μTRISTAN

Ryutaro Matsudo

NTU $\rightarrow$ KEK

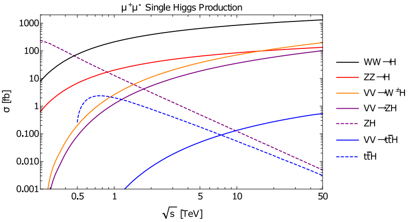
Feb. 13, 2024

Based on 2201.06664, Yu Hamada (DESY), Ryuichiro Kitano(KEK), RM, Takaura Hiromasa(YITP), Mitsuhiro Yoshida(KEK)
2210.11083, Yu Hamada, Ryuichiro Kitano, RM, Takaura Hiromasa
Work in progress with Lukas Treuer (Sokendai), Shohei Okawa (KEK) Koji Nakamura (KEK), Sayuka Kita (Tsukuba U.)
Toshiki Kaji (Waseda U.), Taiki Yoshida (Waseda U.), Kohei Yorita (Waseda U.)

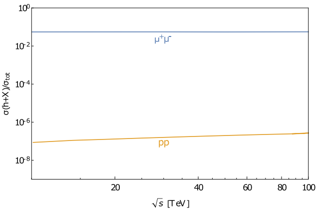
Hokkaido Workshop on Particle Physics at Crossroads

μTRISTAN

- In order to uncover BSM physics, we need to probe higher energy. Higher energy is beneficial not only for direct searches of BSM, but also for Higgs precision because vector boson fusion processes logarithmically grow with energy.
- **Muon colliders** are highly attractive for the both of direct search and precision measurement.
- Compared to electron colliders, muon colliders can achieve higher energy while requiring smaller sizes since muons are heavier.
- Compared to pp colliders, muon colliders expect to have less background.



[M. Forslund, P. Meade, JHEP 08, 185 (2022)]



[H. A. Ali, "The Muon Smasher's Guide", Rept. Prog. Phys. 85, 084201 (2022)]

- The most challenging aspect of muon colliders is achieving sufficient **luminosity** ($\sim 1\ \mathrm{ab}^{-1}$)
- In order to focus the beam in a tiny region, it has to have low emittance, i.e., occupy a small area in the position-momentum phase space.
- We need reduce the emittance **on the timescale of the muon lifetime**.
- In the design by IMCC, ionization cooling is used, which has not yet been established.
- In our proposal of a collider experiment, we use **ultra slow muons**, which are only antimuons. $\Rightarrow$ $\boldsymbol{e^-\mu^+}$ and $\boldsymbol{\mu^+\mu^+}$ colliders.

- How to achieve enough **Luminosity**.
- How many **Higgs** are produced in the $e^-\ \mu^+$ and $\mu^+\mu^+$ colliders.
- Possible **new physics** searches.

Outline

1. Collider design
2. Higgs boson physics
3. New physics searches

Outline

Luminosity

- Toe get a large number of events, we need large luminosity.

$$\# \text{ of events } / \text{s} = \sigma \cdot \mathcal{L}$$

- To get large luminosity, an efficient method of **cooling** is needed.

$$\mathcal{L} = f \frac{N_1 N_2}{4\pi \sigma_x \sigma_y}$$

$N_{1,2}$:# of particles in a bunch of the beam 1,2

$\sigma_{x,y}$: The beam size at the collision point

f: The frequency of the collisions

$$\sigma_x = \sqrt{\frac{\beta_x^* \varepsilon_x}{\gamma \beta}}$$

β_x^*: The beta function at the collision point,

ε_x: The normalized emittance,

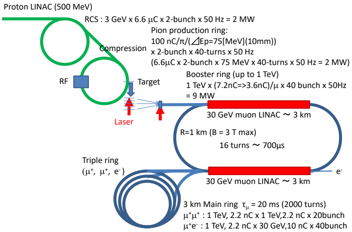
$\beta_{x,y}^* > \sigma_S$, σ_S: Bunch length

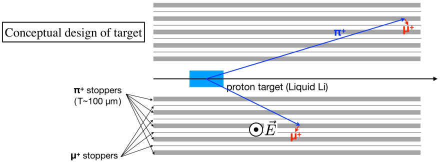
A better cooling gives a smaller emittance and a smaller bunch length.

How to enhance the number of ultra slow muons

- Two bunches of the proton beam repeatedly collides with the pion production target 40 times, and muons from two bunches of proton are gathered and merged to make a single bunch. $\Rightarrow$ **40 bunches of the muon beam are obtained per 2 bunches of the proton beam**.
- A layer of pion production and muonium formation targets creates ultra cold muons as many as possible.

  $\Rightarrow$ 1.4×10^{-3} **muons** are produced per single proton collision according to an ongoing simulation by Yasuhiro Sakaki and Mitsuhiro Yoshida.
- The ultra slow muons are corrected and transferred to the second muonium-formation target, and ionized by laser again. Here the production efficiency of 50% is assumed, and then the number of muons becomes $\sim \mathbf{7 \times 10^{-4}}$.





Luminosity estimation

- The luminosity of the $e^-\mu^+$ collider is estimated from

$$f_{e\mu} = \#\text{ of collision per second} = \frac{\text{Speed of light}(3\times 10^5\text{ km/s})}{\text{Circumference}(3\text{ km})}\times 40\text{ bunches} = 4\text{ MHz},$$

$$f_{\mu\mu} = 2\text{ MHz}$$

$$N_\mu = \text{The averaged }\#\text{ of muons per bunch} = 3.16\text{ nC} = 1.4\times 10^{10},$$

$$N_e = \#\text{ of electrons per bunch} = 10\text{ nC} = 6.2\times 10^{10},$$

$$\sigma_x = \sqrt{\frac{4\ \mu\text{m}\times 30\text{ mm}}{1\text{ TeV}/100\text{ MeV}}} \sim 3\ \mu\text{m},\quad \sigma_y = \sqrt{\frac{4\ \mu\text{m}\times 7\text{ mm}}{1\text{ TeV}/100\text{ MeV}}} \sim 2\ \mu\text{m}$$

$$\mathcal{L}_{e^-\mu^+} = f_{e\mu}\frac{N_\mu N_e}{4\pi\sigma_x\sigma_y} = 4.6\times 10^{33}\text{cm}^{-2}\text{s}^{-1}$$

$$\mathcal{L}_{\mu^+\mu^+} = f_{\mu\mu}\frac{N_\mu N_\mu}{4\pi\sigma_x\sigma_y} = 5.7\times 10^{32}\text{cm}^{-2}\text{s}^{-1}$$

- Integrated luminosities are

$$\mathcal{L}^{\text{int}}_{e^-\mu^+} \sim 1\text{ ab}^{-1}\text{ for }\sim 10\text{ years of running}$$

$$\mathcal{L}^{\text{int}}_{\mu^+\mu^+} \sim 0.1\text{ ab}^{-1}\text{ for }\sim 10\text{ years of running}$$

Comparison to the IMCC design

- We use more conservative values for several parameters that could be used commonly in the both of $\mu^+\mu^+$ and $\mu^+\mu^-$ colliders than the IMCC design.
- The normalized emittance and the bunch length of the ultra cold muon beam are expected to achieve the requirement by IMCC.

	IMCC	μTRISTAN ($e^-\mu^+$)	μTRISTAN ($\mu^+\mu^+$)
Normalized emittance (μm)	25	1 – 4	1 – 4
Bunch length (at 2 TeV) (mm)	7.5	0.1 – 1	0.1 – 1
Beta function at IP (mm)	5	(30,7)	(30,7)
Center-of-mass energy (TeV)	3, 10, 14	0.35	2
Circumference (km)	4.5, 10, 14	3	3
(Initial) bunch charge (10^{10})	220, 180, 180	(6.2, 2.2)	2.2
Number of bunches	1	40	20
Repetition rate (Hz)	5	50	50
# of muons per second ($10^{13}/s$)	2	4	4
Luminosity (10^{34} cm^{-2} s^{-1})	2,20,40	0.4	0.06

[C. Accettura et al., "Towards a Muon Collider", Eur. Phys. J. C 83, 864 (2023)]

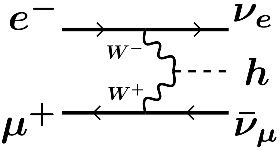
Polarization

- The **polarization** of the beams is important to enhance the Higgs production via fusion processes.
- The electron beam polarization is set to be $\boldsymbol{P_e = 0.7}$, which is the same polarization as the superKEKB.
- The muon beam polarization is assumed to be $\boldsymbol{P_\mu = 0.8}$.
  The polarization of μ^+ can be maintained in the muonium formation by **a longitudinal magnetic field**.
- Even if the longitudinal magnetic field is not used, there remains $P_\mu = 0.25$.
  - All muons from the pion decay are **right-handed**.
  - The half of the muonium state is $|{+}{+}\rangle$ whose spin is preserved, while $|{+}{-}\rangle$ states undergo spin oscillation, and thus under the single process of the muonium formation and laser ionization, **the polarization becomes half**.
  - After the two muonium formation processes, the polarization becomes $P_\mu = 0.25$.
- Even if $P_\mu = 0.25$, the Higgs production cross section is only reduced by 30% in the $e^-\mu^+$ collider.

Outline

Higgs production in $e^-\mu^+$ collider: W-fusion

In the $e^-\mu^+$ collider, **the W boson fusion** is the dominant channel of Higgs production.



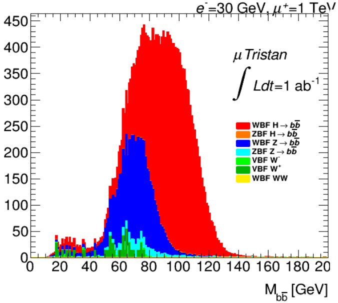
- The beam energies are **30 GeV** and **1 TeV** for e^- and μ^+.
  $\Rightarrow$ $\boldsymbol{\sqrt{s} =}$ **346 GeV**.
- The cross section is $\boldsymbol{\sigma_{\mathrm{WBF}} =}$ **91 fb.** $\Rightarrow$ **# of Higgs** $\boldsymbol{\sim 9000}$ **at 1 ab^{-1}**.
- From this, the statistical error of the kappa parameters are estimated as

$$\Delta(\kappa_W + \kappa_b - \kappa_H) = \frac{1}{2}\frac{1}{\sqrt{N(\text{WBF}) \times \text{Br}(H \to b\bar{b}) \times \text{efficiency}}}$$
$$= 3.1 \times 10^{-3} \times \left(\frac{\text{Integrated luminosity}}{1.0\ \text{ab}^{-1}}\right)^{-1/2} \times \left(\frac{\text{Efficiency}}{0.5}\right)^{-1/2}$$

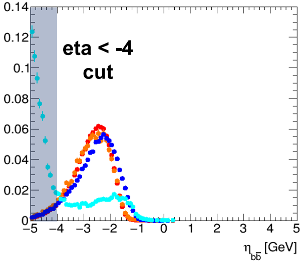
Detector simulation (preliminary)

- The detector simulation using Delphes is in progress with Sayuka Kita and Koji Nakamrua.
- We use the ATLAS (HL-LHC) card.
- Cuts: 1. No muon. 2. No electron. 3. Exact 2 bjets.
  Acceptance $\sim 23\%$

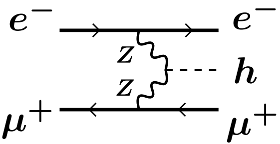
M_{bb} (η_{bb}>-4 region)



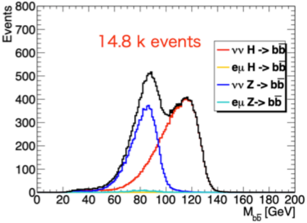
η_{bb}

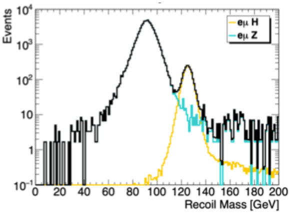


Z boson fusion and recoil mass



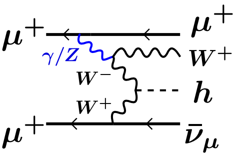
- At $\sqrt{s} = 346$ GeV, $\sigma_{\rm ZBF} \sim 4$ fb. $\Rightarrow$ # of Higgs = 400 at 1 ab^{-1}.
- For the ZZ-fusion process, we can reconstruct the Higgs mass from the momentums of e^- and μ^+. $\Rightarrow$ Total width measurement.

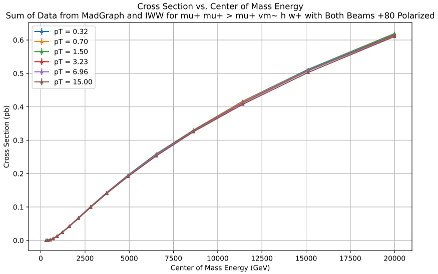




Higgs production in $\mu^+\mu^+$: W-fusion via photon

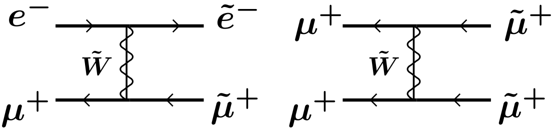
- Even for $\mu^+\mu^+$, we can realize WW-fusion by introducing a photon propagator.
- Despite the additional coupling, the contribution from this graph has the similar value to the usual WW-fusion.
- Due to the pole of the propagator of photon, MadGraph fails to estimate low p_T region of μ^+.
  $\Rightarrow$ The low p_T region ($p_T < 0.1$–10 GeV) should be estimated by IWW (Improved Weizsaecker-Williams) approximation. [Lukas Trouer, First Day 16:50]



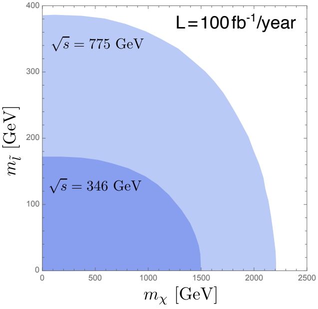


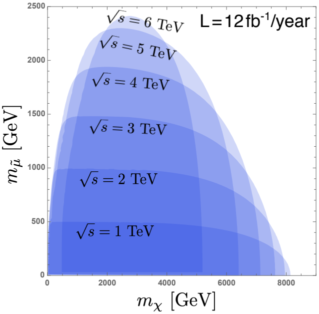
Outline

Slepton production



The region where the amount of charged **slepton pair production per year is larger than 100** at $e^-\mu^+$ and $\mu^+\mu^+$ colliders.





Constraints on dimension-6 SMEFT ops. from the elastic scattering

Precision measurement of the cross section of $e^-\mu^+ \to e^-\mu^+$ and $\mu^+\mu^+ \to \mu^+\mu^+$ can give a limit to the SMEFT ops.

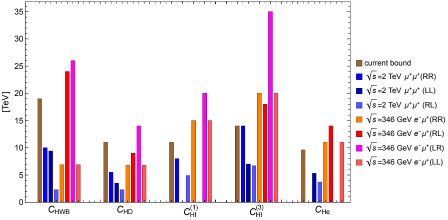
$$S \supset \int \sum_J \frac{1}{\Lambda_J^2} Q_J.$$

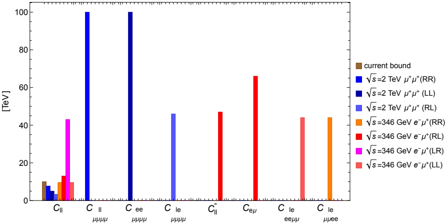
The SM couplings modified by

$$\begin{cases} Q_{HWB} = H^\dagger H B_{\mu\nu} B^{\mu\nu}, \ Q_{HD} = (H^\dagger D_\mu H)^* (H^\dagger D_\mu H), \\ Q_{Hl}^{(1)} = (H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{L}\gamma^\mu L), \ Q_{Hl}^{(3)} = (H^\dagger i \overleftrightarrow{D}^I_\mu H)(\bar{L}\tau^I \gamma^\mu L), \ Q_{He} = (H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{R}\gamma^\mu R) \end{cases}$$

Four fermi interactions:

$$Q_{\substack{ll\\prst}} = (\bar{l}_p \gamma_\mu l_r)(\bar{l}_s \gamma^\mu l_t), \quad Q_{\substack{le\\prst}} = (\bar{l}_p \gamma_\mu l_r)(\bar{e}_s \gamma^\mu e_t), \quad Q_{\substack{ee\\prst}} = (\bar{e}_p \gamma_\mu e_r)(\bar{e}_s \gamma^\mu e_t)$$





Summary

- For μ^+, an efficient cooling method exists.
- The $e^-\mu^+$ and $\mu^+\mu^+$ can give good precision measurement of Higgs couplings.

Other topics:

- Polarization: Is $P_\mu = 0.8$ possible without affecting emittance?
- Neutrino-induced radiation
- Beam induced background
- Neutrino usage
  ["T-violation of neutrino oscillation at μTRISTAN" by Sho Sugama]
- More new physics searches
  ["WIMPS at $\mu^+\mu^+$ collider" by Shag-Fu Wei]