Dark sector searches at the Muon Collider

Chiara Aimè
Università di Pisa & INFN Pisa

IN SUPREMÆ DIGNITATIS 1343

Dipartimento di Fisica "E. Fermi"
UNIVERSITÀ DI PISA

INFN
Istituto Nazionale di Fisica Nucleare

International MUON Collider Collaboration

MuCol

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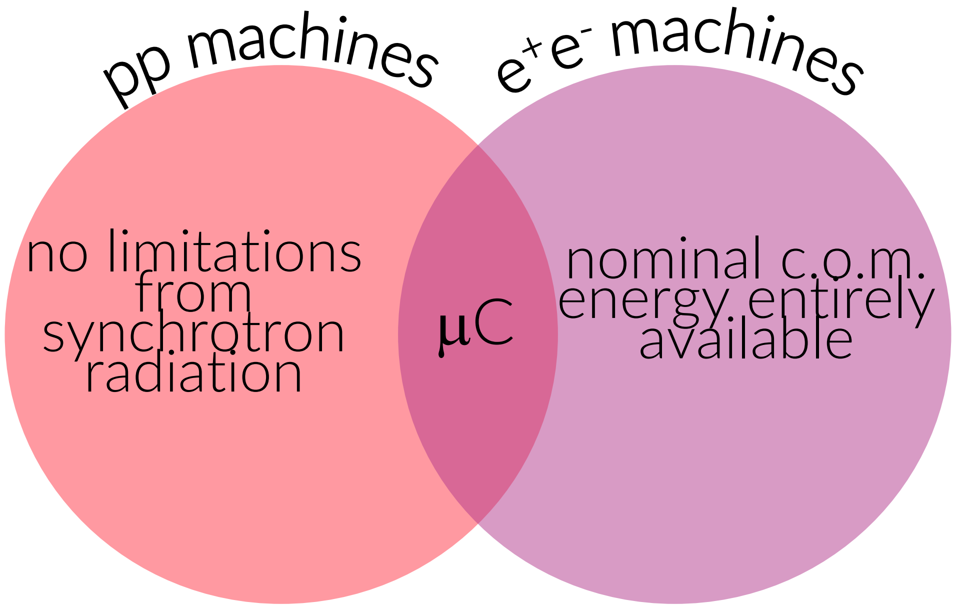
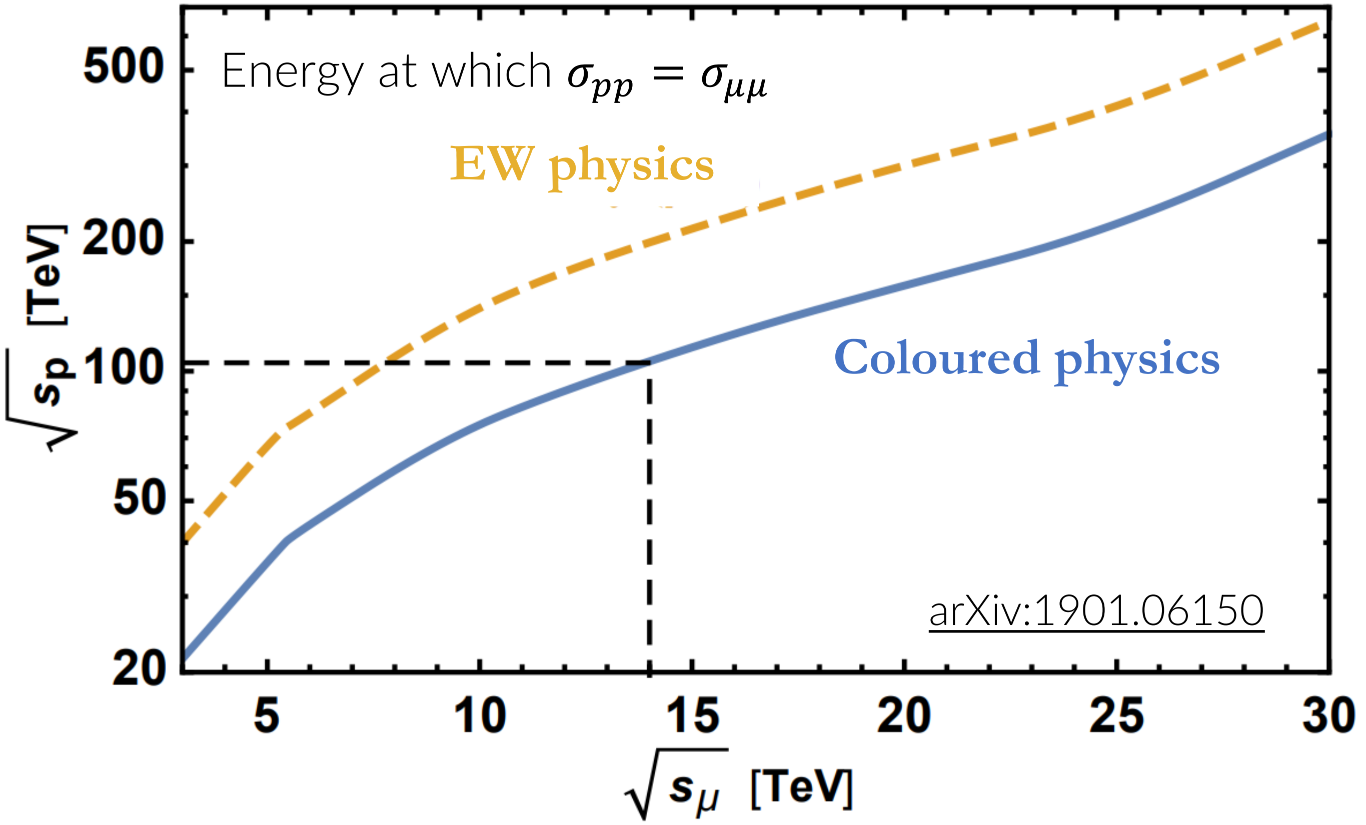
Muon Collider potential

Opportunities





Challenges

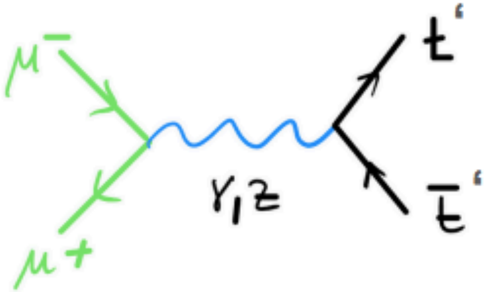
	3 TeV	10 TeV
luminosity	1.8 10^{34} cm^{-2} s^{-1}	2 10^{35} cm^{-2} s^{-1}

$$L_{\text{int}} = 10\,\text{ab}^{-1}\left(\frac{E_{\text{cm}}}{10\,\text{TeV}}\right)^2$$

The Muon Collider combines the precision of a lepton collider with the energy reach of a hadron collider, yielding an unprecedented physics potential

Two machines in one

Muon annihilation

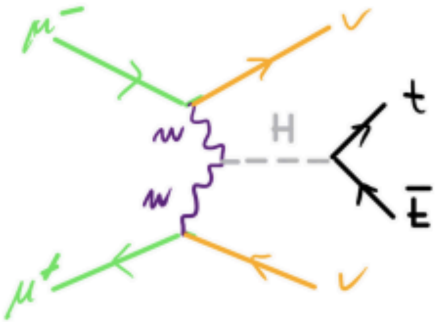


$$\sigma_s \sim \frac{1}{s}$$

$$\sqrt{s} \lesssim 1 - 5 \ \text{TeV}$$

⇥ Energy frontier

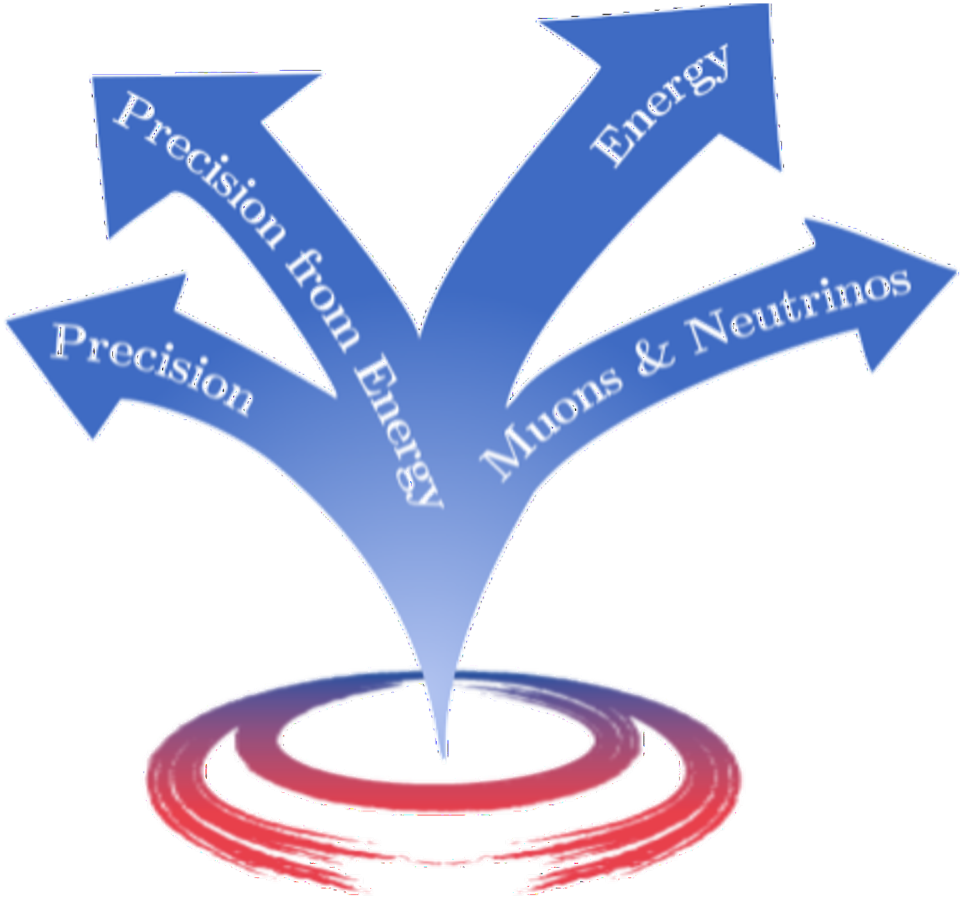
Vector Boson Fusion

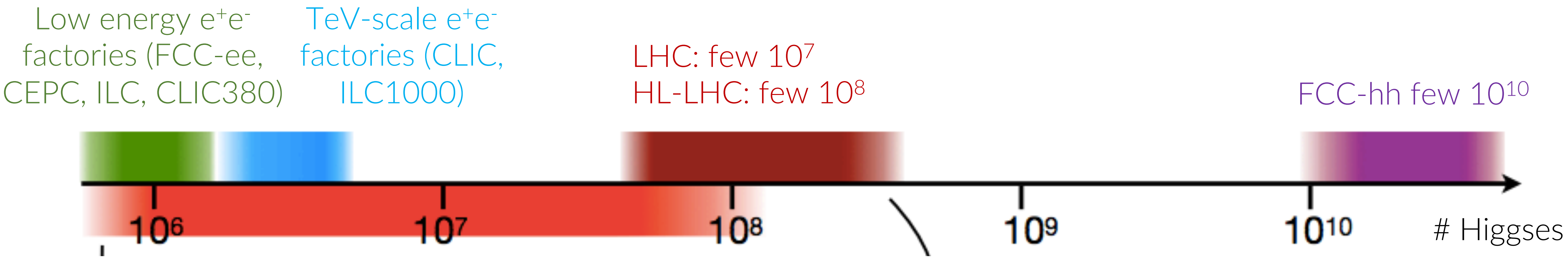


$$\sigma_s \sim \frac{1}{M^2} log^n \frac{s}{M}$$

$$\sqrt{s} \gtrsim 1 - 5 \ \text{TeV}$$

⇥ Precision frontier

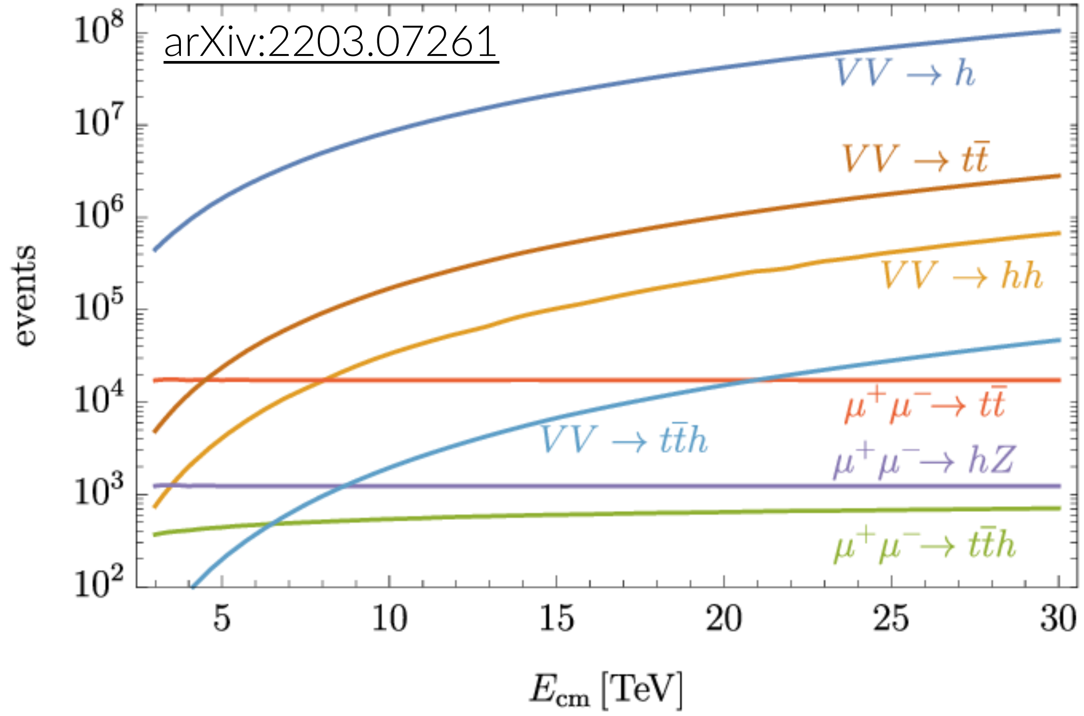




Muon collider: 10^6-10^8

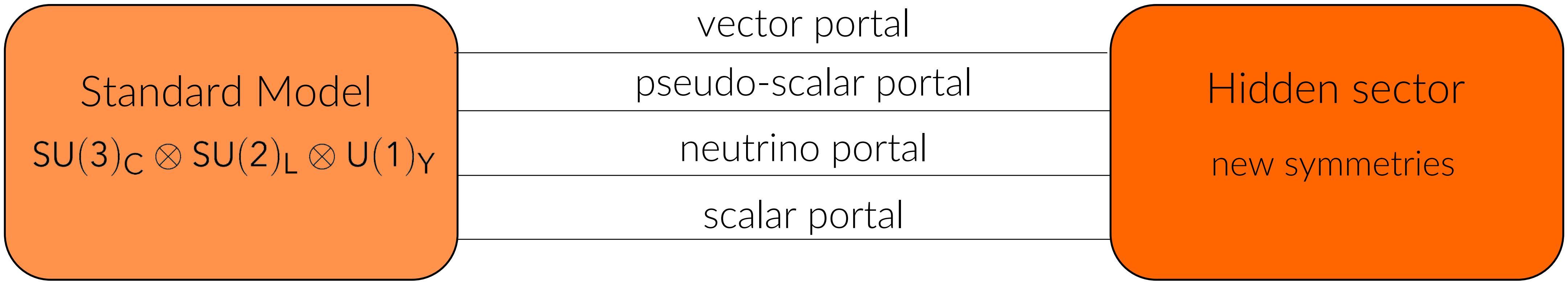
clean environment: Higgs BR measured with 10^{-3} precision

large QCD backgrounds: only rare modes accessible

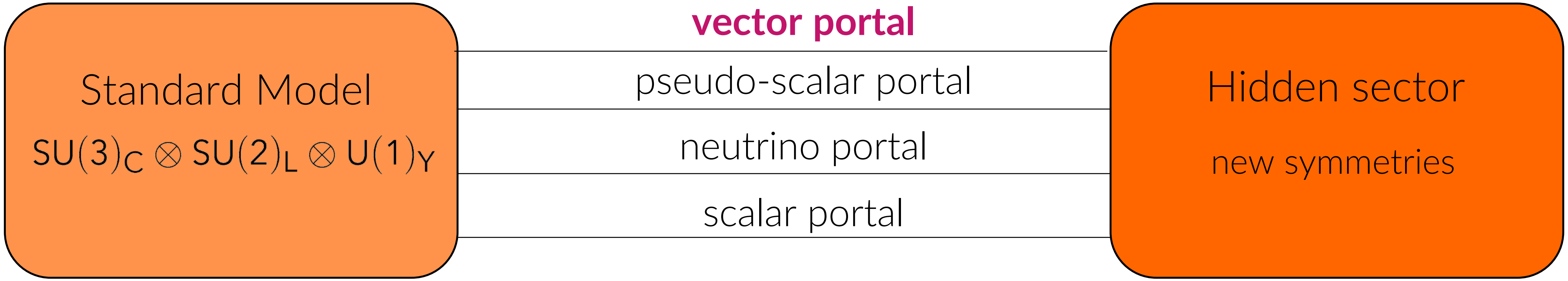


	cross section [fb]		expected events	
	3 TeV	10 TeV	1 ab^{-1} at 3 TeV	10 ab^{-1} at 10 TeV
H	550	930	5.5×10^5	9.3×10^6
ZH	11	35	1.1×10^4	3.5×10^5
$t\bar{t}H$	0.42	0.14	420	1.4×10^3
HH	0.95	3.8	950	3.8×10^4
HHH	3.0×10^{-4}	4.2×10^{-3}	0.30	42

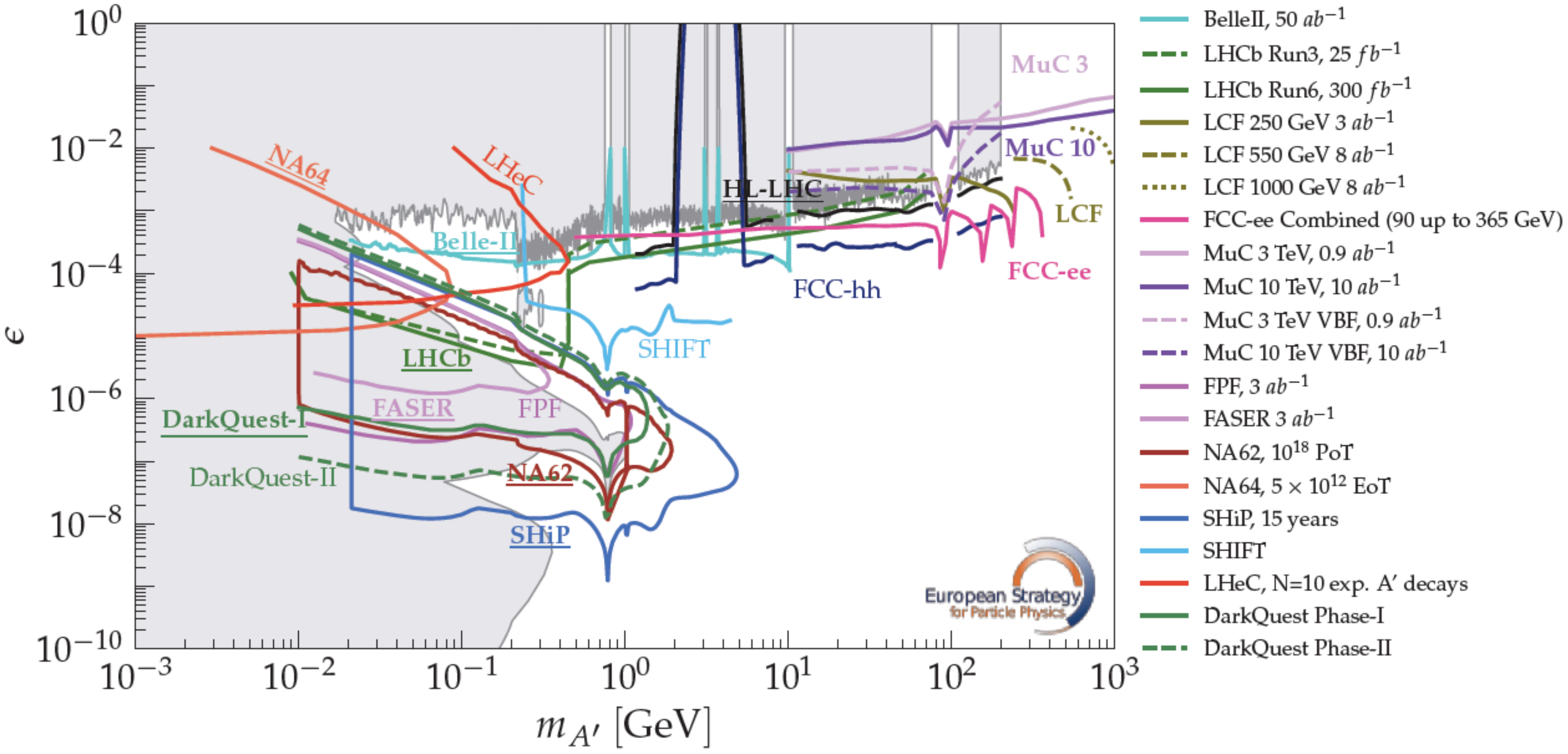
Dark sectors



Dark sectors



Vector portal: dark photon



Vector portal

Vector portals at future lepton colliders
arXiv:2412.09681

$$\mathcal{L}_{int} = g_{Z'} \boldsymbol{J_\mu^{SM}} Z'^\mu + g_D\, J_\mu^{Dark} Z'^\mu$$

1. Dark photon

J_μ^{SM} is the EM current

The dark photon kinematically mixes with SM bosons with parameter $\boldsymbol{\epsilon}$

$$\mathcal{L}_{int} = \frac{\epsilon}{2c_W} Z'_{\mu\nu} B^{\mu\nu} + g_D\, J_\mu^{Dark} Z'^\mu$$

The second parameter is the dark photon mass $\boldsymbol{M_{Z'}}$

$$M_{Z'} \ll M_Z \longrightarrow g_{Z'} \approx e\epsilon$$

$$M_{Z'} \gg M_Z \longrightarrow g_{Z'} \approx \frac{e\epsilon}{c_W^2}$$

2. L_μ-L_τ gauge bosons

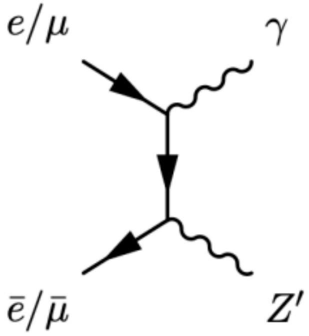
$$J_\rho^{SM} = \bar{\mu}\gamma_\rho\mu - \bar{\tau}\gamma_\rho\tau + \overline{\nu_\mu}\gamma_\rho\nu_\mu - \overline{\nu_\tau}\gamma_\rho\nu_\tau$$

The boson couples to muonic and tauonic number with parameter $\boldsymbol{g_{Z'}}$

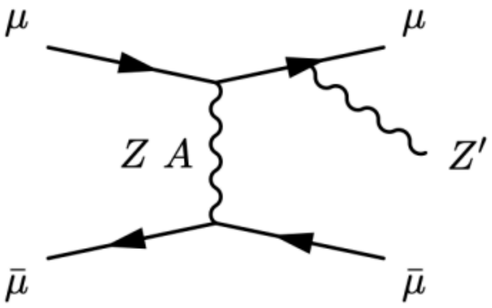
The muon collider offers muon specific opportunities

Production

→ Associated production



→ Z-Bremsstrahlung



This channel benefits from forward detector $2.5 < |\eta| < 7$ placed beyond the detector shielding and the accelerator components

Decay

→ Visible

$g_{Z'} \gg g_D$

The dark sector is too heavy
↳ the dark photon decays exclusively to SM

Signature: muon pairs

→ Invisible

$g_{Z'} \ll g_D$

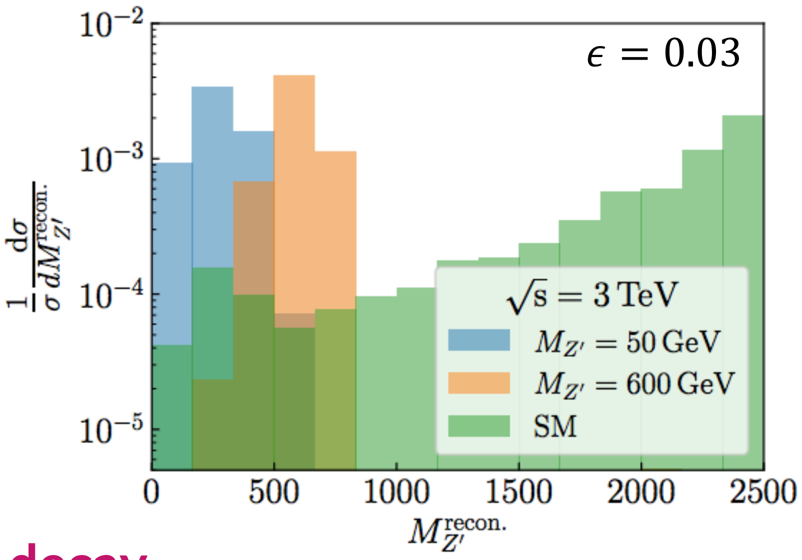
Signature: missing energy

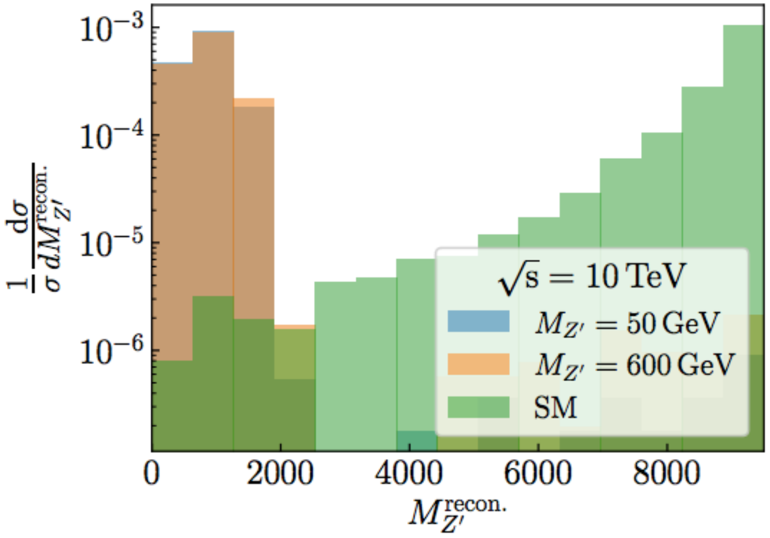
1. Associated production + invisible decay

Background: $\gamma \nu_l \bar{\nu}_l$

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

$$|M_{Z'}^{recon} - M_{Z'}| < 1 \text{ TeV}$$





2. Z-Bremsstrahlung + invisible decay

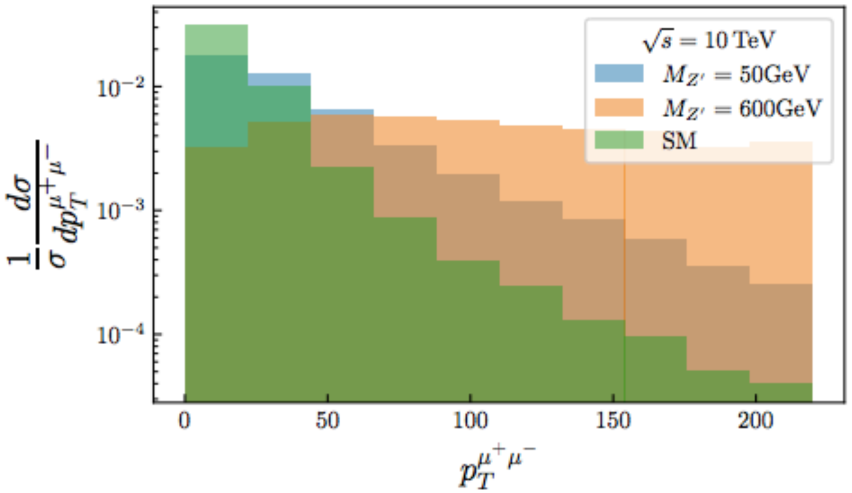
Background: $\mu^+\mu^-\nu_l\bar{\nu}_l,\ \mu^+\mu^-\gamma$

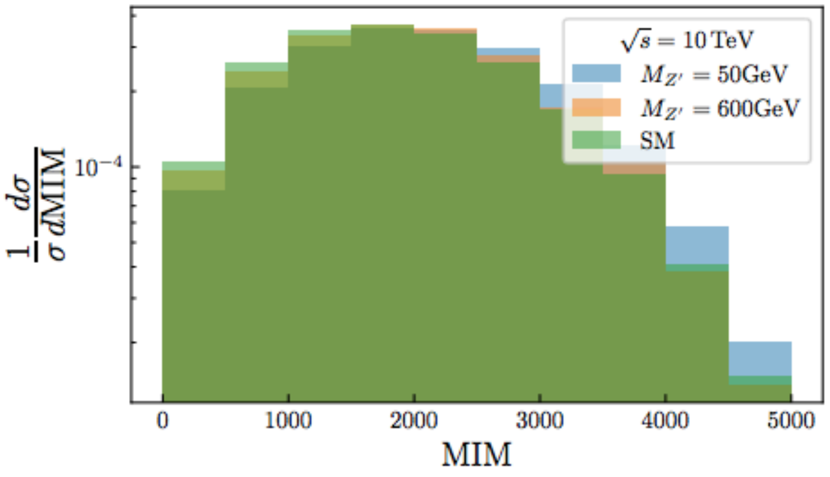
$$MIM_{Z'} = \sqrt{\left(p_i - p_{\mu^+} - p_{\mu^-}\right)^2}$$

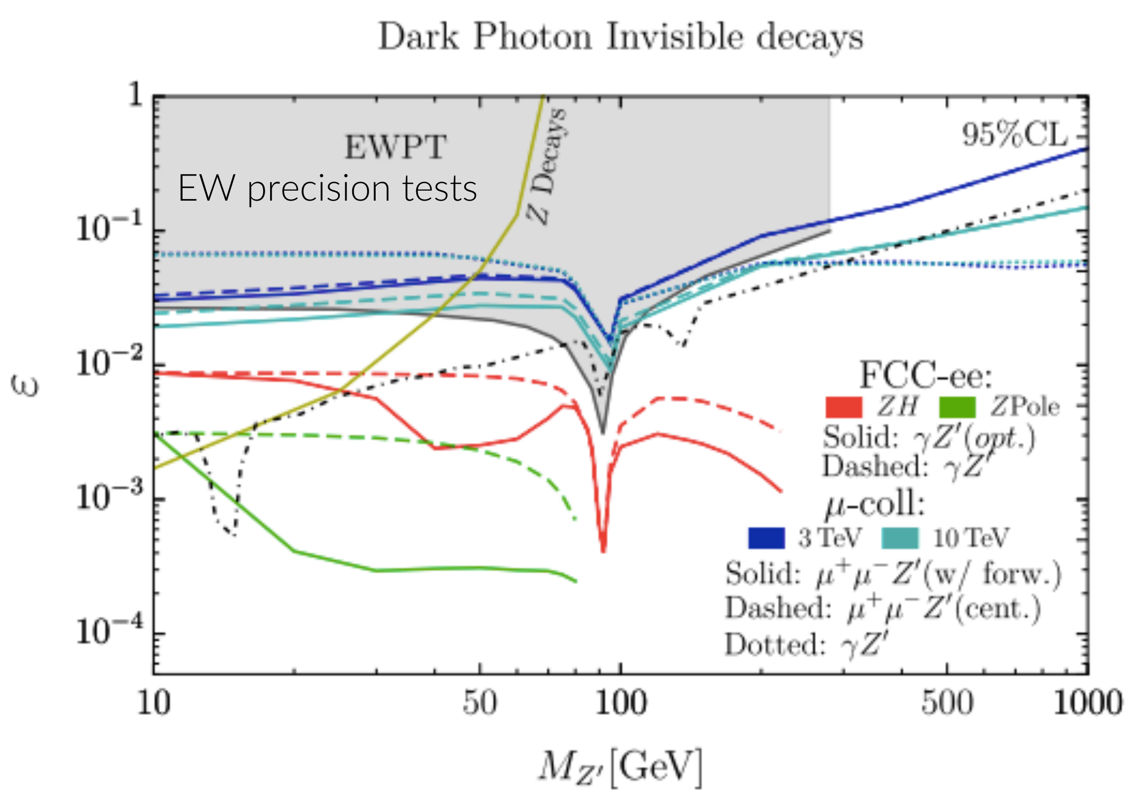
MIM is impractical due to

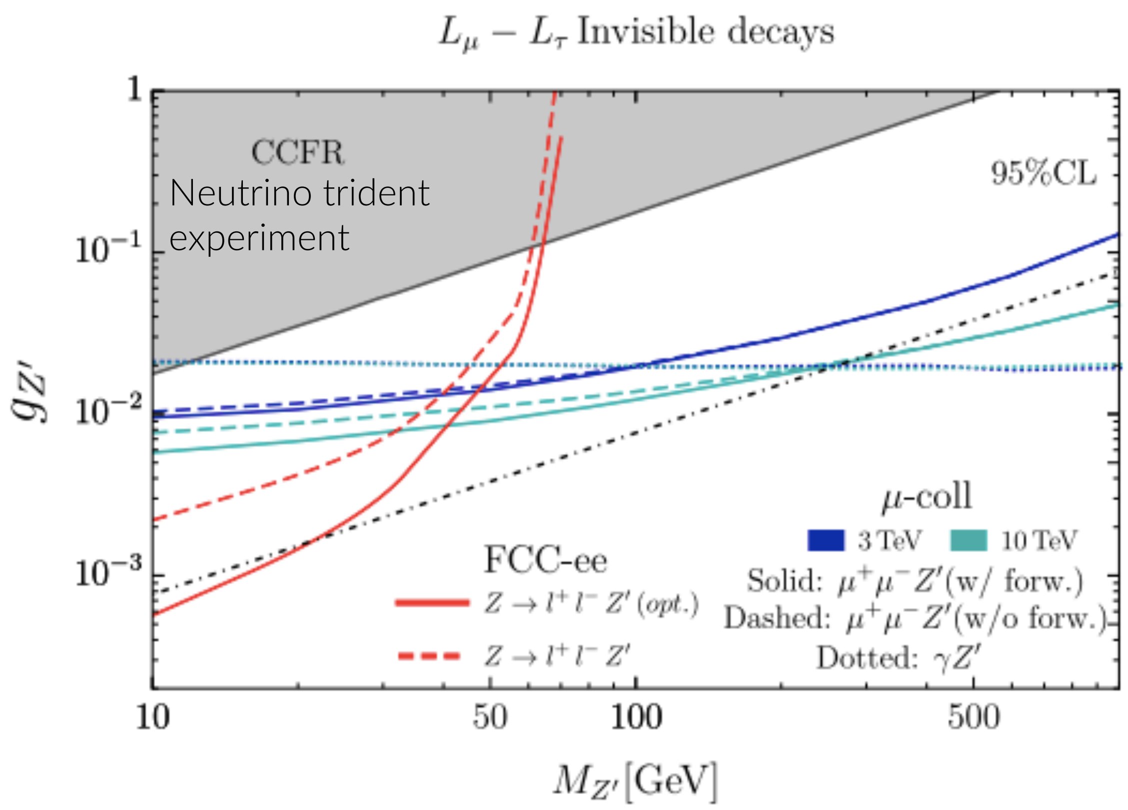
- finite energy resolution
- beam energy spread

↳ $p_T^{\mu\mu}$ exploited







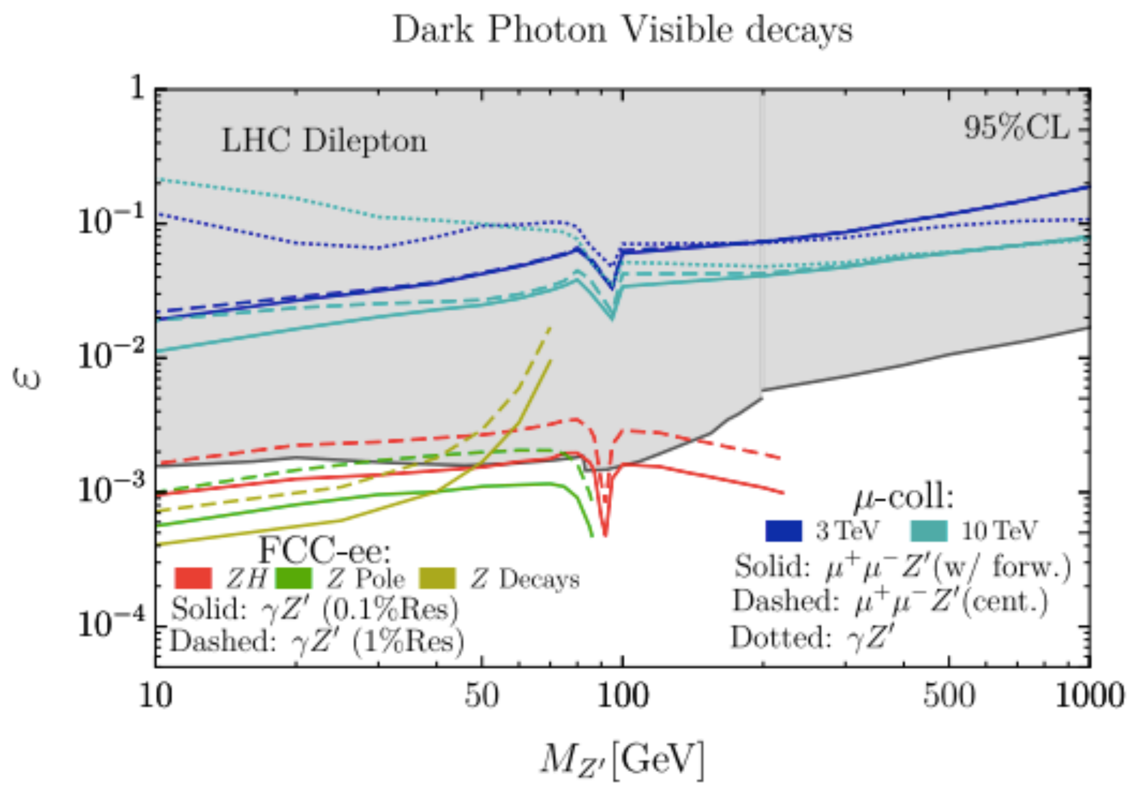


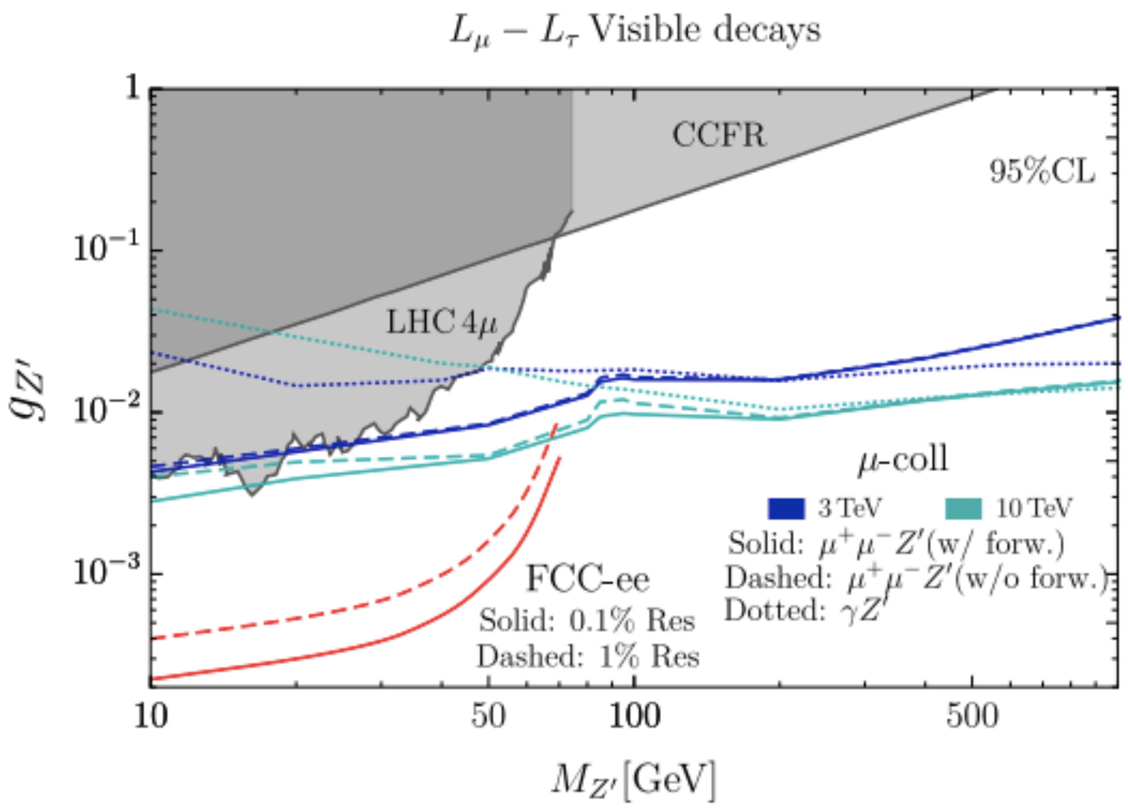
- The forward detector leads to a mild improvement for light dark photon masses
- Mild improvement with collider energy is due to Bremsstrahlung
- Sensitivity of muon collider is limited by luminosity (FCC-ee can probe a a large new portion of parameter space)
- Muon collider is the perfect machine for Z' direct coupled to muons

3. Associated production + visible decay

4. Z-Bremsstrahlung + visible decay

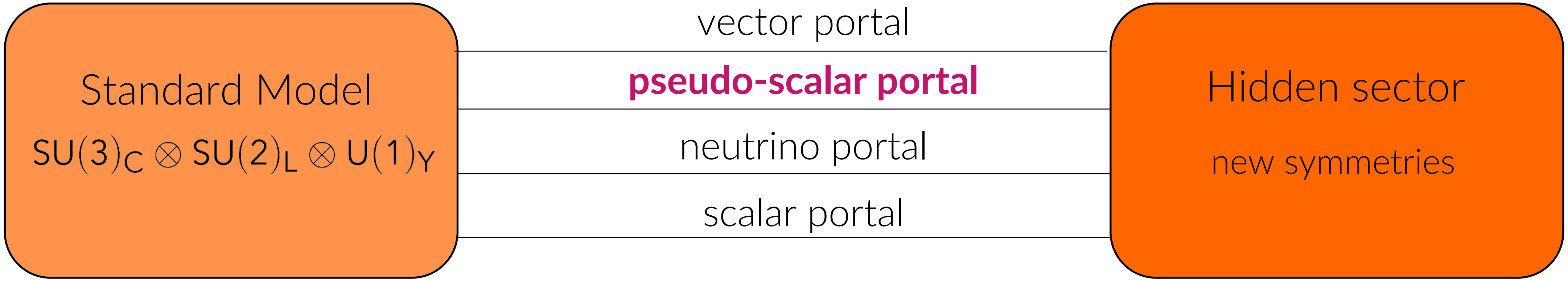
Final state; muon pairs
Background: $\mu^+\mu^-\gamma$



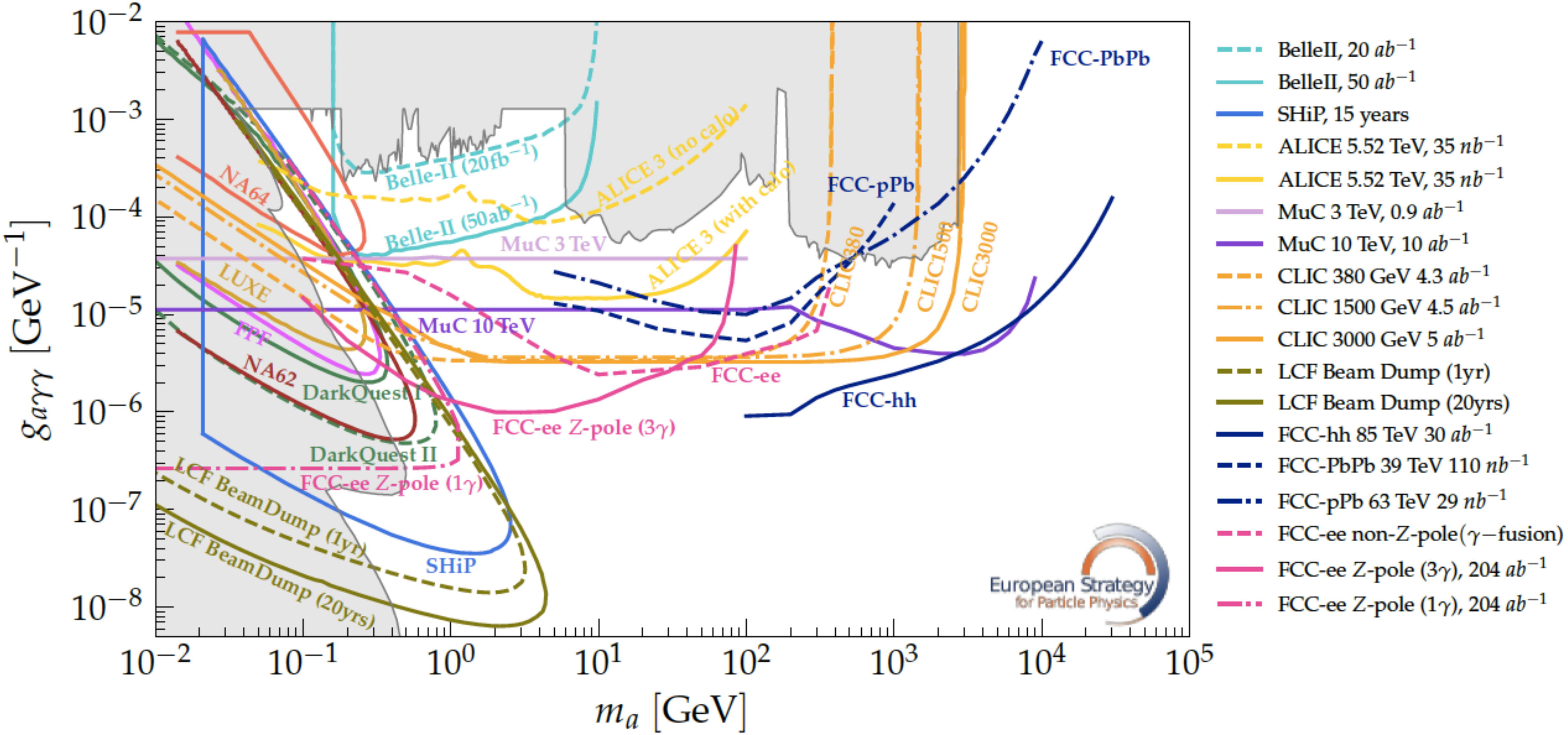


- Mild improvements for the dark photon
- A large new parameter space can be extensively explored for L_μ-L_τ

Dark sectors



Pseudoscalar portal: Axion-Like Particles



Pseudoscalar portal: ALP

Light Axion-Like Particles at future lepton colliders
DOI: 10.1007/JHEP10(2025)122

Effective Field Theory (dim=5) with new physics scale f_a = ALP decay constant

$$\mathcal{L}_{eff} \supset -C_B \frac{a}{f_a} B_{\mu\nu}\tilde{B}^{\mu\nu} - C_W \frac{a}{f_a} \sum_{i=1}^{3} W^i_{\mu\nu}\tilde{W}^{i;\mu\nu}$$

Wilson coefficients **C_W** and **C_B** extracted measuring two of these four couplings

$$g_{a\gamma\gamma} = \frac{4}{f_a}(s_W^2 C_W + c_W^2 C_B), \qquad g_{a\gamma Z} = \frac{8}{f_a} s_W c_W (C_W - C_B),$$

$$g_{aZZ} = \frac{4}{f_a}(c_W^2 C_W + s_W^2 C_B), \quad g_{aWW} = \frac{4}{f_a} C_W,$$

At high-energy colliders these couplings are not suppressed

Decay and production channel

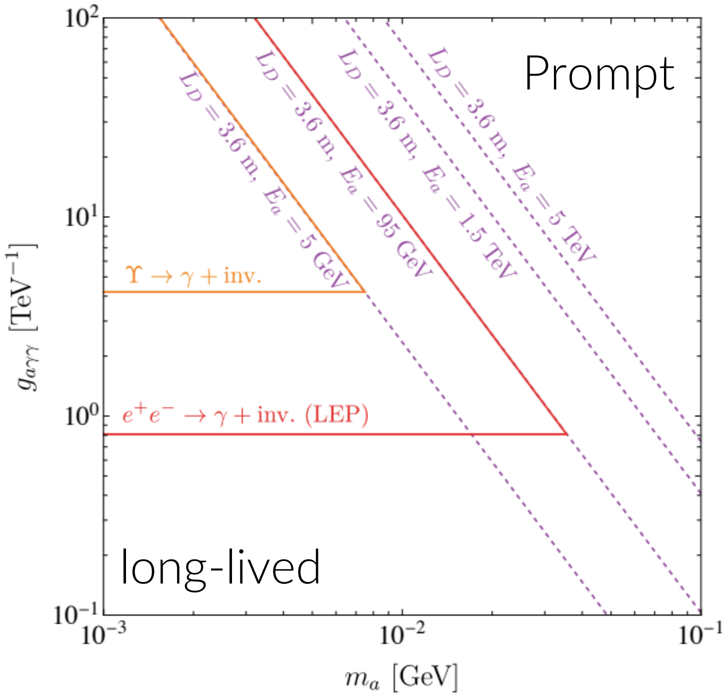
$m_a < 1\ \mathrm{MeV}$ or small coupling ⟶ long lived

mono-γ or mono-Z

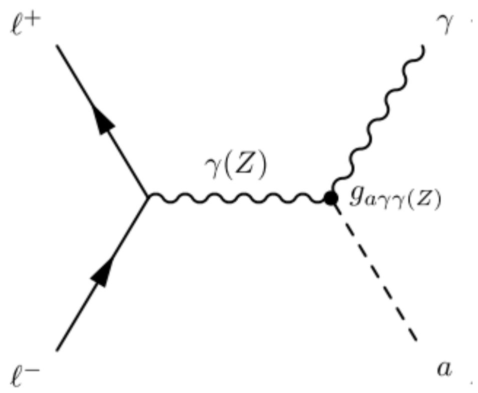
$m_a > 100\ \mathrm{MeV}$ ⟶ prompt

non resonant VBS = ALP exchanged offshell

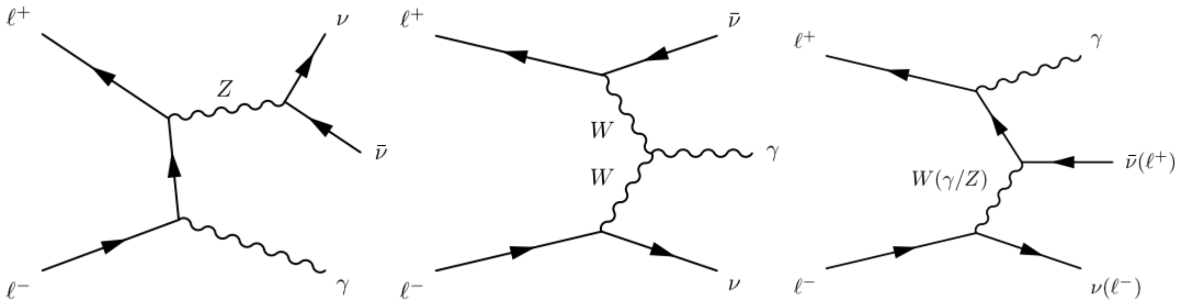
- light-by-light scattering
- EW scattering

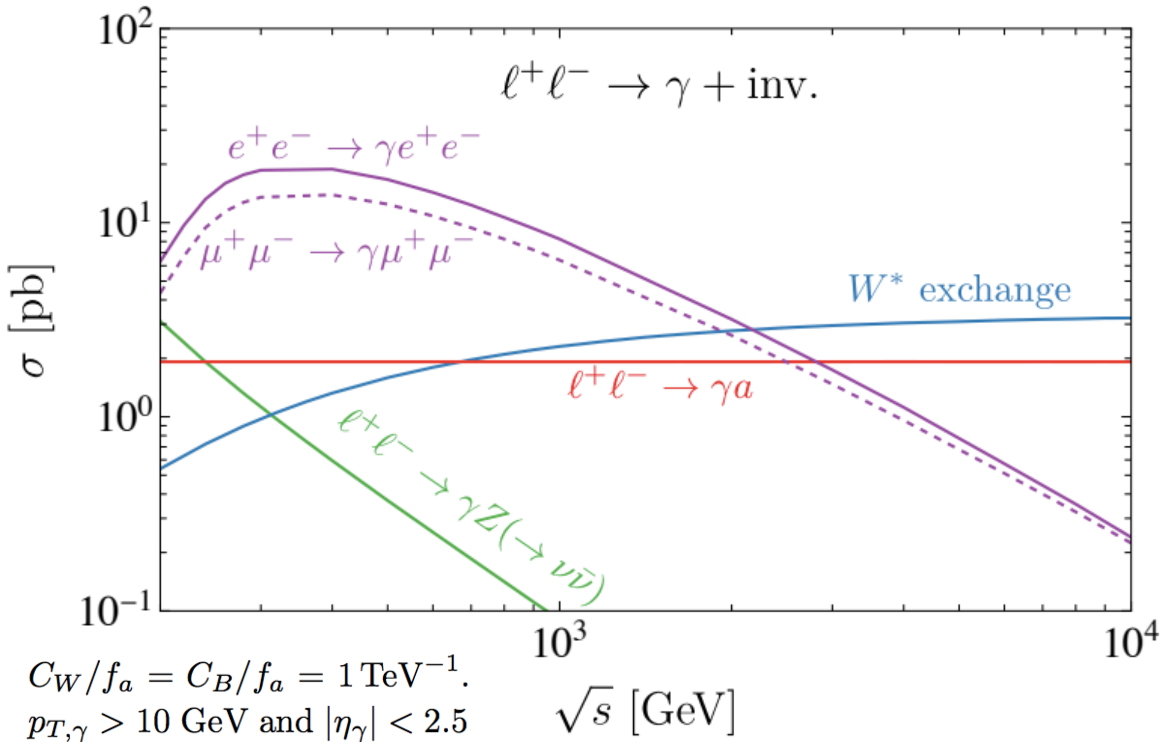


Mono photon production



Background: $\gamma\nu_l\bar{\nu_l}$ or $\gamma\ell^+\ell^-$ (with leptons out of acceptance)



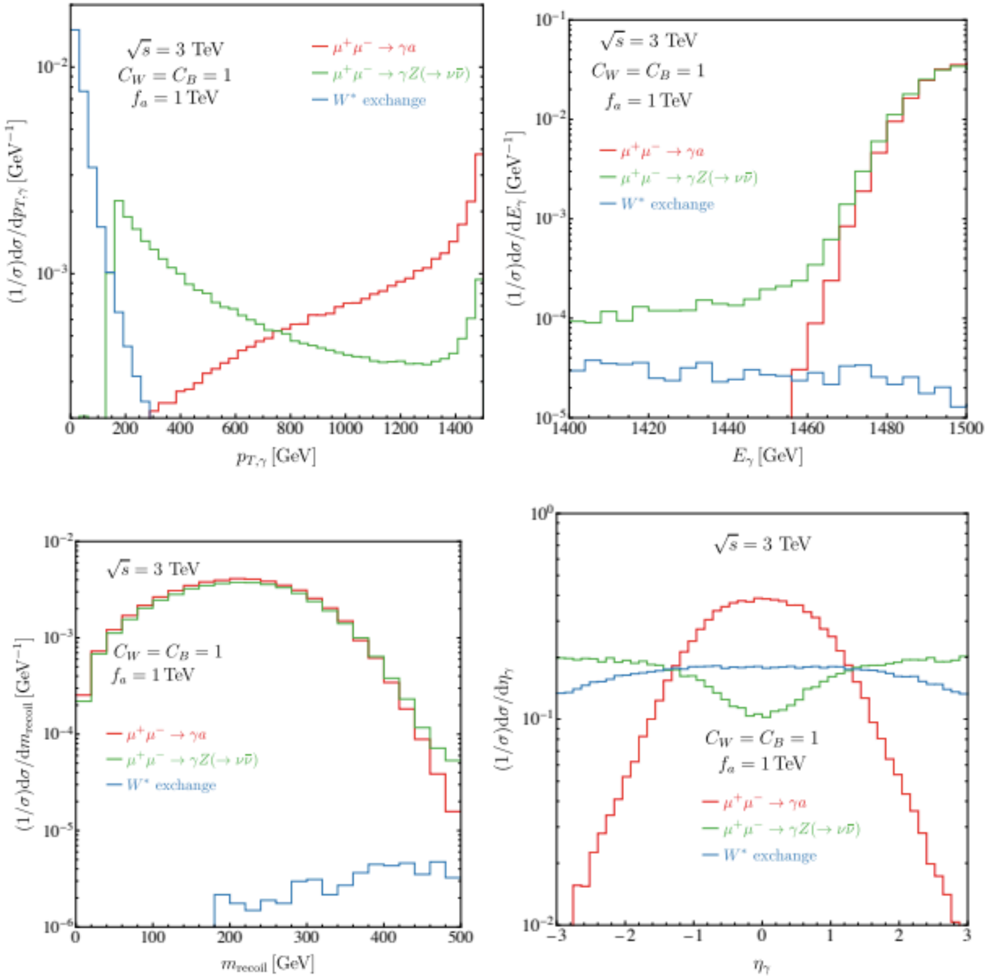


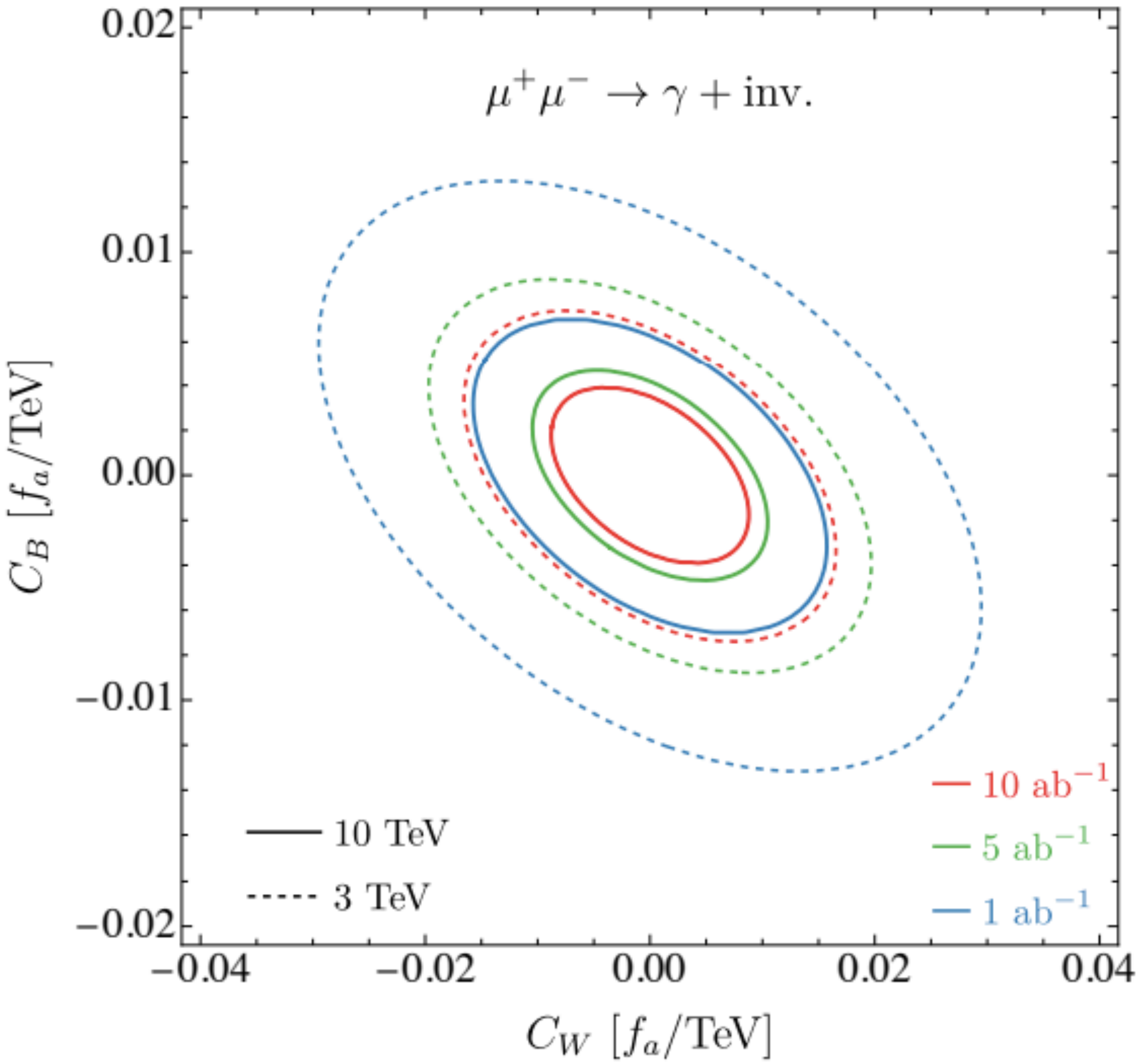
$C_W/f_a = C_B/f_a = 1\,\text{TeV}^{-1}$.
$p_{T,\gamma} > 10$ GeV and $|\eta_\gamma| < 2.5$

$$\sigma_{\ell^+\ell^-\to\gamma a} = \frac{\alpha}{768}\left[32 g_{a\gamma\gamma}^2 + \underbrace{\frac{8 g_{a\gamma\gamma} g_{a\gamma Z}(c_W^2 - 3s_W^2)s}{s_W c_W (s - M_Z^2)} + \frac{g_{a\gamma Z}^2 (6s_W^4 + 2c_W^4 - 1)s^2}{s_W^2 c_W^2 (s - M_Z^2)^2}}\right]$$

dominant at low energies

at high energies also $g_{a\gamma Z}$ is measured
ALP cross section has a minimal dependence on the collision energy

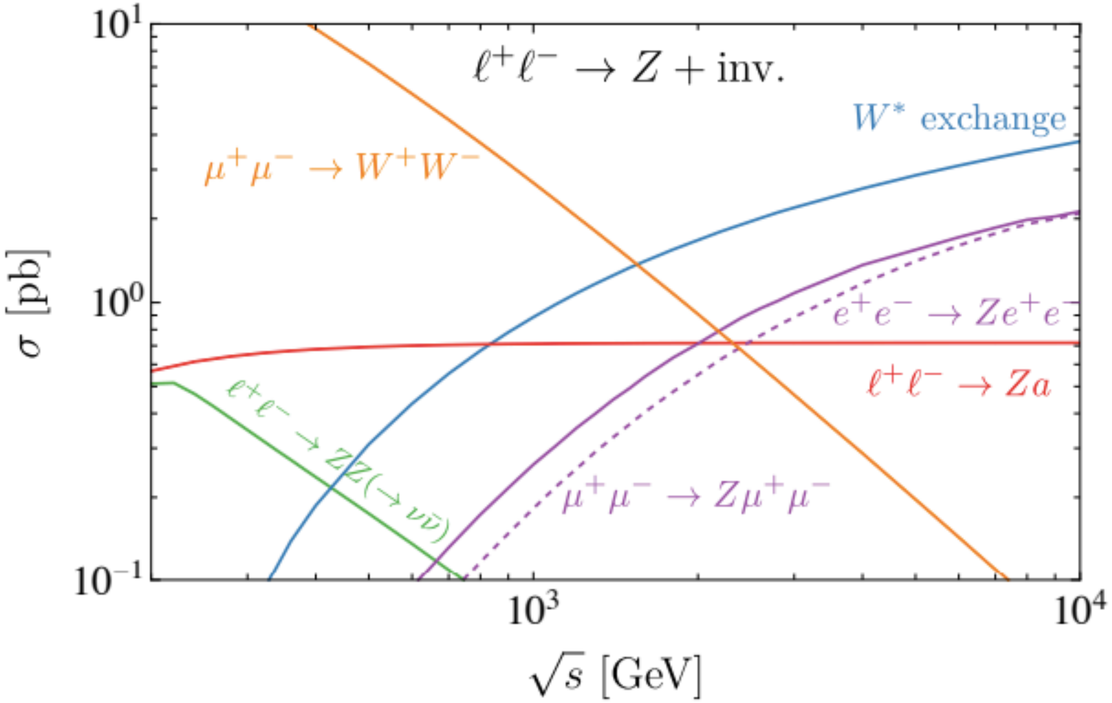




Collider	$\mu^+\mu^-$	
$\sqrt{s}$	3 TeV	10 TeV
$\lvert\eta_\gamma\rvert^{\max}$	2.5	2.5
$p_{T,\gamma}^{\min}$ [GeV]	700	2500
$E_\gamma^{\min}$ [GeV]	1450	4900

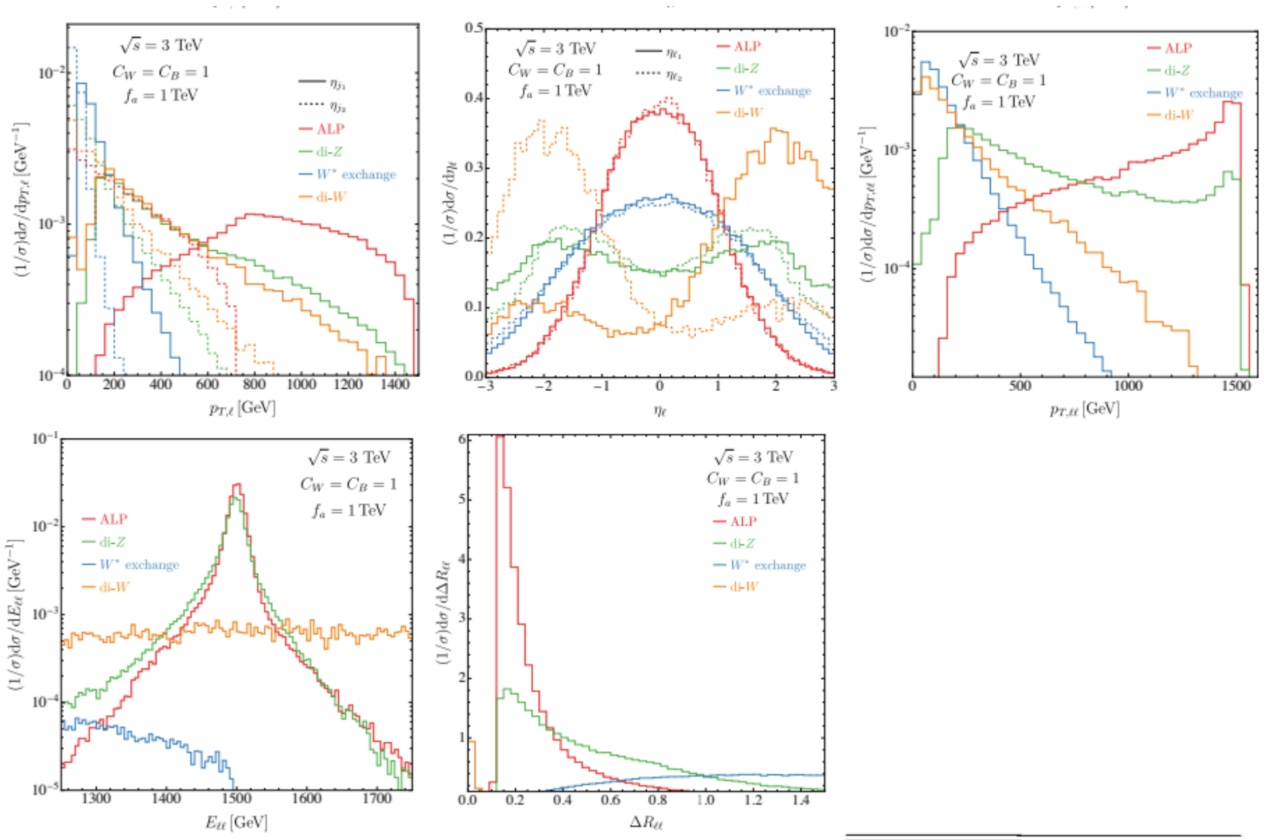
The dominant background is the on-shell Z production; its rate scales as 1/s and so a 10 TeV collider is more sensitive

Mono Z production



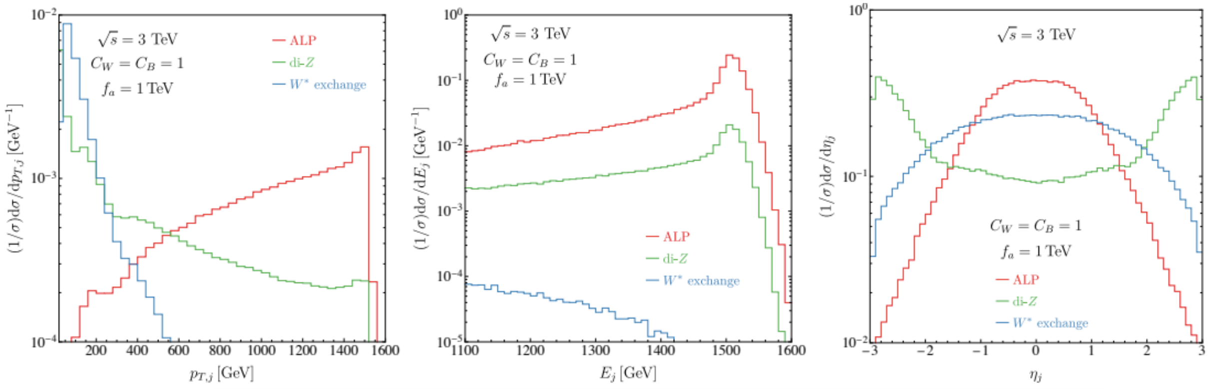
$$\sigma_{\ell^+\ell^-\to Za} = \frac{\alpha}{192}\left[\frac{g_{aZZ}^2(6s_W^4+2c_W^4-1)(s-M_Z^2)}{s_W^2 c_W^2 s} + \frac{2g_{aZZ}g_{a\gamma Z}(c_W^2-3s_W^2)(s-M_Z^2)^2}{s_W c_W s^2} + \frac{2g_{a\gamma Z}^2(s-M_Z^2)^3}{s^3}\right]$$

Z leptonic decay

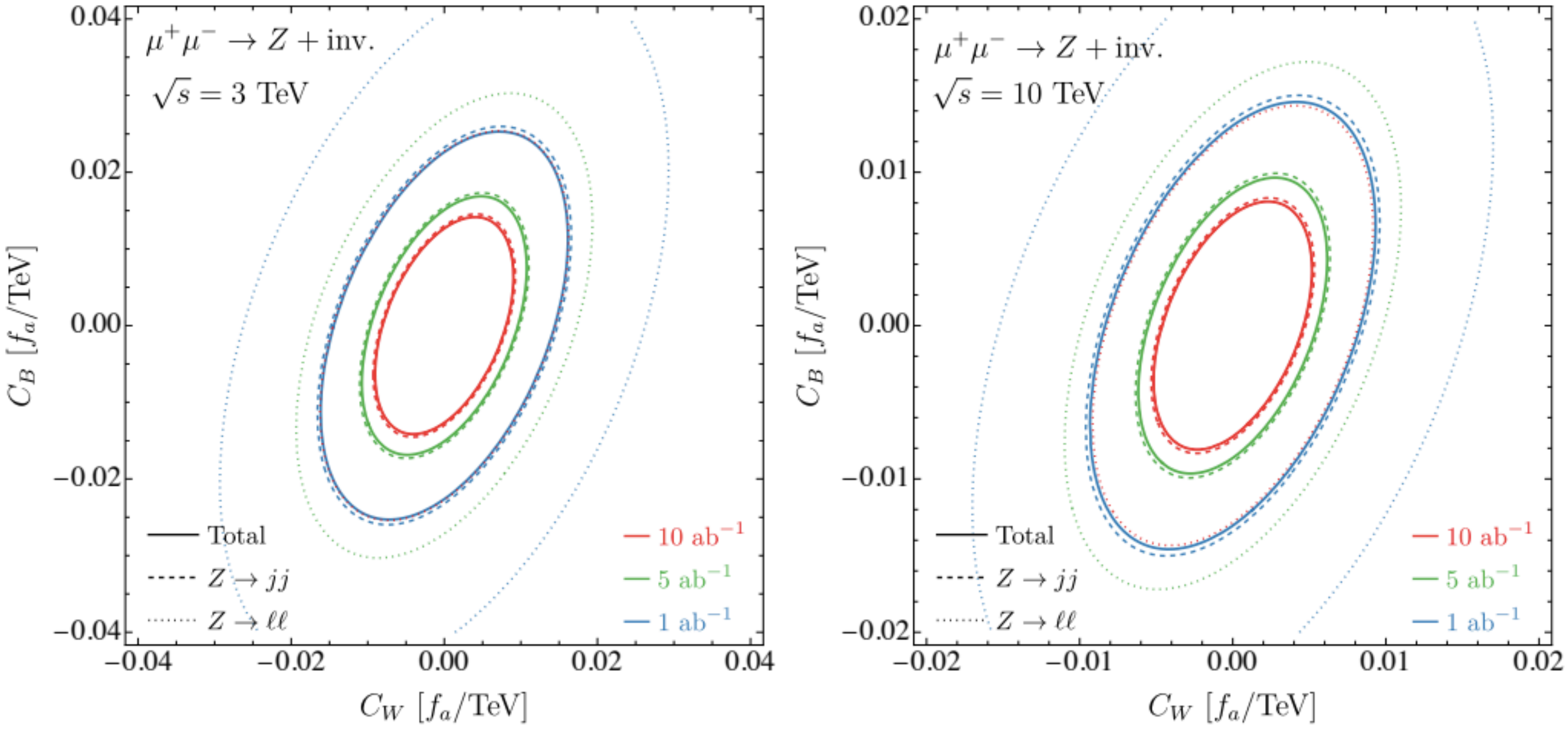


Collider	$\mu^+\mu^-$	
$\sqrt{s}$	3 TeV	10 TeV
$p_{T,\ell_1}^{\text{min}}$ [GeV]	500	1600
$p_{T,\ell_2}^{\text{min}}$ [GeV]	150	500
$E_{\ell\ell}^{\text{min}}$ [GeV]	1450	4800
$p_{T,\ell\ell}^{\text{min}}$ [GeV]	800	2200
$\Delta R_{\ell\ell}^{\text{max}}$	0.4	0.15
$\lvert\eta_\ell\rvert^{\text{max}}$	2.0	2.0

Z hadronic decay

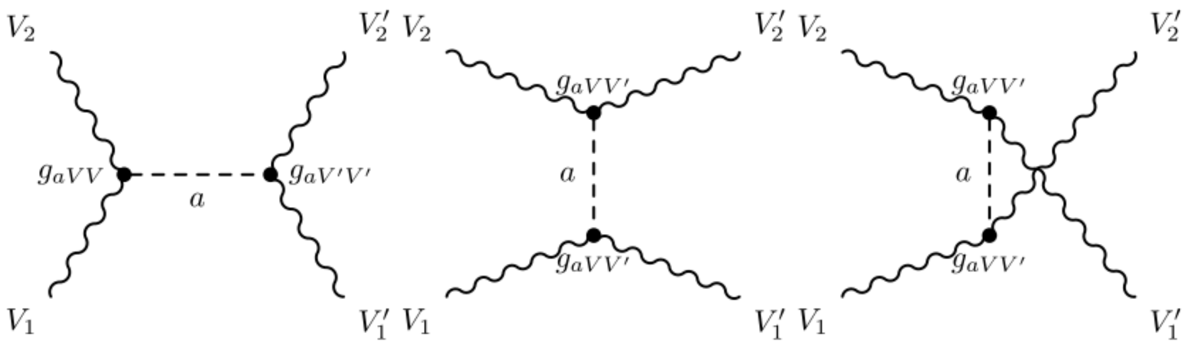


Collider	$\mu^+\mu^-$	
$\sqrt{s}$	3 TeV	10 TeV
$\lvert\eta_j\rvert^{\max}$	1.75	2.0
$p_{T,j_1}^{\min}$ [GeV]	550	1800
$p_{T,j_2}^{\min}$ [GeV]	–	–
$\Delta R_{jj}^{\max}$	–	–
$E_Z^{\min}$ [GeV]	1450	4800

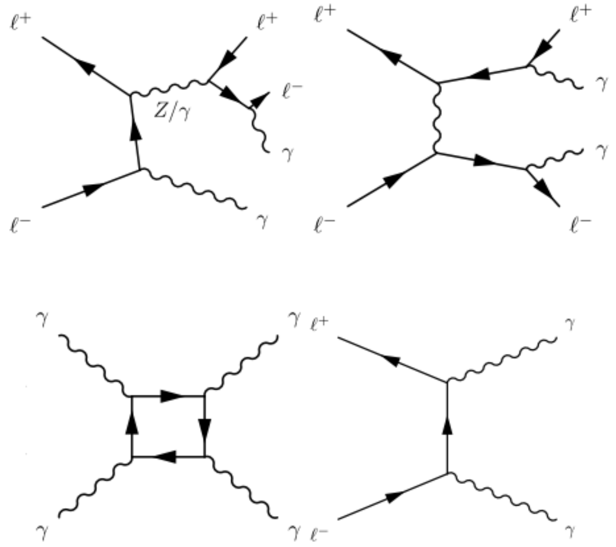


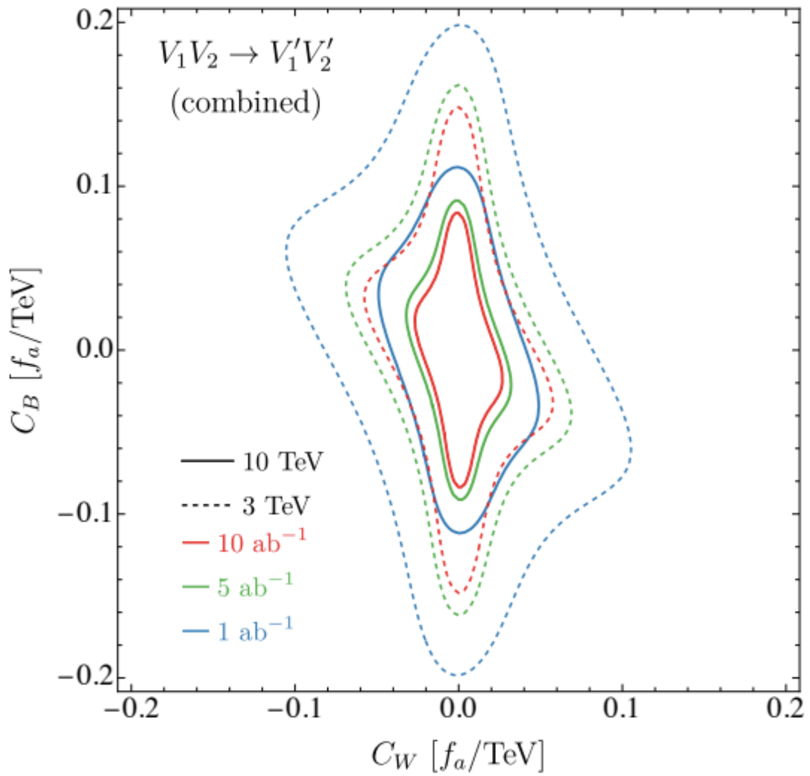
- The hadronic channel gives stronger bounds because of higher BR
- Mono Z is complementary to mono photon

Scattering



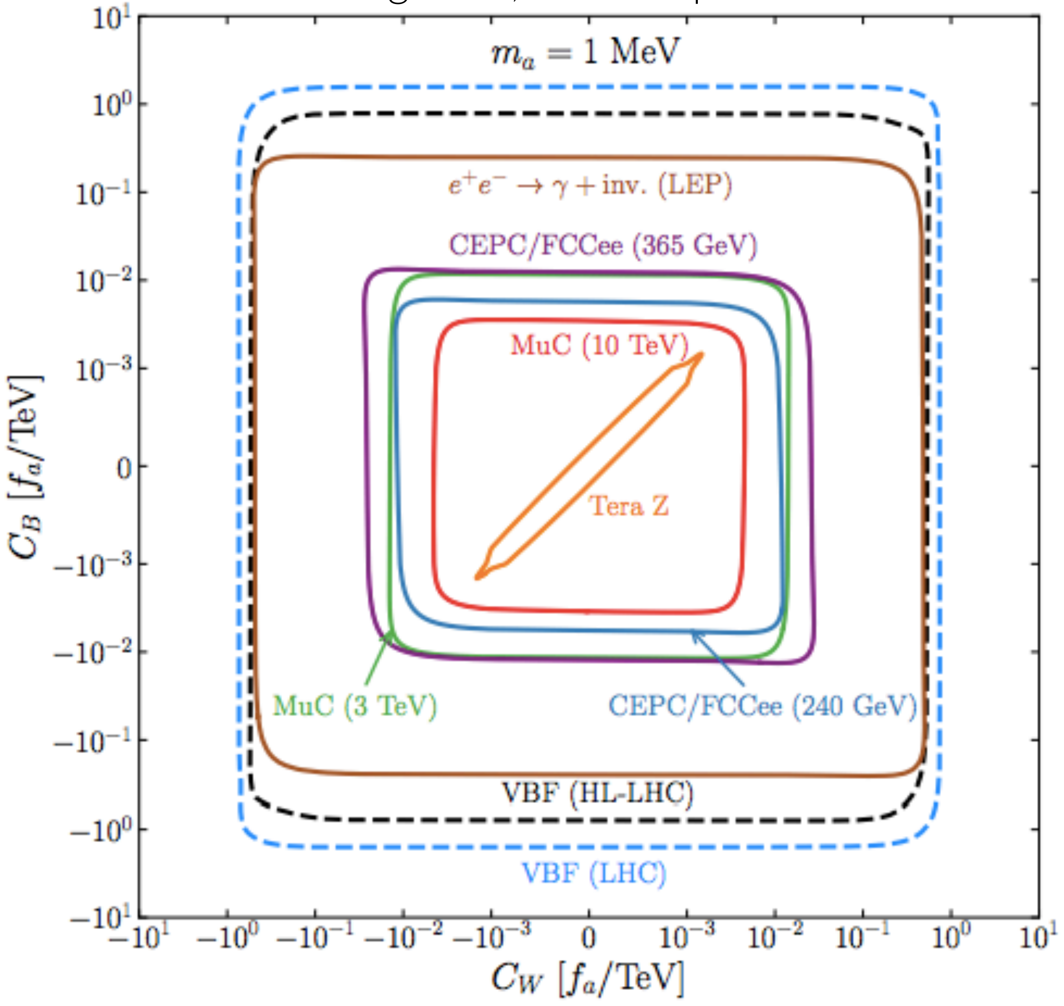
Background:$\gamma\gamma$



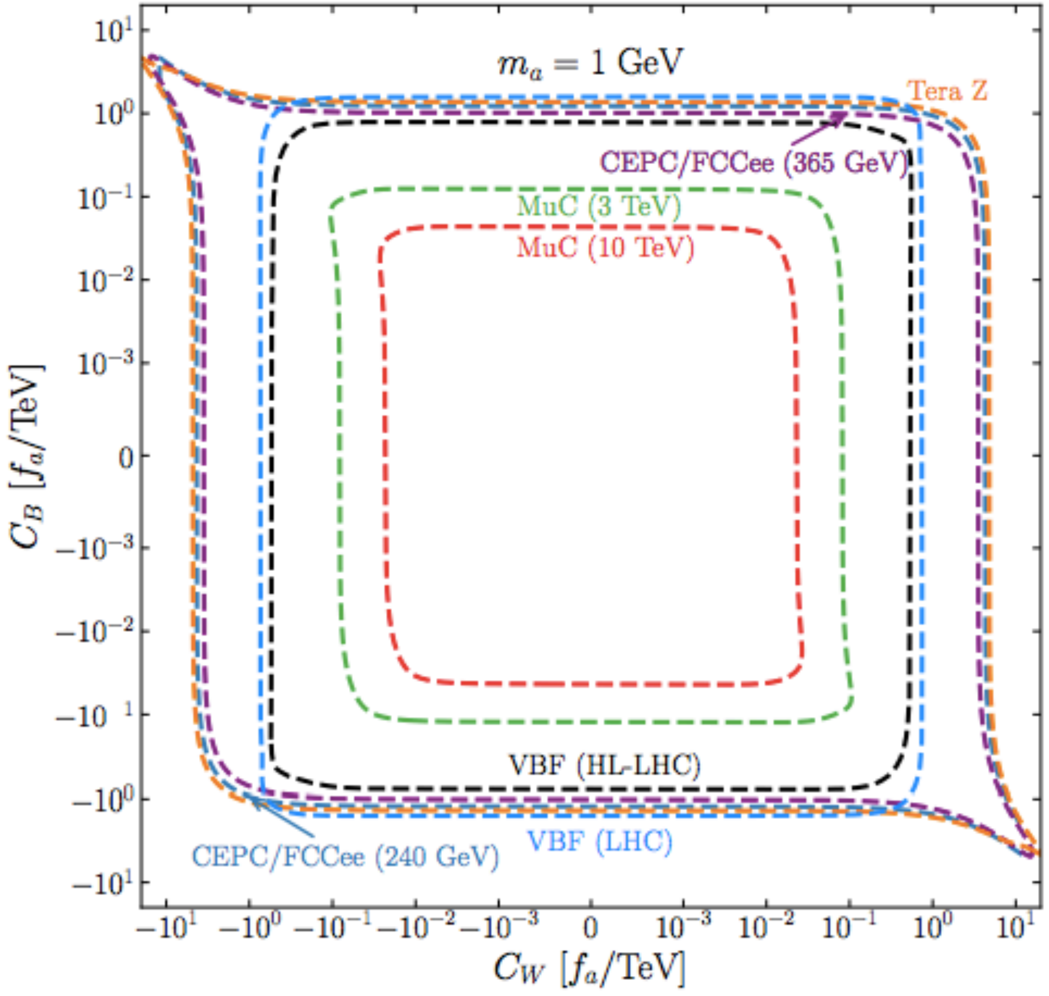


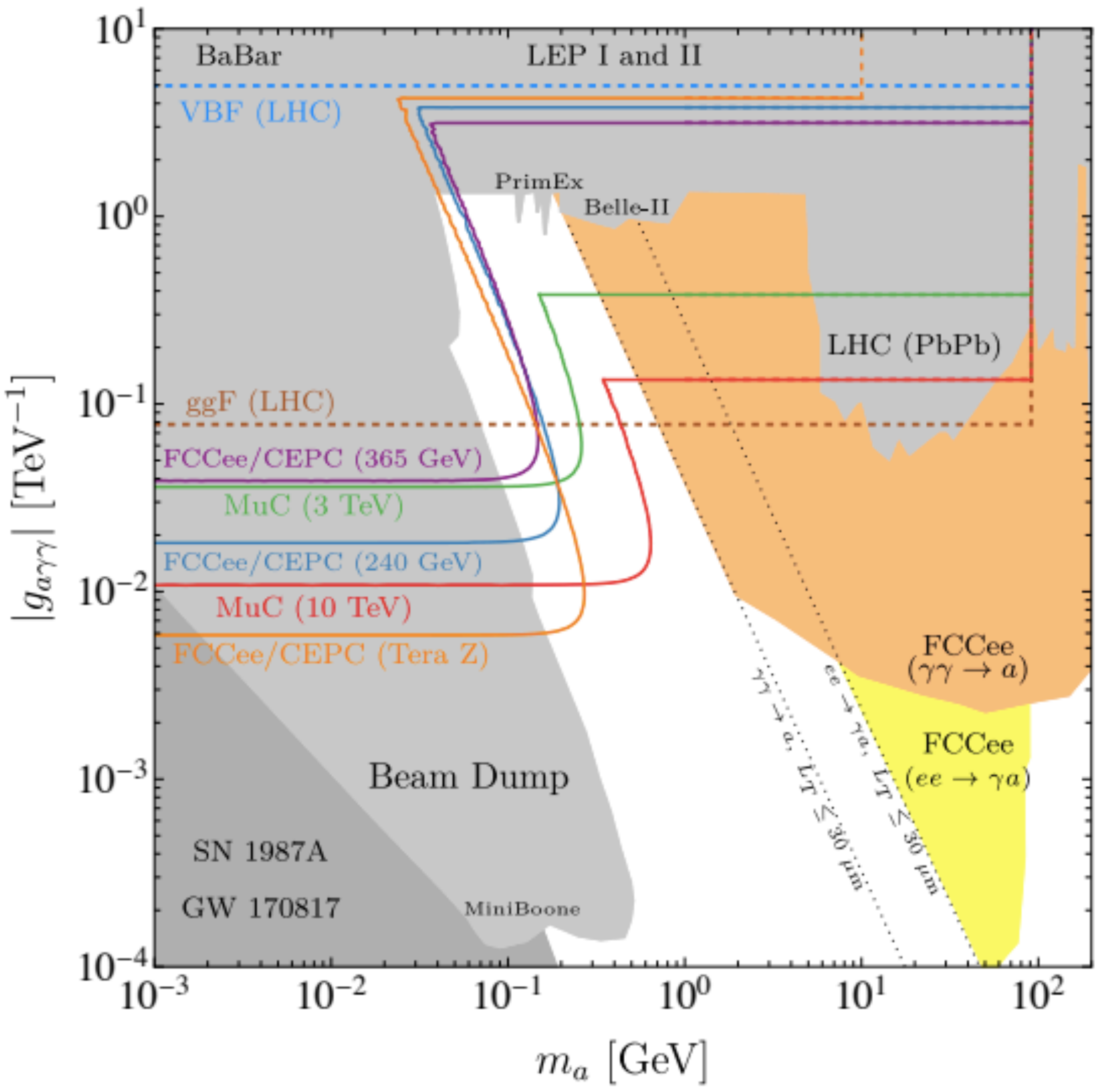
- The light-by-light scattering provides the stringent constraints on $g_{a\gamma\gamma}$
- The EW VBS is the dominant channel for constraining $g_{aZZ}, g_{a\gamma Z}, g_{aWW}$

long-lived, mono-V production

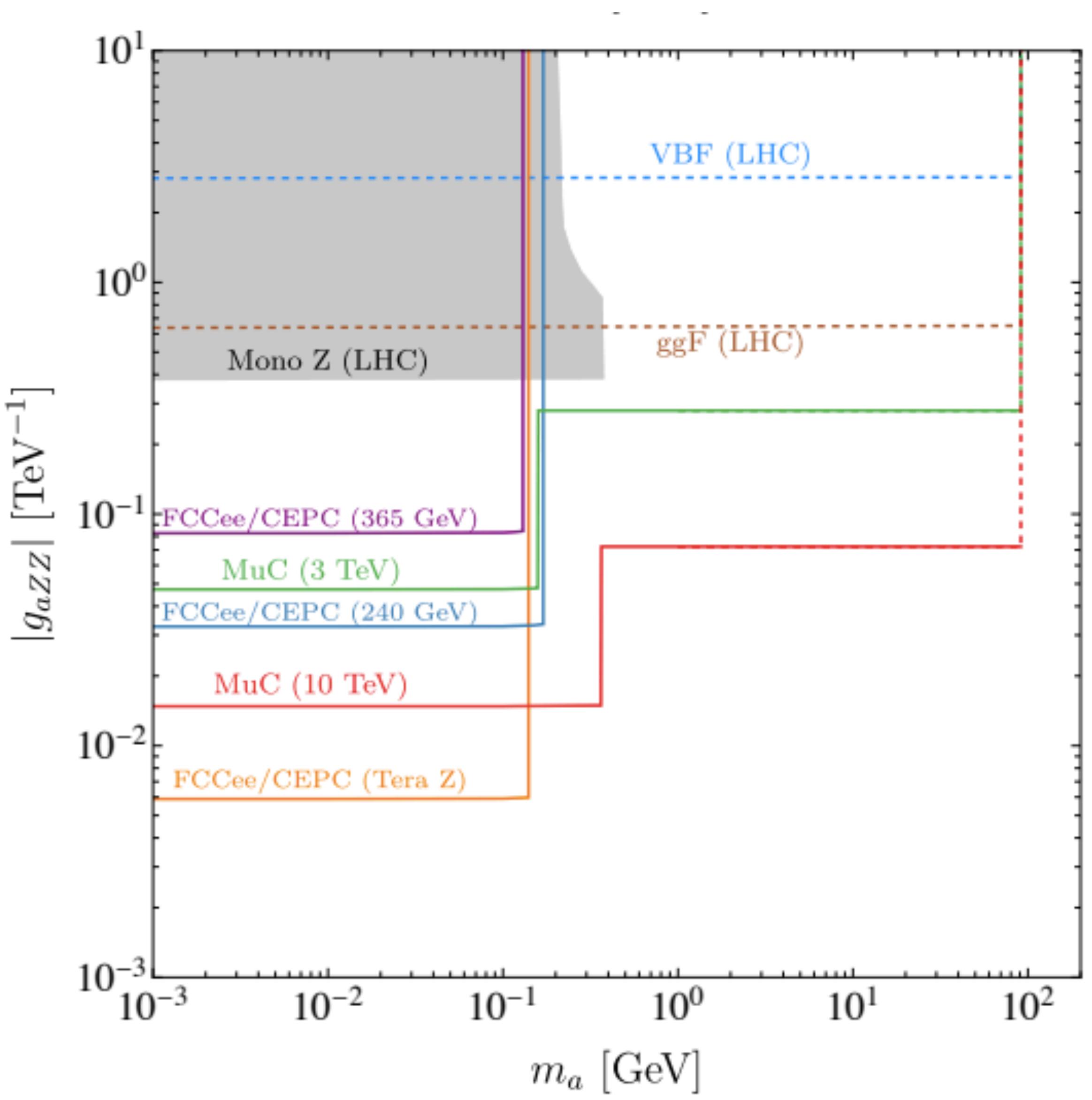


short lived,VBS production



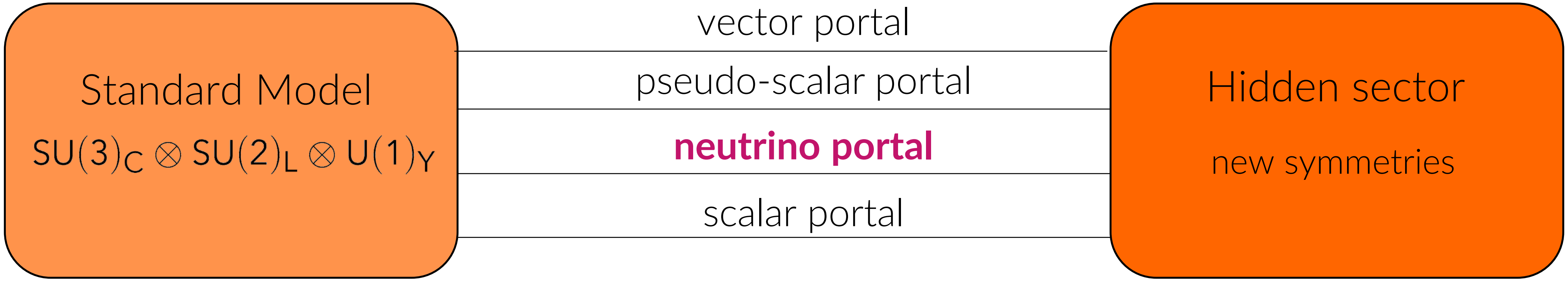


BaBar
LEP I and II
VBF (LHC)
PrimEx
Belle-II
LHC (PbPb)
ggF (LHC)
FCCee/CEPC (365 GeV)
MuC (3 TeV)
FCCee/CEPC (240 GeV)
MuC (10 TeV)
FCCee/CEPC (Tera Z)
FCCee ($\gamma\gamma \to a$)
FCCee ($ee \to \gamma a$)
$\gamma\gamma \to a$, $L_T \leq 30\ \mu m$
$ee \to \gamma a$, $L_T \leq 30\ \mu m$
Beam Dump
SN 1987A
GW 170817
MiniBoone
$|g_{a\gamma\gamma}|$ [TeV^{-1}]
m_a [GeV]

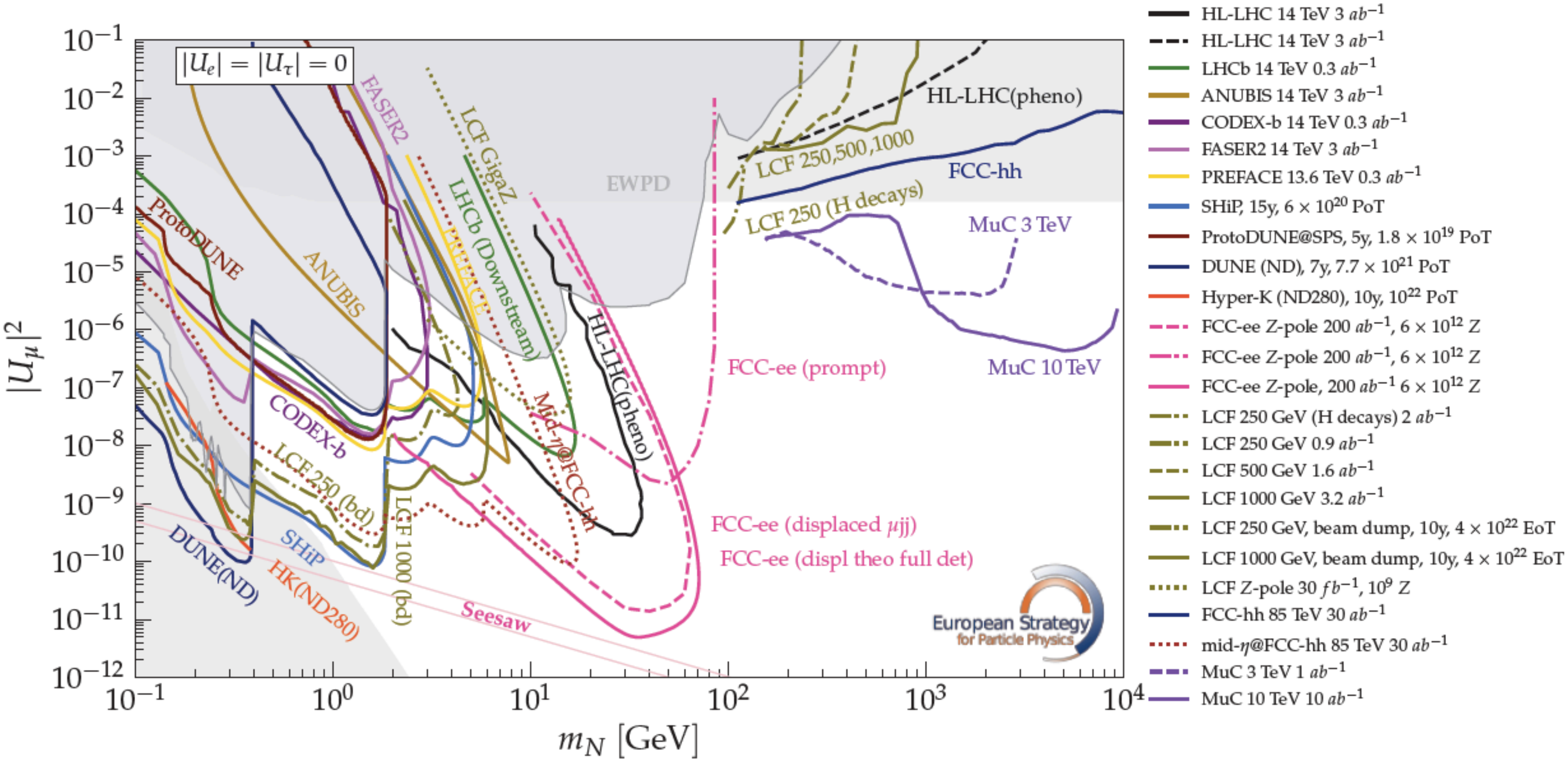


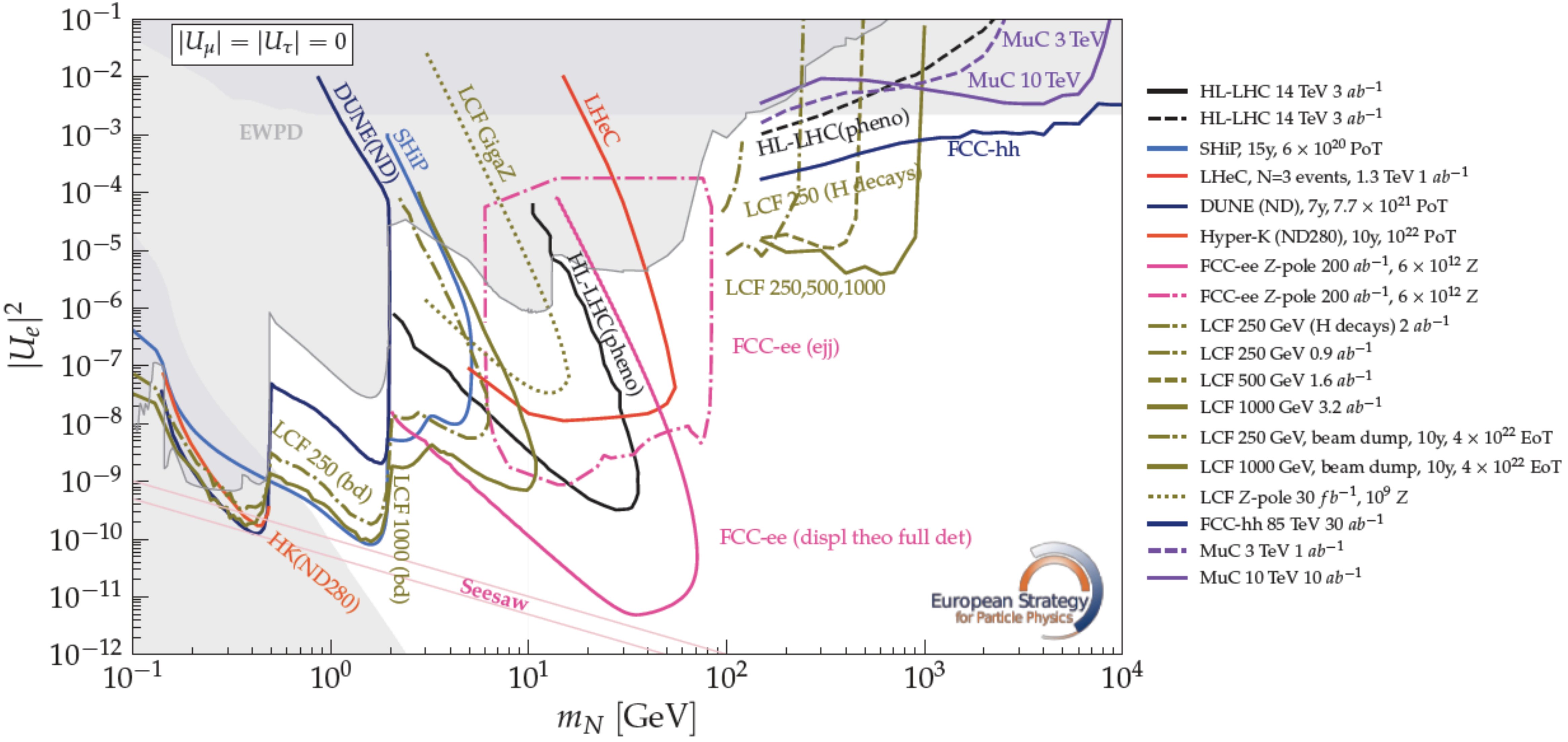
VBF (LHC)
ggF (LHC)
Mono Z (LHC)
FCCee/CEPC (365 GeV)
MuC (3 TeV)
FCCee/CEPC (240 GeV)
MuC (10 TeV)
FCCee/CEPC (Tera Z)
$|g_{aZZ}|$ [TeV^{-1}]
m_a [GeV]

Dark sectors



Neutrino portal: Heavy Neutral Lepton





$|U_\mu| = |U_\tau| = 0$
EWPD
DUNE(ND)
SHiP
LCF GigaZ
LHeC
HL-LHC(pheno)
FCC-hh
MuC 3 TeV
MuC 10 TeV
LCF 250 (H decays)
LCF 250,500,1000
FCC-ee (ejj)
HL-LHC(pheno)
LCF 250 (bd)
LCF 1000 (bd)
HK(ND280)
Seesaw
FCC-ee (displ theo full det)
$|U_e|^2$
m_N [GeV]
HL-LHC 14 TeV 3 ab^{-1}
HL-LHC 14 TeV 3 ab^{-1}
SHiP, 15y, 6×10^{20} PoT
LHeC, N=3 events, 1.3 TeV 1 ab^{-1}
DUNE (ND), 7y, 7.7×10^{21} PoT
Hyper-K (ND280), 10y, 10^{22} PoT
FCC-ee Z-pole 200 ab^{-1}, 6×10^{12} Z
FCC-ee Z-pole 200 ab^{-1}, 6×10^{12} Z
LCF 250 GeV (H decays) 2 ab^{-1}
LCF 250 GeV 0.9 ab^{-1}
LCF 500 GeV 1.6 ab^{-1}
LCF 1000 GeV 3.2 ab^{-1}
LCF 250 GeV, beam dump, 10y, 4×10^{22} EoT
LCF 1000 GeV, beam dump, 10y, 4×10^{22} EoT
LCF Z-pole 30 fb^{-1}, 10^9 Z
FCC-hh 85 TeV 30 ab^{-1}
MuC 3 TeV 1 ab^{-1}
MuC 10 TeV 10 ab^{-1}
European Strategy for Particle Physics

Neutrino portal: HNL

Heavy neutral leptons at muon colliders
DOI: 10.1007/JHEP03(2023)231

Mass: $\boldsymbol{m_N} > O(100\ \mathrm{GeV})$

Type-1 linear seesaw model

$$\mathcal{L}_\nu \supset -\lambda_\nu \bar{L}\tilde{H}N - \frac{m_N}{2}\bar{N}^C N + h.c.$$

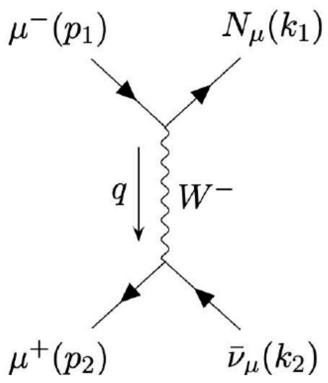
$$M_\nu = \begin{pmatrix} 0 & m_D \\ m_D & m_N \end{pmatrix}$$

$$m_D = \lambda_\nu \mathrm{v}/\sqrt{2}$$

$$m_1 = m_\nu = m_D \sin\theta \qquad \sin\theta = \frac{m_D}{m_N}$$

$$m_2 \approx m_N$$

$\boldsymbol{|U_\ell|^2} = (sin\,\theta)^2$

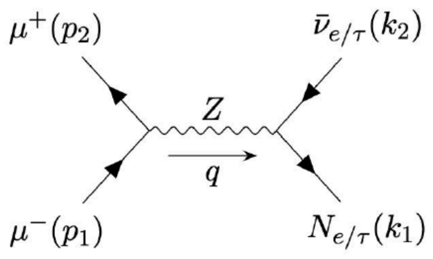


t-channel

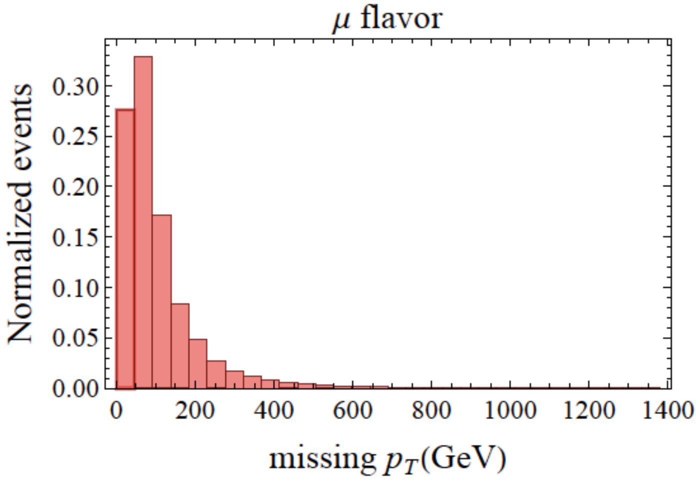
↓

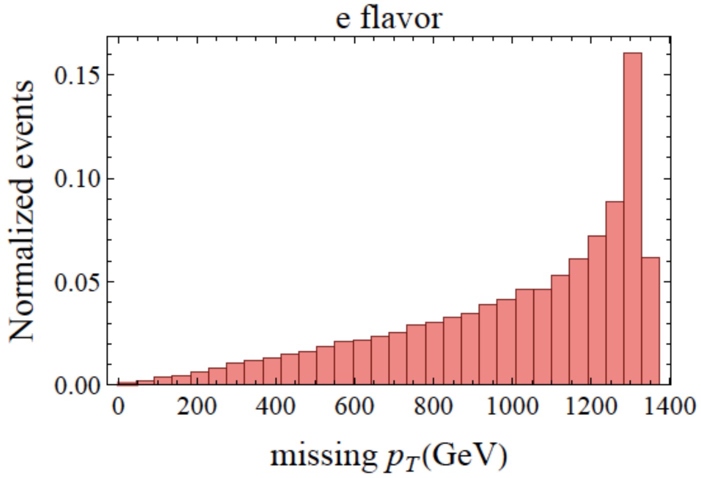
Muon Collider is advantageous for the muon-flavour HNL production

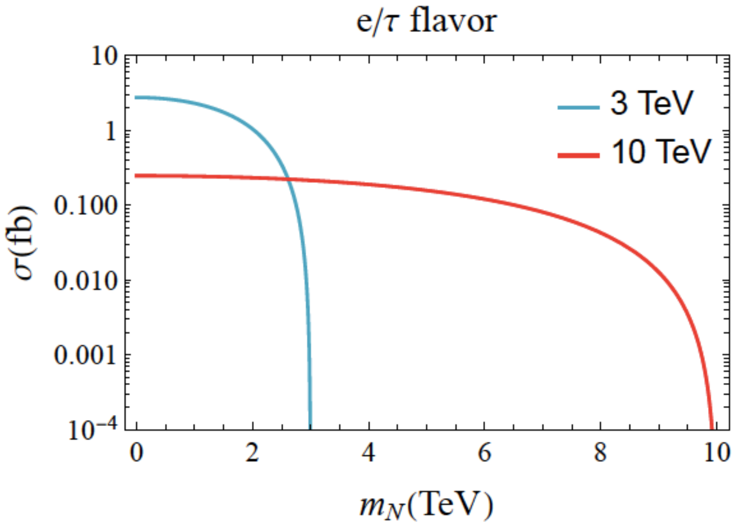
Decay: hadronic W + lepton

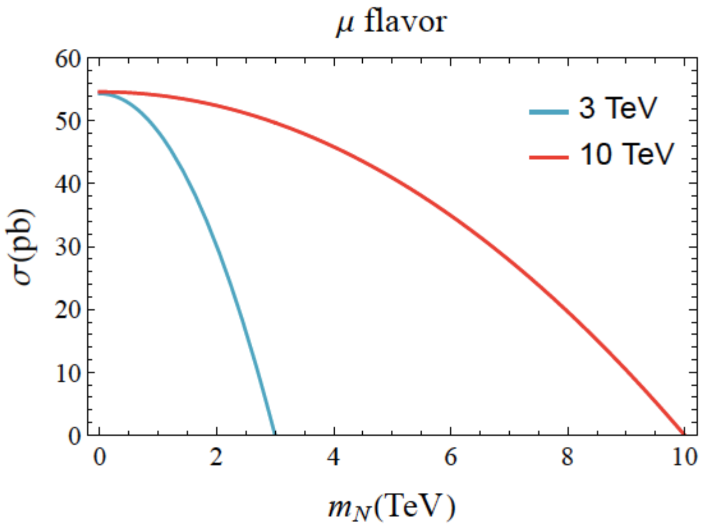


1/s suppression









$$\frac{\sigma_{\text{VBF}}}{\sigma_{\text{s-channel}}} \propto \alpha_W^2 \frac{s}{m_Z^2} \log^2 \frac{s}{m_W^2} \log \frac{s}{m_N^2}$$

@3 TeV

Type	Signal process	$\sigma/\lvert U_\mu\rvert^2$ (w. conj. channel[2]) $m_N = 1\,\text{TeV}$	Pre-selection cut (PSC)	Included
t-channel	$\mu^+\mu^- \longrightarrow N_\mu\bar{\nu}_\mu$	43.5 pb	PSC	Yes
VBF	$\mu^+\mu^- \longrightarrow \mu^+\mu^- N_\mu\bar{\nu}_\mu$	~ 1 pb	—	No
VBF	$\mu^+\mu^- \longrightarrow \bar{\nu}_\mu\nu_\mu N_\mu\bar{\nu}_\mu$	~ 0.1 pb	—	No

@10 TeV

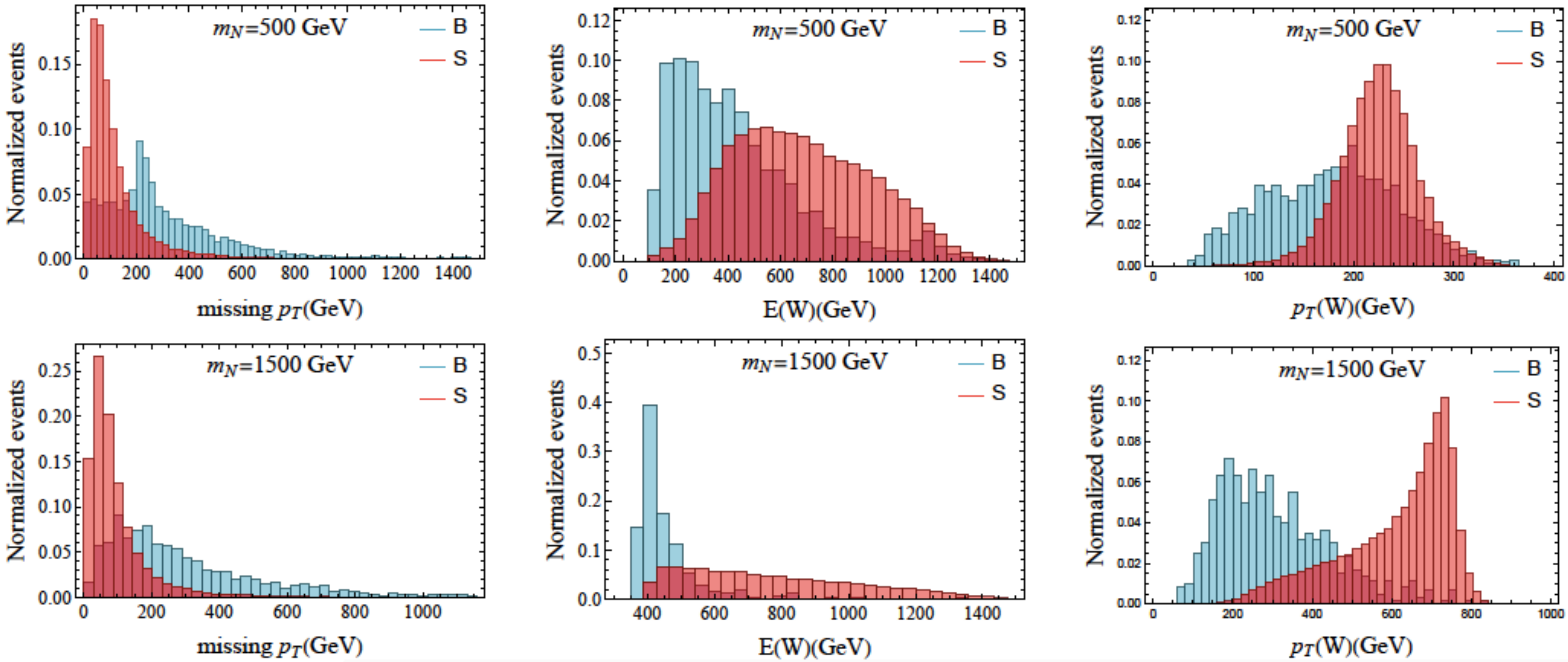
Type	Signal process	$\sigma/\lvert U_\mu\rvert^2$ (w. conj. channel) $m_N = 1\,\text{TeV}$	Pre-selection cut (PSC)	Included
t-channel	$\mu^+\mu^- \longrightarrow N_\mu\bar{\nu}_\mu$	20.28 pb	PSC	Yes
VBF	$\mu^+\mu^- \longrightarrow \mu^+\mu^- N_\mu\bar{\nu}_\mu$	~ 1 pb	—	No
VBF	$\mu^+\mu^- \longrightarrow \bar{\nu}_\mu\nu_\mu N_\mu\bar{\nu}_\mu$	~ 0.1 pb	—	No

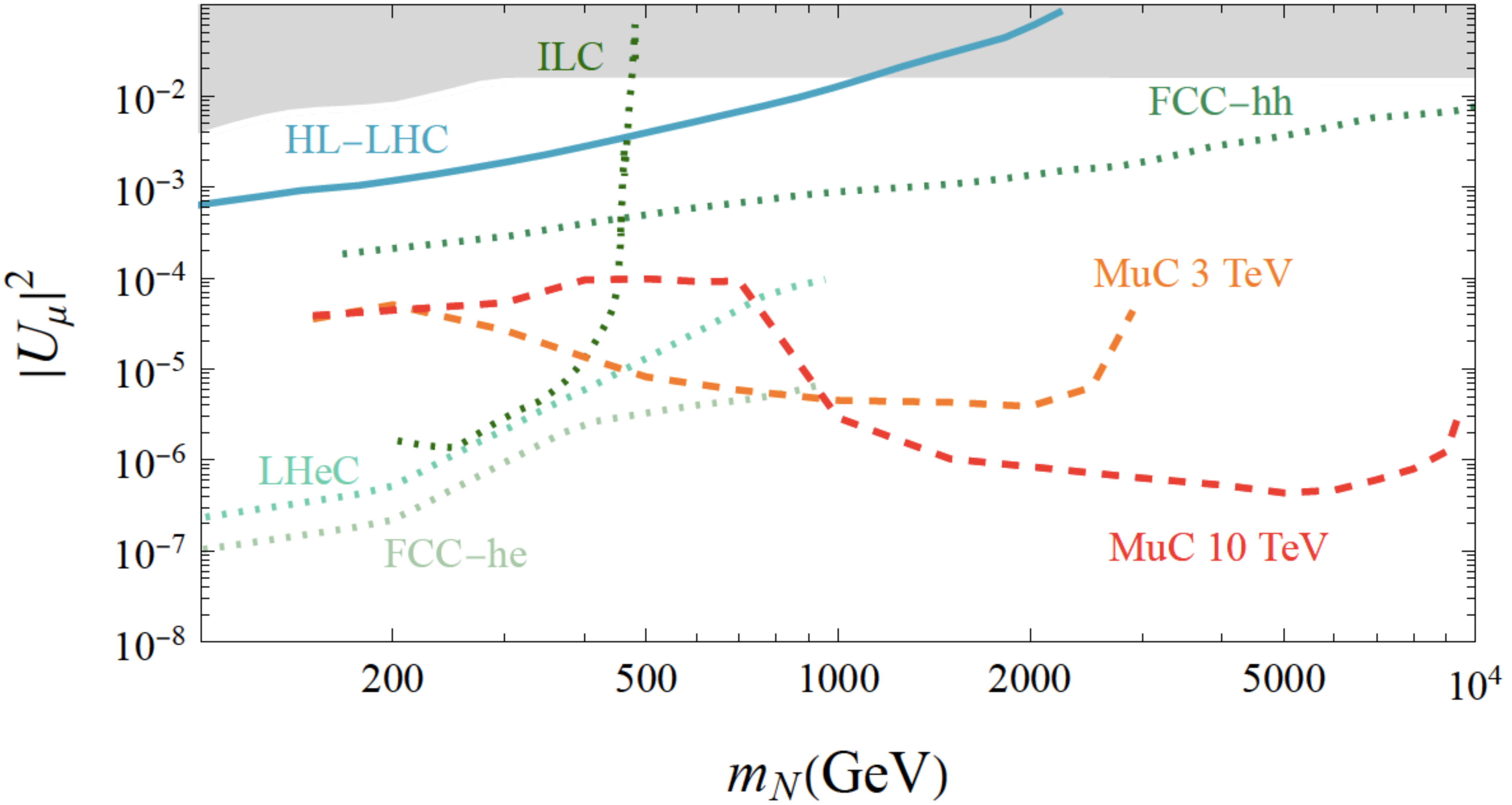
PSC=preselection cut $p_T(\mu^-) > 20\,\text{GeV},\ \lvert\eta(\mu^-)\rvert < 2.5$

Analysis steps

1. Central hadronic W selection because forward are not efficiently detected
2. Mass window for the invariant mass of the HNL decay product system: $m_N \pm 5\% m_N$
3. Customized and optimized cuts on missing transverse momentum and E(W)

Muon-flavored HNL @3 TeV



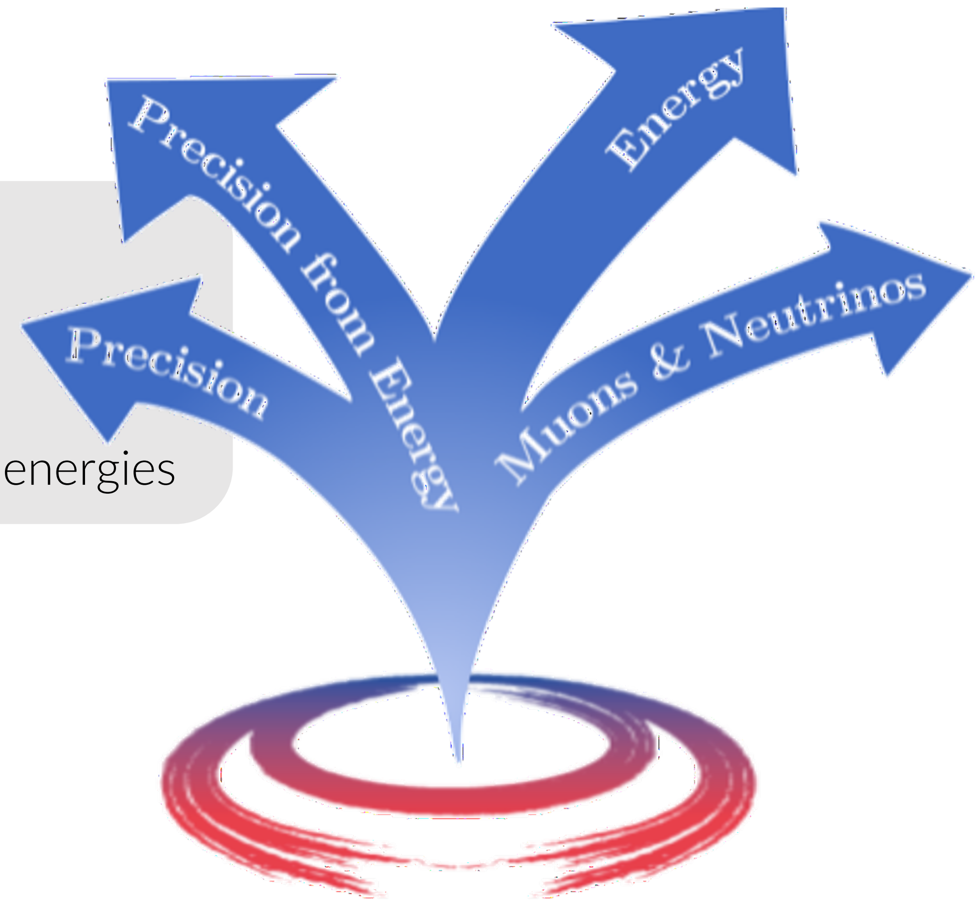


For muon-flavored HNL, Muon Collider can probe $|U_\mu|^2$ down to $\mathcal{O}(10^{-7})$ due to t-channel enhancement

Conclusions

The Muon Collider represents a promising machine for the future
The study of dark sectors can profit from it
The main advantages lie in

- muon specific opportunities
- vector boson fusion and scattering enhanced cross section at high energies



Thank you for your attention