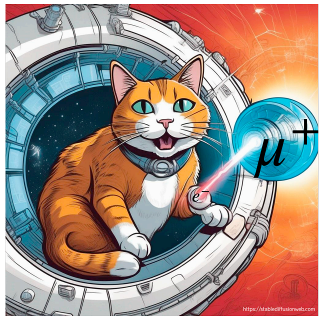


μTRISTAN

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.)

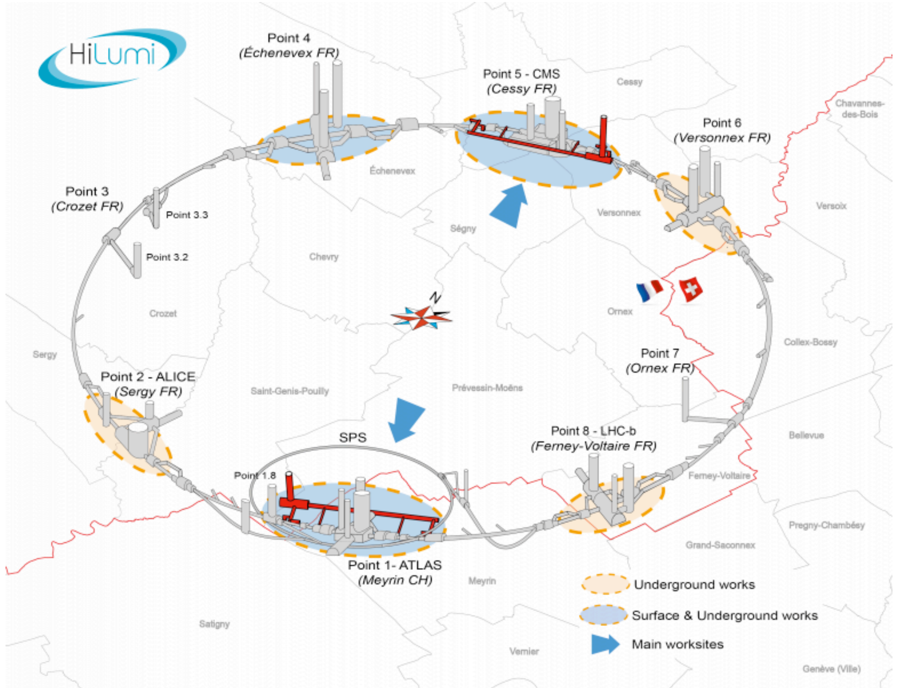
BSM50 Workshop@Quy Nhon, Vietnam, January 7-13, 2024

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

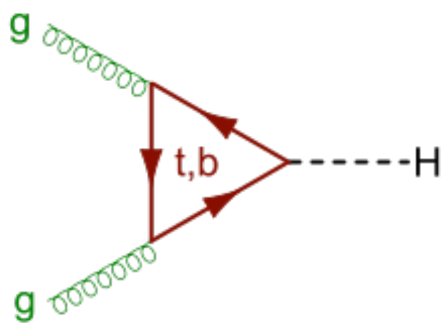


HL-LHC (2029?-)

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

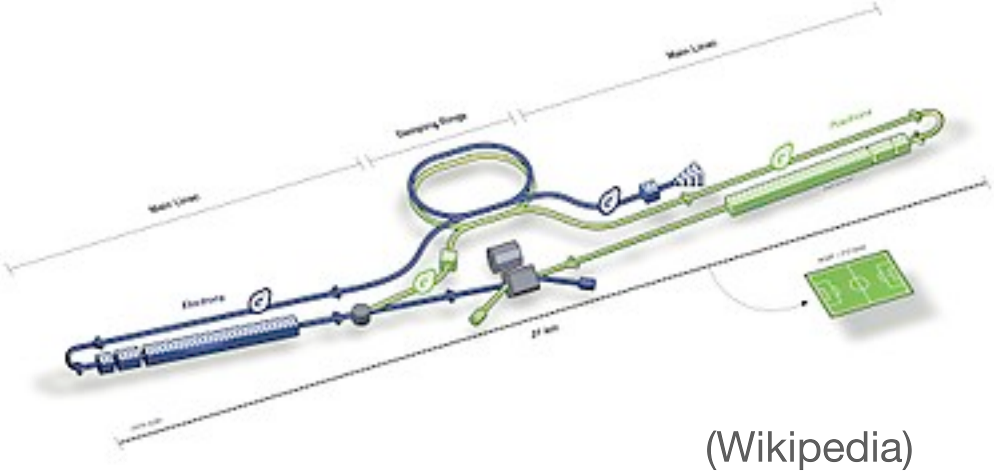
O(100M) Higgs bosons

(Although hard to identify)



Higgs coupling at 1% level.

(LHC measures at a few - 10% level)



(Wikipedia)

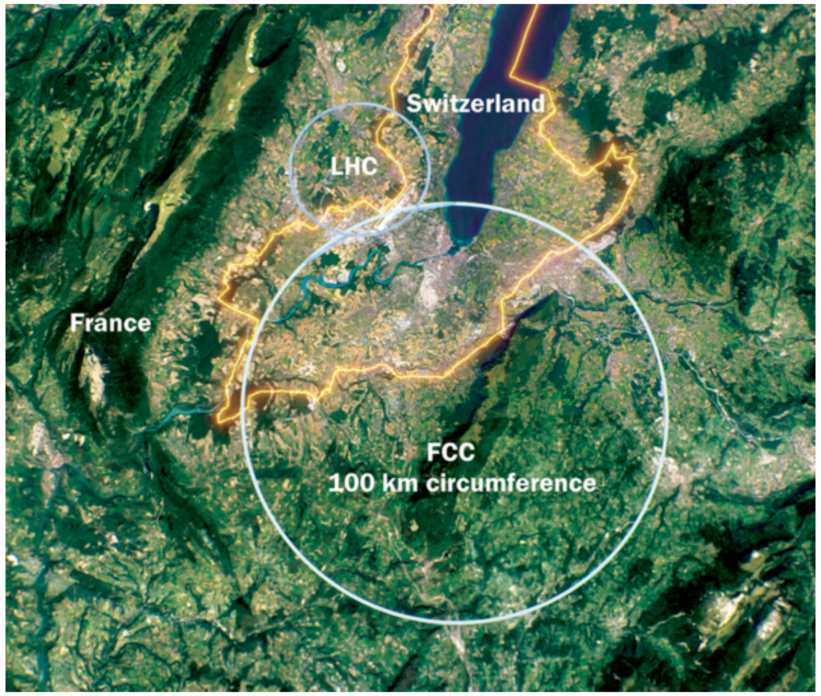
ILC250 (20.5km e^+e^- linear collider) ~ab^{-1}

Extendable to 500GeV, 1TeV

O(1M) Higgs bosons

Measurements of Higgs couplings at the level of 0.1%.

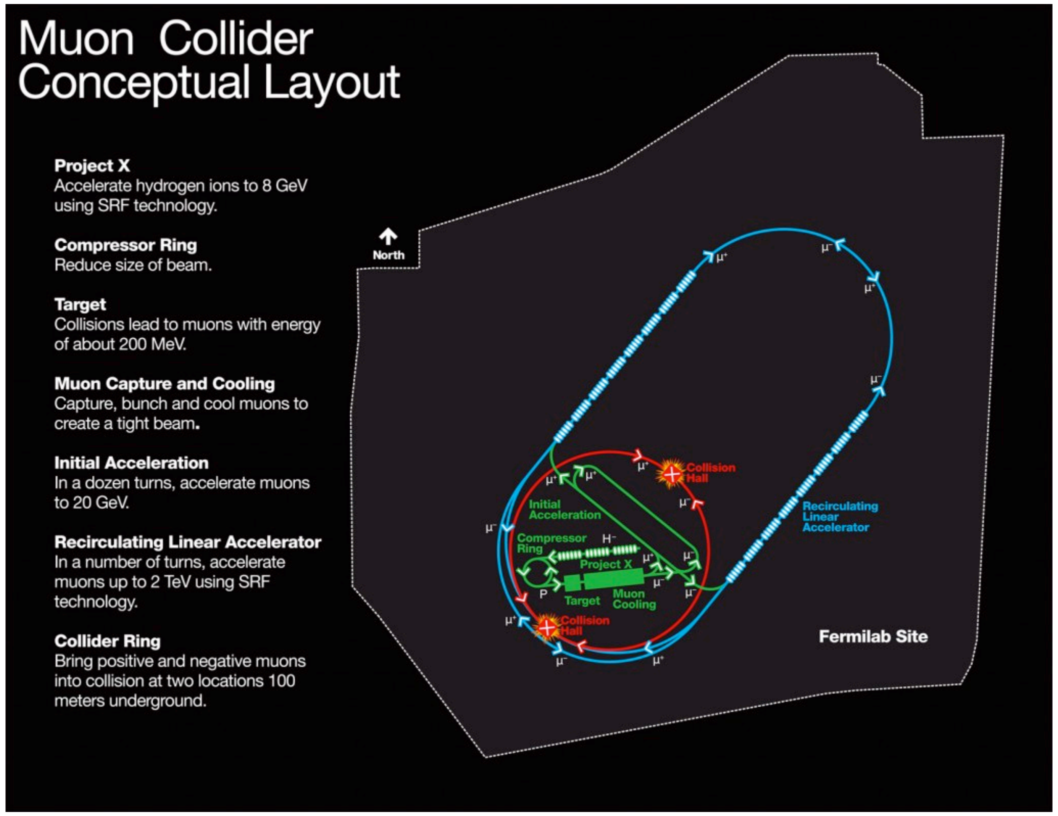
Future colliders?



e^+e^- (90-365GeV) ⟶ pp (100TeV)

Higgs/top factory New physics searches

O(1M) Higgs


Muon Collider Conceptual Layout

Project X
Accelerate hydrogen ions to 8 GeV using SRF technology.

Compressor Ring
Reduce size of beam.

Target
Collisions lead to muons with energy of about 200 MeV.

Muon Capture and Cooling
Capture, bunch and cool muons to create a tight beam.

Initial Acceleration
In a dozen turns, accelerate muons to 20 GeV.

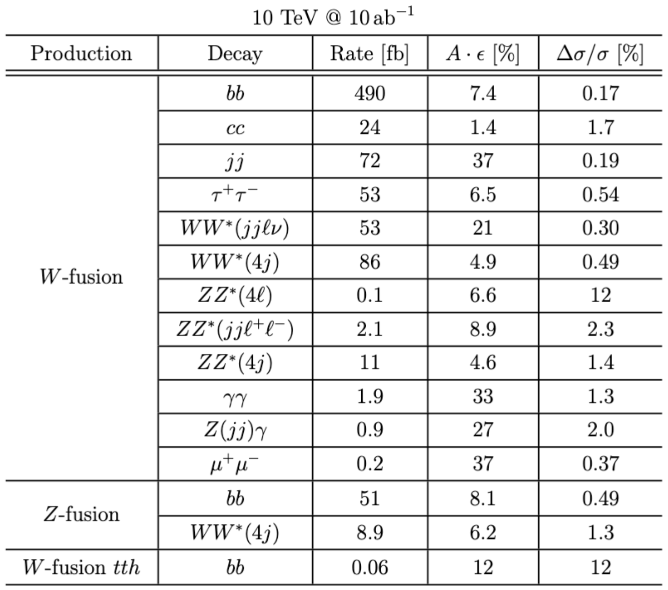
Recirculating Linear Accelerator
In a number of turns, accelerate muons up to 2 TeV using SRF technology.

Collider Ring
Bring positive and negative muons into collision at two locations 100 meters underground.

from symmetry

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

[muon smasher's guide]


10 TeV @ $10\,\mathrm{ab}^{-1}$

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

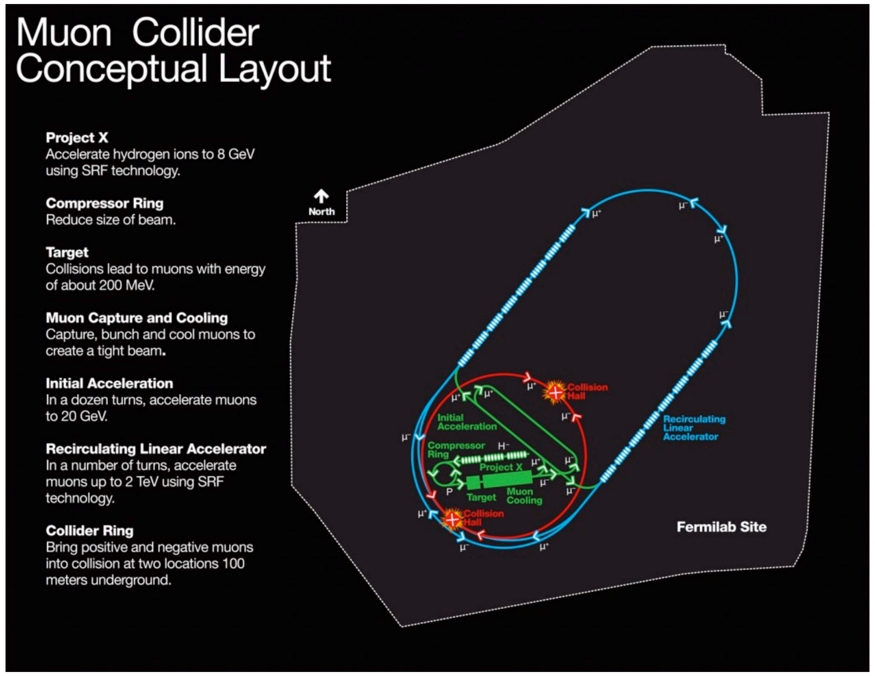
Fantastic!

A lot of Higgs bosons through WW fusion.

Direct reach to 10TeV physics!

muon collider

this is what we want!



Muon Collider
Conceptual Layout

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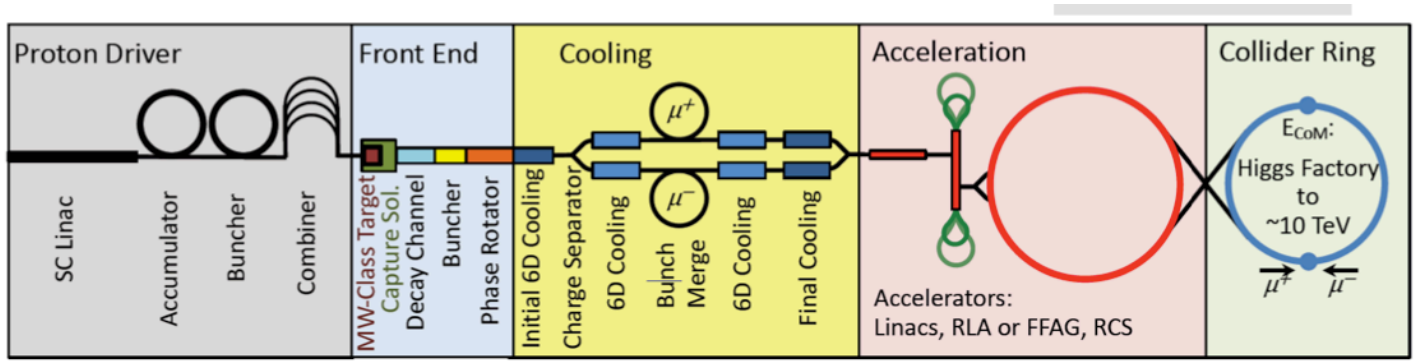
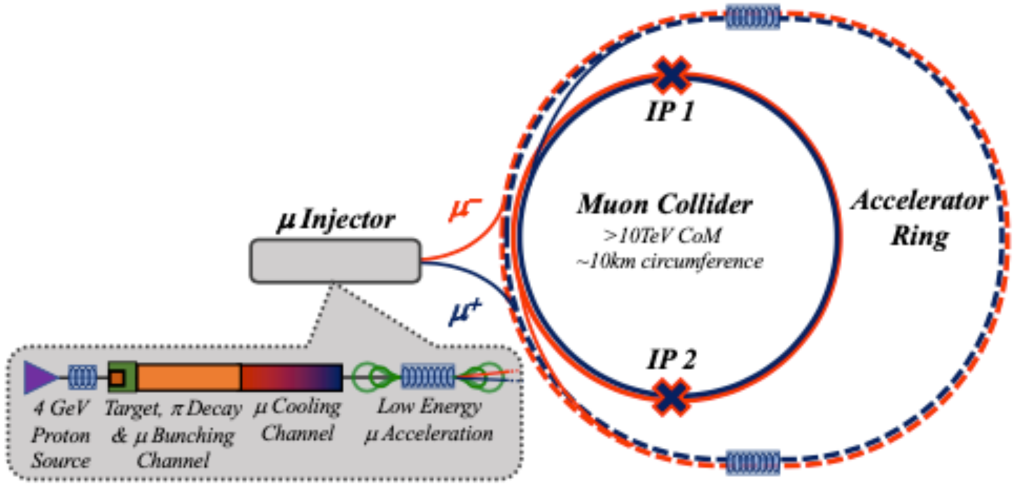
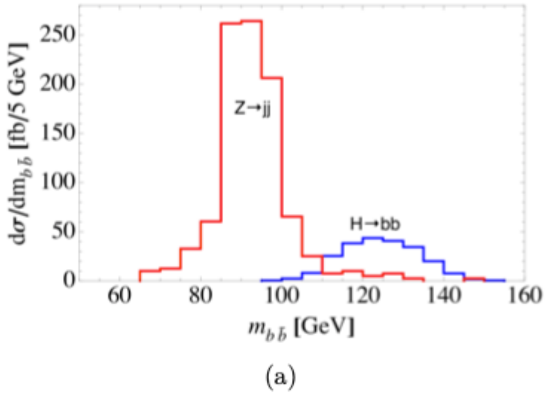


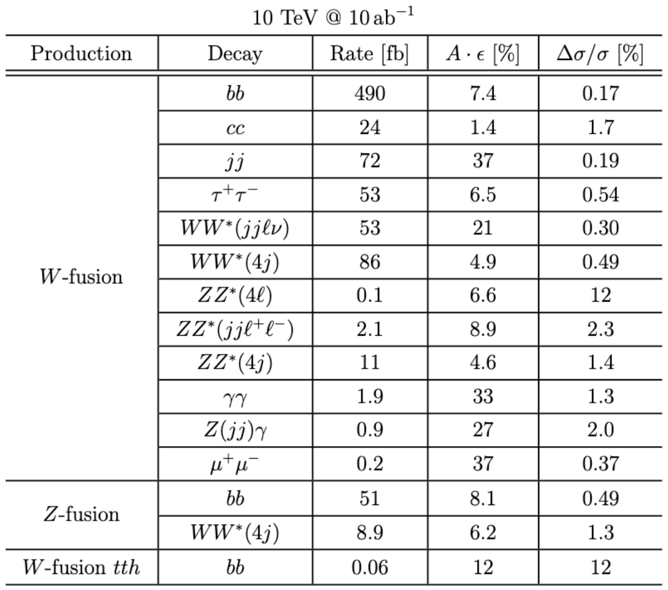


[MAP collaboration]



(a)

[Han, Liu, Low, Wang '20]



10 TeV @ 10 ab^{-1}

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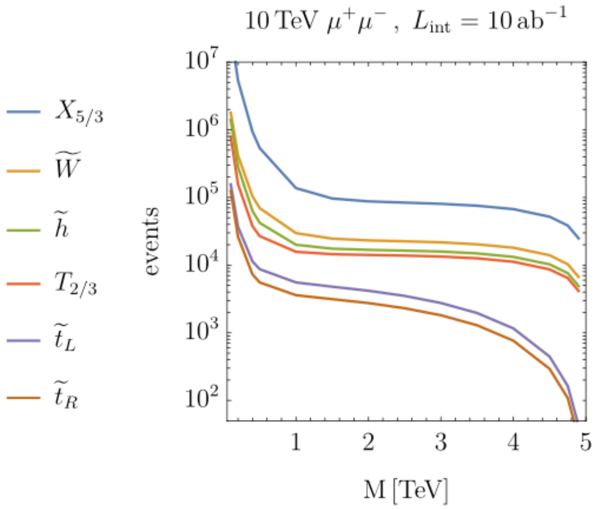
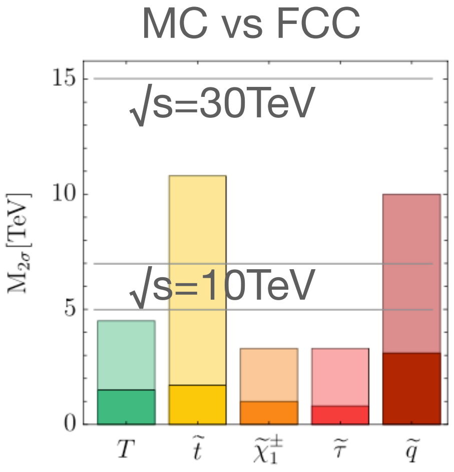
W-fusion tth	bb	0.06	12	12

[muon smasher's guide]





[Buttazzo, Franceschini, Wulzer '20]

[Snowmass report '22]

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

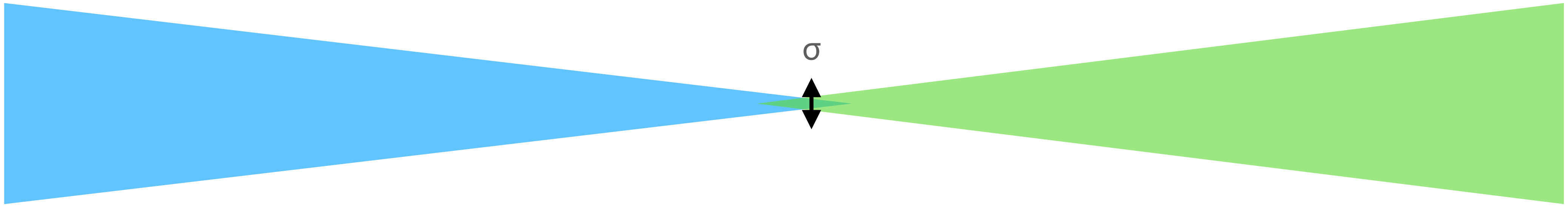
of course, there are technical challenges to realize this collider.

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

$\sigma=1\mu\text{m}$

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

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

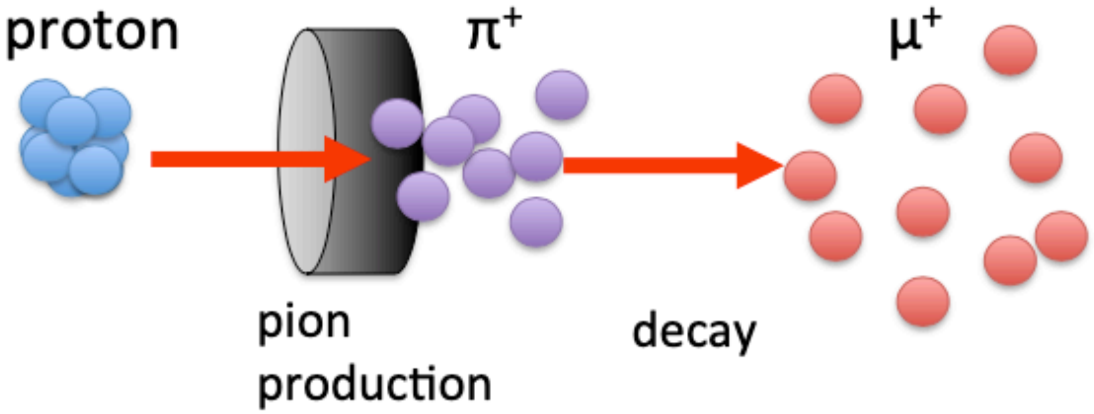
We want ab^{-1} level luminosity for physics (HL-LHC, ILC)

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

Muon beam

Too much spread.

Conventional muon beam



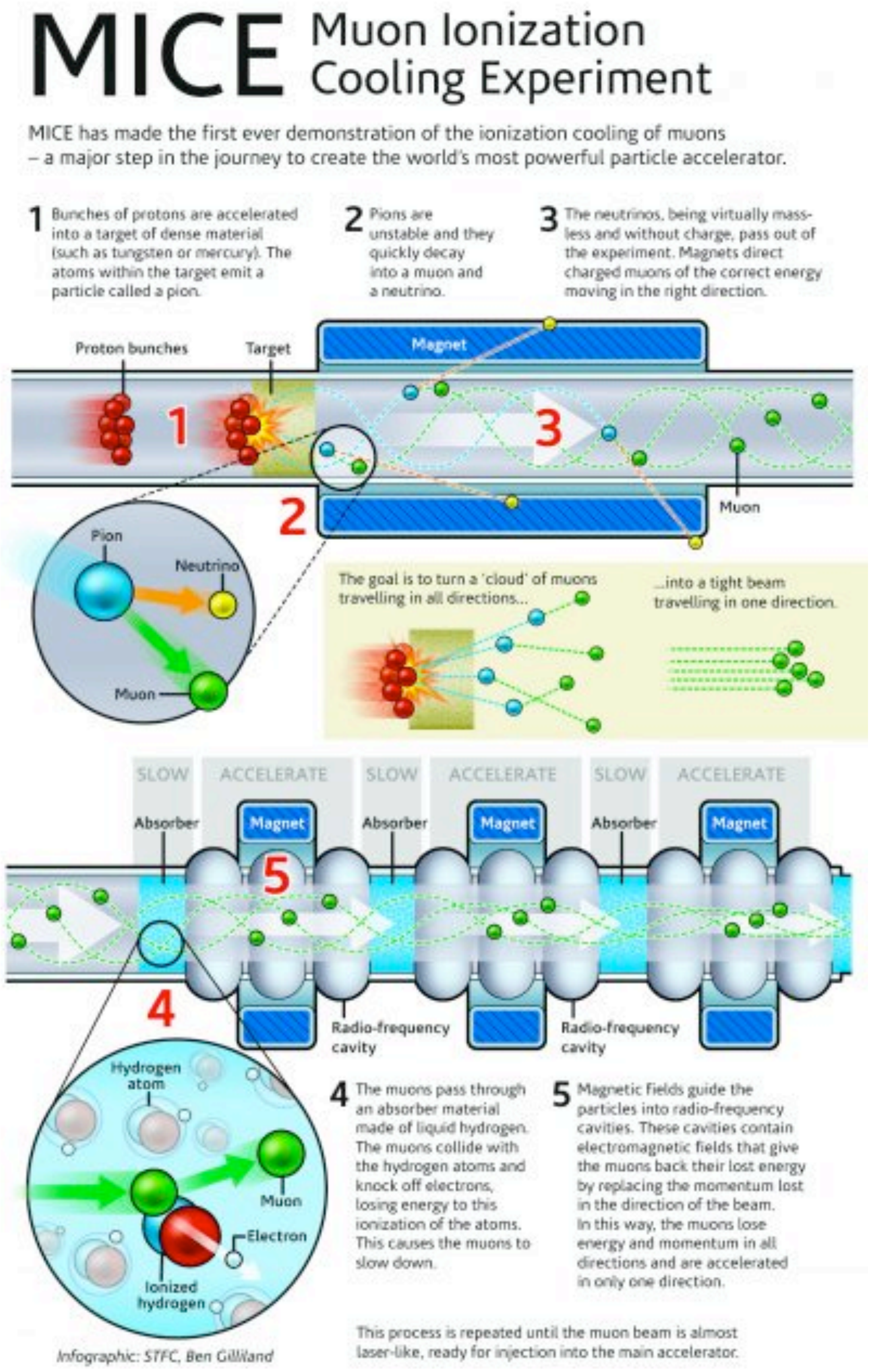
emittance

$\sim 1000\pi$ mm･mrad = π mm

Strong focusing
Muon loss
BG π contamination

Taken from Mibe-san’s lecture slide

Muon cooling



MICE Muon Ionization Cooling Experiment

MICE has made the first ever demonstration of the ionization cooling of muons – a major step in the journey to create the world's most powerful particle accelerator.

1 Bunches of protons are accelerated into a target of dense material (such as tungsten or mercury). The atoms within the target emit a particle called a pion.

2 Pions are unstable and they quickly decay into a muon and a neutrino.

3 The neutrinos, being virtually massless and without charge, pass out of the experiment. Magnets direct charged muons of the correct energy moving in the right direction.

The goal is to turn a 'cloud' of muons travelling in all directions...

...into a tight beam travelling in one direction.

4 The muons pass through an absorber material made of liquid hydrogen. The muons collide with the hydrogen atoms and knock off electrons, losing energy to this ionization of the atoms. This causes the muons to slow down.

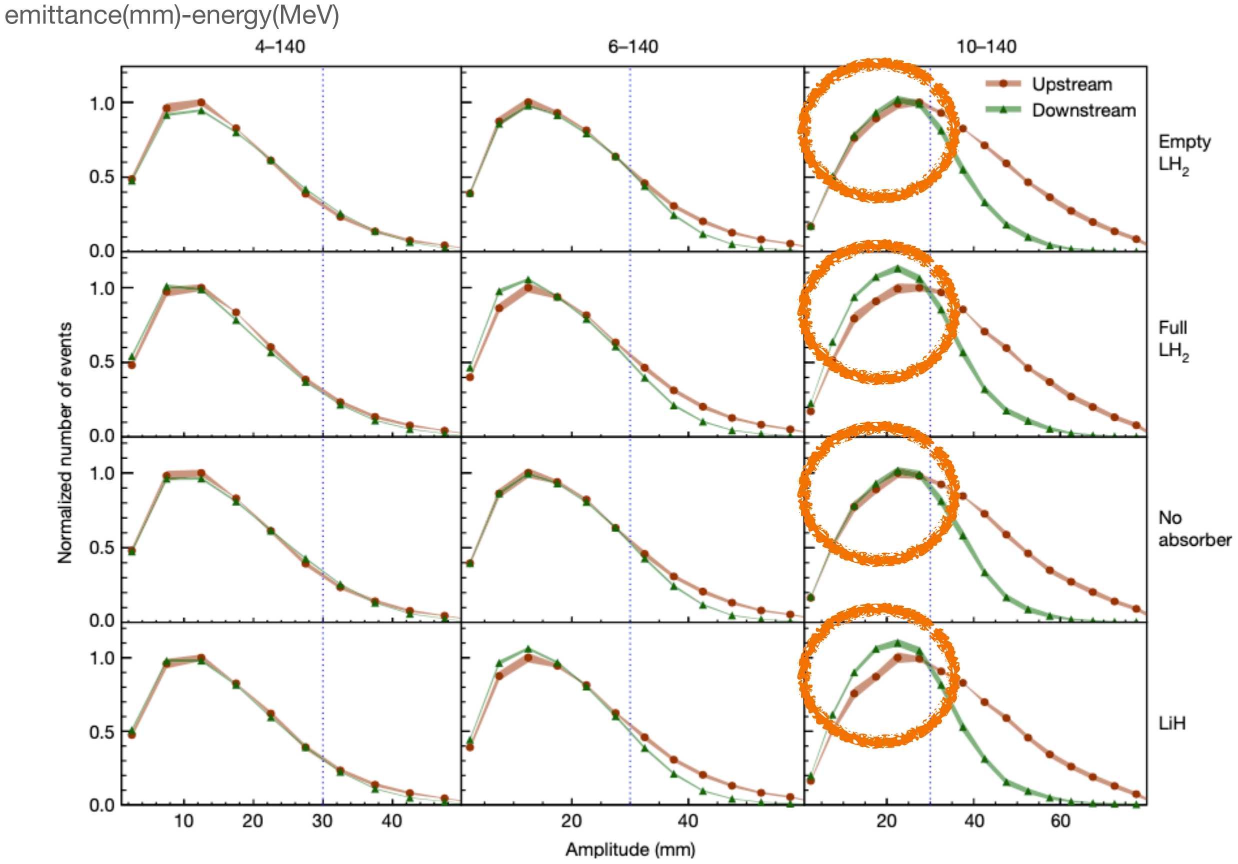
5 Magnetic fields guide the particles into radio-frequency cavities. These cavities contain electromagnetic fields that give the muons back their lost energy by replacing the momentum lost in the direction of the beam. In this way, the muons lose energy and momentum in all directions and are accelerated in only one direction.

This process is repeated until the muon beam is almost laser-like, ready for injection into the main accelerator.

Infographic: STFC, Ben Gilliland

Principle works.

[Nature 2020, MICE collaboration]



simulation and plan for muon cooling of the MAP design

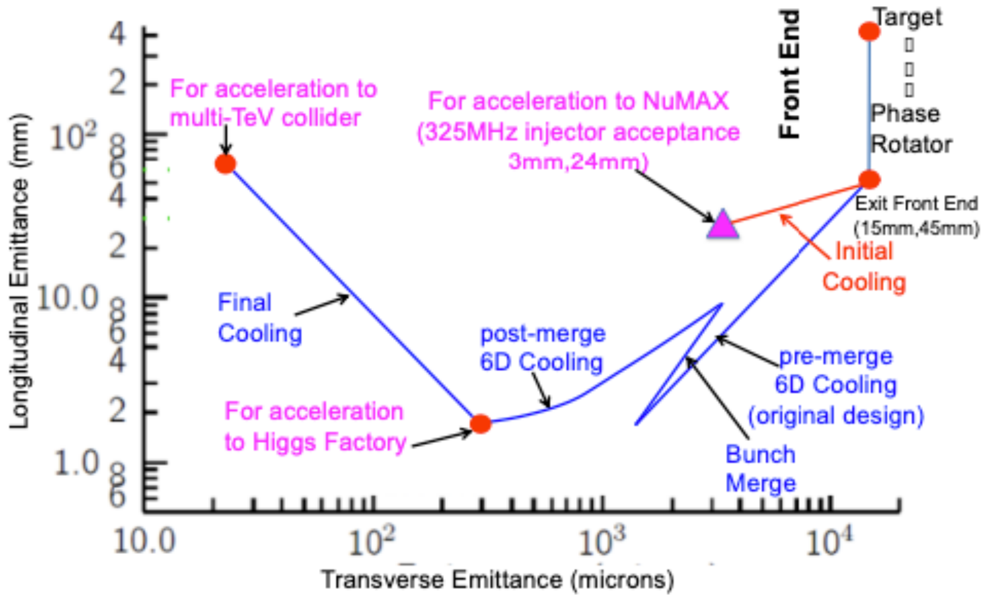
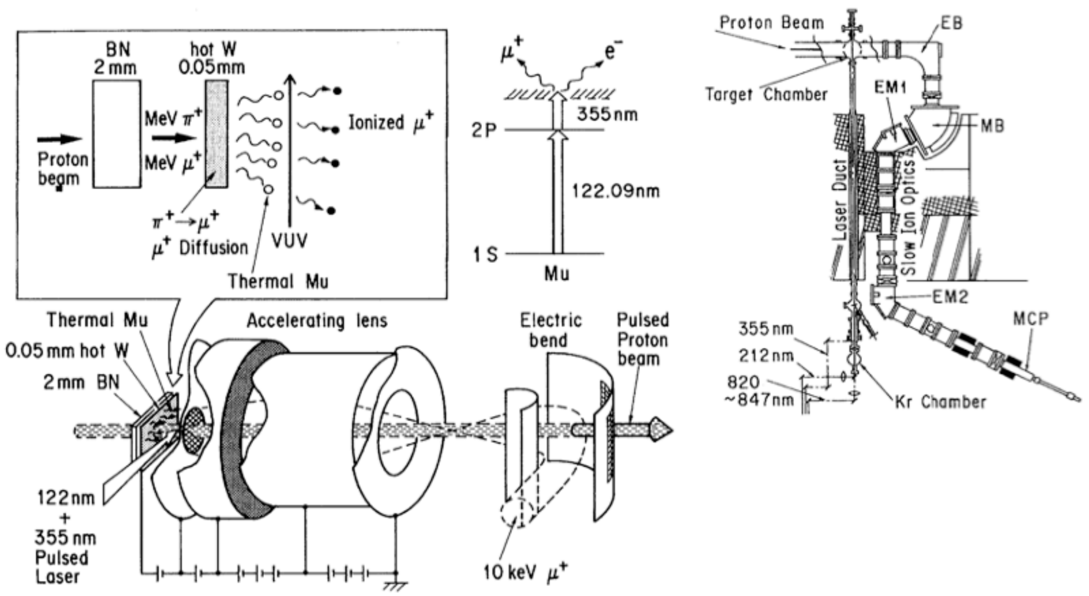


Figure 3. Ionization Cooling path in the 6D phase space.

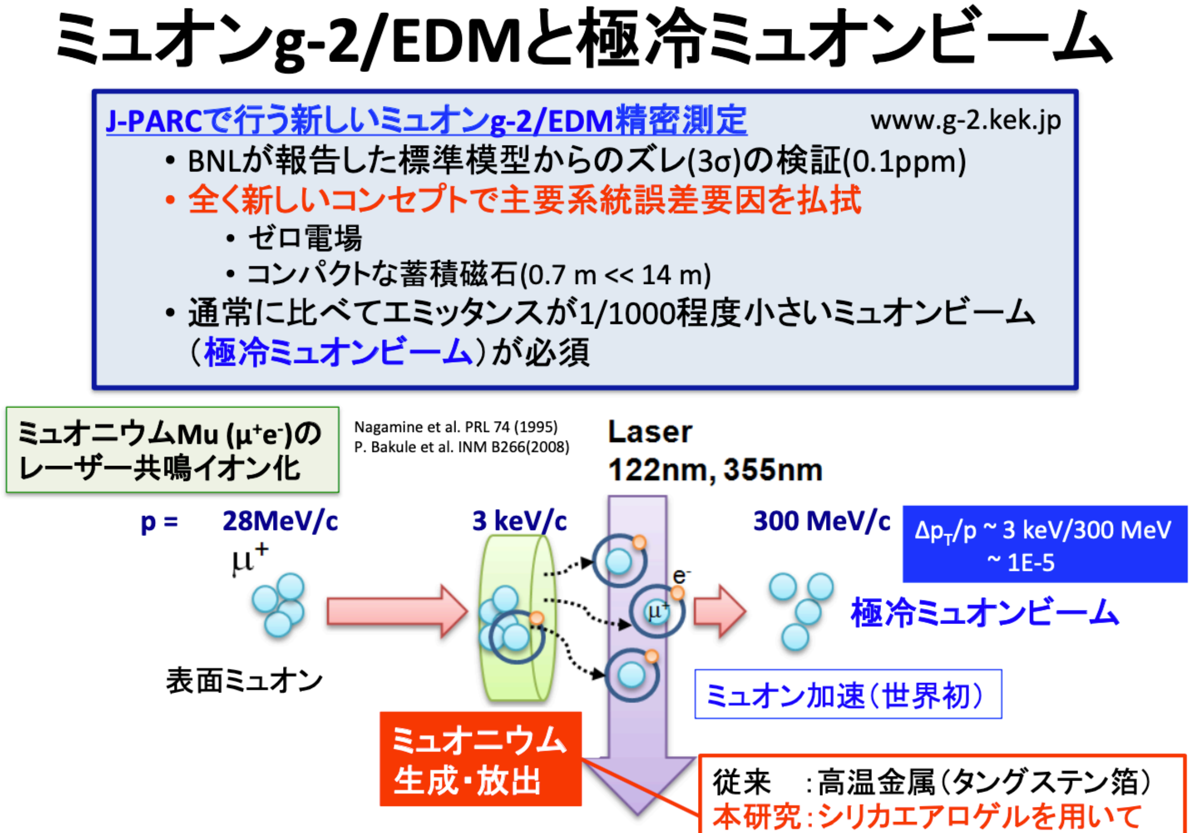
Muon cooling which works for μ+

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.



ミュオンg-2/EDMと極冷ミュオンビーム

J-PARCで行う新しいミュオンg-2/EDM精密測定 www.g-2.kek.jp

- BNLが報告した標準模型からのズレ(3σ)の検証(0.1ppm)
- 全く新しいコンセプトで主要系統誤差要因を払拭
  - ゼロ電場
  - コンパクトな蓄積磁石(0.7 m << 14 m)
- 通常に比べてエミッタンスが1/1000程度小さいミュオンビーム（極冷ミュオンビーム）が必須

ミュオニウムMu (μ^+e^-)のレーザー共鳴イオン化

Nagamine et al. PRL 74 (1995)
P. Bakule et al. INM B266(2008)

Laser
122nm, 355nm

従来　:高温金属（タングステン箔）
本研究:シリカエアロゲルを用いて
室温で高効率生成に成功

Mibe-san's slide

ultra-cold muon is here. ●

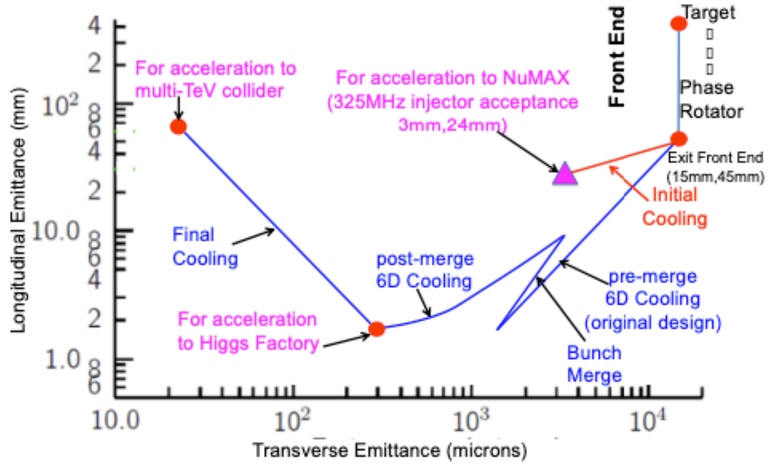
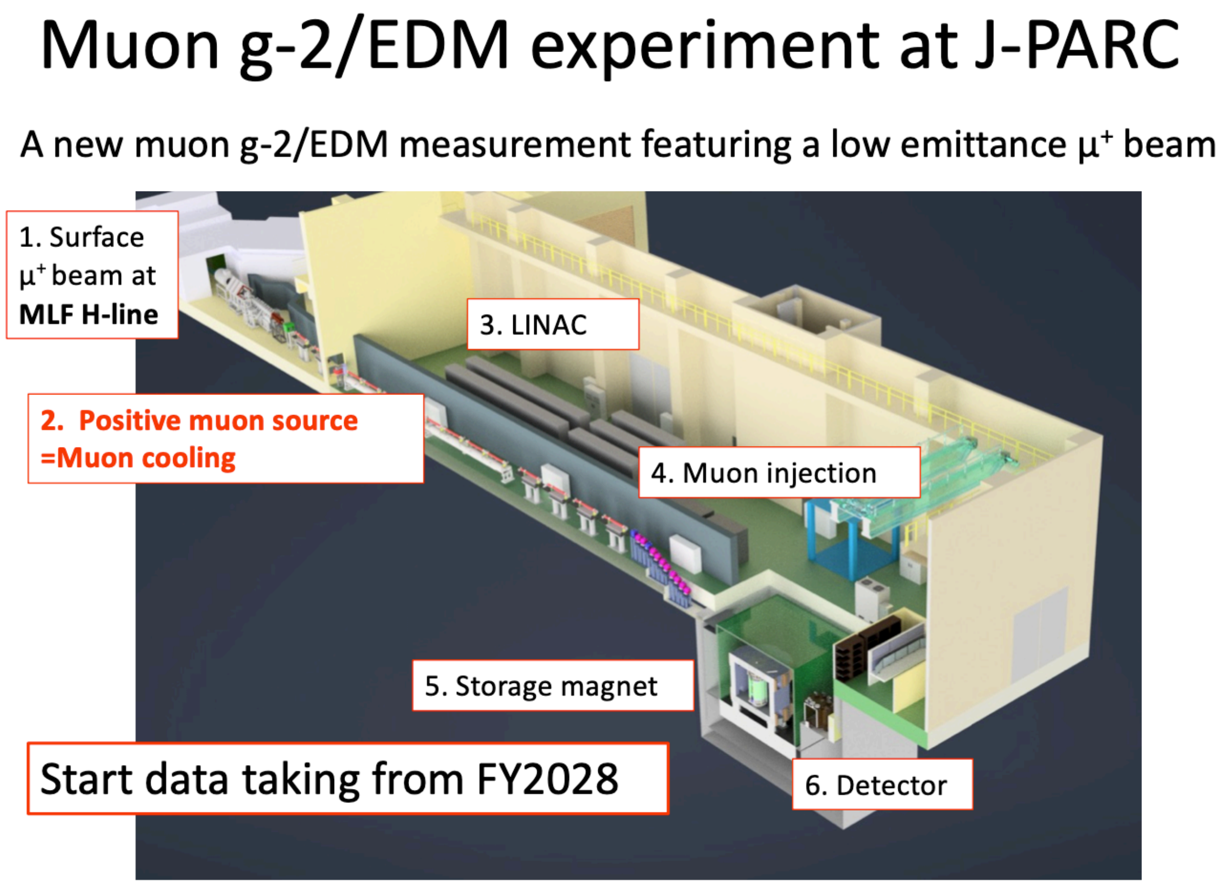


Figure 3. Ionization Cooling path in the 6D phase space.

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

1. Surface μ^+ beam at **MLF H-line**

2. Positive muon source =Muon cooling

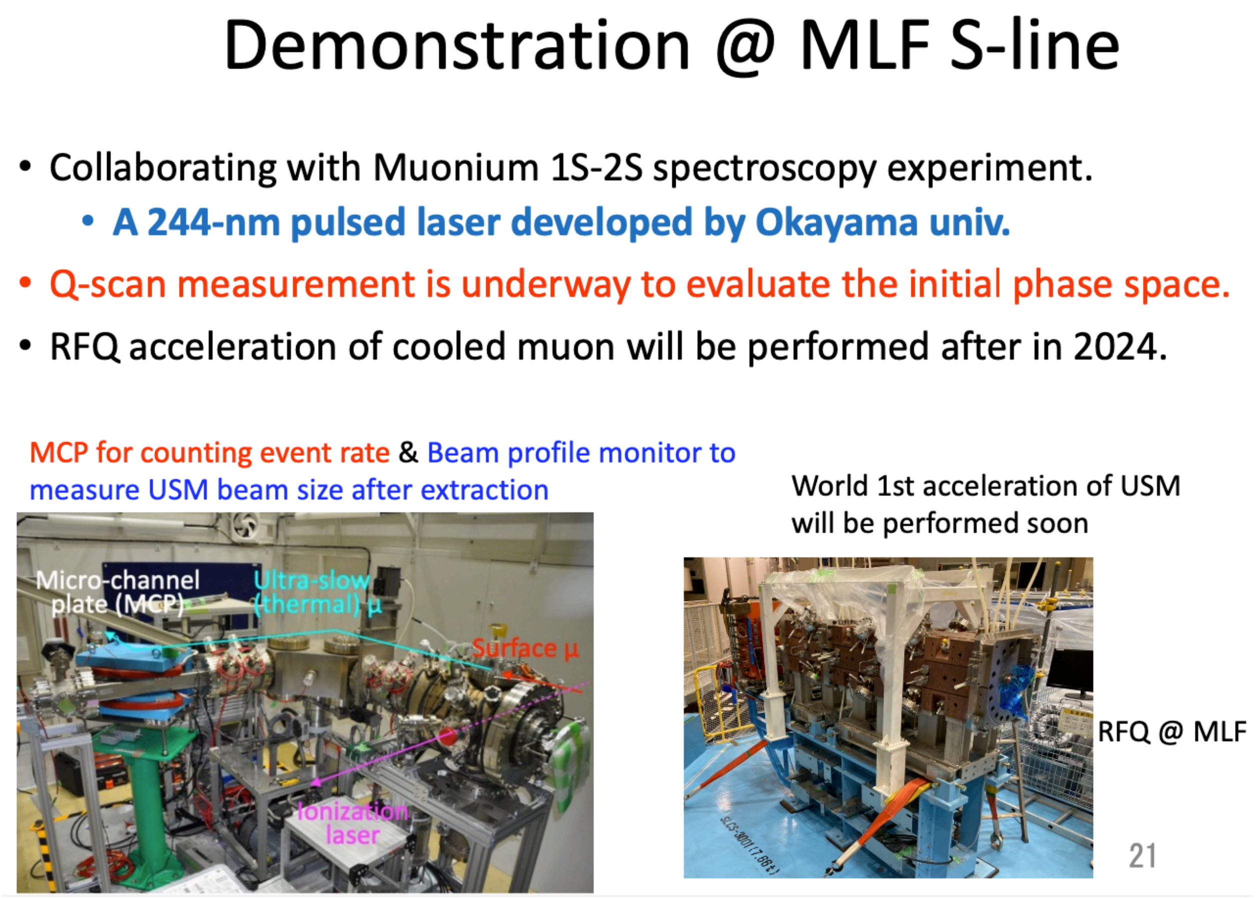
3. LINAC

4. Muon injection

5. Storage magnet

6. Detector

Start data taking from FY2028



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

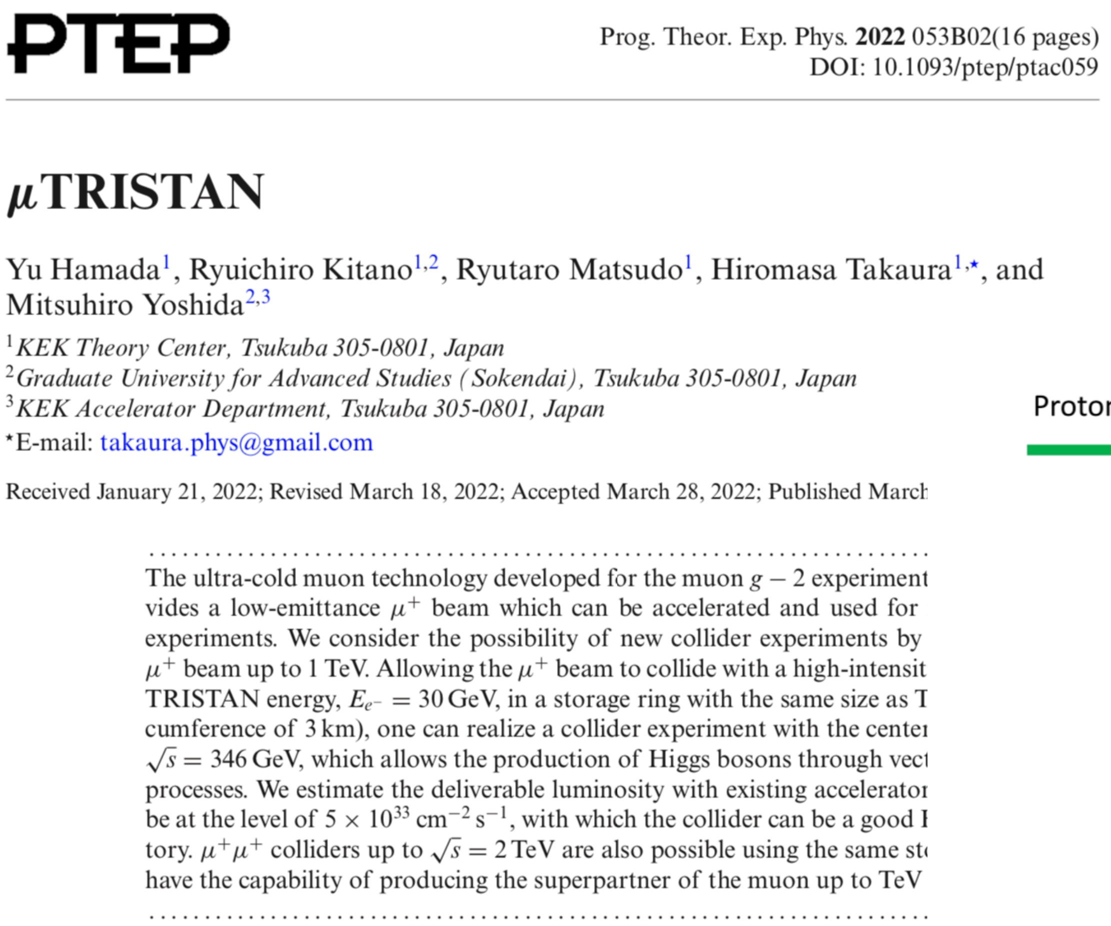
S. Kamioka (talk@muon acceleration workshop, Nov. 2, 2023)

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

μTRISTAN

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[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*
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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, $E_{e^-} = 30\,\text{GeV}$, in a storage ring with the same size as T cumference of 3 km), one can realize a collider experiment with the center $\sqrt{s} = 346\,\text{GeV}$, which allows the production of Higgs bosons through vect processes. We estimate the deliverable luminosity with existing accelerator be at the level of $5 \times 10^{33}\,\text{cm}^{-2}\,\text{s}^{-1}$, with which the collider can be a good I tory. $\mu^+\mu^+$ colliders up to $\sqrt{s} = 2\,\text{TeV}$ are also possible using the same sto have the capability of producing the superpartner of the muon up to TeV

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

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

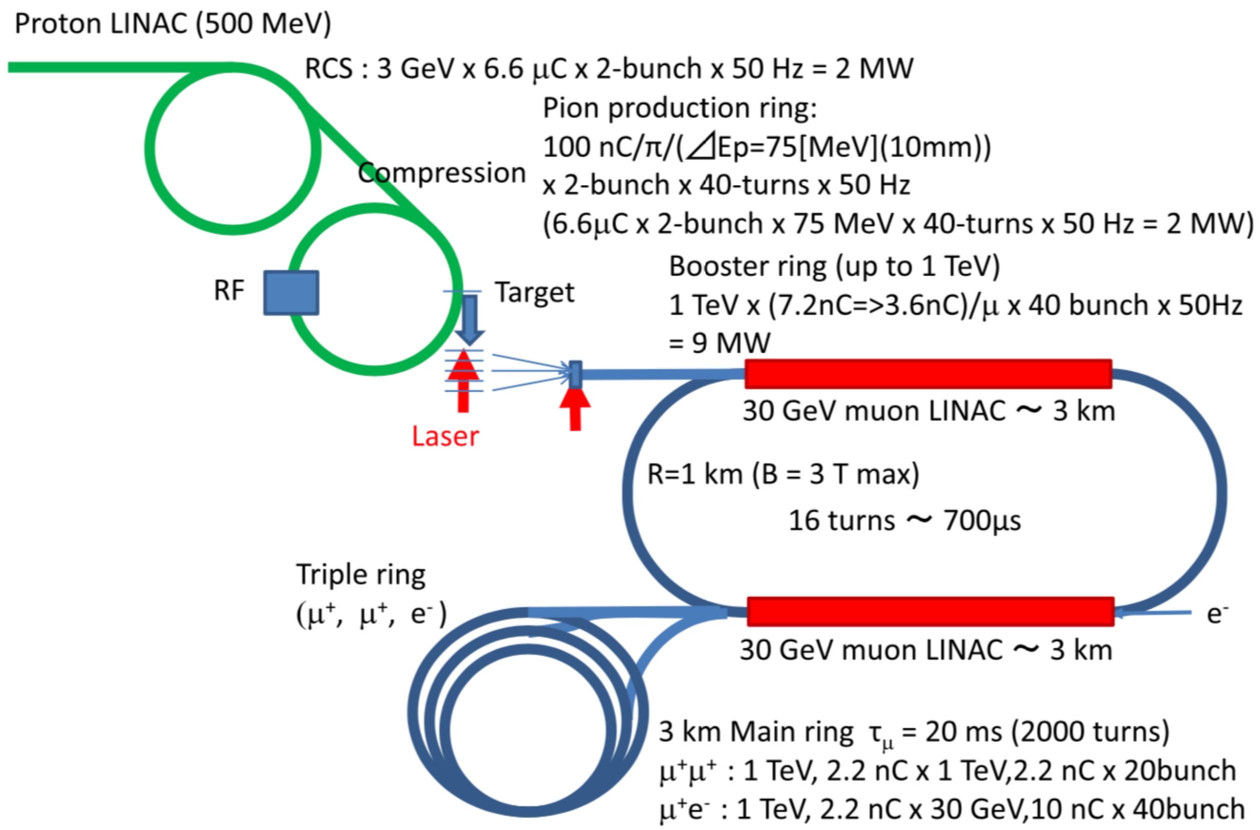


Fig. 1. Conceptual design of the $\mu^+e^-/\mu^+\mu^+$ collider.

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

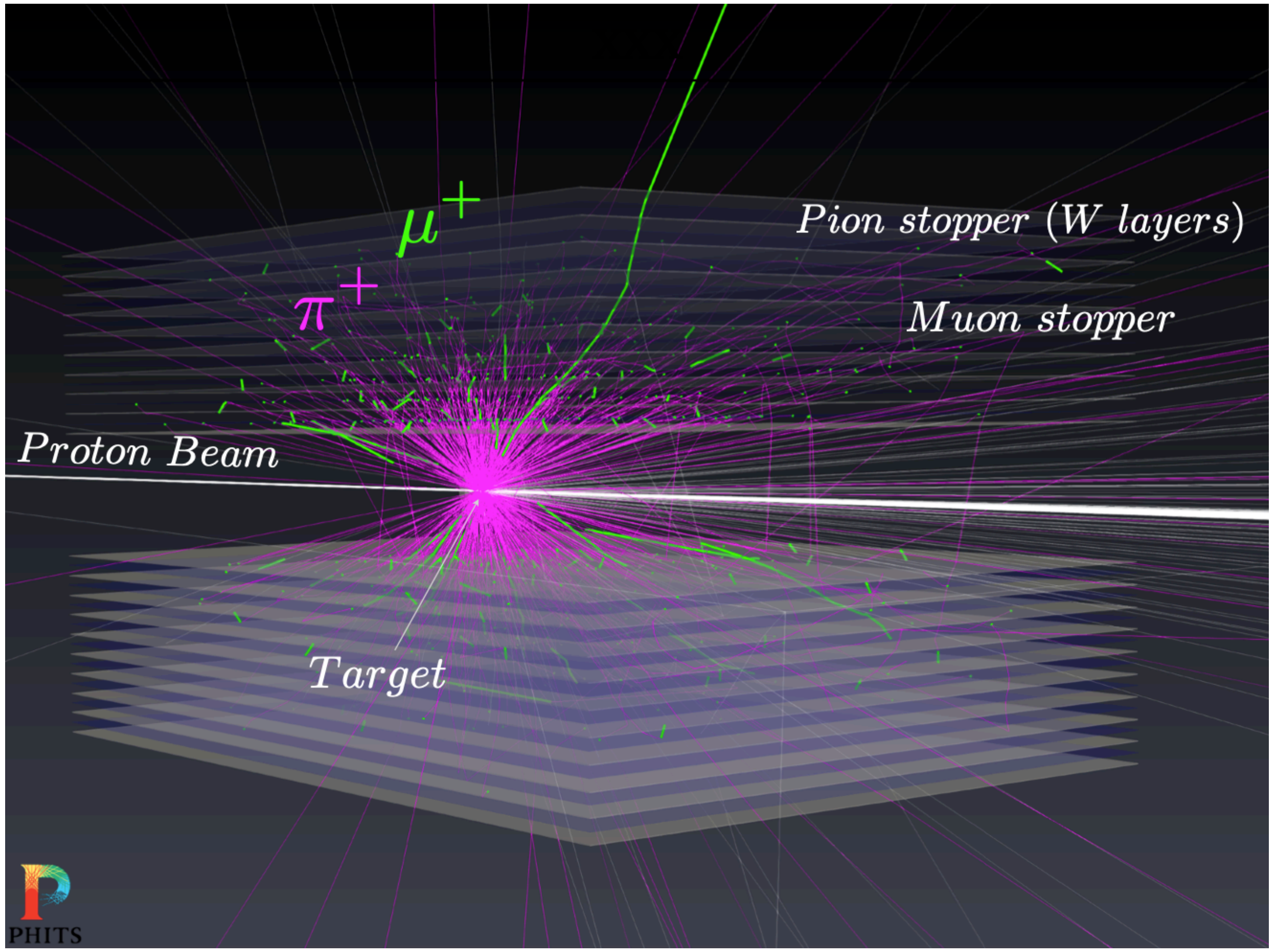
pion production target: 40 hits/bunch 0.016 π^+/proton 2.6 x 10^{15} π^+/s

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)



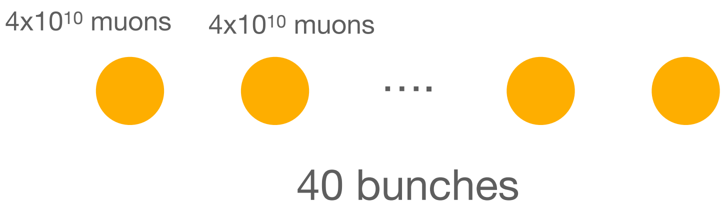
(Thermal muon production rate)
= (Muon stopping number on the layers)
× (MC correction for pion production)
× (Muonium formation)
× (Vacuum yield)
× (Loss of muoniums due to the decay)
= 1.4 * 10^{-3} μ/p
→ **2.4 * 10^{14} μ/s** (J-PARC RCS: 6.6 μC, 2bunch 40 turns)

PTEP 2022 (2022) 5, 053B02

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



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.

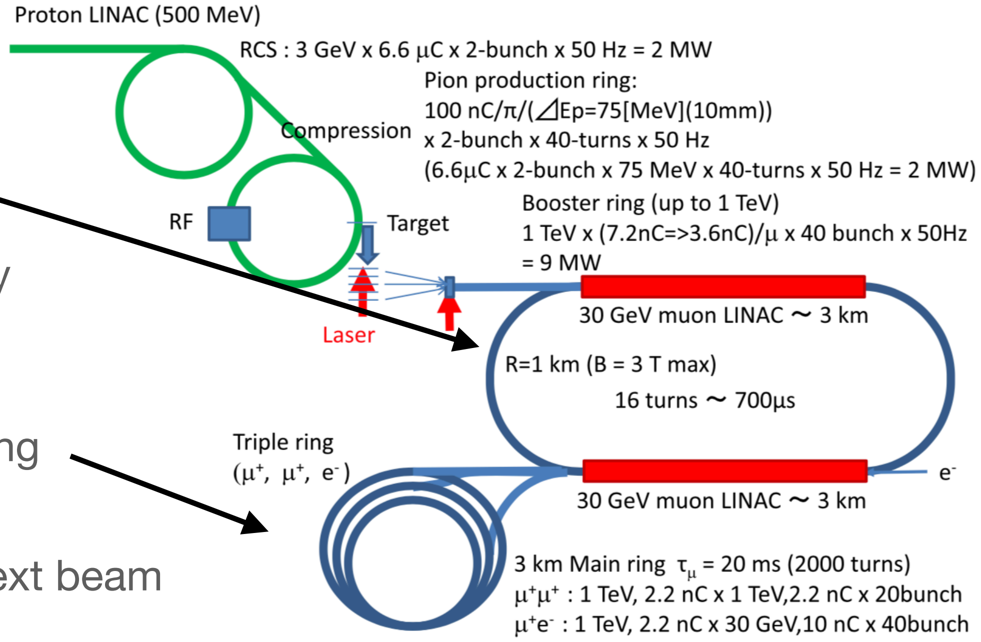


Fig. 1. Conceptual design of the $\mu^+e^-/\mu^+\mu^+$ collider.

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

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

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

$(\mathrm{eff})^2$ / (emittance * bunch length)

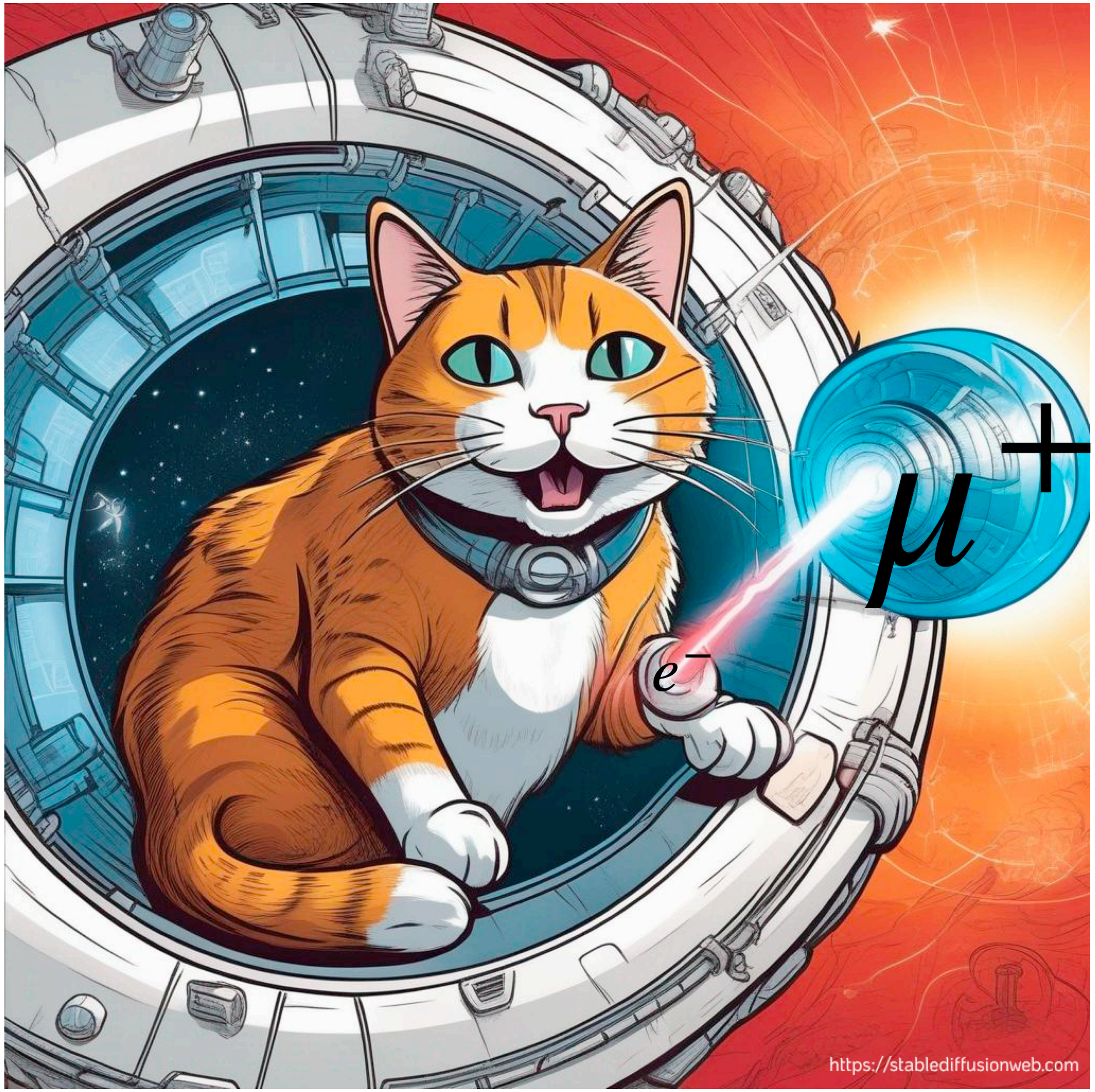
(could be much better for μ^+e^-)

Number of muons may be smaller, but

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

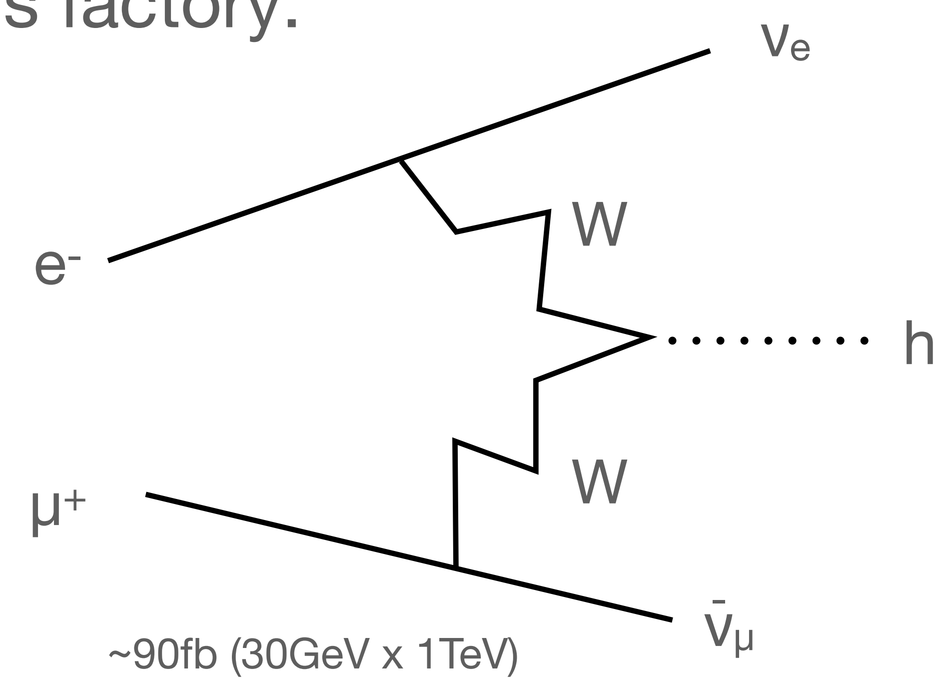
And, the technology is more matured! Express ticket for muon colliders?

mewTRISTAN



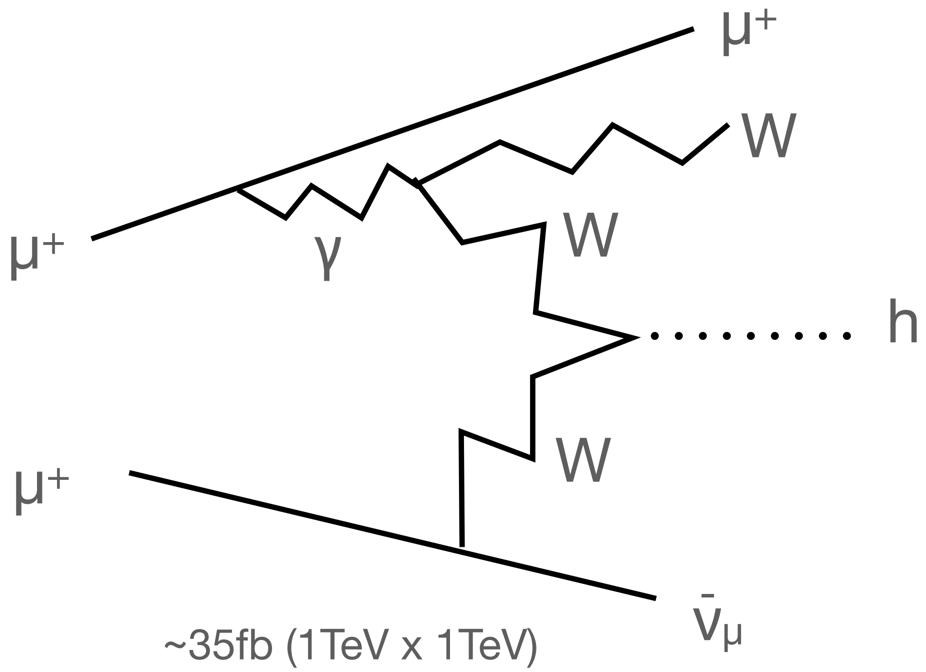
What can we do at μTRISTAN?

Higgs factory:



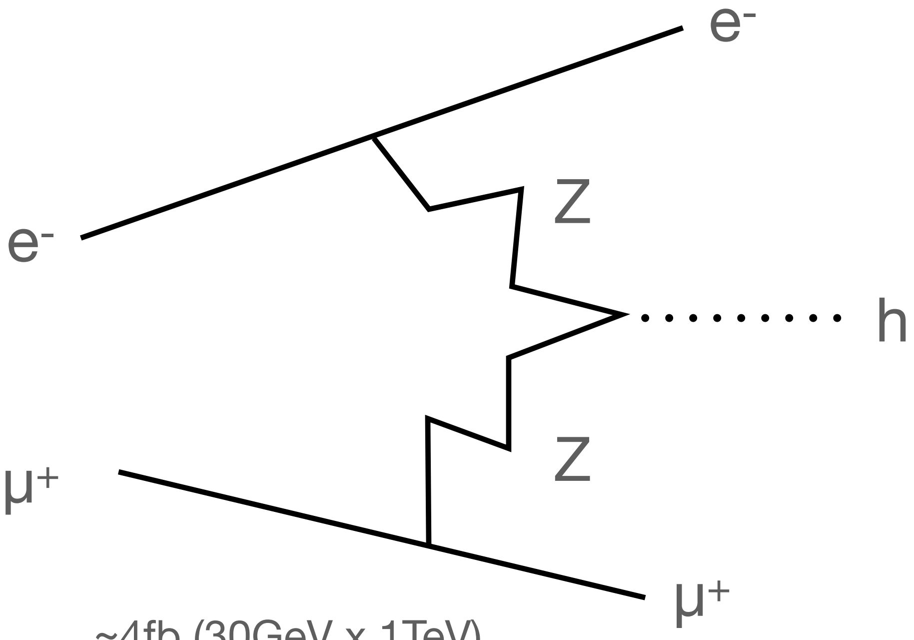
~90fb (30GeV x 1TeV)

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



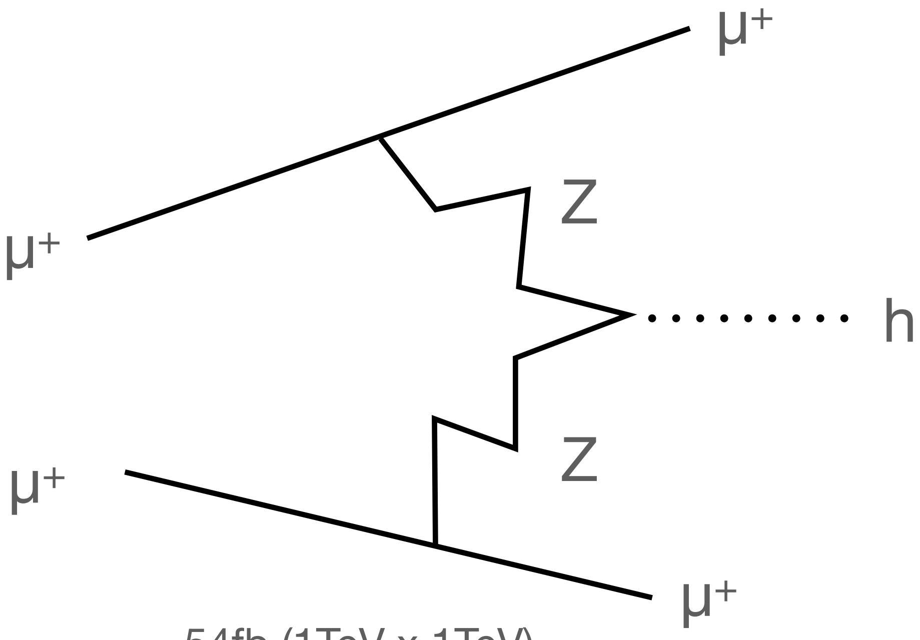
~35fb (1TeV x 1TeV)

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



~4fb (30GeV x 1TeV)

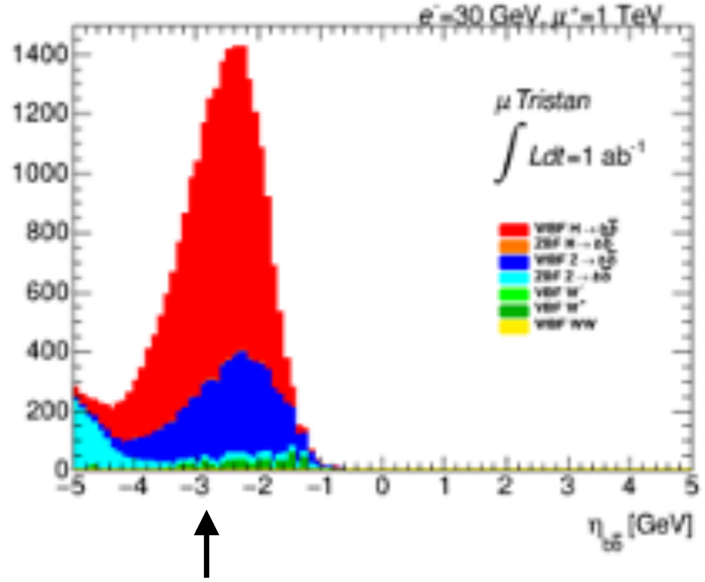
~10^3 Higgs bosons (1ab^{-1})



~54fb (1TeV x 1TeV)

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

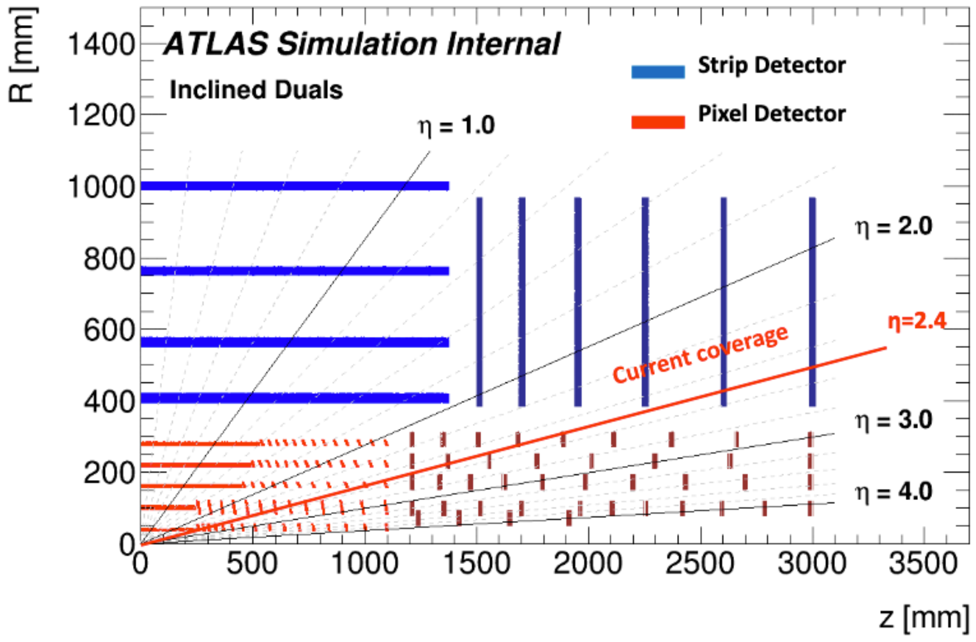
μ⁺e⁻: Very asymmetric

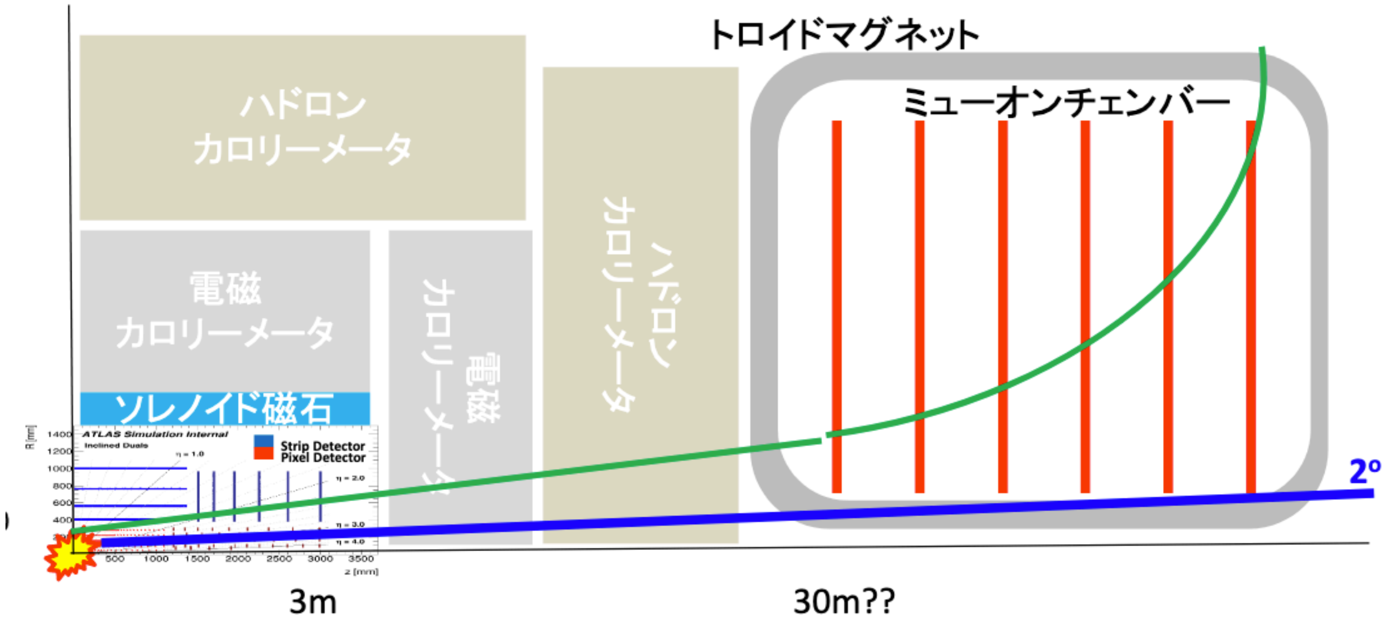


↑

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.

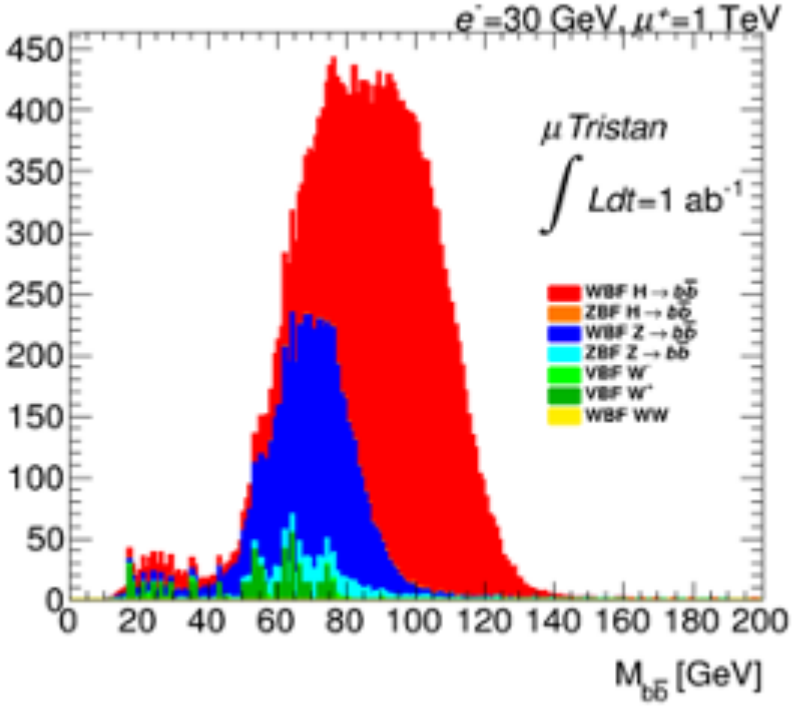




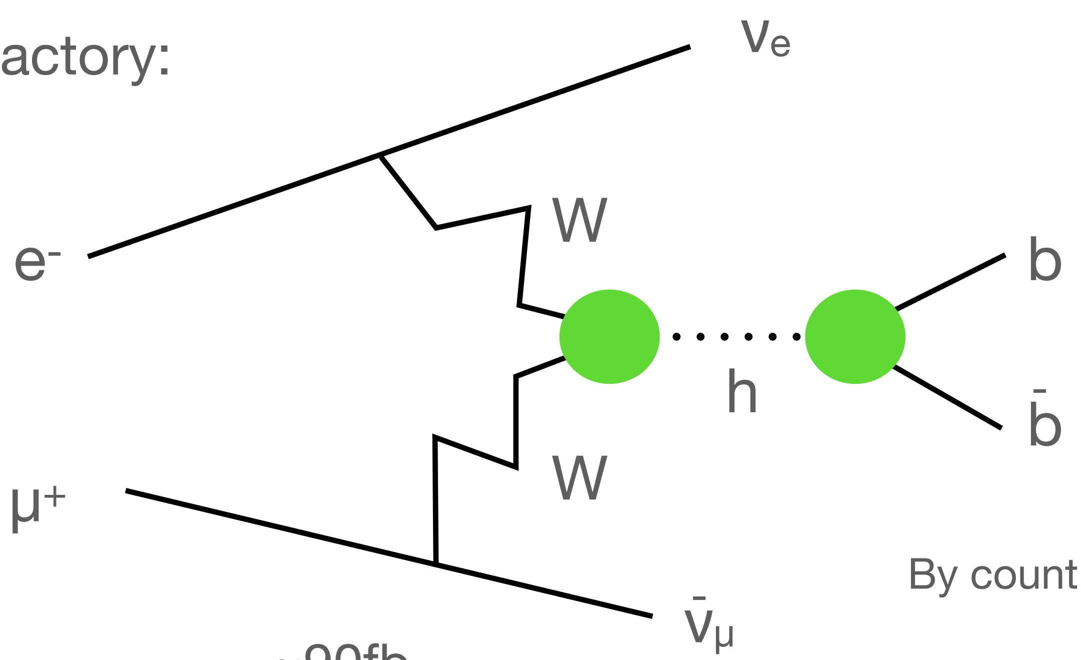
Higgs coupling

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

simulation with the ATLAS detector for HL-LHC



Higgs factory:



~90fb

~10^5 Higgs bosons

acceptance ~ 23%

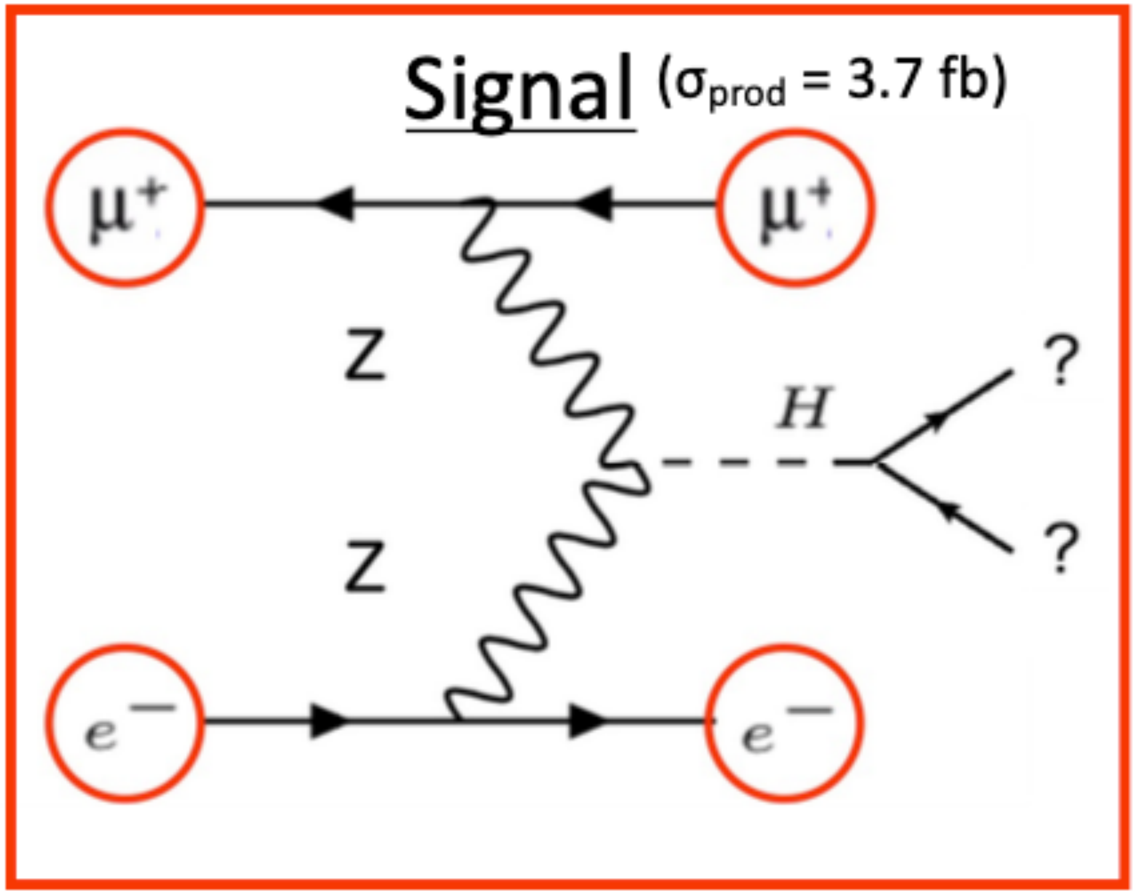
(This should improve a lot with a detector designed for this collider.)

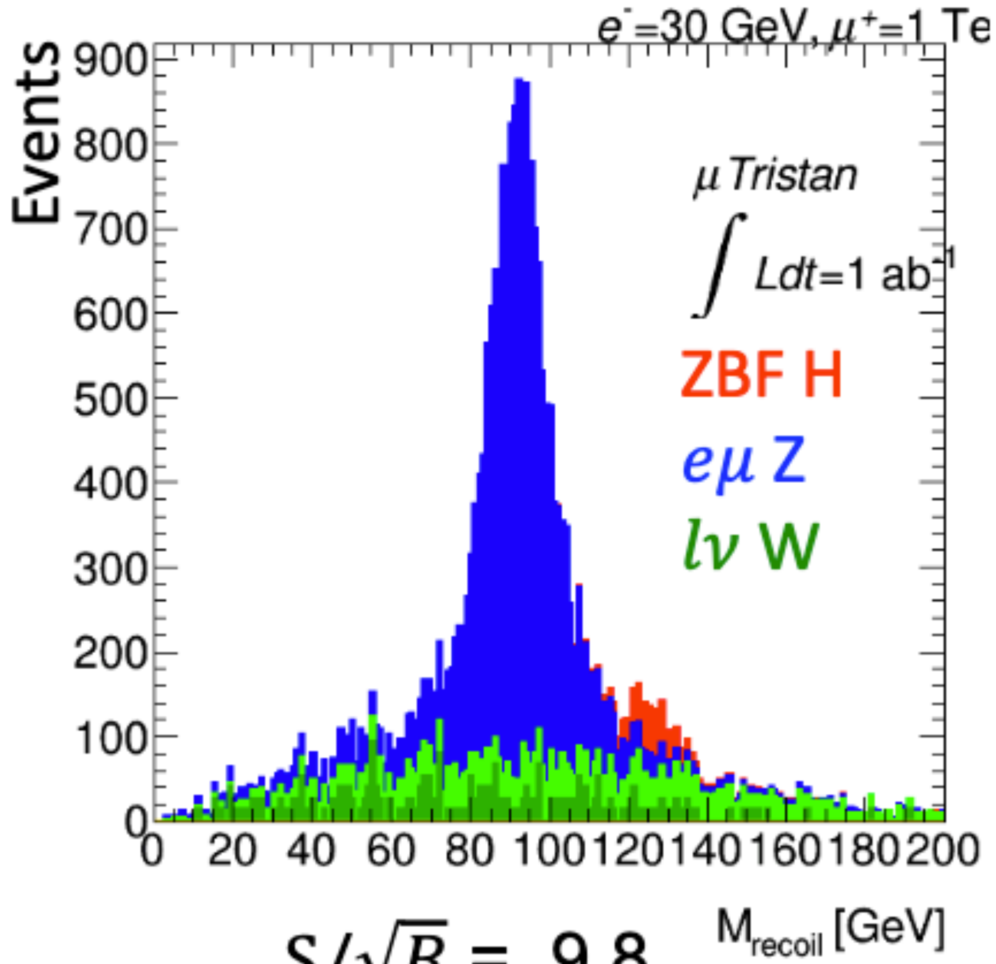
By counting the number of events and compare with the SM prediction

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

sub percent level measurements.

Z boson fusion recoil mass





$S/\sqrt{B}$ = 9.8

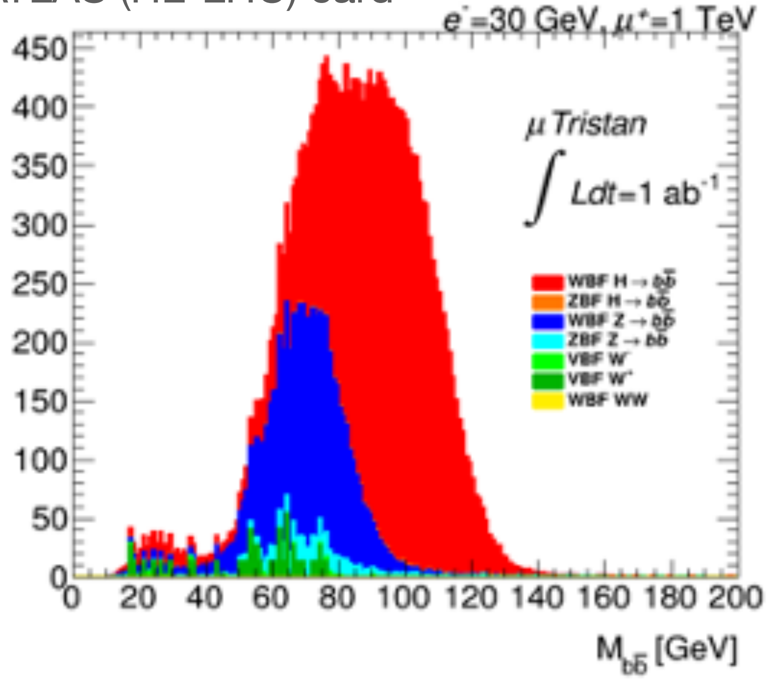
→ 1k events @ 1 ab^{-1}

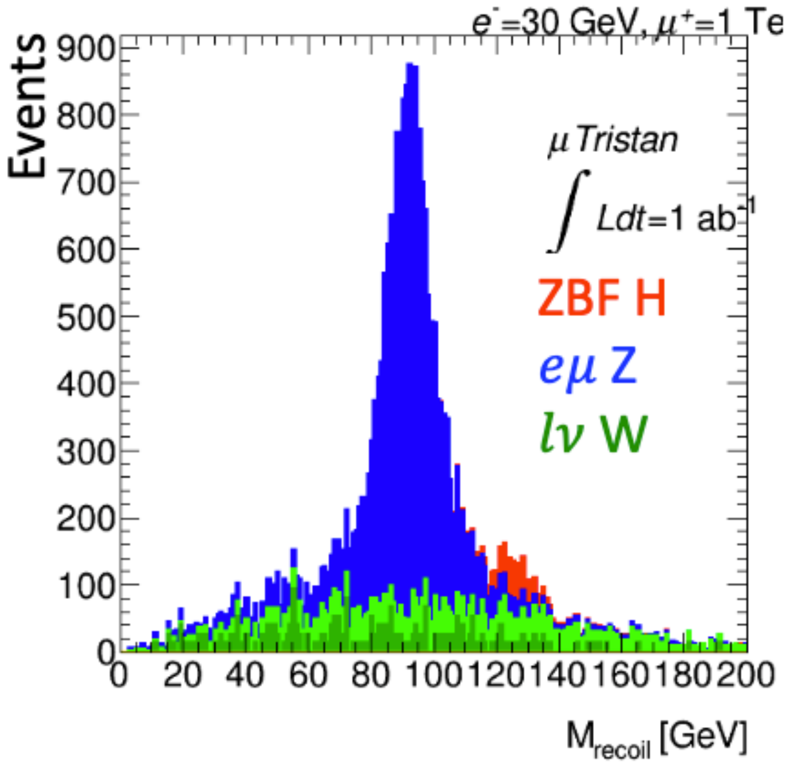
Total width may be measured.

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

Detector matters

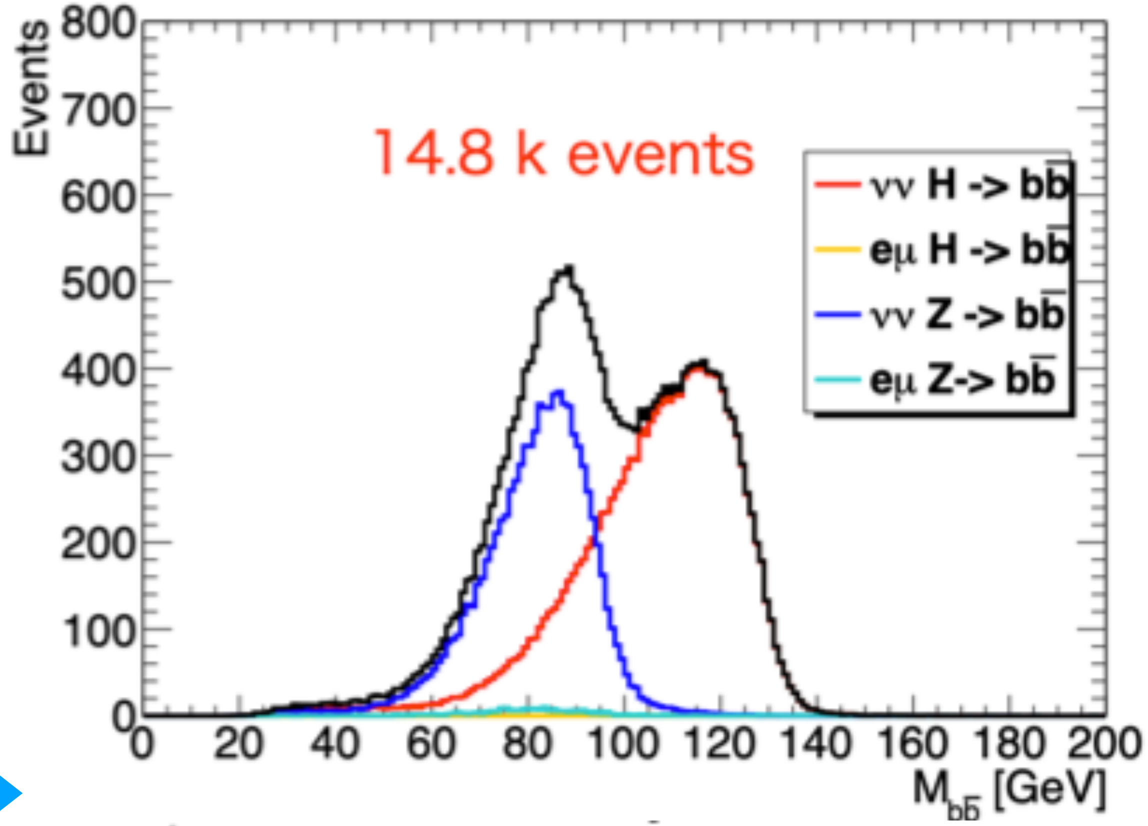
Delphes
ATLAS (HL-LHC) card

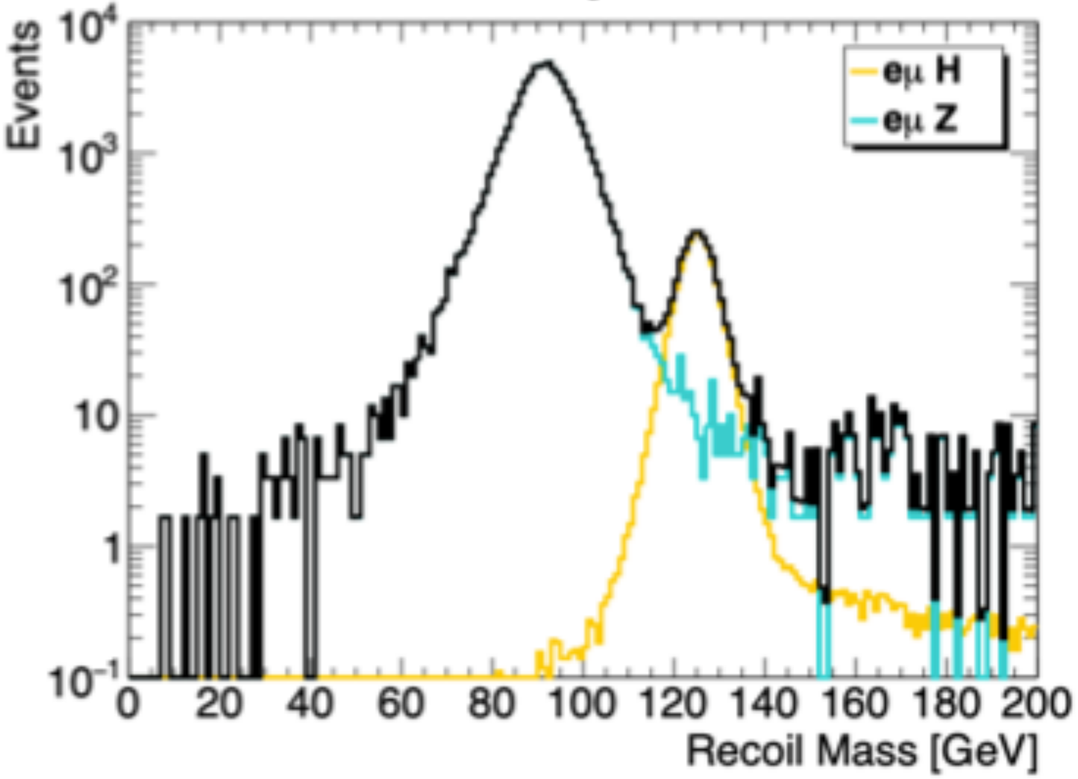




Delphes
ATLAS (LHC) card with a larger forward coverage

Much better!

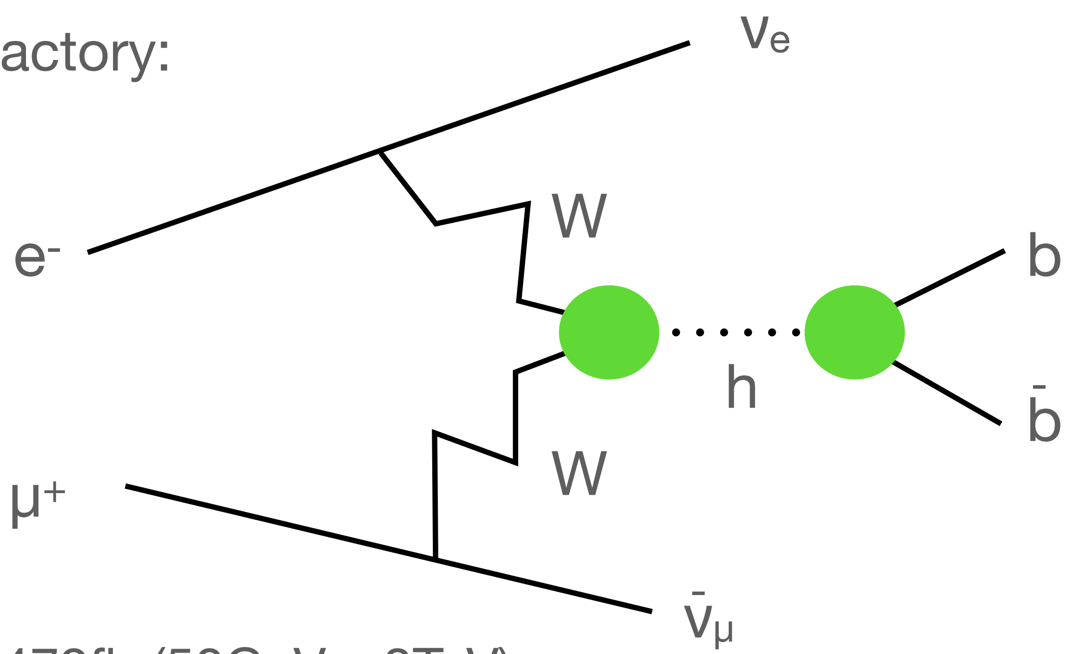




Studies underway.

Higher energy? μTevatron?

Higgs factory:



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

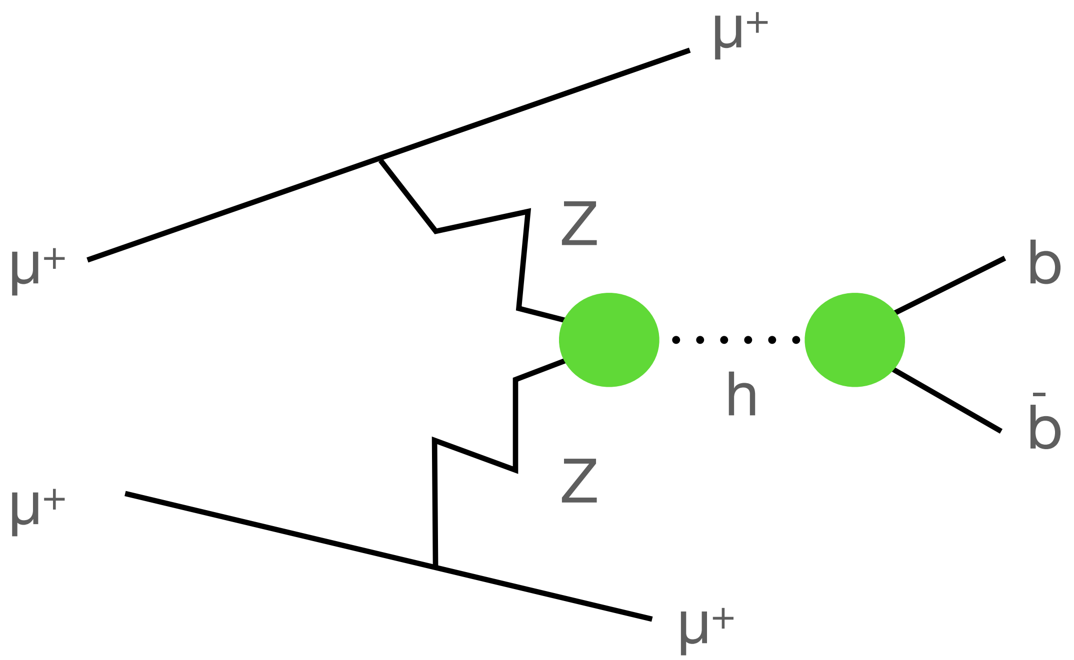
$\sqrt{s}$ = 775 GeV

~472fb (50GeV x 3TeV)

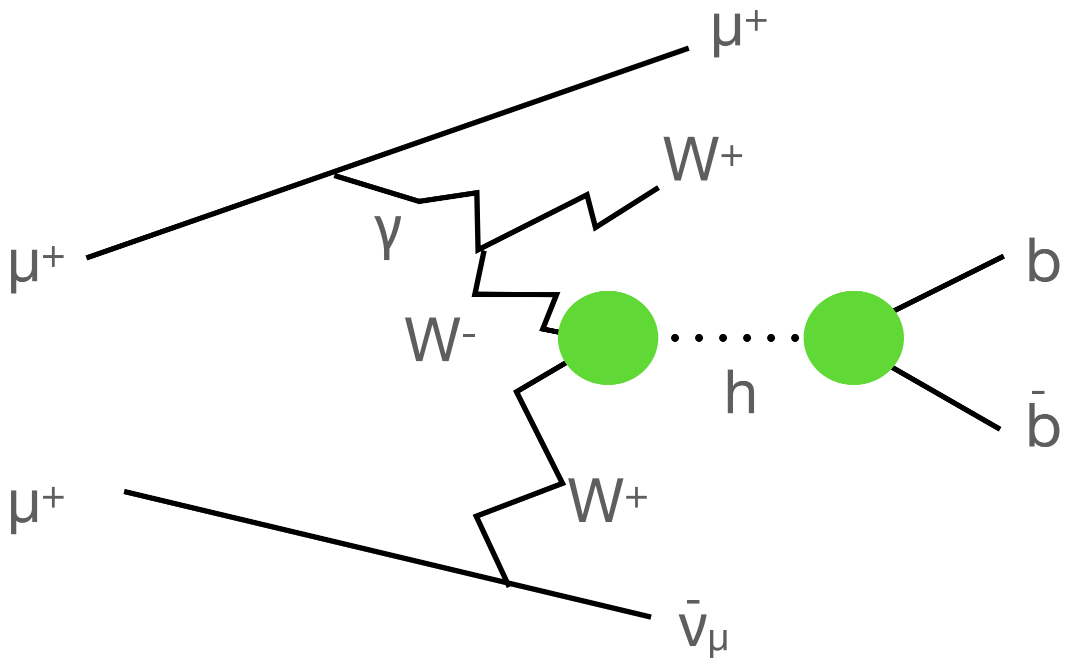
~5×10^5 Higgs bosons (ab^{-1})

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

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



~54fb@2TeV final state all visible

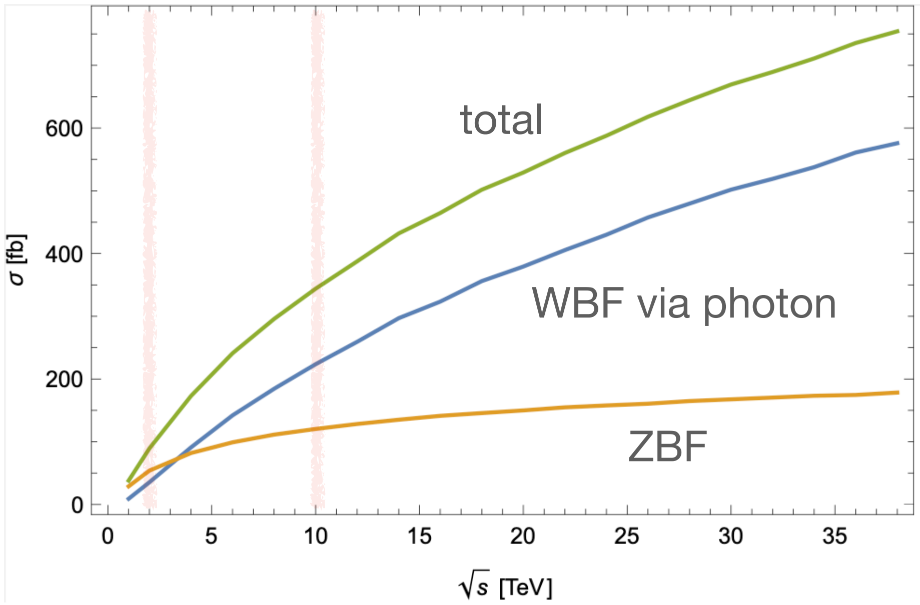


~35fb@2TeV

gets more important at high energy

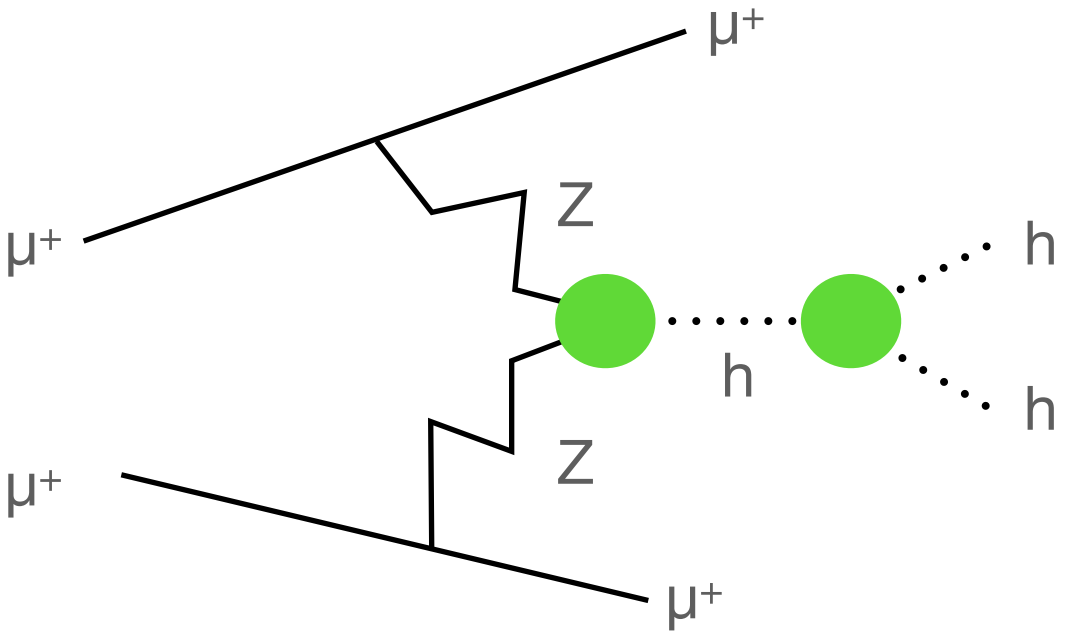
$\sqrt{s}$ [TeV]	ZBF [fb]	Photon emission [fb]
2	54	35
10	121	224
20	150	376

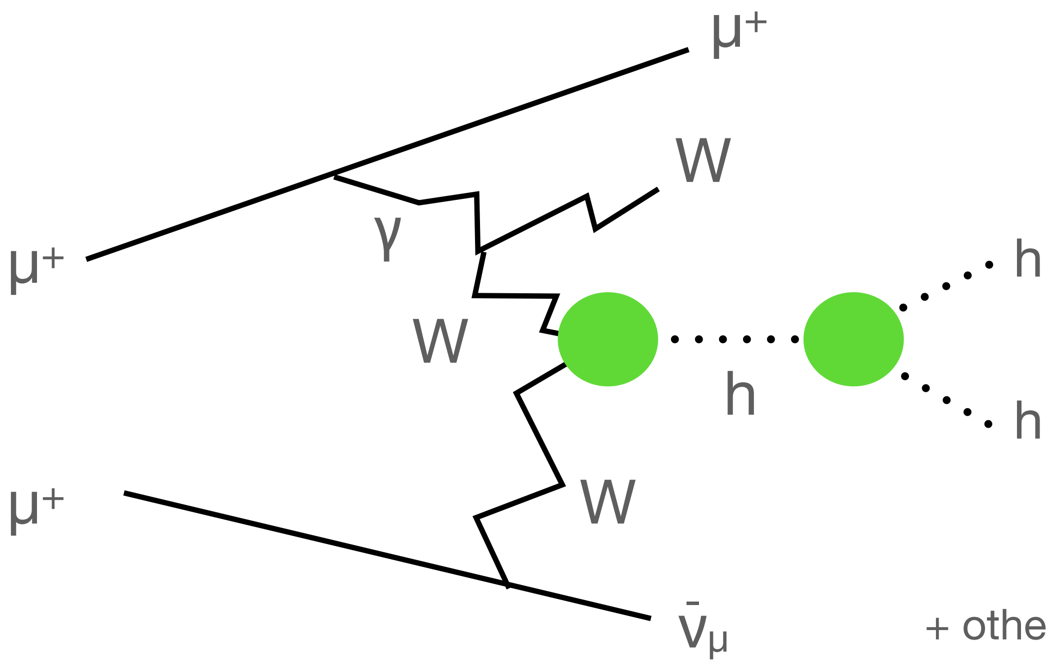
about a factor of two smaller than $\mu^+\mu^-$
(not too bad?)



maybe we should plan 5-10TeV colliders.

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





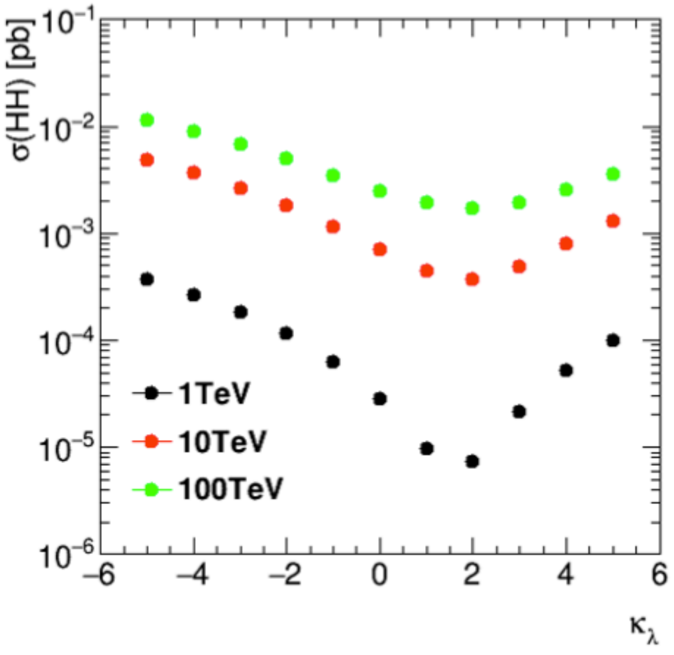
+ others

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

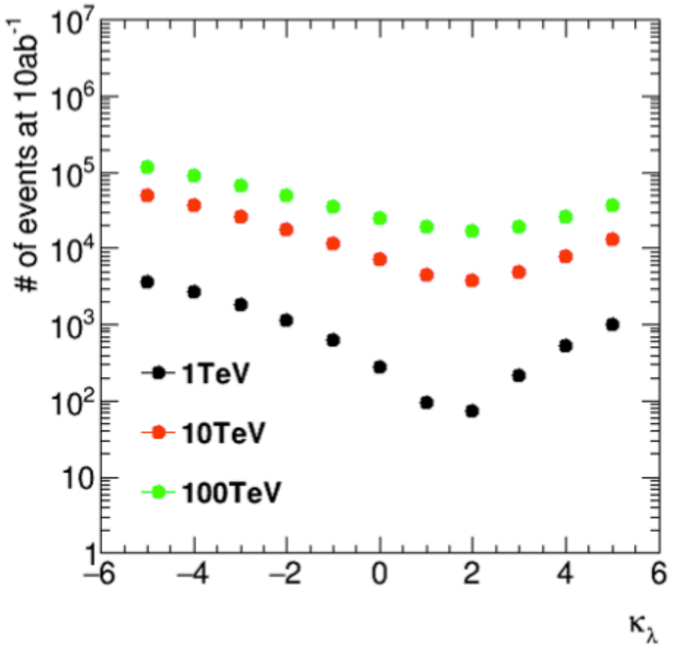
about 1/3 of $\mu^+\mu^-$

ZBF:

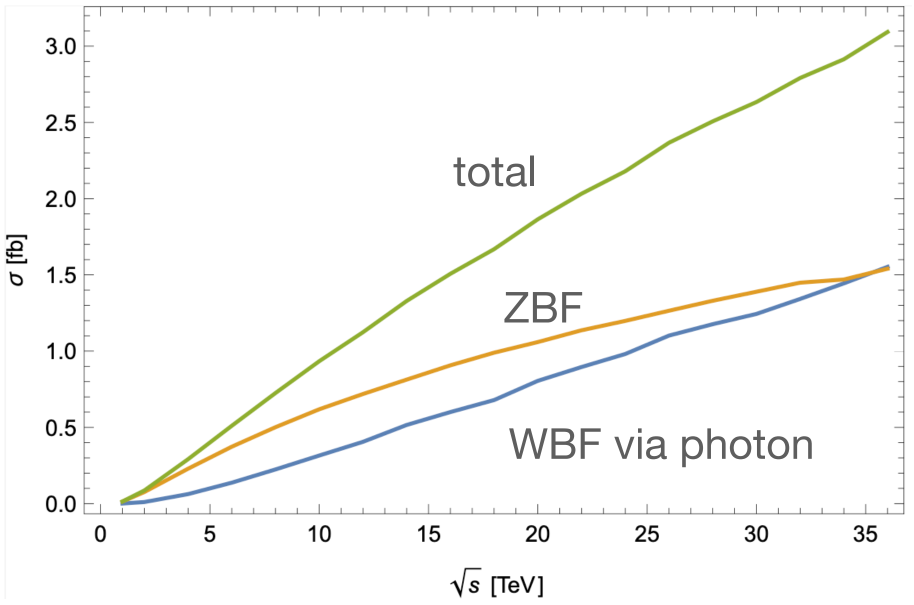
Cross section



# of Events in 10ab^{-1}

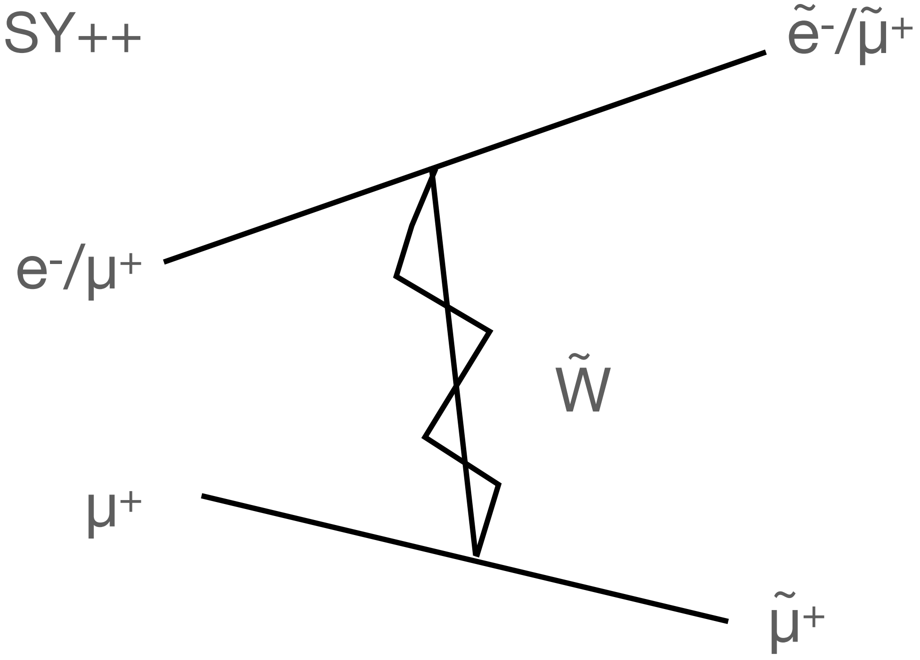


hhh coupling at 5-10% level? (@10TeV, 10ab^{-1})



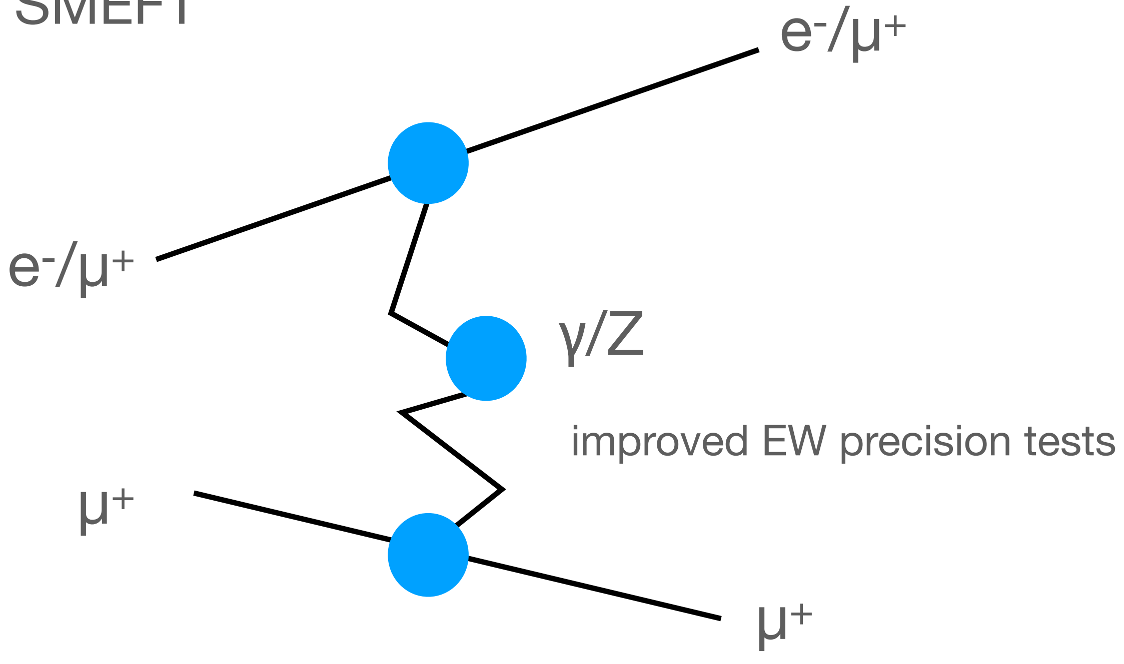
New physics?

SUSY++



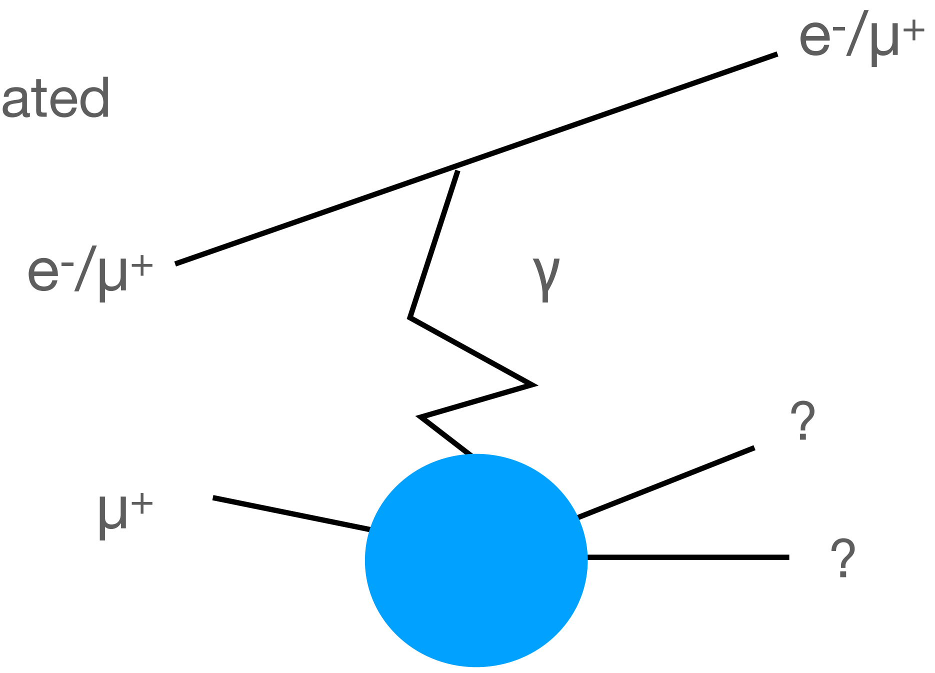
TeV mass new particles

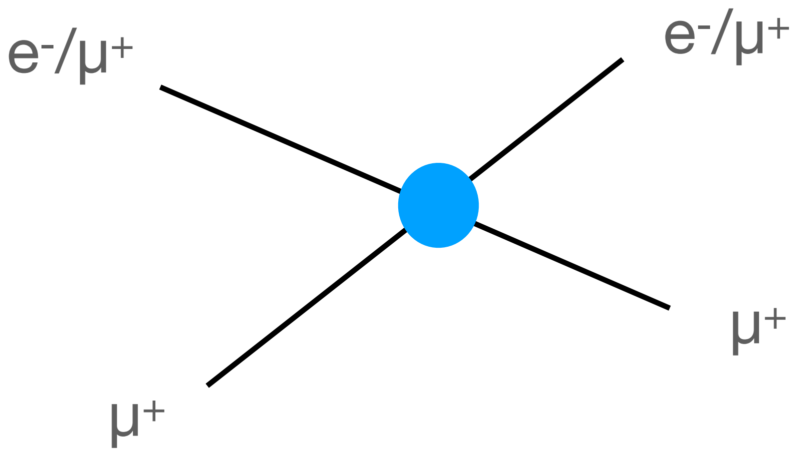
SMEFT



improved EW precision tests

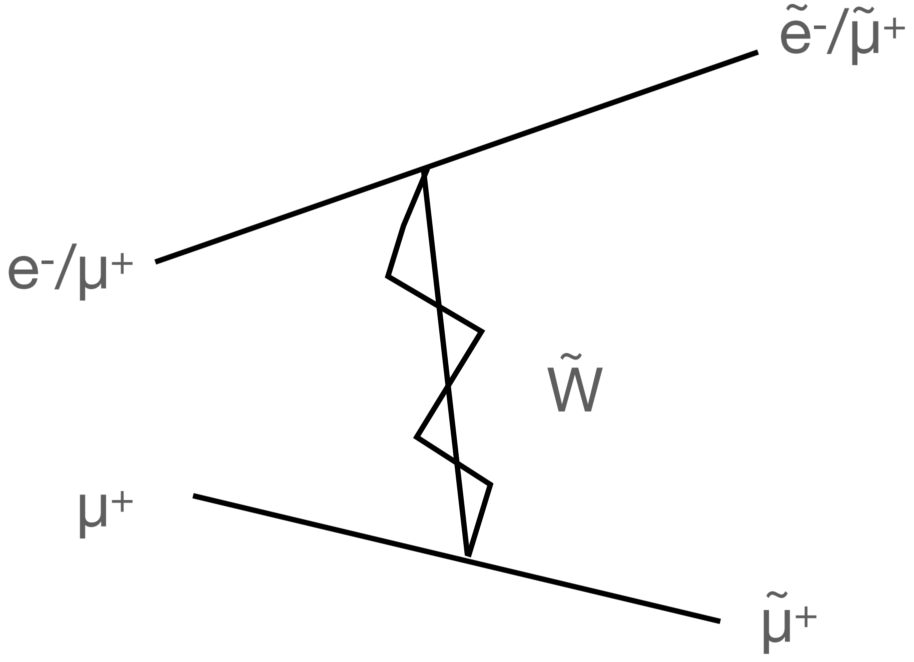
g-2 motivated



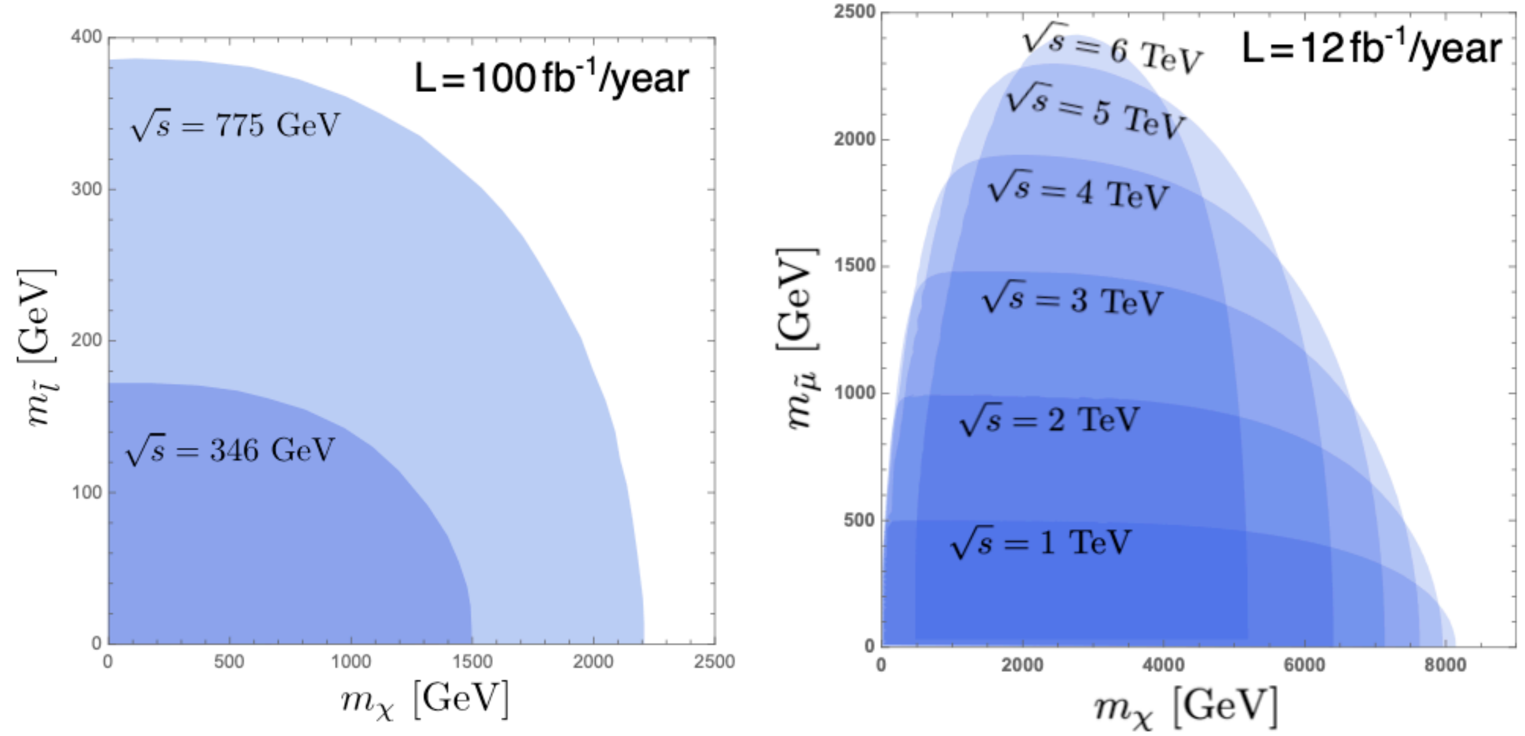


probe 100TeV scale physics!?

Supersymmetrv



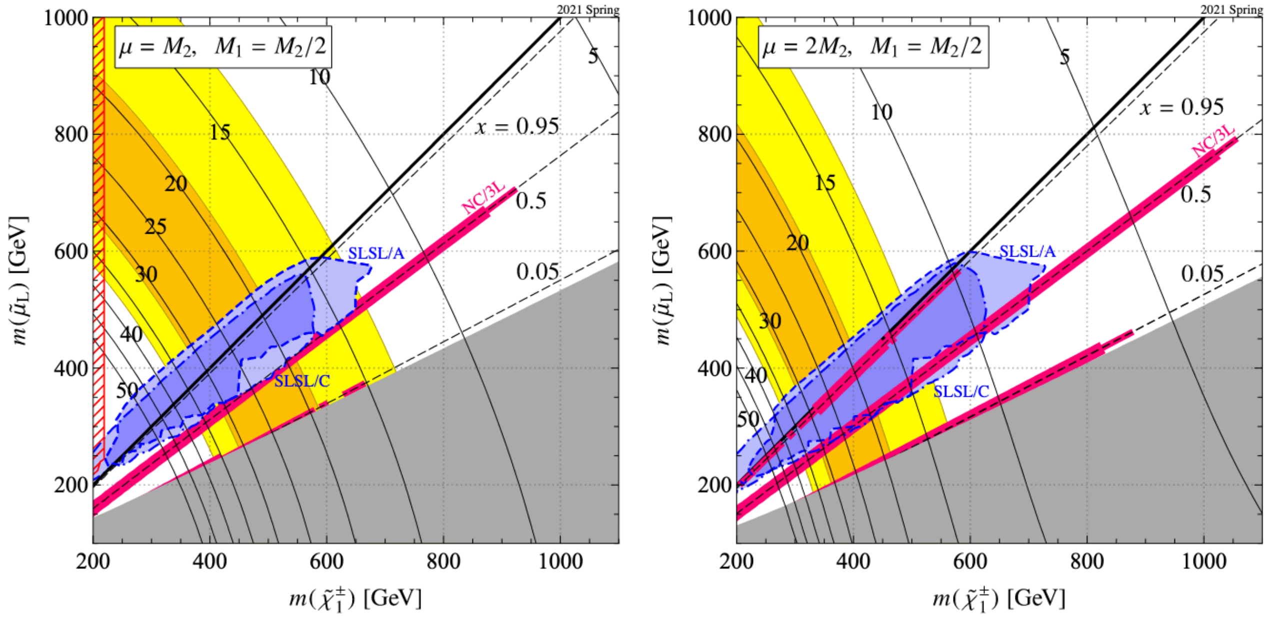
Regions for N_{event}/year > 100.



Scalar muons up to TeV even for very heavy gauginos.

Almost completely cover the muon g-2 motivated region.

[Endo, Hamaguchi, Iwamoto, Kitahara ’21]

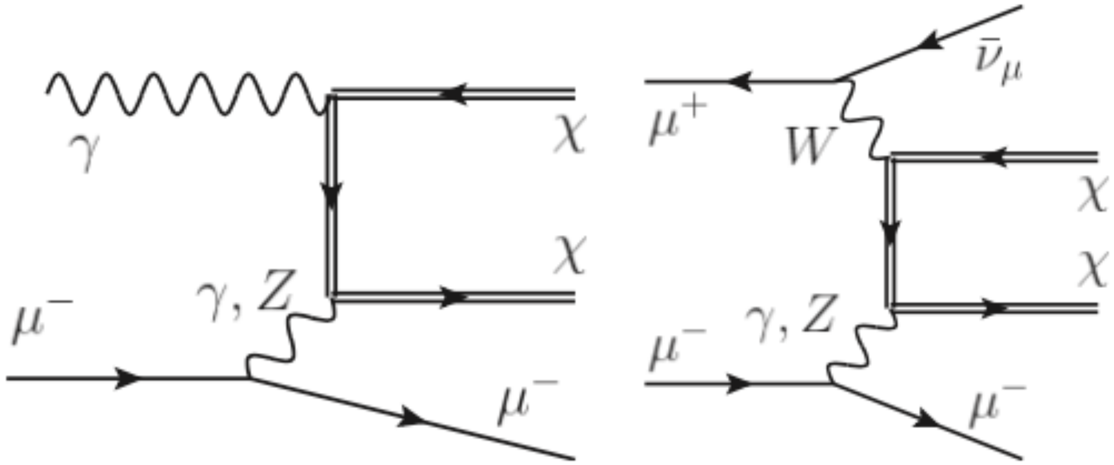


(A) $\mu = M_2, \ M_1 = M_2/2.$

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

DM?

study@$\mu^+\mu^-$ [Han et al. ’20]



same search is possible at $\mu^+\mu^+$

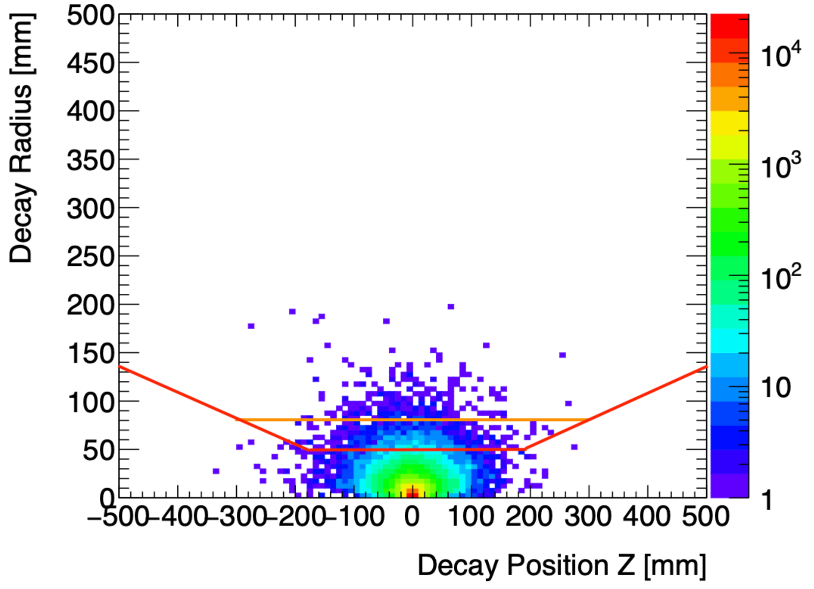
mono-μ

S/B is good in this process.

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

track + VBF search?

$\sqrt{s}$ = 10 TeV, 質量 1 TeV Higgsino の崩壊マップ



崩壊半径

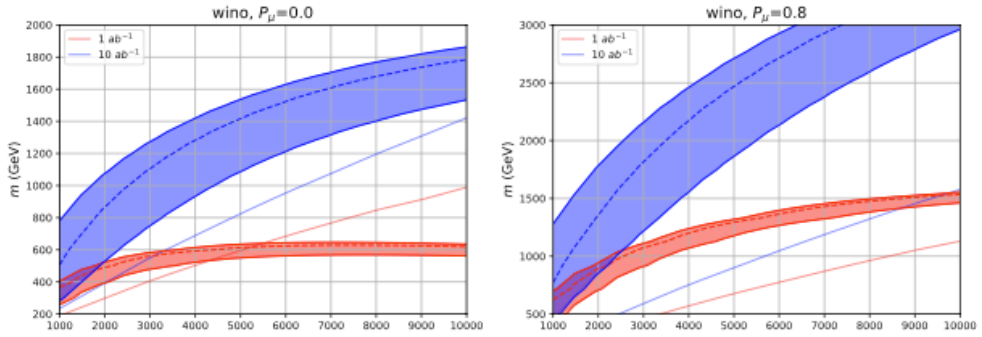
- Case A > 80 mm
- Case B > 50 mm

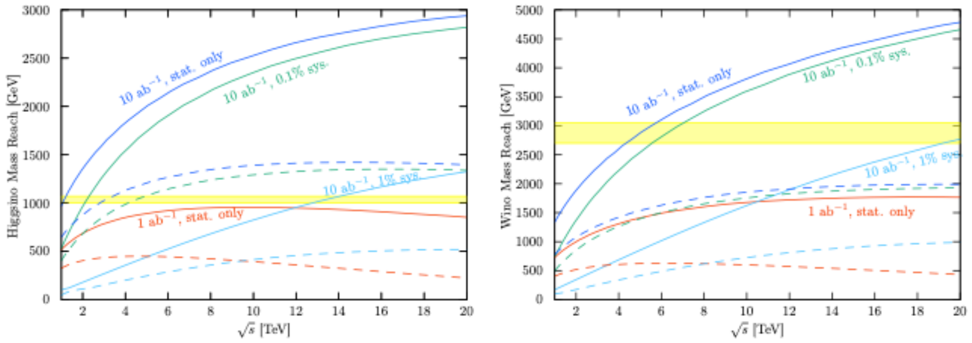
$|\eta| < 2.0$

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]

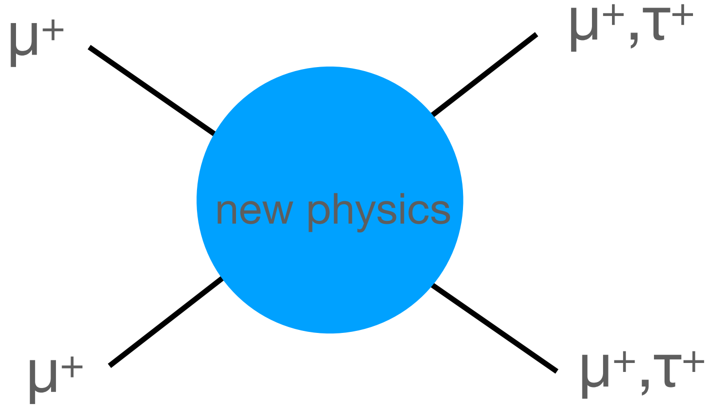




(a) Higgsino (b) Wino

[Okabe, Shirai ’23]

muon specific

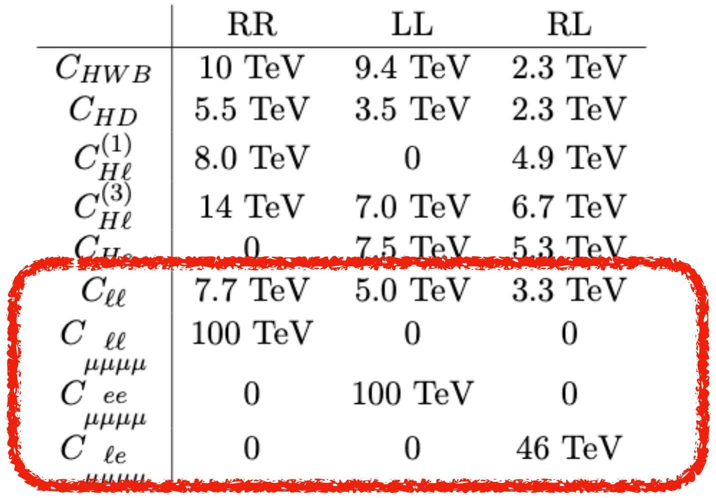


μ+μ+ has a big advantage in looking for new physics associated with the muon.

reach to O(100)TeV physics!

elastic scattering and lepton flavor violating scattering.

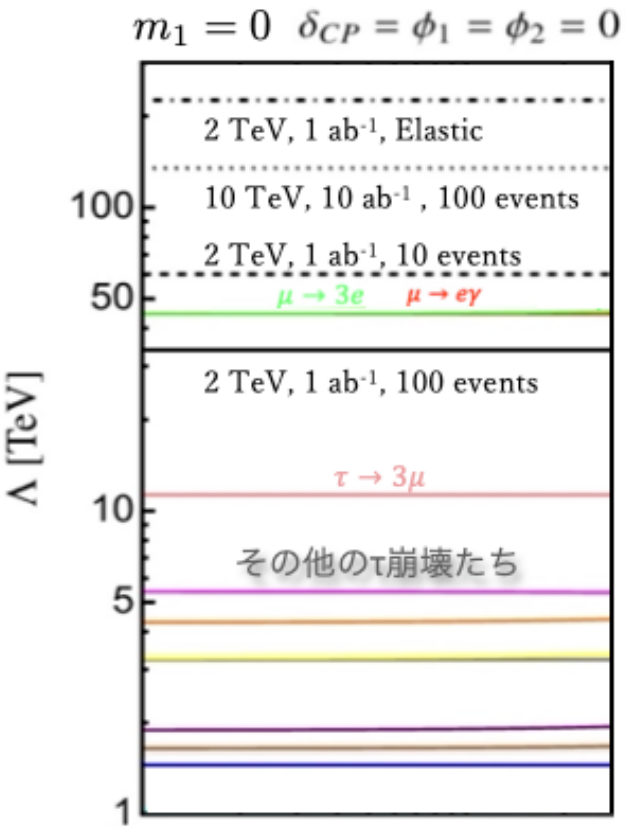
[Hamada, RK, Matsudo, Takaura ’22]



	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
$C_{\substack{\ell\ell\\ \mu\mu\mu\mu}}$	100 TeV	0	0
$C_{\substack{ee\\ \mu\mu\mu\mu}}$	0	100 TeV	0
$C_{\substack{\ell e\\ \mu\mu\mu\mu}}$	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 $\theta_i - 0.5^\circ < \theta < \theta_i + 0.5^\circ$. The considered range of θ_i is $16^\circ \leq \theta_i \leq 164^\circ$.

[Fridell, RK, Takai ’23]



Summary

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

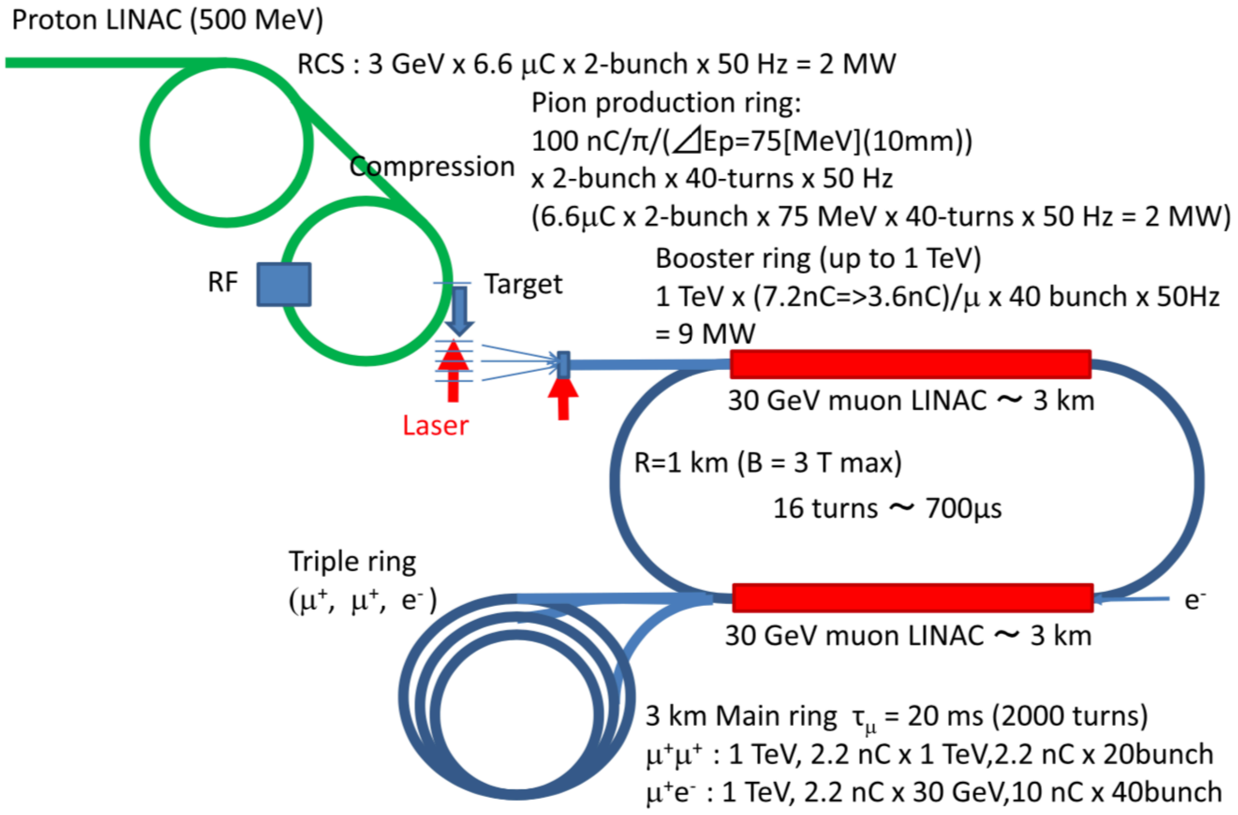


Fig. 1. Conceptual design of the $\mu^+e^-/\mu^+\mu^+$ collider.