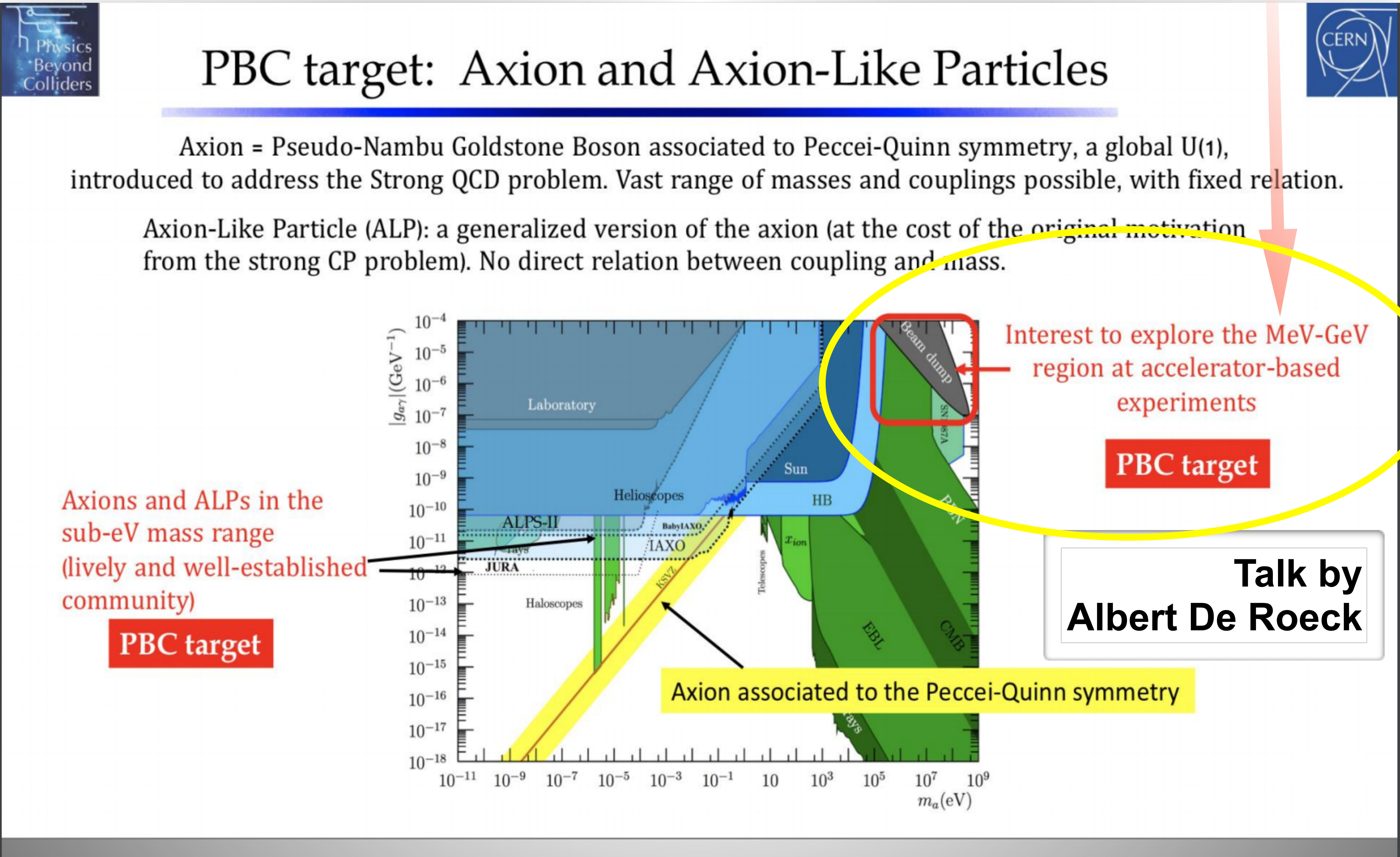
Axion-like-particles at ATLAS/CMS, LHCb, and Kaon factory

July 4, 2019

Kohsaku Tobioka
Florida State University&KEK

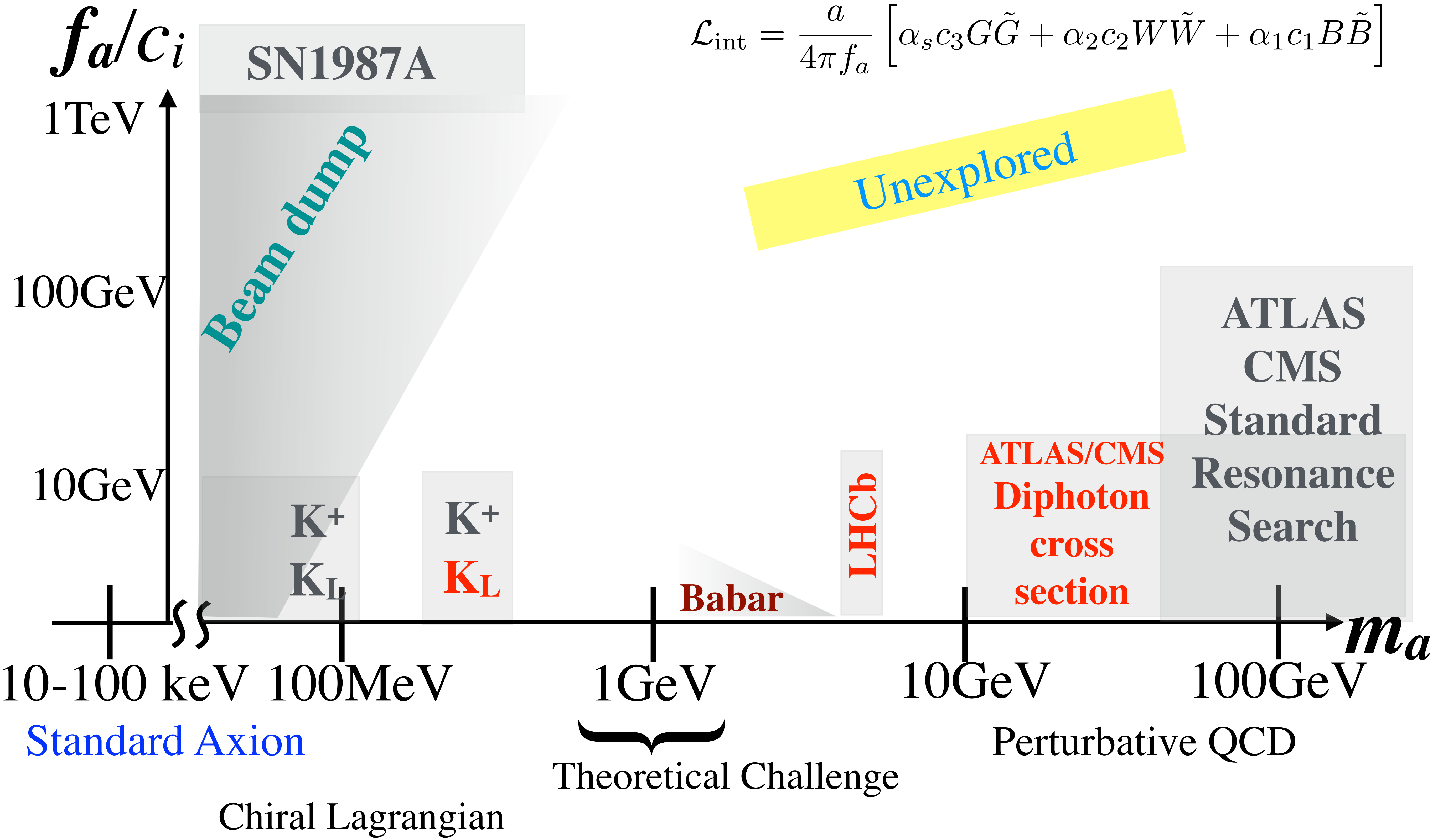
Refs.
[arXiv:1710.01743]Phys.Lett. B783(2018)13 A. Mariotti, D. Redigolo, F. Sala, KT
[arXiv:1810.09452]JHEP1901(2019)113 X. Cid Vidal, A. Mariotti, D. Redigolo, F. Sala, KT
preliminary work with Stefania Gori, Gilad Perez

Introduction



Introduction

$$\mathcal{L}_{\rm int} = \frac{a}{4\pi f_a}\left[\alpha_s c_3 G\tilde{G} + \alpha_2 c_2 W\tilde{W} + \alpha_1 c_1 B\tilde{B}\right]$$



Outline

- Theoretical Motivation
  - Axion-like-Particles and Heavy Axion
- Search at
  - ATLAS/CMS for 10GeV-50GeV
  - LHCb for O(1)GeV-20GeV
  - KOTO for <350MeV
- Summary

Theoretical Motivation

Expect light resonance?

Yes. **pNGB: pseudo Nambu Goldstone bosons** are common among BSM models, mass can be arbitrary light, e.g. π

Focus: **Axion-like-particles**(ALPs) e.g.

Hierarchy problem

- R-axion from low-scale SUSY

  E.g. Bellazzini, Mariotti, Redigolo, Sala, Serra(1702.02152)

- pNGB from composite Higgs

  Barnard, Gherghetta, Ray('13), Ferretti('16)…

Simply new QCD

- New pion from TeV QCD'

  Kilic, Okui, Sundrum('09), Nakai, Sato, KT ('16) …

Strong CP problem

- Heavy Axion/Visible Axion

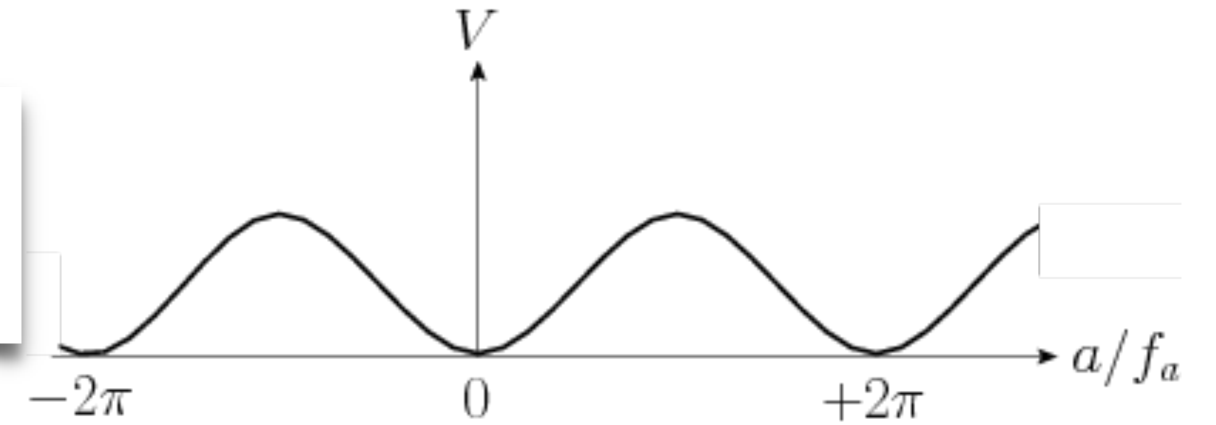
  Rubakov{'97}, Fukuda, Harigaya, Ibe, Yanagida ('15), P. Agrawal, K. Howe('17)

Unlike QCD axion case, $m_a \sim m_\pi f_\pi / f_a$,
mass and coupling ($1/f_a$) are independent

Strong CP problem and Axion

$$\frac{\theta g_s^2}{32\pi^2} G\tilde{G} \Rightarrow \frac{N\alpha_3}{4\pi}\frac{a}{f}G_{\mu\nu}\tilde{G}^{\mu\nu}$$

$$\bar{\theta} \lesssim 10^{-10}$$



Phase promoted to axion field, and settled at minimum

[Peccei, Quinn] [Weinberg; Wilczek; Kim-Shifman-Vainshtein-Zakharov; Dine–Fischler–Srednicki–Zhitnitsky]

Axion window

$$4 \times 10^8\,\mathrm{GeV} \lesssim f_a \lesssim 10^{12}\,\mathrm{GeV}$$

Constraints(e.g. Astro,SN1987) push to **very high f_a**

*Over DM abundance&problem in inflation with $f_a > 10^{12}$GeV

Peccei-Quinn symmetry quality problem

Global symmetry explicitly broken by gravity or cutoff
→PQ symmetry should be extremely robust

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

$$\Delta V_{P\!\!/Q} = \lambda_\Delta \frac{\Phi^\Delta}{\Lambda_{\rm UV}^{\Delta-4}} + {\rm h.c.}$$

→

$$V_a \simeq -\Lambda_{\rm QCD}^4 \cos\frac{Na}{f} + \frac{1}{2^{\frac{\Delta}{2}-1}} \frac{|\lambda_\Delta| f^\Delta}{\Lambda_{\rm UV}^{\Delta-4}} \cos\left(\alpha_\Delta + \Delta\frac{a}{f}\right)$$

Even gravity breaking with Δ=12 shifts min. ($f_a \sim 10^{12}$GeV)

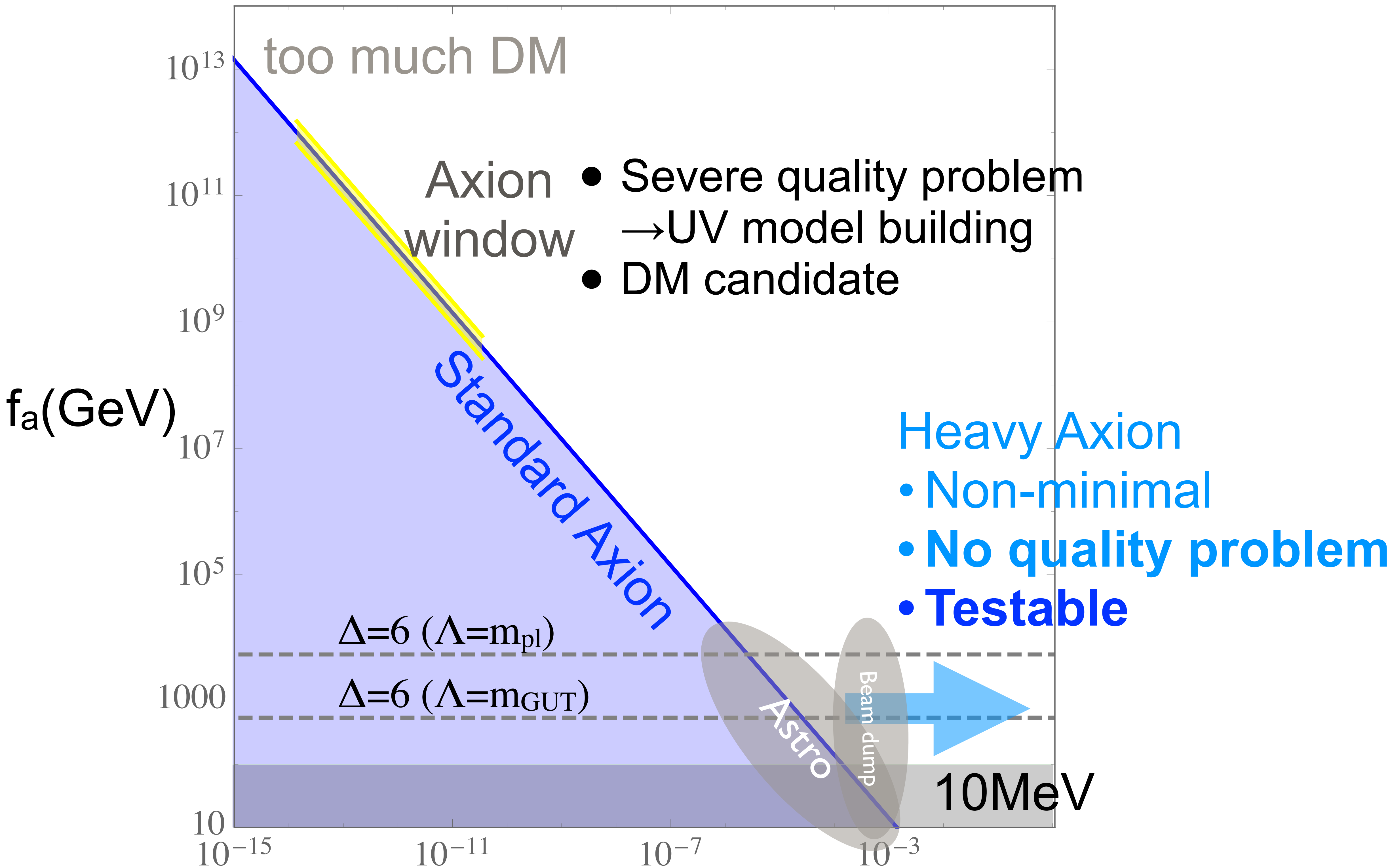
$\boldsymbol{\delta\theta > 10^{-10}}$

- With **Δ<12** operators, strong CP problem is not solved
- Standard scenario requires complex UV

Extended gauge group, discrete symmetry, extra dimension…

[Dine('92); R. Holman et al('92); Randall ('92); E. Chun and A. Lukas('92); HC Cheng, D.E.Kaplan('01), Dias, Pleitez, Tonasse ('12),… K. Harigaya, et al ('13); M. Redi, R. Sato('16), Fukuda, Ibe, Suzuki('17)…]

PQ quality problem motivates Heavy Axion



Need ALP-gluon coupling

Effective Lagrangian

$$\mathcal{L}_{\rm int} = \frac{a}{4\pi f_a}\left[\alpha_s c_3 G\tilde{G} + \alpha_2 c_2 W\tilde{W} + \alpha_1 c_1 B\tilde{B}\right]$$

$f_a \sim 0.1 - 10$ TeV and $c_3 \neq 0$

Loops of gluinos, tops. Necessary to solve strong CP problem

benchmark $c_1 = c_2 = c_3 = 10$

- production@LHC is gluon fusion,
- prompt decay to dijet or diphoton due to (m_a<m_Z)

Effective Lagrangian

$$\mathcal{L}_{\rm int} = \frac{a}{4\pi f_a}\left[\alpha_s c_3 G\tilde{G} + \alpha_2 c_2 W\tilde{W} + \alpha_1 c_1 B\tilde{B}\right]$$

$f_a \sim 0.1 - 10\ \text{TeV}$ and $c_3 \neq 0$

Loops of gluinos, tops. Necessary to solve strong CP problem

benchmark $c_1 = c_2 = c_3 = 10$

- production@LHC is gluon fusion,
- prompt decay to dijet or diphoton due to (m_a<m_Z)

Many previous ALP studies with c_3=0 ($Br_{a\to\gamma\gamma}$~100%)

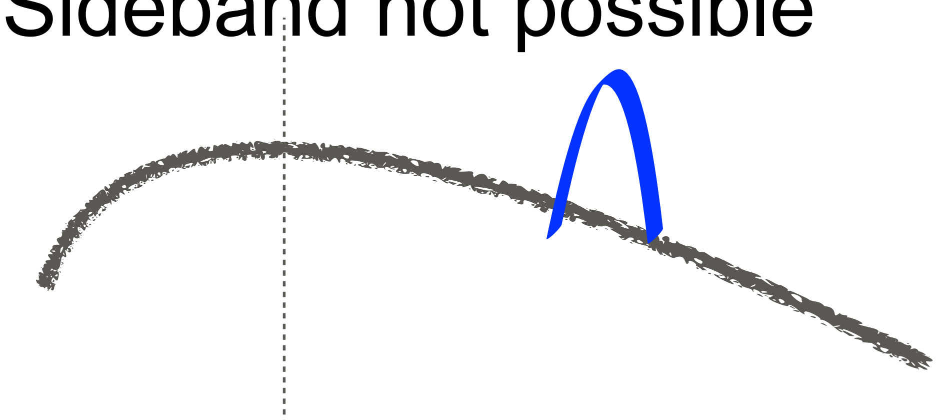
Photonphilic ALP: LEP[Jaeckel, Spannowsky('15)]
Heavy-ion[Knapen et al('16)], Beamdump with NA62 [B. Dobrich et al ('16)],
Sub 10GeV, ALP-W int. induces FCNC(B->Ka) [Izaguirre, Lin, Shuve('16)], etc.

Search at ATLAS/CMS m_a=10-50GeV

Existing constraints from LEP to LHC

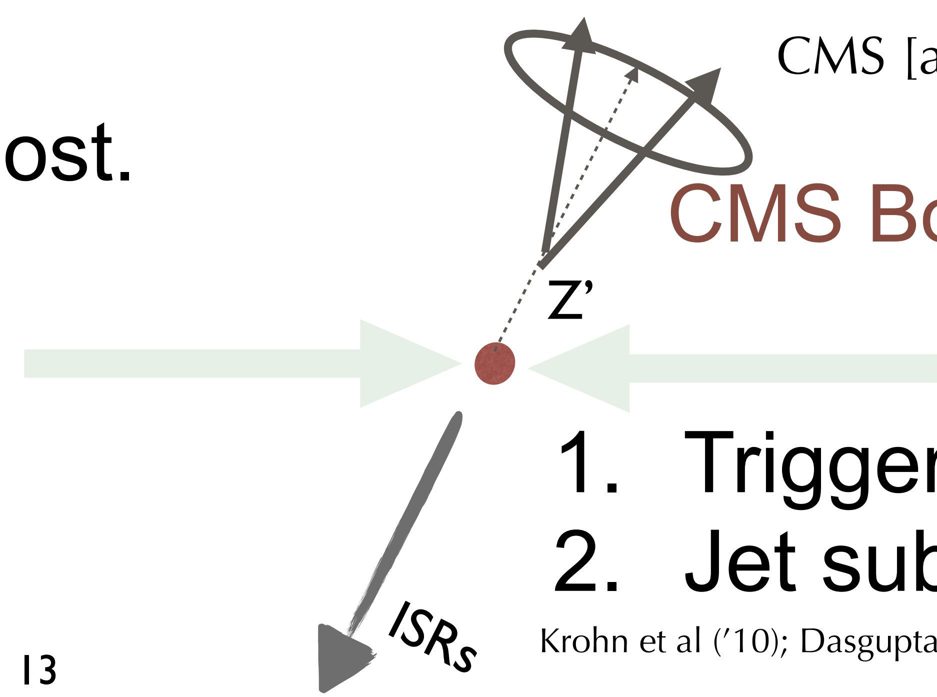
Experiment	Process	Lumi	$\sqrt{s}$	low mass reach	ref.
LEPI	$e^+e^- \to Z \to \gamma a \to \gamma jj$	12 pb^{-1}	Z-pole	10 GeV	[29]
LEPI	$e^+e^- \to Z \to \gamma a \to \gamma\gamma\gamma$	78 pb^{-1}	Z-pole	3 GeV	[30]
LEPII	$e^+e^- \to Z^*, \gamma^* \to \gamma a \to \gamma jj$	9.7,10.1,47.7 pb^{-1}	161,172,183 GeV	60 GeV	[31]
LEPII	$e^+e^- \to Z^*, \gamma^* \to \gamma a \to \gamma\gamma\gamma$	9.7,10.1,47.7 pb^{-1}	161,172,183 GeV	60 GeV	[31, 32]
LEPII	$e^+e^- \to Z^*, \gamma^* \to Za \to jj\gamma\gamma$	9.7,10.1,47.7 pb^{-1}	161,172,183 GeV	60 GeV	[31]
D0/CDF	$p\bar{p} \to a \to \gamma\gamma$	7/8.2 fb^{-1}	1.96 TeV	100 GeV	[33]
ATLAS	$pp \to a \to \gamma\gamma$	20.3 fb^{-1}	8 TeV	65 GeV	[34]
CMS	$pp \to a \to \gamma\gamma$	19.7 fb^{-1}	8 TeV	80 GeV	[35]
CMS	$pp \to a \to \gamma\gamma$	19.7 fb^{-1}	8 TeV	150 GeV	[36]
CMS	$pp \to a \to \gamma\gamma$	35.9 fb^{-1}	13 TeV	70 GeV	[37]
CMS	$pp \to a \to jj$	18.8 fb^{-1}	8 TeV	500 GeV	[38]
ATLAS	$pp \to a \to jj$	20.3 fb^{-1}	8 TeV	350 GeV	[39]
CMS	$pp \to a \to jj$	12.9 fb^{-1}	13 TeV	600 GeV	[40]
ATLAS	$pp \to a \to jj$	3.4 fb^{-1}	13 TeV	450 GeV	[41]
CMS	$pp \to ja \to jjj$	35.9 fb^{-1}	13 TeV	50 GeV	[42]

Below lowest mass,
smooth background structure is lost.
Sideband not possible



CMS [arXiv:1710.00159]

CMS Boosted dijet

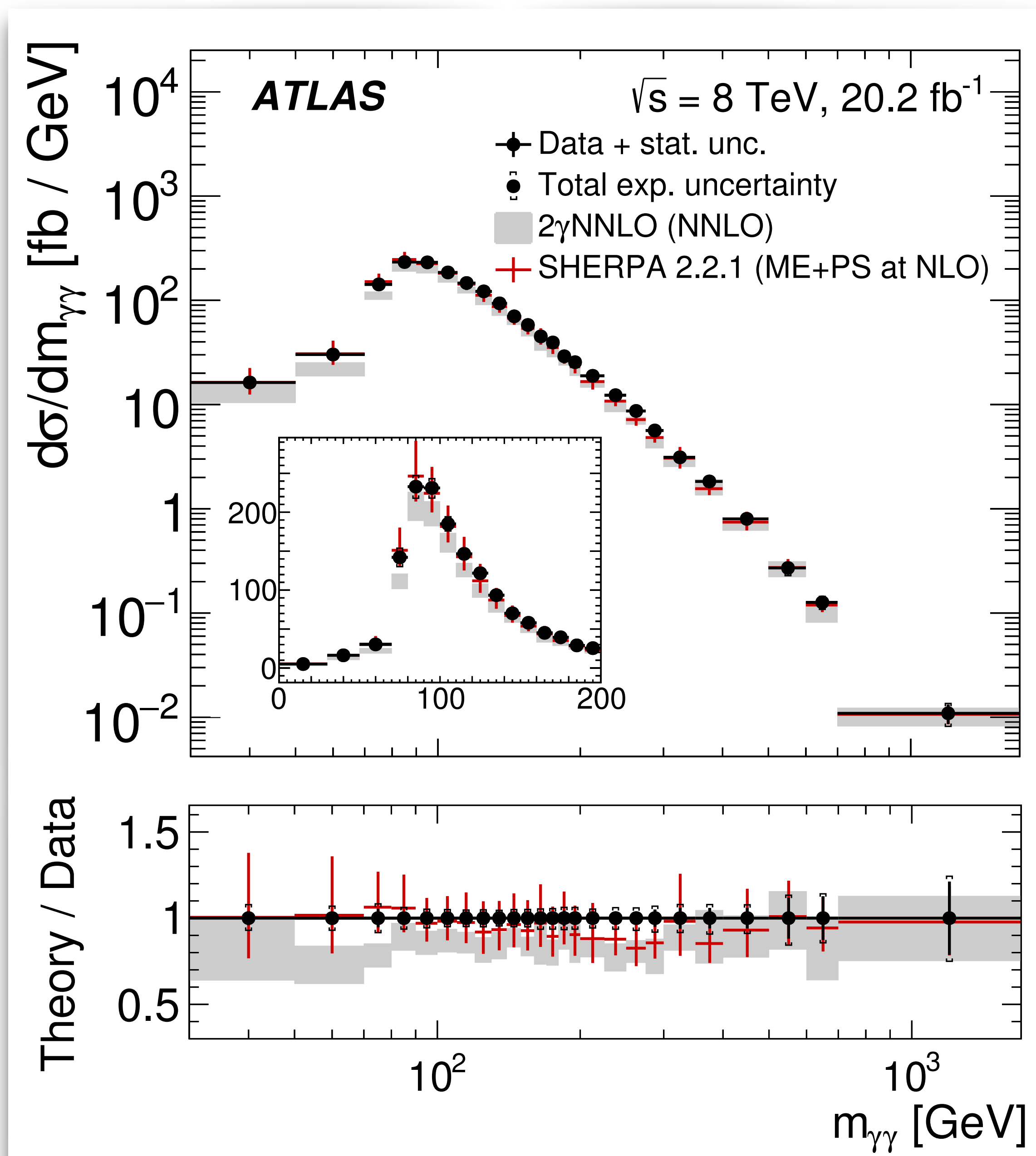


1. Trigger ISR
2. Jet substructure

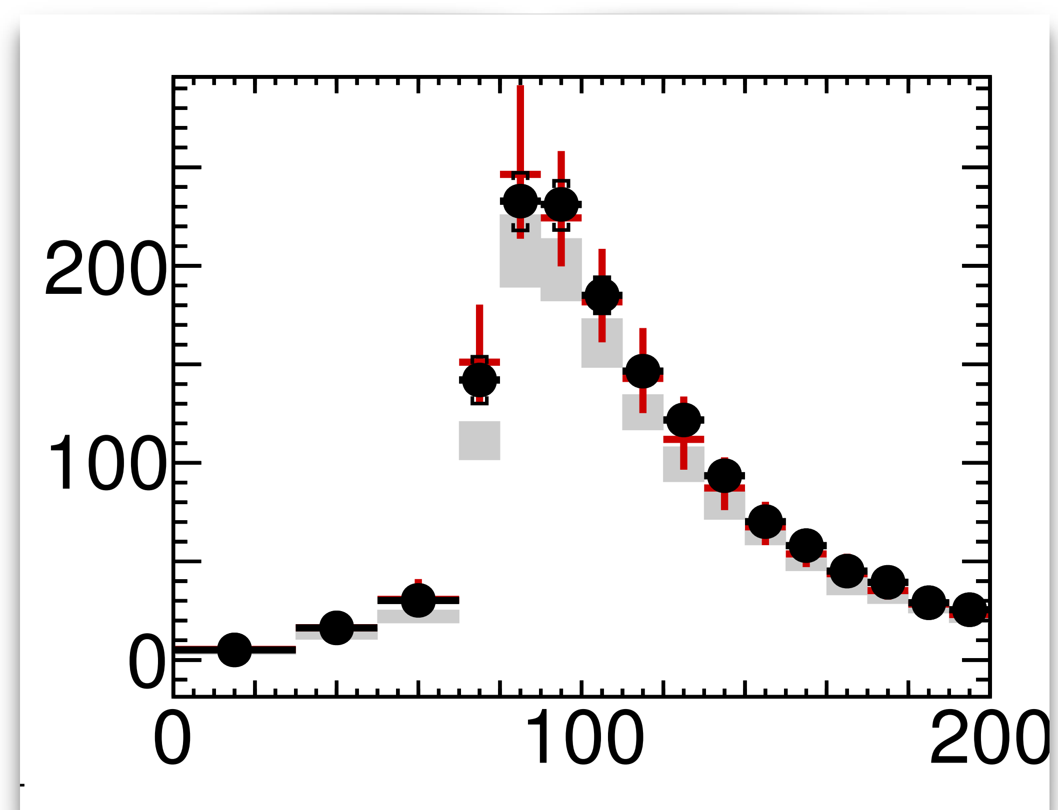
Krohn et al ('10); Dasgupta et al ('13); Larkoski et al ('14)

Diphoton x-section measurements

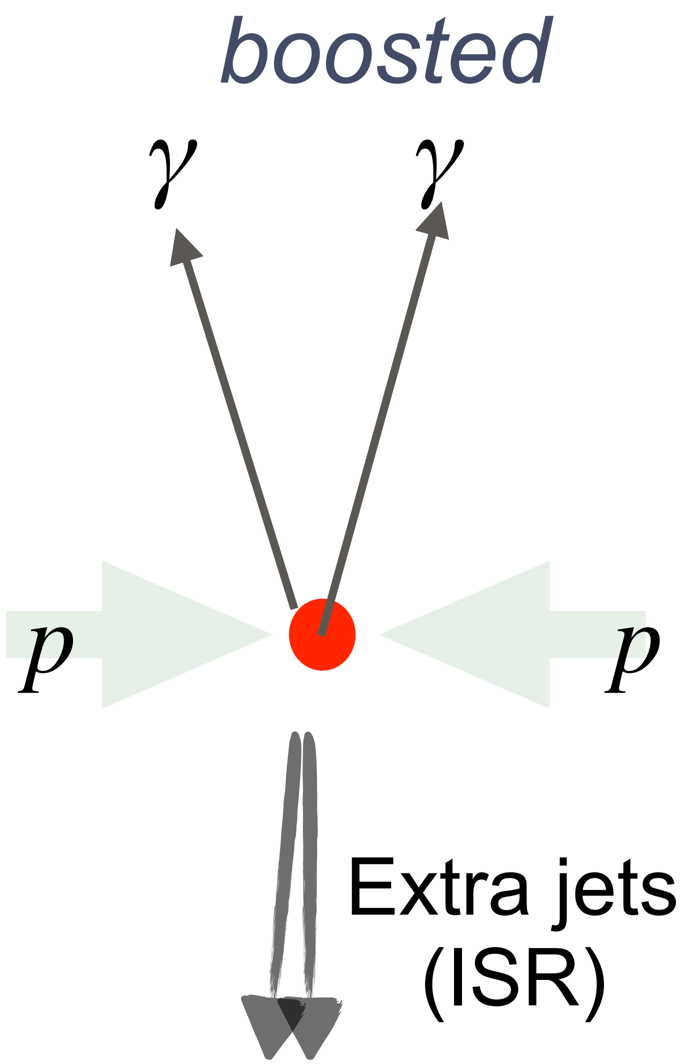
D0 ($\sigma_{\gamma\gamma}$)	$p\bar{p} \to a \to \gamma\gamma$	4.2 fb^{-1}	1.96 TeV	$p_{T_1,T_2} > 21\,,20$ GeV	m_a> 8.2GeV
CDF ($\sigma_{\gamma\gamma}$)	$p\bar{p} \to a \to \gamma\gamma$	5.36 fb^{-1}	1.96 TeV	$p_{T_1,T_2} > 17\,,15$ GeV	(m_a> 6.4 GeV)
ATLAS	$pp \to a \to \gamma\gamma$	4.9 fb^{-1}	7 TeV	$p_{T_1,T_2} > 25\,,22$ GeV	m_a> 9.4 GeV
ATLAS	$pp \to a \to \gamma\gamma$	20.2 fb^{-1}	8 TeV	$p_{T_1,T_2} > 40\,,30$ GeV	m_a>13.9 GeV
CMS	$pp \to a \to \gamma\gamma$	5.0 fb^{-1}	7 TeV	$p_{T_1,T_2} > 40\,,25$ GeV	m_a>14.2 GeV



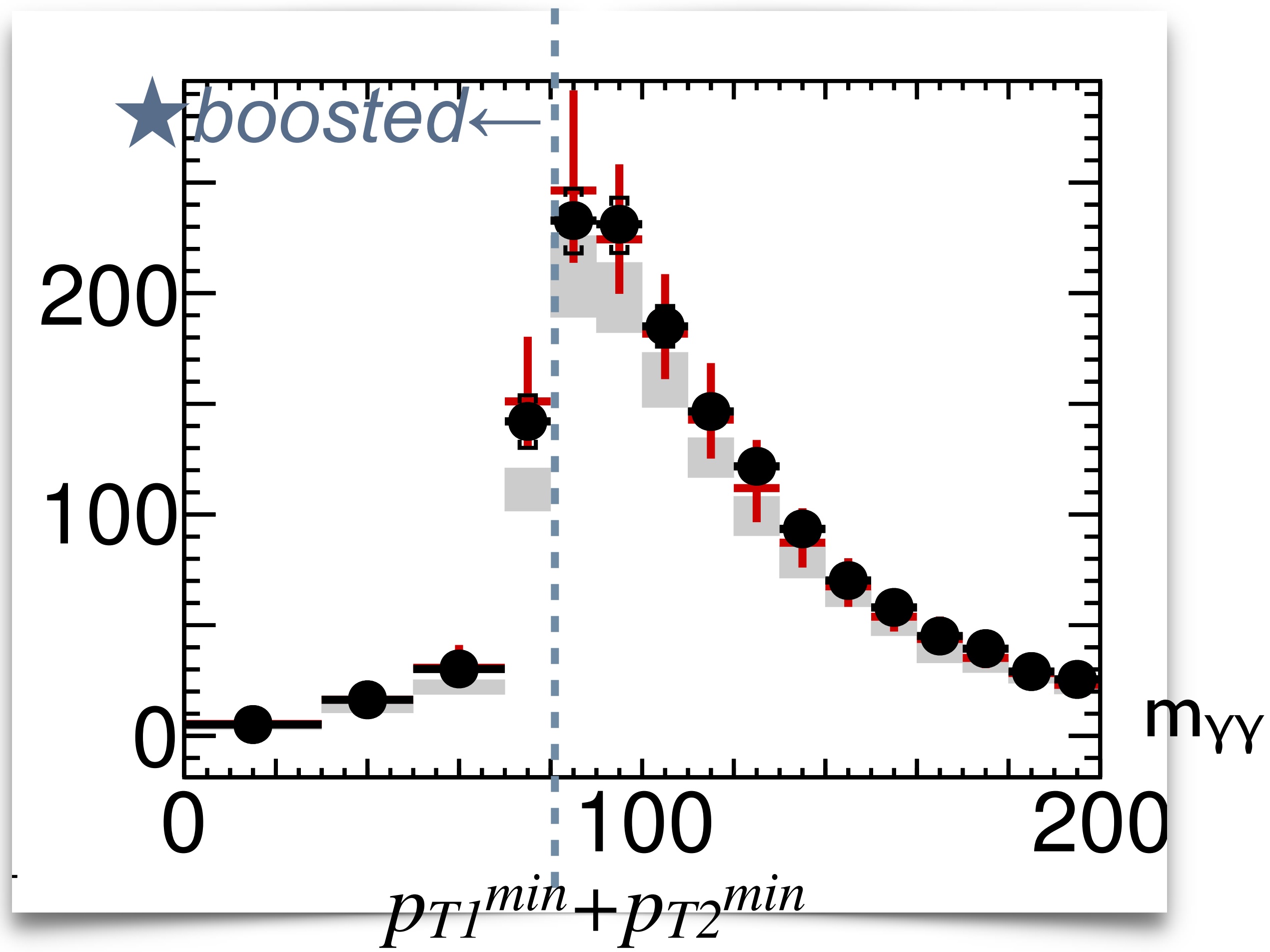
They report lower mass!

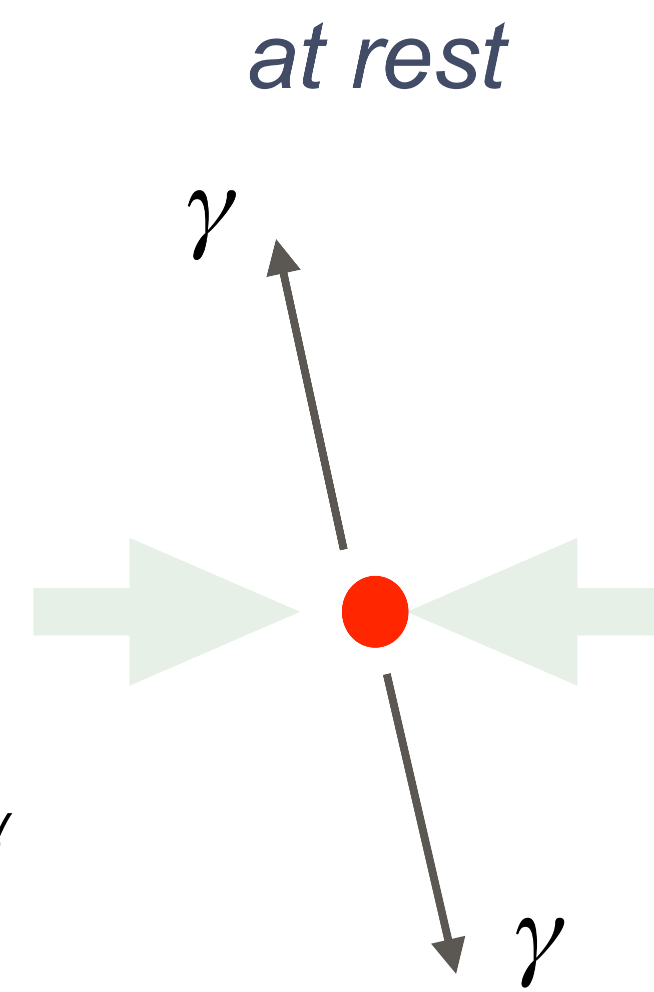


Diphoton x-section measurements



$p_{T1,2}$>40, 30GeV





★strict lower bound of $m_{\gamma\gamma}$ from ΔR>0.4

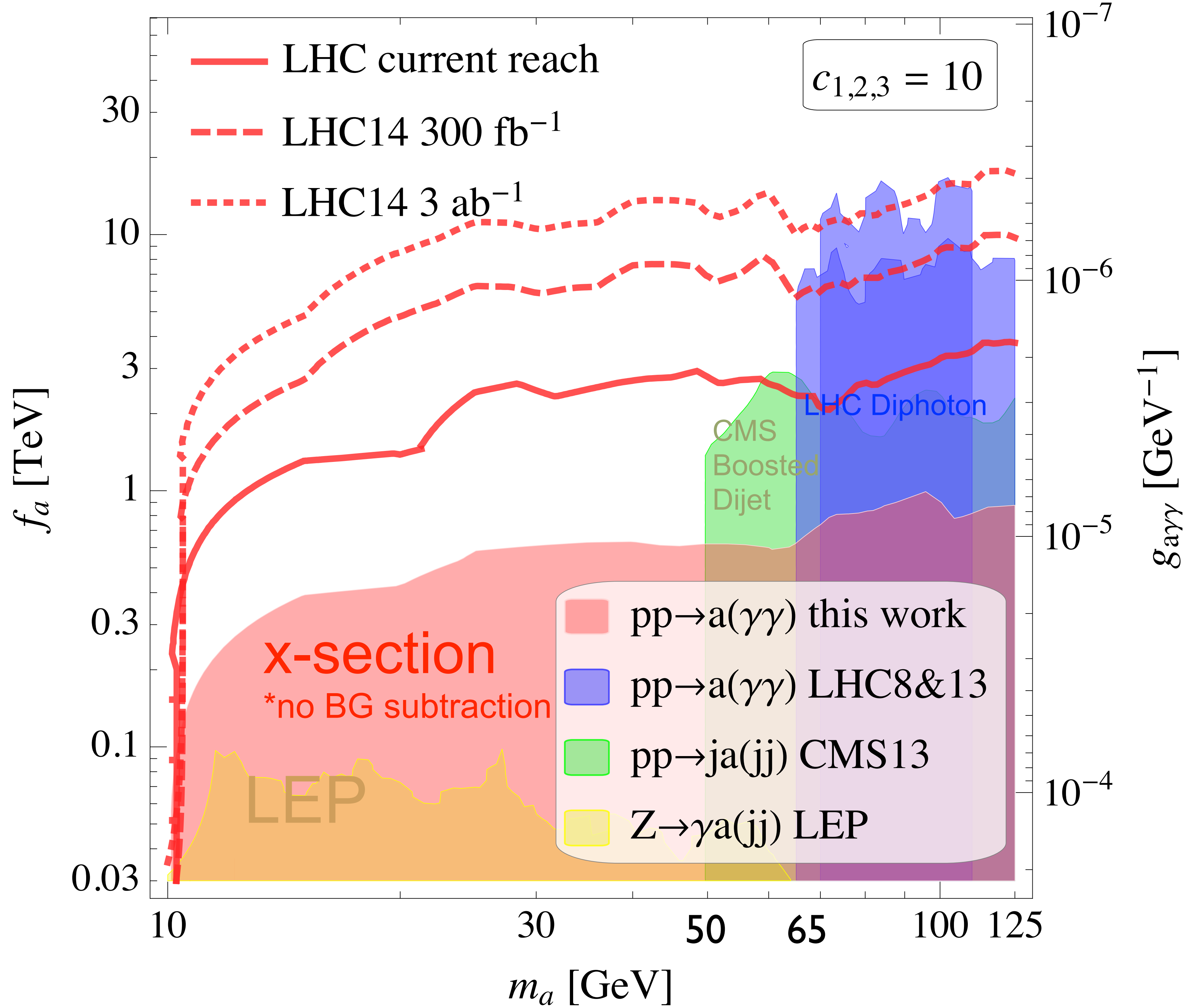
diphoton angular separation

$$m_{\gamma\gamma} > \Delta R \cdot \sqrt{p_{T1}^{\min} p_{T2}^{\min}}$$ ~13.8GeV

m_a in GeV	10	20	30	40	50	60	70	80	90	100	110	120
ϵ_S for $\sigma_{8\text{TeV}}$ ATLAS [9]	0	0.0007	0.008	0.014	0.024	0.037	0.071	0.233	0.347	0.419	0.452	0.484

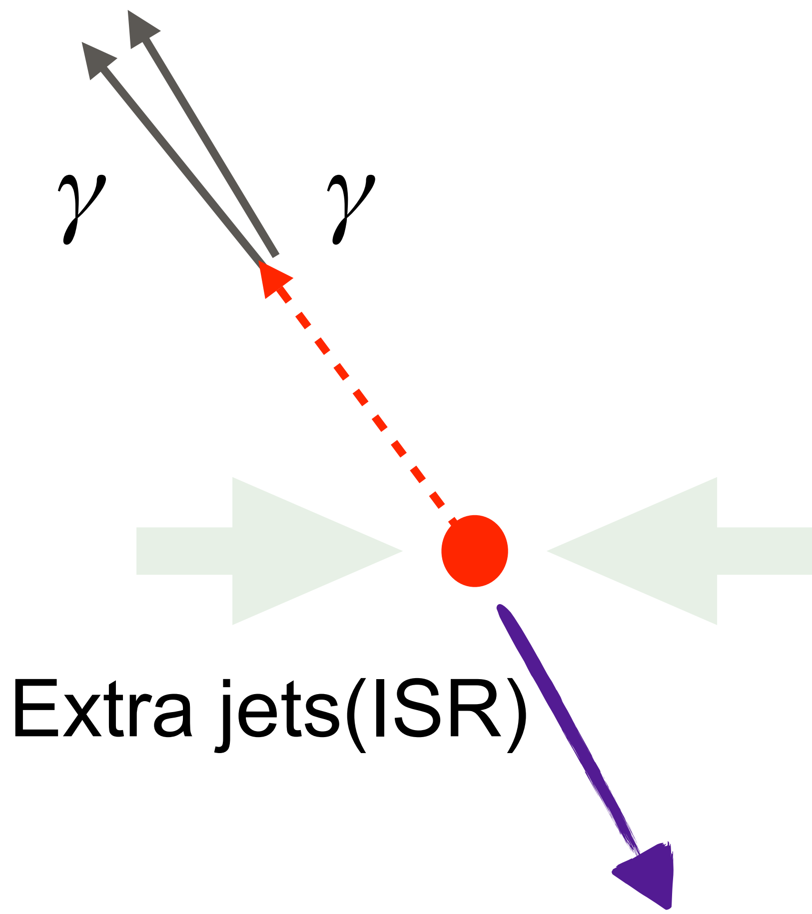
Signal Efficiency

ALP parameter space



A. Mariotti, D. Redigolo, F. Sala, **KT** ('17)

Trigger and Isolation

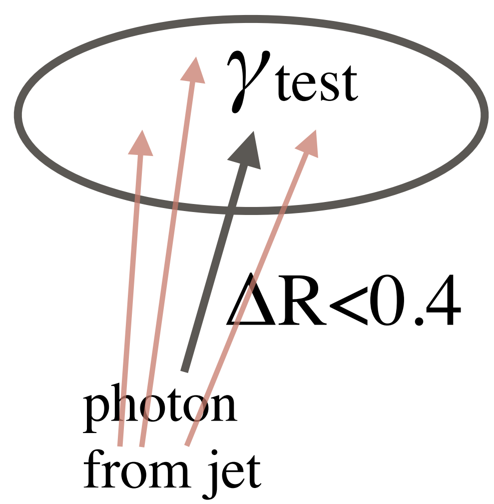


ATLAS/CMS diphoton trigger requires
$\Delta R_{\gamma\gamma}>0.4$ and $pT_\gamma>20$GeV
Also, pT_γ will increases.

$$m_a = \Delta R_{\gamma\gamma}\sqrt{p_{T\gamma_1}p_{T\gamma_2}}$$
$$\sim \Delta R_{\gamma\gamma}\frac{p_T^{\rm ISR}}{2}$$

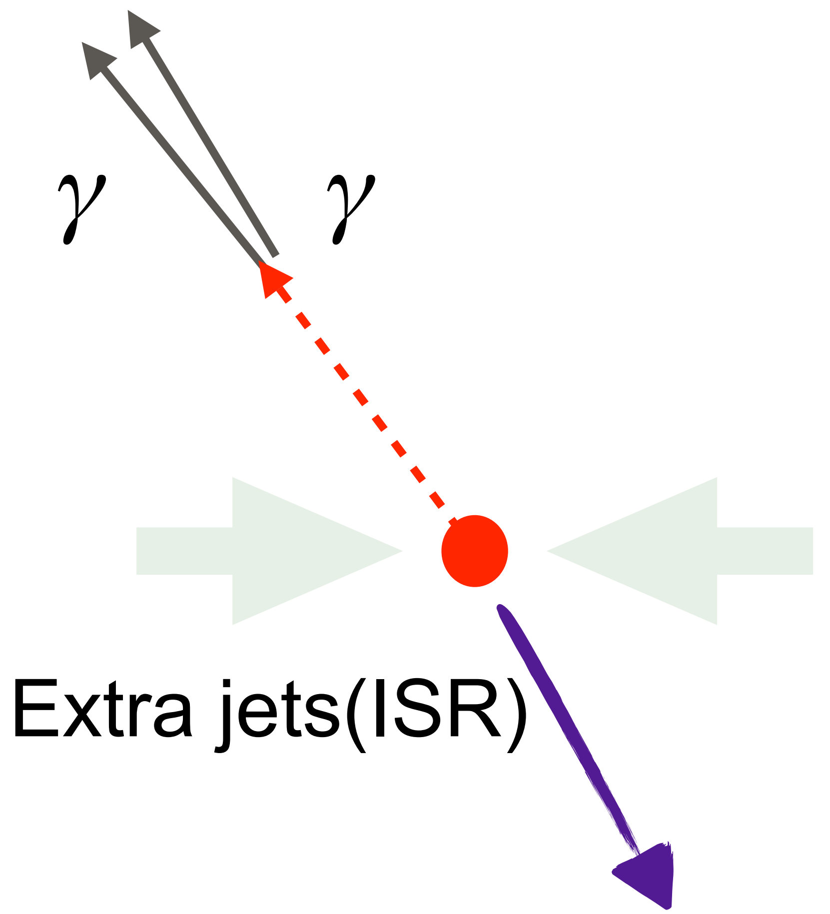
Mono-j/Mono-γ trigger,
e.g. $pT_j>500$GeV

&**modify Isolation**
to probe $0.15<\Delta R_{\gamma\gamma}<0.4$



Simply diphoton trigger
with **lower** $\mathbf{pT_\gamma}$
prescaled trigger or **LHCb**

Trigger and Isolation

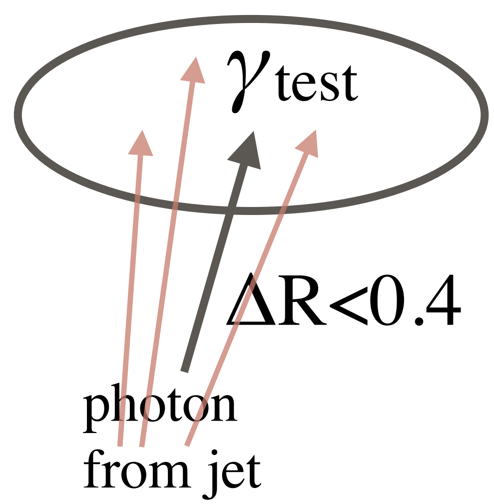


ATLAS/CMS diphoton trigger requires
⊿$R_{\gamma\gamma}$>0.4 and pT_γ>20GeV
Also, pT_γ will increases.

$$m_a = \Delta R_{\gamma\gamma}\sqrt{p_{T\gamma_1} p_{T\gamma_2}}$$
$$\sim \Delta R_{\gamma\gamma}\frac{p_T^{\rm ISR}}{2}$$

Mono-j/Mono-γ trigger,
e.g. pT_j>500GeV

&**modify Isolation**
to probe 0.15<⊿$R_{\gamma\gamma}$<0.4



standard

$$E_T^{\rm iso} \equiv \sum_{i\neq\gamma_{\rm test}}^{\Delta R_{i,\gamma_{\rm test}}<0.4} E_{T_i}$$ <10GeV

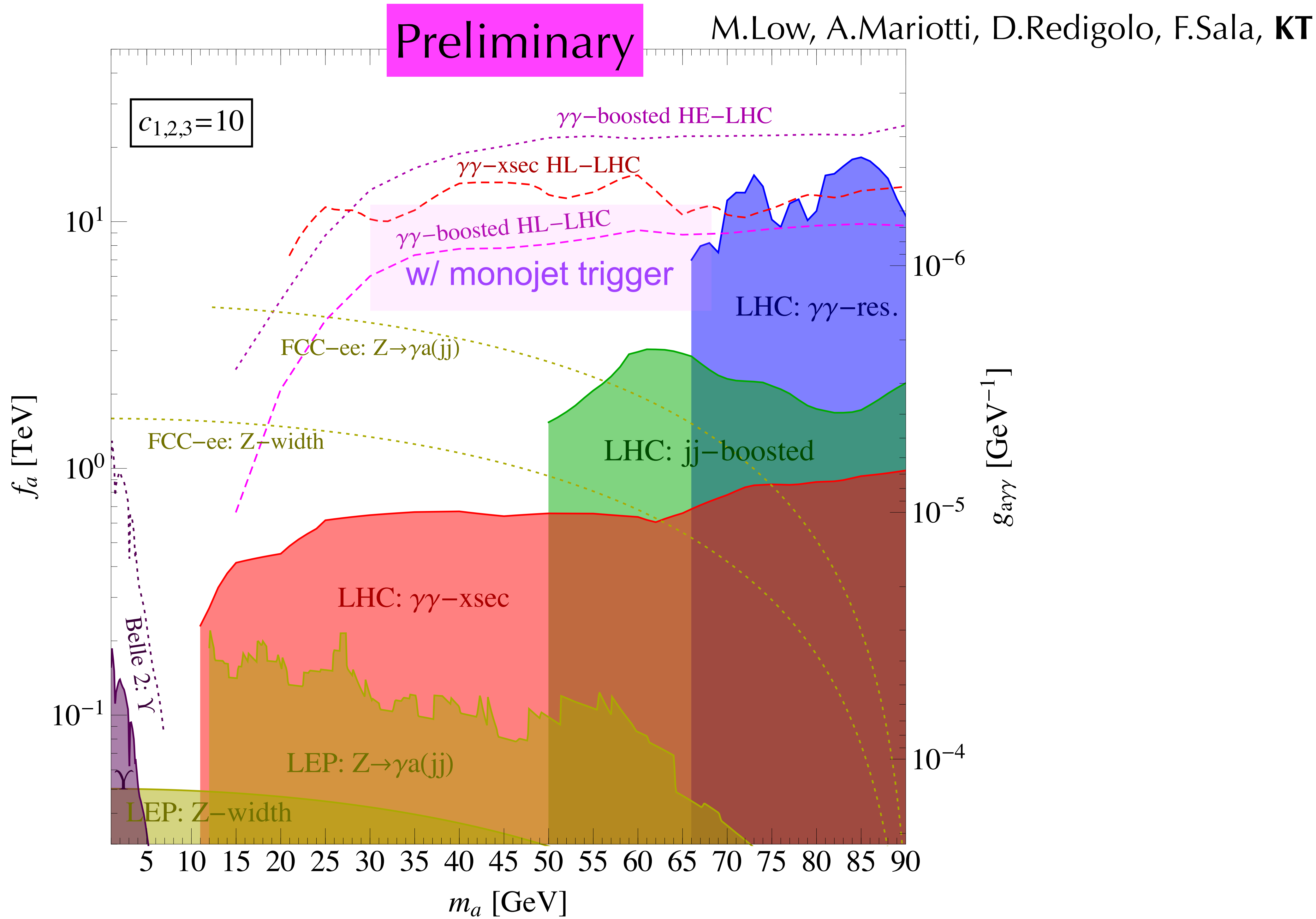
modified

$$E_T^{\rm iso} - E_{T_{\gamma_1}}$$ <10GeV

ATLAS h->aa->4γ [arXiv:1509.05051]

almost same rejection rate for fake photon

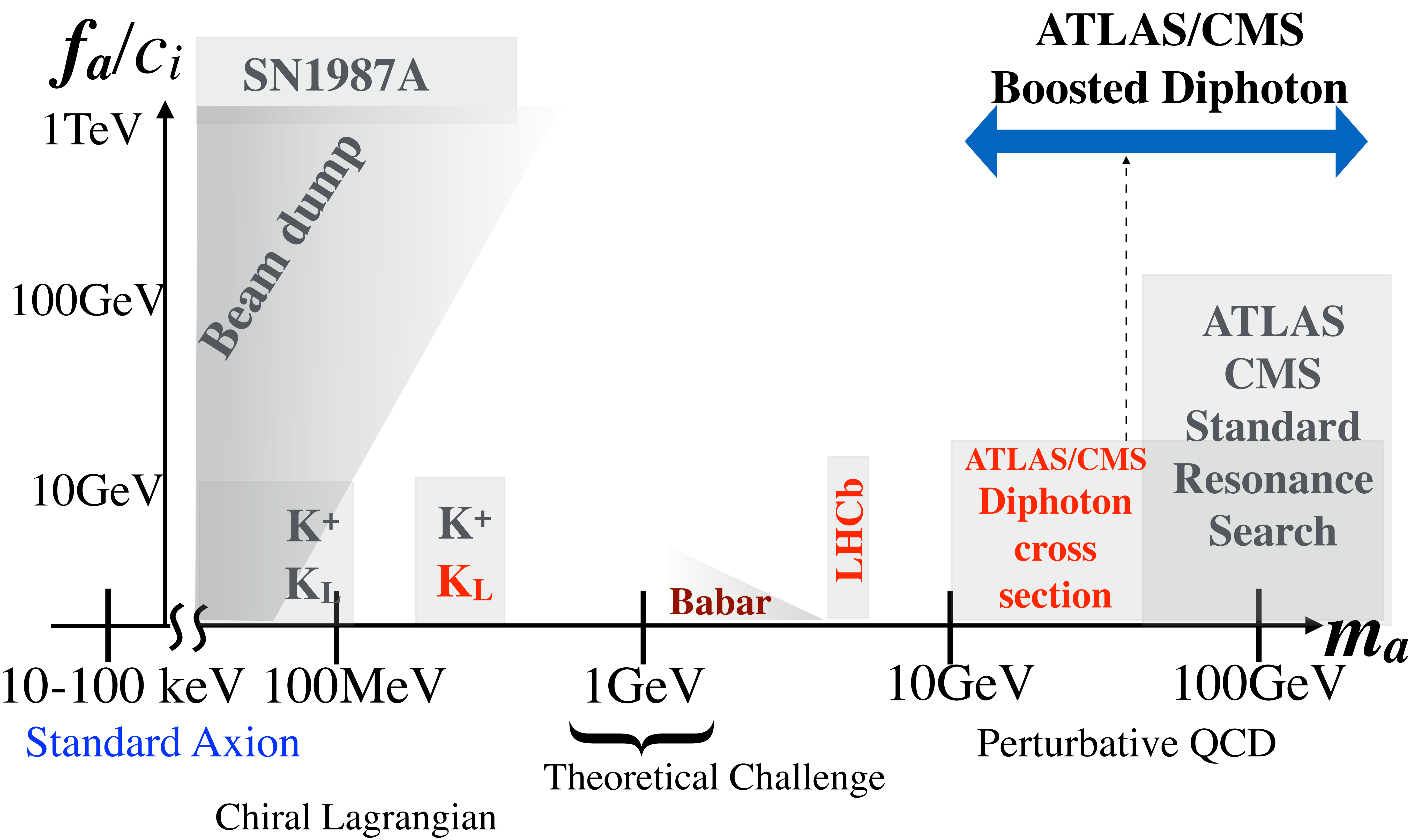
LHC bound +Projections



Study monojet(>500GeV)+Boosted Diphoton w/ mod Iso

one w/ mono photon trigger goes below 10GeV (in progress)

Future Prospect



Search at LHCb
m_a=O(1)-20GeV

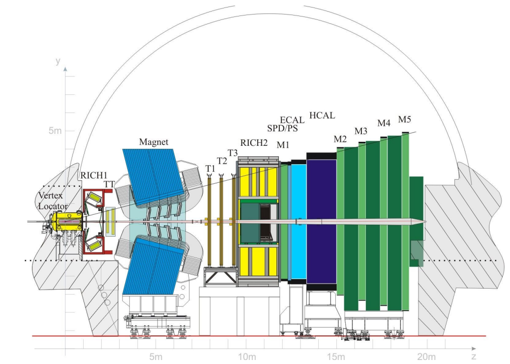
Diphoton resonance at LHCb

LHCb-PUB-2018-006
May 11, 2018

Triggering $B_s^0 \to \gamma\gamma$ at LHCb

Abstract

The trigger strategy used in the search for the $B_s^0 \to \gamma\gamma$ decay in Run 2 is described. A sample of data is also provided, corresponding to $80\,\text{pb}^{-1}$ of diphoton candidates collected in 2015.



Followup 1906.09058v1

Real-time discrimination of photon pairs using machine learning at the LHC

Category:	0CV	1CV	2CV
	2 unconverted	unconverted &converted	2 converted

trigger: diphoton

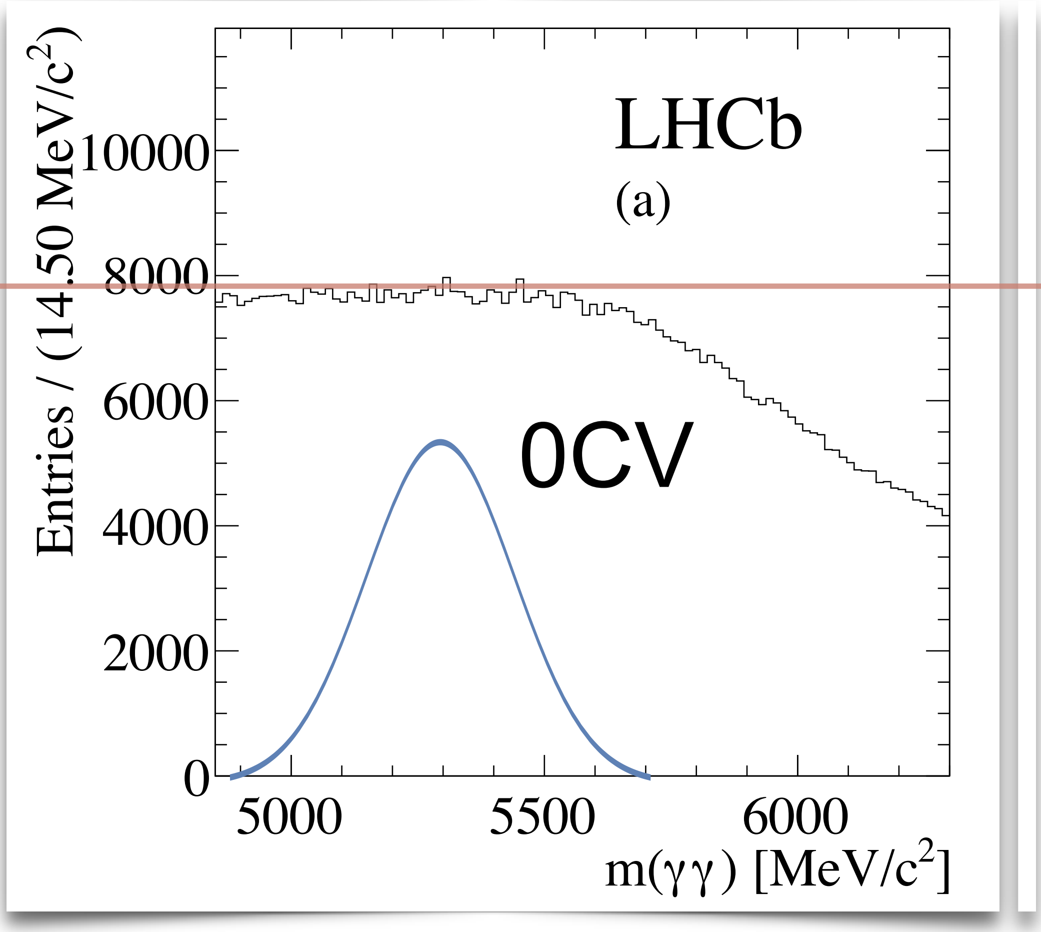
electron candidate
displaced vertex

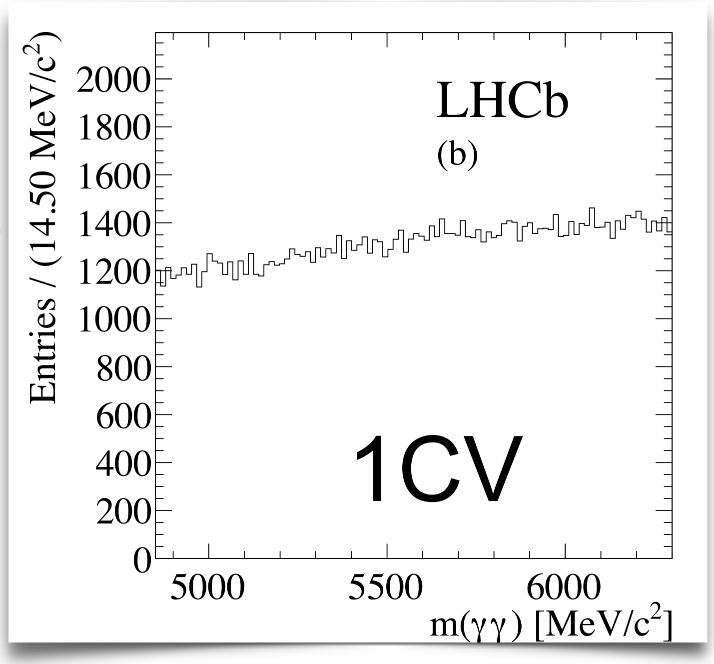
Recast 0CV analysis to ALP

`Hlt1B2GammaGamma` HLT1 trigger line.

Requirement	Value
$E_{\rm T}(\gamma)$ [GeV]	> 3.5
$E_{\rm T}(\gamma_1) + E_{\rm T}(\gamma_2)$ [GeV]	> 8
$M(\gamma_1\gamma_2)$ [GeV/c^2]	$[3.5, 6.0]$
$p_{\rm T}(\gamma_1\gamma_2)$ [GeV/c]	> 2

Diphoton resonance at LHCb





Assume: constant Acceptance&Efficiency. (of $B_s \to \gamma\gamma$)

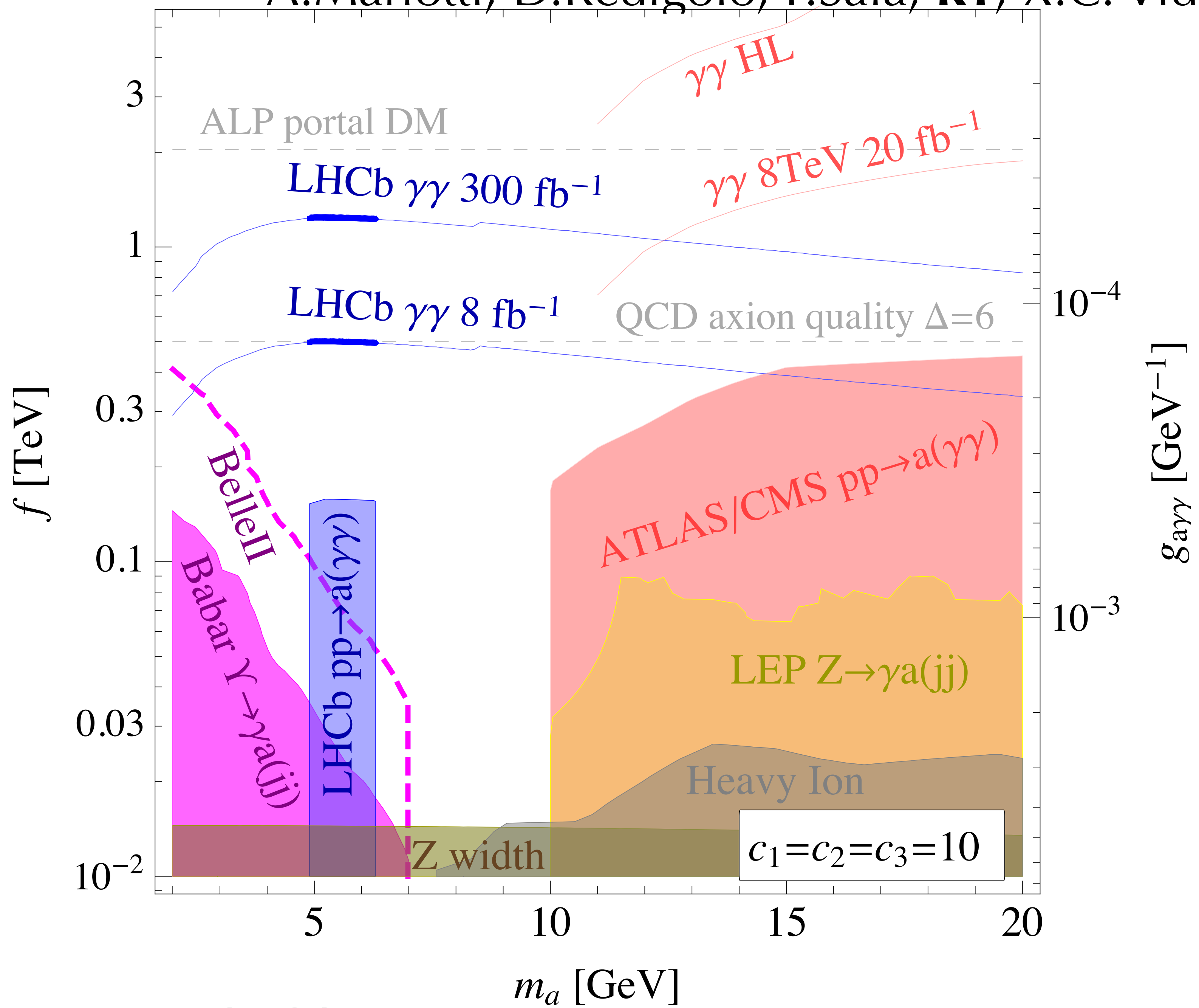
$A(2<\eta<5)=0.13, \quad \varepsilon=0.14$

data(~BG) is also const

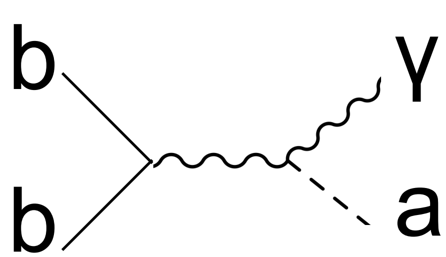
Then, require $S<2\sqrt{D}$ (no subtraction of BG)

LHCb+Babar+Belle2

A.Mariotti, D.Redigolo, F.Sala, **KT**, X.C. Vidal ('18)

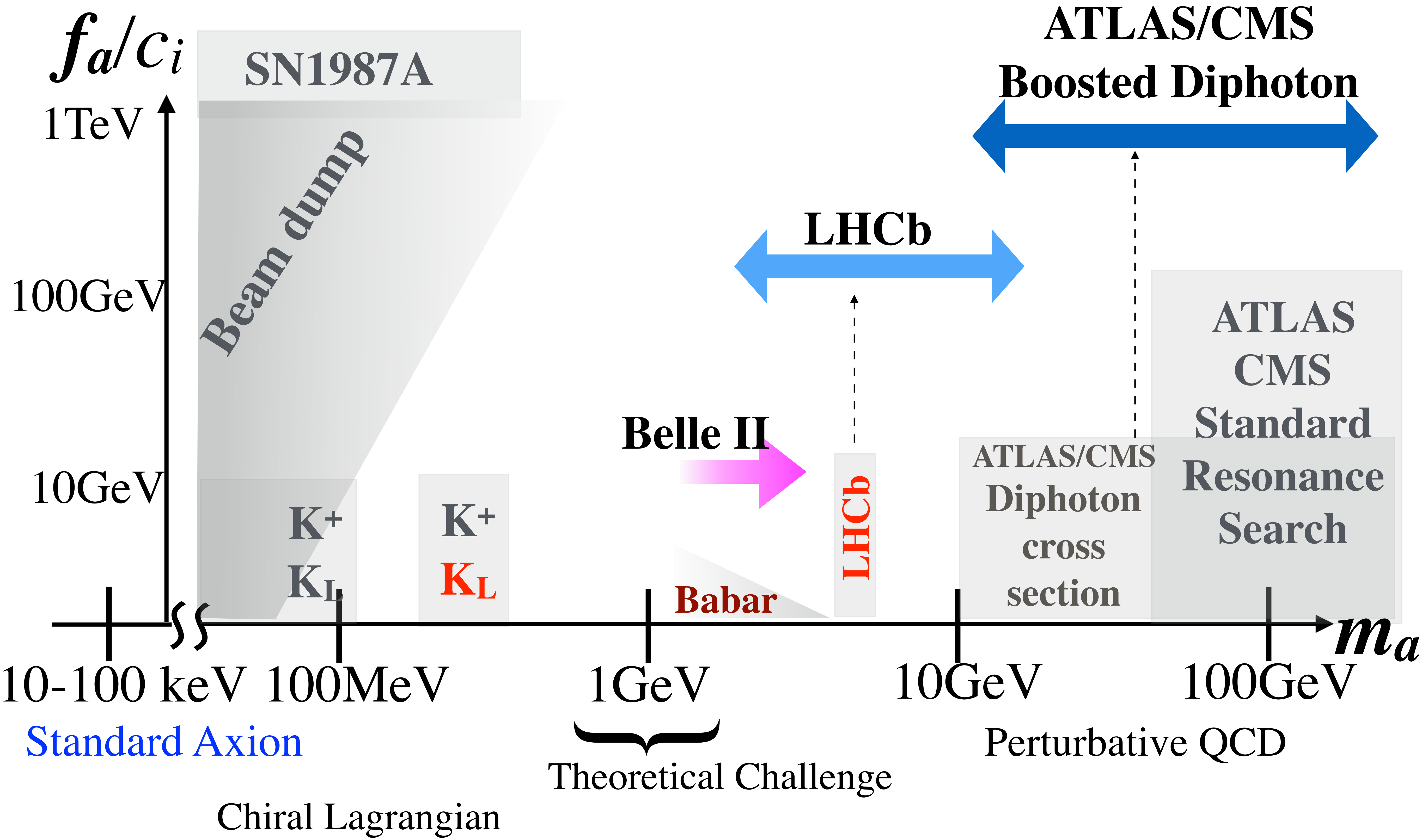


*Also Babar/Belle2 Y(3S)



$$\frac{\mathrm{BR}(\Upsilon \to \gamma a)}{\mathrm{BR}(\Upsilon \to \mu\bar{\mu})} \simeq 8\, E^2 \frac{\alpha_{\rm em}}{4\pi} \left(\frac{m_\Upsilon}{4\pi f}\right)^2 \left(1 - \frac{m_a^2}{m_\Upsilon^2}\right)^3$$

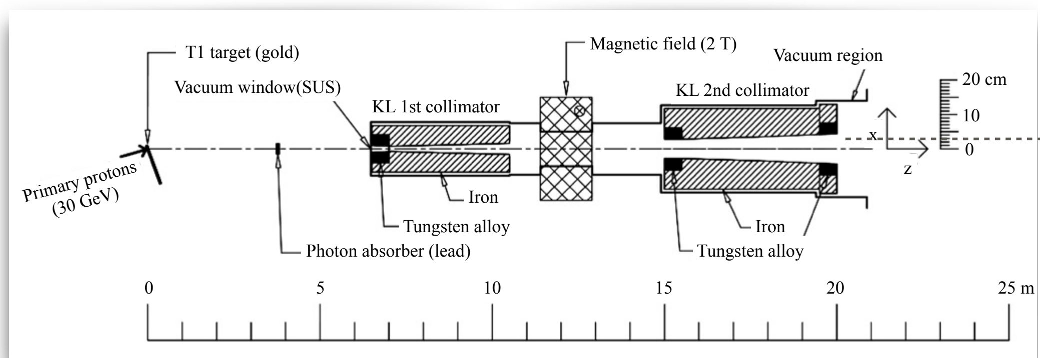
LHCb/Belle II projection



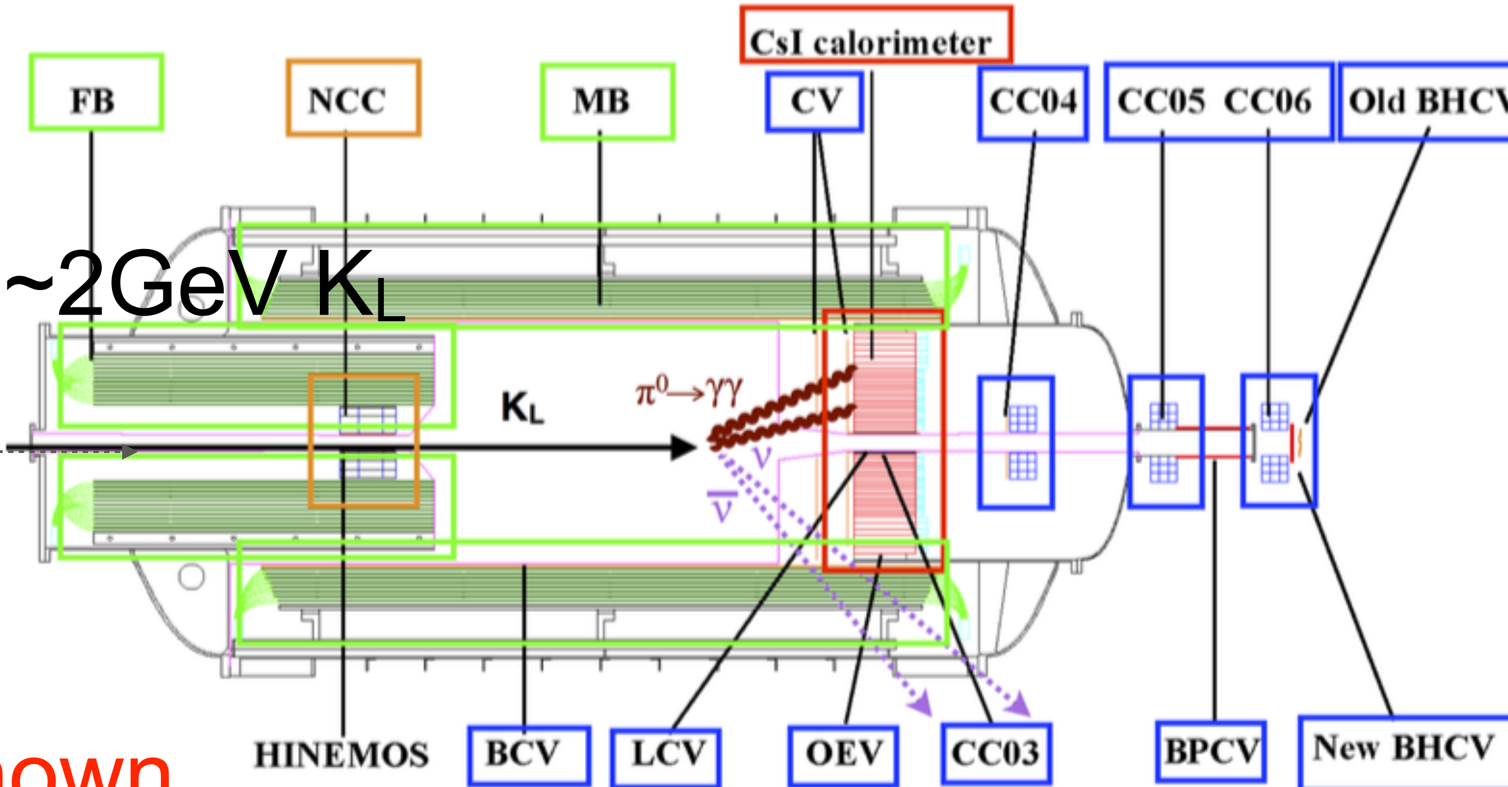
Search at KOTO m_a<350MeV

$K_L \to \pi^0 a \to 4\gamma$ at KOTO

30GeV p @J-PARC



~2GeV K_L



*K_L decay point is unknown

Main Target	$K_L \to \pi^0(\gamma\gamma)\nu\nu$
Signal	**Photon, invisible**
BG	$K_L \to 3\pi$, 2π
VETO	Charged particle
Decayed N_K ('15)	~10^11

Future(~2026)

→ **~10^13**

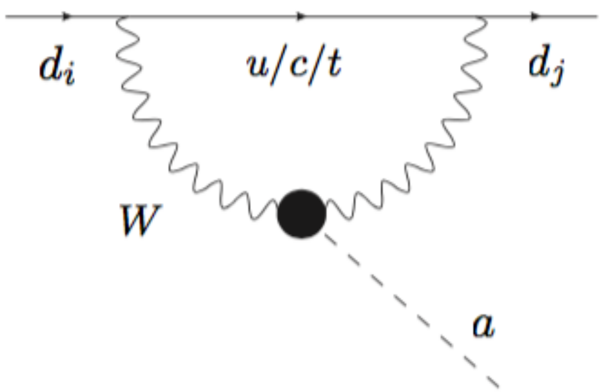
$K_L \to \pi^0 a \to 4\gamma$ at KOTO

Heavy Axion EFT=ALP EFT

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

Induce K_L/K^+ decay to axion by π-a mixing or FCNC with W

$K_L \to \pi^0 a$ **$K^+ \to \pi^+ a$**



$$\mathrm{BR}(K \to \pi a) \sim \left(\frac{0.1 f_\pi}{f_a/c_3}\right)^2 \mathrm{BR}(K \to \pi\pi^0)$$

E. Izaguirre,T. Lin,B. Shuve ('16)

Only decay channel is **$a \to 2\gamma$**, (**$a \to 3\pi$** kinematically forbidden)

KOTO can search for **$K_L \to \pi^0 a$** with N_{KL}~10^13

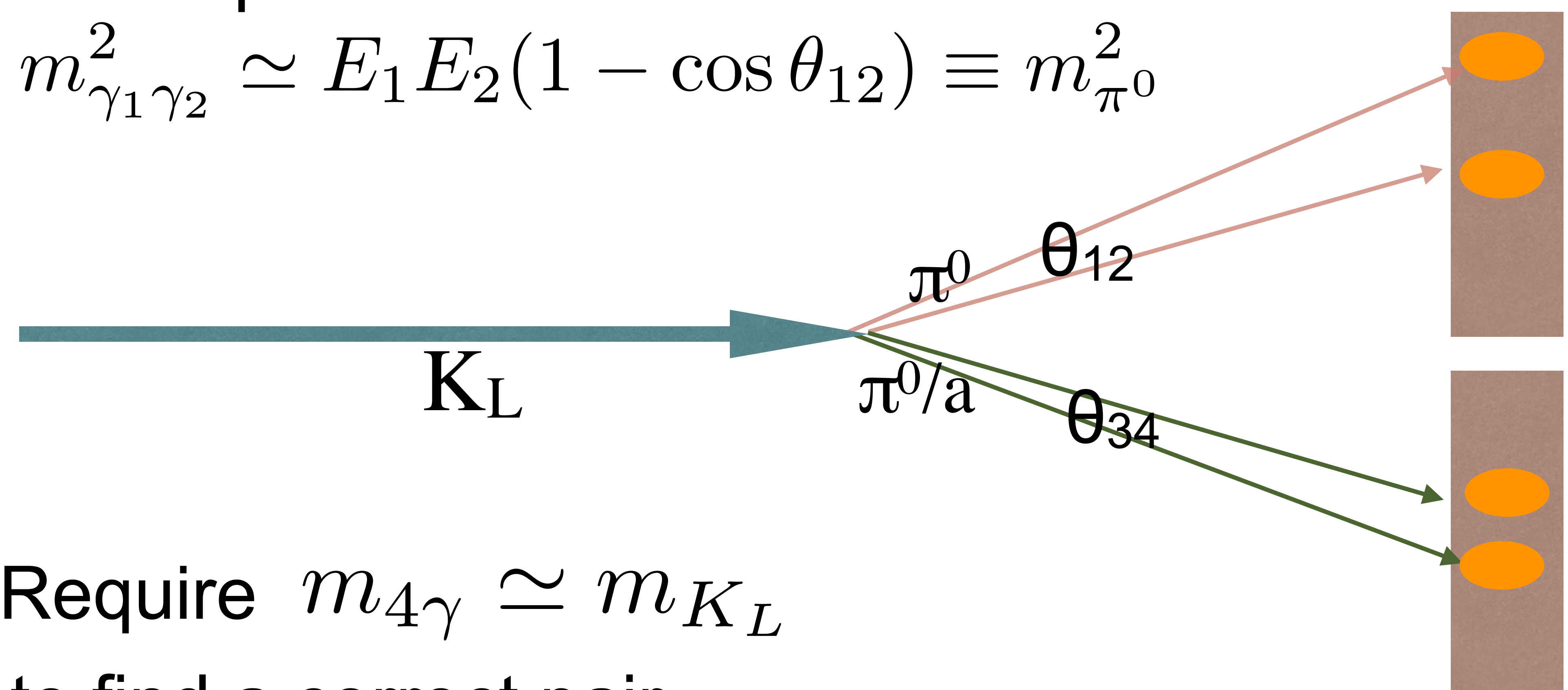
ALP hunt at KOTO

Physics target: $K_L \to \pi^0 a \to 4\gamma$

Challenges
- **decay point unknown (only Ecal, no tracker)**
- **combinatorics of γγ pairs**

1. assumption for reconstruction

$$m^2_{\gamma_1\gamma_2} \simeq E_1 E_2 (1 - \cos\theta_{12}) \equiv m^2_{\pi^0}$$

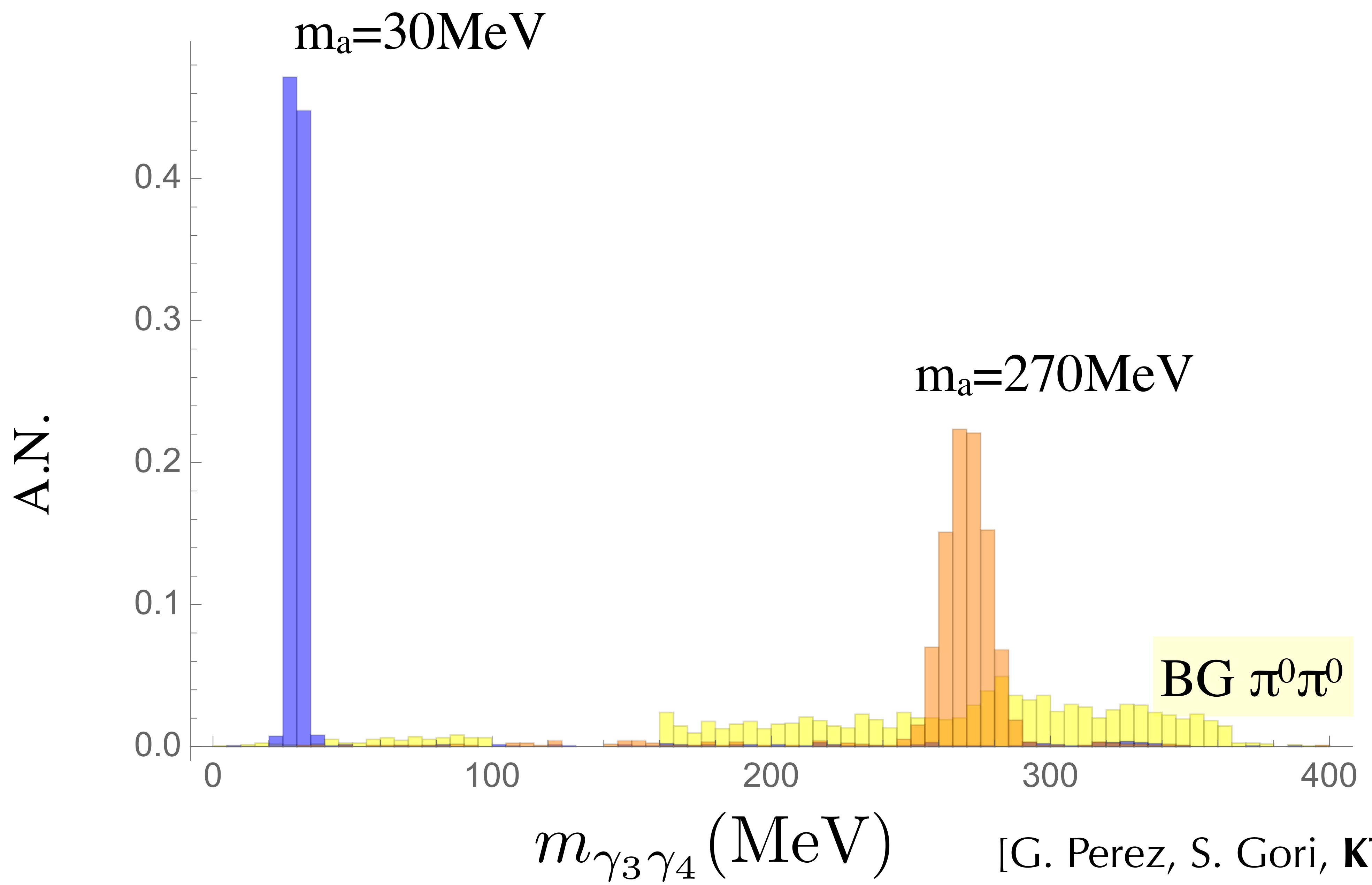


2. Require $m_{4\gamma} \simeq m_{K_L}$ to find a correct pair

[G. Perez, S. Gori, **KT** (Preliminary)]

ALP hunt at KOTO

K_L generator+ detector simulation

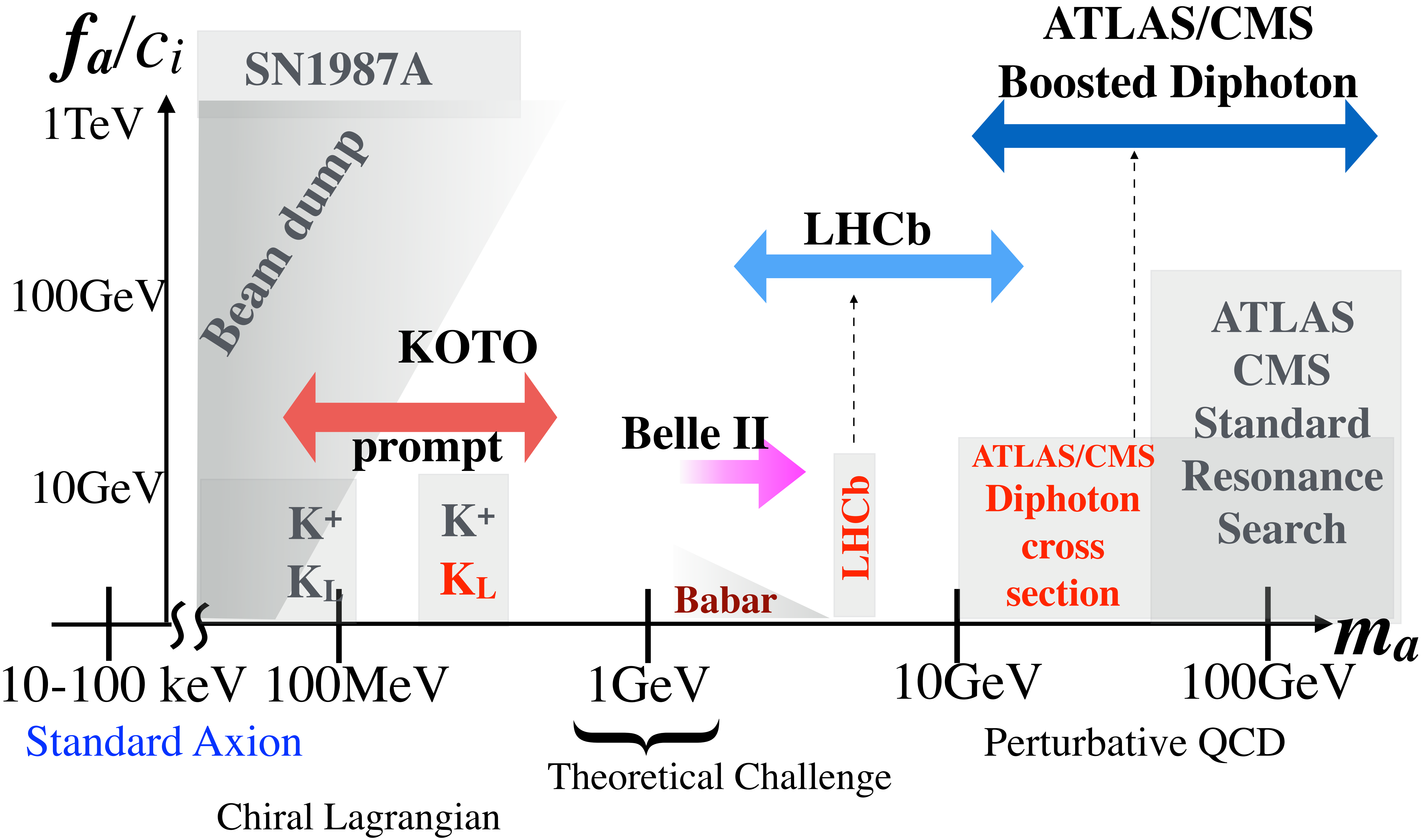


[G. Perez, S. Gori, **KT** (Preliminary)]

Expected bound on Br($K_L \to \pi^0 a$)~10^{-8}

Translated to f_a/c_3 **~10GeV or** f_a/c_2 **~100GeV**

KOTO projection



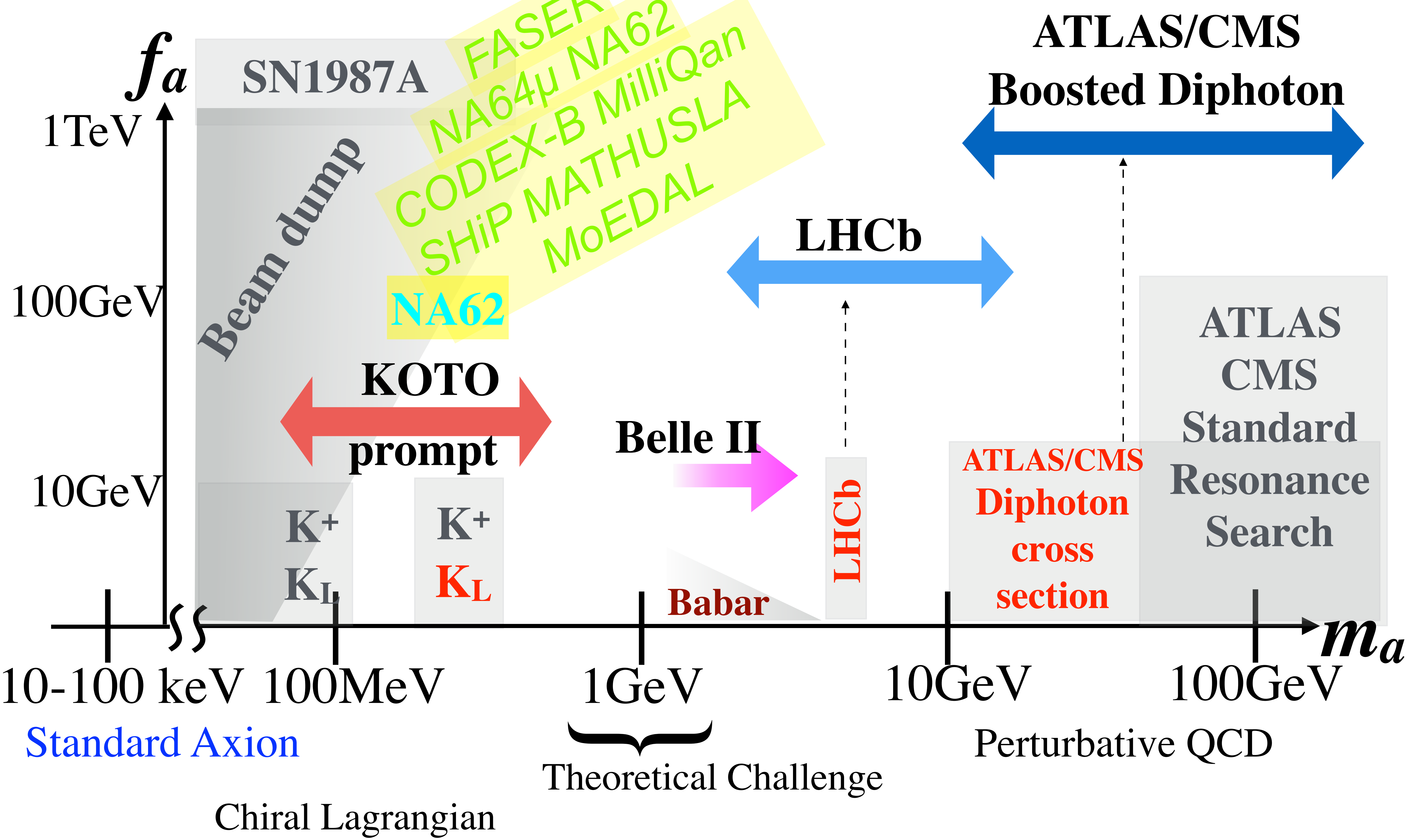
Summary

- Axion-like-particles with gluon coupling and low f_a is motivated by various models.
- The heavy axion with low f_a is a good guidepost for experiments.

- ATLAS/CMS covers >10 GeV mass region with diphoton or mono-triggers.
- LHCb covers O(1)-20GeV with diphoton trigger
- KOTO covers <350MeV with N_{KL}~10^13

- Long-lived particle searches are relevant for sub-GeV mass and higher f_a region.

Summary



f_a
1TeV
100GeV
10GeV
SN1987A
Beam dump
FASER
NA64μ NA62
CODEX-B MilliQan
SHiP MATHUSLA
MoEDAL
NA62
KOTO
prompt
K+
KL
K+
KL
Belle II
Babar
LHCb
LHCb
ATLAS/CMS
Boosted Diphoton
ATLAS/CMS
Diphoton
cross
section
ATLAS
CMS
Standard
Resonance
Search
m_a
10-100 keV
100MeV
1GeV
10GeV
100GeV
Standard Axion
Theoretical Challenge
Perturbative QCD
Chiral Lagrangian