合肥工業大學
HEFEI UNIVERSITY OF TECHNOLOGY

Dark sector-photon interactions at electron colliders

Yu Zhang (张　宇)

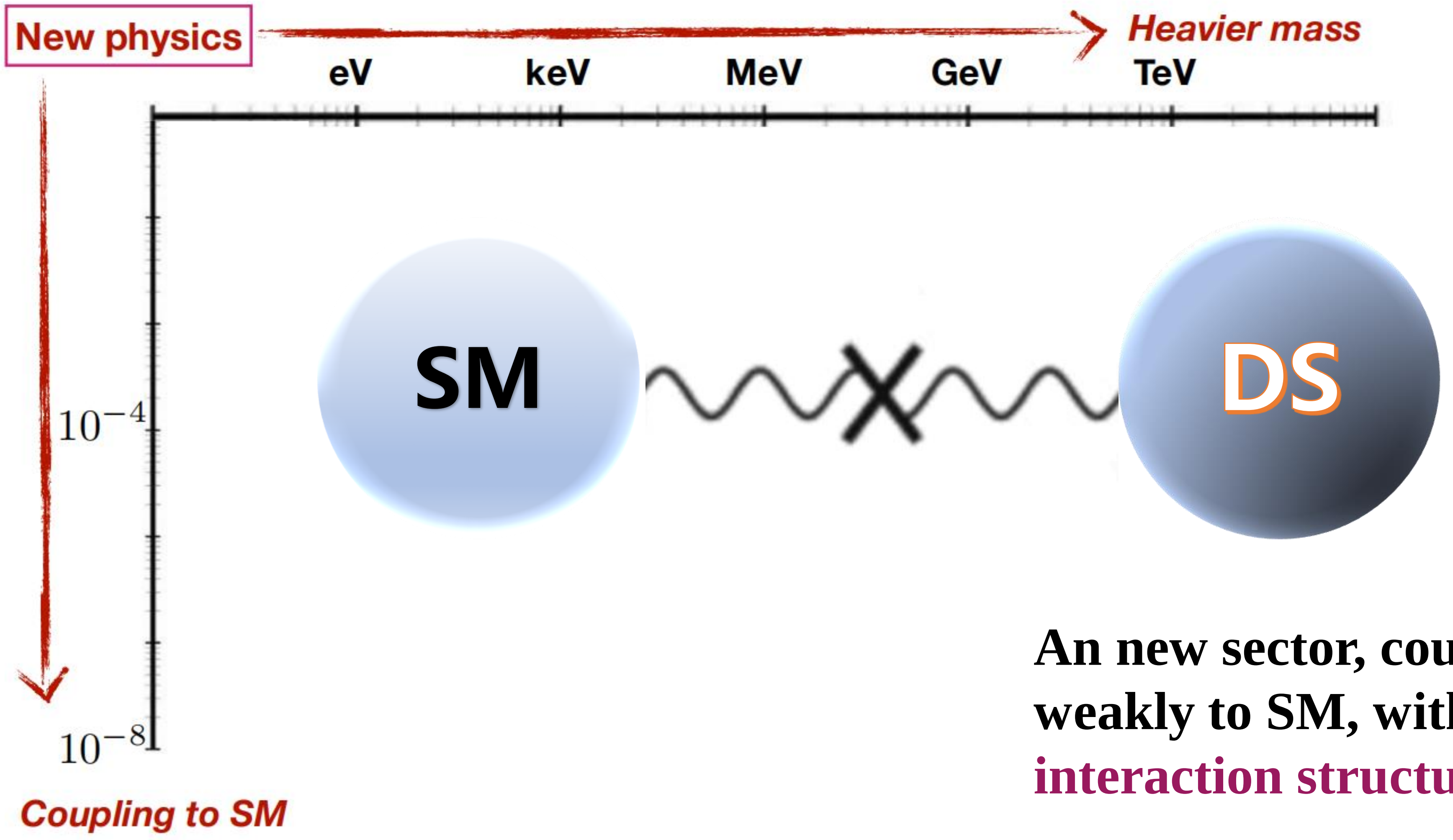
School of Physics, Hefei University of Technology

Email：dayu@hfut.edu.cn

The 2022 international workshop on the high energy CEPC
2022年10月27日

Motivations for a dark sector

Primary goal: to find **dark matter** particles, or a portal to them



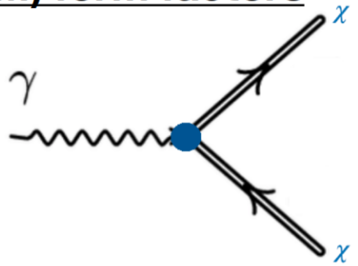
An new sector, coupled very weakly to SM, with its own interaction structures

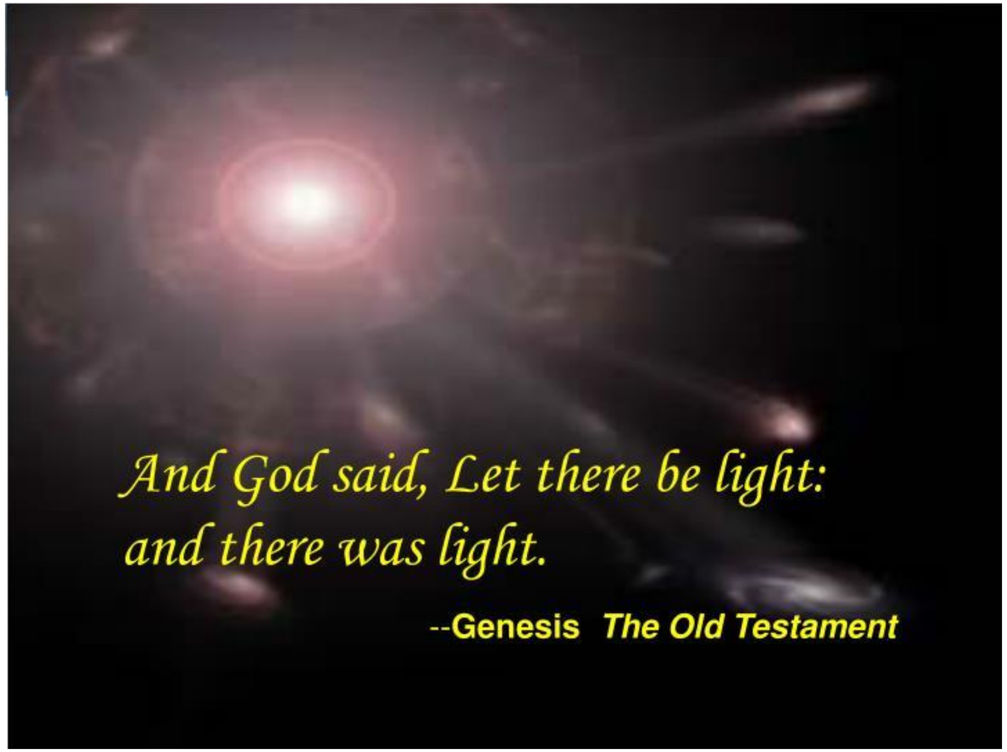
Dark state-photon interactions

Vector Portal	$F_{\mu\nu}X^{\mu\nu}$
Higgs Portal	$H^\dagger H \phi^\dagger \phi$
Neutrino Portal	HLN_R

Dark current with electromagnetic (EM) form factors

$$A_\mu(\bar{\chi}\,\Gamma^\mu\,\chi)$$





From X. Chu

Dark state-photon interactions

A **milli-charged** dark current $\epsilon e A_\mu(\bar{\chi}\gamma^\mu\chi)$ dimension-4

and its generalizations

via compositeness or loop

[e.g. Pospelov, Veldhuis 2000, Sigurdson, Doran, Kurylov, Caldwell, Kamionkowski 2004, Ho, Scherrer 2012, Kadota, Silk 2014, Mohanty, Rao 2015, Chu, Pradler, Semmelrock 2018...]

New neutral states with electromagnetic (EM) form factors

$-d_\chi(\boldsymbol{E}\cdot\boldsymbol{\sigma}_\chi)$ → electric dipole (EDM): $+\frac{i}{2}d_\chi\,\bar{\chi}\sigma^{\mu\nu}\gamma^5\chi F_{\mu\nu}$,

$-\mu_\chi(\boldsymbol{B}\cdot\boldsymbol{\sigma}_\chi)$ → magnetic dipole (MDM): $+\frac{1}{2}\mu_\chi\,\bar{\chi}\sigma^{\mu\nu}\chi F_{\mu\nu}$,

(dimension-5)

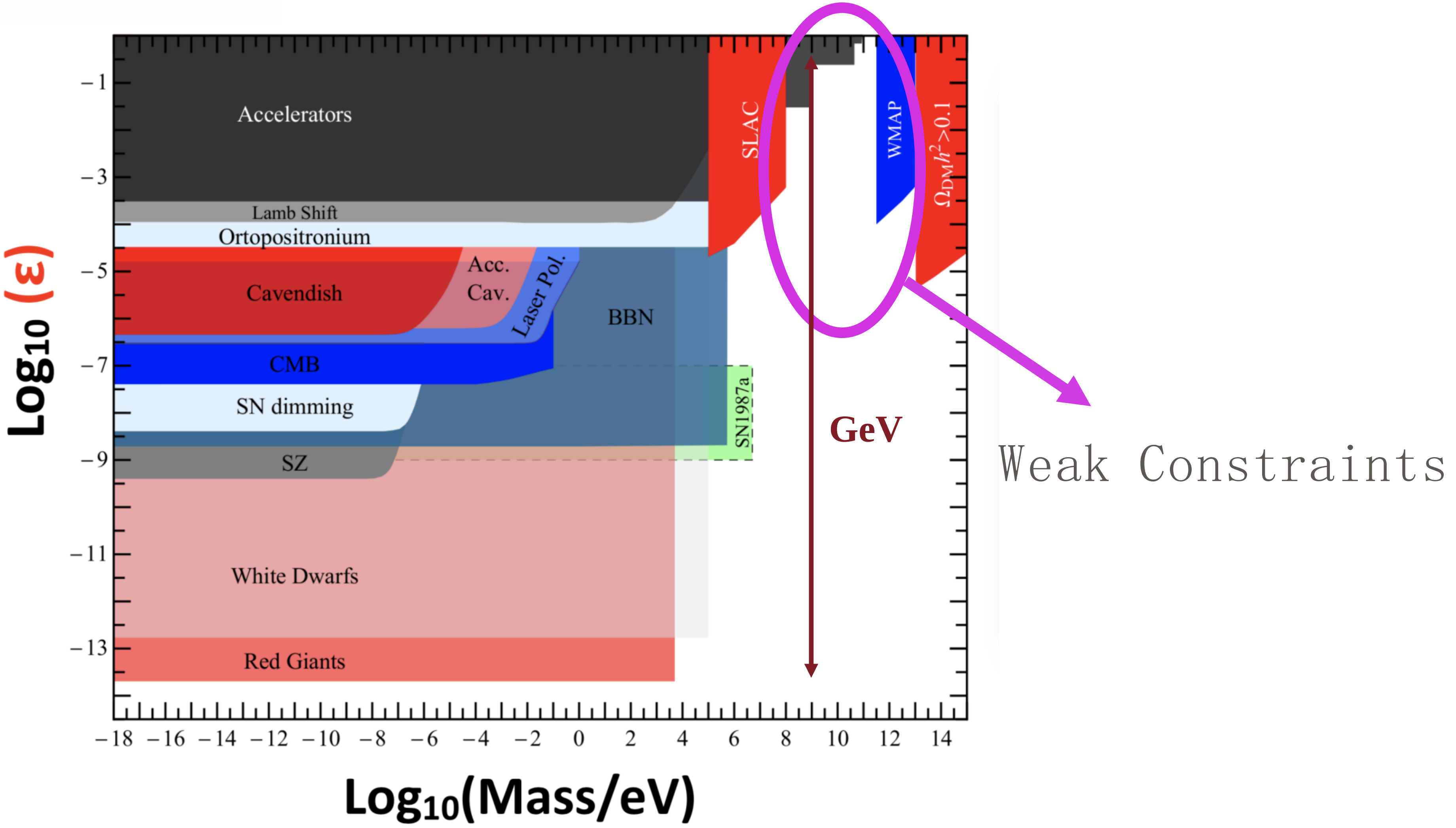
$-a_\chi(\boldsymbol{J}\cdot\boldsymbol{\sigma}_\chi)$ → anapole moment (AM): $-a_\chi\,\bar{\chi}\gamma^\mu\gamma^5\chi\partial^\nu F_{\mu\nu}$,

$-b_\chi(\boldsymbol{\nabla}\cdot\boldsymbol{E})$ → charge radius (CR): $+b_\chi\,\bar{\chi}\gamma^\mu\chi\partial^\nu F_{\mu\nu}$.

(dimension-6)

From X. Chu

Current constraints on millicharge



Jaeckel, Ringwald, arXiv: 1002.0329

Dark state-photon interactions

$$\mathcal{L}_\chi = \frac{1}{2}\mu_\chi \bar{\chi}\sigma^{\mu\nu}\chi F_{\mu\nu} + \frac{i}{2}d_\chi \bar{\chi}\sigma^{\mu\nu}\gamma^5\chi F_{\mu\nu} - a_\chi \bar{\chi}\gamma^\mu\gamma^5\chi\partial^\nu F_{\mu\nu} + b_\chi \bar{\chi}\gamma^\mu\chi\partial^\nu F_{\mu\nu}$$

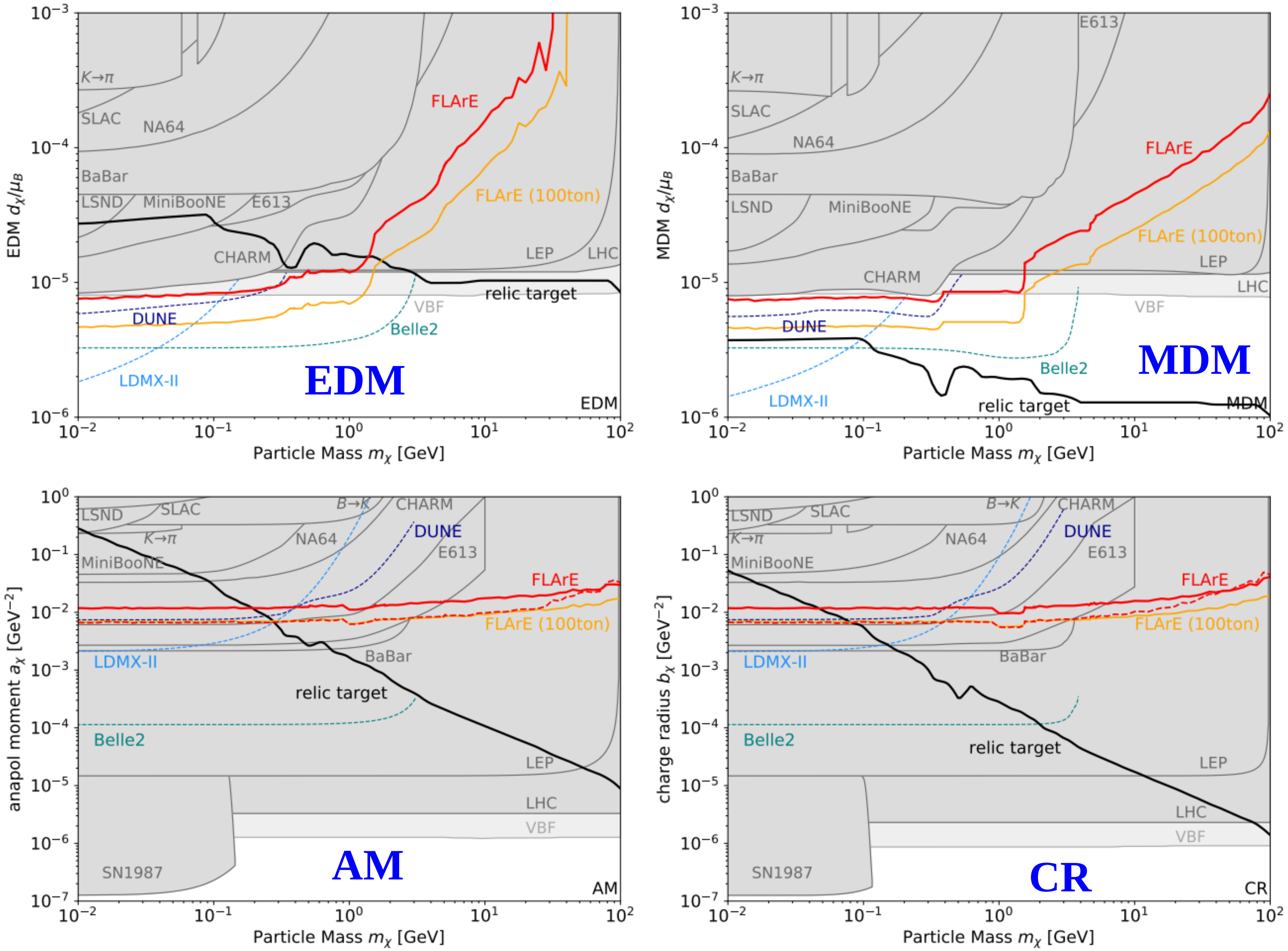
$$\mathcal{L}_\chi = \frac{1}{2}\mu^B_\chi \bar{\chi}\sigma^{\mu\nu}\chi B_{\mu\nu} + \frac{i}{2}d^B_\chi \bar{\chi}\sigma^{\mu\nu}\gamma^5\chi B_{\mu\nu} - a^B_\chi \bar{\chi}\gamma^\mu\gamma^5\chi\partial^\nu B_{\mu\nu} + b^B_\chi \bar{\chi}\gamma^\mu\chi\partial^\nu B_{\mu\nu}$$

dimension-5

dimension-6

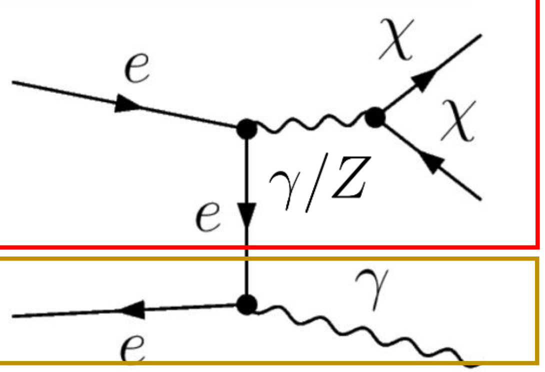
$\mathcal{C}_\chi = \mathcal{C}^B_\chi c_W$ with $\mathcal{C}_\chi = \mu_\chi,\ d_\chi,\ a_\chi,\ b_\chi$

Current constraints on χ with EM form factors



Felix Kling, et. al., arXiv: 2205.09137

Pair production at electron colliders



$$\frac{d^2\sigma}{dx_\gamma dz_\gamma} = H\left(x_\gamma, z_\gamma; s\right)\sigma_0(s_\gamma)$$

$$z_\gamma = \cos\theta_\gamma$$

$$H\left(x_\gamma, z_\gamma; s\right) = \frac{\alpha}{\pi}\frac{1}{x_\gamma}\left[\frac{1+(1-x_\gamma)^2}{1-z_\gamma^2} - \frac{x_\gamma^2}{2}\right]$$

$$\sigma_0(s) = \frac{\alpha}{4}\frac{f\left(s\right)}{s^2}\sqrt{\frac{s-4m_\chi^2}{s}}\left[c_W^2+(g_L+g_R)\frac{s(s-M_Z^2)}{(s-M_Z^2)^2+M_Z^2\Gamma_Z^2}+\frac{1}{2}\frac{1}{c_W^2}(g_L^2+g_R^2)\frac{s^2}{(s-M_Z^2)^2+M_Z^2\Gamma_Z^2}\right]$$

$$\mathrm{MDM}: f\left(s\right) = \frac{2}{3}\mu_\chi^2 s^2\left(1+\frac{8m_\chi^2}{s}\right)$$

$$\mathrm{EDM}: f\left(s\right) = \frac{2}{3}d_\chi^2 s^2\left(1-\frac{4m_\chi^2}{s}\right)$$

$$\mathrm{AM}: f\left(s\right) = \frac{4}{3}a_\chi^2 s^3\left(1-\frac{4m_\chi^2}{s}\right)$$

$$\mathrm{CR}: f\left(s\right) = \frac{4}{3}b_\chi^2 s^3\left(1+\frac{2m_\chi^2}{s}\right)$$

BEPCII/BESIII

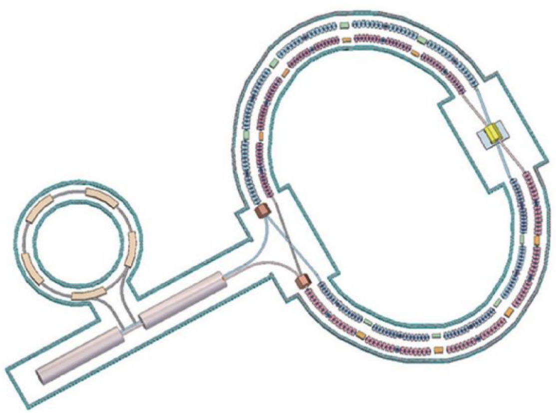
Super Tau-Charm Facility (STCF)

- Peak luminosity $0.5\text{-}1\times10^{35}$ $cm^{-2}s^{-1}$ at 4 GeV
- Energy range E_{cm} = 2–7GeV
- Polarization available on electron beam (Phase II)
- Basic Features of machine :
  - Symmetric machine with dual-ring
  - Large Piwinski angle collision + crabbed waist solution for the IR
  - Siberia snake for polarization
  - Total cost 4B RMB

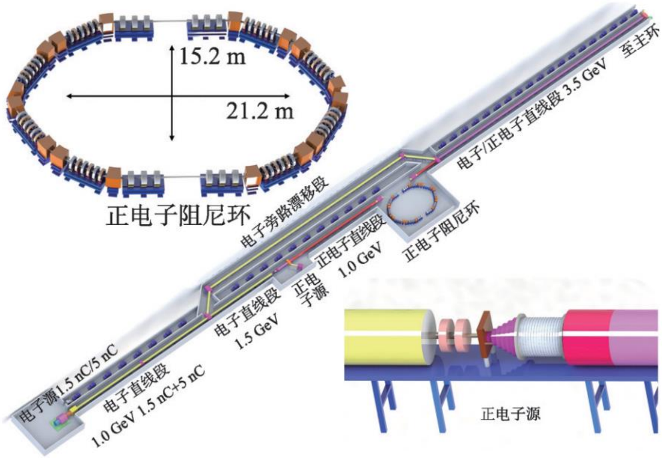
From H. Peng @CHARM18

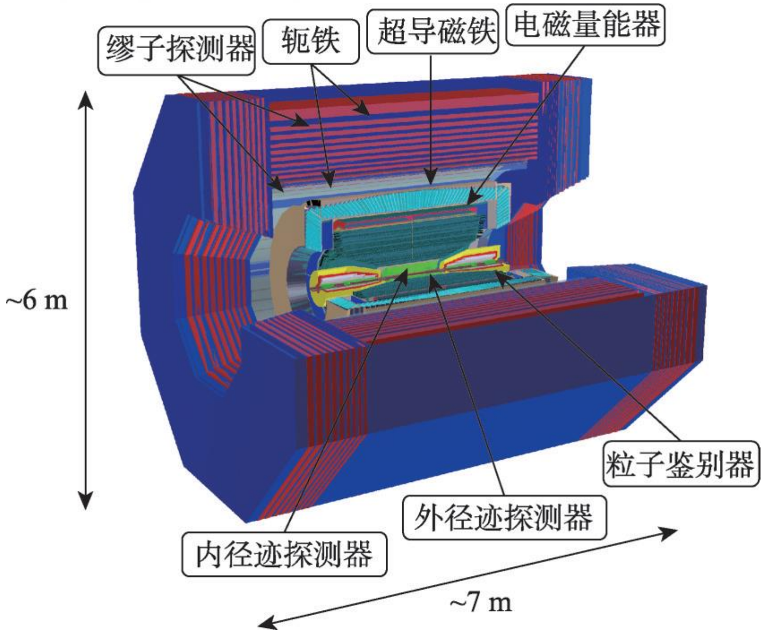
STCF

(a)



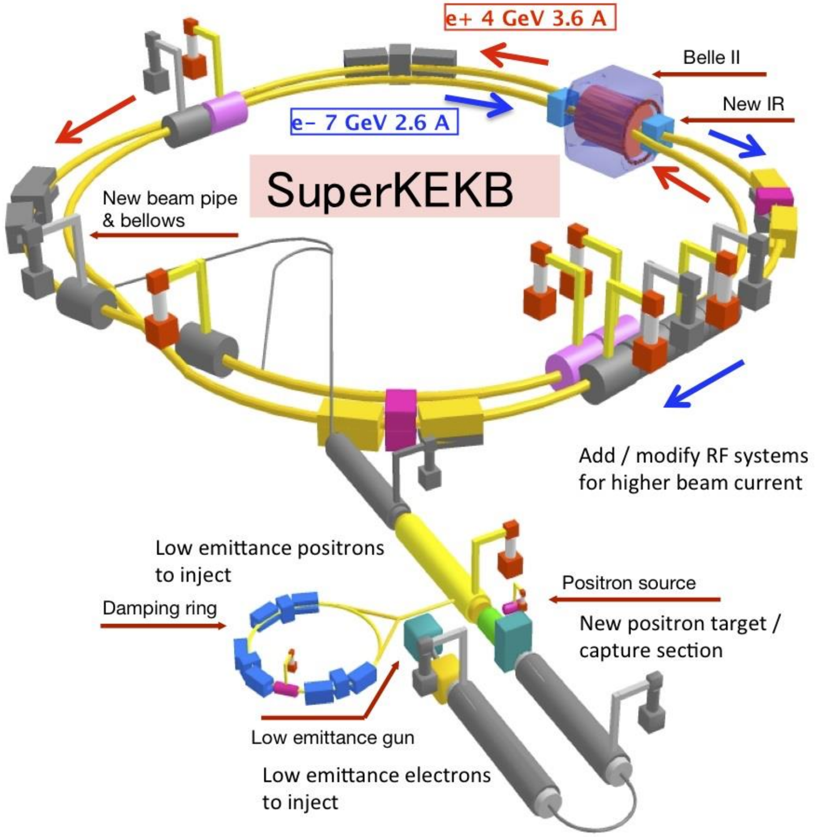
(b)

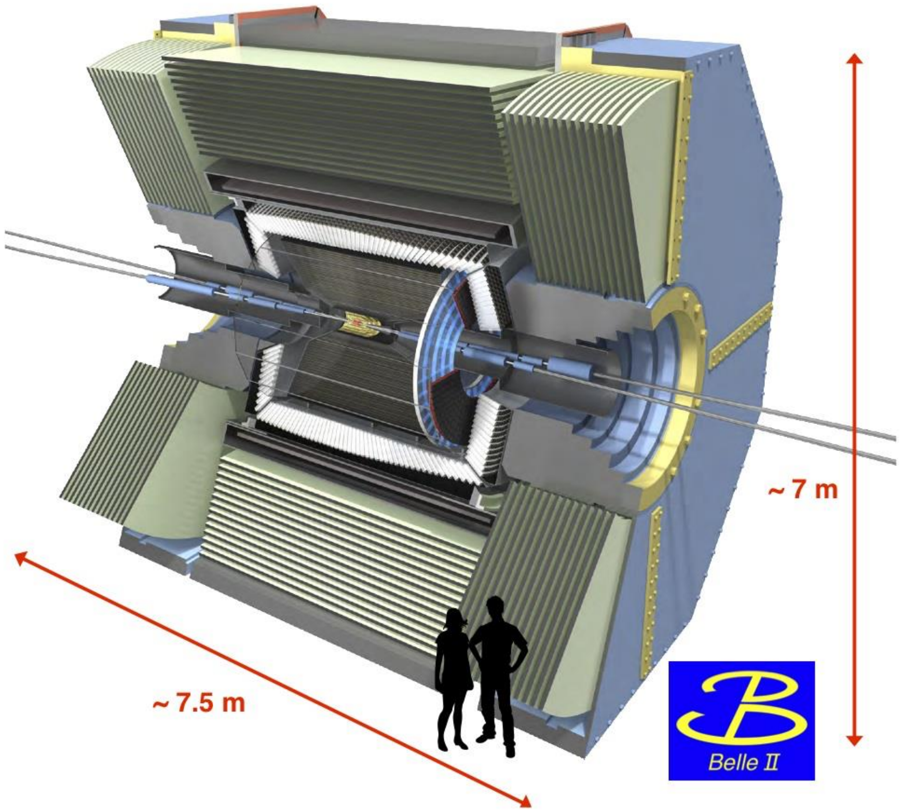




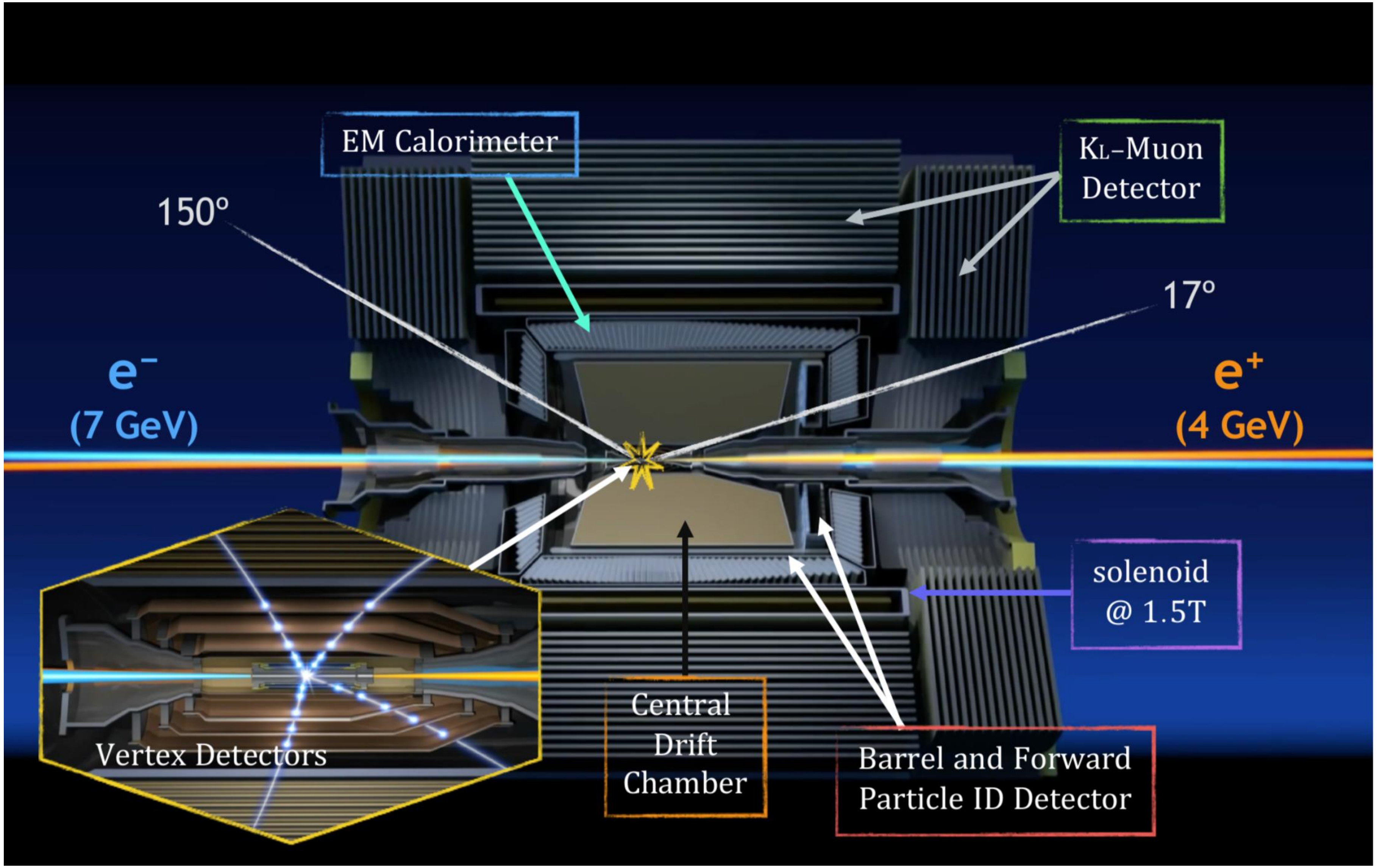
彭海平,郑阳恒,周小蓉. 中国超级陶粲装置[J]. 物理,2020,49(8):513-524. DOI:10.7693/wl20200803.

SuperKEKB/Belle-II





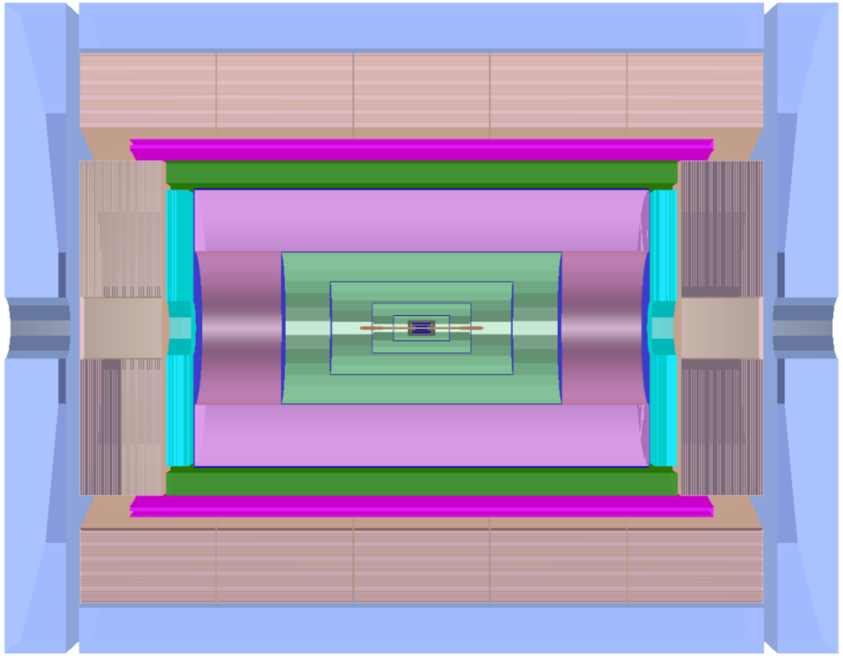
SuperKEKB/Belle-II



From X. Wang @HFCPV19

Operation mode	$\sqrt{s}$ (GeV)	L per IP (10^{34} cm^{-2}s^{-1})	Years	Total $\int L$ (ab^{-1}, 2 IPs)	Event yields
H	240	3	7	5.6	1×10^6
Z	91.2	32 (*)	2	16	7×10^{11}
W^+W^-	158–172	10	1	2.6	2×10^7 (†)

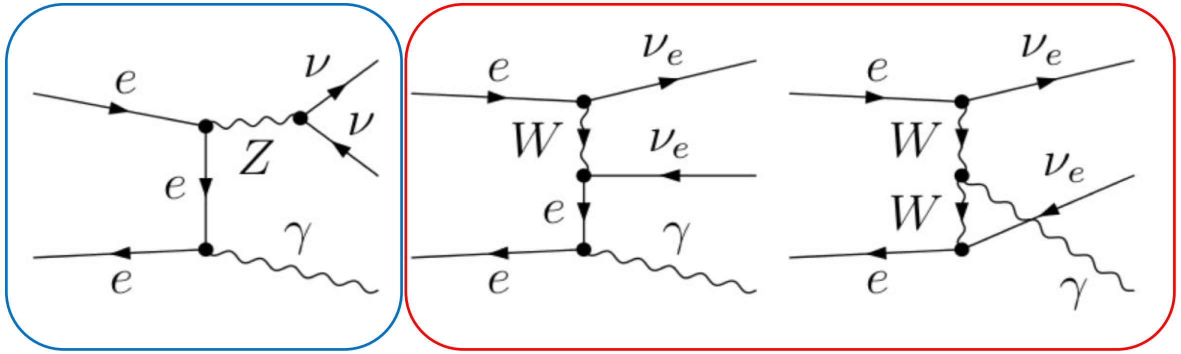
Operation mode	Z factory	WW threshold	Higgs factory	$t\bar{t}$
$\sqrt{s}$ (GeV)	91.2	160	240	360
Run time (year)	2	1	10	5
Instantaneous luminosity ($10^{34} cm^{-2} s^{-1}$, per IP)	191.7	26.6	8.3	0.83
Integrated luminosity (ab^{-1}, 2 IPs)	100	6	20	1
Event yields	3×10^{12}	1×10^8	4×10^6	5×10^5



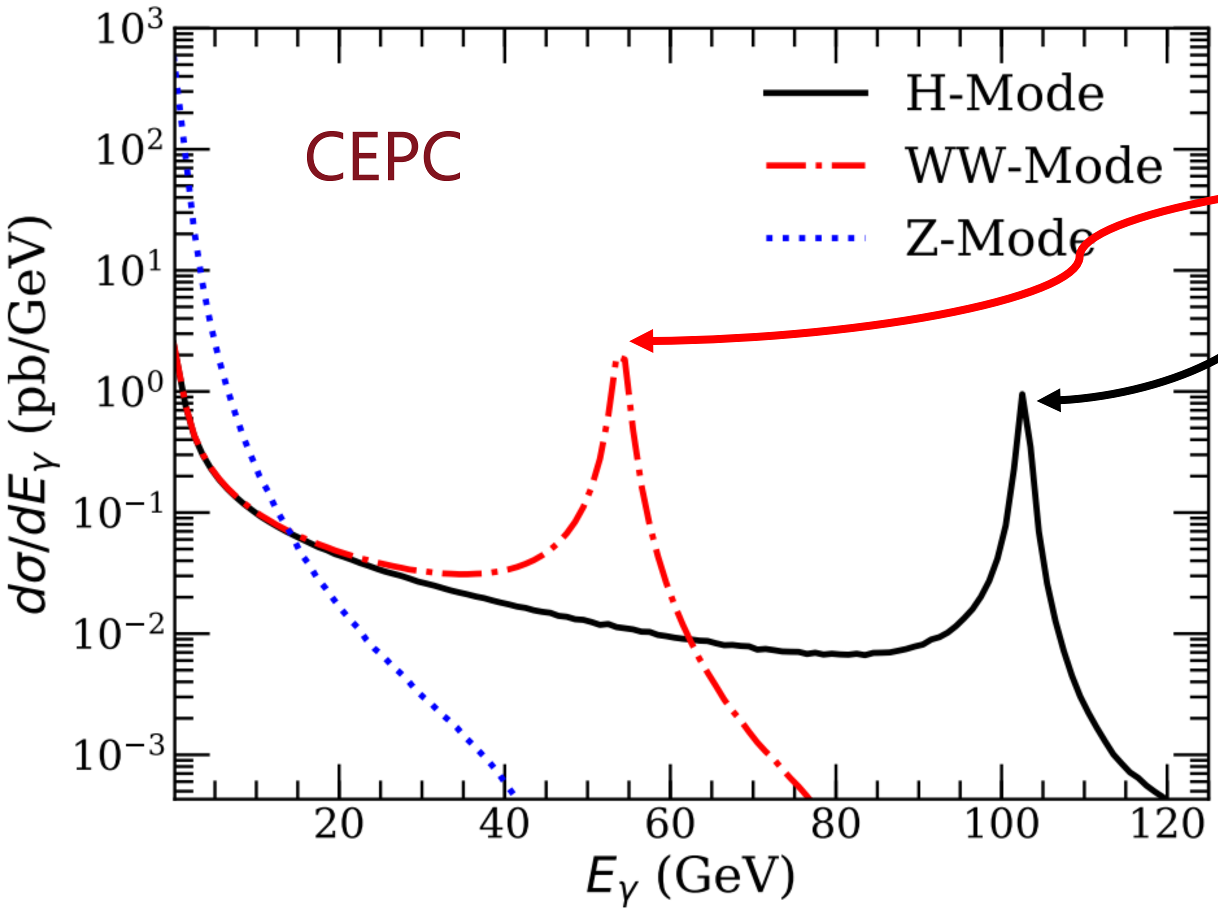
Backgrounds For Mono-γ

Irreducible Backgrounds

$$e^+e^- \to \nu\bar{\nu}\gamma$$



Differential cross section for the IB



$E_\gamma > 0.1\,\mathrm{GeV}$ and $|\cos\theta_\gamma| < 0.99$

$$E_\gamma^Z = \frac{s - M_Z^2}{2\sqrt{s}}$$

$E_\gamma^Z \simeq 54\,\mathrm{GeV}$

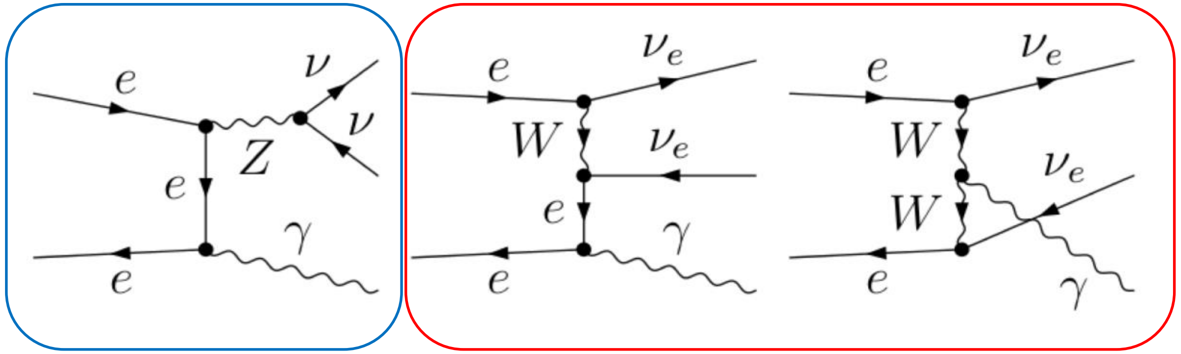
$E_\gamma^Z \simeq 103\,\mathrm{GeV}$

Z. Liu, Y.-H. Xu, **YZ**, JHEP 06 (2019) 009

Backgrounds For Mono-γ

Irreducible Backgrounds

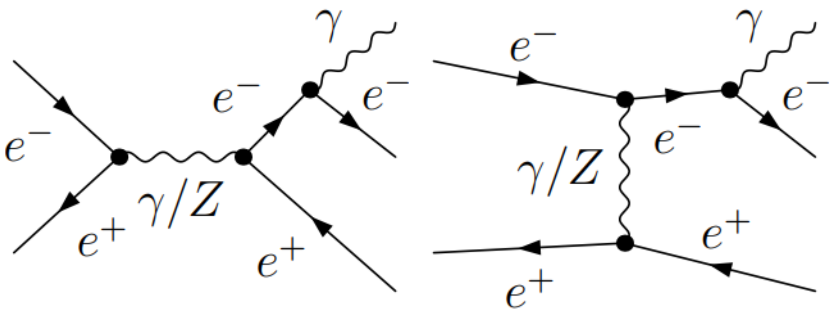
$$e^+e^- \to \nu\bar{\nu}\gamma$$



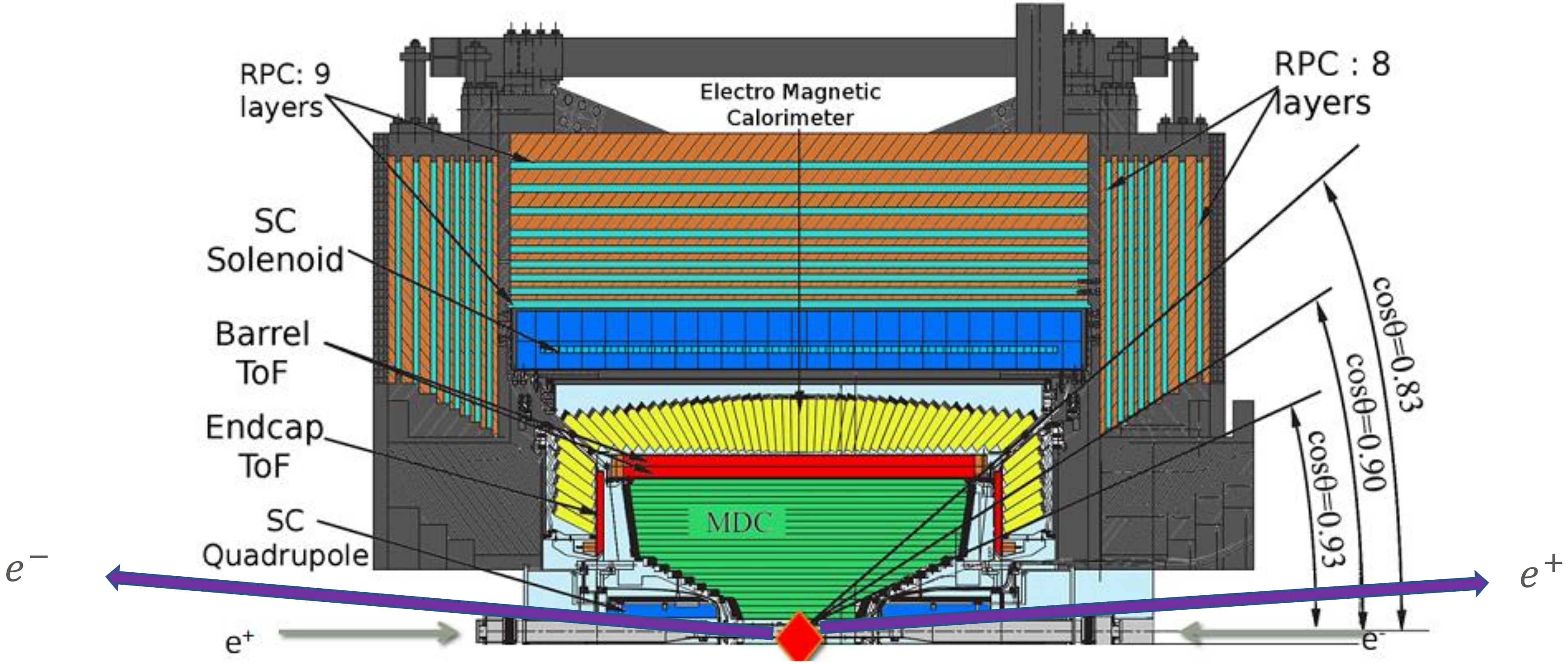
Reducible Backgrounds

$$e^+e^- \to e^+e^-\gamma$$

$$e^+e^- \to \gamma\gamma(\gamma)$$

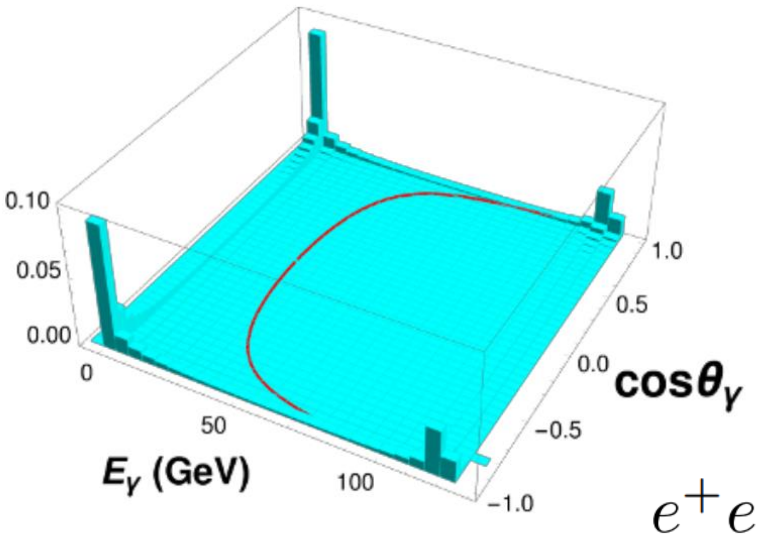


Reducible background

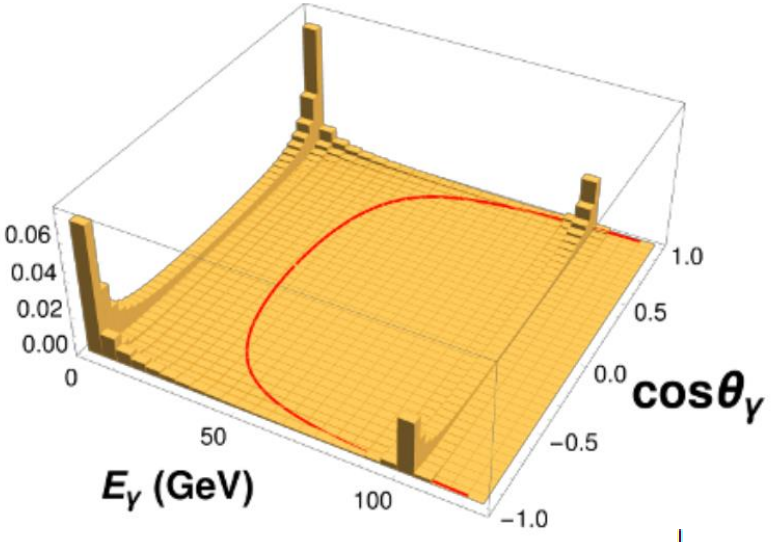


$$e^+e^- \to e^+e^-\gamma$$

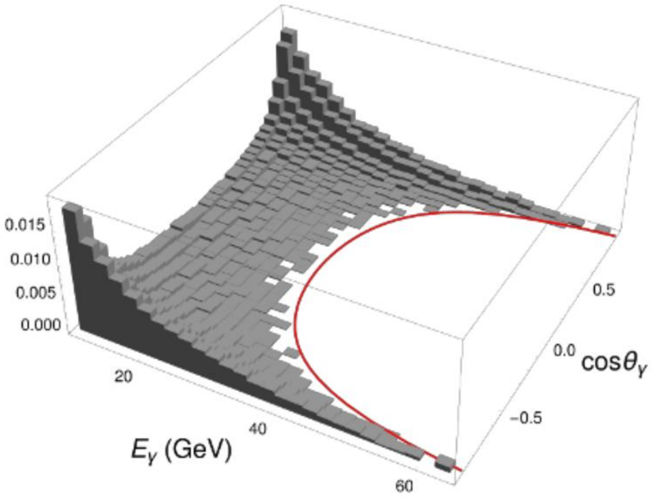
Differential cross section for BG and signal



$e^+e^- \to \chi\bar{\chi}\gamma$



$e^+e^- \to \nu\bar{\nu}\gamma$

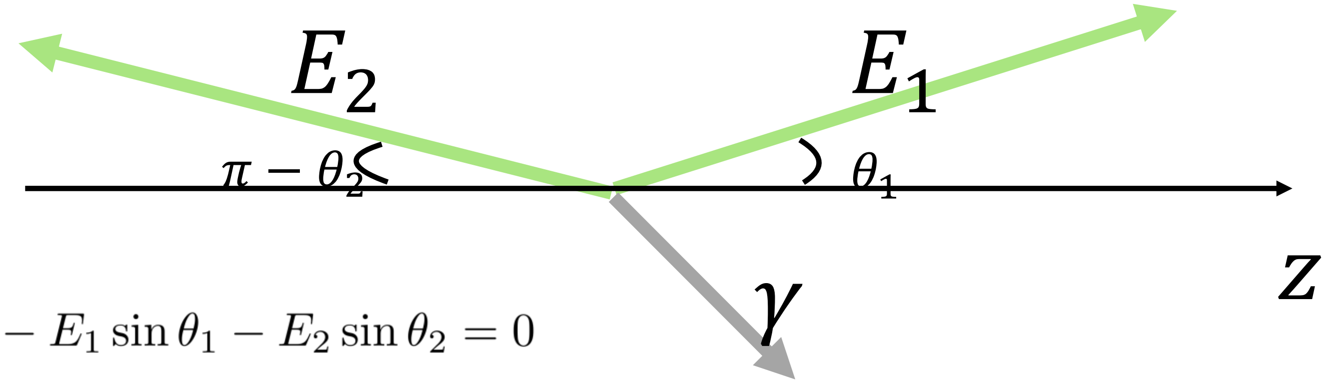


$e^+e^- \to e^+e^-\gamma$

For certain polar angle of final photon, the maximum energy of the photon in the reducible background occurs.

Z. Liu, Y.-H. Xu, **YZ**, JHEP 06 (2019) 009

Cuts to remove RB



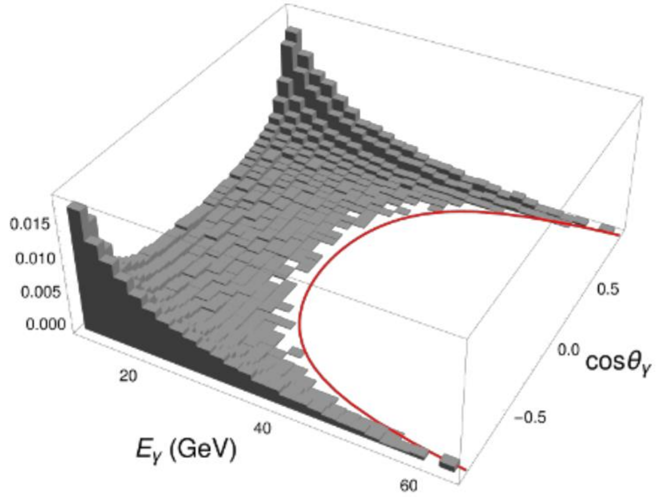
$$\begin{cases} E_\gamma^m \sin\theta_\gamma - E_1 \sin\theta_1 - E_2 \sin\theta_2 = 0 \\ E_\gamma^m \cos\theta_\gamma + E_1 \cos\theta_1 + E_2 \cos\theta_2 = 0 \\ E_\gamma^m + E_1 + E_2 = \sqrt{s}, \end{cases}$$

$$E_\gamma^m(\theta_\gamma) = \frac{\sqrt{s}(A\cos\theta_1 - \sin\theta_1)}{A(\cos\theta_1 - \cos\theta_\gamma) - (\sin\theta_\gamma + \sin\theta_1)}$$

$$A = (\sin\theta_1 - \sin\theta_2)/(\cos\theta_1 - \cos\theta_2)$$

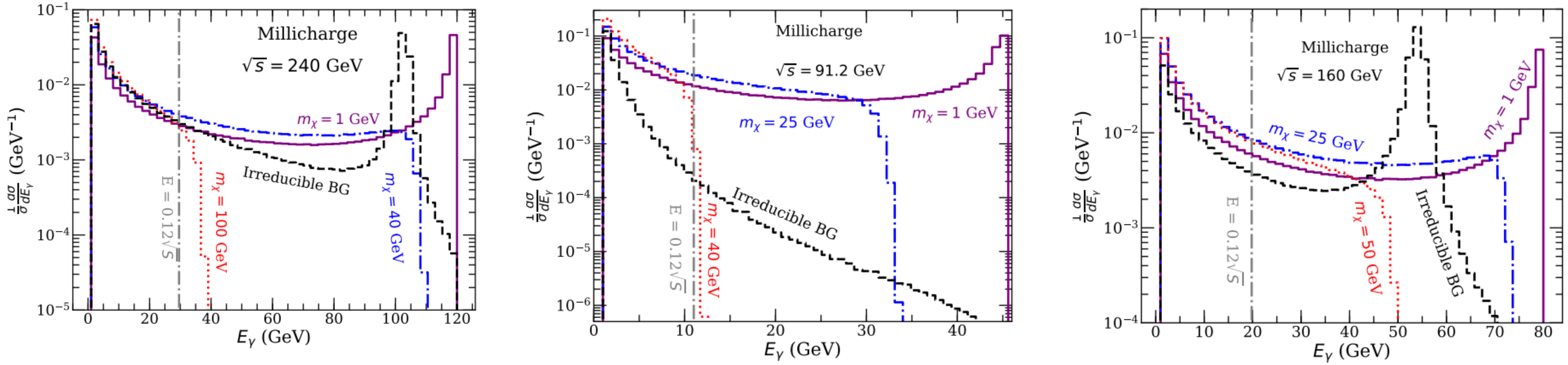
$$\sin\theta_1 = \sin\theta_2 = \sin\theta_b$$

$$E_\gamma^m(\theta_\gamma) = \sqrt{s}\left(1 + \frac{\sin\theta_\gamma}{\sin\theta_b}\right)^{-1}$$



When $\sin\theta_\gamma = 1$ $\quad (E_B^m)_{\min} \simeq 0.12\sqrt{s}.$

合肥工業大學
HEFEI UNIVERSITY OF TECHNOLOGY



Z. Liu, Y.-H. Xu, **YZ**, JHEP 06 (2019) 009

(1) $E_\gamma > 0.1\,\text{GeV}$,

(2) $|\cos\theta_\gamma| < |\cos\theta_b| = 0.99$,

EMC coverage

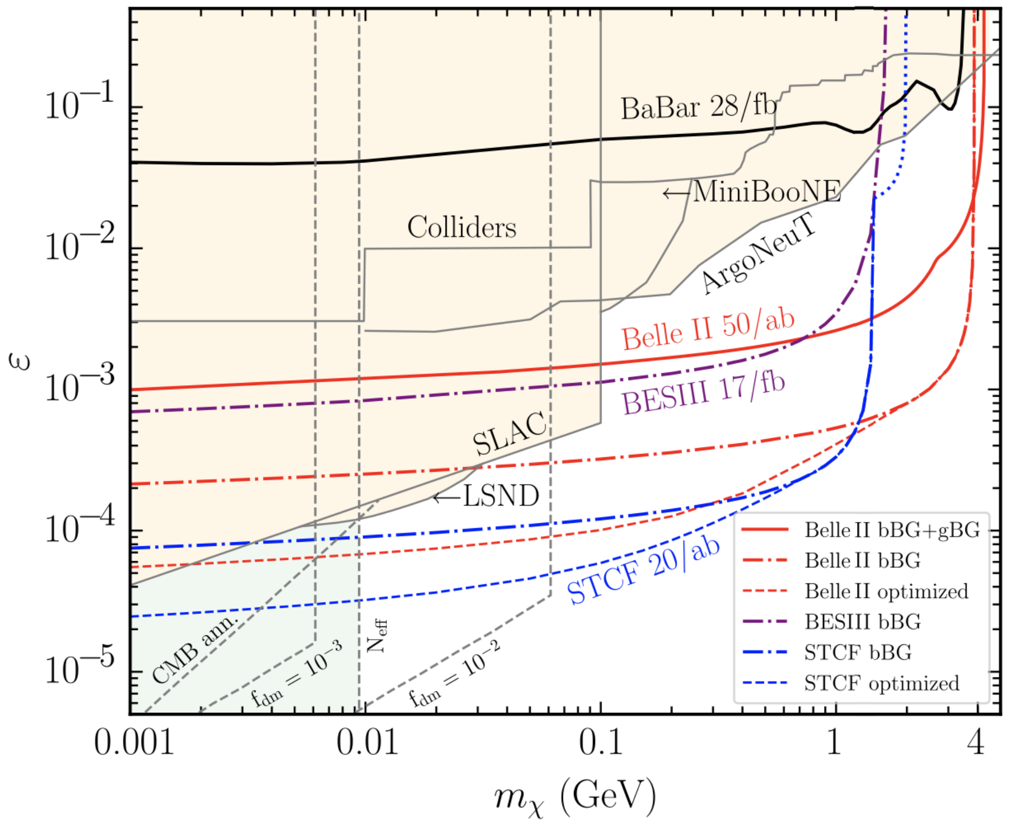
(3) $E_\gamma < E_\chi^m = (s - 4m_\chi^2)/(2\sqrt{s})$, Photon maximum energy for the signal

(4) veto $E_\gamma \in (E_\gamma^Z \pm 5\Gamma_\gamma^Z)$, $\Gamma_\gamma^Z = M_Z\Gamma_Z/\sqrt{s}$ Veto Z resonance in irreducible background

(5) $E_\gamma(\theta_\gamma) > E_B^m(\theta_\gamma) = \sqrt{s}(1 + \sin\theta_\gamma/\sin\theta_b)^{-1}$. Remove reducible background

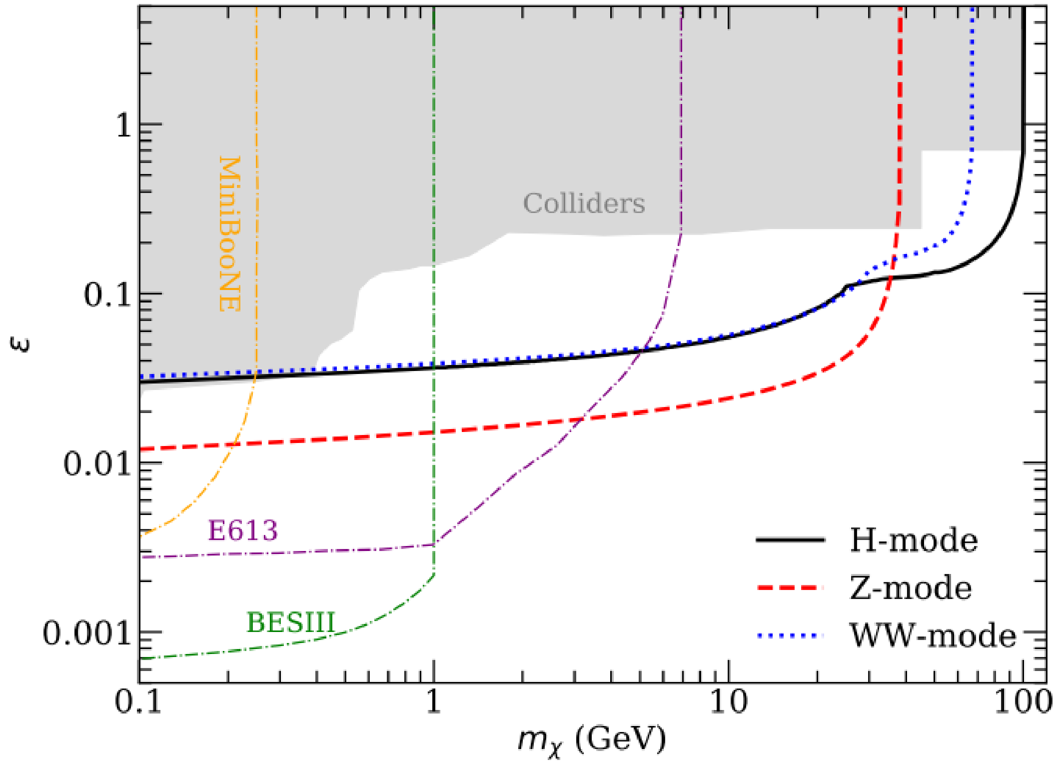
Sensitivity on millicharge

J. Liang, Z. Liu, Y. Ma, **YZ**, Phys.Rev.D 102 (2020), 015002



The expected limit on MCPs from BESIII is near ϵ ~ 0.001 for 100 MeV mass.

Z. Liu, Y.-H. Xu, **YZ**, JHEP 06 (2019) 009



The CEPC Z-mode with 16/ab has a better sensitivity than the other two running modes in the millicharged DM mass range m<40 GeV, beyond which the H-mode dominates the reach.

Constraints on χ-photon interactions from LEP

on Z-pole

with an integrated luminosity of 100/pb at CM energies $\sqrt{s}$ = 89.45−91.34 GeV
1 GeV < E_γ < 10 GeV
45° < θ_γ < 135°

[L3], Phys. Lett. B 431 (1998), 199

off Z-pole

with an integrated luminosity of 619/pb at CM energies $\sqrt{s}$ = 188.6−209.2 GeV
$p_T^\gamma > 0.02\sqrt{s}$
45° < θ_γ < 135°

[L3], Phys. Lett. B 587 (2004), 16

$$|\sigma^{\rm SM} + \sigma^{\chi} - \sigma^{\rm exp}| \leq \delta\sigma^{\rm exp}$$

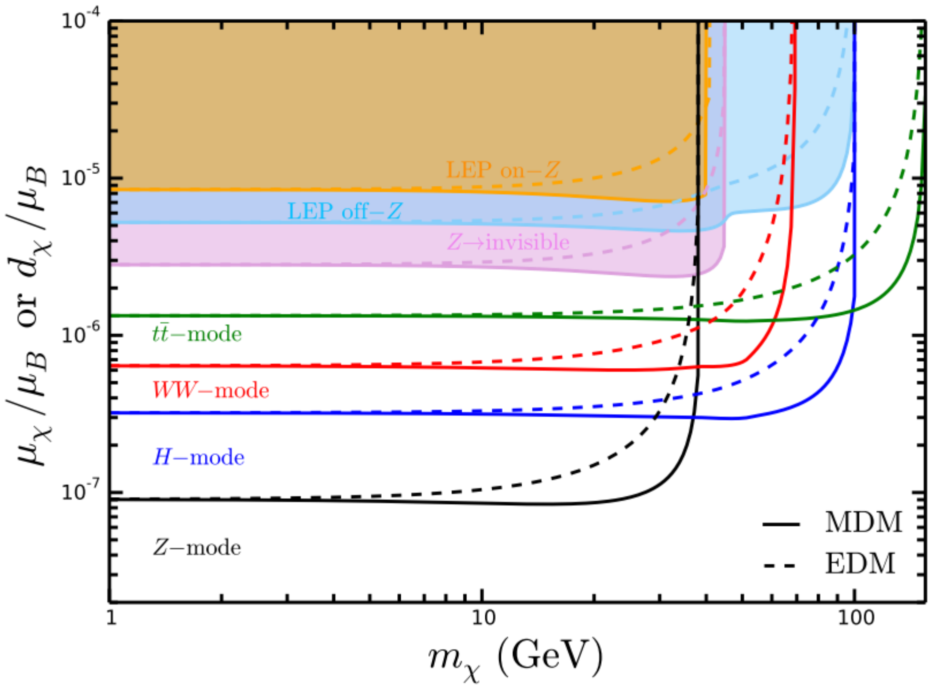
$$\Gamma_{Z\to\chi\bar{\chi}} = \frac{s_W^2 f(M_Z^2)}{16\pi M_Z}\sqrt{\frac{M_Z^2 - 4m_\chi^2}{M_Z^2}}$$

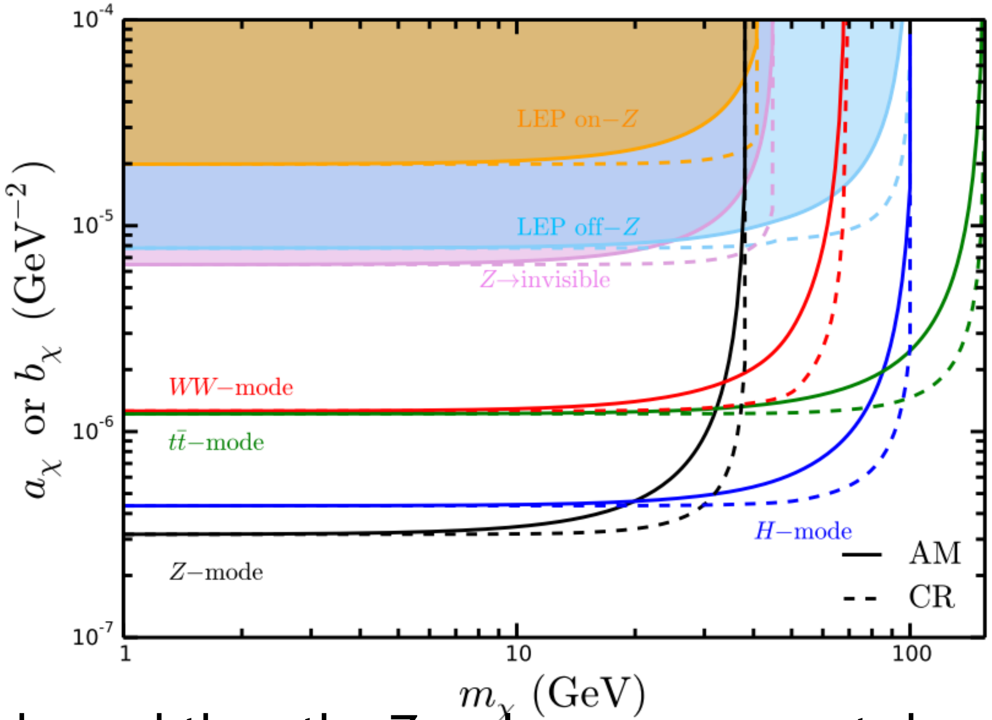
$$\Gamma_{Z\to\chi\bar{\chi}} < 2.0 \text{ MeV at } 95\% \text{ C.L.}$$

hep-ex/0509008

LEP & CEPC sensitivity on χ-photon interactions

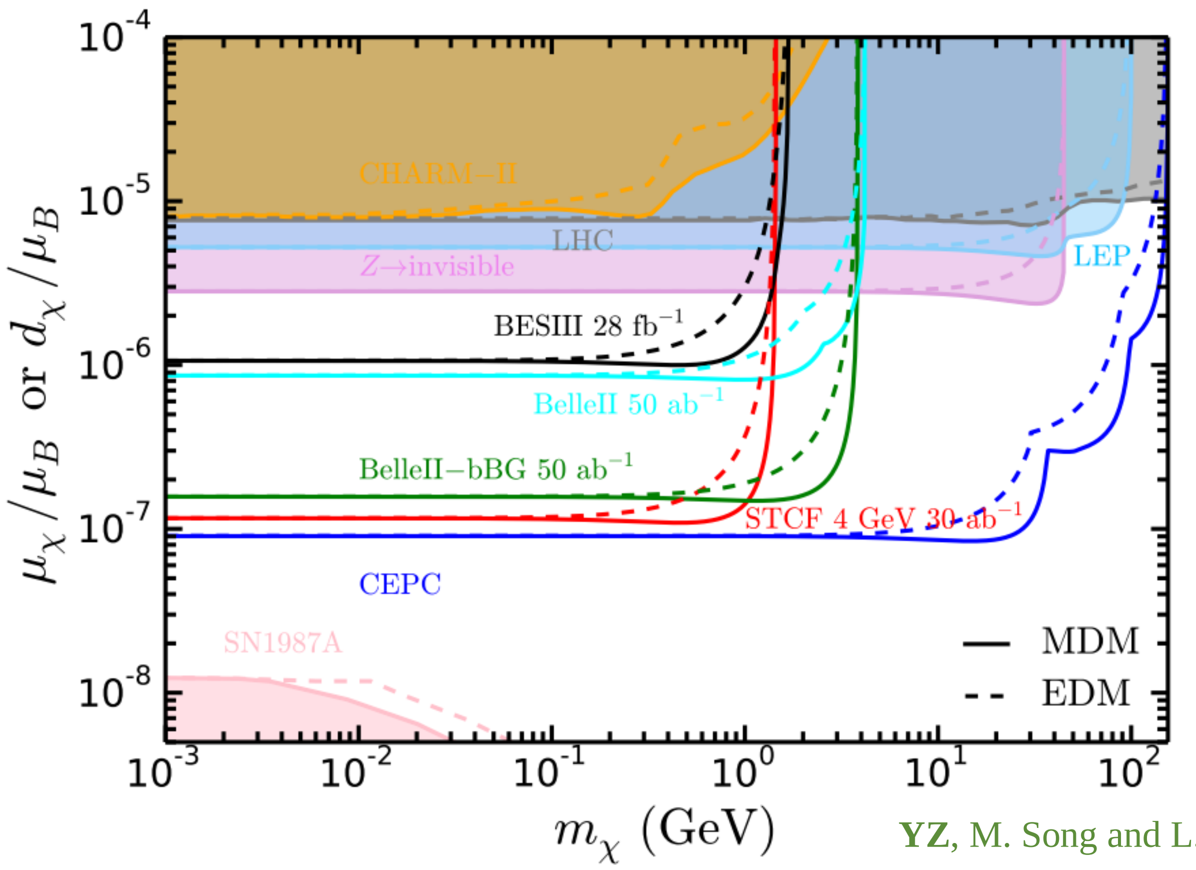
YZ, M. Song and L. Chen, arXiv: 2208.08142

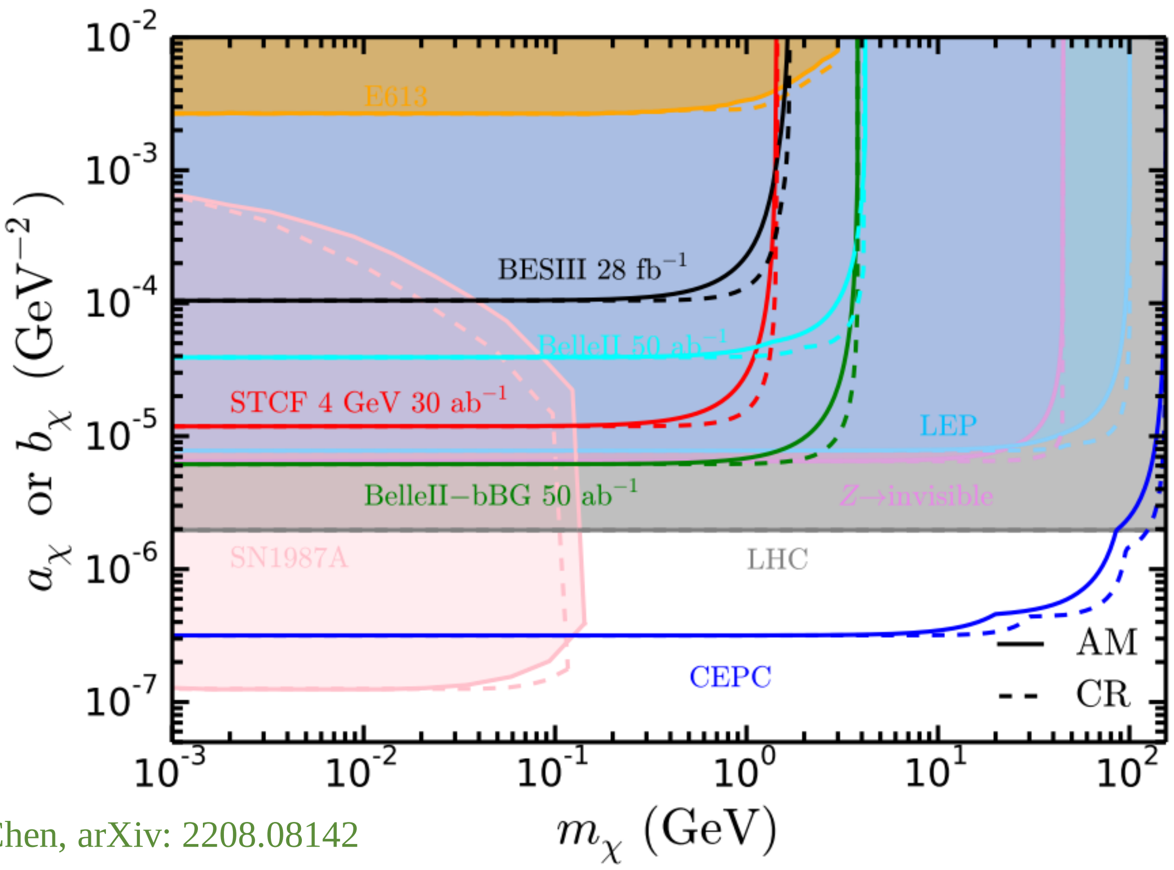




- off Z-pole measurement imposes more stringent bound than the Z-pole measurement does at LEP
- the limits on dark states with electromagnetic form factors by invisible Z decay are stricter than those by monophton searches at LEP
- The Z-mode with 100/ab has the best sensitivity for the light dark states.

Results





YZ, M. Song and L. Chen, arXiv: 2208.08142

The low-energy electron colliders can secure a place in the future to probe low-mass light dark states with electromagnetic form factors via mass-dimension 5 operators.

Summary

- Consider new particles that are millicharged or electrically neutral but couple to the electromagnetic current via higher dimensional operators, such as magnetic- and electric-dipole moments (dim-5) as well as through an anapole moment and charge radius interactions (dim-6).

- The electron colliders including BESIII, STCF, Belle II, which operate with the center-of-mass at several GeV, have leading sensitivity on millicharge and the corresponding electromagnetic form factors for the mass-dimension 5 operators with dark states lighter than several GeV, while they can not provide competitive upper limits for the mass-dimension 6 operators. CEPC will have better sensitivity.

谢谢！
Thank You!