Exotica Theory at LHCb

Implications of LHCb measurements and future prospects
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Kohsaku Tobioka
Florida State University

BSM exotics at LHCb

Exotics at B-factories. For BSM using B [e.g. see talks by M. Santimaria, and by M. Borsato]

Advantage compared to ATLAS/CMS or K-factories.
Particularly for O(**1-20 GeV**) new states.

In conventional final states (e,μ,γ,had),

- Too light for ATLAS and CMS, trigger issues.
- Inaccessible at other precision experiments,
  BESIII(~J/ψ), GlueX(~η), KOTO(K_L), NA62(K^+), pion physics.

LHCb vs Belle II

Hadronic production is accessible at LHC
But actually Belle II could test the same particle differently.

Example: Axion-like particles

Axion-like particles (**ALPs**): pseudo NG boson from global symmetry.

**Not well-defined term*. Here, couplings are similar to those of axion, but $m_a \sim 0.1\mathrm{GeV}/f_a$ is NOT imposed. m_a is a parameter.

Couplings

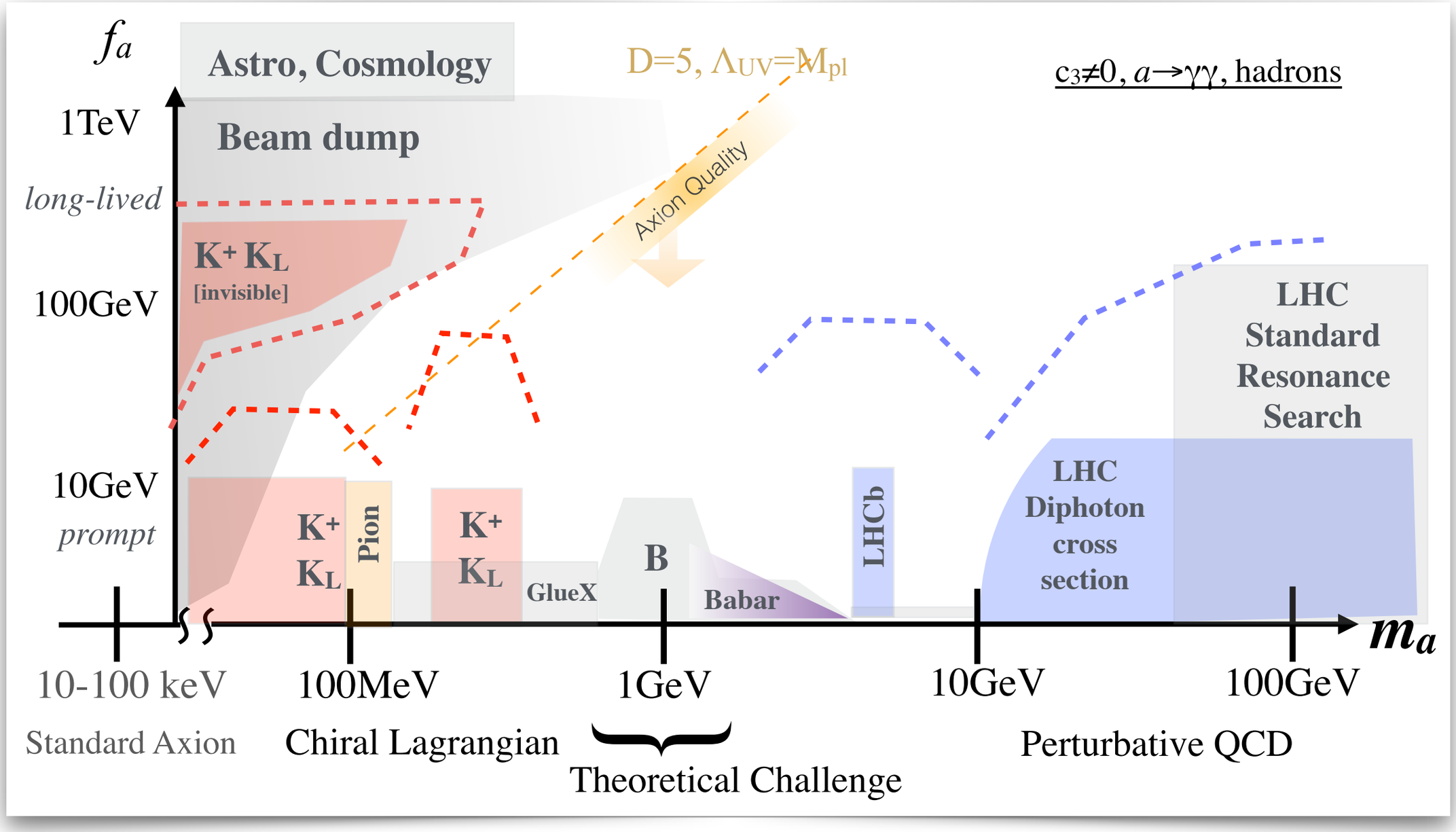
- If the lepton coupling is present, similar to dark photon search
  pp → X → $\mu^+\mu^-$ or e^+e^- [S. Knapen's talk]

- Assume leading couplings are from gauge bosons.
  Coupling to gluon: necessary to address *Strong CP problem*.
  Photon coupling: induced at IR or from UV. expected to be in the same order

- EFT $\frac{a}{4\pi f_a}\left[\alpha_s c_3 G\tilde{G} + \alpha_2 c_2 W\tilde{W} + \alpha_1 c_1 B\tilde{B}\right]$ +mass term

Since $m_{Z/W} >> m_a$, basically photon and gluon couplings.

10MeV-10GeV is poorly explored



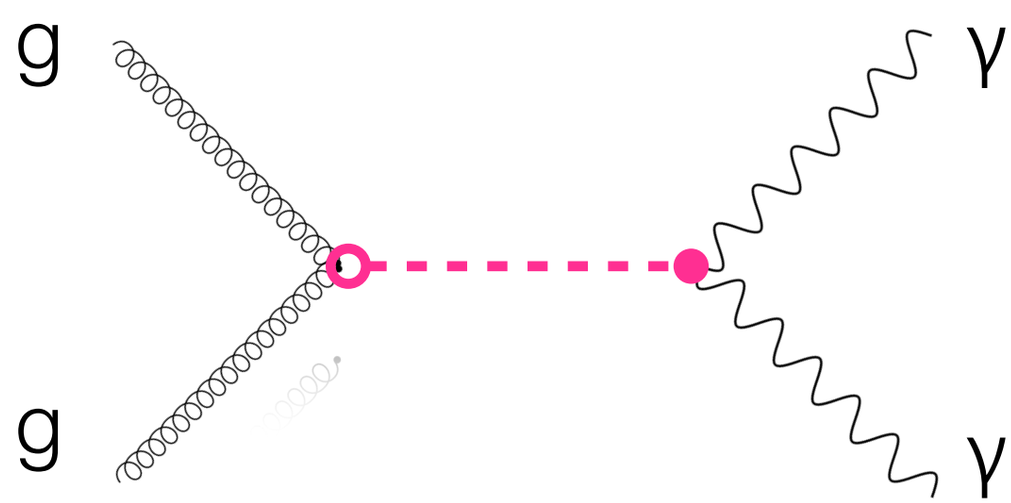
For K bounds,
see 2005.05170
S. Gori, G. Perez, KT

*If photon coupling is enhanced,
heavy-ion collision gives a bound for ma~10GeV.
[1607.06083, 1709.07110 S. Knapen, T. Lin, H. K. Lou, T. Melia]

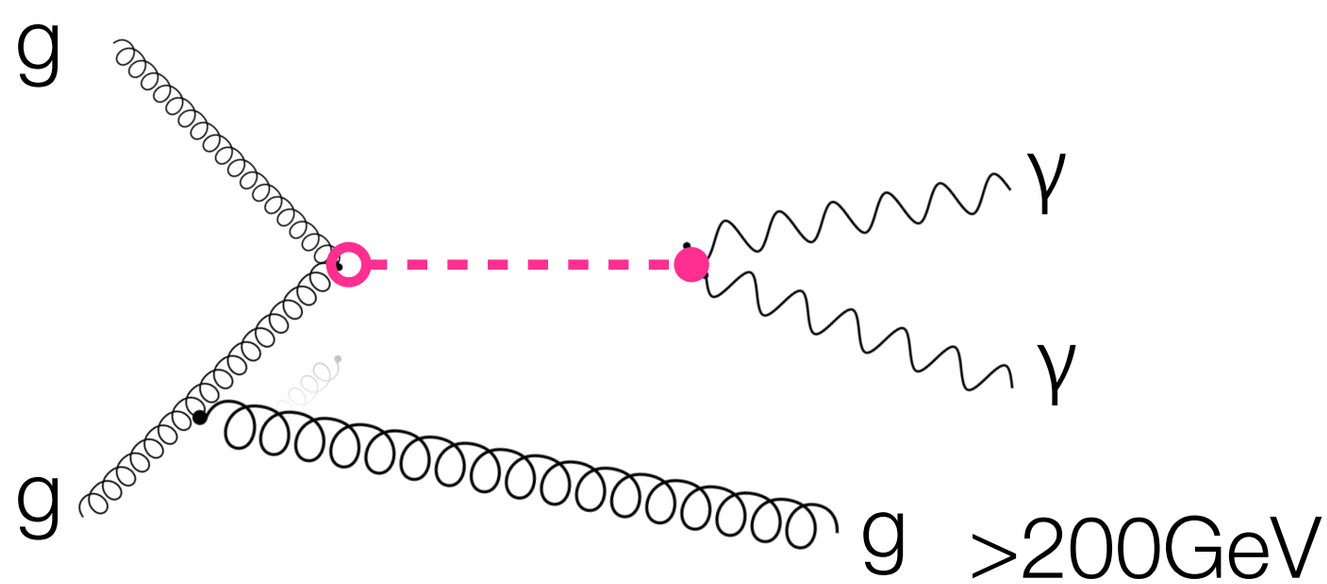
Search channels at ATLA, CMS

- Diphoton at ATLAS, CMS require $p_{T\gamma}$>40,30GeV, $\Delta R_{\gamma\gamma}$>0.4

$$m_{\gamma\gamma} > \Delta R \cdot \sqrt{p_{T1}^{\min} p_{T2}^{\min}}$$ ~13GeV



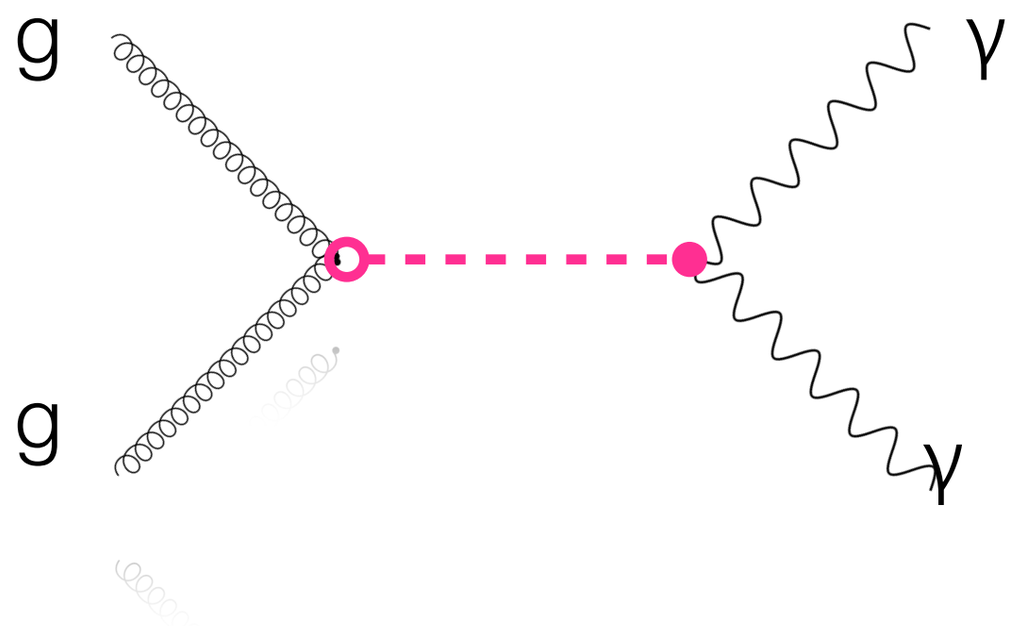
- Use mono-trigger with ISR. Need good resolution for $\Delta R_{\gamma\gamma}$.



Search channels at LHCb, Belle II

- At LHCb, simply lower $p_{T\gamma}$ threshold, e.g. $B_s \to \gamma\gamma$ search

S. Benson and A. Puig Navarro, Tech. Rep. LHCb-PUB-2018-006. CERN-LHCb-PUB-2018-006



$$\mathcal{A}: \quad 2 < \eta(\gamma) < 5$$

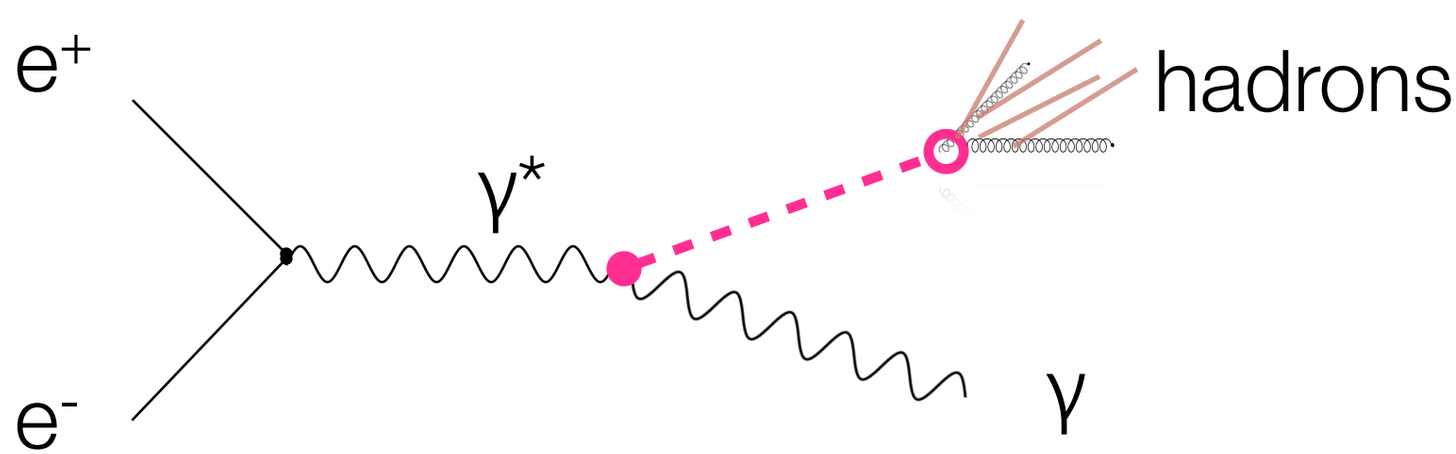
$$\epsilon: \begin{cases} E_T(\gamma) > 3.5 \text{ GeV}, \\ E_T^{\gamma_1} + E_T^{\gamma_2} > 8 \text{ GeV} \\ p_T(\gamma_1\gamma_2) > 2 \text{ GeV} \end{cases}$$

ALP motivated study moving forward

LHCb 1906.09058

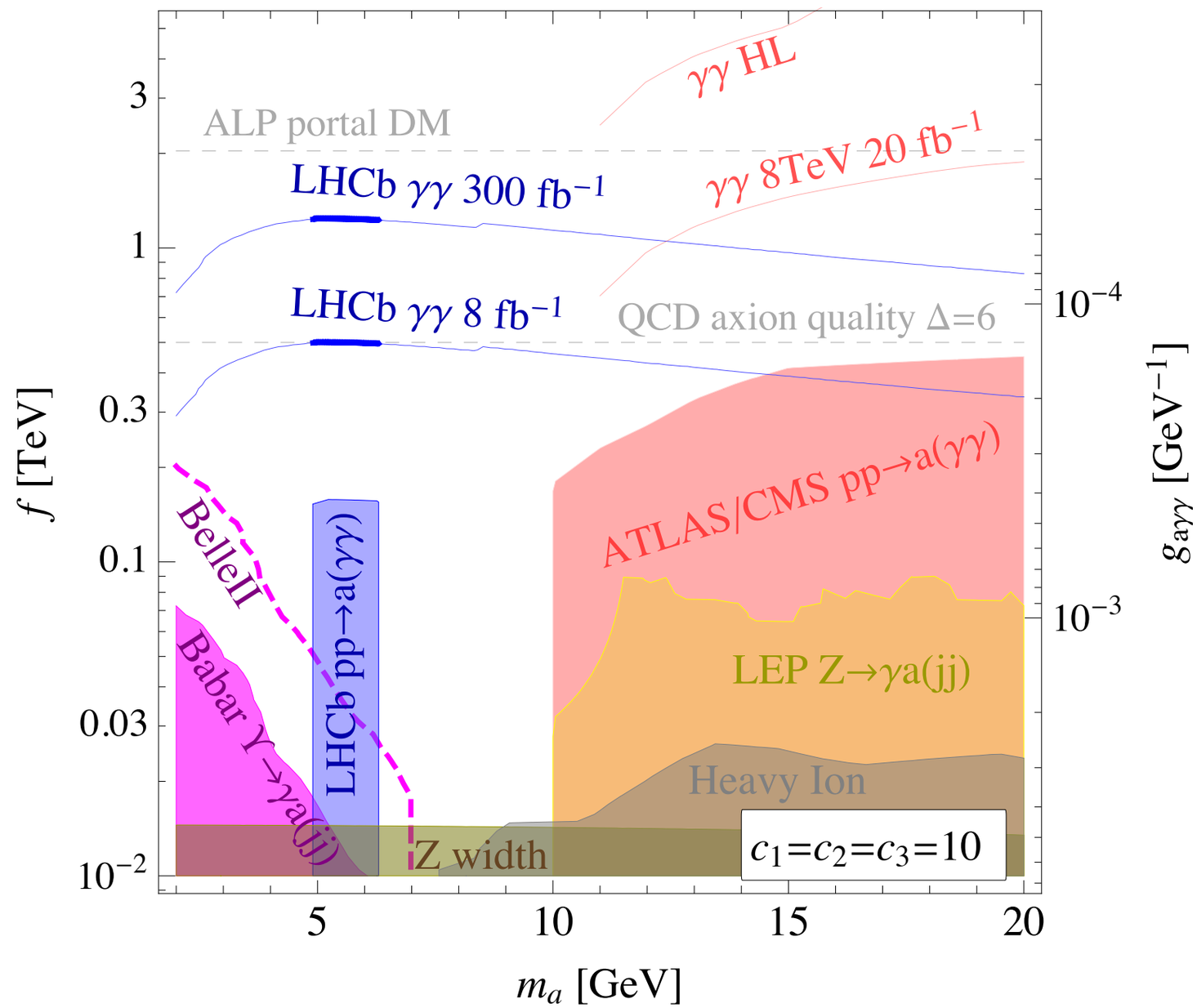
- At Belle II (Babar), produced by γ coupling, and decay by g coupling

BABAR 1108.3549



applicable to m_a>2GeV

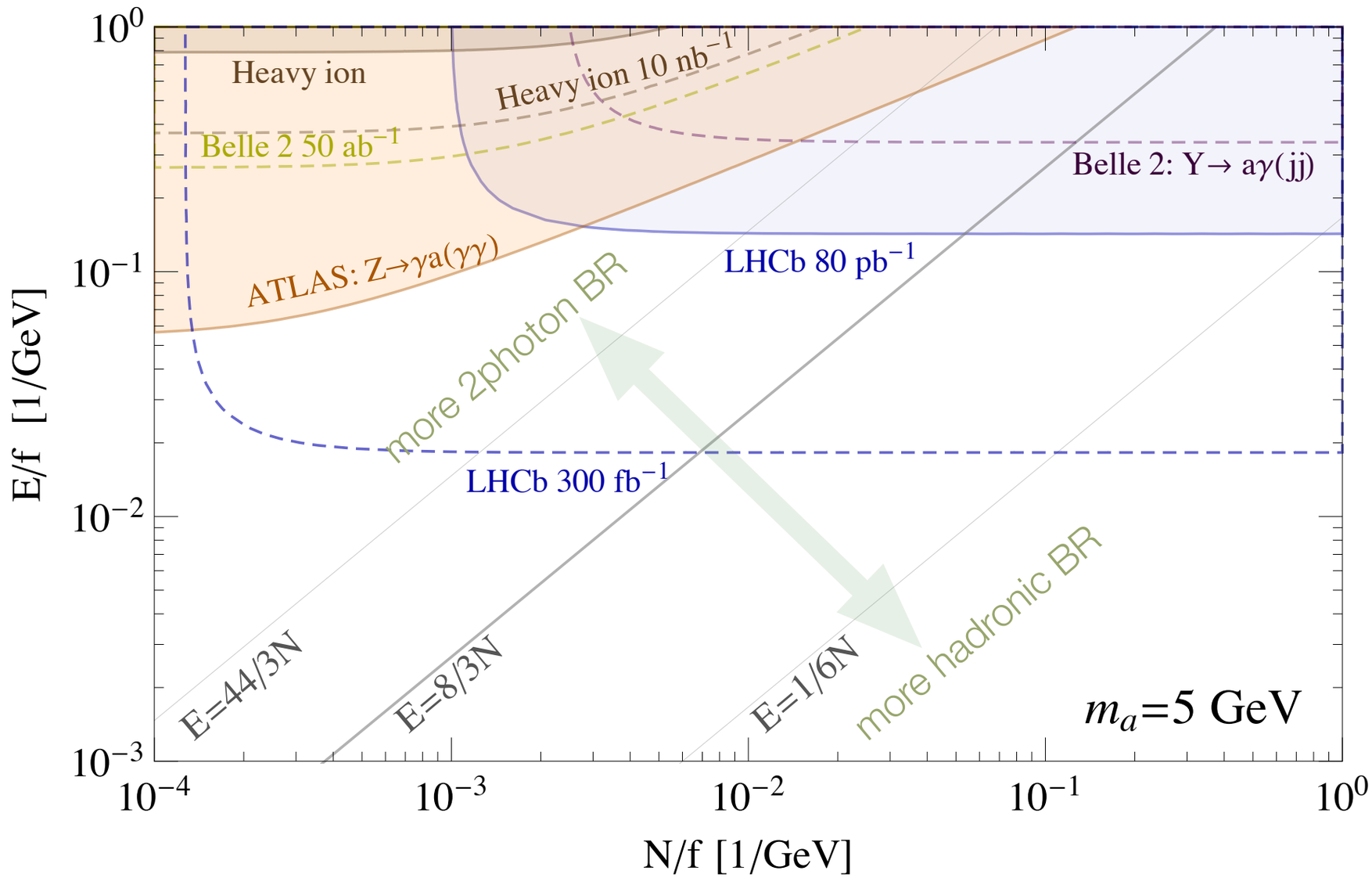
Search channels at LHCb, Belle II

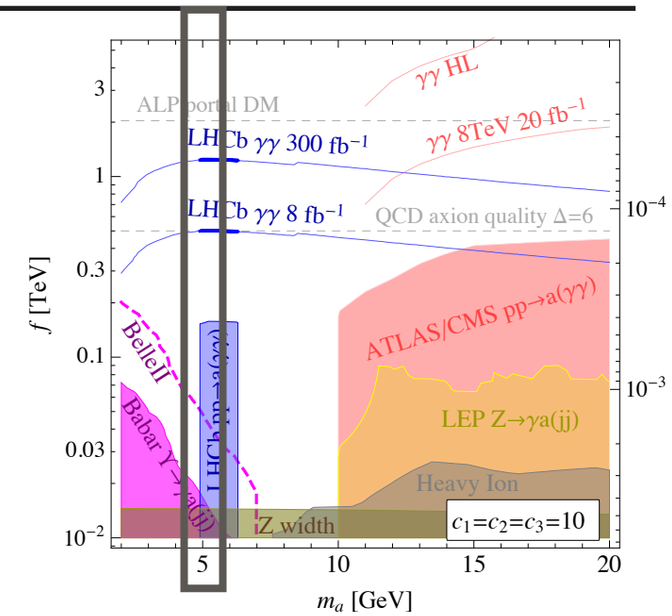


[1810.09452] X. Cid Vidal, A. Mariotti, D. Redigolo, F. Sala, KT

thanks to LHCb photon experts: S. Benson and A. Puig Navarro

Change photon/gluon ratio





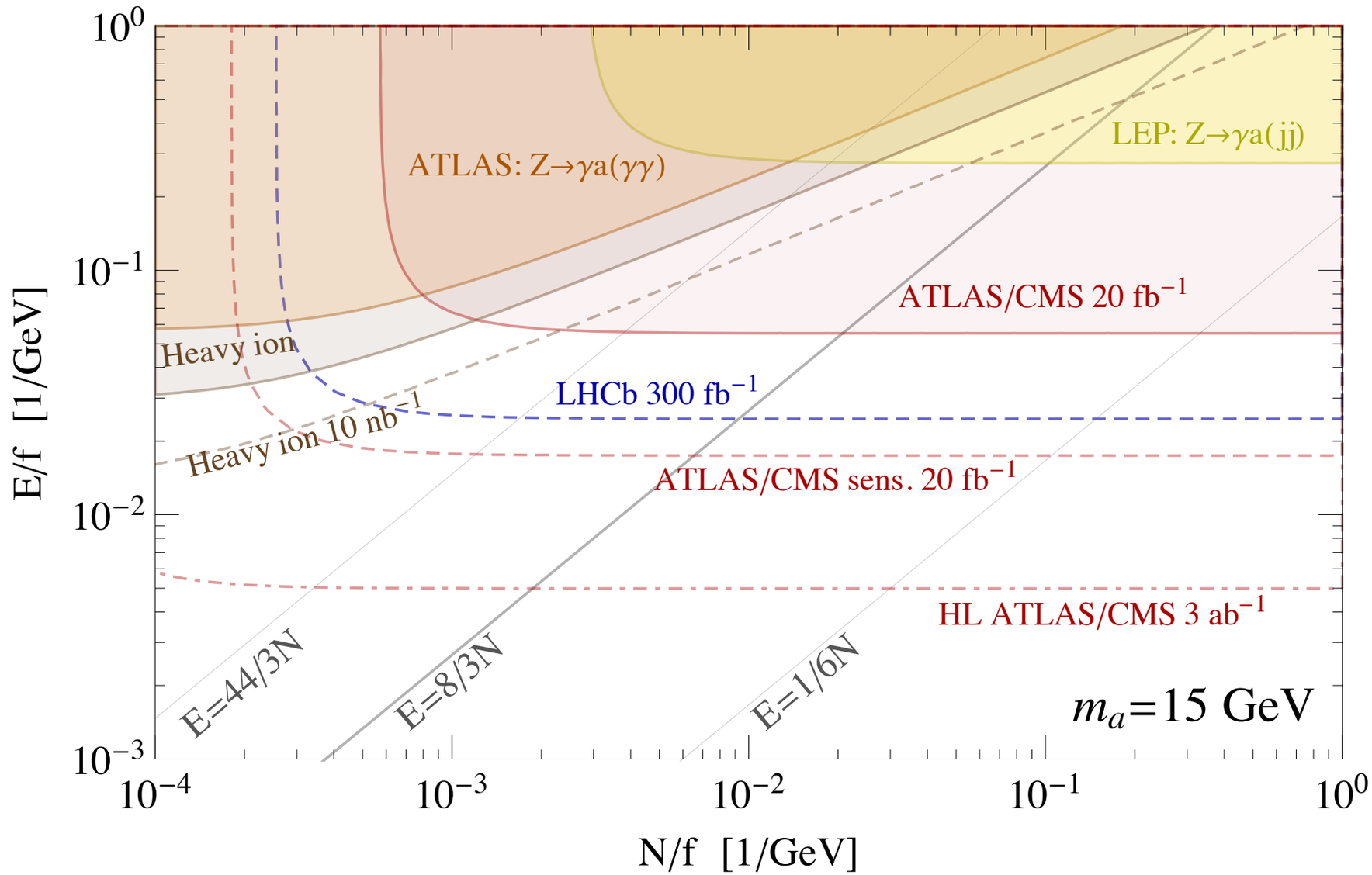
LHCb can cover unexplored region

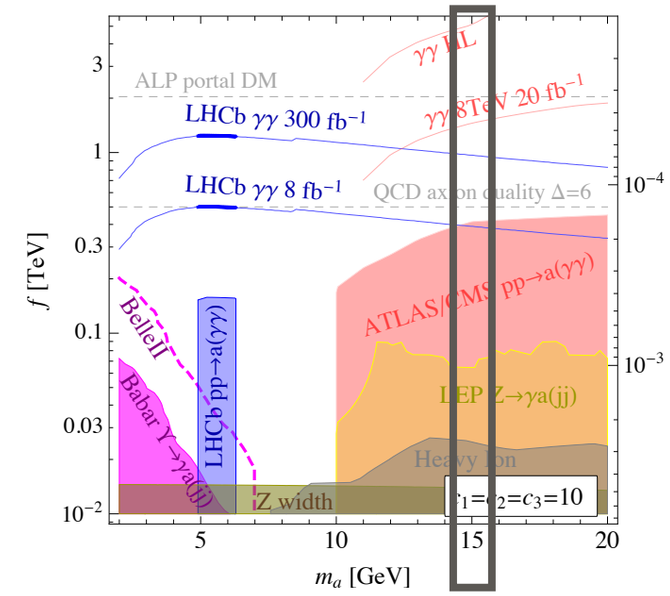
$c_1 = c_2$ →Z coupling

$N = c_3 \quad , \quad E = c_2 + 5c_1/3$

$$\mathcal{L}_{\rm eff} \supset \frac{N\alpha_3}{4\pi}\frac{a}{f}G_{\mu\nu}\tilde{G}^{\mu\nu} + \frac{E\alpha_{\rm em}}{4\pi}\frac{a}{f}F_{\mu\nu}\tilde{F}^{\mu\nu}$$

Change photon/gluon ratio





LHCb can cover unexplored region

assume current diphoton triggers at ATLAS&CMS

$c_1 = c_2$ →Z coupling

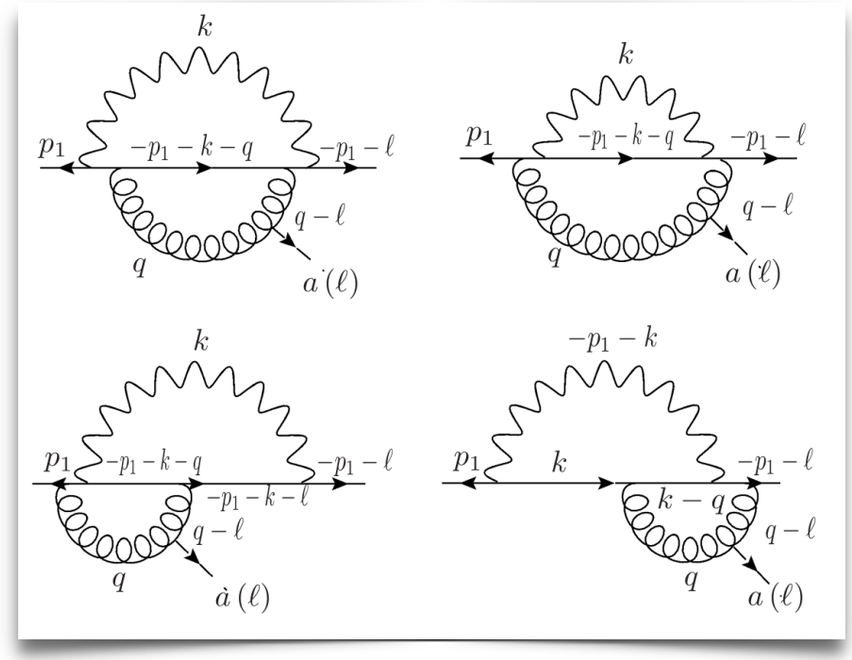
$N = c_3 \quad , \quad E = c_2 + 5c_1/3$

$$\mathcal{L}_{\rm eff} \supset \frac{N\alpha_3}{4\pi}\frac{a}{f}G_{\mu\nu}\tilde{G}^{\mu\nu} + \frac{E\alpha_{\rm em}}{4\pi}\frac{a}{f}F_{\mu\nu}\tilde{F}^{\mu\nu}$$

More hadronic case for $m_\eta < m_a < 3$GeV

Production estimate for B→Ka ($b \to sa$) @2-loop

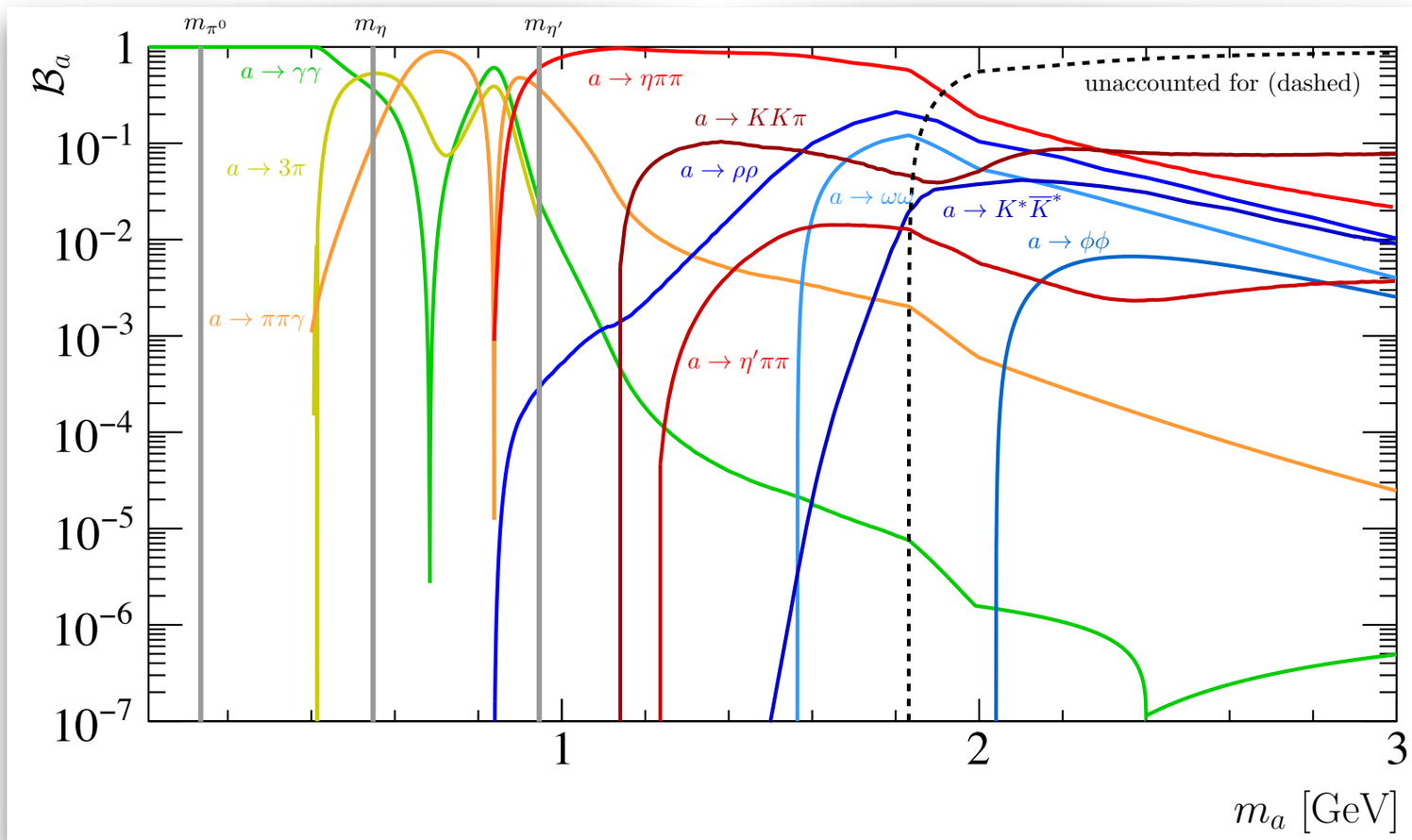
[0911.4938, B. Batell, M. Pospelov, A. Ritz]
also hep-ph/0404220, G. Hiller; hep-ph/0104284, C. Bobeth, T. Ewerth, F. Kruger, and J. Urban; 1708.00021, K. Choi, S. H. Im, C. B. Park, and S. Yun



2-loop calculation. 2011.xxxxx
Sabyasachi Chakraborty, Manfred Kraus, Vazha Loladze, Takemichi Okui, **KT**

Hadronic decays, data driven approach

[1811.03474, D. Aloni, Y. Soreq, M. Williams]

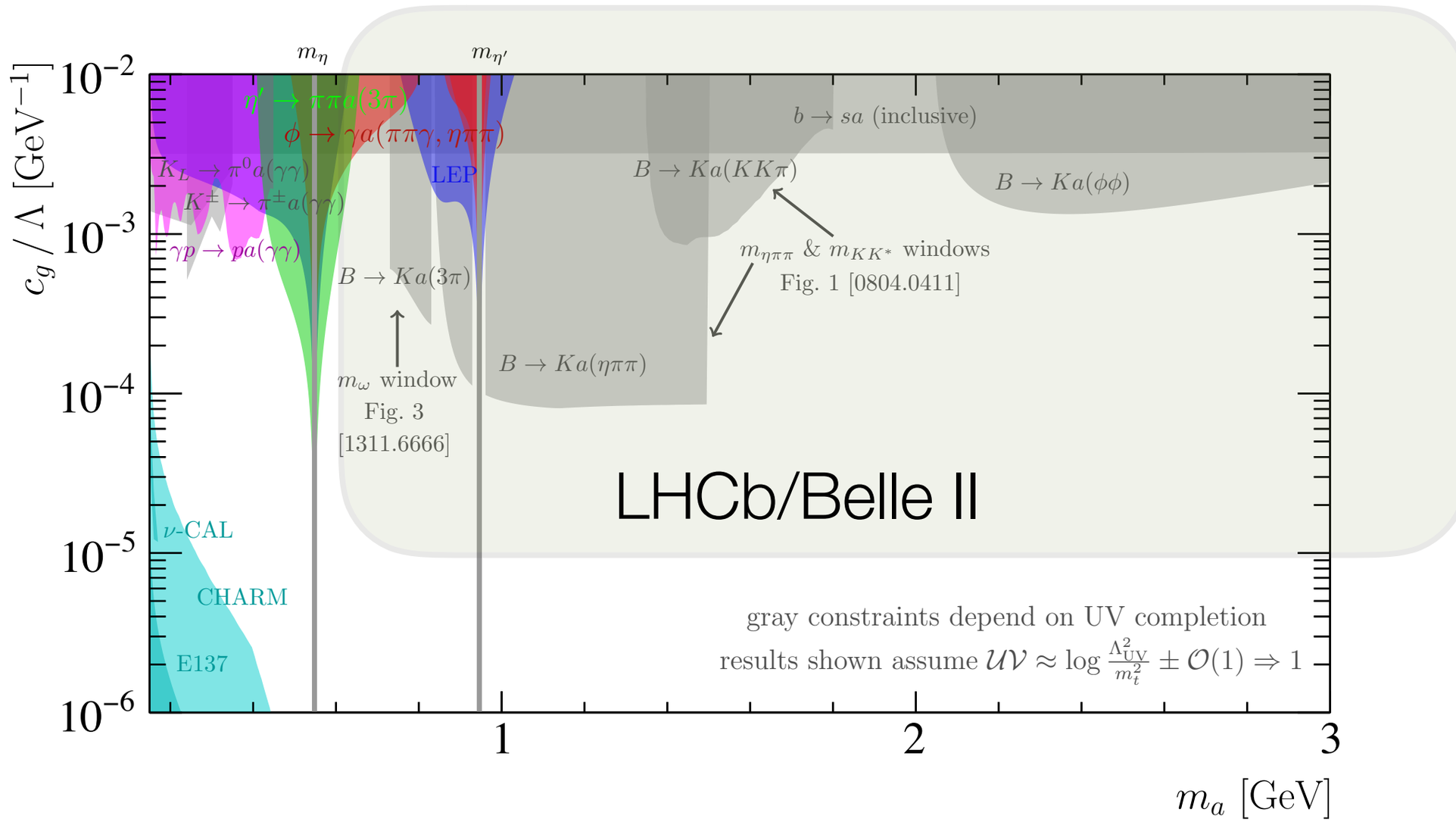


- Belle II could do same.
- Possible at **LHCb** too?
- Also $a \to \rho\rho$, $\omega\omega$?

Babar/Belle studied [0804.0411, 1311.6666]

$B \to K\pi\pi\pi$, $K\eta\pi\pi$, $KKK\pi$, $K\phi\phi$

More hadronic case for $m_\eta < m_a < 3$GeV



[1811.03474, D. Aloni, Y. Soreq, M. Williams]

Summary and Prospects

- LHCb has unique opportunities for exotic resonences
- Fill the gap between ATLAS/CMS and other flavor exes
- Axion-like particles with gluon coupling
  - well-motivated example
  - can be produced at LHC(b)
  - LHCb will give the best sensitivities for O(2-20GeV)
- X→diphoton, hadronic final states will be interesting addition to on-going search programs.

Backup

Theory perspectives for ALPs

- Consider an ALP with $\frac{\alpha_s}{8\pi F_a} a G\tilde{G}$ for the strong CP problem
- PQ quality problem: $\Phi|\Phi|^{D-1}/\Lambda_{UV}^{D-4}$
  Global symmetry is not robust. The ALP potential ruined even by gravity.
- Large m_a and small f_a are favored

$$V(a) = m_a^2 F_a^2 \left\{1 - \cos\left(\frac{a}{F_a}\right)\right\} + \frac{F_a^2}{\Lambda_{UV}^{D-4}} \cos\left(\frac{a}{F_a} + \Delta\right)$$

$$\to \delta\bar{\theta} = \frac{\delta a_{min}}{F_a} \sim \frac{F_a^{D-2}}{m_a^2 \Lambda_{UV}^{D-4}},$$

[S. M. Barr, D. Seckel ('92); M. Kamionkowski, J. March-Russell ('92)]

- Models Mirror QCD (QCD'x Z_2) $m_a \gg 0.1\mathrm{GeV}/f_a$

[**V. Rubakov ('97)**;…Fukuda, K. Harigaya, M. Ibe, T. T. Yanagida('15);
S. Dimopoulos, A. Hook, J. Huang, G. Marques-Tavares('16),
P. Agrawal, K. Howe('17)]

- Important to search for exotics colored states, $m \sim 4\pi f_a$