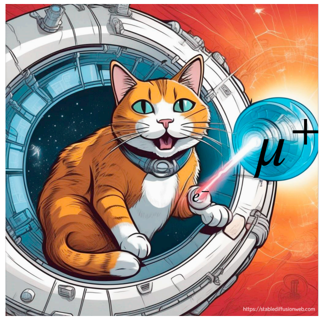


by Cari Cesarotti

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.)

MuC physics benchmark workshop@Pittsburgh, November 16-18, 2023

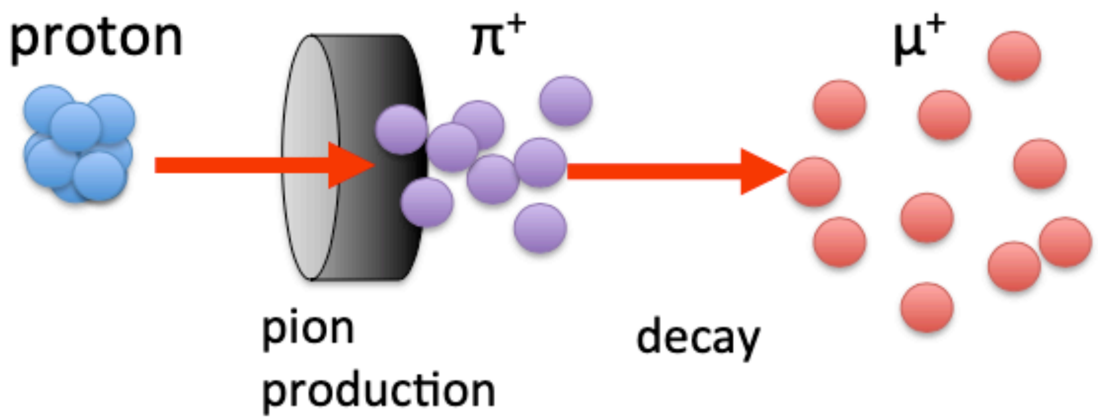
Today, I talk about possibly a realistic scenario of **μ^+ based** colliders.

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

Muon beam

Too much spread.

Conventional muon beam

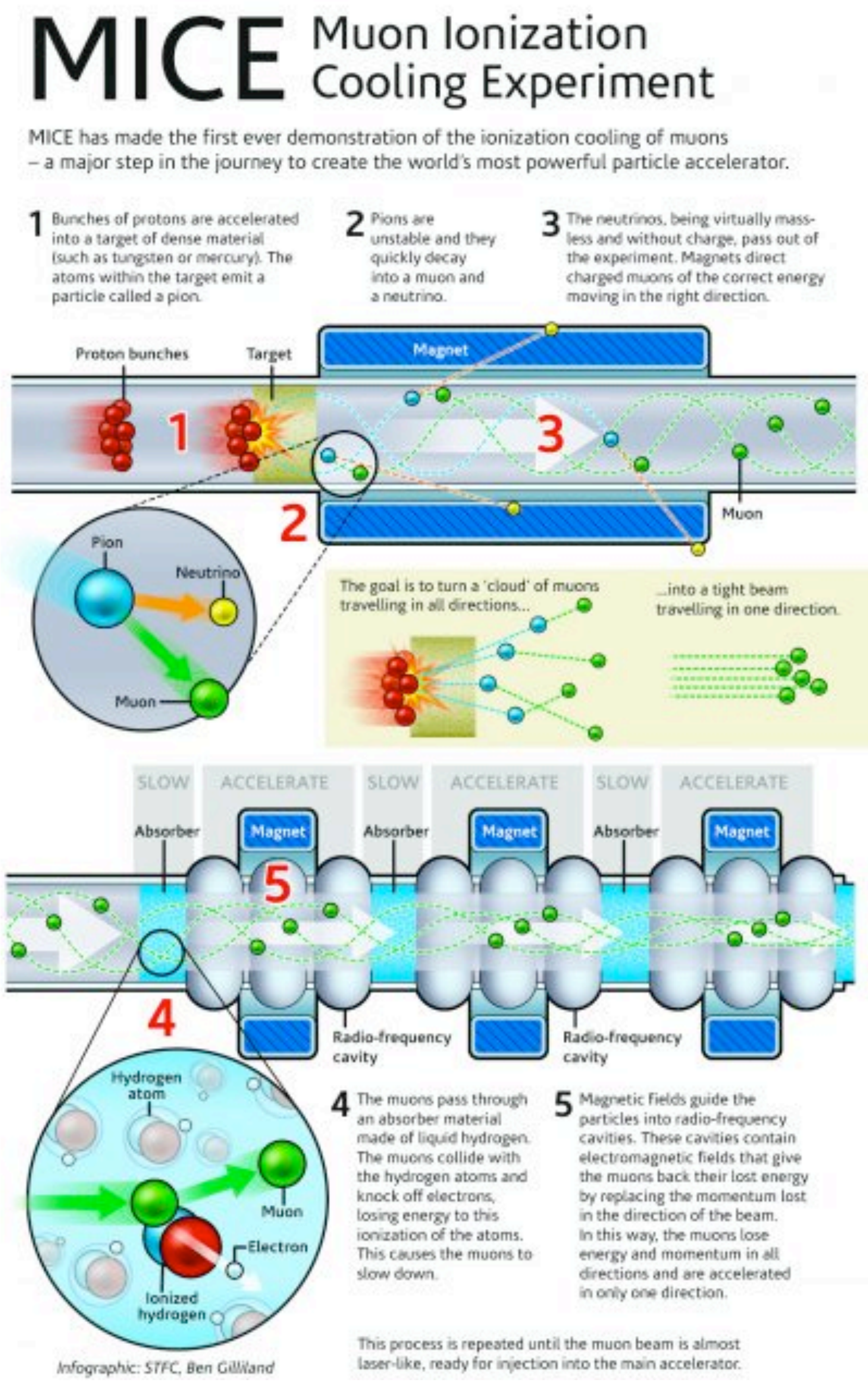


emittance
~1000π mm・mrad = π mm

Strong focusing
Muon loss
BG π contamination

Taken from Mibe-san's lecture slide

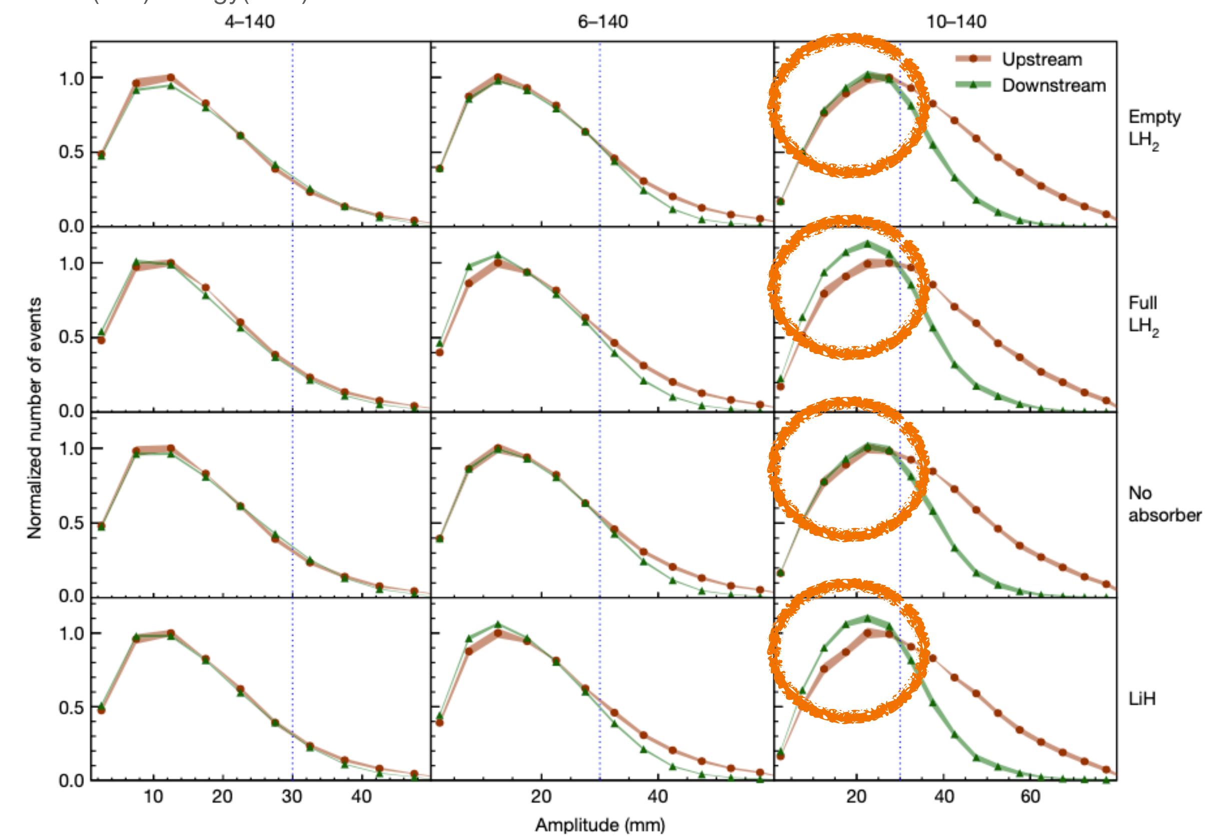
Muon cooling



Principle works.

[Nature 2020, MICE collaboration]

emittance(mm)-energy(MeV)



simulation and plan for muon cooling of the MAP design

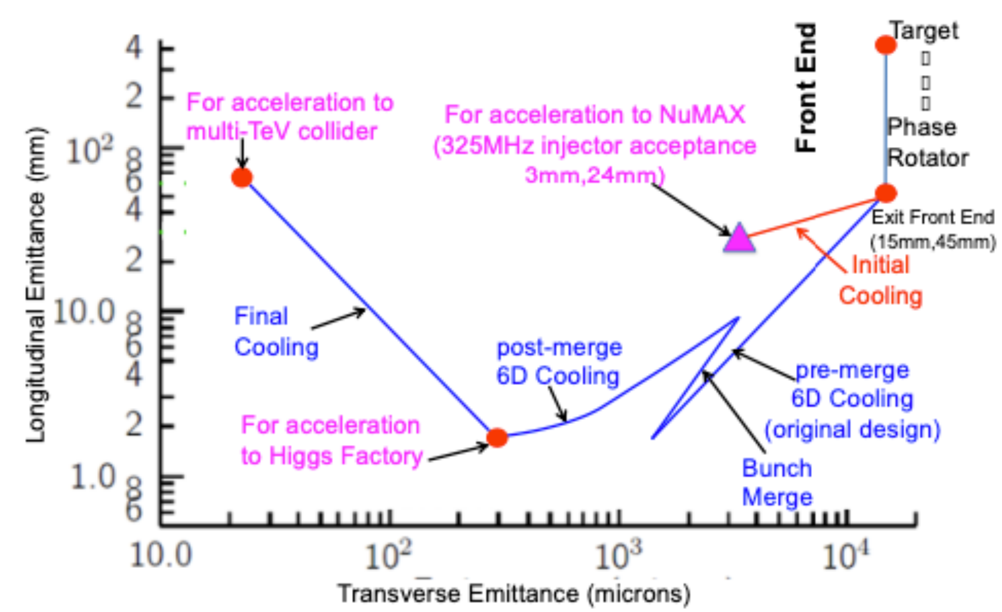
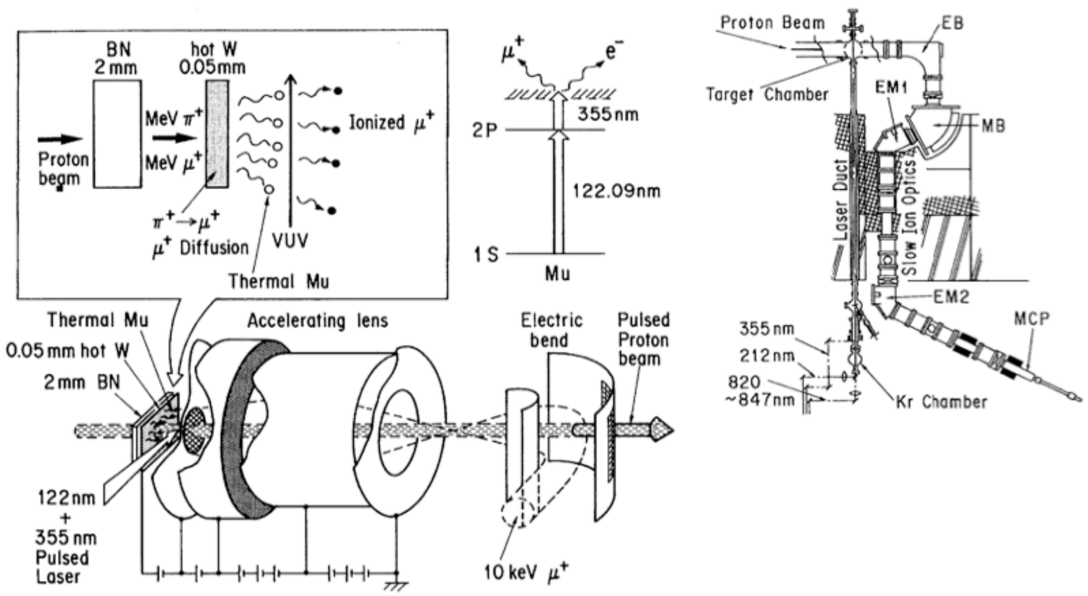


Figure 3. Ionization Cooling path in the 6D phase space.

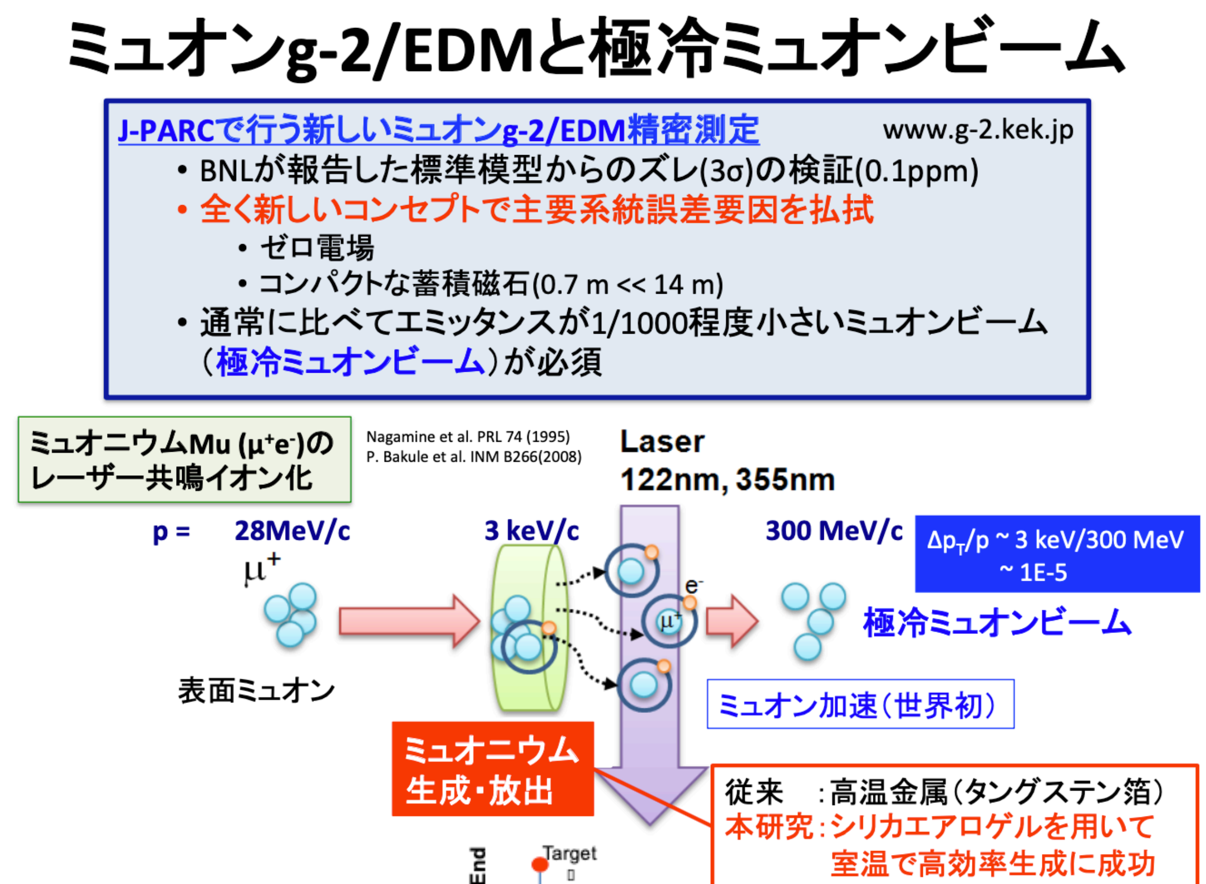
Muon cooling which works for μ+

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. ●

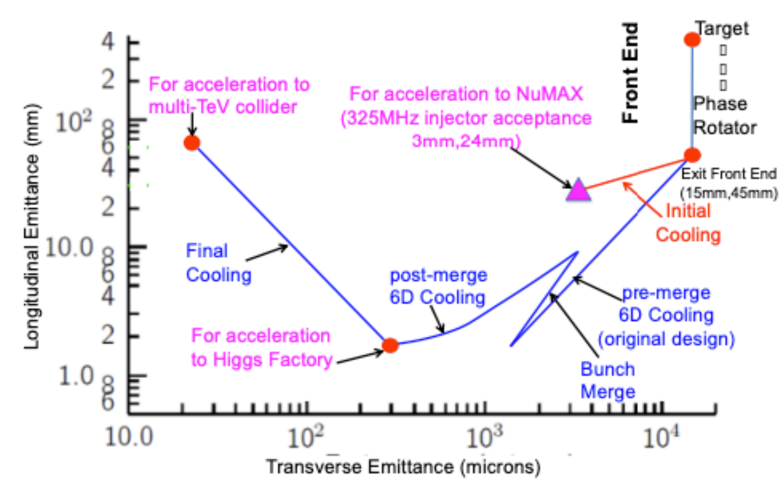


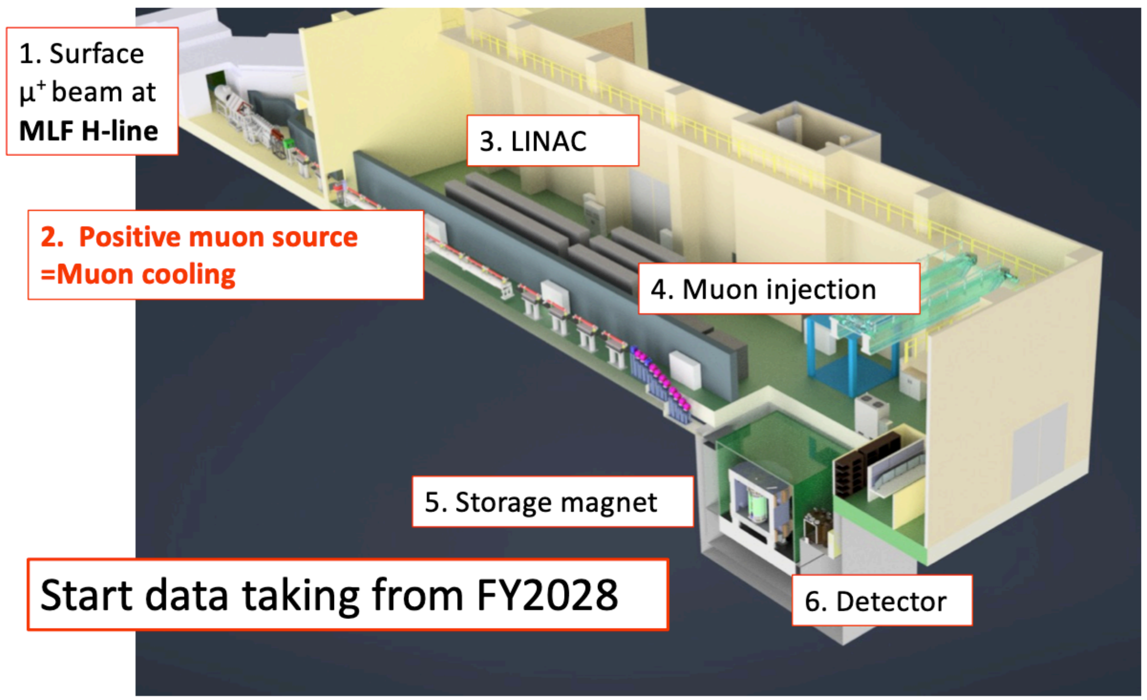
Figure 3. Ionization Cooling path in the 6D phase space.

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

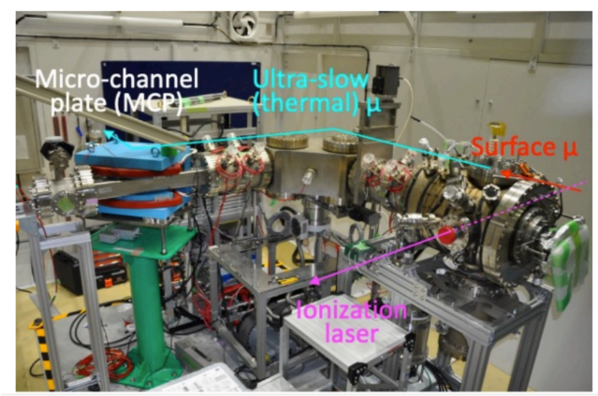
A new muon g-2/EDM measurement featuring a low emittance μ^+ beam



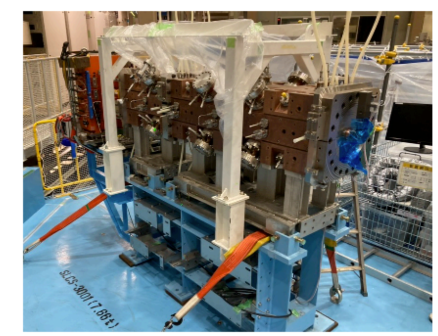
Demonstration @ MLF S-line

- 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

$\mu^+e^-/\mu^+\mu^+$ collider with 1TeV μ^+ beam.

PTEP

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

30GeV e^- / 1TeV μ^+ : Higgs factory, $\sqrt{s}$=346GeV

1TeV μ^+ / 1TeV μ^+ : new physics search, $\sqrt{s}$=2TeV

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

Received January 21, 2022; Revised March 18, 2022; Accepted March 28, 2022; Published March

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

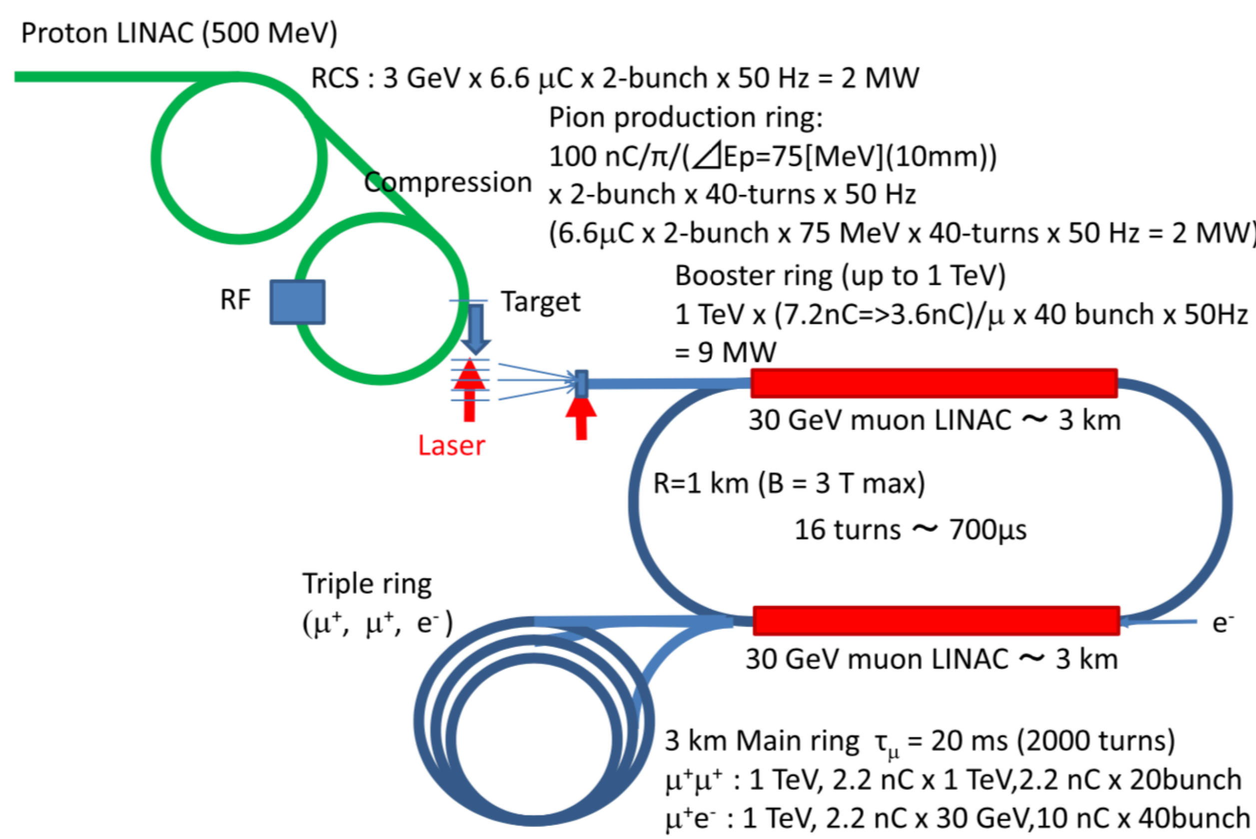


Fig. 1. Conceptual design of the $\mu^+e^-/\mu^+\mu^+$ collider.

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 = 4.1×10^{15} protons/s

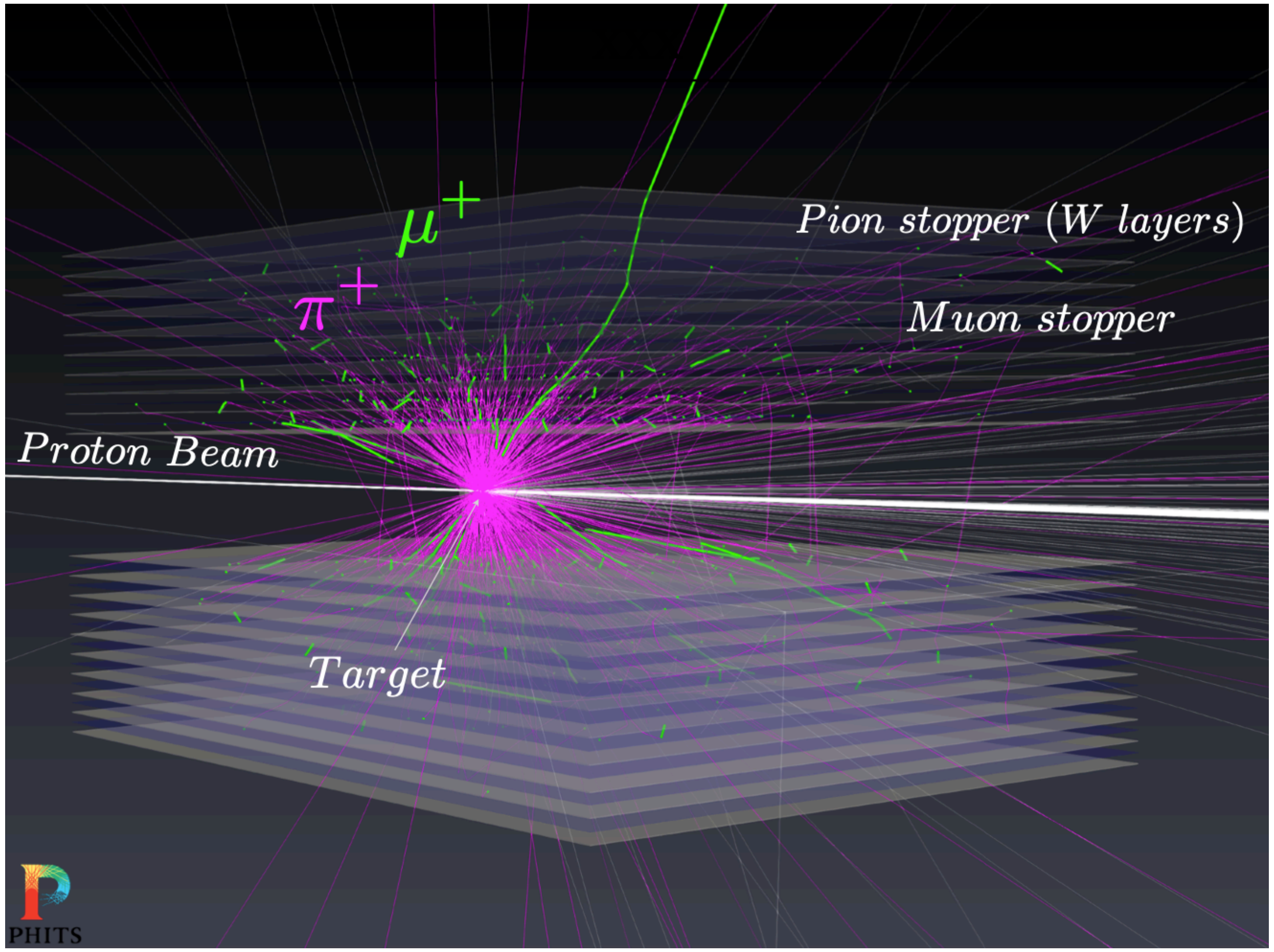
pion production target: 40 hits/bunch 0.016 π^+/proton 2.6×10^{15} π^+/s

pion stopping target: 0.5 stopping efficiency * 0.07 muons/π^+ 9×10^{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

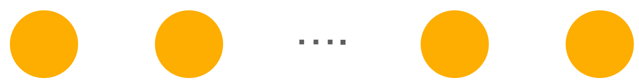
= $1.4 * 10^{-3}$ μ/p

→ **$2.4 * 10^{14}$ 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

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

$\sigma \sim$ 2-3 μm ($\beta^* \sim$ cm)

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

storage ring

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

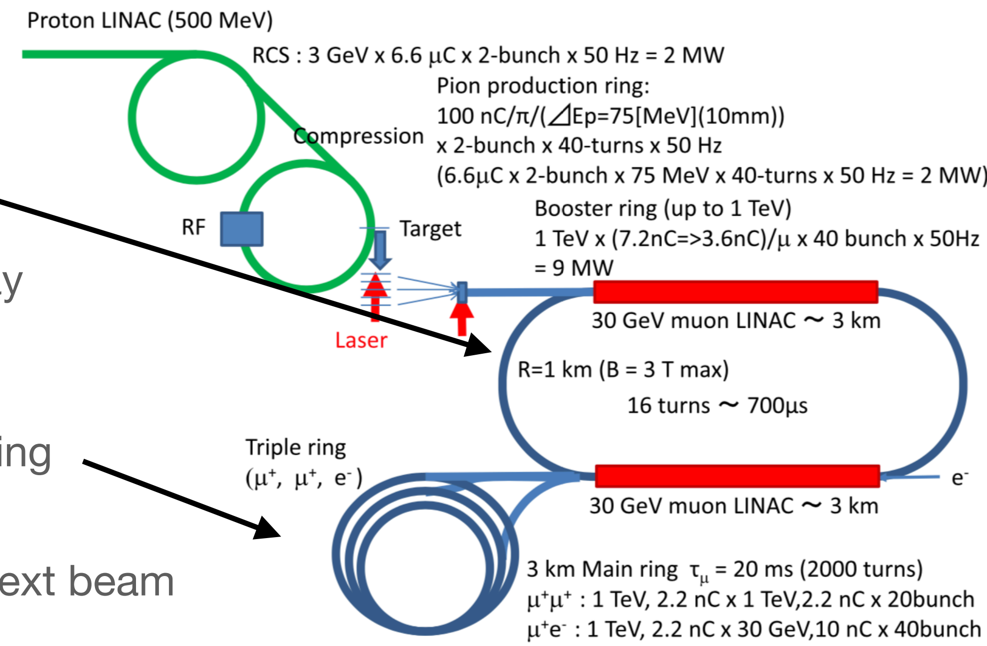


Fig. 1. Conceptual design of the $\mu^+e^-/\mu^+\mu^+$ collider.

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

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

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)

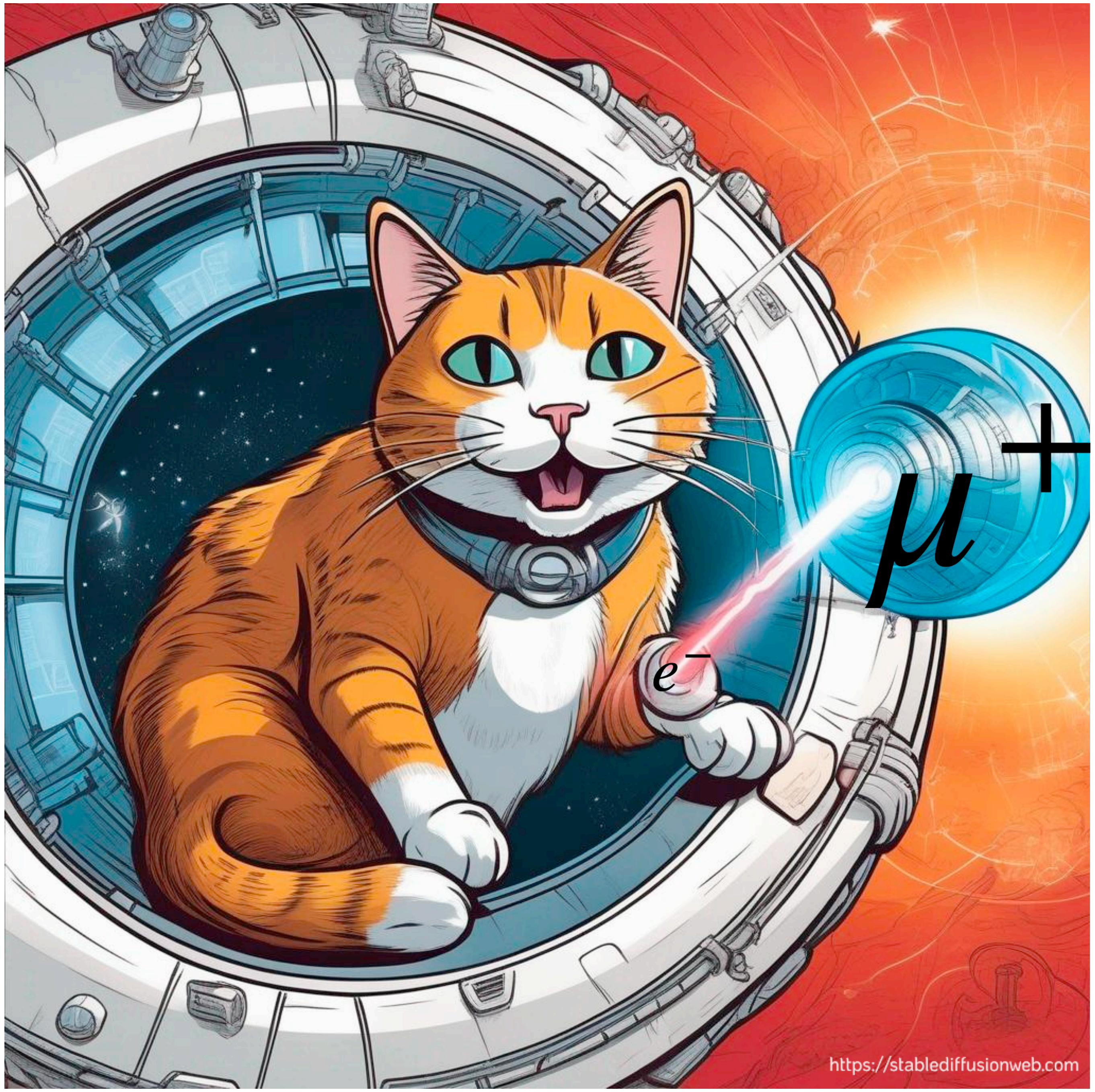
(could be much better for μ^+e^-)

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?

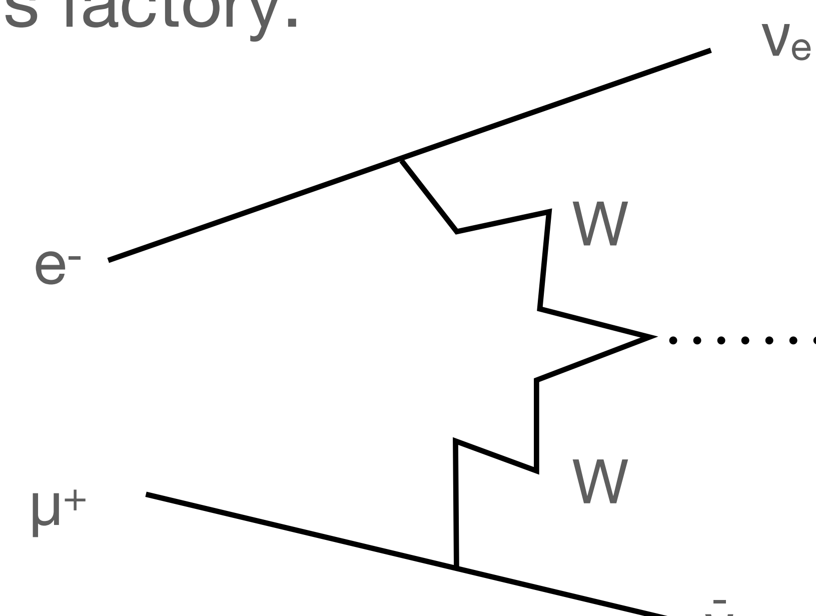
mewTRISTAN



by Cari Cesarotti

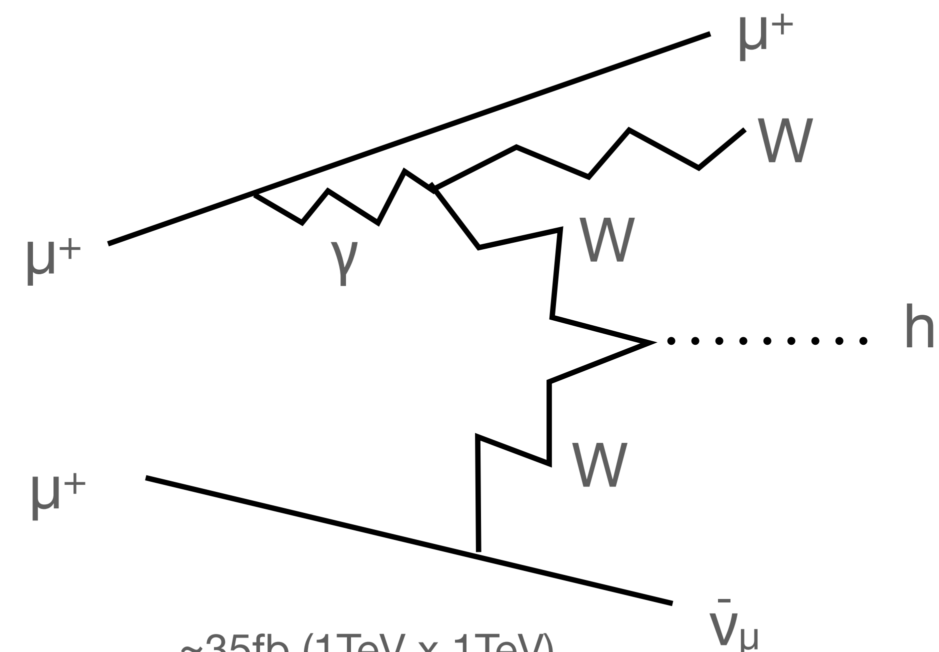
What can we do at μTRISTAN?

Higgs factory:



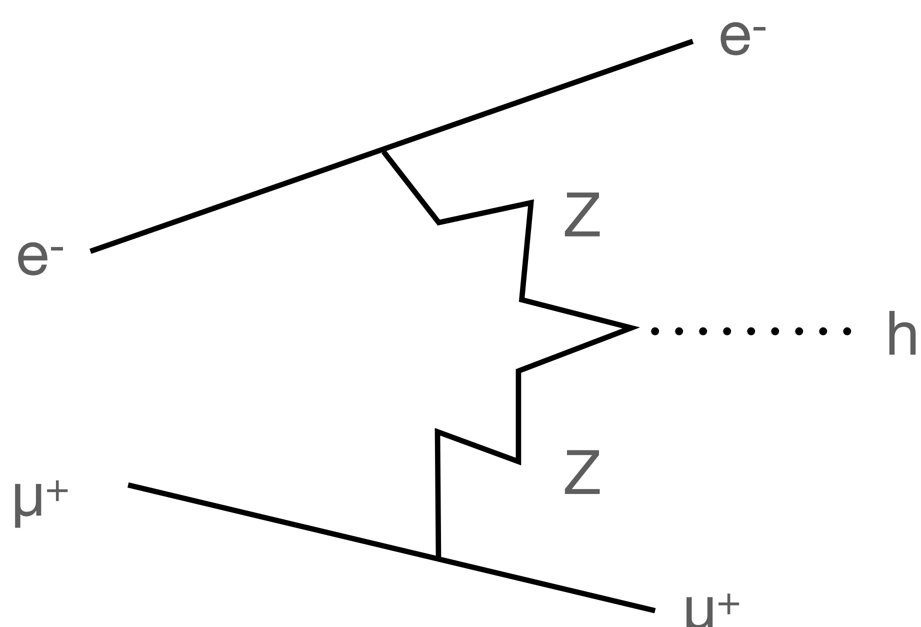
~90fb (30GeV x 1TeV)

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



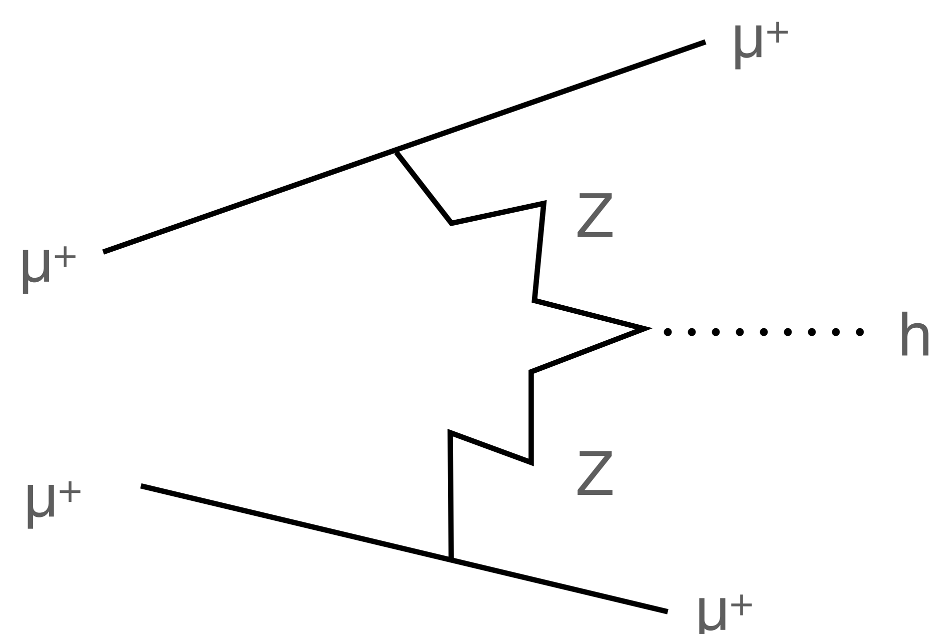
~35fb (1TeV x 1TeV)

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



~4fb (30GeV x 1TeV)

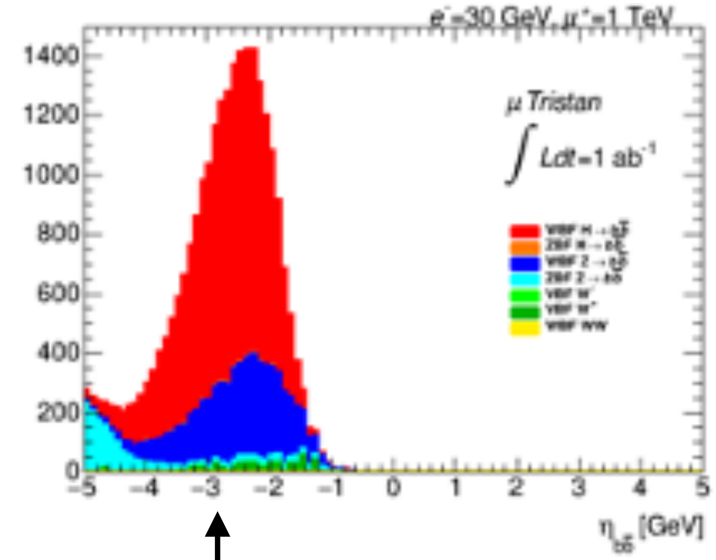
~10^3 Higgs bosons ($1ab^{-1}$)



~54fb (1TeV x 1TeV)

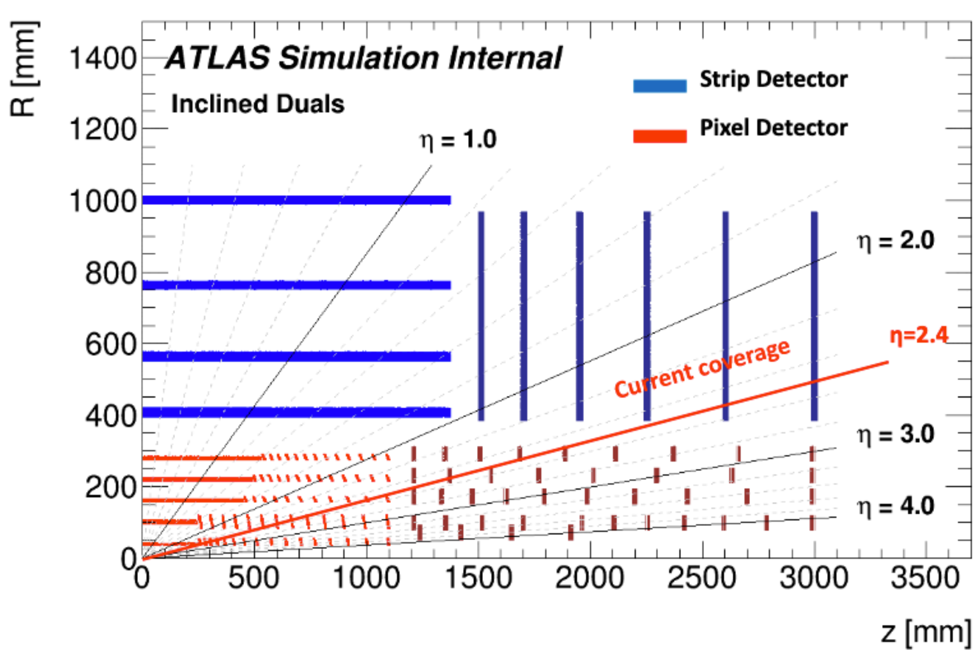
~10^{4-5} Higgs bosons ($1ab^{-1}$)

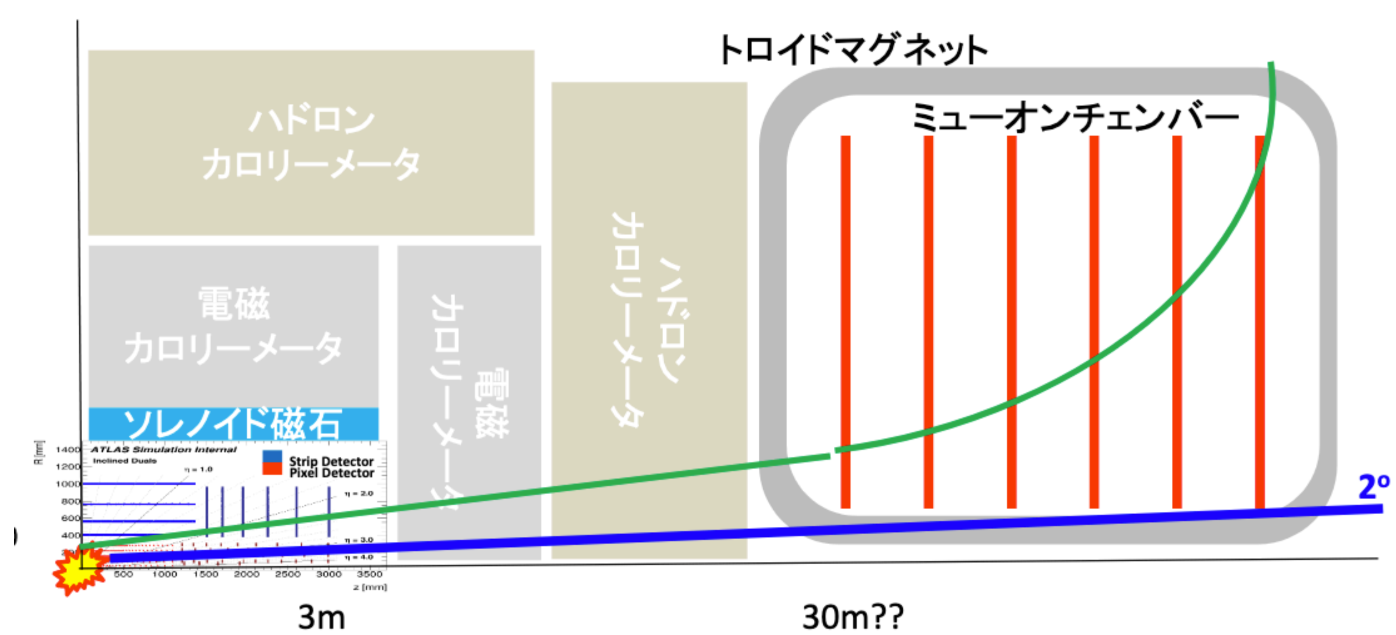
μ^+e^-: Very asymmetric



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.

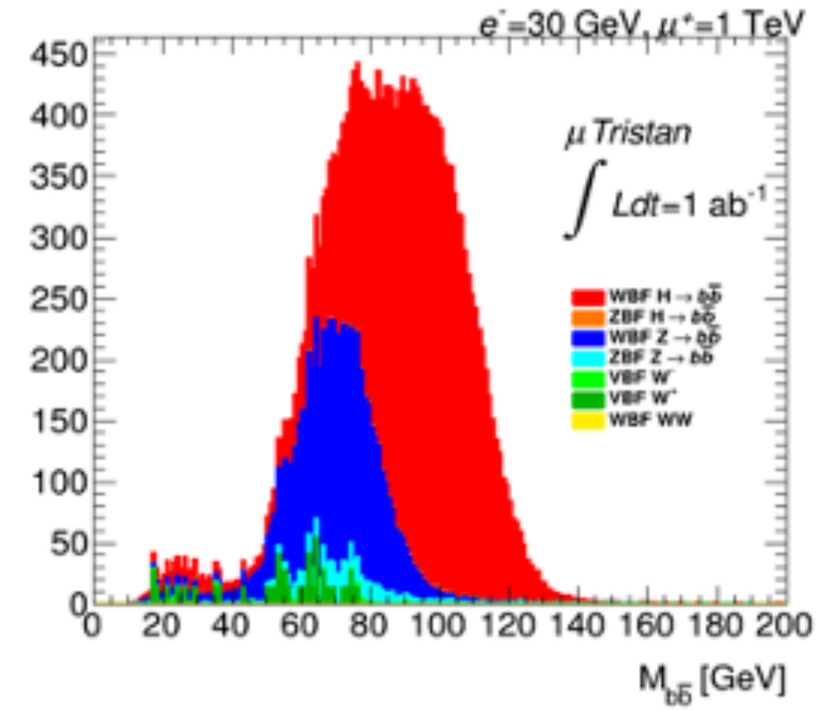




Higgs coupling

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

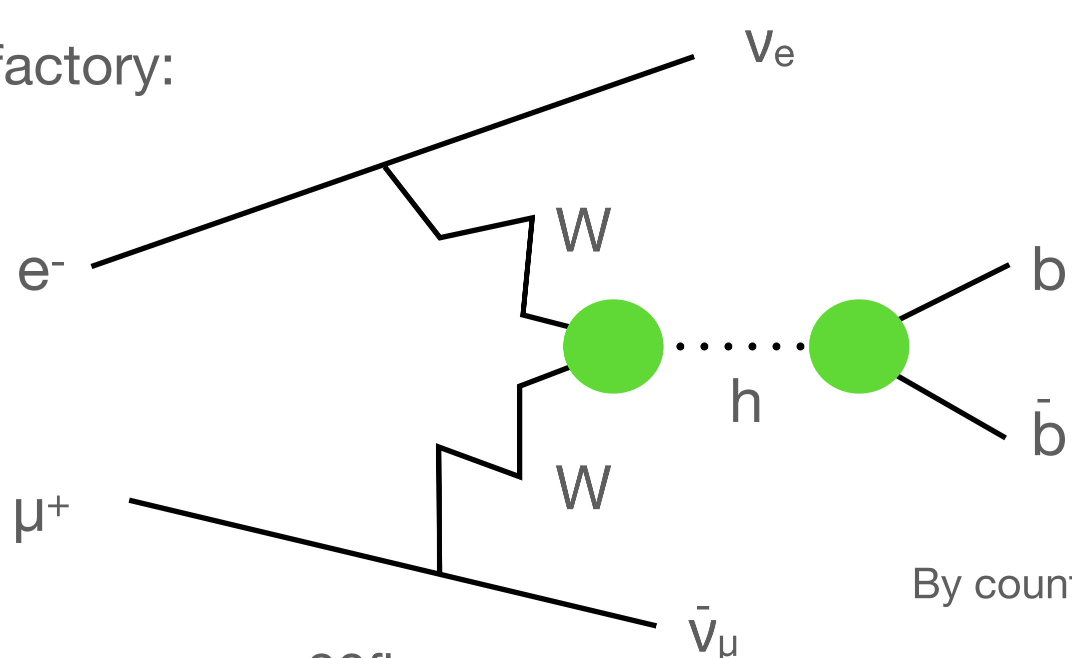
simulation with the ATLAS detector for HL-LHC



acceptance ~ 23%

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

Higgs factory:



~90fb

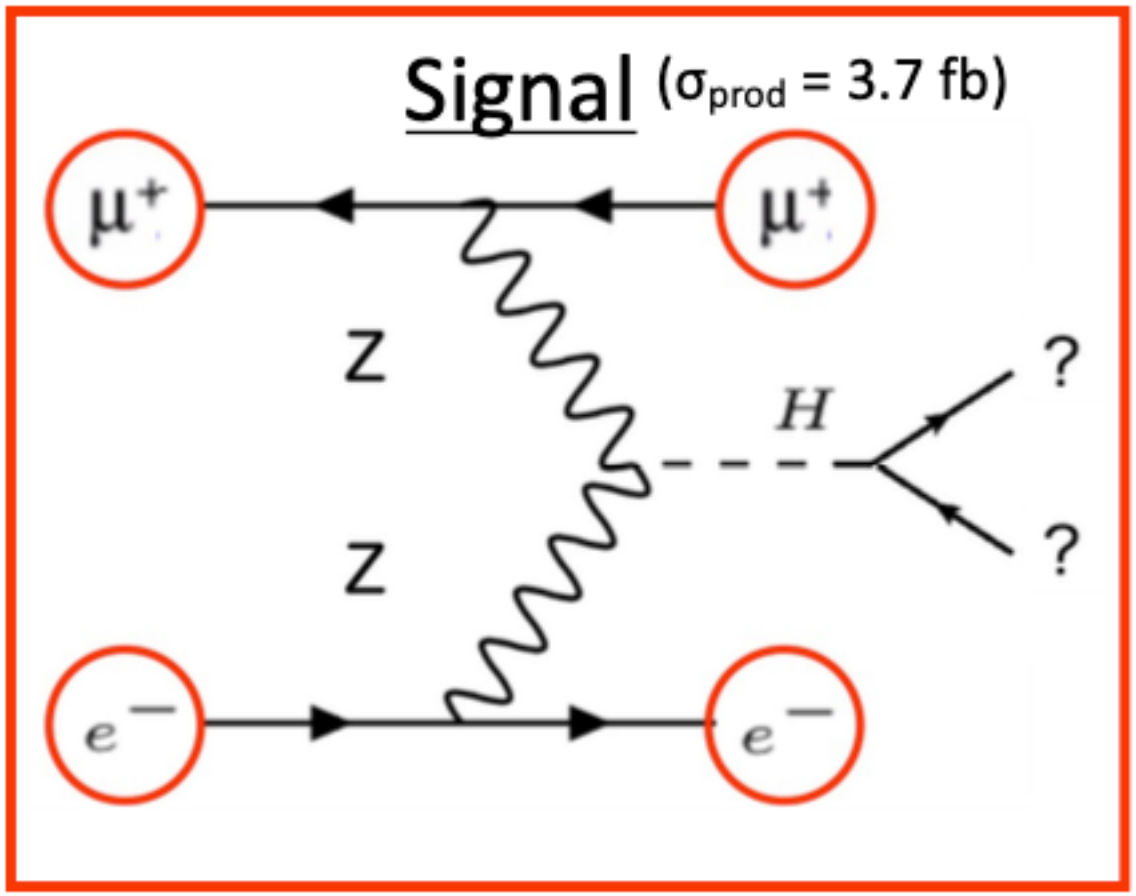
~10^5 Higgs bosons

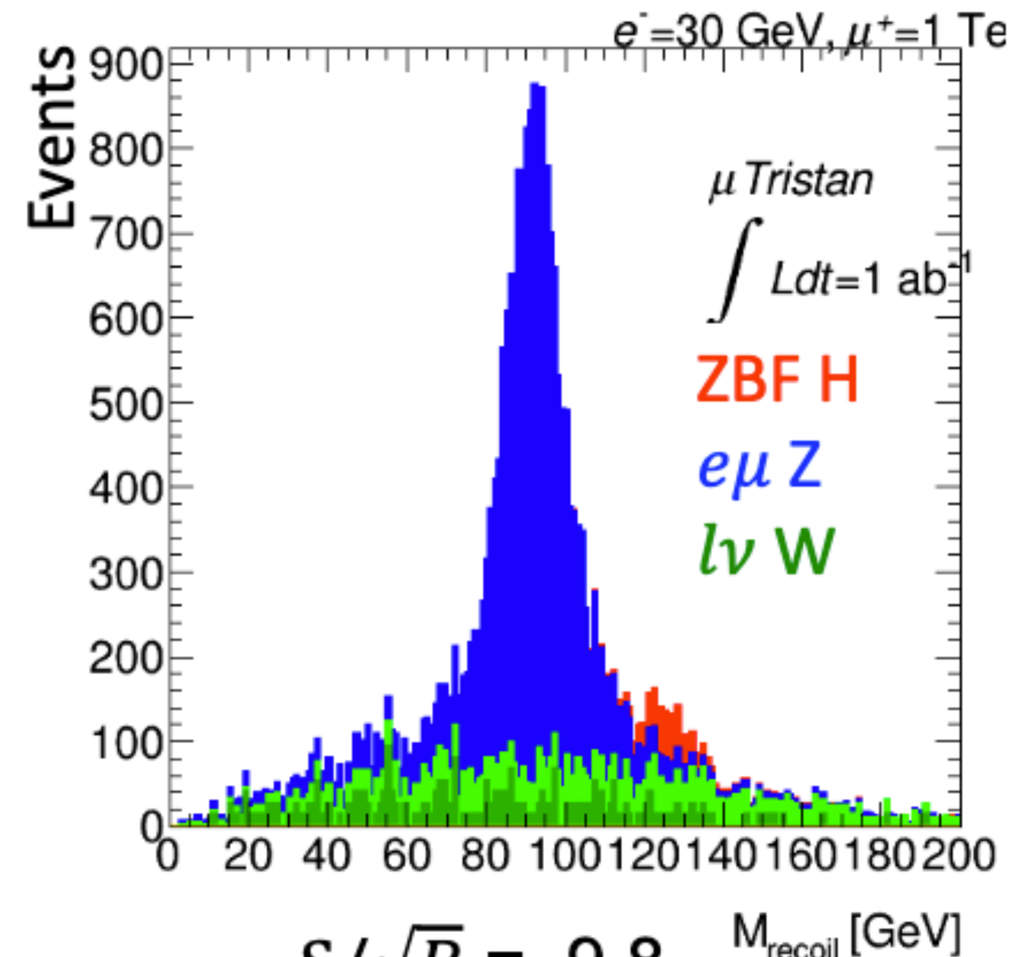
By counting the number of events and compare with the SM prediction

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

sub percent level measurements.

Z boson fusion recoil mass





$S/\sqrt{B}$ = 9.8

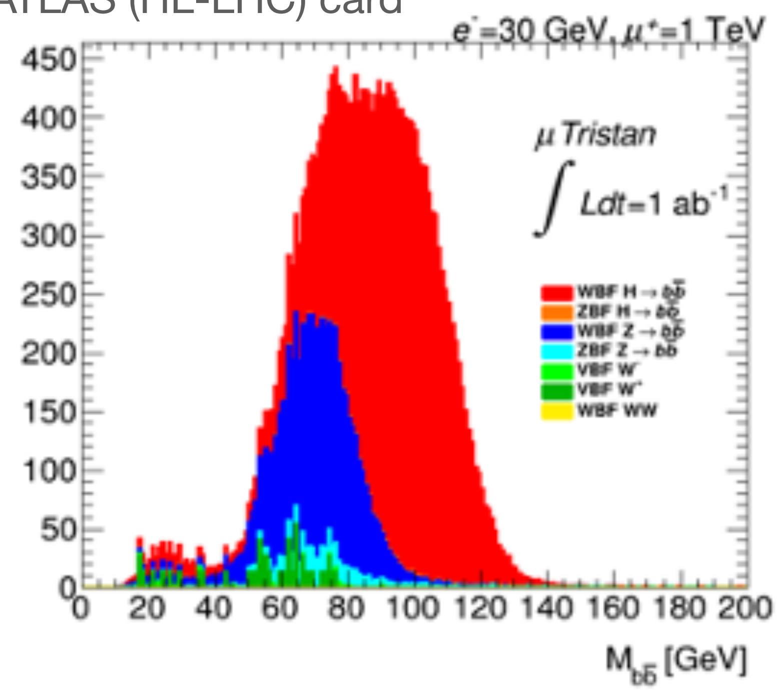
→ 1k events @ 1 ab^{-1}

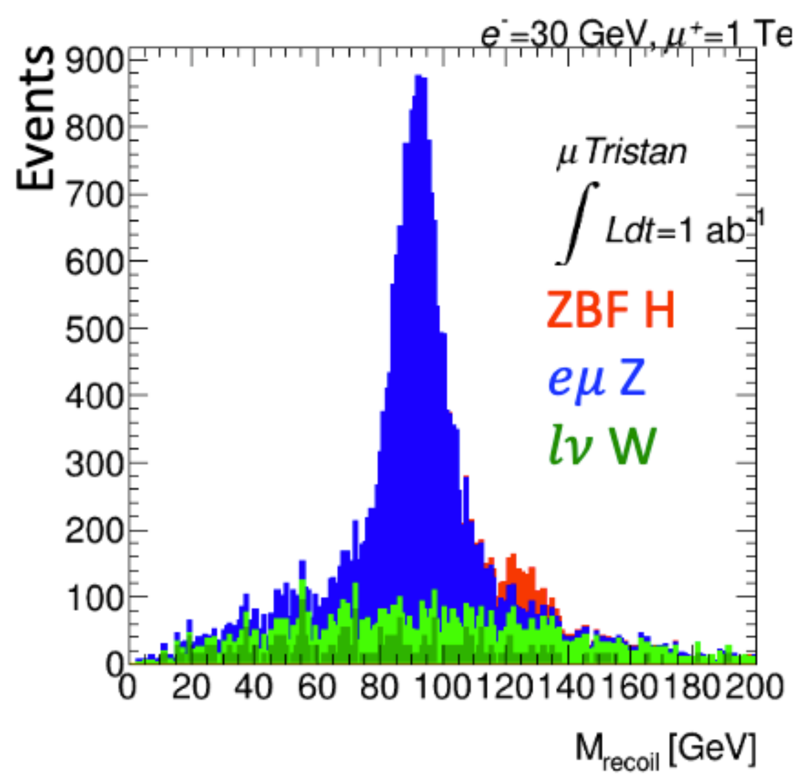
Total width may be measured.

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

Detector matters

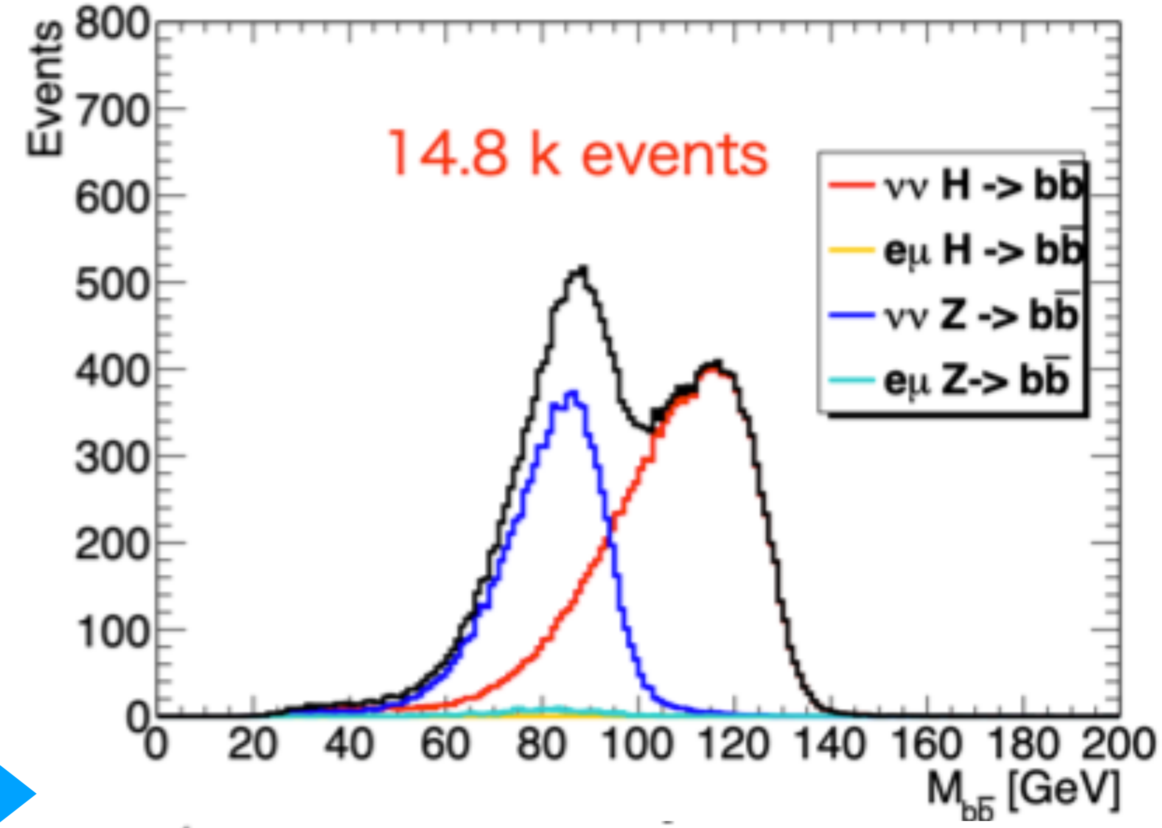
Delphes
ATLAS (HL-LHC) card

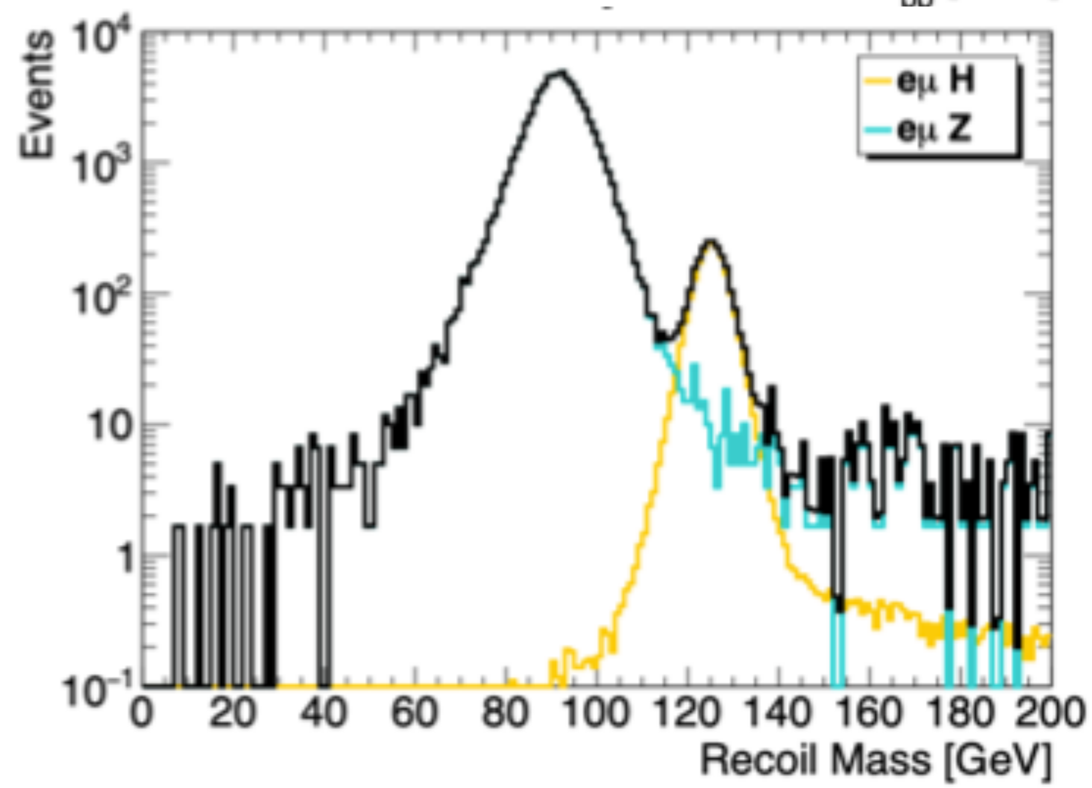




Delphes
ATLAS (LHC) card with a larger forward coverage

Much better!

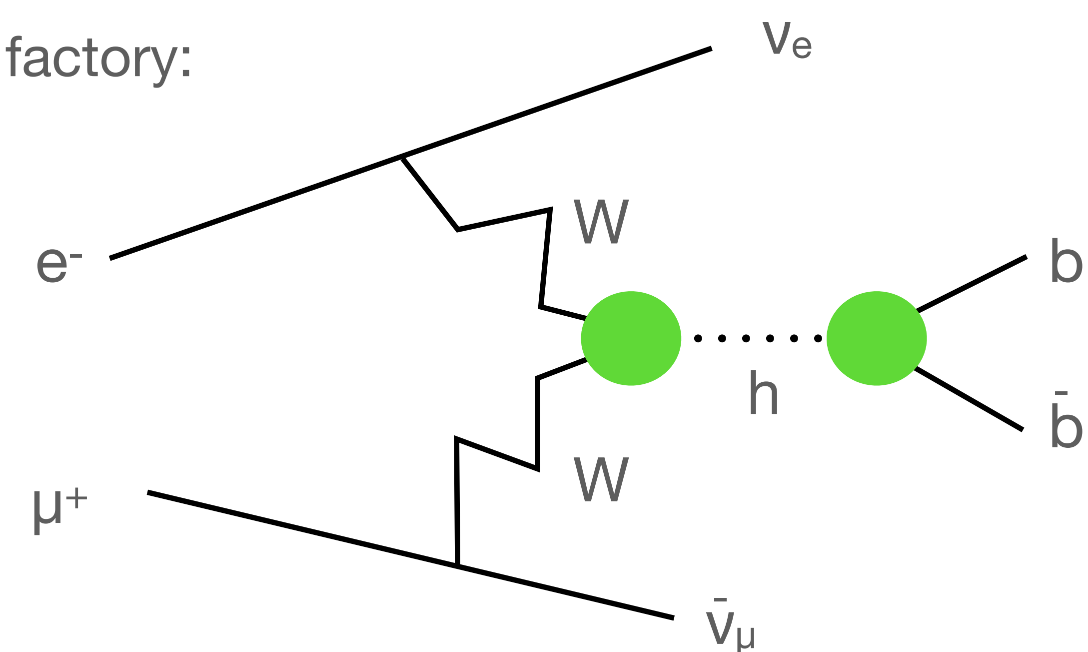




Studies underway.

Higher energy? μTevatron?

Higgs factory:



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

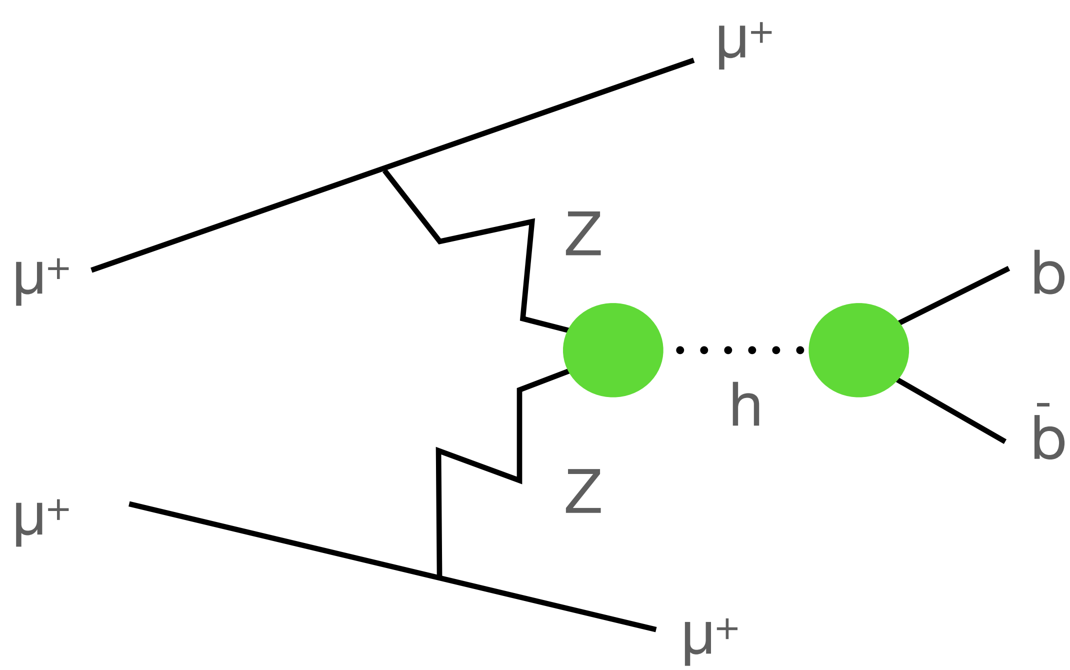
$\sqrt{s}$ = 775 GeV

~472fb (50GeV x 3TeV)

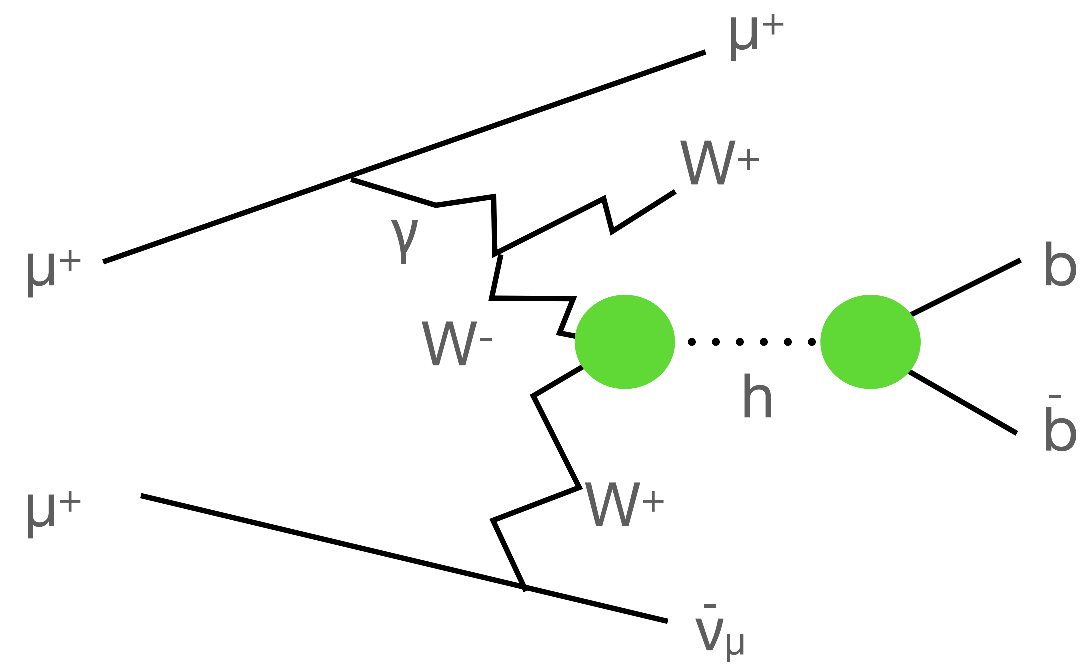
~5x10^5 Higgs bosons (ab^{-1})

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

Higgs production@μ⁺μ⁺



~54fb@2TeV final state all visible

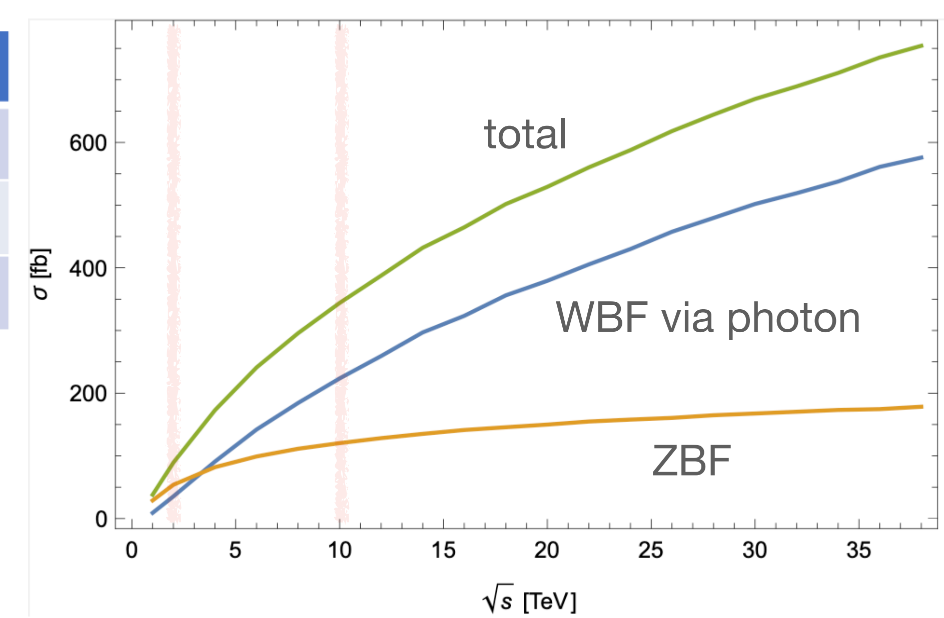


~35fb@2TeV

gets more important at high energy

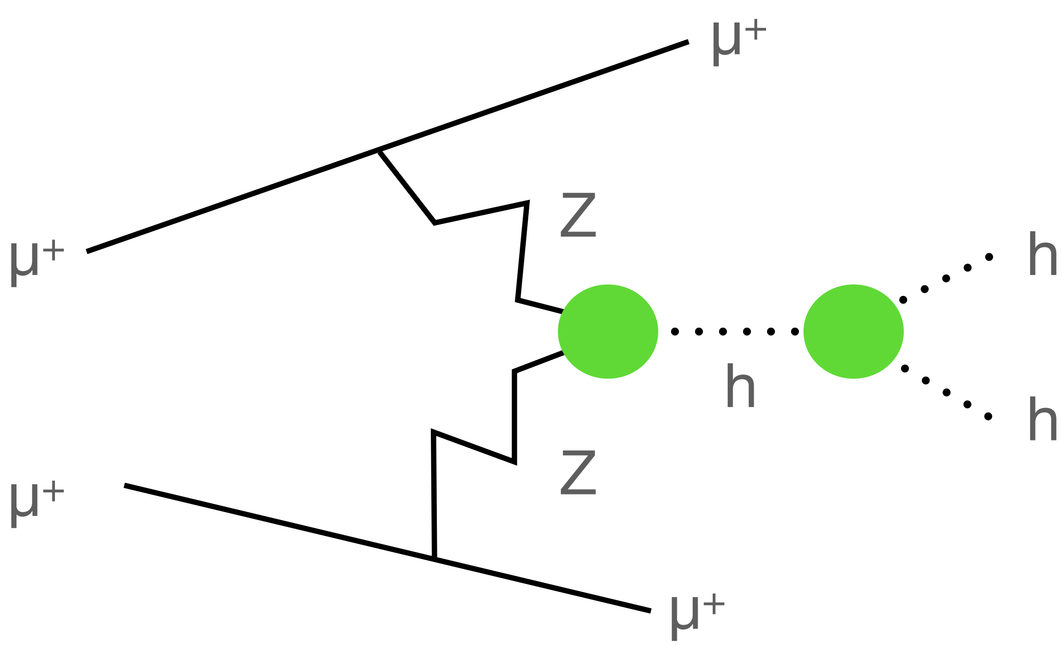
$\sqrt{s}$ [TeV]	ZBF [fb]	Photon emission [fb]
2	54	35
10	121	224
20	150	376

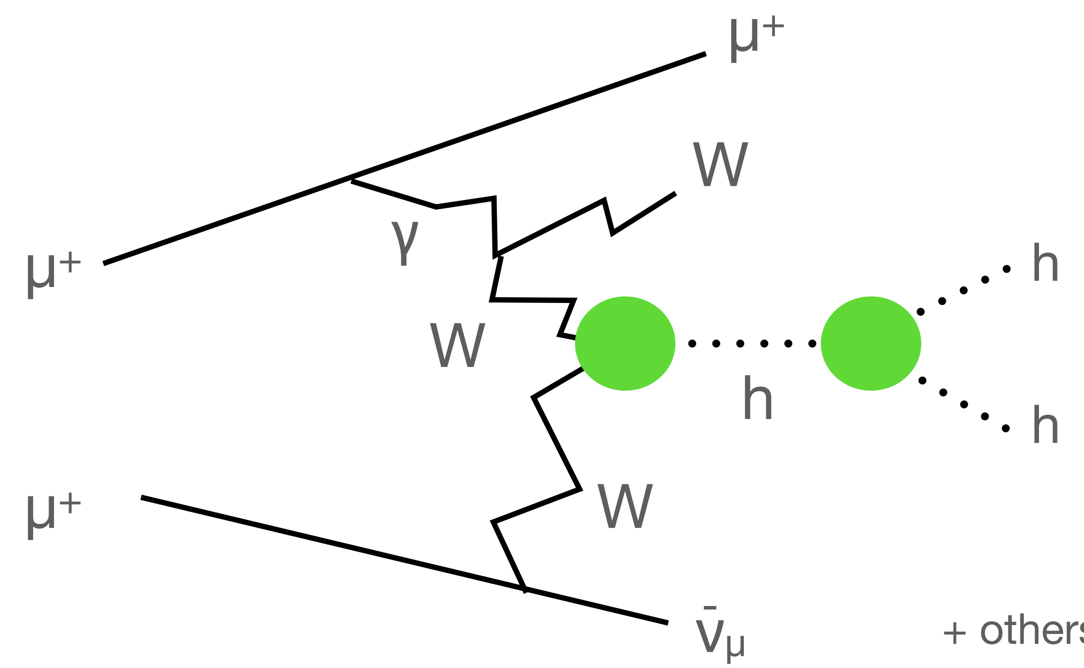
about a factor of two smaller than $\mu^+\mu^-$
(not too bad?)



maybe we should plan 5-10TeV colliders.

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





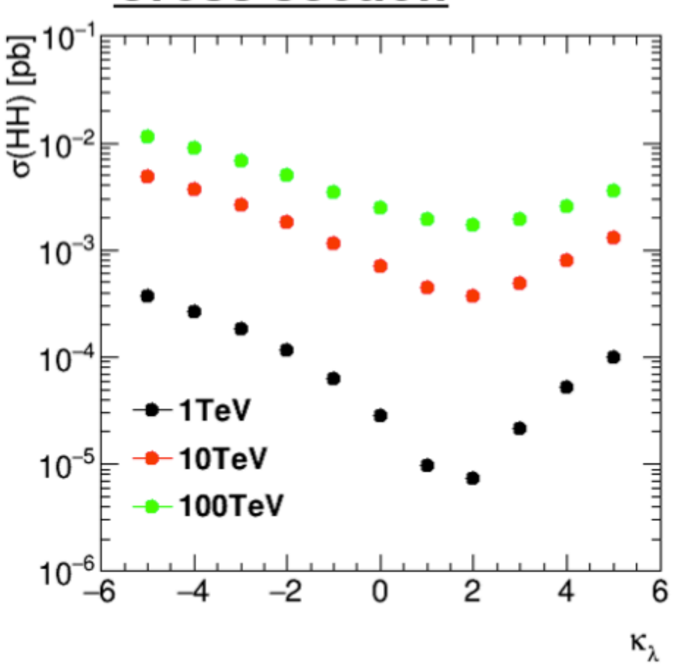
+ others

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

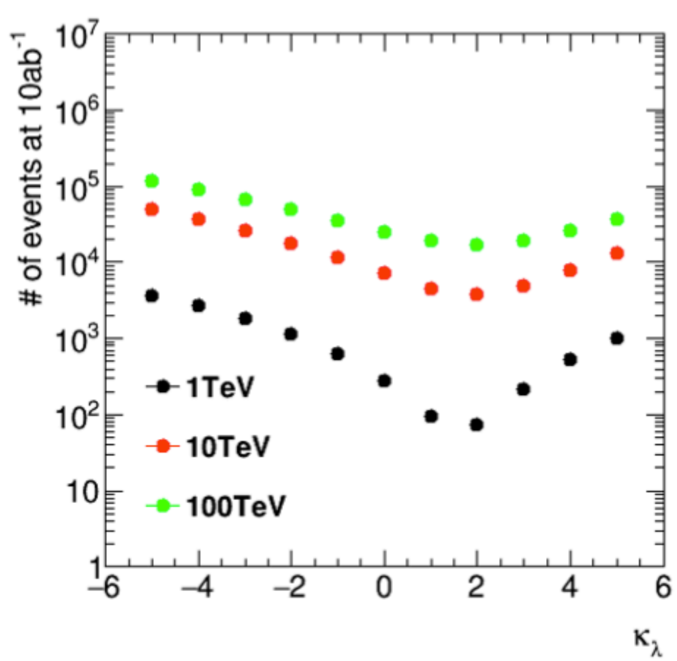
$\sqrt{s}$ [TeV]	ZBF [fb]	Photon emission [fb]
2	0.075	0.010
10	0.62	0.30
20	1.1	0.75

ZBF:

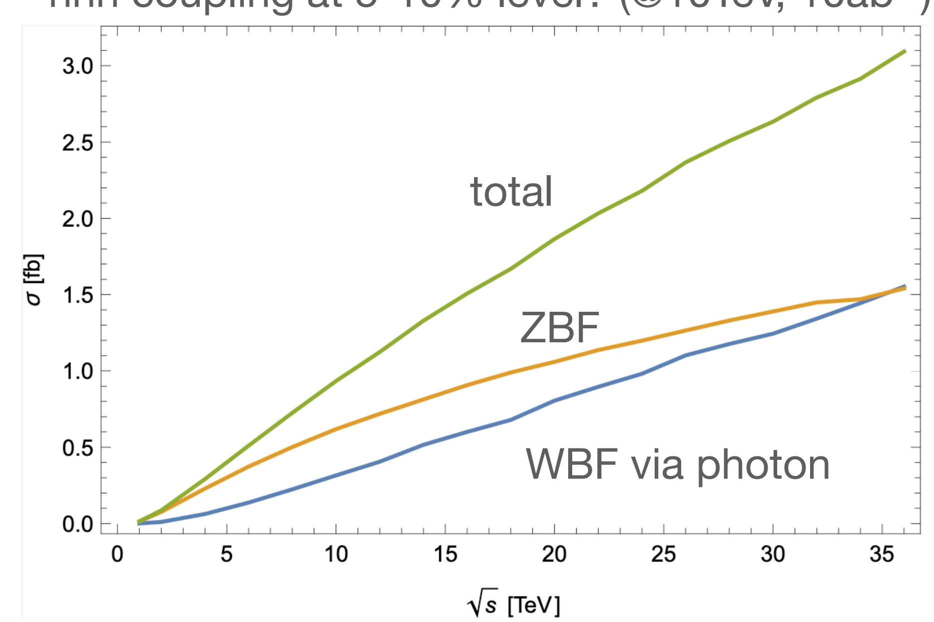
Cross section



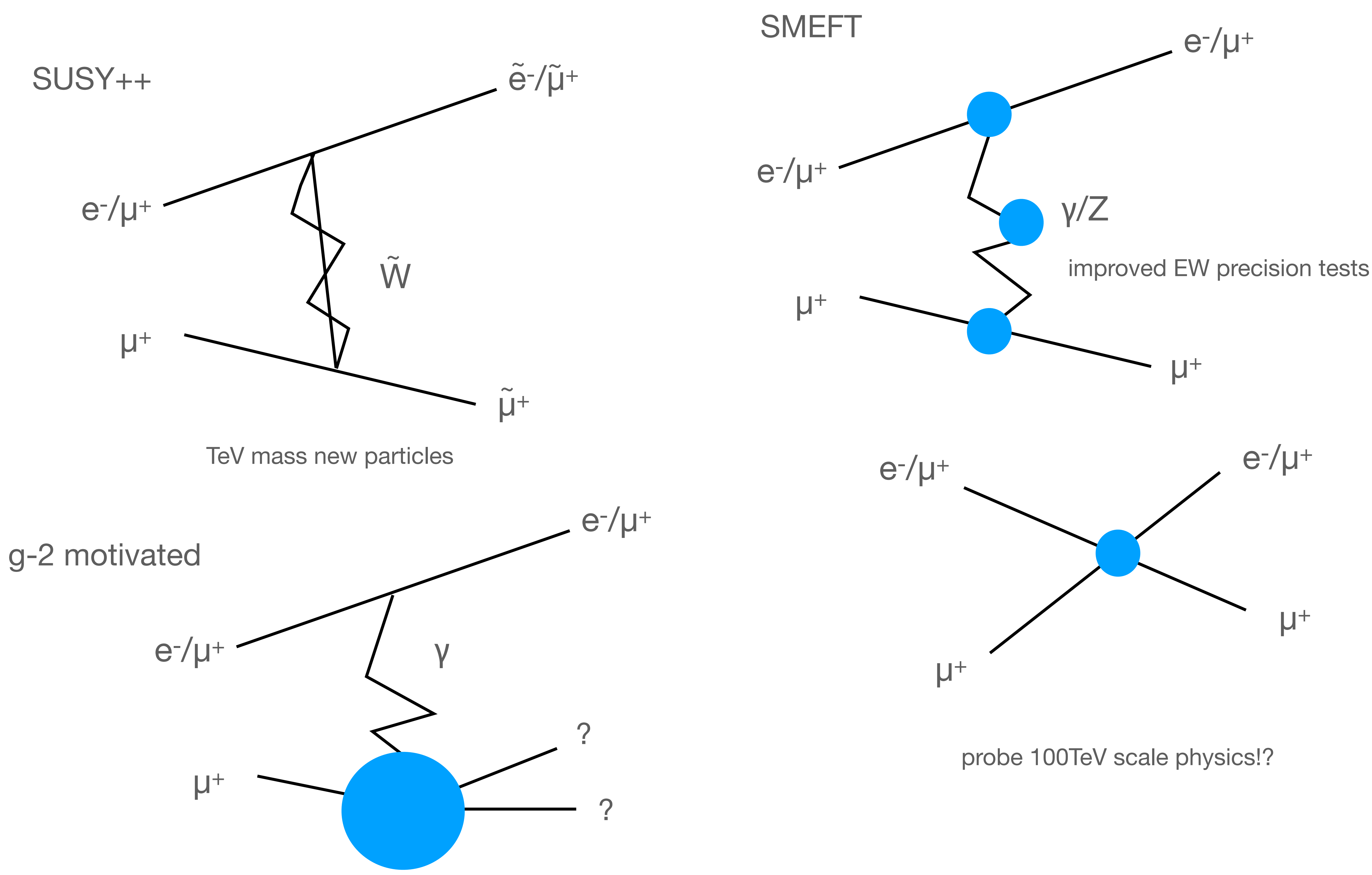
# of Events in 10ab^{-1}



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



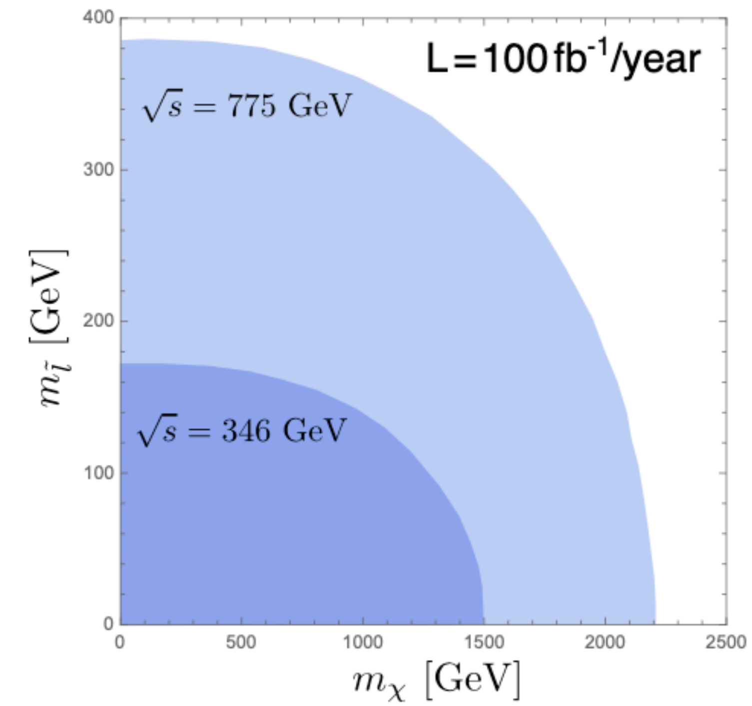
New physics?

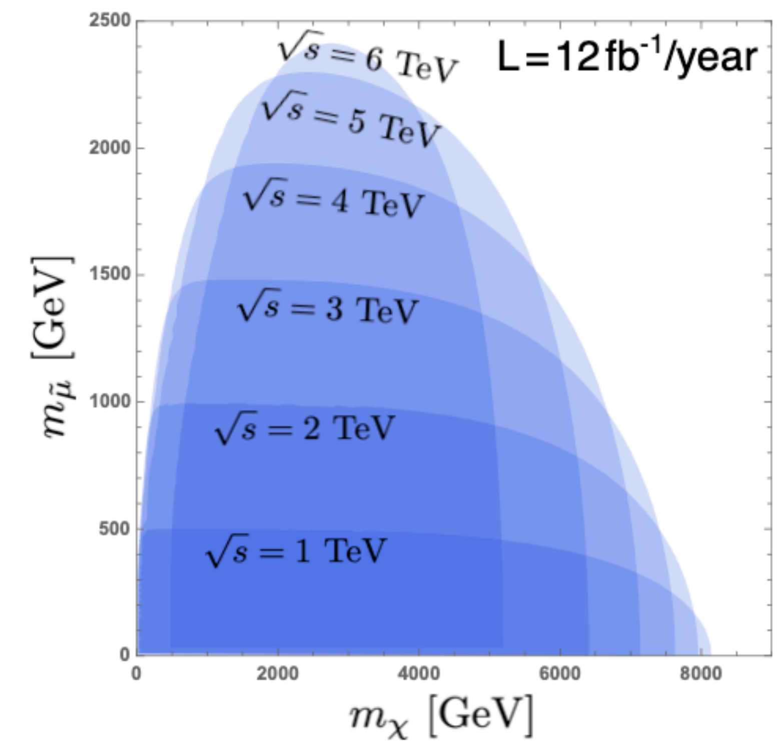


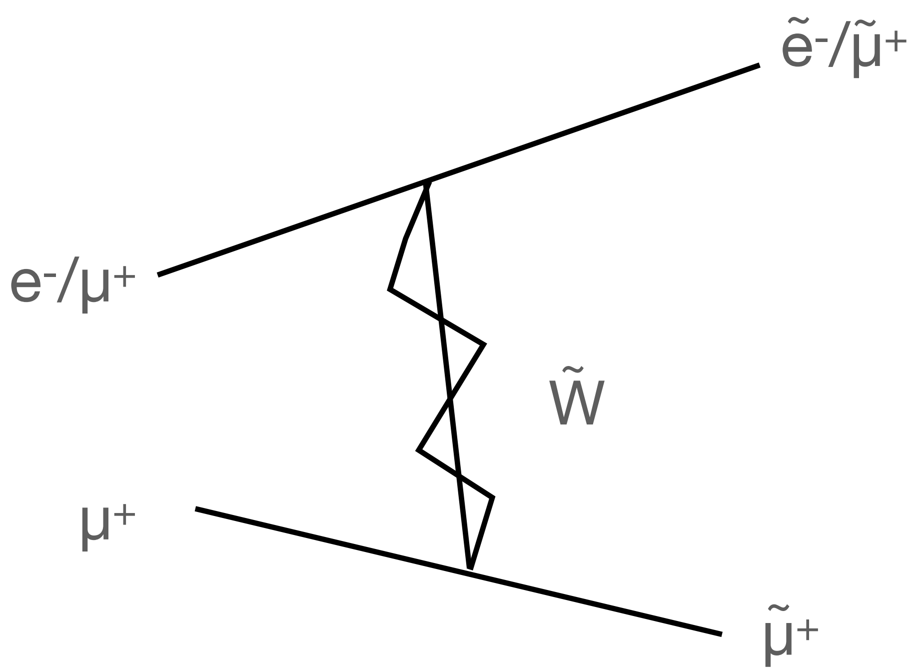
SUSY++
ẽ-/μ̃+
e-/μ+
W̃
μ+
μ̃+
TeV mass new particles
SMEFT
e-/μ+
e-/μ+
γ/Z
improved EW precision tests
μ+
μ+
e-/μ+
e-/μ+
μ+
μ+
probe 100TeV scale physics!?
g-2 motivated
e-/μ+
e-/μ+
γ
?
μ+
?

Supersymmetry

Regions for N_{event}/year > 100.



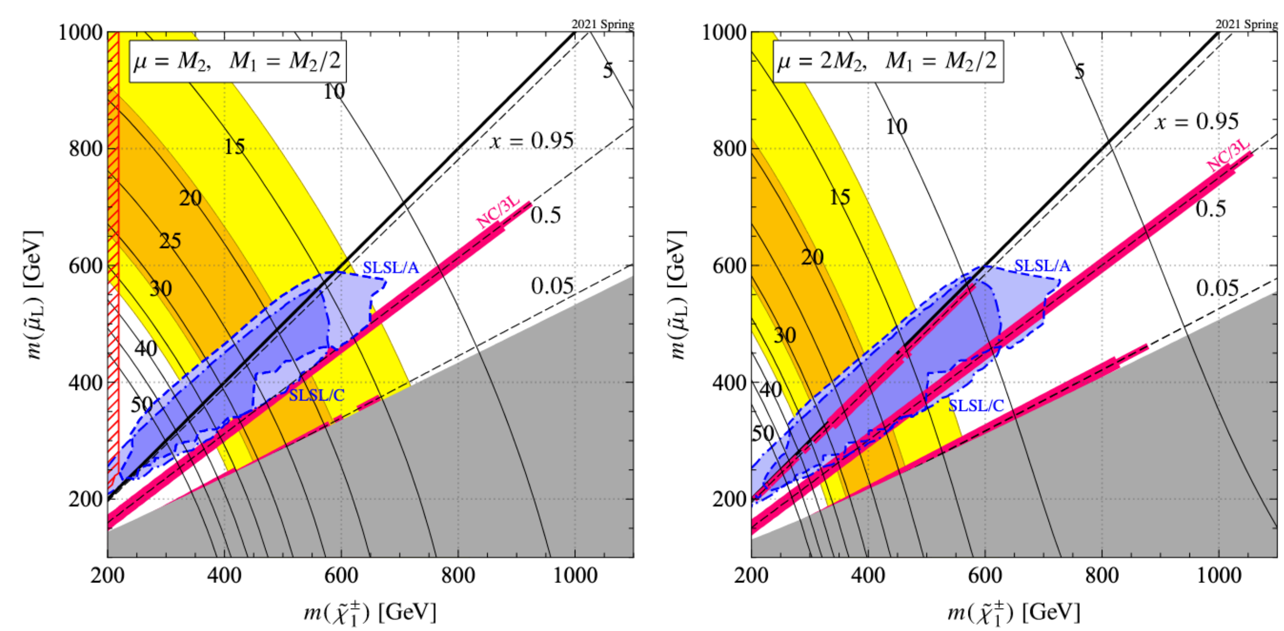




Scalar muons up to TeV even for very heavy gauginos.

Almost completely cover the muon g-2 motivated region.

[Endo, Hamaguchi, Iwamoto, Kitahara ’21]

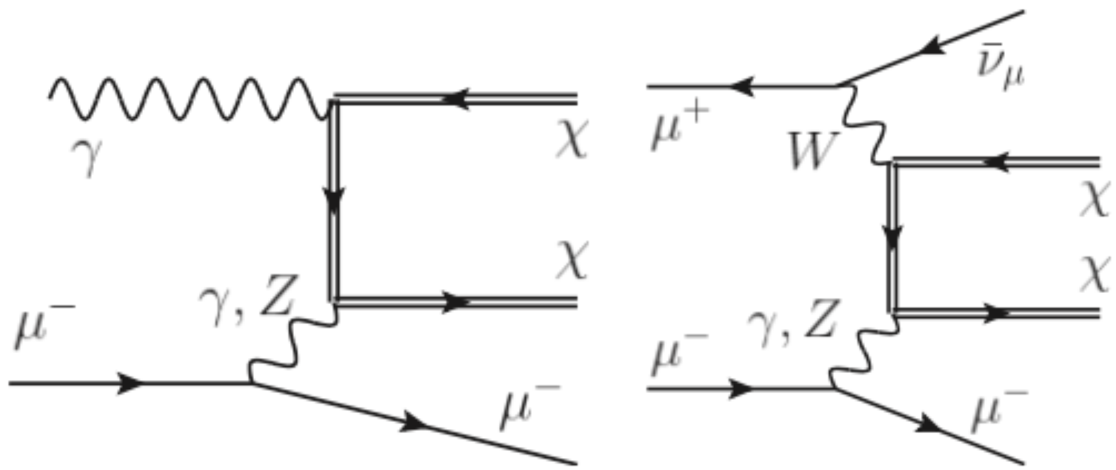


(A) $\mu = M_2,\ M_1 = M_2/2$.

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

DM?

study@μ⁺μ⁻ [Han et al. '20]



same search is possible at μ⁺μ⁺

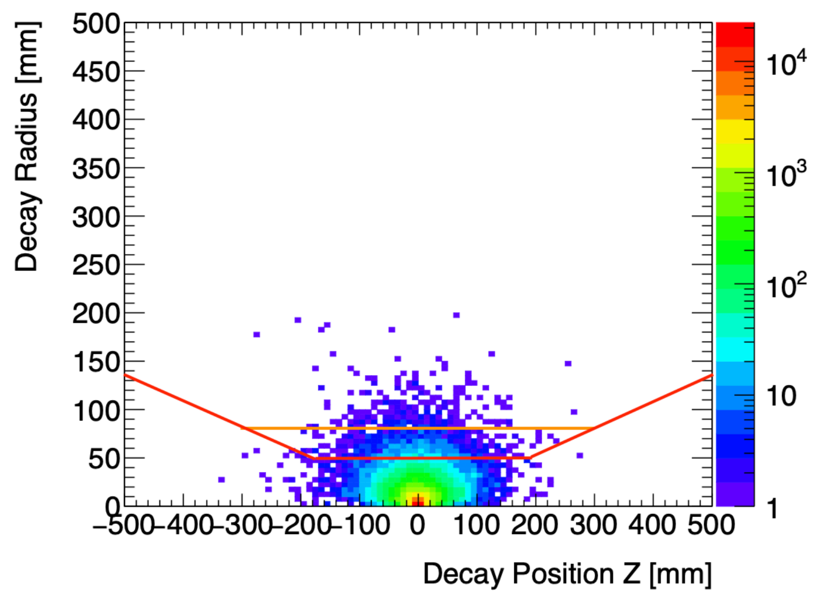
mono-μ

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

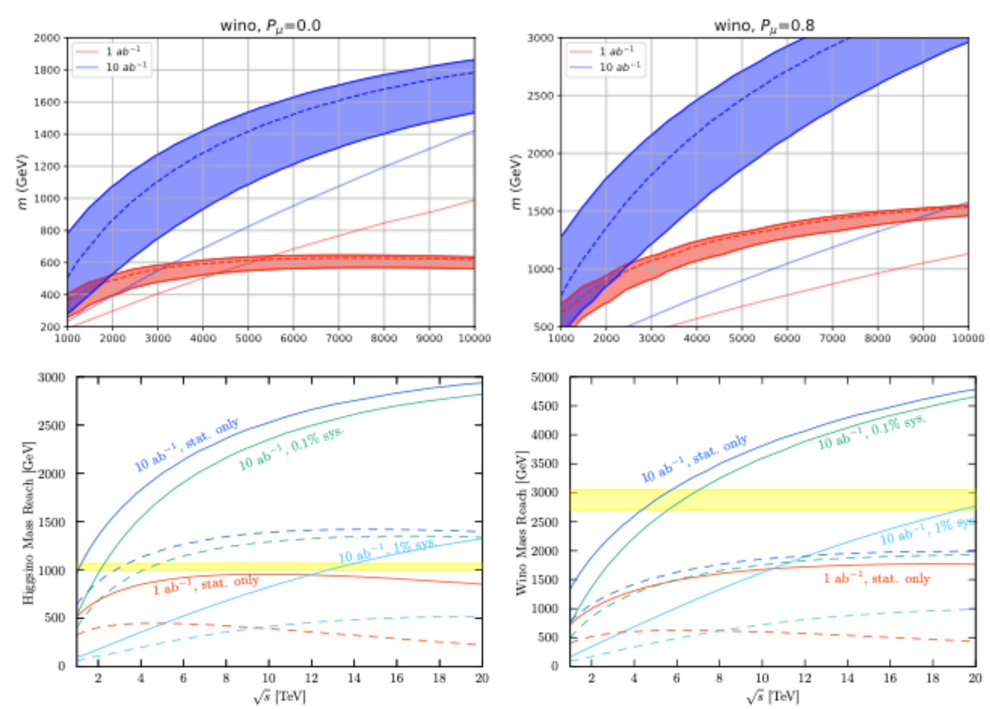


崩壊半径
- Case A > 80 mm
- Case B > 50 mm

$|\eta| < 2.0$
を再構成できると仮定

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

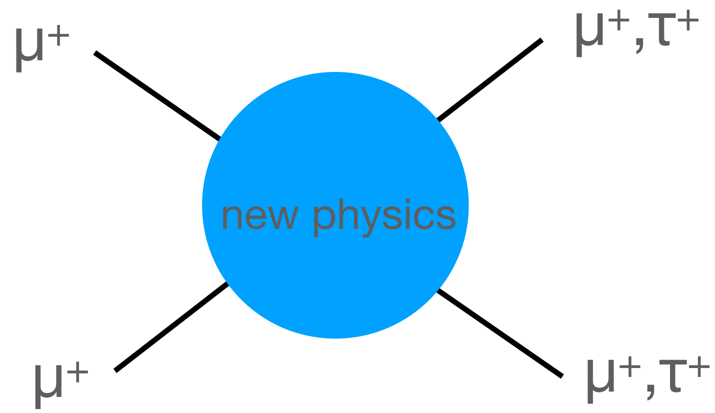
indirect search: [Fukuda, Moroi, Niki, Wei '23]



(a) Higgsino (b) Wino

[Okabe, Shirai '23]

muon specific



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

reach to O(100)TeV physics!

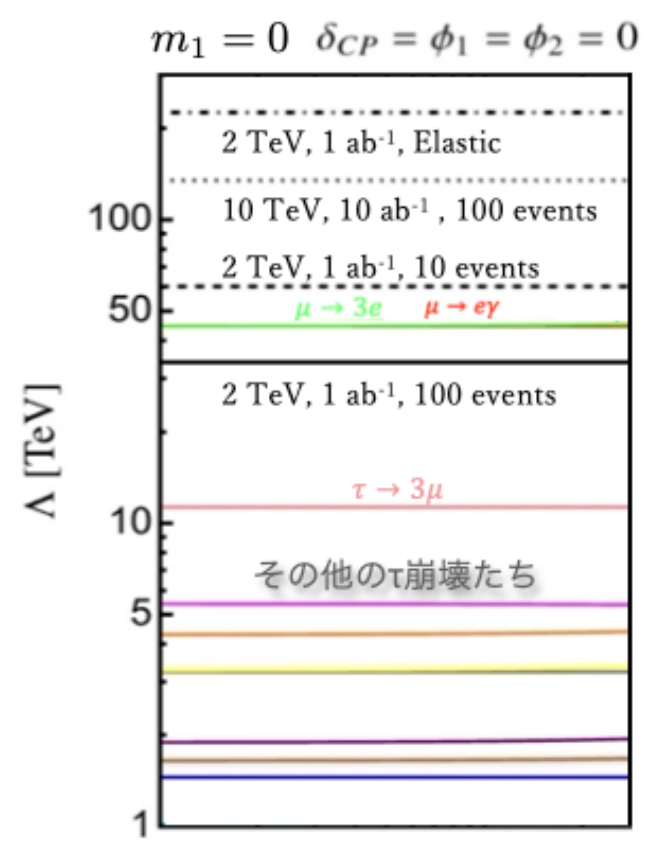
elastic scattering and lepton flavor violating scattering.

[Fridell, RK, Takai ’23]

[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
$C_{\underset{\mu\mu\mu\mu}{\ell\ell}}$	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 $16° \leq \theta_i \leq 164°$.



Summary

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

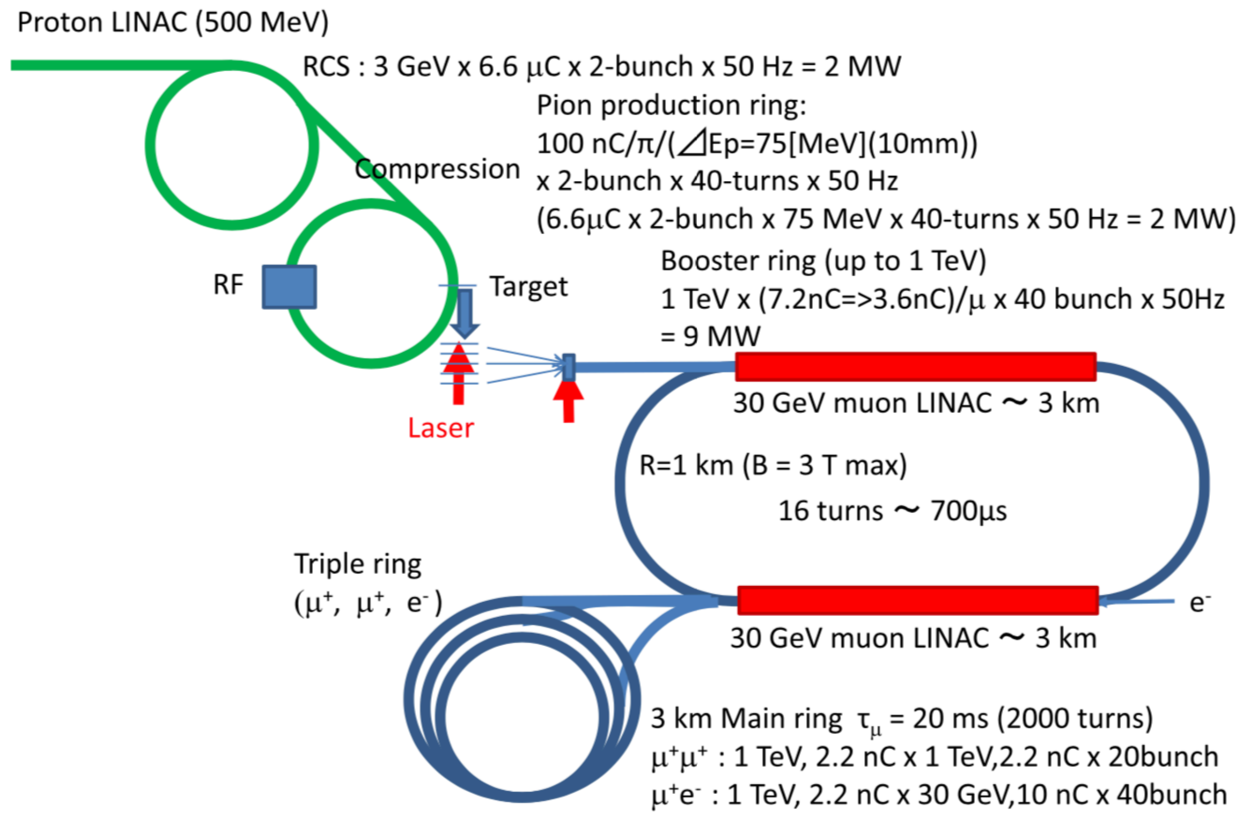


Fig. 1. Conceptual design of the $\mu^+e^-/\mu^+\mu^+$ collider.

by Cari Cesarotti