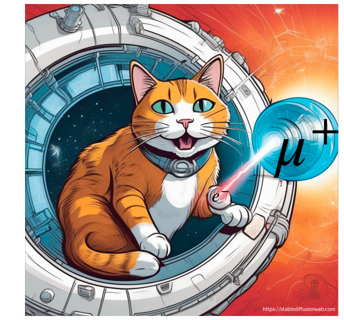


μTRISTAN

Ryuichiro Kitano (KEK)

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

2210.11083, Yu Hamada (KEK -> DESY), 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.)

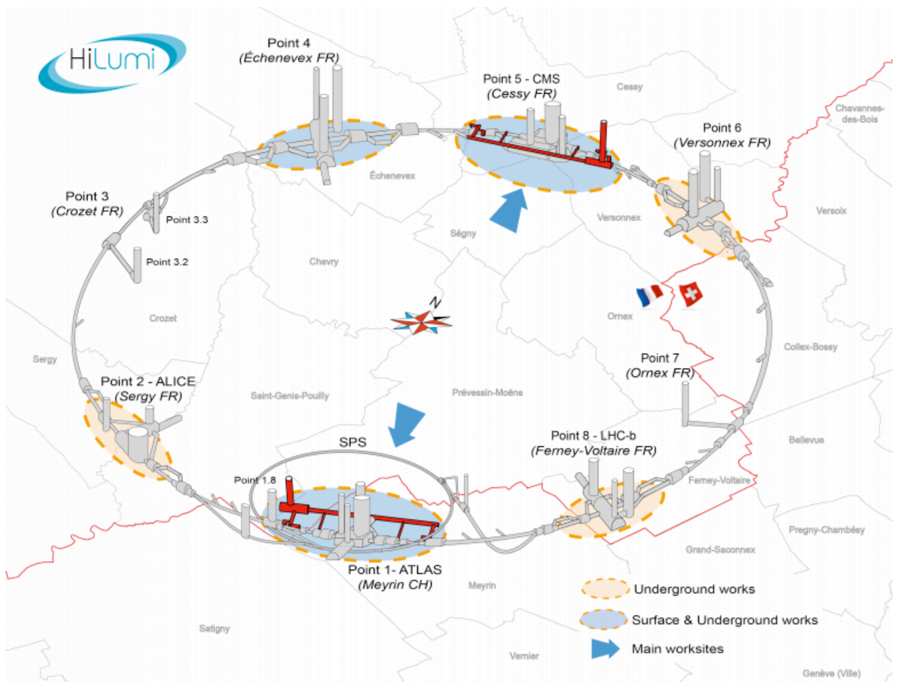
Muons in Minneapolis Workshop@Minneapolis, December 6-8, 2023

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.

Higgs factories

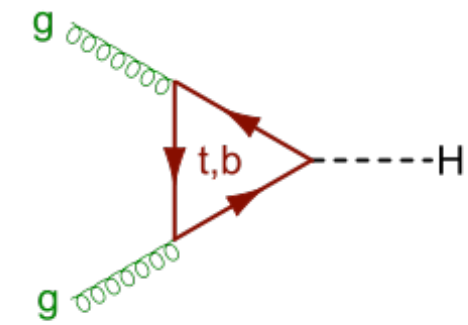


HL-LHC (2029?-)

14TeV pp collider, 3ab^{-1}

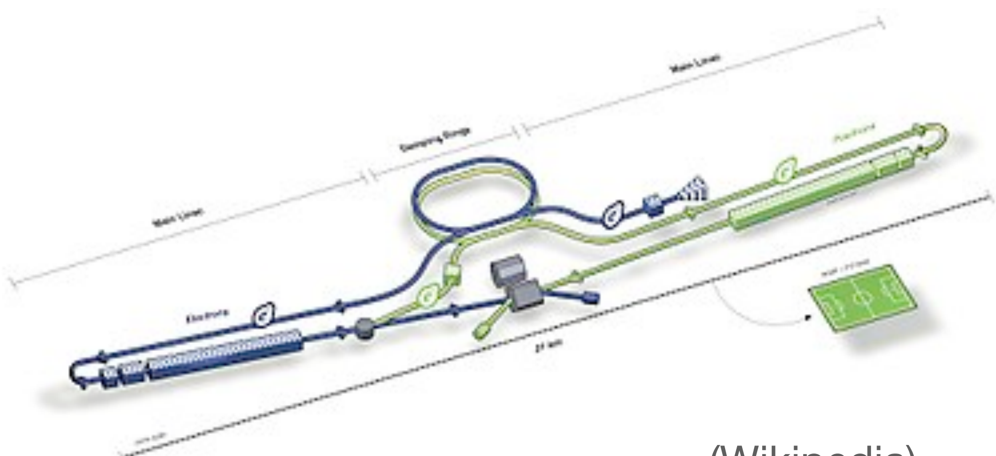
O(100M) Higgs bosons

(Although hard to identify)



Higgs coupling at 1% level.

(LHC measures at a few - 10% level)



(Wikipedia)

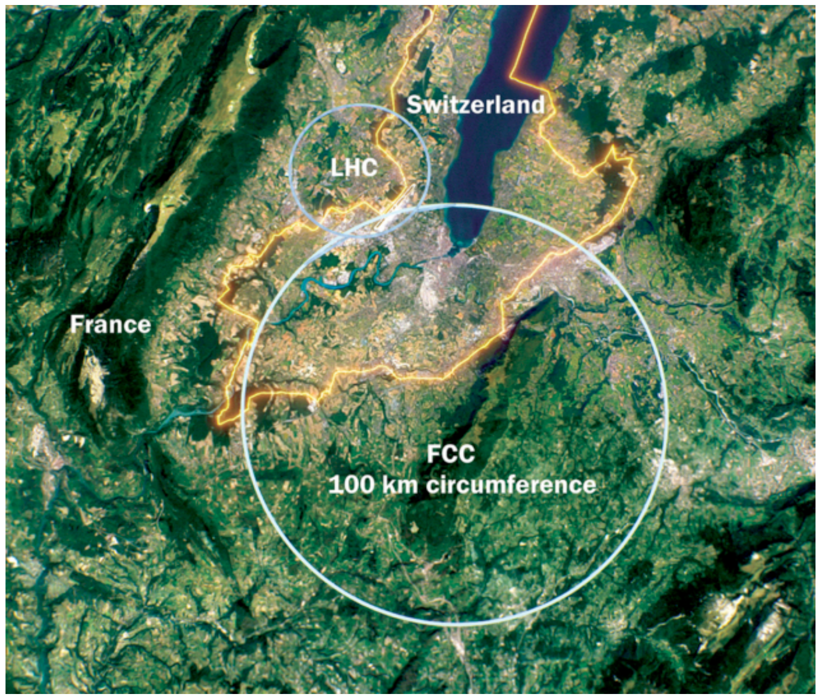
ILC250 (20.5km e^+e^- linear collider) ~ab^{-1}

Extendable to 500GeV, 1TeV

O(1M) Higgs bosons

Measurements of Higgs couplings at the level of 0.1%.

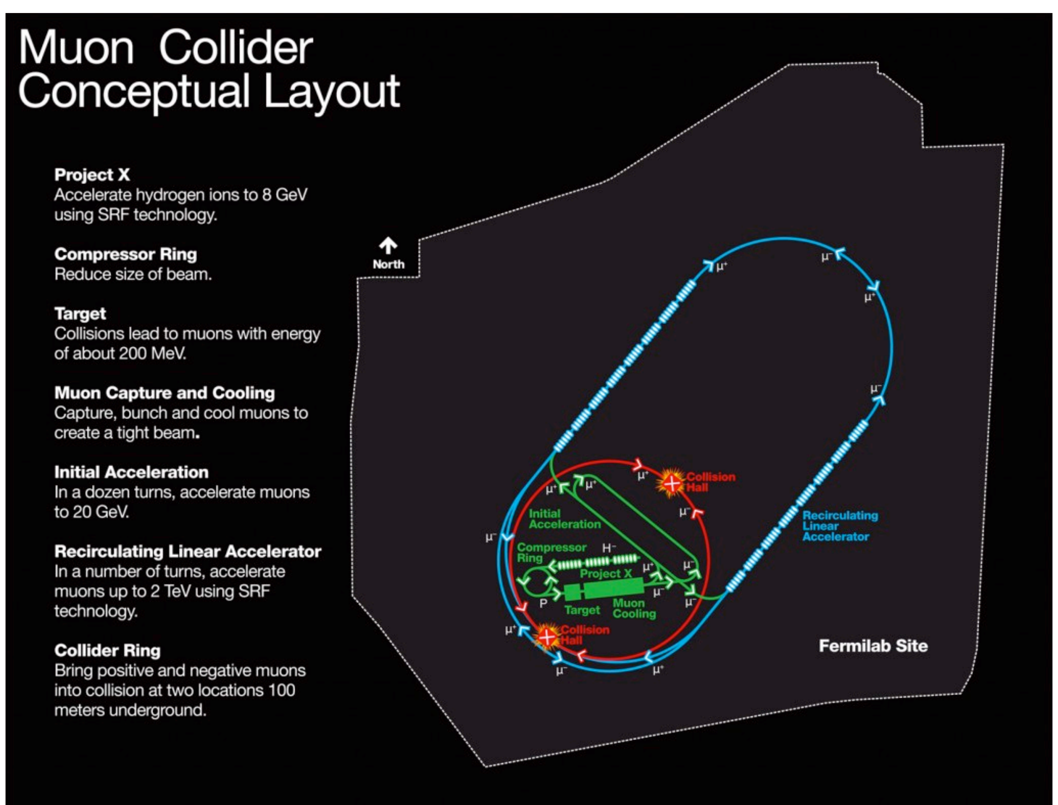
Future colliders?



e^+e^- (90-365GeV) ⟶ pp (100TeV)

Higgs/top factory   New physics searches

O(1M) Higgs



from symmetry

$\mu^+\mu^-$ (10TeV?)

[muon smasher's guide]

10 TeV @ 10 ab^{-1}

Production	Decay	Rate [fb]	$A \cdot \epsilon$ [%]	$\Delta\sigma/\sigma$ [%]
W-fusion	bb	490	7.4	0.17
	cc	24	1.4	1.7
	jj	72	37	0.19
	$\tau^+\tau^-$	53	6.5	0.54
	$WW^*(jj\ell\nu)$	53	21	0.30
	$WW^*(4j)$	86	4.9	0.49
	$ZZ^*(4\ell)$	0.1	6.6	12
	$ZZ^*(jj\ell^+\ell^-)$	2.1	8.9	2.3
	$ZZ^*(4j)$	11	4.6	1.4
	$\gamma\gamma$	1.9	33	1.3
	$Z(jj)\gamma$	0.9	27	2.0
	$\mu^+\mu^-$	0.2	37	0.37
Z-fusion	bb	51	8.1	0.49
	$WW^*(4j)$	8.9	6.2	1.3
W-fusion tth	bb	0.06	12	12

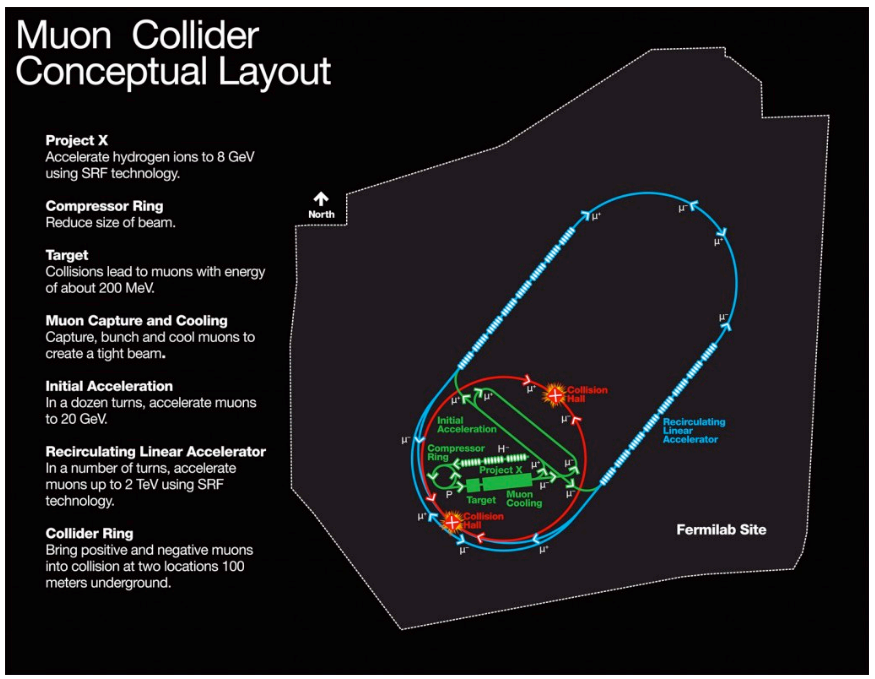
Fantastic!

A lot of Higgs bosons through WW fusion.

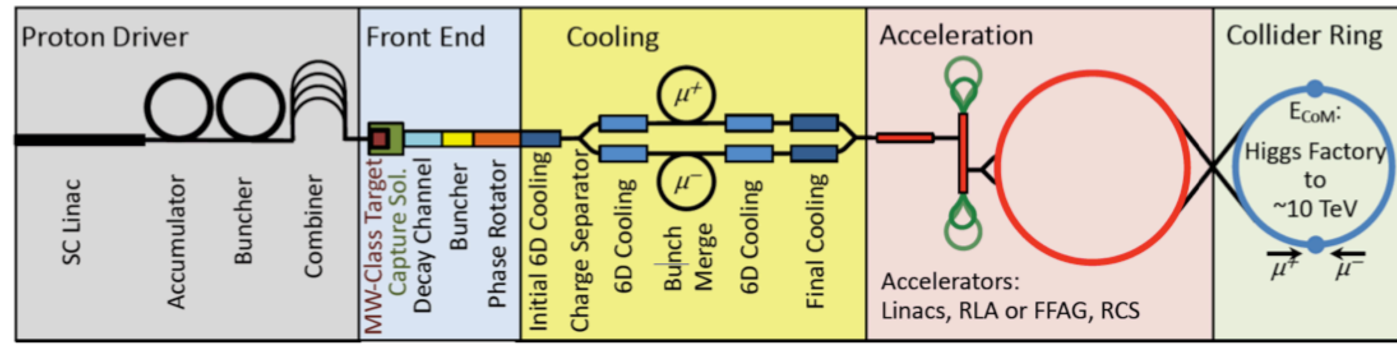
Direct reach to 10TeV physics!

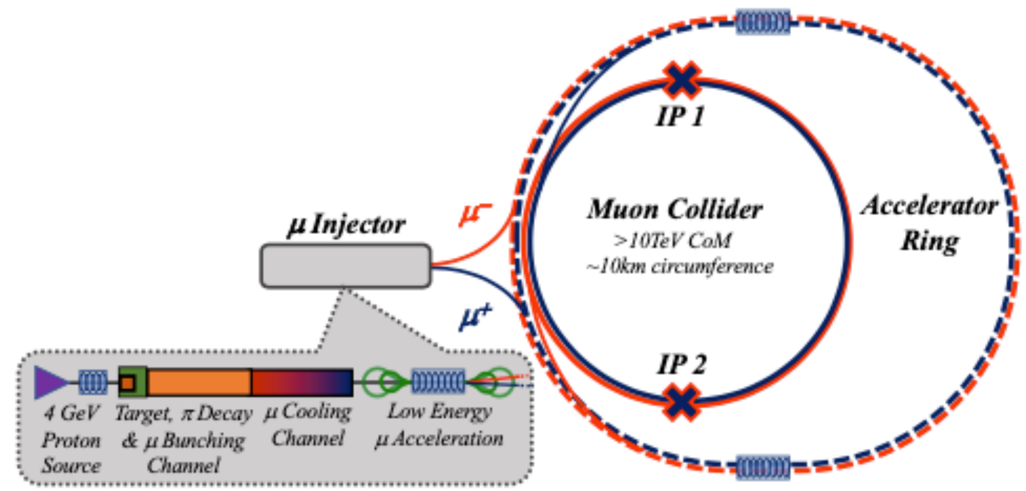
muon collider

this is what we want!

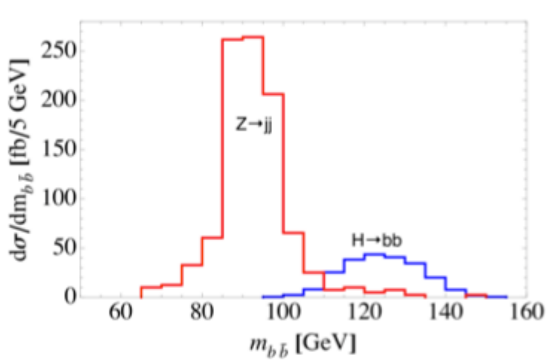


from symmetry





[MAP collaboration]



(a)

[Han, Liu, Low, Wang '20]

10 TeV @ 10 ab^{-1}

Production	Decay	Rate [fb]	$A\cdot\epsilon$ [%]	$\Delta\sigma/\sigma$ [%]
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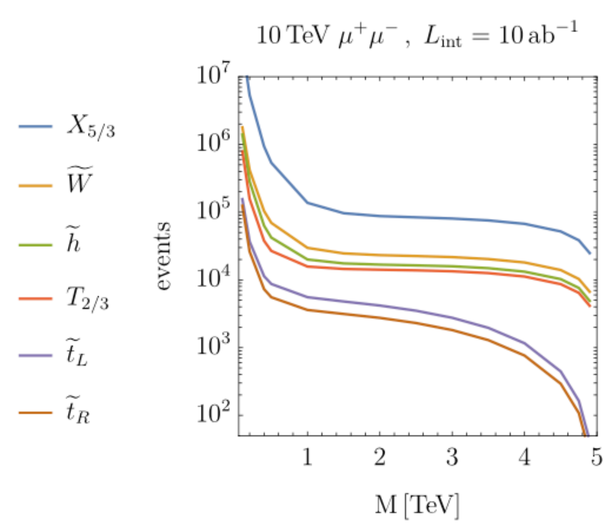
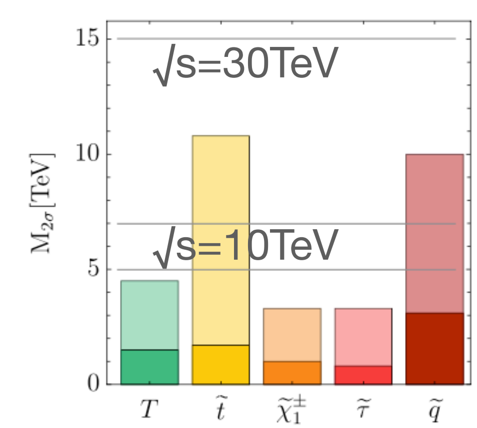
[muon smasher's guide]





[Buttazzo, Franceschini, Wulzer '20]

[Snowmass report '22]

Very nice. Why don't we just do it now!

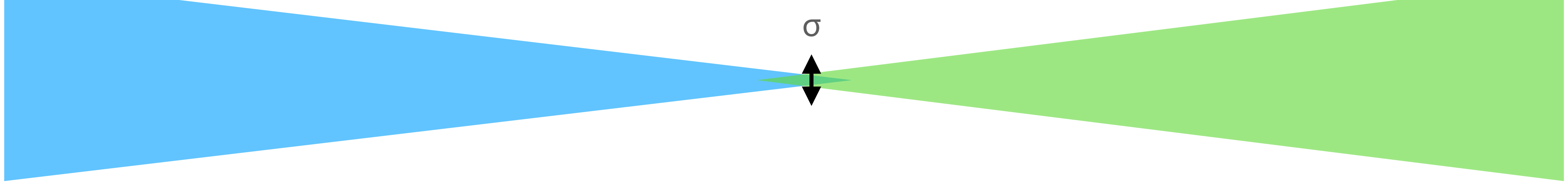
of course, there are technical challenges to realize this collider.

The most challenging part is to obtain enough luminosities.

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

Luminosity

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



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

As a reference,

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

$\sigma=1\mu m$

$f_{\text{rep}}=1MHz$

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

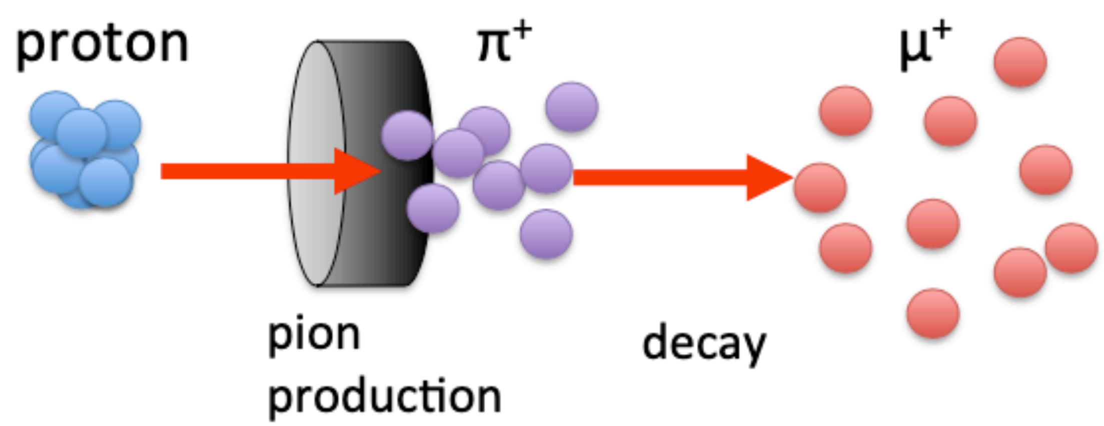
We want ab^{-1} level luminosity for physics (HL-LHC, ILC)

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

Muon beam

Too much spread.

Conventional muon beam



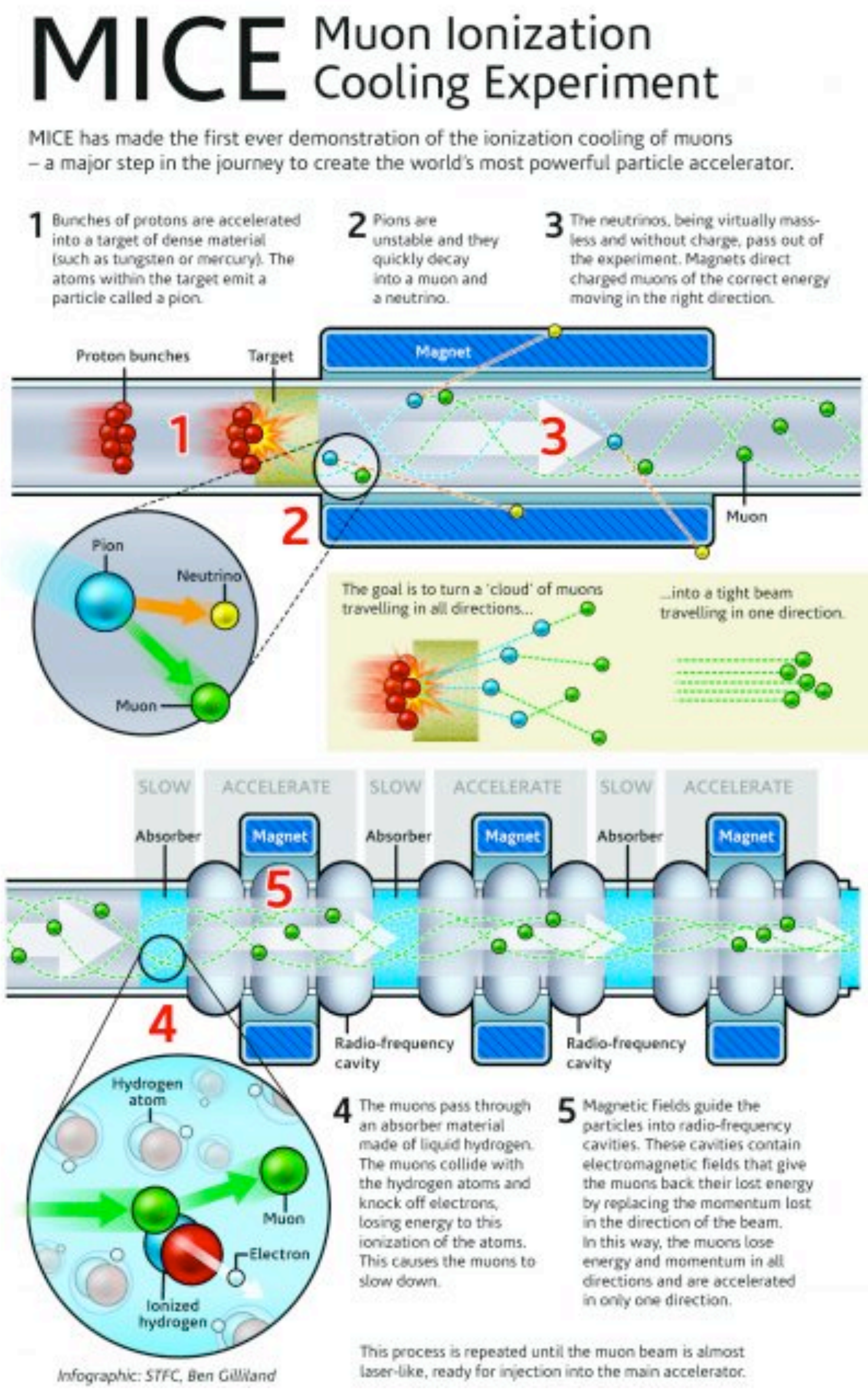
emittance

~1000π mm ·mrad = π mm

Strong focusing
Muon loss
BG π contamination

Taken from Mibe-san's lecture slide

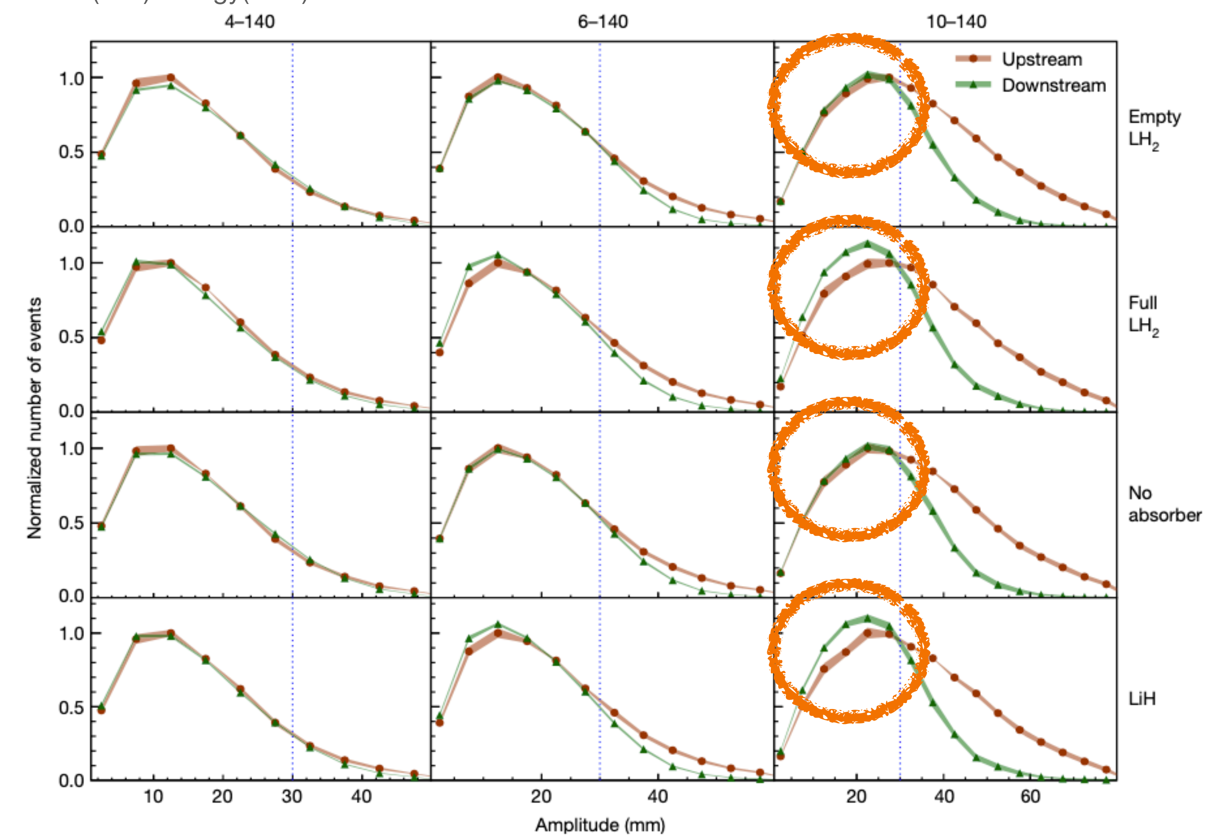
Muon cooling



Principle works.

[Nature 2020, MICE collaboration]

emittance(mm)-energy(MeV)



simulation and plan for muon cooling of the MAP design

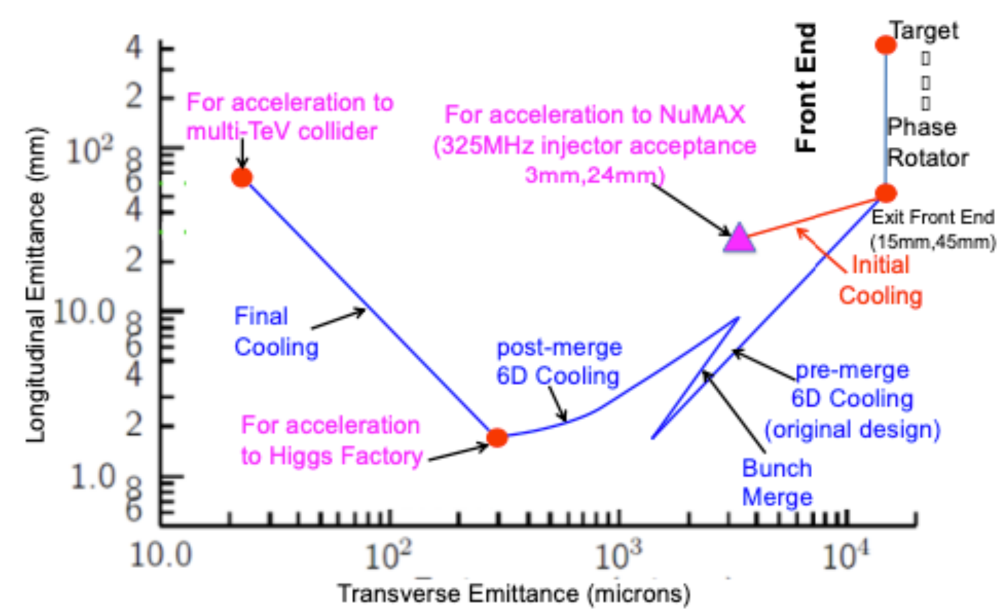
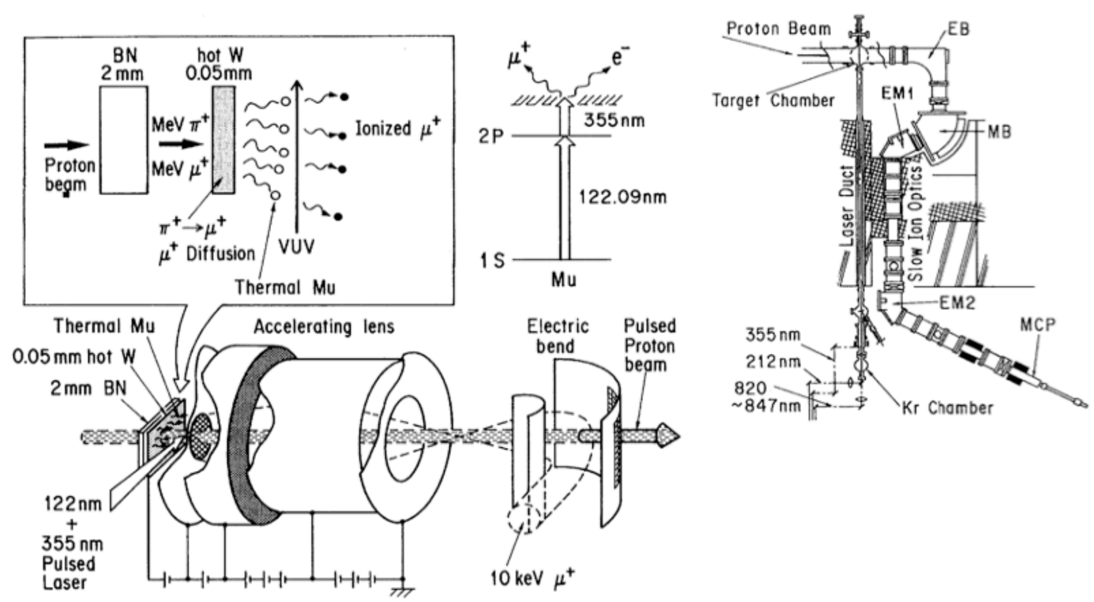


Figure 3. Ionization Cooling path in the 6D phase space.

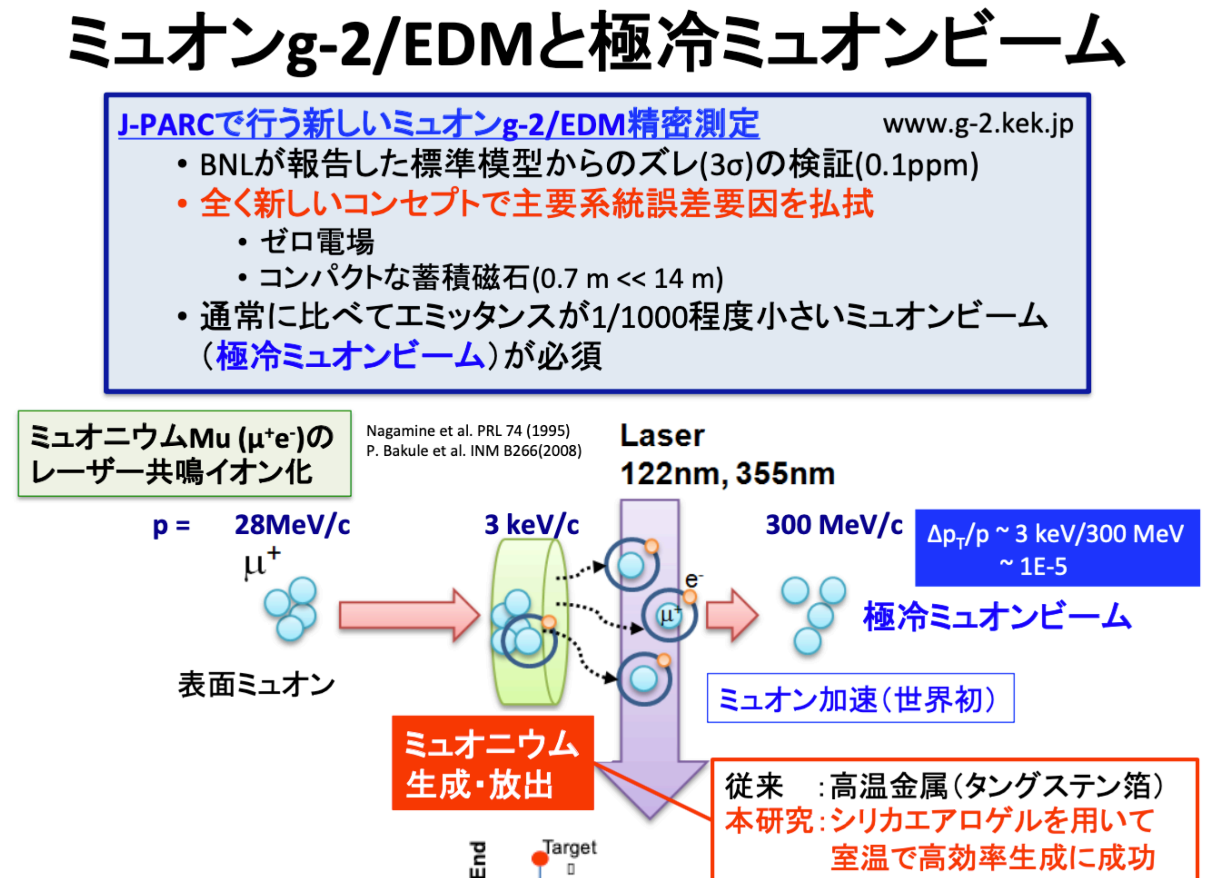
Muon cooling which works for μ+

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

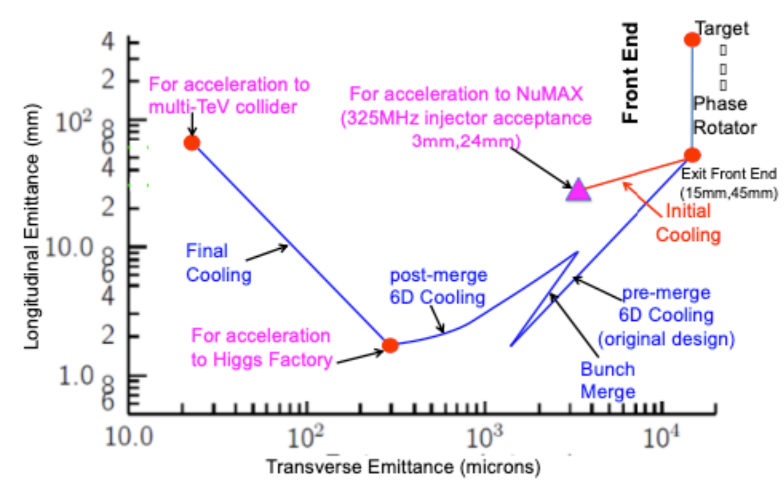
Ultracold muon technology [K.Nagamine et al. 1995]



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



Mibe-san's slide



ultra-cold muon is here. ●

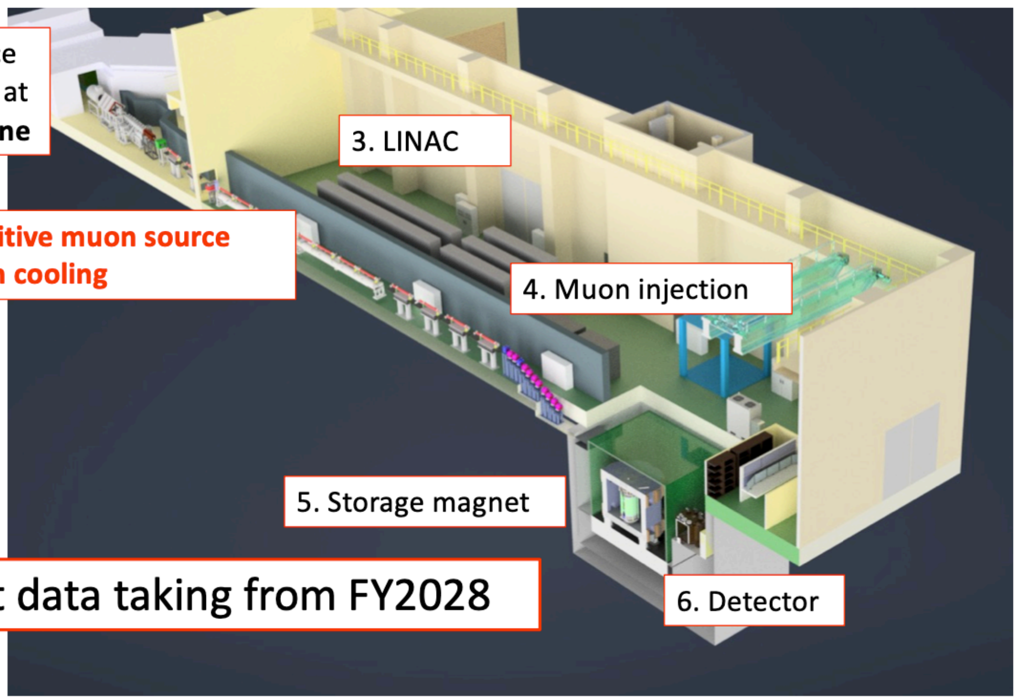
Figure 3. Ionization Cooling path in the 6D phase space.

Looks like there is a good chance of realizing a low-emittance μ+ beam!

g-2/EDM experiment @ KEK J-PARC

Muon g-2/EDM experiment at J-PARC

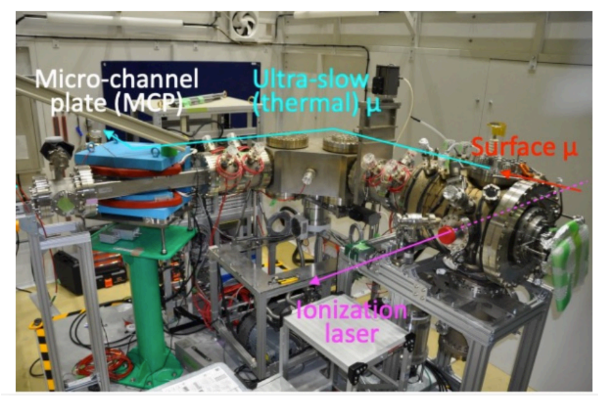
A new muon g-2/EDM measurement featuring a low emittance μ^+ beam



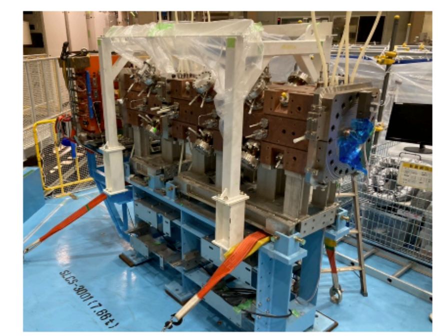
Demonstration @ MLF S-line

- Collaborating with Muonium 1S-2S spectroscopy experiment.
  - **A 244-nm pulsed laser developed by Okayama univ.**
- Q-scan measurement is underway to evaluate the initial phase space.
- RFQ acceleration of cooled muon will be performed after in 2024.

MCP for counting event rate & Beam profile monitor to measure USM beam size after extraction



World 1st acceleration of USM will be performed soon



RFQ @ MLF

21

S. Kamioka (talk@muon acceleration workshop, Nov. 2, 2023)

Yes, it has already been cooled and to be accelerated soon!!

(Actually, the acceleration of the $\mu^+e^-e^-$ bound state has already been demonstrated!!)

μTRISTAN

μ+e-/μ+μ+ collider with 1TeV μ+ beam.

PTEP

Prog. Theor. Exp. Phys. **2022** 053B02(16 pages)
DOI: 10.1093/ptep/ptac059

μTRISTAN

Yu Hamada[1], Ryuichiro Kitano[1,2], Ryutaro Matsudo[1], Hiromasa Takaura[1,*], and Mitsuhiro Yoshida[2,3]

[1] *KEK Theory Center, Tsukuba 305-0801, Japan*
[2] *Graduate University for Advanced Studies (Sokendai), Tsukuba 305-0801, Japan*
[3] *KEK Accelerator Department, Tsukuba 305-0801, Japan*
*E-mail: takaura.phys@gmail.com

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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

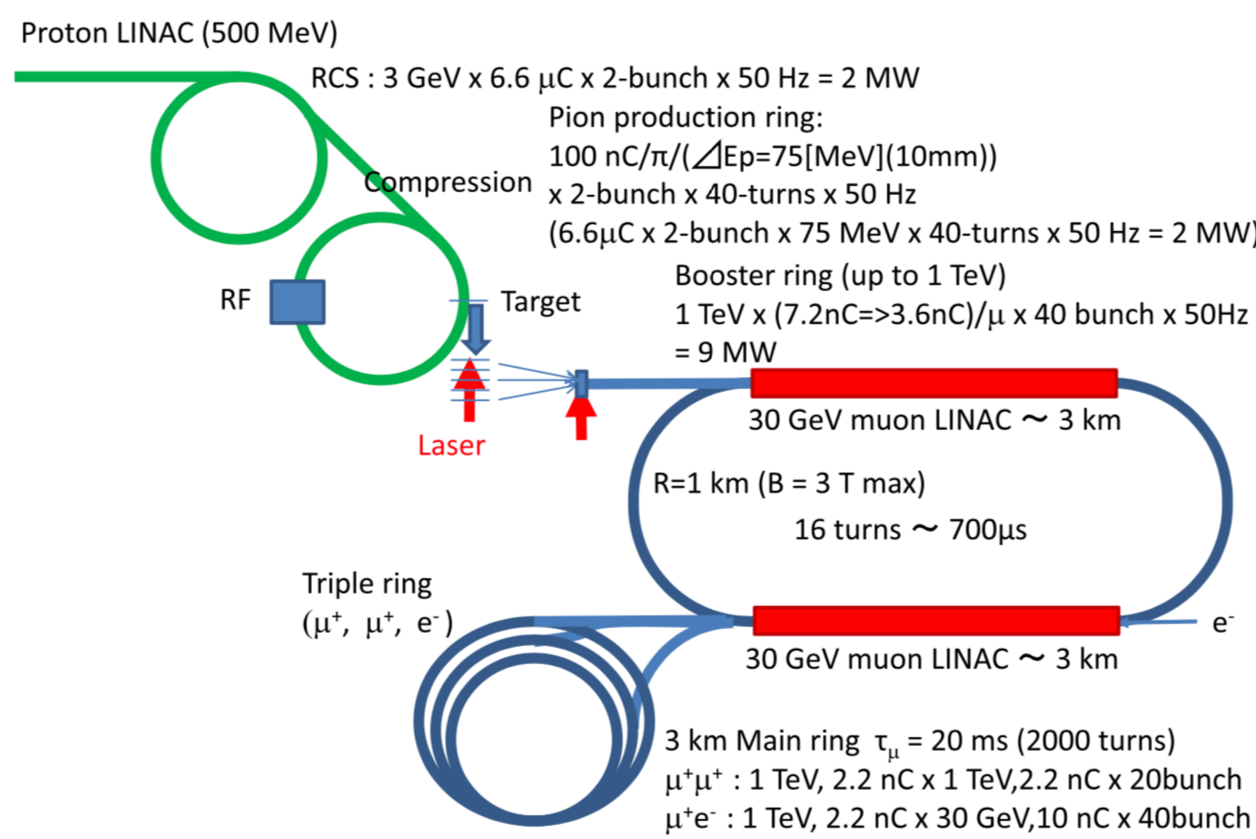


Fig. 1. Conceptual design of the $\mu^+e^-/\mu^+\mu^+$ collider.

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

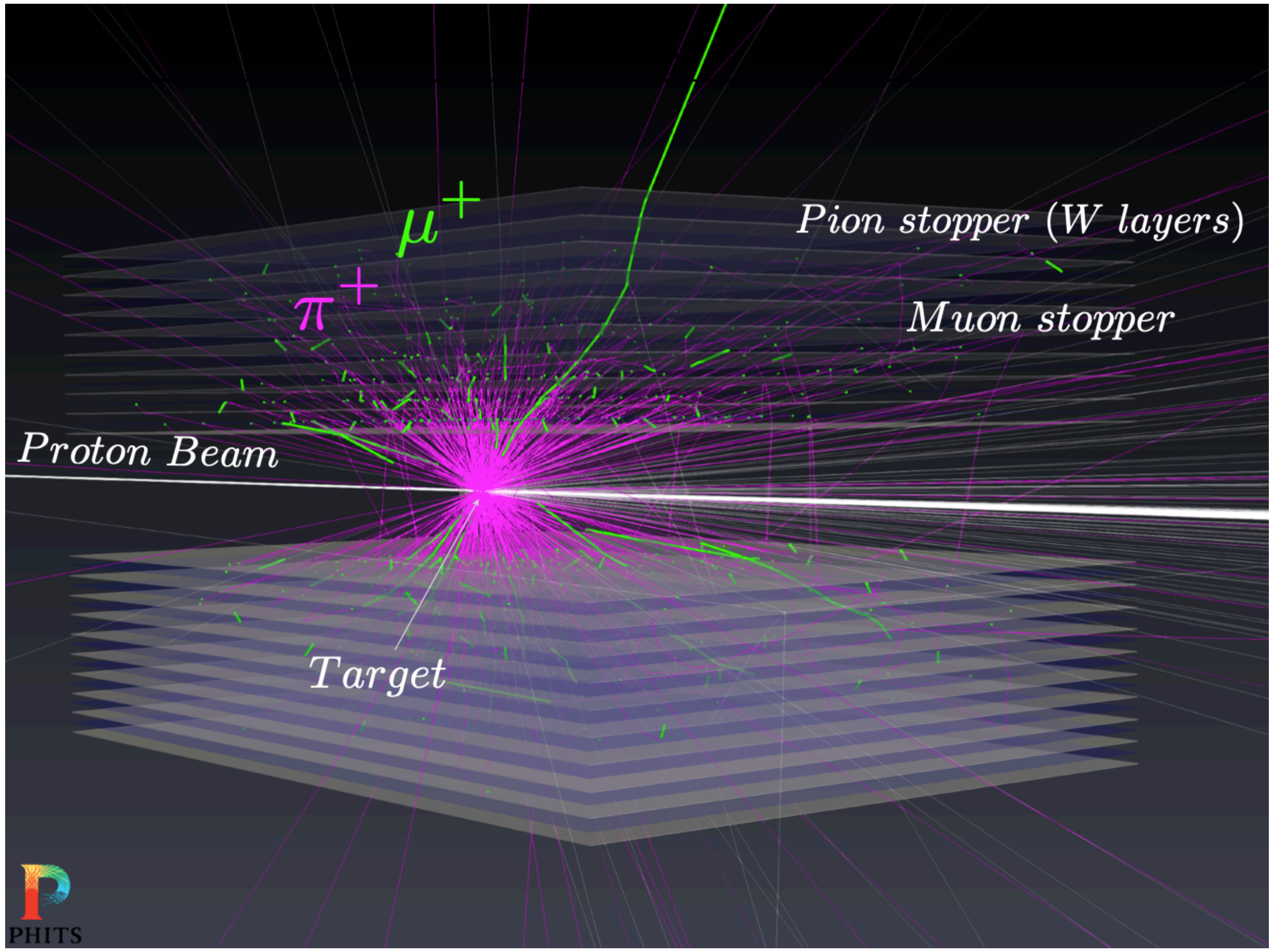
pion production target: 40 hits/bunch 0.016 π^+/proton 2.6 x 10^{15} π^+/s

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

10^5 larger than J-PARC MLF.

Super muon factory!

simulation: (Yoshida, Sakaki … in progress)



(Thermal muon production rate)

= (Muon stopping number on the layers)

× (MC correction for pion production)

× (Muonium formation)

× (Vacuum yield)

× (Loss of muoniums due to the decay)

PTEP 2022 (2022) 5, 053B02

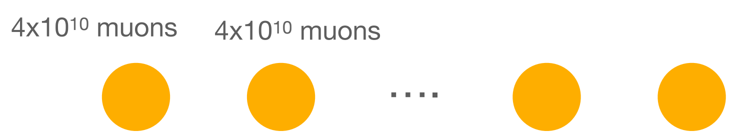
= 1.4 * 10^{-3} μ/p

→ **2.4 * 10^{14} μ/s** (J-PARC RCS: 6.6 μC, 2bunch 40 turns)

O(10^{13} μ/s) will be available for collider experiment

Luminosity?

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.

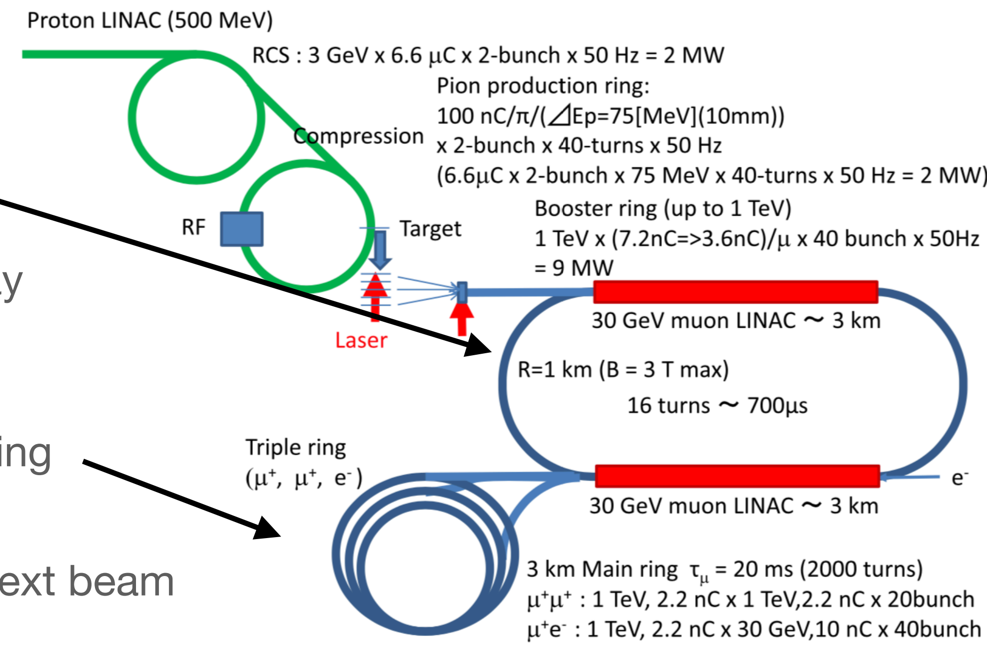


Fig. 1. Conceptual design of the $\mu^+e^-/\mu^+\mu^+$ collider.

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

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

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

not bad.

Actually, these numbers are pretty much conservative ones compared to MAP estimates.

Luminosity comparison

	MAP	μTRISTAN($\mu^+\mu^+$)
normalized emittance	25π mm mrad	0.1-1π mm mrad
bunch length	1 cm	0.01-0.1 cm
efficiency	0.1	0.01 - 0.07
total luminosity (arb. unit)	1	2.5 - 10000

(eff)^2 / (emittance * bunch length)

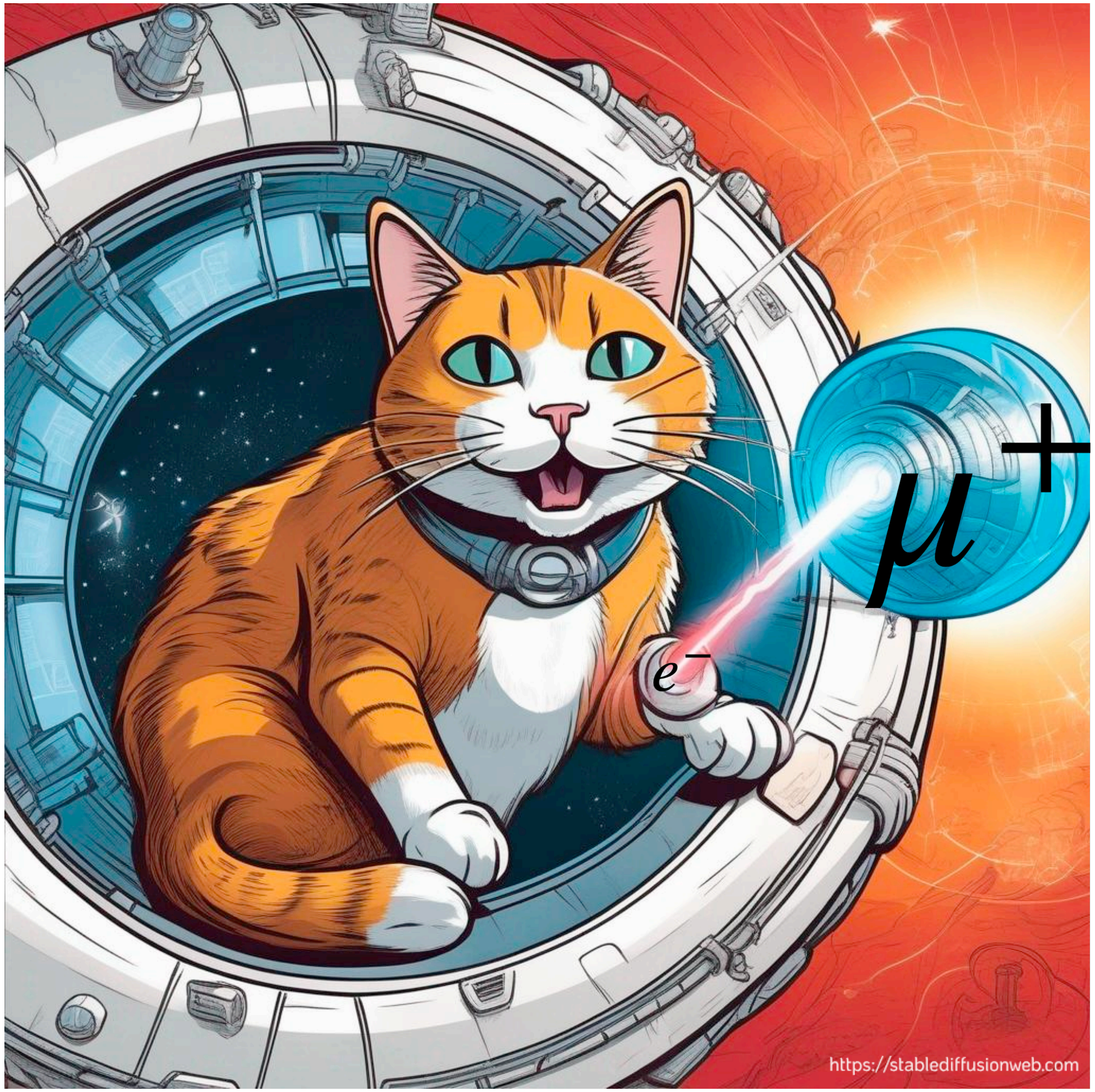
(could be much better for μ^+e^-)

Number of muons may be smaller, but

we see that if we only use μ^+, we can have (much) better luminosities.

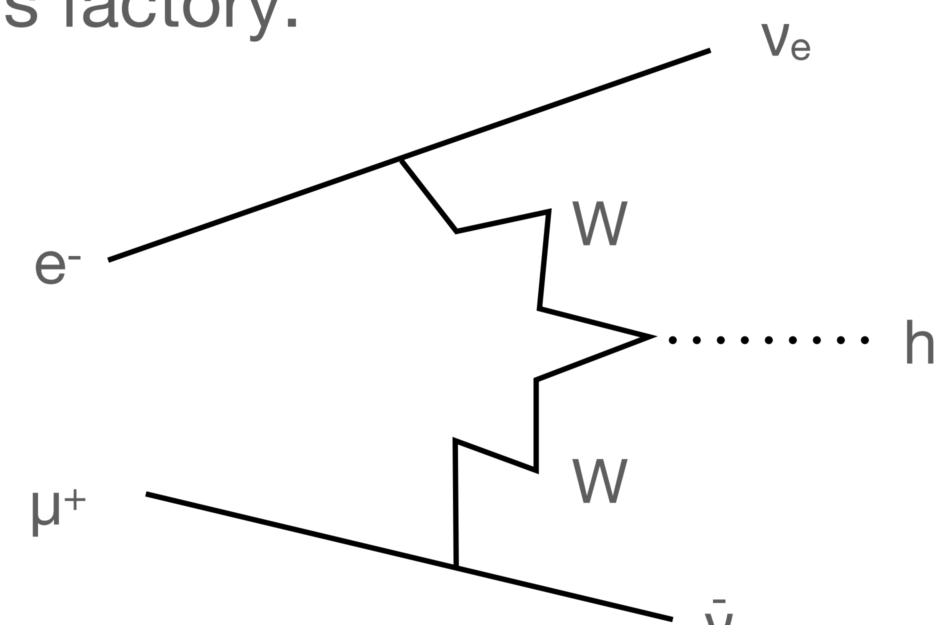
And, the technology is more matured! Express ticket for muon colliders?

mewTRISTAN



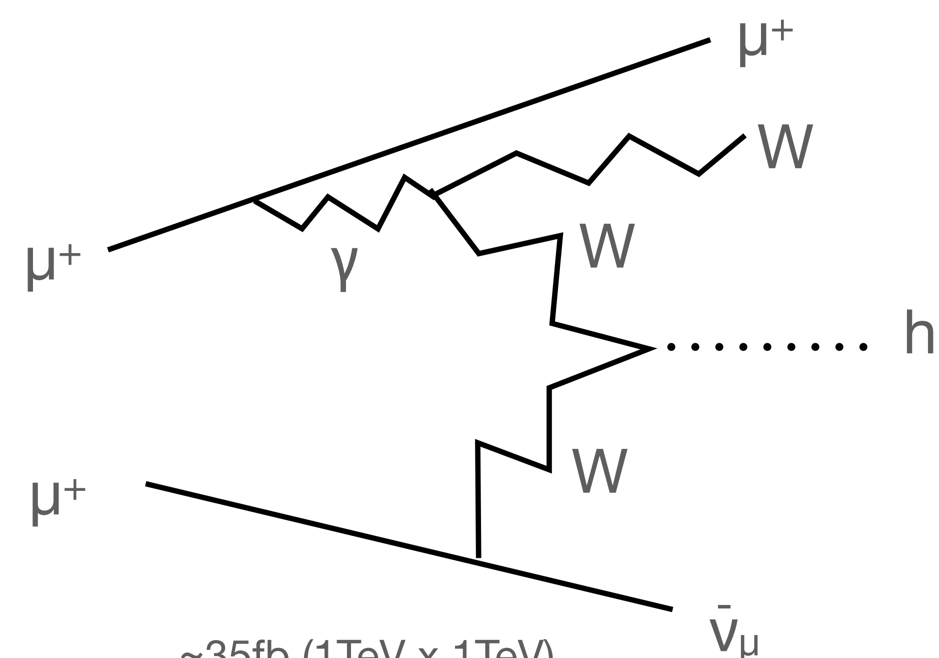
What can we do at μTRISTAN?

Higgs factory:



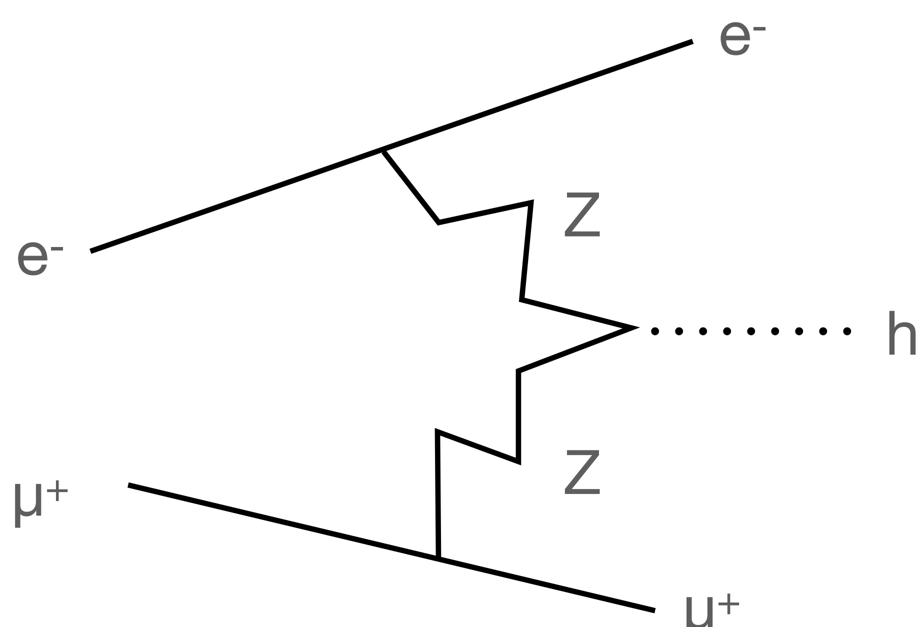
~90fb (30GeV x 1TeV)

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



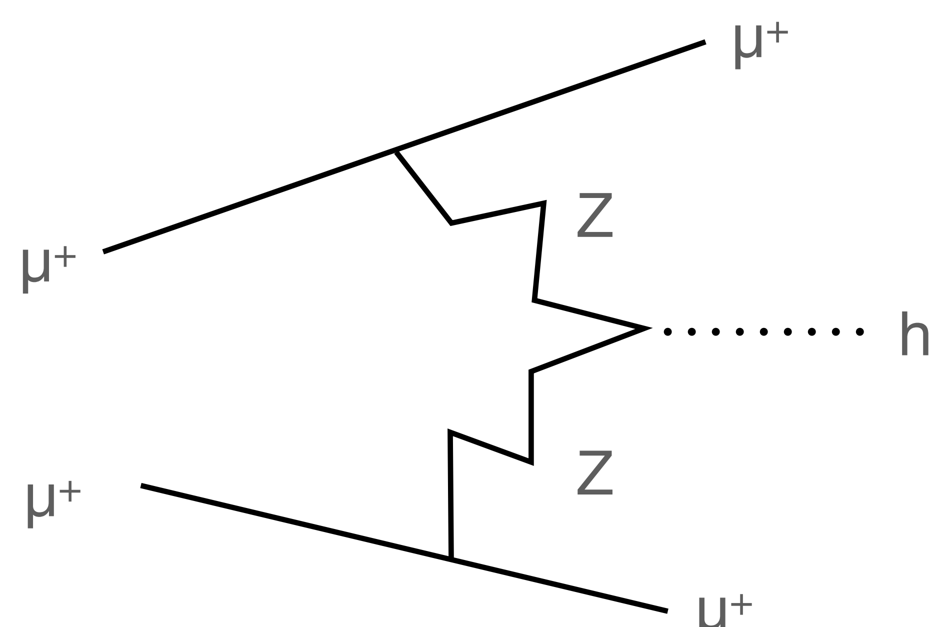
~35fb (1TeV x 1TeV)

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



~4fb (30GeV x 1TeV)

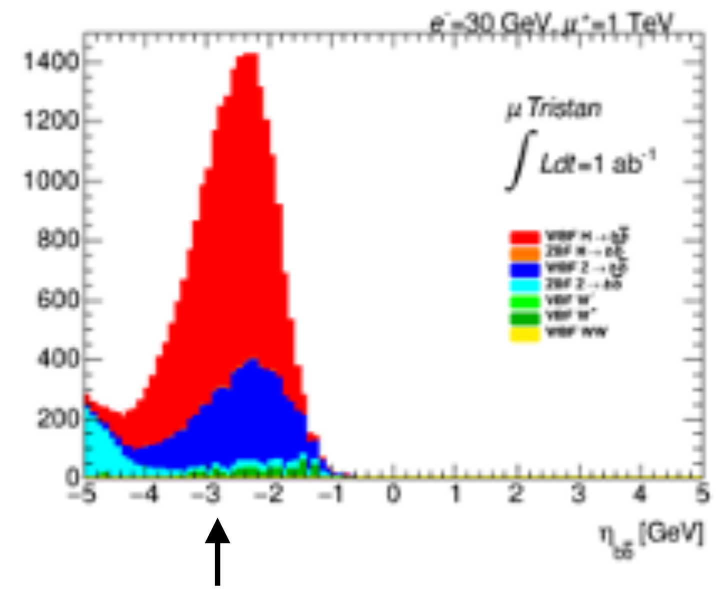
~10^3 Higgs bosons ($1ab^{-1}$)



~54fb (1TeV x 1TeV)

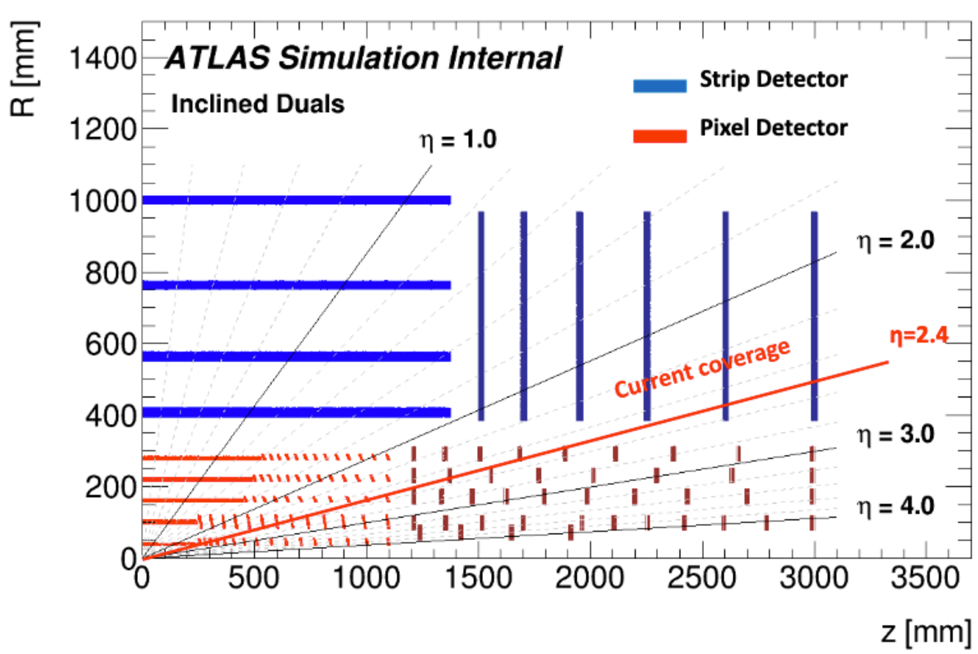
~10^{4-5} Higgs bosons ($1ab^{-1}$)

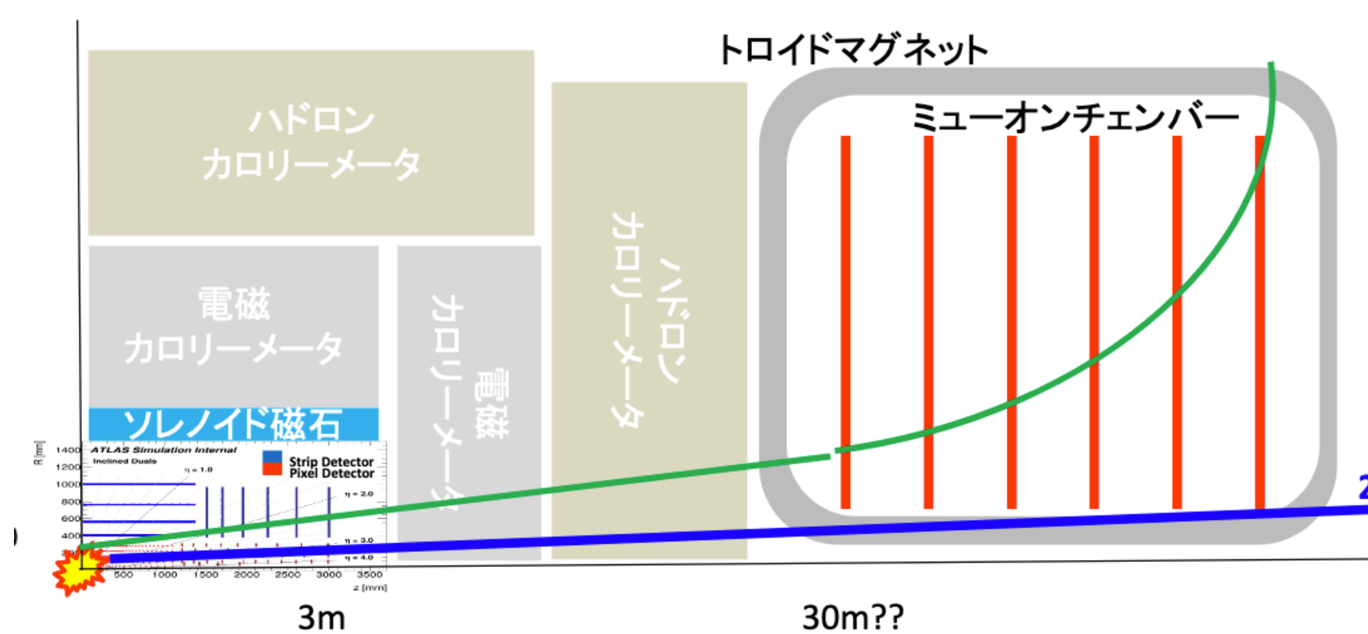
μ^+e^-: Very asymmetric



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.

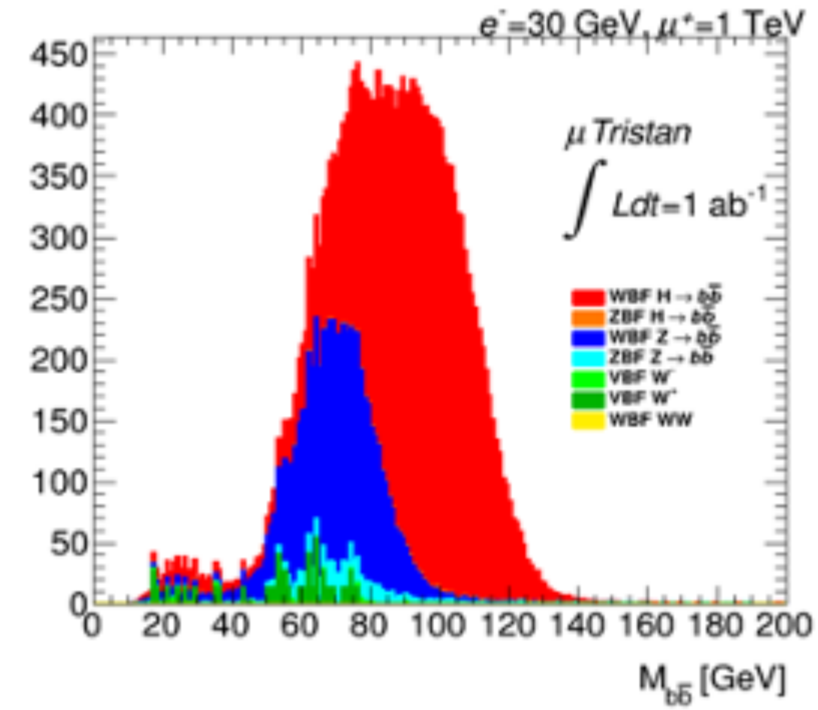




Higgs coupling

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

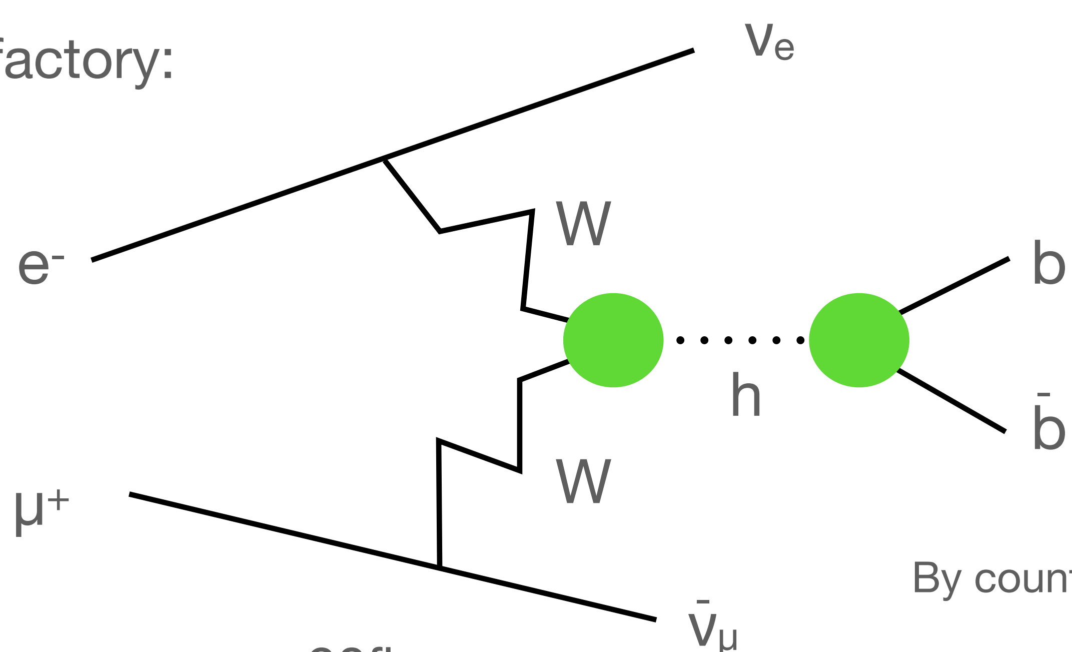
simulation with the ATLAS detector for HL-LHC



acceptance ~ 23%

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

Higgs factory:



~90fb

~10^5 Higgs bosons

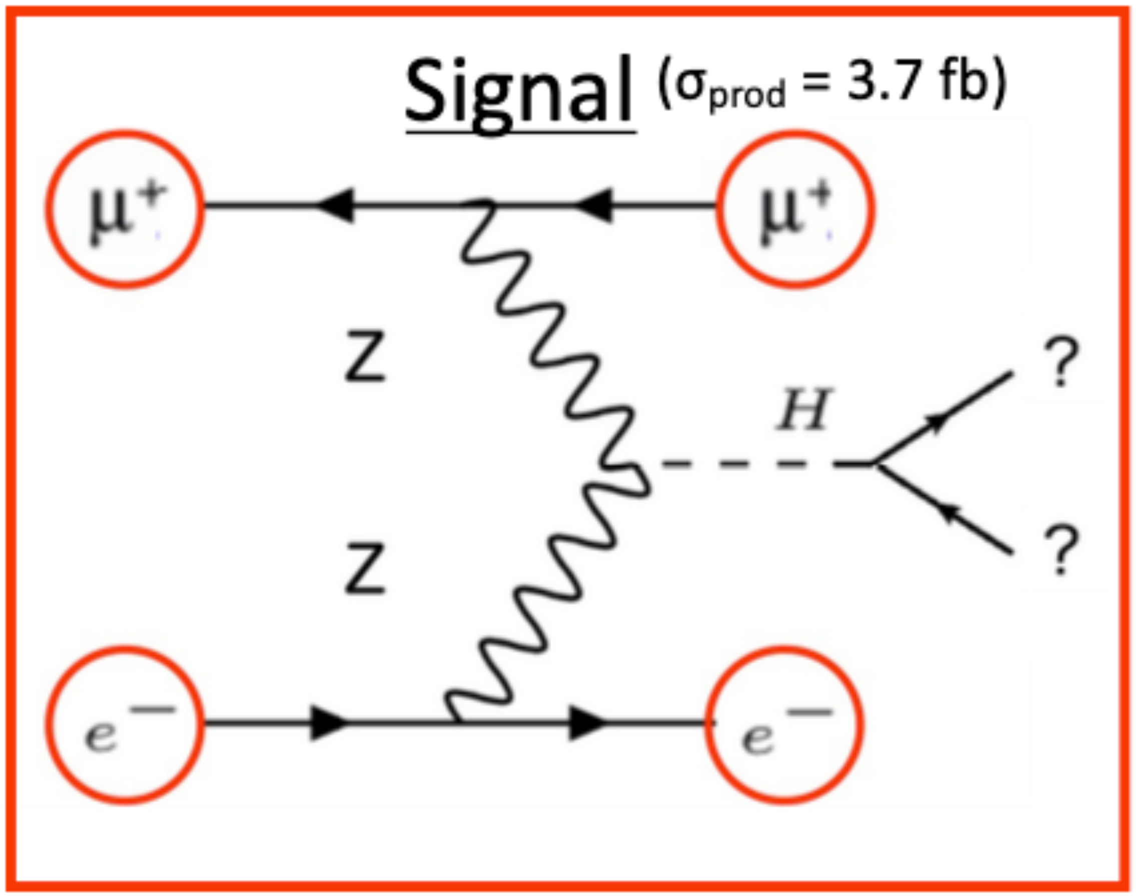
By counting the number of events and compare with the SM prediction

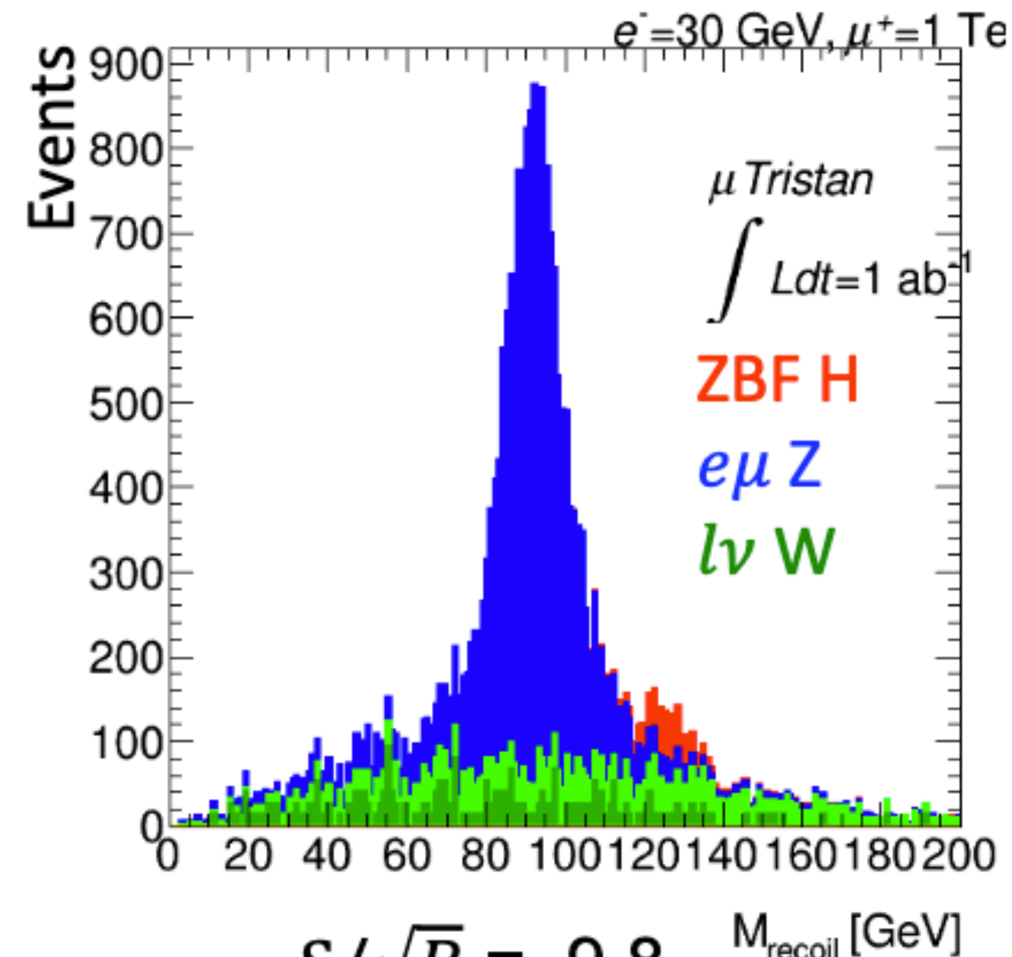
$$\Delta(\kappa_W + \kappa_b - \kappa_H)_{\rm stat} = \frac{1}{2}\frac{1}{\sqrt{N({\rm WBF}) \times {\rm Br}(h \to b\bar{b}) \times {\rm efficiency}}}$$

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

sub percent level measurements.

Z boson fusion recoil mass





$S/\sqrt{B}$ = 9.8

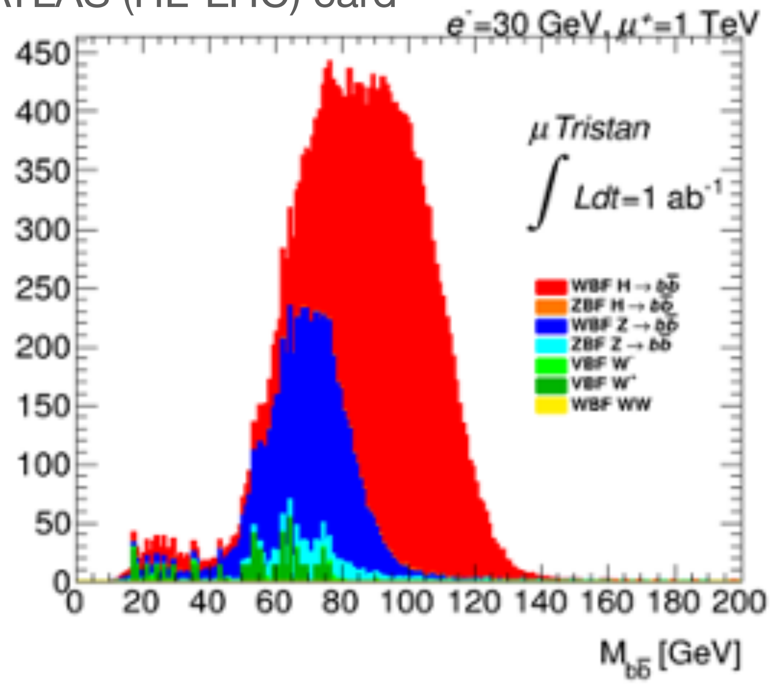
→ 1k events @ 1 ab^{-1}

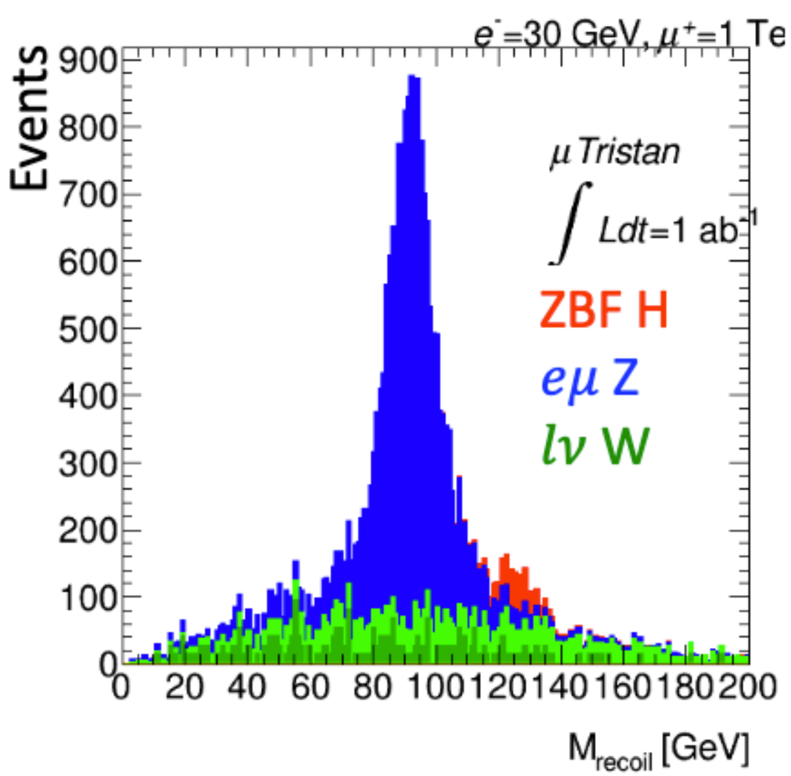
Total width may be measured.

[K. Nakamura, S. Kita, T. Kaji, K. Yorita]

Detector matters

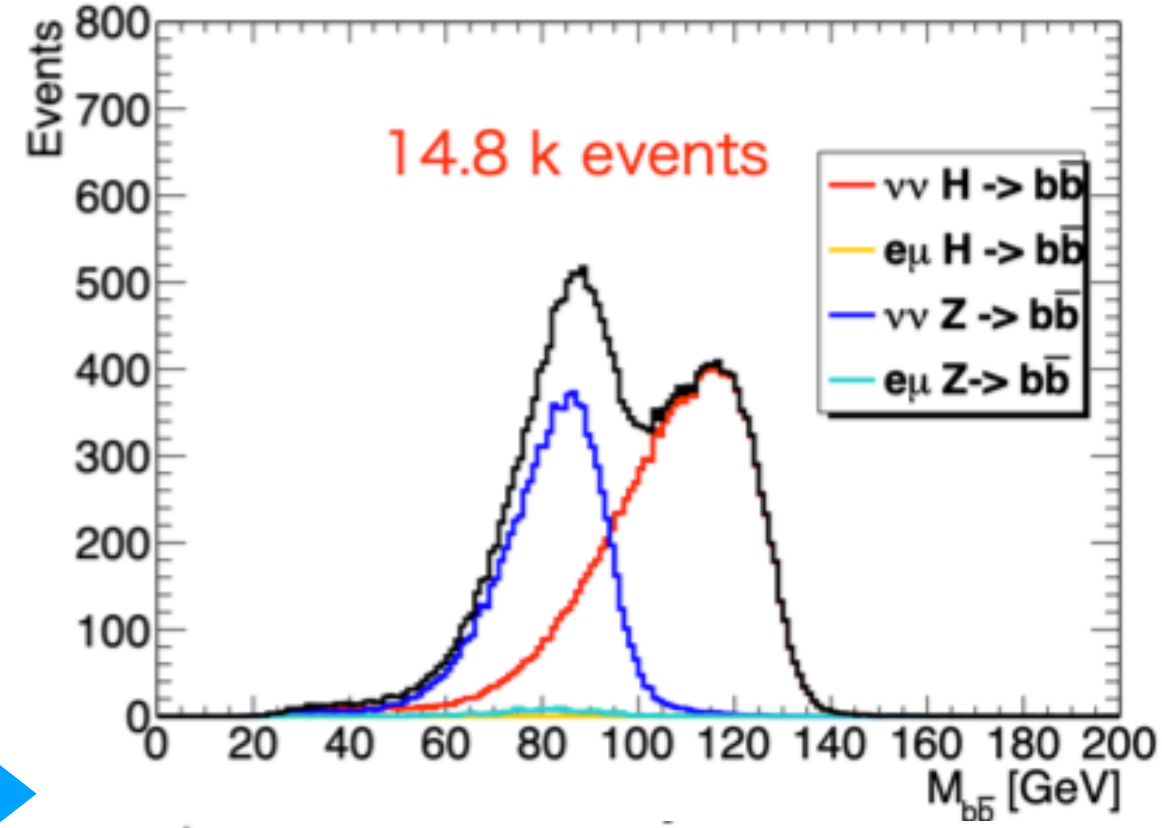
Delphes
ATLAS (HL-LHC) card

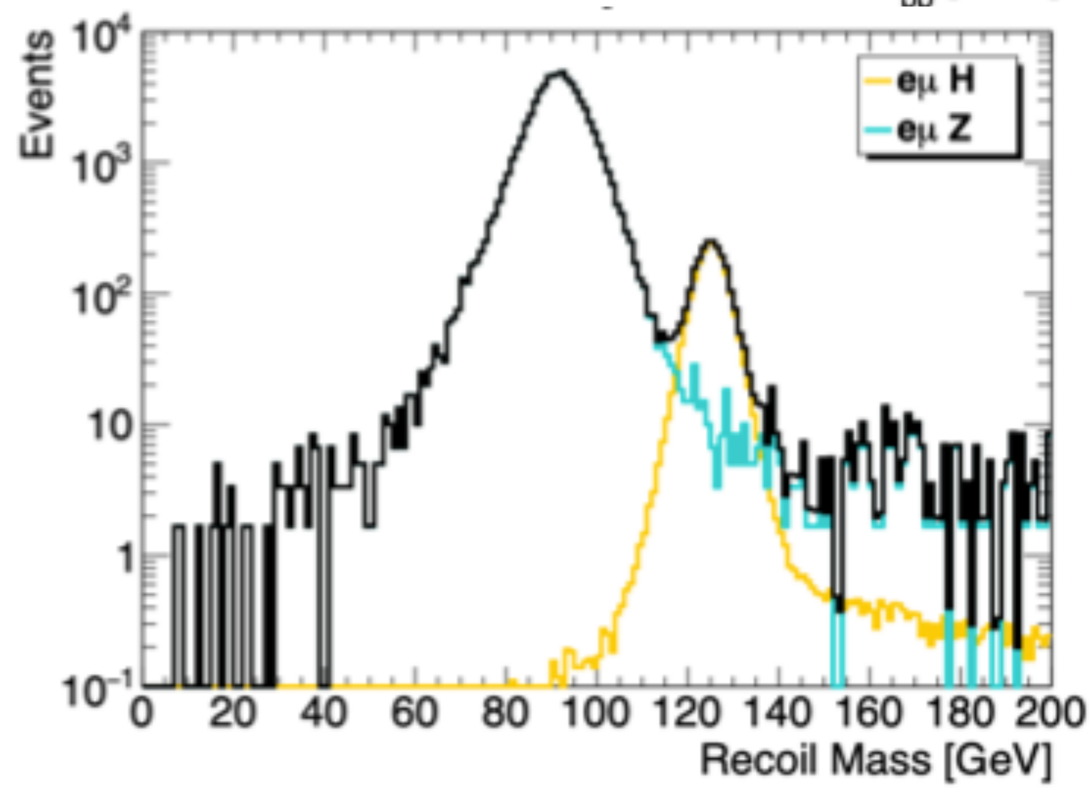




Delphes
ATLAS (LHC) card with a larger forward coverage

Much better!

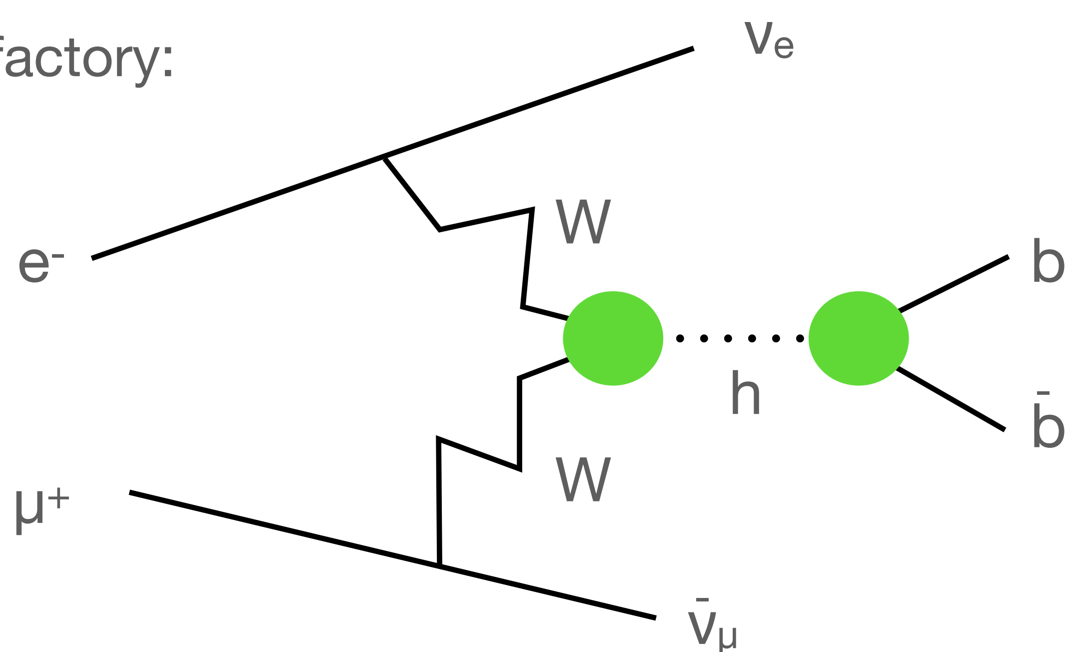




Studies underway.

Higher energy? μTevatron?

Higgs factory:



~472fb (50GeV x 3TeV)

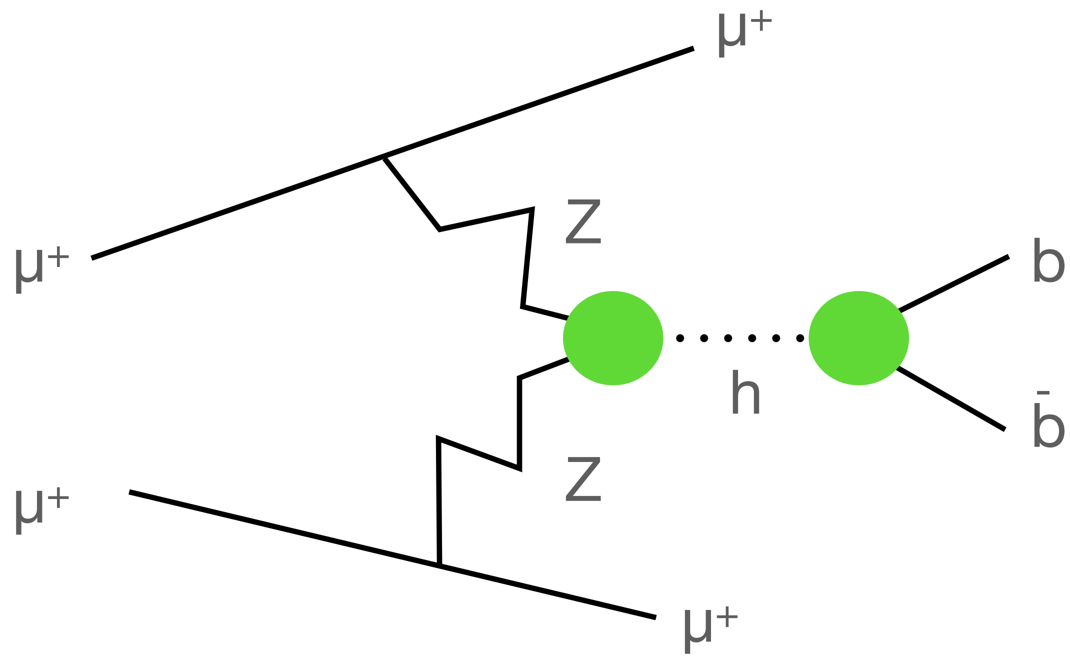
~5x10^5 Higgs bosons (ab^{-1})

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

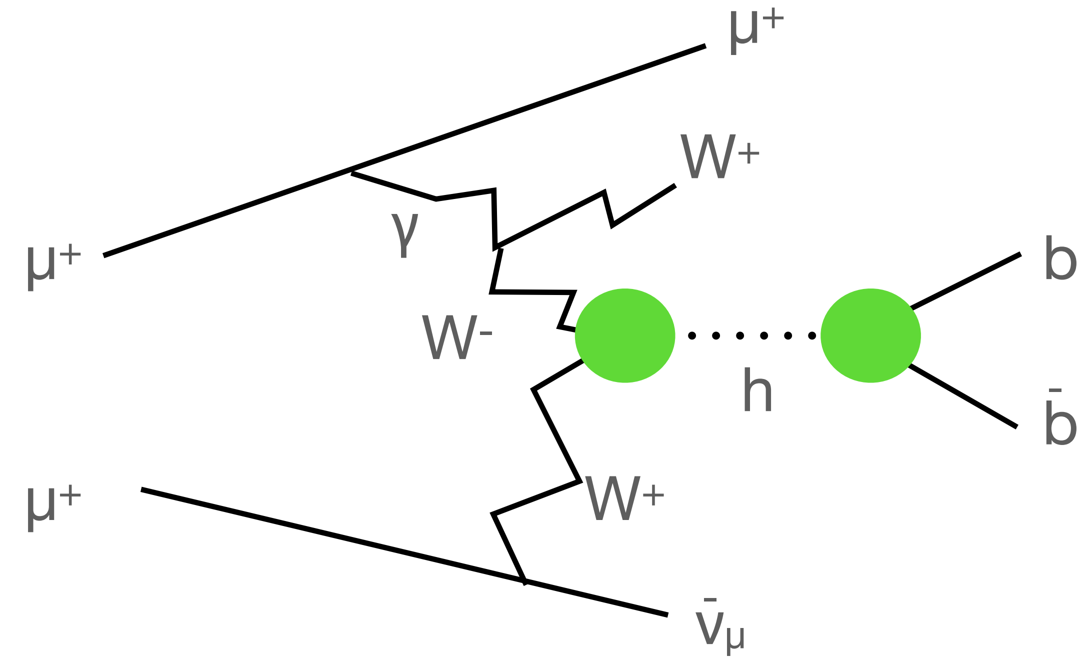
$\sqrt{s}$ = 775 GeV

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

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



~54fb@2TeV final state all visible

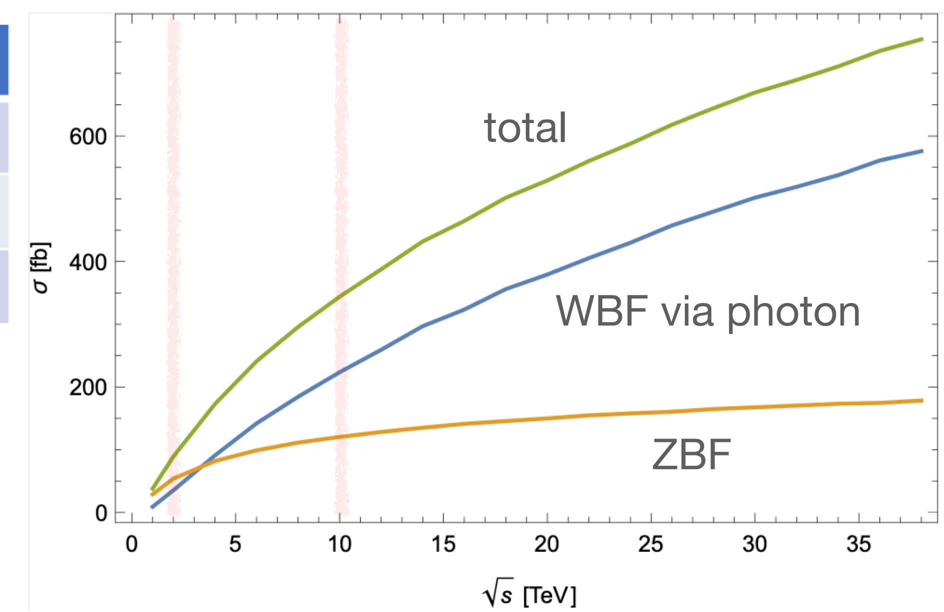


~35fb@2TeV

gets more important at high energy

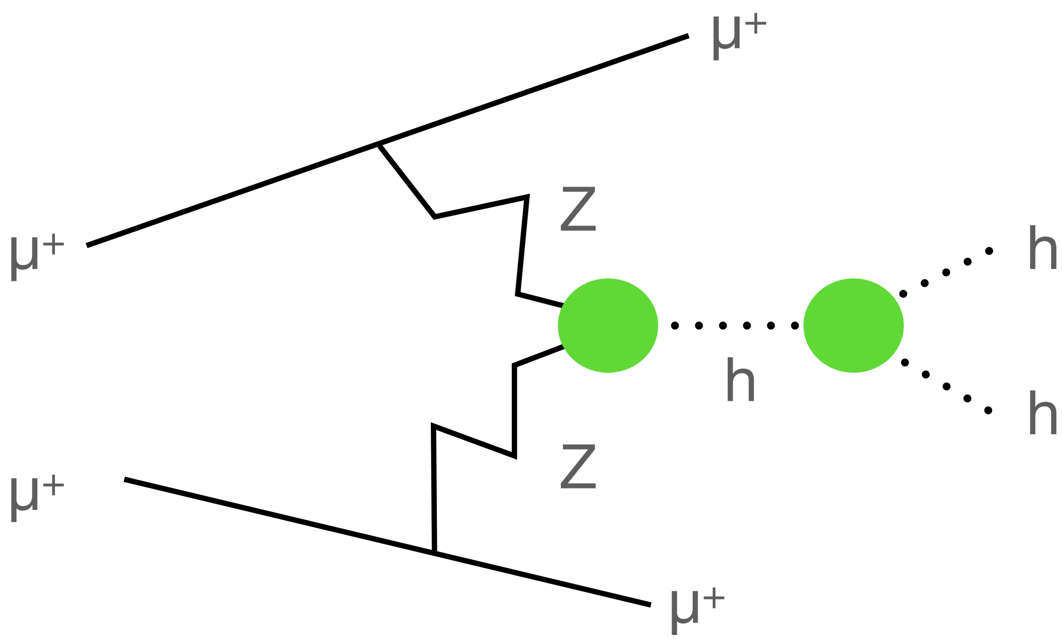
$\sqrt{s}$ [TeV]	ZBF [fb]	Photon emission [fb]
2	54	35
10	121	224
20	150	376

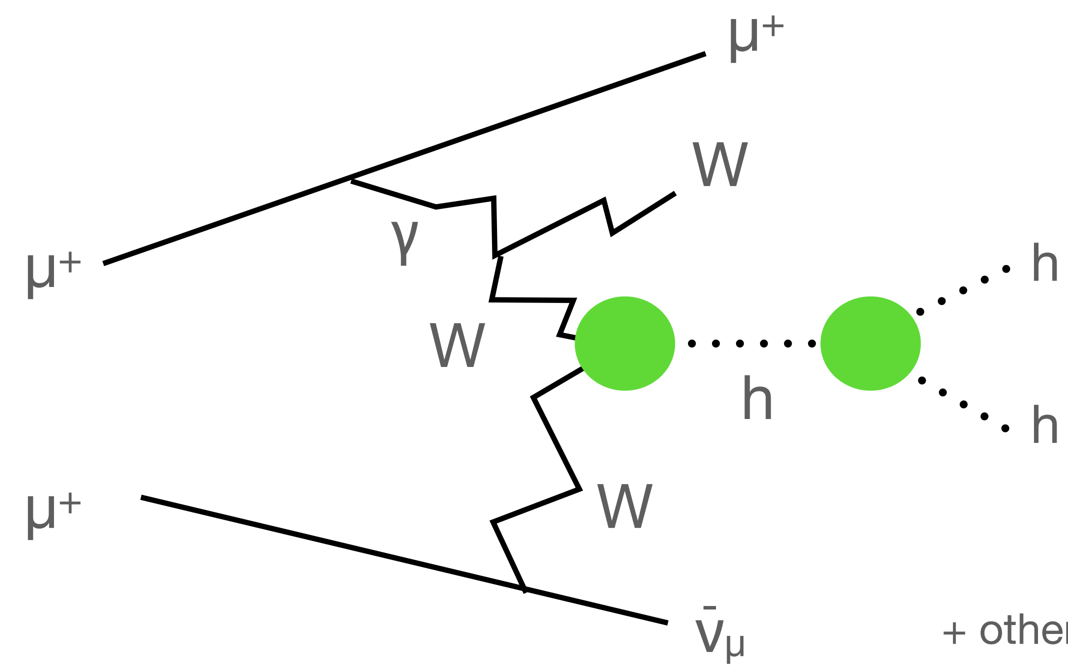
about a factor of two smaller than $\mu^+\mu^-$
(not too bad?)



maybe we should plan 5-10TeV colliders.

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





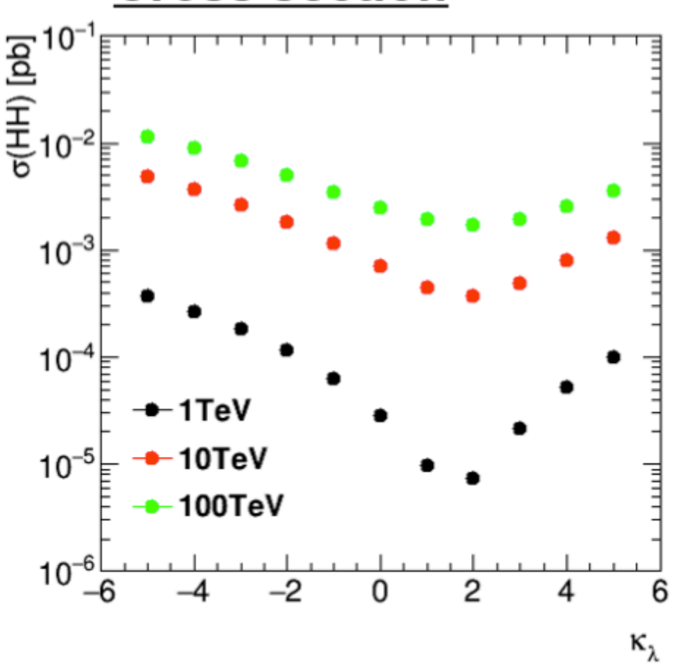
+ others

about 1/3 of $\mu^+\mu^-$

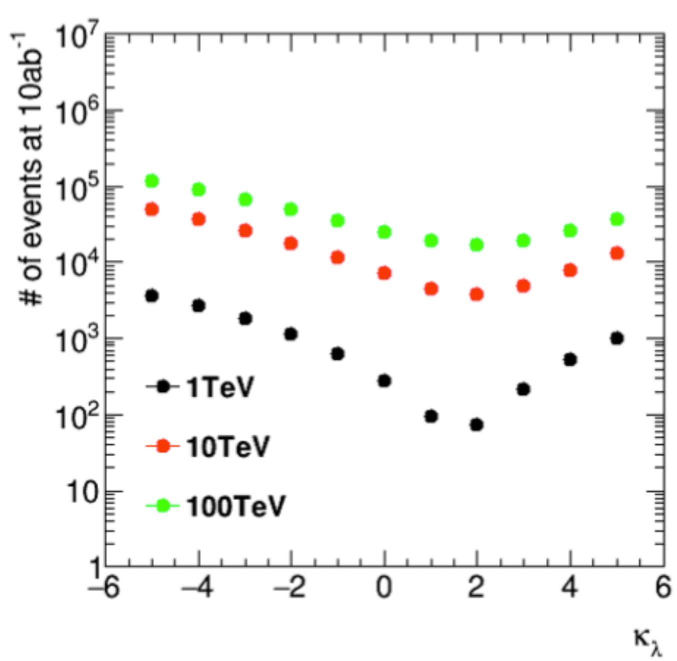
$\sqrt{s}$ [TeV]	ZBF [fb]	Photon emission [fb]
2	0.075	0.010
10	0.62	0.30
20	1.1	0.75

ZBF:

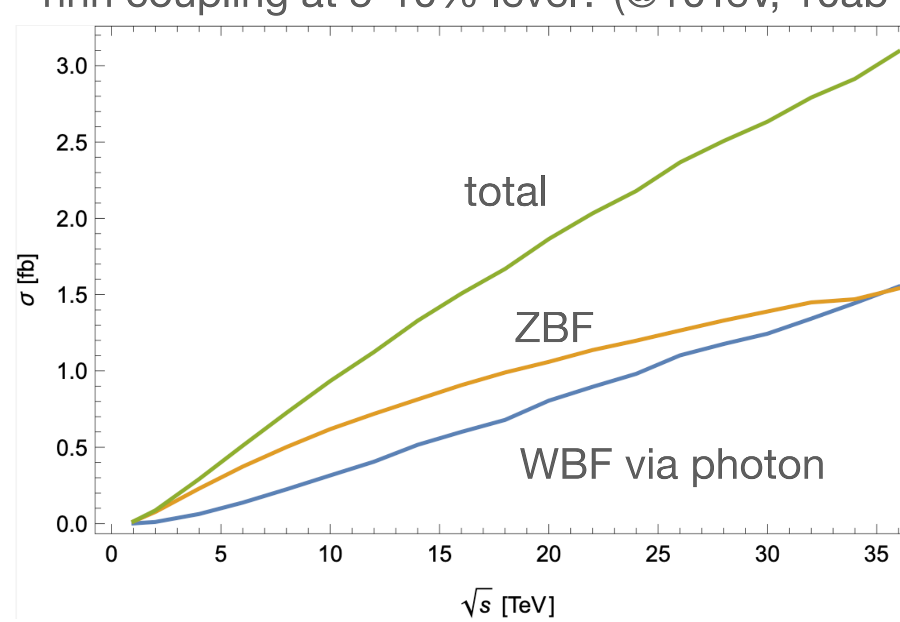
Cross section



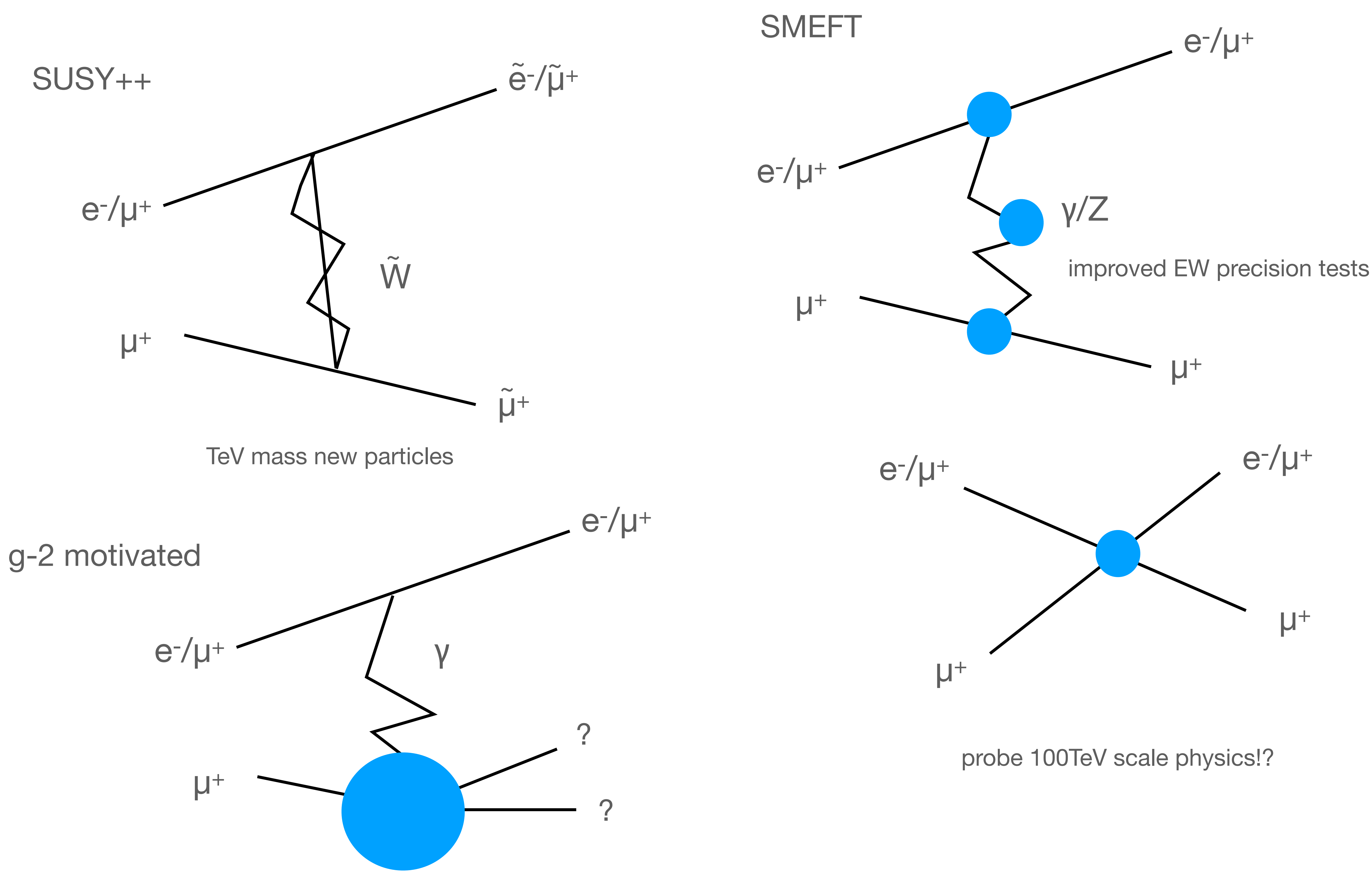
# of Events in 10ab^{-1}



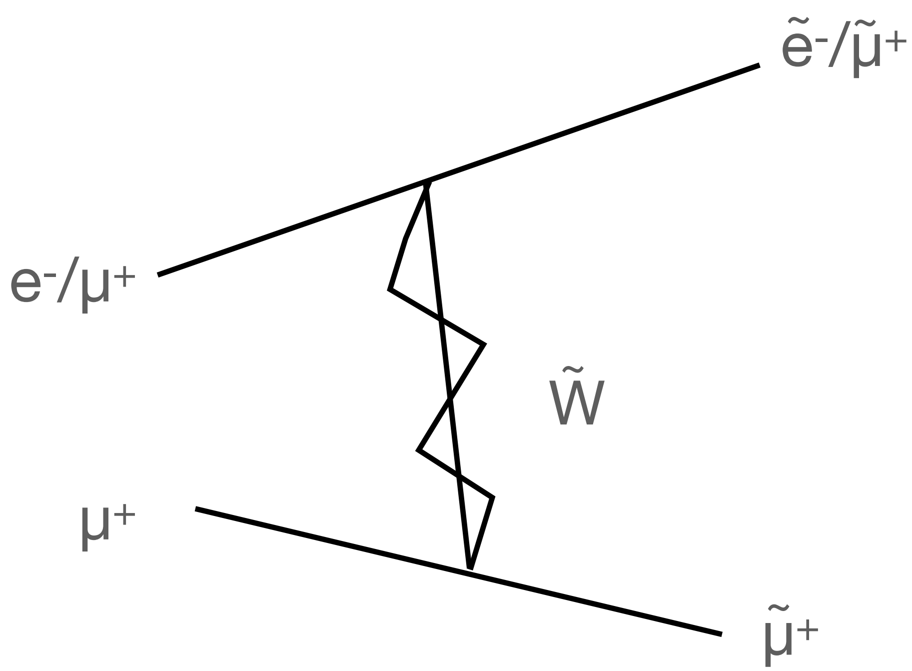
hhh coupling at 5-10% level? (@10TeV, 10ab^{-1})



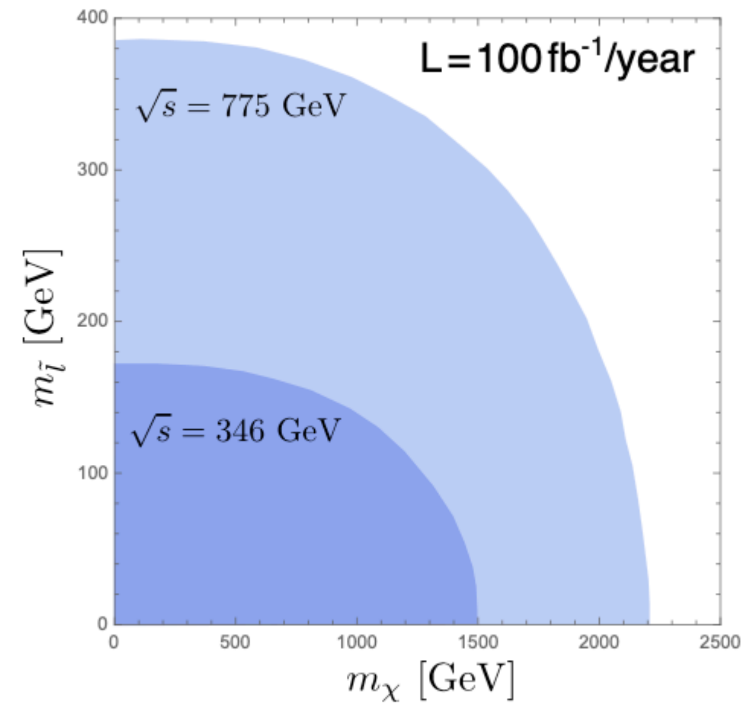
New physics?

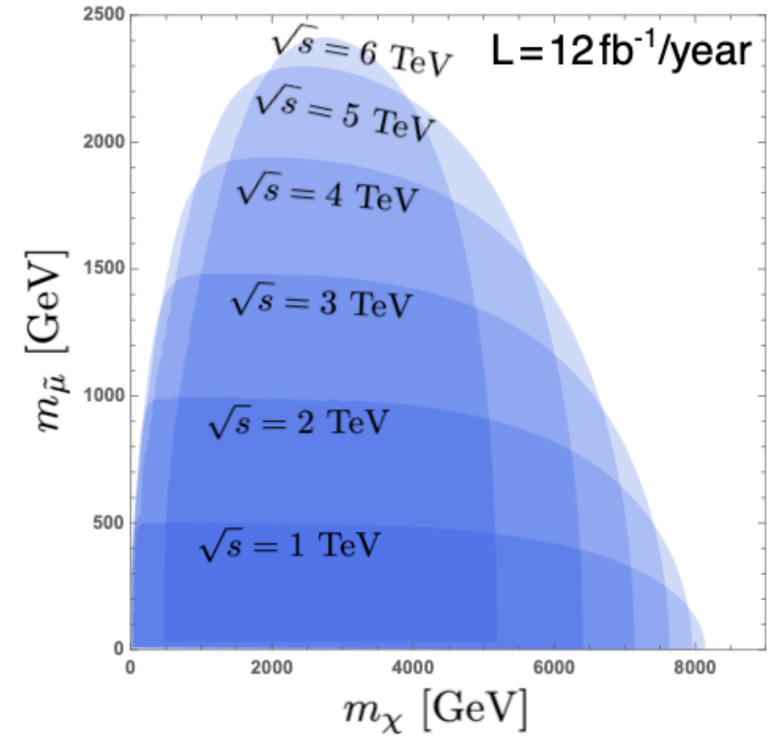

SUSY++
$\tilde{e}^-/\tilde{\mu}^+$
e^-/μ^+
$\tilde{W}$
μ^+
$\tilde{\mu}^+$
TeV mass new particles
SMEFT
e^-/μ^+
e^-/μ^+
γ/Z
improved EW precision tests
μ^+
μ^+
e^-/μ^+
e^-/μ^+
μ^+
μ^+
probe 100TeV scale physics!?
g-2 motivated
e^-/μ^+
e^-/μ^+
γ
μ^+
?
?

Supersymmetry



Regions for N_{event}/year > 100.

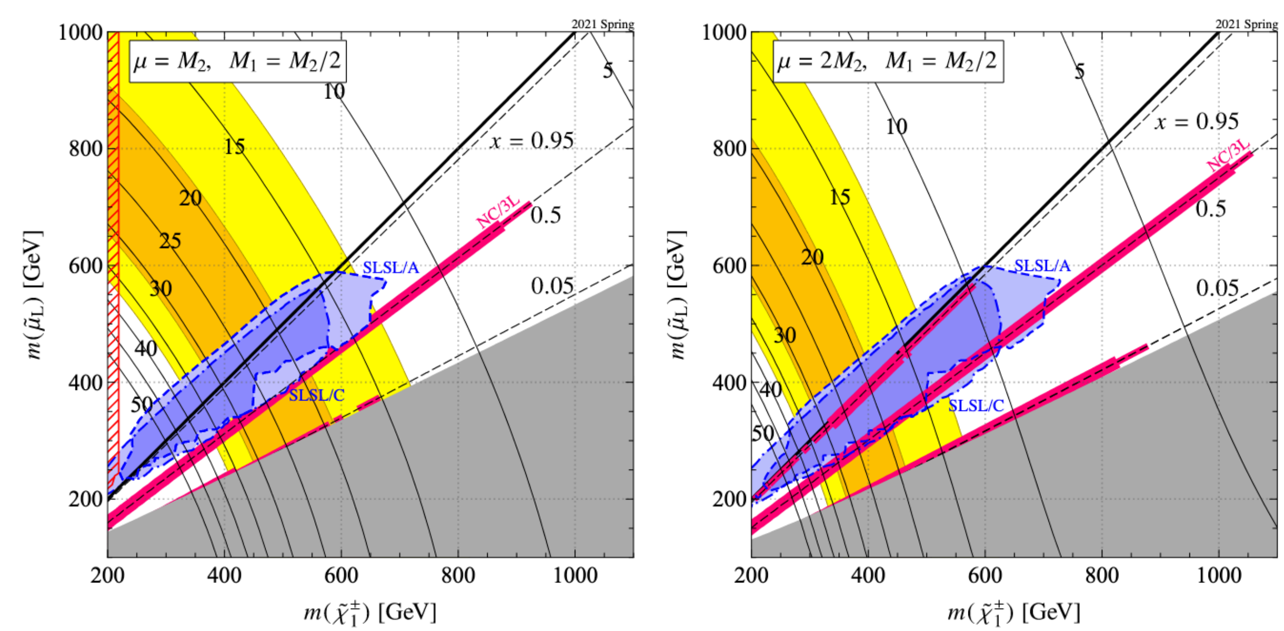




Scalar muons up to TeV even for very heavy gauginos.

Almost completely cover the muon g-2 motivated region.

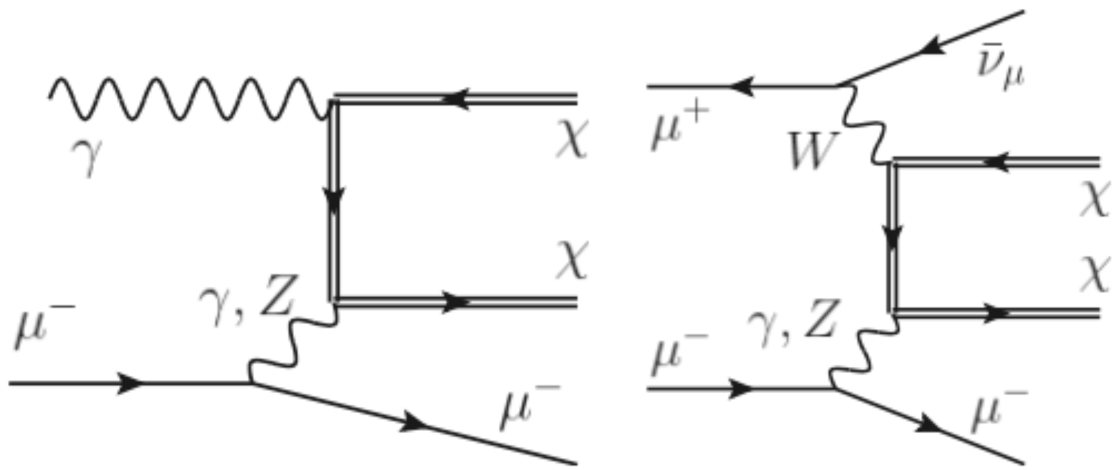
[Endo, Hamaguchi, Iwamoto, Kitahara '21]



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

DM?

study@μ⁺μ⁻ [Han et al. ’20]



same search is possible at μ⁺μ⁺

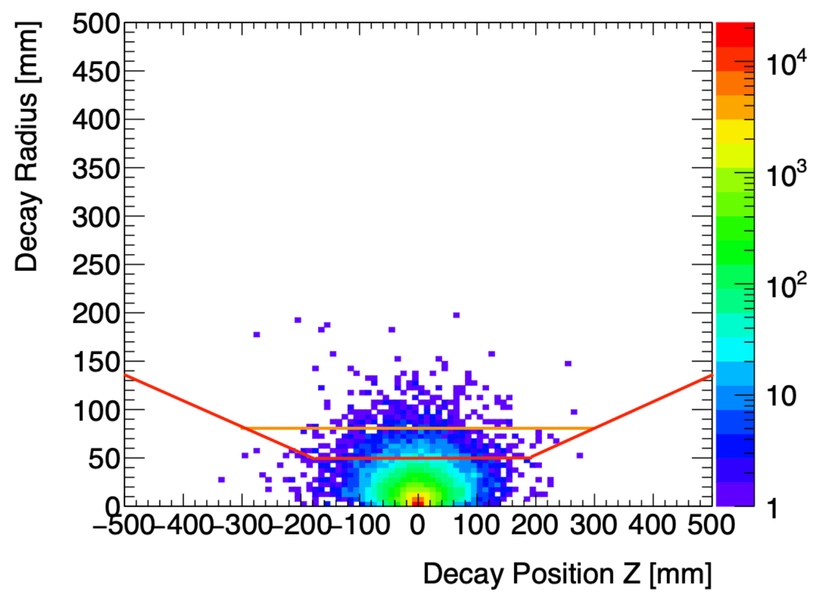
mono-μ

S/B is good in this process.

10TeV machine can cover 1TeV Higgsino and 1-2TeV Wino.

track + VBF search?

√s = 10 TeV, 質量 1 TeV Higgsino の崩壊マップ

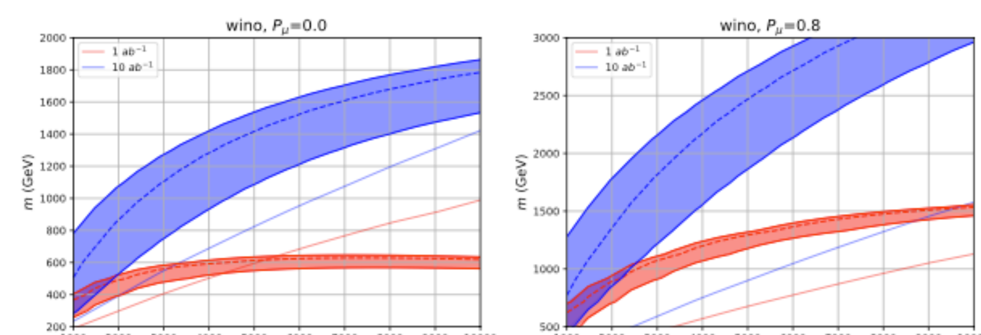


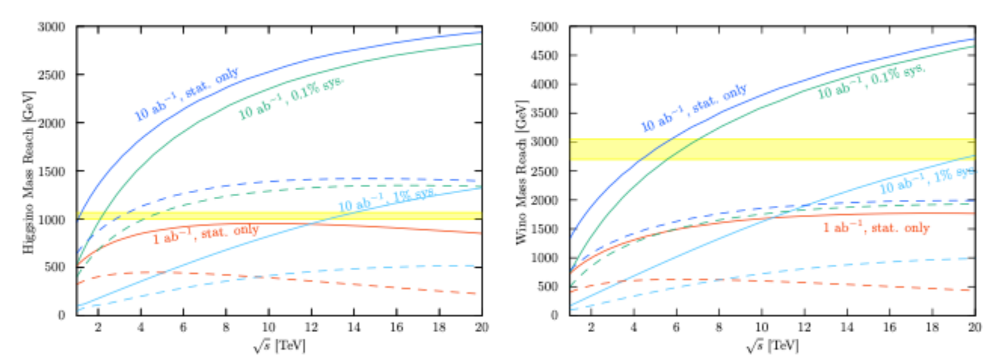
崩壊半径
- Case A > 80 mm
- Case B > 50 mm

$|\eta| < 2.0$
を再構成できると仮定

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

indirect search: [Fukuda, Moroi, Niki, Wei ’23]

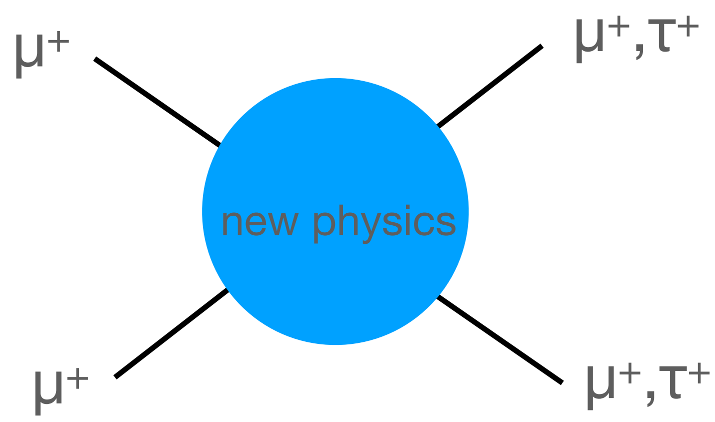




(a) Higgsino (b) Wino

[Okabe, Shirai ’23]

muon specific



elastic scattering and lepton flavor violating scattering.

$\mu^+\mu^+$ has a big advantage in looking for new physics associated with the muon.

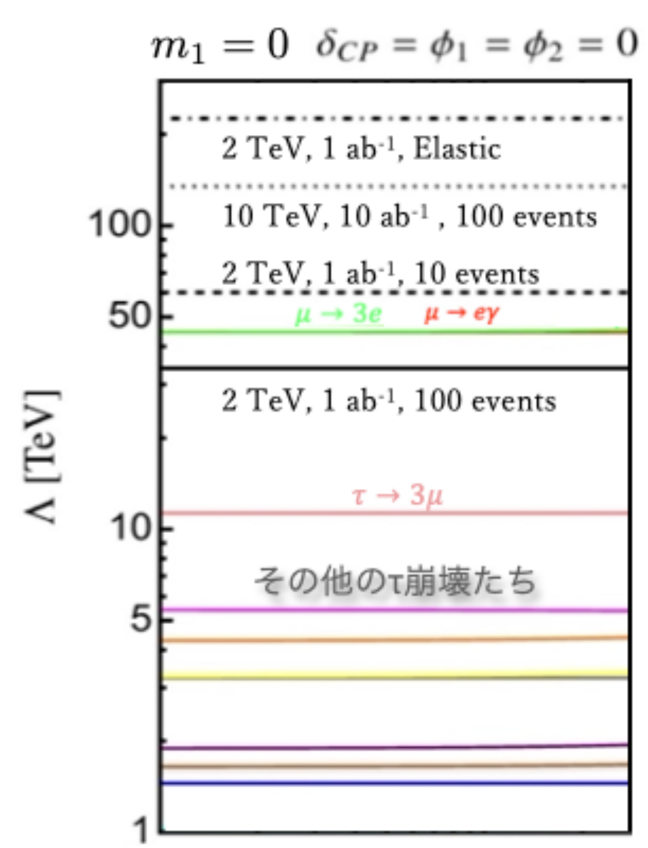
reach to O(100)TeV physics!

[Hamada, RK, Matsudo, Takaura '22]

	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
$C_{\ell\ell\,\mu\mu\mu\mu}$	100 TeV	0	0
$C_{ee\,\mu\mu\mu\mu}$	0	100 TeV	0
$C_{\ell e\,\mu\mu\mu\mu}$	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 $16° \leq \theta_i \leq 164°$.

[Fridell, RK, Takai '23]



Summary

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

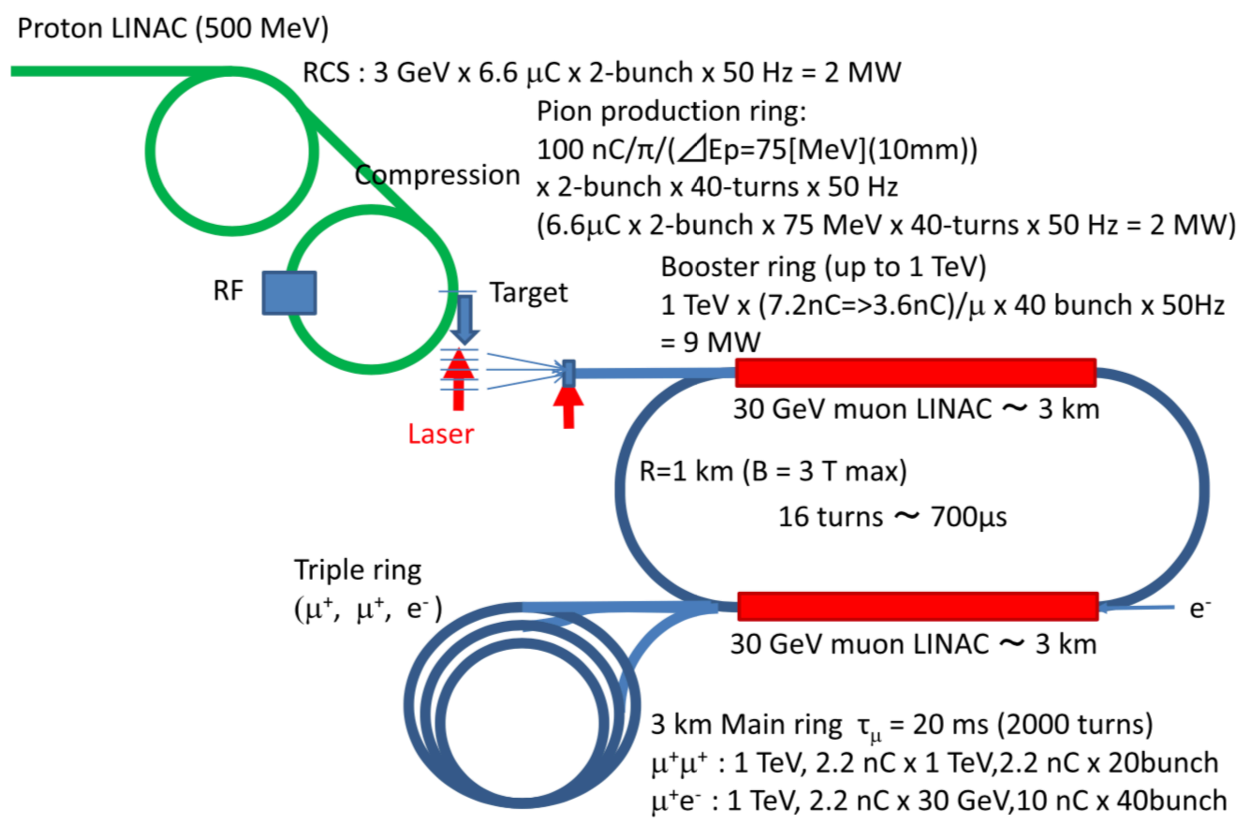


Fig. 1. Conceptual design of the $\mu^+ e^- / \mu^+ \mu^+$ collider.