Leptophilic Gauge Bosons at ILC Beam Dump Experiment

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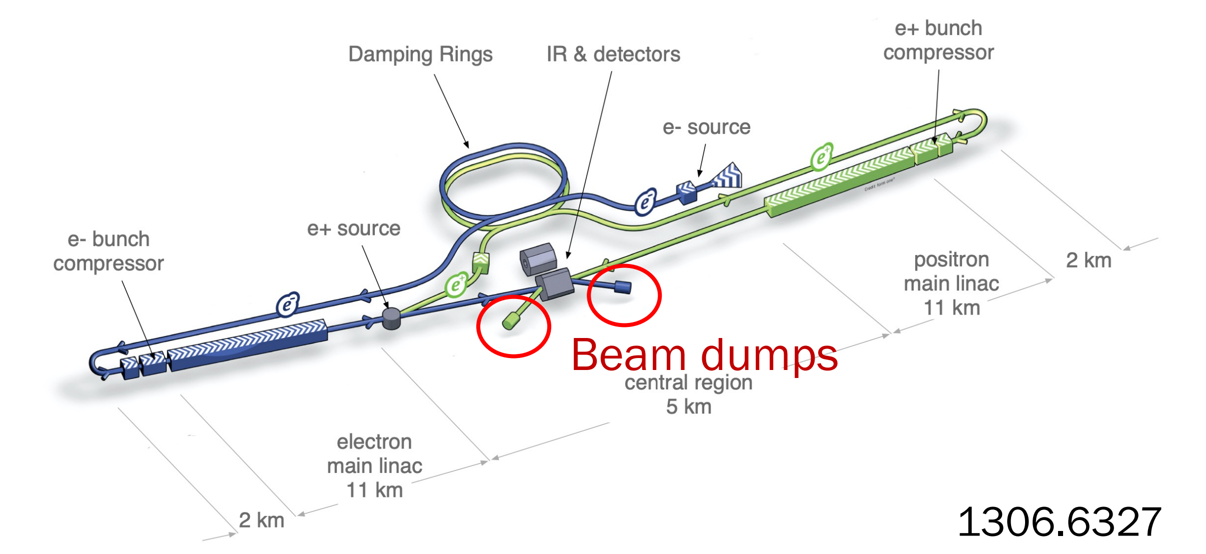
ILC Beam Dump Experiment

Beam dump experiment in ILC

= **Fixed target experiment** w/

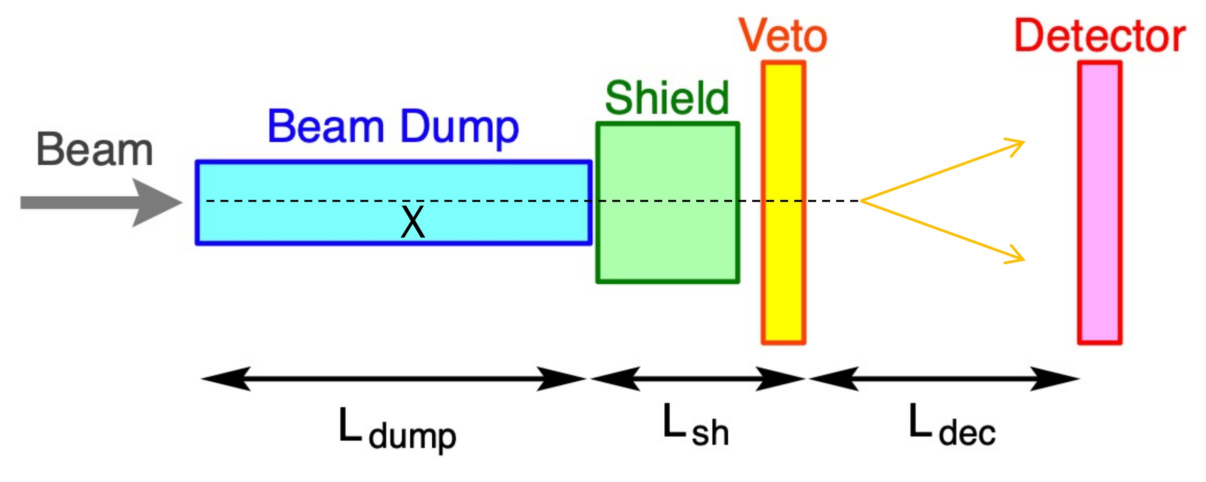
Beam: electron or positron (E = 125 GeV, N~10^{21}/year)

Target: O in H_2O (Z=8, A=16, $\rho \sim 1$)



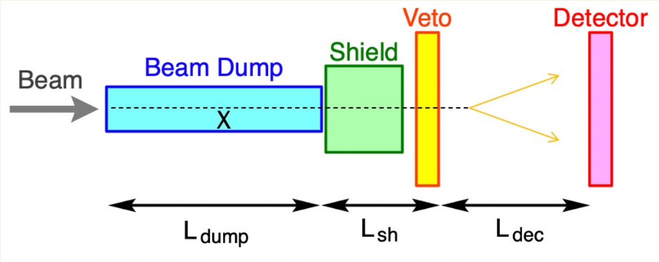
1306.6327

- ✓ Sensitive to very weak interactions
- ✓ Higher energy beam than the previous experiments (e.g. SLAC E137)
- ✓ Positron beam (cf. previous talks)
- ✓ Polarized beam (no proposals in ILC BD, but maybe it is useful)



S. Kanemura et al., 1507.02809

Models



Fixed target experiment has advantage to search for weakly coupling particles.

In our experimental setup (visible decay search), **long-lived particle** which decays into SM charged particles can be searched with few BG.

Some papers about ILC beam dump experiment are submitted as following:

Model	production	paper
Dark Photon	Bremsstrahlung	S. Kanemura et al., 1507.02809
Dark Photon	Annihilation	K. Asai et al., 2105.13768
ALP	Bremsstrahlung	Y. Sakaki et al., 2009.13790
ALP	Annihilation Primakoff	K. Asai et al., 2105.13768

In our work, we consider **the leptophilic gauge boson**, which may be weakly coupled to SM and long-lived particle

Leptophilic Gauge Bosons

$U(1)_{e-\mu}$ $U(1)_{e-\tau}$ $U(1)_{\mu-\tau}$

new U(1) **gauge** symmetries which **depend** on flavor of leptons

$\rightarrow$ **new gauge boson X**

$$\mathcal{L} = -\frac{1}{4}A_{\mu\nu}A^{\mu\nu} - \frac{1}{4}X_{\mu\nu}X^{\mu\nu} - \frac{\epsilon_0}{2}A_{\mu\nu}X^{\mu\nu} + \frac{1}{2}m_X^2 X_\mu X^\mu + \sum_{\ell=e,\mu,\tau}\left[\bar{\ell}\left\{\gamma^\mu\left(\partial_\mu - ie_{\mathrm{EM}}A_\mu - \underline{igQ_\ell X_\mu}\right) - m_\ell\right\}\ell + \bar{\nu}_\ell\gamma^\mu\left(\partial_\mu - \underline{igQ_f X_\mu}\right)P_L\nu_\ell\right]$$

Unknown parameters

w/ (Q_e, Q_μ, Q_τ) = (1,-1,0) for $e-\mu$, (1,0,-1) for $e-\tau$, (0,1,-1) for $\mu-\tau$

- ✓ without gauge anomaly
- ✓ $U(1)_{\mu-\tau}$ contributes to the muon anomalous magnetic moments
- ✓ alleviate the Hubble tension

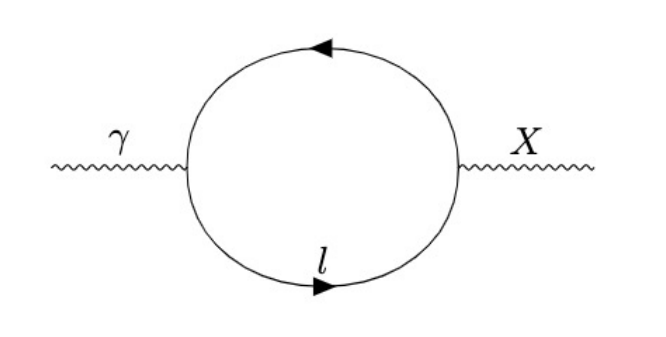
etc.

- **Kinetic mixing** between new gauge boson and photon:

$$\epsilon_{eff} = |\epsilon_0 + \Delta\epsilon| \equiv \kappa_\epsilon \, |\Delta\epsilon\,|$$

w/ ϵ_0 : tree-level, $\Delta\epsilon$: 1-loop contribution

$$\Delta\epsilon(q^2) \equiv -\frac{e_{\rm EM} g}{2\pi^2} \sum_{\ell=e,\mu,\tau} Q_\ell \int_0^1 dx x(1-x) \log\left[m_\ell^2 - q^2 x(1-x) - i0\right],$$



e.g. κ_ϵ=1 ↔ ϵ_0=0, no tree-level mixing

- **Dominant decay modes** are to leptons, not to hadrons:

Charged lepton pair:

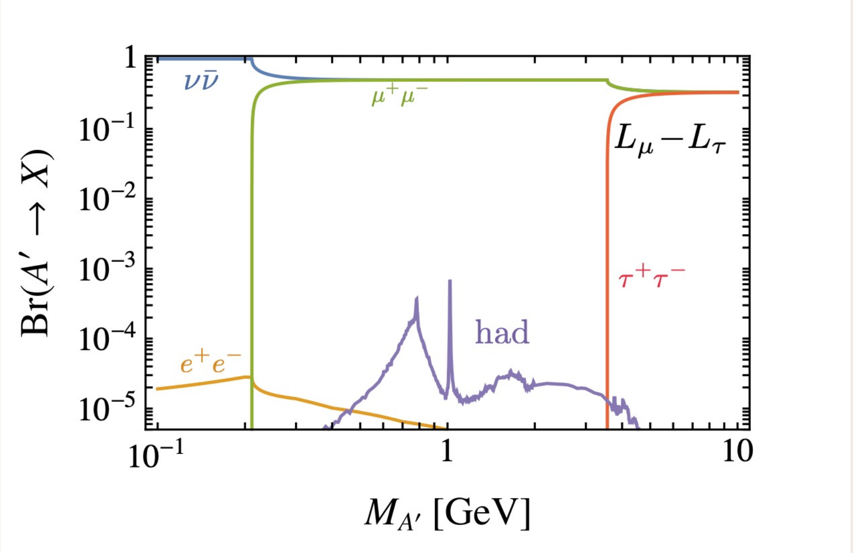
$$\Gamma(X \to l^+ l^-) = \frac{g_l^2}{12\pi} m_X \left(1 + \frac{2m_l^2}{m_X^2}\right)\sqrt{1 - \frac{4m_l^2}{m_X^2}}$$

w/ $g_\ell \equiv \begin{cases} g & : \; Q_\ell = \pm 1, \\ e_{\rm EM}|\epsilon_{\rm eff}| & : \; Q_\ell = 0, \end{cases}$

Neutrino pair:

$$\Gamma(X \to \nu_l \bar{\nu}_l) = \frac{g^2 Q_l^2}{24\pi} m_X$$

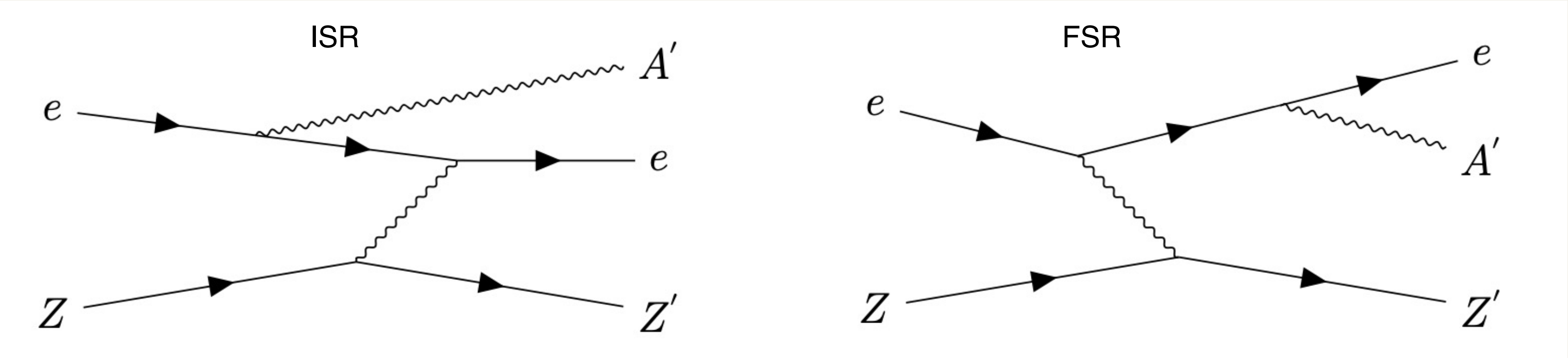
e.g. $U(1)_{\mu-\tau}$



M. Bauer et. al. 1803.05466

Production of Leptophilic Gauge Bosons

Leptophilic gauge bosons are produced by **Bremsstrahlung** process from e^- , e^+ beam:



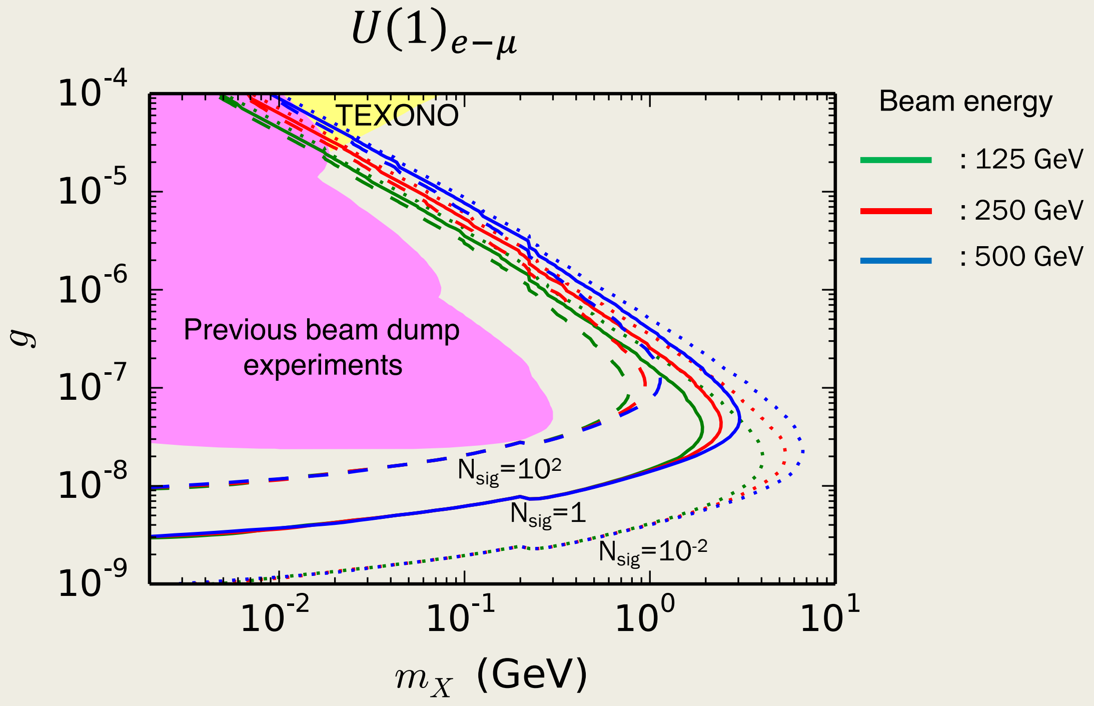
Z: nucleus, A': new gauge boson

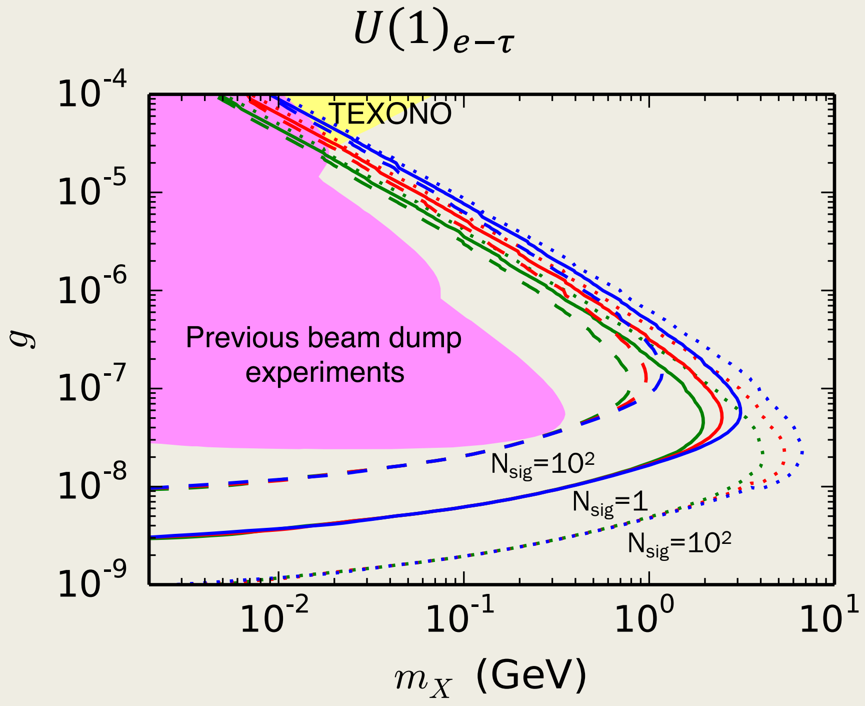
Event rate N_{sig} is given by the following formula and can be calculated numerically:

$$N_{\text{sig}} = N_e \frac{N_{\text{Avo}} X_0}{A} B_{\text{sig}} \int_{m_X}^{E_{\text{beam}}-m_e} dE_X \int_{E_X+m_e}^{E_{\text{beam}}} dE_e \int_0^T dt \frac{I_e(E_{\text{beam}}, E_e, t)}{E_e} \left.\frac{d\sigma}{dx}\right|_{x=E_X/E_e} P_{\text{dec}},$$

We calcuarete N_{sig} at each (m_X, g) numerically and show the contours which correspond to 10^{-2},1,10^2 events on the (m_X, g) plane.

Discovery Reaches at ILC BD

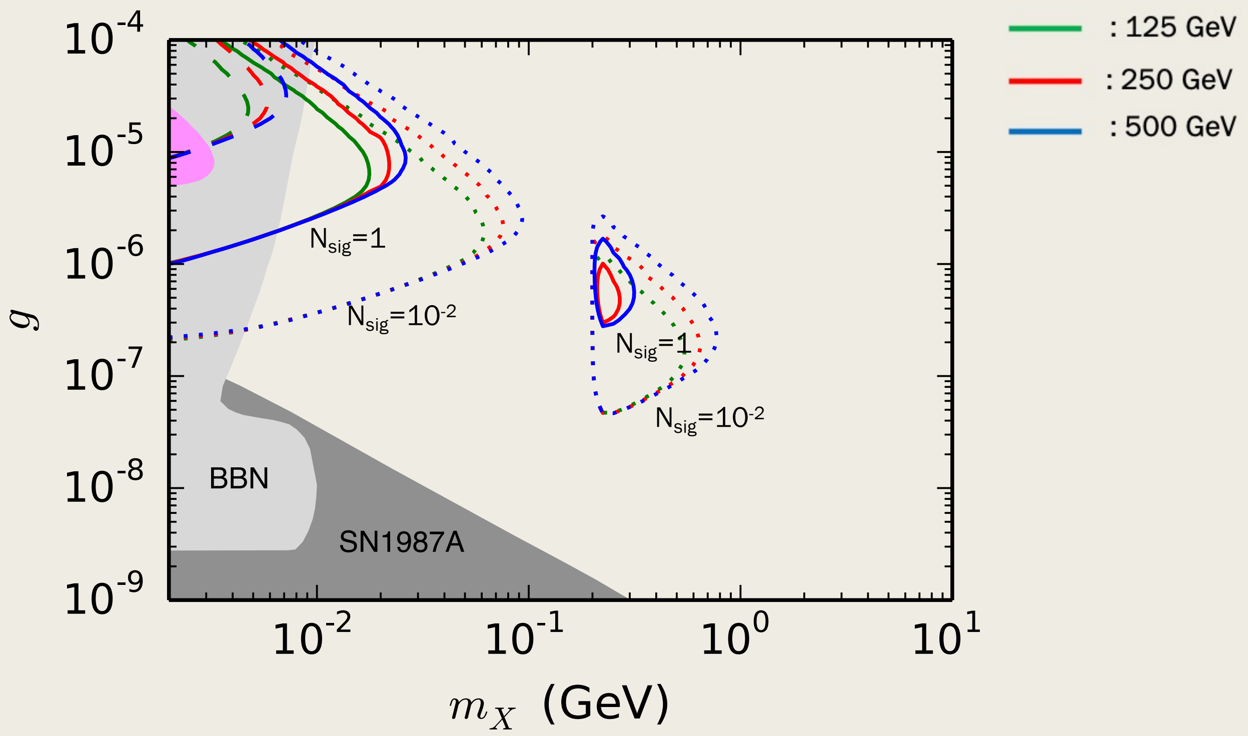




Color ↔ Beam energy: 125 GeV (green), 250 GeV (red), 500 GeV (blue)
Line shape ↔ event rate: 10^{-2} (dotted), 1 (solid), 10^2 (dashed line)

Discovery reaches are similar because new gauge bosons directly couples to electron in both of the models.

$U(1)_{\mu-\tau}$



- ✓ (m_X, g)~(10 MeV, 10^{-5}) can be covered:
  In this region Hubble tension is alleviated. [M. Escudero et al., 1901.02010].
- ✓ Event rates are suppressed because new gauge boson couples to electron only via photon mixing, and branching ratio $Br(X \to e^+e^-)$ is very small in this model.
- ✓ If $m_X \geq 2m_\mu$, $X \to \mu^+\mu^-$ is kinematically allowed and has sizable branching ratio. ILC BD has sensitivity to this region.

Discrimination of Models after the Discovery

the final states (observed particles) depend on the model;

observables $r_e = \frac{\Gamma(X \to e^+ e^-)}{\Gamma_X^{vis}}, r_\mu = \frac{\Gamma(X \to \mu^+ \mu^-)}{\Gamma_X^{vis}}, r_h = \frac{\Gamma(X \to hadrons)}{\Gamma_X^{vis}}$

	r_e	r_μ	r_h
$U(1)_{e-\mu}$	0.5	0.5	0
$U(1)_{e-\tau}$	1.0	0	0
$U(1)_X$	$\frac{1}{2+R}$	$\frac{1}{2+R}$	$\frac{R}{2+R}$

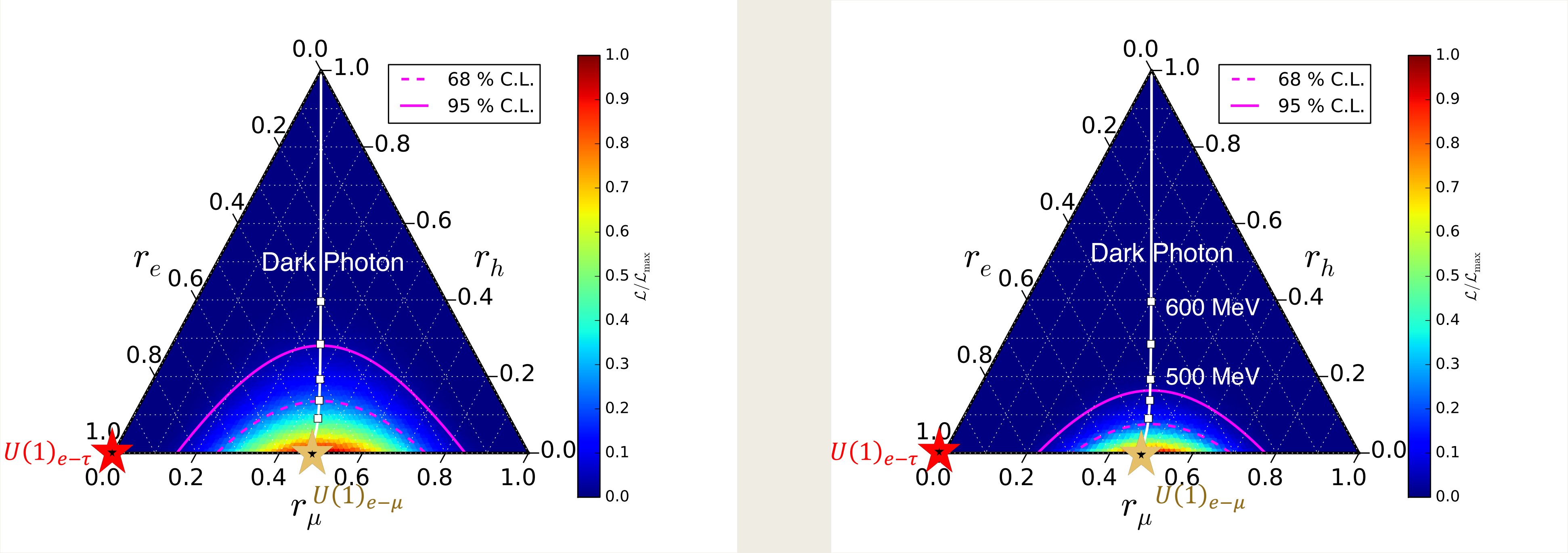
w/ R: R-ratio

✓ **Model:** it may be identified using information about final states and its mass.

We estimate how much we can discriminate the models, adopting Poisson distribution like likelihood function.

e.g. $U(1)_{e-\mu}$ Gauge Boson

$U(1)_{e-\mu}$, $\boldsymbol{N_{sig}} = \mathbf{10}$, $(n_e, n_\mu, n_h) = (5,5,0)$, $U(1)_{e-\mu}$, $\boldsymbol{N_{sig}} = \mathbf{20}$, $(n_e, n_\mu, n_h) = (10,10,0)$



White line: theoretical prediction of dark photon model
White points: Dark photon prediction with mass = 400, 450, 500, 550, 600 MeV from below

We can discriminate $U(1)_{e-\tau}$ model 95% level with 10 signals.
With 20 signals and $m_X \geq 500\ MeV$, we can discriminate dark photon model.

Summary

We proposed the search for leptophilic gauge ($U(1)_{e-\mu}$, $U(1)_{e-\tau}$, $U(1)_{\mu-\tau}$) bosons at ILC beam dump experiment.

- ILC beam dump experiment can cover the parameter region which haven't been covered yet.
- We may know the mass of newly found particle, then we can discriminate the models by using information of final states.

In our work, the experimental setup is the same one as the previous work (1507.02809).

- Using positron beam the other production processes(annihilation, radiative return) is available. This extends the discovery reach especially for $U(1)_{e-\mu}$, $U(1)_{e-\tau}$ models. We have already checked that annihilation process is important even for $U(1)_{\mu-\tau}$.
- If incident muon is available, the discovery reach of $U(1)_{\mu-\tau}$ is improved. This may be done by introducing long shield, or muon beam.

Backup

Event rate

$$N_{\text{sig}} = N_e \frac{N_{\text{Avo}} X_0}{A} B_{\text{sig}} \int_{m_X}^{E_{\text{beam}}-m_e} dE_X \int_{E_X+m_e}^{E_{\text{beam}}} dE_e \int_0^T dt \frac{I_e(E_{\text{beam}}, E_e, t)}{E_e} \frac{d\sigma}{dx}\Big|_{x=E_X/E_e} P_{\text{dec}},$$

N_e: number of electrons in beam
B_{sig}: branching ratio of X which decays into visible signal
I_e: energy distribution of incident electron
σ: cross section of Brems.
$P_{dec} = e^{-\frac{L_{sh}}{l_X}}(1-e^{-\frac{L_{sh}}{l_X}})$: probability that X can go through the dump and the shield

- Limits from brems. productions

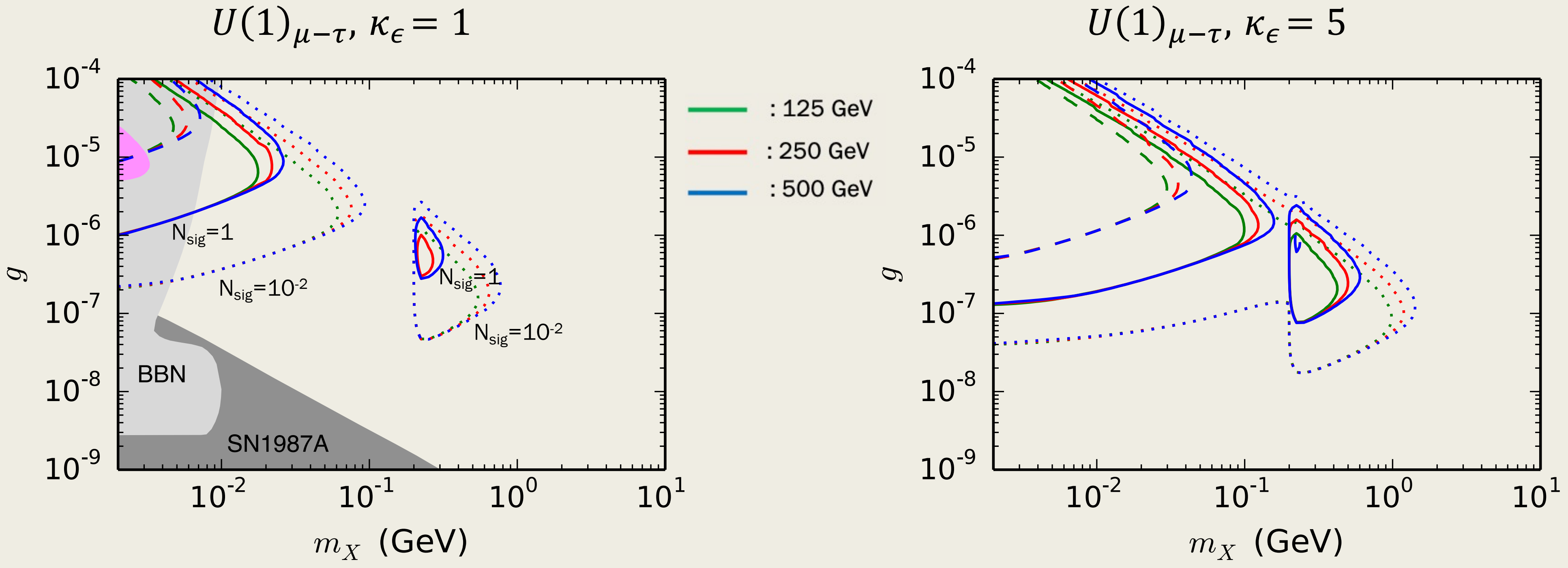
Upper limit → X cannot penetrate the shields, determined by P_{dec};

$$N_{sig} = const. \leftrightarrow m_X^2 g'^2 = const.$$

Lower limit → due to very weak coupling, not sufficient number of particles are produced;

$$N_{sig} \propto \int_{E_{X,min}} dE_X \underbrace{\frac{m_X^2 g'^2}{E_X}}_{P_{dec}} * \underbrace{\frac{g'^2}{m_X^2}}_{\sigma} \propto (const. - \log(m_X))\, g'^4$$

$U(1)_{\mu-\tau}$



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Discrimination of Models

After the discovery, **properties** of newly found particle have to be discussed.

✓ **Mass:** it can be measured if we can take the final states momentum information.

If $(2\mathrm{m}_\tau \geq)\ m_X \geq 2\mathrm{m}_\mu$, **the final states(observed particle) depend on the model**;

observables $r_e = \frac{\Gamma(X \to e^+ e^-)}{\Gamma_X^{vis}}$, $r_\mu = \frac{\Gamma(X \to \mu^+ \mu^-)}{\Gamma_X^{vis}}$, $r_h = \frac{\Gamma(X \to hadrons)}{\Gamma_X^{vis}}$

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We estimate how much we can discriminate the models, adopting Poisson distribution like likelihood function.

e.g. $U(1)_{e-\tau}$ Gauge Boson

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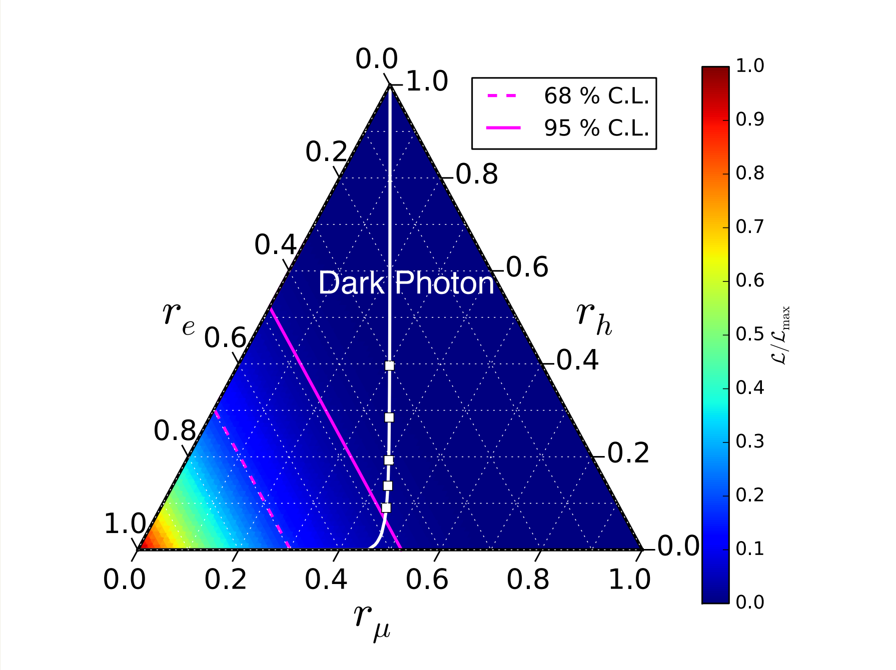
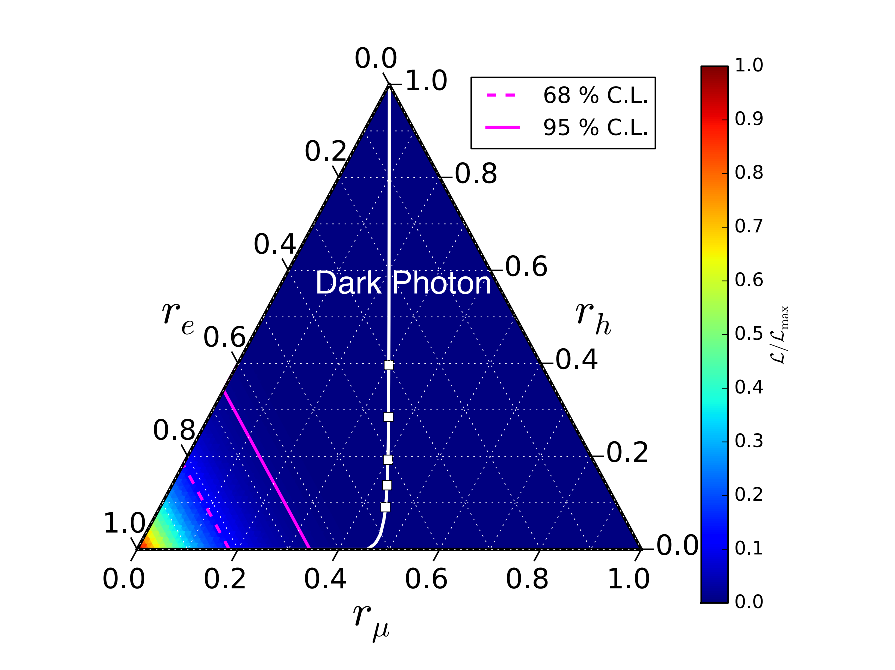


$U(1)_{e-\tau}$, $\boldsymbol{N_{sig}} = \mathbf{10}$, $(n_e, n_\mu, n_h) = (10,0,0)$



600 MeV

500 MeV

Dark Photon

White line: theoretical prediction of dark photon model

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