Argonne NATIONAL LABORATORY

BROWN

Exposing Dark Sector with Z Factory

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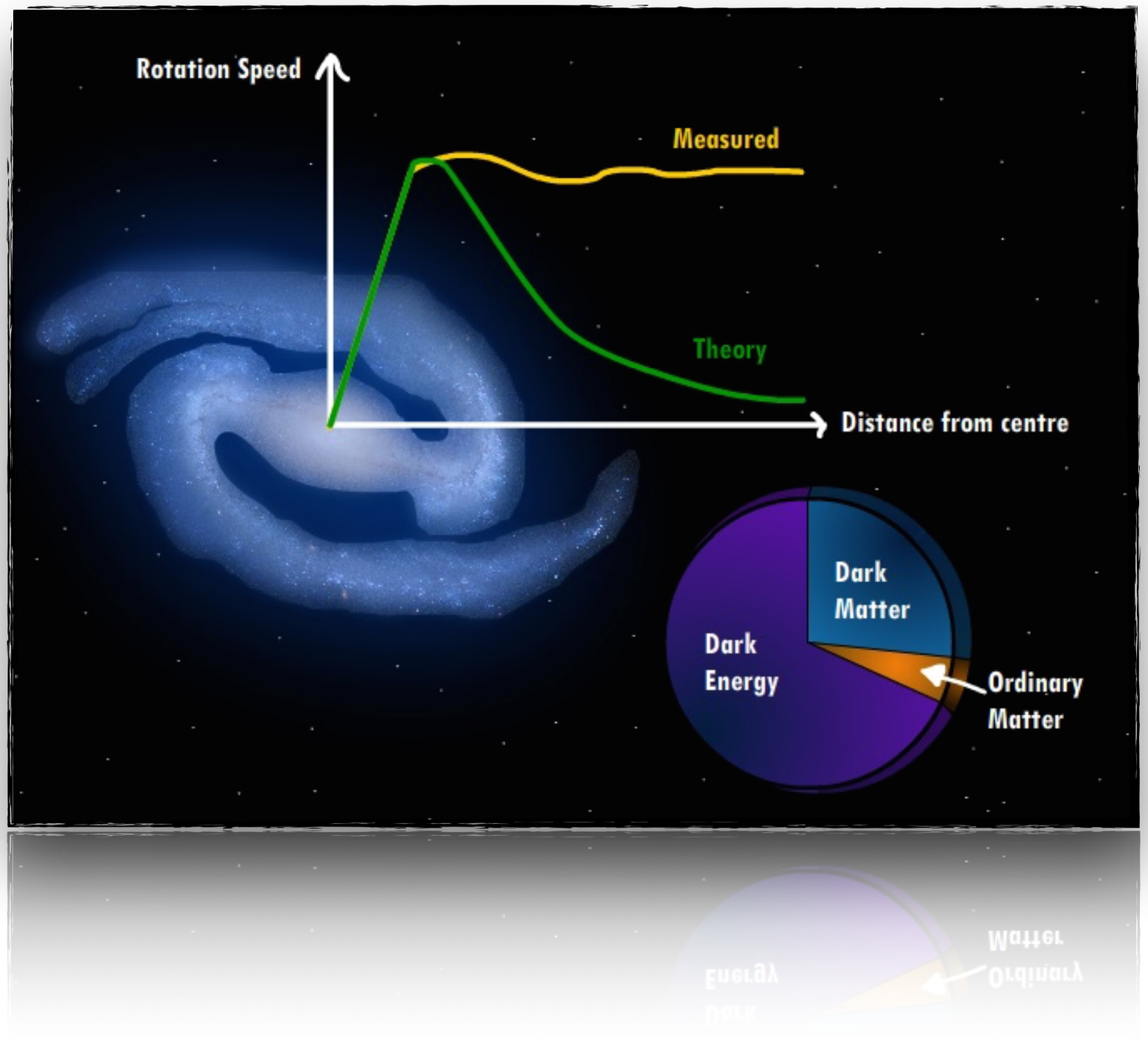
Dark matter Introduction



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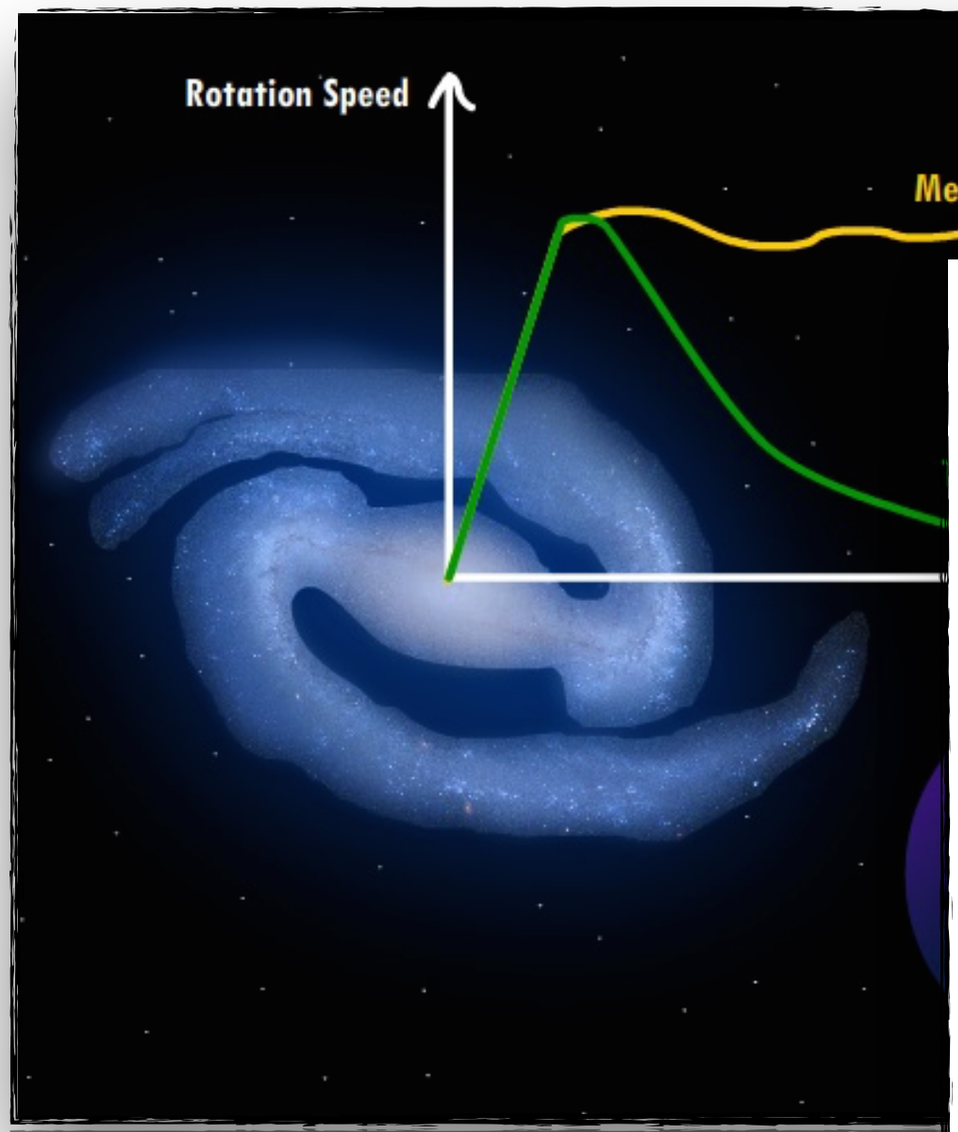

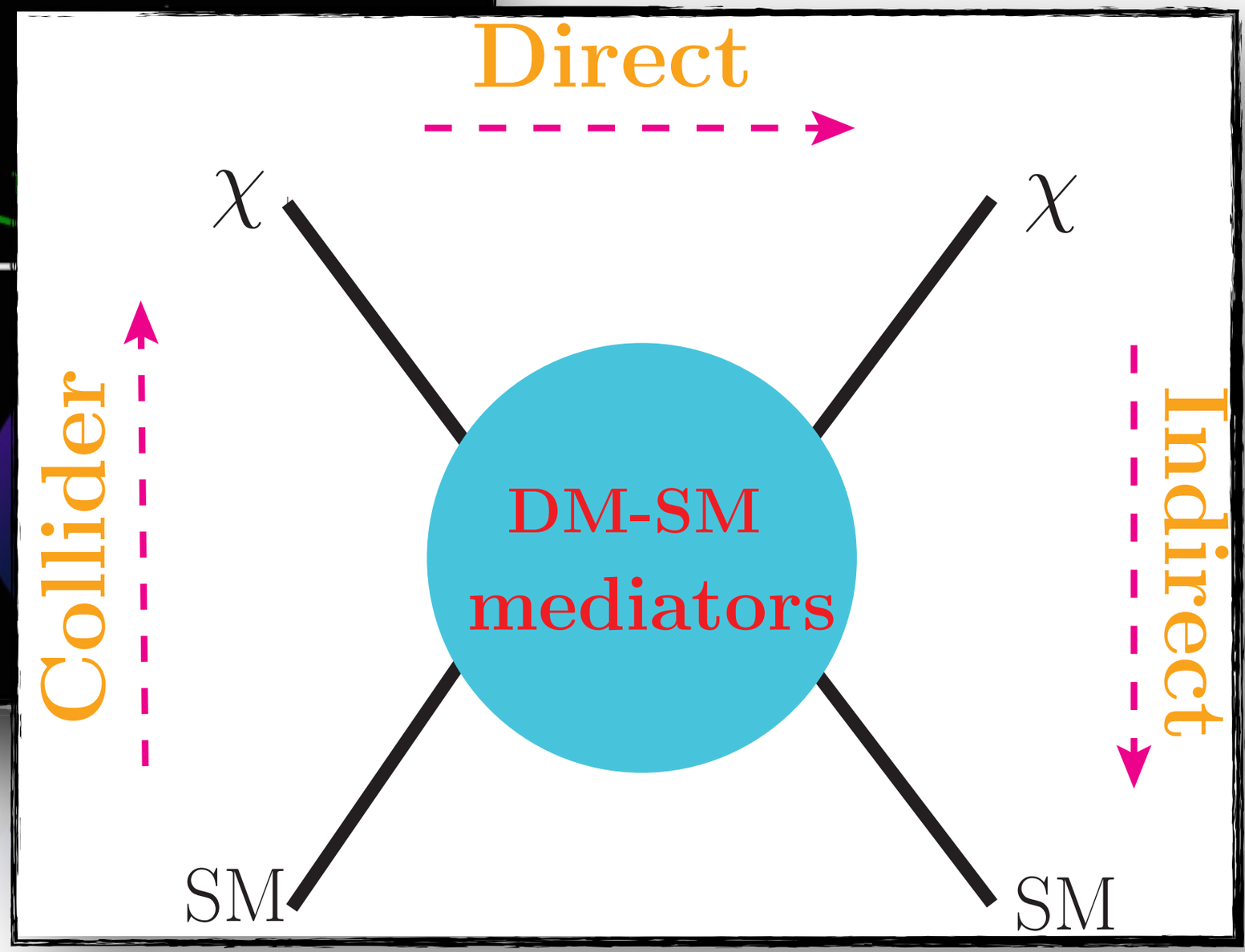

Dark matter search @ collider

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

Dark matter search @ collider

Dark Portal:

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

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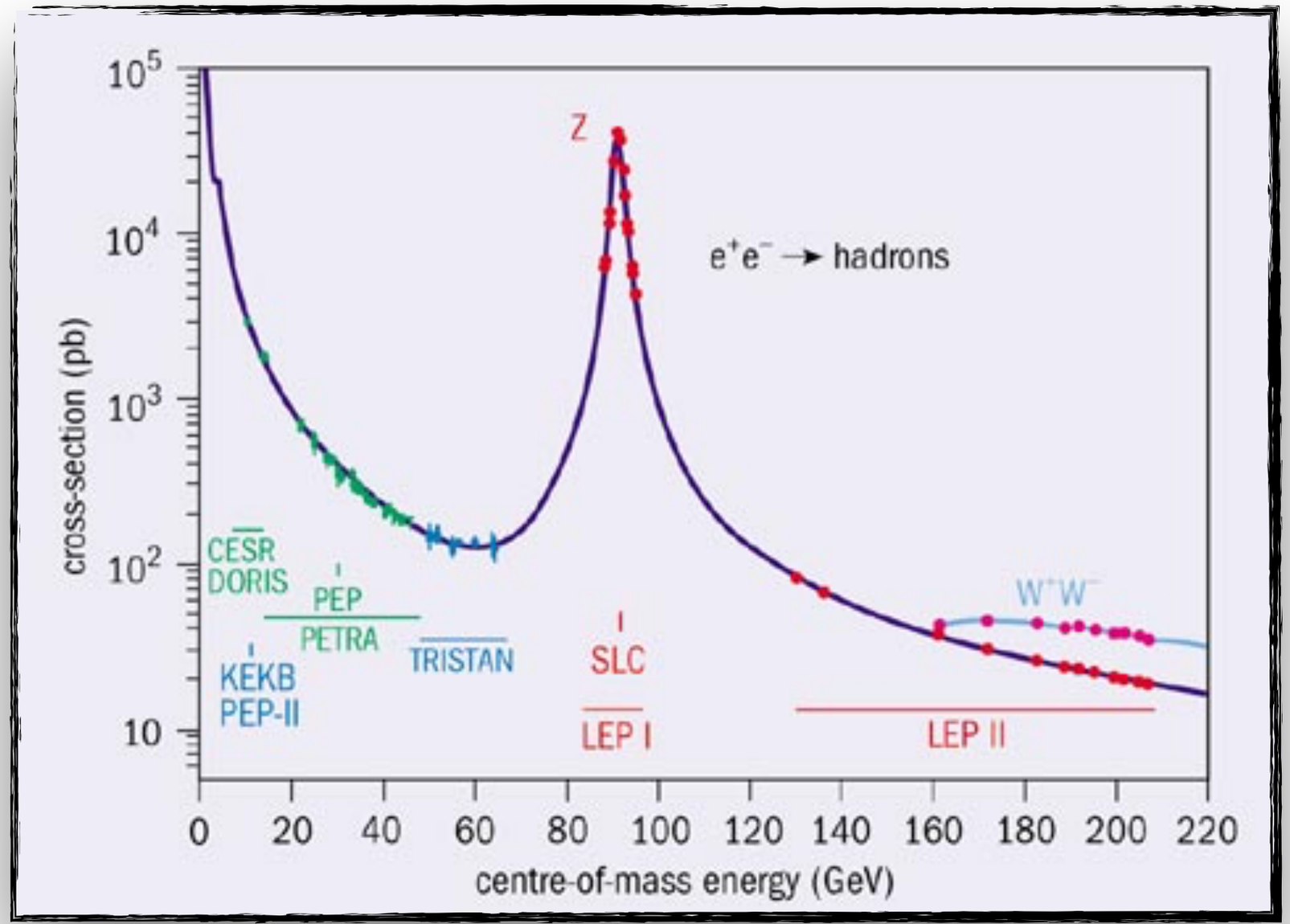
★ Neutrino Portal: LHN

can be searched via Exotic Z decay!!!

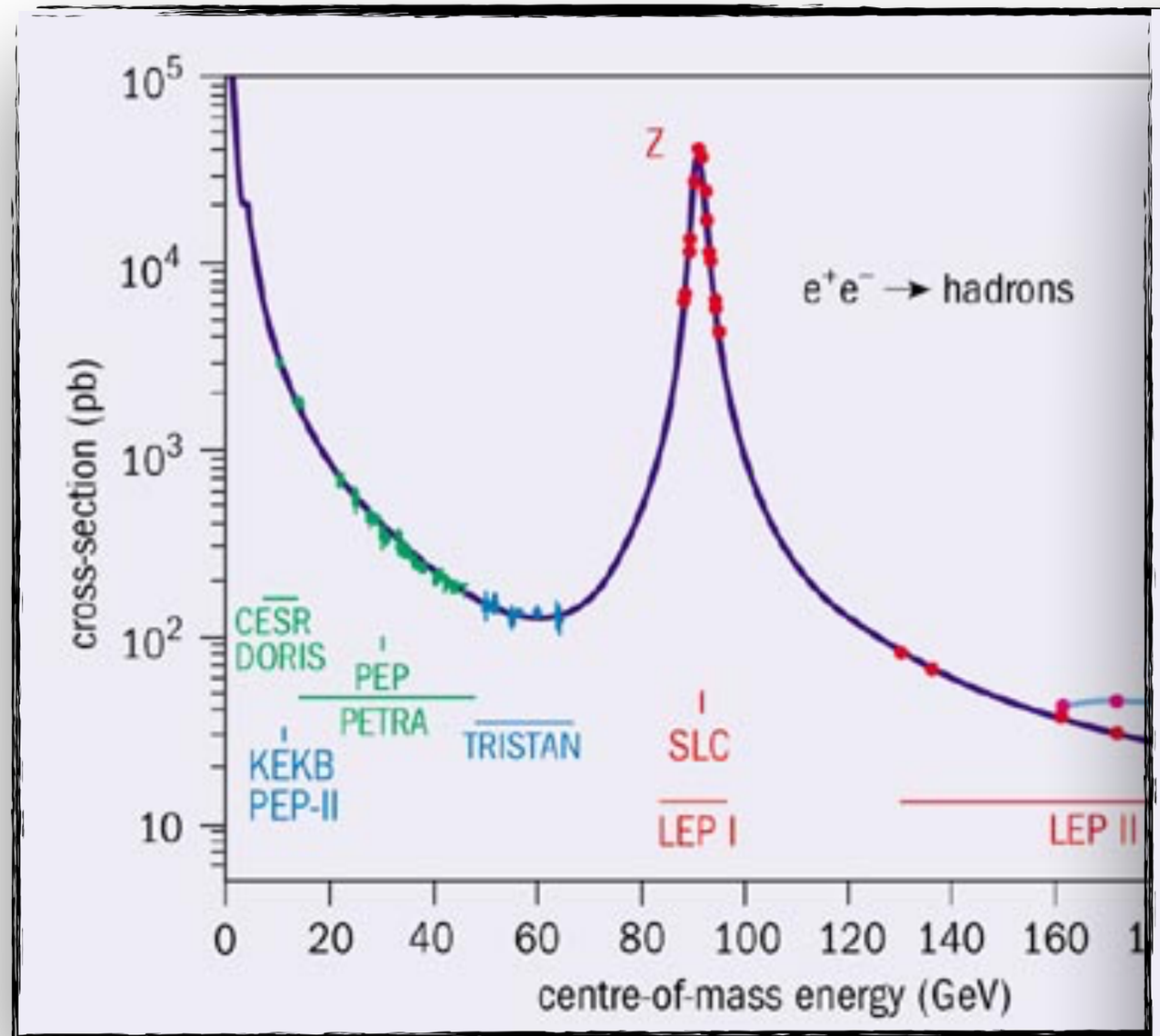
Why Z Factory?

	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

EWPT @ LEP


10^5
10^4
10^3
10^2
10
cross-section (pb)
Z
$e^+e^- \rightarrow$ hadrons
CESR
DORIS
PEP
PETRA
TRISTAN
KEKB
PEP-II
SLC
LEP I
W^+W^-
LEP II
0
20
40
60
80
100
120
140
160
180
200
220
centre-of-mass energy (GeV)

EWPT @ LEP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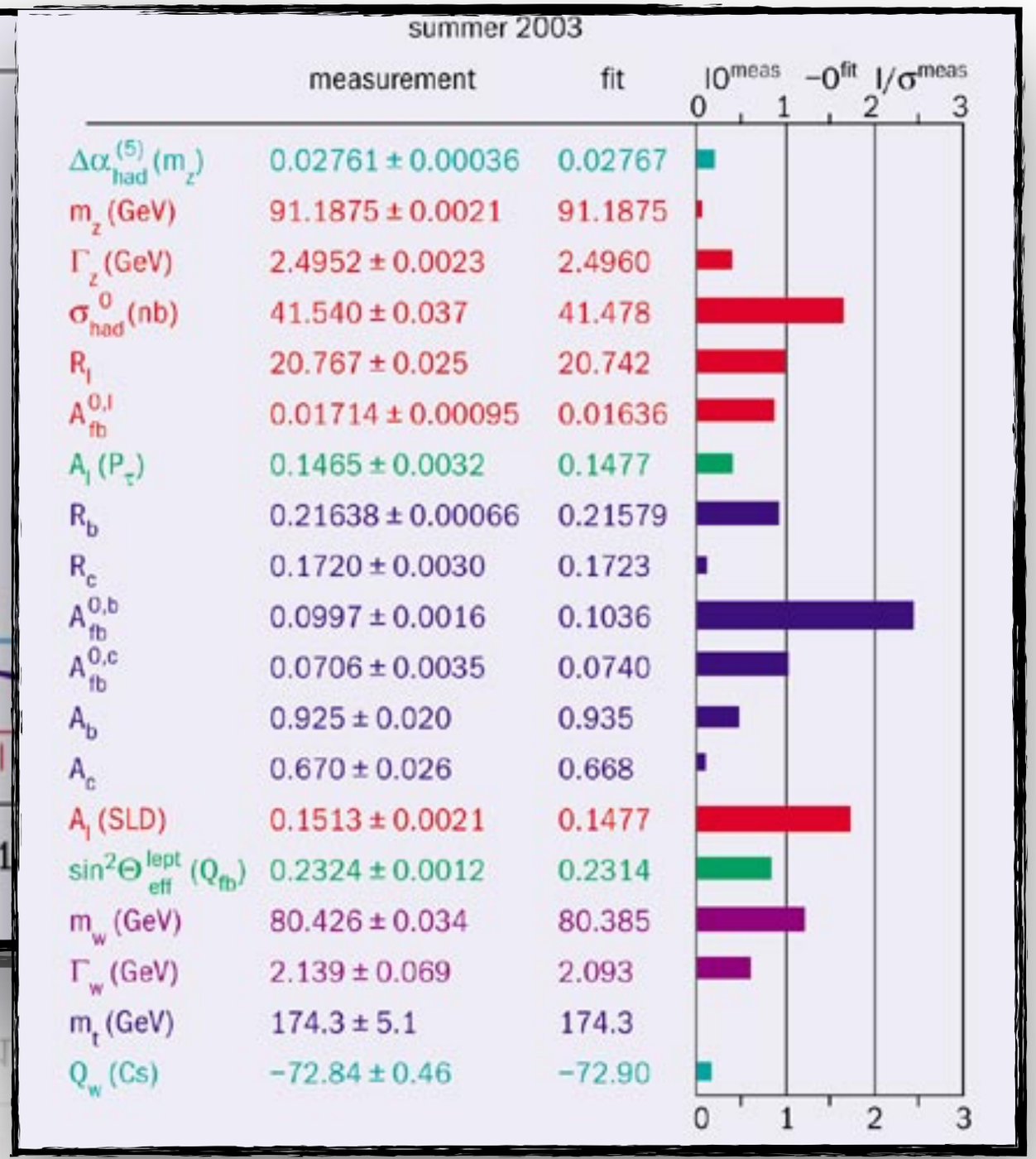
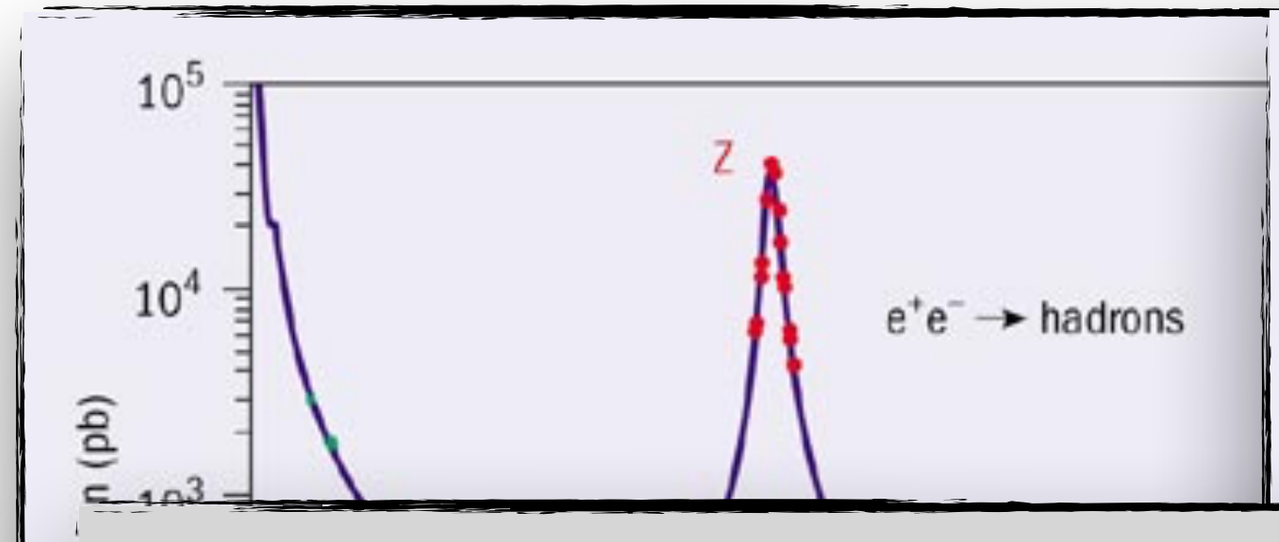
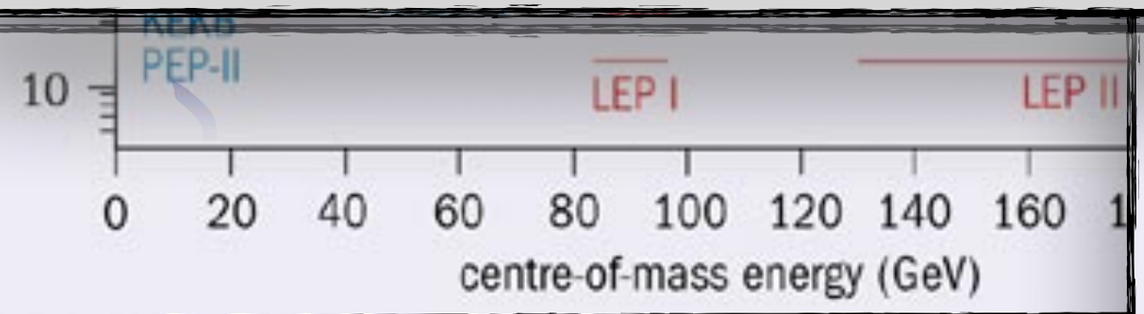

summer 2003
measurement
fit
$|O^{meas} - O^{fit}|/\sigma^{meas}$
0
1
2
3
$\Delta\alpha^{(5)}_{had}(m_z)$ 0.02761 ± 0.00036 0.02767
m_z (GeV) 91.1875 ± 0.0021 91.1875
Γ_z (GeV) 2.4952 ± 0.0023 2.4960
σ^0_{had} (nb) 41.540 ± 0.037 41.478
R_l 20.767 ± 0.025 20.742
$A^{0,l}_{fb}$ 0.01714 ± 0.00095 0.01636
A_l (P_τ) 0.1465 ± 0.0032 0.1477
R_b 0.21638 ± 0.00066 0.21579
R_c 0.1720 ± 0.0030 0.1723
$A^{0,b}_{fb}$ 0.0997 ± 0.0016 0.1036
$A^{0,c}_{fb}$ 0.0706 ± 0.0035 0.0740
A_b 0.925 ± 0.020 0.935
A_c 0.670 ± 0.026 0.668
A_l (SLD) 0.1513 ± 0.0021 0.1477
$\sin^2\Theta^{lept}_{eff}$ (Q_{fb}) 0.2324 ± 0.0012 0.2314
m_w (GeV) 80.426 ± 0.034 80.385
Γ_w (GeV) 2.139 ± 0.069 2.093
m_t (GeV) 174.3 ± 5.1 174.3
Q_w (Cs) −72.84 ± 0.46 −72.90

EWPT @ LEP



Giga/Tera Z @ Z factory?



Outline

- **Dark Sector Models**
  - ★ Higgs portal + DM
  - ★ Vector portal + DM
  - ★ Axion-like particle
  - ★ Magnetic inelastic DM, Rayleigh DM
- **Exotic Z decay topologies**
  - ★Classifying by final states and resonance

Higgs Portal DM

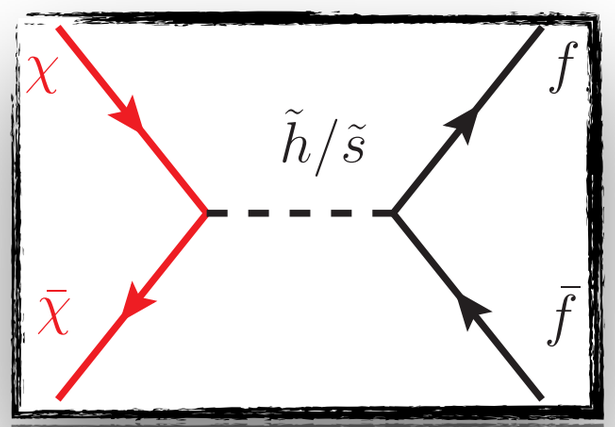
- **Higgs Portal Lagrangian:**

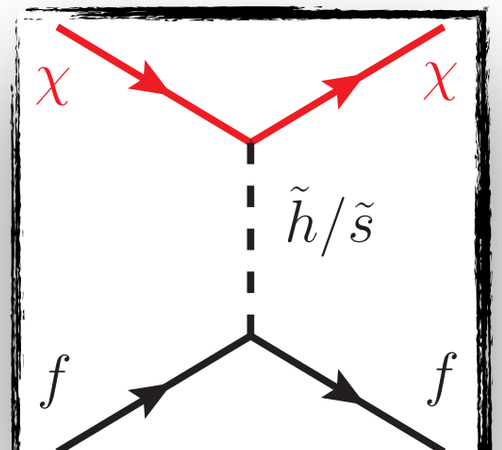
$$\mathcal{L} = \frac{1}{2}\partial_\mu S \partial^\mu S - \lambda_1 \left(H^\dagger H\right) S - \lambda_2 \left(H^\dagger H\right) S^2 + \bar{\chi}\left(i\partial^\mu \gamma_\mu - m_\chi^0\right)\chi - y_\chi S \bar{\chi}\chi + ...$$

- **Scalar Mixing**

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

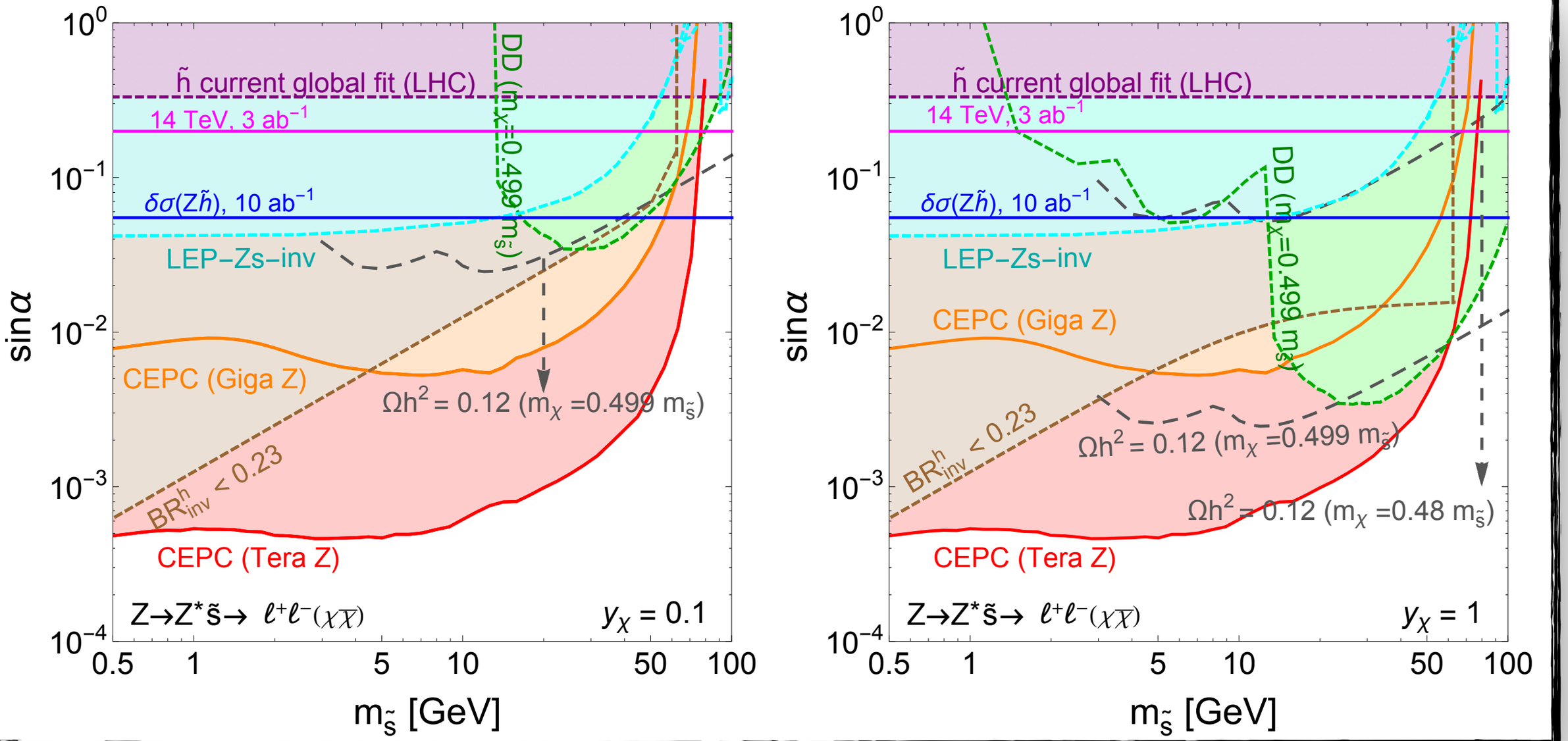
- **Relic abundance and Direct detection**





Higgs Portal DM

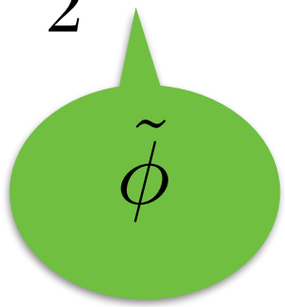
✤ Z factory Search



Vector Portal DM

✣ Vector Portal Lagrangian

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



✣ Vector Mixing

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

✣ Interaction

$$\mathcal{L}_{\text{int}} = \tilde{Z}_\mu \left(gJ^\mu_Z - g_D \frac{m^2_Z t_W}{m^2_Z - m^2_{A'}}\epsilon J^\mu_D \right) + \tilde{A}'_\mu \left(g_D J^\mu_D + g\frac{m^2_{A'}t_W}{m^2_Z - m^2_{A'}}\epsilon J^\mu_Z + e\epsilon J^\mu_{\text{em}} \right)$$

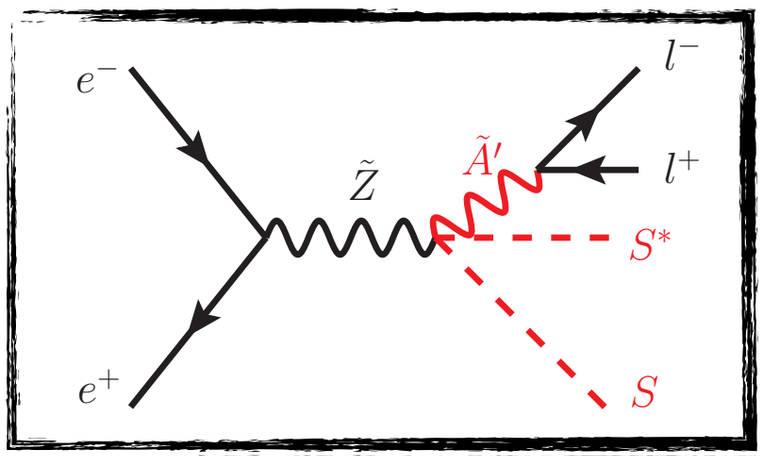
Vector Portal DM

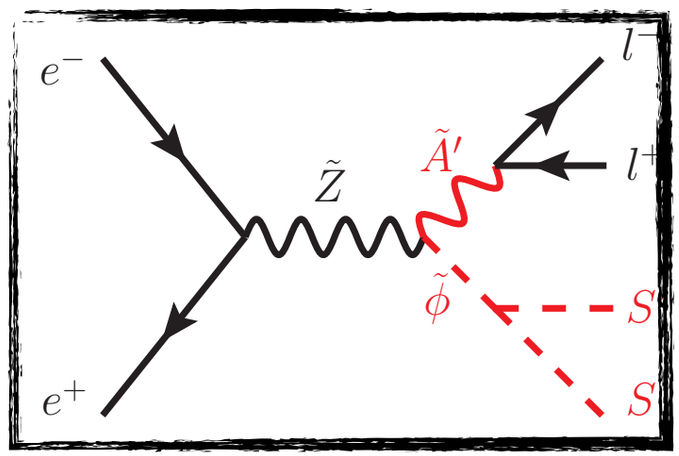
- **Complex scalar DM Lagrangian:**

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

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

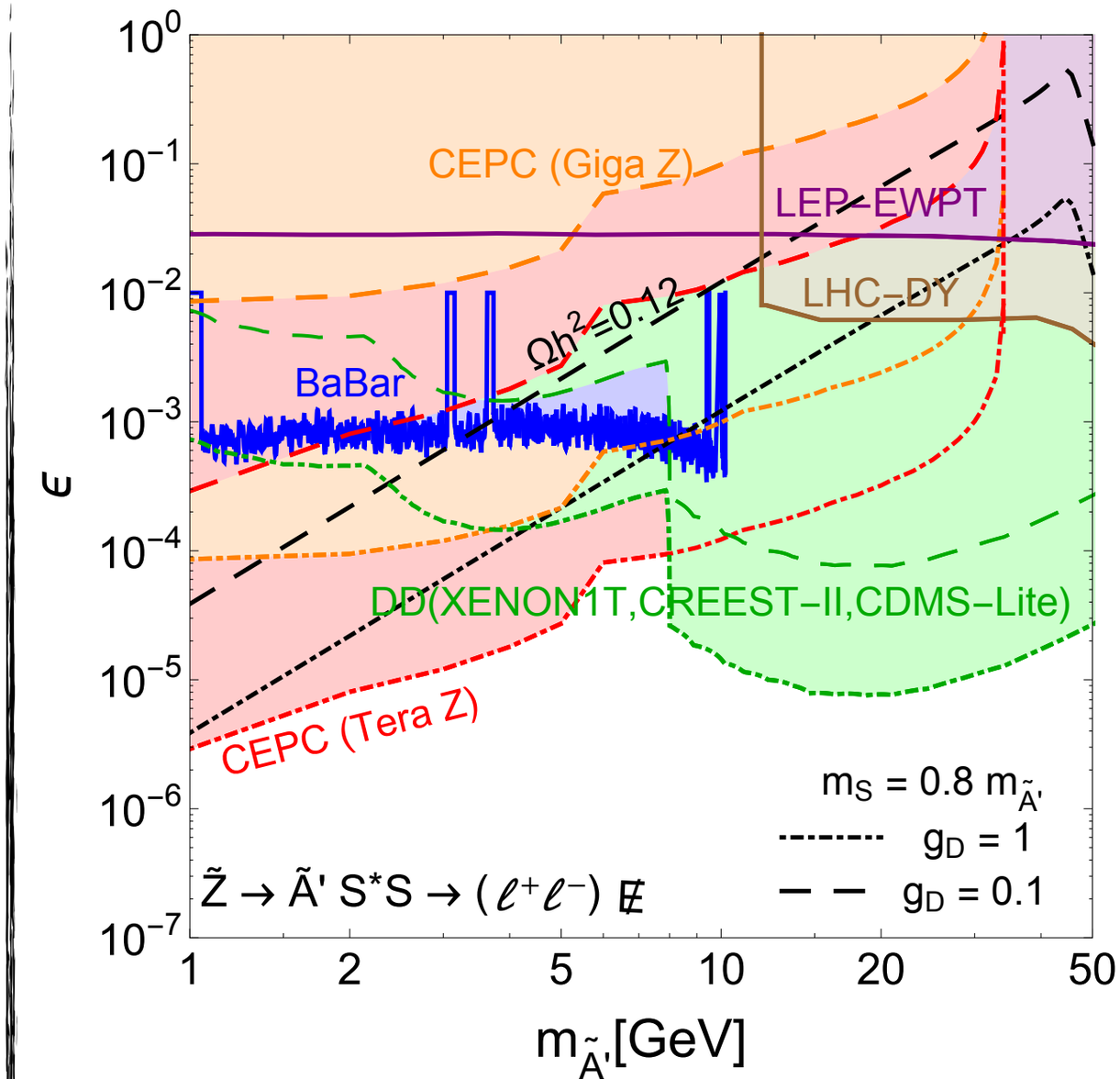
- **Dark Sector Search @ Z factory**

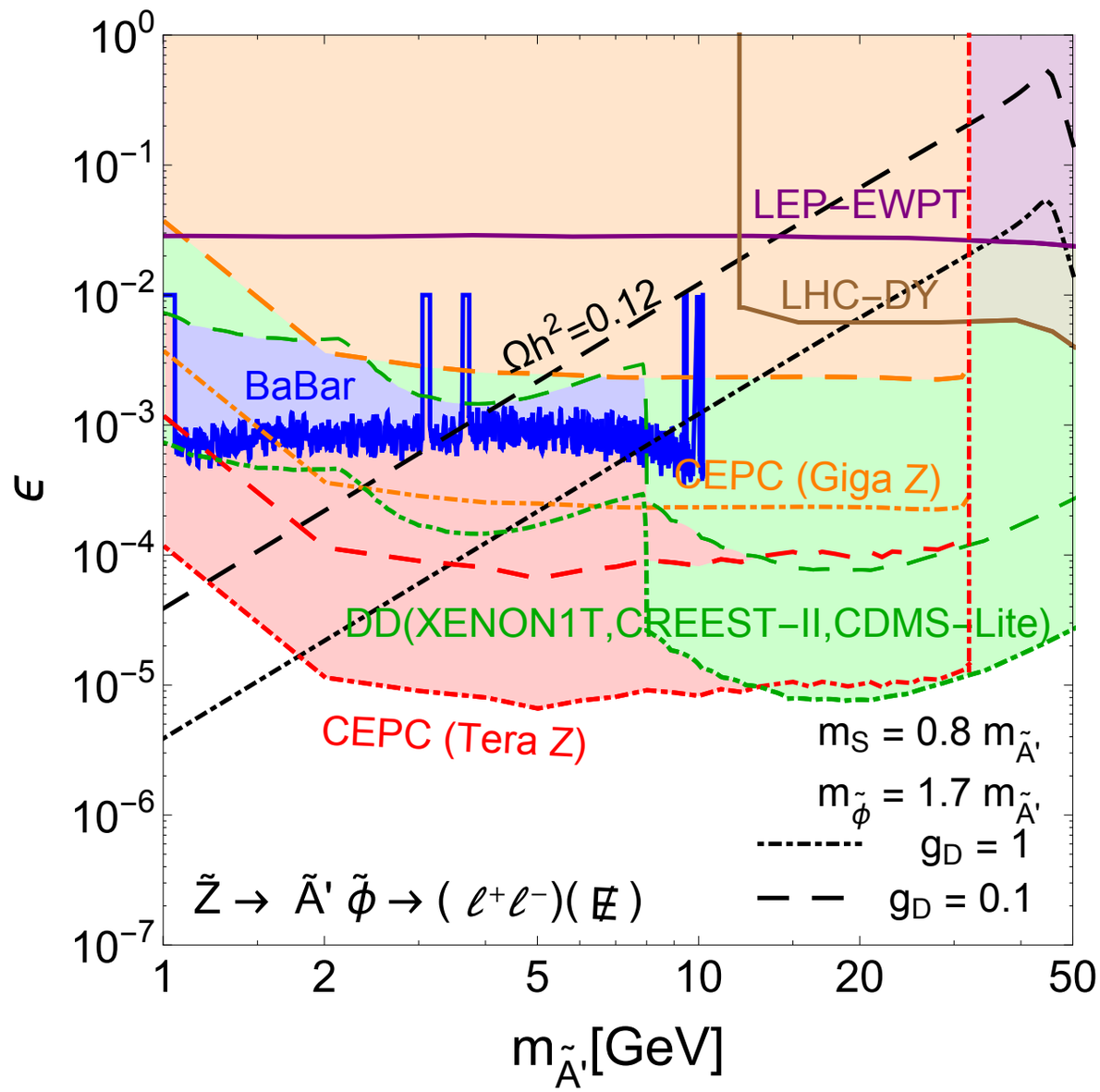




Vector Portal DM

✣ Constraint results





Axion-like Particle

- **Axion-like particle Lagrangian:**

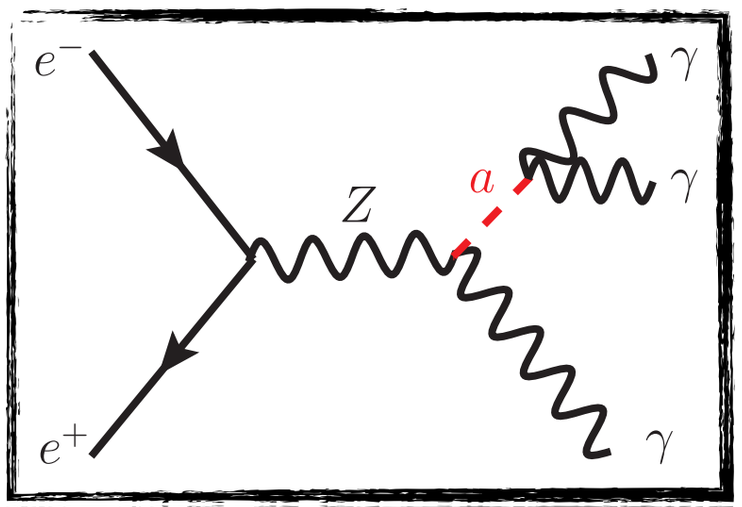
$$\mathcal{L}_{\mathrm{ALP}} = \frac{1}{4\Lambda_{aBB}} a B_{\mu\nu} \tilde{B}^{\mu\nu}$$

- **Interactions and decays**

$$\Gamma\left(a \to \gamma\gamma\right) = \frac{1}{64\pi} \frac{1}{\Lambda_{aBB}^2} \cos^4\theta_w m_a^3$$

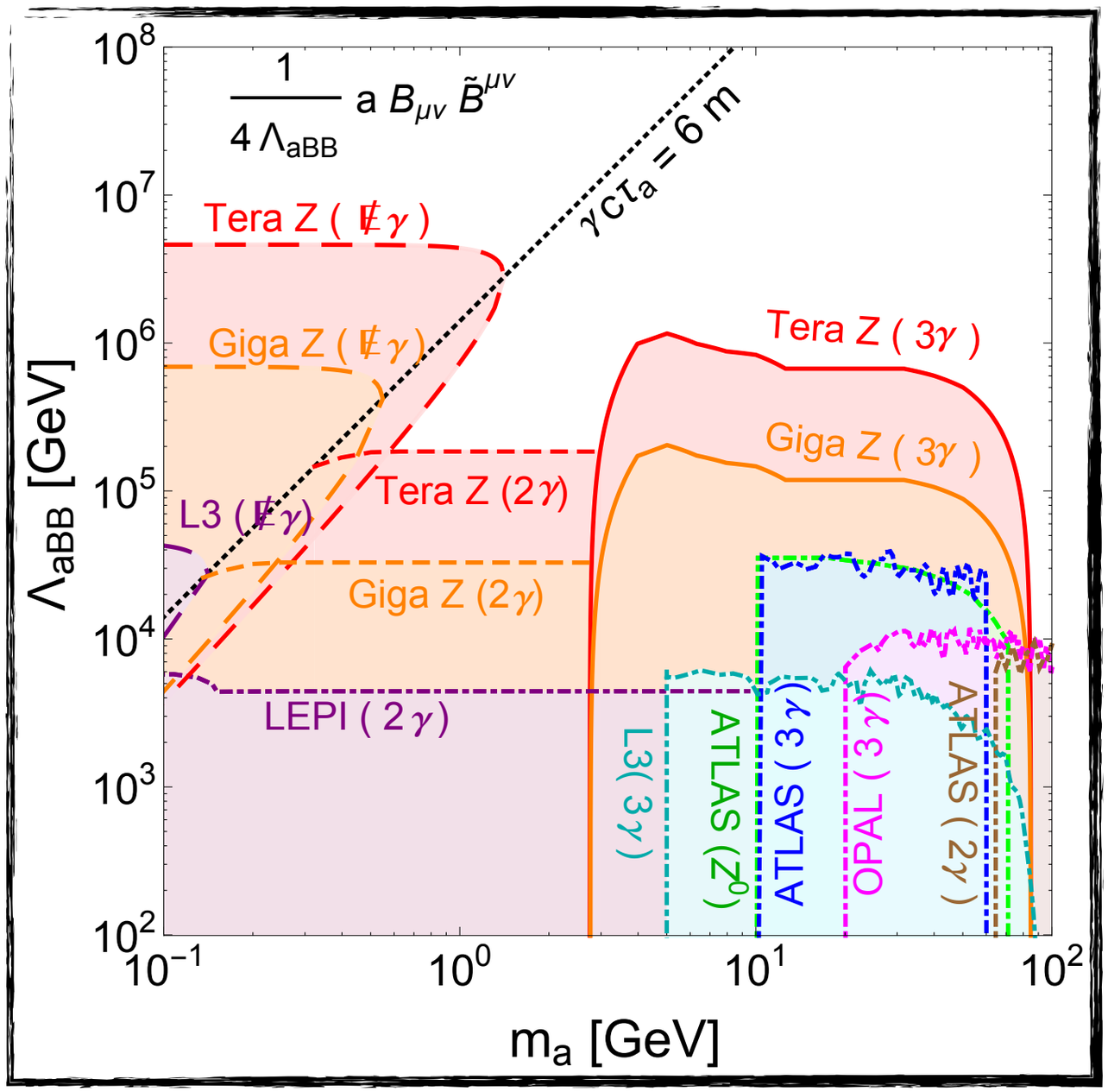
$$\Gamma\left(Z \to \gamma a\right) = \frac{1}{64\pi} \frac{1}{\Lambda_{aBB}^2} \cos^2\theta_w \sin^2\theta_w m_Z^3$$

- **Search @ Z factory**



Axion-like Particle

✣ Constraints

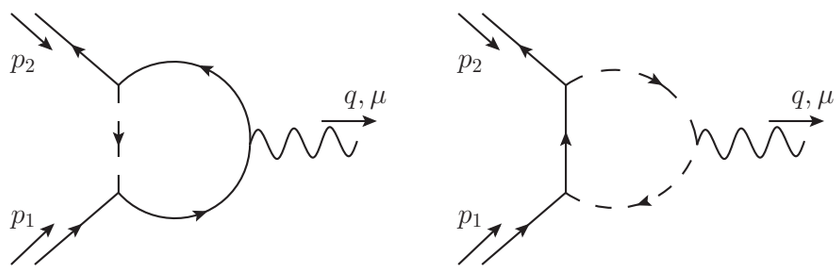
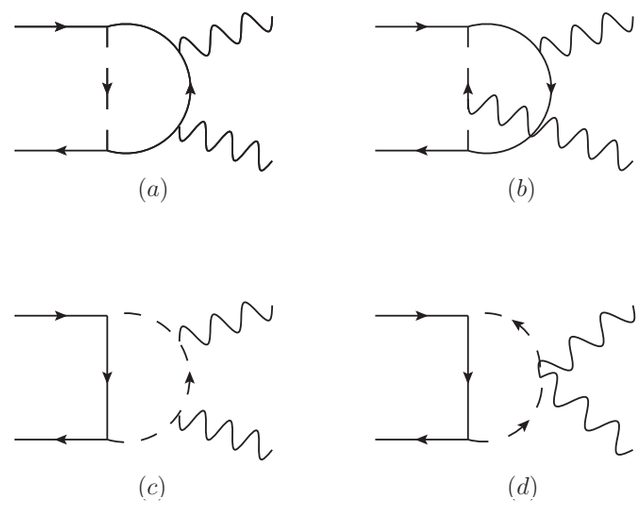


Magnetic inelastic DM, Rayleigh DM

- **UV complete Lagrangian:**

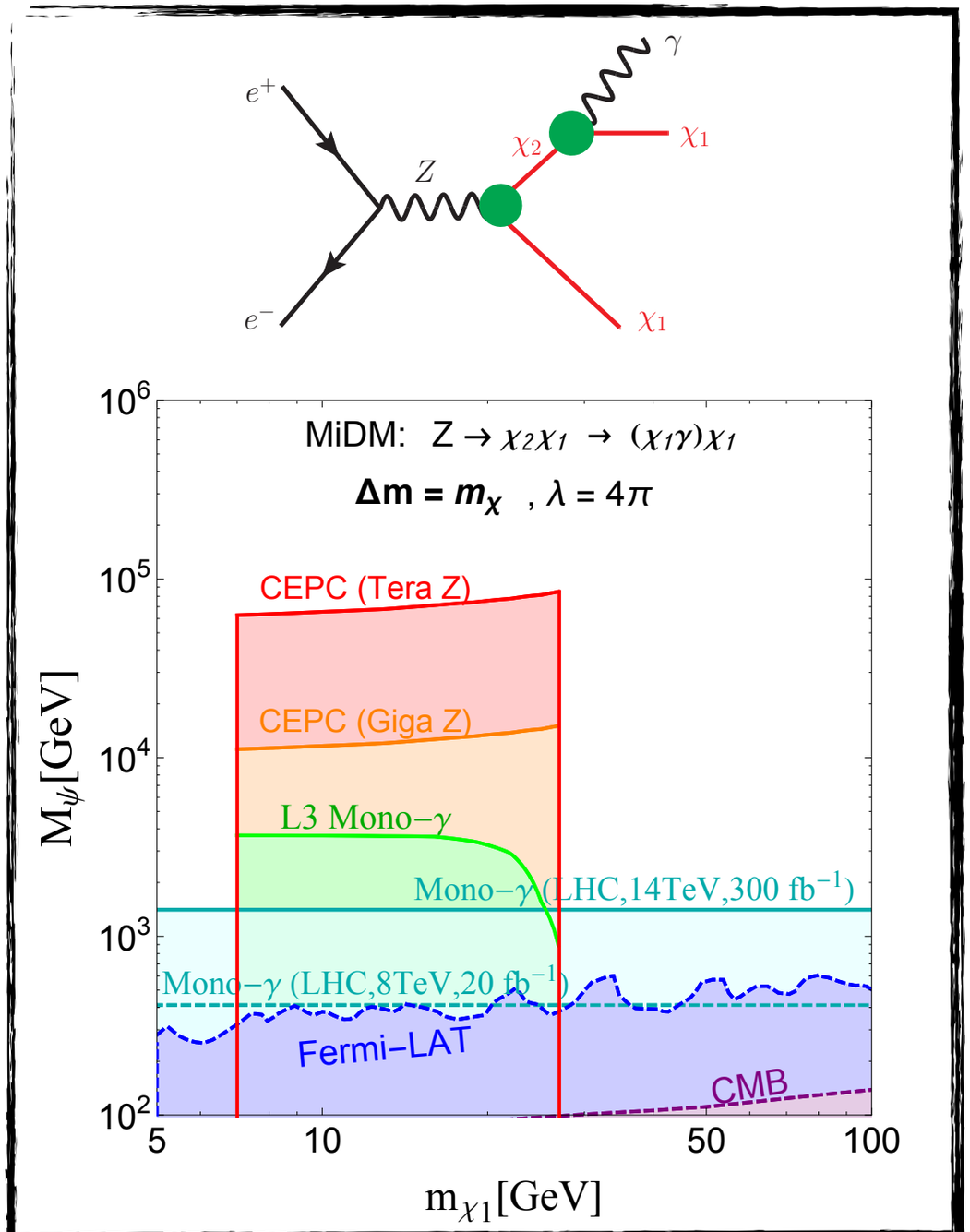
$$\mathcal{L} = \bar{\chi}(i\partial_\mu\gamma^\mu - m_\chi)\chi + \bar{\psi}(iD_\mu\gamma^\mu - M_\psi)\psi + (D^\mu\phi)^\dagger(D_\mu\phi) - M_\phi^2\phi^\dagger\phi$$
$$- \frac{1}{2}\delta m\bar{\chi}^c\chi + (\lambda\bar{\psi}\chi\phi + h.c.)$$

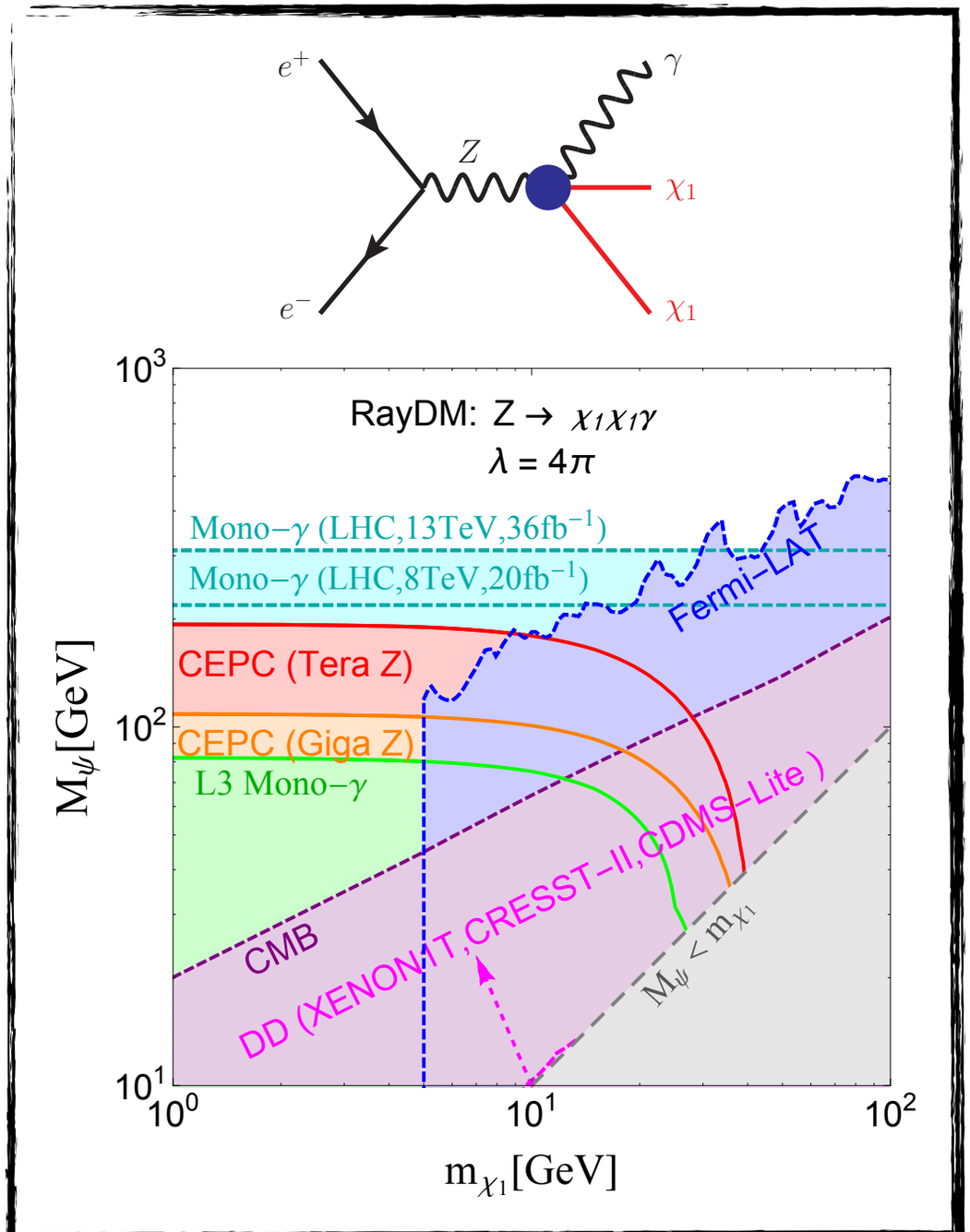
- **From UV model to Effective Operator**

	Magnetic	Rayleigh
Interaction	$\frac{1}{\Lambda_{\rm MIDM}}\bar{\chi}_2\sigma^{\mu\nu}\chi_1 B_{\mu\nu}$ $\frac{1}{\Lambda_{\rm MIDM}} \approx \frac{\lambda^2 g_Y}{32\pi^2 M_\psi}$	$\frac{1}{\Lambda^3_{\rm RayDM}}\bar{\chi}_1\chi_1 B^{\mu\nu}B_{\mu\nu}$ $\frac{1}{\Lambda^3_{\rm RayDM}} \approx \frac{\lambda^2 g_Y^2}{24\pi^2 M_\psi^3}$
Loop diagrams		

Magnetic inelastic DM, Rayleigh DM

✣ Search from Z factory





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

Z Factory Set Up

✤ Detector Performance

$$\text{Photon energy resolution: } \frac{\delta E_\gamma}{E_\gamma} = \frac{0.16}{\sqrt{E_\gamma/\text{GeV}}} \oplus 0.01\,,$$

$$\text{Lepton momentum resolution: } \Delta\frac{\text{GeV}}{p_T^\ell} = 2\times 10^{-5} \oplus \frac{10^{-3}\text{GeV}}{p_T^\ell \sin\theta}\,,$$

$$\text{Jet energy resolution: } \frac{\delta E_j}{E_j} = \frac{0.3}{\sqrt{E_j/\text{GeV}}} \oplus 0.02\,.$$

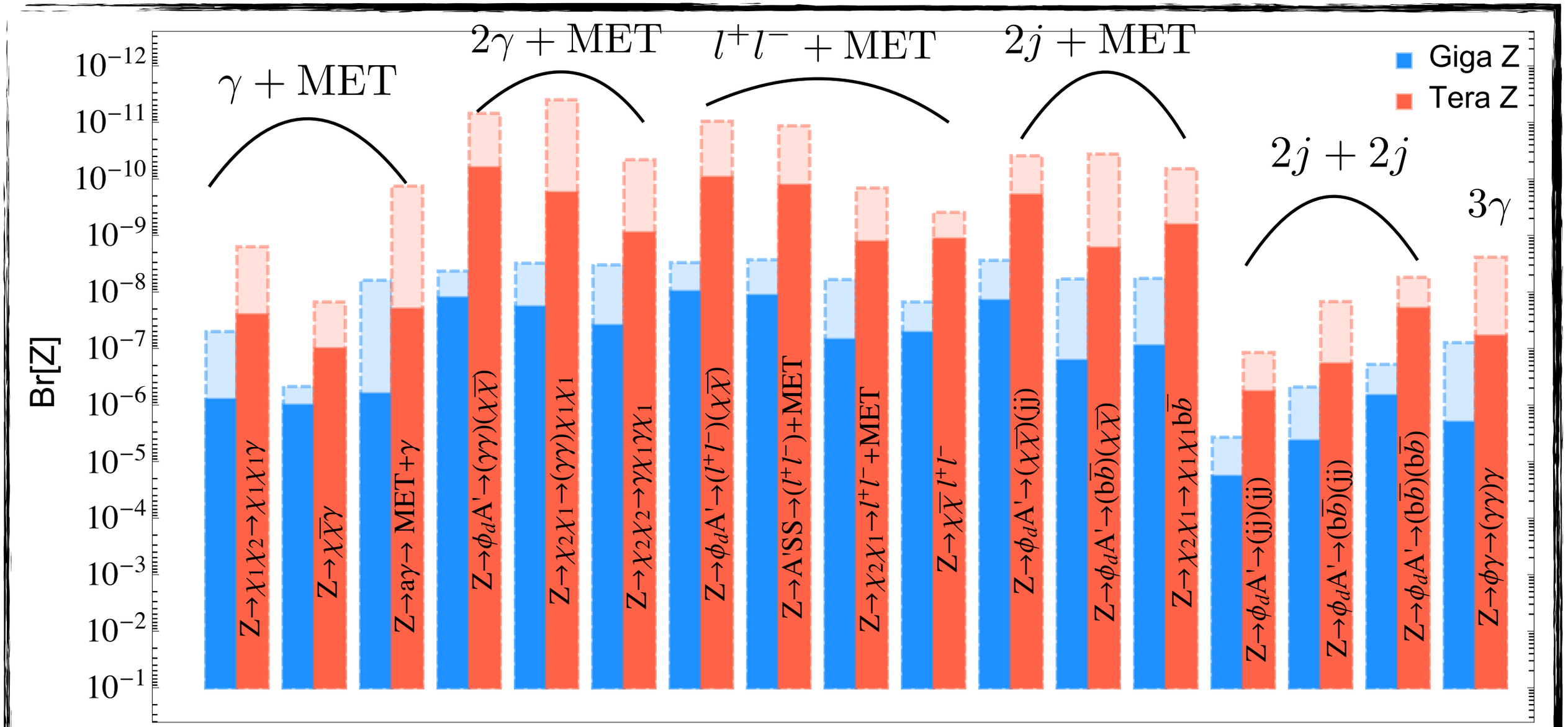
✤ Preliminary Cut

$$|\eta| < 2.3, E_\gamma > 10\text{GeV}, E_\ell > 5\text{GeV}, E_j > 10\text{GeV}, E_{(\text{MET})} > 10\text{GeV},$$

$$y_{ij} \equiv \frac{2\text{Min}(E_i^2, E_j^2)\,(1-\cos\theta_{ij})}{E_{vis}^2} \geq 0.001$$

✤ SM Background include one photon from ISR

Results on Different Topologies



Summary

- **Dark Sector models:**

  ★ Can provide **leading and complementary** constraints comparing to current collider limits and DM limits

- **Exotic Z decay topologies:**

  ★ Giga Z limit on BR $10^{-6} \sim 10^{-8.5}$

  ★ Tera Z limit on BR $10^{-7.5} \sim 10^{-11}$

  ★ Sensitivities on BR

$$2\gamma + \mathrm{MET} \sim \mathrm{l}^{+}\mathrm{l}^{-} + \mathrm{MET} > 2\mathrm{j} + \mathrm{MET} > \gamma + \mathrm{MET}$$

Any Questions?