μTRISTAN

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@ FFA’25

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Contents

1. Overview –background and motivation

2. Collider facility

3. Higgs physics

4. SMEFT

5. Direct search for new physics

6. Summary

Current status of particle physics

Standard Model (SM) is an incomplete but very precise theory

Incompleteness

-Dark matter

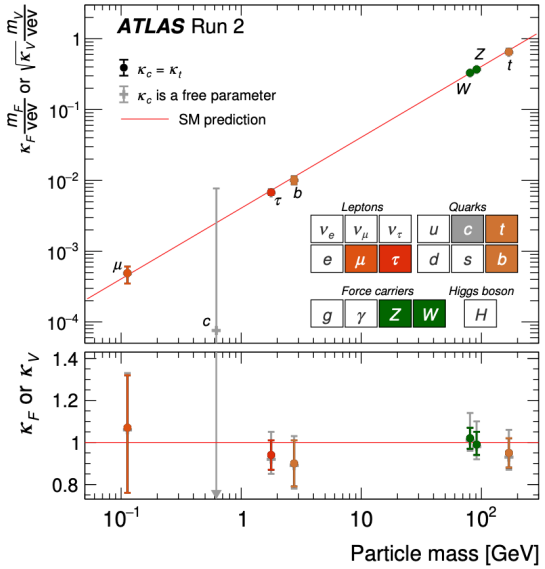
-Baryon asymmetry

-Neutrino masses

Very precise theory

-consistency with plenty of high-energy measurements

2207.00092



SM is neither an ultimate theory nor rough approximation of nature.

What is the extension? -no unified view among theorists, *How precise* is it?

These (at least the latter) are what we should and can address using future colliders.

How to address these questions?

There are mainly two experimental approaches:

(i) Go to higher energy

Production of new particles $\longrightarrow$ Direct and clear guide to BSM physics

(ii) Precision measurement

Devaitions from SM predictions provide indirect evidence of BSM

Even if no deviations, we understand how precise the SM is
and obtain constraints on BSM (→ Lower bound for new physics scale)

Next generation colliders

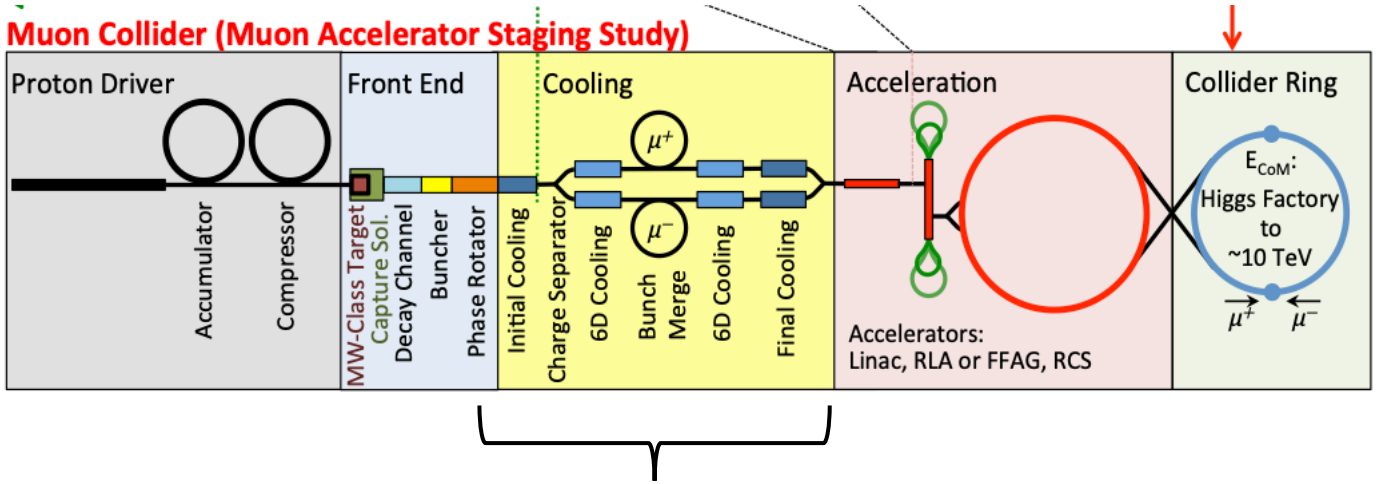
Pros and cons

HL-LHC (pp collider) : will improve precision
not clean enough

ILC (linear $e^+ e^-$ collider)
FCC-ee, CPEC (circular $e^+ e^-$ collider)
: suitable for precision measurements
chances of discovering new particles could be limited by its collision energy

Muon collider ($\mu^+ \mu^-$ collider) : suitable for precision measurements,
compact, high energy (due to less synchrotron radiation)
(a few-kilometer ring enables TeV scale collisions)
Challenges of realizing low-emittance muon beams

Muon cooling



Muon Ionization Cooling

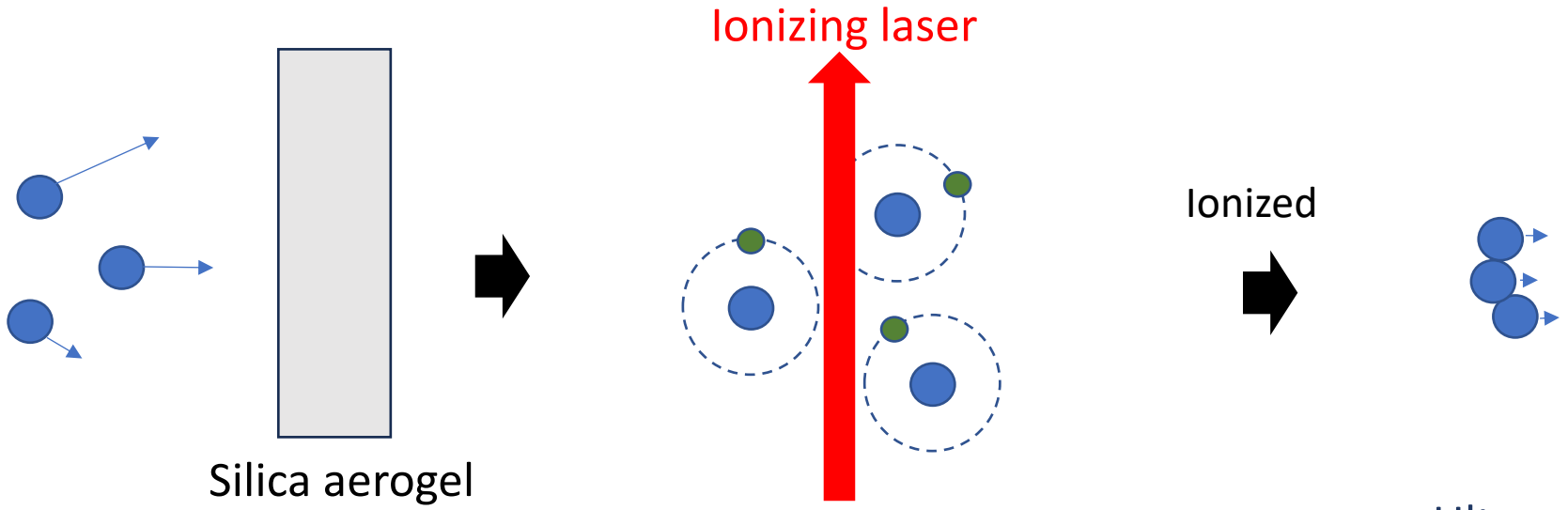
Under development (cf. MICE)

...Actually there is an alternative cooling technology that is already established and applicable (only) to μ^+ !

Technology for cooling μ^+ exists!

Muon g-2 experiment planned at J-PARC

The key technology is cooling of μ^+ , which is available today!



μ^+ produced from π^+ decay

Muonium formation inside the material ($\mu^+ e^-$ bound state)

Ultracold μ^+

High-quality μ^+ beam realized by accelerating ultracold muons to 300 MeV in g-2 exp.

Slide from R. Kitano

ultra-cold muon is here.

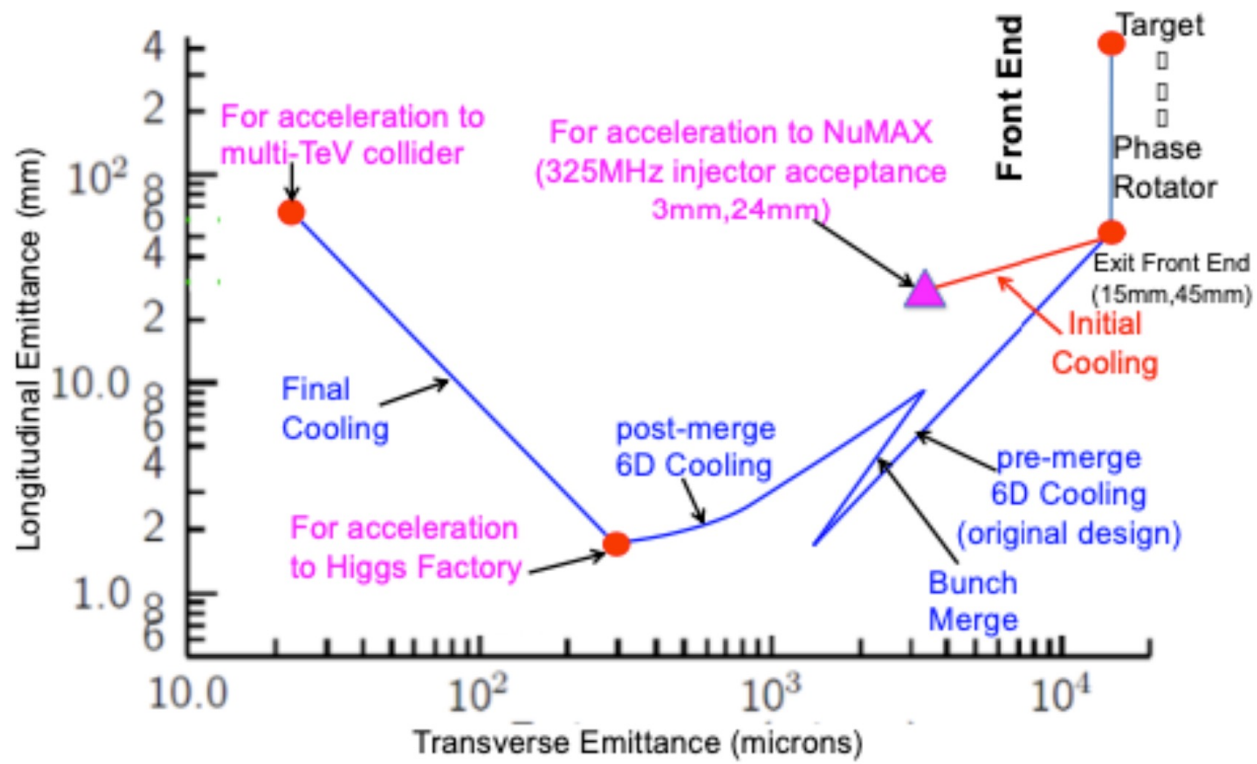
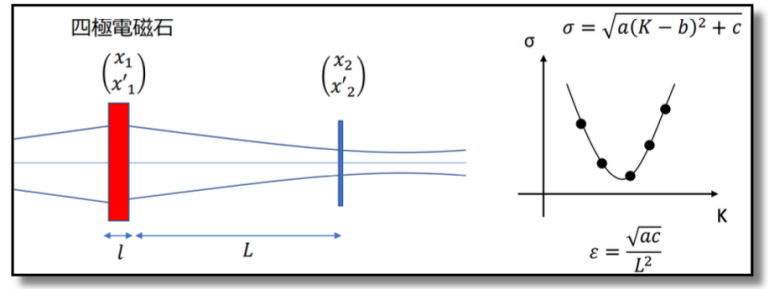


Figure 3. Ionization Cooling path in the 6D phase space.

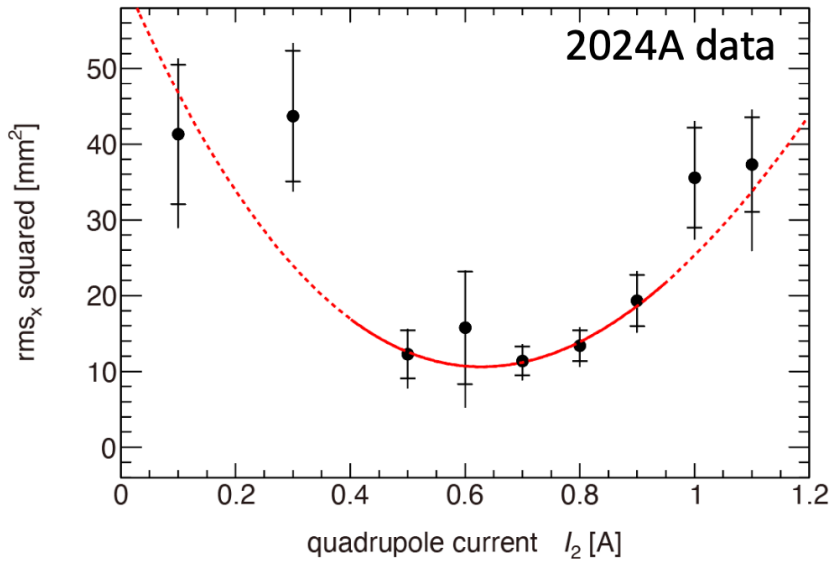
Slide from T. Mibe

Results: transverse emittance at 100 keV

arXiv:2410.11367



horizontal



before cooling

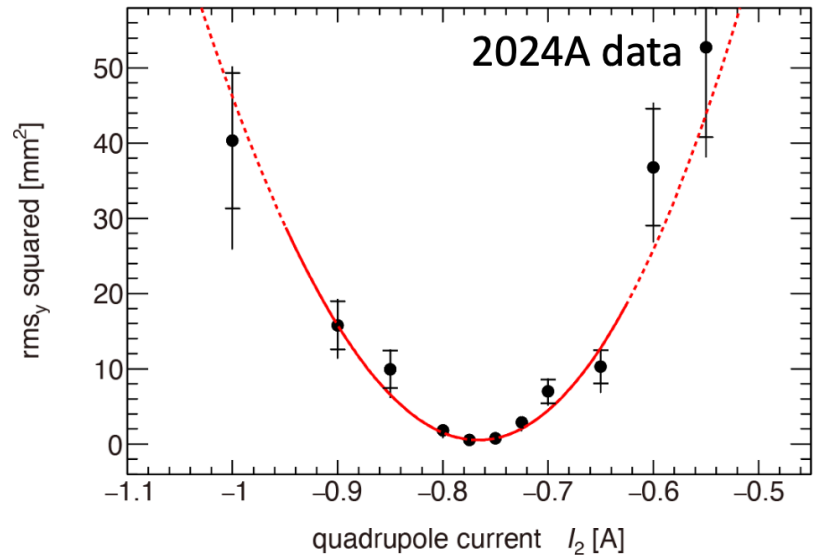
ε_x = 170 π mm mrad

x 1/200

after cooling + acceleration

$\varepsilon_x = 0.85 \pm 0.25^{+0.22}_{-0.13}$ π mm mrad

vertical



before cooling

ε_y = 130 π mm mrad

x 1/400

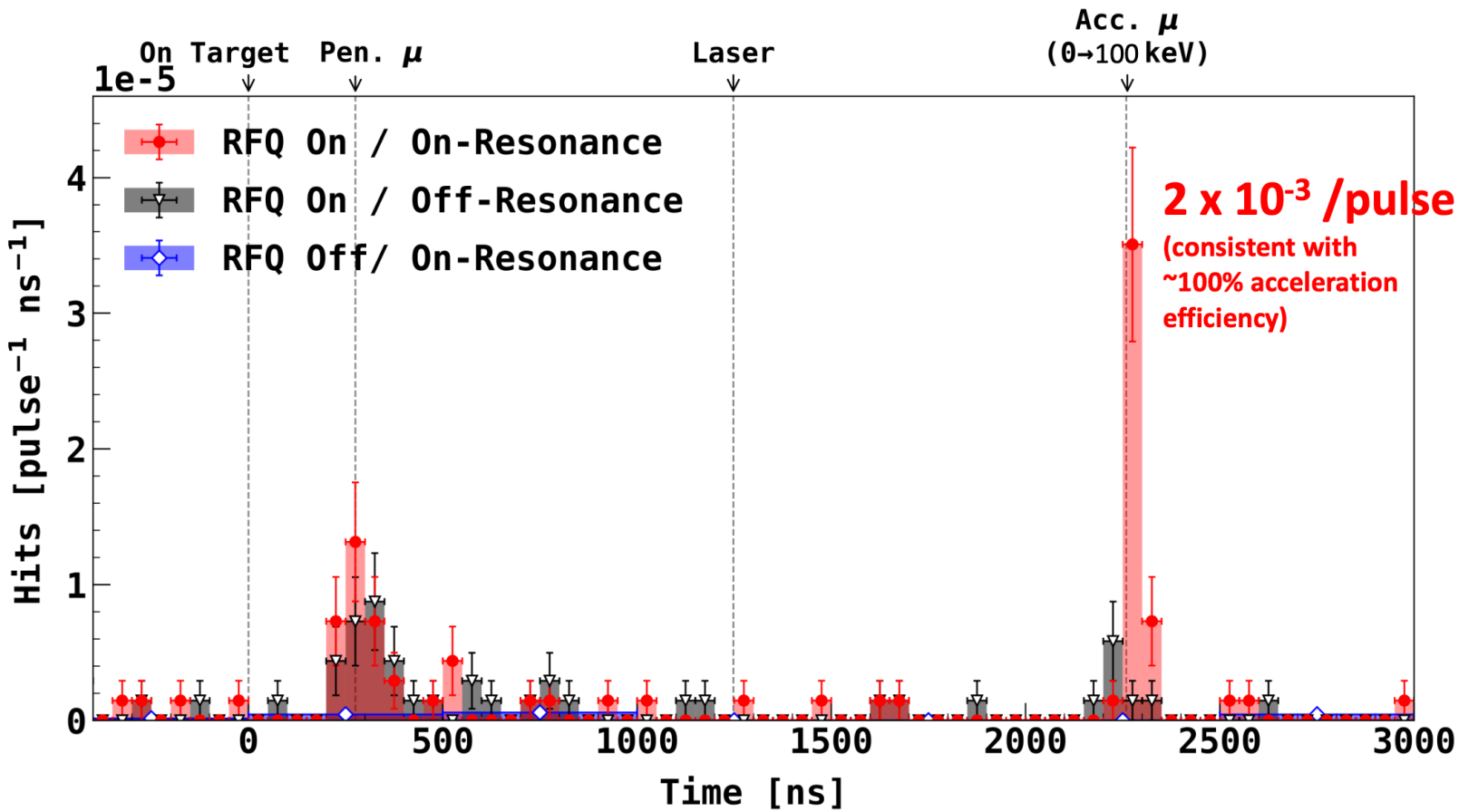
after cooling + acceleration

$\varepsilon_y = 0.23 \pm 0.03^{+0.05}_{-0.02}$ π mm mrad

The birth of low-emittance muon beam

Slide from T. Mibe

Results: time of flight



Proposal of new collider experiments

We propose collider experiments using high-quality μ^+ beam (not relying on μ^-) and accelerating it to TeV scale!

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

- μ^+e^- collider

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

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

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

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

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

μTRISTAN

2201.06664

Y. Hamada (KEK->DESY) , R. Kitano (KEK->YITP in 2025), R. Matsudo (KEK->YITP in 2025), HT (KEK->YITP in 2023) (four theorists)
&
M. Yoshida (KEK) (an experimentalist)

Next generation colliders

Pros and cons

HL-LHC (pp collider) : will improve precision
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compact, high energy (due to less synchrotron radiation)
(a few-kilometer ring enables TeV scale collisions)
Challenges of realizing low-emittance muon beams

μTRISTAN ($\mu^+ e^-$ and $\mu^+\mu^+$ colliders): suitable for precision measurements,
compact, high energy (due to less synchrotron radiation),
high luminosity expected
No μ^-

a good balance between established and challenging

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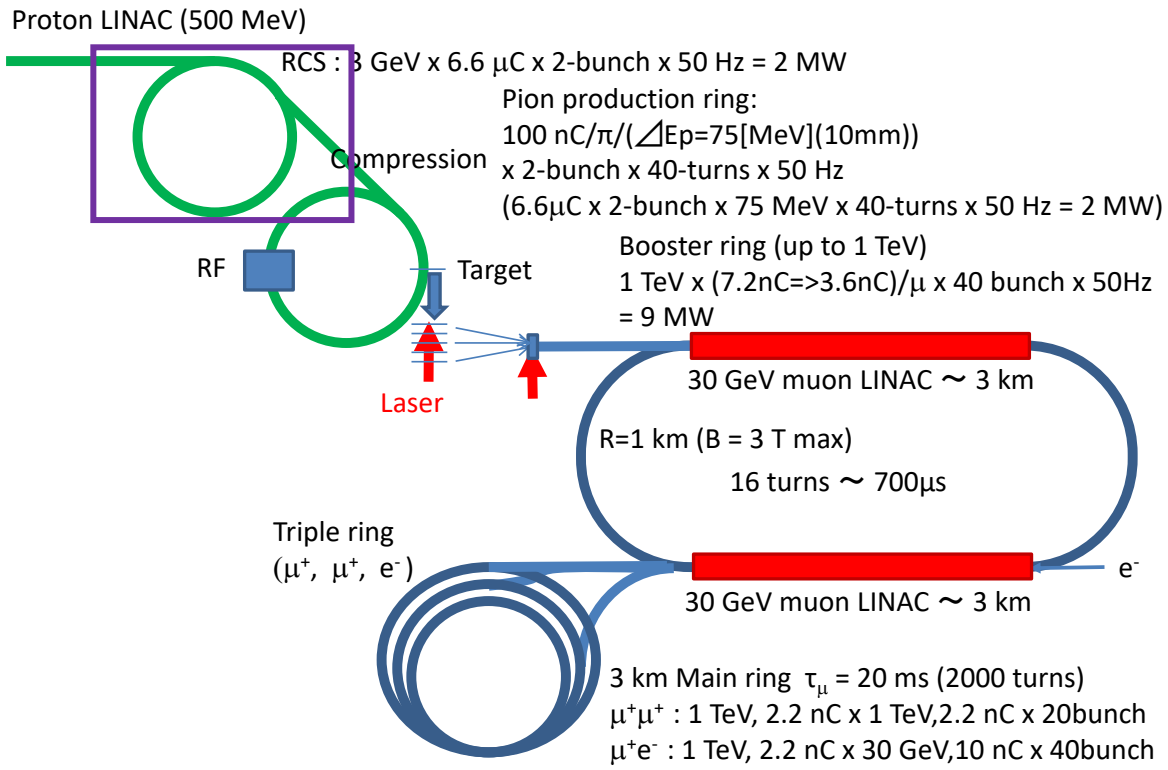
Proton acceleration (Proton LINAC & RCS)

$$\boldsymbol{p}(3\,\mathrm{GeV})$$

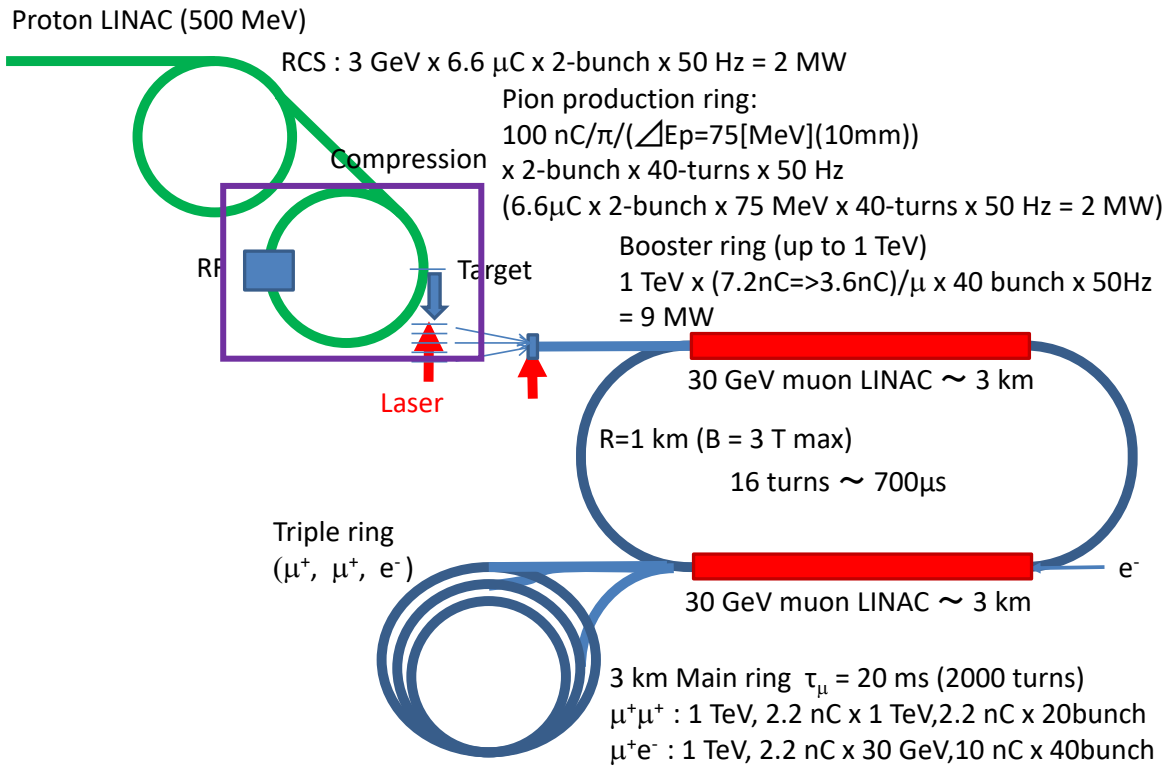


$$\tau_{\mu(1\,\mathrm{TeV})} = 20\ \mathrm{ms}$$

New beam injected every 20 ms.

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

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



$\tau_{\mu(1\,\mathrm{TeV})} = 20$ ms

New beam injected every 20 ms.

Proton acceleration (Proton LINAC & RCS) $\longrightarrow$ Pion production (Pion production ring)

$$p(3\,\mathrm{GeV})$$

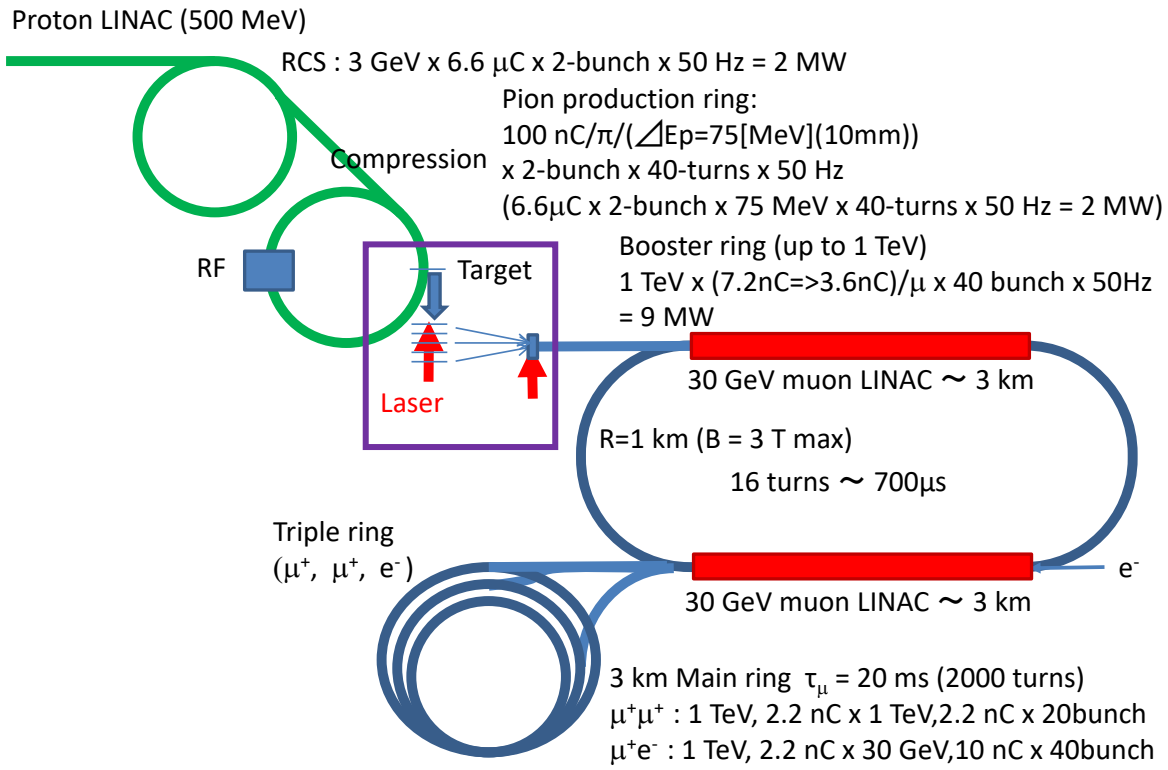
$$p(3\,\mathrm{GeV}) + C \rightarrow \pi^+ + X$$

$\longrightarrow$ Ultra-cold muon production

$\pi^+ \rightarrow \mu^+ + \nu_\mu$ Ultra-cold muon

Ionized by laser

Muonium $(\mu^+ e^-)$ formation in silica aerogel



$$\tau_{\mu(1\,\mathrm{TeV})} = 20\ \mathrm{ms}$$

New beam injected every 20 ms.

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

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

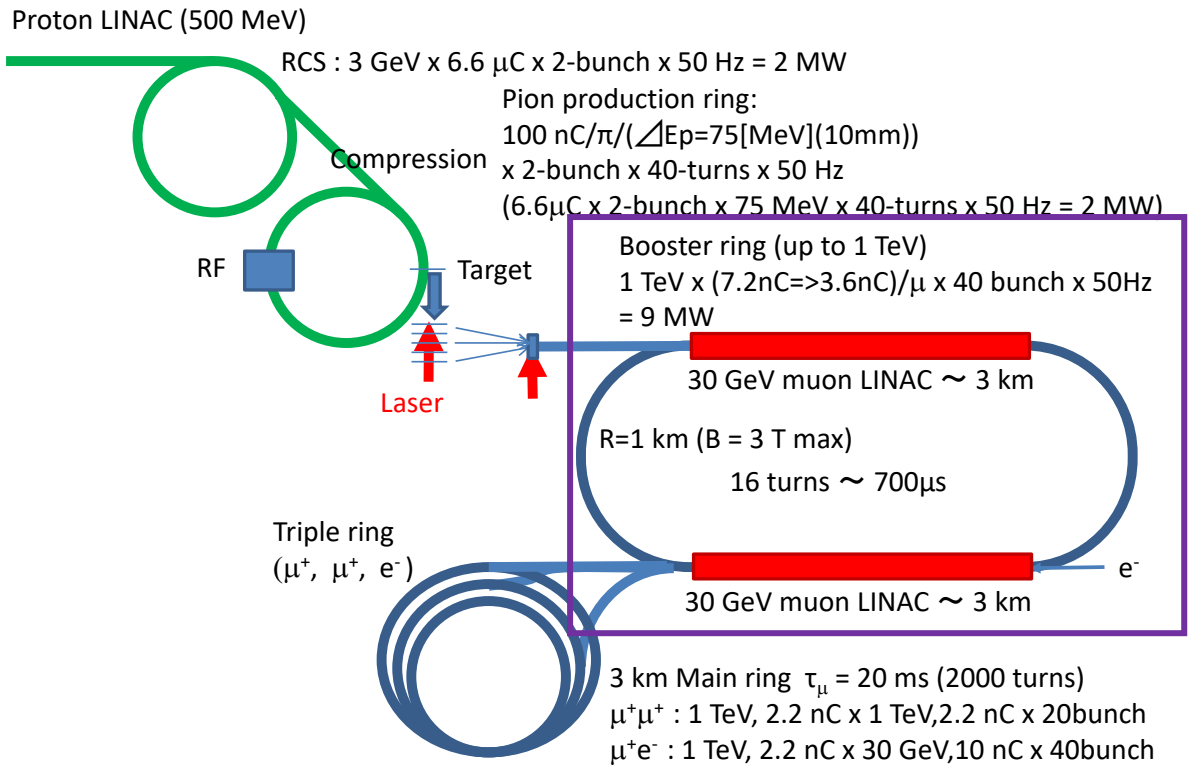
→ Ultra-cold muon production → Muon acceleration (Booster ring)

$\pi^+ \to \mu^+ + \nu_\mu$ Ultra-cold muon

Ionized by laser

Muonium $(\mu^+ e^-)$ formation in silica aerogel

$\mu^+(1\,\mathrm{TeV})$



$\tau_{\mu(1\,\mathrm{TeV})} = 20$ ms

New beam injected every 20 ms.

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

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

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

$\pi^+ \to \mu^+ + \nu_\mu$ Ultra-cold muon

Ionized by laser

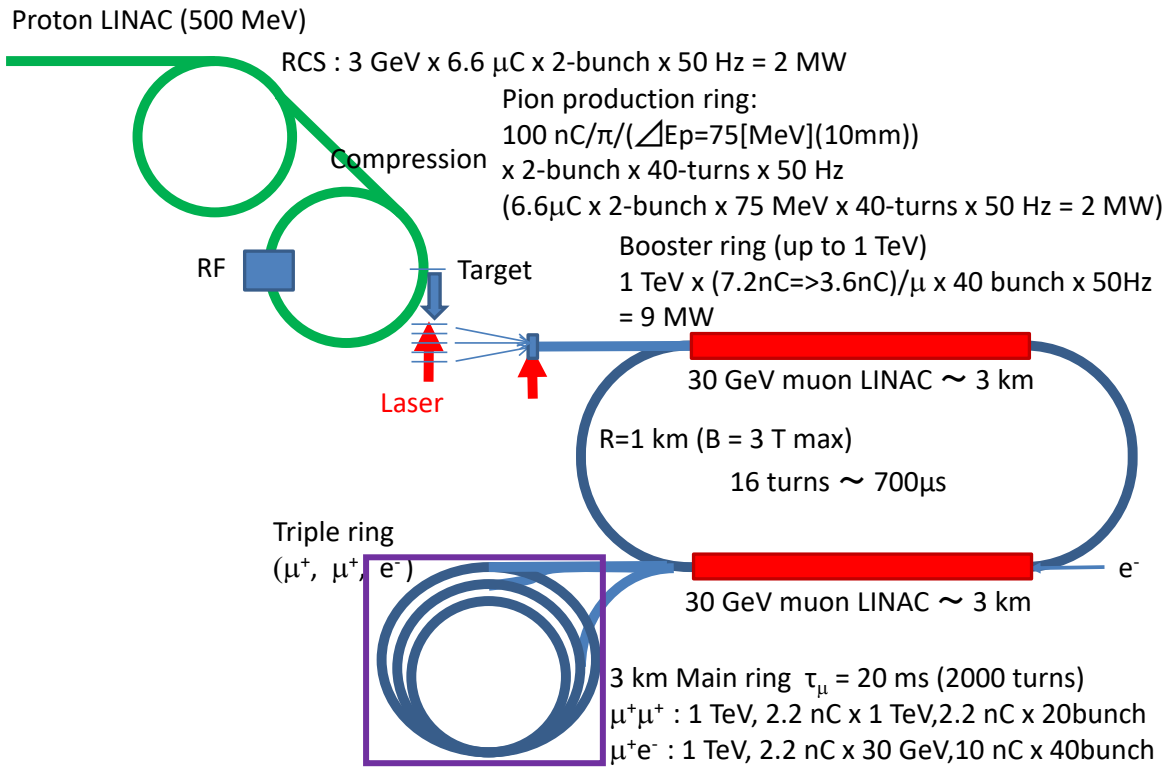
Muonium $(\mu^+ e^-)$ formation in silica aerogel

$\mu^+(1\,\mathrm{TeV})$

$[\mu^+(1\,\mathrm{TeV}), e^-(30\,\mathrm{GeV})]$

or

$[\mu^+(1\,\mathrm{TeV}), \mu^+(1\,\mathrm{TeV})]$



$\tau_{\mu(1\,\mathrm{TeV})} = 20$ ms

New beam injected every 20 ms.

Booster ring

(Based on private communication with M. Yoshida)

Acceleration of muons up to 1 TeV is required.

Potential candidates: FFA, RCS (also considered in the standard muon colliders)

Possible challenges of FFA (in the context of 1 TeV muon acceleration):

- Is scaling range compatible with acceleration up to 1 TeV?
- Maximum magnetic field ⟷ compactness of the facility

…under consideration

Luminosity

Assuming

- similar proton beam power to J-PARC exp.
  source of muon production (efficiency to collect muons was discussed in 2201.06664.)
- similar magnet power to HL-LHC

we estimate the luminosity as

Ten-year running w/ 70 % duty factor

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

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

Polarization

Polarization:
helps enhance various cross sections and extract physics information

We assume

$$P_{e^-} = \pm 0.7$$ ← Targeted at SuperKEKB

$$P_{\mu^+} = \pm 0.8$$ ← To be studied
(Considering our production method, at least $P_{\mu^+} = \pm 0.25$ seems possible)

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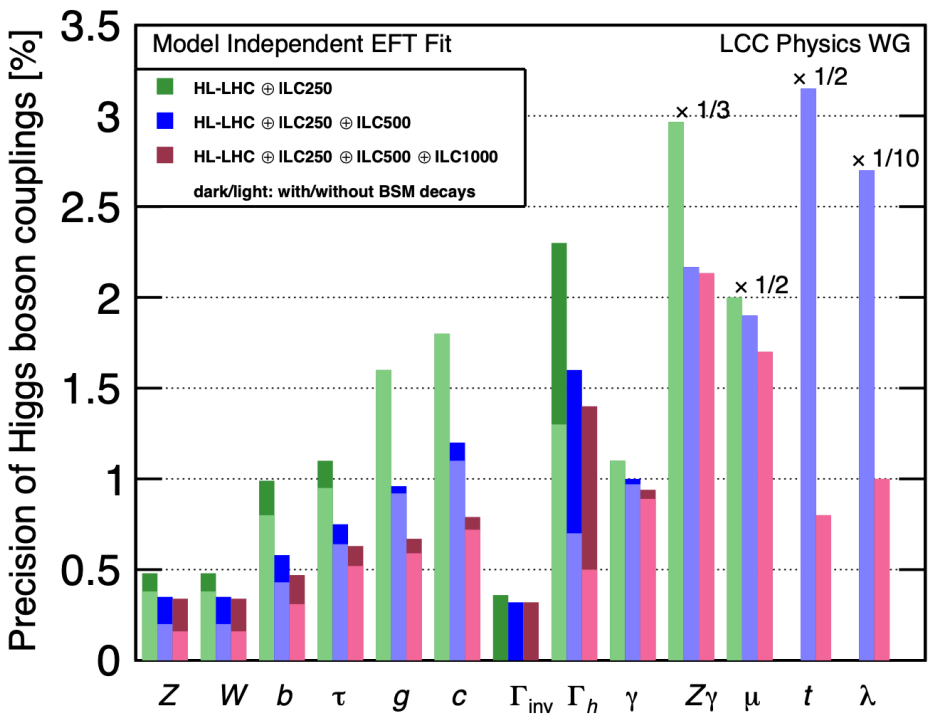
Higgs physics

The Higgs precision measurment is one of major targets at next generation colliders.

This is because Higgs is considered the key to new physics:

It causes EWSB, and can couple to right-handed neutrinos, SM singlet scalars, Z',...



LCC Physics WG
1908.11299

Roughly speaking,

HL-LHC: a few per cent
ILC: sub per cent

What is the potential of μTRISTAN? We estimate # of higgs boson productions.

μ^+e^- collider

Higgs production

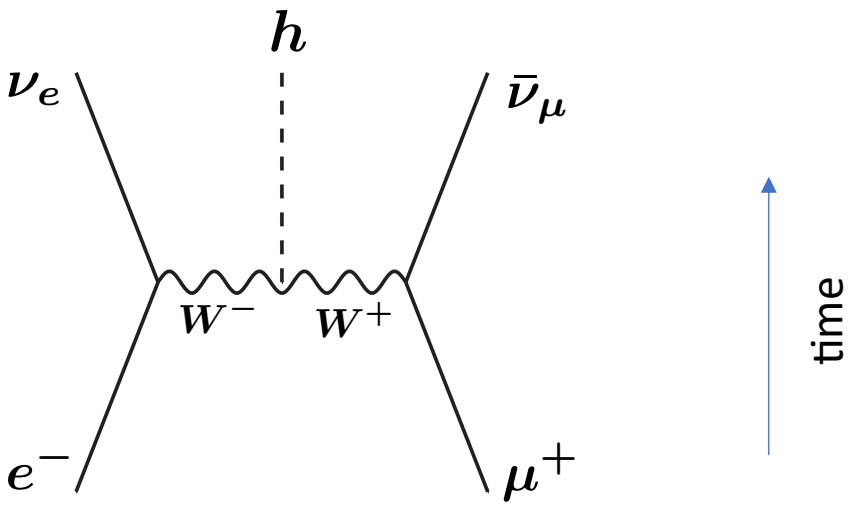
MadGraph5 J. Alwall et al.

Main Higgs production: W boson fusion (WBF)

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

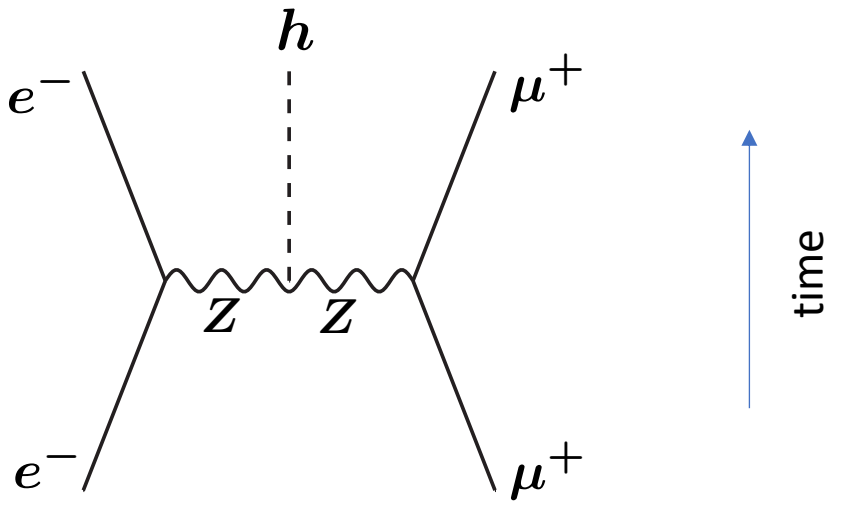
$$(P_{\mu^+}, P_{e^-}) = (0.8, -0.7)$$

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



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)

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

Hundred thousand Higgs bosons!

Coupling measurement

Focus on the WBF channel

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

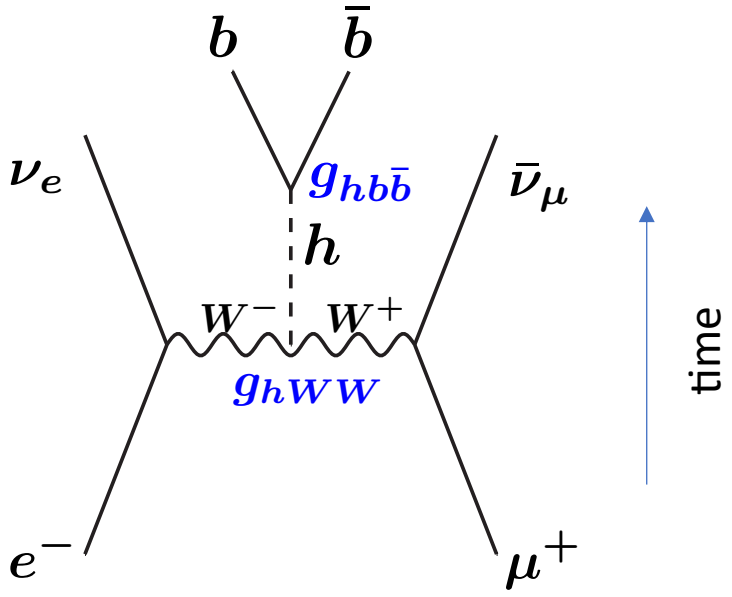
(Branching ratio 58.2 % in SM)

$$\sigma_{\mathrm{SM}} = \sigma_{\mathrm{WBF}}^{\mathrm{SM}} \frac{\Gamma_{H\to b\bar{b}}^{\mathrm{SM}}}{\Gamma_H^{\mathrm{SM}}}$$

can be modified

$$\longrightarrow \quad \sigma = \frac{\kappa_W^2 \kappa_b^2}{\kappa_H^2} \sigma_{\mathrm{SM}}$$

$$\kappa_W = 1 + \Delta\kappa_W \text{ etc.}$$



$$g_{hWW} = \kappa_W g_{hWW}^{\mathrm{SM}}$$

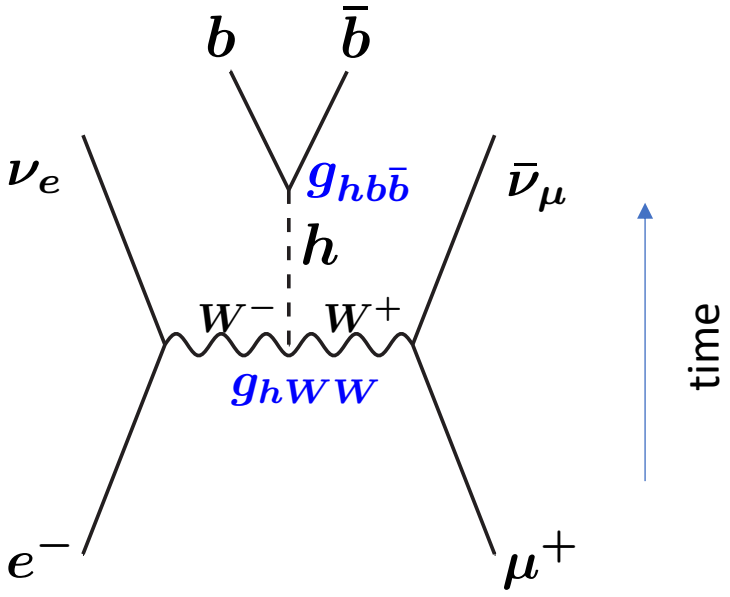
$$g_{hb\bar{b}} = \kappa_b g_{hb\bar{b}}^{\mathrm{SM}}$$

$$\Gamma_H = \kappa_H^2 \Gamma_H^{\mathrm{SM}}$$

Coupling measurement

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

$$\kappa_W = 1 + \Delta\kappa_W \quad \text{etc.}$$



We obtain a constraint

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

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

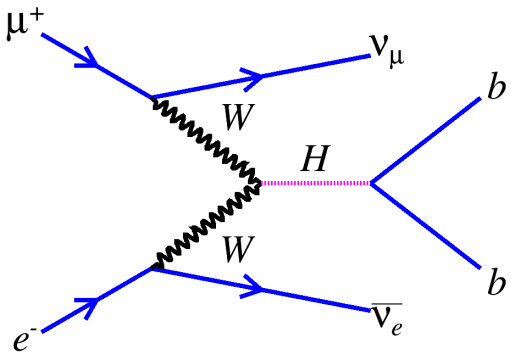
$$= 3.1 \times 10^{-3} \times \left(\frac{\text{integrated luminosity}}{1.0\ \text{ab}^{-1}}\right)^{-1/2} \left(\frac{\text{efficiency}}{0.5}\right)^{-1/2}$$

Sub per-cent measurement *Statistical error only

Slide from S. Kita

WBF Higgs

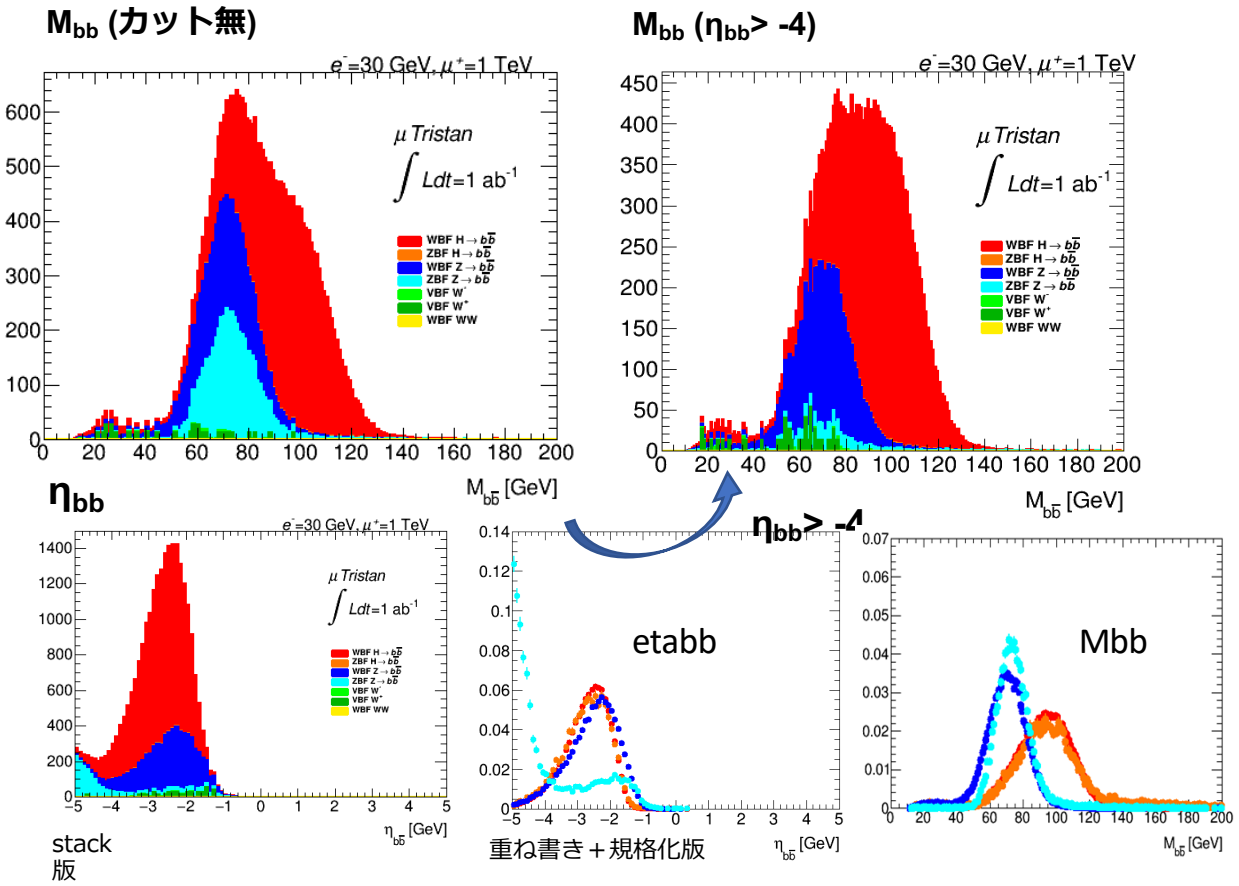
Signal



Event selection

1. No muon
2. No electron
3. bjet x 2

acceptance : ~23%

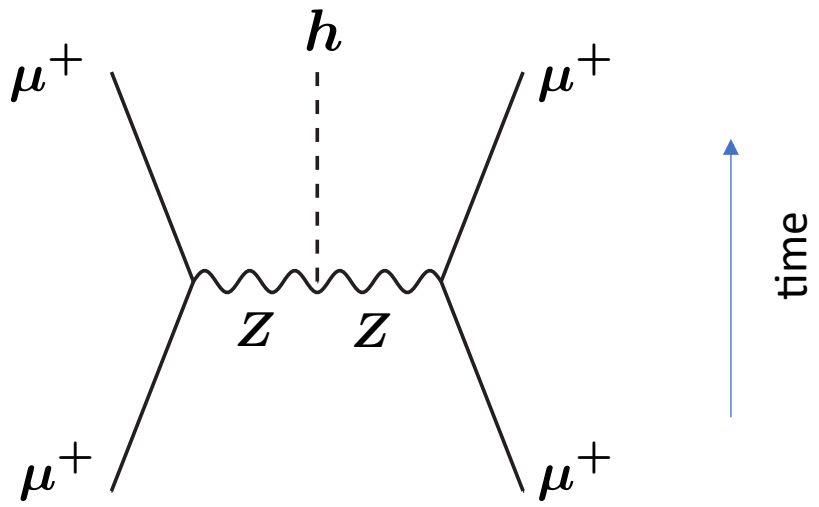


Results are preliminary

$$|\Delta\kappa_W + \Delta\kappa_b - \Delta\kappa_H| \lesssim 4.6 \times 10^{-3}$$

$\mu^+\mu^+$ collider

Z boson fusion: leading-order higgs production



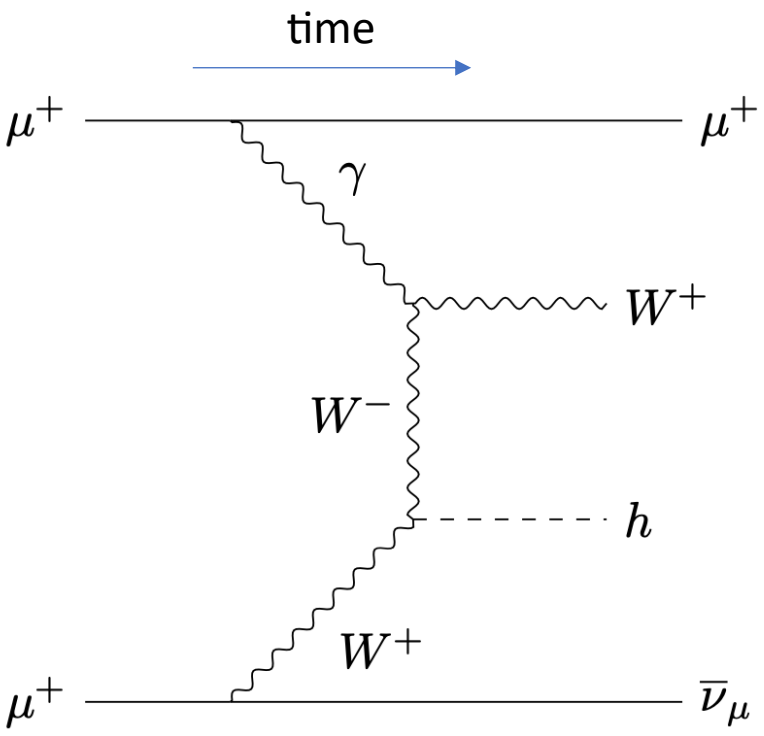
$\sigma_{\mathrm{ZBF}} \approx 54\,\mathrm{fb}$: Unfortunately, this is about 6 times smaller production cross section than $\mu^+\mu^-$ colliders (where W boson fusion is possible).

Absense of μ^- is spoiling??

Actually, no! We have identified a higher order process, whose corss section grows very rapidly at high energies.

2408.01068 Hamada, Kitano, Matsudo, Okawa, Takai, HT, and Treuer

γ-mediated W boson fusion



$$\sigma_\gamma(s) \simeq 2 \int_{xys>s_{\rm min}} {\rm d}x{\rm d}y\, f_{\gamma/\mu^+}(x,\mu_f^2)\, f_{W_{\rm L}^+/\mu^+}(y)\, \sigma_{\gamma W}(xys)$$

$$\sim \frac{(1+P_{\mu^+})\,\alpha^4}{4\pi m_W^2 \sin^4\theta_{\rm W}} \left[\log\frac{s}{m_\mu^2}\left(\log\frac{s}{s_{\rm min}}\right)^2 - \frac{2}{3}\left(\log\frac{s}{s_{\rm min}}\right)^3\right]$$

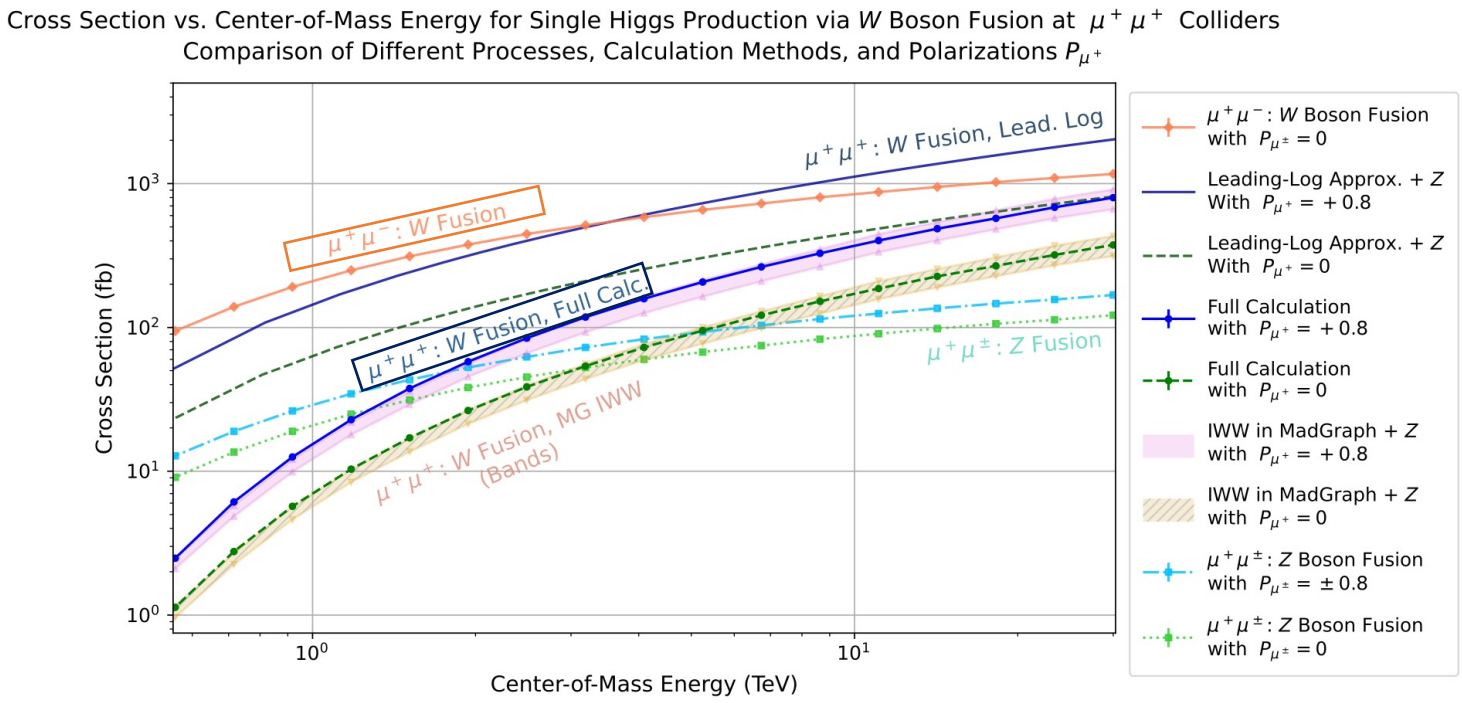
The cross section grows as log^3 at higher energies!

On the other hand, the standard WBF and ZBF are linear in log:

$$\sigma_{\rm ZBF}(s) \sim \frac{\alpha^3(1-4\sin^2\theta_{\rm W}+8\sin^4\theta_{\rm W})^2}{64 m_Z^2 \sin^6\theta_{\rm W}\cos^6\theta_{\rm W}} \log\frac{s}{m_h^2}$$

$$\sigma_{\rm WBF}(s) \sim \frac{\alpha^3}{16 m_W^2 \sin^6\theta_{\rm W}} \log\frac{s}{m_h^2}$$

2408.01068 Hamada, Kitano, Matsudo, Okawa, Takai, HT, and Treuer



At 10 TeV, the production cross section becomes the same order of magnitude as that at $\mu^+\mu^-$ colliders!

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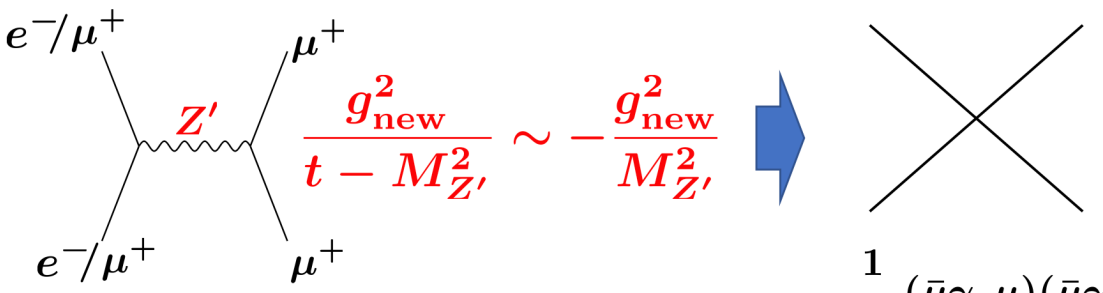
SMEFT

How precise is the SM?

→ Standard model effetive field theory (SMEFT) is
a good framework to address this generic question.

Information from new physics at higher energies is encoded in Wilson coefficients of higher dimensional ($\geq$ dim 6) operators in the SMEFT Lagrangian.



$$\frac{g_{\rm new}^2}{t - M_{Z'}^2} \sim -\frac{g_{\rm new}^2}{M_{Z'}^2}$$

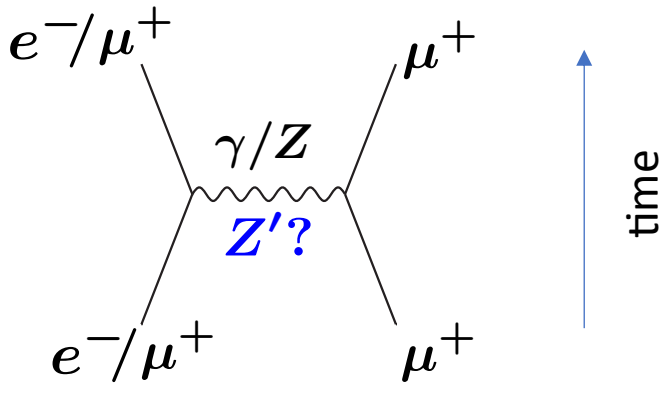
$$\frac{1}{\Lambda^2}(\bar{\mu}\gamma_\rho\mu)(\bar{\mu}\gamma^\rho\mu)$$

w/ $\frac{1}{\Lambda^2} \sim \frac{g_{\rm new}^2}{M_Z'^2}$

Λ : new physics scale

Elastic lepton scatterings

- $e^-\mu^+ \to e^-\mu^+$ O(10^6) events
- $\mu^+\mu^+ \to \mu^+\mu^+$ O(10^6) events



Huge number of events enables detection/constraint on new physics.

Dim 6 operators

Adopt basis of
2013 Alonso, Jenkins, Manohar, Trott

$1: X^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$
$Q_{\widetilde{G}}$	$f^{ABC} \widetilde{G}_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$
Q_W	$\epsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$
$Q_{\widetilde{W}}$	$\epsilon^{IJK} \widetilde{W}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$

$2: H^6$	
Q_H	$(H^\dagger H)^3$

$3: H^4 D^2$	
$Q_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$
Q_{HD}	$\left(H^\dagger D_\mu H\right)^* \left(H^\dagger D_\mu H\right)$

$5: \psi^2 H^3 + \text{h.c.}$	
Q_{eH}	$(H^\dagger H)(\bar{l}_p e_r H)$
Q_{uH}	$(H^\dagger H)(\bar{q}_p u_r \widetilde{H})$
Q_{dH}	$(H^\dagger H)(\bar{q}_p d_r H)$

$4: X^2 H^2$	
Q_{HG}	$H^\dagger H\, G_{\mu\nu}^A G^{A\mu\nu}$
$Q_{H\widetilde{G}}$	$H^\dagger H\, \widetilde{G}_{\mu\nu}^A G^{A\mu\nu}$
Q_{HW}	$H^\dagger H\, W_{\mu\nu}^I W^{I\mu\nu}$
$Q_{H\widetilde{W}}$	$H^\dagger H\, \widetilde{W}_{\mu\nu}^I W^{I\mu\nu}$
Q_{HB}	$H^\dagger H\, B_{\mu\nu} B^{\mu\nu}$
$Q_{H\widetilde{B}}$	$H^\dagger H\, \widetilde{B}_{\mu\nu} B^{\mu\nu}$
Q_{HWB}	$H^\dagger \tau^I H\, W_{\mu\nu}^I B^{\mu\nu}$
$Q_{H\widetilde{W}B}$	$H^\dagger \tau^I H\, \widetilde{W}_{\mu\nu}^I B^{\mu\nu}$

$6: \psi^2 X H + \text{h.c.}$	
Q_{eW}	$(\bar{l}_p \sigma^{\mu\nu} e_r) \tau^I H W_{\mu\nu}^I$
Q_{eB}	$(\bar{l}_p \sigma^{\mu\nu} e_r) H B_{\mu\nu}$
Q_{uG}	$(\bar{q}_p \sigma^{\mu\nu} T^A u_r) \widetilde{H}\, G_{\mu\nu}^A$
Q_{uW}	$(\bar{q}_p \sigma^{\mu\nu} u_r) \tau^I \widetilde{H}\, W_{\mu\nu}^I$
Q_{uB}	$(\bar{q}_p \sigma^{\mu\nu} u_r) \widetilde{H}\, B_{\mu\nu}$
Q_{dG}	$(\bar{q}_p \sigma^{\mu\nu} T^A d_r) H\, G_{\mu\nu}^A$
Q_{dW}	$(\bar{q}_p \sigma^{\mu\nu} d_r) \tau^I H\, W_{\mu\nu}^I$
Q_{dB}	$(\bar{q}_p \sigma^{\mu\nu} d_r) H\, B_{\mu\nu}$

$7: \psi^2 H^2 D$	
$Q_{Hl}^{(1)}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{l}_p \gamma^\mu l_r)$
$Q_{Hl}^{(3)}$	$(H^\dagger i \overleftrightarrow{D}_\mu^I H)(\bar{l}_p \tau^I \gamma^\mu l_r)$
Q_{He}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{e}_p \gamma^\mu e_r)$
$Q_{Hq}^{(1)}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{q}_p \gamma^\mu q_r)$
$Q_{Hq}^{(3)}$	$(H^\dagger i \overleftrightarrow{D}_\mu^I H)(\bar{q}_p \tau^I \gamma^\mu q_r)$
Q_{Hu}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{u}_p \gamma^\mu u_r)$
Q_{Hd}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{d}_p \gamma^\mu d_r)$
Q_{Hud} + h.c.	$i(\widetilde{H}^\dagger D_\mu H)(\bar{u}_p \gamma^\mu d_r)$

$8: (\bar{L}L)(\bar{L}L)$	
Q_{ll}	$(\bar{l}_p \gamma_\mu l_r)(\bar{l}_s \gamma^\mu l_t)$
$Q_{qq}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{q}_s \gamma^\mu q_t)$
$Q_{qq}^{(3)}$	$(\bar{q}_p \gamma_\mu \tau^I q_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$
$Q_{lq}^{(1)}$	$(\bar{l}_p \gamma_\mu l_r)(\bar{q}_s \gamma^\mu q_t)$
$Q_{lq}^{(3)}$	$(\bar{l}_p \gamma_\mu \tau^I l_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$

$8: (\bar{R}R)(\bar{R}R)$	
Q_{ee}	$(\bar{e}_p \gamma_\mu e_r)(\bar{e}_s \gamma^\mu e_t)$
Q_{uu}	$(\bar{u}_p \gamma_\mu u_r)(\bar{u}_s \gamma^\mu u_t)$
Q_{dd}	$(\bar{d}_p \gamma_\mu d_r)(\bar{d}_s \gamma^\mu d_t)$
Q_{eu}	$(\bar{e}_p \gamma_\mu e_r)(\bar{u}_s \gamma^\mu u_t)$
Q_{ed}	$(\bar{e}_p \gamma_\mu e_r)(\bar{d}_s \gamma^\mu d_t)$
$Q_{ud}^{(1)}$	$(\bar{u}_p \gamma_\mu u_r)(\bar{d}_s \gamma^\mu d_t)$
$Q_{ud}^{(8)}$	$(\bar{u}_p \gamma_\mu T^A u_r)(\bar{d}_s \gamma^\mu T^A d_t)$

$8: (\bar{L}L)(\bar{R}R)$	
Q_{le}	$(\bar{l}_p \gamma_\mu l_r)(\bar{e}_s \gamma^\mu e_t)$
Q_{lu}	$(\bar{l}_p \gamma_\mu l_r)(\bar{u}_s \gamma^\mu u_t)$
Q_{ld}	$(\bar{l}_p \gamma_\mu l_r)(\bar{d}_s \gamma^\mu d_t)$
Q_{qe}	$(\bar{q}_p \gamma_\mu q_r)(\bar{e}_s \gamma^\mu e_t)$
$Q_{qu}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{u}_s \gamma^\mu u_t)$
$Q_{qu}^{(8)}$	$(\bar{q}_p \gamma_\mu T^A q_r)(\bar{u}_s \gamma^\mu T^A u_t)$
$Q_{qd}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{d}_s \gamma^\mu d_t)$
$Q_{qd}^{(8)}$	$(\bar{q}_p \gamma_\mu T^A q_r)(\bar{d}_s \gamma^\mu T^A d_t)$

$8: (\bar{L}R)(\bar{R}L) + \text{h.c.}$	
Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s q_{tj})$

$8: (\bar{L}R)(\bar{L}R) + \text{h.c.}$	
$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r) \epsilon_{jk} (\bar{q}_s^k d_t)$
$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r) \epsilon_{jk} (\bar{q}_s^k T^A d_t)$
$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r) \epsilon_{jk} (\bar{q}_s^k u_t)$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j \sigma_{\mu\nu} e_r) \epsilon_{jk} (\bar{q}_s^k \sigma^{\mu\nu} u_t)$

SMEFT

Adopt basis of
2013 Alonso, Jenkins, Manohar, Trott

What we can detect

$$Q_{HWB} = H^\dagger \tau^I H W^I_{\mu\nu} B^{\mu\nu}$$ ⟵ S parameter

$$Q_{HD} = (H^\dagger D_\mu H)^* (H^\dagger D_\mu H)$$ ⟵ T parameter

$$Q^{(1)}_{H\ell} = (H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{L}\gamma^\mu L)$$

$$Q^{(3)}_{H\ell} = (H^\dagger i \overleftrightarrow{D}^I_\mu H)(\bar{L}\tau^I\gamma^\mu L)$$

$$Q_{H\mu} = (H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{\mu}\gamma^\mu P_+ \mu)$$

$$Q_{\substack{ll \\ prst}} = (\bar{l}_p \gamma_\mu l_r)(\bar{l}_s \gamma^\mu l_t)$$

$$Q_{\substack{le \\ prst}} = (\bar{l}_p \gamma_\mu l_r)(\bar{e}_s \gamma^\mu e_t)$$

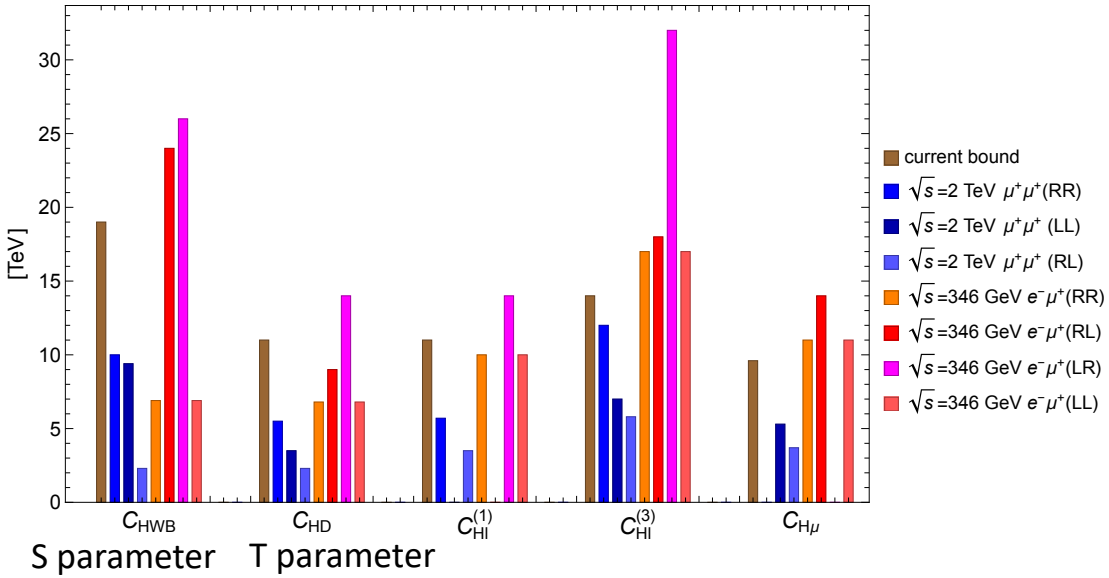
$$Q_{\substack{ee \\ prst}} = (\bar{e}_p \gamma_\mu e_r)(\bar{e}_s \gamma^\mu e_t)$$

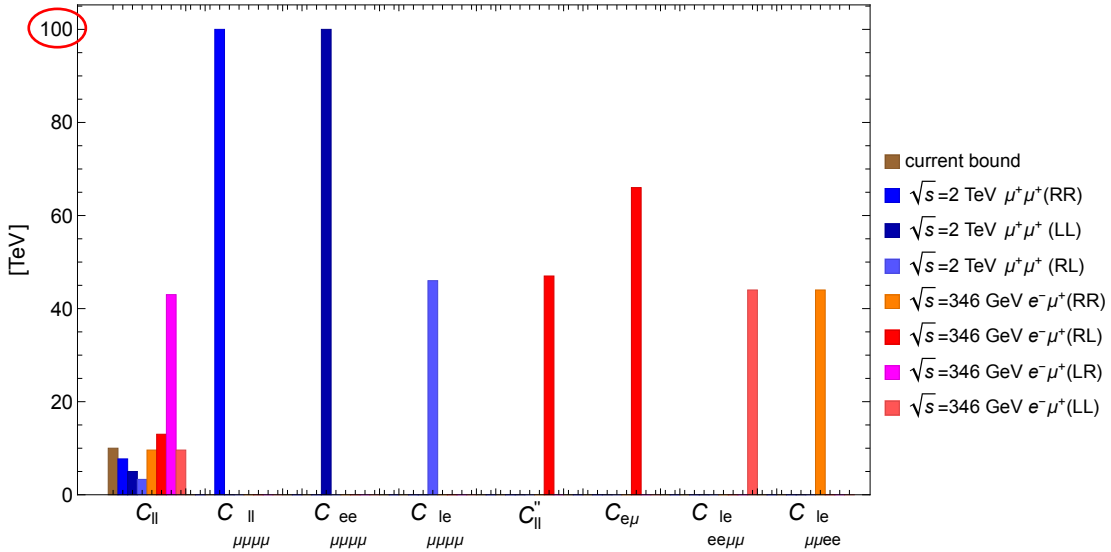
Estimated constraints

PTEP 2023 (2023) 1, 013B07
Hamada, Kitano, Matsudo, HT

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \sum_X C_X Q_X \qquad \left(C_X = \frac{1}{\Lambda_X^2}\right)$$

Λ_X~new physics scale





Can significantly improve the current constraints
Capable of detecting up to 100 TeV regarding 4-fermi interaction
Muon involved operators can be measured for the first time

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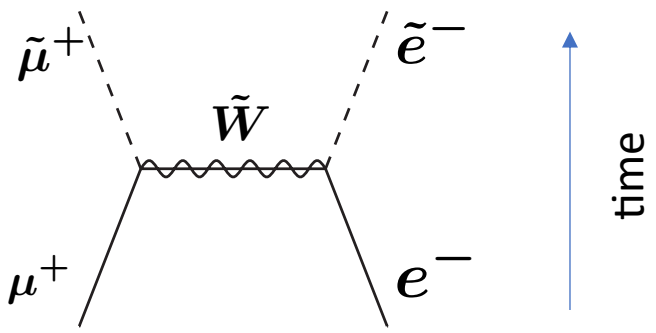
SUSY

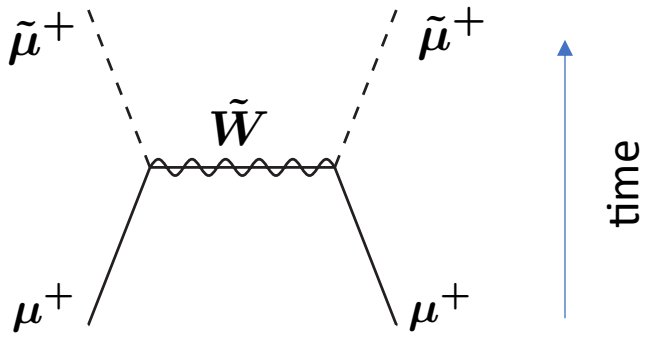
For simplicity, we only consider the diagrams where Wino $\tilde{W}$ is exchanged.

superpartner of $SU(2)_L$ gauge boson

- μ^+e^- collider



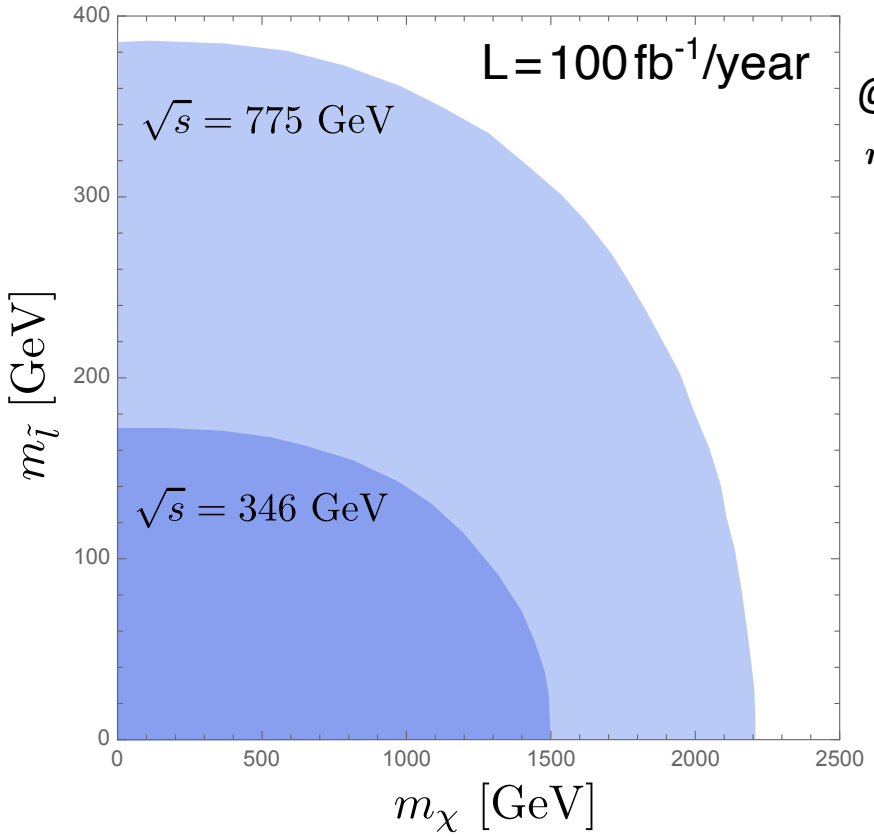
- $\mu^+\mu^+$ collider



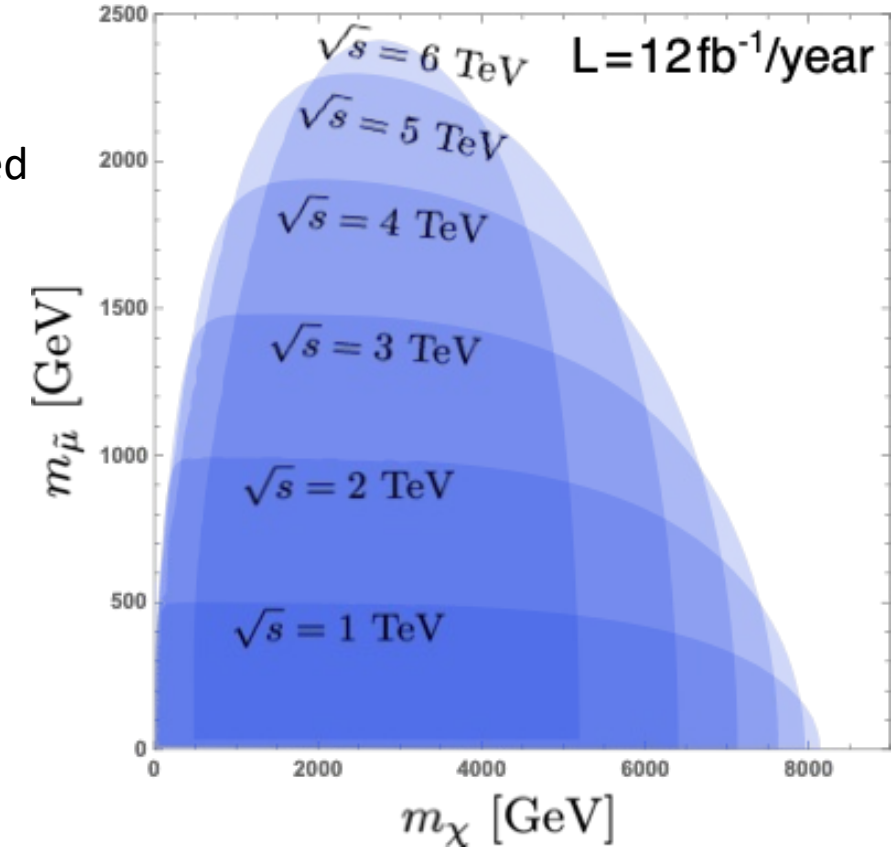
SUSY

PTEP 2022 (2022) 5, 053B02
Hamada, Kitano, Matsudo, HT, Yoshida

Mass region where # of events exceeds 100 per year.



@ μ^+e^- collider
$m_{\tilde{e}} = m_{\tilde{\mu}}$ assumed



@$\mu^+\mu^+$ collider

TeV scale SUSY particles are within the reach

2304.04483 Jiang et al.
(See also 2304.1402 Fridel et al.,
2309.06463 Bhupal Dev et al., 2405.02819 Santiago et al.,
2410.21956 Das et al.,…)

- Majorana neutrino causes lepton-number violating processes

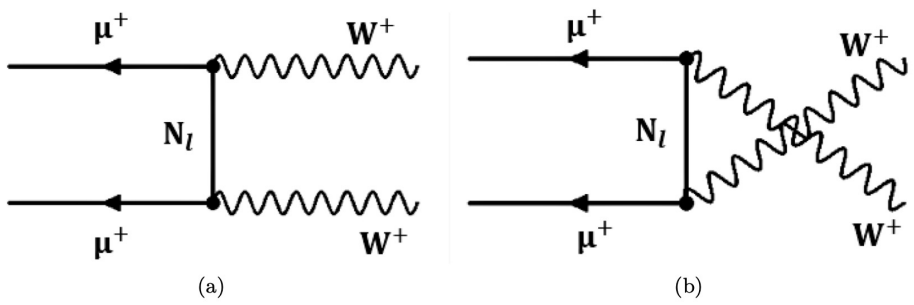
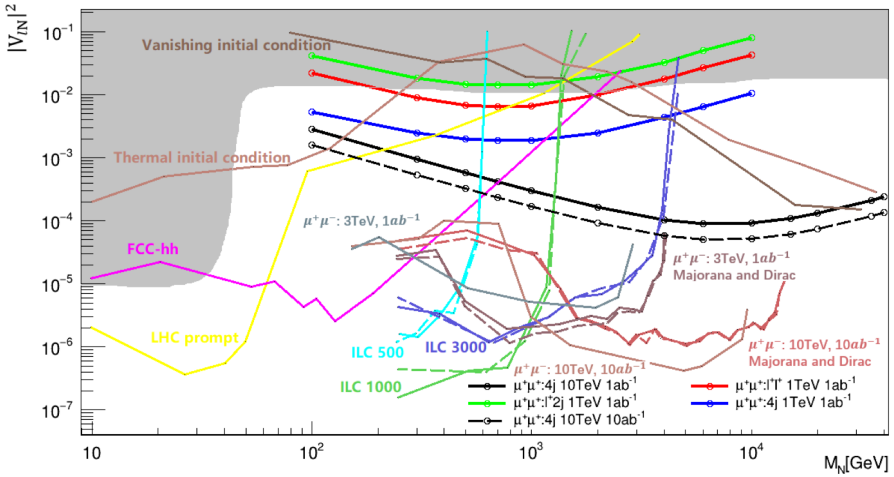


Figure 1: Signal processes at a same sign muon collider :(a) t-channel, (b) u-channel



2407.05807 Kitano, Sato, Sugama

- Using lots of ν_e as decay product of μ+ beam,
  one can measure T violation (CP phase) through $P(\nu_e \to \nu_\mu) - P(\nu_\mu \to \nu_e)$
  T2K
- WIMP search 2310.07162 Fukuda et al.
- Axion-like particle search 2310.11018 Chigusa et al., 2406.13234 Calibbi et al.

⋮

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Summary

- Next generation colliders should address precision measurement of the SM and ideally also direct search for new physics.

- Utlilizing muon beams is an attractive option from both viewpoints: clean environment & high energy

- We take advantage of the fact that cooling technology for μ^+ is much ahead of that for μ^- .

  Why not start with μ^+-based colliders? → μTRISTAN!

- μTRISTAN, μ^+e^- collider & $\mu^+\mu^+$ collider, indeed have physics potential

  -Higgs factory (Absence of μ^- is not very serious)

  -Indirect search for new physics up to 100 TeV through SMEFT

  -TeV scale direct search for new physics

Discussion

- Detailed studies on Higgs precision measurements are to be performed.
  (Disentaglement of different Higgs couplings, Measurement of Higgs decay width, Higgs triple coupling,…)

- Proposal of related collider experiments based on ultra-cold muon

2406.02647 Akturk, Dagli, Ketenoglu, Ozturk, Sultansoy

Proposal to collide μ^+ beams with p or A beams using LHC/Tevatron/FCC/SppC facilities

Much higher energy can be achieved than using e^- beam:
suitable for exploring large-Q^2 region of PDF and enhancing higgs production cross sections

- $\mu^+\mu^-$ collider is also desirable in the future to explore higher energies of particle physics more extensively.

Muon acceleration is indispensable to realizing these attractive colliders.