DARK PHOTONS AND ALPS: CURRENT AND (NEAR) FUTURE

Yotam Soreq

Israeli Input for European Strategy for Particle Physics
town hall meeting, Weizmann Institute, Dec. 5, 2018

portals
SM
dark
sector

portals
SM
dark
sector

dark photons like

X_μ

spin-1 (vector)

couples to currents

(axial vector in progress)

dark photons like

X_μ

spin-1 (vector)

couples to currents

(axial vector in progress)

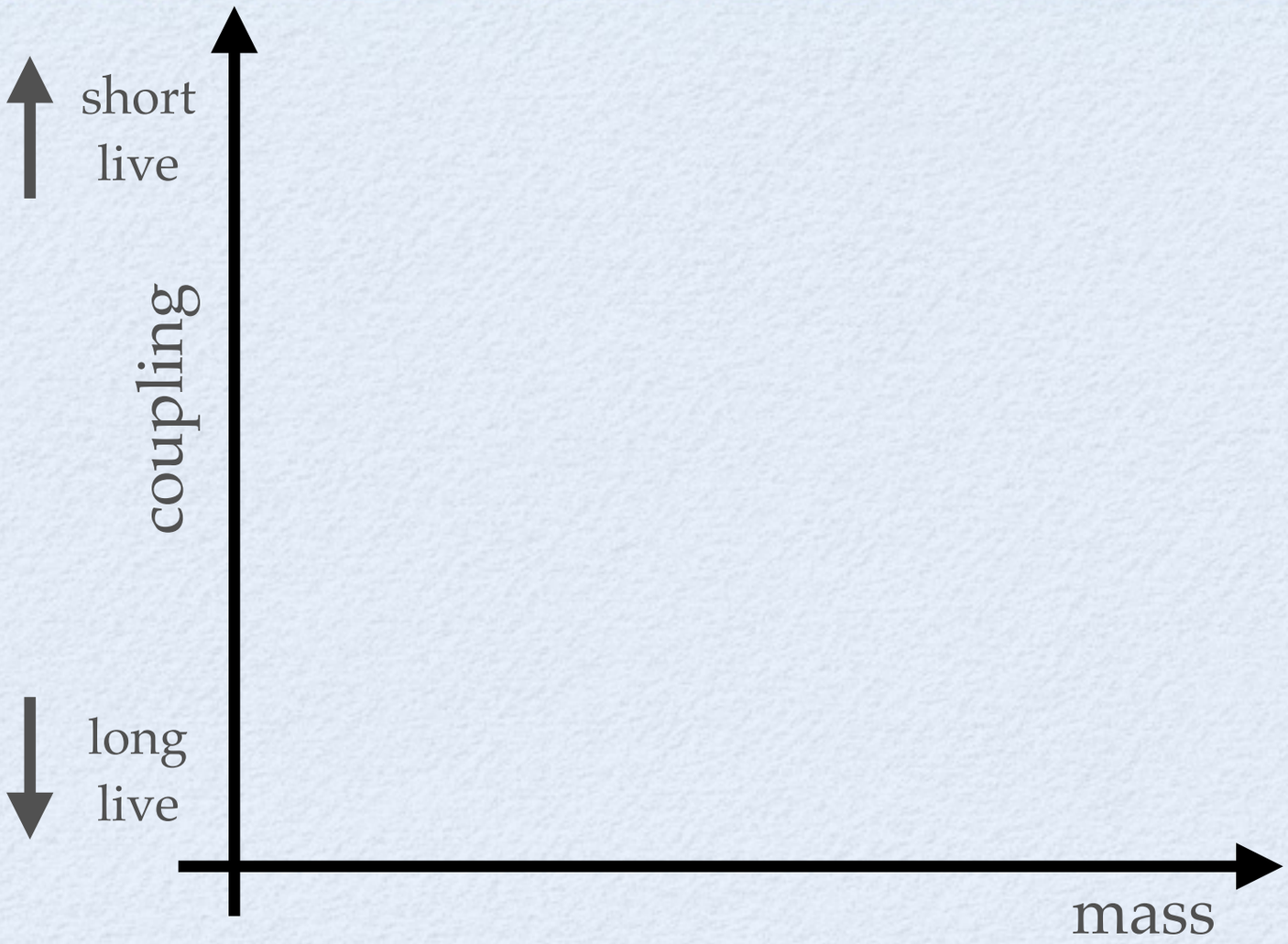
axion like particles

a

pseudo-scalars

couples photons / gluons

SIGNATURES AND EXPERIMENTS



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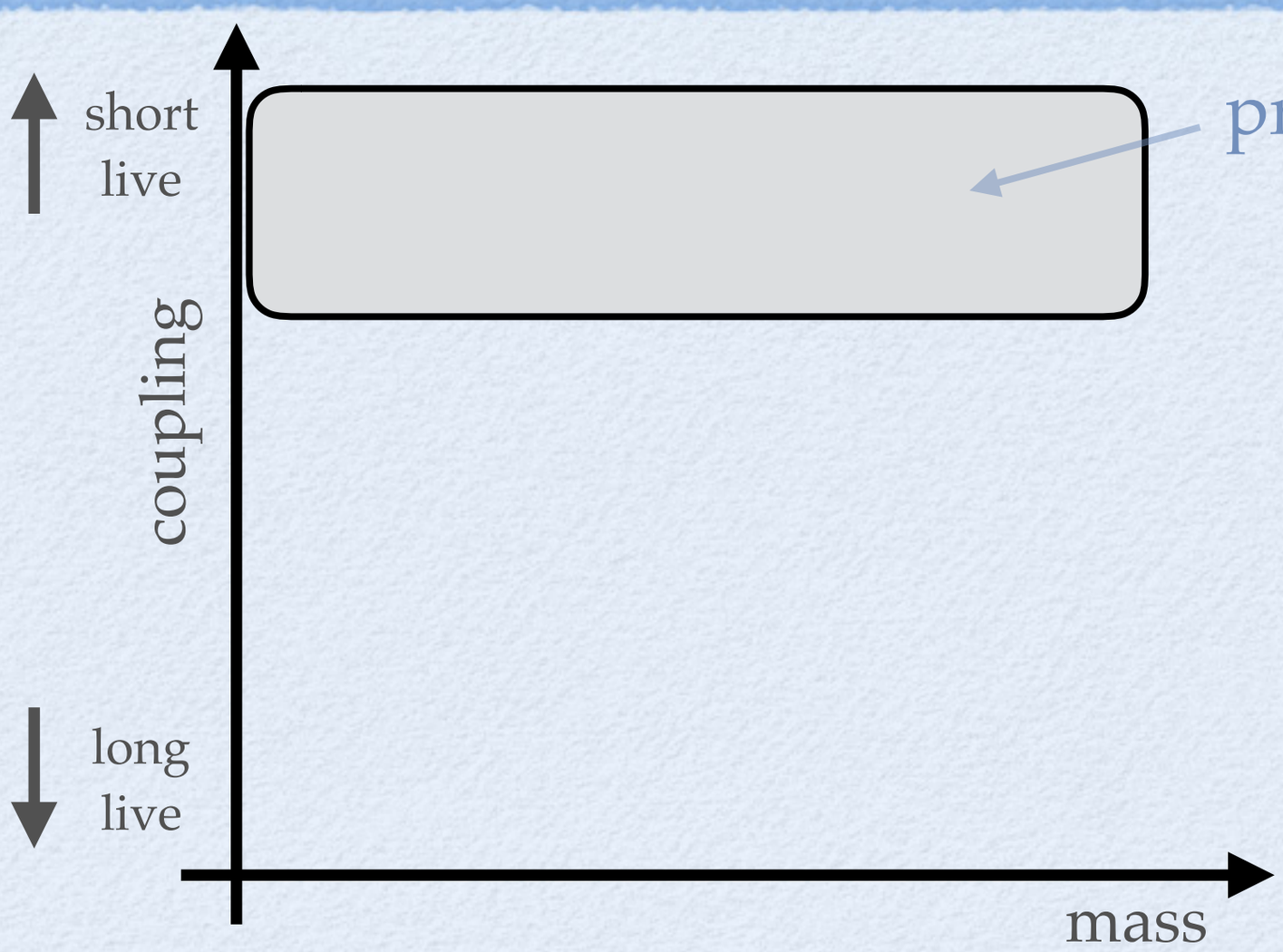

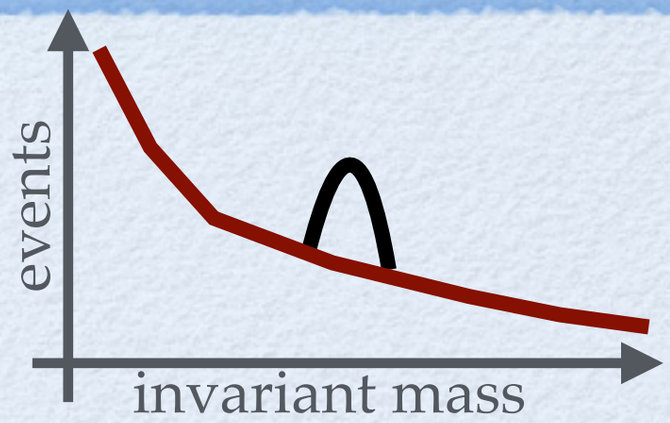

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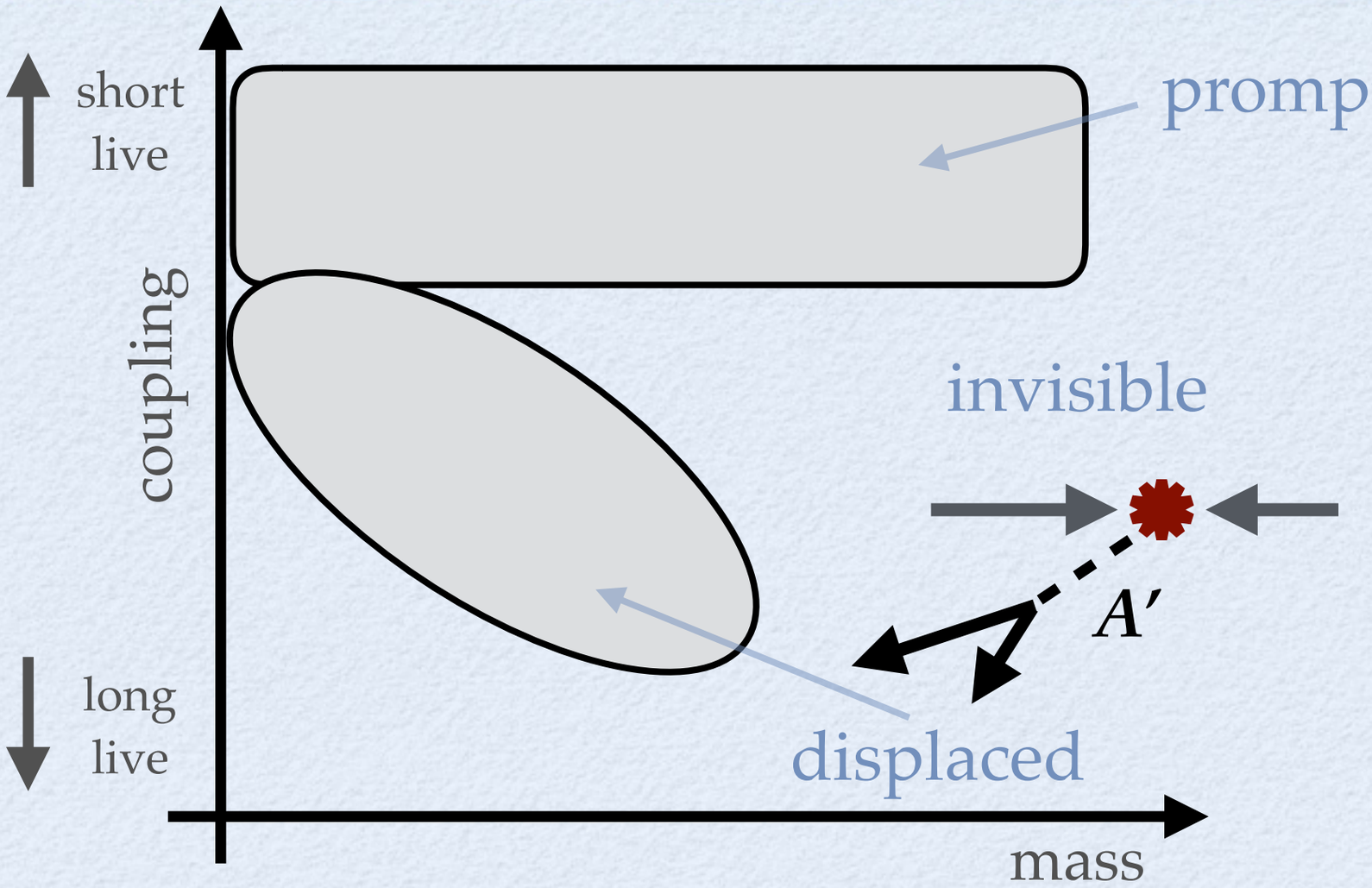

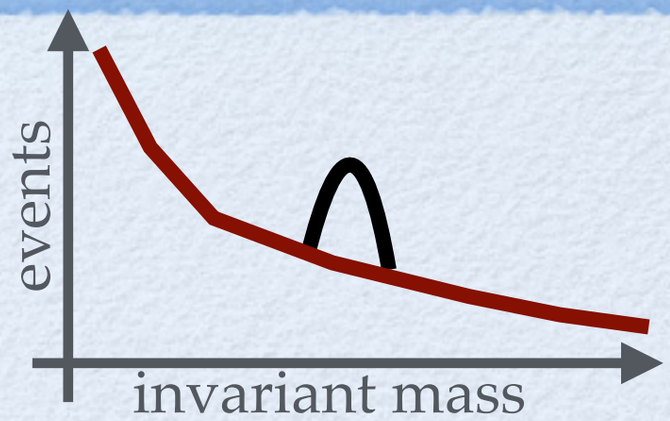

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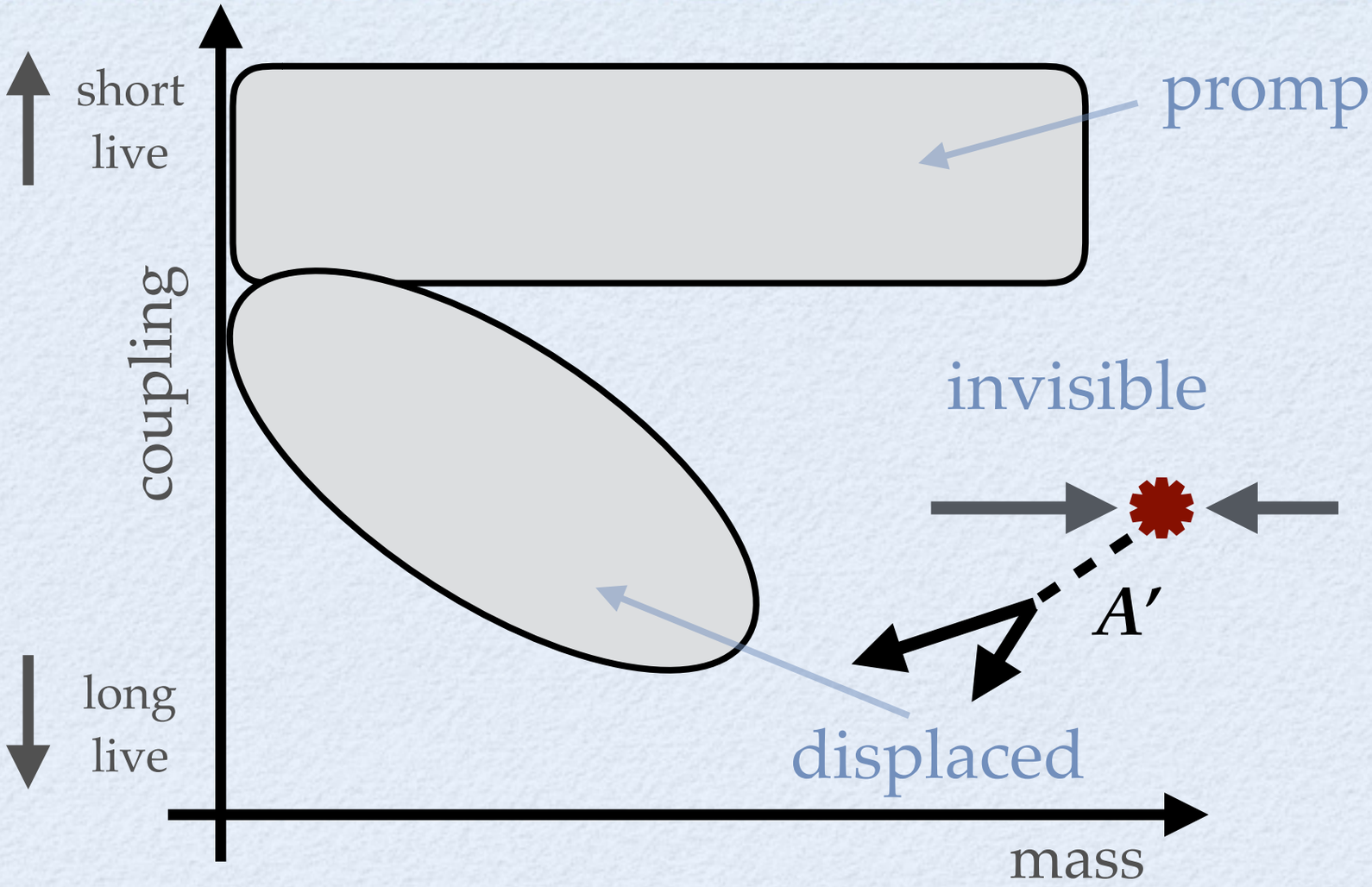
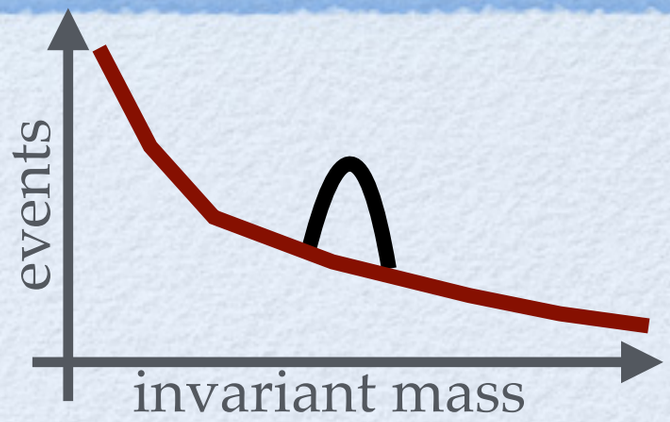


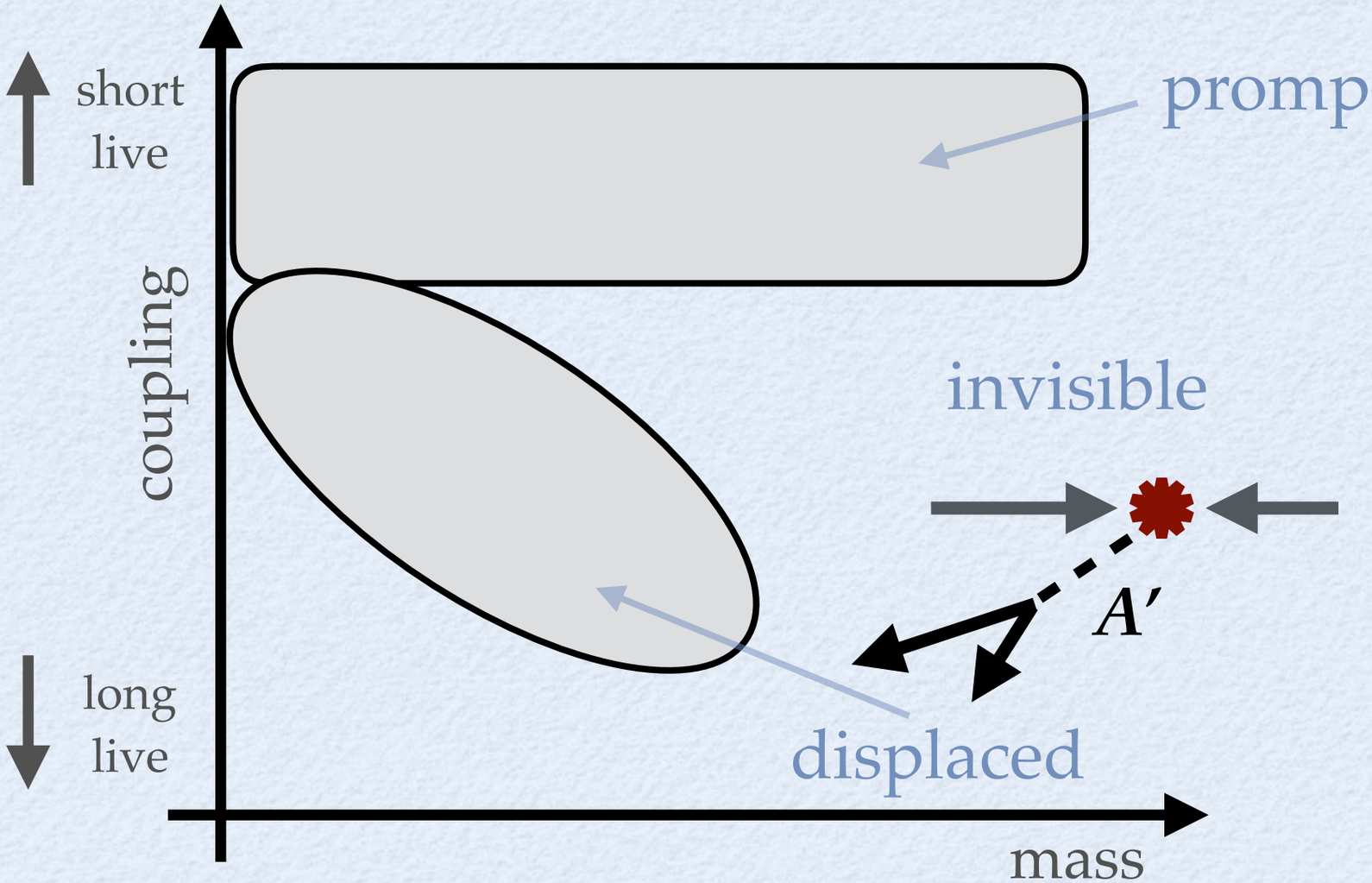


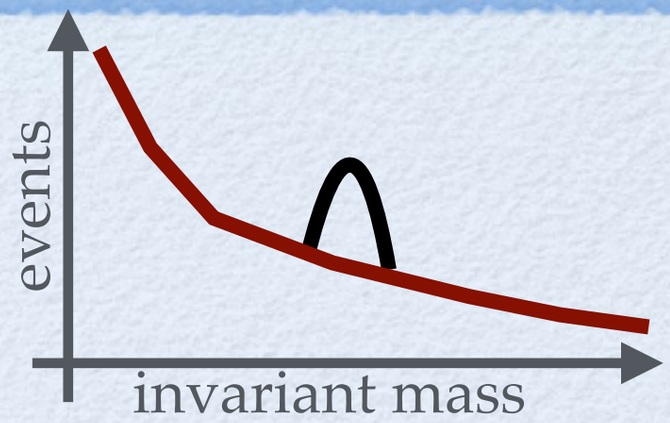
collider:
B-factories
LHCb / ATLAS / CMS
KLOE

rare decays:
NA48, NA62
B-factories, LHCb,
Mu3e

fixed target:
HPS, PrimEx, GlueX

SIGNATURES AND EXPERIMENTS





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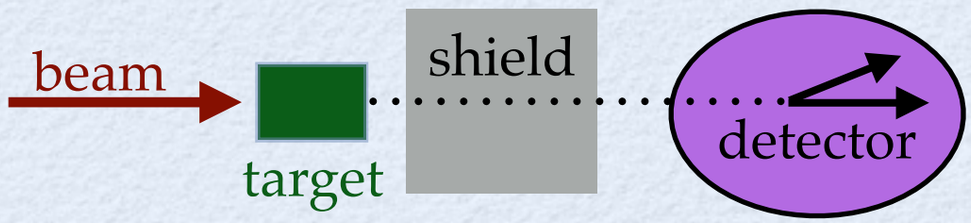
fixed target:
HPS, PrimEx, GlueX

beam-dump:
E774, NA64, E141, KE, Orsay, E137,
NOMAD, PS191, nuCAL, FASER



DARK PHOTON

$X_\mu = A'_\mu$:

(kinetic mixing)

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

Holdom, 86′

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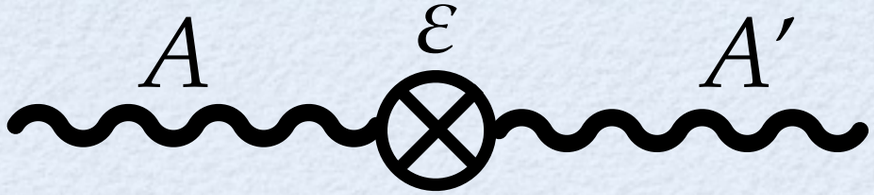
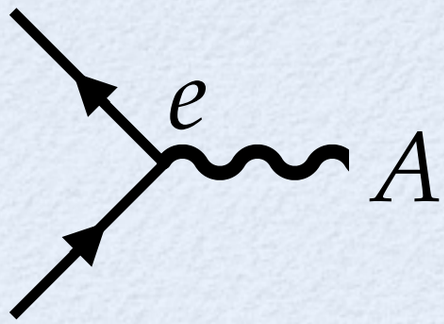


(kinetic mixing)

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

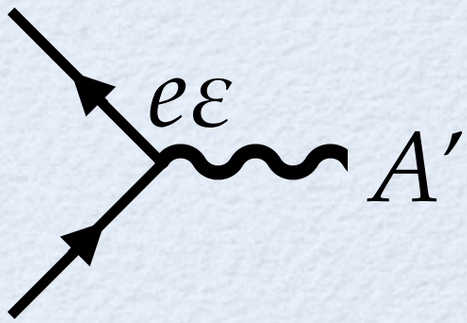
Holdom, 86′

electromagnetic process



$m_A = 0$

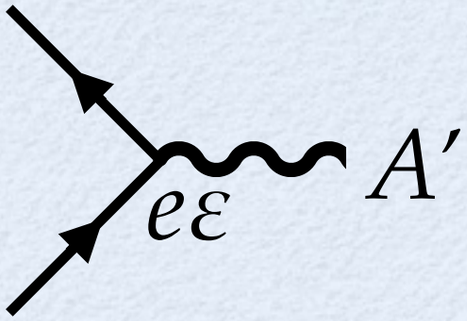
dark photon process

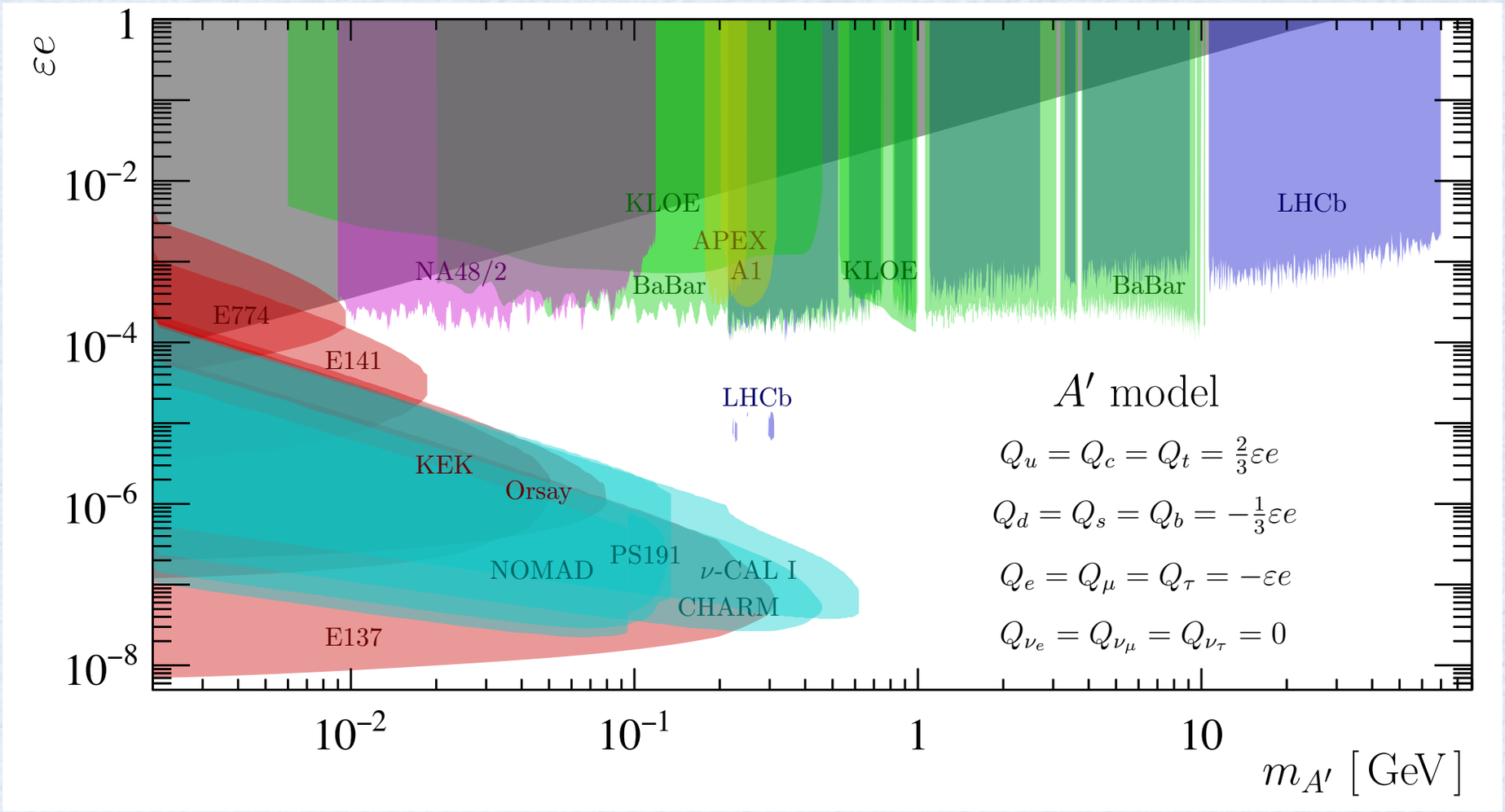


+ mass effect

($m_{A'} > 0$)

DARK PHOTON





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

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

$$\sigma_{A'} \mathrm{BR}_{A' \to \mathcal{F}} \varepsilon(\tau_{A'}) = \sigma_X \mathrm{BR}_{X \to \mathcal{F}} \varepsilon(\tau_X)$$

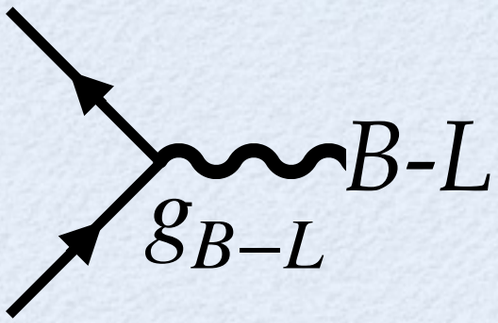
constrain generic vector resonances - X

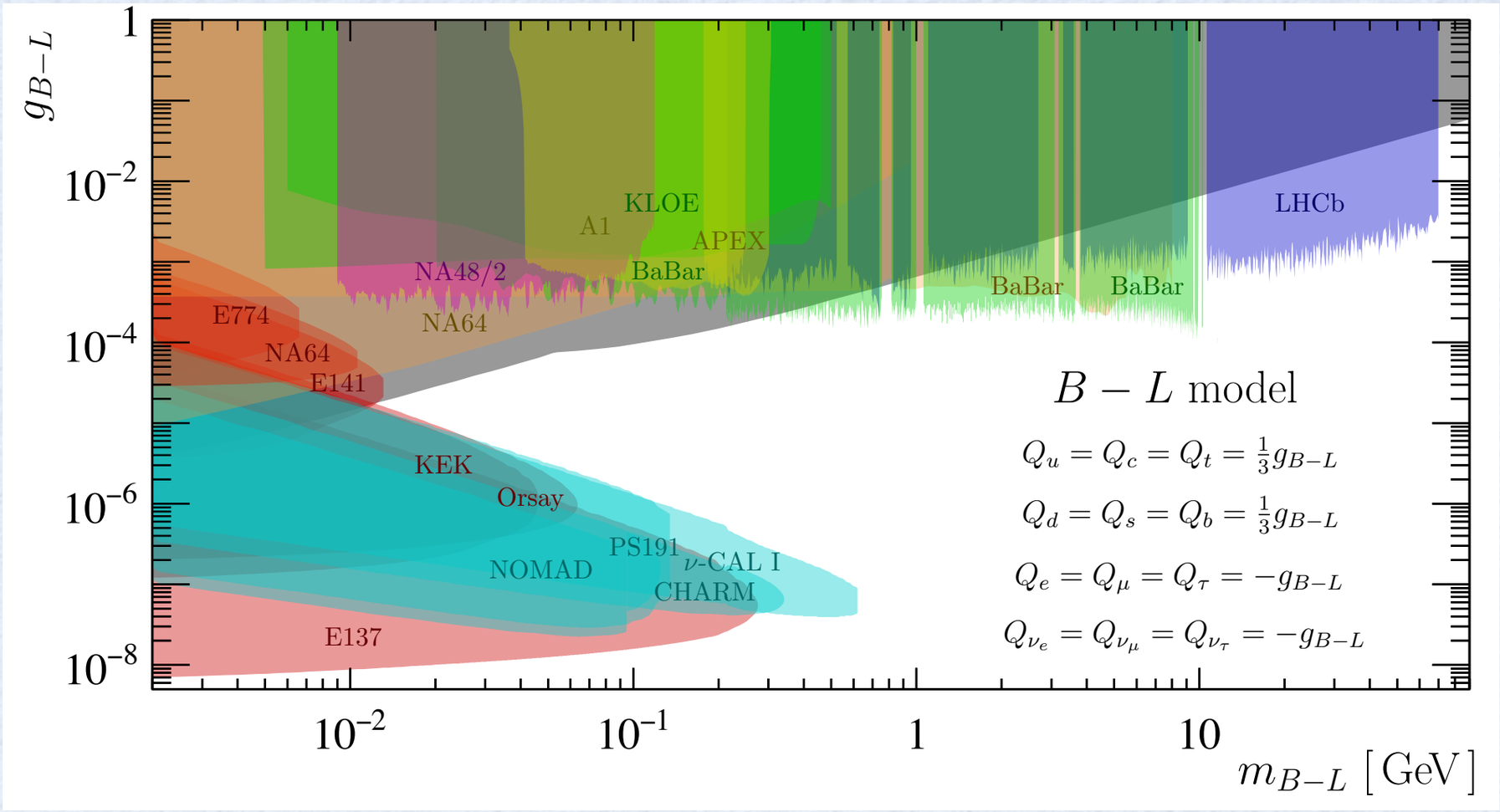
$$g_X^2 = \epsilon^2 \frac{\bar{\sigma}_{A'} \mathrm{BR}_{A' \to \mathcal{F}} \varepsilon(\tau_{A'})}{\bar{\sigma}_X \mathrm{BR}_{X \to \mathcal{F}} \varepsilon(\tau_X)}$$

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

Ilten, YS, Williams, Xue, 1801.04847

B-L GAUGE BOSON





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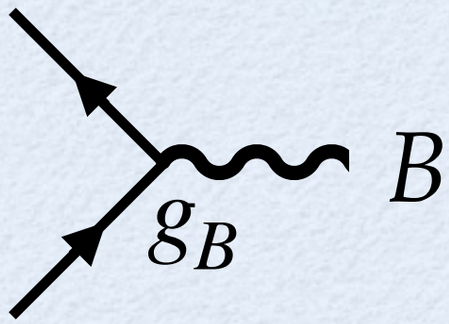
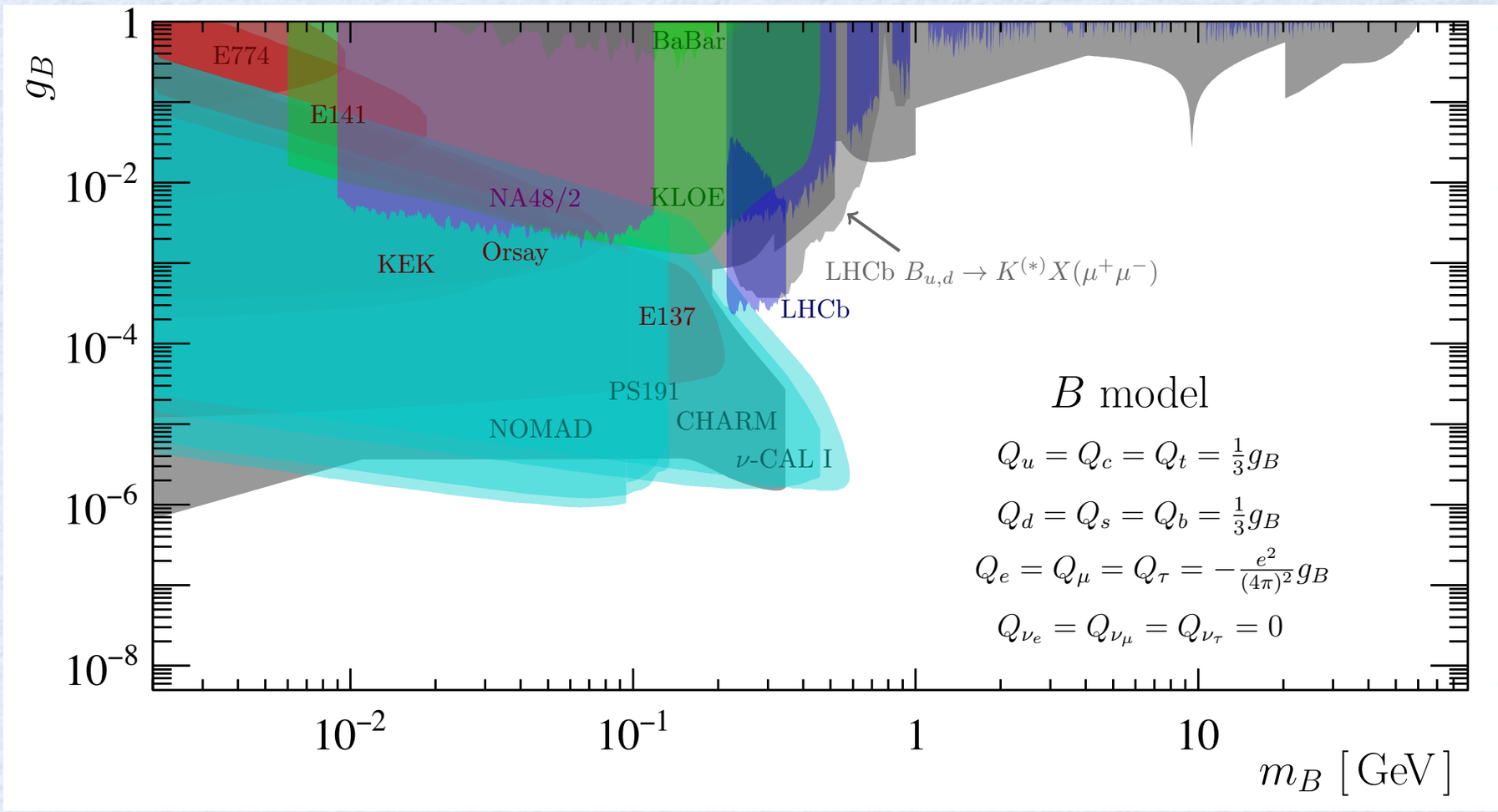
B GAUGE BOSON





electron beam dump — *pp* collider

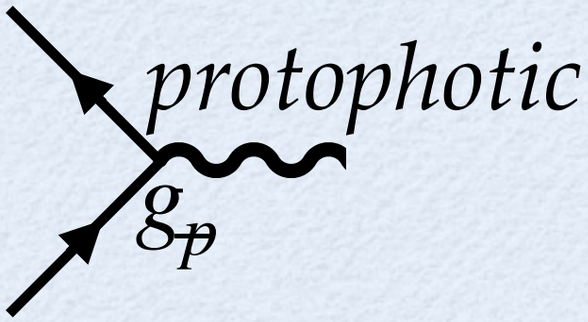
proton beam dump — meson decays

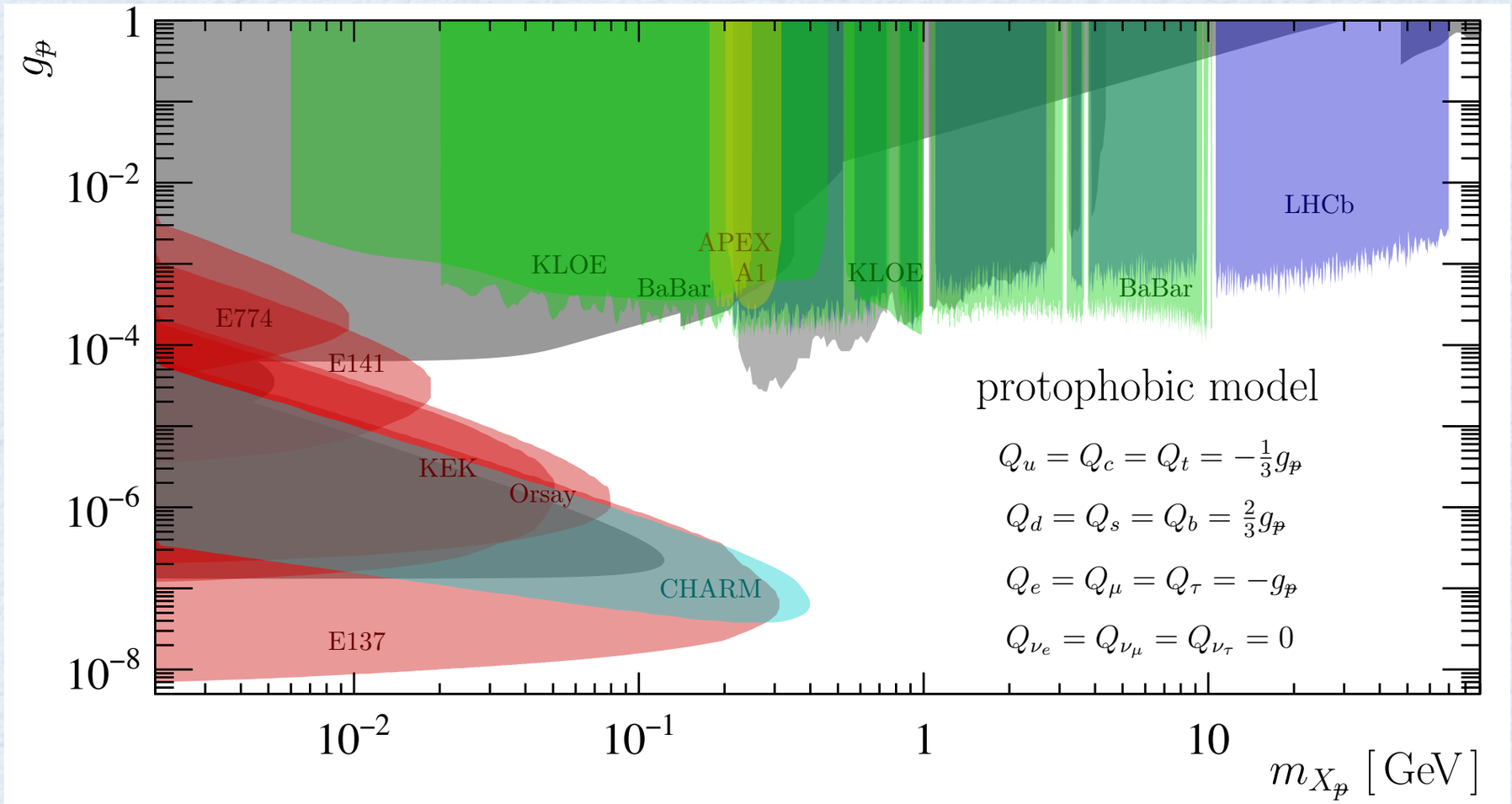
e^+e^- collider — *e* on fixed target

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

Ilten, YS, Williams, Xue, 1801.04847

PROTOPHOBIC GAUGE BOSON





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

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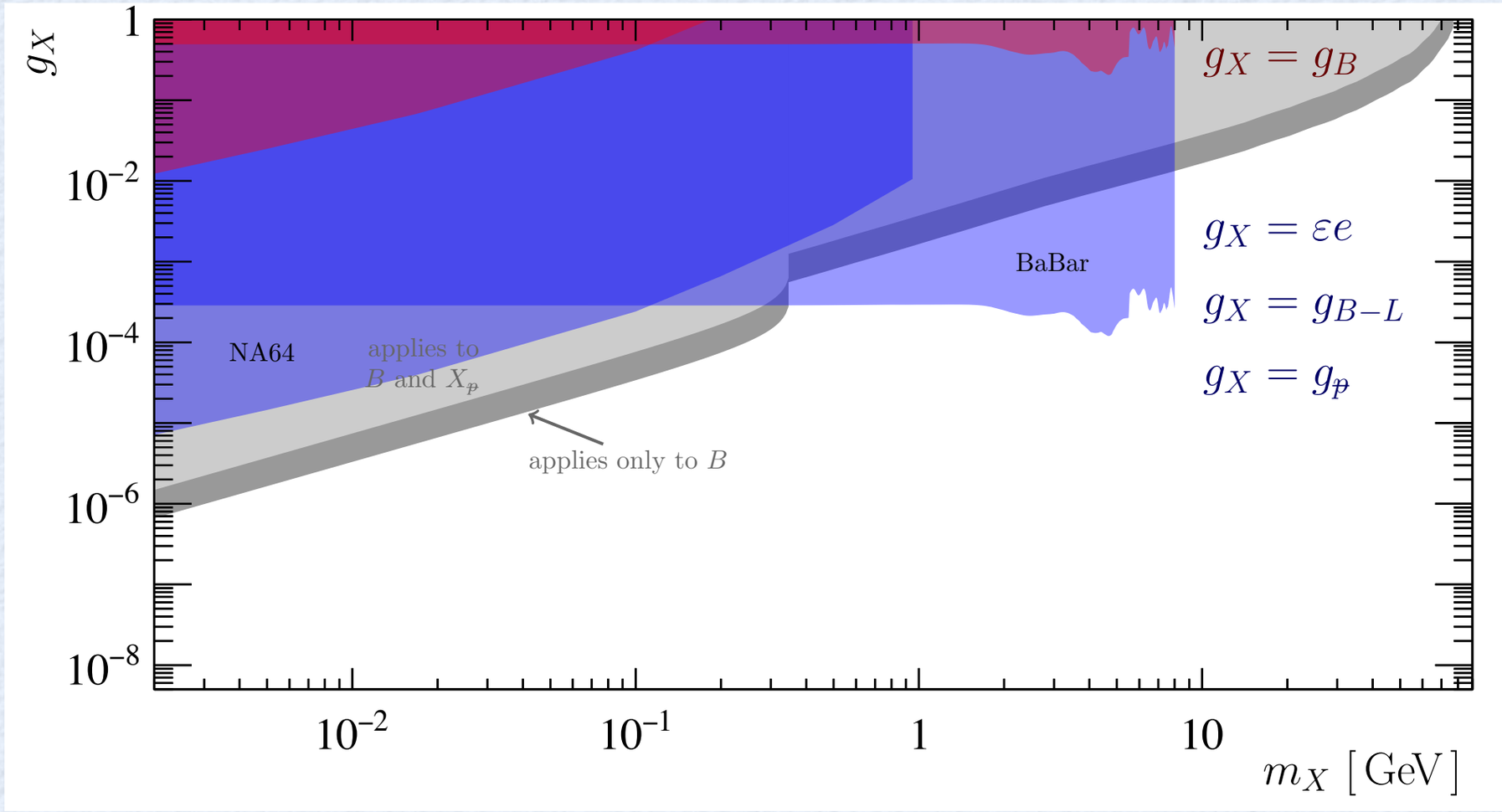
Ilten, YS, Williams, Xue, 1801.04847

BEYOND THE DARK PHOTON MODEL

assuming dominant invisible decay



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Ilten, YS, Williams, Xue, 1801.04847

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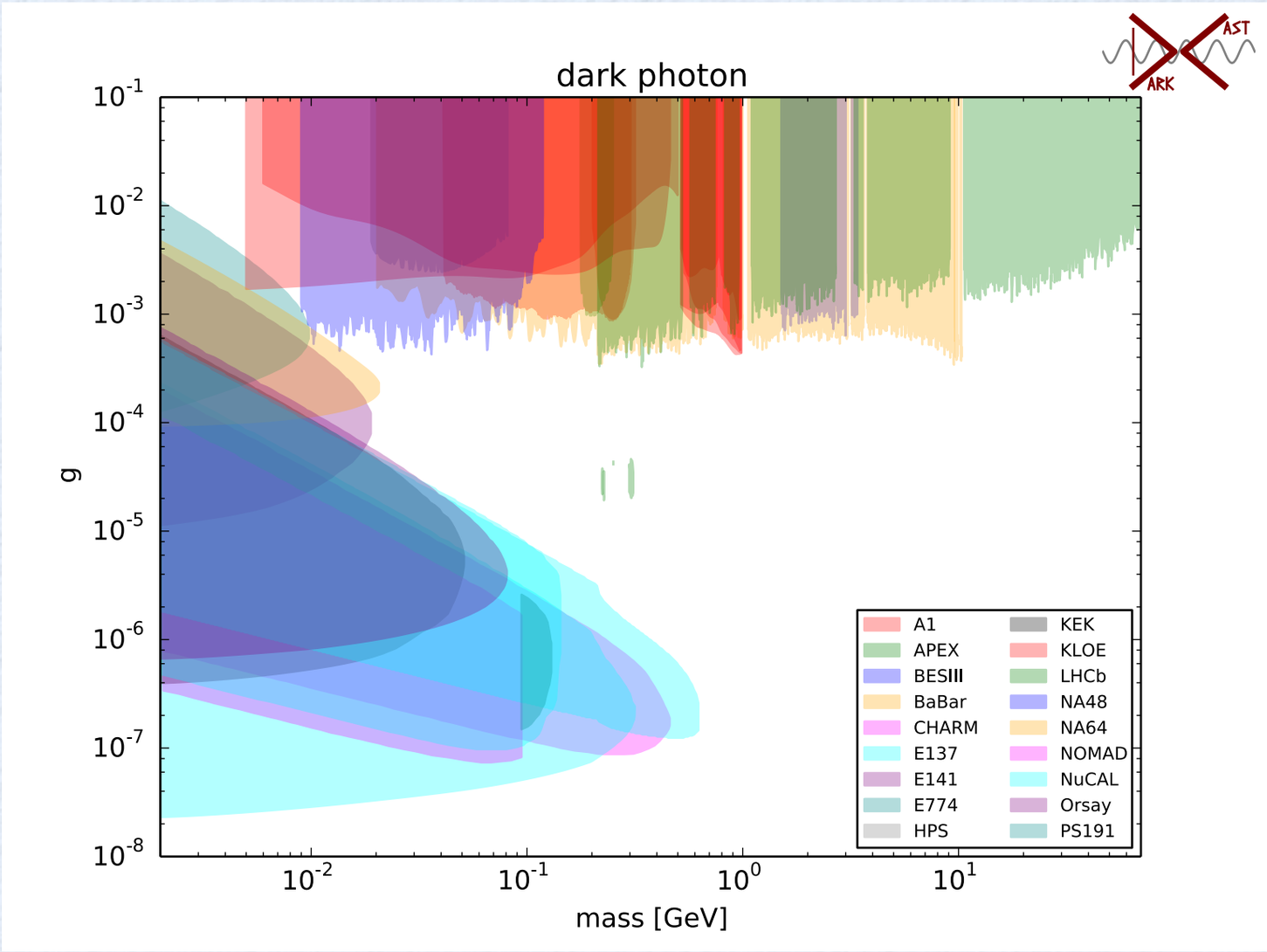

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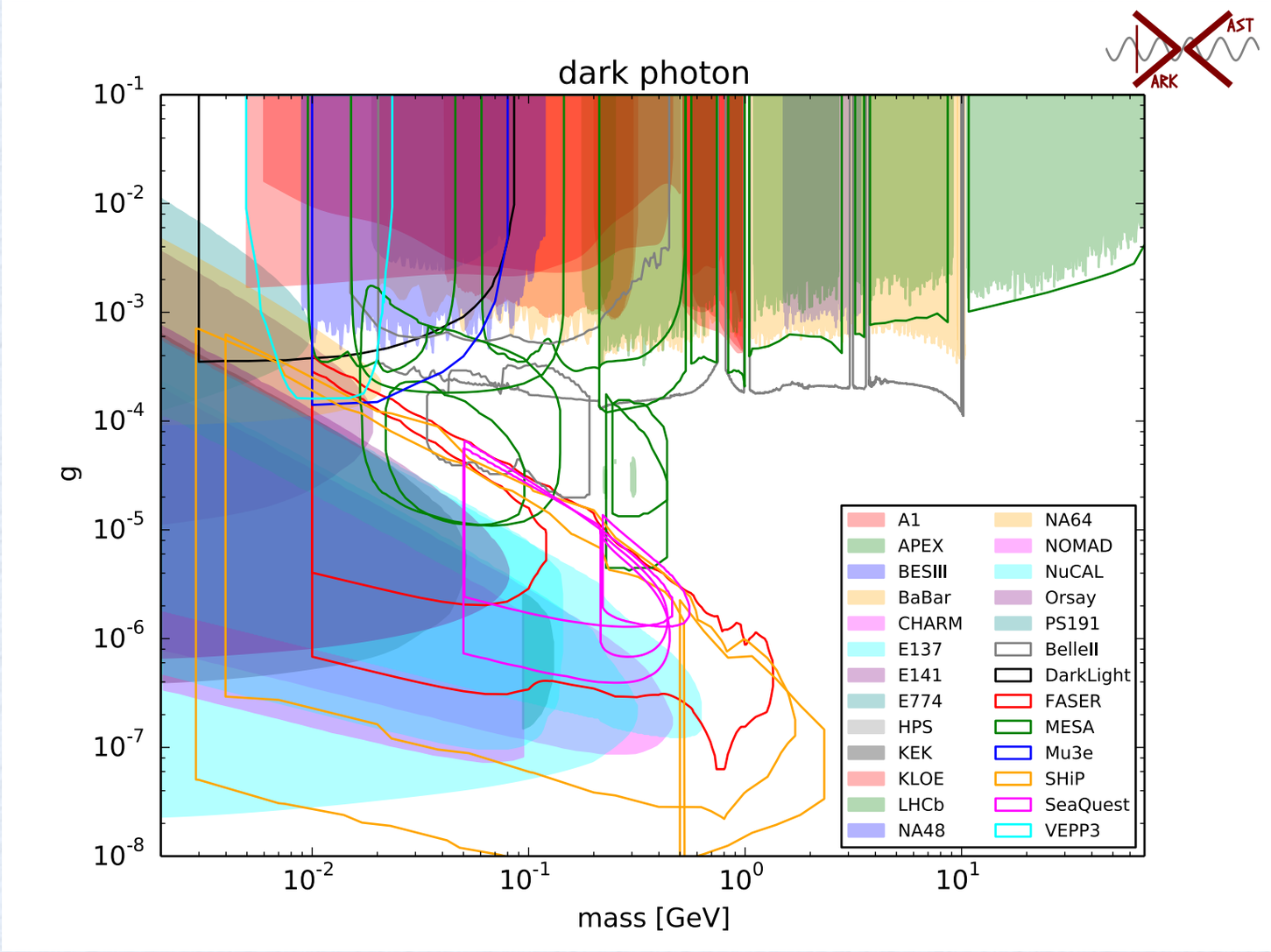

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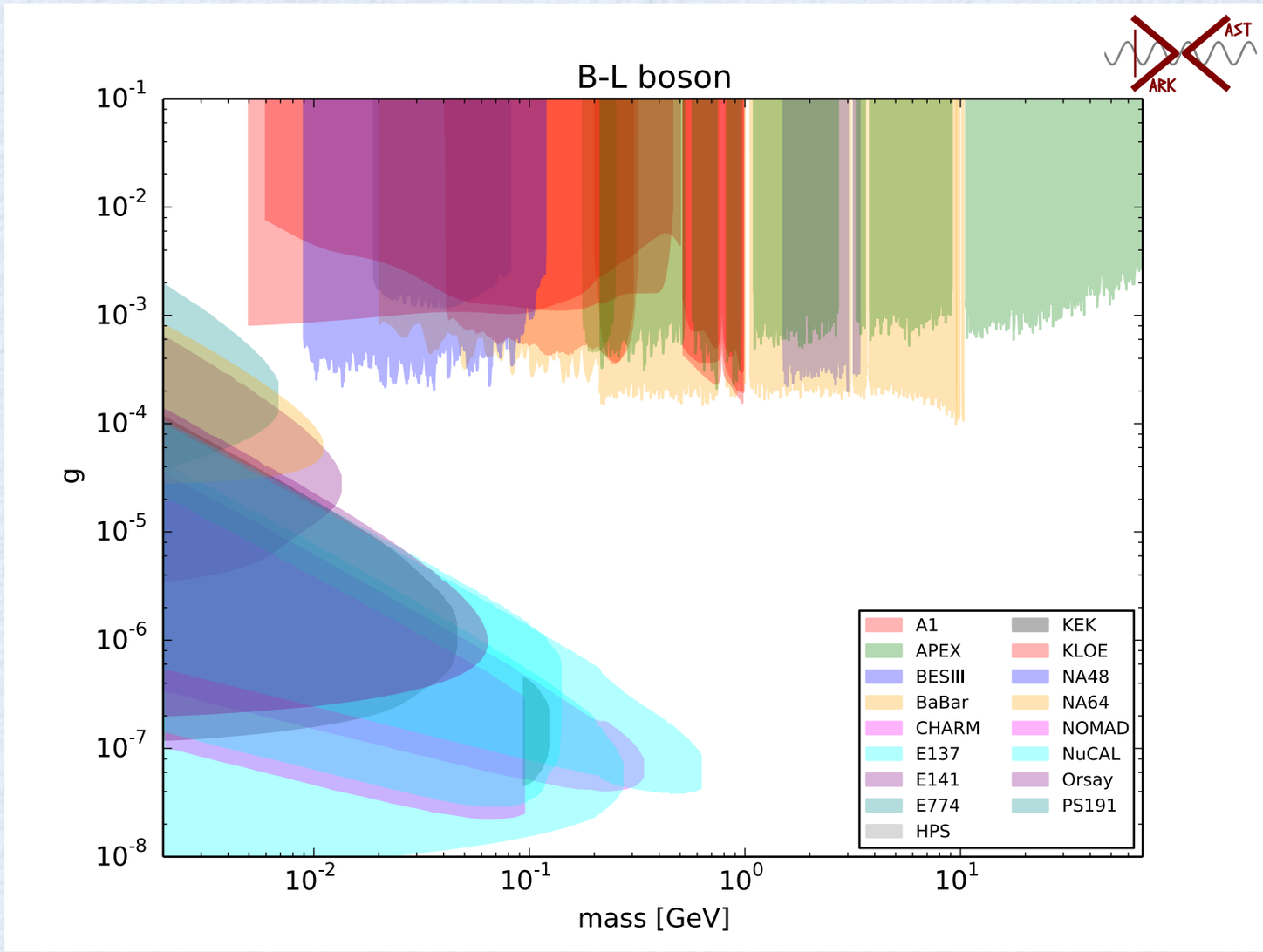

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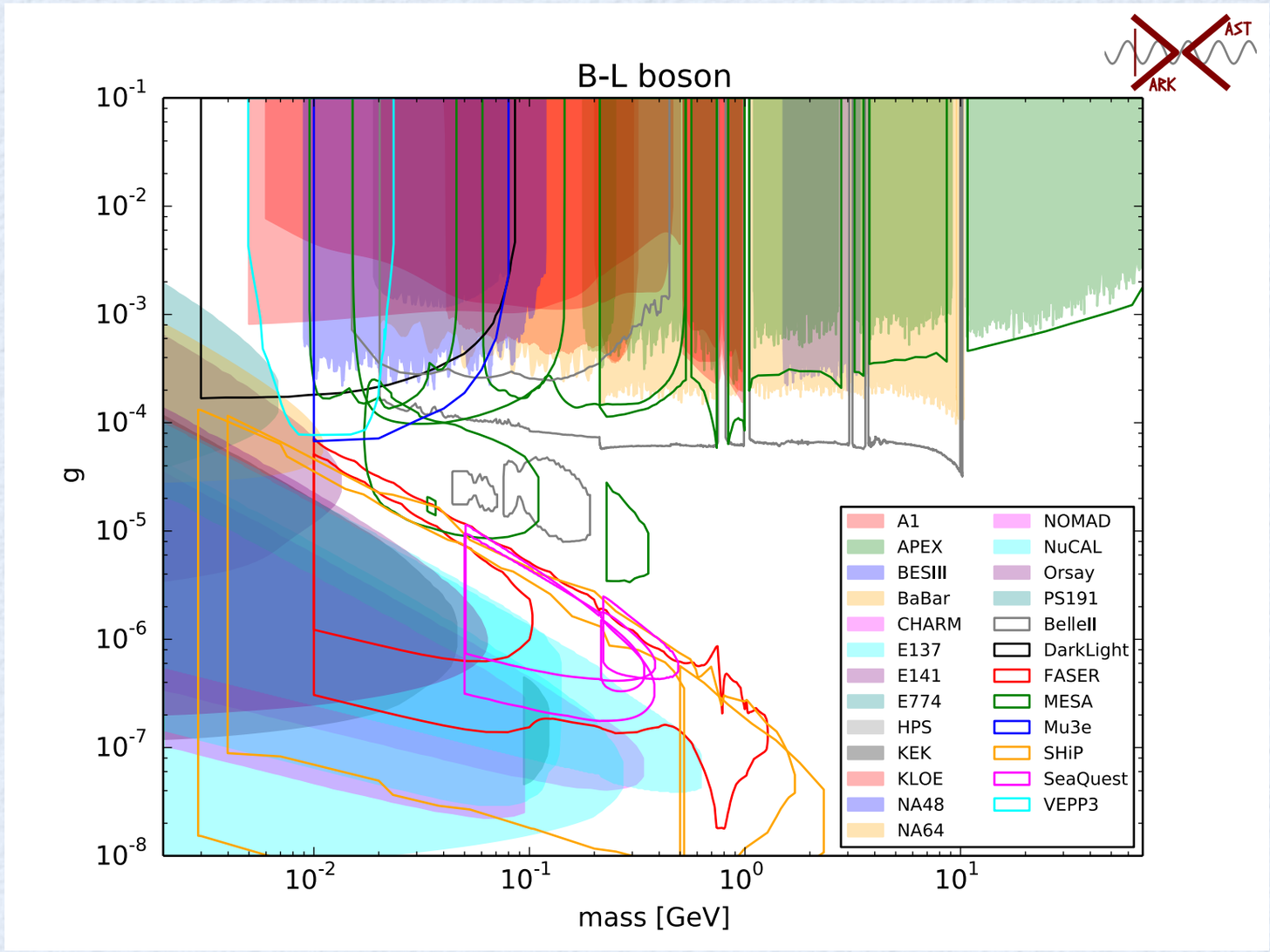

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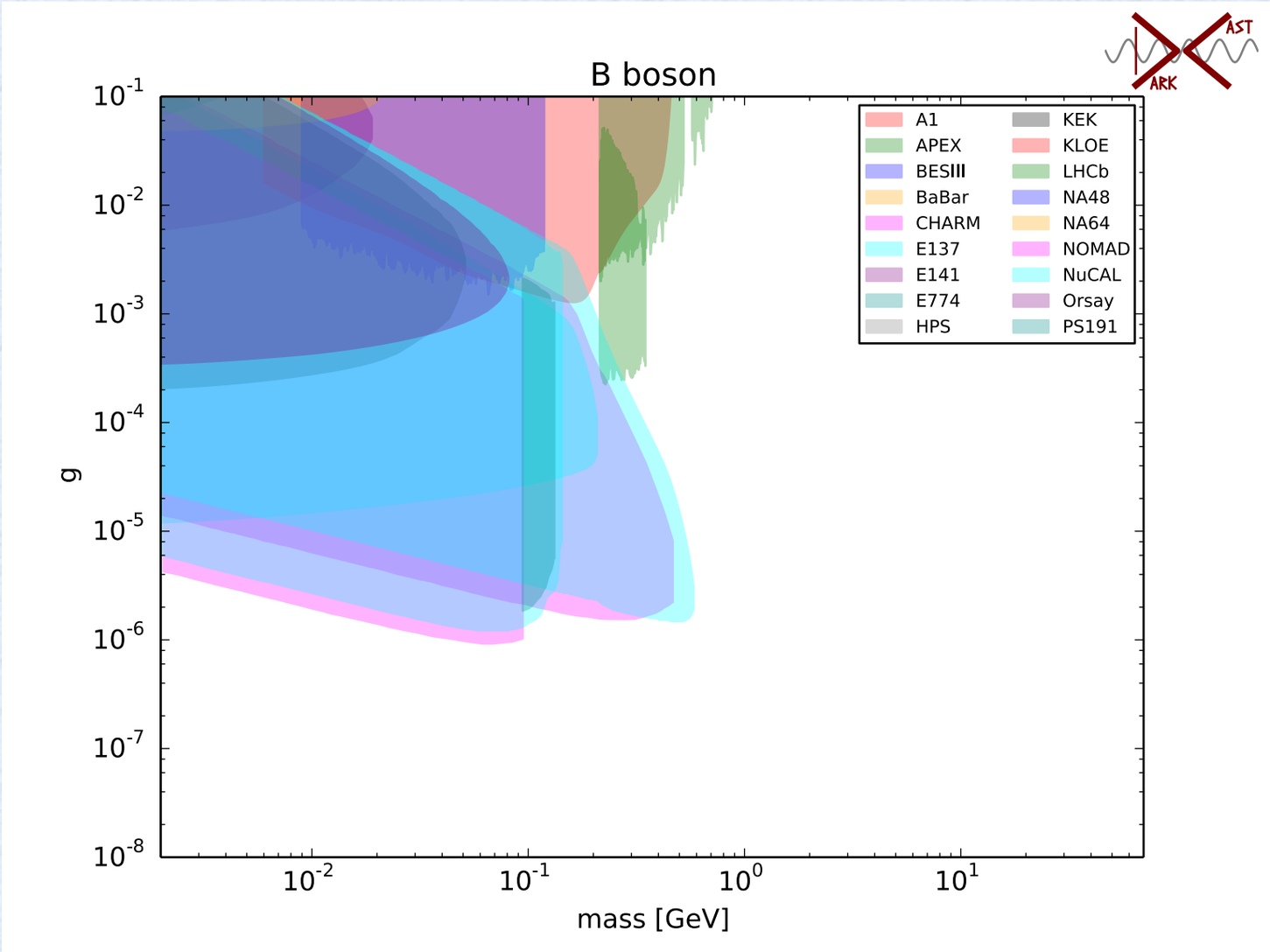

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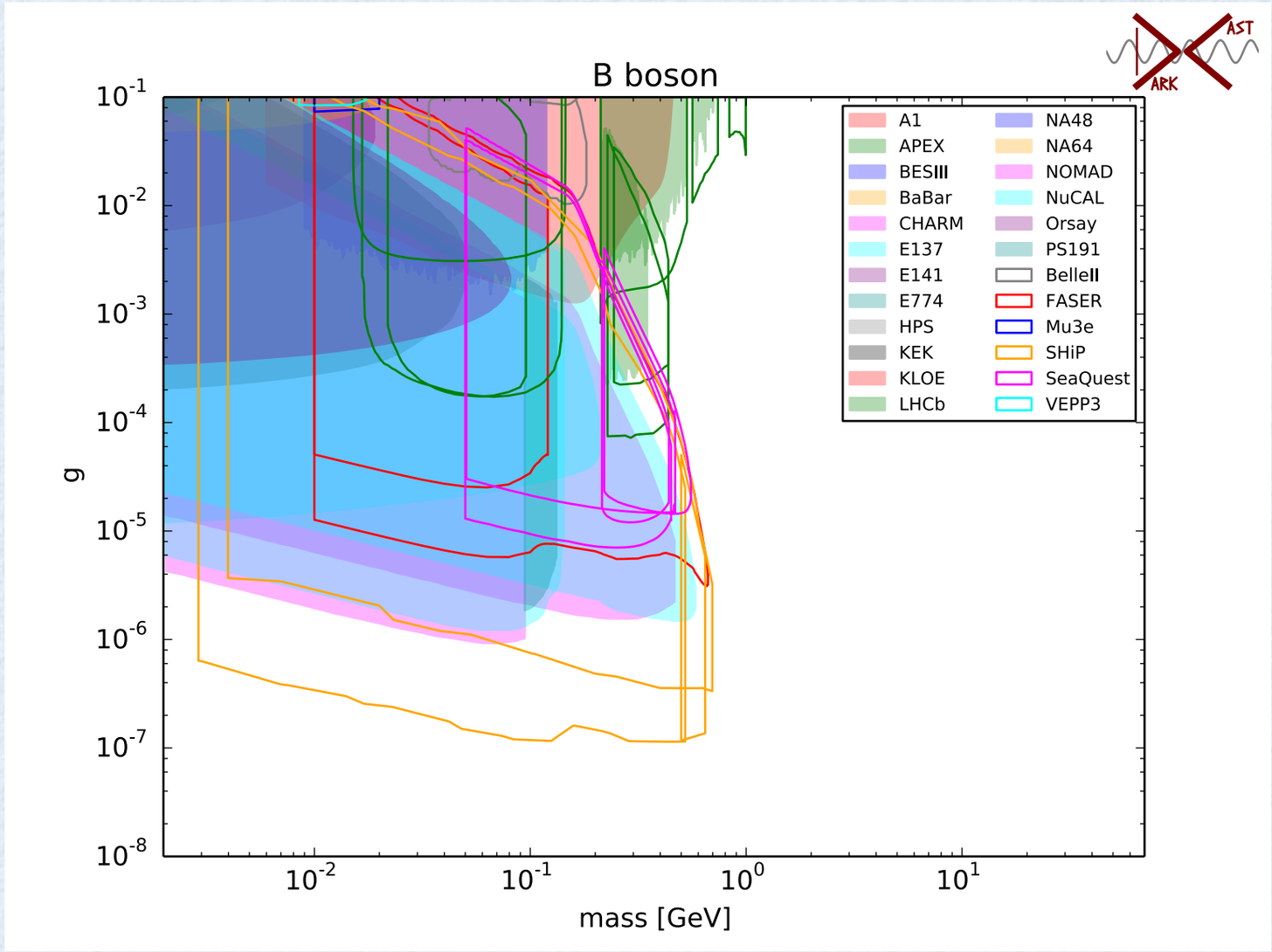

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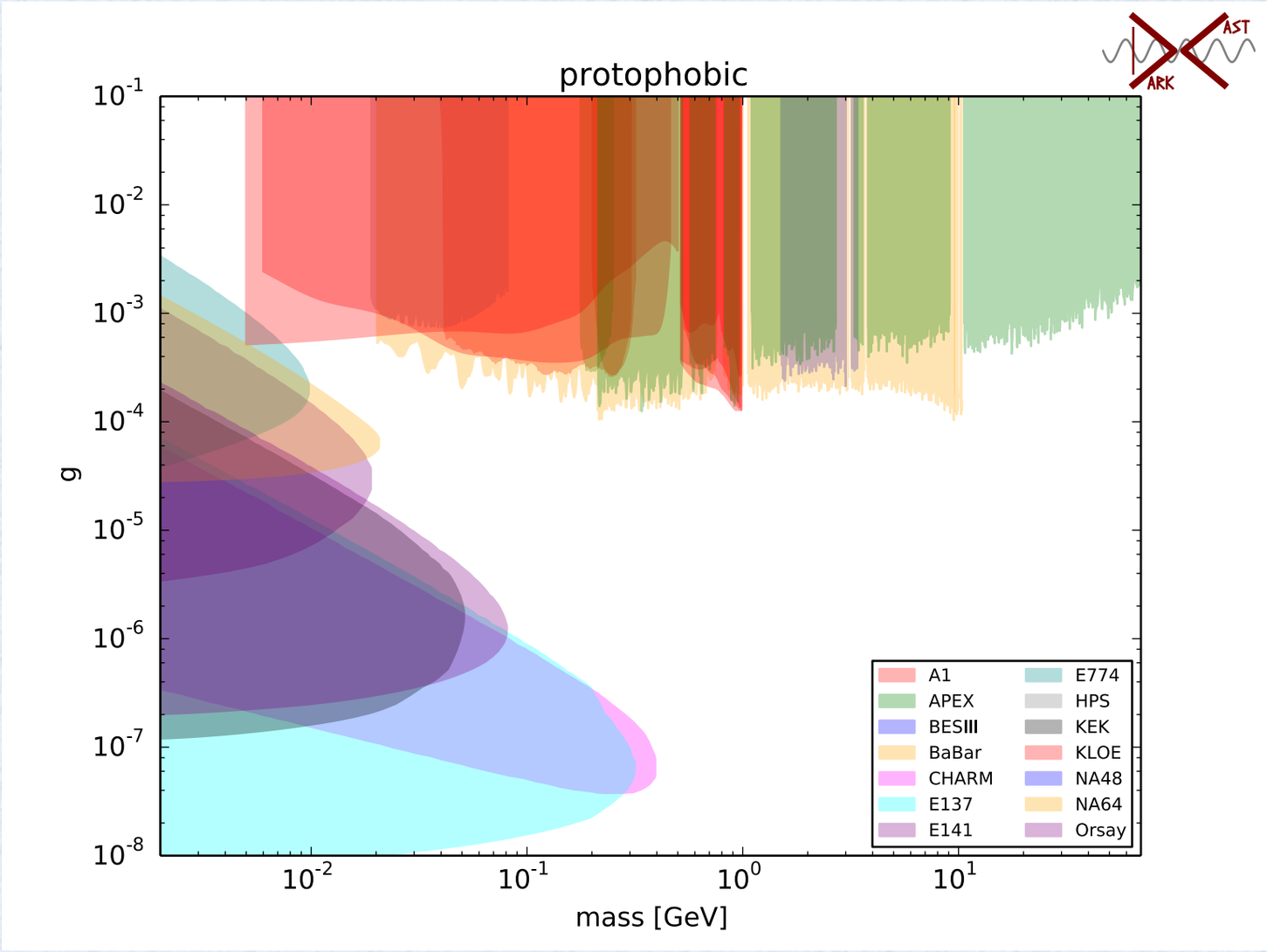

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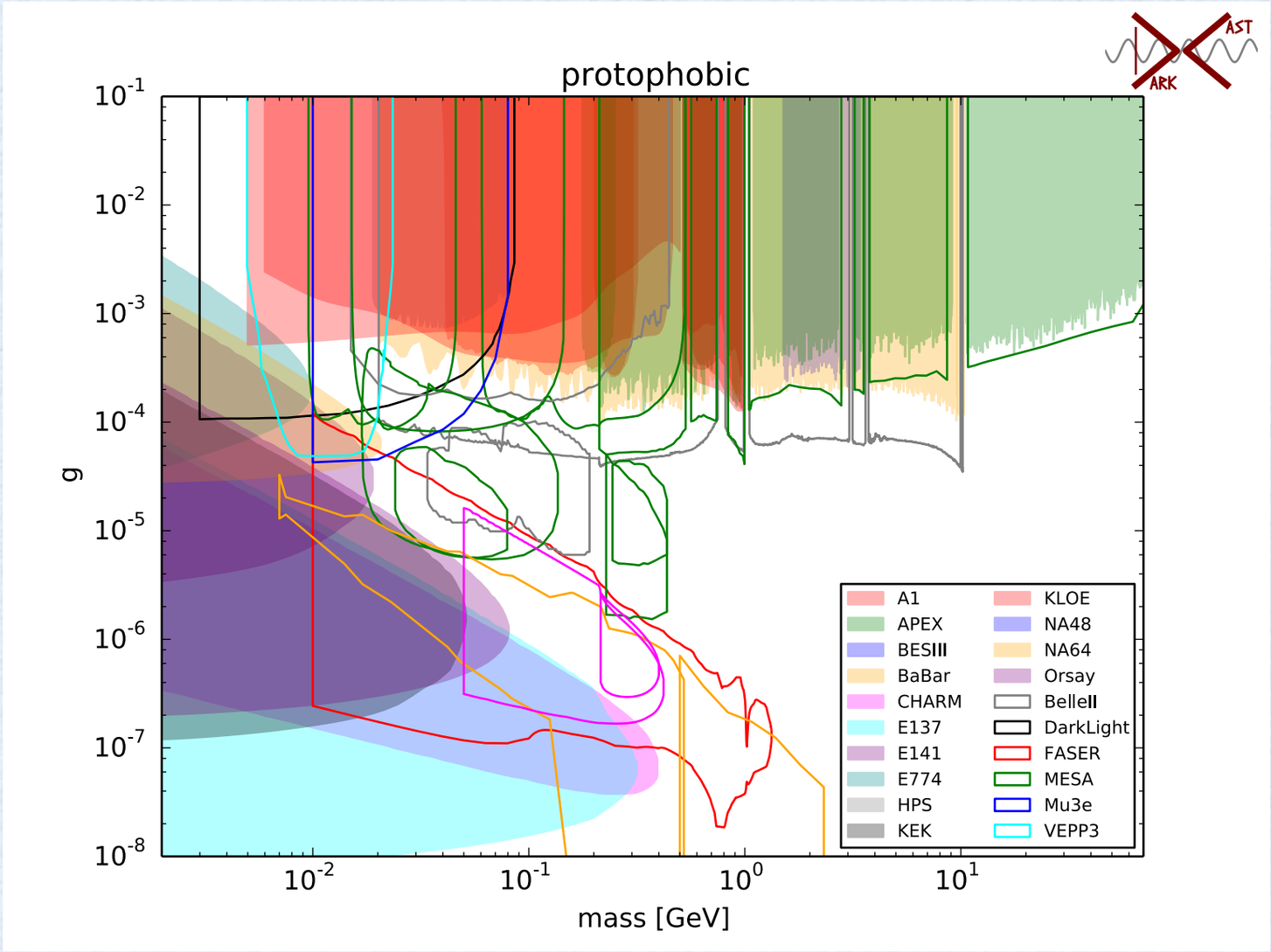

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Ilten, YS, Williams, Xue, 1801.04847

AXION LIKE PARTICLES

pseudo scalars

(appears in various motivated BSM models)

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

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

Aloni, YS, Williams, 1811.03474
Aloni, Fanelli, YS, Williams, work in progress

ALP AT PRIMEX AND GLUEX

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

Aloni, Fanelli, YS, Williams, **work in progress**

ALP AT PRIMEX AND GLUEX

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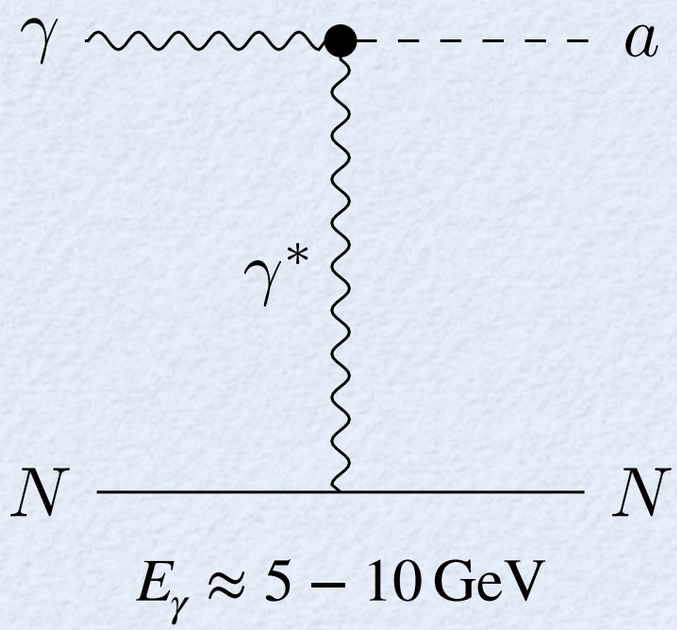
photon on fixed target



data driven signal estimation

Aloni, Fanelli, YS, Williams, **work in progress**

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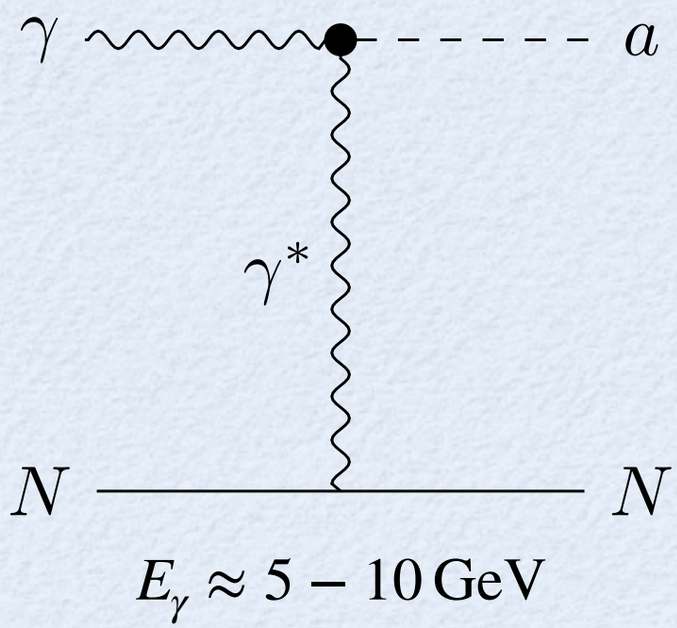

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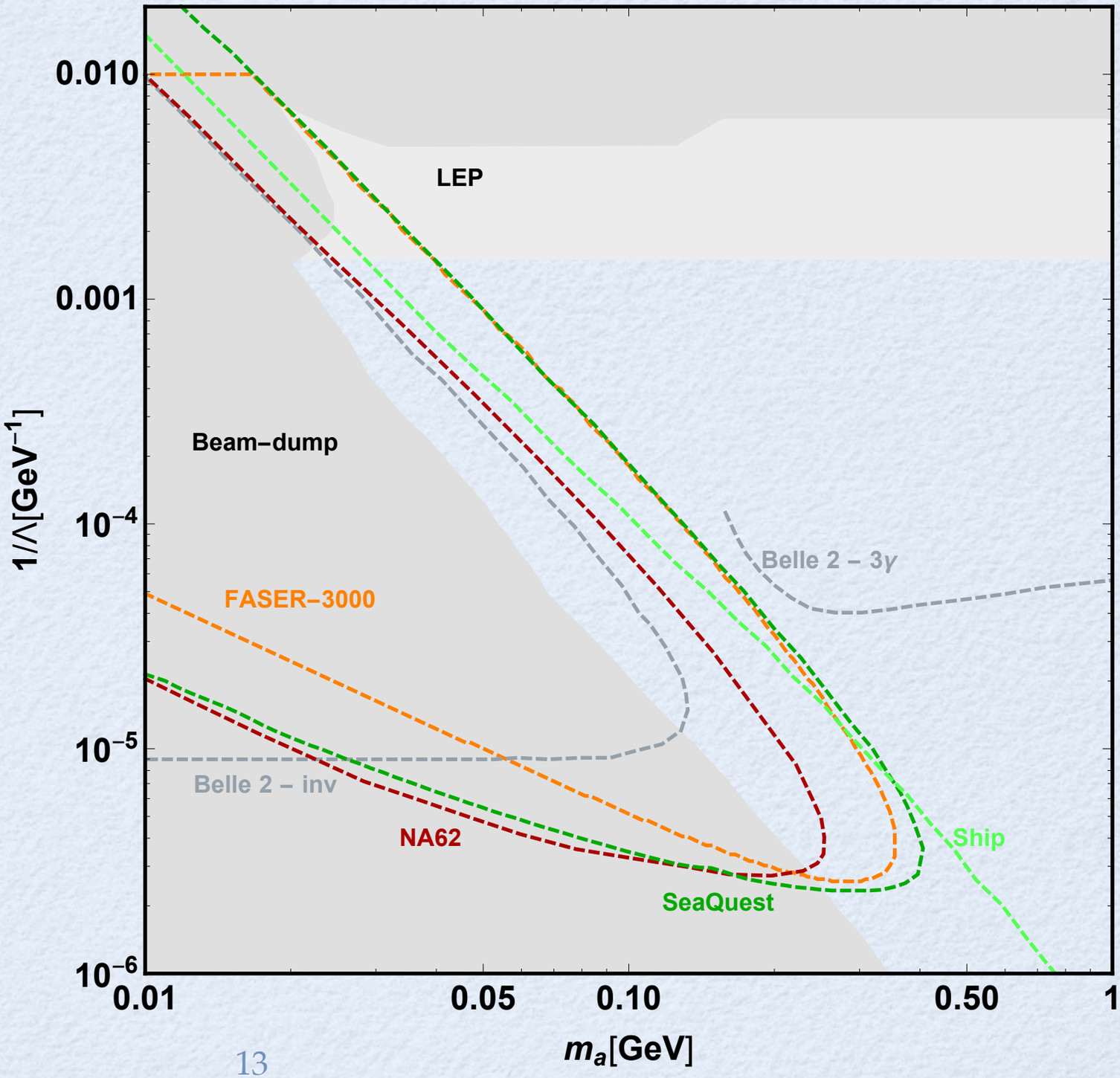

Aloni, Fanelli, YS, Williams, **work in progress**

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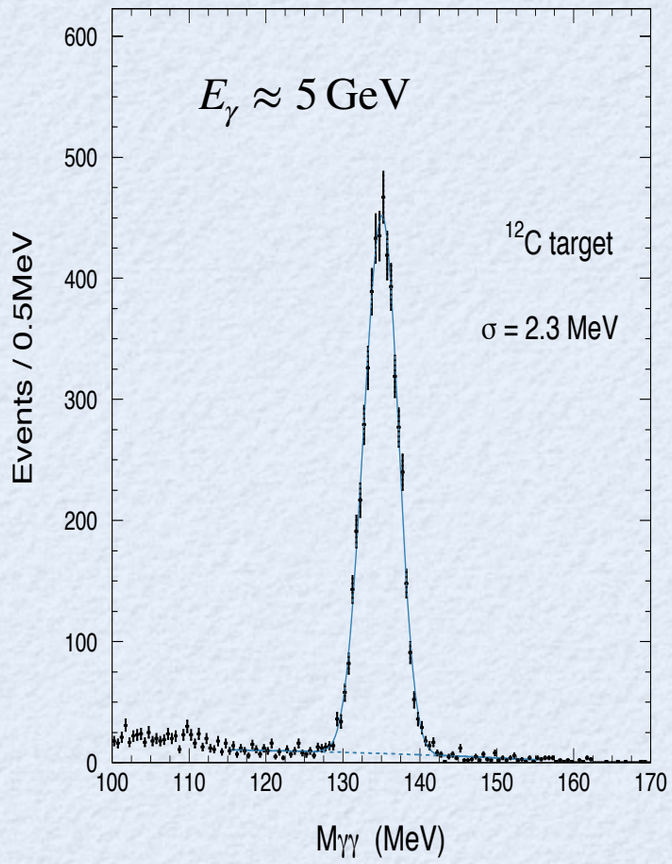
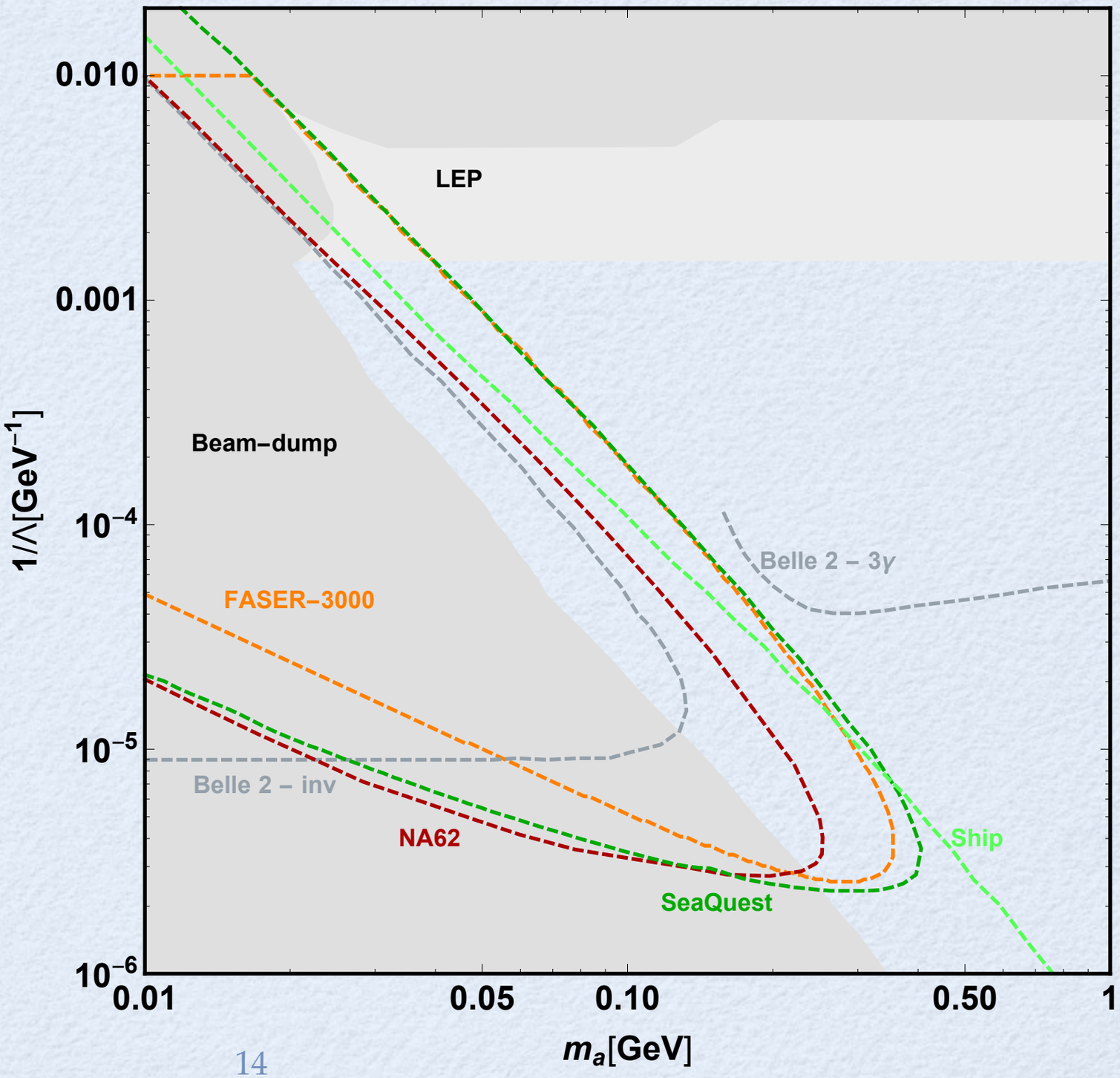
PrimEx,1009.1681





Aloni, Fanelli, YS, Williams, **work in progress**

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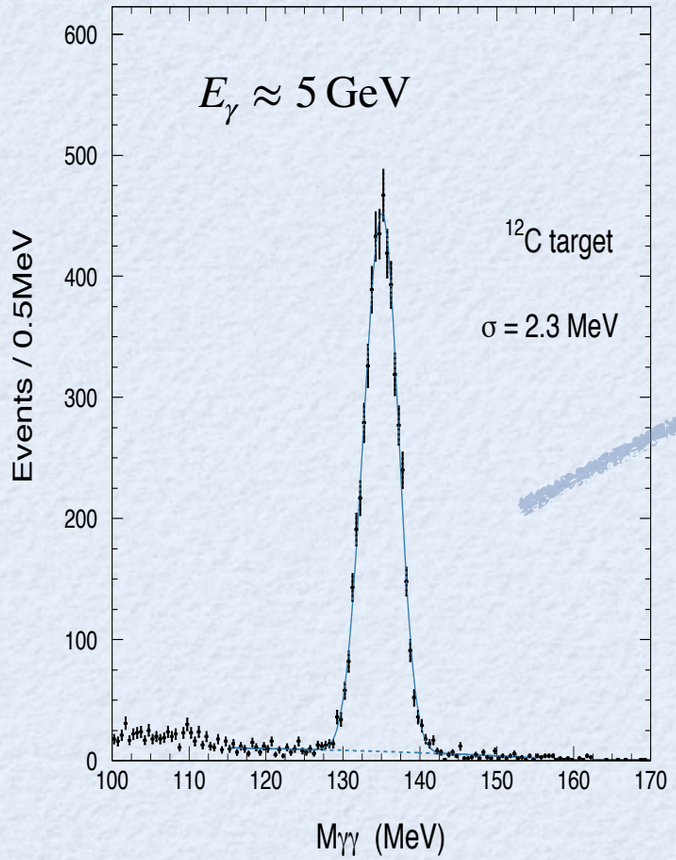

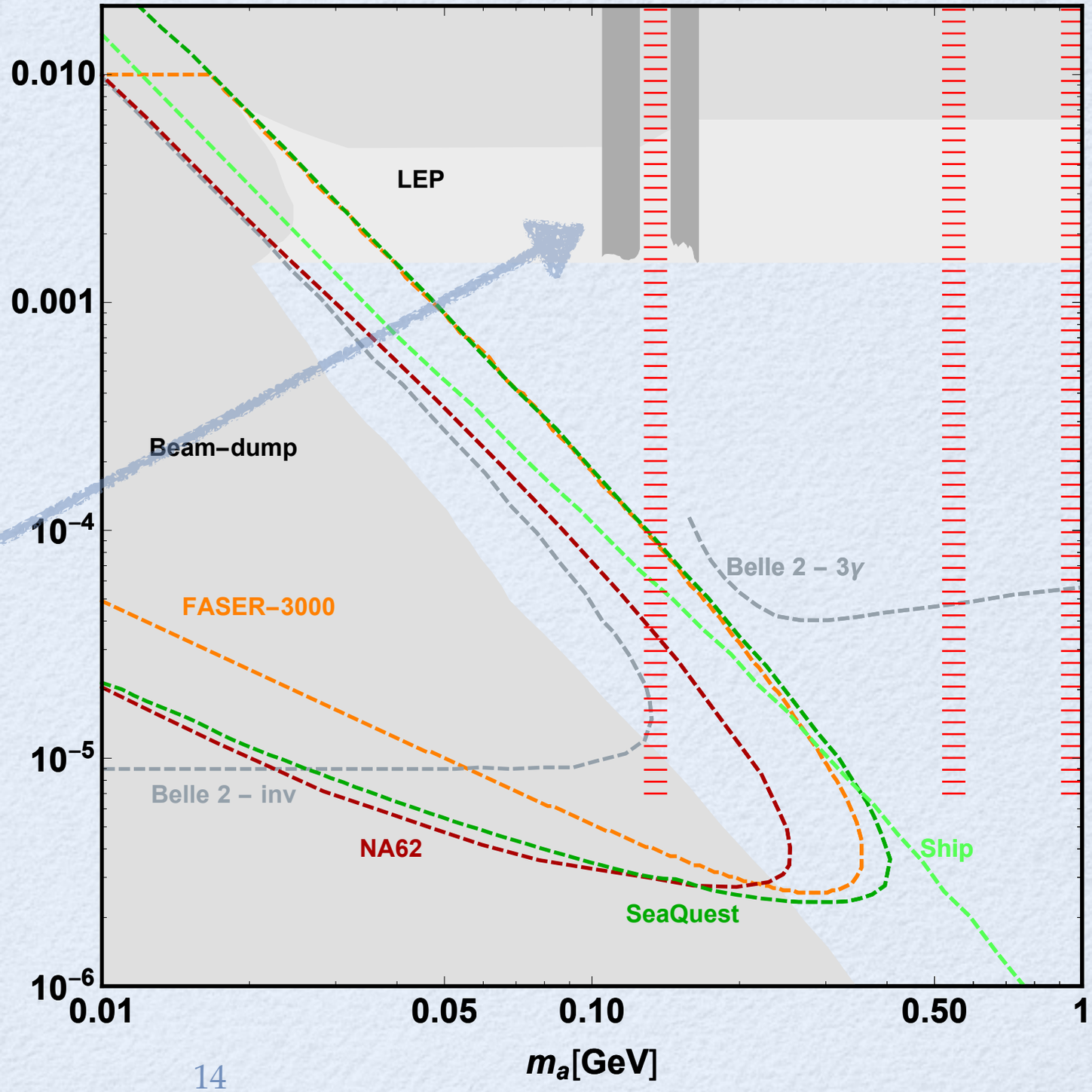

Aloni, Fanelli, YS, Williams, **work in progress**

ALP AT PRIMEX AND GLUEX

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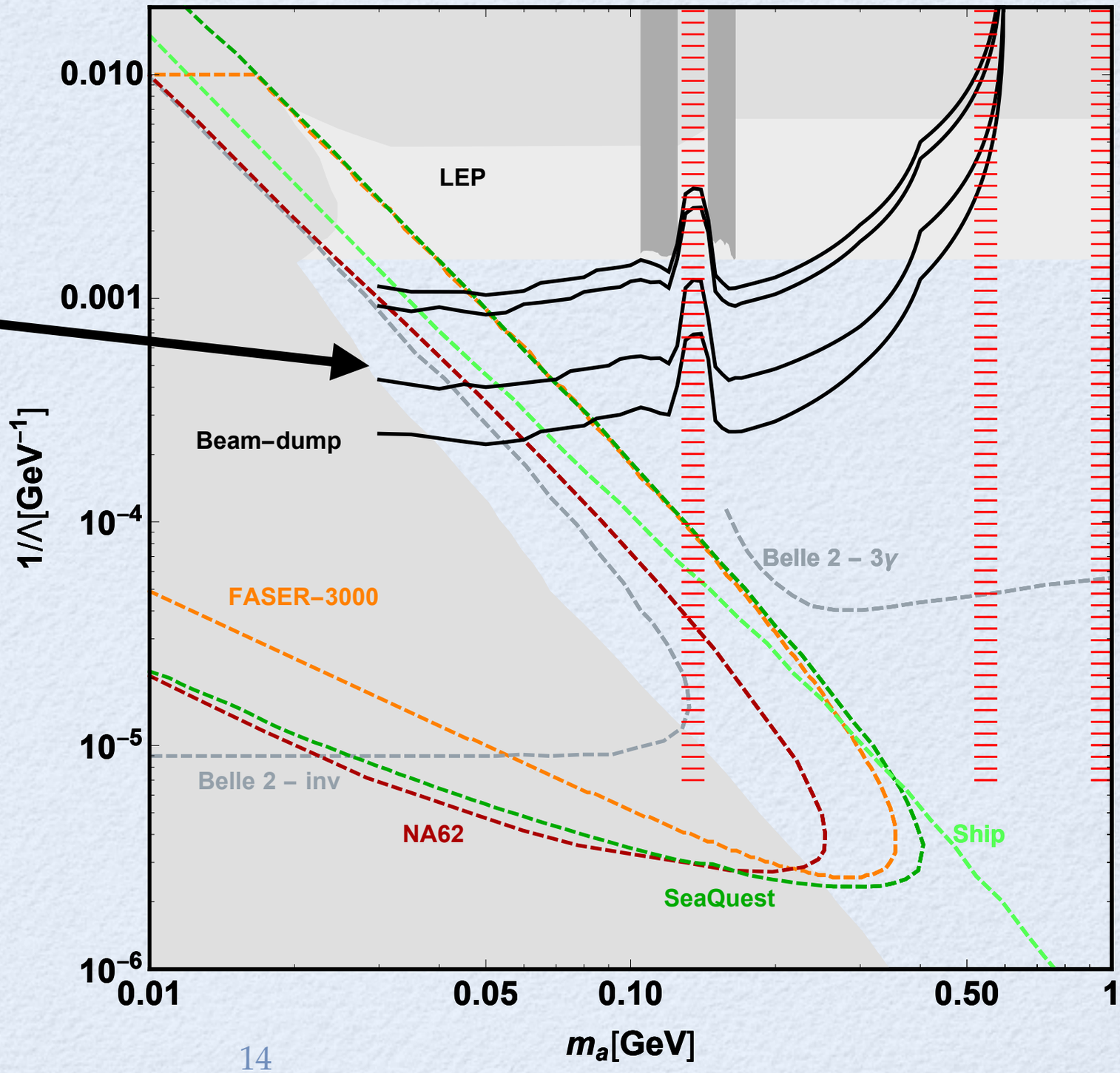
photon on fixed target

PrimEx, 5GeV

(C, Si, Pb - data on tape)



Aloni, Fanelli, YS, Williams, **work in progress**

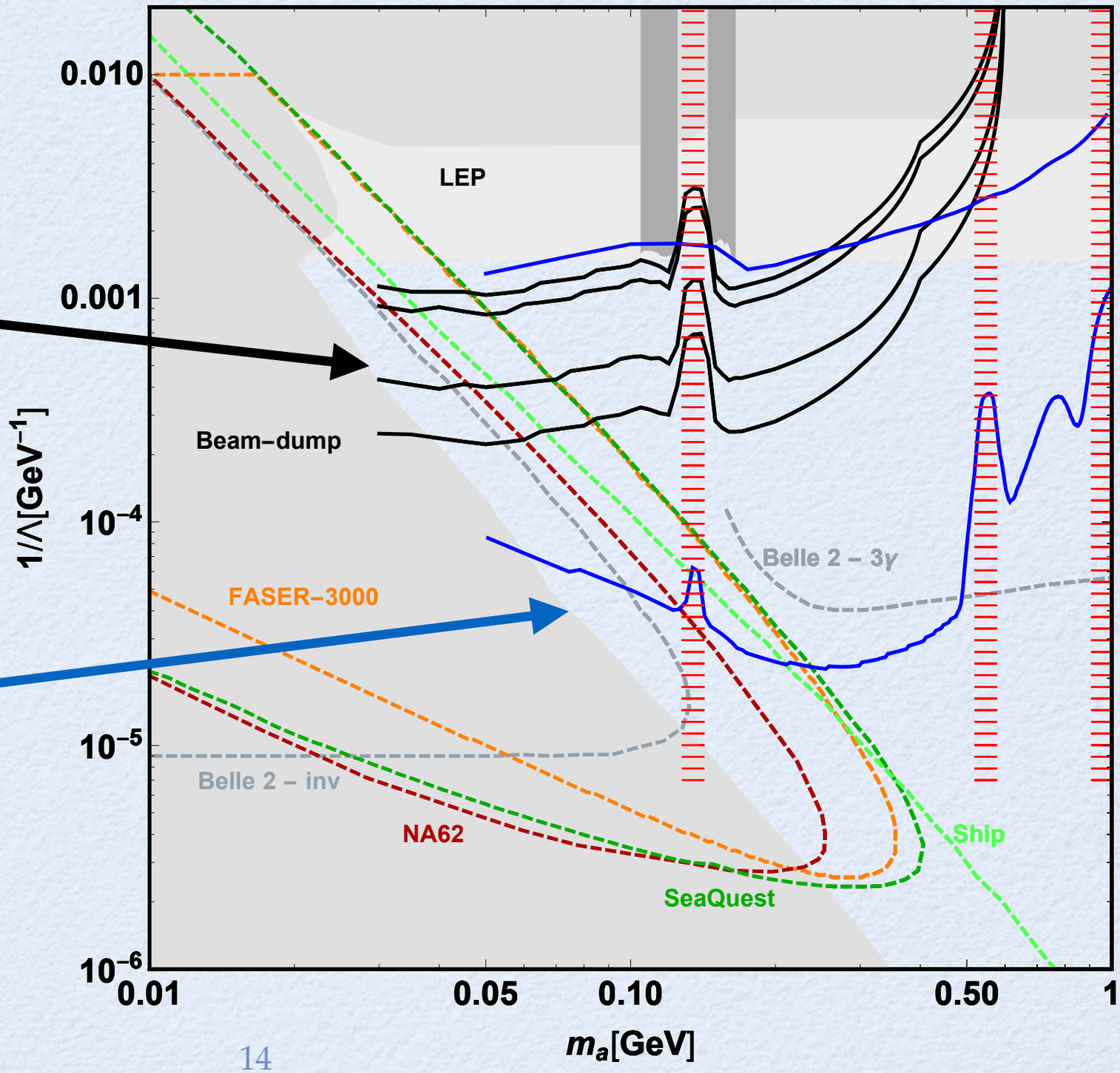
ALP AT PRIMEX AND GLUEX

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

photon on fixed target

PrimEx, 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 TO HADRONS

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

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

Aloni, YS, Williams, 1811.03474

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

$m_a \lesssim GeV$

chiral PT

???

$m_a \gtrsim 2GeV$

pQCD

Aloni, YS, Williams, 1811.03474

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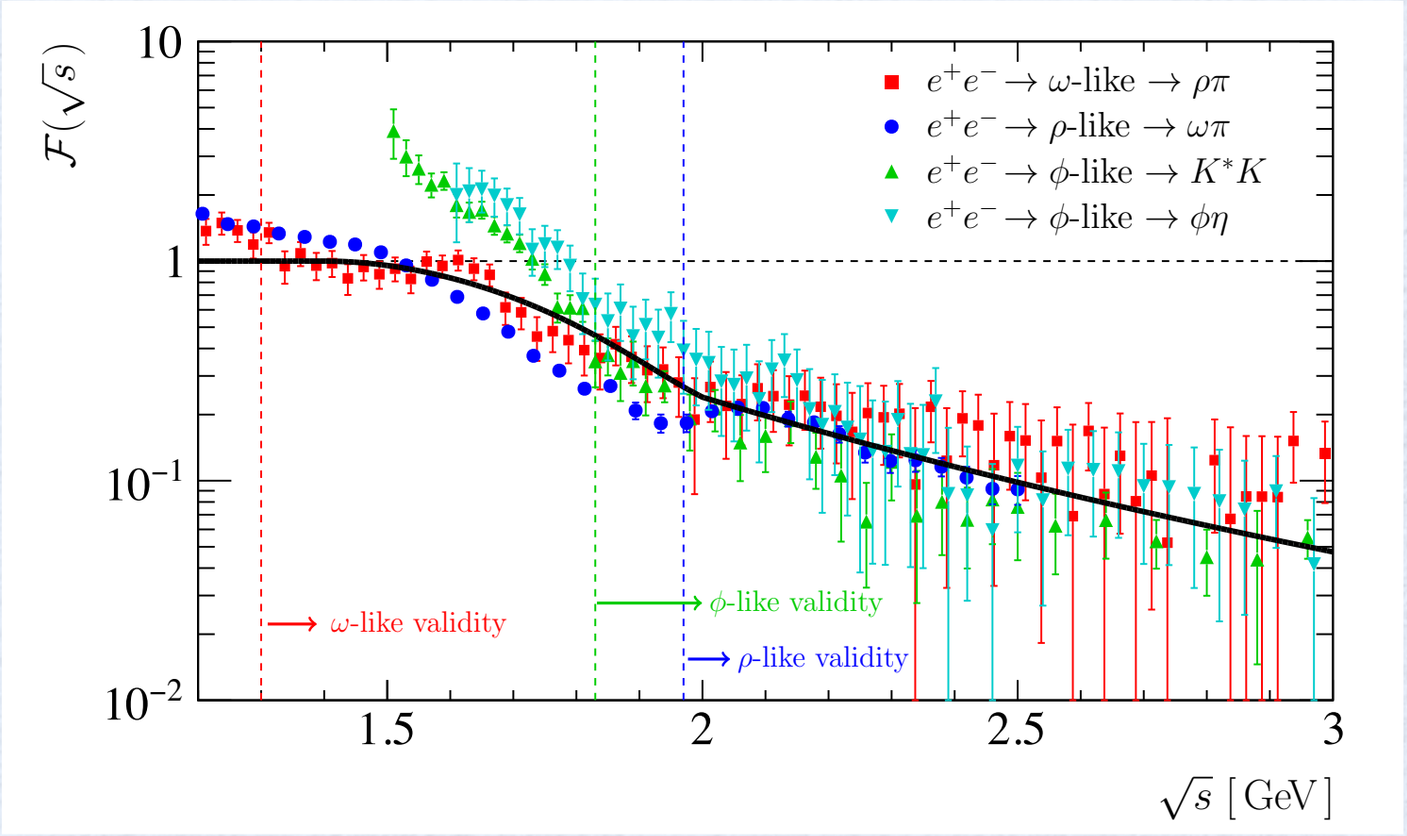
how to estimate hadronic rates for ALPs with GeV scale mass?

$m_a \lesssim GeV$ chiral PT

??? use data!

$m_a \gtrsim 2GeV$ pQCD



Aloni, YS, Williams, 1811.03474

ALPS TO HADRONS

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

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

$m_a \lesssim GeV$ chiral PT

??? use data!

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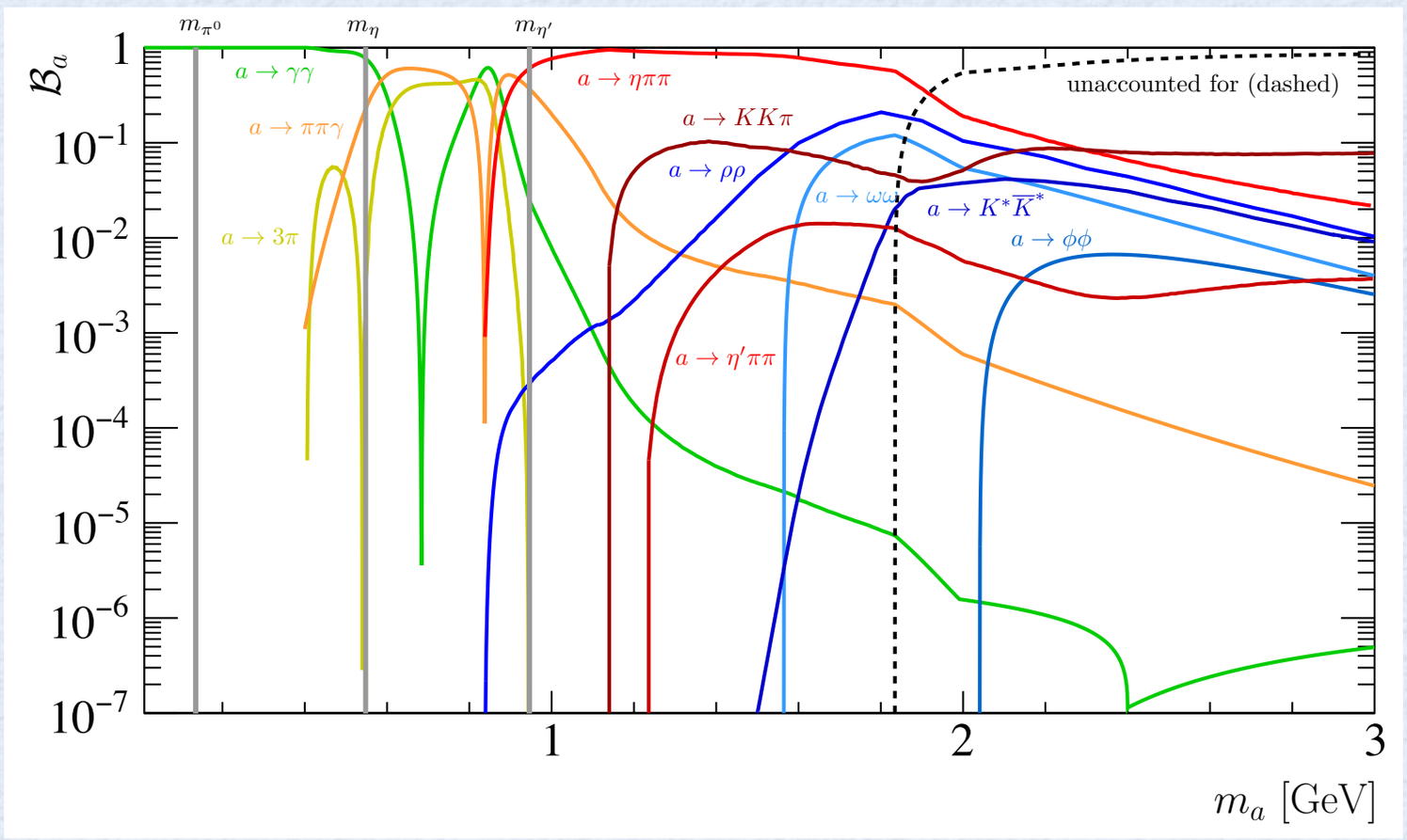

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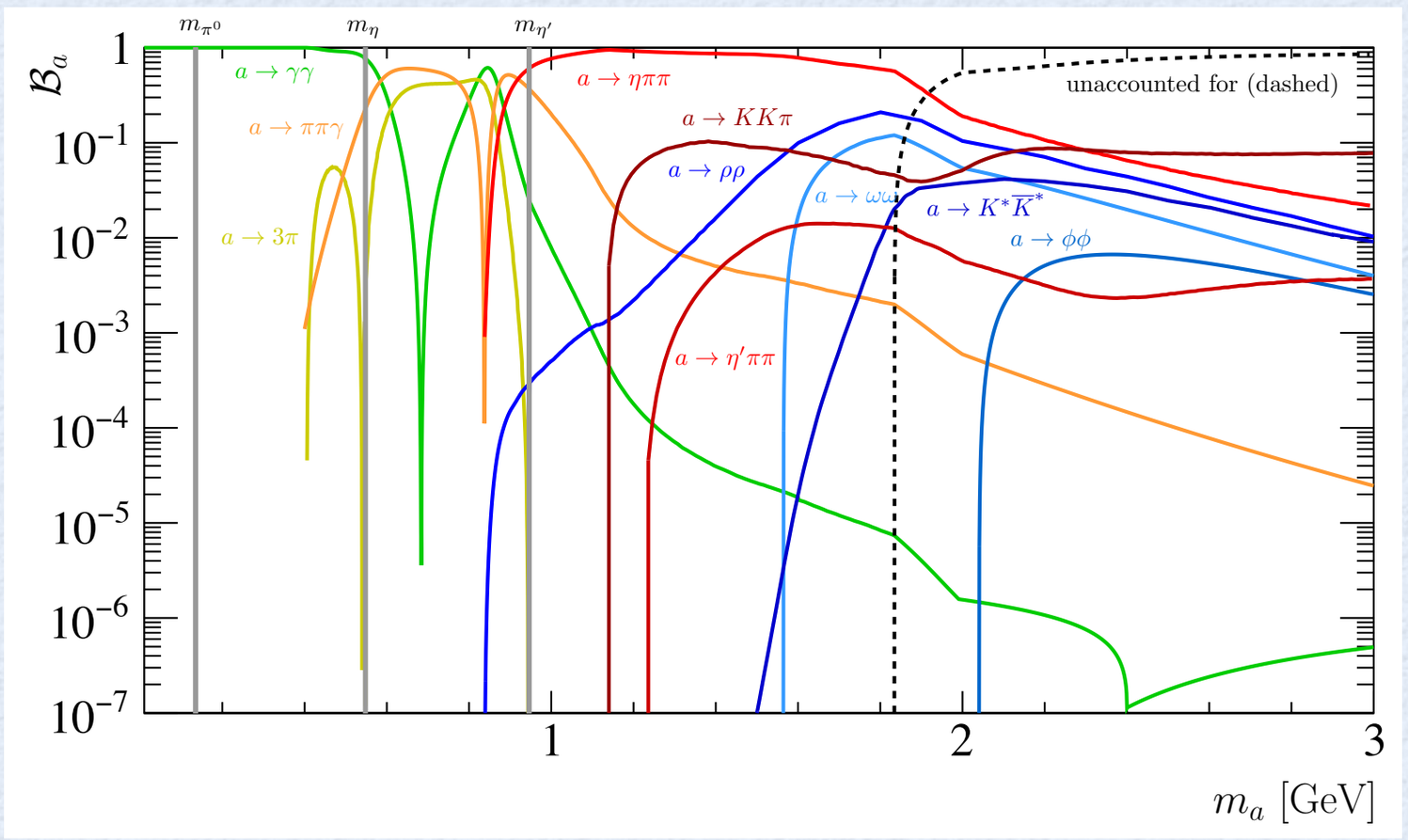

ηc cross check

	This Work	Experiment	
	VMD$\times|\mathcal{F}(m)|^2$	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 TO HADRONS

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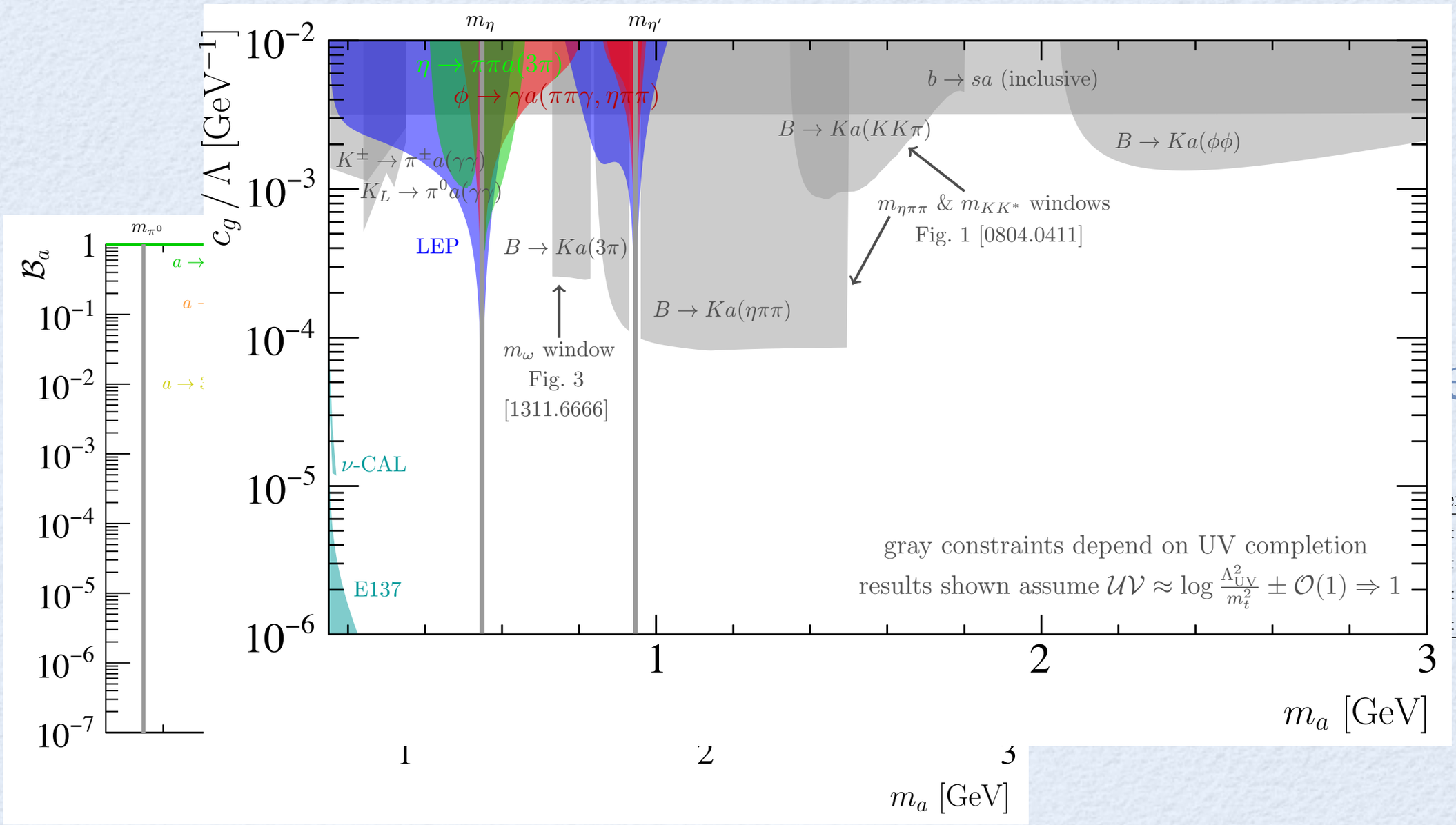


eck

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

SUMMARY

- Dark vector - are probed by current and near future experiments. The bounds can be easily recasted to a given model.
- Current PrimEx like experiment can probed unexplored parameter space of ALP.
- Hadronic rates of ALP and vector can be estimated in a data-driven methods based on e^+e^- data.

BACKUP SLIDES

DARK PHOTON SIGNAL

differential relation:

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

per mass bin:

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

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

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

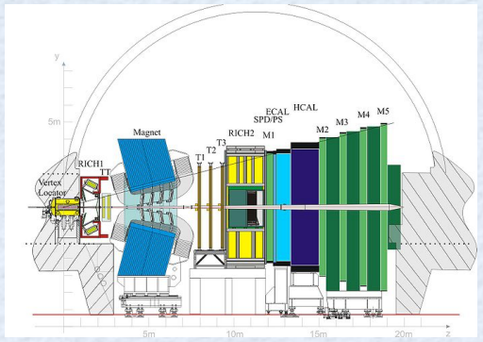
$$\frac{\sigma_{e^+e^-\to\mathrm{hadrons}}}{\sigma_{e^+e^-\to\mu^+\mu^-}}$$

Bjorken, Essig, Schuster, Toro, 0906.0580

DARK PHOTON AT LHCB

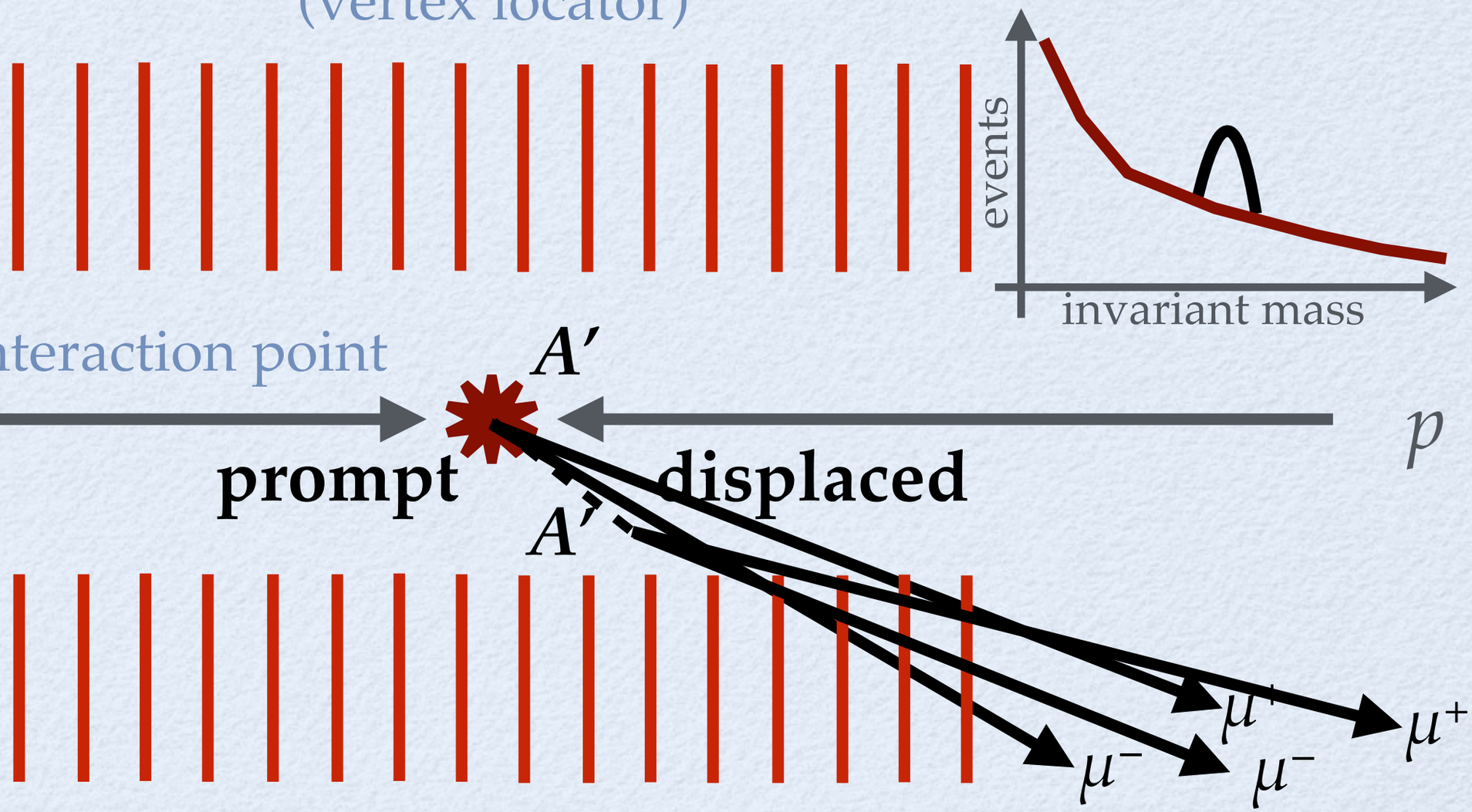
- real time data analysis (trigger-less) for Run 3
- particle identification
- muons detection:
  - dimuon invariant mass ($m_{\mu\mu}$) resolution:
    - 4 MeV, $m_{\mu\mu}$<1 GeV
    - 0.4% $m_{\mu\mu}$, $m_{\mu\mu}$>1 GeV
  - time resolution: σ_τ~50fs (almost constant in proper lifetime)

DARK PHOTON AT LHCB



VELO

(vertex locator)



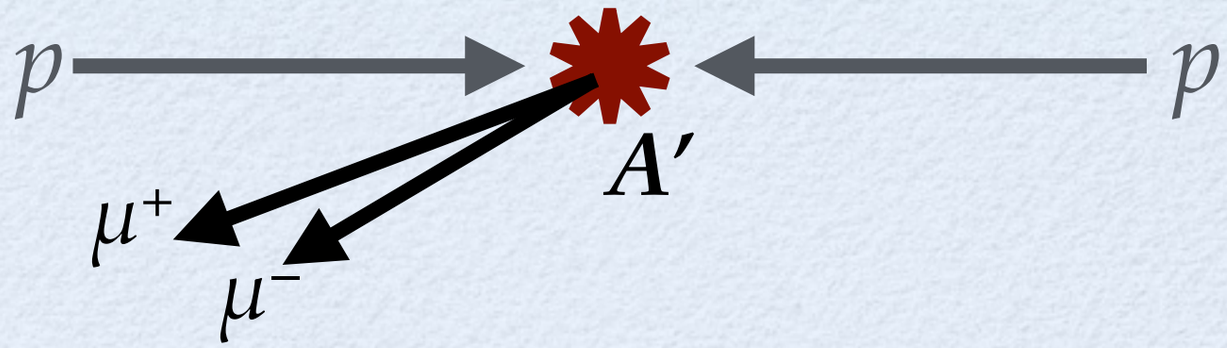
Ilten, **YS**, Thaler, Williams, Xue,
PRL 1603.08926

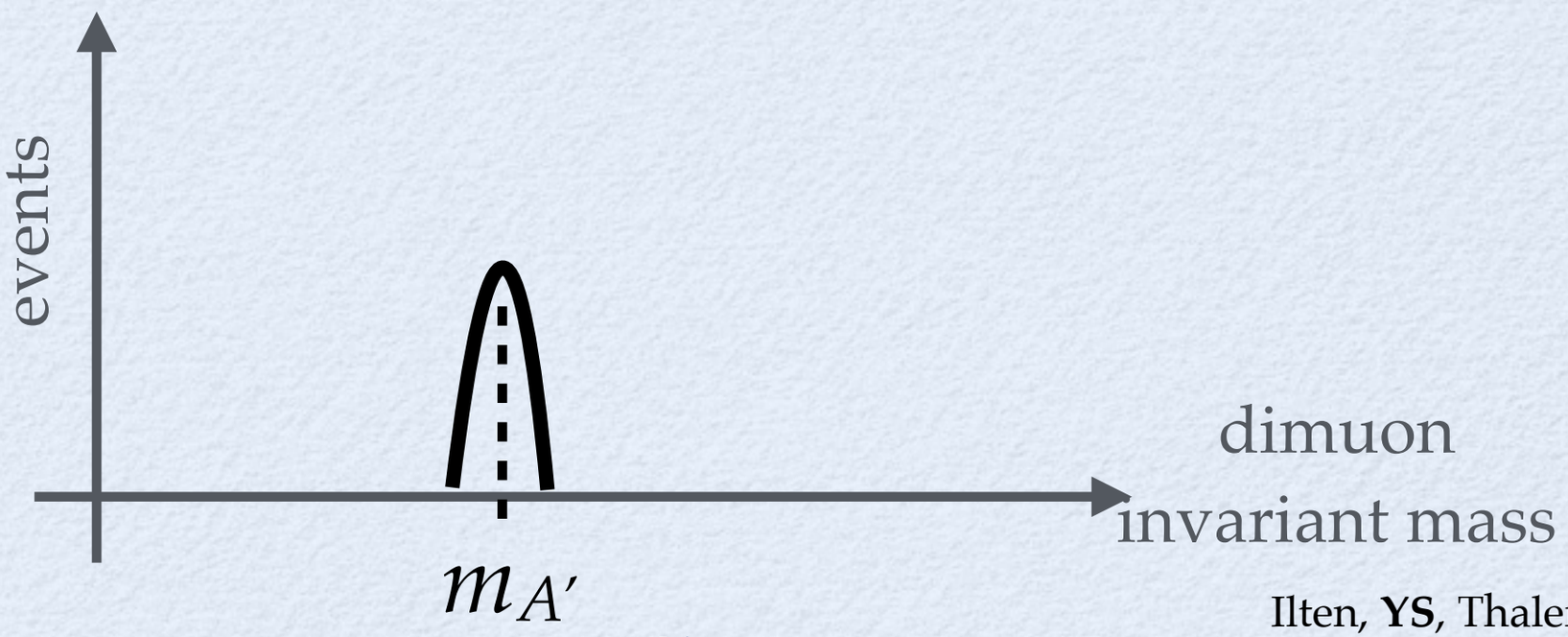
SIGNAL AND BACKGROUNDS

prompt

short lifetime

larger ε





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

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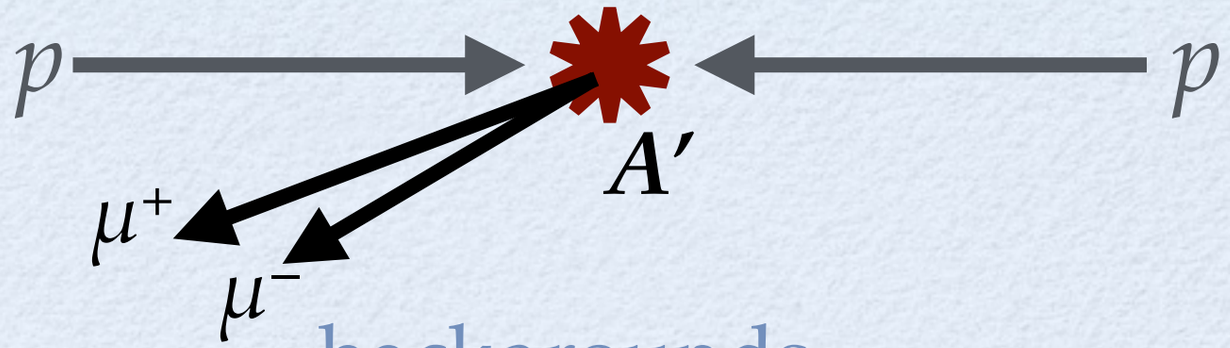
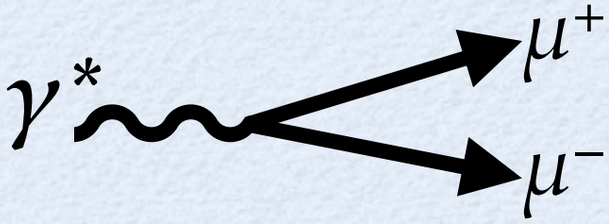
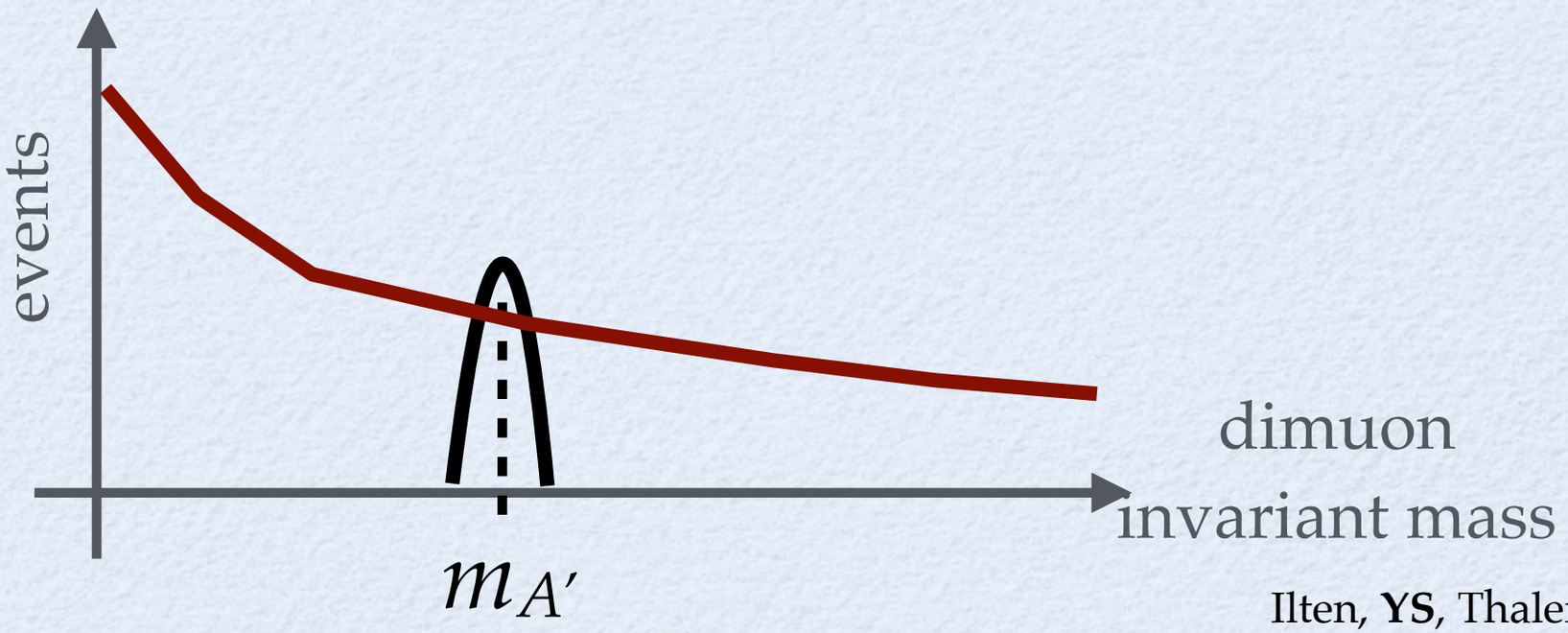


"good" backgrounds

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



meson decays
Drell-Yan



Ilten, **YS**, Thaler, Williams, Xue,
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SIGNAL AND BACKGROUNDS

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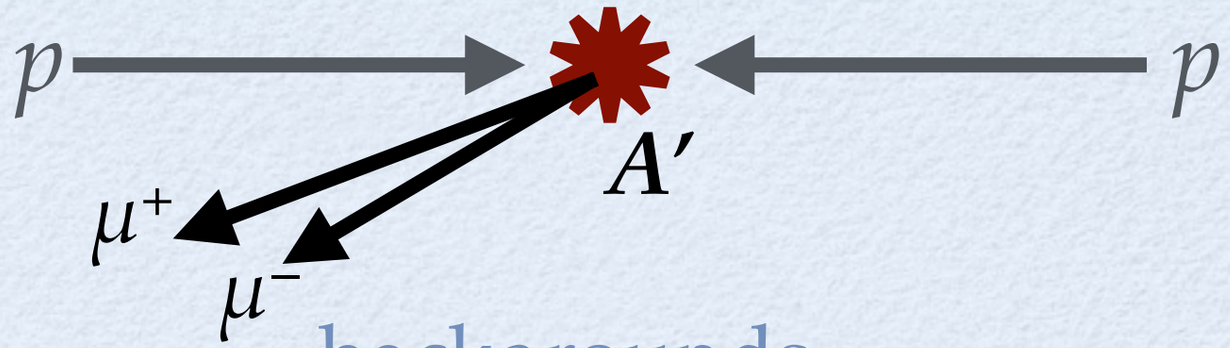
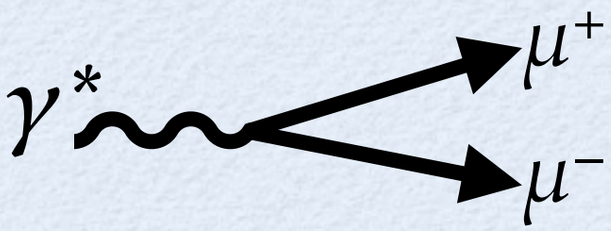


"good" backgrounds "bad"

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



meson decays
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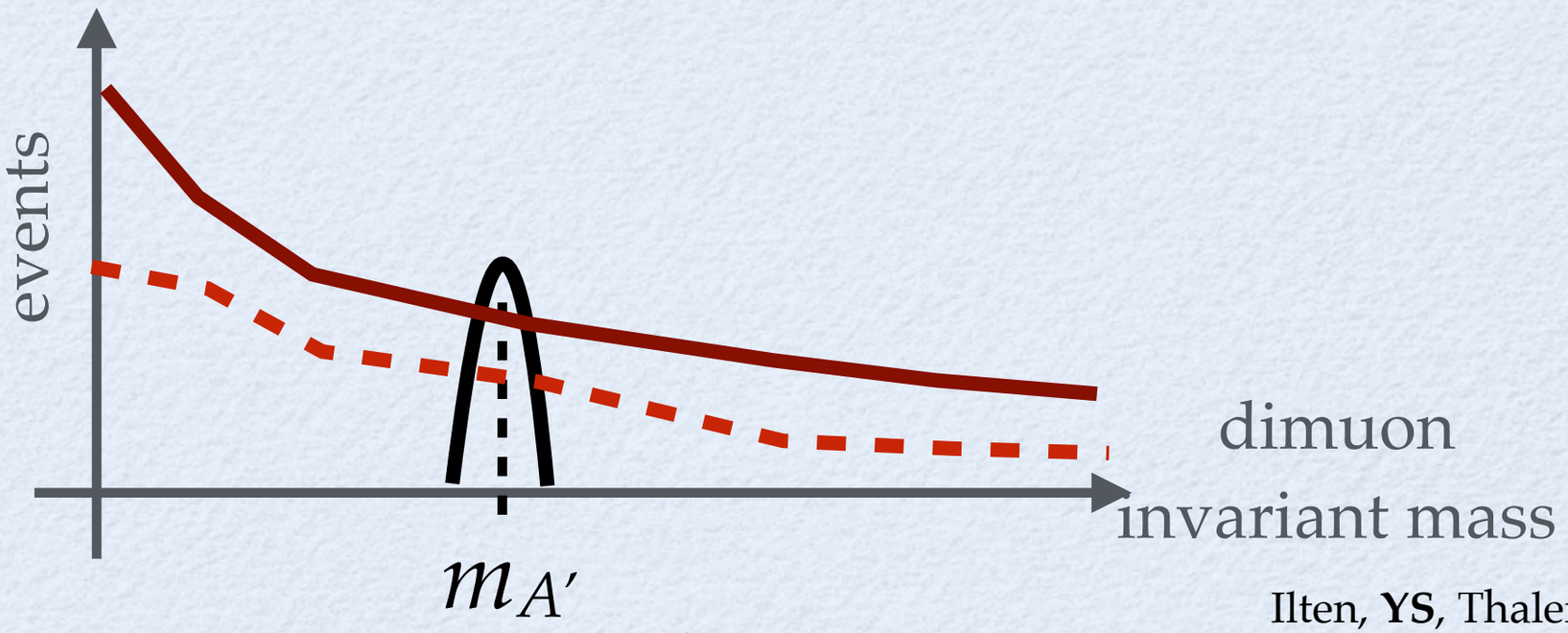
misidentified hadrons
(pions, kaons)



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

SIGNAL AND BACKGROUNDS

prompt

short lifetime

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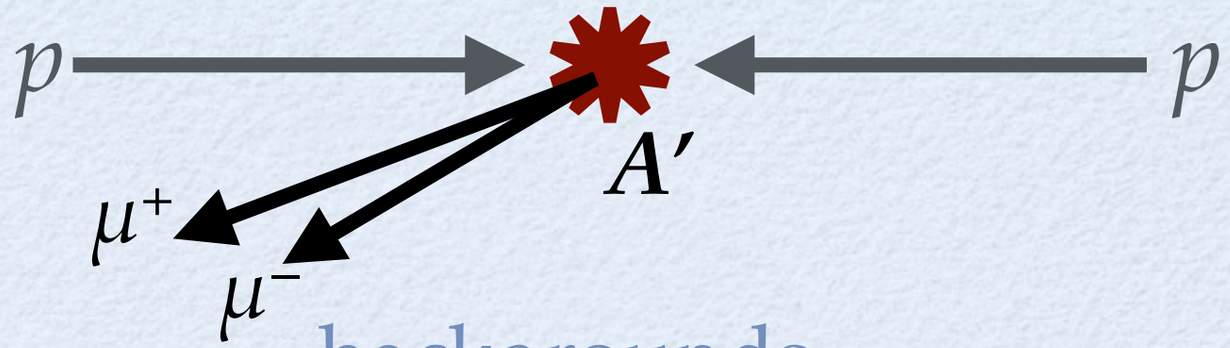

"good" backgrounds "bad"

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

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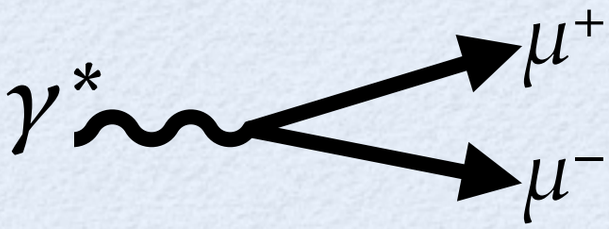


meson decays

Drell-Yan

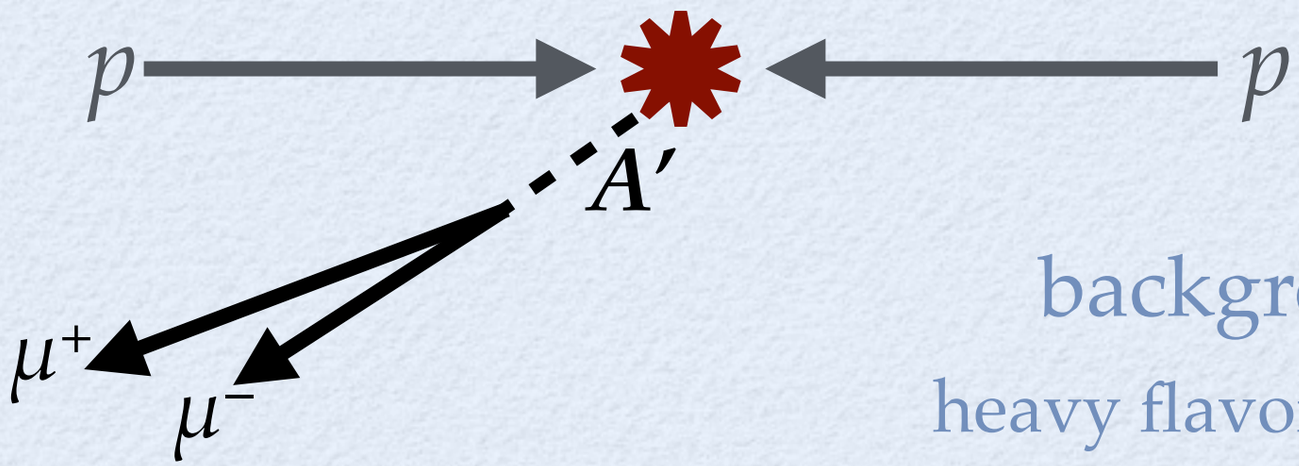
misidentified hadrons

(pions, kaons)

displaced

long lifetime

smaller ε



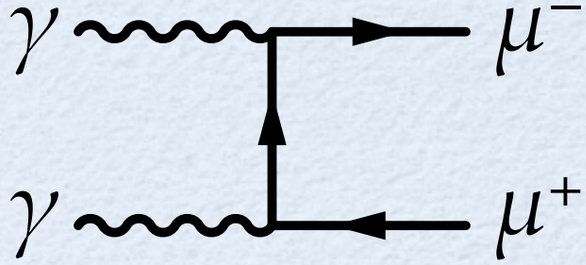
backgrounds

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

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

PROMPT BACKGROUNDS

- misidentified pions:
  - $B^{\pi\pi}$ - two pions are misidentified $\varepsilon_\pi \approx 10^{-3}$
  - $B^{\pi\mu}$ - one pion is misidentified and one real muon
- B_{BH} - Bethe-Heitler background, subdominant due to small photon luminosity function



$$B_{\text{prompt}} = \underbrace{B_M + B_{\text{FSR}} + B_{\text{DY}}}_{B_{\text{EM}}} + \underbrace{B^{\pi\pi}_{\text{misID}} + B^{\pi\mu}_{\text{misID}}}_{B_{\text{misID}}}$$

"good" — scales as signal

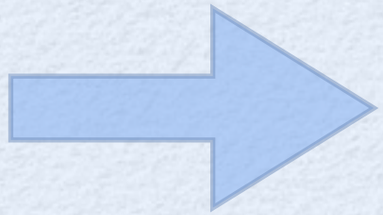
"bad" — does not scale as signal

PROMPT BACKGROUNDS

subtracting fake pions by using the same-sign sample:

$$n^{\pi\pi}_{\pm\pm} = \frac{n^{\pi}_{\pm}(n^{\pi}_{\pm}-1)}{2}$$

$$n^{\pi\pi}_{+-} = n^{\pi}_{+} n^{\pi}_{-}$$



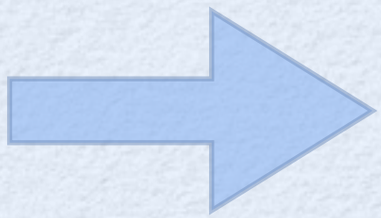
$$n^{\pi\pi}_{+-} \approx 2\sqrt{n^{\pi\pi}_{++} n^{\pi\pi}_{--}} \approx n^{\pi\pi}_{++} + n^{\pi\pi}_{--}$$

number of same(opposite) sign events per bin

generalize to all bins and for one fake:

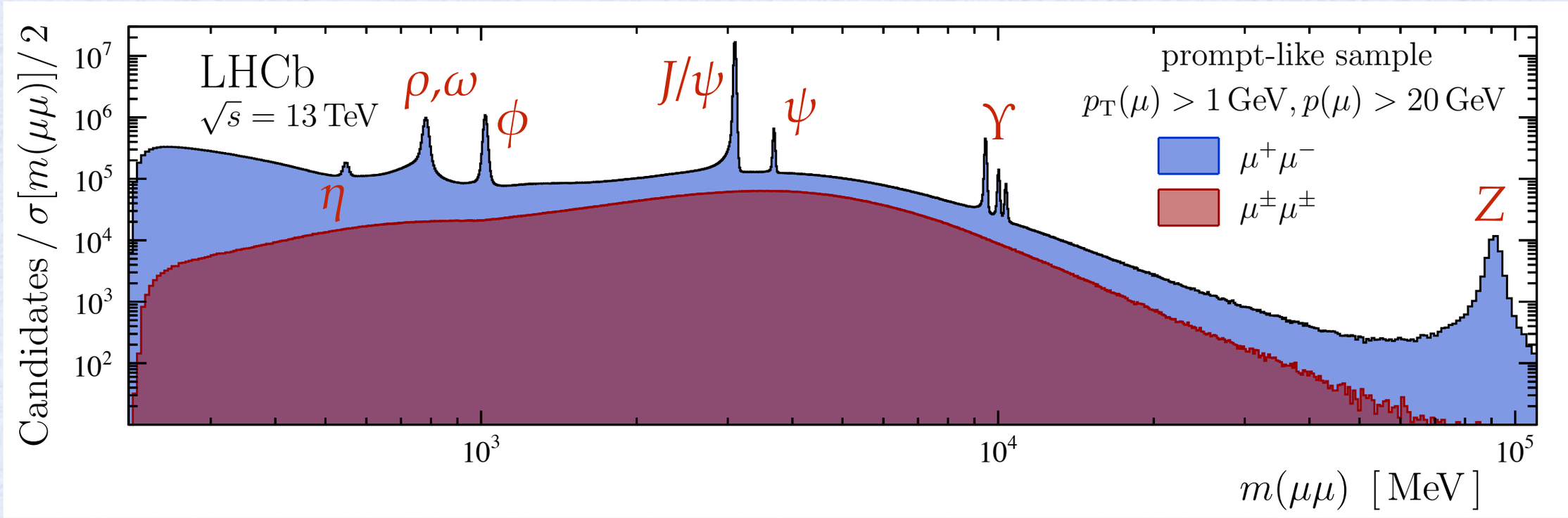
$$N^{\pi\pi}_{+-} \approx N^{\pi\pi}_{++} + N^{\pi\pi}_{--}$$

$$N^{\pi\mu}_{+-} \approx N^{\pi\mu}_{++} + N^{\pi\mu}_{--}$$



$$B^{\pi\pi}_{\mathrm{misID}} + B^{\pi\mu}_{\mathrm{misID}} \approx N_{++} + N_{--}$$

LHCb result with 2016 data



LHCb, 1710.02867

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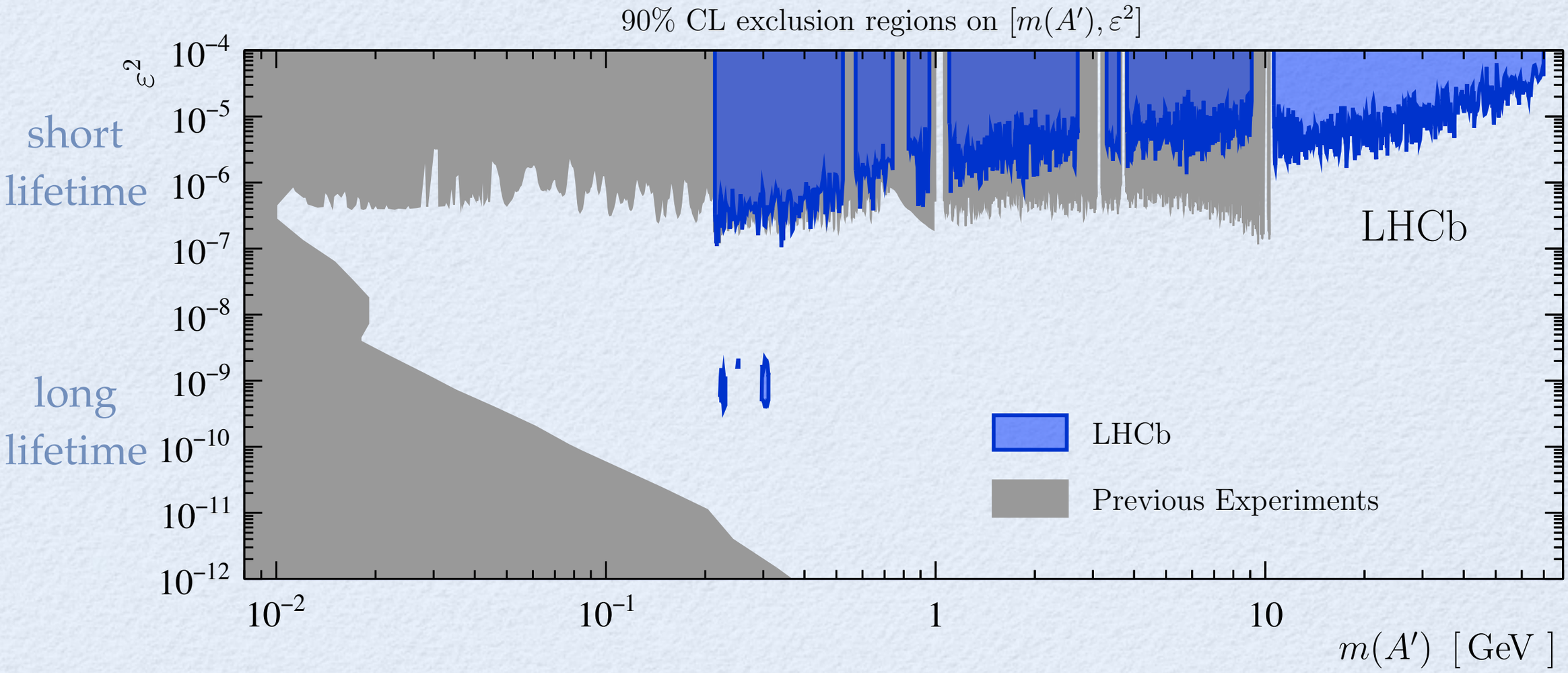

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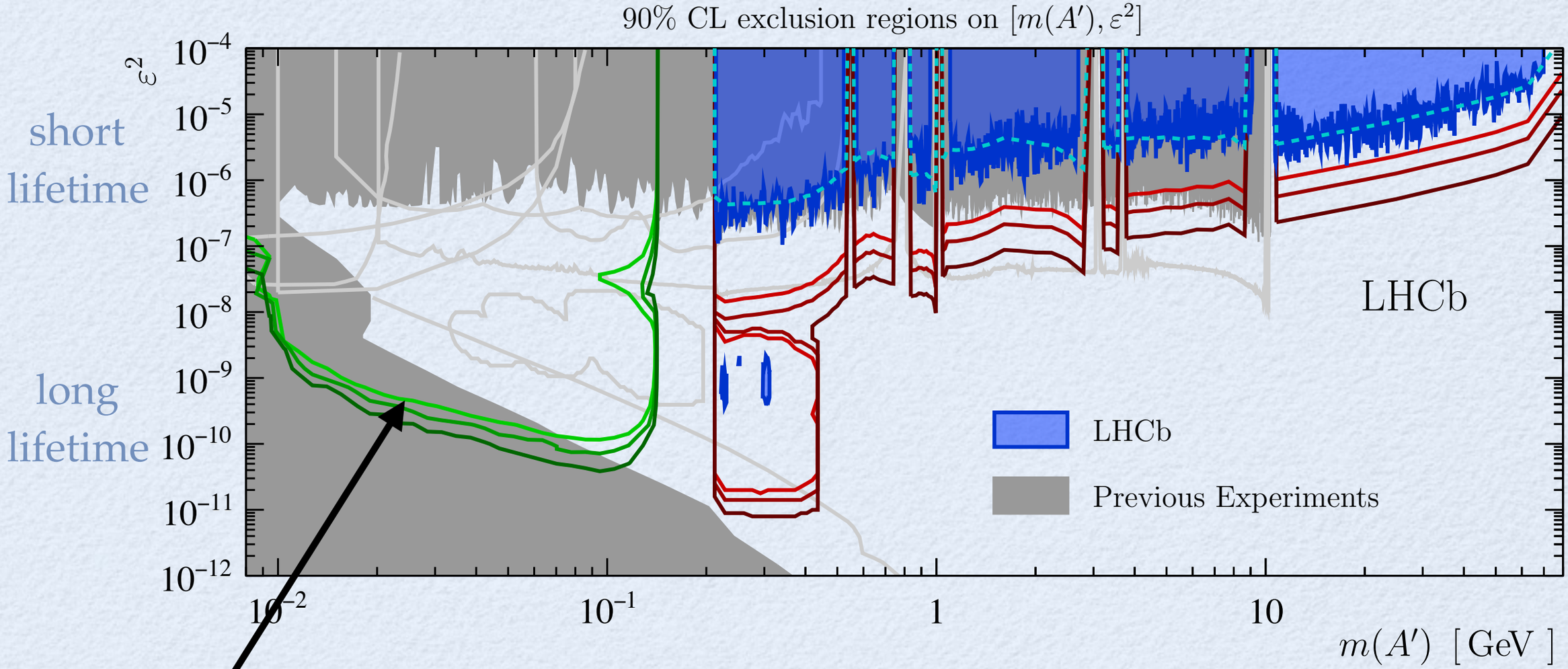
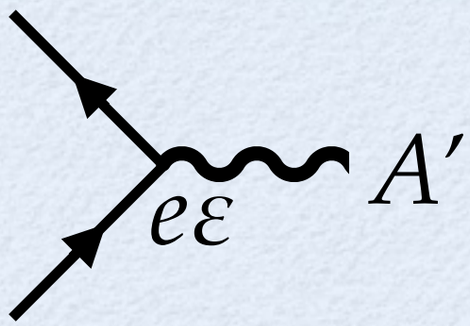


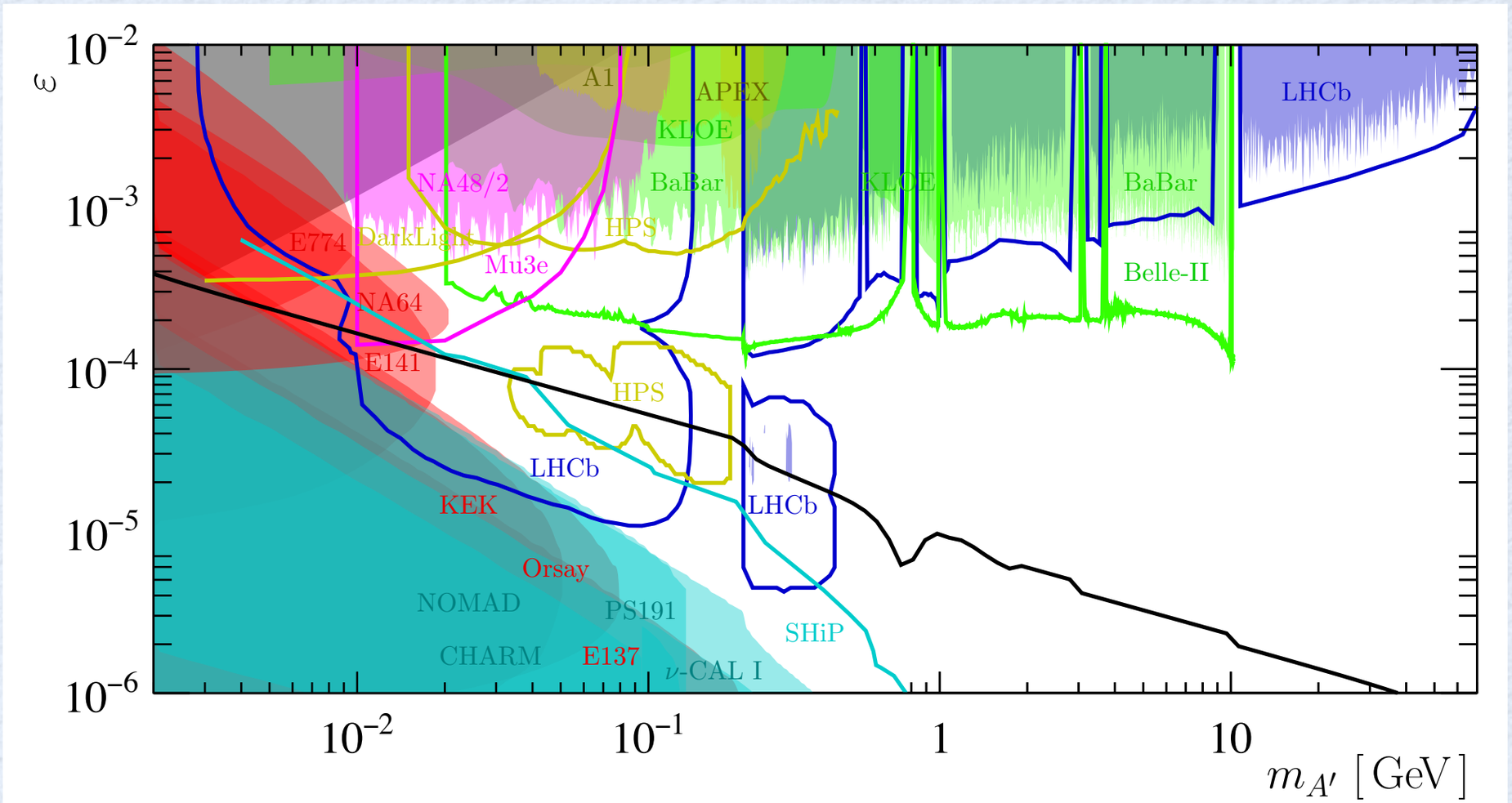
$D^* \to D A',\ A' \to e^+e^-$

Ilten, Thaler, Williams, Xue, 1509.06765

LHCb, 1710.02867

DARK PHOTON





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

Ilten, YS, Williams, Xue, 1801.04847

DISPLACED BACKGROUNDS

- **pre-module:**
  - main backgrounds: $b \to c\mu^{\pm} X$, $c \to \mu^{\pm} Y$
  - 10000 background events per mass bin
- **post-module:**
  - mostly material interactions, rescaled from $K_S \to \mu^+\mu^-$ search
  - 25 background events pre mass bin
- backgrounds from misidentifications are subdominants

DISPLACED RECAST

$$\epsilon(\tau) = e^{-\tilde{t}_0/\tau} - e^{-\tilde{t}_1/\tau}$$

$$\tilde{t}_1 = \tilde{t}_0(1 + L_{\rm dec}/L_{\rm sh})$$

decay volume
shielding

$$\varepsilon^2_{\rm max}\epsilon[\tau_{A'}(\varepsilon^2_{\rm max})] = \varepsilon^2_{\rm min}\epsilon[\tau_{A'}(\varepsilon^2_{\rm min})]$$

approximate upper edge $\tau_X(g_X^{\rm max}) \approx \tau_{A'}(\varepsilon^{\rm max})$

approximate lower edge $\left[\frac{\sigma_X \mathcal{B}_{X\to\mathcal{F}}}{\tau_X}\right]_{g_X^{\rm min}} \approx \left[\frac{\sigma_{A'} \mathcal{B}_{A'\to\mathcal{F}}}{\tau_{A'}}\right]_{\varepsilon^{\rm min}}$

PRIMAKOFF ALP PRODUCTION

photon on fixed target

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

29 Aloni, Fanelli, YS, Williams, work in progress

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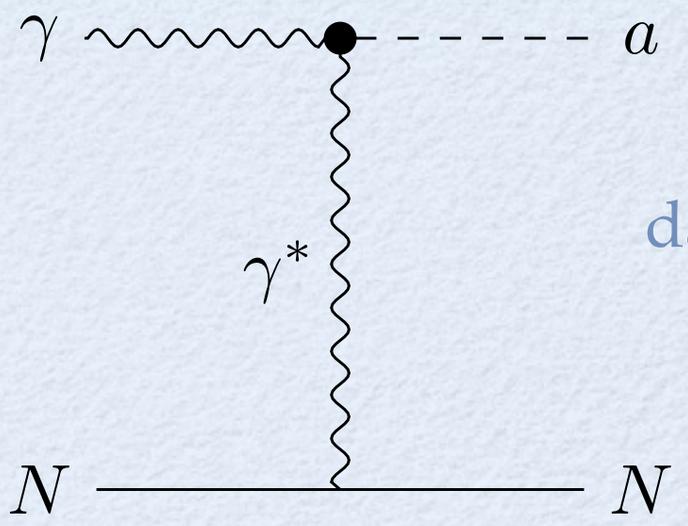

data driven signal estimation

[29] Aloni, Fanelli, YS, Williams, work in progress

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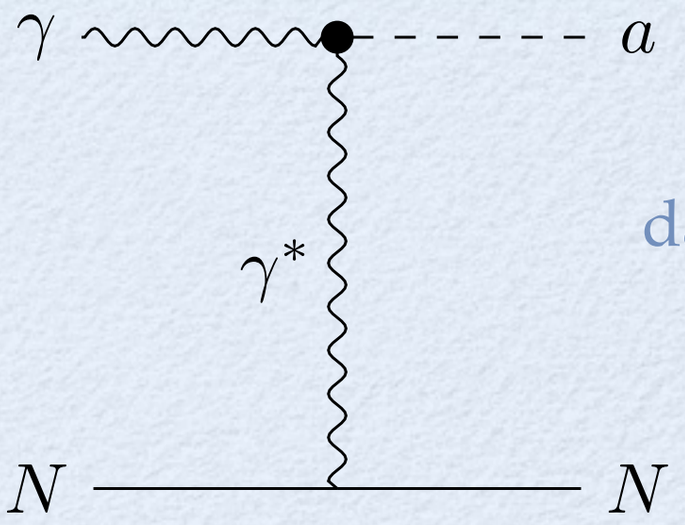
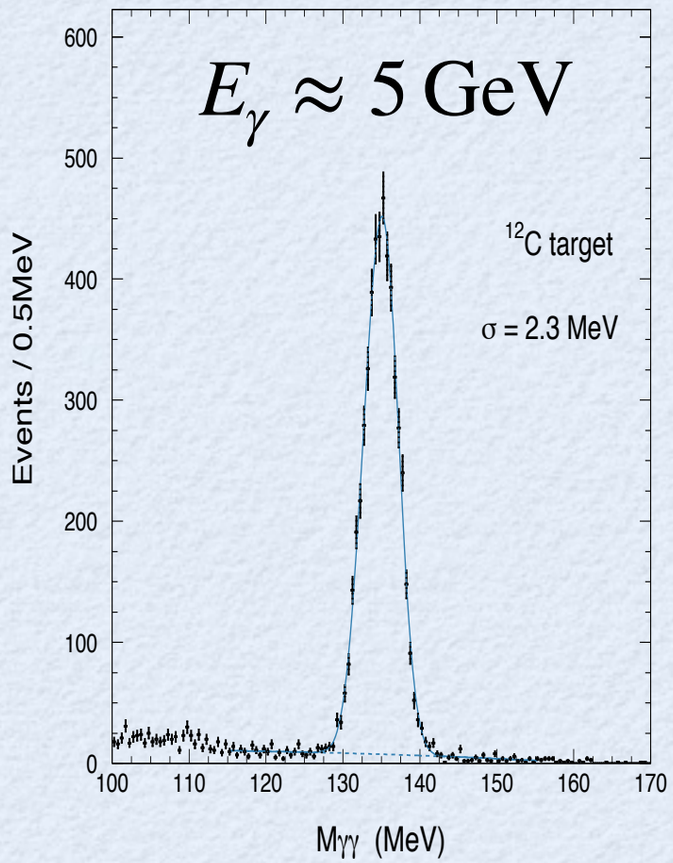


data driven signal estimation

PrimeEx,1009.1681



 Aloni, Fanelli, YS, Williams, work in progress

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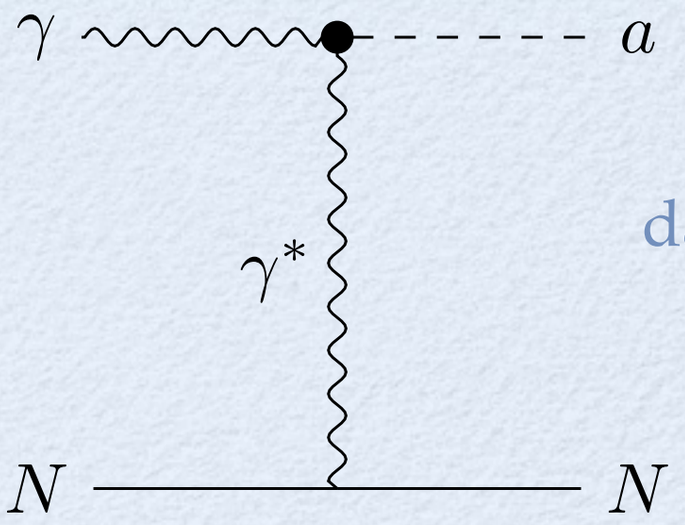

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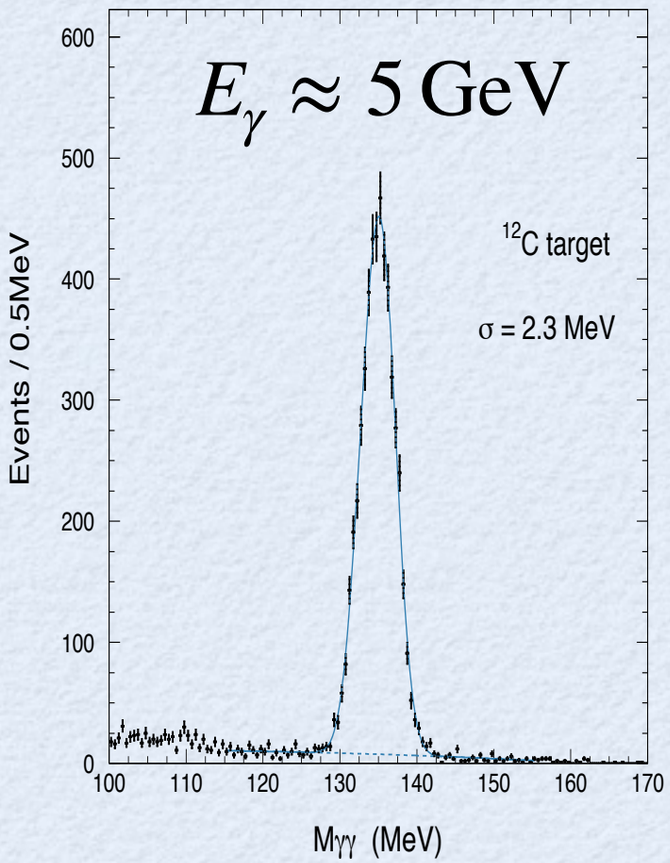

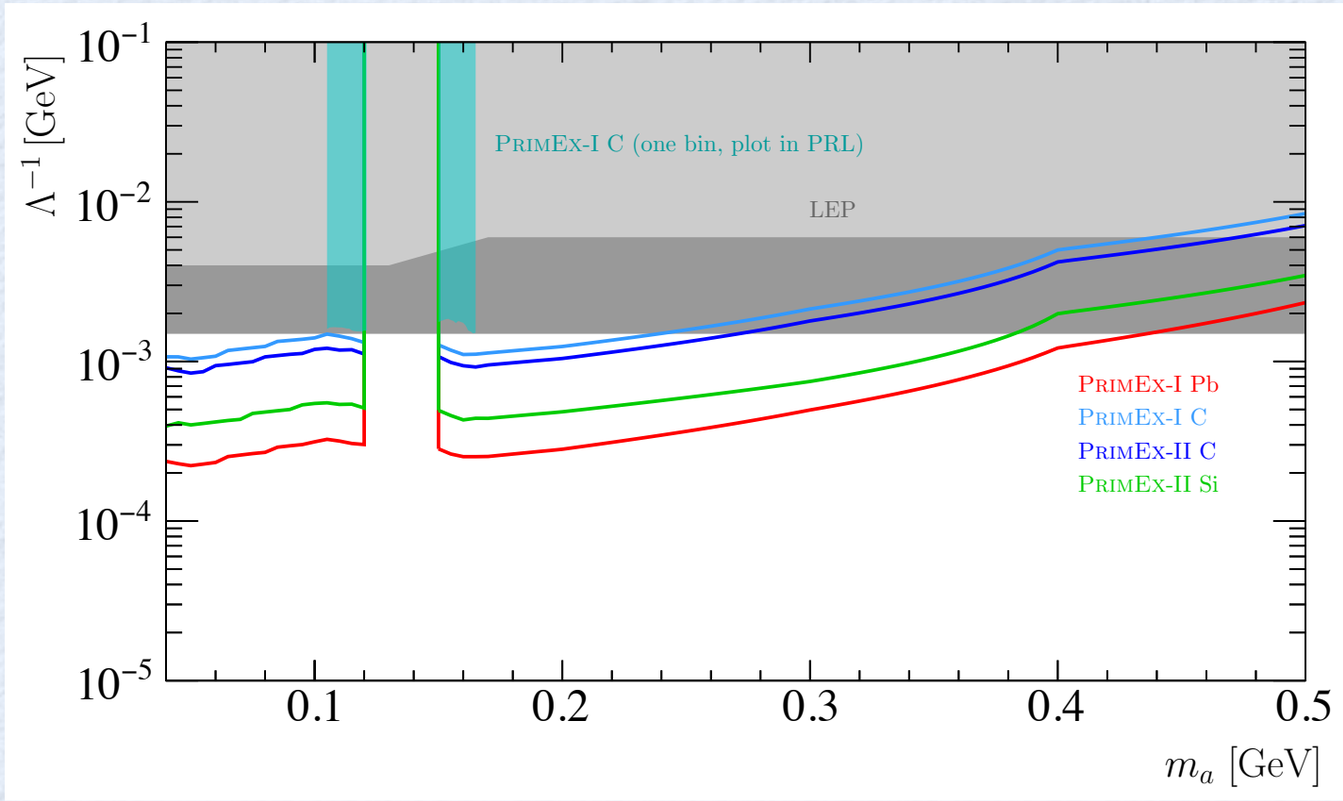

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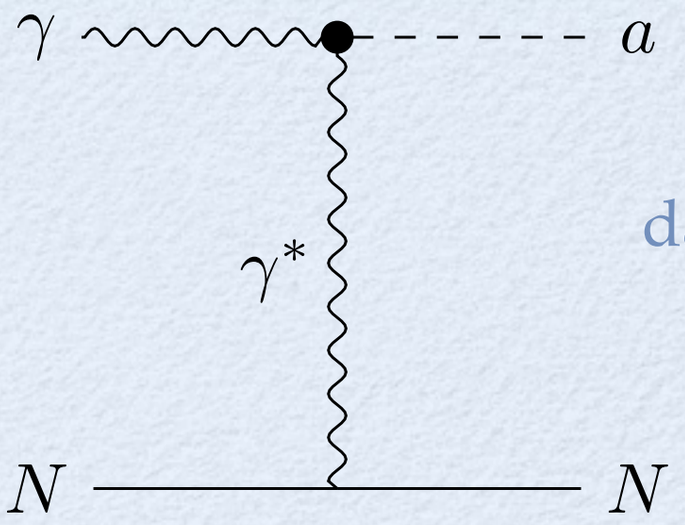

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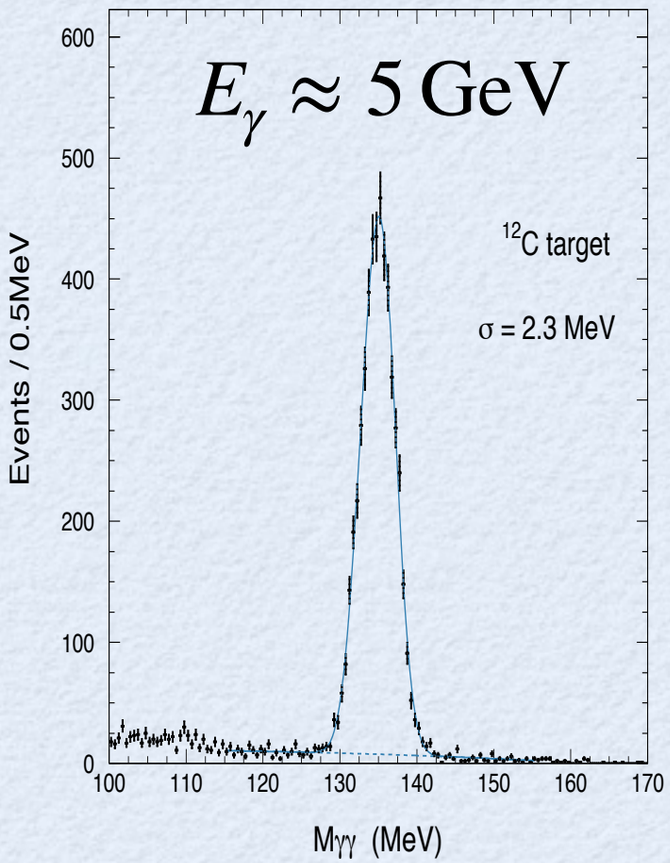

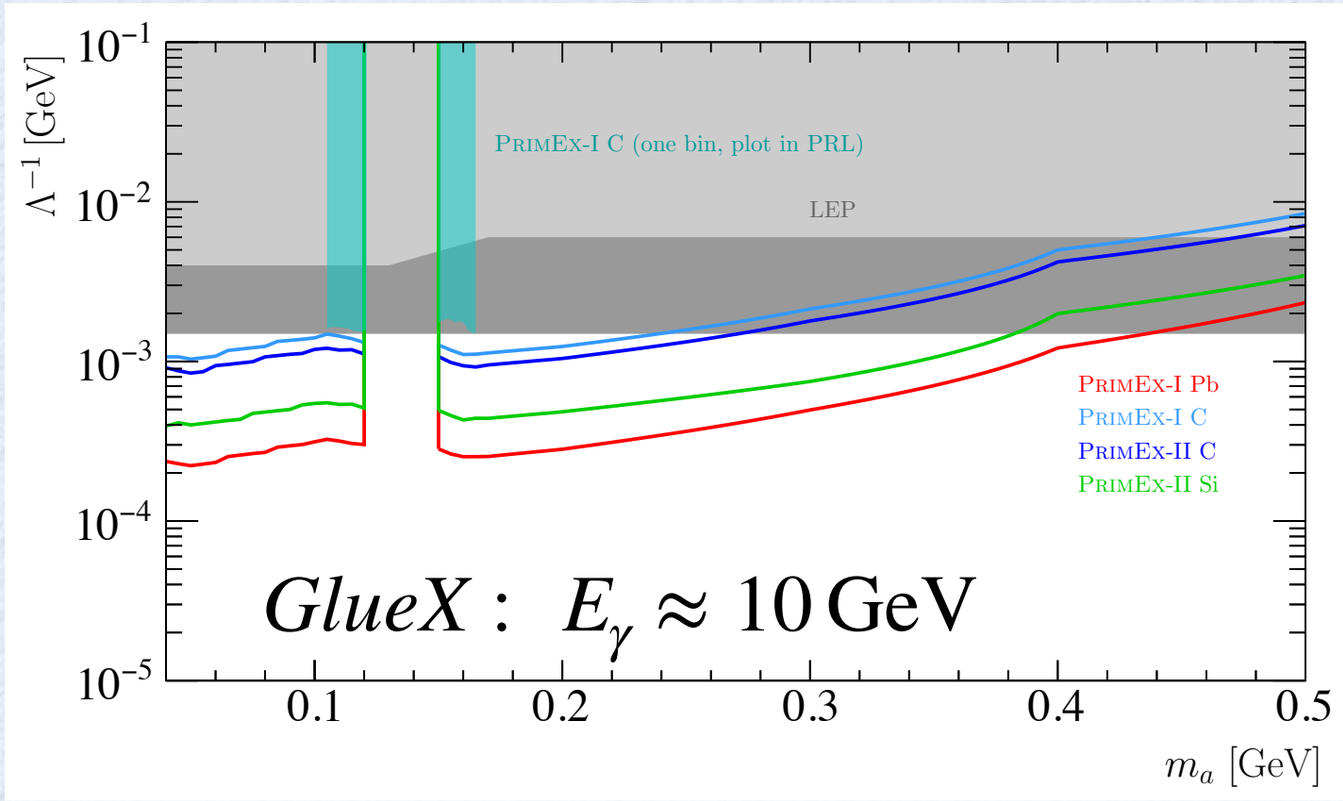

 Aloni, Fanelli, YS, Williams, work in progress