BSM Overview

Lake Louise, Feb 10, 2020

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&KEK

Why Beyond the SM?

Hints for BSM

See other lectures/review
- LHC (day1), Martyniuk
- Flavor (day2), Wormser
- Neutrino (day3), Huber
- Dark Matter (day3) Kahn
- Atomic Interf (day3) Müller
- Top quark (day4) Mitov
- Heavy Ion (day4) McLerran

Evidence

- Neutrino Mass
- Dark Matter
- Baryon Asymmetry
- Dark Energy
- Inflation

Theoretical Issue

- Higgs Mass ($m_h \ll \Lambda$)
- Strong CP

Puzzle

- SM vacuum stability?
- Why 3 gen. w/ hierarchy
- Why …

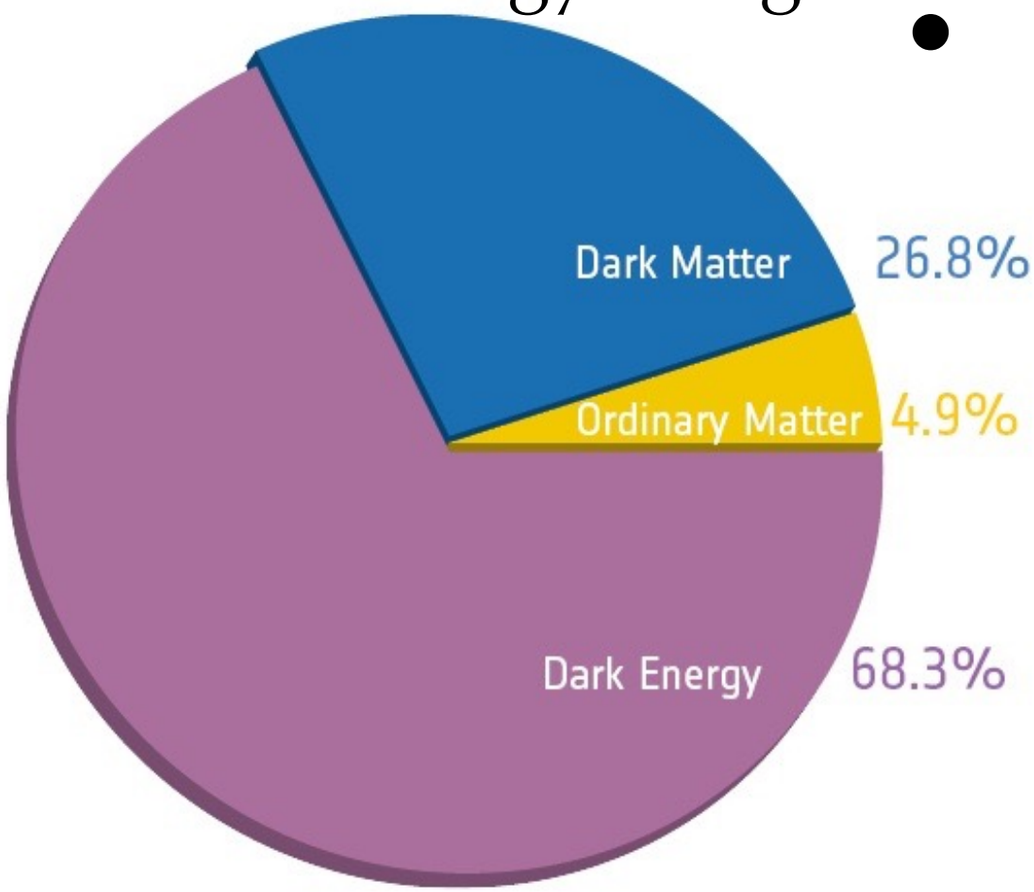
Anomaly

- Muon g-2 (3.5σ)
- B anomalies, RD$^{(*)}$, RK
- H0 tension (4+σ)
- Short baseline neutrino
- Proton radius, 21cm….

Evidence

Evidence from Cosmology&Astrophysics

Current energy budget



Planck satellite

- Dark energy (accelerating expansion)
- Dark matter >80% matter

New BSM particle?

- Baryon asymmetry is non-zero

$$\frac{n_B}{n_\gamma} \sim 6 \times 10^{-10}$$

but SM CP-violation is not enough

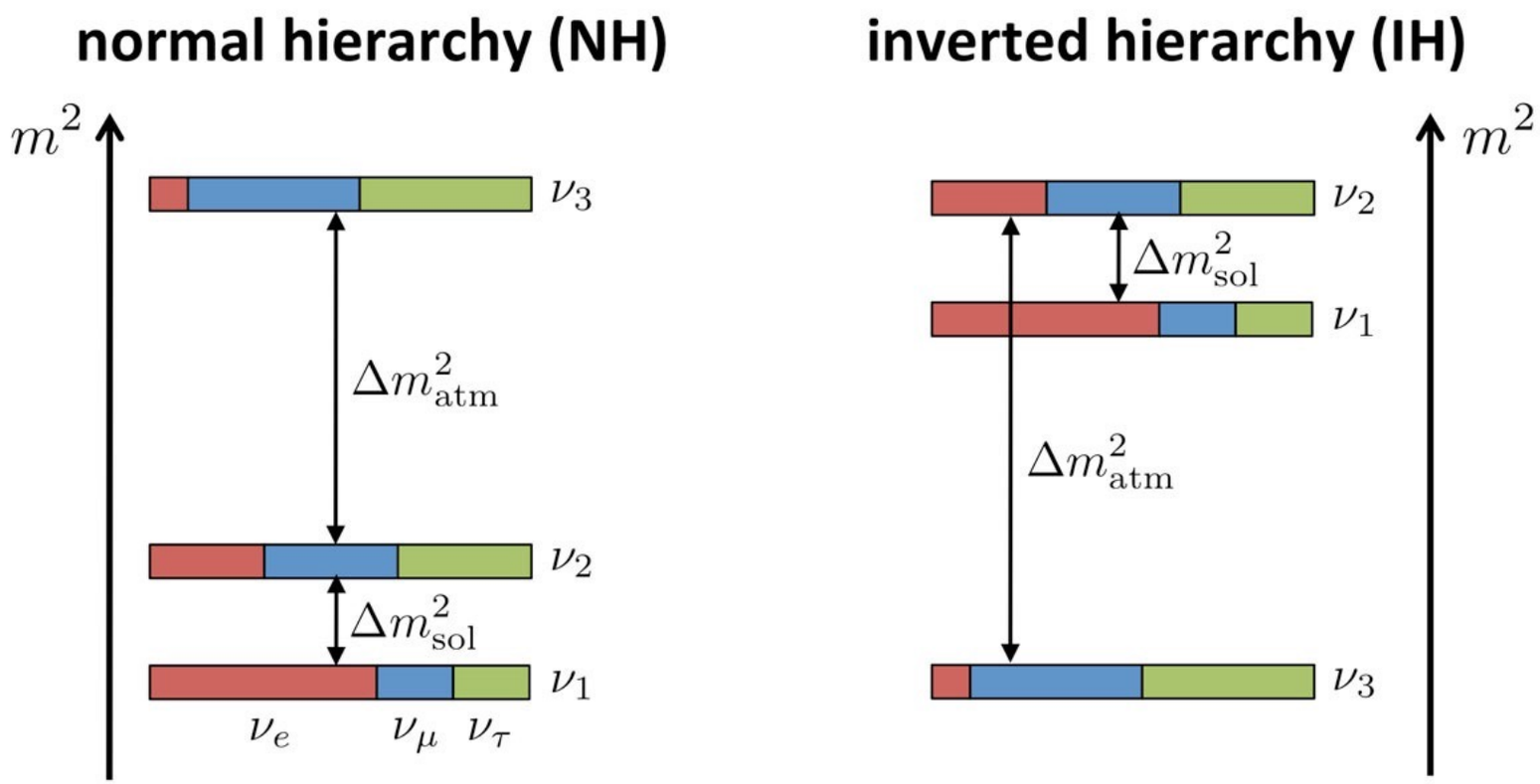
SM extension needed
(EW baryogenesis, Leptogenesis..)

- Acausal correlation across the sky
  →Exponential expansion (Inflation)

DE and Inflation could be decoupled from SM

Neutrino Mass

Solar&atmospheric neutrino oscillation
→direct contraction of SM
(no neutrino mass in the renormalizable level→no oscillation)



Known: mass splittings (50meV, 8meV), also angles

Unknown: absolute mass, Dirac or Majorana type?

Theoretical Issues

3 naturalness problems

Higgs Mass

$(125\text{GeV})^2 \ll \Lambda^2$

CP phase in strong sector

$\theta \ll 1$

Cosmological constant (D.E.)

$\Lambda_{cc}^4 \sim 10^{-48}\ \text{GeV}^4 \ll \Lambda^4$

Small parameters NOT associated with symmetry restoration

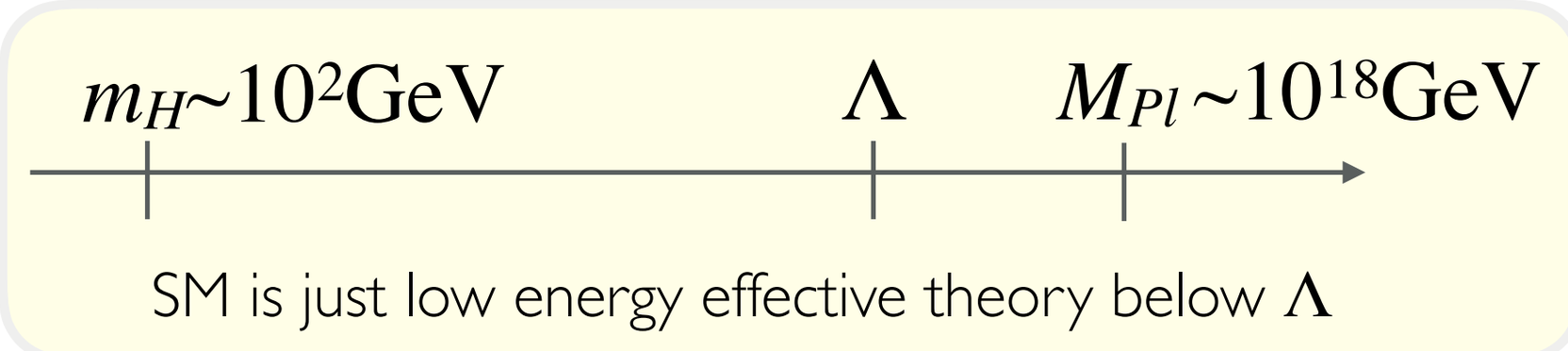
some new mechanism?

Higgs Mass

- Given that BSM is needed, SM is effective up to Λ

$$V = \mu_H^2 |H|^2 + \frac{\lambda_H}{4}|H|^4$$

No symmetry to protect mass scale in SM



Higgs mass is sensitive to Λ^2 [**relevant operator**]

$$\mu_H^2 = \mu_{H0}^2 + \sum \frac{g^2}{16\pi^2}\Lambda^2 \sim (100\mathrm{GeV})^2$$ Naturalness problem

BSM scenarios:

Supersymmetry, Composite Higgs, Twin Higgs, Extra Dim…

→Predict TeV heavy states (some light)→LHC

Strong CP problem

Also naturalness problem for CPV parameter of SM

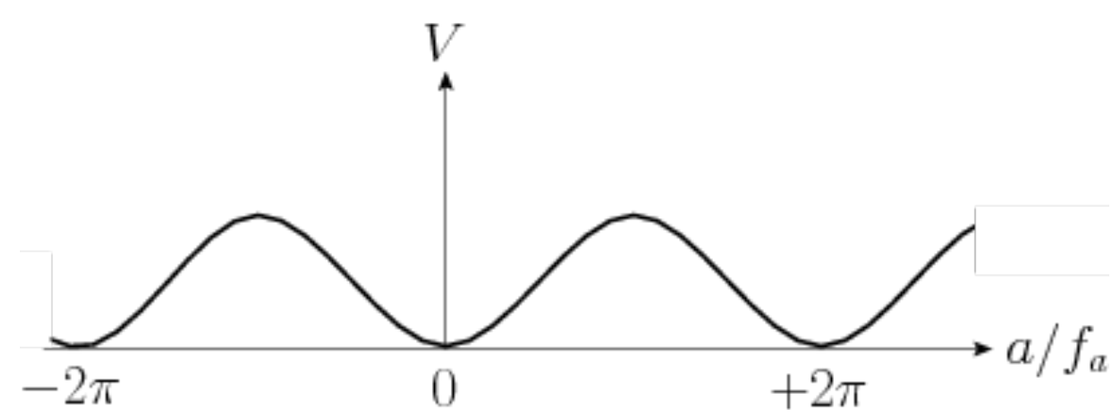
$$\frac{\theta g_s^2}{32\pi^2} G\tilde{G}$$ Neutron EDM $\bar{\theta} \lesssim 10^{-10}$

- **No symmetry restoration in the SM in θ→0**

  because CP is violated in the quark sector with O(1) CKM phase!

Peccei-Quinn symmetry (Axion), Left-Right, Nelson-Barr..

Axion solution is attractive
(1) IR solution
(2) detectable signal=axion
(3) could be cold DM



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

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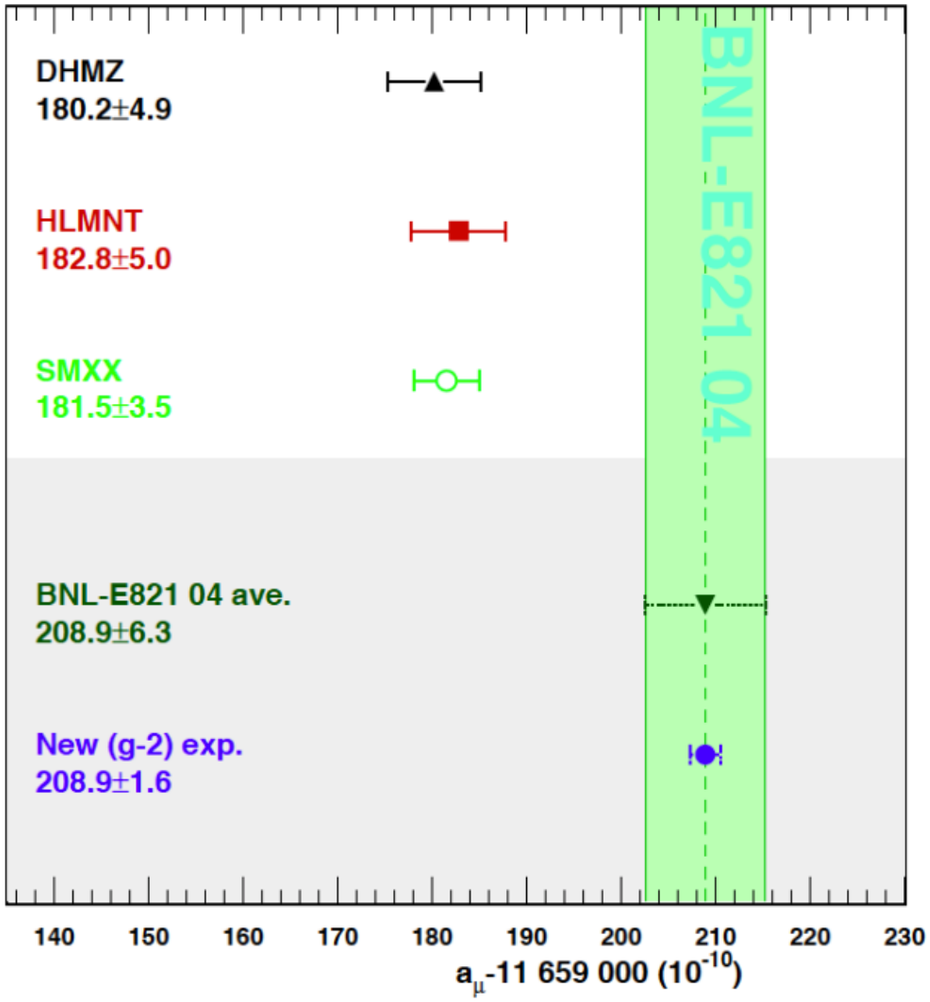
Anomalies

Anomalies

No anomalies at LHC

- Muon g-2 (~3.5σ)

  slepton, new force



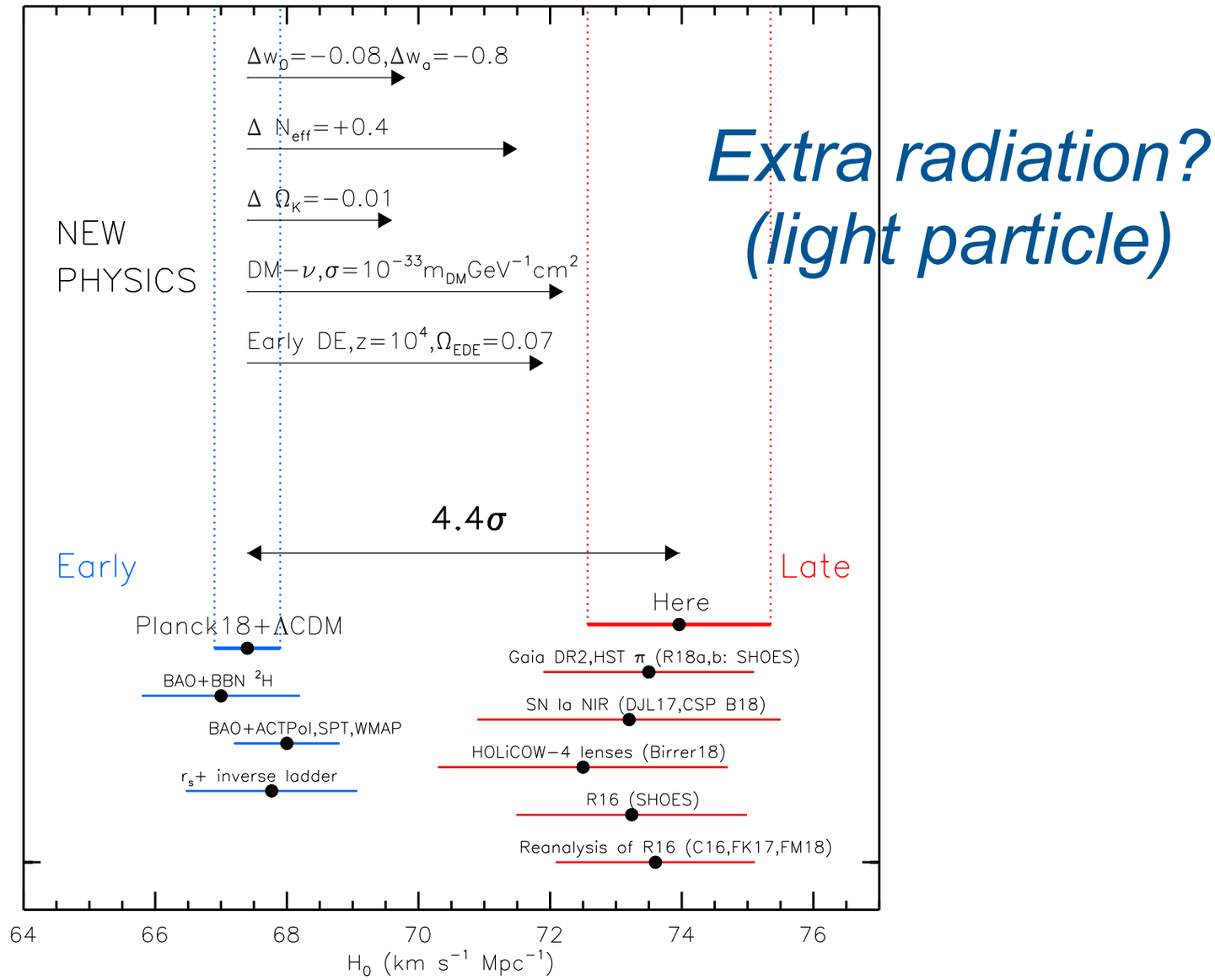
- Flavor physics(B), ~2-3σ. Lepton Flavor Universality?
- Neutrino, 4.5σ Miniboone ($\nu_\mu \rightarrow \nu_e$ excess)

  Leptoquark, exotic sterile neutrino(?)

- Proton radius anomaly (gone? with new lamb shift result)…

Anomalies

- H0 tension ~4σ, ΛCDM vs Local measurements



Extra radiation? (light particle)

- DM (small structure, galactic center)
- Edges 21cm line …

BSM is required.

Where to start?

BSM physics through SM particles

What sector of the SM less known?

Higgs

Most mysterious part of SM
Responsible to EWSB&Flavor

VERY IMPORTANT to TEST

Direct connection to BSM?
[Higgs portal]
Vacuum Stability?

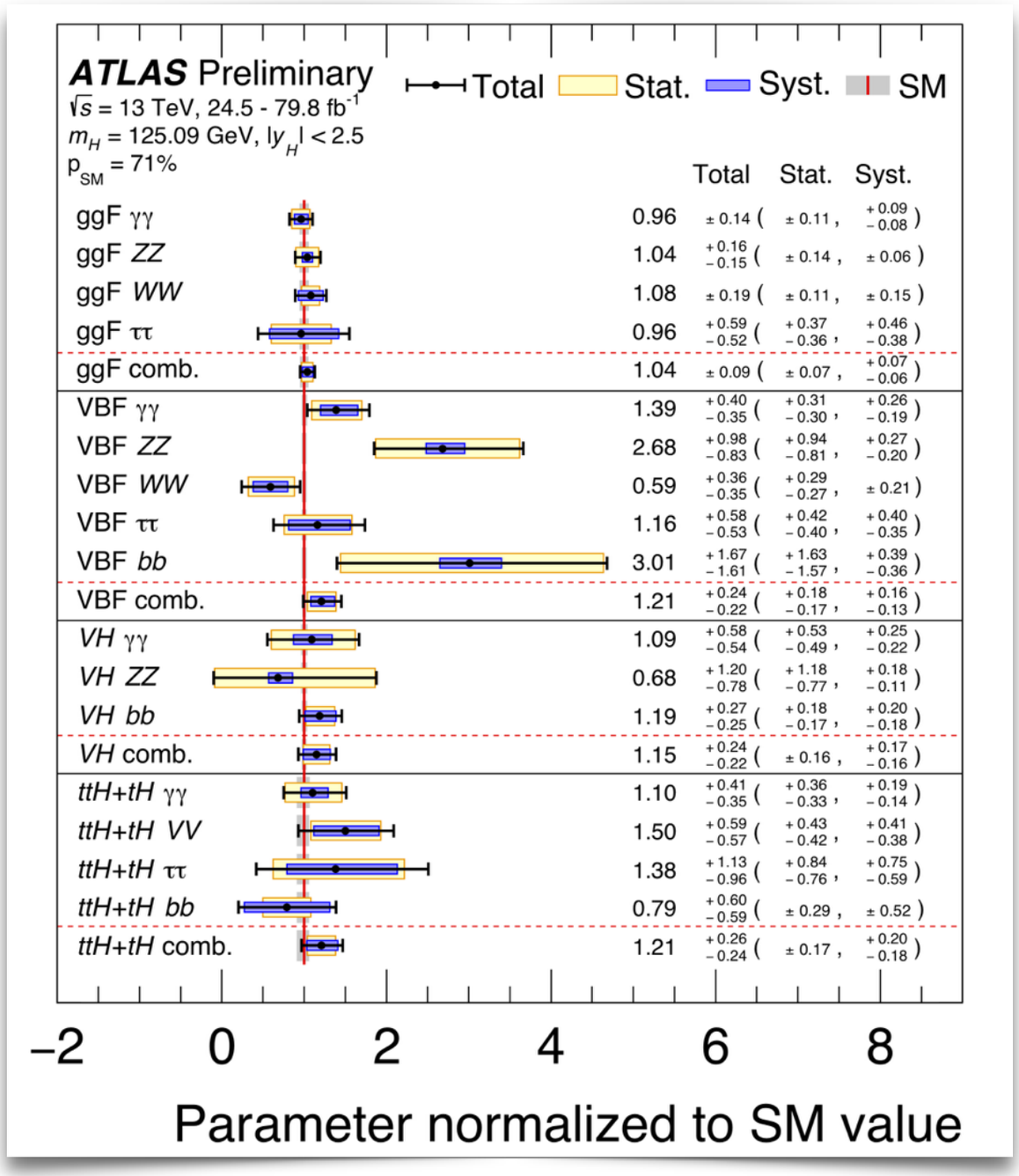
Neutrino

Mass, mixing
Majorana& Dirac?

Roles in cosmology.
Majorana neutrino
→Leptogenesis

→ Neutrino review talk(day3)

Higgs Coupling and Impact in EFT

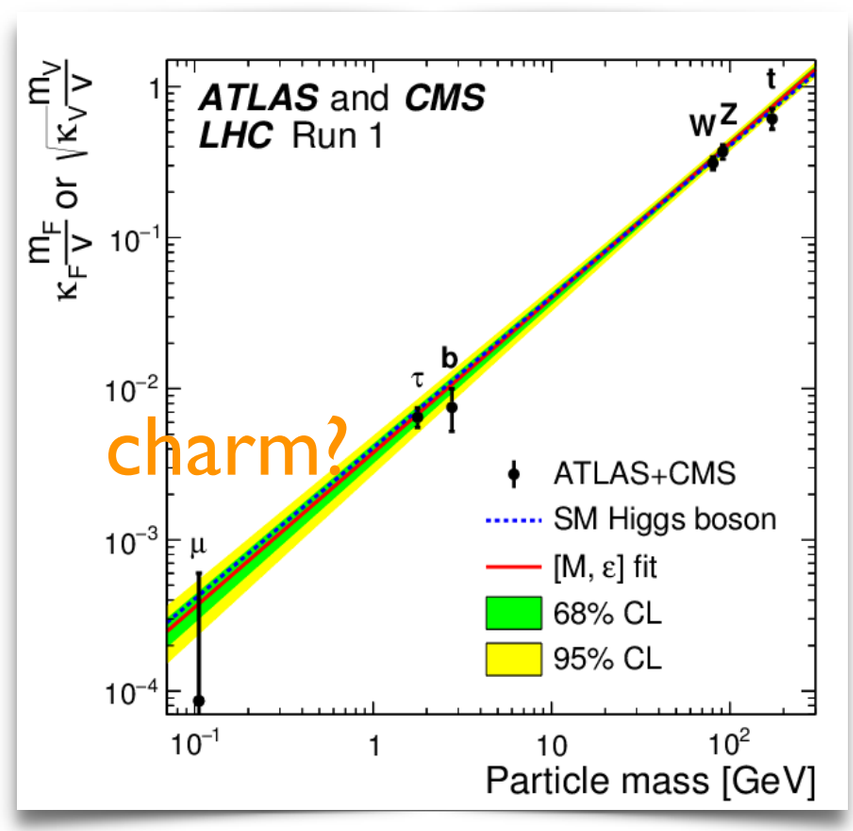


10% precision

$$\frac{|H|^2}{\Lambda^2}\mathcal{L}_{SM} \rightarrow \frac{\Delta g_x}{g_x} \sim \frac{v^2}{\Lambda^2}$$

Probe ~1TeV scale.
Improvement is essential.

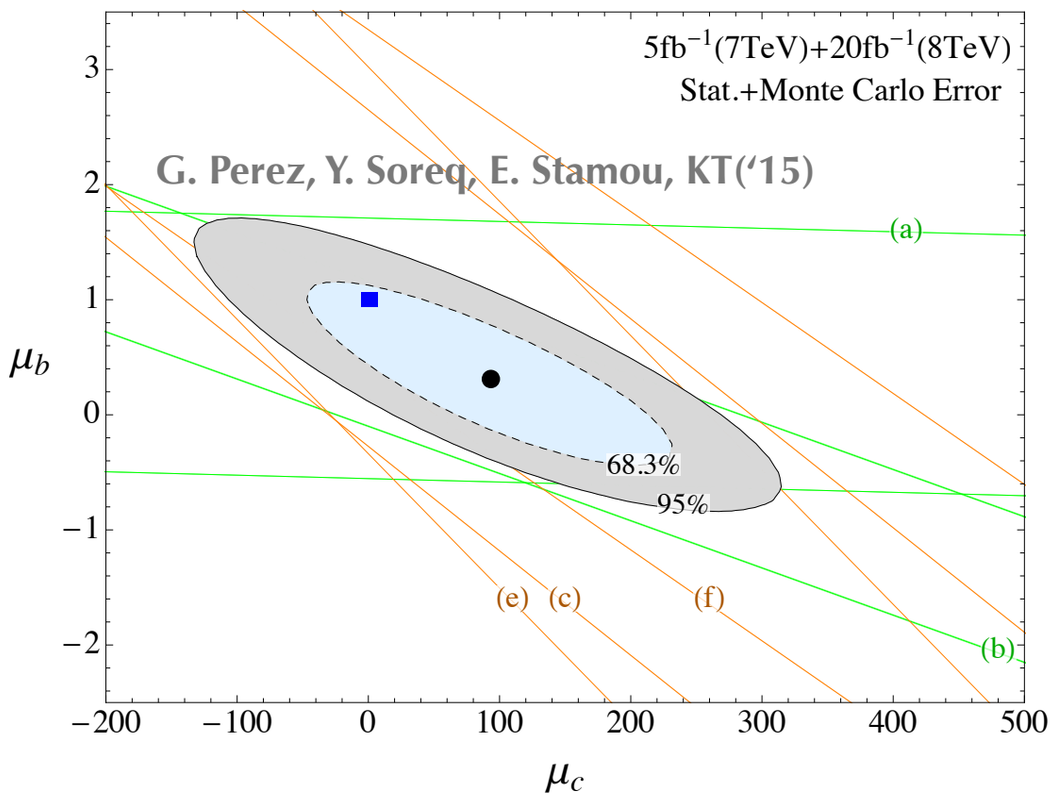
Many channels still challenging!



Higgs Coupling and Impact in EFT

- Recent development on charm-h, direct and indirect

Vh, h→cc with charm-tagging

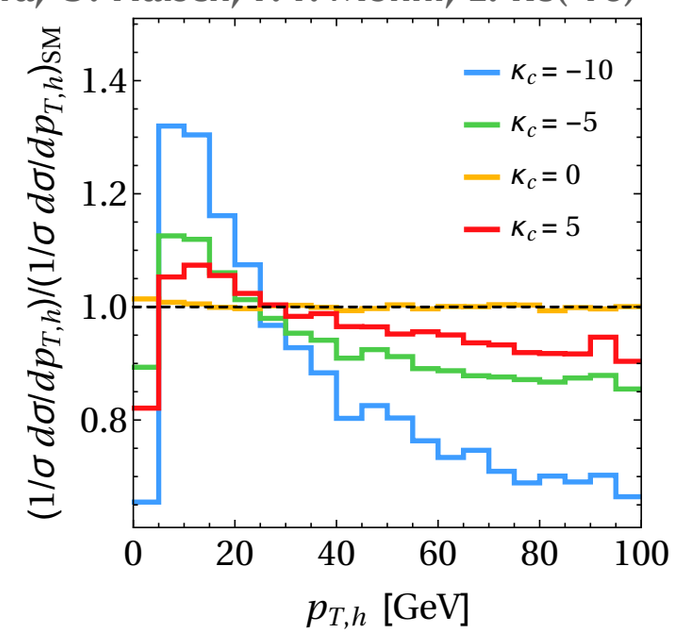


$$\mu_c = 95^{+90(175)}_{-95(180)} \text{ at } 68.3(95)\% \text{ CL.}$$

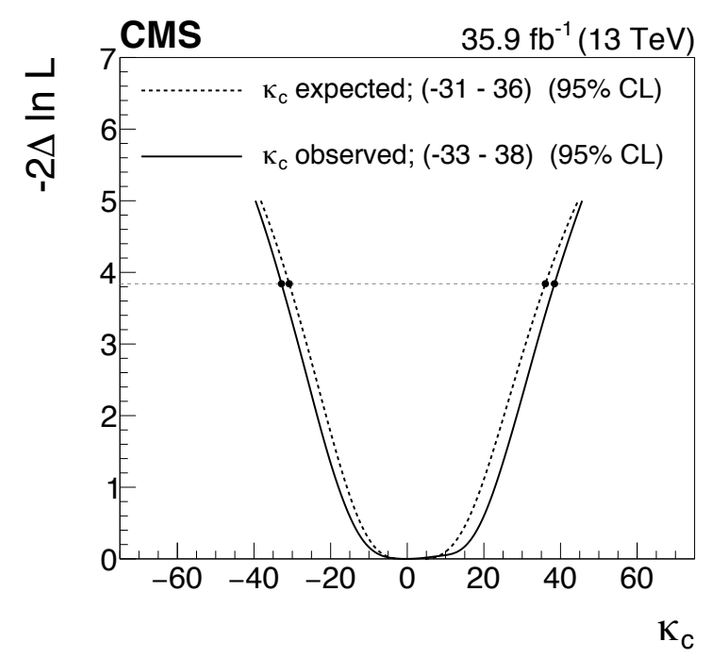
Now measured (with μ_b=1)
μ_c<110@95CL, ATLAS('17)
μ_c<70@95CL at CMS('18)

h→γγ + ISR(g) distribution

F. Bishara, U. Haisch, P. F. Monni, E. Re('16)



CMS[1812.06504]



Higgs Couplings without Higgs

High energy property is useful.

B. Henning, D. Lombardo, M. Riembau, F. Riva('18)

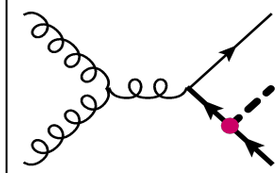
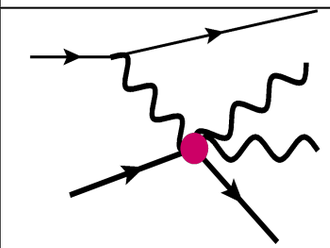
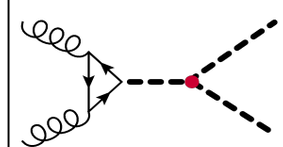
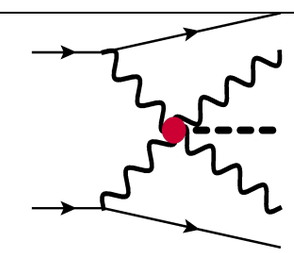
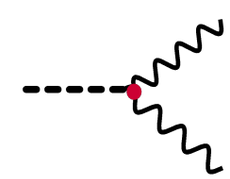
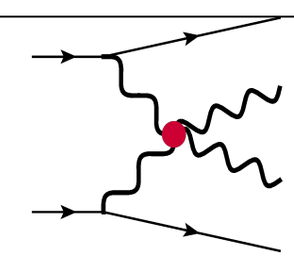
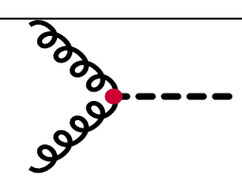
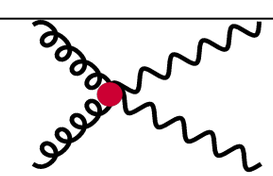
Goldstone equivalence theorem

$$|H|^2 = \frac{1}{2}\left(v^2 + 2hv + h^2 + 2\phi^+\phi^- + (\phi^0)^2\right)$$

$$W_L^\pm \simeq \phi^\pm \quad \text{(high energy)}$$

- Operators change HC&HwH

$$\mathcal{O}_r = |H|^2 \partial_\mu H^\dagger \partial^\mu H \qquad \mathcal{O}_{y_\psi} = Y_\psi |H|^2 \psi_L H \psi_R$$
$$\mathcal{O}_{BB} = g'^2 |H|^2 B_{\mu\nu} B^{\mu\nu} \qquad \mathcal{O}_{WW} = g^2 |H|^2 W^a_{\mu\nu} W^{a\,\mu\nu}$$
$$\mathcal{O}_{GG} = g_s^2 |H|^2 G^a_{\mu\nu} G^{a\,\mu\nu} \qquad \mathcal{O}_6 = |H|^6 \qquad (1)$$

		HC	HwH	Growth
κ_t	$\mathcal{O}_{y_t}$			$\sim \frac{E^2}{\Lambda^2}$
κ_λ	$\mathcal{O}_6$			$\sim \frac{vE}{\Lambda^2}$
$\kappa_{Z\gamma}$ $\kappa_{\gamma\gamma}$ κ_V	$\mathcal{O}_{WW}$ $\mathcal{O}_{BB}$ $\mathcal{O}_r$			$\sim \frac{E^2}{\Lambda^2}$
κ_g	$\mathcal{O}_{gg}$			$\sim \frac{E^2}{\Lambda^2}$

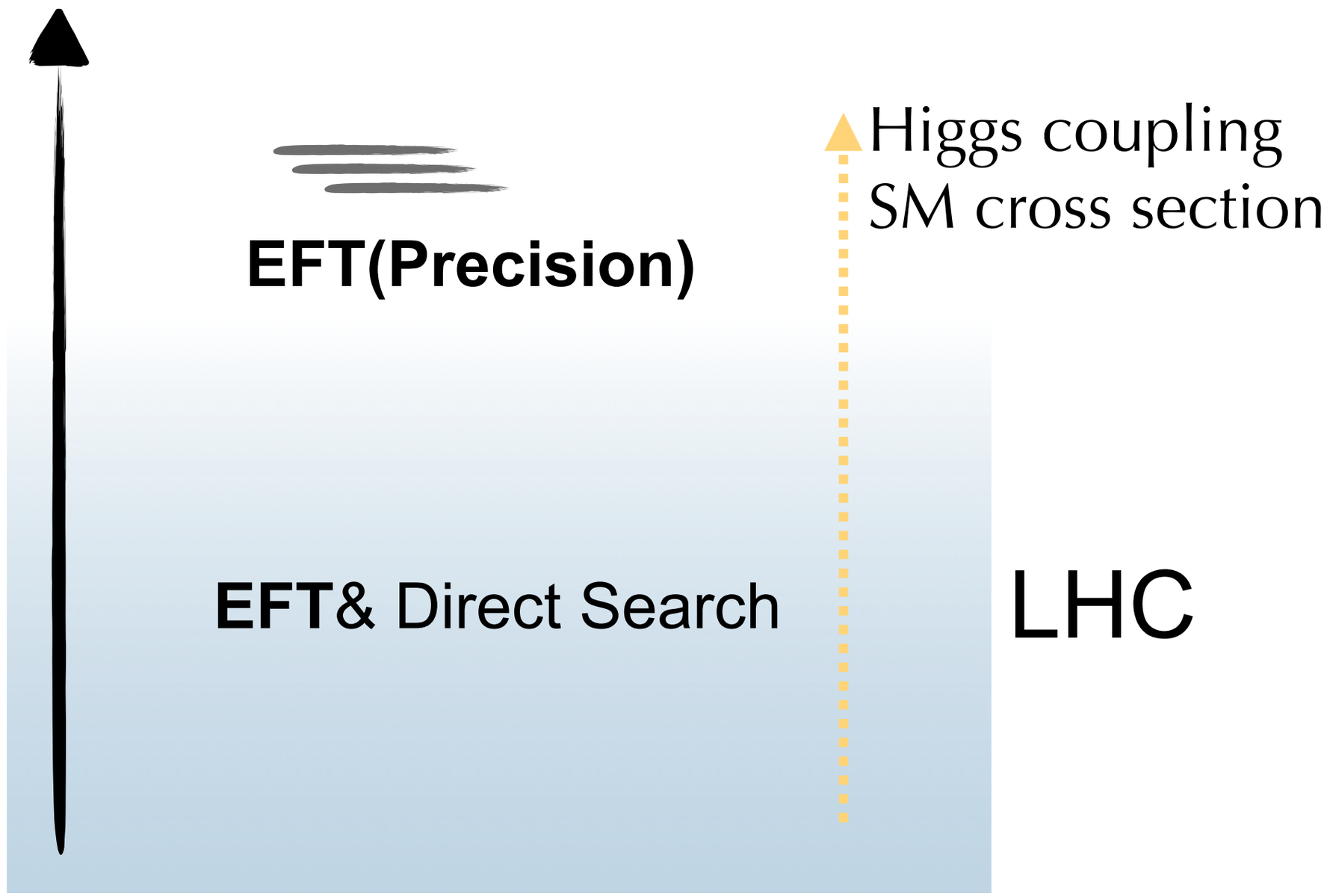
HwH(HL-LHC)

$$\delta y_t \sim 0.1 \qquad \delta\kappa_\lambda \sim 5$$

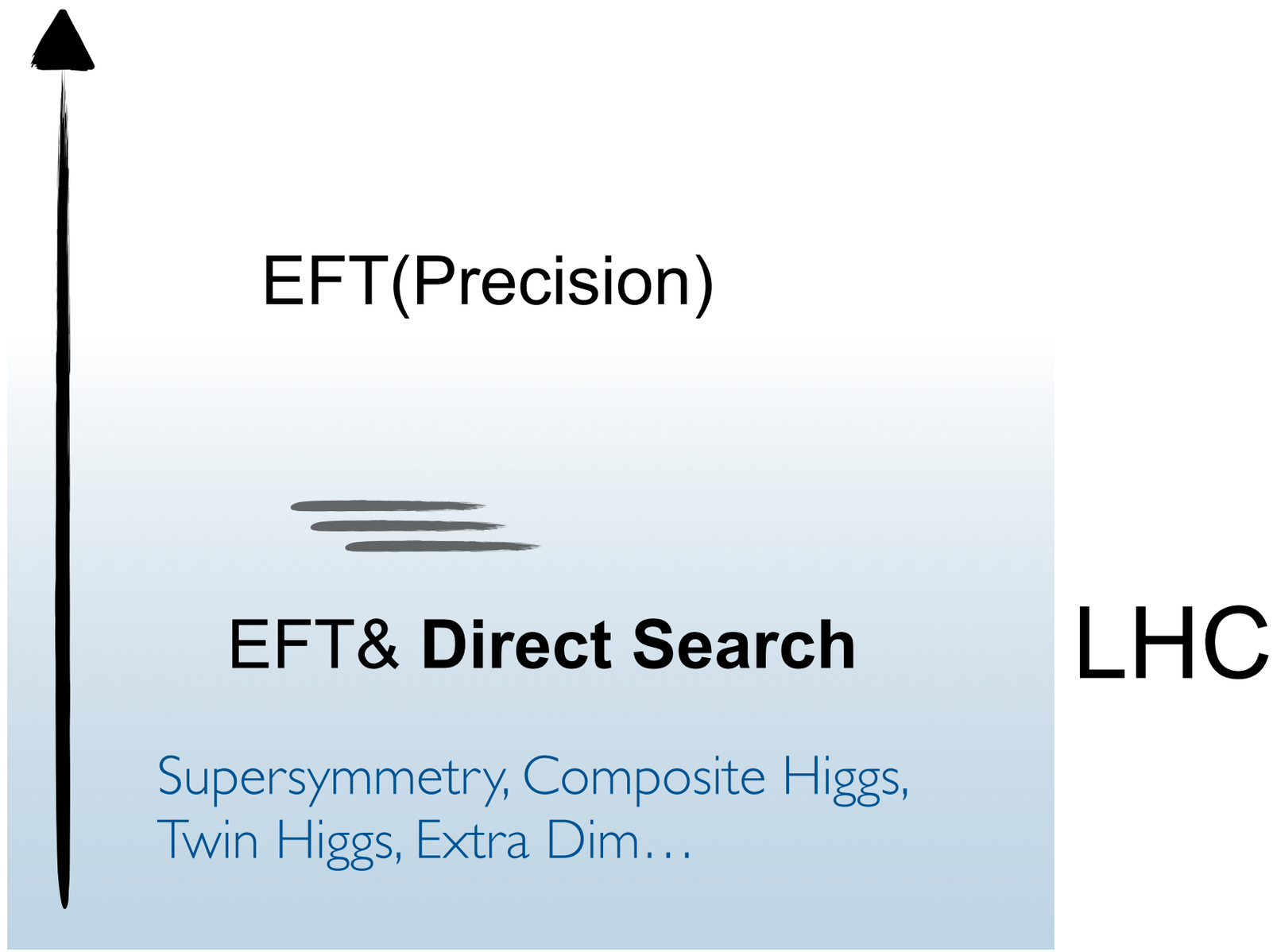
$$\frac{\mathcal{A}_n^{\mathcal{O}}}{\mathcal{A}_n^{\rm SM}} \sim \frac{E^2}{\Lambda^2}$$

can be combined with Higgs Coupling

Precision and Direct Search



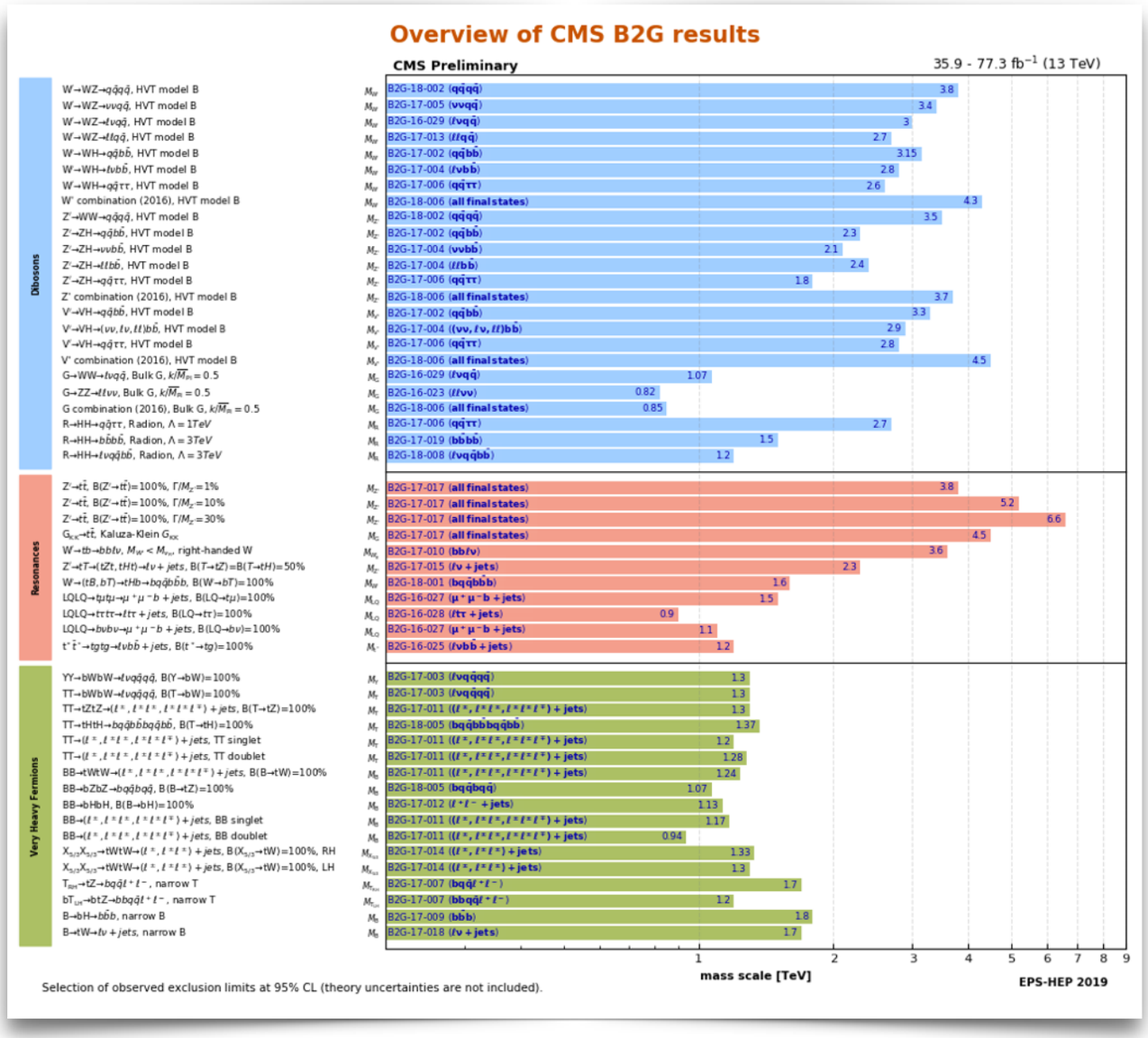
Precision and Direct Search



Direct BSM Search at LHC

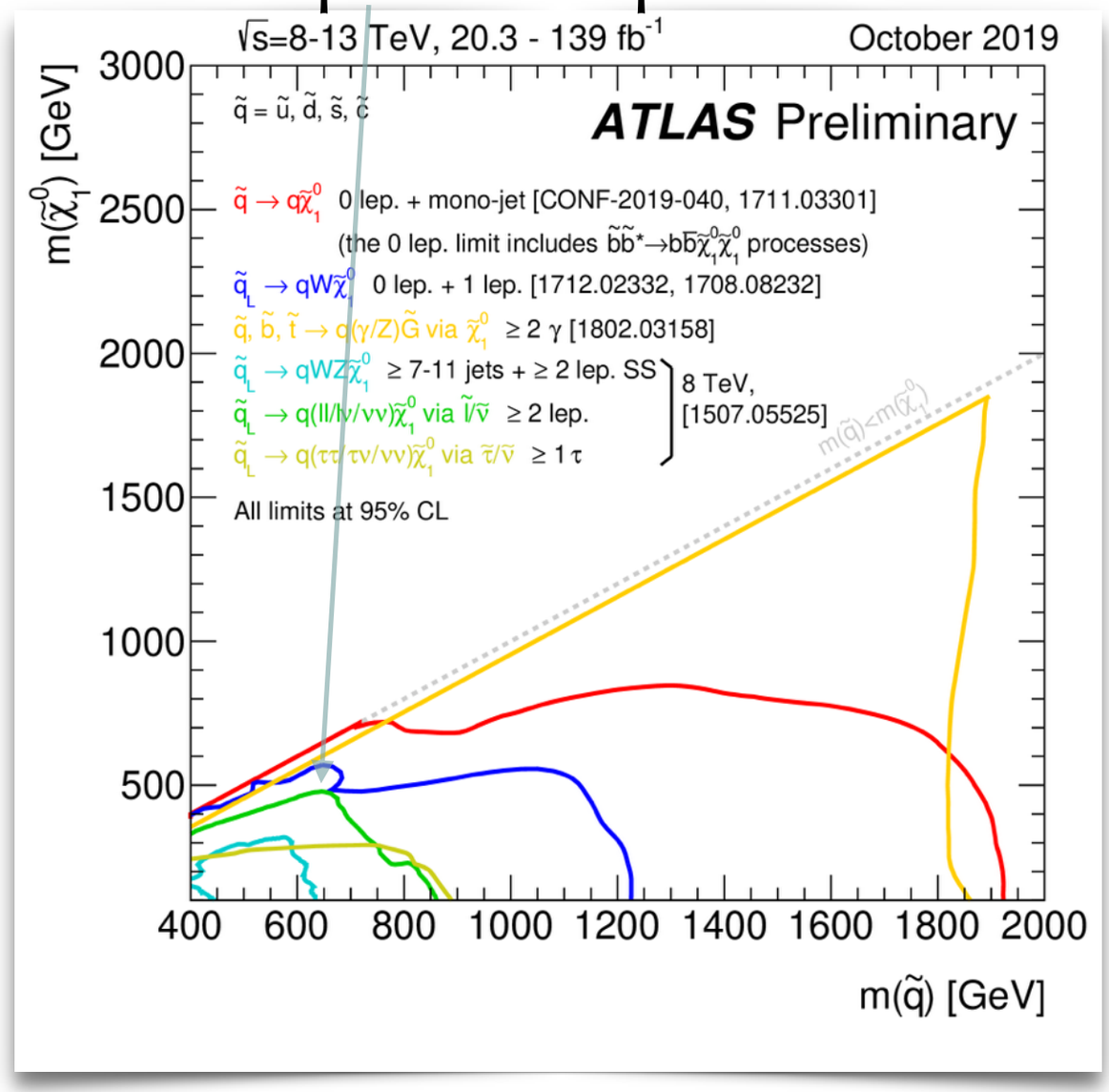
Already many programs targeting various models

[see day1 talks]



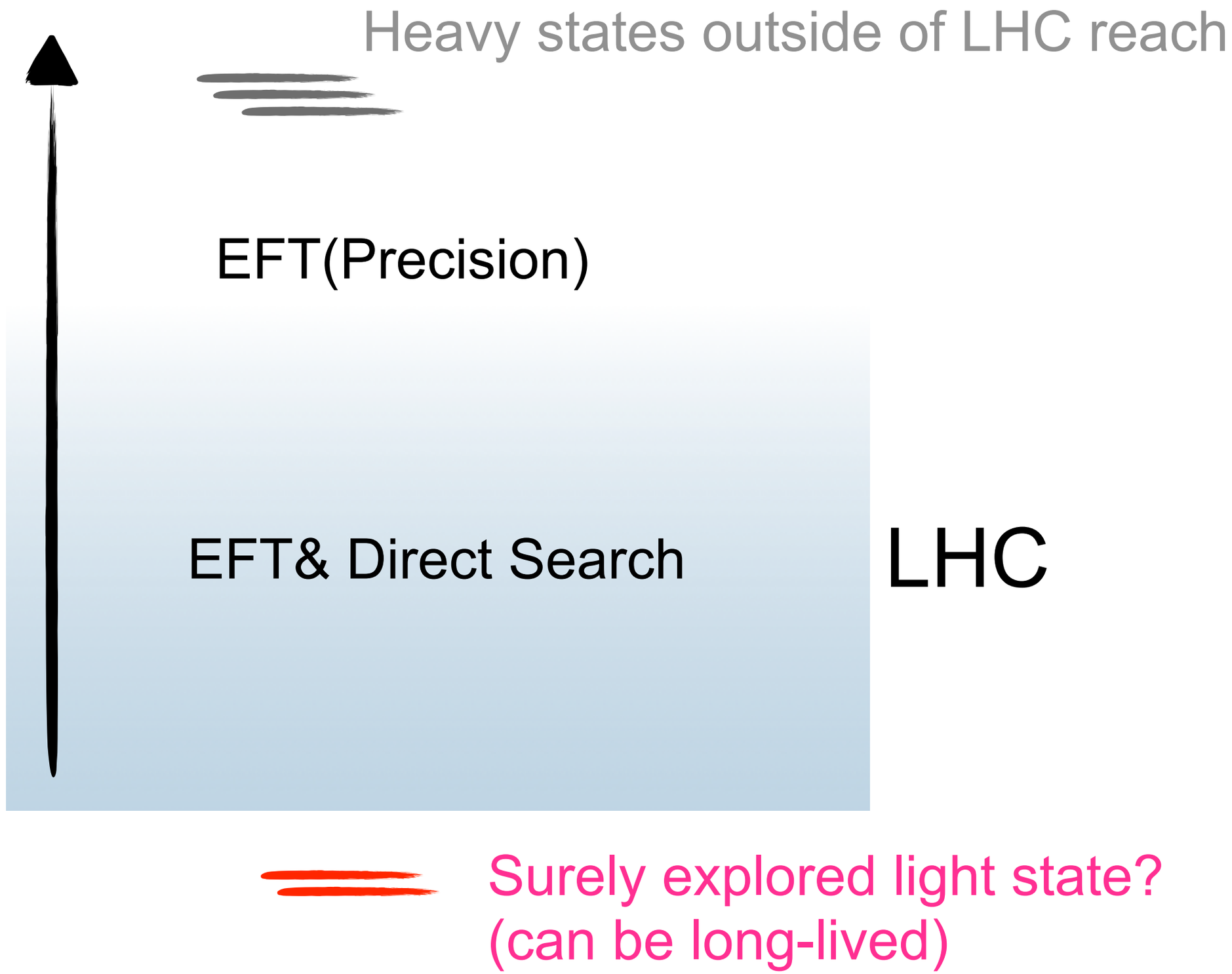
Loop-hole coverage improved!

compressed spectrum



+Long-lived, DM…

Precision and Direct Search



BSM light states

Light state

- Even with weak-scale interaction
  an unexplored **pseudo-NG boson** (first signal?)

  Axion-like particle

- Also light state with **small coupling<10^{-3}** not well-tested

  Muonic force, vector portal, Higgs portal…

Possible relation to
various anomalies, DM, or portal to Hidden sector

LHC+many different experiments (B, K, ν factories)
have potential to probe the light state
[complementary or competetive]

Axion vs Axion-like Particle

Standard QCD Axion

$$m_a \simeq \frac{m_\pi f_\pi}{f_a}$$

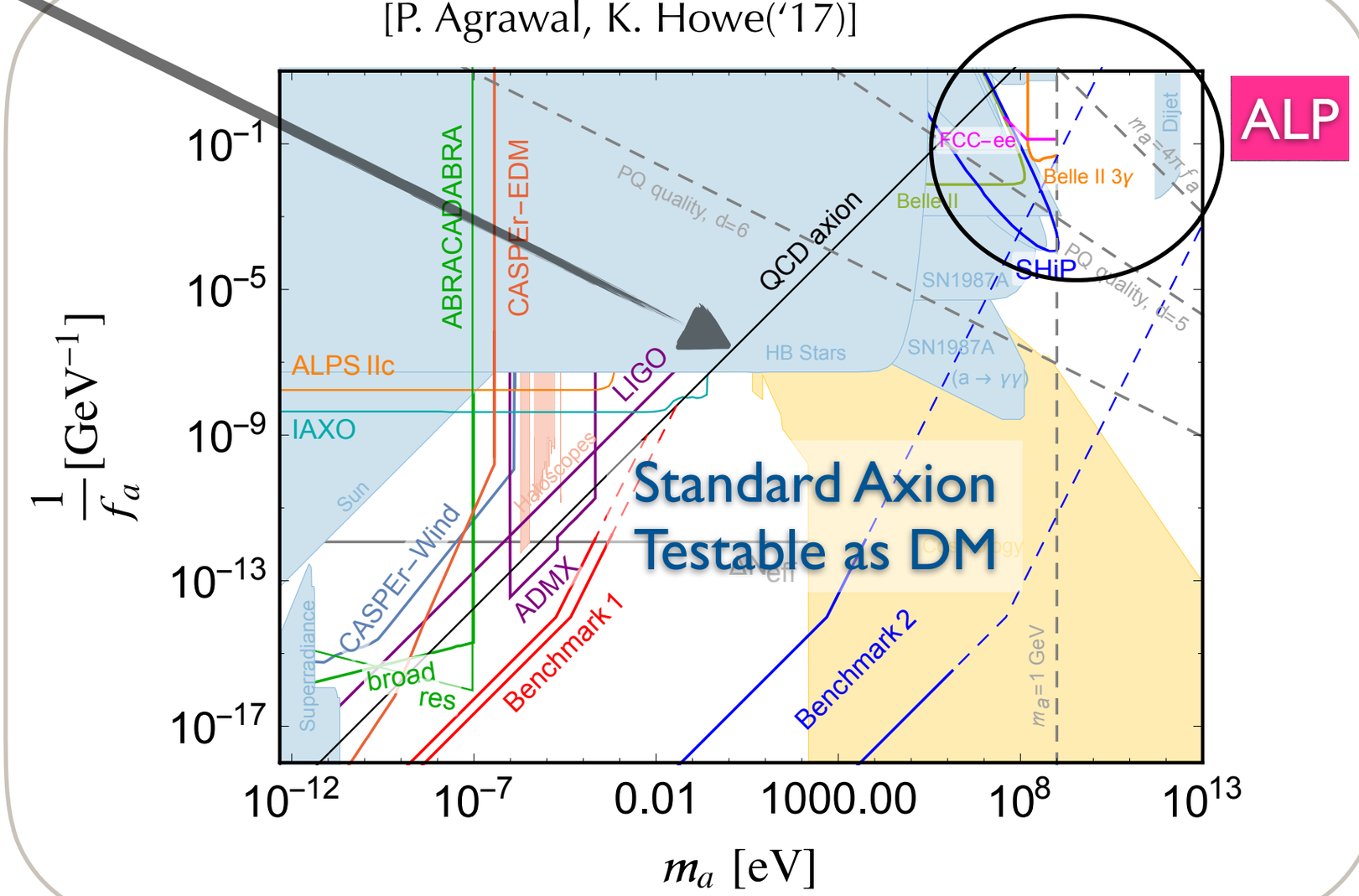
$$\frac{a}{4\pi f_a}\left[\alpha_s c_3 G\tilde{G} + \alpha_2 c_2 W\tilde{W} + \alpha_1 c_1 B\tilde{B}\right]$$

Axion-like particle

$$m_a \neq \frac{m_\pi f_\pi}{f_a}$$

- Not explored
- But many exp. can be involved

[P. Agrawal, K. Howe('17)]



Motivations and Phenomenology for ALPs

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'

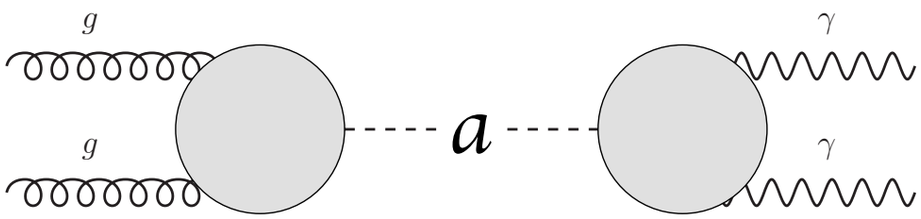
  Kilic, Okui, Sundrum('09), Nakai, Sato, KT ('16) …

Strong CP problem

- Heavy Axion/Visible Axion

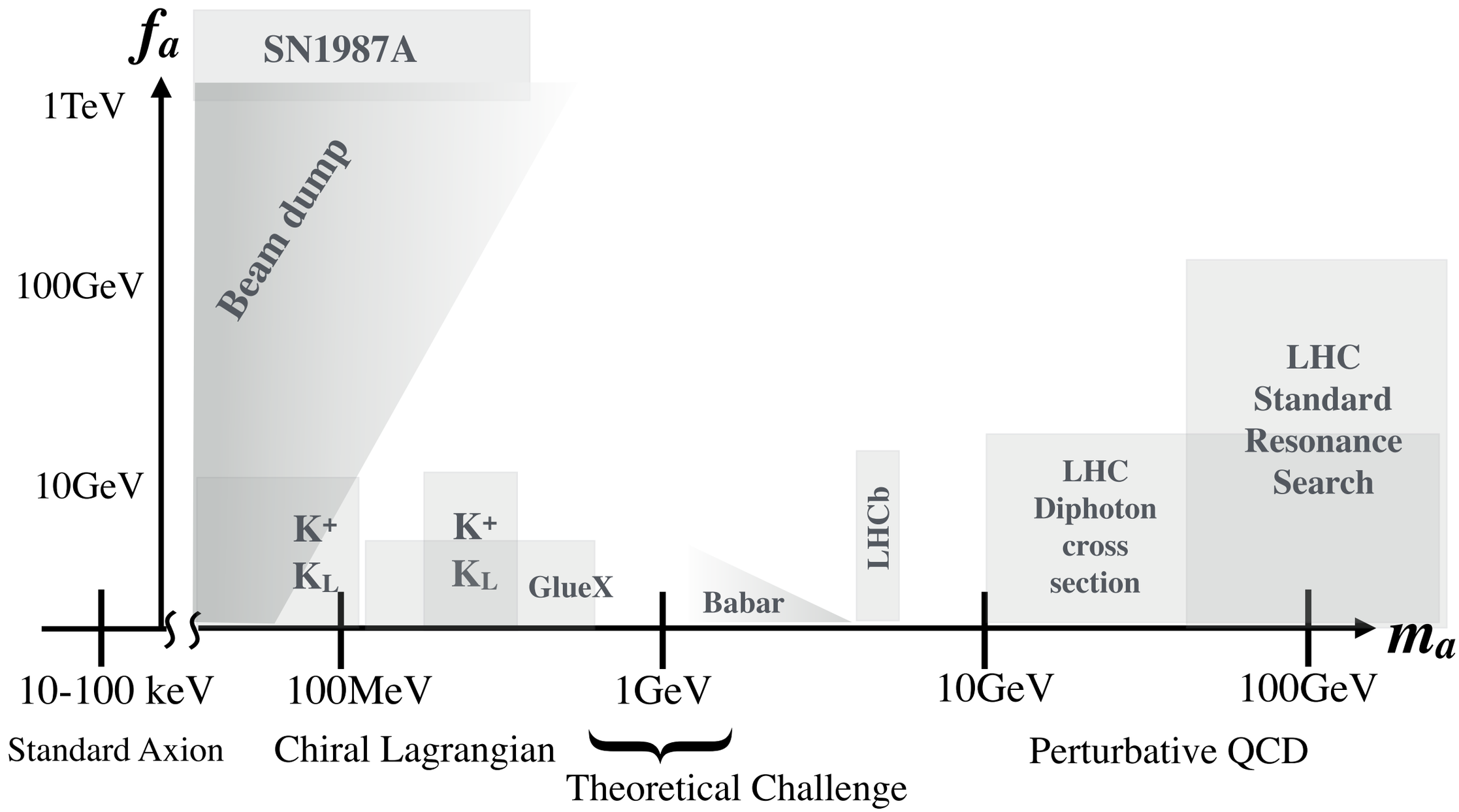
  Rubakov{'97}, Fukuda, Harigaya, Ibe, Yanagida ('15), P. Agrawal, K. Howe('17)

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



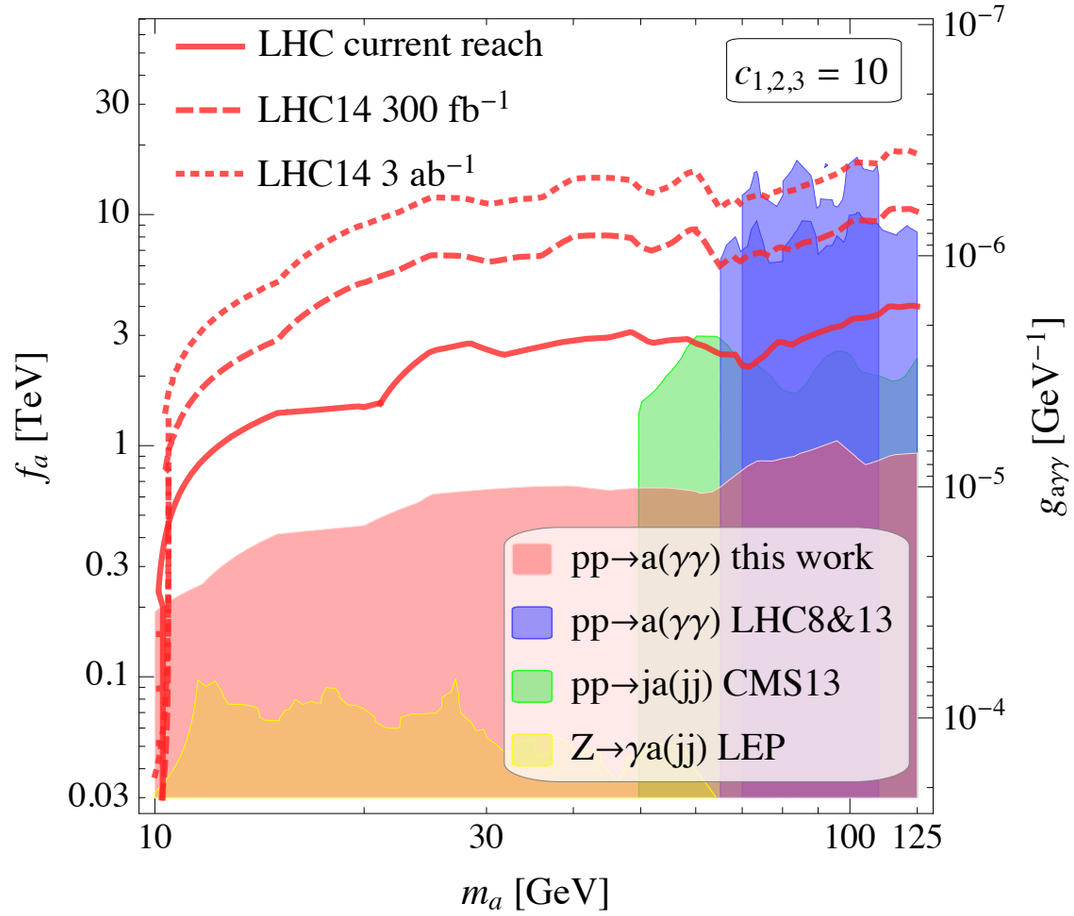
- production@LHC is gluon fusion,
- decay to dijet or diphoton due to kinematics (**m_a<m_Z**)

10MeV-100GeV ALP



10MeV-100GeV ALP

A. Mariotti, D. Redigolo, F. Sala, KT('18)

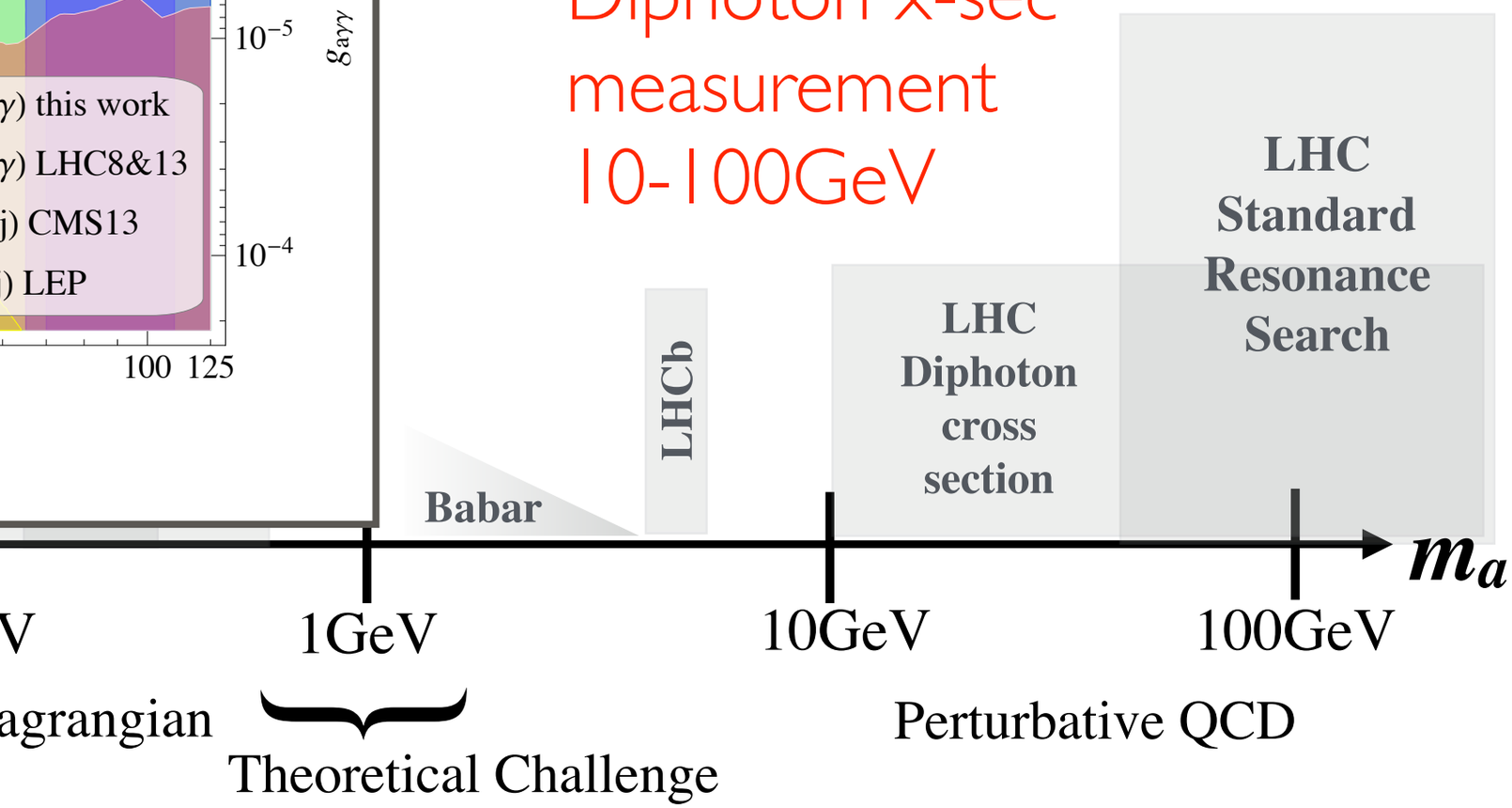


Diphoton resonance ends at ~65GeV due to side-band

e.g. ATLAS[1606.03833]

CMS Dijet-analysis down to 50GeV CMS [1710.00159]

Diphoton x-sec measurement 10-100GeV



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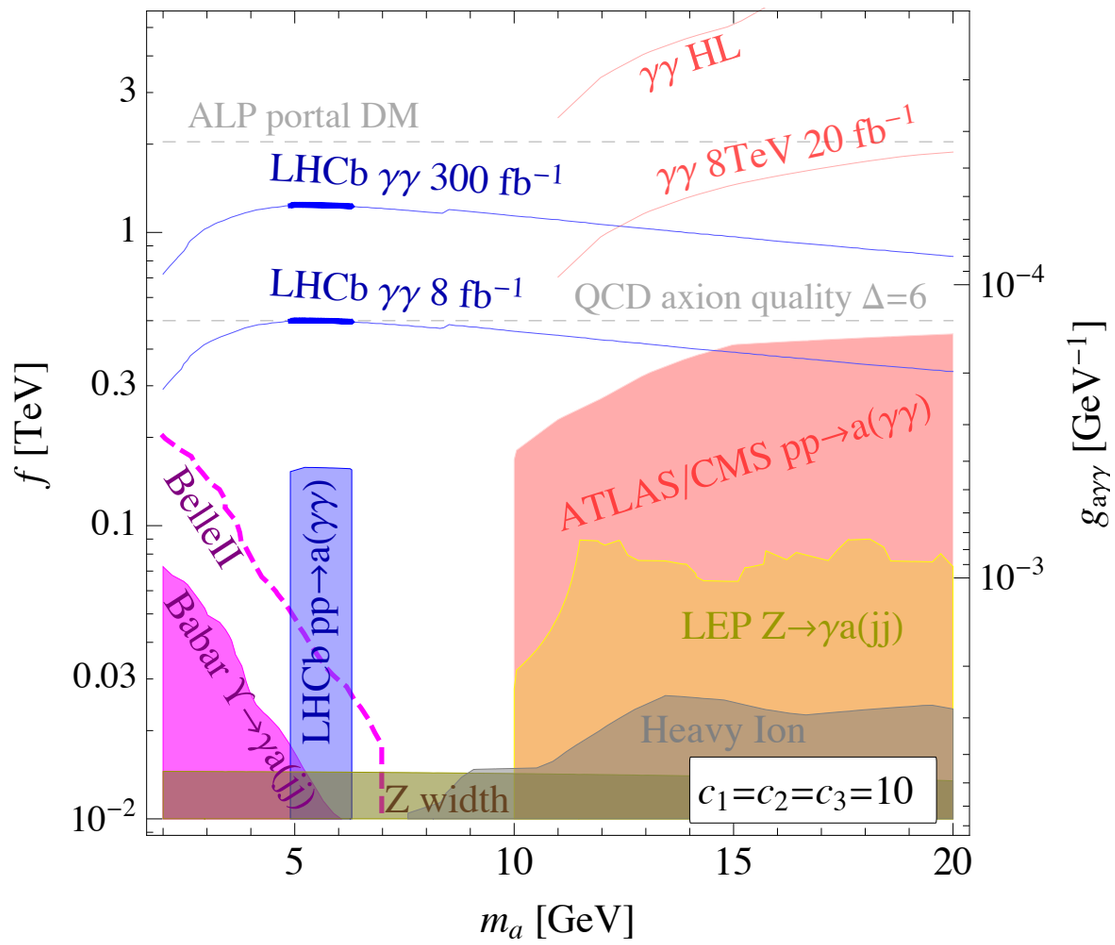
X. Cid Vidal, A. Mariotti, D. Redigolo, F. Sala, KT('18)



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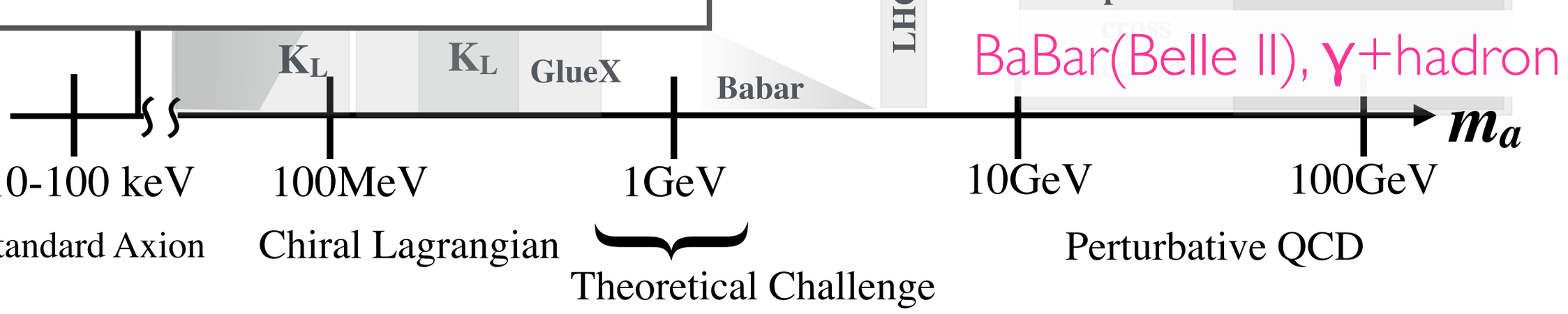
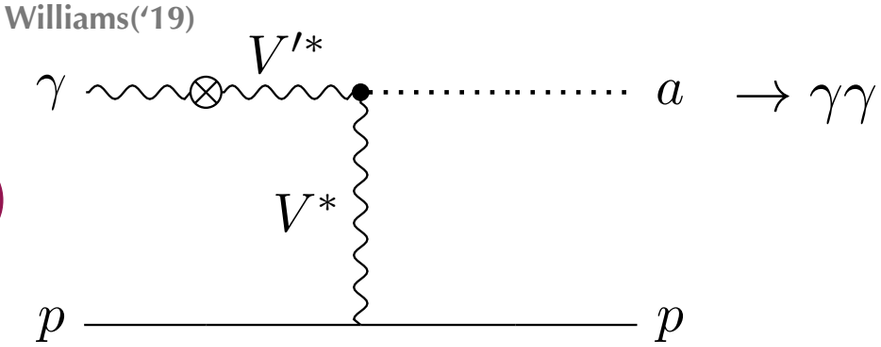


10MeV-100GeV ALP

D. Aloni, C. Fanelli, Y. Soreq, M. Williams('19)

GlueX
(photon beam)



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e.g. ATLAS[1606.03833]

$K_L \to \pi^0 a$ (KOTO)

$K^+ \to \pi^+ a$ (NA62)

E. Izaguirre,T. Lin,B. Shuve ('16)
S. Gori, G. Perez, KT (to appear)

CMS Dijet-analysis down to 50GeV CMS [1710.00159]

Diphoton x-sec measurement 10-100GeV

LHCb diphoton 2-20GeV

BaBar(Belle II), γ+hadron

1TeV
100GeV
10GeV

K^+ K_L
K^+ K_L
GlueX
Babar
LHCb
Diphoton
LHC Standard

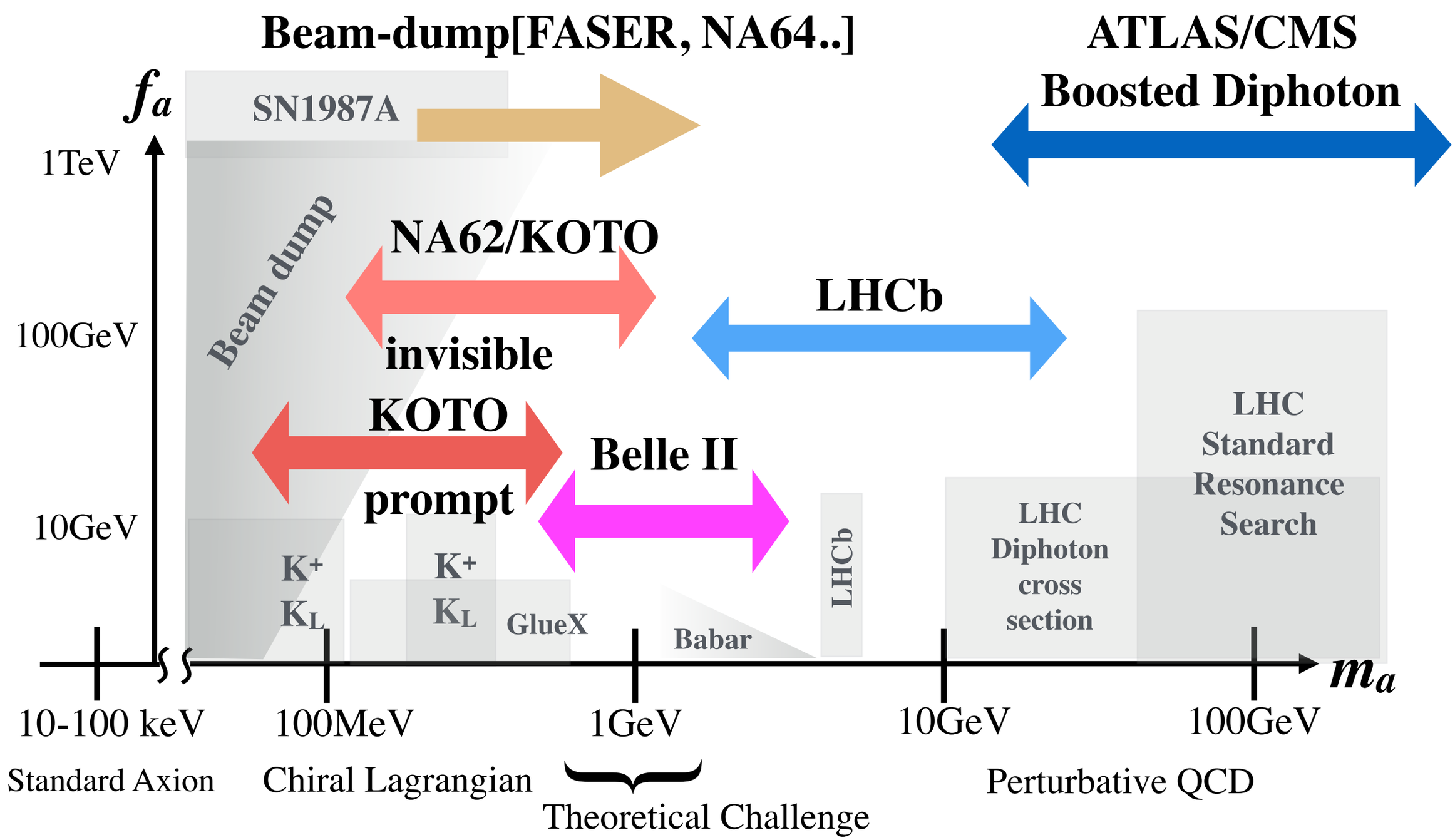
m_a

10-100 keV
100MeV
1GeV
10GeV
100GeV

Standard Axion
Chiral Lagrangian
Theoretical Challenge
Perturbative QCD

ALP-mesons mixing

Future Challenges



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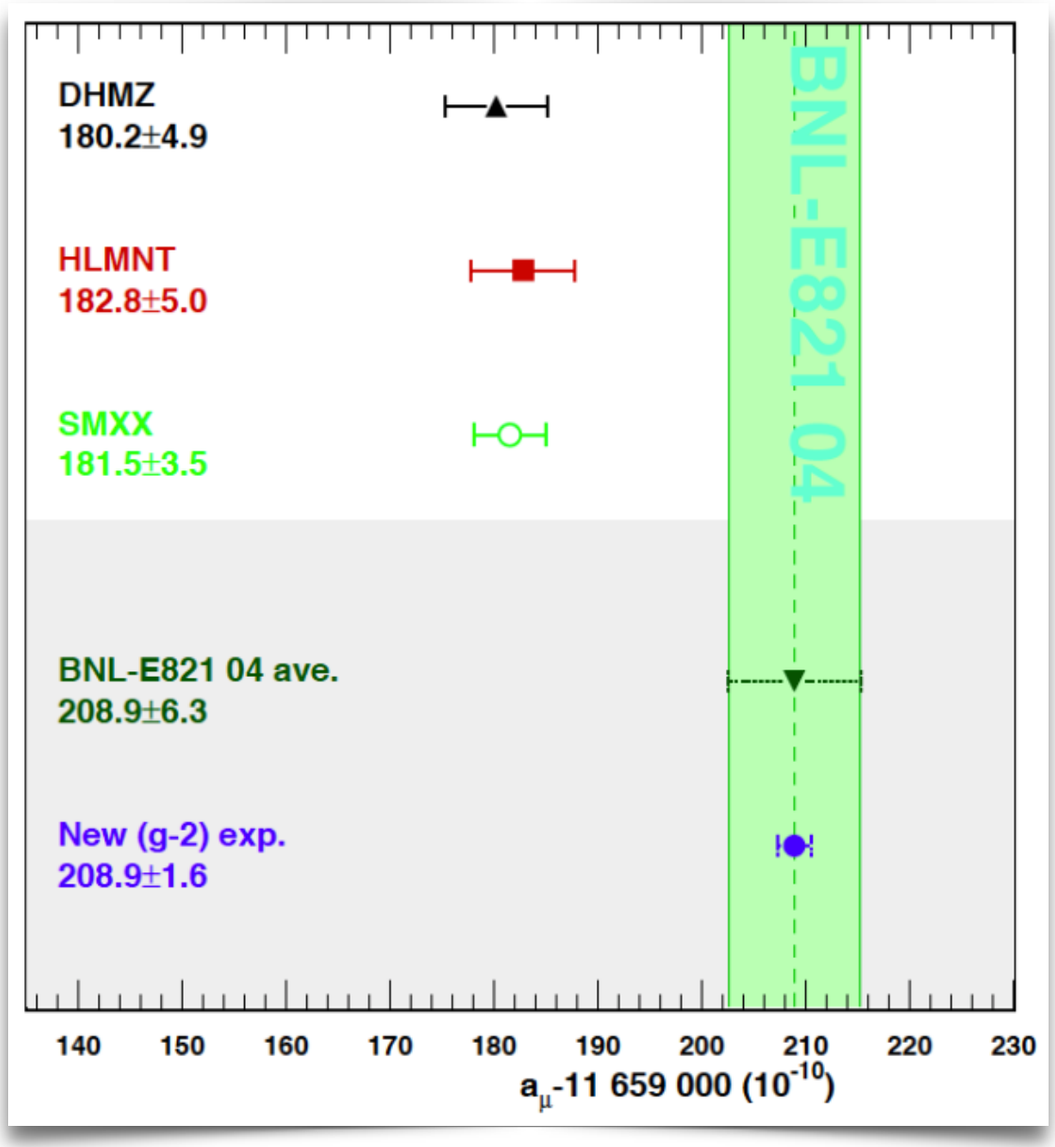
Muon g-2

Magnetic moment(g-factor)

$$\vec{\mu} = g \left(\frac{e}{2m}\right) \vec{S}$$

Anomalous part

$$a_\mu = \frac{g-2}{2}$$



Precise measurement & Precise calculation

$$\Delta a_\mu = (a_\mu)_{\rm exp} - (a_\mu)_{SM} = 287(63)(49) \times 10^{-11}$$

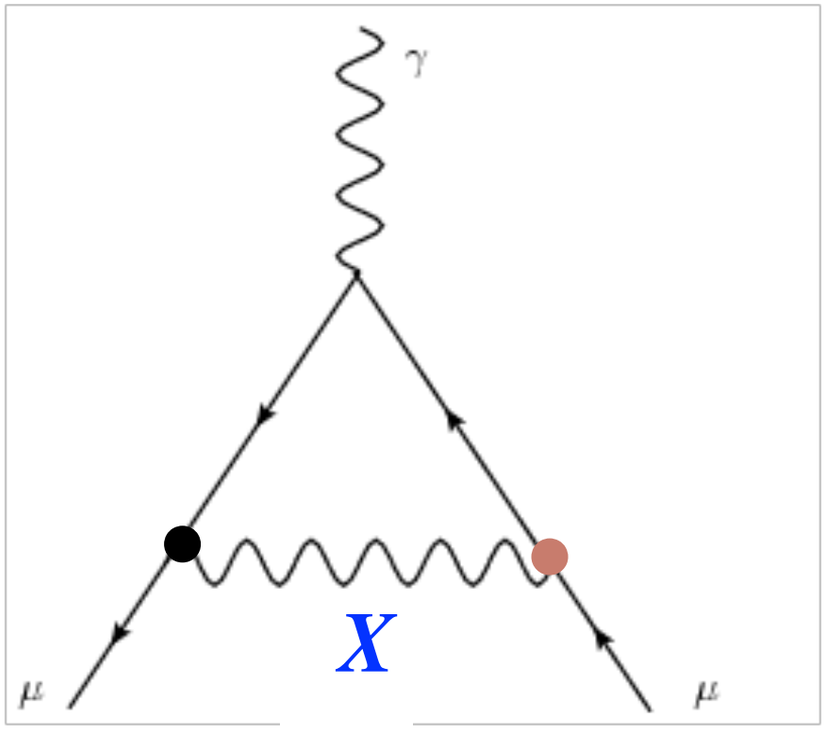
~3.5σ

Fermilab g-2 experiment
already more data than BNL
>>new result would appear *soon*

Muon g-2 and BSM

Effective operator

$$-\delta a_\mu \frac{e}{4m_\mu} \bar{\mu}_L \sigma^{\alpha\beta} F_{\alpha\beta} \mu_R + h.c.$$



Size of anomaly

$$\delta a_\mu = (26.1 \pm 8.0) \times \ 10^{-10}$$

★dimensional analysis for BSM

$$\sim \frac{\alpha_X f_{\rm loop}}{4\pi} \frac{e}{4m_\mu} \bar{\mu}_L \sigma^{\alpha\beta} F_{\alpha\beta} \mu_R$$

$$\frac{\alpha_X f_{\rm loop}}{4\pi} \simeq \frac{\alpha_X}{4\pi} \min\left[1, \frac{m_\mu^2}{m_X^2}\right] \to 10^{-9}$$

$\alpha_X \sim \alpha_{em}$ $\quad m_X \sim 100\text{GeV}$

SUSY, etc

$m_X \lesssim m_\mu$ $\quad \alpha_X \sim 10^{-8}$

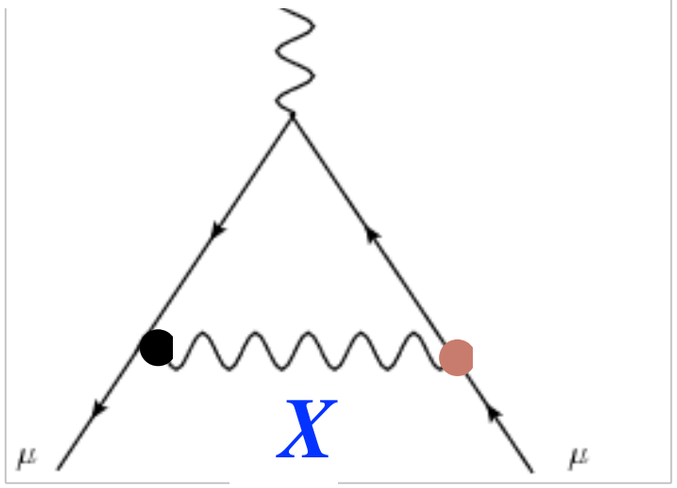
$(g_X \sim 4 \times 10^{-4})$

*Two-loop (Barr-Zee) is relevant for $\alpha_X \sim \alpha_{em}$

Light Muonic Force

$\alpha_X \sim 10^{-8}$

g-2 sign ✓: Vector, Scalar ✘: Axial-vector, pseudo-Scalar*



$g_V \bar{\mu}\gamma_\mu V^\mu \mu$ $y_\phi \phi \bar{\mu}\mu$

Simple extension of SM

*Gauging Lepton(**L**) or Baryon(**B**) number*

Anomaly free combination

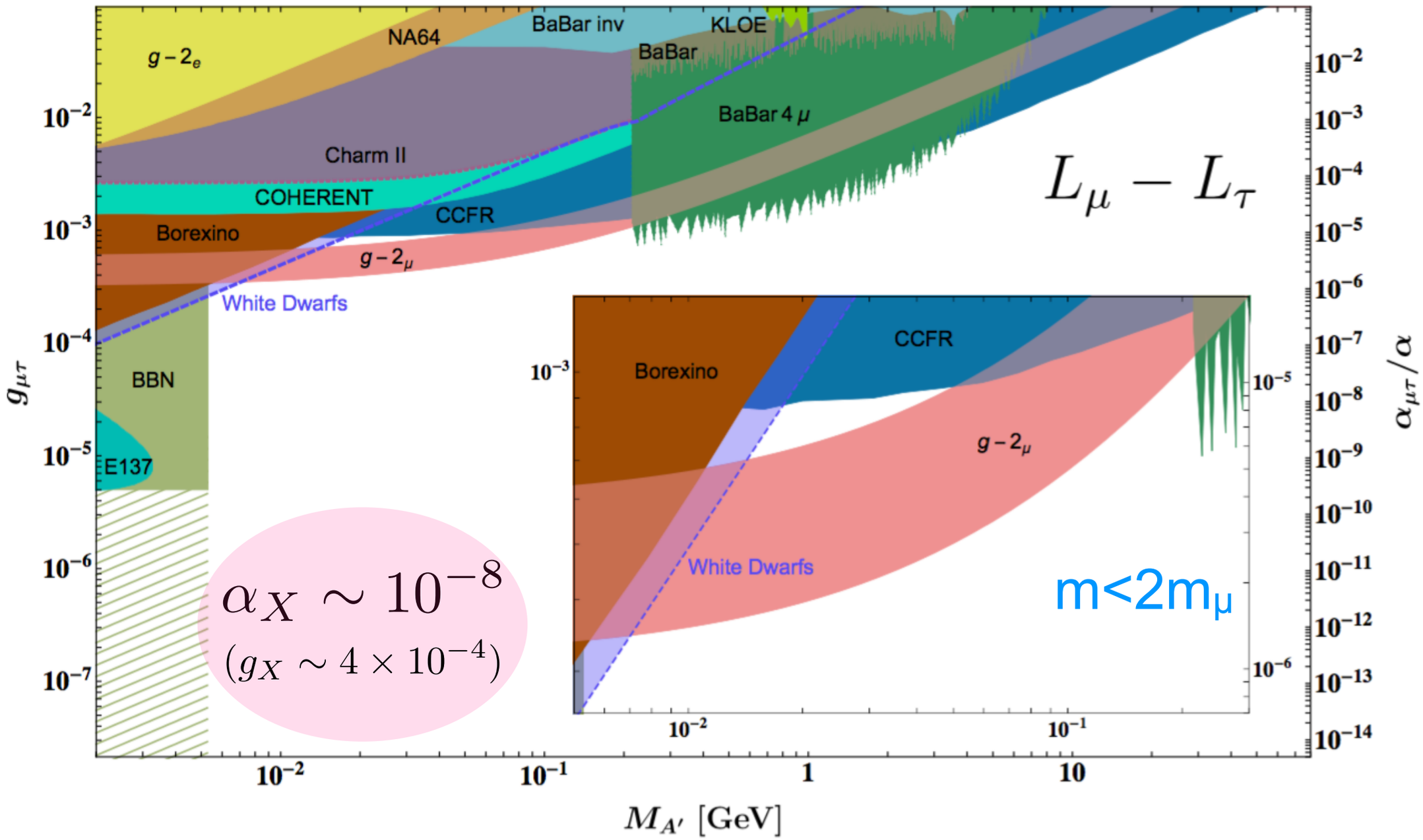
$$B - L, \quad B - 3L_\mu, \quad L_\mu - L_e, \quad L_\tau - L_e, \quad L_\mu - L_\tau \ \ldots$$

V can be mediator of sub-GeV DM

1901.02010,1812.03829,
1804.03144, 1801.10448, …

Light Muonic Force

[M. Bauer, P. Foldenauer, J. Jaeckel ('19)]



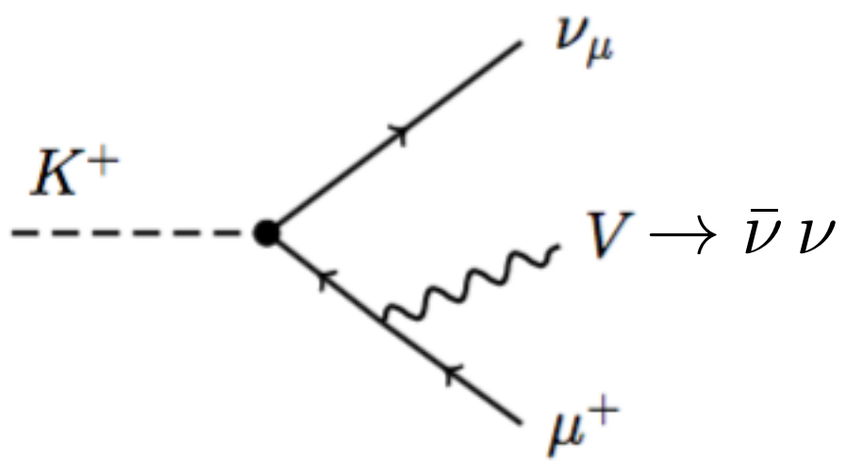
Test by NA62, Belle II, ATLAS, DUNE, etc.

Muonic Force at NA62

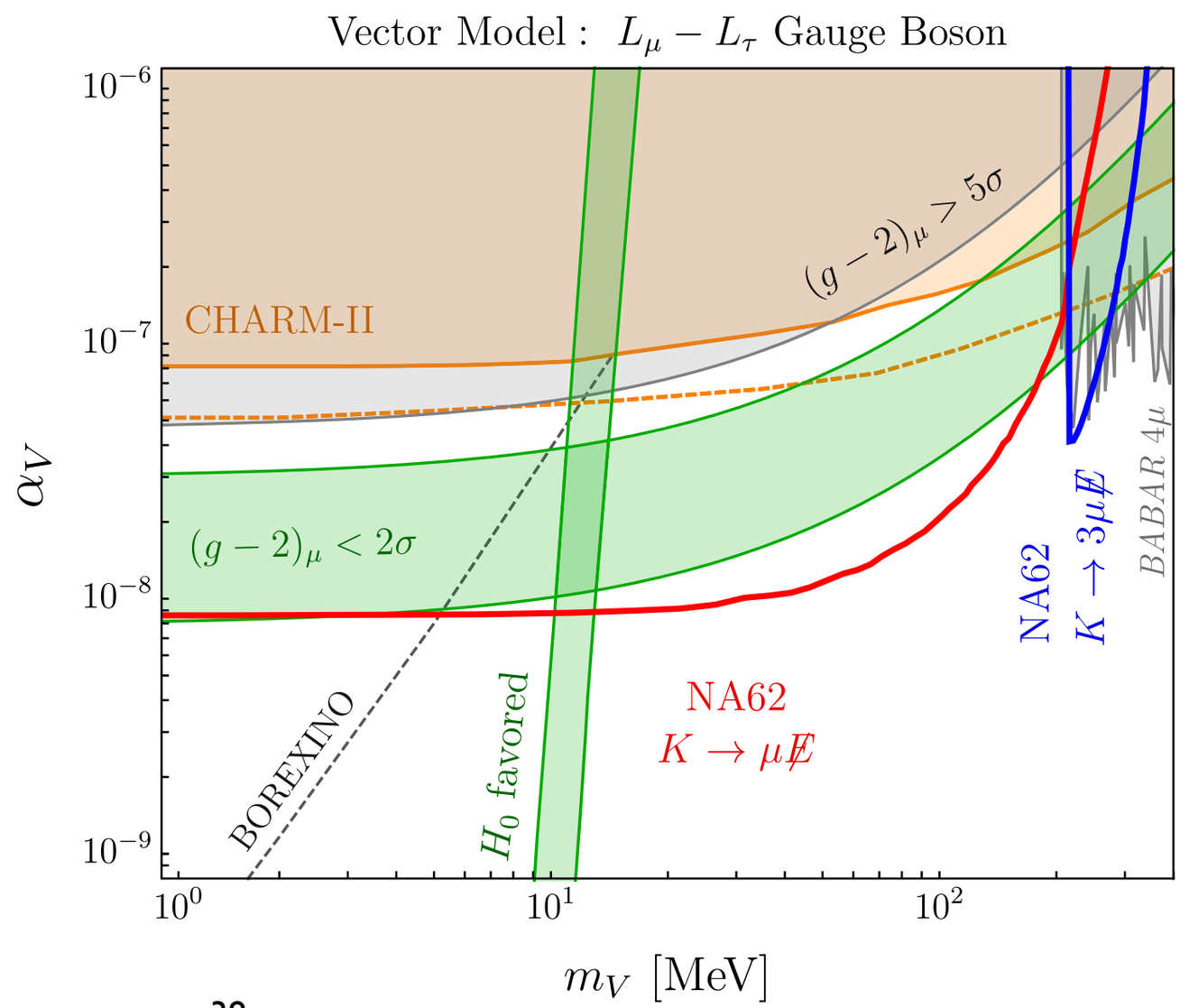
$N_{K^+}=10^{13}$ at NA62

G. Krnjaic, G. Marques-Tavares, D. Redigolo, KT('19), M. Ibe, W. Nakano, and M. Suzuki('17)

$$\mathrm{Br}(K^+ \to \mu^+ \nu) = 60\% \quad \times \left(\frac{\alpha_V}{\pi} \sim 10^{-8}\right)$$



$$\boxed{\mathrm{Br}(K^+ \to \mu\nu V) \simeq O(1) \times 10^{-8}}$$



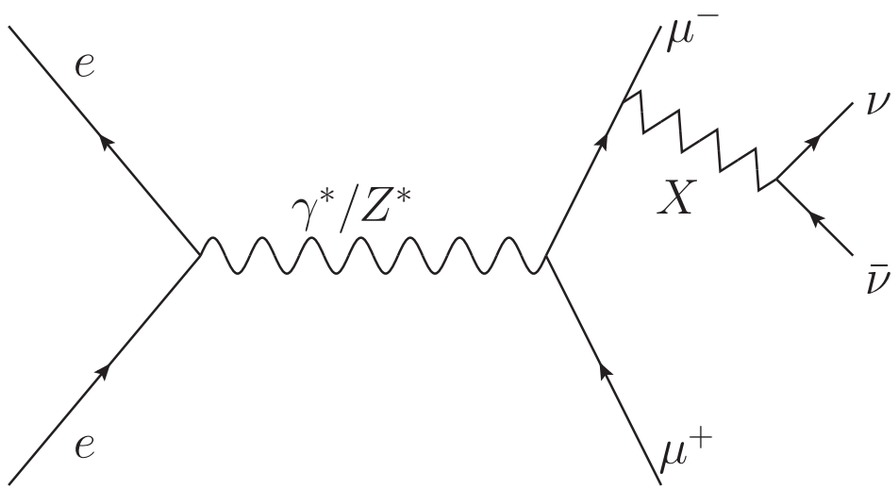
NA62 could cover parameter space!

- Binned likelihood analysis

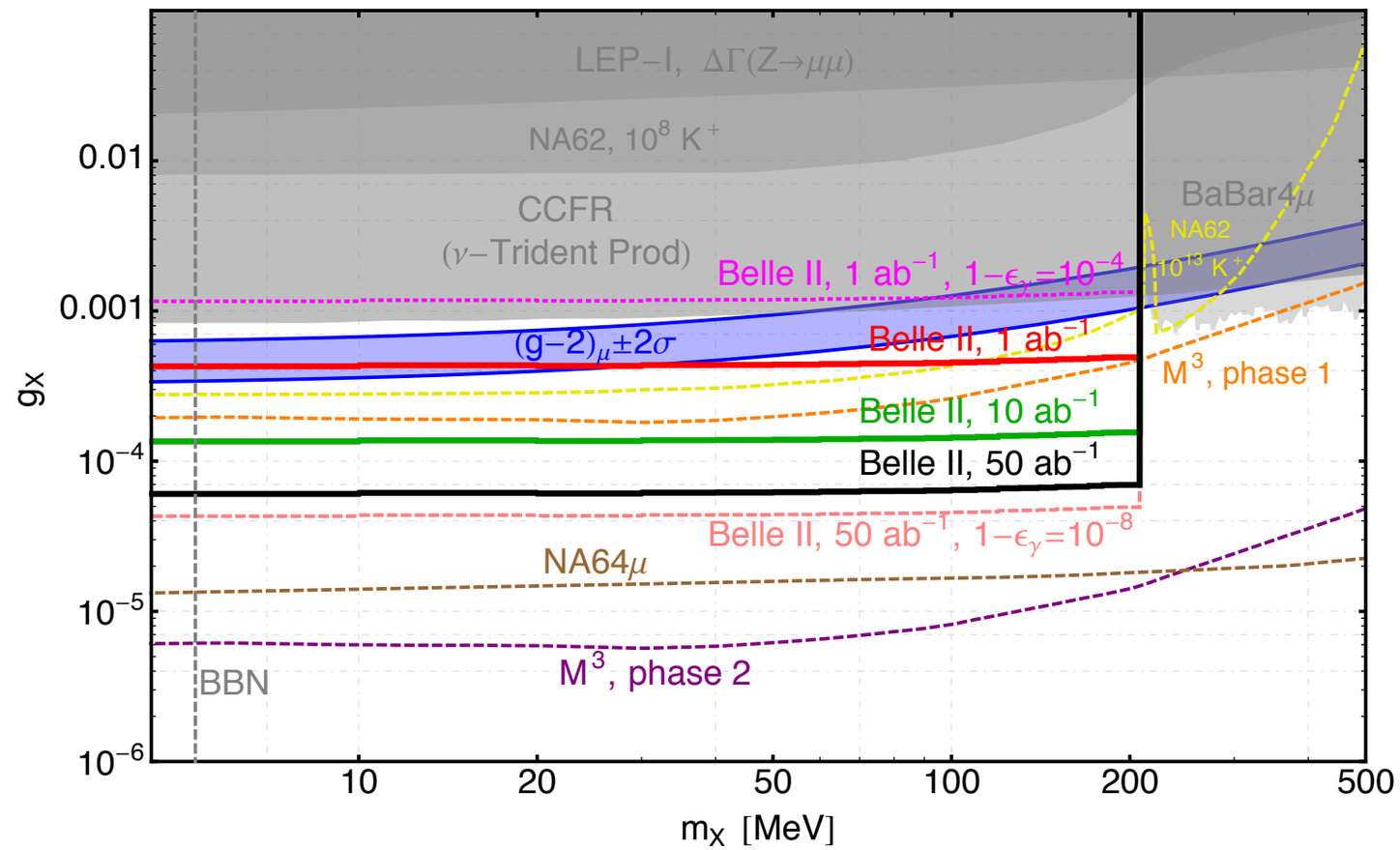
A=0.3, BG reduced by 2

Muonic Force at Belle II

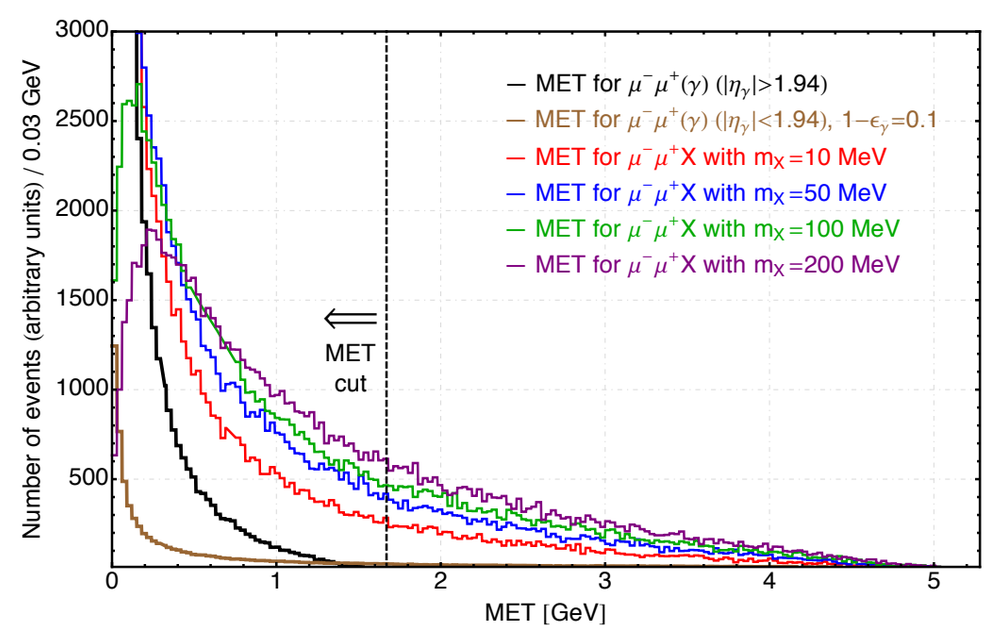
2mu+missing



[Y. Jho, Y. Kwon, S. C. Park, P. Tseng('19)]

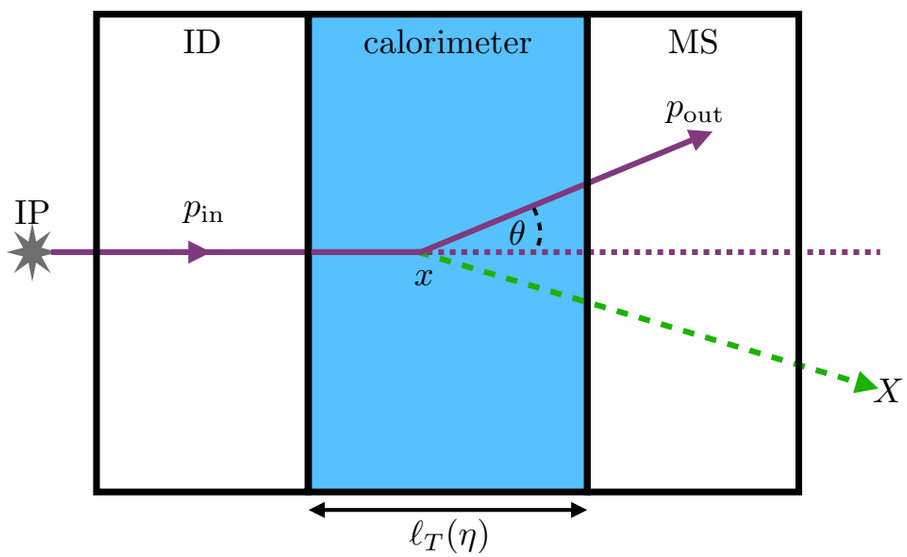


Main BG: non-detection of photon



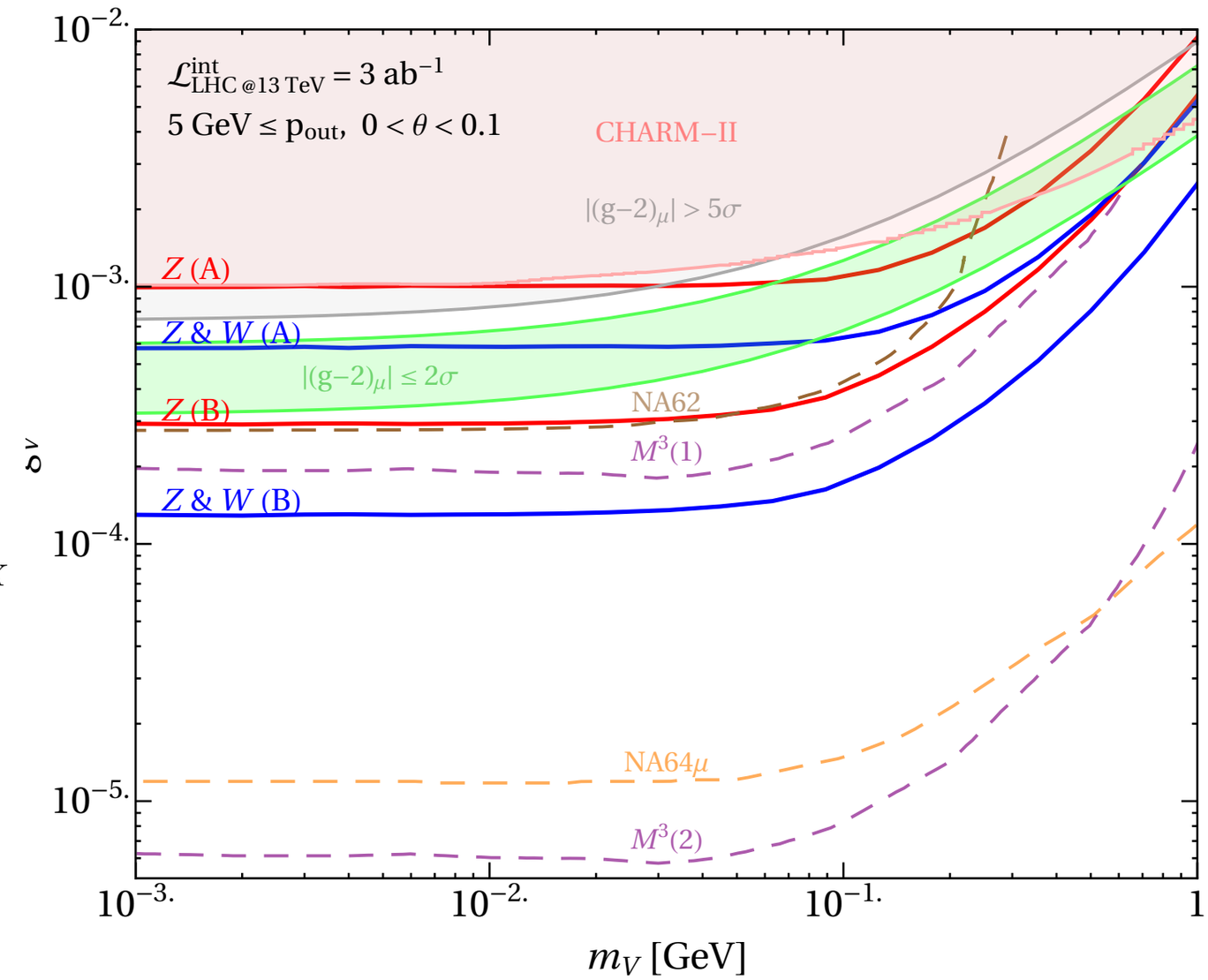
Muonic Force at ATLAS

ATLAS
as fixed target exp.



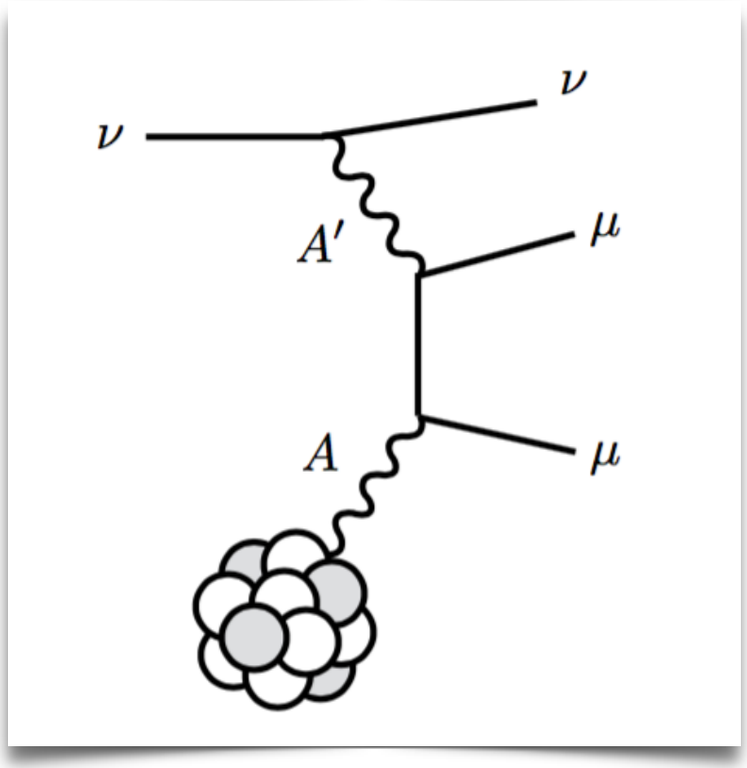
p measurement
before/after CAL

I. Galon, E. Kajamovitz, D. Shih, Y. Soreq, S. Tarem ('19)

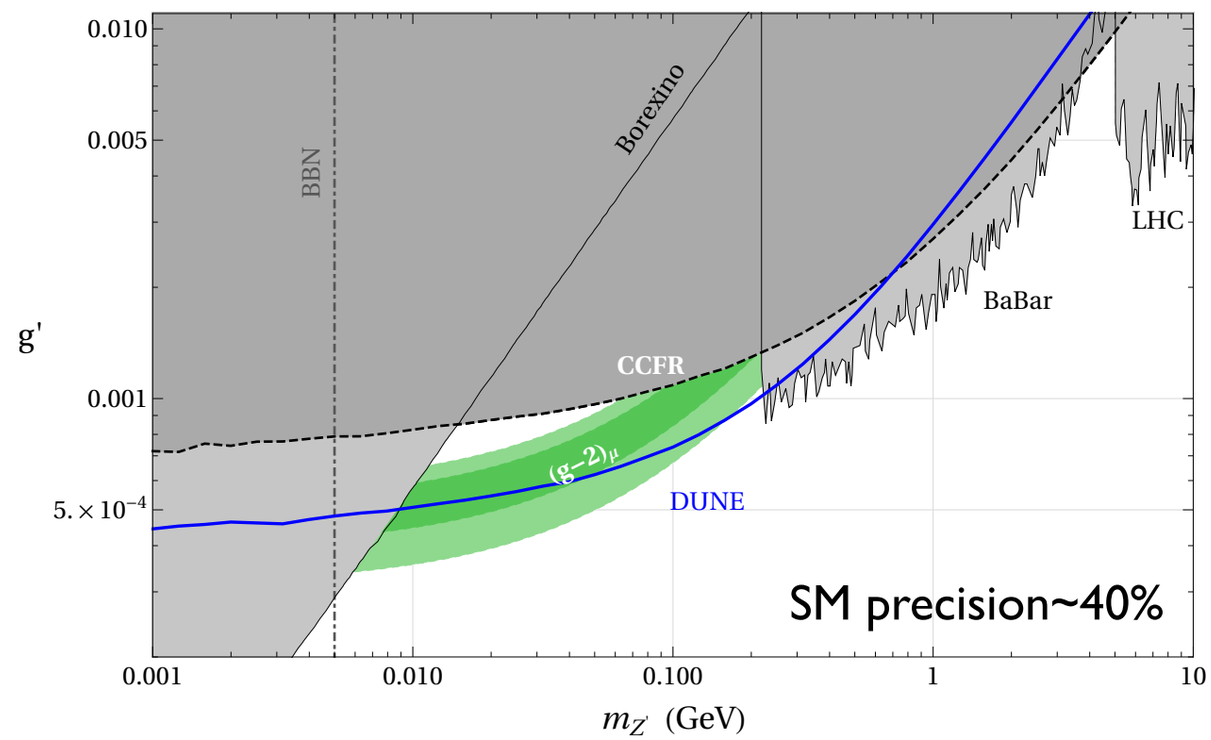


A(broad resolution), B(1 gaussian)
Source of muons from Z or W

Muonic Force at DUNE



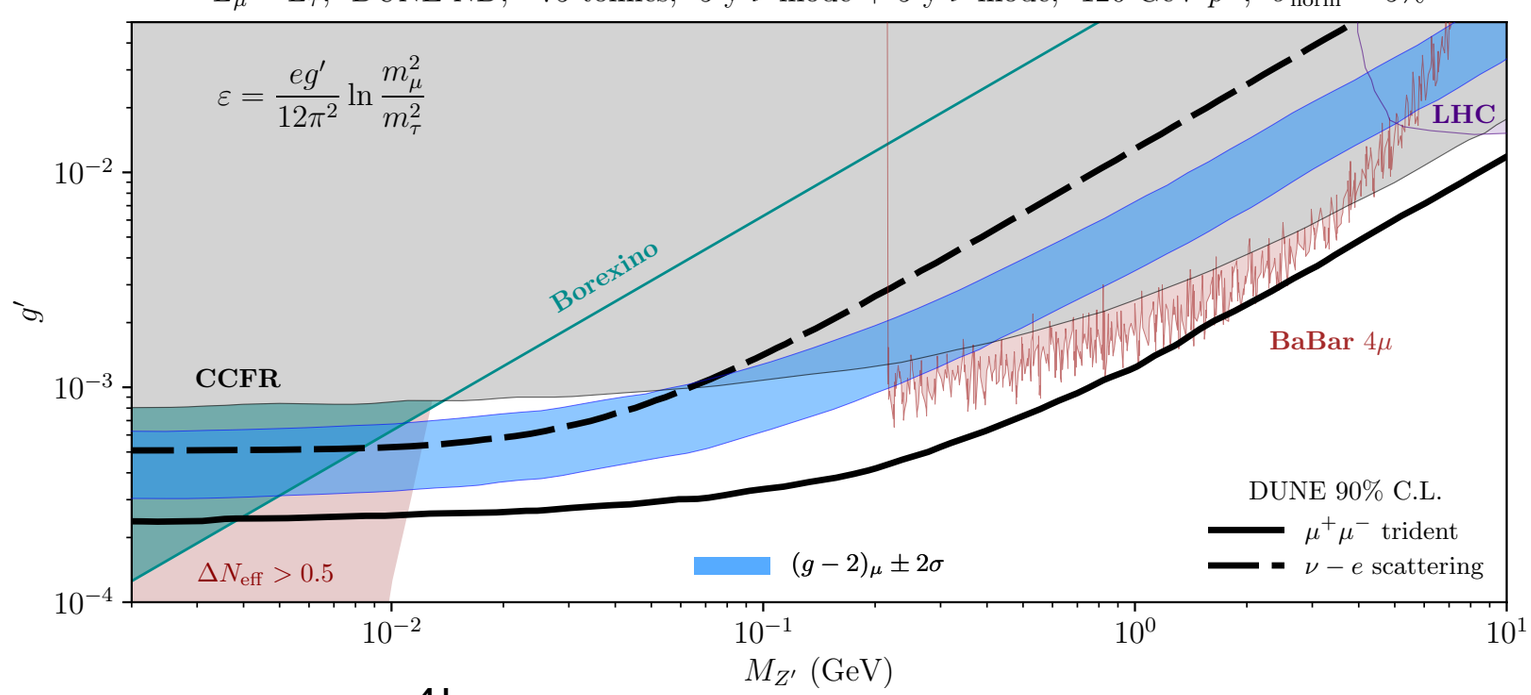
W. Altmannshofer, S. Gori, J. Martin-Albo, A. Sousa, M. Wallbank('19)



Neutrino Trident (2μ+ν)

P. Ballett, M. Hostert, S. Pascoli, Y. F. Perez-Gonzalez, Z. Tabrizi, R. Zukanovich Funchal('19)

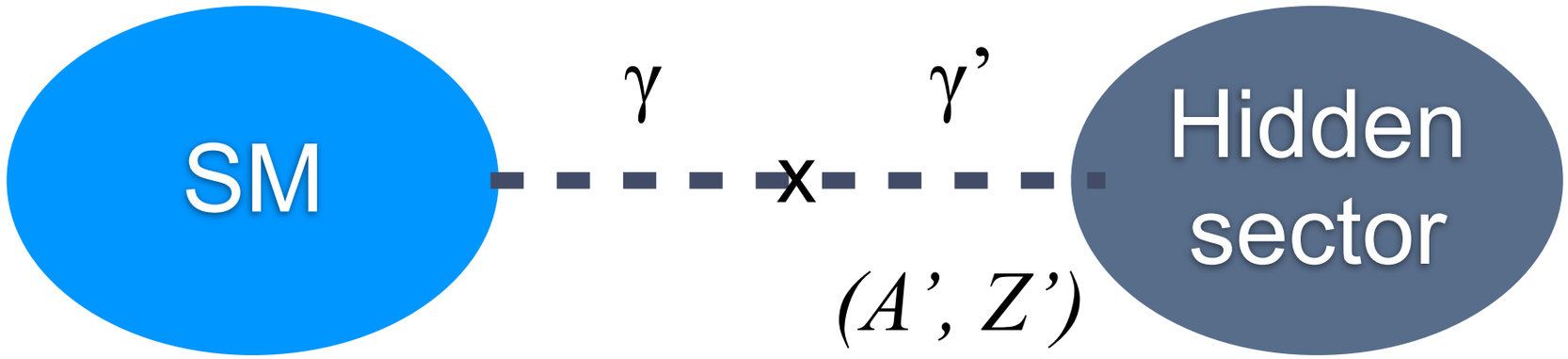
$L_\mu - L_\tau$, DUNE ND, 75 tonnes, 5 y ν-mode + 5 y $\bar{\nu}$-mode, 120 GeV p^+, $\sigma_{\rm norm} = 5\%$



Portals
Simplified Model

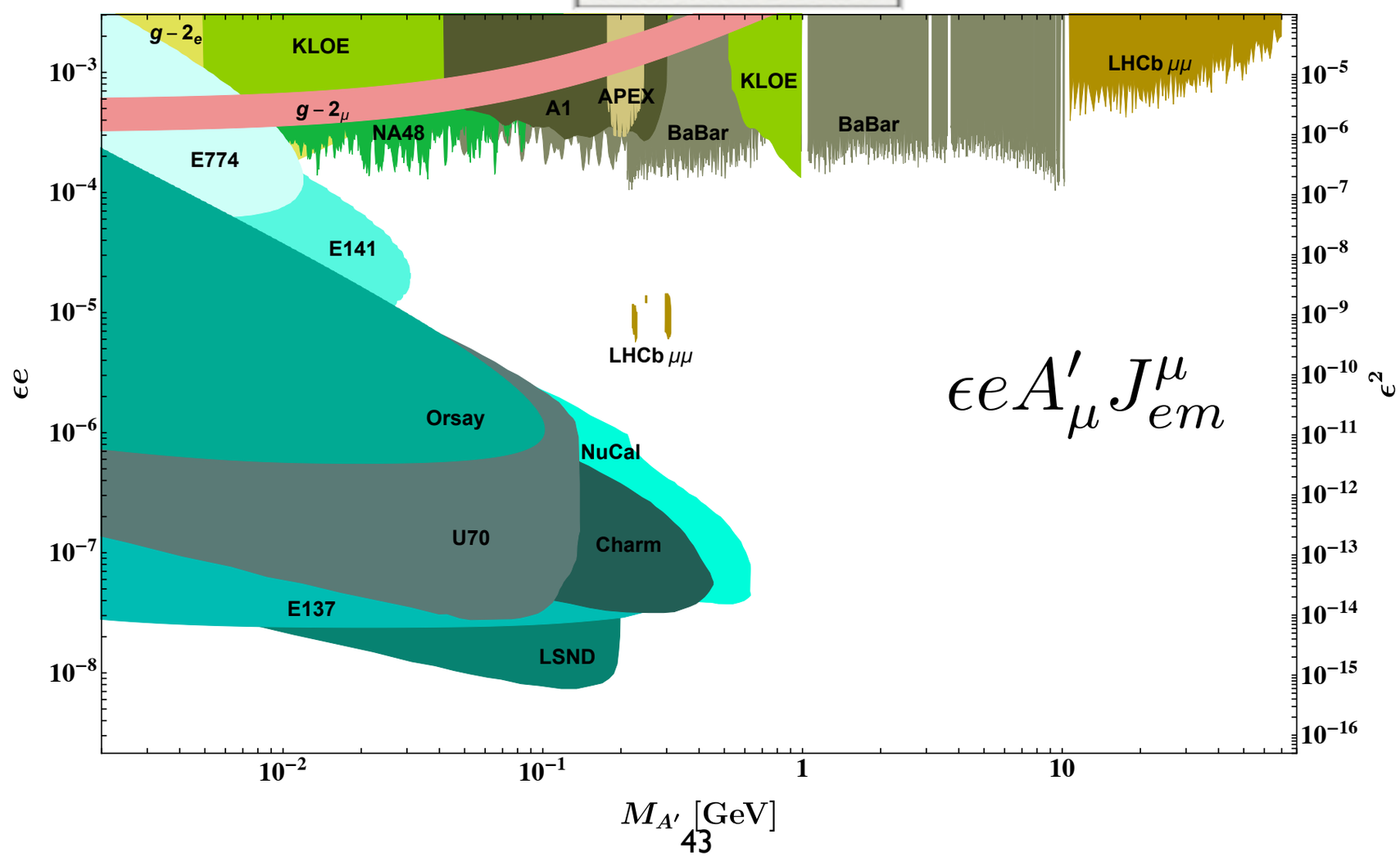
Easy to parametrize in the search

Dark Photon, Vector Portal

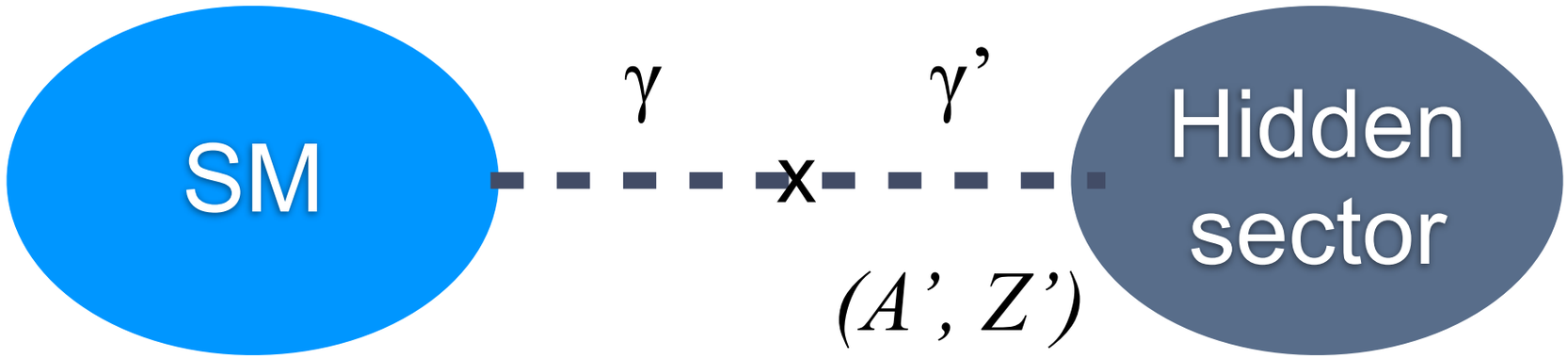


Dimension 4 operator $\frac{\epsilon}{2} F^{\mu\nu} F'_{\mu\nu}$

Light DM,
Various anomalies

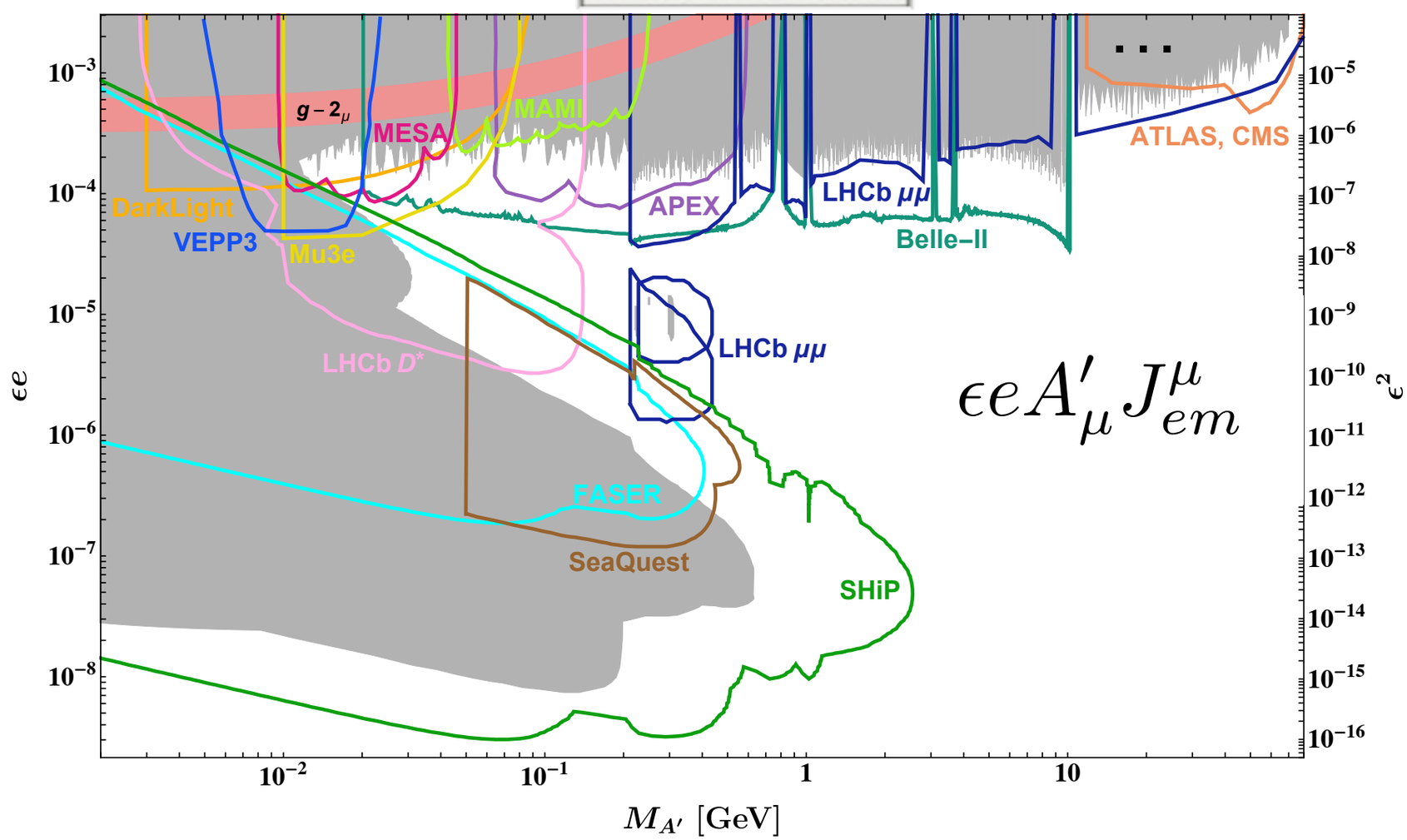


Dark Photon, Vector Portal

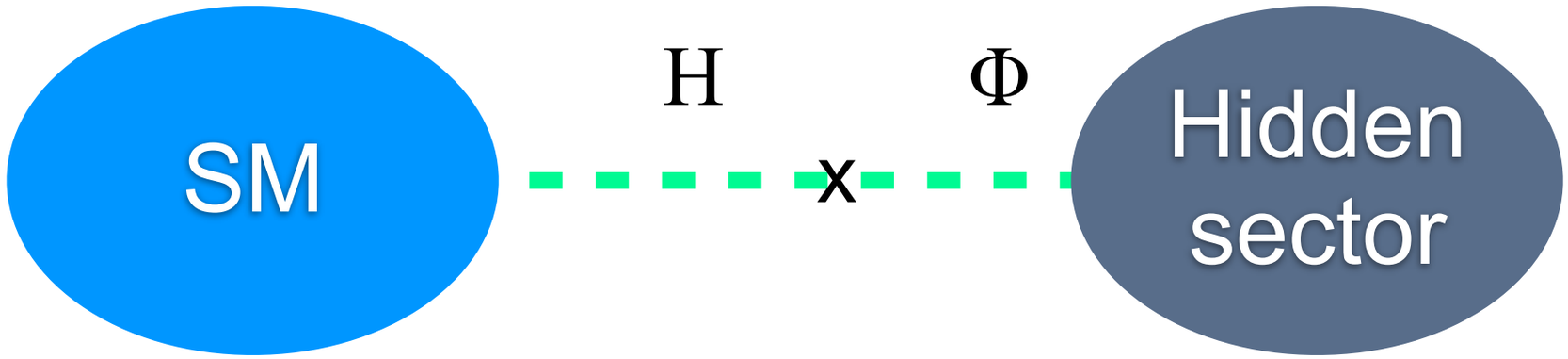


Dimension 4 operator $\frac{\epsilon}{2} F^{\mu\nu} F'_{\mu\nu}$

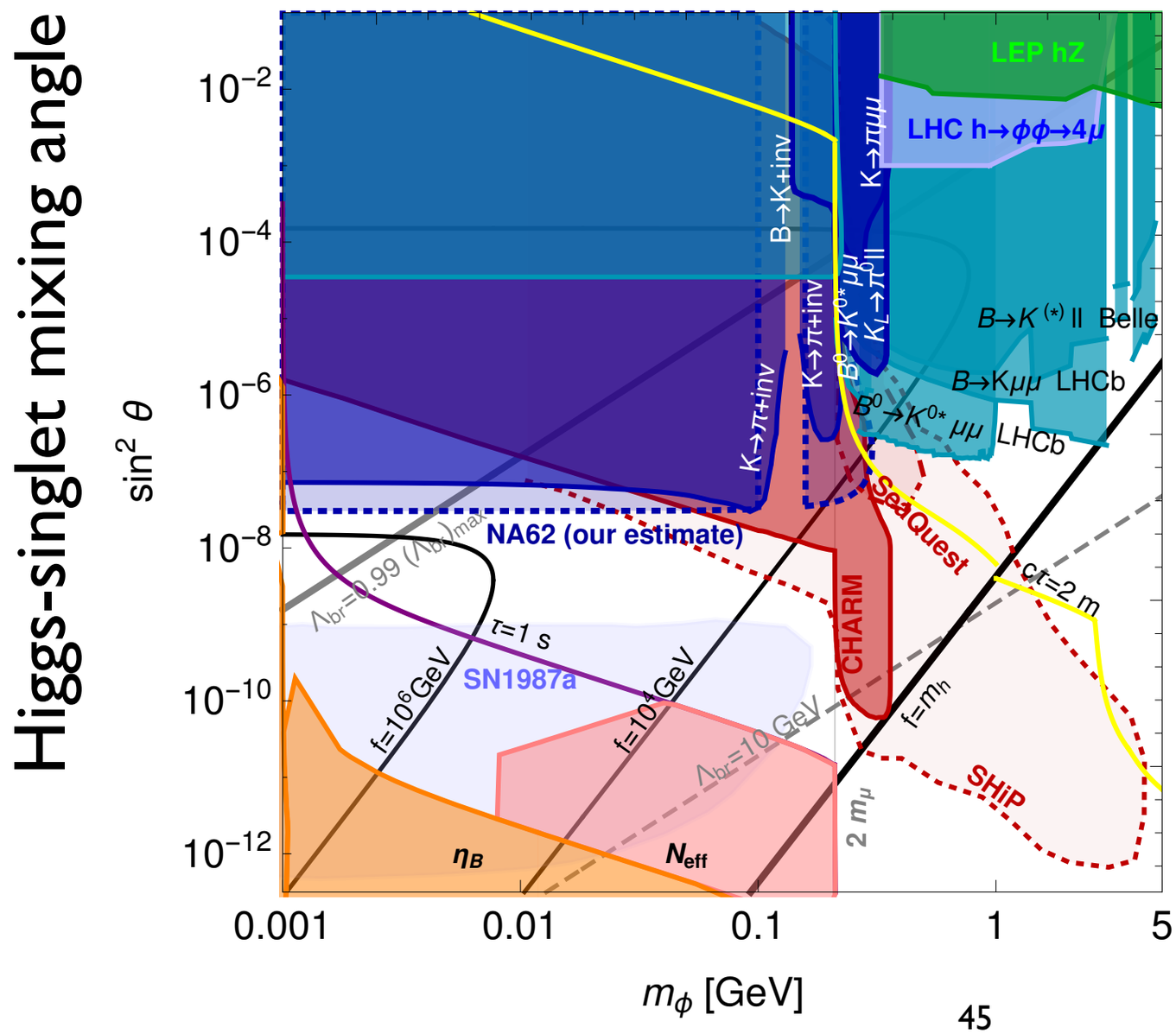
Light DM,
Various anomalies



Higgs Portal, Relaxion



T. Flacke, C. Frugiuele, E. Fuchs, R. S. Gupta, G. Perez('17)



Naturalness [Relaxion]
Various anomalies
…

D<=4 operator

$$m\Phi|H|^2 + h.c.$$
$$+\lambda|\Phi|^2|H|^2$$

Summary

- Overwhelming evidence for BSM physics
- Understand Higgs property as much as possible
- Direct search programs at LHC are powerful especially for weak-TeV scale particles
- Maybe overlooked light states; should be covered by LHC, B/K/v factories, beam dump, and other exp!