μTRISTAN
-proposal of new collider experiments-

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Standard Model (SM) and physics beyond SM

The standard model (SM) has been established as a good effective theory.

Lots of phenomena can be explained consistently by the SM.

Some problems in SM:

- Neutrino masses
- Dark matter
- muon g-2 anomaly(?)
- Fine-tuning problem of the Higgs mass

What is the UV physics or unknown sector??

One of the most important questions for the current particle physics

How to uncover BSM

There are some experimental ways to approach this question.

(i) Go to higher energy

Production of new particles

(ii) Precision measurement of couplings to Higgs

Couplings to the Higgs boson are completely predicted within the SM

→ Deviation from the SM values indicates new physics!

The Higgs is relevant to

SUSY, right handed neutrinos, SM singlet scalars, Z',...

Future lepton colliders

- ILC, CLIC ($e^+ e^-$ collider)

Good colliders for Higgs coupling measurements (if they are built)

- Muon colliders ($\mu^+ \mu^-$ colliders) Recently attracting attention

Precision measurements are possible

because it's a lepton collider

High energy (TeV or O(10) TeV) beam can be realized

because of less synchrotron energy than electrons

μ^- beam and μ^+ beam

To realize high-quality beam for good luminosity, the number of beam particles and smallness of the beam size are important.

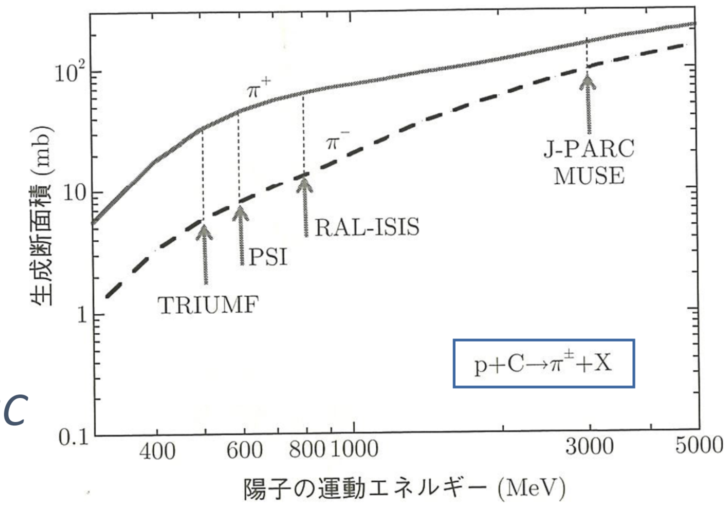
μ^- beam

- Production of large amount of μ^- is difficult
- Method to make small μ^- beam is still under investigation

μ^+ beam

- Production of large amount of μ^+ is easier
- There is an established method to make small μ^+ beam (ultra-cold muon)

Key technology for muon g-2 experiment at J-PARC



Proposal of new collider experiments

We propose collider experiments using high-quality μ^+ beam and accelerating it to TeV scale!

Using the 3 km ring (same ring size as TRISTAN), we can realize

- $\mu^+ e^-$ collider

$$E_{\mu^+} = 1 \text{ TeV}, \ E_{e^-} = 30 \text{ GeV} \quad \text{(TRISTAN energy)}$$
$$\longrightarrow \sqrt{s} = 346 \text{ GeV}$$

- $\mu^+ \mu^+$ collider

$$E_{\mu^+} = 1 \text{ TeV}, \ E_{\mu^+} = 1 \text{ TeV}$$
$$\longrightarrow \sqrt{s} = 2 \text{ TeV}$$

μTRISTAN!

Proposal of new collider experiments

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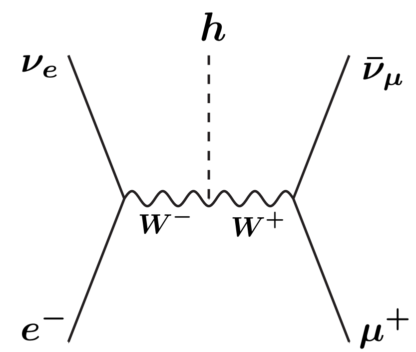
Using the 3 km ring, we can realize

- μ^+e^- collider Higgs factory

$$E_{\mu^+} = 1\ \mathrm{TeV},\ E_{e^-} = 30\ \mathrm{GeV}$$ (TRISTAN energy)

$$\longrightarrow \sqrt{s} = 346\ \mathrm{GeV}$$



- $\mu^+\mu^+$ collider New physics search

$$E_{\mu^+} = 1\ \mathrm{TeV},\ E_{\mu^+} = 1\ \mathrm{TeV}$$

$$\longrightarrow \sqrt{s} = 2\ \mathrm{TeV}$$

μTRISTAN!

Proton acceleration (Proton LINAC & RCS) → Pion production (Pion production ring)

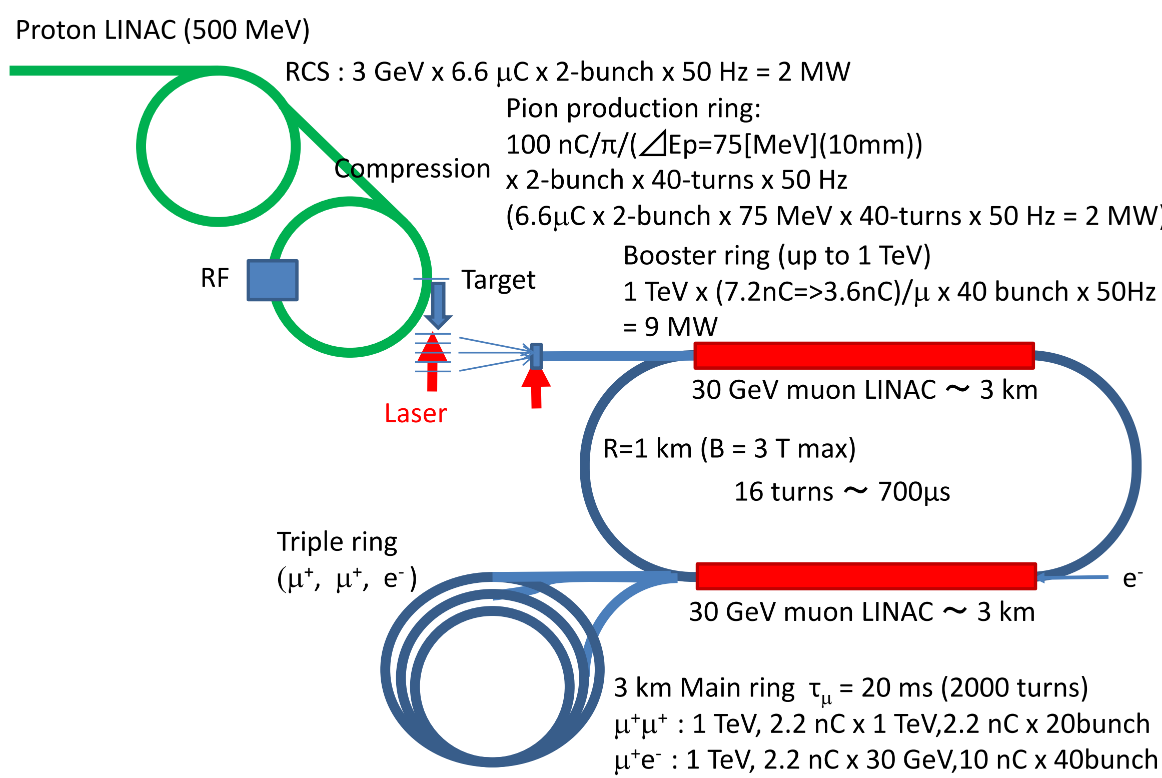
$p(3\,\mathrm{GeV})$ → $p(3\,\mathrm{GeV}) + C \to \pi^{+} + X$

→ Ultra-cold muon production → Muon acceleration (Booster ring) → Collide (Main ring)

$\pi^{+} \to \mu^{+} + \nu_{\mu}$ → Muonium $(\mu^{+}e^{-})$ formation in silica aerogel → Ionized by laser → Ultra-cold muon

Muon acceleration (Booster ring): $\mu^{+}(1\,\mathrm{TeV})$

Collide (Main ring): $[\mu^{+}(1\,\mathrm{TeV}), e^{-}(30\,\mathrm{GeV})]$ or $[\mu^{+}(1\,\mathrm{TeV}), \mu^{+}(1\,\mathrm{TeV})]$



Luminosity

Assuming

- similar proton beam power to J-PARC exp.
  source of muon production
- similar magnet power to HL-LHC

we estimate the luminosity as

Ten-year running w/ 70 % duty factor

$$\mathcal{L}_{\mu^+ e^-} = 4.6 \times 10^{33}\ \mathrm{cm}^{-2}\mathrm{s}^{-1} \longrightarrow \int \mathcal{L}_{\mu^+ e^-} dt = 1.0\ \mathrm{ab}^{-1}$$

$$\mathcal{L}_{\mu^+ \mu^+} = 5.7 \times 10^{32}\ \mathrm{cm}^{-2}\mathrm{s}^{-1} \longrightarrow \int \mathcal{L}_{\mu^+ e^-} dt = 130\ \mathrm{fb}^{-1}$$

MadGraph5
J. Alwall et al.

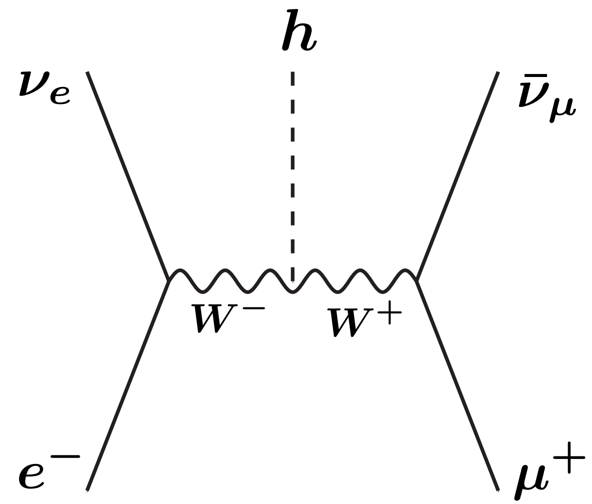
Higgs production

Main Higgs production: W boson fusion (WBF)

$$\sqrt{s} = 346 \text{ GeV} \quad (E_{\mu^+} = 1 \text{ TeV},\ E_{e^-} = 30 \text{ GeV})$$

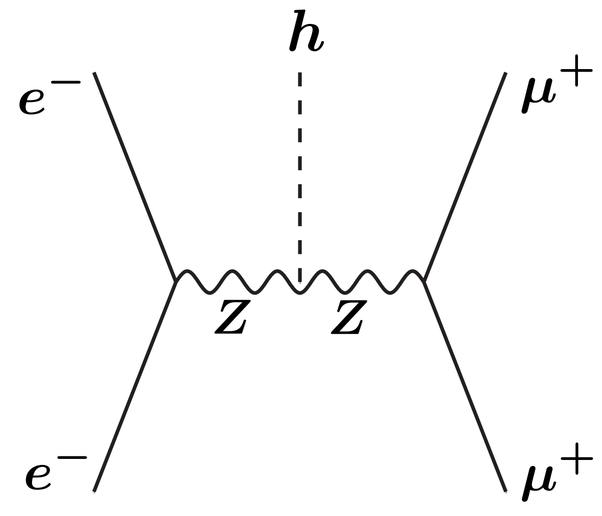
$$(P_{\mu^+}, P_{e-}) = (0.8, -0.7)$$

$$\sigma_{\mathrm{WBF}} \approx 91\,\mathrm{fb}$$



Z boson fusion (ZBF)

$$\sigma_{\mathrm{ZBF}} \approx 4\,\mathrm{fb}$$



Number of Higgs bosons

Assuming the integrated luminosity of 1.0 ab^{-1}
(can be achieved by ten-year running with 70 % duty factor)

$$\boldsymbol{N(\mathbf{Higgs}) = 9.5 \times 10^4 \times \frac{(\mathbf{integrated\ luminosity})}{\mathbf{1.0\,ab^{-1}}}}$$

Coupling measurement

Focus on the WBF channel

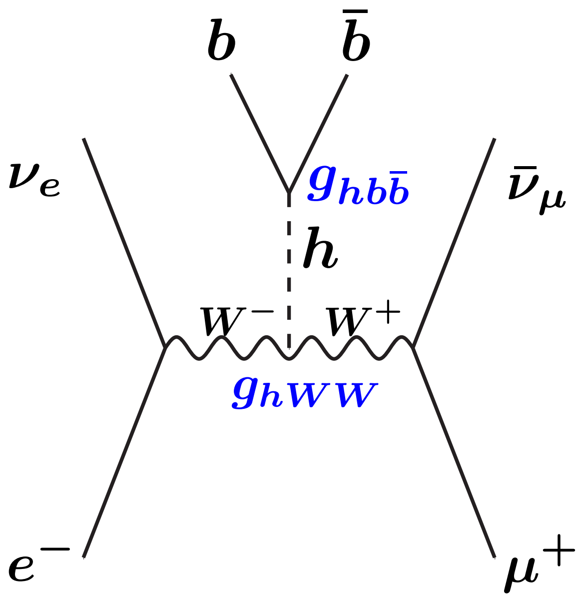
Higgs mainly decays into b$\bar{b}$

(Branching ratio 58.2 % in SM)

$$\sigma_{\rm SM} = \sigma^{\rm SM}_{\rm WBF} \frac{\Gamma^{\rm SM}_{H\to b\bar{b}}}{\Gamma^{\rm SM}_{H}}$$

can be modified $\longrightarrow$ $$\sigma = \frac{\kappa_W^2 \kappa_b^2}{\kappa_H^2} \sigma_{\rm SM}$$

$\kappa_W = 1 + \Delta\kappa_W$ etc.



$$g_{hWW} = \kappa_W g^{\rm SM}_{hWW}$$

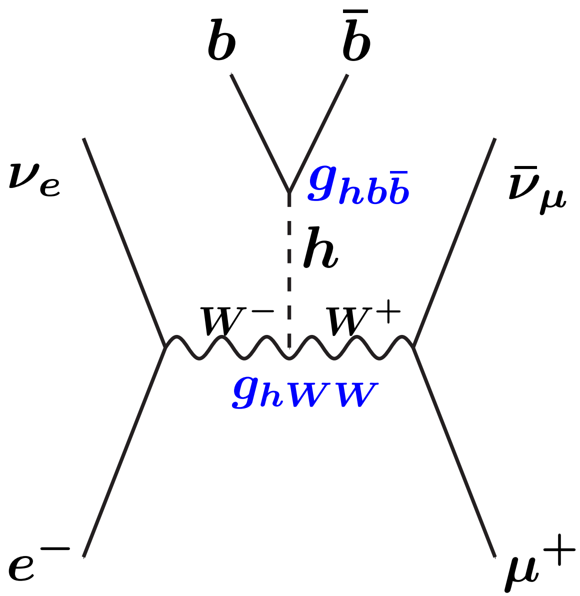
$$g_{hb\bar{b}} = \kappa_b g^{\rm SM}_{hb\bar{b}}$$

$$\Gamma_H = \kappa_H^2 \Gamma^{\rm SM}_H$$

Coupling measurement

$$\sigma = \frac{\kappa_W^2 \kappa_b^2}{\kappa_H^2} \sigma_{\rm SM}$$

$$\kappa_W = 1 + \Delta\kappa_W$$ etc.



We obtain a constraint

$$|\Delta\kappa_W + \Delta\kappa_b - \Delta\kappa_H|$$

$$\lesssim \frac{1}{2}\frac{\Delta_{\rm stat}\sigma}{\sigma} \approx \frac{1}{2}\frac{1}{\sqrt{N({\rm WBF}) \times {\rm Br} \times {\rm efficiency}}}$$

$$= 3.1 \times 10^{-3} \times \left(\frac{\text{integrated luminosity}}{1.0\ {\rm ab}^{-1}}\right)^{-1/2} \left(\frac{\text{efficiency}}{0.5}\right)^{-1/2}$$

Sub per-cent measurement *Statistical error only

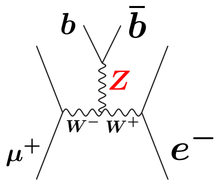
Efficiency

The efficiency to detect the events is important.

Main issues

- Background events

Electron number=+1, Muon number=-1 → Small number of background events



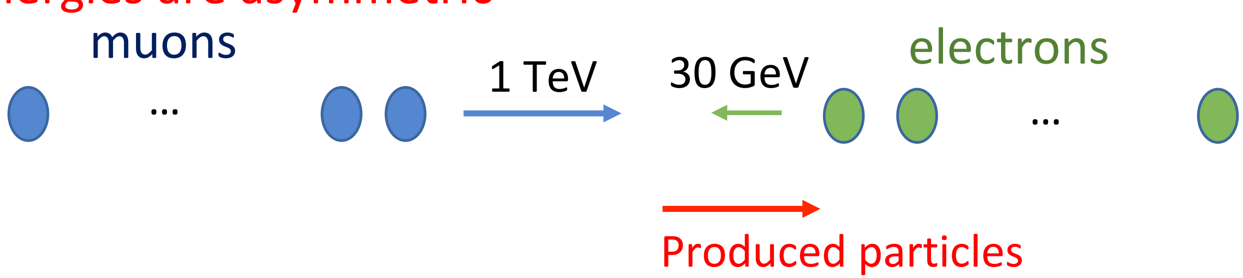
The invariant mass analysis of b-jets would significantly suppress the BG events.

cf. 1403.7734 C. Durig, K. Fujii, J. List, J. Tian

parallel BG events are cut by 90 - 95 % for ILC 250 and 500 GeV

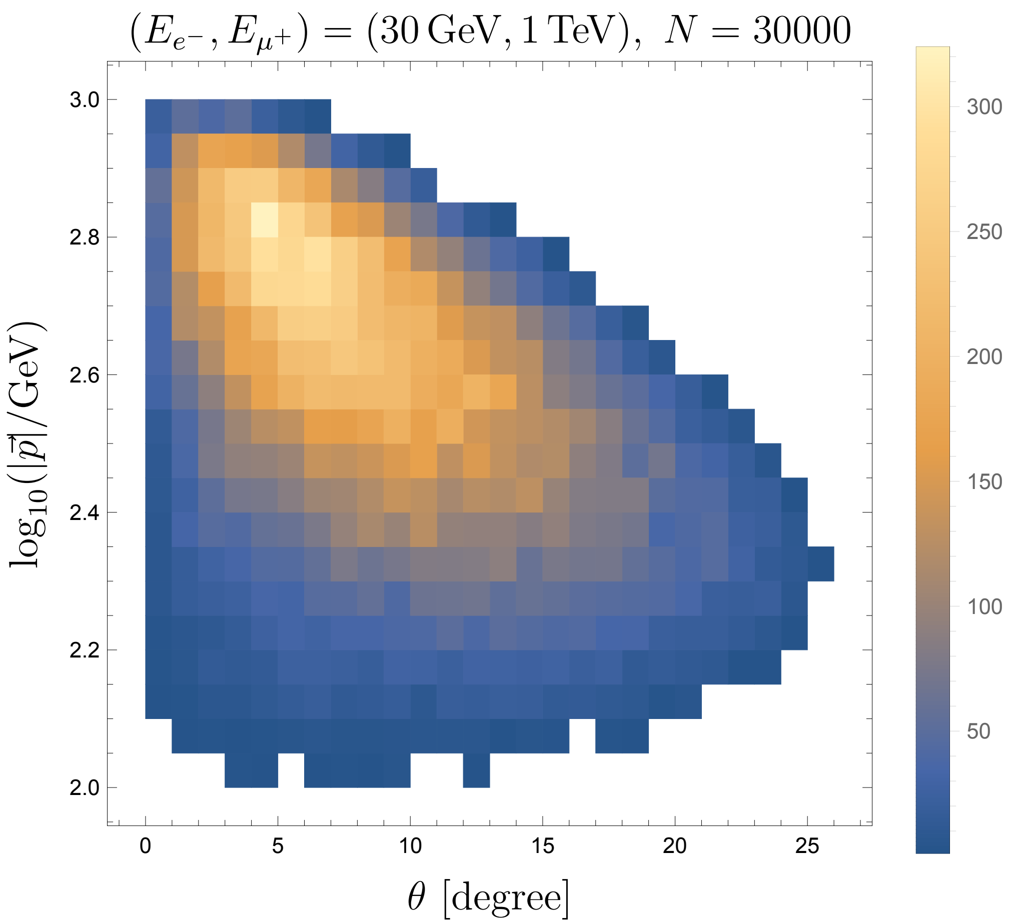
- Coverage of detector in a small angle region

Energies are asymmetric



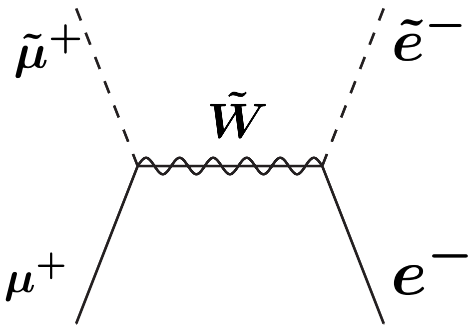
Kinematics of produced Higgs boson

Angle & spatial momentum of produced Higgs boson

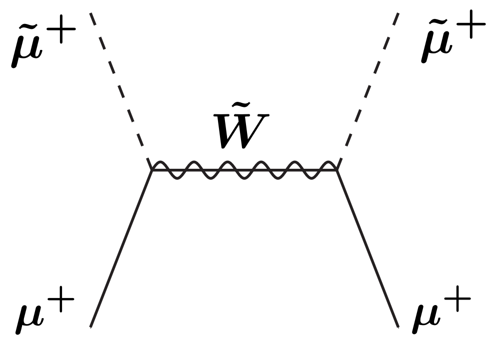


Scalar lepton production at μTRISATN

- $\mu^+ e^-$ collider



- $\mu^+ \mu^+$ collider



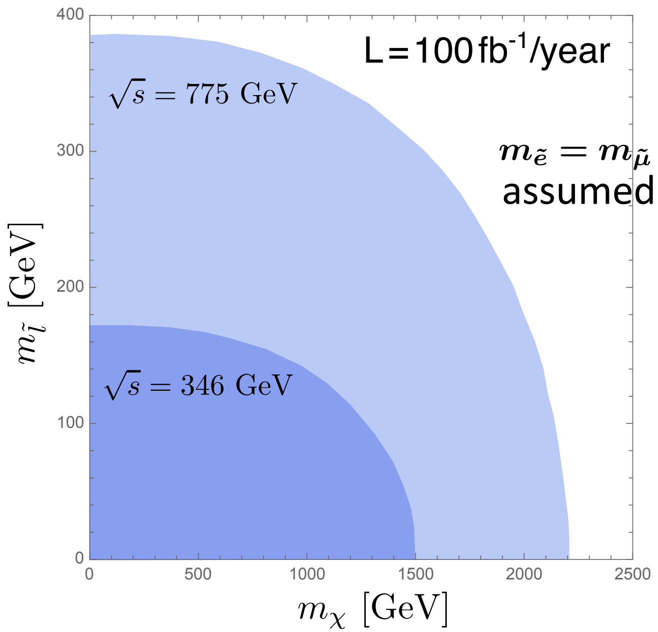
We only consider the diagram where the Wino $\tilde{W}$ is exchanged for simplicity.

superpartner of $SU(2)_L$ gauge boson

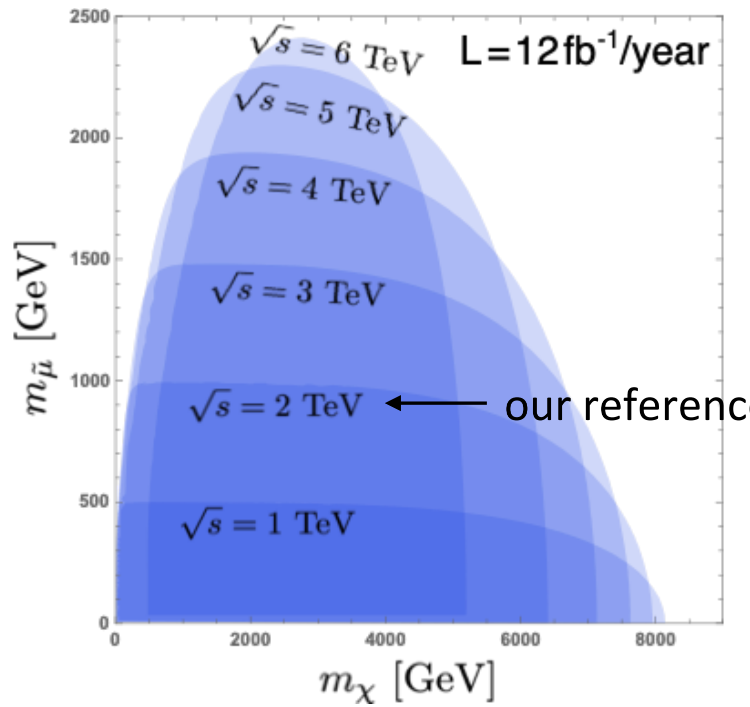
Scalar lepton search

Mass parameter regions where # of events exceeds 100

μ⁺ e⁻ collider



μ⁺ μ⁺ collider



our reference energy

$m_{\tilde{\mu}} \lesssim 1$ TeV can be detected.

Interesting region in terms of muon g-2 anomaly

Conclusions

- We proposed new collider experiments, μ^+e^- collider and $\mu^+\mu^+$ collider, utilizing the technology for providing high-quality μ^+ beam.

- We estimated the luminosity of these colliders.

$$\mathcal{L}_{\mu^+e^-} = 4.6 \times 10^{33}\ \mathrm{cm^{-2}s^{-1}} \longrightarrow \int \mathcal{L}_{\mu^+e^-} dt = 1.0\ \mathrm{ab^{-1}}$$

$$\mathcal{L}_{\mu^+\mu^+} = 5.7 \times 10^{32}\ \mathrm{cm^{-2}s^{-1}} \longrightarrow \int \mathcal{L}_{\mu^+e^-} dt = 130\ \mathrm{fb^{-1}}$$

May be achieved by extension of *the existing technology*

- $\mu^+ e^-$ collider can be a good Higgs boson factory.

- $\mu^+ \mu^+$ collider ($\sqrt{s}$=2 TeV) is suited for new physics search.

Detailed studies on luminosity and detector are necessary.
Further interesting studies at this collider would be possible.