μTRISTAN

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Based on 2201.06664, Yu Hamada (KEK), RK, Ryutaro Matsudo (KEK -> NTU), Hiromasa Takaura (KEK -> YITP), Mitsuhiro Yoshida (KEK)

2210.11083, Yu Hamada (KEK), RK, Ryutaro Matsudo (KEK -> NTU), Hiromasa Takaura (KEK -> YITP)

2304.14020, Kåre Fridell (KEK/Florida State U.), RK, Ryoto Takai (KEK/Sokendai)

Also, study in progress with Koji Nakamura (KEK), Sayuka Kita (Tsukuba U.), Toshiaki Kaji (Waseda U.), Taiki Yoshida (Waseda U.), Kohei Yorita (Waseda U.)

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Clearly, we need next generation colliders.

1. We must investigate the form of the Higgs potential by the observation of self-interactions.
2. We must check the possibility that one can actually produce dark matter artificially.
3. We must look for new physics at least up to about 10TeV (~ a loop factor higher than the EW scale).

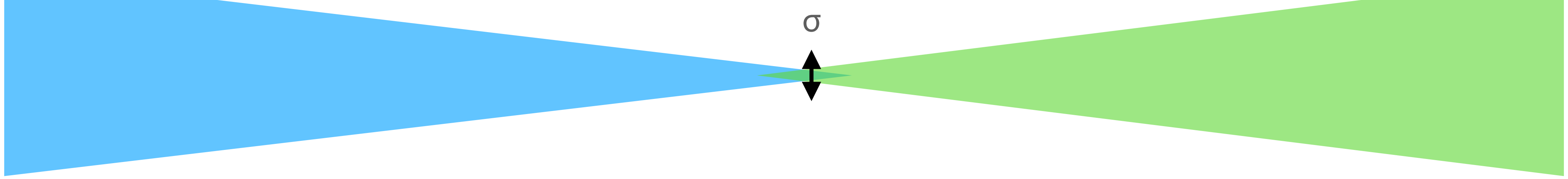
We cannot stop here.

Today, I talk about possibly a realistic scenario of **μ^+ based** colliders.

As you know, the most important (difficult) part of muon colliders is to obtain enough **luminosity** for particle physics.

Luminosity

$$\mathcal{L} = \frac{N_{\mathrm{beam1}} N_{\mathrm{beam2}}}{4\pi\sigma_x\sigma_y} f_{\mathrm{rep}}$$



We need a large number of muons and/or narrow beams.

As a reference,

$N_{beam}=10^{10}$ (1.6nC) / bunch

$\sigma=1\mu m$

$f_{rep}=1MHz$

~ 8×10^{32} $cm^{-2}s^{-1}$ ~ 25 fb^{-1}/year

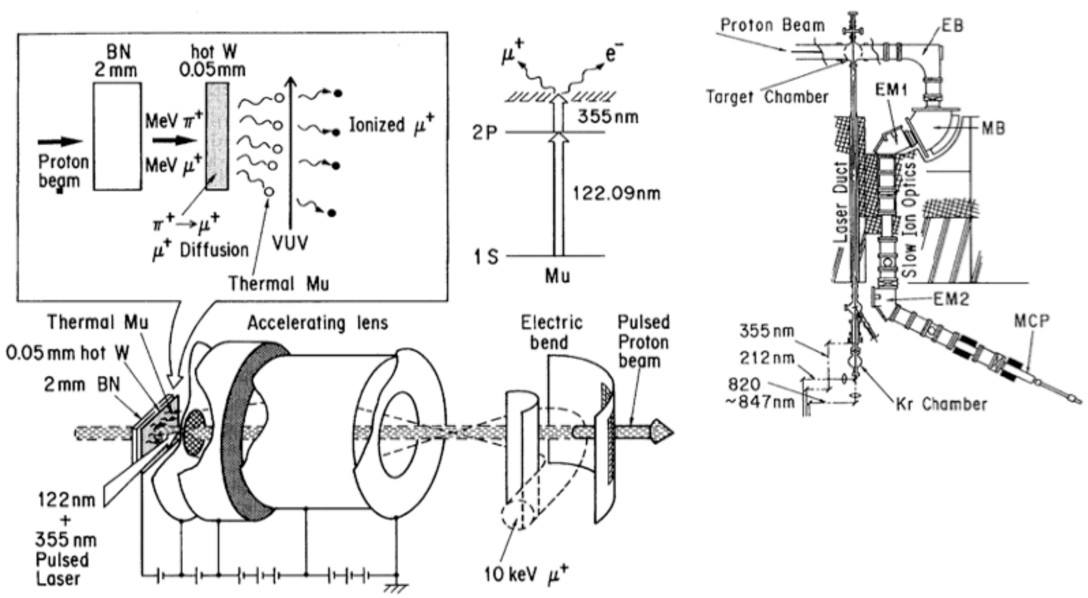
We want ab^{-1} level luminosity for physics (HL-LHC, ILC)

σ is the most difficult part. The **cooling** is the key.

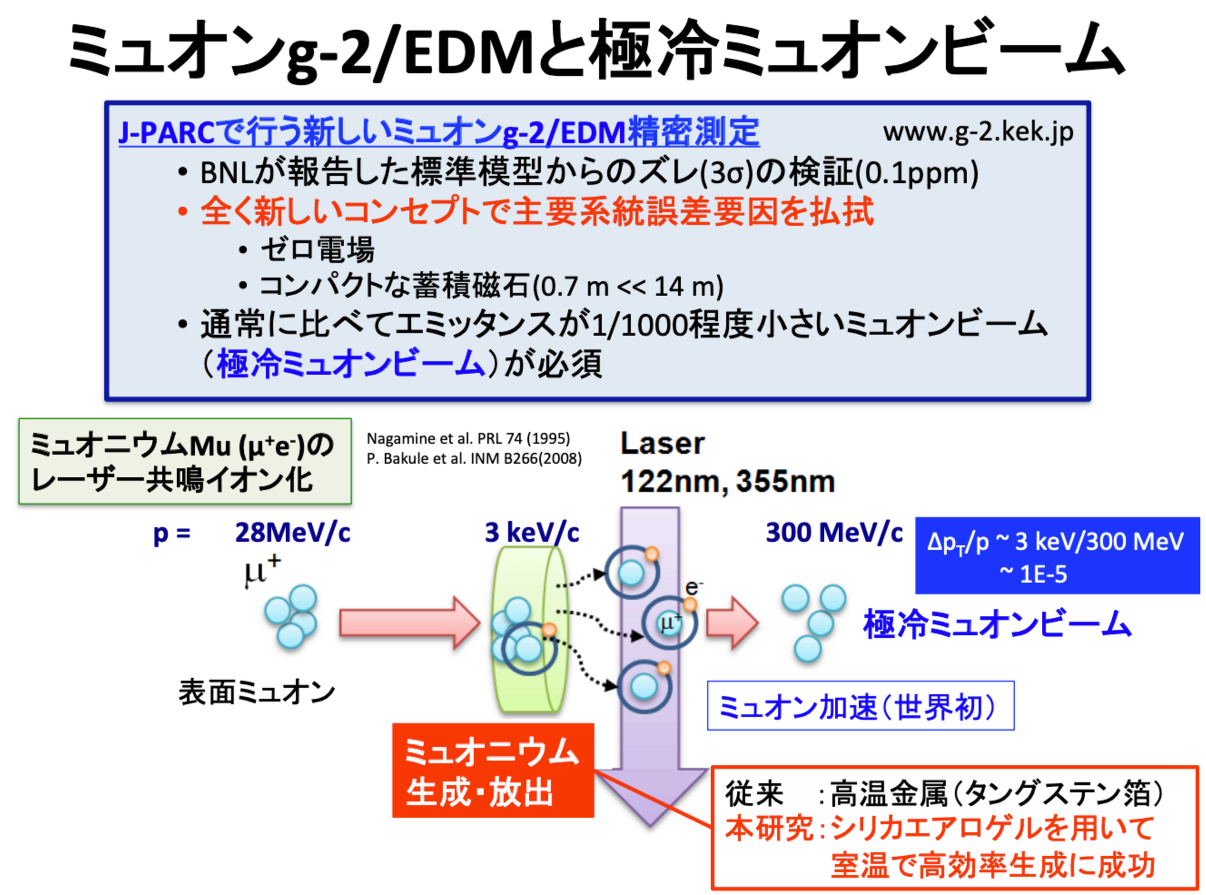
Muon cooling

There is a rather mature(?) technology works for μ+.

Ultracold muon technology [K.Nagamine et al. 1995]



This has been the key technology for the J-PARC muon g-2/EDM experiment.

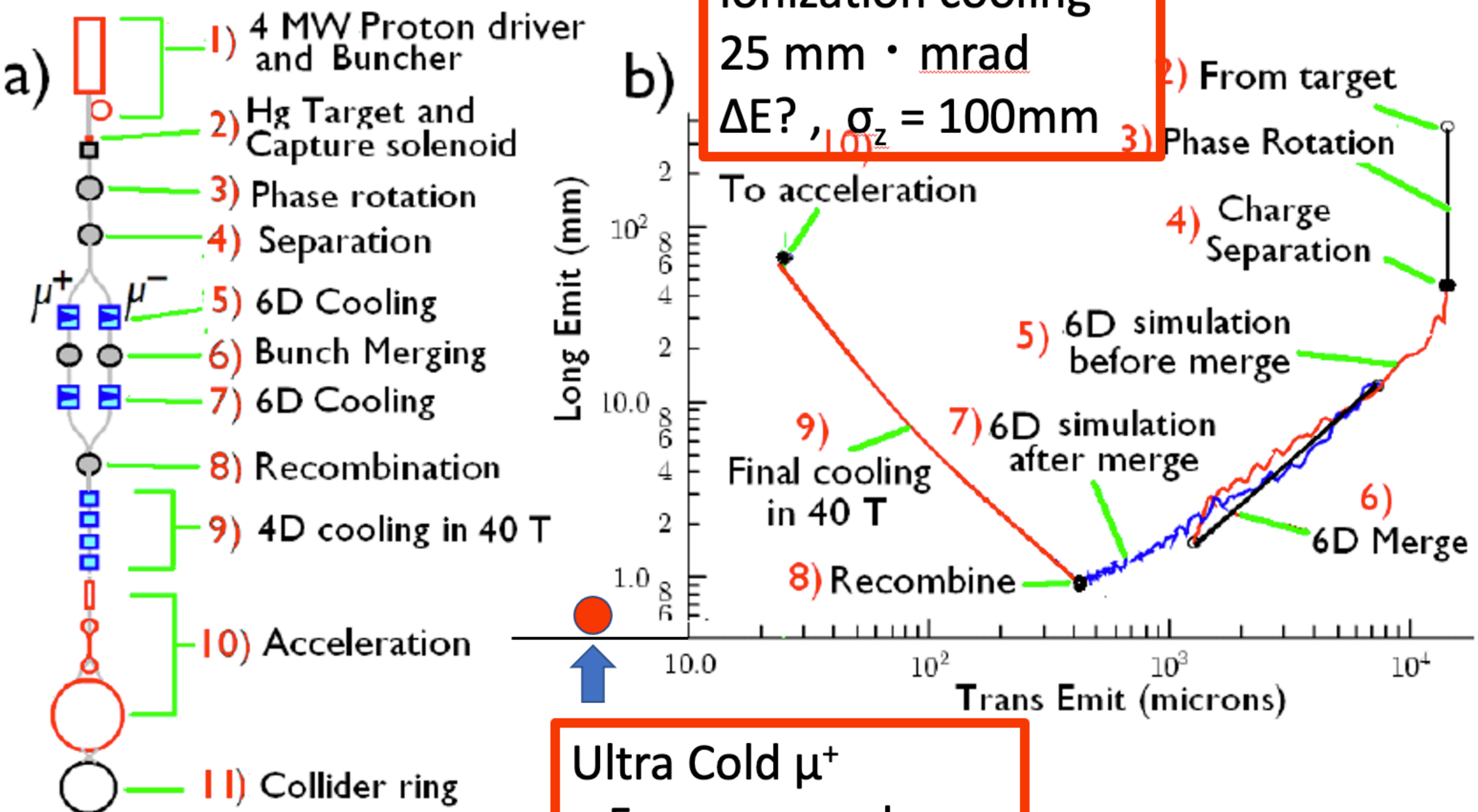


Mibe-san's slide

Looks like a low-emittance μ+ beam is already there!

Also, polarized beam is possible. (non-trivial though)

Emittance : Ionization cooling vs Ultra Cold

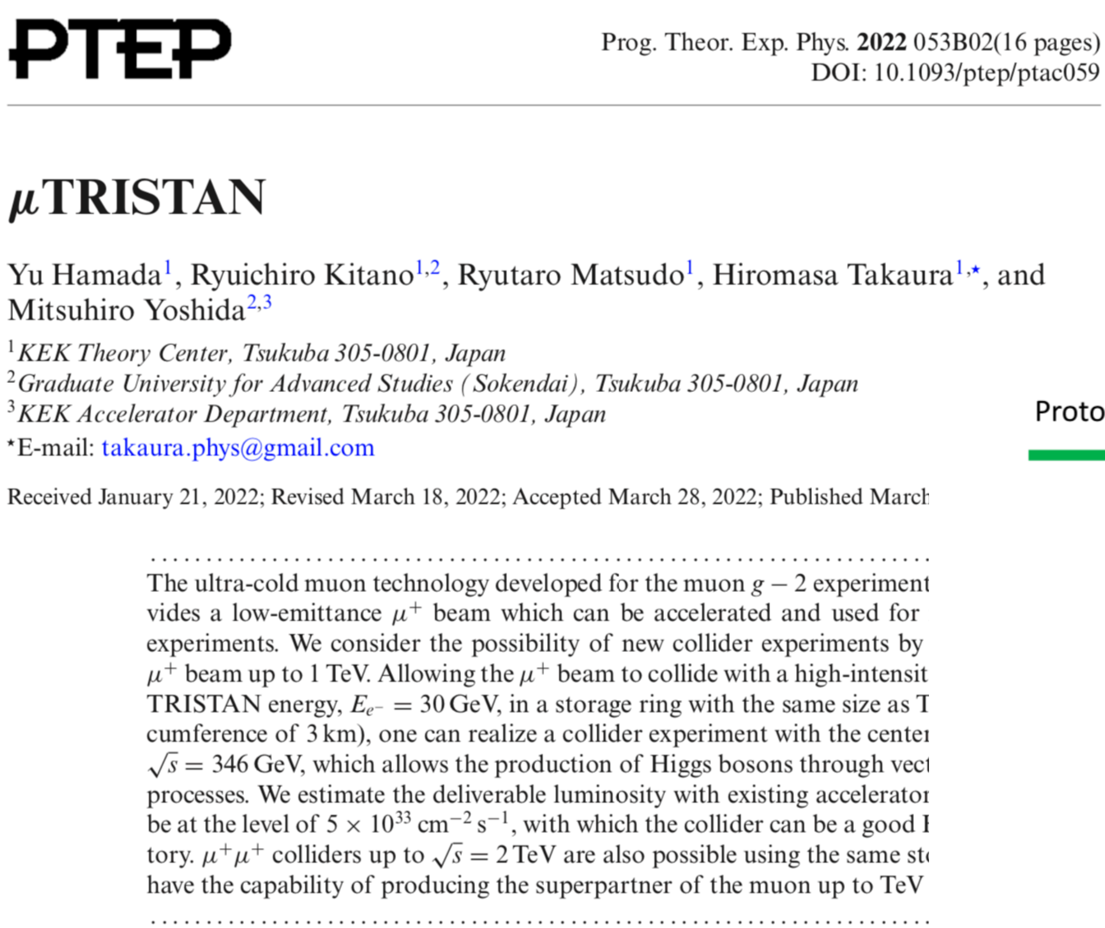


Ionization cooling
25 mm・mrad
ΔE? , σ_z = 100mm

Ultra Cold μ^+
< 5 mm・mrad
ΔE = 1 eV, σ_z = 1mm

µTRISTAN

µ+e-/µ+µ+ collider with 1TeV µ+ beam.



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μTRISTAN

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The ultra-cold muon technology developed for the muon $g-2$ experiment vides a low-emittance μ^+ beam which can be accelerated and used for experiments. We consider the possibility of new collider experiments by μ^+ beam up to 1 TeV. Allowing the μ^+ beam to collide with a high-intensit TRISTAN energy, $E_{e^-} = 30$ GeV, in a storage ring with the same size as T cumference of 3 km), one can realize a collider experiment with the center $\sqrt{s} = 346$ GeV, which allows the production of Higgs bosons through vect processes. We estimate the deliverable luminosity with existing accelerator be at the level of 5×10^{33} cm^{-2} s^{-1}, with which the collider can be a good I tory. $\mu^+\mu^+$ colliders up to $\sqrt{s} = 2$ TeV are also possible using the same st have the capability of producing the superpartner of the muon up to TeV

30GeV e- / 1TeV µ+ : Higgs factory, √s=346GeV

1TeV µ+ / 1TeV µ+ : new physics search, √s=2TeV

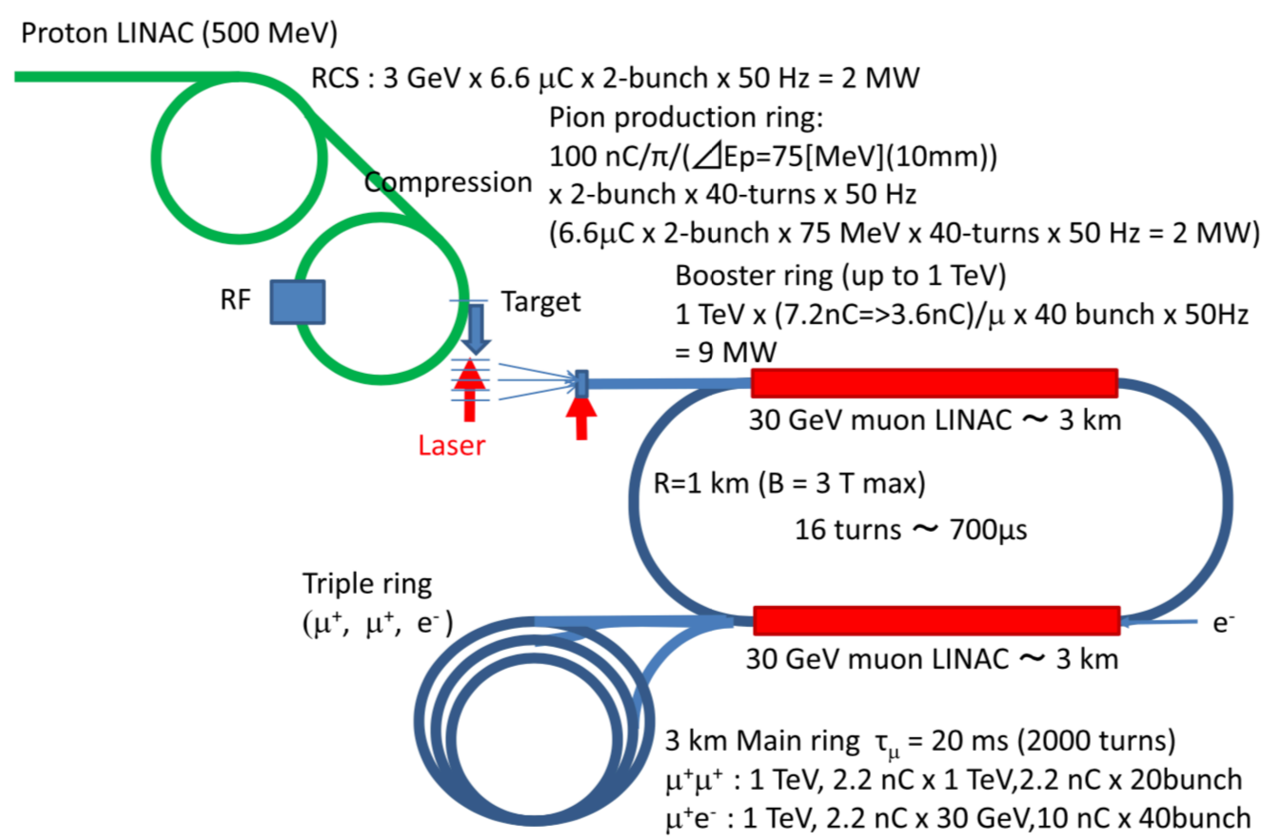


Fig. 1. Conceptual design of the $\mu^+e^-/\mu^+\mu^+$ collider.

How many cold muons?

1/(20ms) where 20ms is the lifetime of the 1TeV muon

J-PARC like proton driver: 6.6 μC * 50 Hz * 2 bunches = 4.1 x 10^{15} protons/s realistic

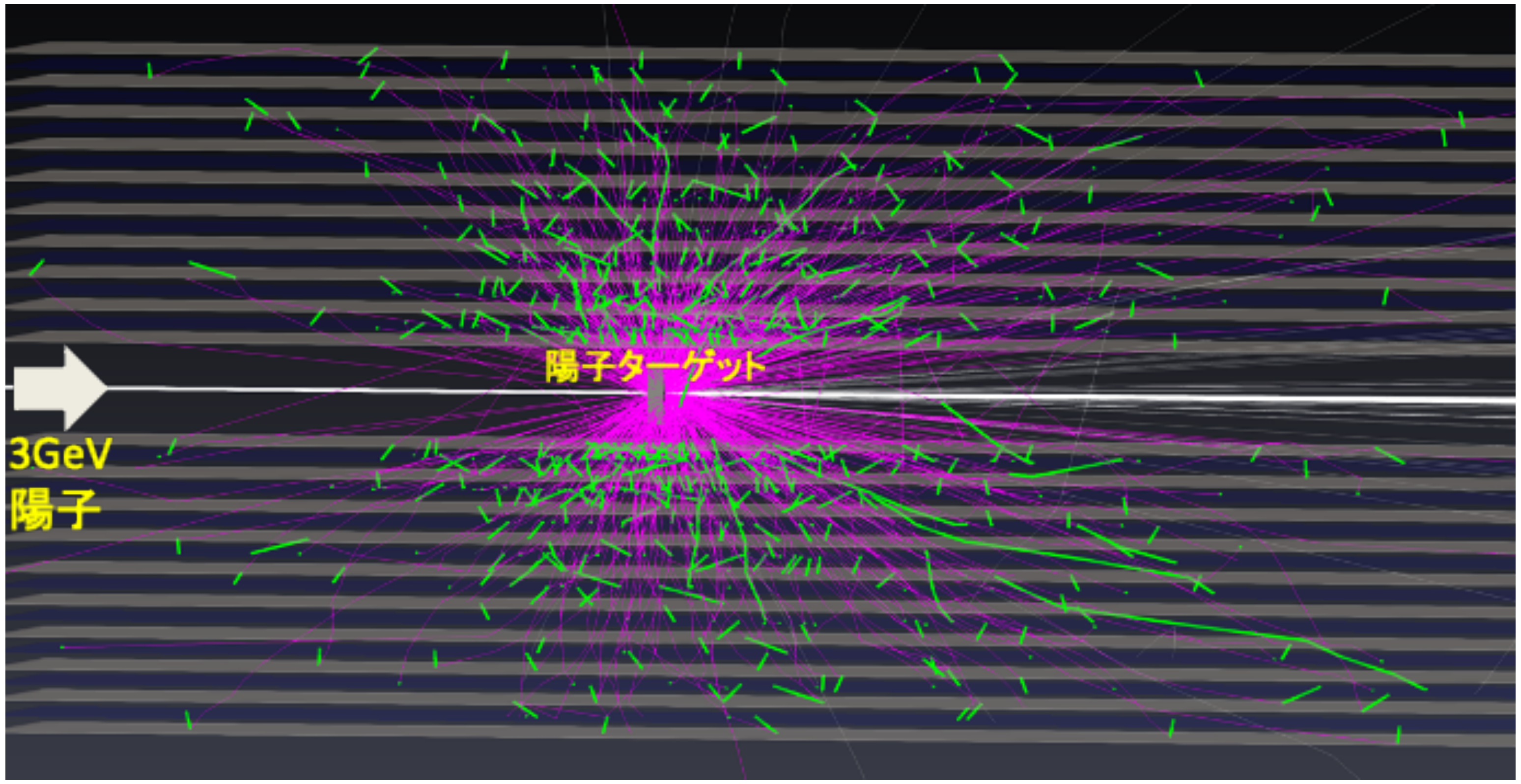
pion production target: 40 hits/bunch 0.016 π^+/proton 2.6 x 10^{15} π^+/s maybe realistic

pion stopping target: 0.5 stopping efficiency * 0.07 muons/π^+ 9 x 10^{13} μ^+/s maybe challenging

10^5 larger than J-PARC MLF.

Super muon factory!

simulation: (in progress)



pink: pion

green: muon

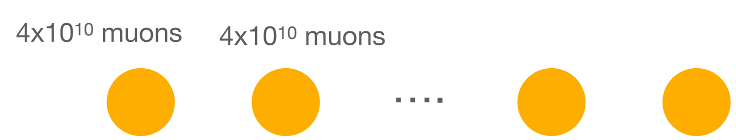
Luminosity?

J-PARC like proton driver: 6.6 μC * 50 Hz * 2 bunches = 4.1 x 10^{15} protons/s

pion production target: 40 hits/bunch 0.016 π^+/proton 2.6 x 10^{15} π^+/s

pion stopping target: 0.5 stopping efficiency * 0.07 muons/π^+ 9 x 10^{13} μ^+/s

6.6 μC x 2 x 0.016 x 0.5 x 0.07 ~ 7 nC / bunch ~ 4 x 10^{10} muons/bunch



40 bunches

accelerate up to 1TeV → bunch charge reduced to half by decay
storage ring → 2000 turns. further reduced by half

$N_\mu \sim 10^{10}$ $N_e \sim 6 \times 10^{10}$

σ ~ 2-3 μm (β* ~ cm)

f_{rep} ~ (c/3km) x 40 bunches
~ 100 kHz *40 bunches = 4 MHz

storage ring

1μs for one turn.
2000 turns before next beam is coming.

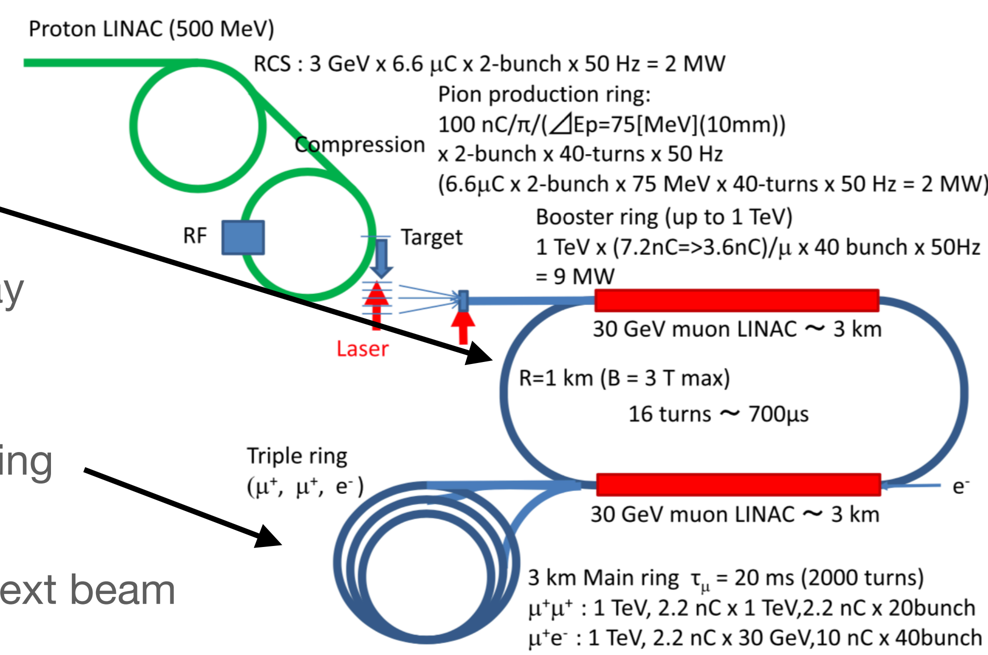


Fig. 1. Conceptual design of the $\mu^+e^-/\mu^+\mu^+$ collider.

$$\mathcal{L}_{\mu^+e^-} = 4.6 \times 10^{33}\,\mathrm{cm^{-2}\,s^{-1}}.$$

$$\mathcal{L}_{\mu^+\mu^+} = 5.7 \times 10^{32}\,\mathrm{cm^{-2}\,s^{-1}}.$$

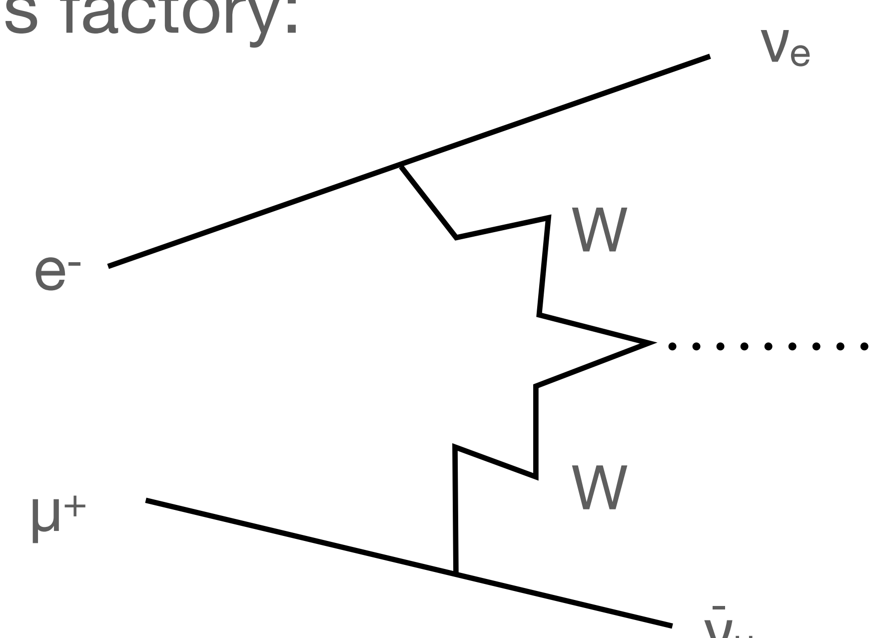
(β* may be much smaller?)

ab^{-1} level for 10yrs running.

not bad.

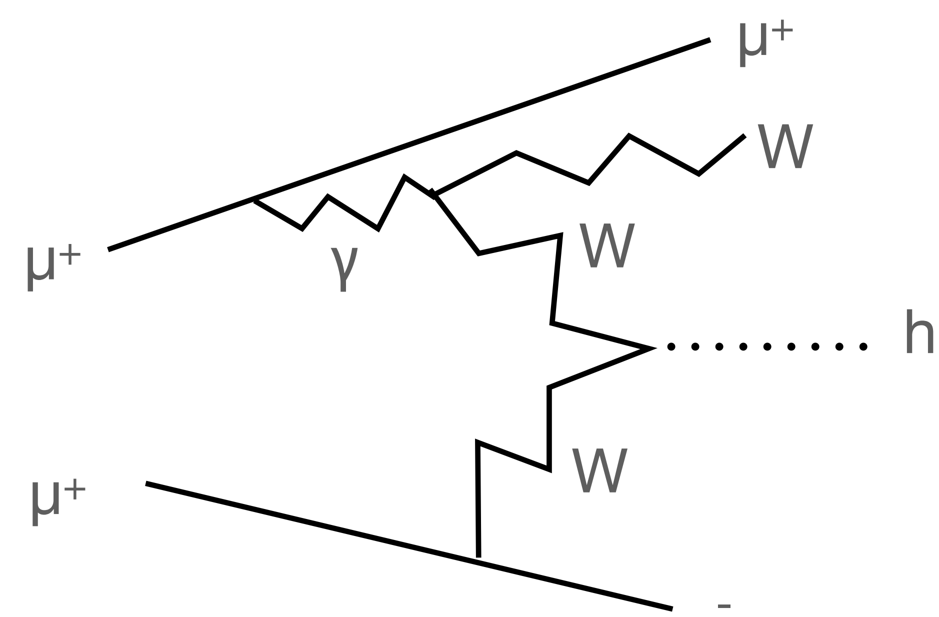
What can we do at μTRISTAN?

Higgs factory:



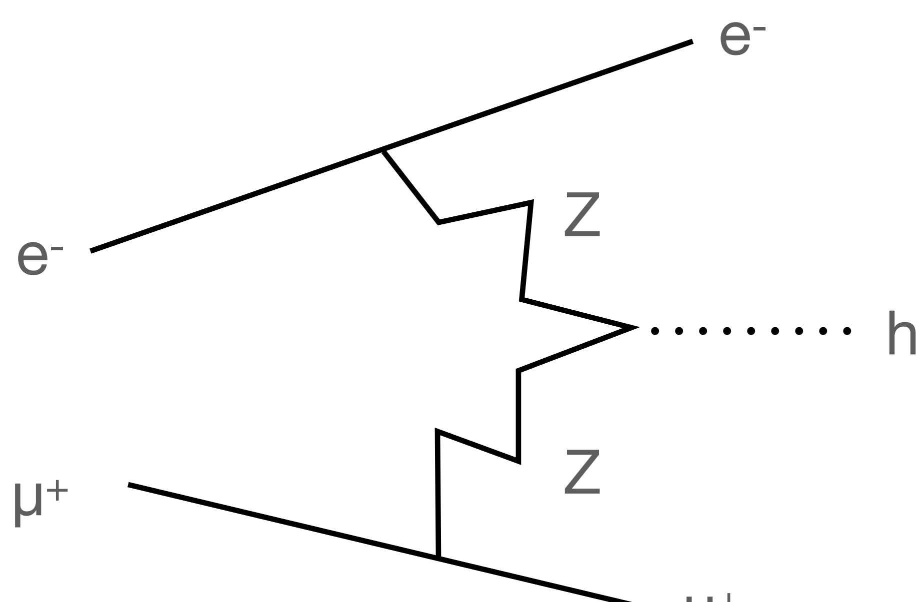
~90fb (30GeV x 1TeV)

~10^5 Higgs bosons ($1ab^{-1}$)



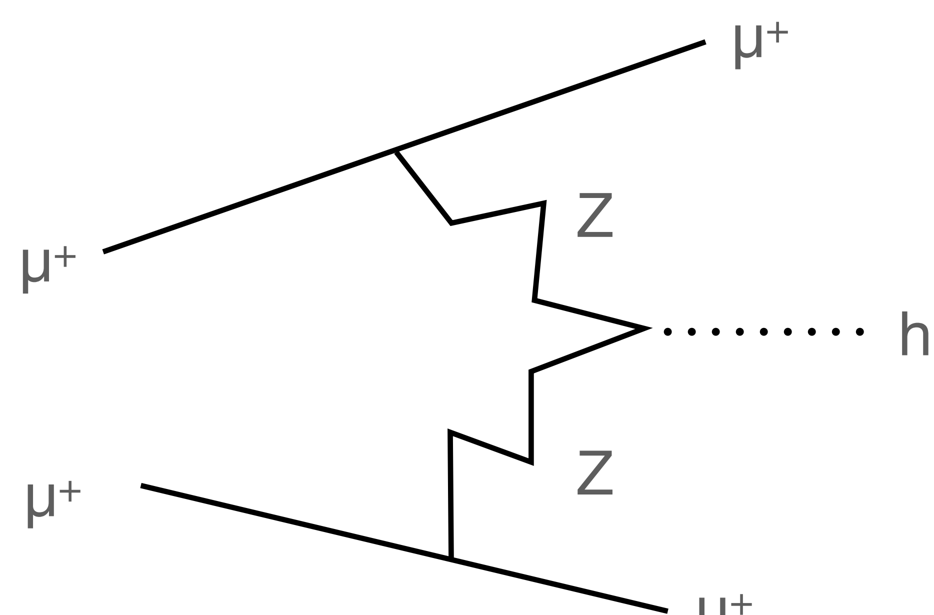
~35fb (1TeV x 1TeV)

~$10^{4\text{-}5}$ Higgs bosons ($1ab^{-1}$)



~4fb (30GeV x 1TeV)

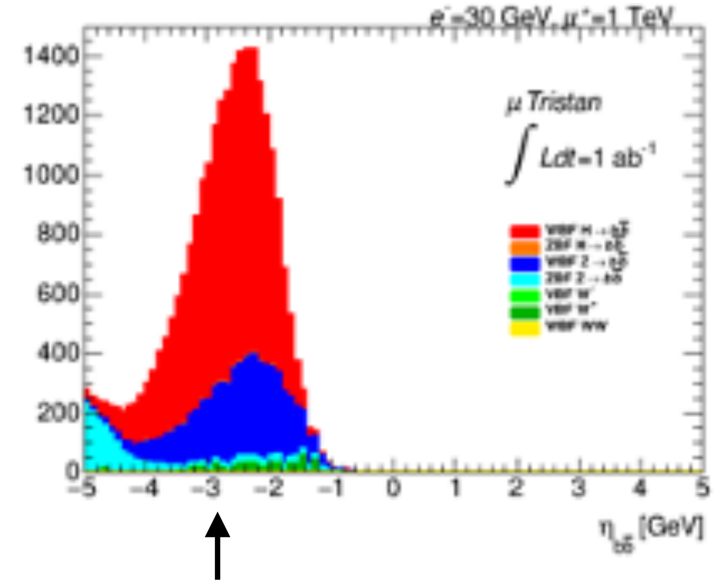
~10^3 Higgs bosons ($1ab^{-1}$)



~54fb (1TeV x 1TeV)

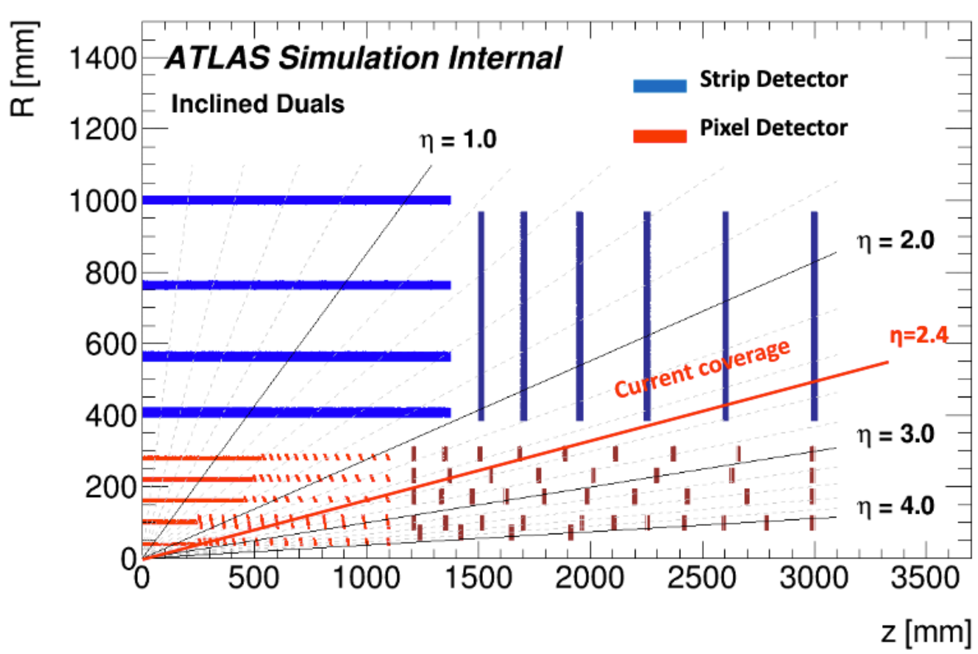
~$10^{4\text{-}5}$ Higgs bosons ($1ab^{-1}$)

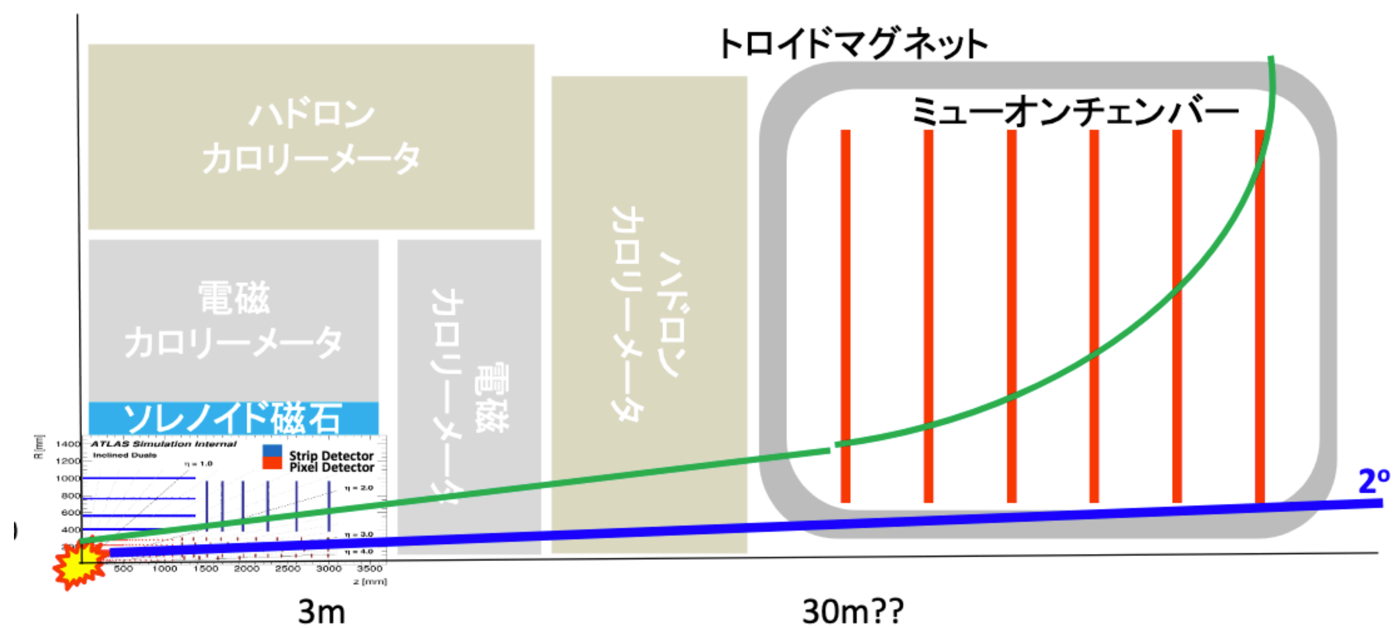
μ+e-: Very asymmetric



All the particles go to the direction of the muon.

We need a coverage of η~-4 (2°), which is the same level as the design of the ATLAS at HL-LHC.

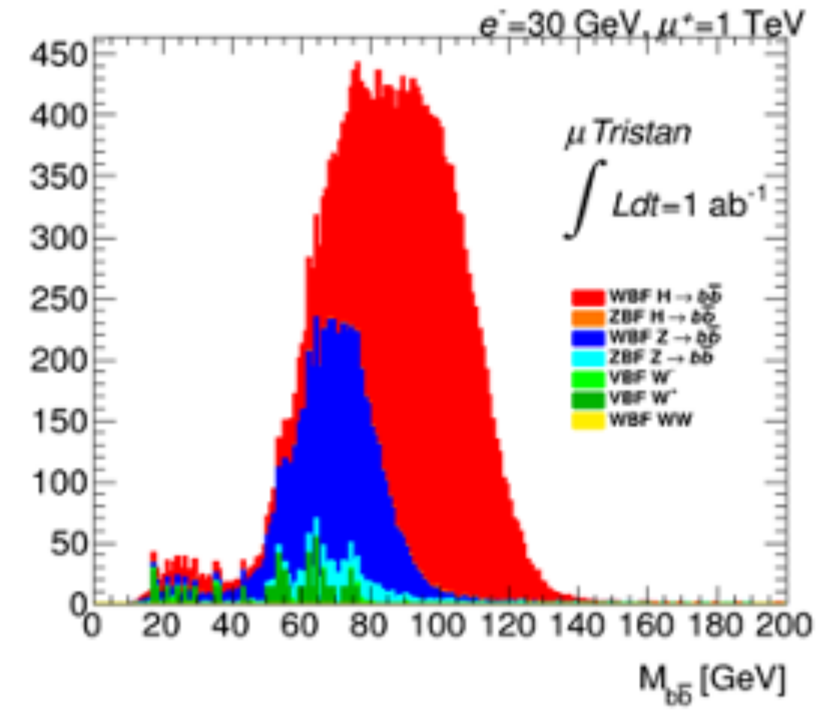




Higgs coupling

Study in progress in collaboration with Koji Nakamura and Sayuka Kita.

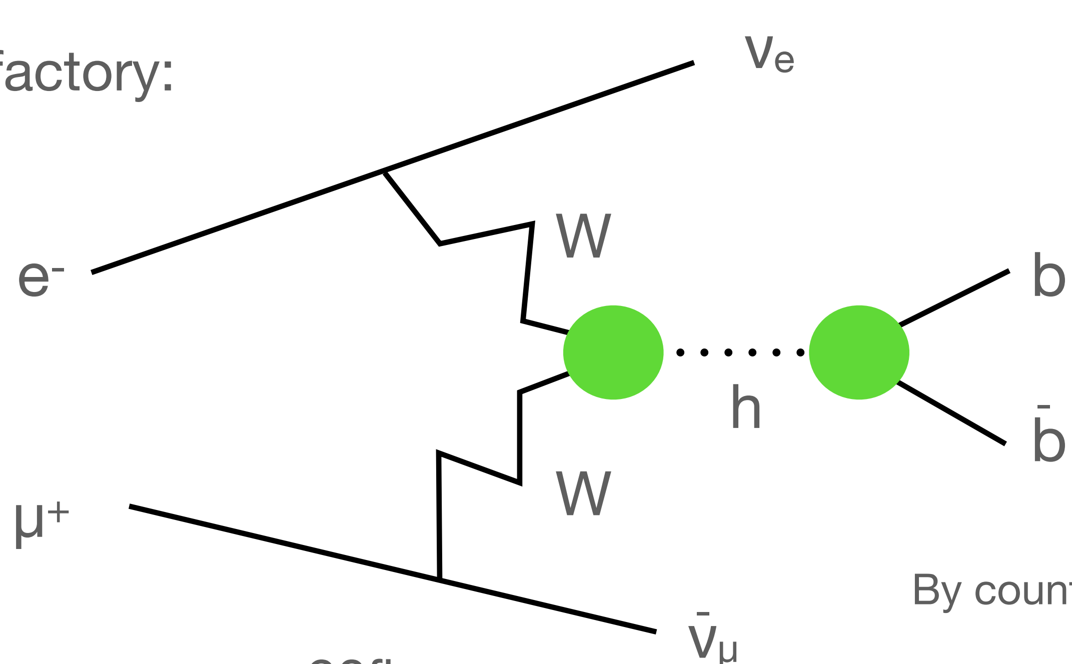
simulation with the ATLAS detector for HL-LHC



acceptance ~ 23%

(This should improve a lot with a detector designed for this collider.)

Higgs factory:



~90fb

~10^5 Higgs bosons

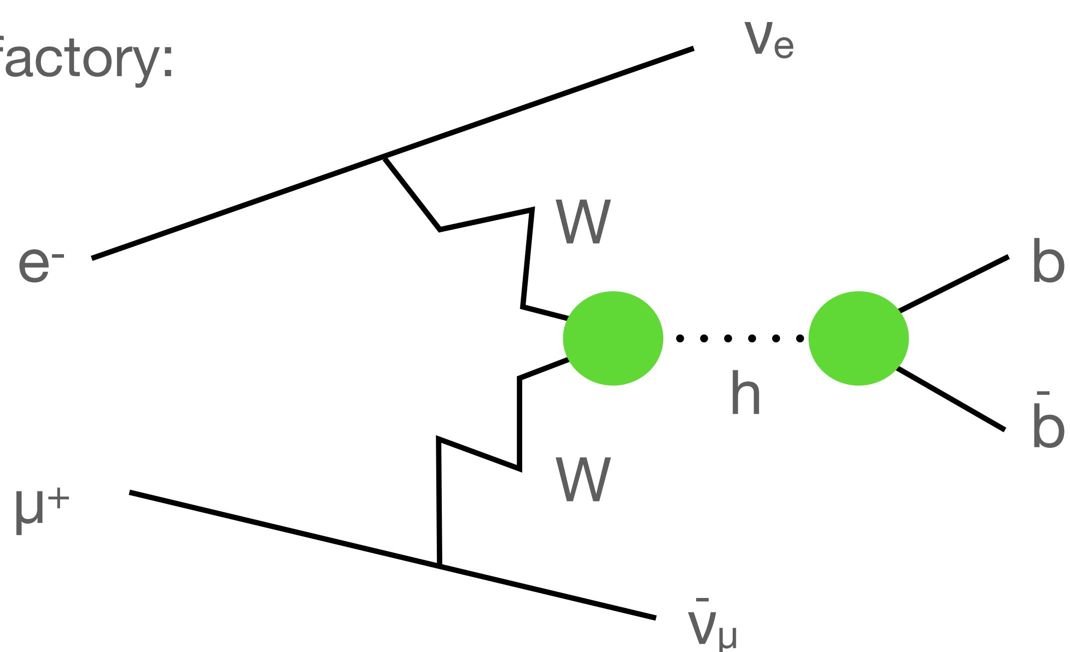
By counting the number of events and compare with the SM prediction

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

sub percent level measurements.

Higher energy? μTevatron?

Higgs factory:



~472fb (50GeV x 3TeV)

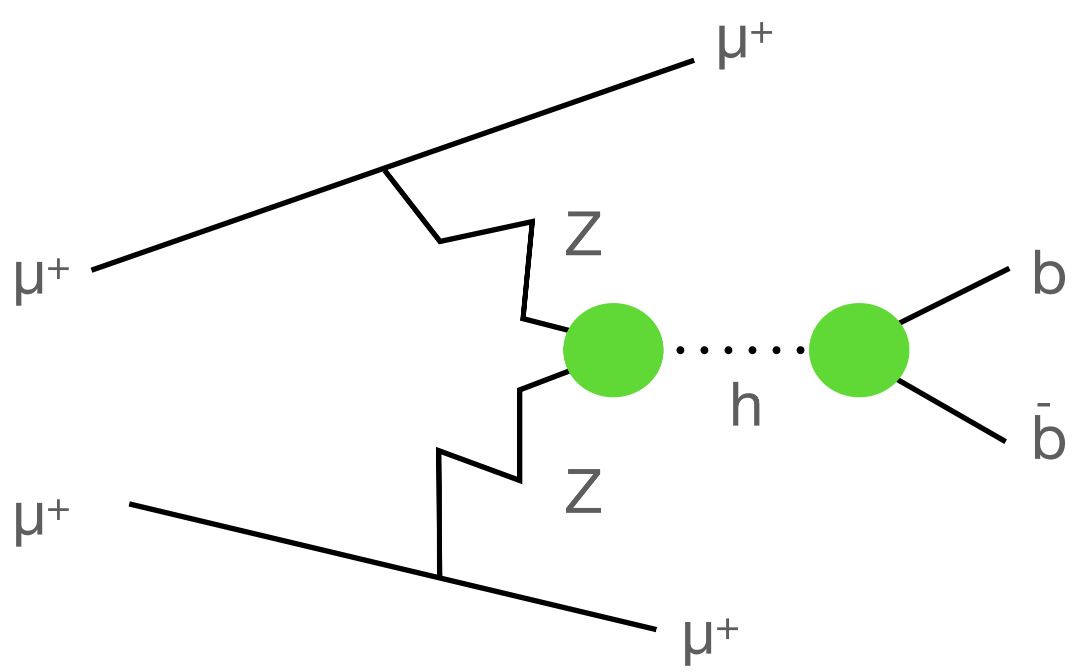
~5x10^5 Higgs bosons (ab^{-1})

50GeV electron + 3TeV muon at a **6km** ring

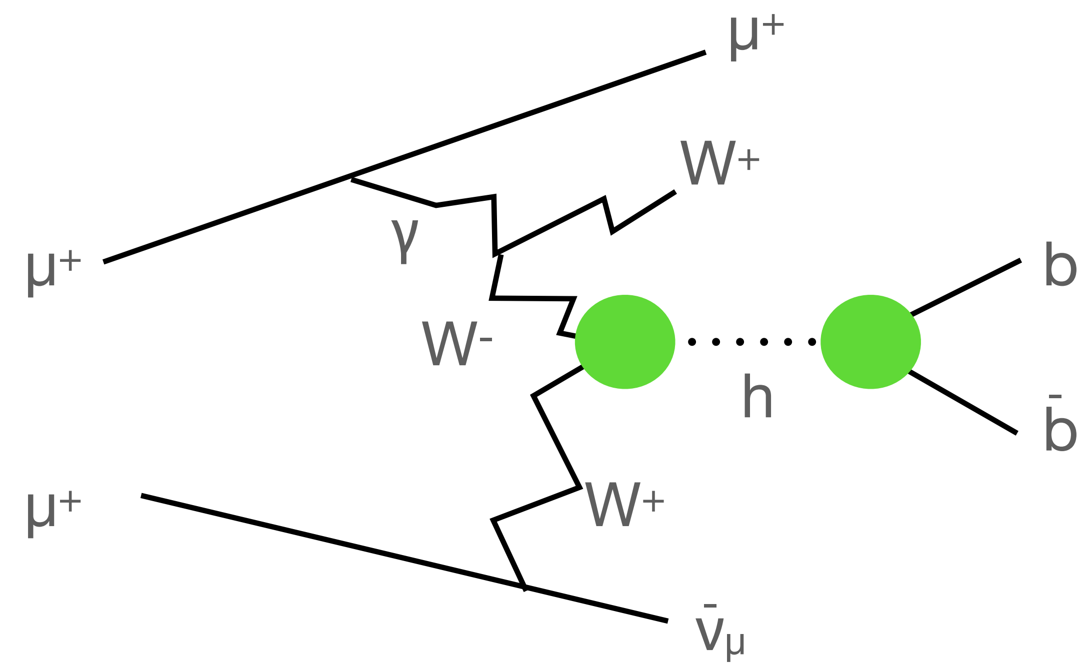
$\sqrt{s}$ = 775 GeV

hh production: 89 events/ab^{-1} (maybe we need more for coupling measurements)

Higgs production@$\mu^+\mu^+$



~54fb@2TeV final state all visible

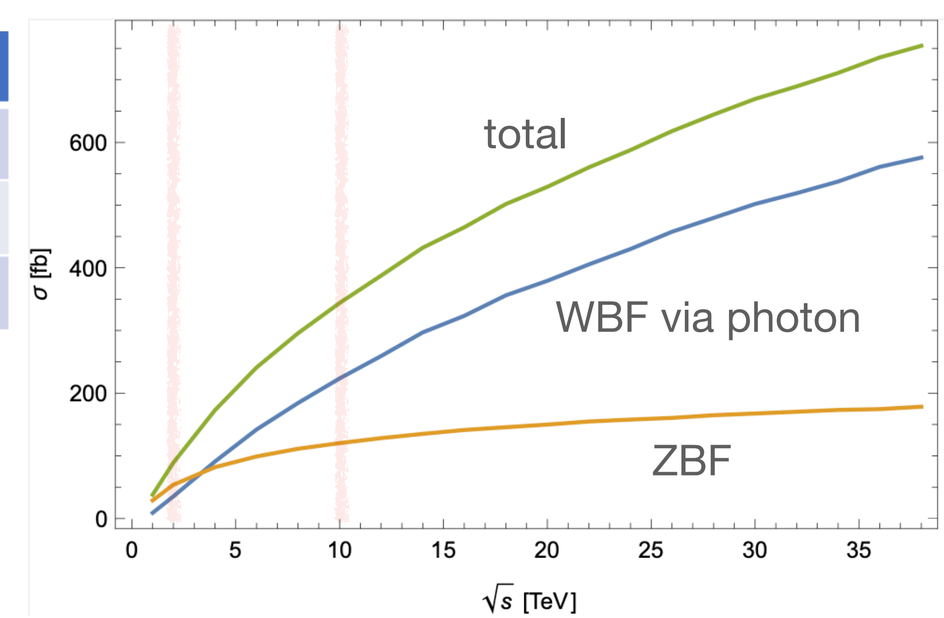


~35fb@2TeV

gets more important at high energy

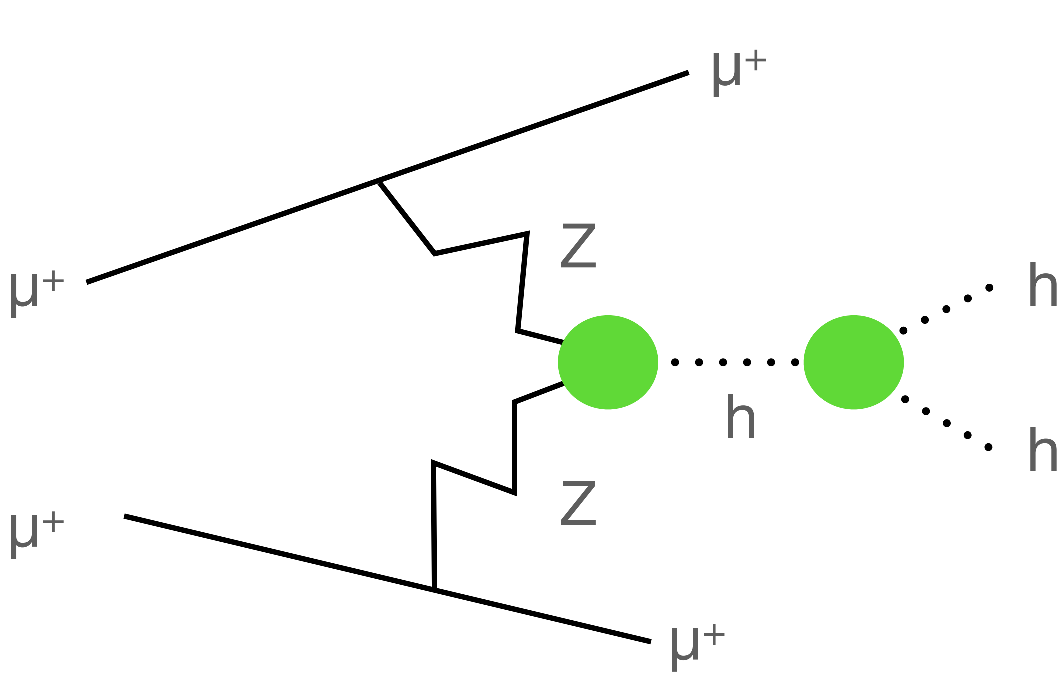
$\sqrt{s}$ [TeV]	ZBF [fb]	Photon emission [fb]
2	54	35
10	121	224
20	150	376

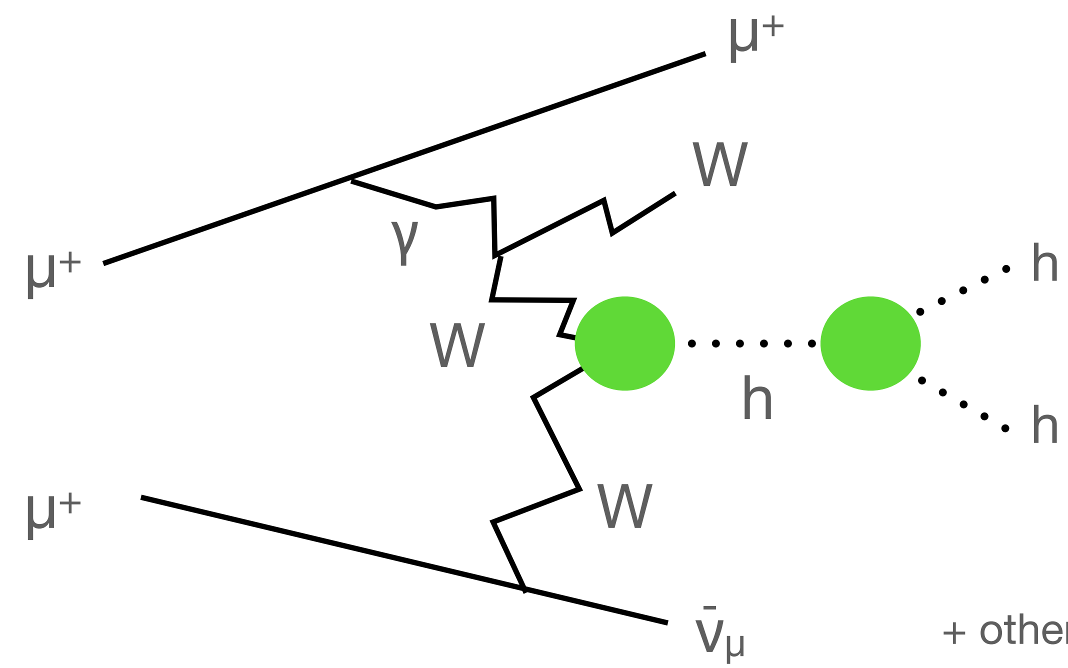
about a factor of two smaller than $\mu^+\mu^-$
(not too bad?)



maybe we should plan 5-10TeV colliders.

Higgs production@μ⁺μ⁺





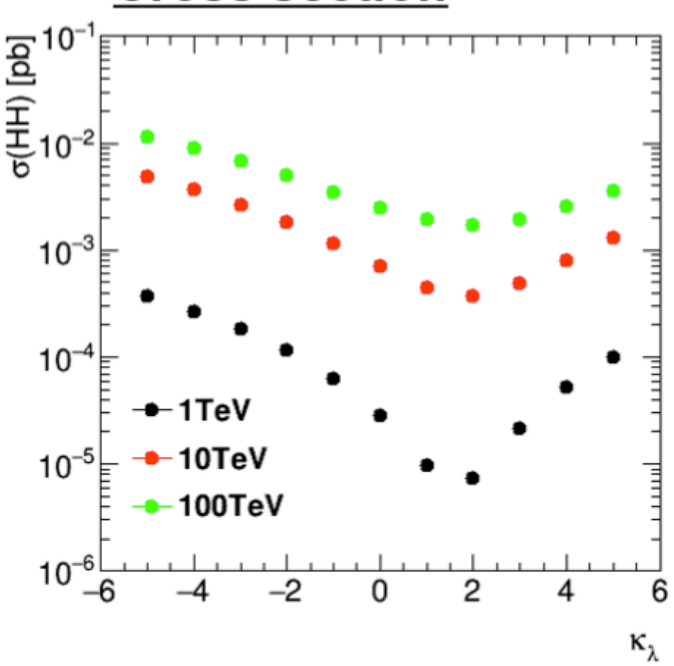
+ others

about 1/3 of μ⁺μ⁻

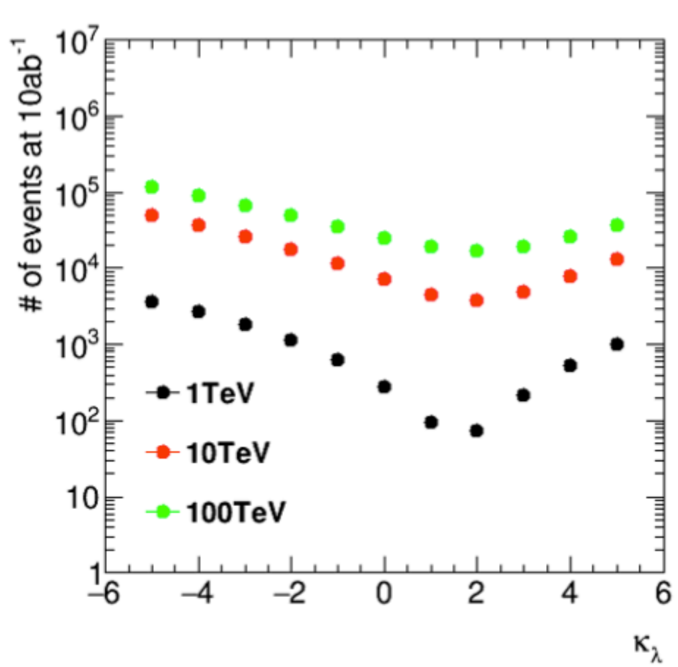
$\sqrt{s}$ [TeV]	ZBF [fb]	Photon emission [fb]
2	0.075	0.010
10	0.62	0.30
20	1.1	0.75

ZBF:

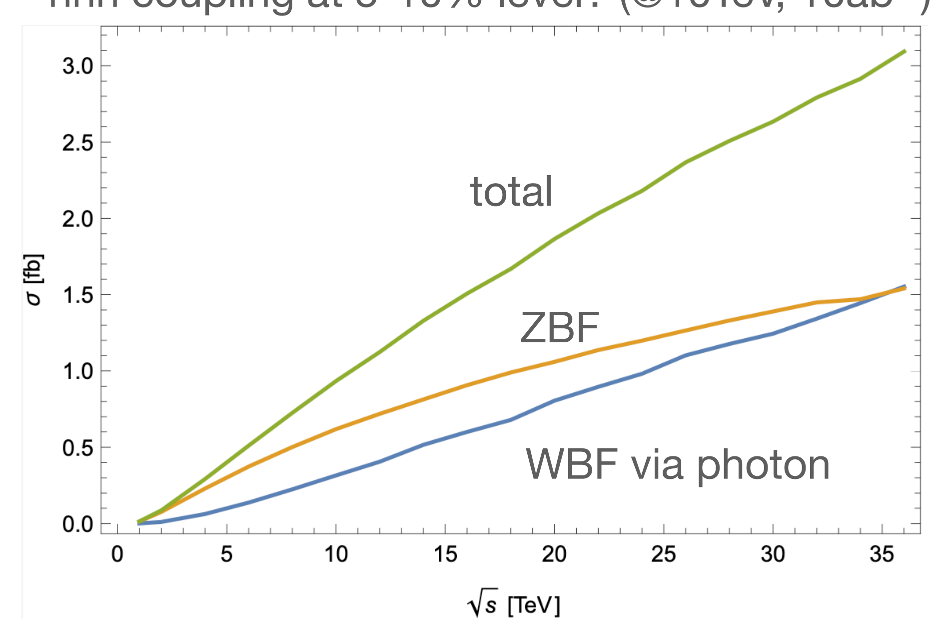
Cross section



# of Events in 10ab⁻¹

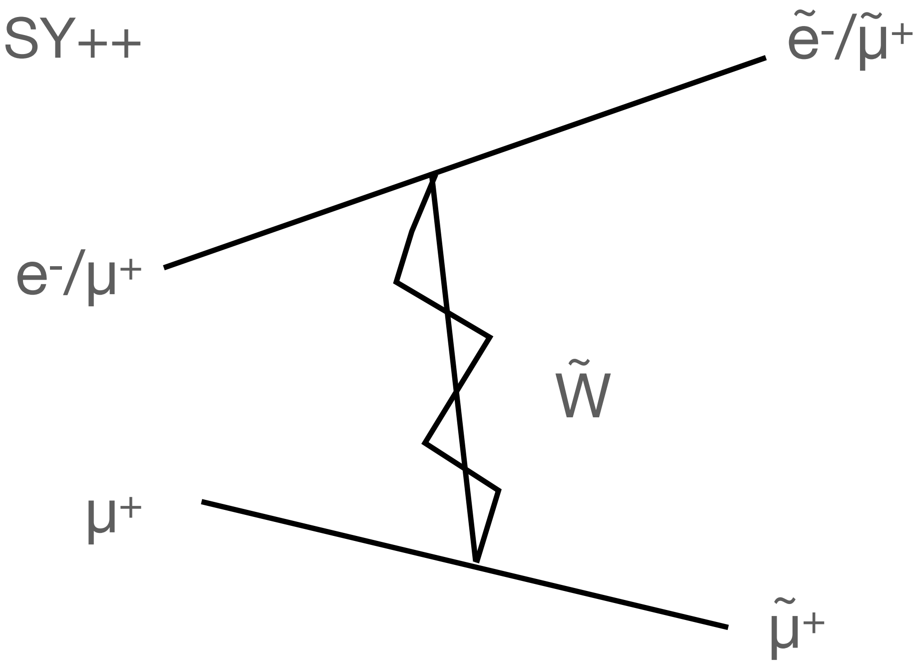


hhh coupling at 5-10% level? (@10TeV, 10ab⁻¹)



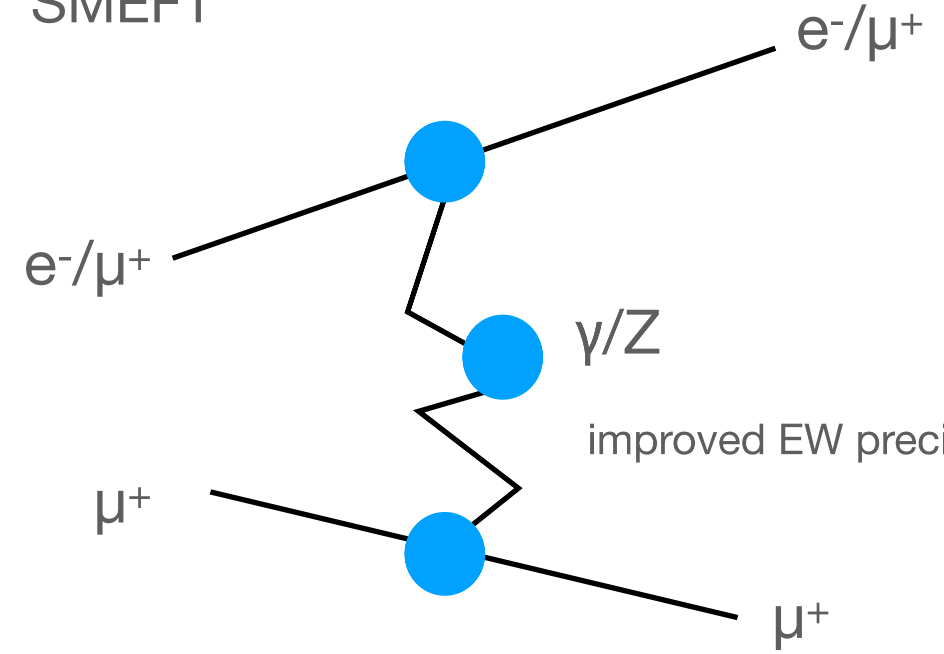
New physics?

SUSY++



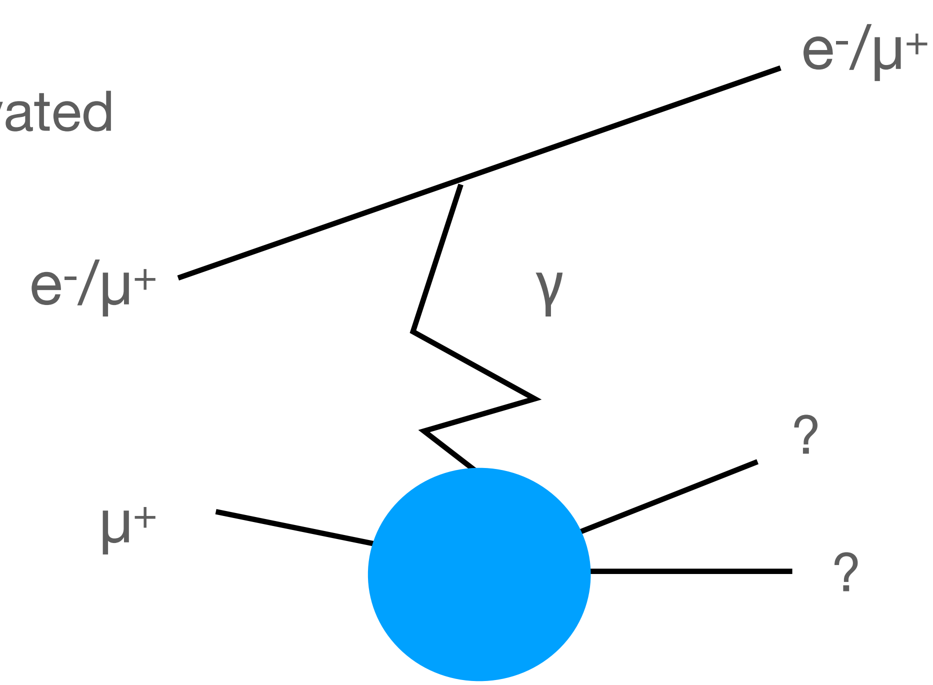
TeV mass new particles

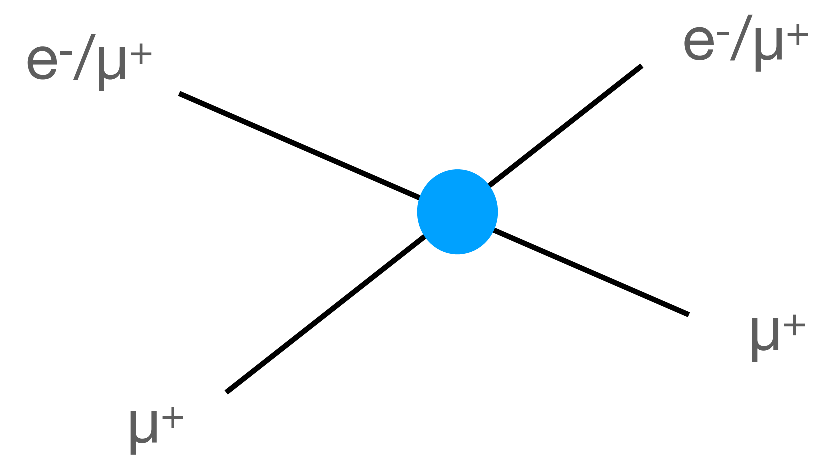
SMEFT



improved EW precision tests

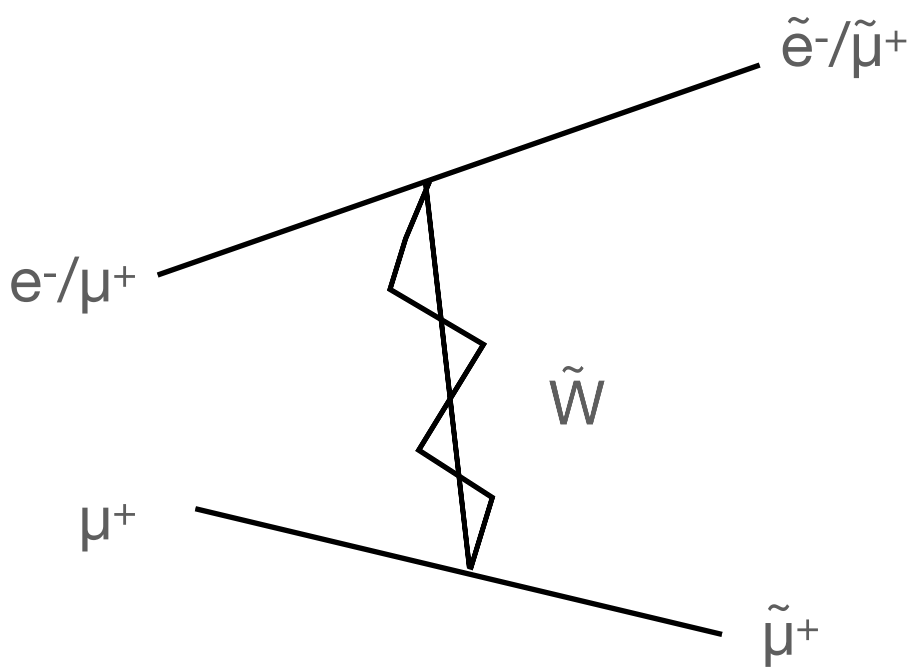
g-2 motivated



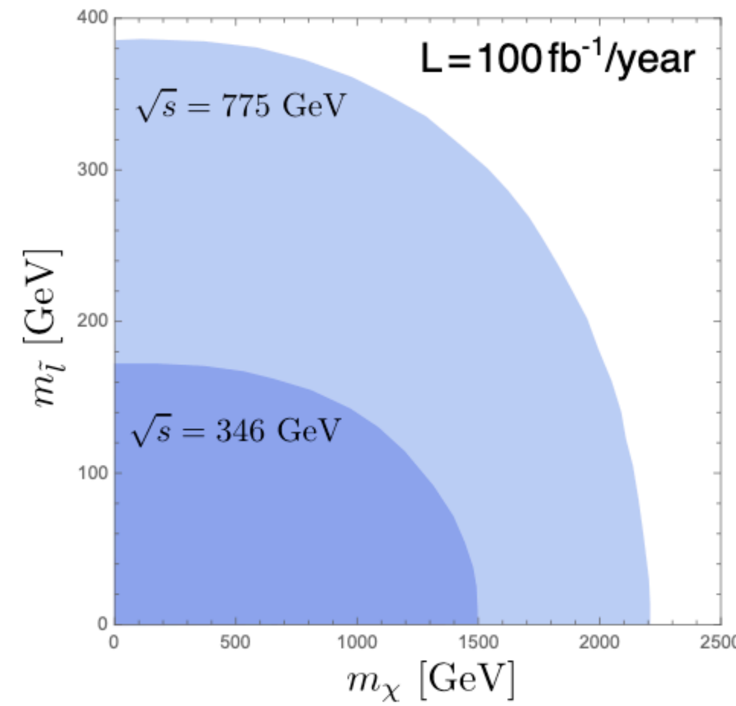


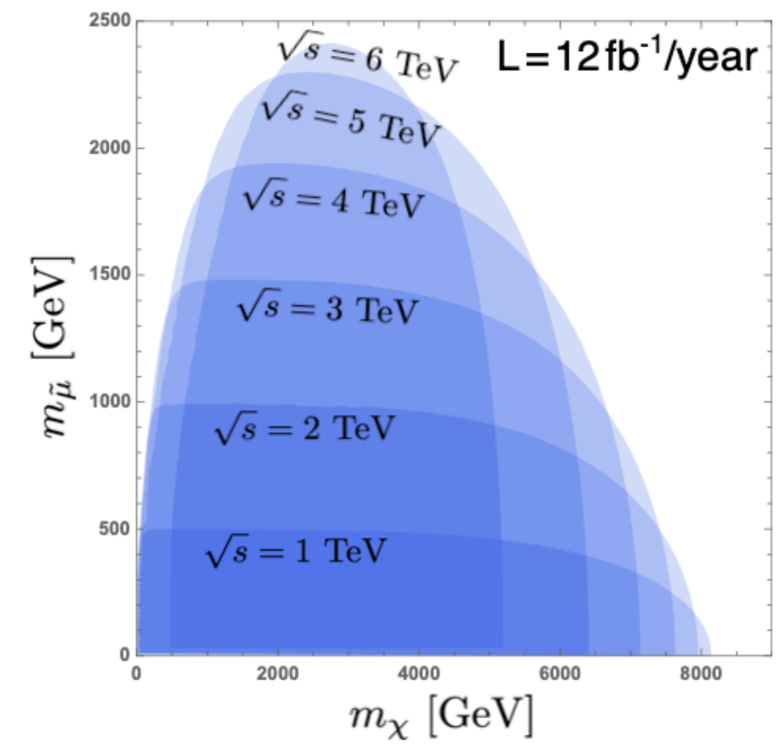
probe 100TeV scale physics!?

Supersymmetry



Regions for N_{event}/year > 100.

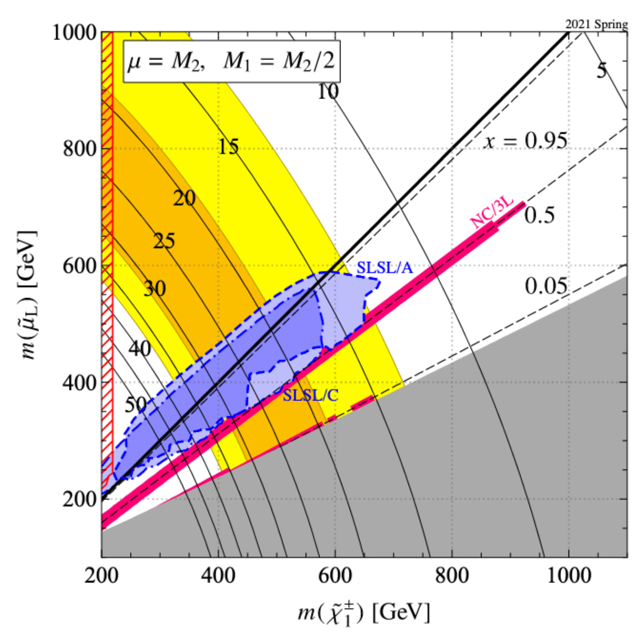




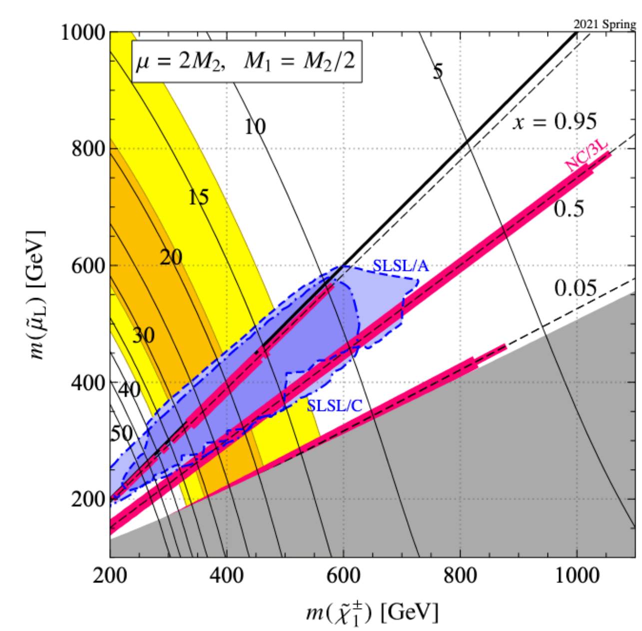
Scalar muons up to TeV even for very heavy gauginos.

Almost completely cover the muon g-2 motivated region.

[Endo, Hamaguchi, Iwamoto, Kitahara '21]



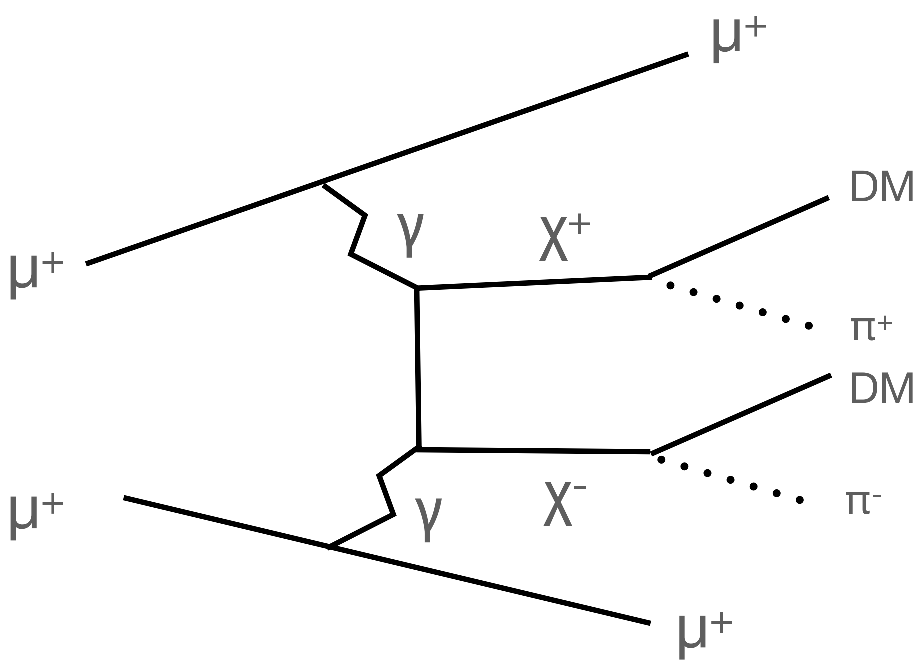
(A) $\mu = M_2$, $M_1 = M_2/2$.



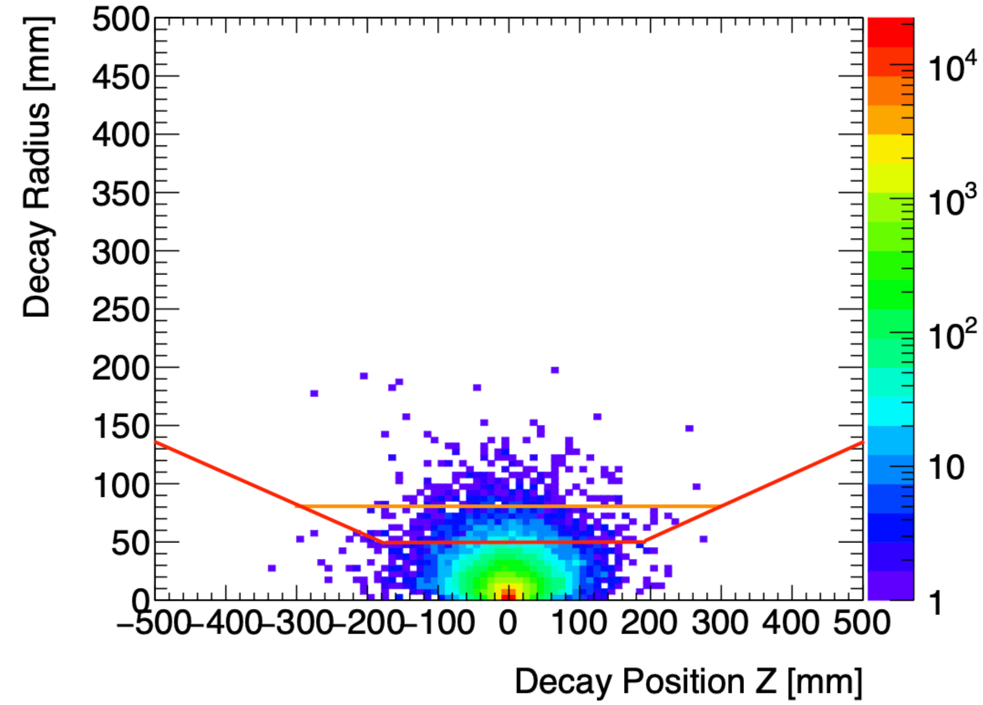
(B) $\mu = 2M_2$, $M_1 = M_2/2$.

[with T. Kaji, T. Yoshida, K. Yorita in progress]

DM search



√s = 10 TeV, 質量 1 TeV Higgsino の崩壊マップ



崩壊半径
- Case A > 80 mm
- Case B > 50 mm

$|\eta| < 2.0$
を再構成できると仮定

of expected events @ 1 ab^{-1}

σ = 124.7 ab	R > 50 mm	R > 80 mm
$\mu^+\mu^+ \rightarrow \chi^+\chi^-\mu^+\mu^+$ (2 muons + at least 1 chargino)	2.4	0.5

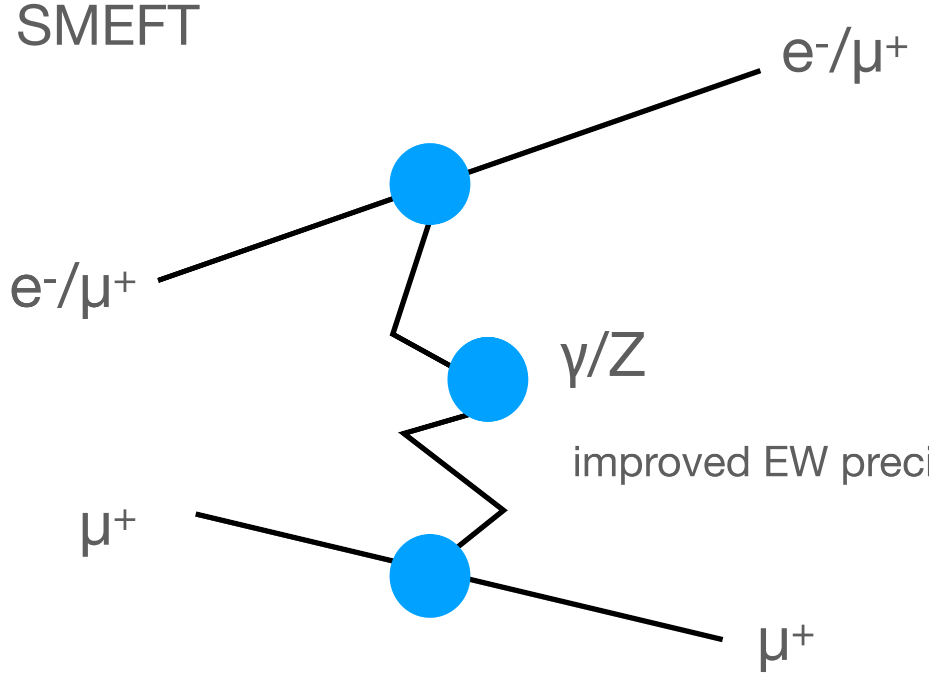
assumed a muon system which can detect forward muons (|η|<6)

Looks like 1TeV Higgsino is within the reach.
(@10TeV machine)

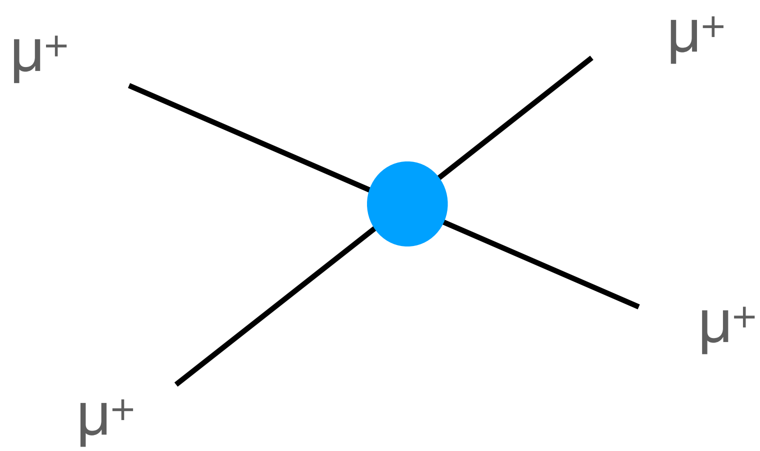
Indirect searches

Basically the SM process has peak at the forward region, while interference with new physics (dim-6 operators) give events in the central region.

SMEFT



improved EW precision tests



S, T: C_{HWB}, C_{HD}; (H current)(L current): $C_{H\ell}^{(1)}$, $C_{H\ell}^{(3)}$, C_{He}; 4-fermi: remaining operators

	RR	RL	LR	LL
C_{HWB}	6.9 TeV	24 TeV	26 TeV	6.9 TeV
C_{HD}	6.8 TeV	9.0 TeV	14 TeV	6.8 TeV
$C_{H\ell}^{(1)}$	15 TeV	0	20 TeV	15 TeV
$C_{H\ell}^{(3)}$	20 TeV	18 TeV	35 TeV	20 TeV
C_{He}	16 TeV	19 TeV	0	16 TeV
$C_{\ell\ell}$	9.6 TeV	13 TeV	43 TeV	9.6 TeV
$C''_{\ell\ell}$	0	0	47 TeV	0
$C_{e\mu}$	0	66 TeV	0	0
$C_{\underset{ee\mu\mu}{\ell e}}$	0	0	0	44 TeV
$C_{\underset{\mu\mu ee}{\ell e}}$	44 TeV	0	0	0

Table 2: Constraints on SMEFT operators at two-sigma level. $E_e = 30$ GeV and $E_\mu = 1$ TeV, which amounts to $\sqrt{s} = 346$ GeV. The bin size for Θ_e is taken as $1°$. We require both muon and electron to go into the range of $15.4° \lesssim \Theta \lesssim 178°$, corresponding to $\eta_{max} = 2$ for the muon beam side and $\eta_{max} = 4$ for the electron beam side. As a result, the angle range of the electron is $62.8° \lesssim \Theta_e \lesssim 178°$.

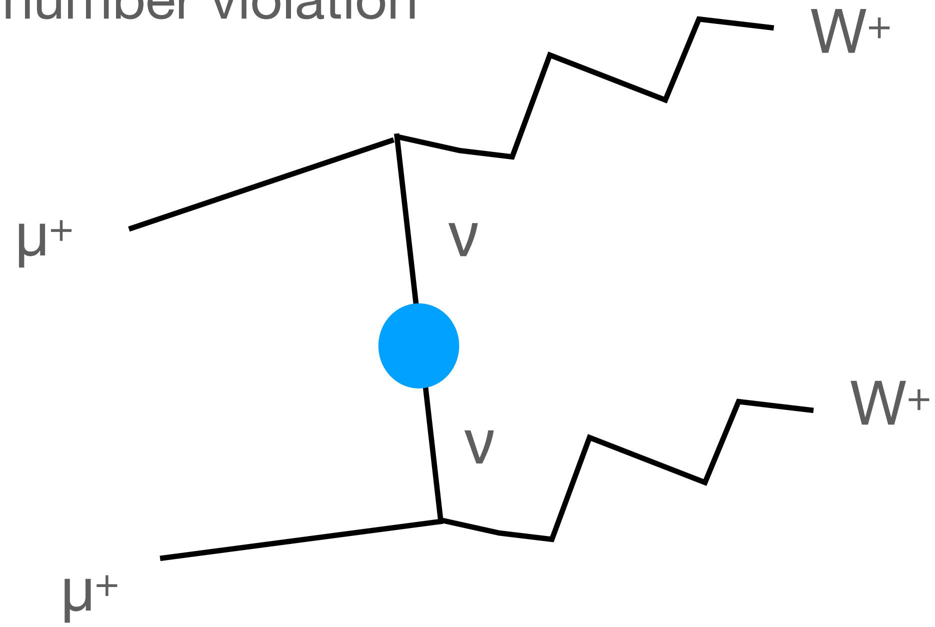
S, T: C_{HWB}, C_{HD}; (H current)(L current): $C_{H\ell}^{(1)}$, $C_{H\ell}^{(3)}$, C_{He}; 4-fermi: remaining operators

	RR	LL	RL
C_{HWB}	10 TeV	9.4 TeV	2.3 TeV
C_{HD}	5.5 TeV	3.5 TeV	2.3 TeV
$C_{H\ell}^{(1)}$	8.0 TeV	0	4.9 TeV
$C_{H\ell}^{(3)}$	14 TeV	7.0 TeV	6.7 TeV
C_{He}	0	7.5 TeV	5.3 TeV
$C_{\ell\ell}$	7.7 TeV	5.0 TeV	3.3 TeV
$C_{\underset{\mu\mu\mu\mu}{\ell\ell}}$	100 TeV	0	0
$C_{\underset{\mu\mu\mu\mu}{ee}}$	0	100 TeV	0
$C_{\underset{\mu\mu\mu\mu}{\ell e}}$	0	0	46 TeV

Table 1: Constraints on SMEFT operators at 2-sigma level. $\sqrt{s} = 2$ TeV. The bin size for θ is taken as $1°$ and each bin covers the range $\theta_i - 0.5° < \theta < \theta_i + 0.5°$. The considered range of θ_i is $16° \leq \theta_i \leq 164°$.

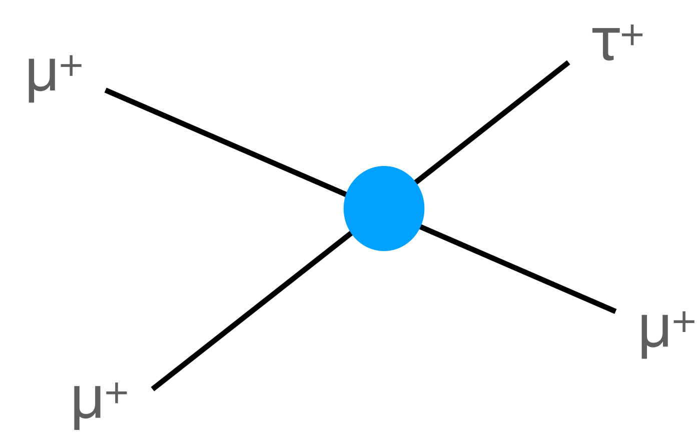
Lepton number/flavor violation?

lepton number violation



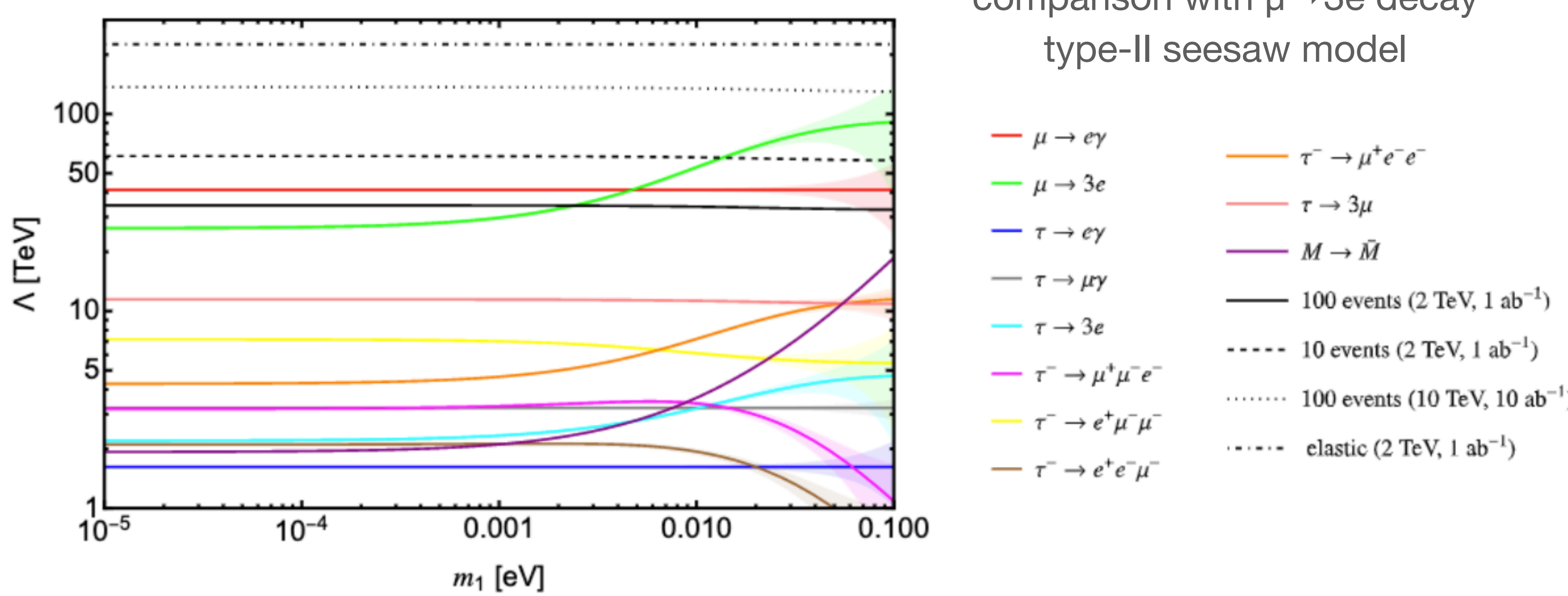
lepton flavor violation

[Fridell , RK and Takai '23]



Can be better than rare decays!

comparison with μ→3e decay
type-II seesaw model



Summary

We are not satisfied with the current understanding of particle physics. Too much unknowns. Full of mysteries.

μ^+ may have a chance. Interesting to consider a km size experiment as a relatively near future project.

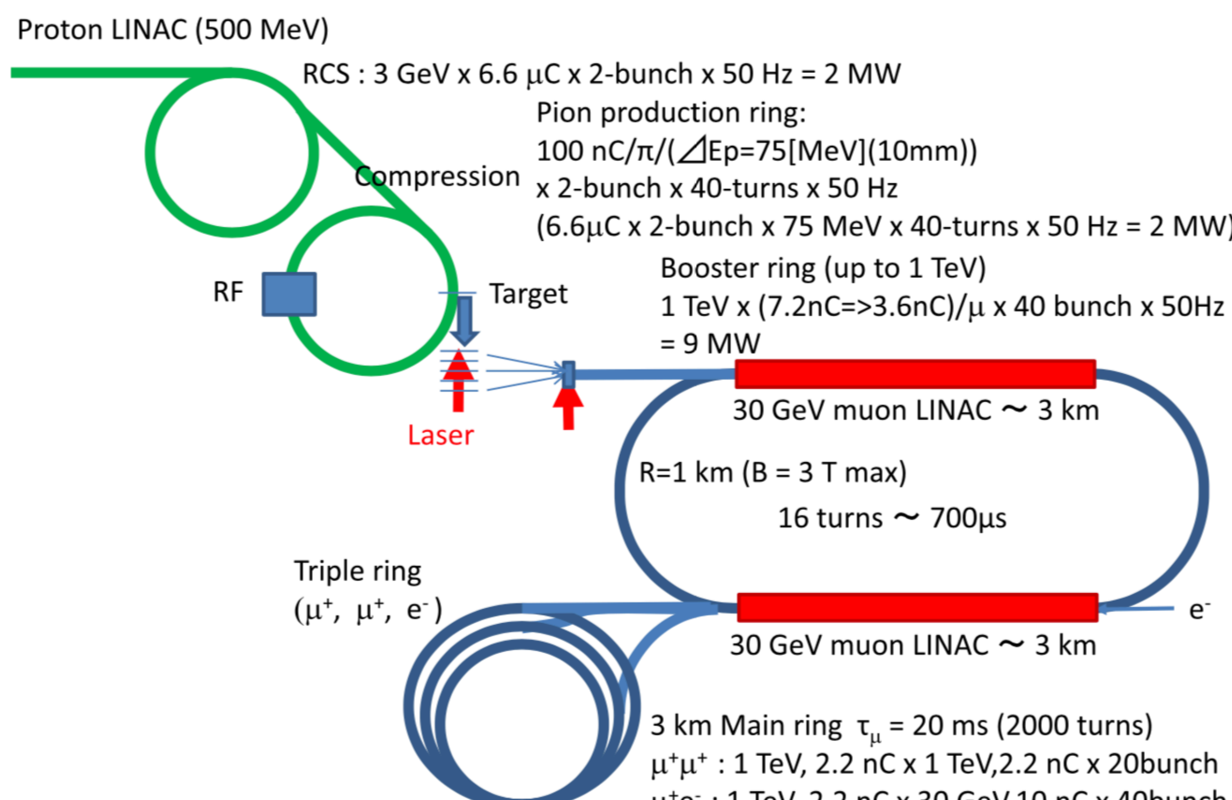


Fig. 1. Conceptual design of the $\mu^+e^-/\mu^+\mu^+$ collider.