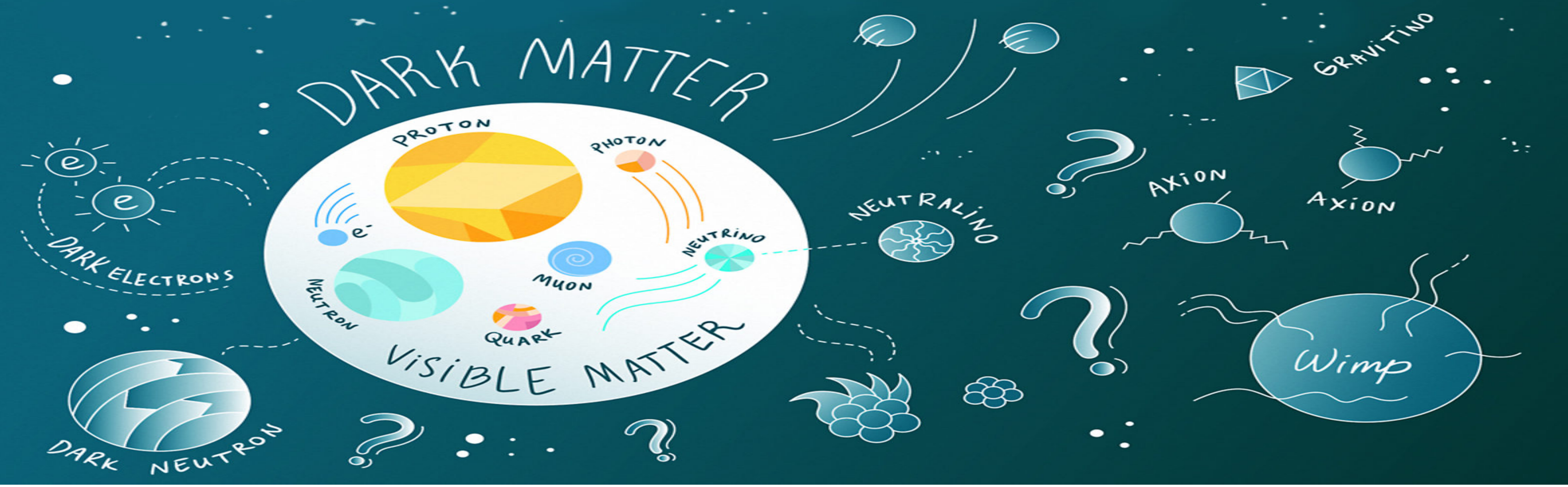


Exploring New Physics related to Dark Matter at Higgs factories

Xiao-Ping Wang（王小平）

Mar, 23 @ CCAST

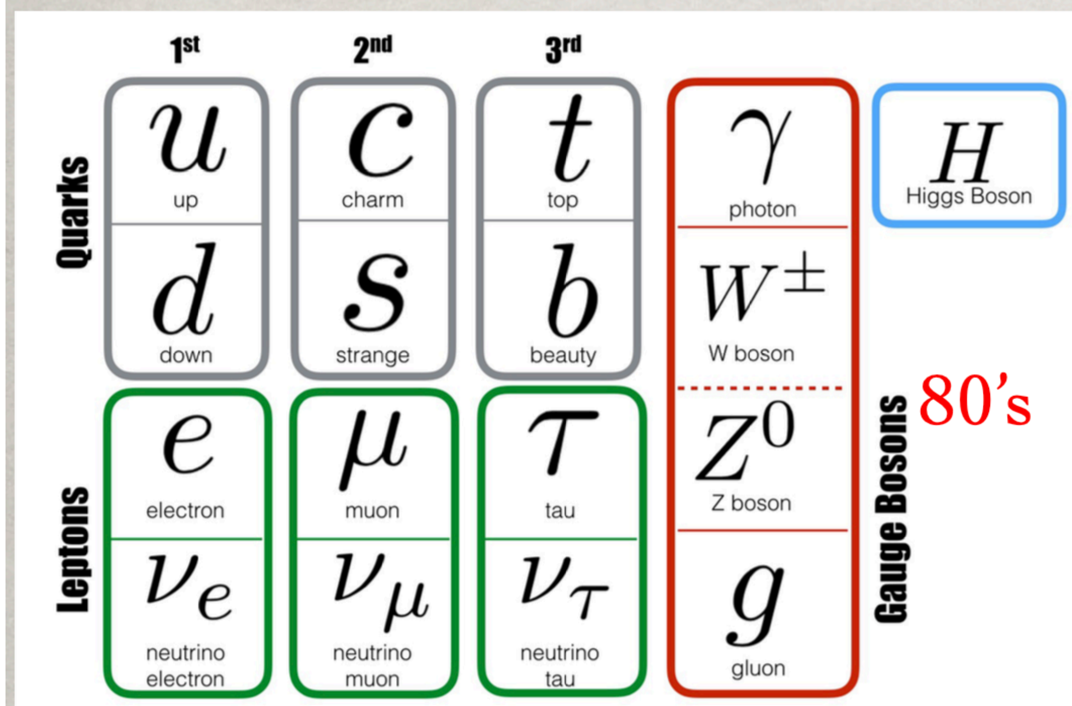
Base On: *JHEP* 06 (2017) 077
Phys.Rev.D 97 (2018) 9
arXiv:2210.09335

Successful of SM

The field of HEP has been vibrant & exciting!

HEP has enjoyed the remarkable achievement of 50+-year uninterrupted discoveries! From quarks to the Higgs boson, with heroic efforts in theory and experiments:

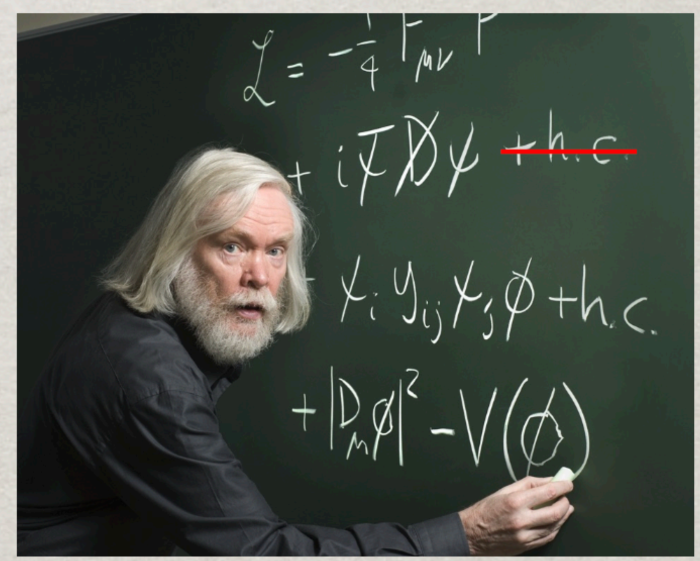
60's 70's 90's 2012



80's

1930/1956 1962 2000

A highly successful theory

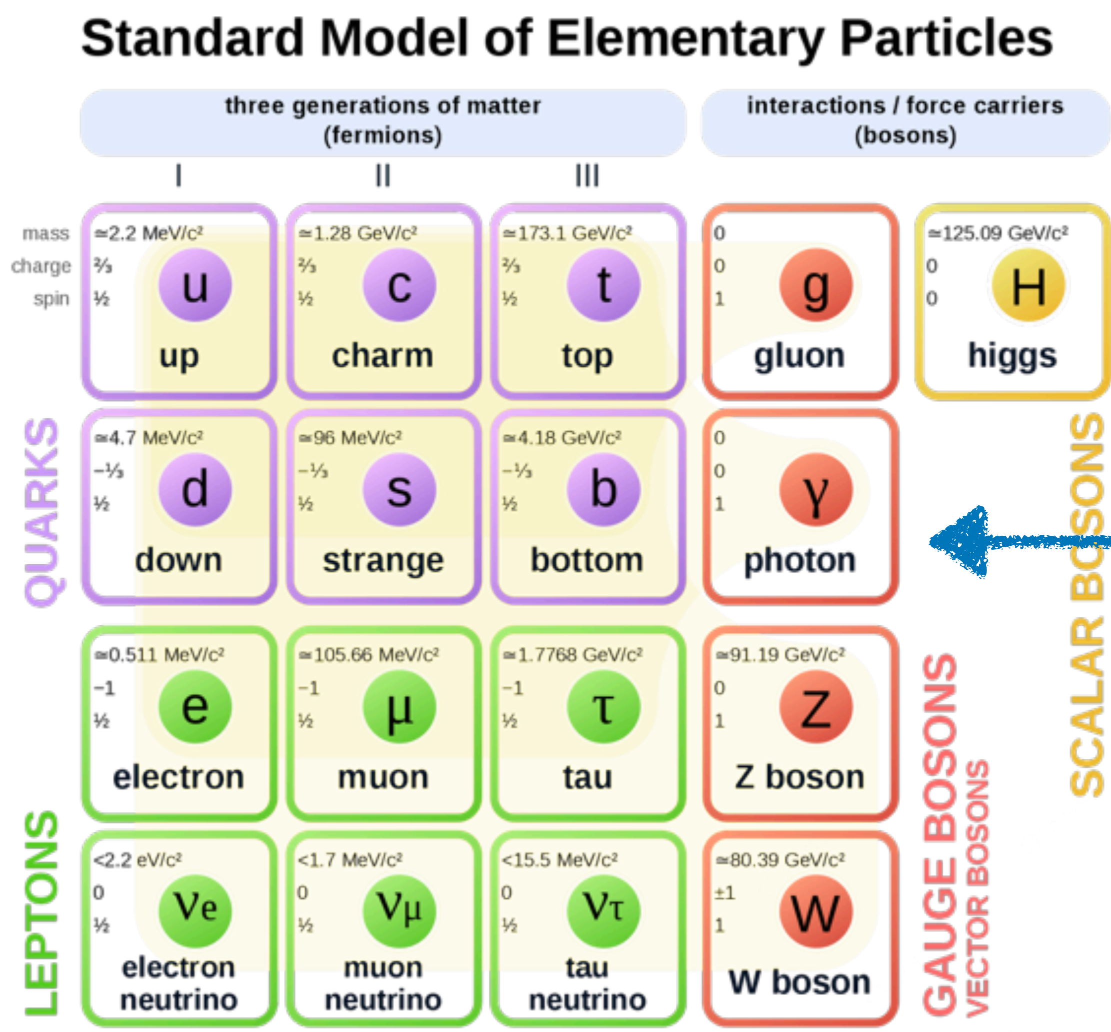


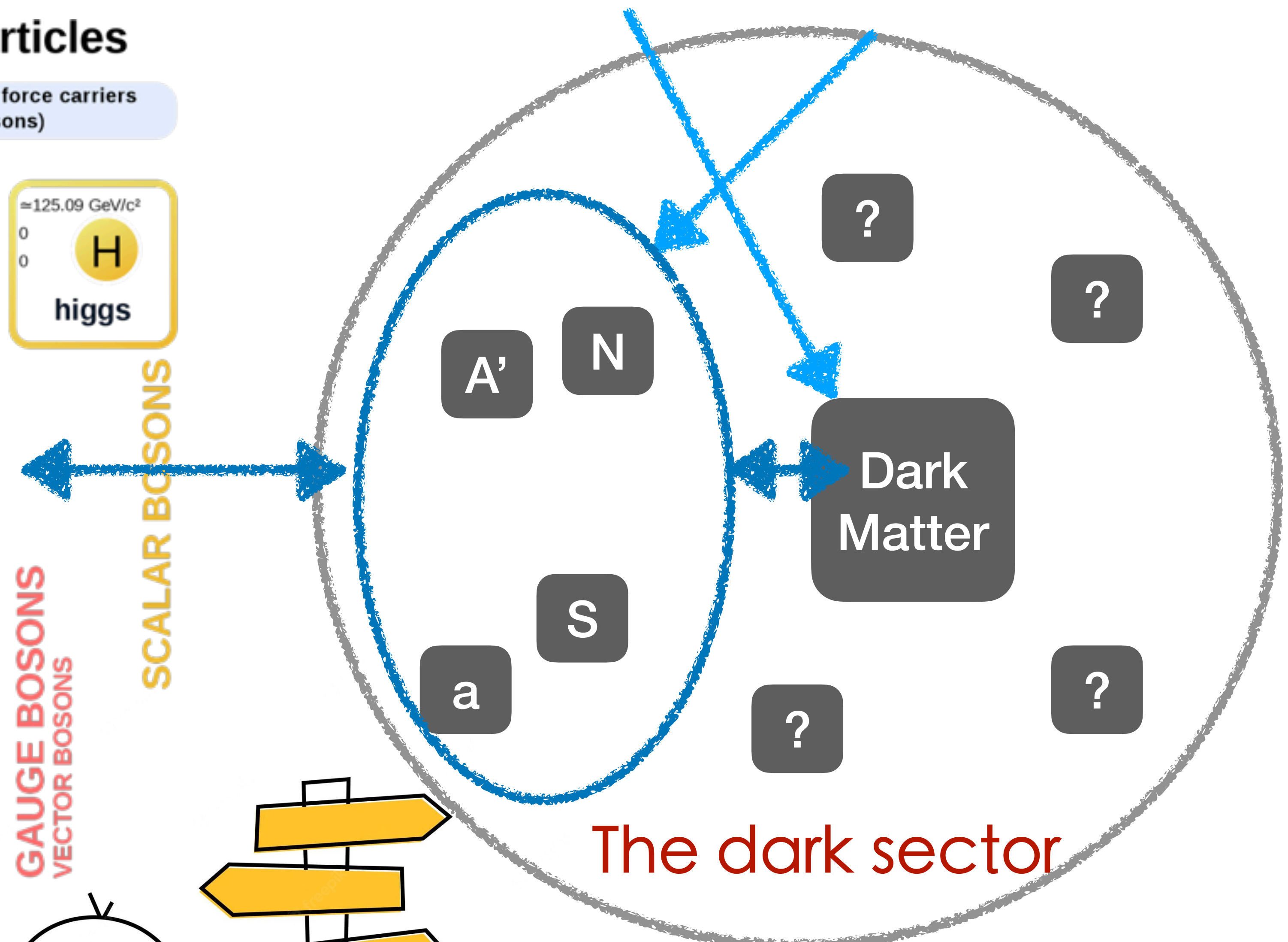
Credit: Tao Han

We are at a cross road

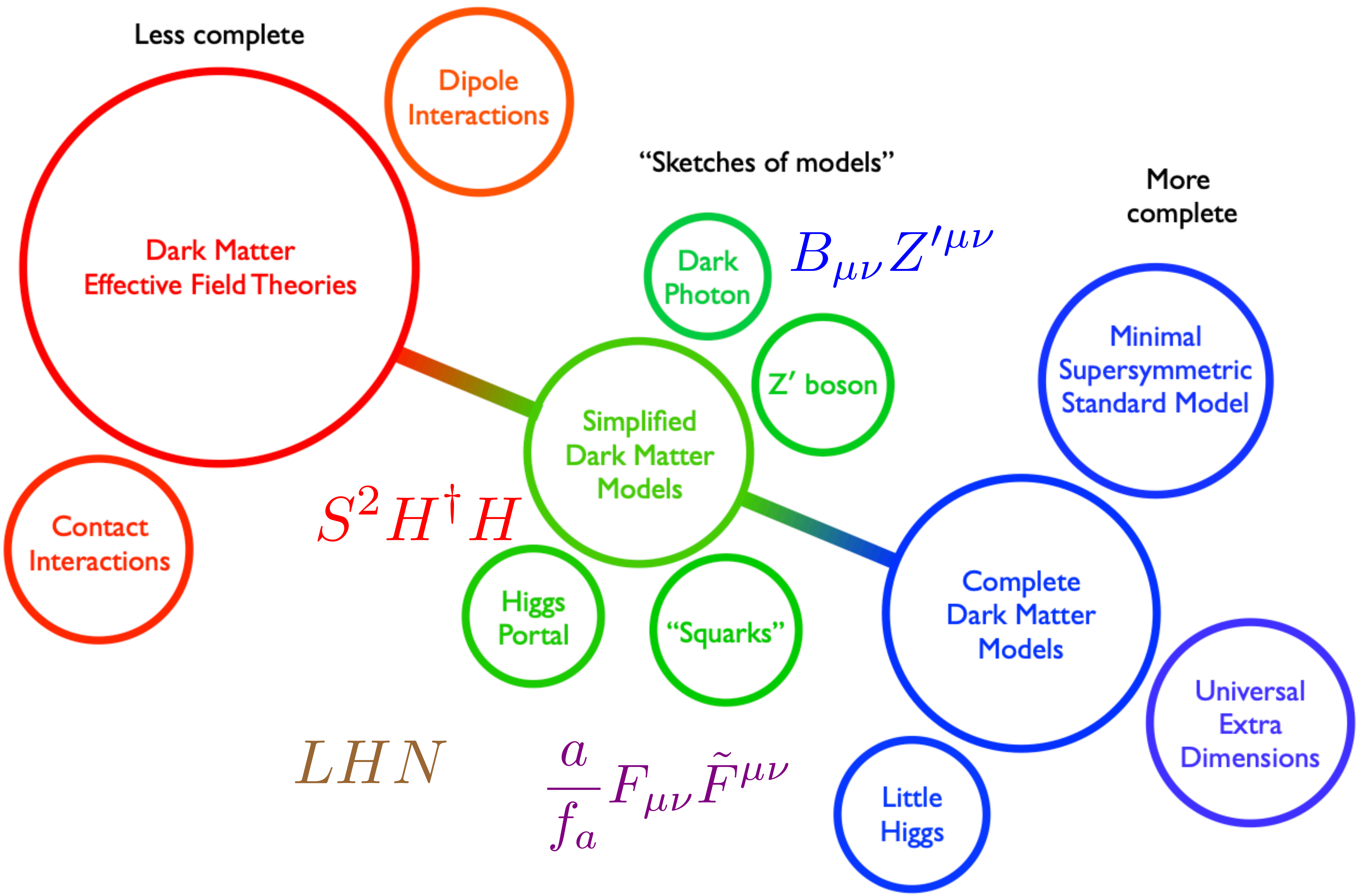
- Standard Model
  =fermions+force

- Dark sector
  =DM+dark





New Physics related to dark sector



Future lepton collider

	Hadron Collider	Lepton Collider
Signal	MET+X	MET+(X)
Control C.M. Energy	No	Yes
MET reconstruction	No	Yes
Background	Huge	Small
EWPT	Reasonable	Extreme

Outline

- A’ search at e-e+ collider
- Higgs Portal search at e-e+ collider
- ALP for muon g-2 tested at e+e- collider
- Summary

Vector Portal DM

✤ Vector Portal Lagrangian

$$\mathcal{L} = -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}A'_{\mu\nu}A'^{\mu\nu} + \frac{\epsilon}{2c_W}B_{\mu\nu}A'^{\mu\nu} + \frac{1}{2}m_{A'}^2 A'^{\mu}A'_{\mu}$$

$\tilde{\phi}$

✤ Vector Mixing

$$\begin{pmatrix} Z_\mu \\ A_\mu \\ A'_\mu \end{pmatrix} = \begin{pmatrix} 1 & 0 & \frac{m_{A'}^2 t_W}{-m_{A'}^2 + m_Z^2}\epsilon \\ 0 & 1 & \epsilon \\ \frac{m_Z^2 t_W}{m_{A'}^2 - m_Z^2}\epsilon & 0 & 1 \end{pmatrix} \begin{pmatrix} \tilde{Z}_\mu \\ \tilde{A}_\mu \\ \tilde{A}'_\mu \end{pmatrix}$$

✤ Interaction

$$\mathcal{L}_{\text{int}} = \tilde{Z}_\mu \left(g J_Z^\mu - g_D \frac{m_Z^2 t_W}{m_Z^2 - m_{A'}^2}\epsilon J_D^\mu \right) + \tilde{A}'_\mu \left(g_D J_D^\mu + g \frac{m_{A'}^2 t_W}{m_Z^2 - m_{A'}^2}\epsilon J_Z^\mu + e\epsilon J_{\text{em}}^\mu \right)$$

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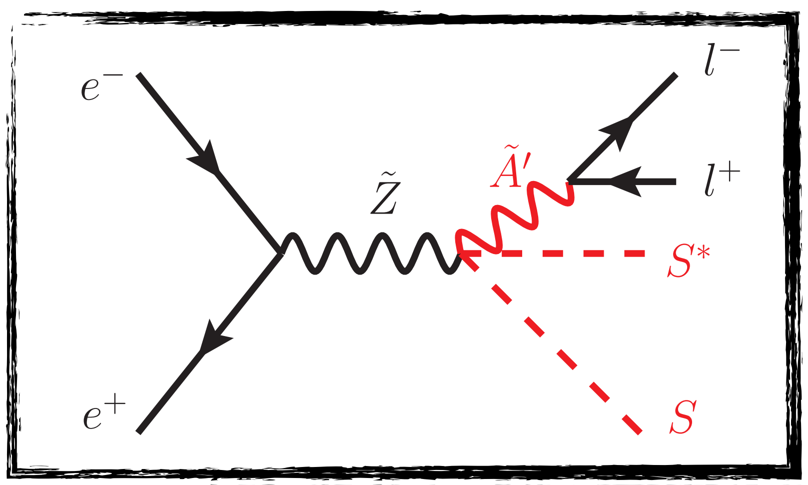
Vector Portal DM

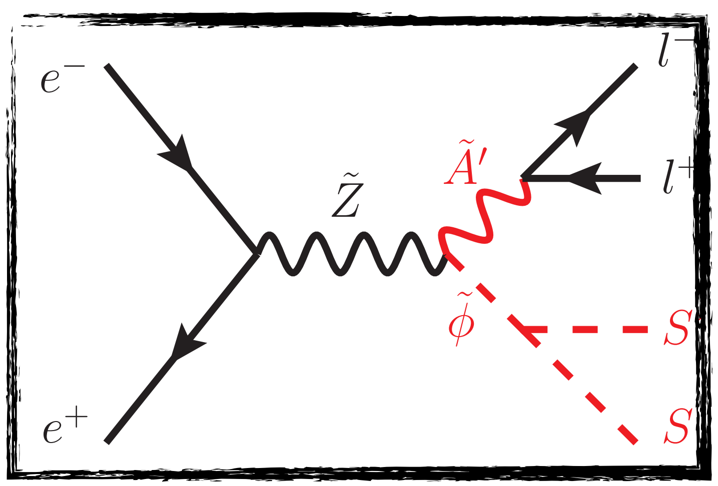
- **Complex scalar DM Lagrangian:**

$$\mathcal{L}_S = (\partial_\mu S + i g_D A'_\mu S)^* (\partial^\mu S + i g_D A'^\mu S) - m_S^2 S^* S$$

$$g_D^2 S^* S(\tilde{A}'_\mu + \epsilon \frac{m_Z^2 t_W}{(m_{A'}^2 - m_Z^2)} \tilde{Z}_\mu)^2$$

- **Dark Sector Search @ Z factory**





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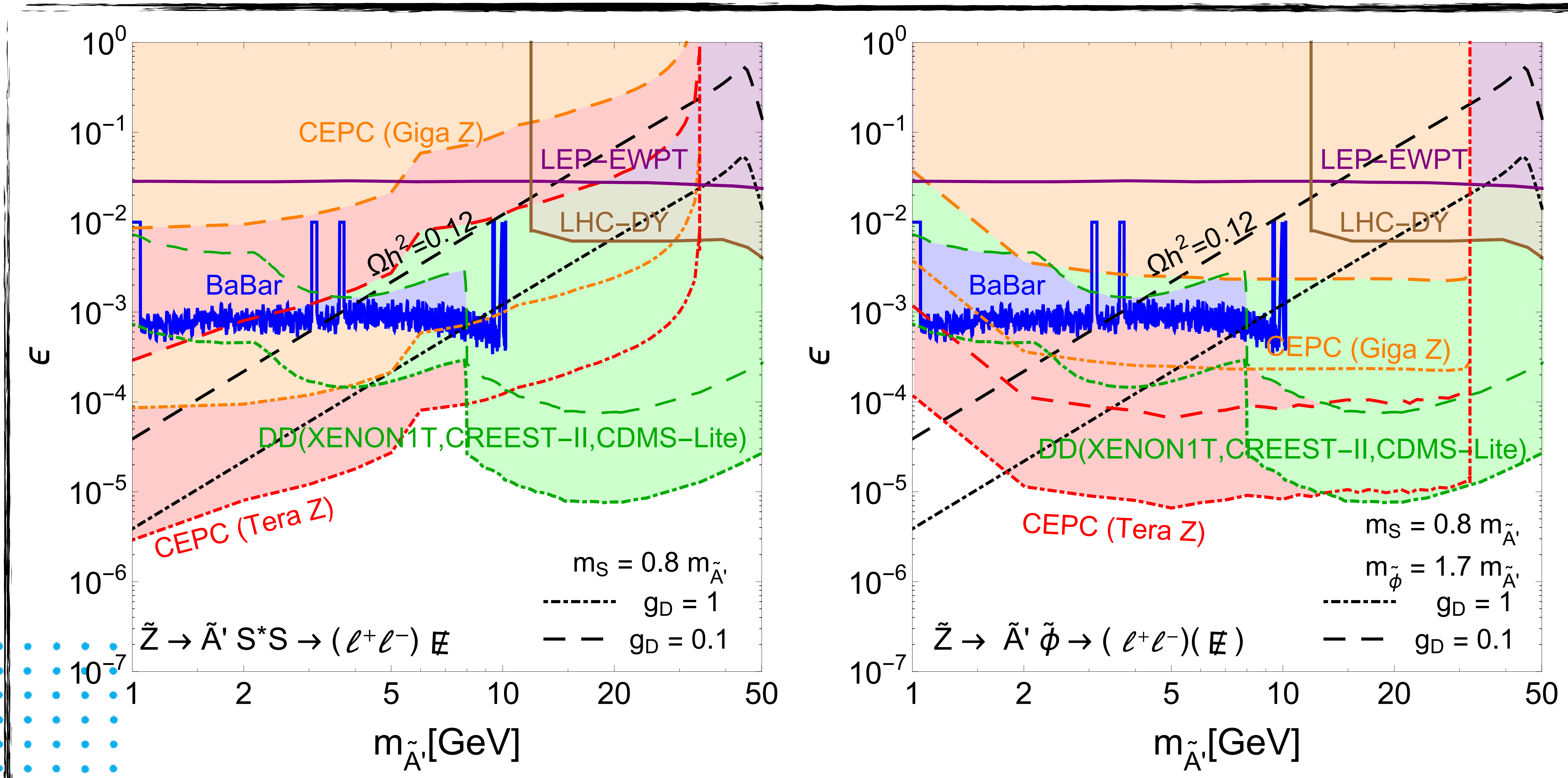
Phys.Rev.D 97 (2018) 9

Vector Portal DM

✤ Constraint results



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Outline

- A’ search at e-e+ collider
- Higgs Portal search at e-e+ collider
- ALP for muon g-2 tested at e+e- collider
- Summary

Higgs Portal DM

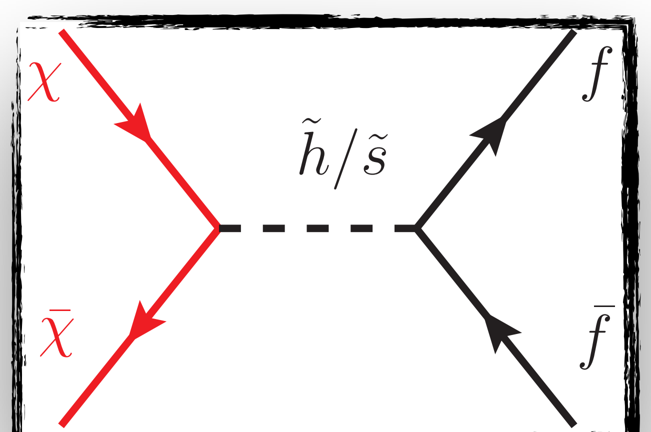
- **Higgs Portal Lagrangian:**

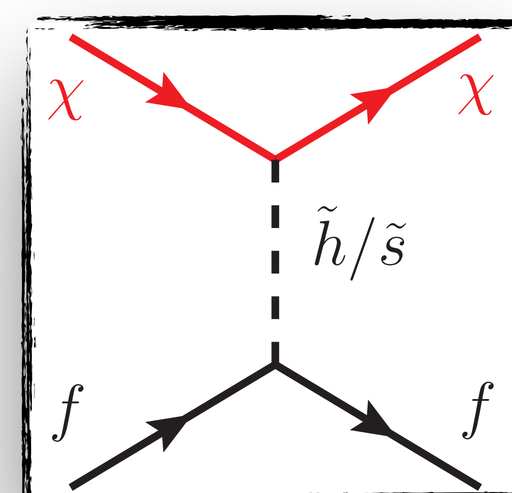
$$\mathcal{L} = \frac{1}{2}\partial_\mu S \partial^\mu S - \lambda_1 \left(H^\dagger H\right) S - \lambda_2 \left(H^\dagger H\right) S^2 + \bar{\chi}\left(i\partial^\mu \gamma_\mu - m_\chi^0\right)\chi - y_\chi S \bar{\chi}\chi + \ldots\ldots$$

- **Scalar Mixing**

$$\begin{pmatrix} \tilde{h} \\ \tilde{s} \end{pmatrix} = \begin{pmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} h \\ s \end{pmatrix}$$

- **Relic abundance and Direct detection**





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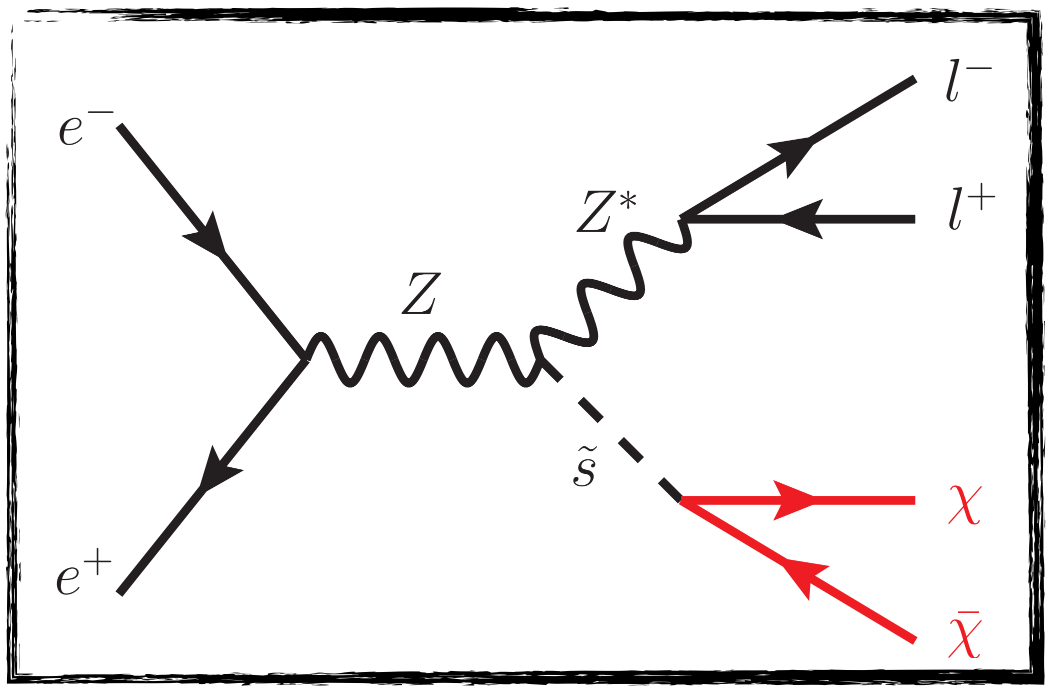
Phys.Rev.D 97 (2018) 9

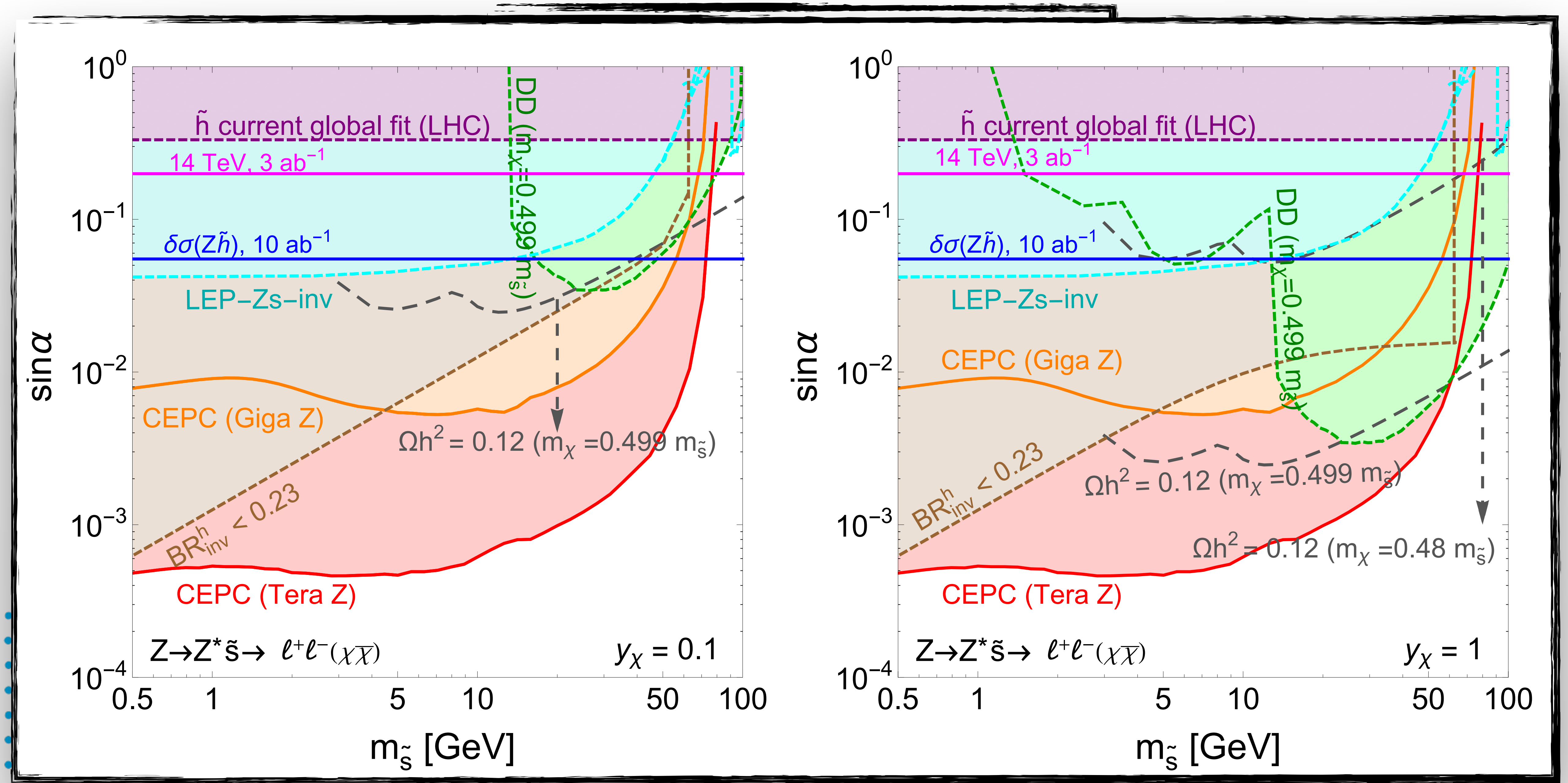
Higgs Portal DM

✤ Z factory Search



Higgs Portal DM

✤ Z factory Search



Vector+ Higgs Portal

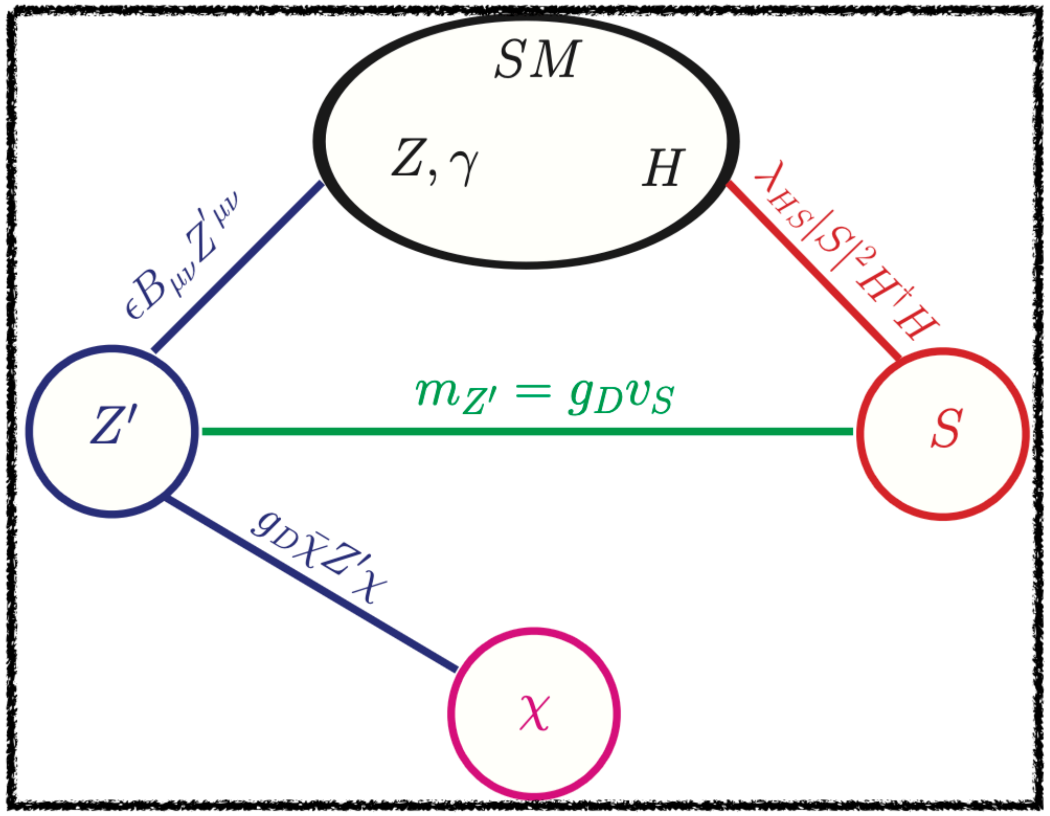
Dark Portal:

★ Vector Portal: $B_{\mu\nu}Z'^{\mu\nu}$

★ Higgs Portal: $S^2 H^\dagger H$

★ Axion portal: $\frac{a}{f_a}F_{\mu\nu}\tilde{F}^{\mu\nu}$

★ Neutrino Portal: LHN



UV complete model

$$\mathscr{L} \supset -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}W^{i}_{\mu\nu}W^{i,\mu\nu} - \frac{1}{4}K_{\mu\nu}K^{\mu\nu} + \frac{\epsilon}{2\cos\theta_W}B_{\mu\nu}K^{\mu\nu}$$

$$+\left|D_\mu H\right|^2 + \mu_H^2|H|^2 - \lambda_H|H|^4 + \left|D_\mu \Phi\right|^2 + \mu_D^2|\Phi|^2 - \lambda_D|\Phi|^4 - \lambda_{HP}|H|^2|\Phi|^2$$

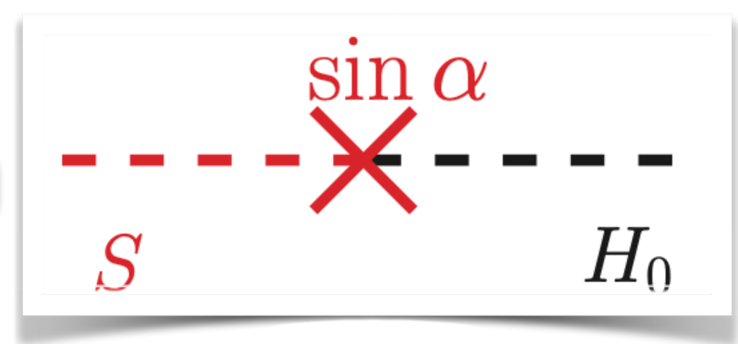
$$+\bar{\chi}\left(i\gamma^\mu D_\mu - m_\chi\right)\chi$$

$$\mathscr{L} \supset m_{Z,\mathrm{SM}}^2\frac{\cos\alpha}{v_H}\tilde{Z}_\mu\tilde{Z}^\mu H_0 - m_{\tilde{K}}^2\frac{\sin\alpha}{v_D}\tilde{K}_\mu\tilde{K}^\mu H_0$$

$$+2\epsilon t_W\frac{m_{\tilde{K}}^2 m_{Z,\mathrm{SM}}^2}{\left(m_{Z,\mathrm{SM}}^2 - m_{\tilde{K}}^2\right)}\left(\frac{\cos\alpha}{v_H} + \frac{\sin\alpha}{v_D}\right)\tilde{Z}_\mu\tilde{K}^\mu H_0$$

$$+m_{Z,\mathrm{SM}}^2\frac{\sin\alpha}{v_H}\tilde{Z}_\mu\tilde{Z}^\mu S + m_{\tilde{K}}^2\frac{\cos\alpha}{v_D}\tilde{K}_\mu\tilde{K}^\mu S$$

$$+2\epsilon t_W\frac{m_{\tilde{K}}^2 m_{Z,\mathrm{SM}}^2}{\left(m_{Z,\mathrm{SM}}^2 - m_{\tilde{K}}^2\right)}\left(-\frac{\cos\alpha}{v_D} + \frac{\sin\alpha}{v_H}\right)\tilde{Z}_\mu\tilde{K}^\mu S$$



Mass Hierarchy:

$$m_\chi < \frac{m_{\tilde{K}}}{2} < \frac{m_S}{4} < \frac{m_{H_0}}{8}$$

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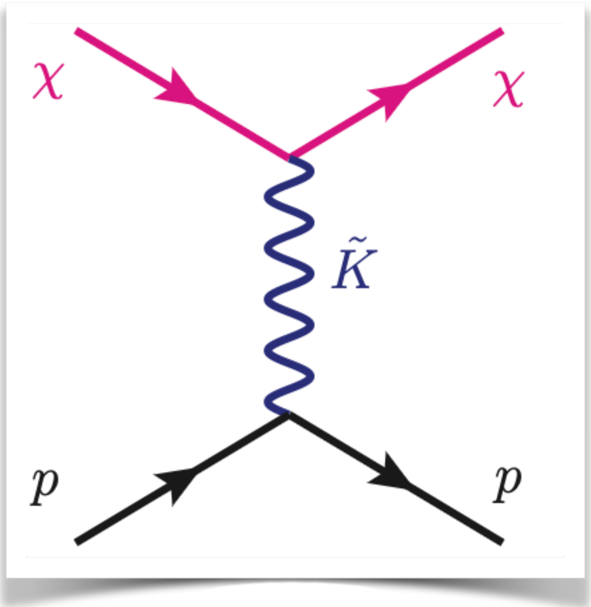
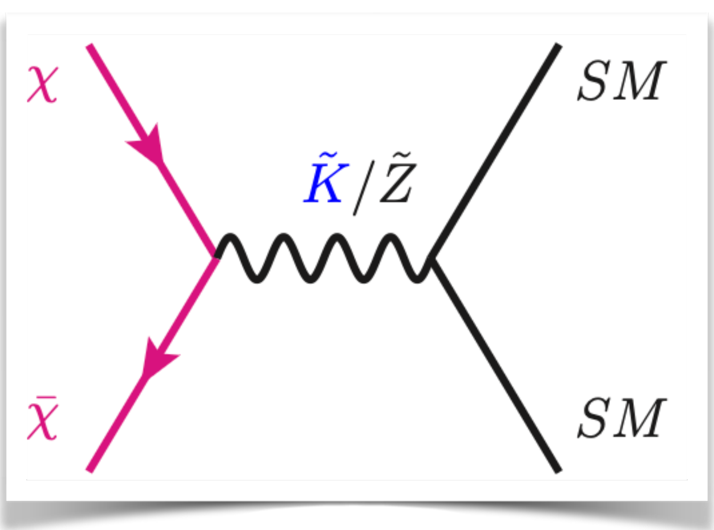
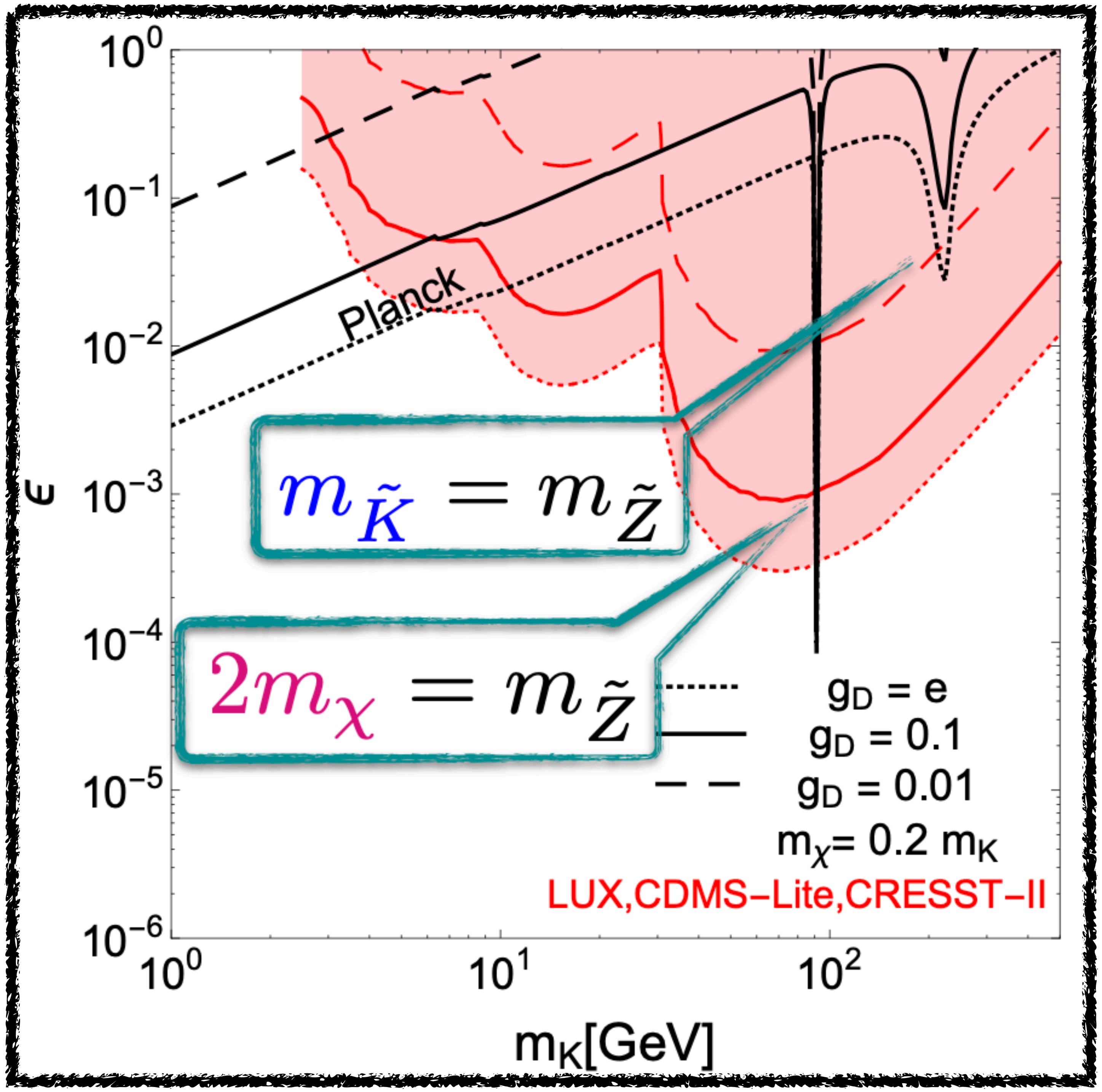
DM direct detection

Direct Detection:



Annihilation





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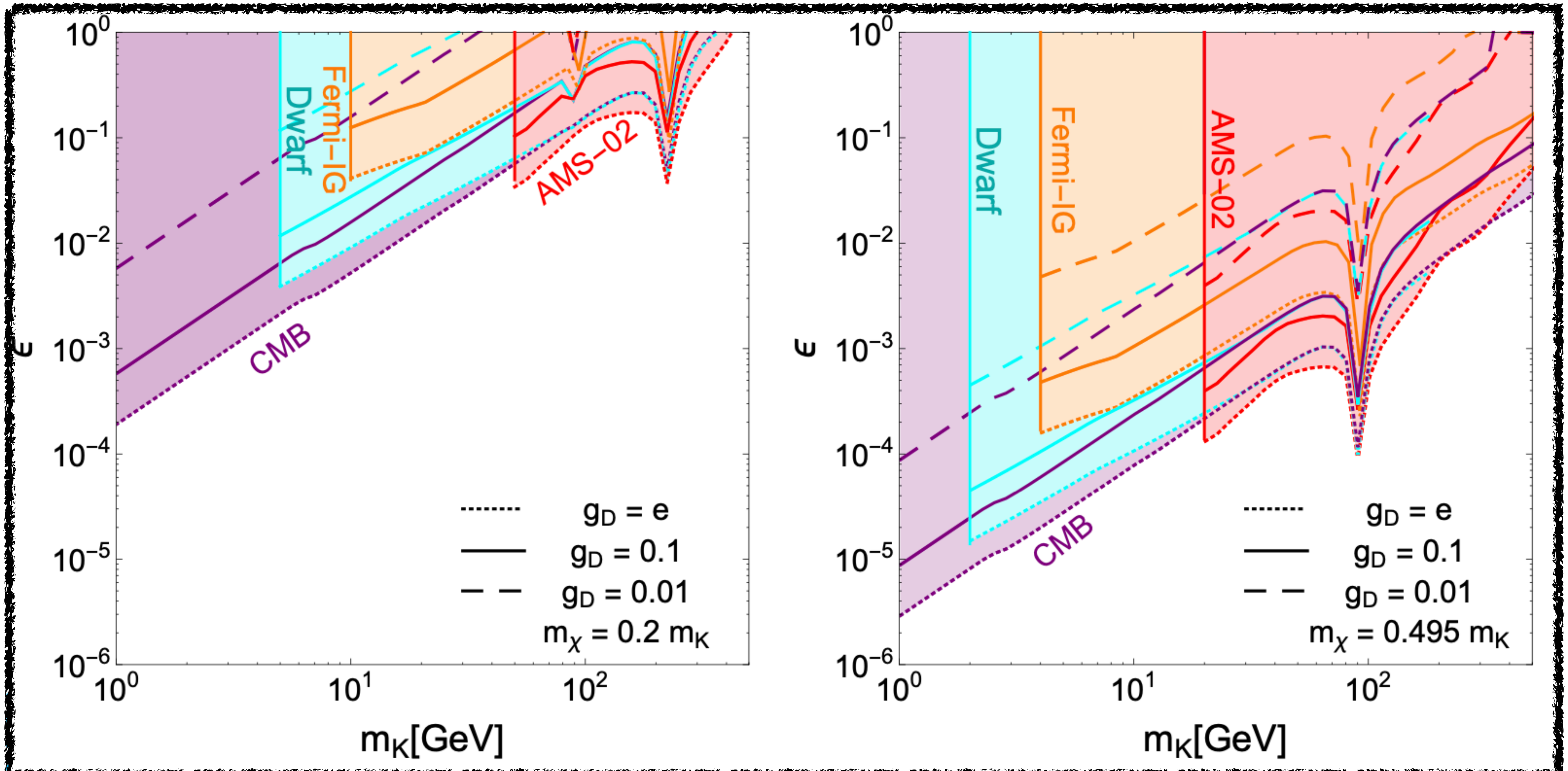
DM indirect detection



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Collider search

Pheno	$\sin\alpha$	ϵ
Electroweak Precision	$e^+e^- \to \tilde{Z}S$ LEP	$e^+e^- \to f\bar{f}$ LEP
Higgs	$H_0 \to SS \to 4(\chi\bar{\chi})$, $H_0 \to \tilde{K}\tilde{K} \to 2(\chi\bar{\chi})$ LHC	
Drell-Yan		$p\bar{p} \to \tilde{Z}, \tilde{K} \to l^+l^-$ LHC
Radiative		$e^+e^- \to \tilde{A}\tilde{K}$ Babar

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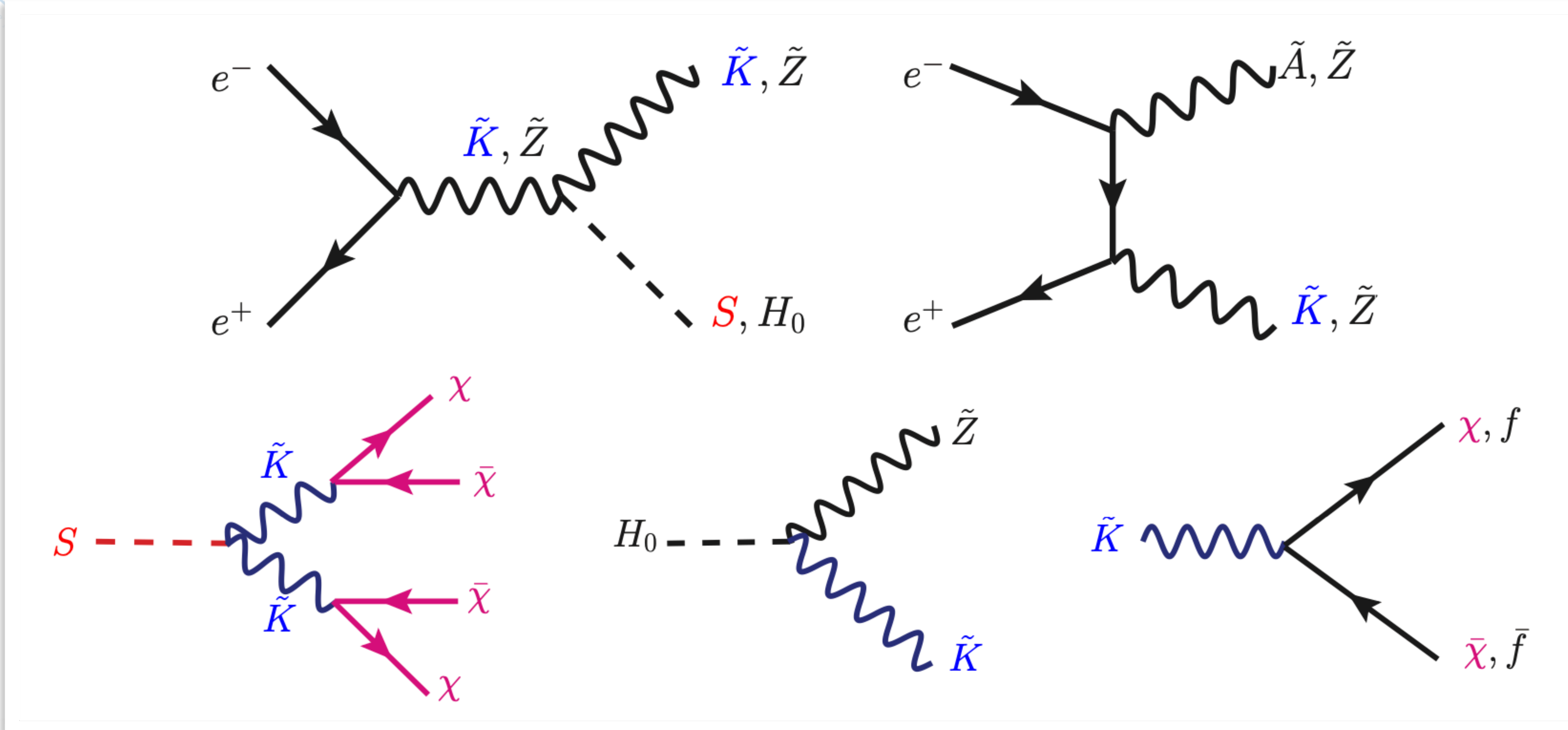
Prospects for Higgs factory



$$m_X = \sqrt{s + m_Y^2 - 2E_Y\sqrt{s}}$$

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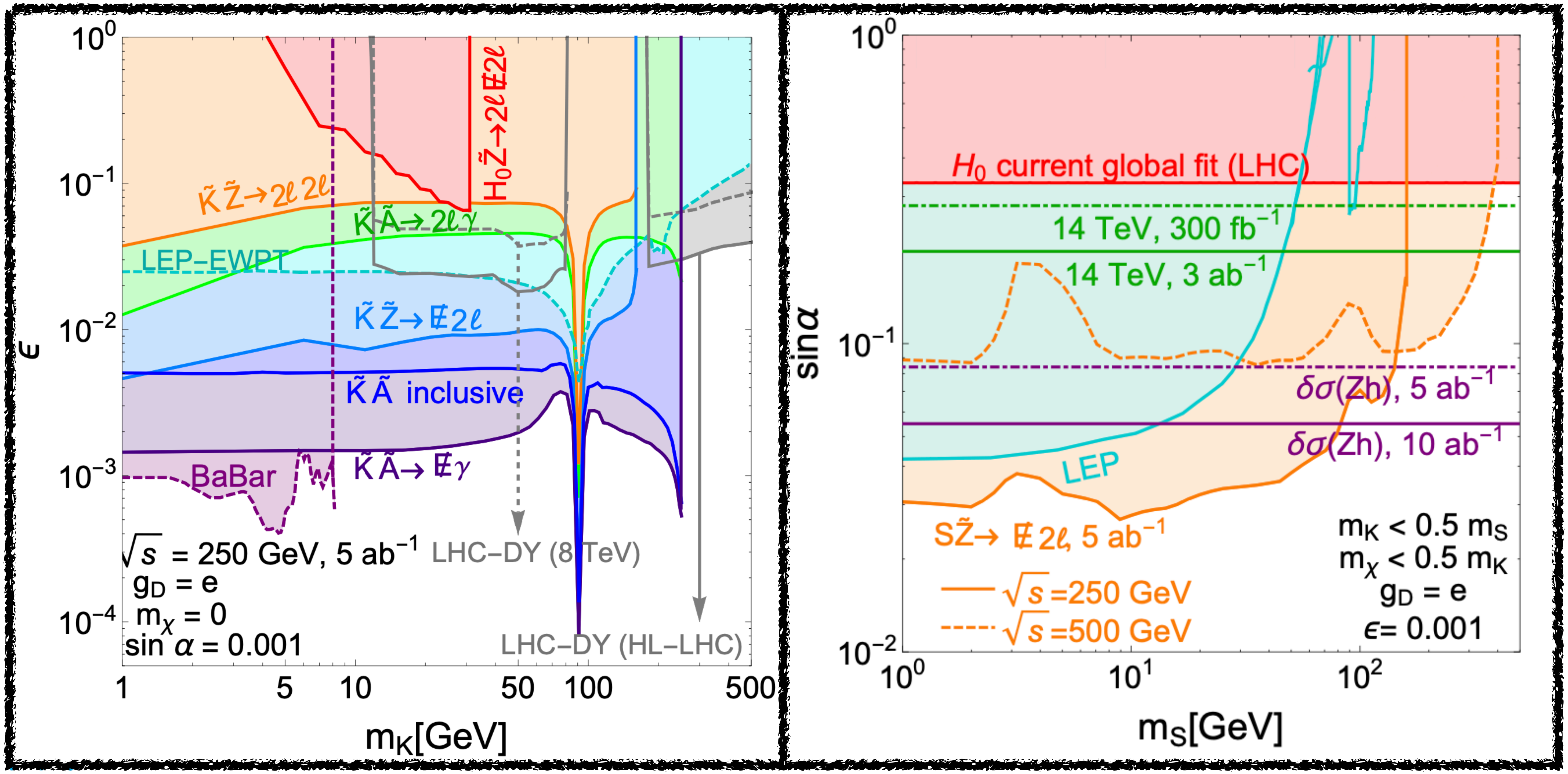
Prospects for CEPC



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Outline

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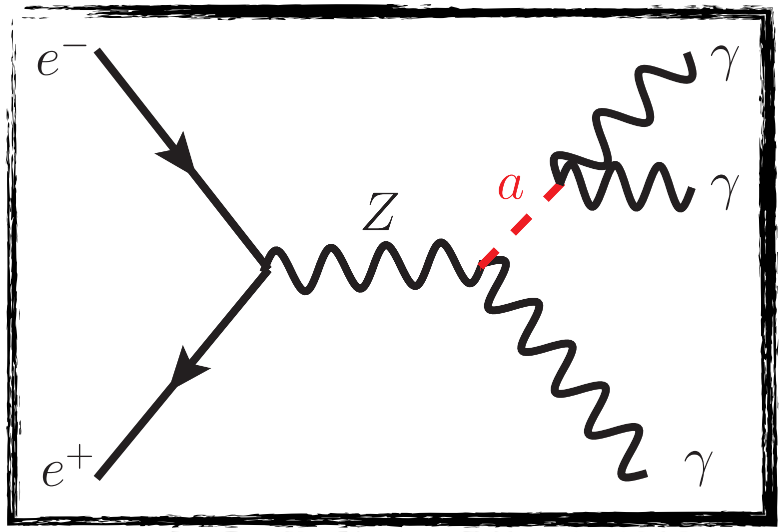
- **Summary**

Axion-like Particle

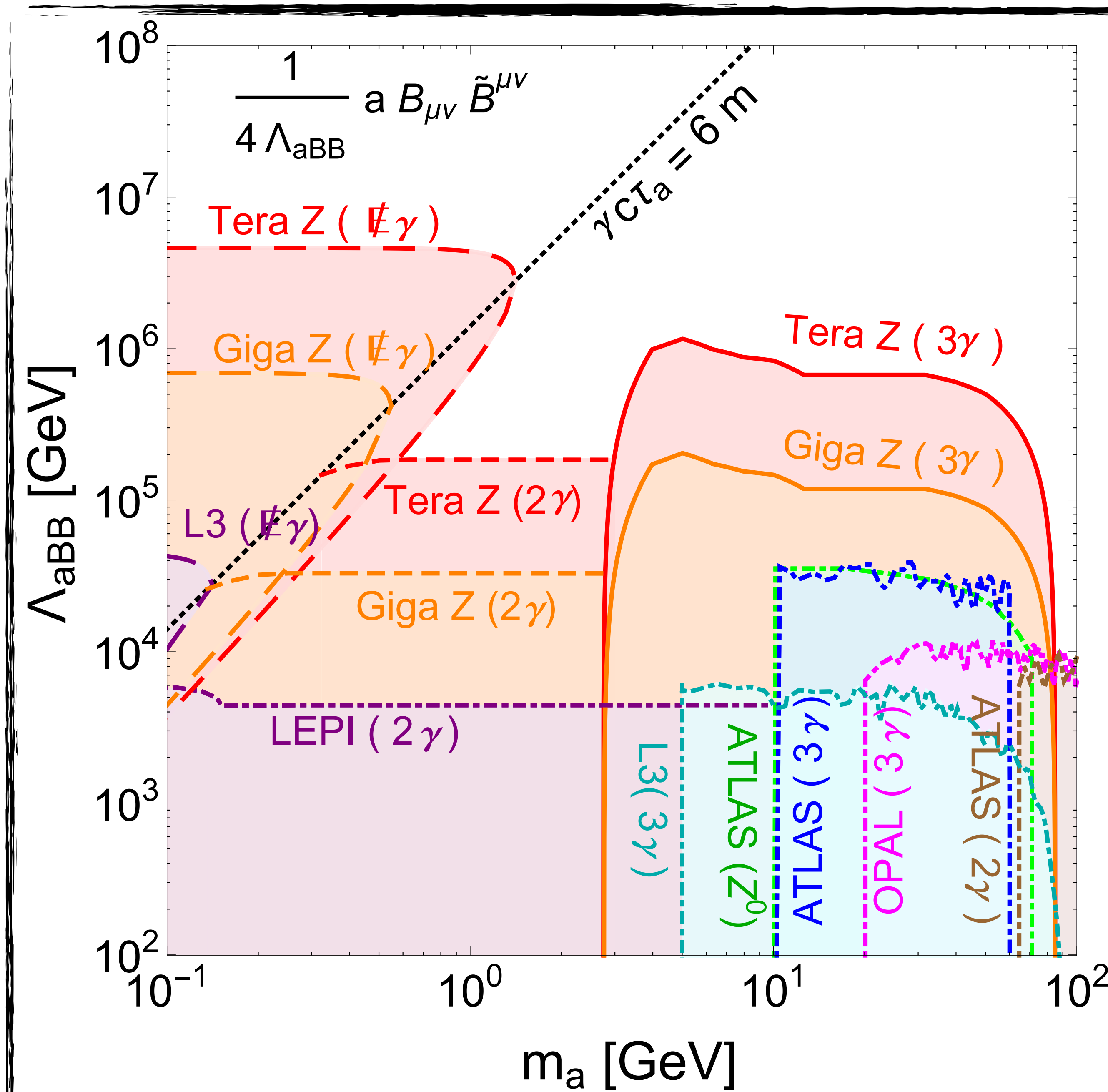
✤ Lagrangian:

$$\mathcal{L}_{\rm ALP} = \frac{1}{4\Lambda_{aBB}} a B_{\mu\nu}\tilde{B}^{\mu\nu}$$

✤ Search @ Z factory



✤ Constraints



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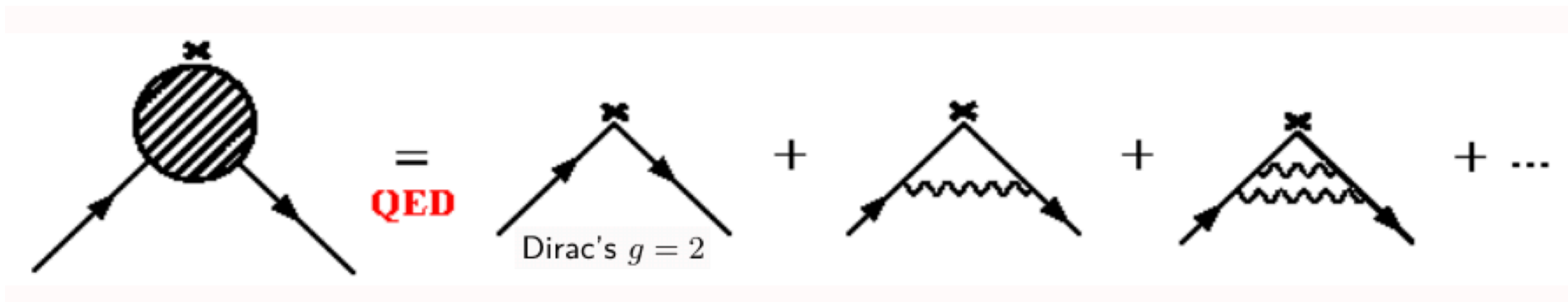
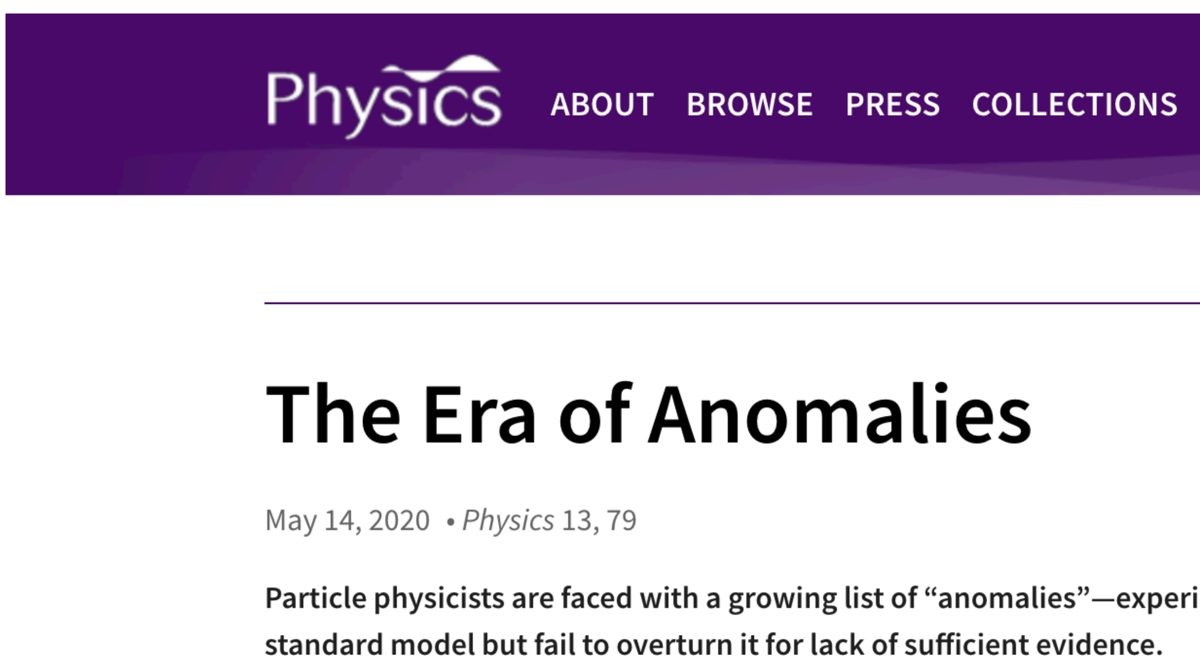
Introduction to g-2

Anomalous magnetic moment of the lepton



Positive value and a 4.2 σ (Fermilab + Brookhaven)

$$\Delta a_\mu = a_\mu^{\text{exp}} - a_\mu^{\text{th}} = (25.1 \pm 5.9) \times 10^{-10}$$

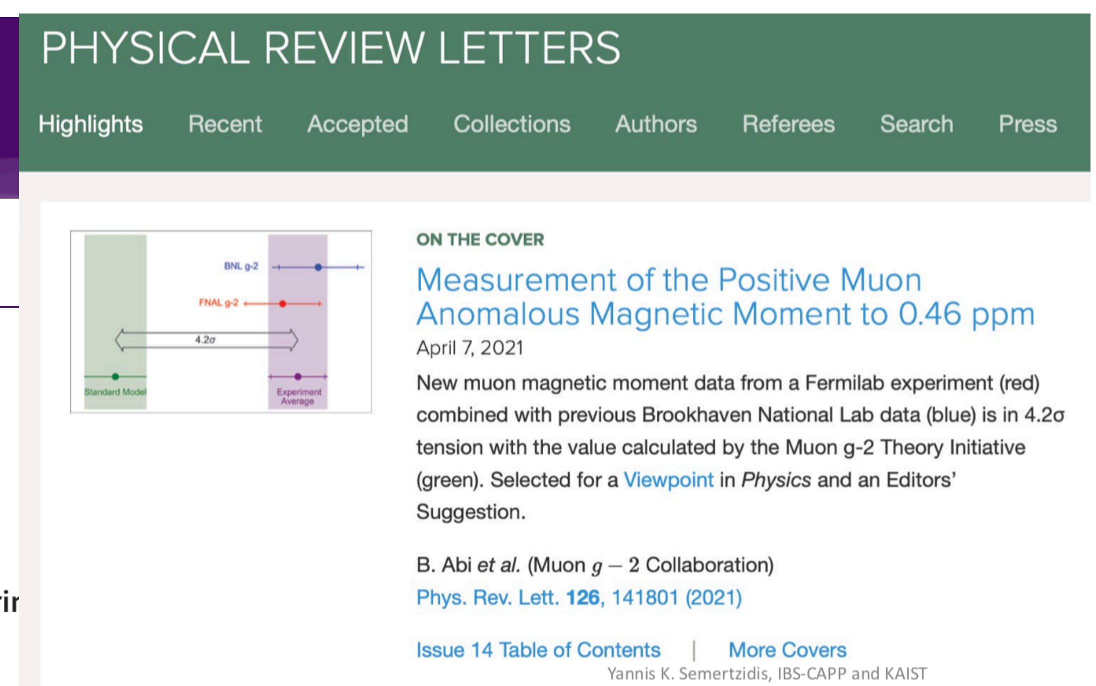


Physics ABOUT BROWSE PRESS COLLECTIONS

The Era of Anomalies

May 14, 2020 • *Physics* 13, 79

Particle physicists are faced with a growing list of "anomalies"—experir
standard model but fail to overturn it for lack of sufficient evidence.



PHYSICAL REVIEW LETTERS

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ON THE COVER

Measurement of the Positive Muon Anomalous Magnetic Moment to 0.46 ppm

April 7, 2021

New muon magnetic moment data from a Fermilab experiment (red) combined with previous Brookhaven National Lab data (blue) is in 4.2σ tension with the value calculated by the Muon g-2 Theory Initiative (green). Selected for a Viewpoint in *Physics* and an Editors' Suggestion.

B. Abi *et al.* (Muon $g-2$ Collaboration)

Phys. Rev. Lett. **126**, 141801 (2021)

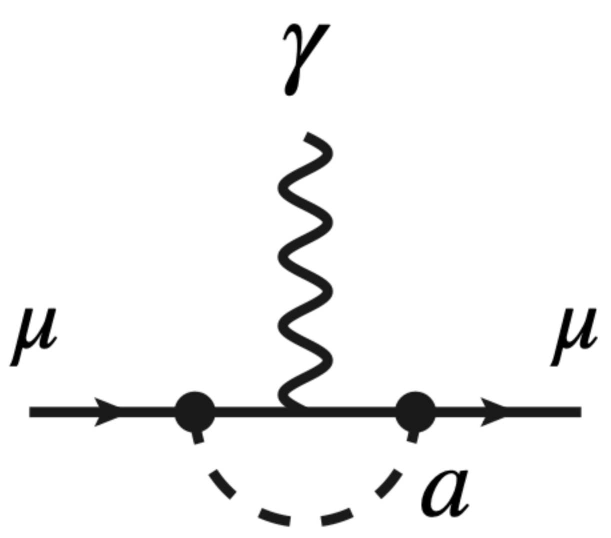
Issue 14 Table of Contents | More Covers

Yannis K. Semertzidis, IBS-CAPP and KAIST

The Scalar for Muon g-2

The (pseudo)scalar Yukawa coupling to lepton

$$\mathscr{L}_{\text{yuk}} = \phi\bar{\ell}\left(g_R + i g_I \gamma_5\right)\ell$$



The 1-loop contribution to g-2

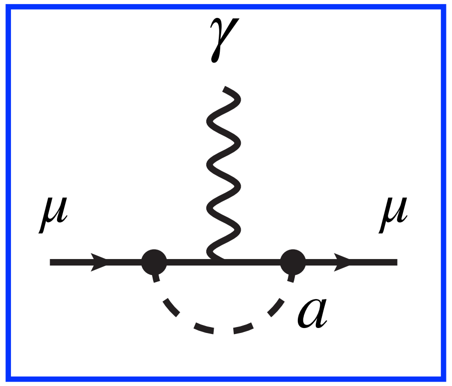
$$\Delta a_\ell = \frac{1}{8\pi^2}\int_0^1 dx \frac{(1-x)^2\left((1+x)g_R^2 - (1-x)g_I^2\right)}{(1-x)^2 + x\left(m_\phi/m_\ell\right)^2}$$

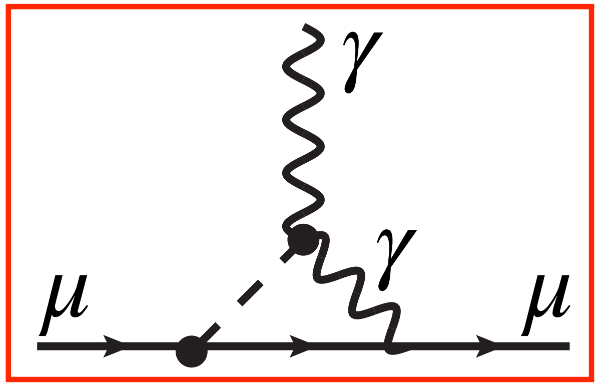
- For scalar, $\Delta a_\ell > 0$
- For (psudo)scalar, $\Delta a_\ell < 0$

The pseudo-scalar solution

Further requirement for pseudo-scalar

$$\mathscr{L} = i y_{a\psi} a \bar{\psi} \gamma_5 \psi + \frac{1}{4} g_{a\gamma\gamma} a \tilde{F} F$$





- Assumes $g_{a\gamma\gamma}$ remains essentially constant throughout the integration over virtual photon-loop momentum
- $g_{a\gamma\gamma}$ and $y_{a\ell}$ can adjust its sign to give positive result

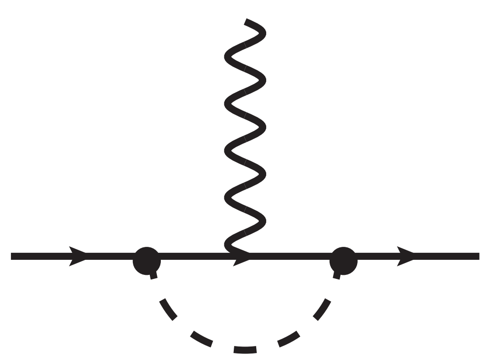
Complete calculation for ALP

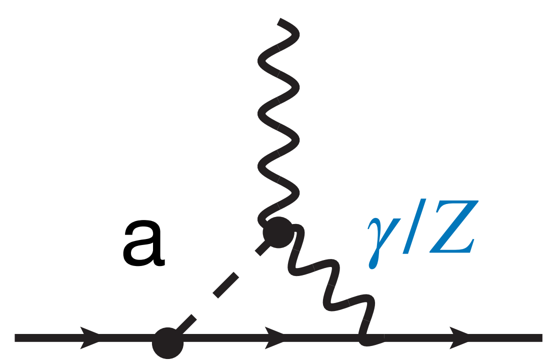
The axion-like particle Lagrangian

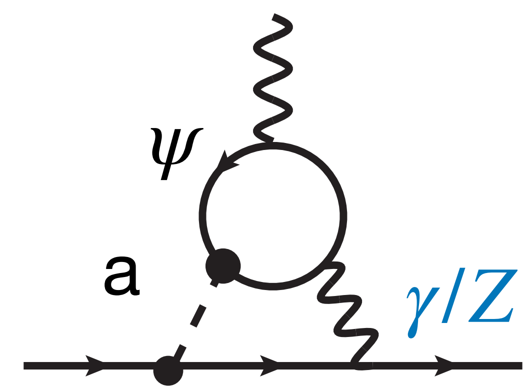
$$\mathscr{L}_{\text{eff}}^{D\le 5} = \sum_f \frac{C_{ff}}{2}\frac{\partial^\mu a}{f_a}\bar{f}\gamma_\mu\gamma_5 f + \frac{\alpha C_{\gamma\gamma}}{4\pi}\frac{a}{f_a}F_{\mu\nu}\tilde{F}^{\mu\nu} + \frac{\alpha C_{\gamma Z}}{2\pi s_w c_w}\frac{a}{f_a}F_{\mu\nu}\tilde{Z}^{\mu\nu} + \frac{\alpha C_{ZZ}}{4\pi s_w^2 c_w^2}\frac{a}{f_a}Z_{\mu\nu}\tilde{Z}^{\mu\nu}$$

$$+\frac{\alpha C_{WW}}{\pi s_w^2}\frac{a}{f_a}\epsilon_{\mu\nu\rho\sigma}\partial^\mu W_+^\nu \partial^\rho W_-^\sigma + \dots$$

$C_{\gamma\gamma} = C_{WW} + C_{BB}$ $\quad$ $C_{\gamma Z} = c_w^2 C_{WW} - s_w^2 C_{BB}$ $\quad$ $C_{ZZ} = c_w^4 C_{WW} + s_w^4 C_{BB}$





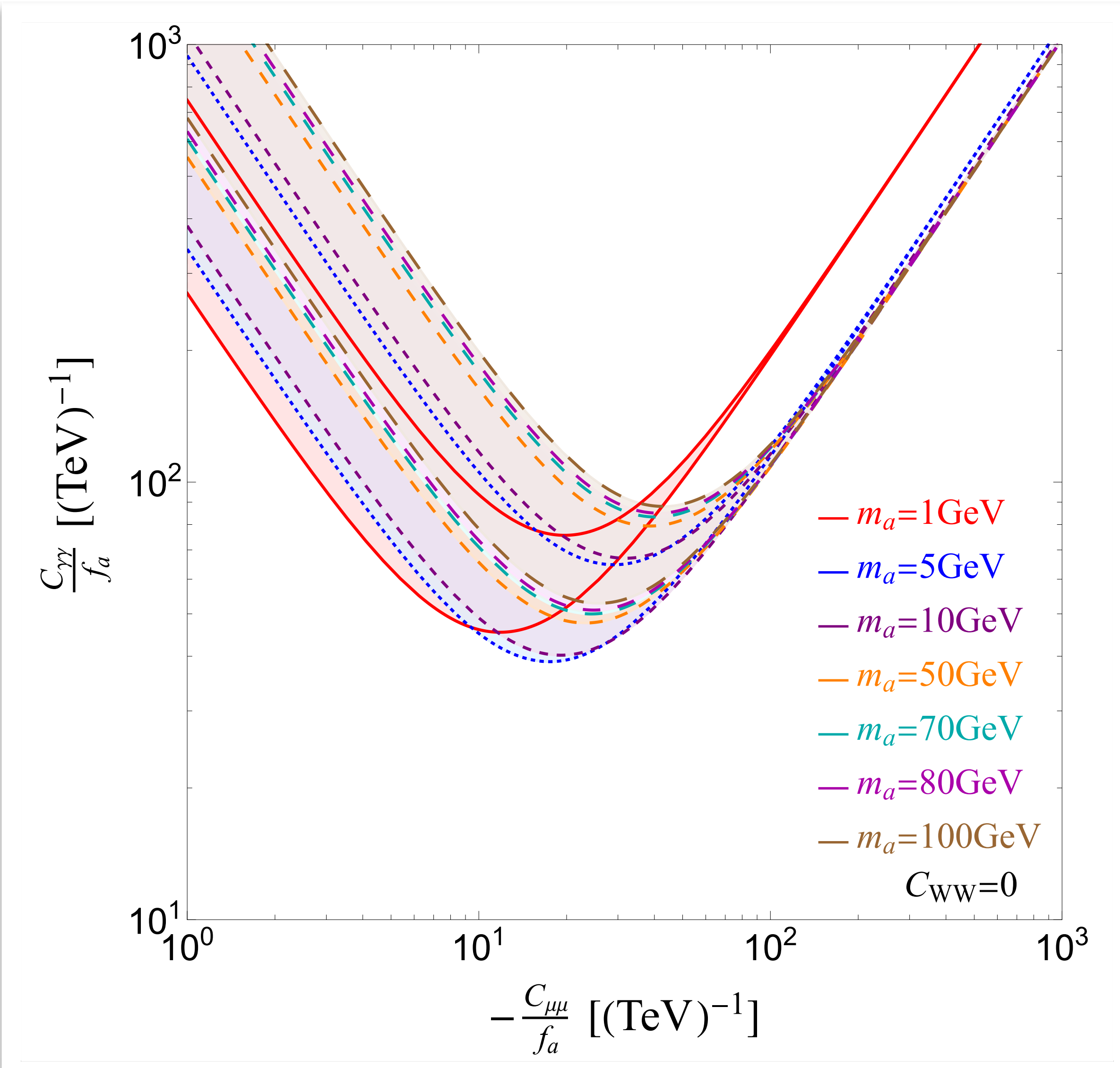


$$\Delta a_{2Z} = \frac{\alpha c_{\gamma z} c_{\mu\mu} m_\mu^2 \left(4s_w^2 - 1\right)}{32\pi^3 c_w^2 s_w^2 f_a^2} \cdot h_Z(x, y, \mu)$$

$m_\psi \to \infty,\ \Delta a_3 \to 0$

$$\Delta a_{3Z} = -\frac{\alpha c_{\mu\mu}^2 m_\mu^2 \left(4s_w^2 - 1\right)^2}{128\pi^3 c_w^2 s_w^2 f_a^2}\left[H_Z(\textbf{two loop}) + h_Z(\textbf{counter term})\right]$$

Muon g-2 solution $C_{ww} = 0$

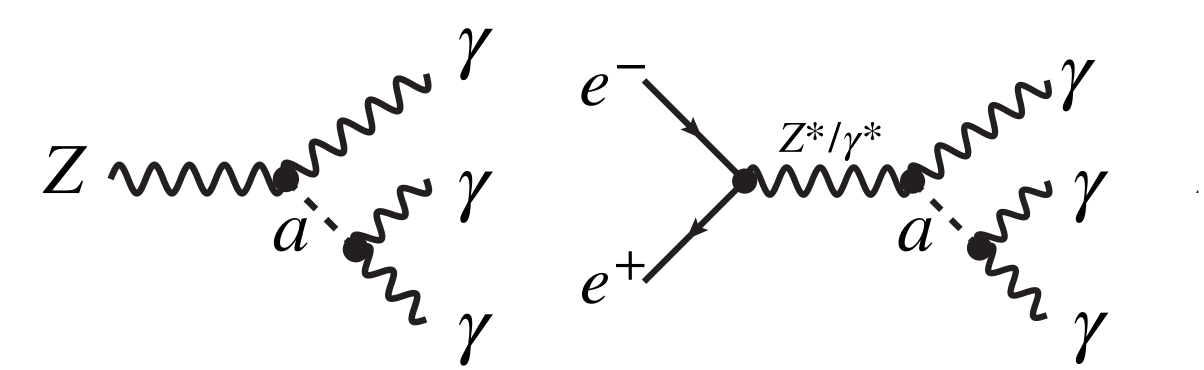


- In g-2 solution region, mostly decay to $a \to \mu^+\mu^-$
- The inclusion of Z diagram makes some difference for large m_a
- Exotic Z decay should happen

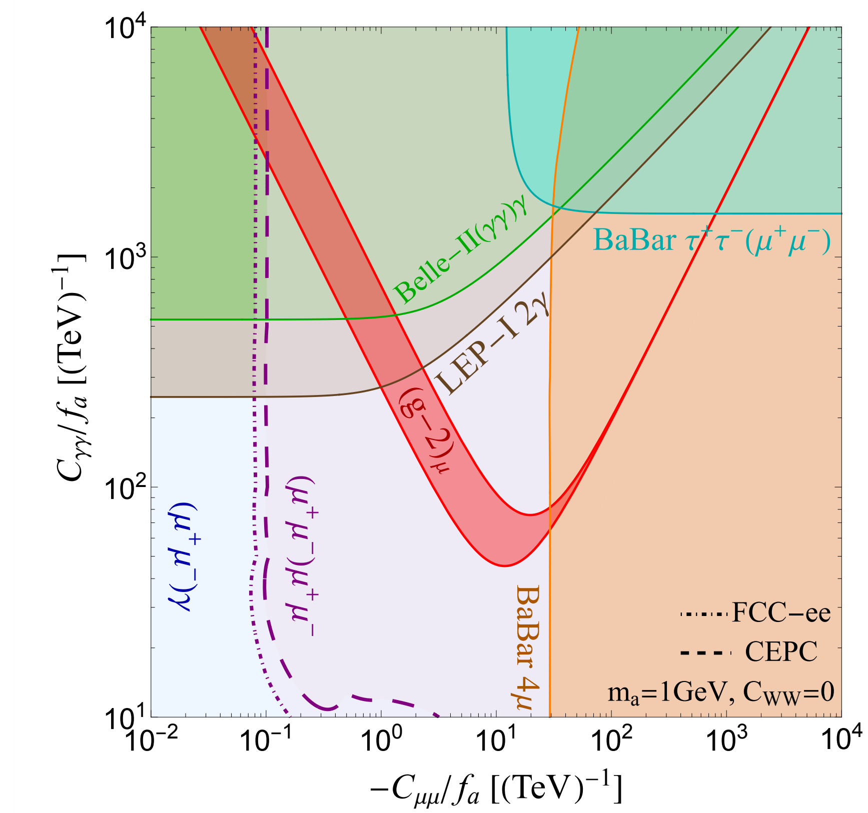
J.L, X.-L.M,L-T.W, ***X-P,Wang,*** *arXiv:2210.09335*

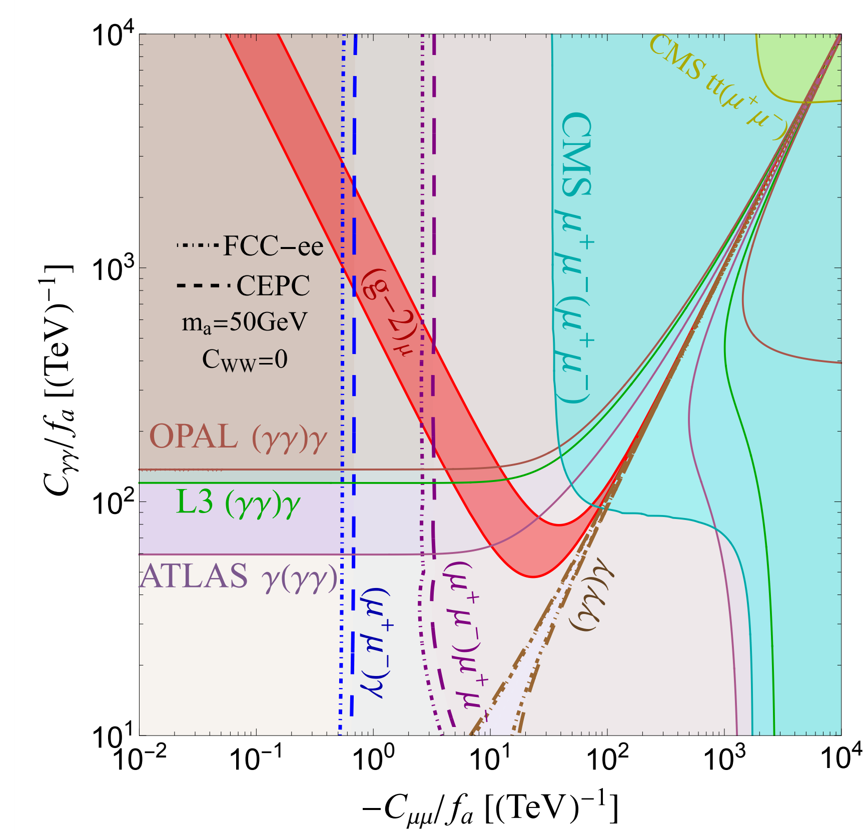
Existing constraints $C_{ww} = 0$

- Constraining a-γ coupling only:
  - Belle-II, LEP:
    $e^+e^- \to a\gamma \to (\gamma\gamma)\gamma$
  - LHC: $pp \to a\gamma \to (\gamma\gamma)\gamma$



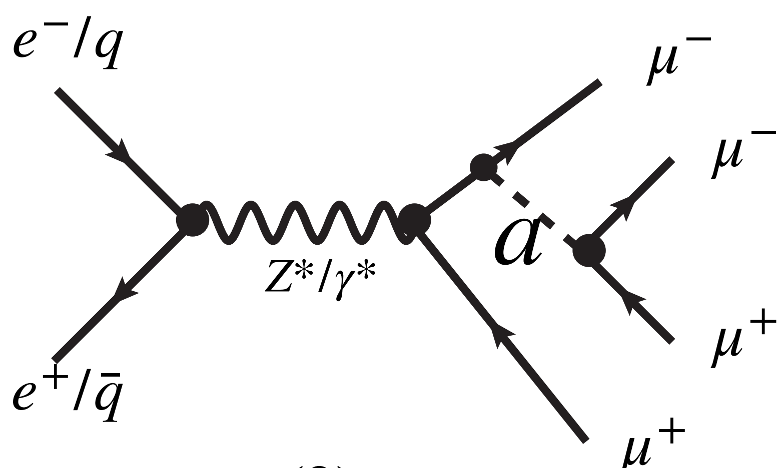
J.L, X.-L.M,L-T.W, ***X-P,Wang,*** *arXiv:2210.09335*





Existing constraints $C_{ww} = 0$

- Constraining a-μ coupling only:
  - BaBar: recast $e^+e^- \to \mu^+\mu^- Z'$
  - CMS(4μ): $pp \to \mu^+\mu^-\phi$



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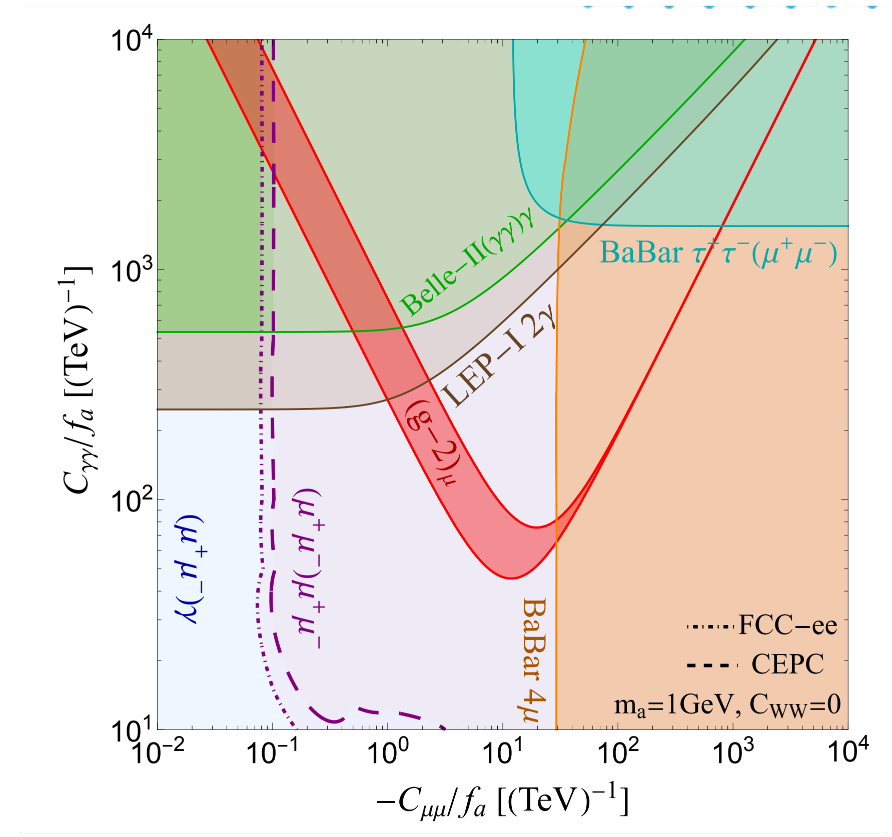
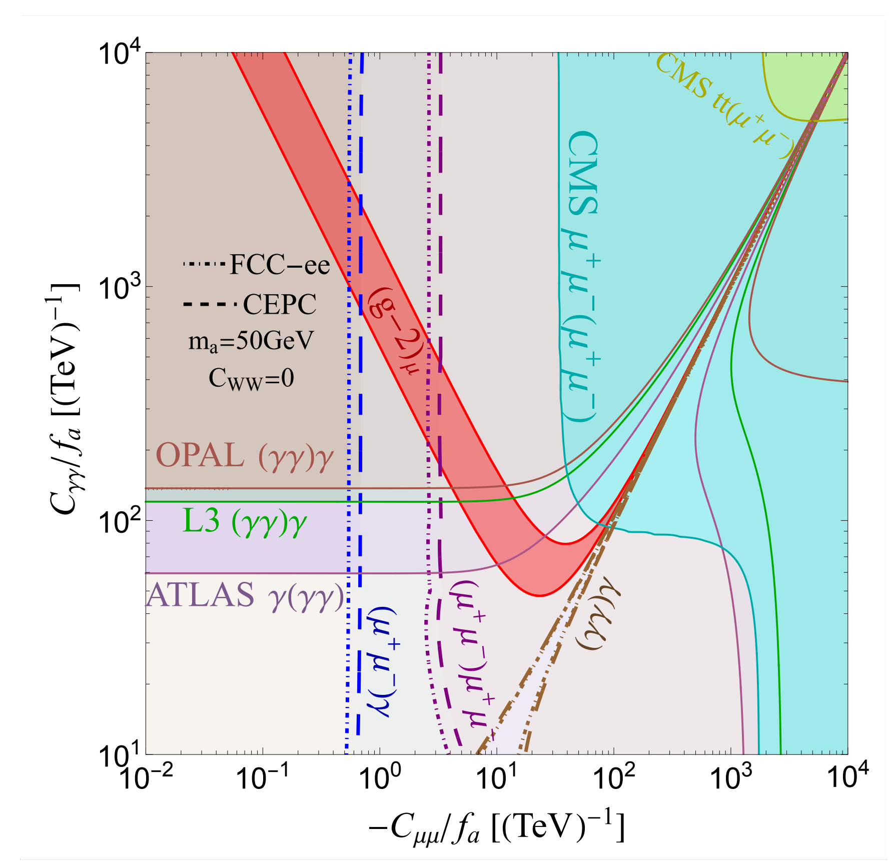
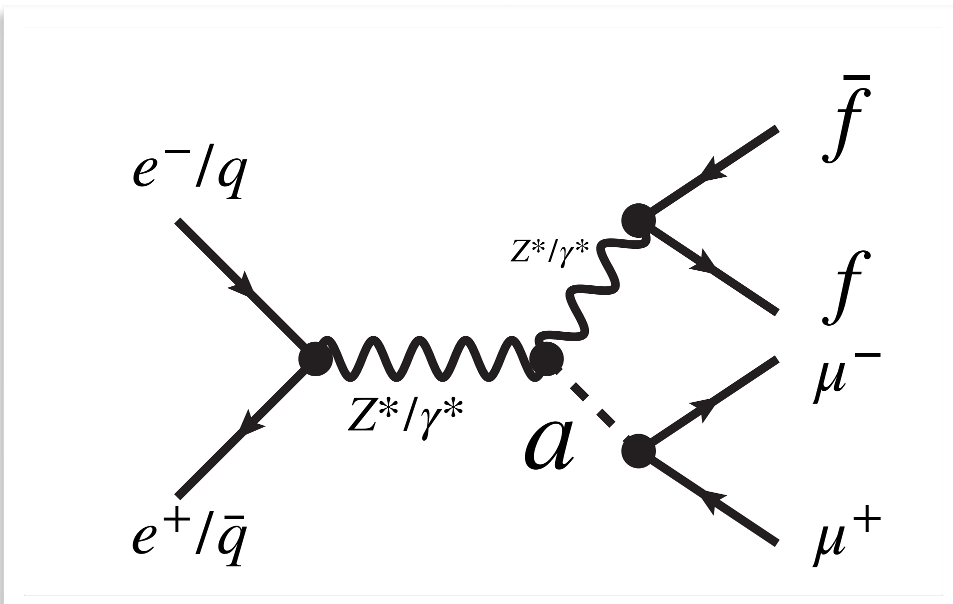


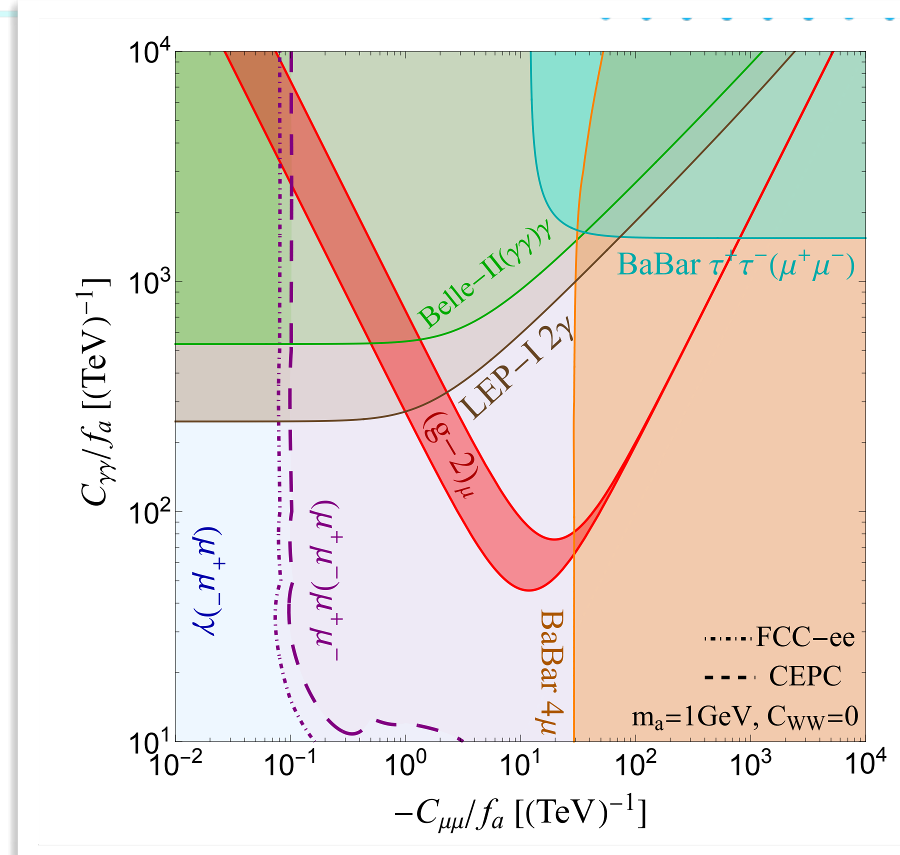


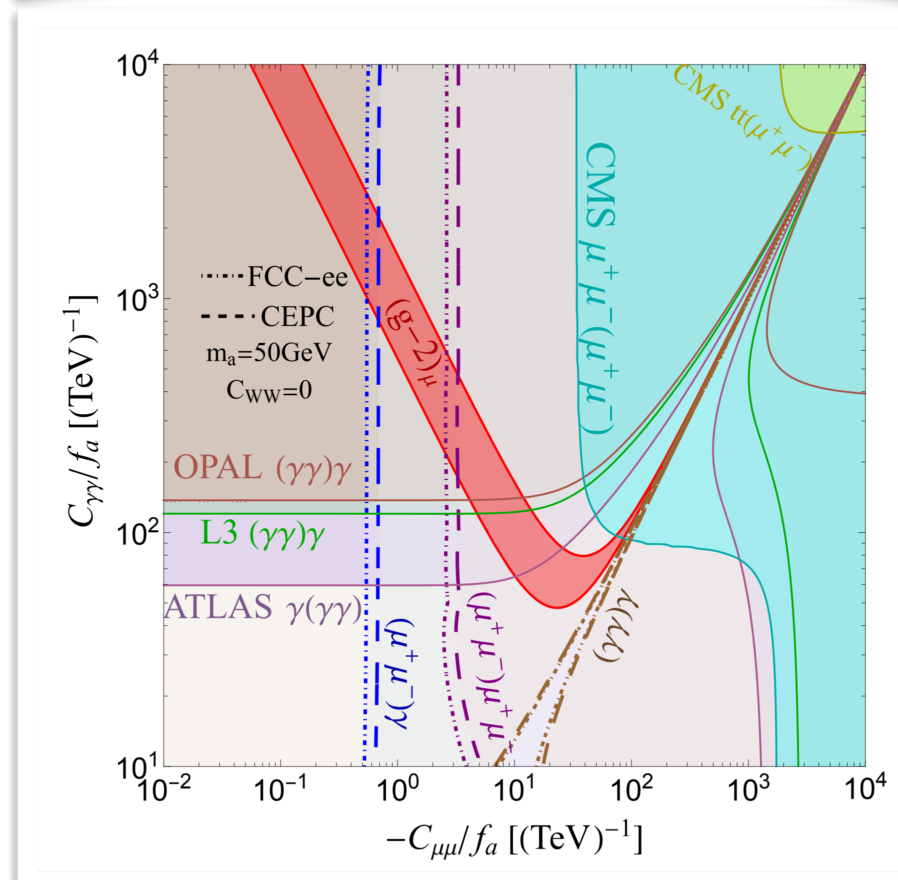
*J.L, X.-L.M,L-T.W, **X-P,Wang,** arXiv:2210.09335*

Existing constraints $C_{ww} = 0$

- Constraining both coupling
  - CMS($\bar{t}t + 2\mu$): $pp \to \bar{t}t\phi \to \bar{t}t(\mu^+\mu^-)$







J.L, X.-L.M,L-T.W, ***X-P,Wang,***
arXiv:2210.09335

Outline

- A' search at e-e+ collider
- Higgs Portal search at e-e+ collider
- ALP for muon g-2 tested at e+e- collider
- **Summary**

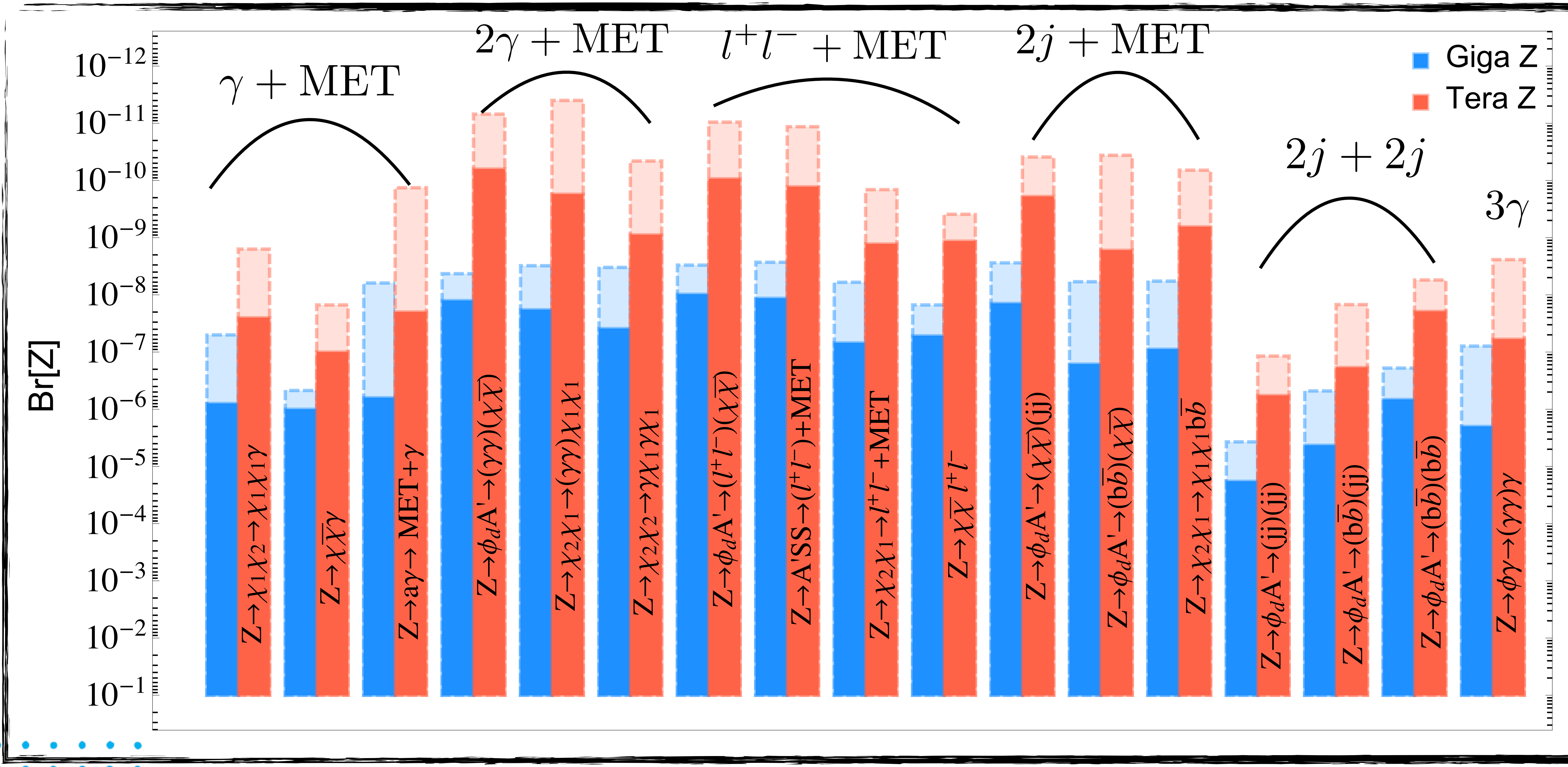
Exotic Z decay Topology

exotic decay	topologies	n_{res}	models
$Z \to \not{E} + \gamma$	$Z \to \chi_1\chi_2, \chi_2 \to \chi_1\gamma$	0	2A: $\frac{1}{\Lambda}\bar{\chi}_2\sigma$
	$Z \to \chi\bar{\chi}\gamma$	0	2B: $\frac{1}{\Lambda^3}\bar{\chi}$
	$Z \to a\gamma \to (\not{E})\gamma$	1	2C: $\frac{1}{\Lambda_{2C}}$
	$Z \to A'\gamma \to (\bar{\chi}\chi)\gamma$	1	2D: $\epsilon^{\mu\nu\rho}$
$Z \to \not{E} + \gamma\gamma$	$Z \to \phi_d A'$, $\phi_d \to (\gamma\gamma)$, $A' \to (\bar{\chi}\chi)$	2	3A: Vect
	$Z \to \phi_H\phi_A$, $\phi_H \to (\gamma\gamma)$, $\phi_A \to (\bar{\chi}\chi)$	2	3B: 2HD
	$Z \to \chi_2\chi_1$, $\chi_2 \to \chi_1\phi$, $\phi \to (\gamma\gamma)$	1	3C: Inela
	$Z \to \chi_2\chi_2$, $\chi_2 \to \gamma\chi_1$	0	3D: MID
$Z \to \not{E} + \ell^+\ell^-$	$Z \to \phi_d A'$, $A' \to (\ell^+\ell^-)$, $\phi_d \to (\bar{\chi}\chi)$	2	4A: Vect
	$Z \to A'SS \to (\ell\ell)SS$	1	4B: Vect
	$Z \to \phi(Z^*/\gamma^*) \to \phi\ell^+\ell^-$	1	4C: Long
	$Z \to \chi_2\chi_1 \to \chi_1 A'\chi_1 \to (\ell^+\ell^-)\not{E}$	1	4D: Vect
	$Z \to \chi_2\chi_1$, $\chi_2 \to \chi_1\ell^+\ell^-$	0	4E: MID
	$Z \to \bar{\chi}\chi\ell^+\ell^-$	0	4F: RayI

exotic decay	topologies	n_{res}	models
$Z \to (JJ)(JJ)$	$Z \to \phi_d A', \phi_d \to jj, A' \to jj$	2	6A: Vec
	$Z \to \phi_d A', \phi_d \to b\bar{b}, A' \to jj$	2	6B: vect
	$Z \to \phi_d A', \phi_d \to b\bar{b}, A' \to b\bar{b}$	2	6C: vect
$Z \to \gamma\gamma\gamma$	$Z \to \phi\gamma \to (\gamma\gamma)\gamma$	1	7A: ALI

*J.L, L-T.W, **X-P Wang**, W.X, Phys.Rev.D 97 (2018) 9*

Summary



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