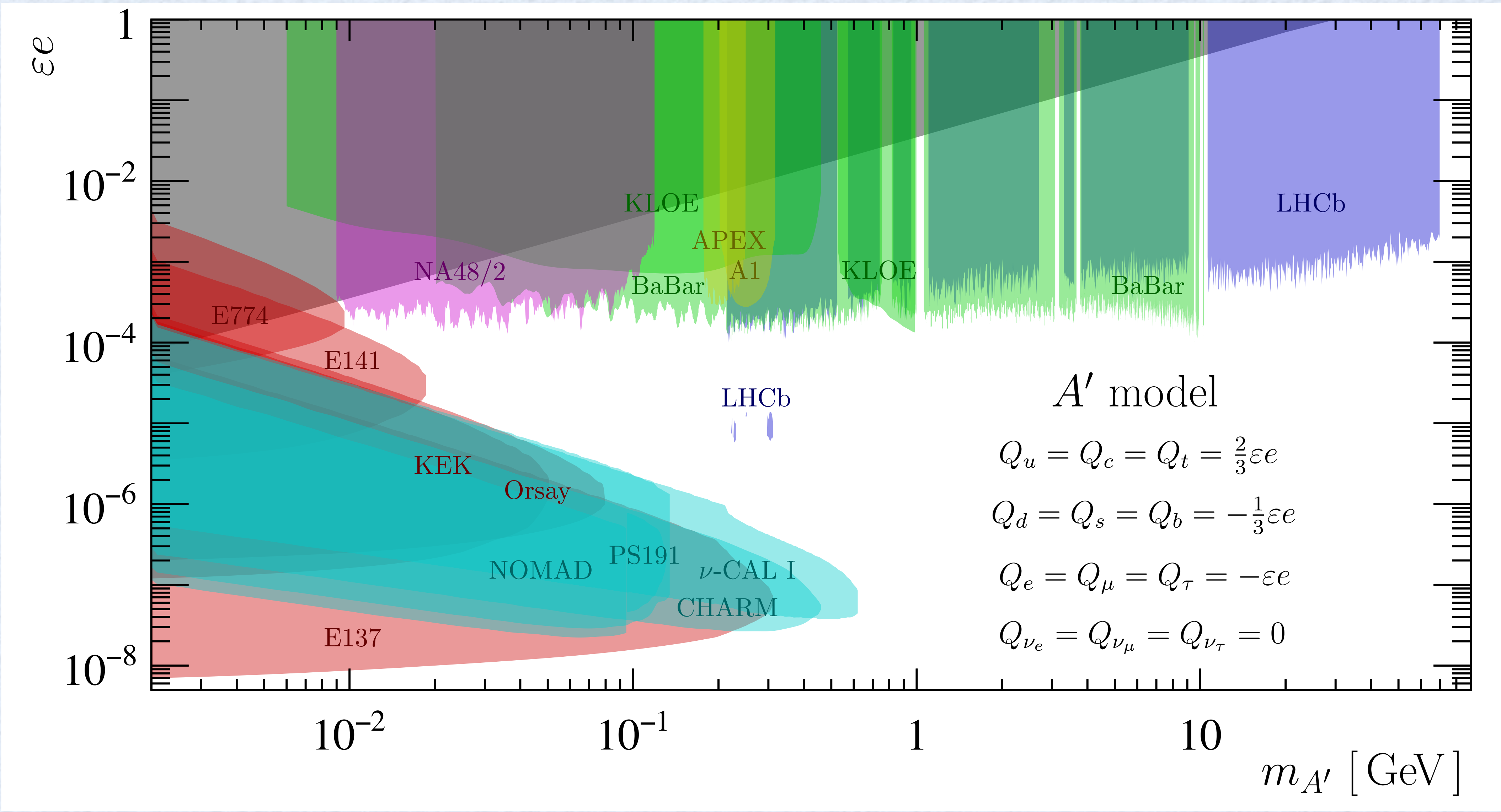
constrain generic vector resonances - X

$$g_X = \epsilon^2 \frac{\bar{\sigma}_{A'} \mathcal{B}_{A'\to\mathcal{F}} \epsilon(\tau_{A'})}{\bar{\sigma}_X \mathcal{B}_{X\to\mathcal{F}} \epsilon(\tau_X)}$$

see also https://gitlab.com/philten/darkcast

Ilten, **YS**, Williams, Xue, 1801.04847

Beyond the Dark Photon Model

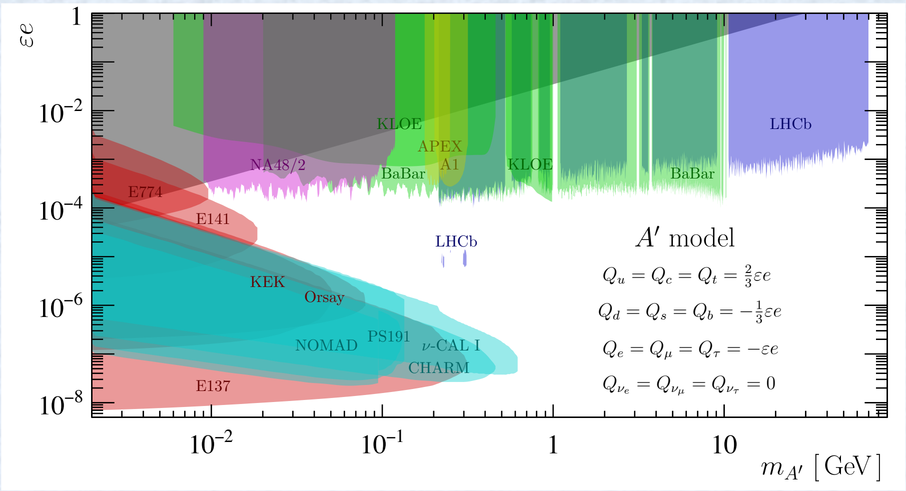


electron beam dump
proton beam dump
e^+e^- collider

pp collider
meson decays
e on fixed target

Ilten, **YS**, Williams, Xue, 1801.04847

Beyond the Dark Photon Model



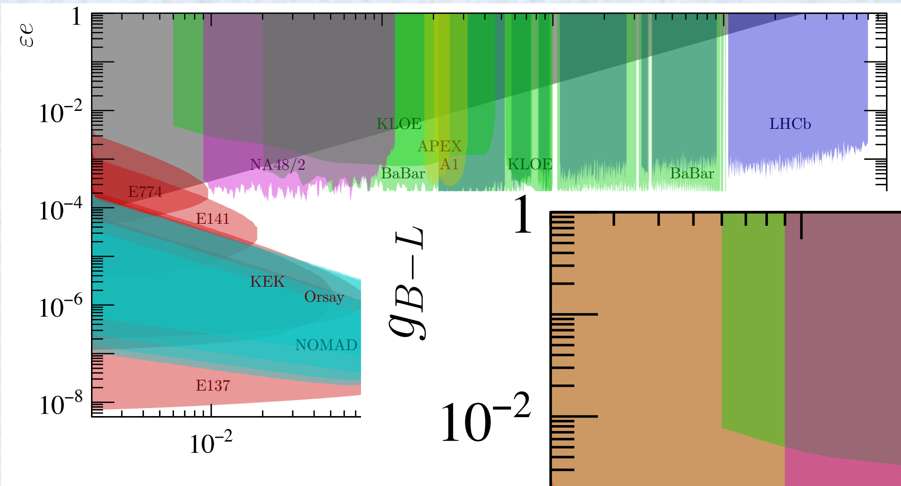
electron beam dump
proton beam dump
e^+e^- collider

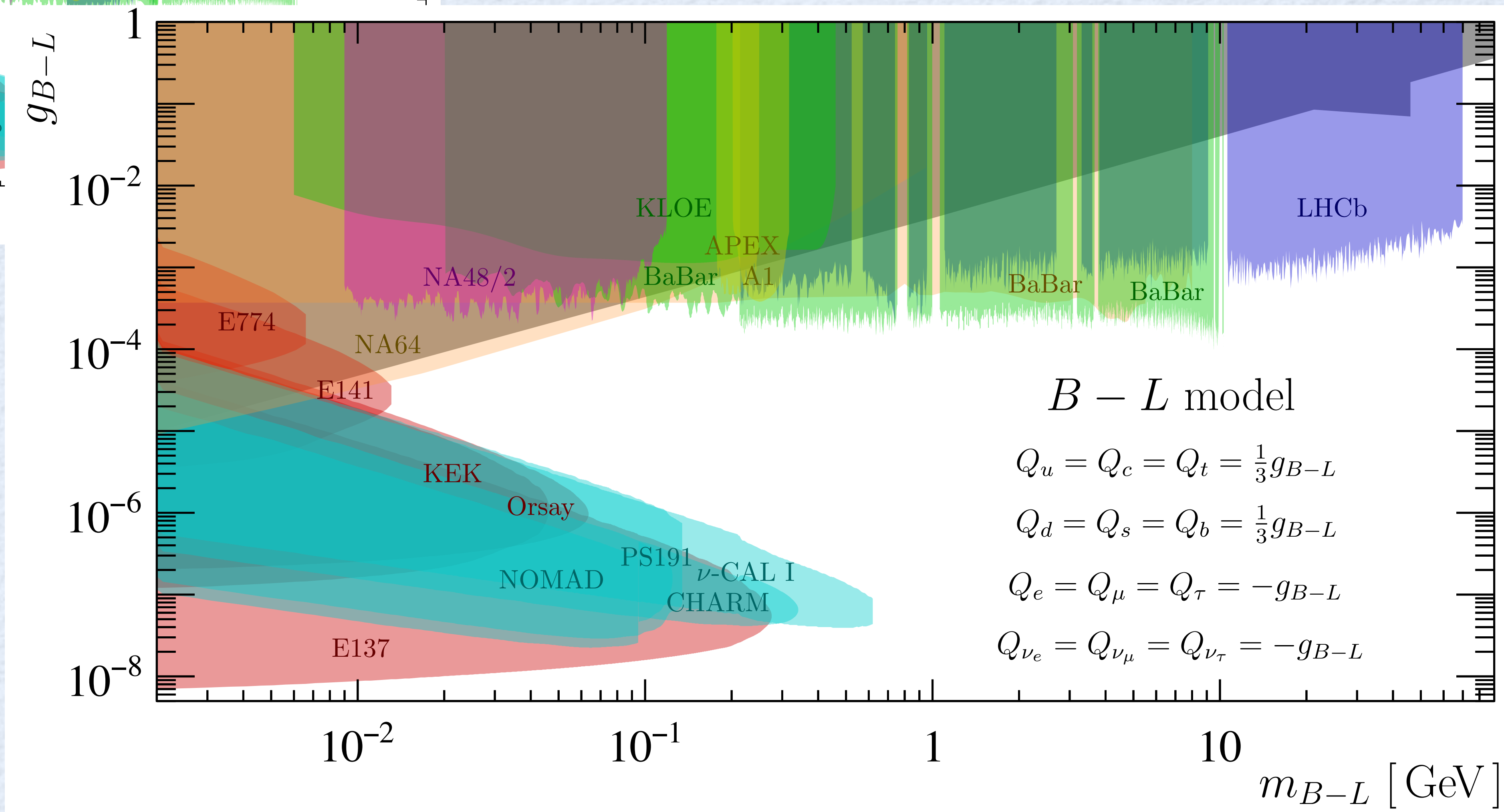
pp collider
meson decays
e on fixed target

invisible decays

Ilten, **YS**, Williams, Xue, 1801.04847

Beyond the Dark Photon Model





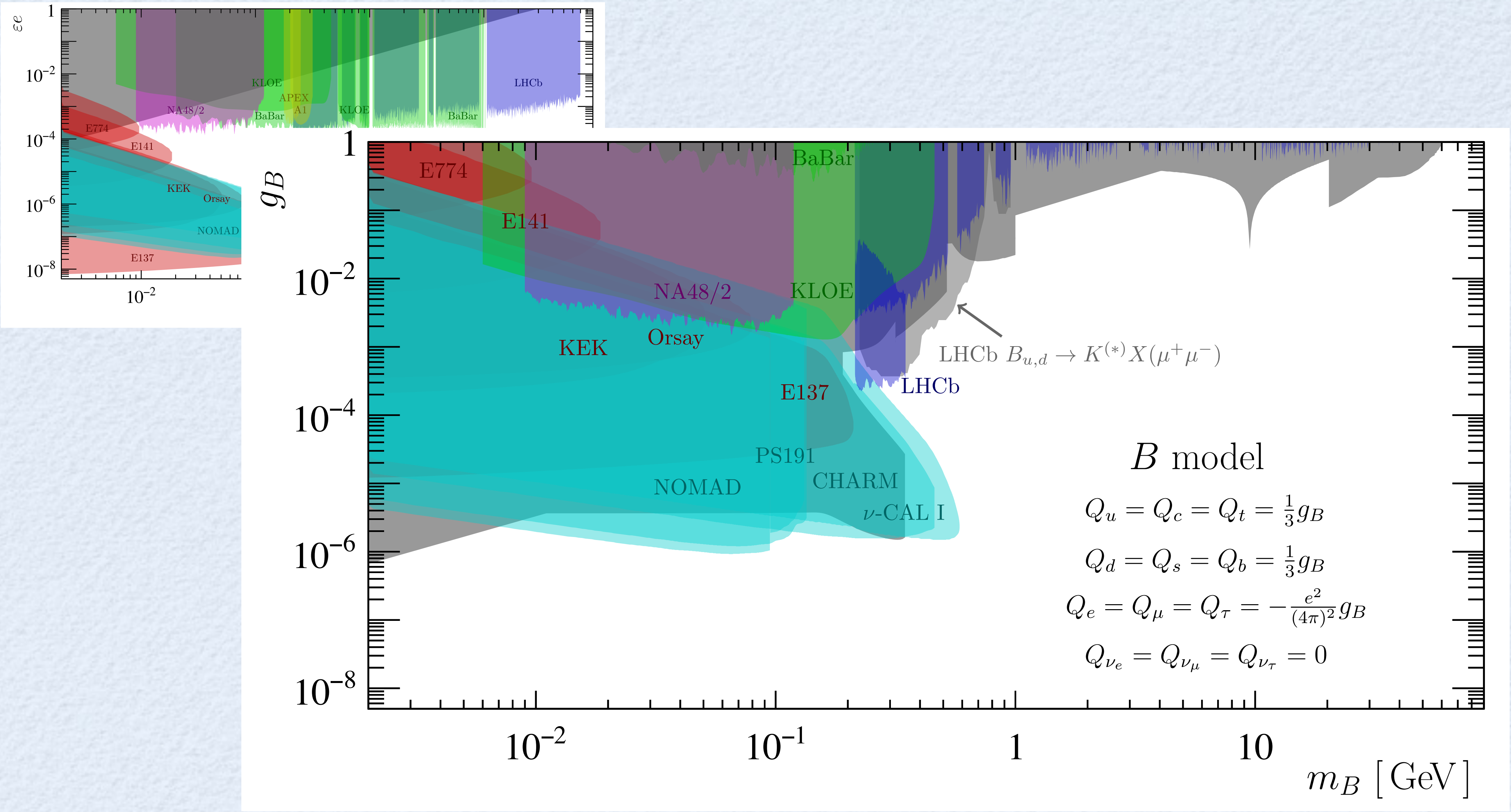
electron beam dump
proton beam dump
e^+e^- collider

pp collider
meson decays
e on fixed target

invisible decays

Ilten, **YS**, Williams, Xue, 1801.04847

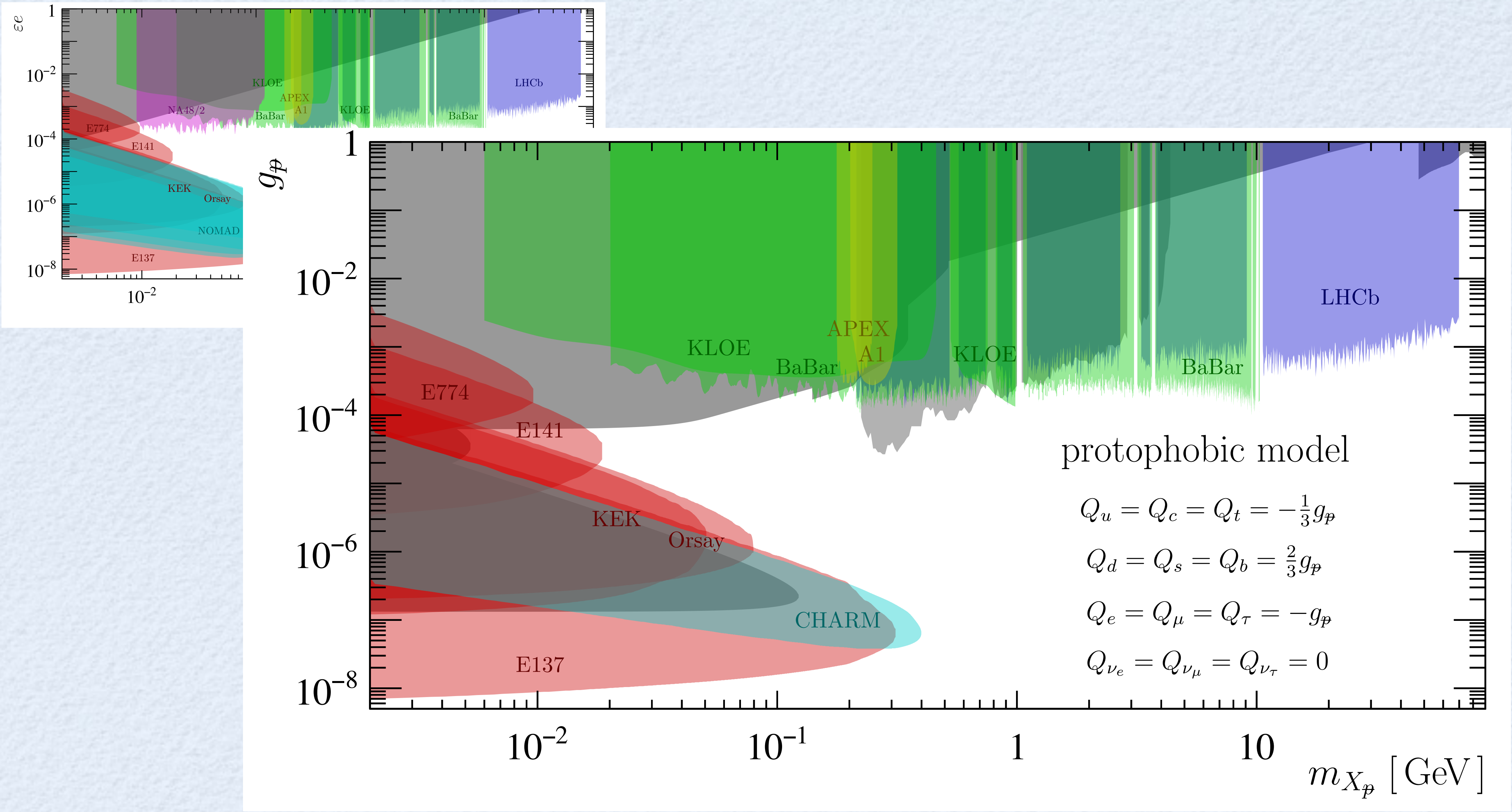
Beyond the Dark Photon Model



electron beam dump
proton beam dump
e^+e^- collider
pp collider
meson decays
e on fixed target
invisible decays

Ilten, **YS**, Williams, Xue, 1801.04847

Beyond the Dark Photon Model



electron beam dump
proton beam dump
e^+e^- collider

pp collider
meson decays
e on fixed target

invisible decays

Ilten, **YS**, Williams, Xue, 1801.04847

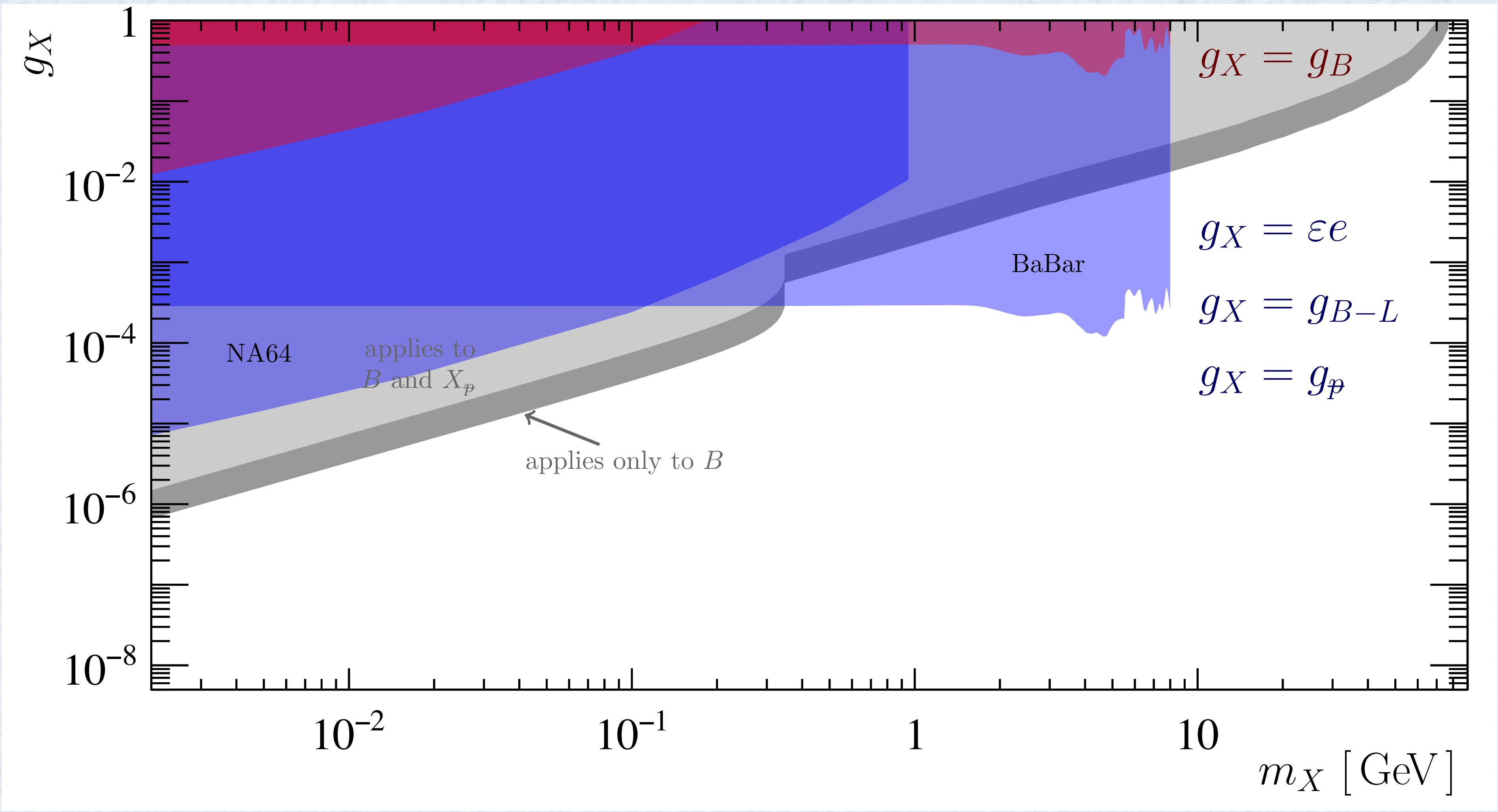
Beyond the dark photon model

assuming dominant invisible decay

Ilten, **YS**, Williams, Xue,
1801.04847

Beyond the Dark Photon Model

assuming dominant invisible decay

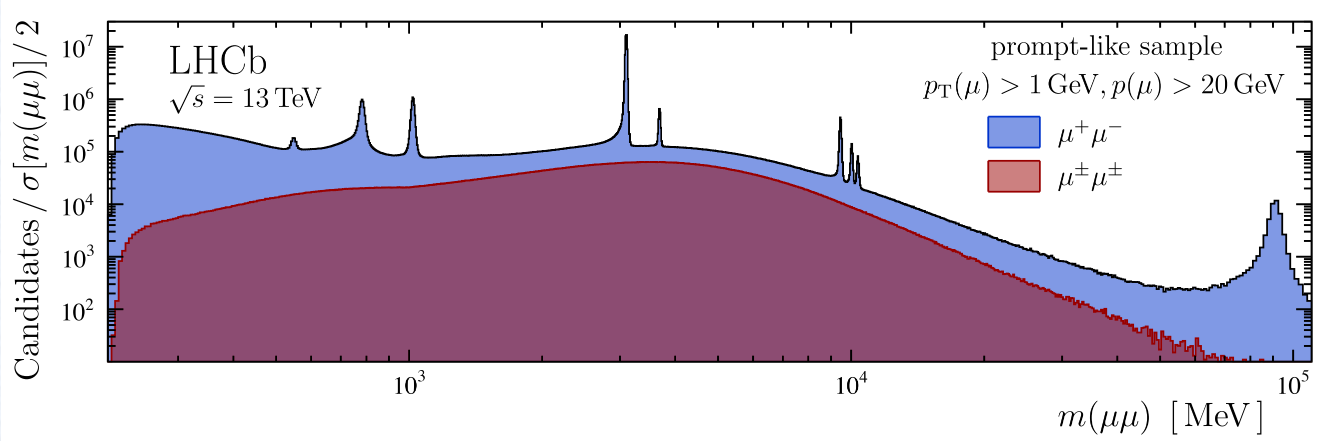


Ilten, **YS**, Williams, Xue, 1801.04847

Dark Photon at LHCb

a portal, dark photon

standard model ⟷ dark matter

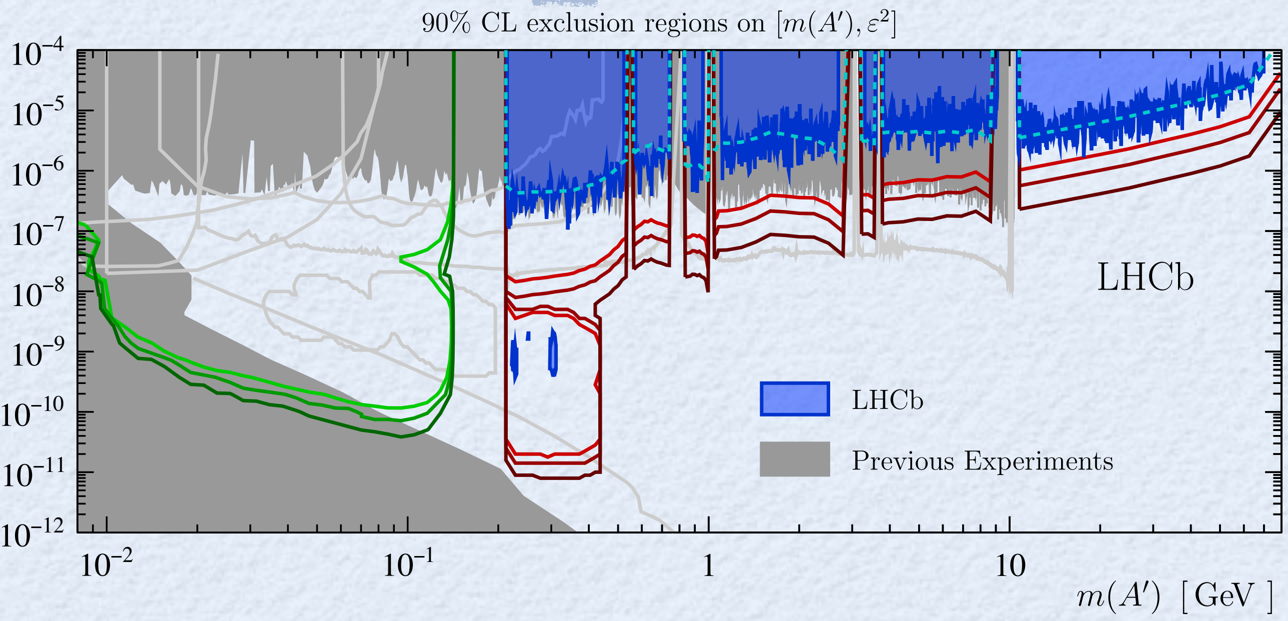


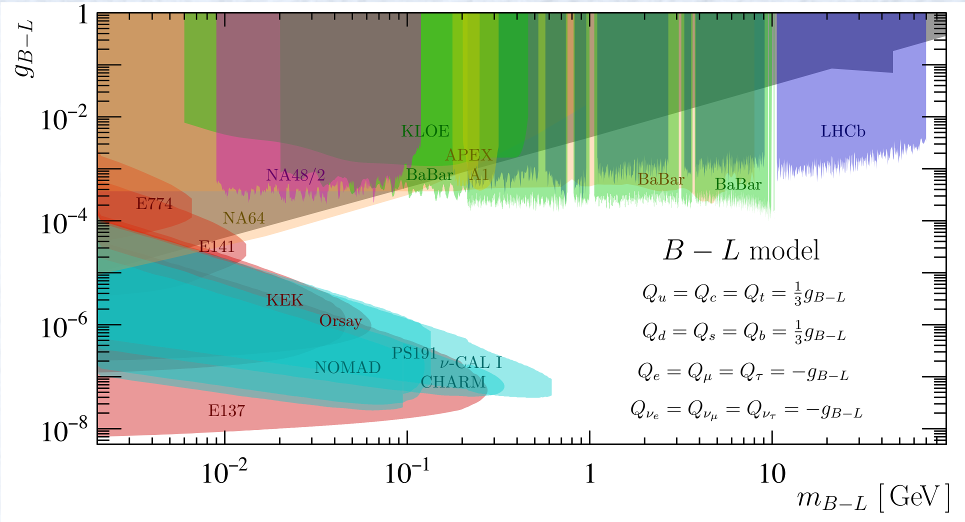
LHCb, 1710.02867

Ilten, **YS**, Thaler, Williams, Xue, PRL 1603.08926

dark photon

generic models





Ilten, **YS**, Williams, Xue, 1801.04847

Axion like particles

pseudo scalars

(appears in different BSM models)

$$\mathcal{L}_{\text{eff}} = -\frac{4\pi\alpha_s c_g}{\Lambda} a G^{\mu\nu}\tilde{G}_{\mu\nu} + \frac{c_\gamma}{4\Lambda} a F^{\mu\nu}\tilde{F}_{\mu\nu}$$

$$c_g \neq 0 \text{ or } c_\gamma \neq 0$$

Aloni, YS, Williams, 1811.03474

Aloni, Fanelli, YS, Williams, work in progress

Primakoff ALP production

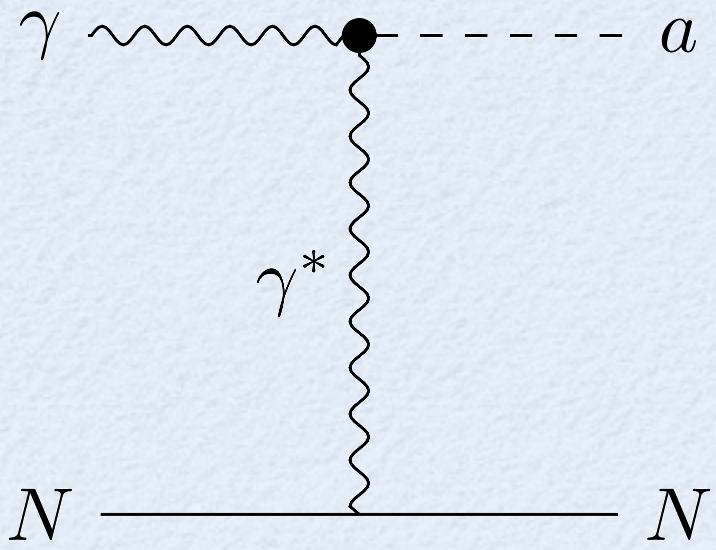
$$\mathscr{L}_{\rm eff} = \frac{c_\gamma}{4\Lambda} a F^{\mu\nu} \tilde{F}_{\mu\nu}$$

Aloni, Fanelli, YS, Williams, work in progress

PRIMAKOFF ALP PRODUCTION

$$\mathscr{L}_{\text{eff}} = \frac{c_\gamma}{4\Lambda} a F^{\mu\nu} \tilde{F}_{\mu\nu}$$

photon on fixed target



$E_\gamma \approx 5 - 10\,\text{GeV}$

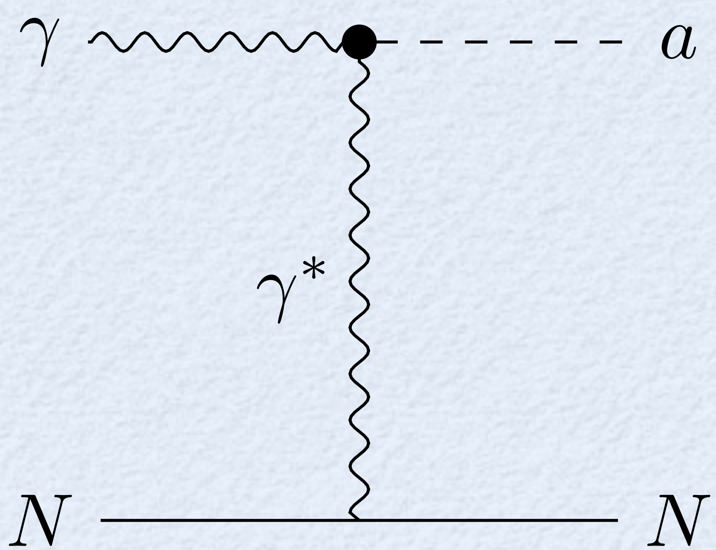
data driven signal estimation

Aloni, Fanelli, YS, Williams, work in progress

PRIMAKOFF ALP PRODUCTION

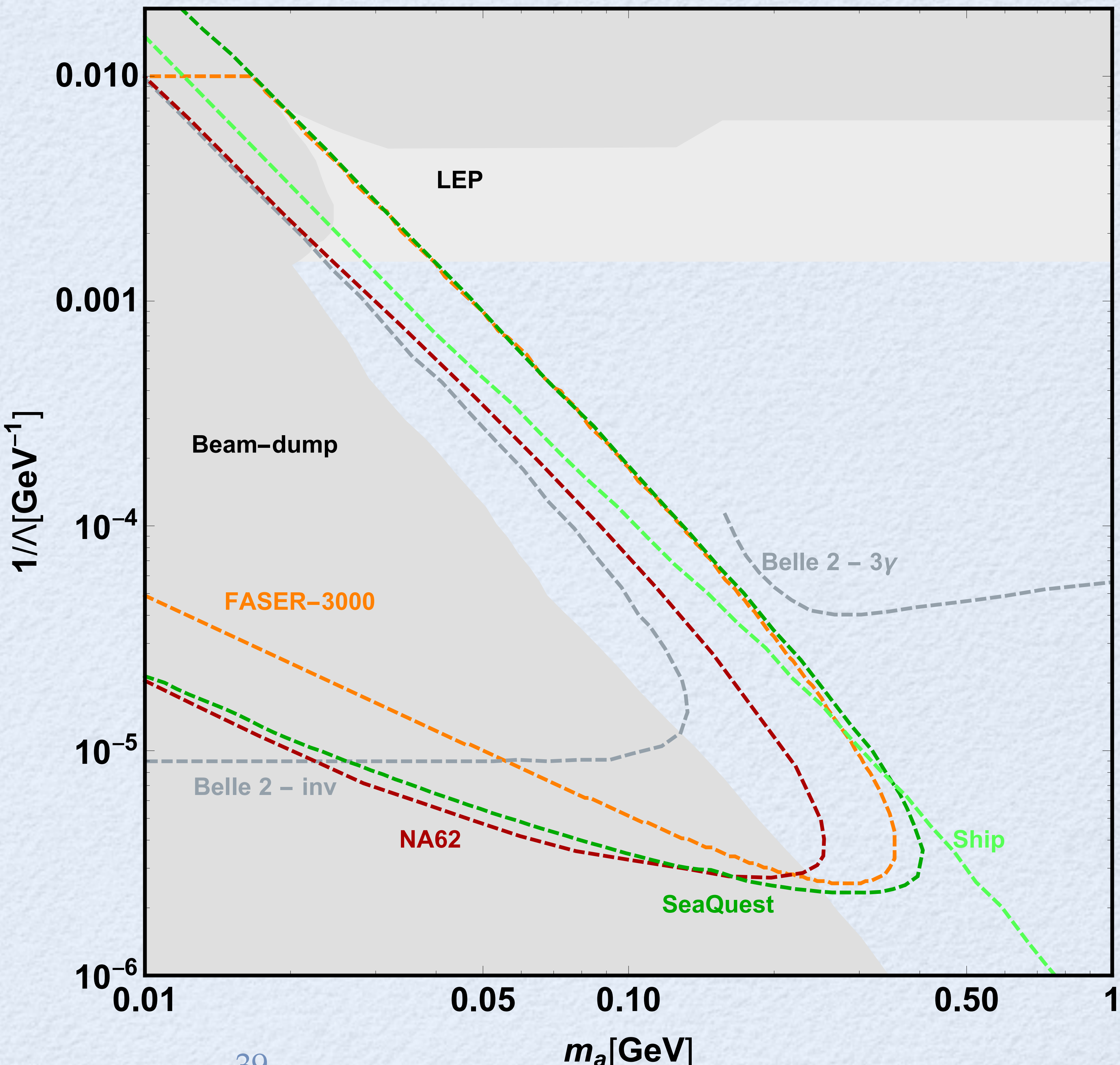
$$\mathscr{L}_{\text{eff}} = \frac{c_\gamma}{4\Lambda} a F^{\mu\nu} \tilde{F}_{\mu\nu}$$

photon on fixed target



$E_\gamma \approx 5 - 10\,\text{GeV}$

data driven signal estimation



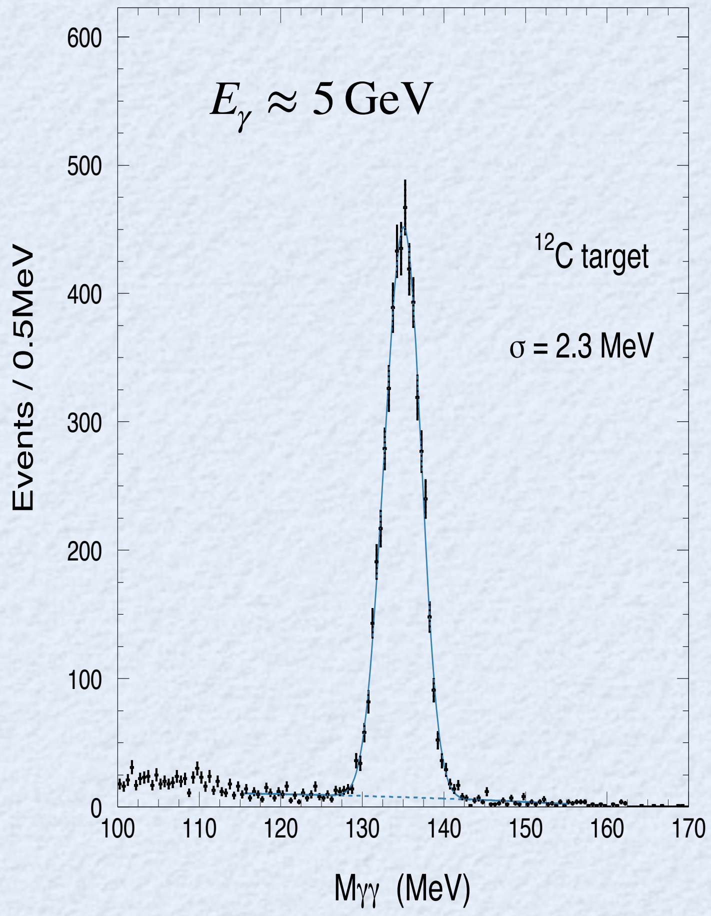
Aloni, Fanelli, YS, Williams, work in progress

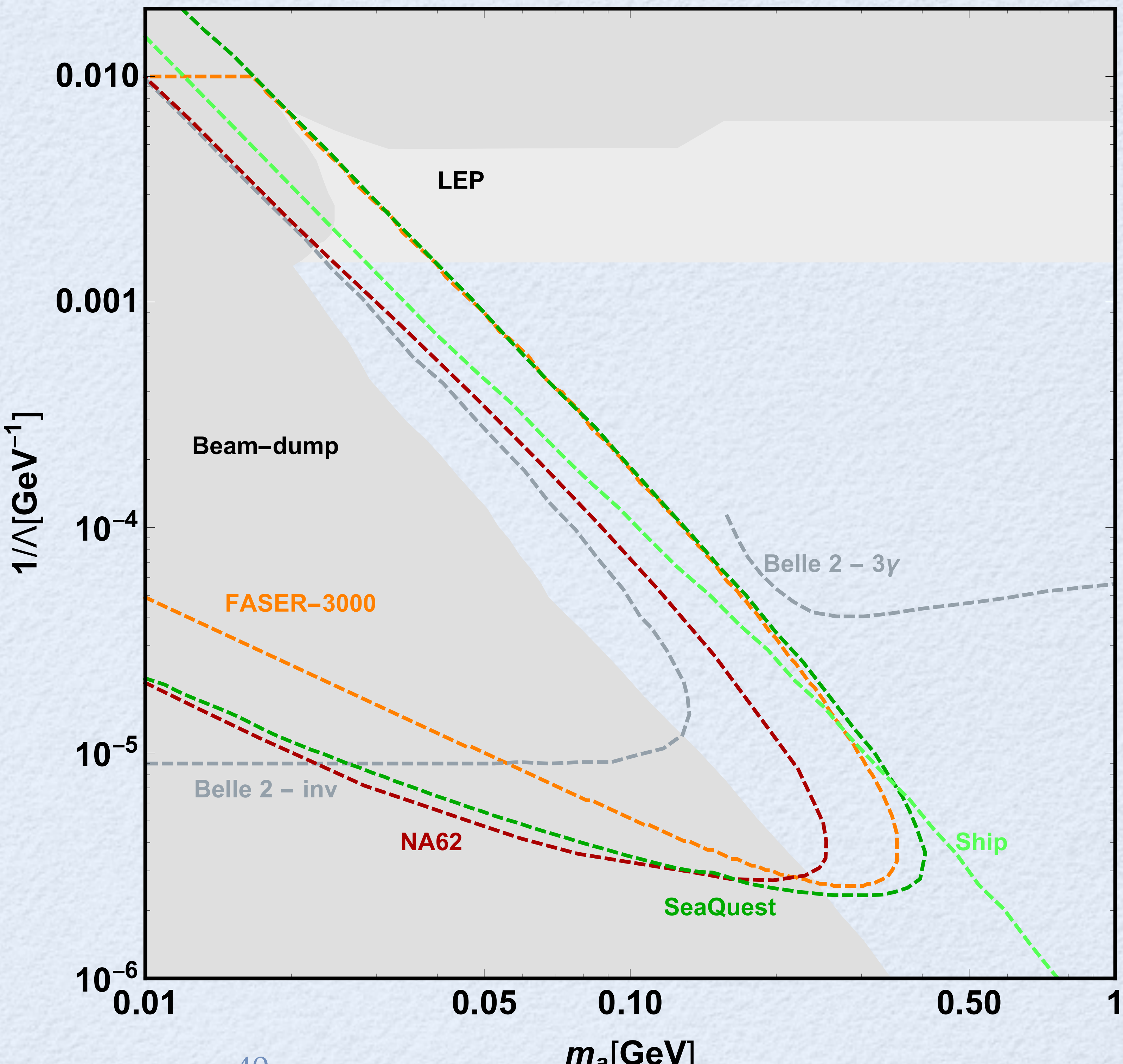
PRIMAKOFF ALP PRODUCTION

$$\mathscr{L}_{\text{eff}} = \frac{c_\gamma}{4\Lambda} a F^{\mu\nu} \tilde{F}_{\mu\nu}$$

photon on fixed target

PrimeEx,1009.1681





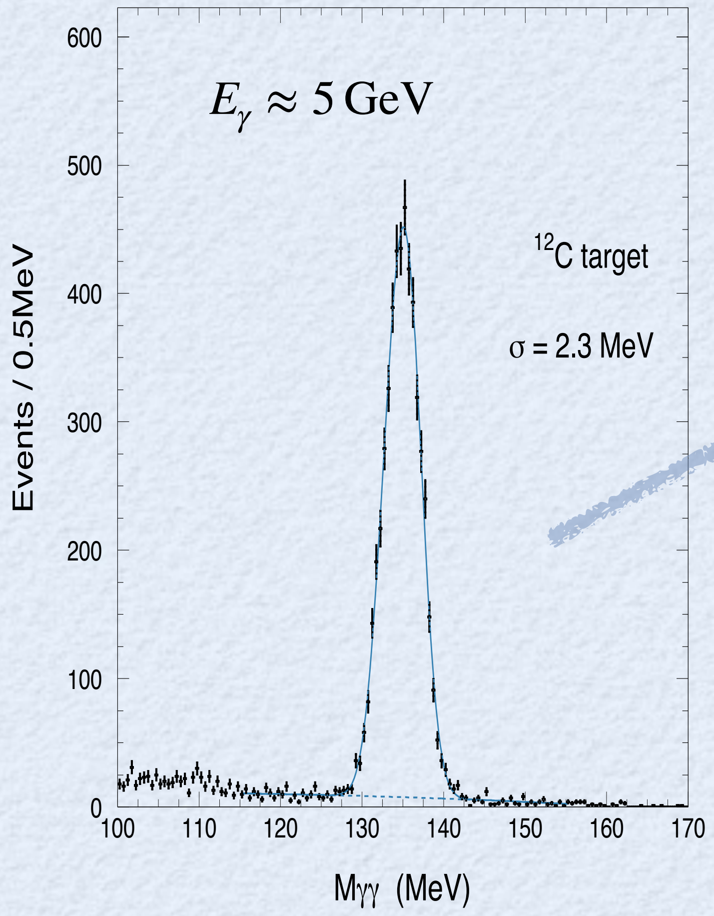
Aloni, Fanelli, YS, Williams, work in progress

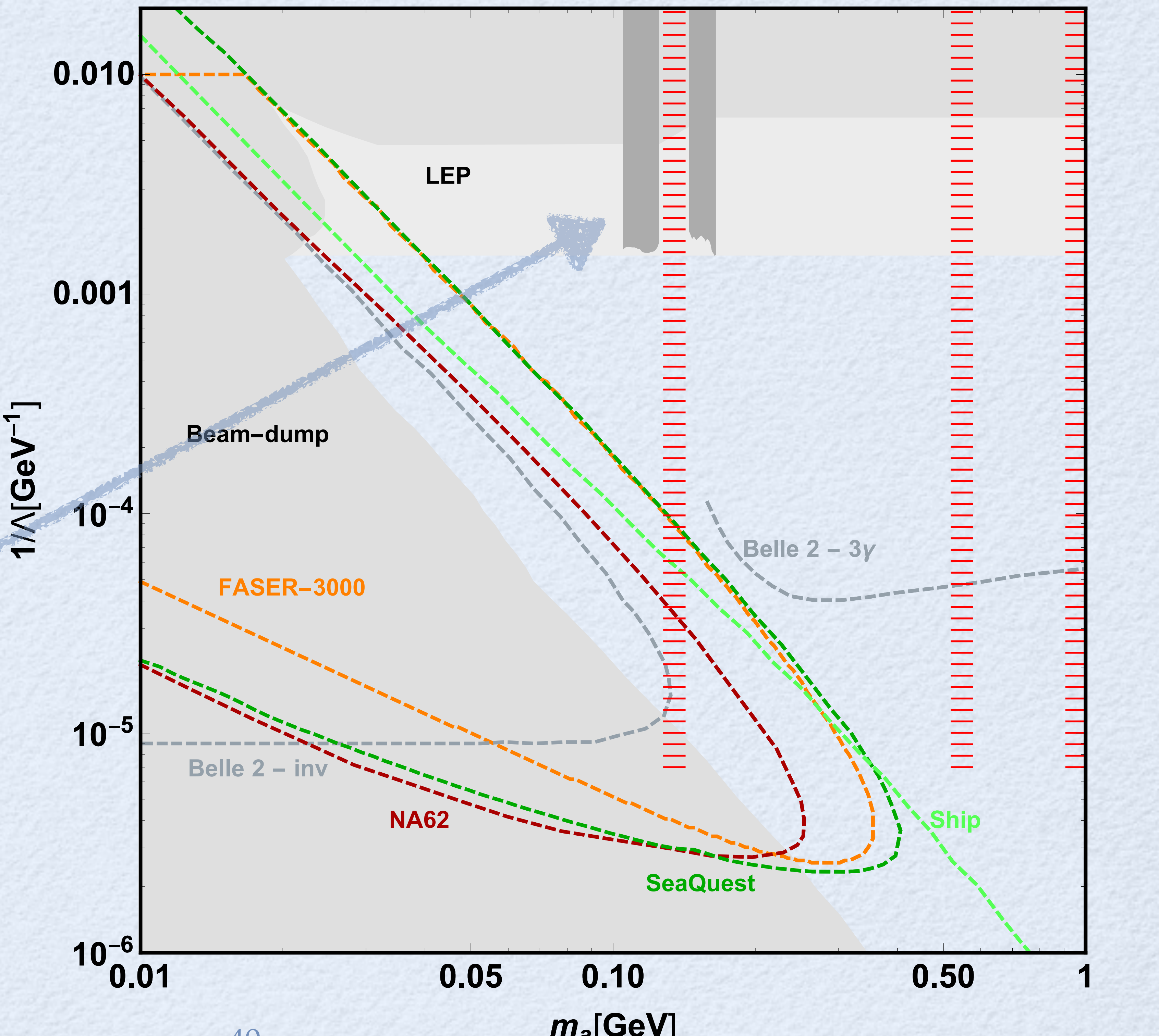
PRIMAKOFF ALP PRODUCTION

$$\mathscr{L}_{\text{eff}} = \frac{c_\gamma}{4\Lambda} a F^{\mu\nu} \tilde{F}_{\mu\nu}$$

photon on fixed target

PrimeEx,1009.1681





Aloni, Fanelli, YS, Williams, work in progress

PRIMAKOFF ALP PRODUCTION

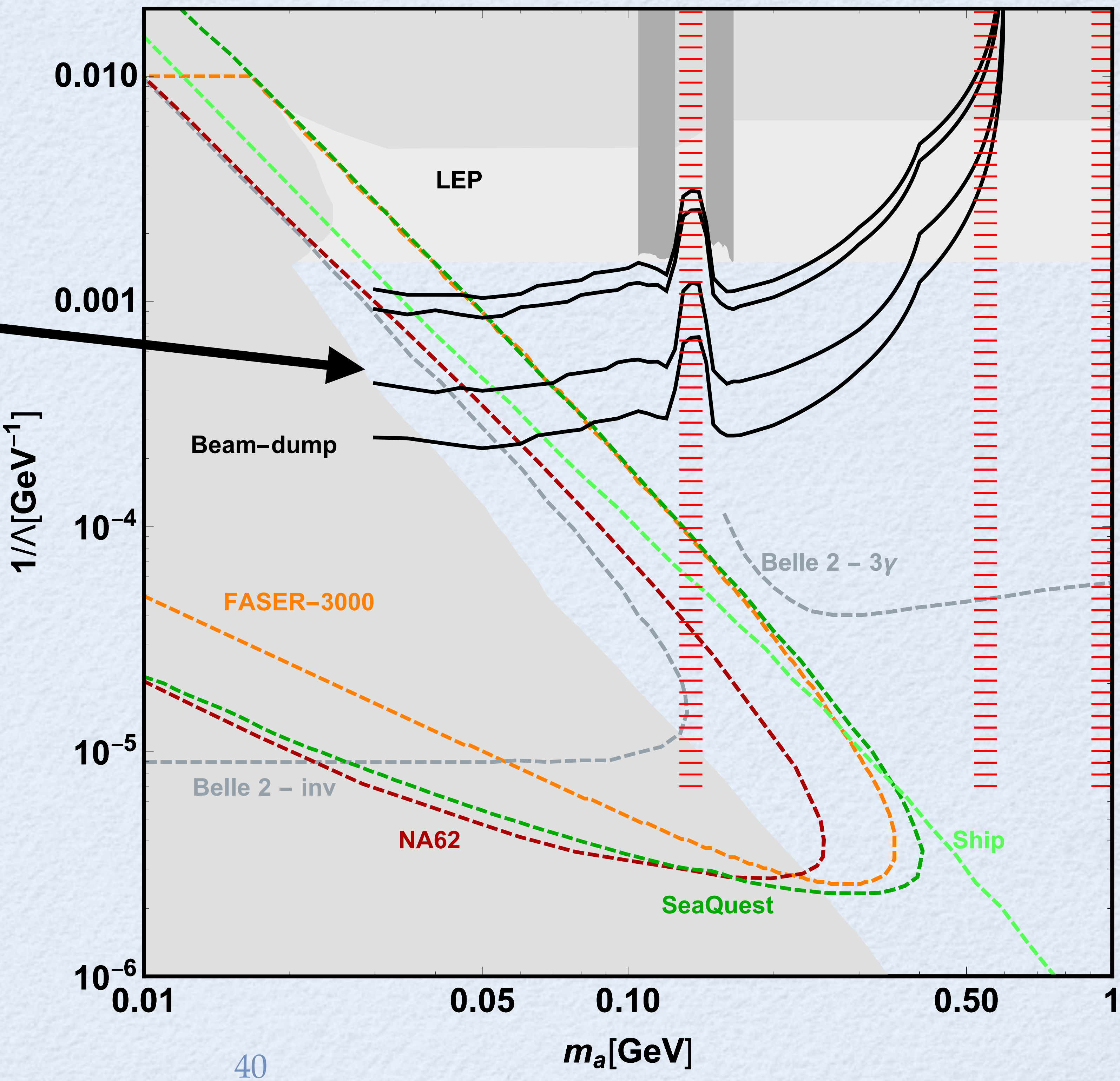
$$\mathscr{L}_{\text{eff}} = \frac{c_\gamma}{4\Lambda} a F^{\mu\nu} \tilde{F}_{\mu\nu}$$

photon on fixed target

PrimeEx, 5GeV

(C, Si, Pb

data on tape)



Aloni, Fanelli, YS, Williams, work in progress

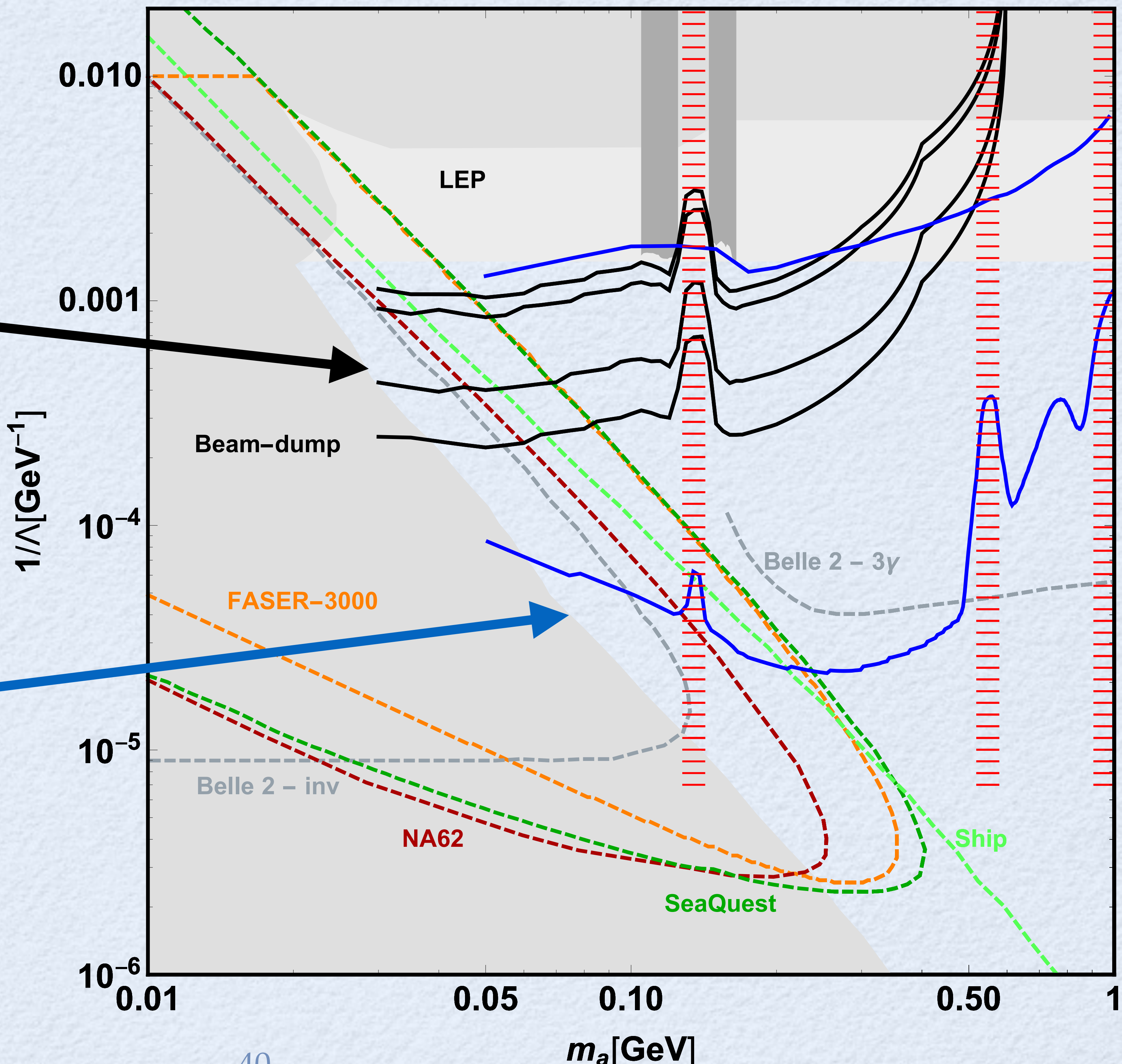
Primakoff ALP production

$$\mathscr{L}_{\text{eff}} = \frac{c_\gamma}{4\Lambda} a F^{\mu\nu} \tilde{F}_{\mu\nu}$$

photon on fixed target

PrimeEx, 5GeV
(C, Si, Pb
data on tape)

GlueX, 8.5GeV
(p and Pb future run
1/fb)



Aloni, Fanelli, YS, Williams, work in progress

ALPs at the GeV scale

$$\mathscr{L}_{\rm eff} = -\frac{4\pi\alpha_s c_g}{\Lambda} a G^{\mu\nu}\tilde{G}_{\mu\nu}$$

how to estimate hadronic rates for ALPs with GeV scale mass?

Aloni, YS, Williams, 1811.03474

ALPs at the GeV scale

$$\mathscr{L}_{\text{eff}} = -\frac{4\pi\alpha_s c_g}{\Lambda} a G^{\mu\nu}\tilde{G}_{\mu\nu}$$

how to estimate hadronic rates for ALPs with GeV scale mass?

$m_a \lesssim GeV$	???	$m_a \gtrsim 2GeV$
chiral PT		pQCD

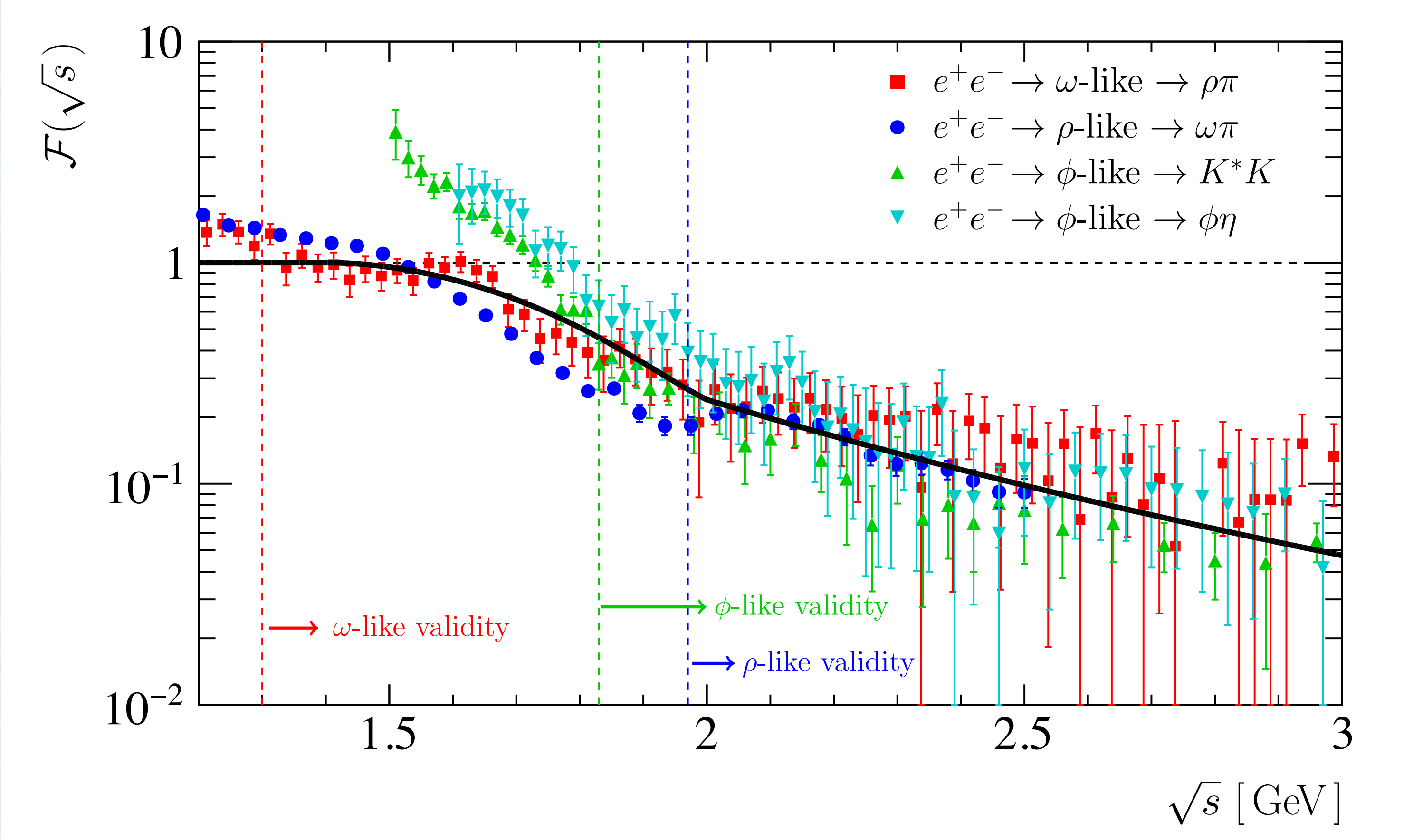
Aloni, YS, Williams, 1811.03474

ALPs at the GeV scale

$$\mathcal{L}_{\text{eff}} = -\frac{4\pi\alpha_s c_g}{\Lambda} a G^{\mu\nu}\tilde{G}_{\mu\nu}$$

how to estimate hadronic rates for ALPs with GeV scale mass?

$m_a \lesssim GeV$	???	$m_a \gtrsim 2GeV$
chiral PT	use data!	pQCD



Aloni, YS, Williams, 1811.03474

ALPs at the GeV Scale

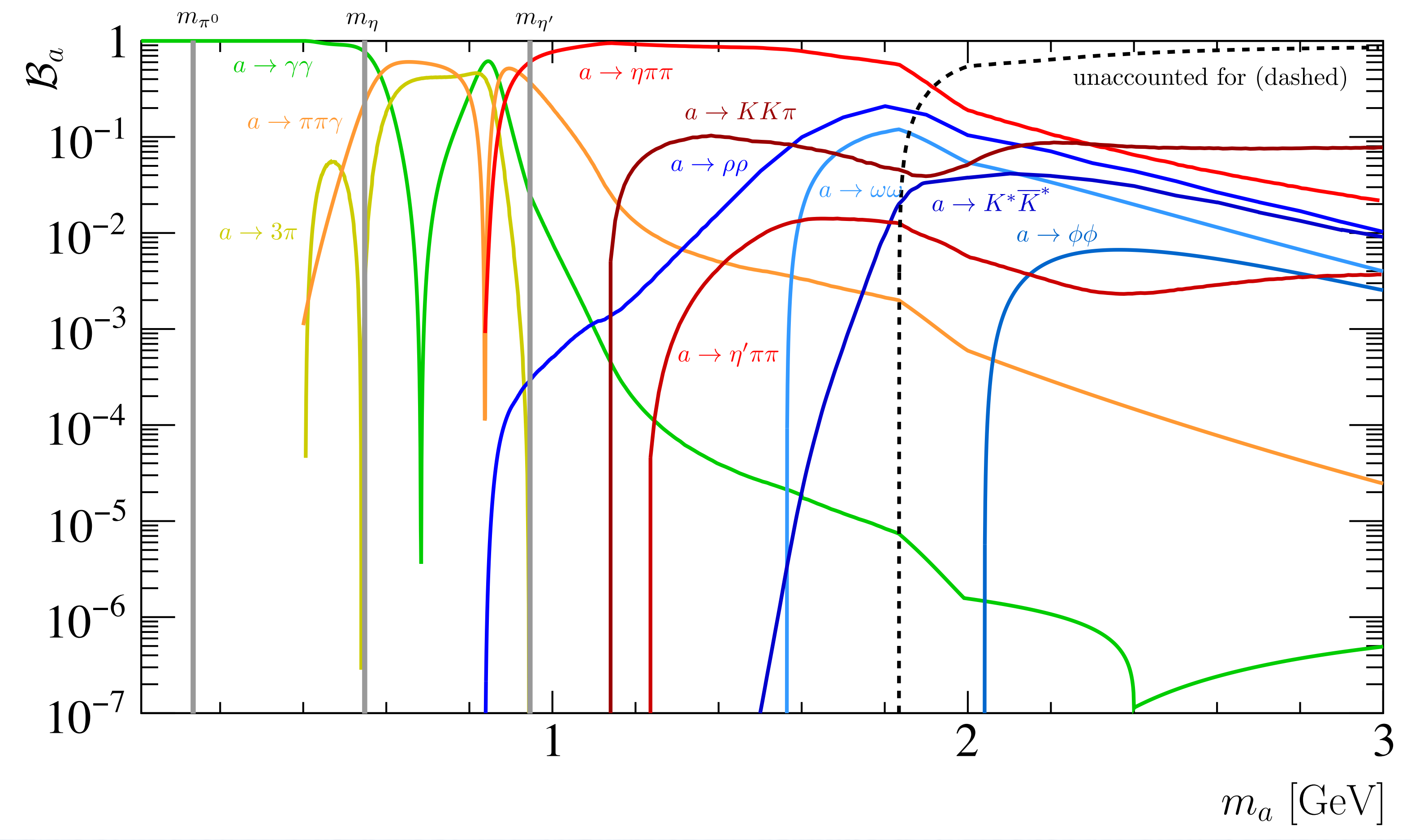
$$\mathscr{L}_{\text{eff}} = -\frac{4\pi\alpha_s c_g}{\Lambda} a G^{\mu\nu}\tilde{G}_{\mu\nu}$$

how to estimate hadronic rates for ALPs with GeV scale mass?

$m_a \lesssim GeV$ chiral PT

??? use data!

$m_a \gtrsim 2GeV$ pQCD



Aloni, YS, Williams, 1811.03474

ALPS AT THE GEV SCALE

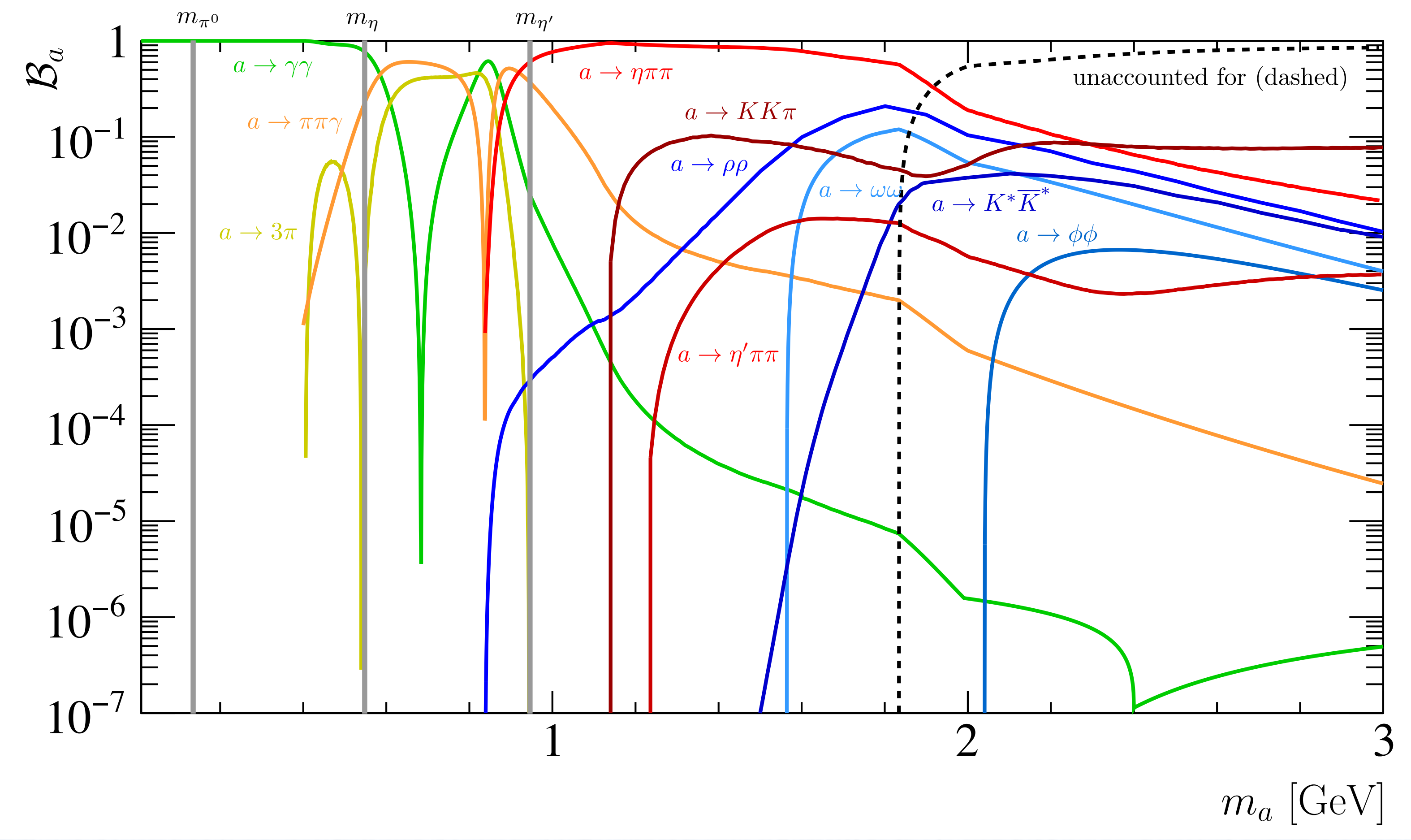
$$\mathscr{L}_{\text{eff}} = -\frac{4\pi\alpha_s c_g}{\Lambda} a G^{\mu\nu}\tilde{G}_{\mu\nu}$$

how to estimate hadronic rates for ALPs with GeV scale mass?

$m_a \lesssim GeV$ chiral PT

??? use data!

$m_a \gtrsim 2GeV$ pQCD



ηc cross check

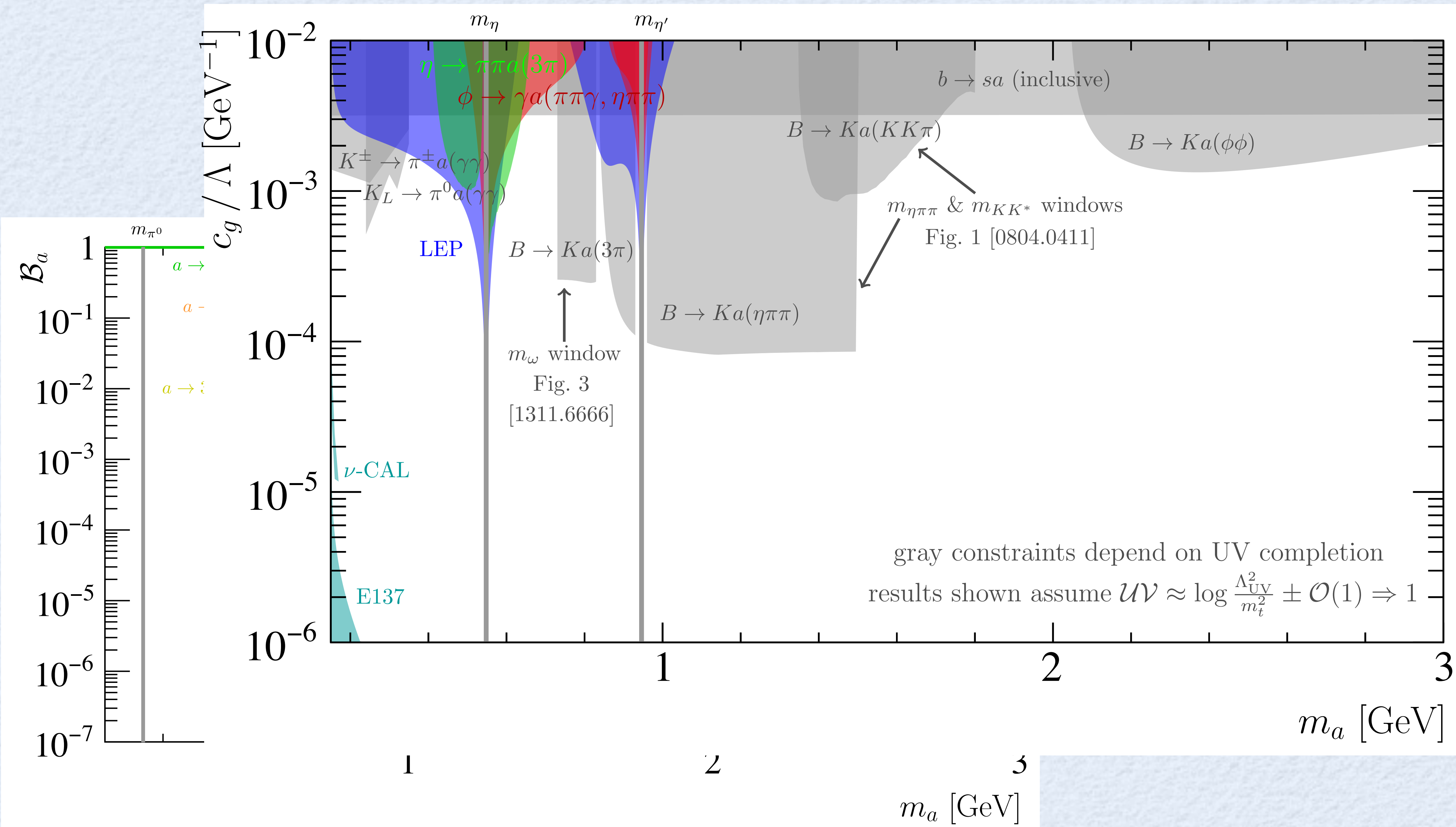
	This Work	Experiment	
	VMD$\times\lvert\mathcal{F}(m)\rvert^2$	Average	$SU(3)$
$\mathcal{B}(\eta_c \to \rho\rho)$	1.0%	$1.8 \pm 0.5\%$	$1.10 \pm 0.14\%$
$\mathcal{B}(\eta_c \to \omega\omega)$	0.40%	$0.20 \pm 0.10\%$	$0.44 \pm 0.06\%$
$\mathcal{B}(\eta_c \to \phi\phi)$	0.25%	$0.28 \pm 0.04\%$	$0.28 \pm 0.04\%$
$\mathcal{B}(\eta_c \to K^*\overline{K}^*)$	0.91%	$0.91 \pm 0.26\%$	$1.00 \pm 0.13\%$

Aloni, YS, Williams, 1811.03474

ALPs at the GeV scale

$$\mathscr{L}_{\text{eff}} = -\frac{4\pi\alpha_s c_g}{\Lambda} a G^{\mu\nu}\tilde{G}_{\mu\nu}$$

how to estimate hadronic rates for ALPs with GeV scale mass?



eck

	Experiment	
	erage	$SU(3)$
	0.5%	$1.10 \pm 0.14\%$
	0.10%	$0.44 \pm 0.06\%$
	0.04%	$0.28 \pm 0.04\%$
	0.26%	$1.00 \pm 0.13\%$

Aloni, YS, Williams, 1811.03474


OUTLOOK

- new physics beyond the standard model is well motivated, but with unknown scale
- we saw examples how to probe new forces in intensity and precision frontiers
- each of these examples probes unexplored territories and improve our understanding of Nature