μTRISTAN

Ryuichiro Kitano (KEK)

Based on 2201.06664, Yu Hamada, RK, Ryutaro Matsudo, Hiromasa Takaura, Mitsuhiro Yoshida

Also, study in progress with Koji Nakamura and Sayuka Kita

seminar@Nagoya U., February 28, 2023

Clearly, we need next generation colliders.

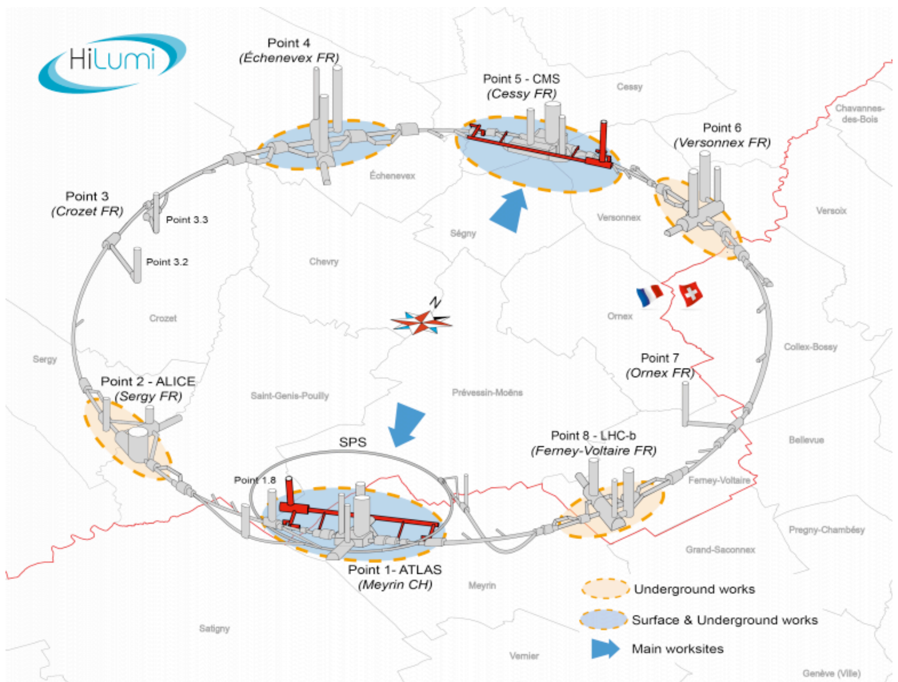
1. We must investigate the form of the Higgs potential by the observation of self-interactions.
2. We must check the possibility that one can actually produce dark matter artificially.
3. We must look for new physics at least up to about 10TeV (~ a loop factor higher than the EW scale).

We cannot stop here.

The next step should be

Higgs?

Higgs factories

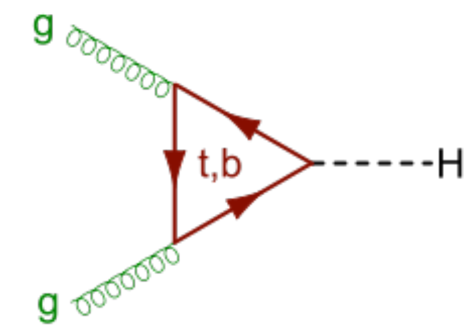


HL-LHC (2029?-)

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

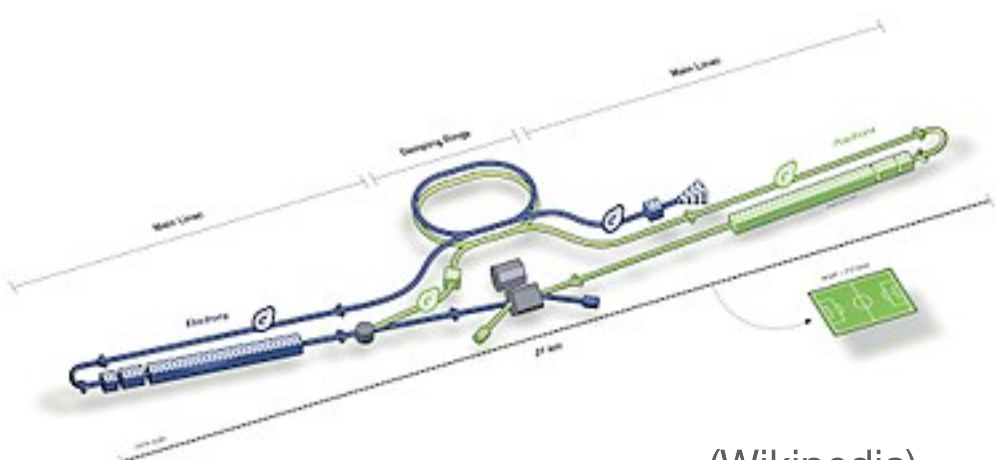
O(100M) Higgs bosons

(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}

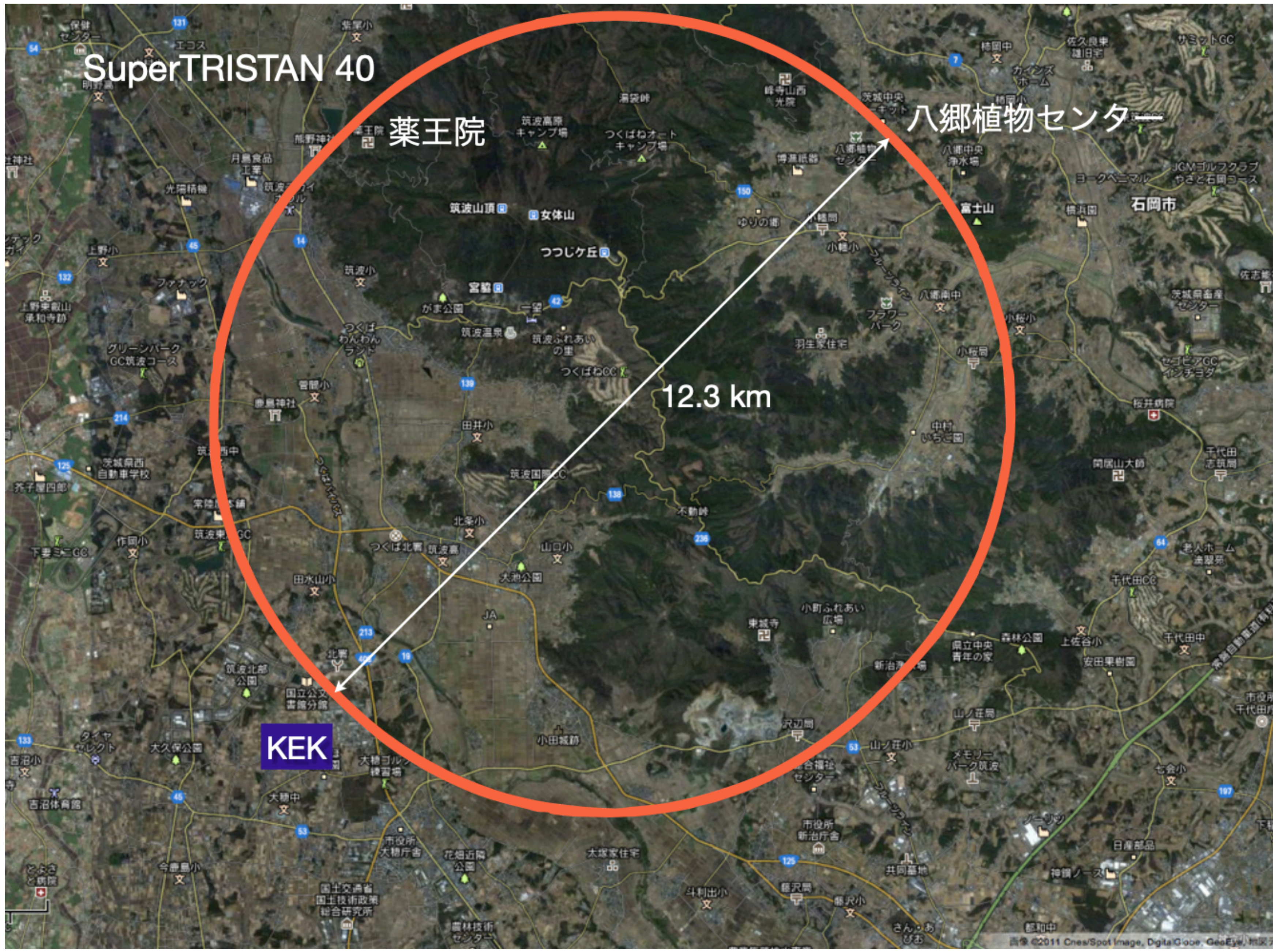
Extendable to 500GeV, 1TeV

O(1M) Higgs bosons

Measurements of Higgs couplings at the level of 0.1%.

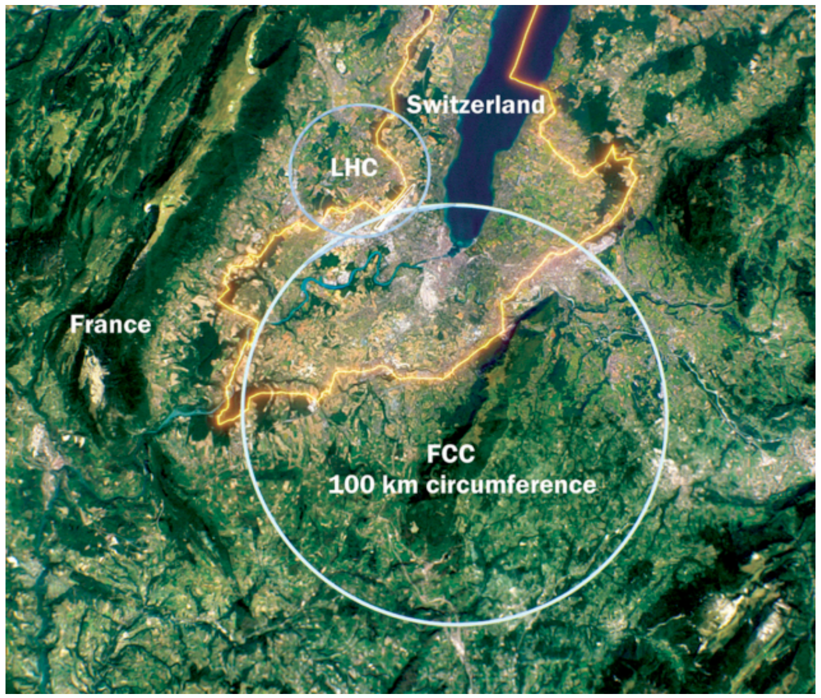
Higgs factories at KEK?

[Oide '12]



Very nice.

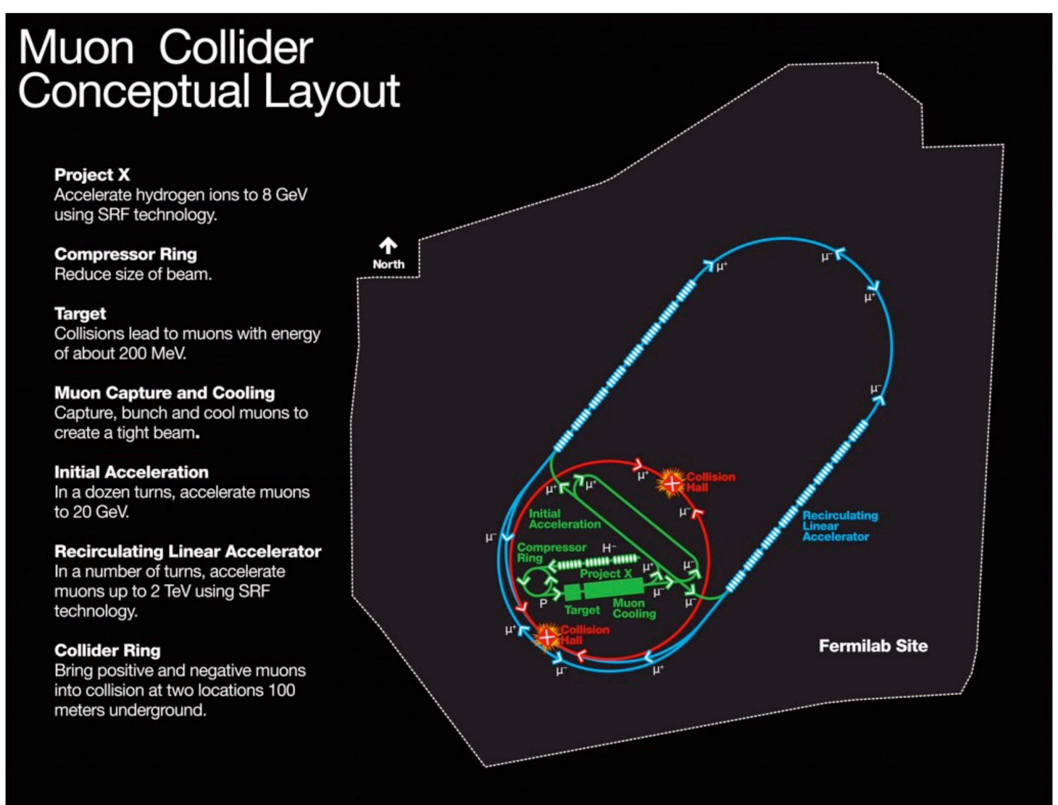
Future colliders?



e^+e^- (90-365GeV) → pp (100TeV)

Higgs/top factory — New physics searches

O(1M) Higgs



from symmetry

$\mu^+\mu^-$ (1TeV — 100TeV?)

[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!

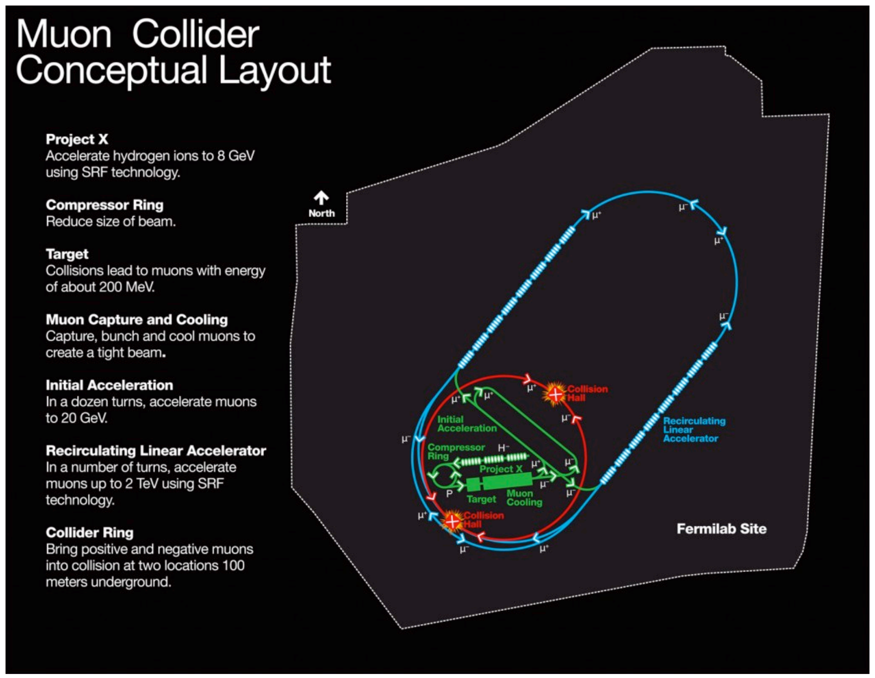
A lot of Higgs bosons through WW fusion.

Direct reach to 100TeV physics!

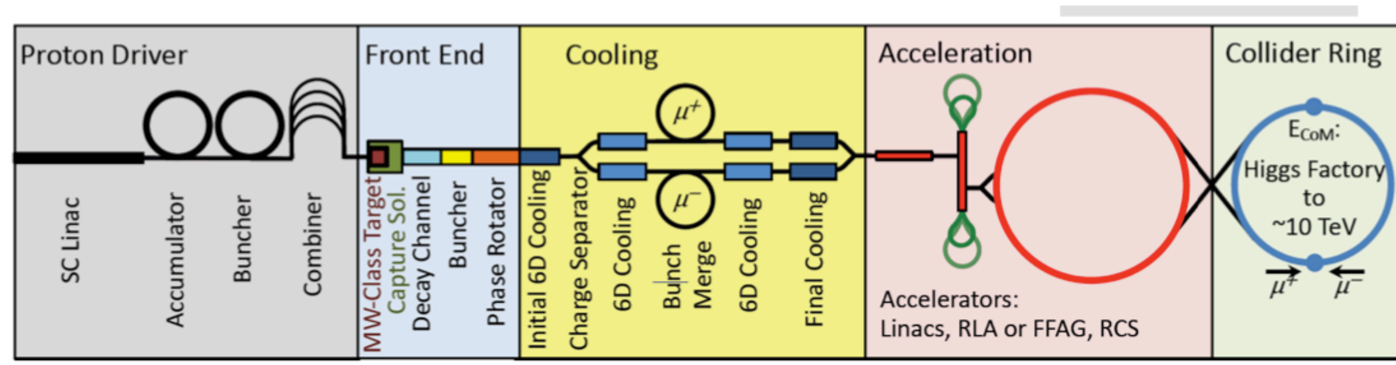
… if one can get enough luminosity.

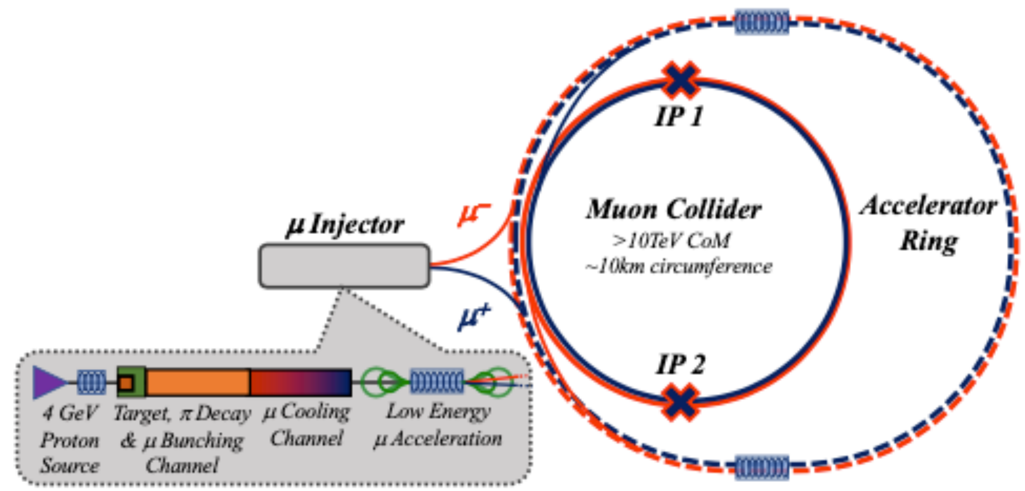
muon collider

this is what we want!

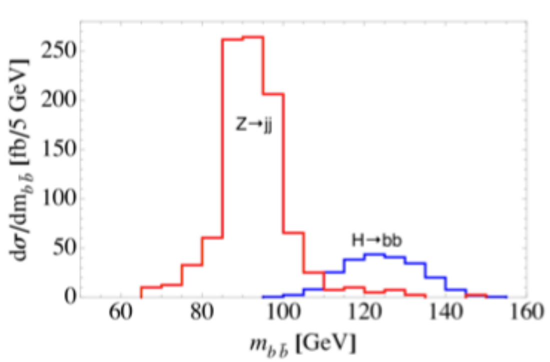


from symmetry





[MAP collaboration]



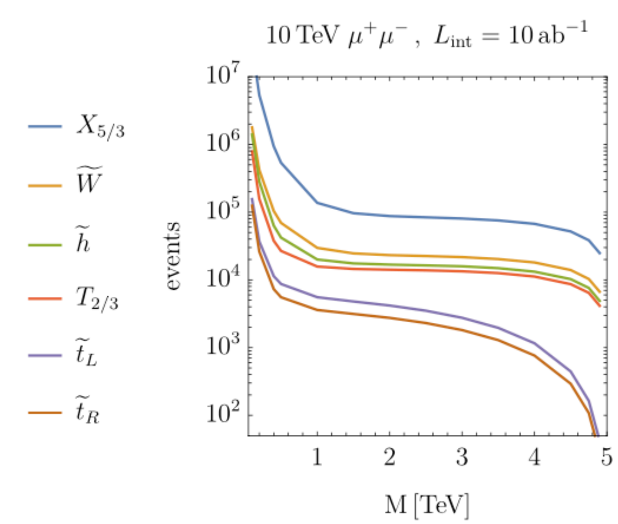
(a)

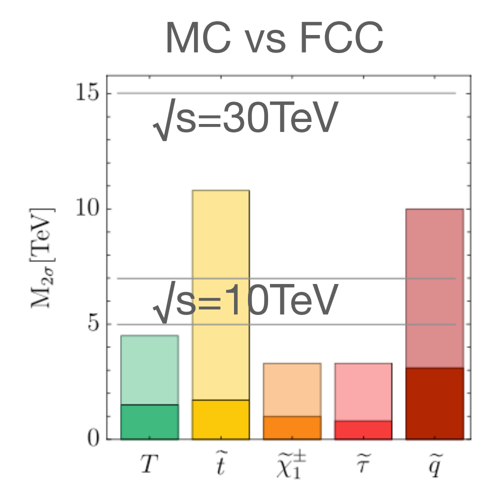
[Han, Liu, Low, Wang '20]

10 TeV @ 10 ab^{-1}

Production	Decay	Rate [fb]	$A\cdot\epsilon$ [%]	$\Delta\sigma/\sigma$ [%]
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

[muon smasher's guide]



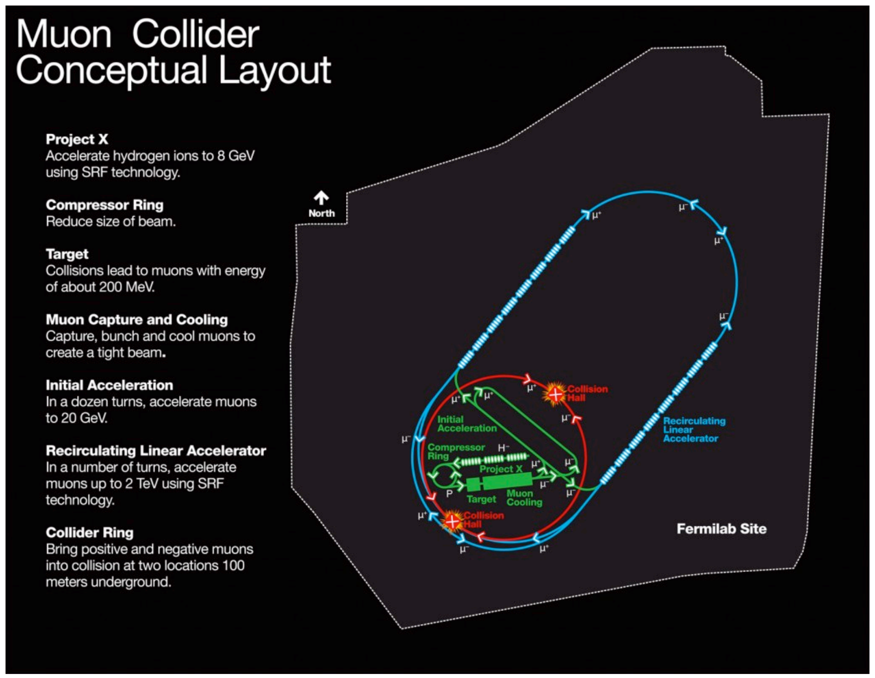


[Buttazzo, Franceschini, Wulzer '20]

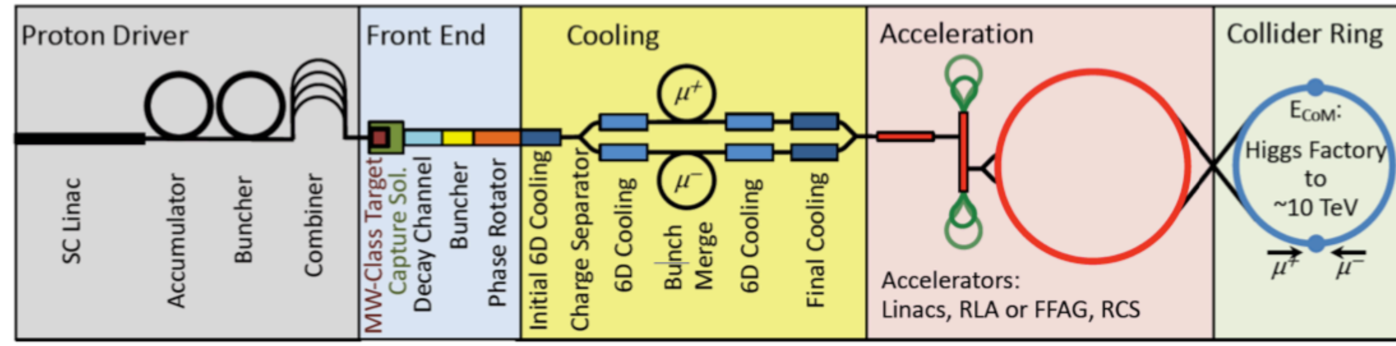
[Snowmass report '22]

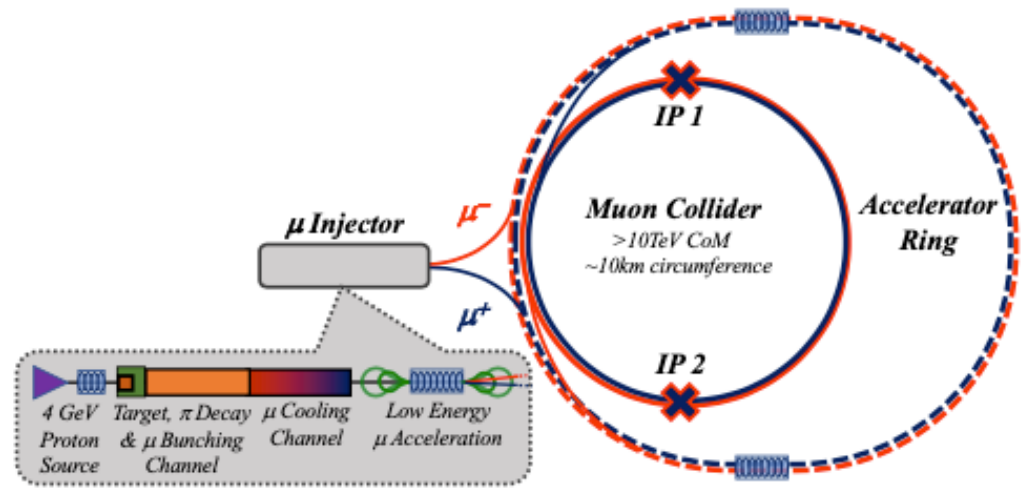
muon collider

this is what we want!

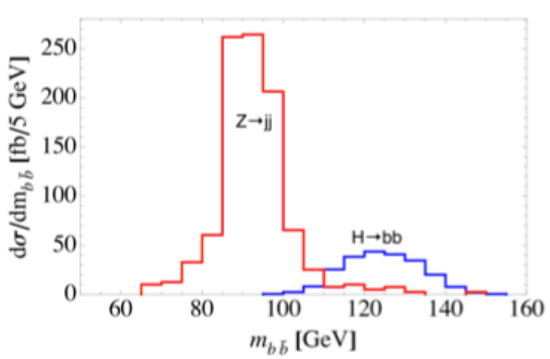


from symmetry





[MAP collaboration]



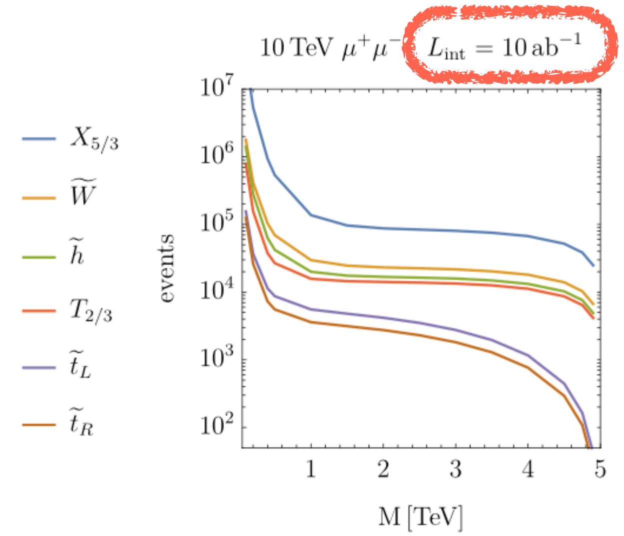
(a)

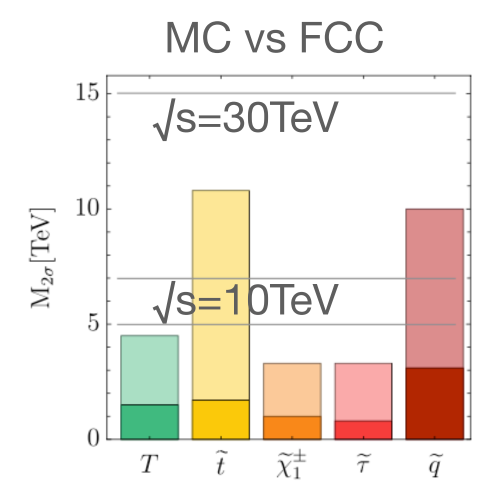
[Han, Liu, Low, Wang '20]

10 TeV @ 10 ab^{-1}

Production	Decay	Rate [fb]	$A \cdot \epsilon$ [%]	$\Delta\sigma/\sigma$ [%]
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

[muon smasher's guide]



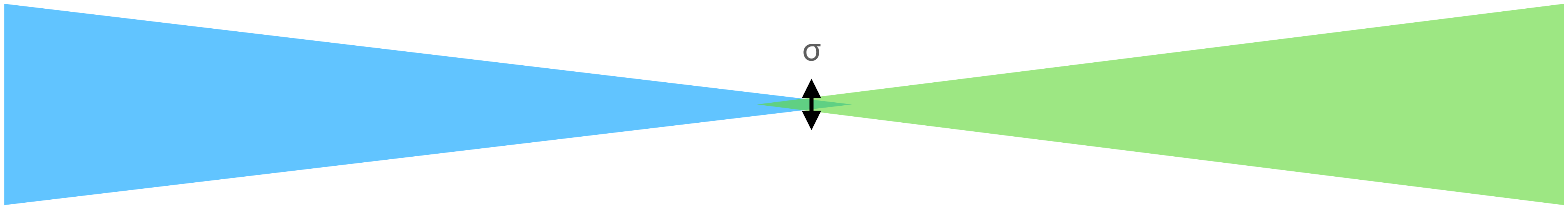


[Buttazzo, Franceschini, Wulzer '20]

[Snowmass report '22]

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

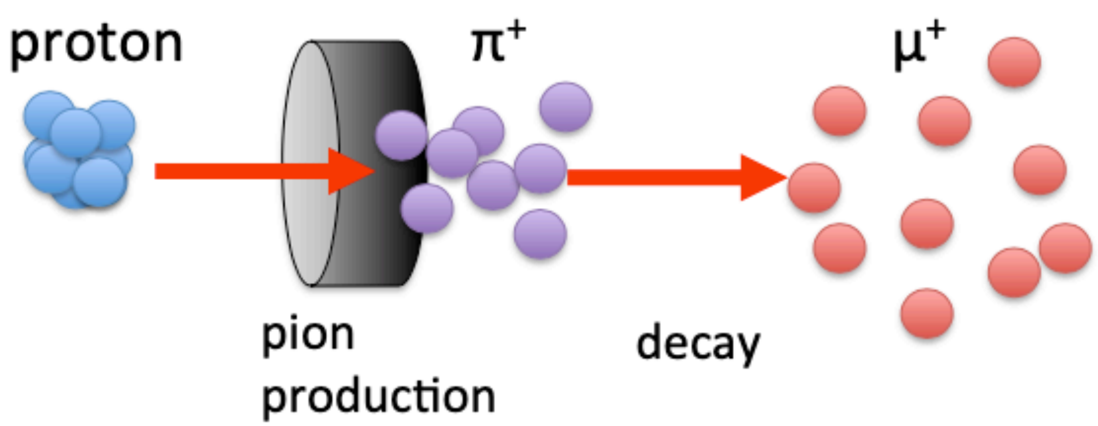
We want ab^{-1} level luminosity for physics (HL-LHC, ILC)

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

Muon beam

Too much spread.

Conventional muon beam



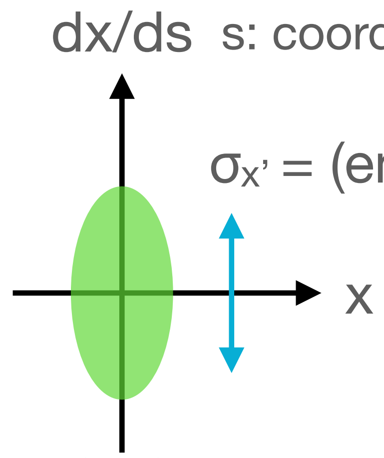
emittance

~1000π mm・mrad = π mm

Strong focusing
Muon loss
BG π contamination

Taken from Mibe-san's lecture slide

Emittance

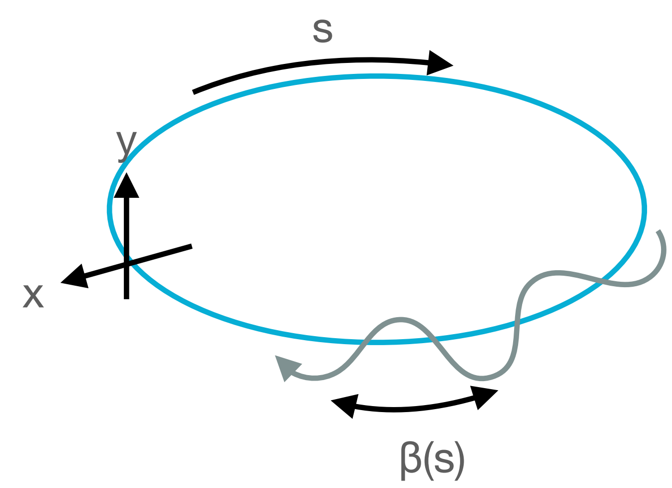


s: coordinate along the beam center

$\sigma_{x'}$ = (emittance / $\beta(s))^{1/2}$

emittance ~ area

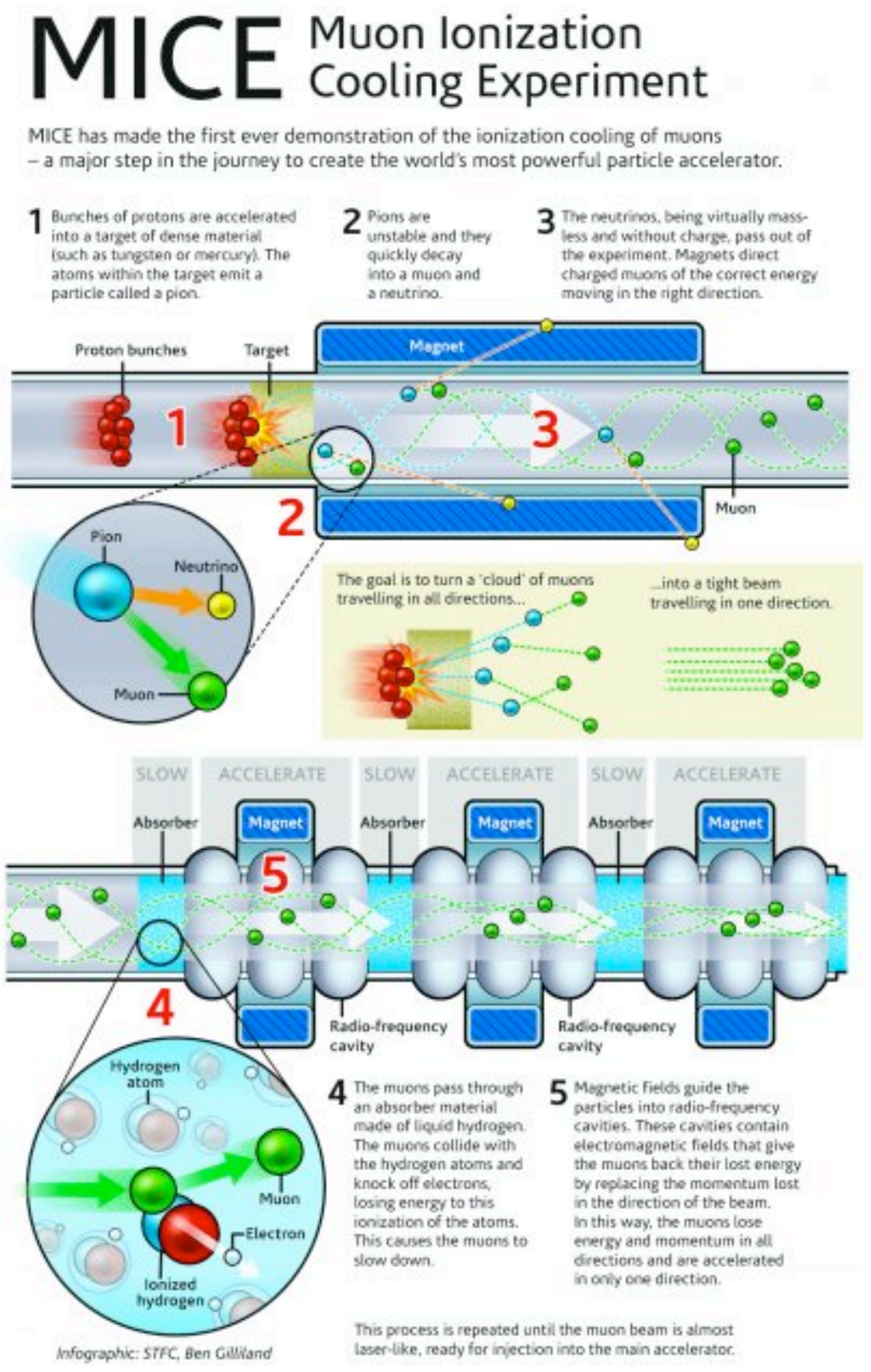
σ_x = (emittance x $\beta(s))^{1/2}$



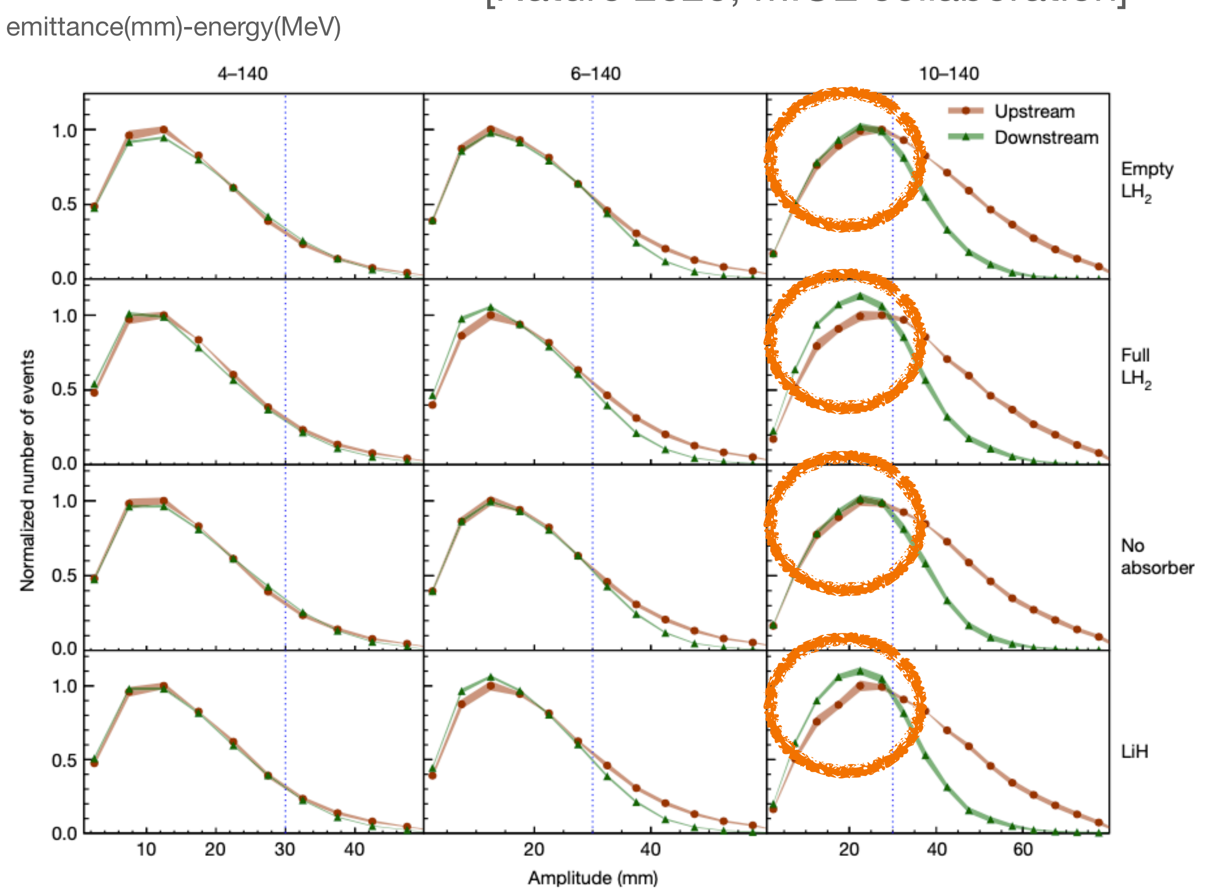
For β^*~1cm, σ^2~ (60 μm)^2 (E_μ/TeV)$^{-1}$ (emittance/3mm)

We need a much narrower beam for good luminosity.

Muon cooling



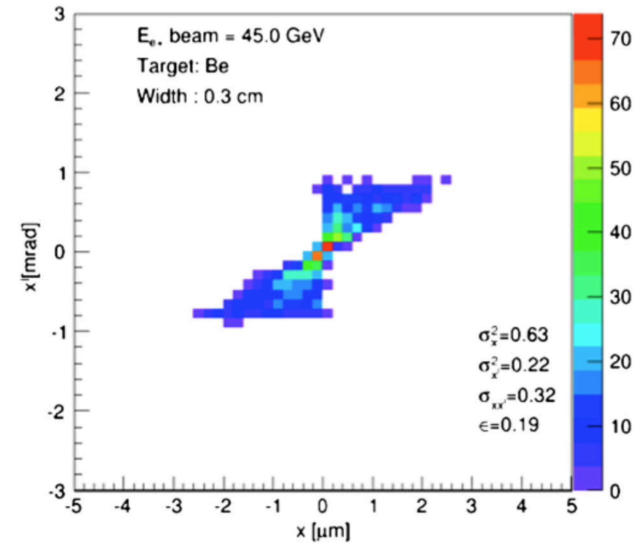
[Nature 2020, MICE collaboration]



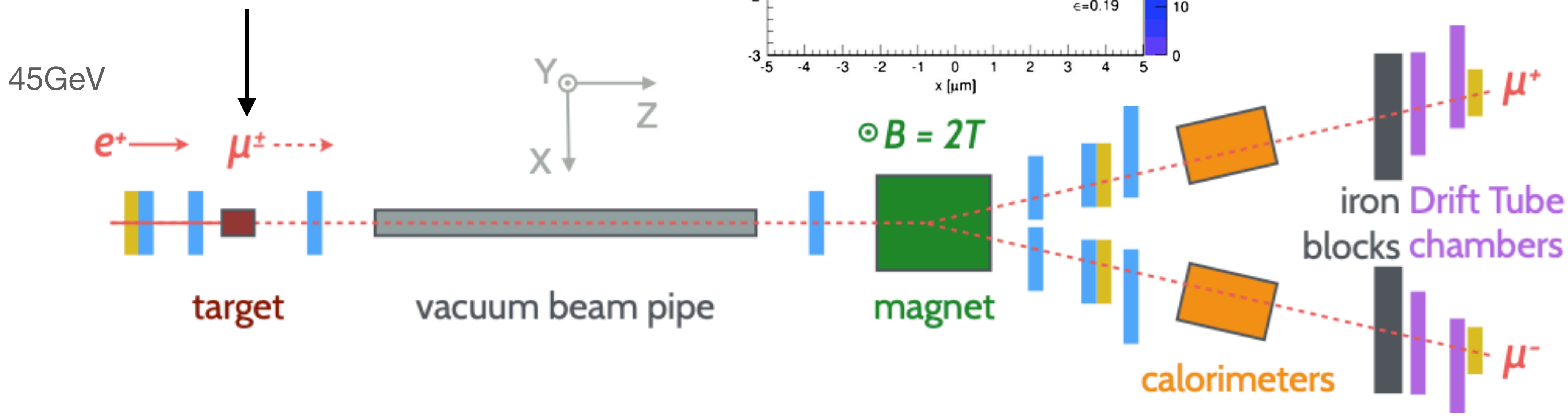
Principle works.

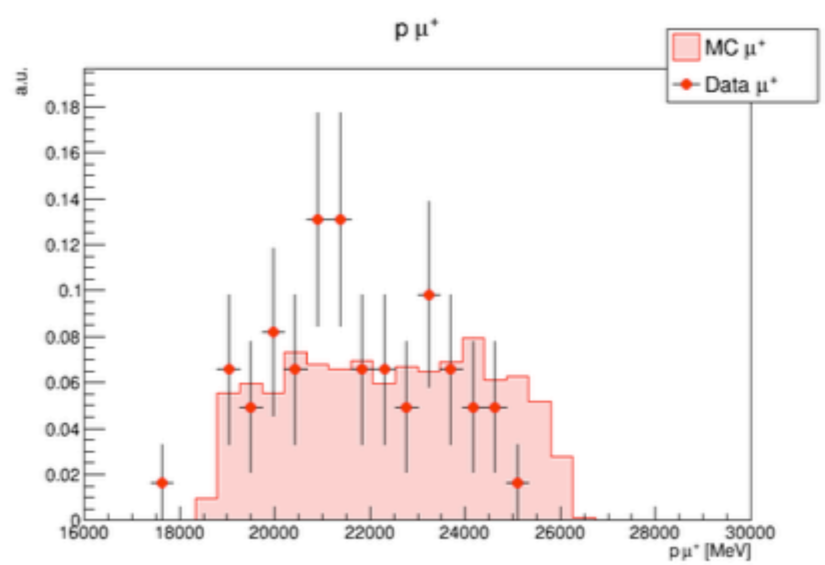
Muon cooling

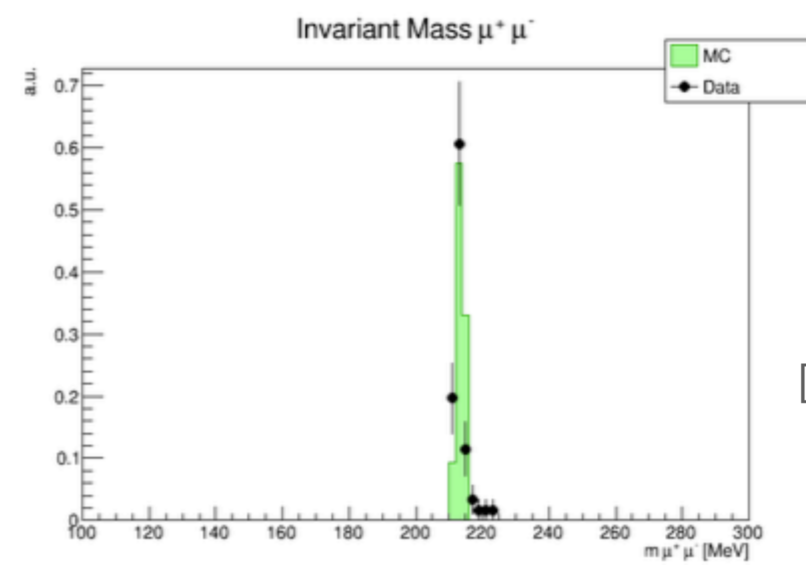
[LEMMA]



Pair production at threshold







[LeptonPhoton ’19]

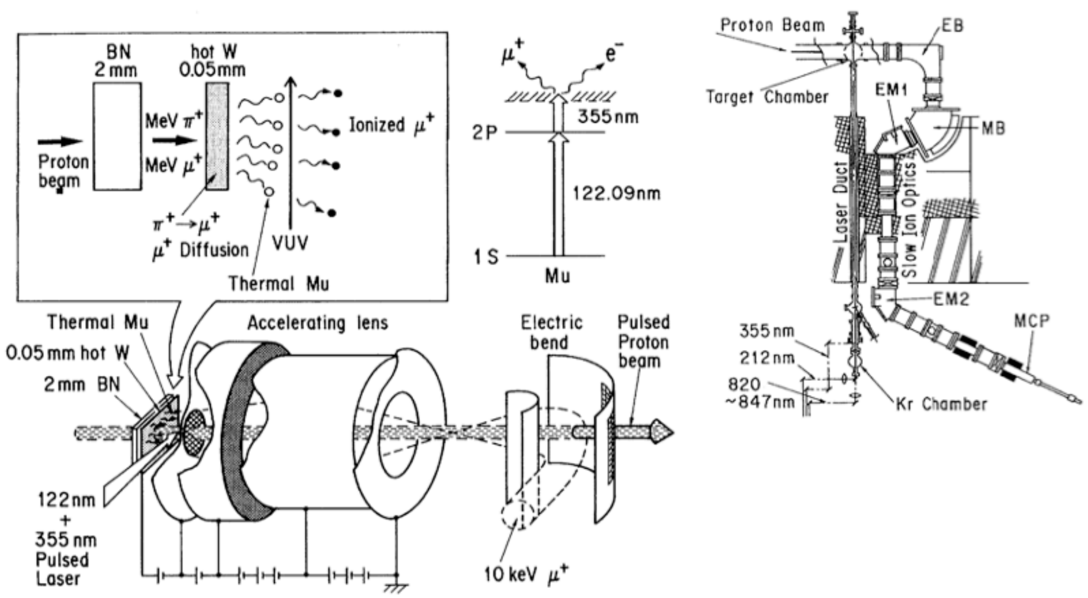
Fewer muons than the case of proton drivers, but much narrower beam possible.

If **nm** size is possible, one can obtain ab^{-1}/year luminosity.

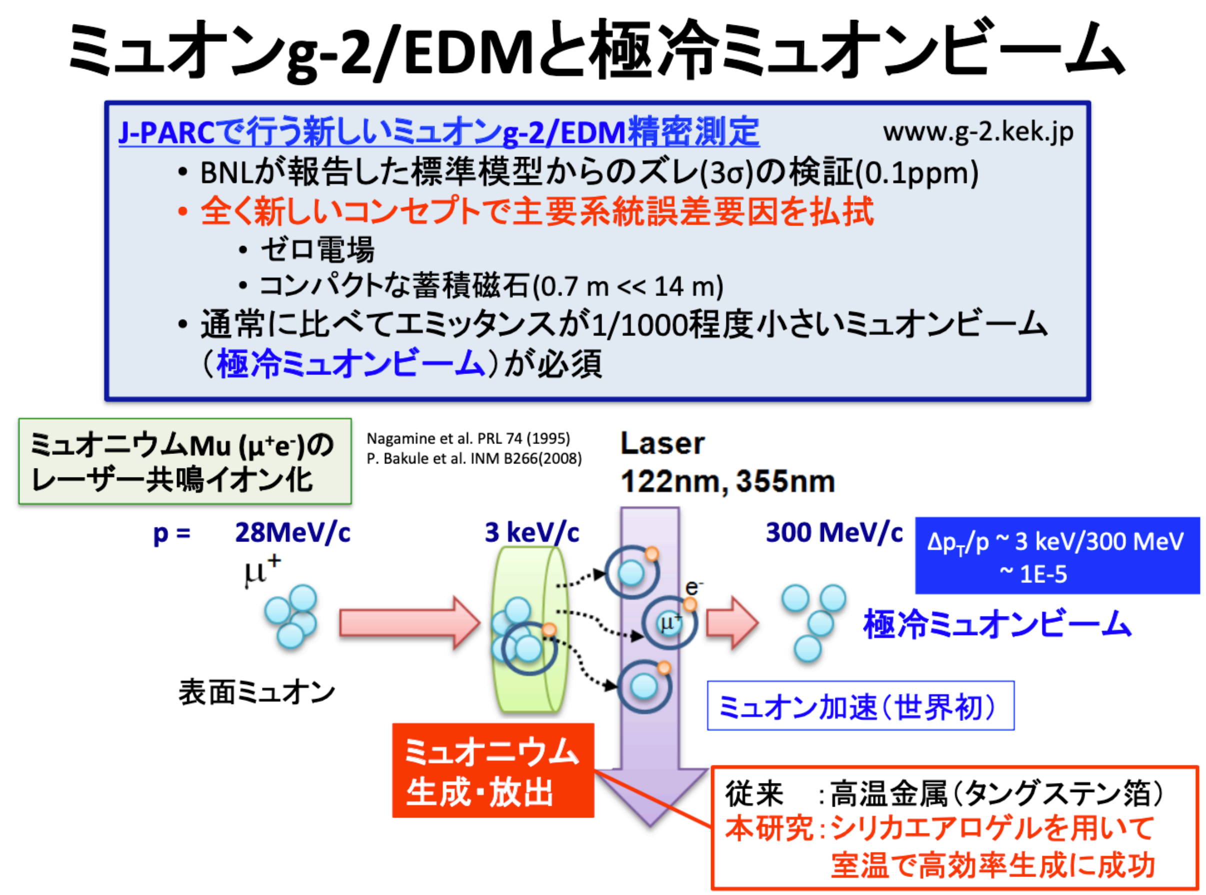
Muon cooling

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/EDM experiment.



Mibe-san's slide

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

μTRISTAN

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

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

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

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

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

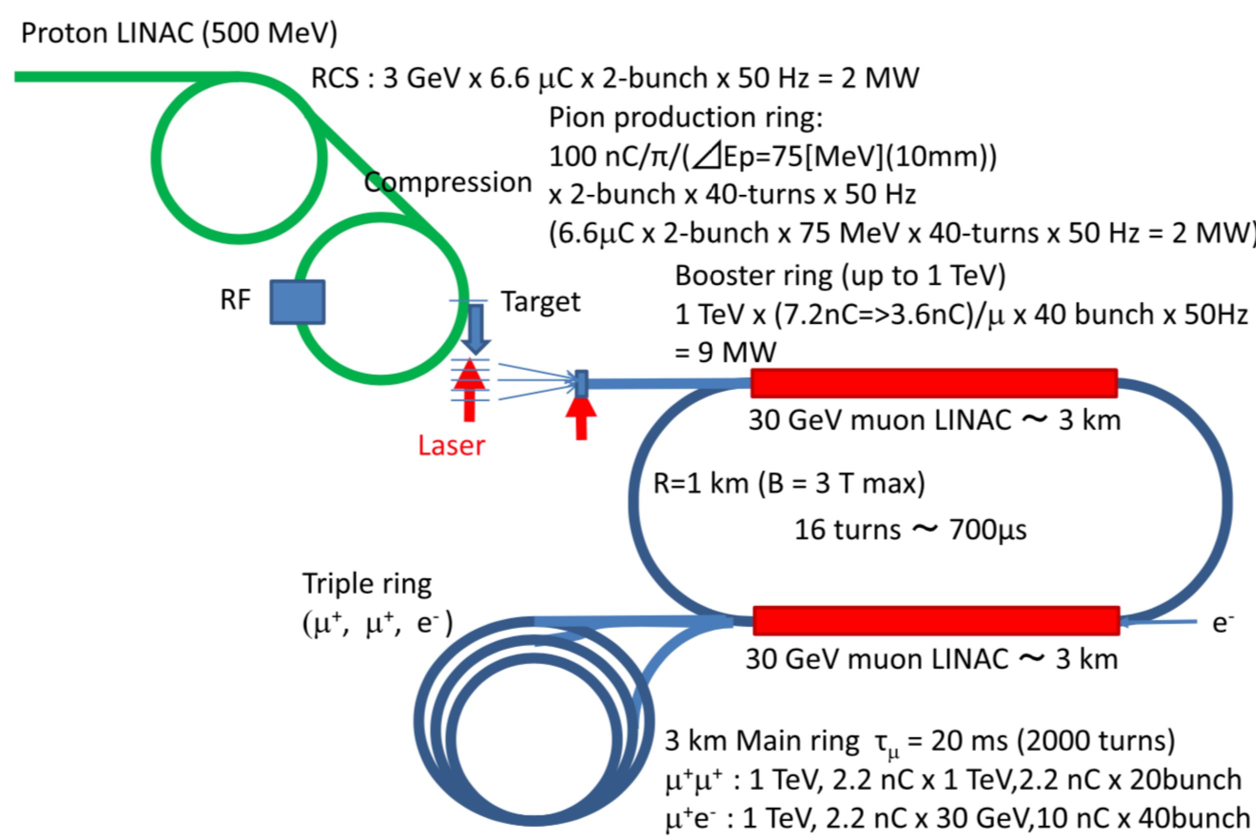
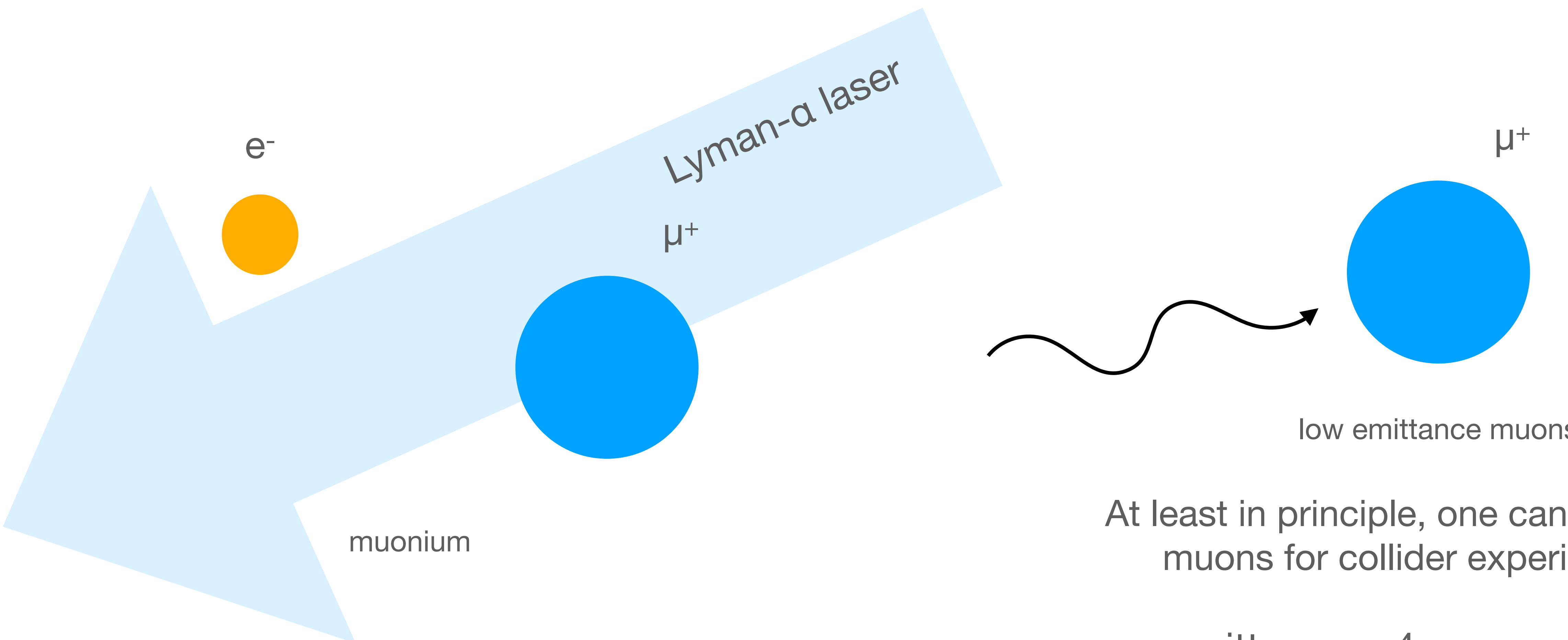


Fig. 1. Conceptual design of the $\mu^+e^-/\mu^+\mu^+$ collider.

μTRISTAN

Why μ+?

because our Universe is e^- rich. → Ultra-cold muon technology.

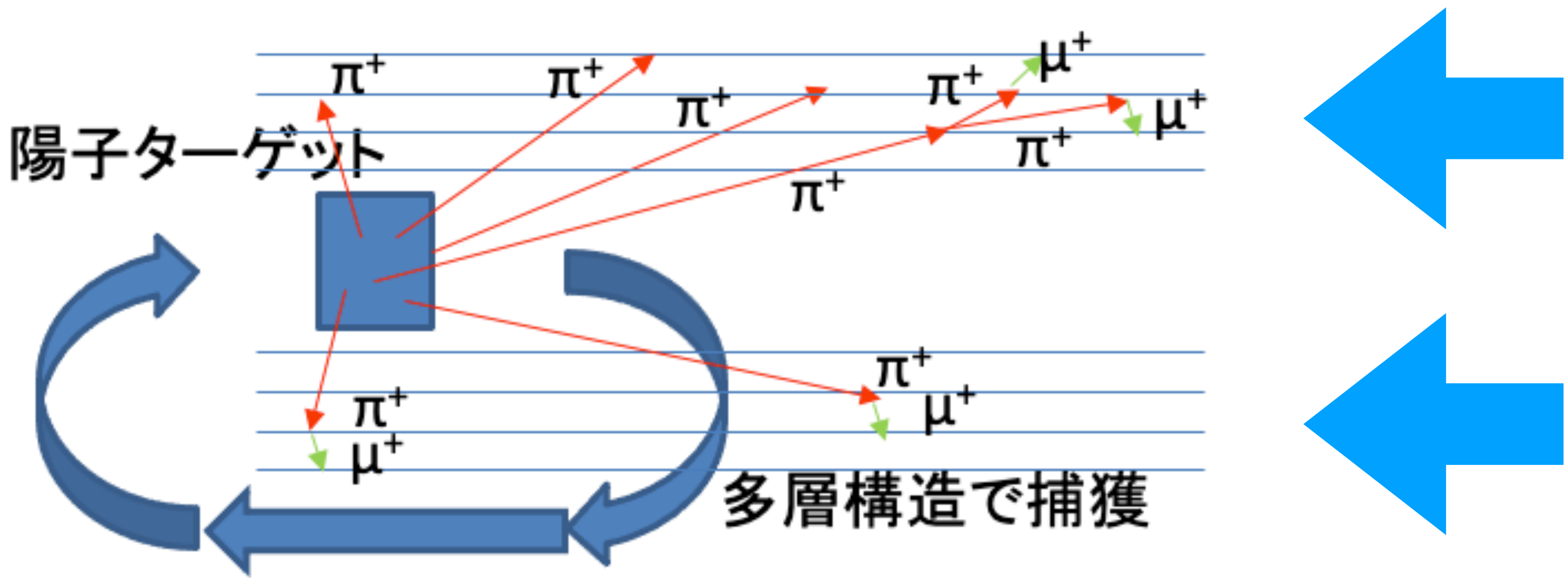


At least in principle, one can use these muons for collider experiments.

emittance ~ 4 μm

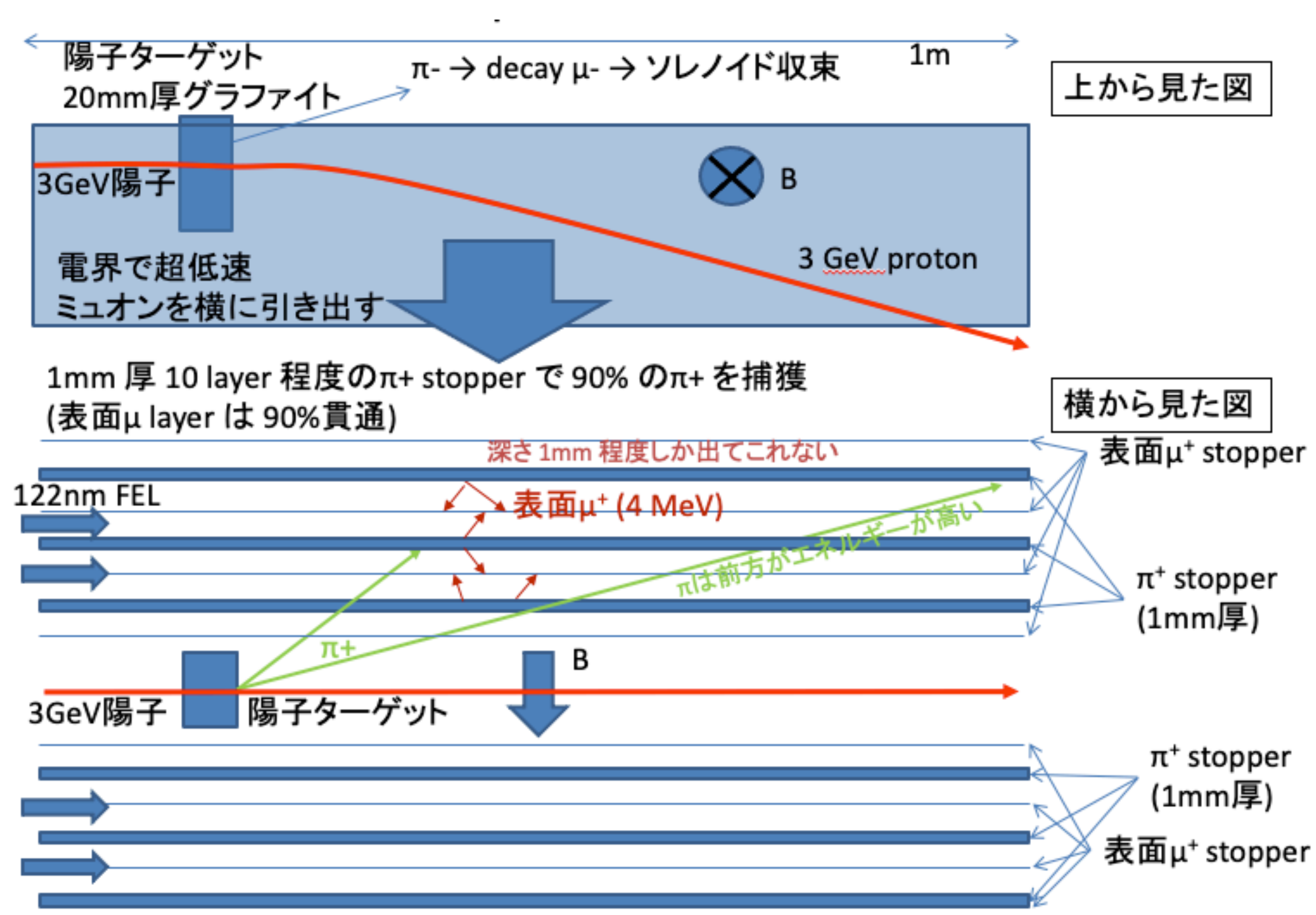
→ 0.4 nm @ TeV

muon production and cooling



Lyman-α laser

3GeV proton driver



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 realistic

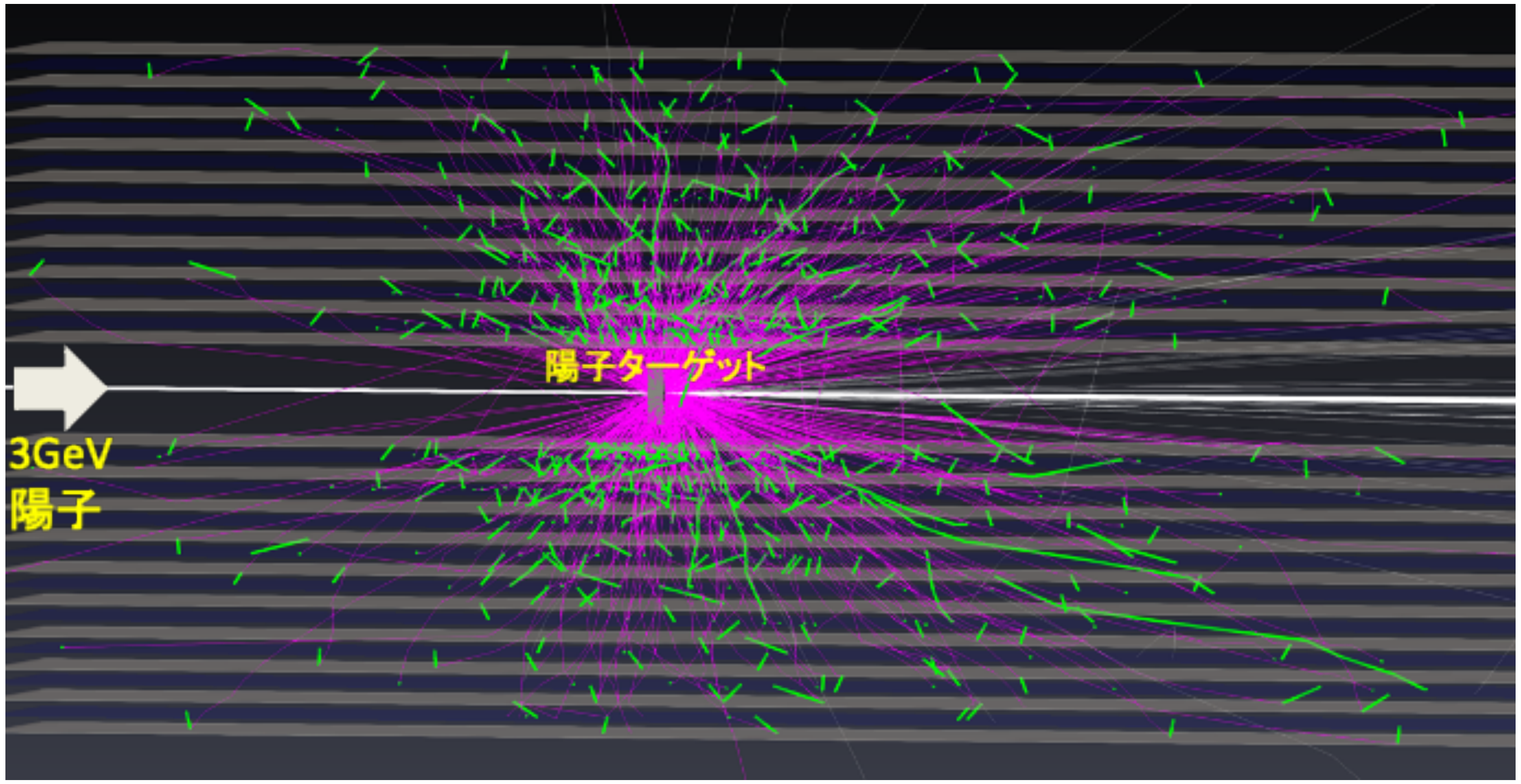
pion production target: 40 hits/bunch 0.016 π^+/proton 2.6×10^{15} π^+/s maybe realistic

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

10^5 larger than J-PARC MLF.

Super muon factory!

simulation: (in progress)



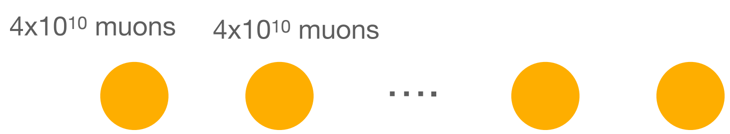
Luminosity?

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.

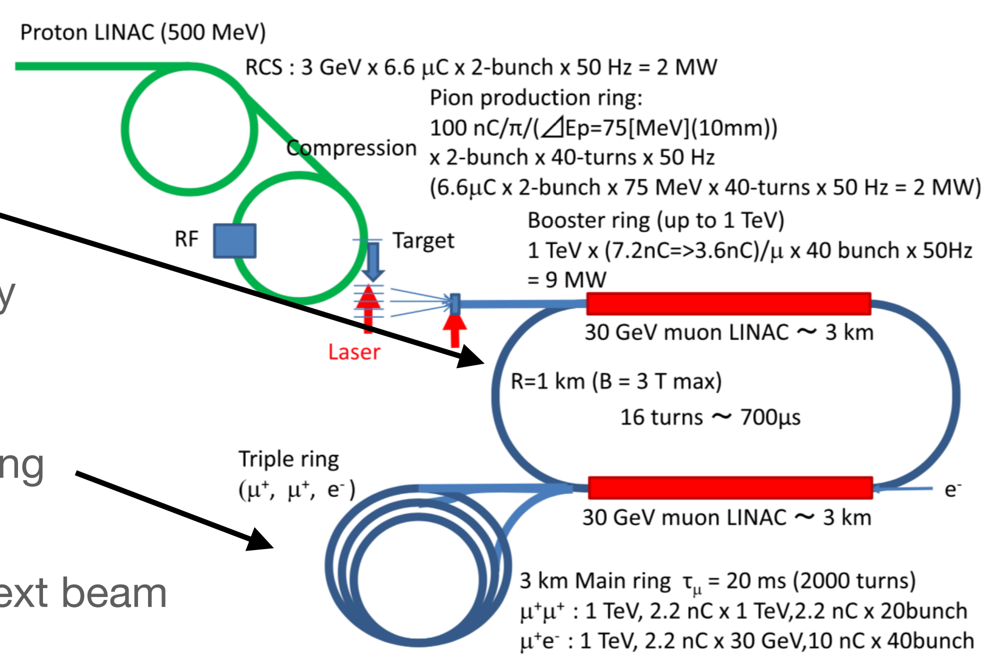


Fig. 1. Conceptual design of the $\mu^+e^-/\mu^+\mu^+$ collider.

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

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

(β* may be much smaller?)

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

not bad.

How much?

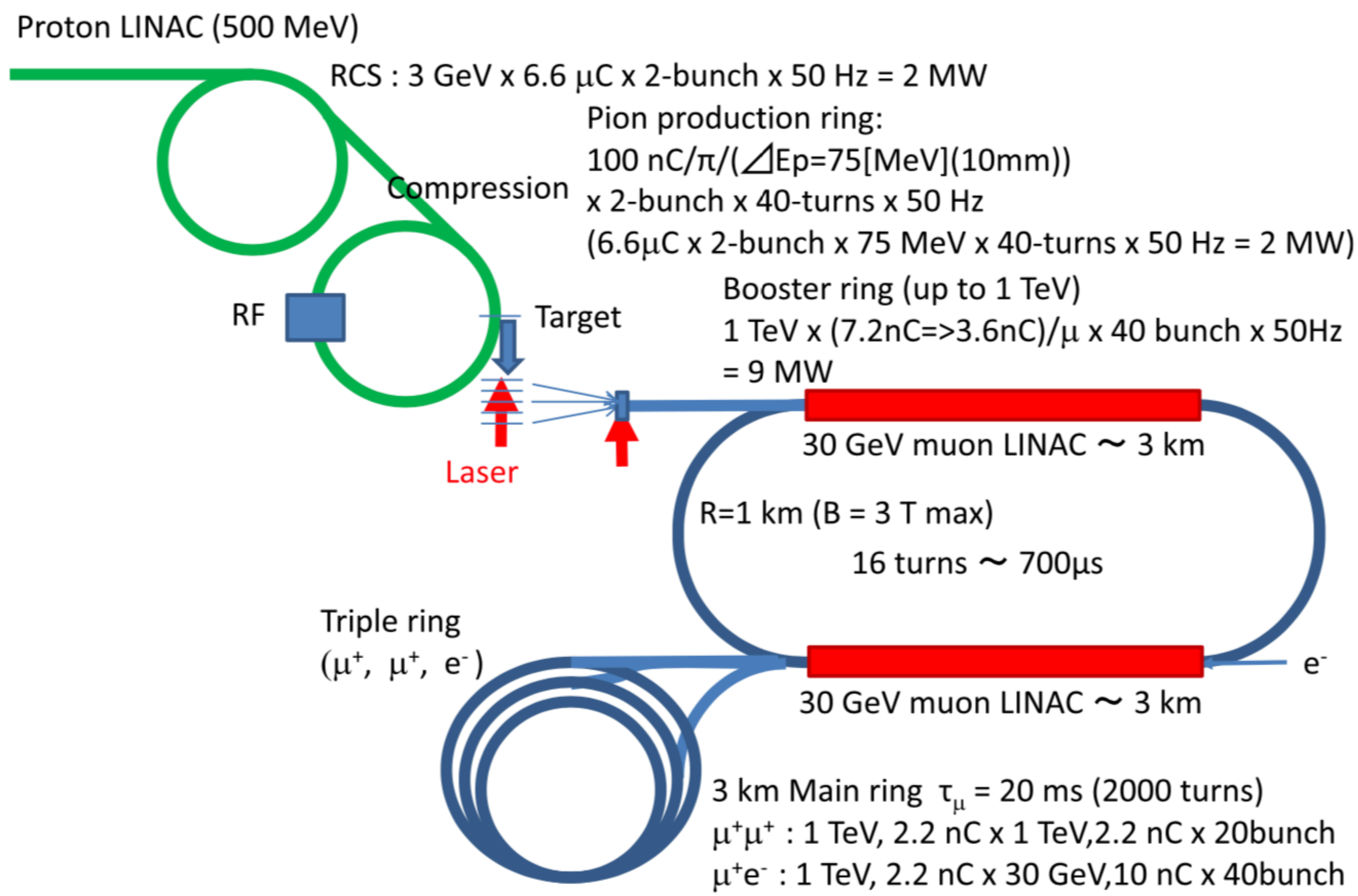
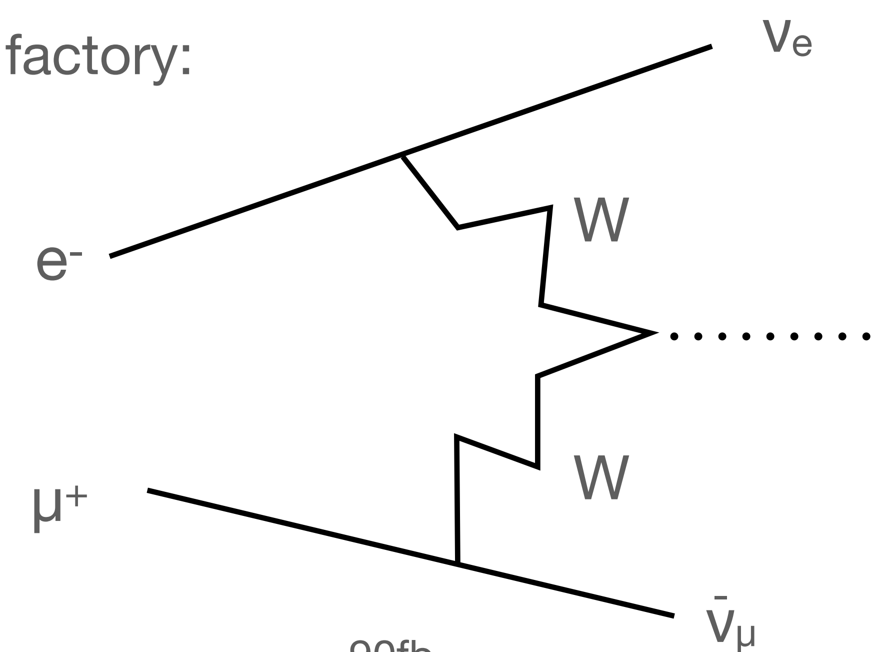


Fig. 1. Conceptual design of the $\mu^+e^-/\mu^+\mu^+$ collider.

We don't know yet. But at least the size can be much more compact than next generation ee/pp colliders.

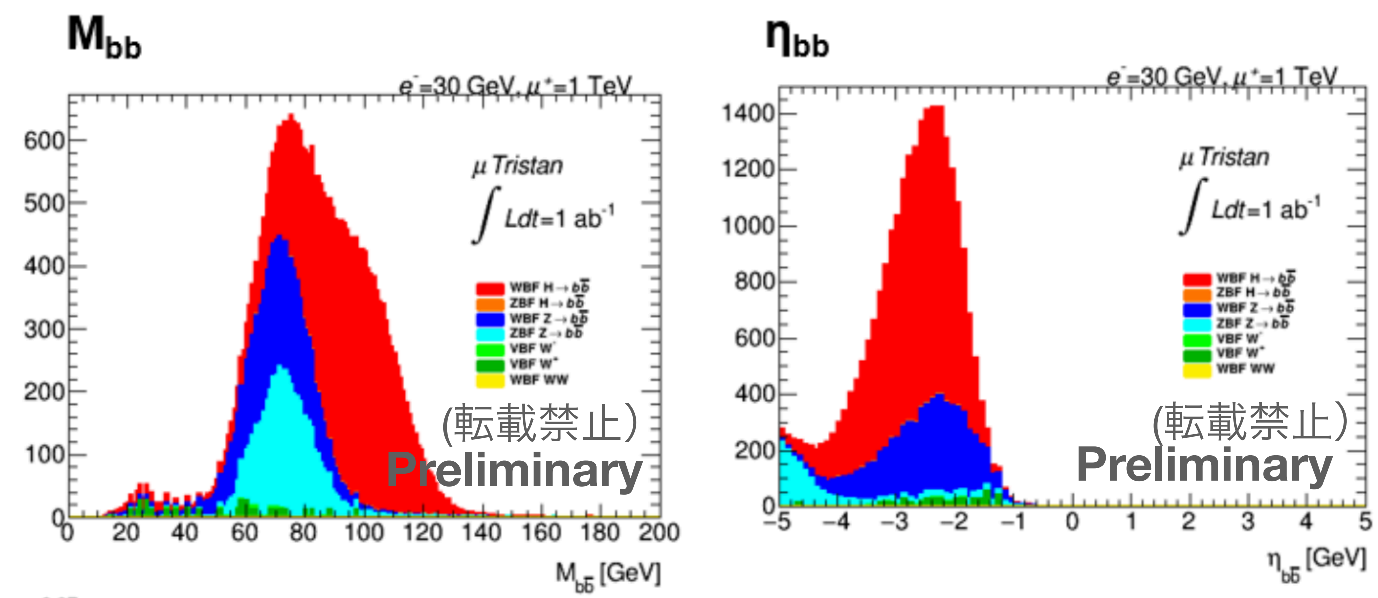
What can we do at μTRISTAN?

Higgs factory:

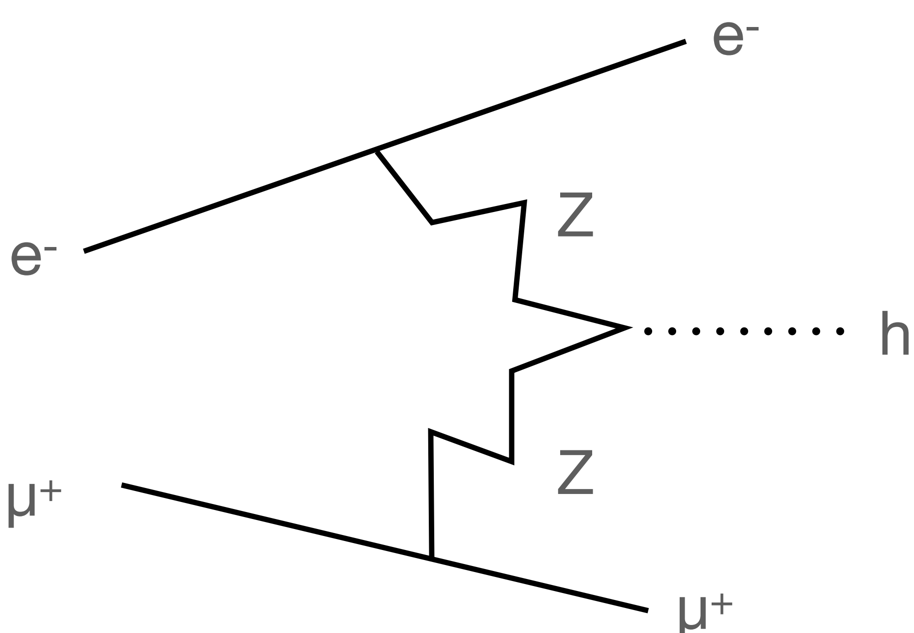


~90fb
~10^5 Higgs bosons

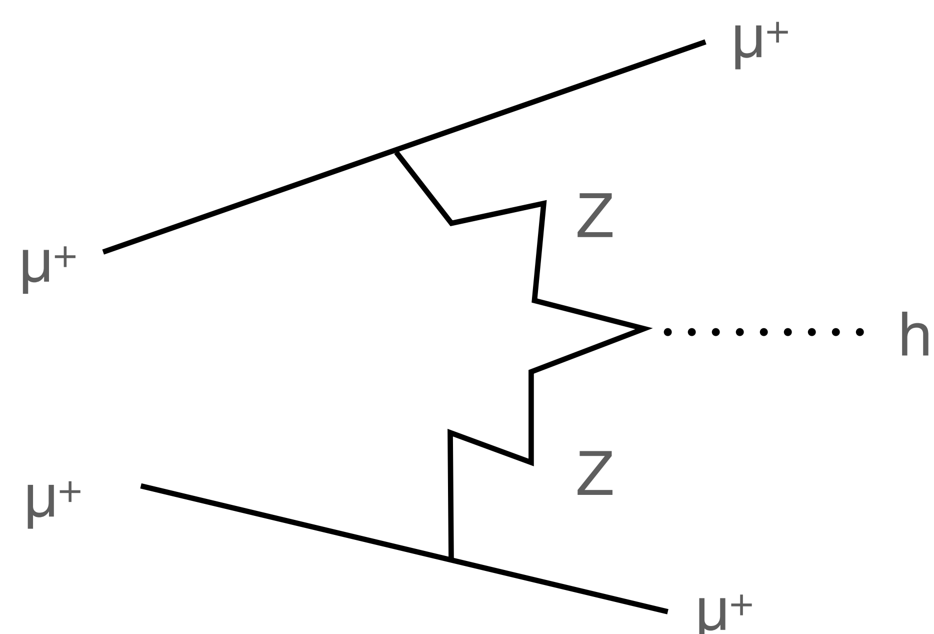
simulation with the ATLAS detector for HL-LHC



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

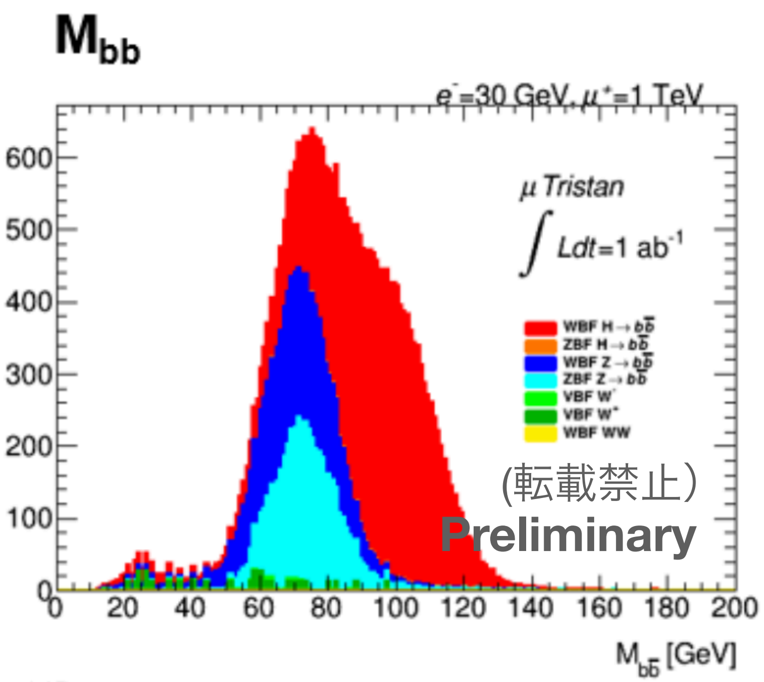


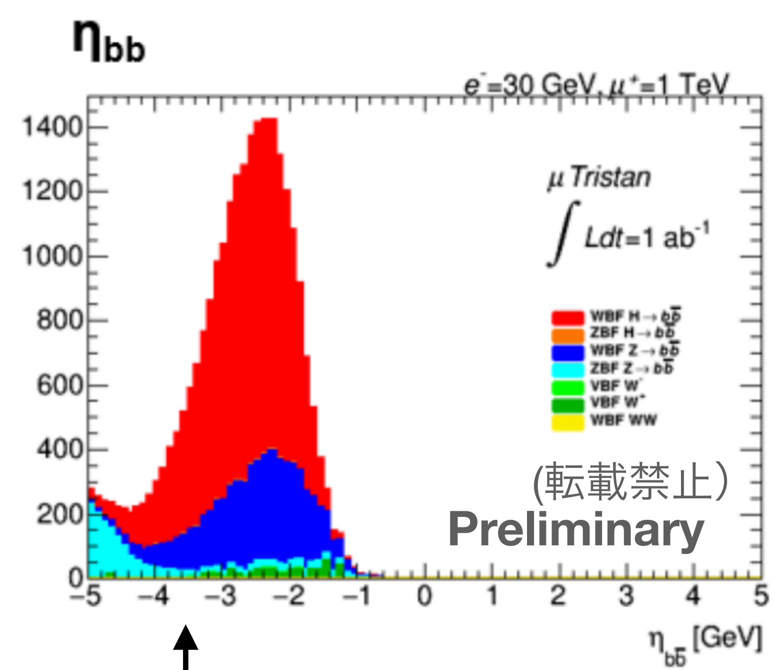
~4fb
~10^3 Higgs bosons



~54fb
~10^4 Higgs bosons

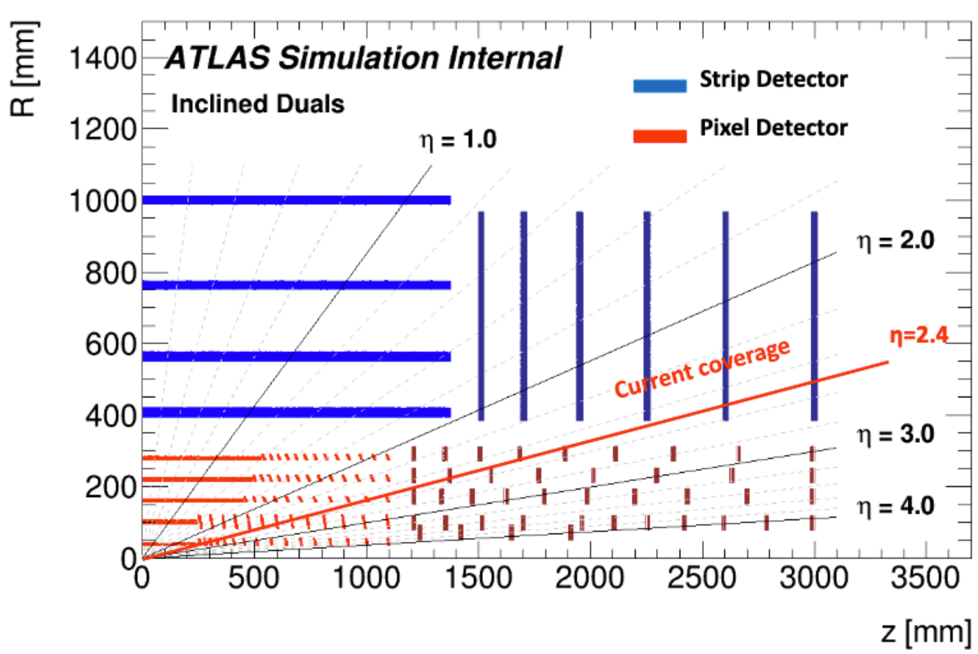
Very asymmetric

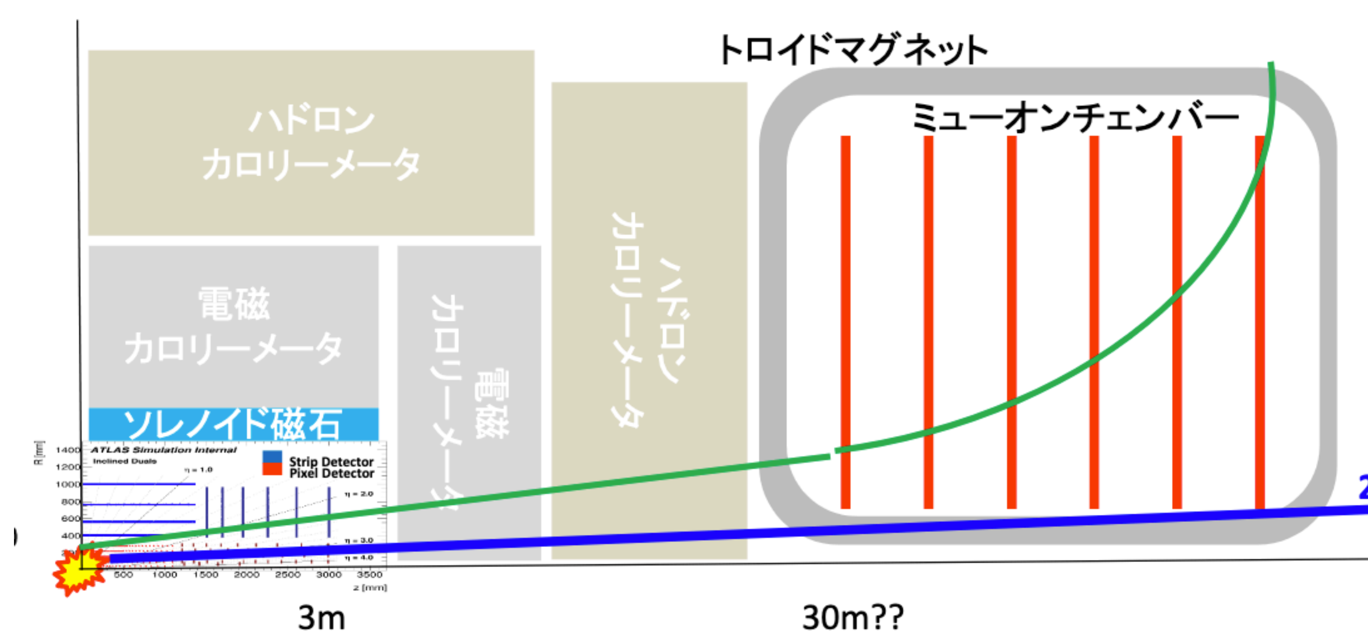




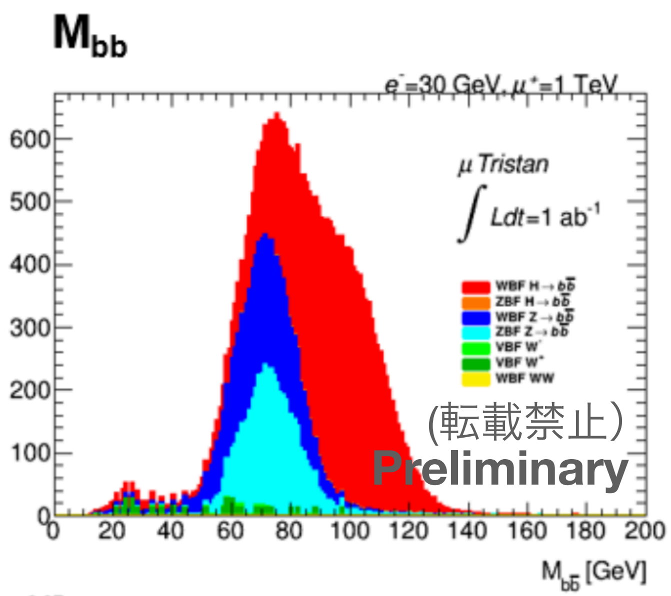
All the particles go to the direction of the muon.

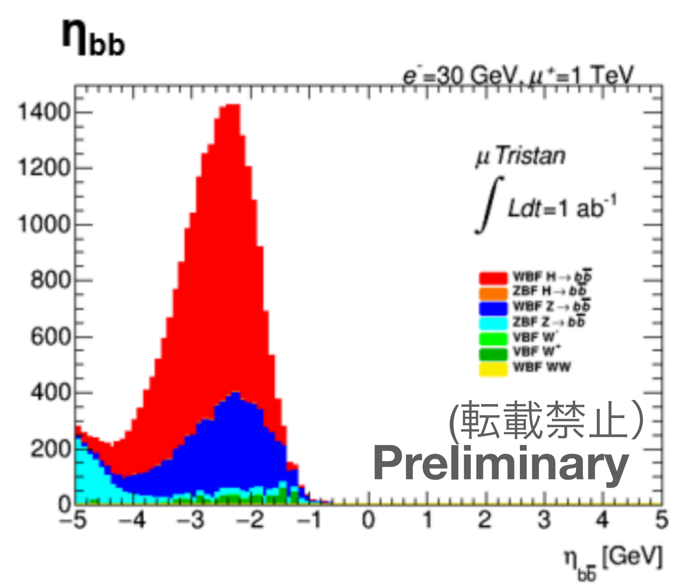
We need a coverage of η~-4 (2°), which is the same level as the design of the ATLAS at HL-LHC.



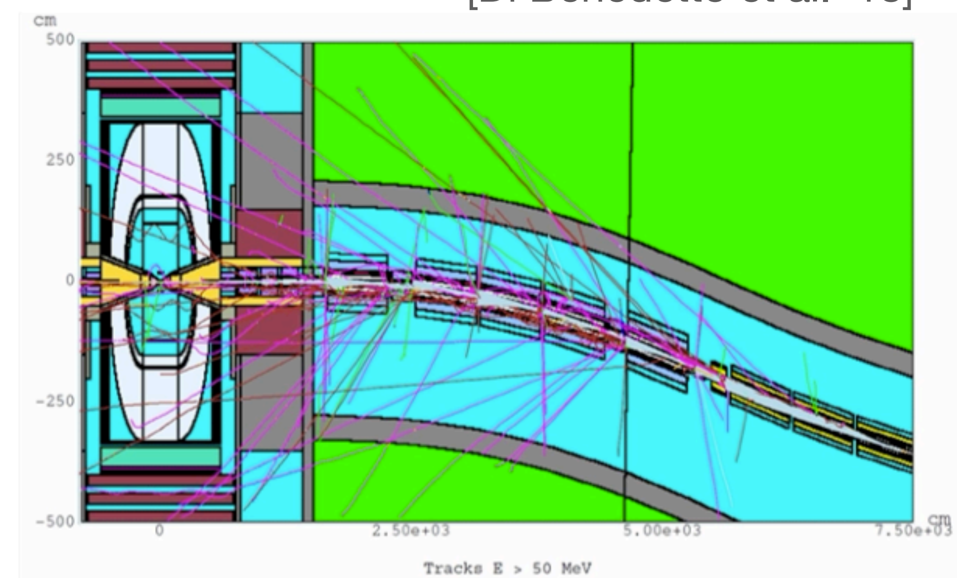


Muon decays in the beam





[Di Benedetto et al. ’18]



Beam induced background from muon side

We need a shielding at about 10°. No detector can be placed below such angles.

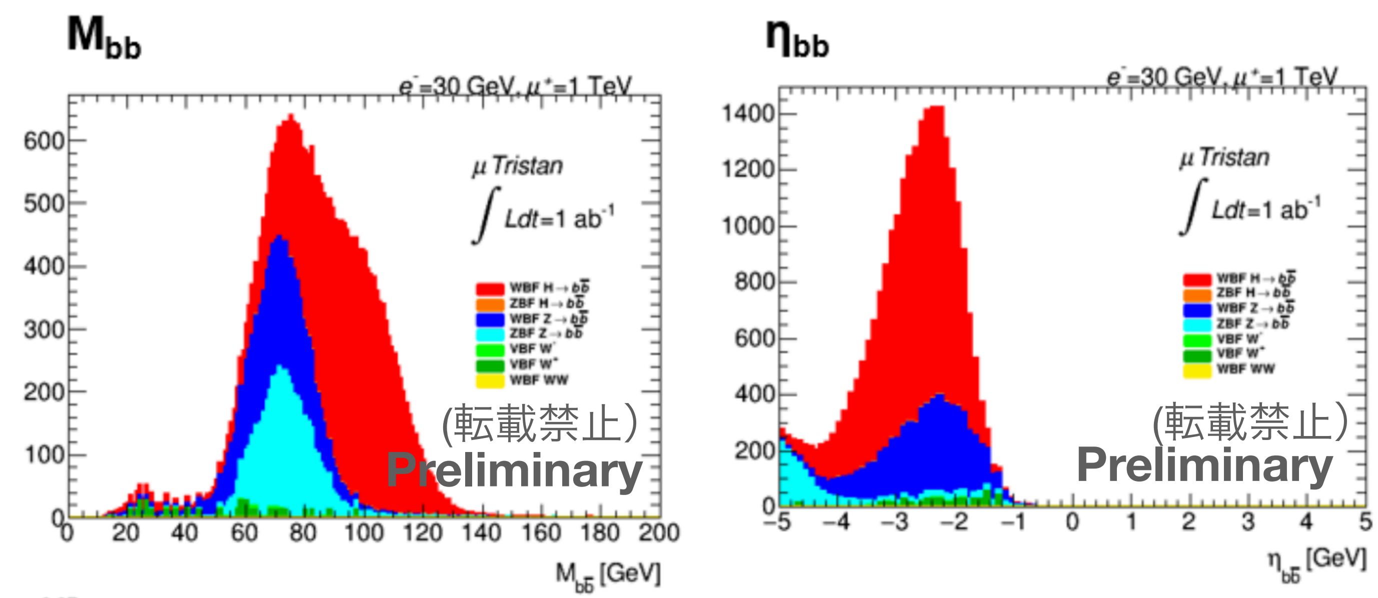
Fortunately, all the particles goes the other side.

In any case, we need dedicated detector designs for this collider.

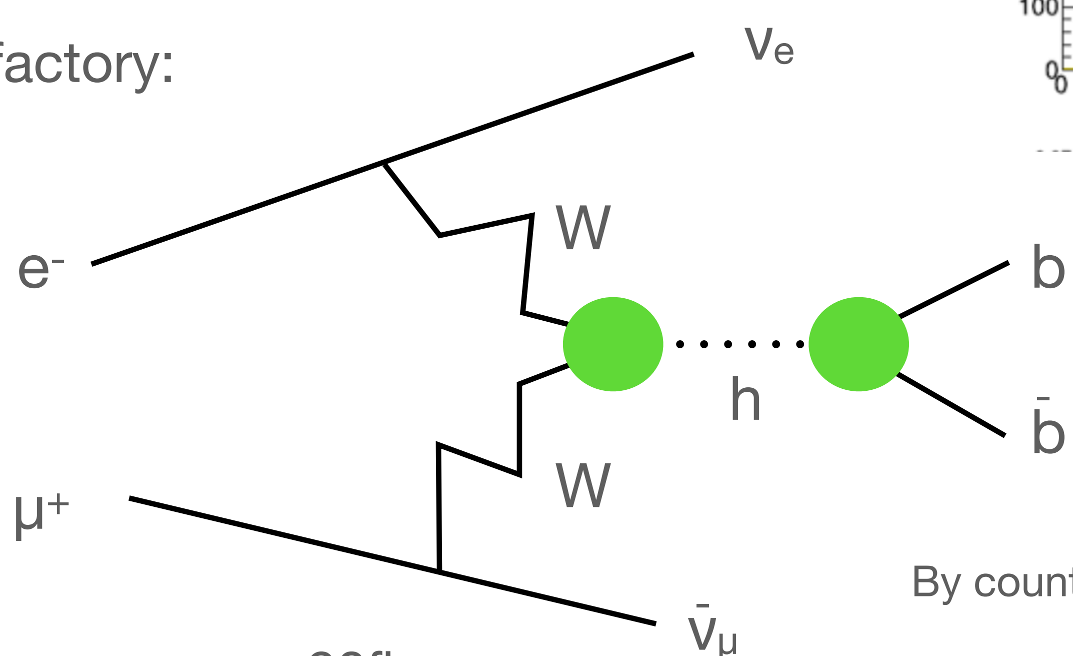
Higgs coupling

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

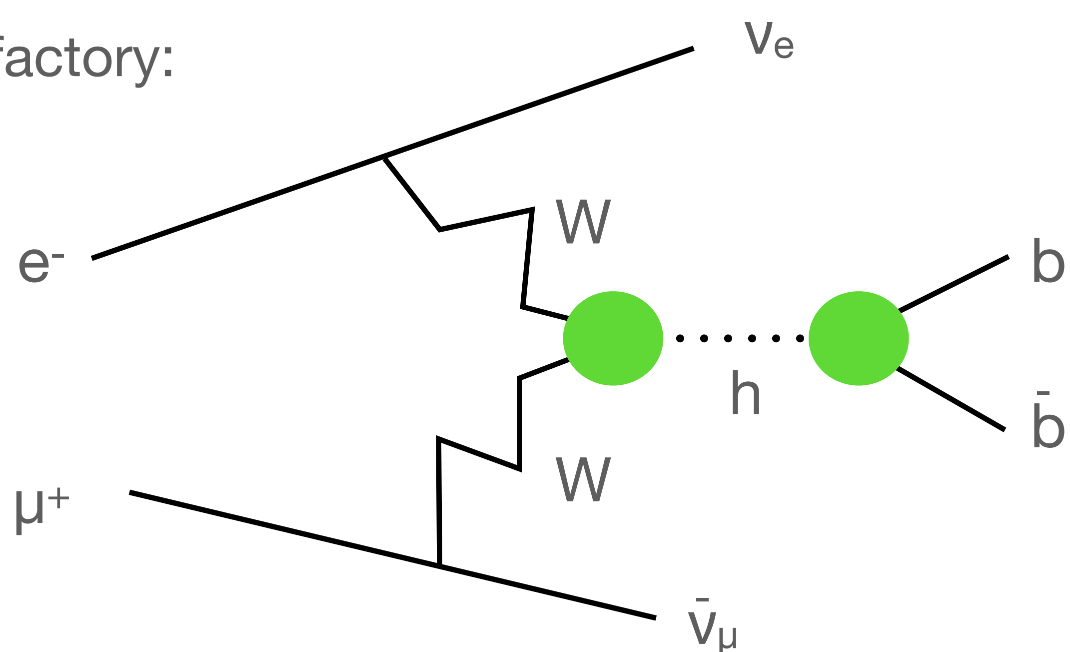
By counting the number of events and compare with the SM prediction

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

sub percent level measurements.

Higher energy? μTevatron?

Higgs factory:



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

$\sqrt{s}$ = 775 GeV

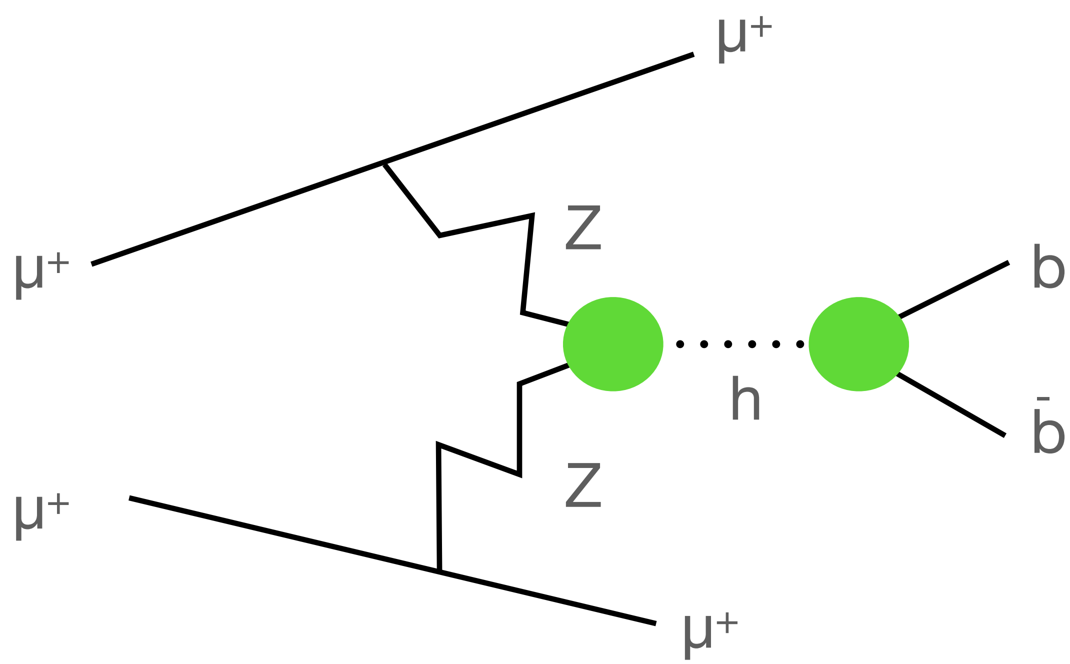
~472fb

~5x10^5 Higgs bosons ← Assuming the same luminosity as μTRISTAN

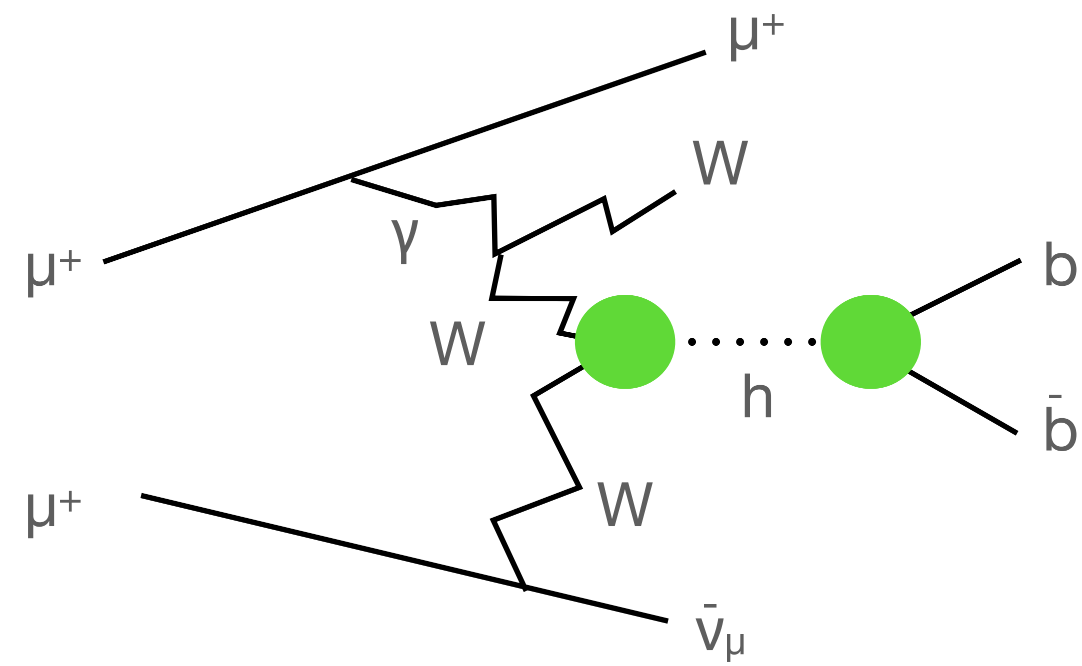
hh production: 89 events/ab^{-1} (maybe we need more for coupling measurements)

Indirect measurement of three-point Higgs coupling ~20% level

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



~54fb@2TeV final state all visible

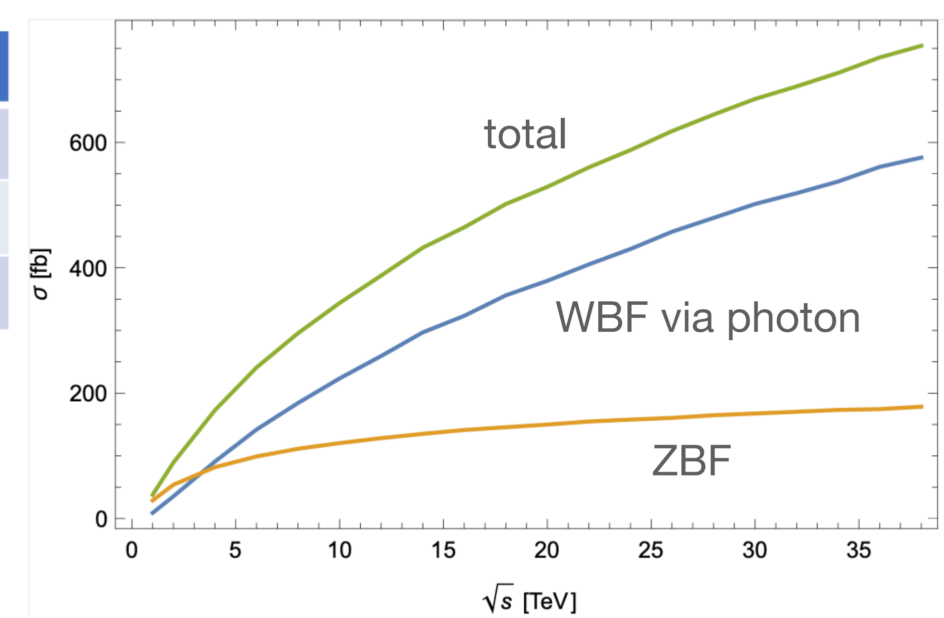


~35fb@2TeV

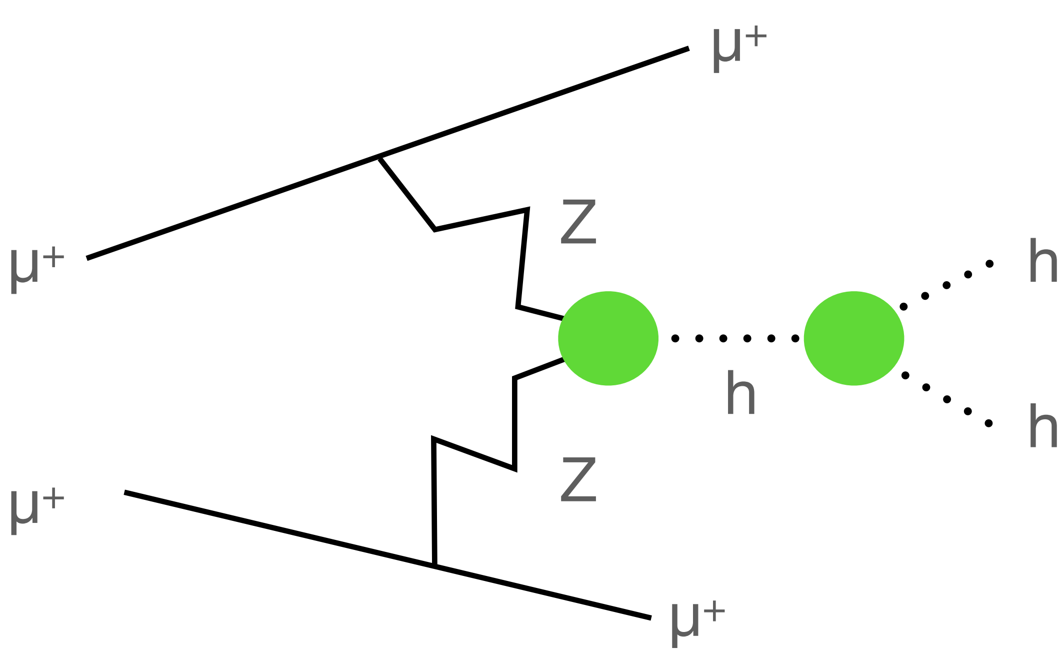
gets more important at high energy

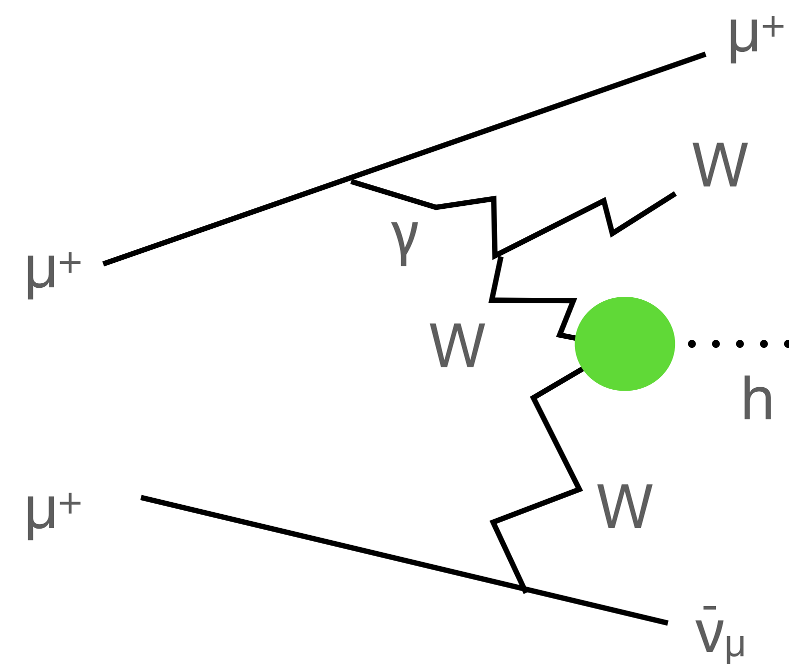
$\sqrt{s}$ [TeV]	ZBF [fb]	Photon emission [fb]
2	54	35
10	121	224
20	150	376

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



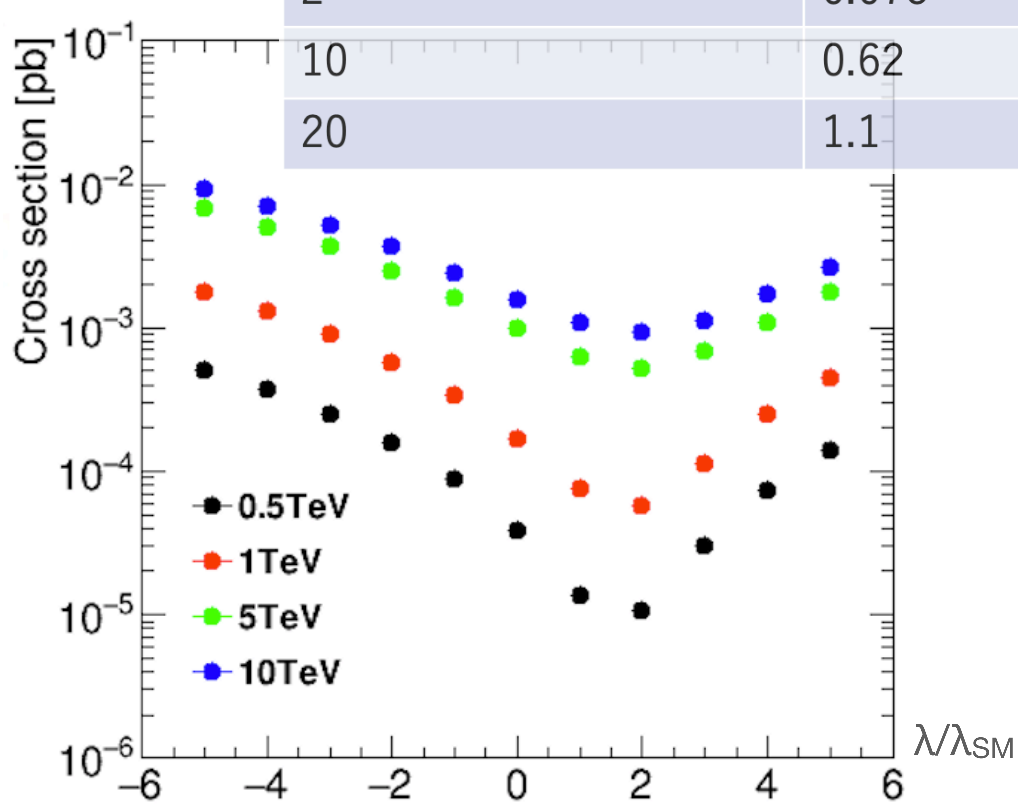
Higgs production@$\mu^+\mu^+$



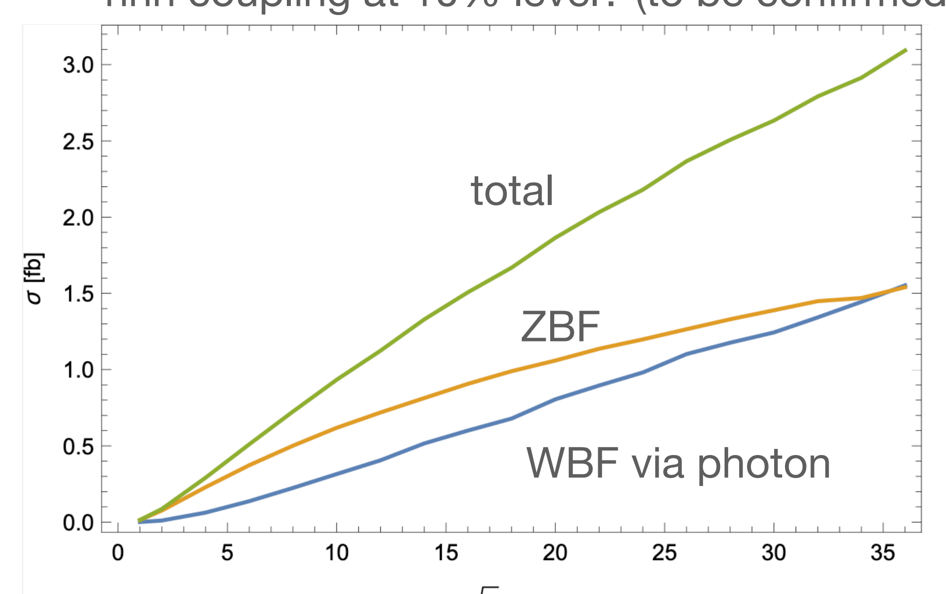


+ others

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



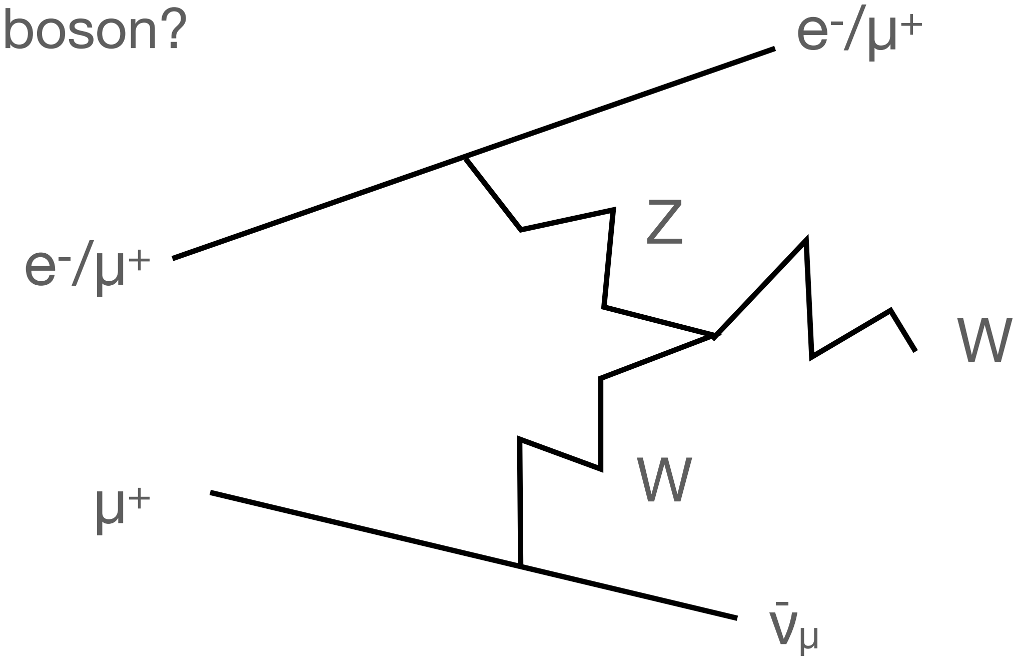
hhh coupling at 10% level? (to be confirmed)



What else?

[CDF 2022]

W-boson?



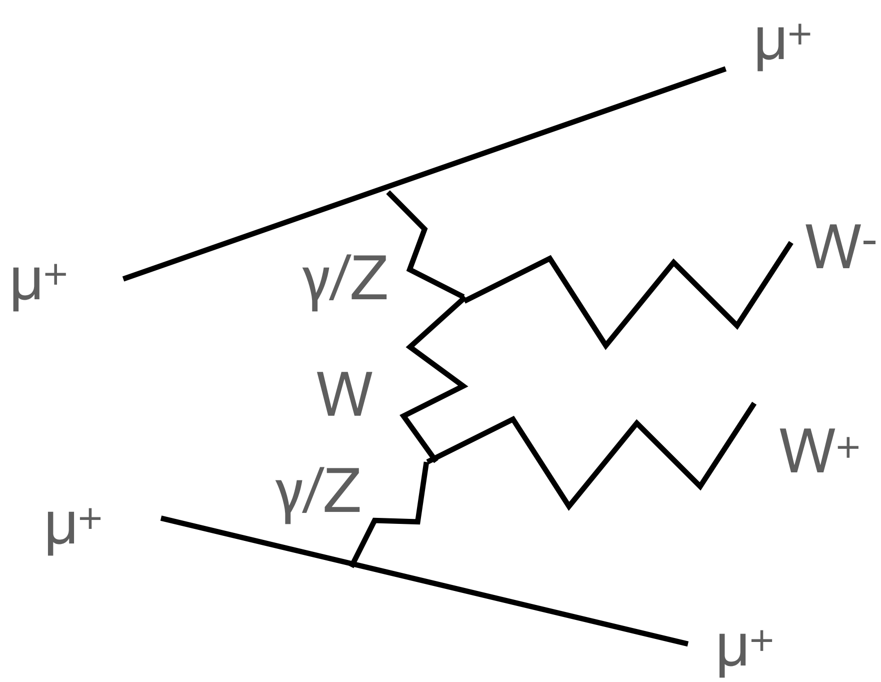
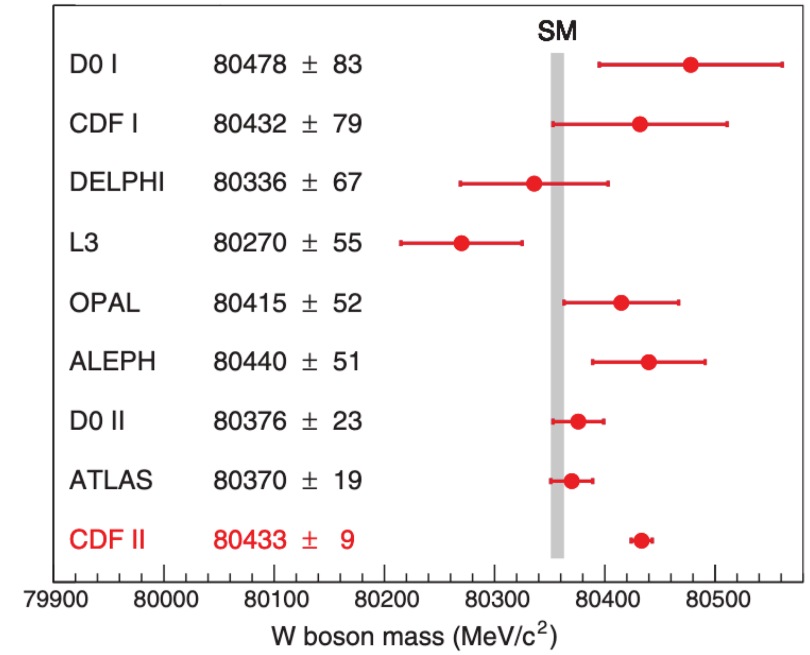
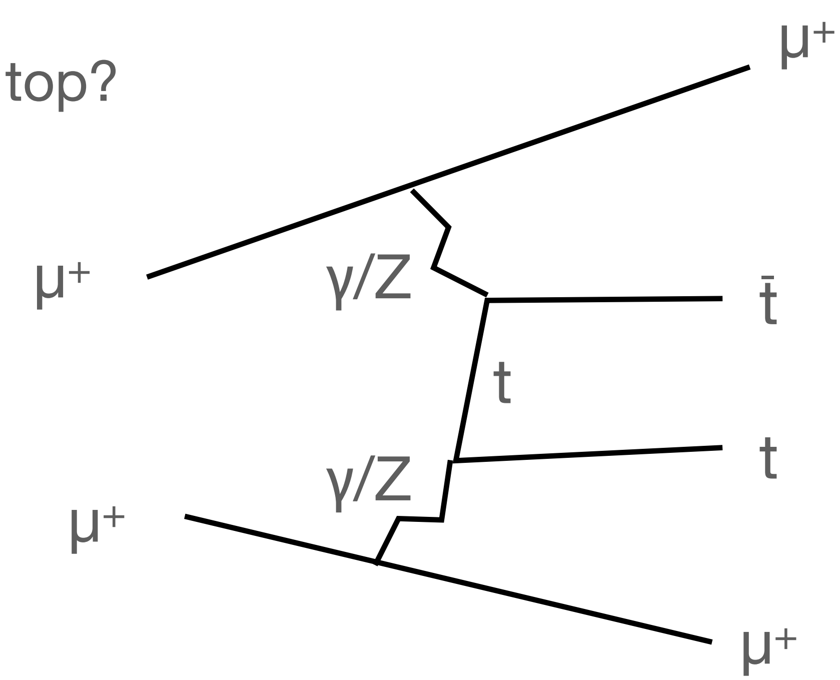


Fig. 5. Comparison of this CDF II measurement and past M_W measurements with the SM expectation. The latter includes the published estimates of the uncertainty (4 MeV) due to missing higher-order quantum corrections, as well as the uncertainty (4 MeV) from other global measurements used as input to the calculation, such as m_t. c, speed of light in a vacuum.



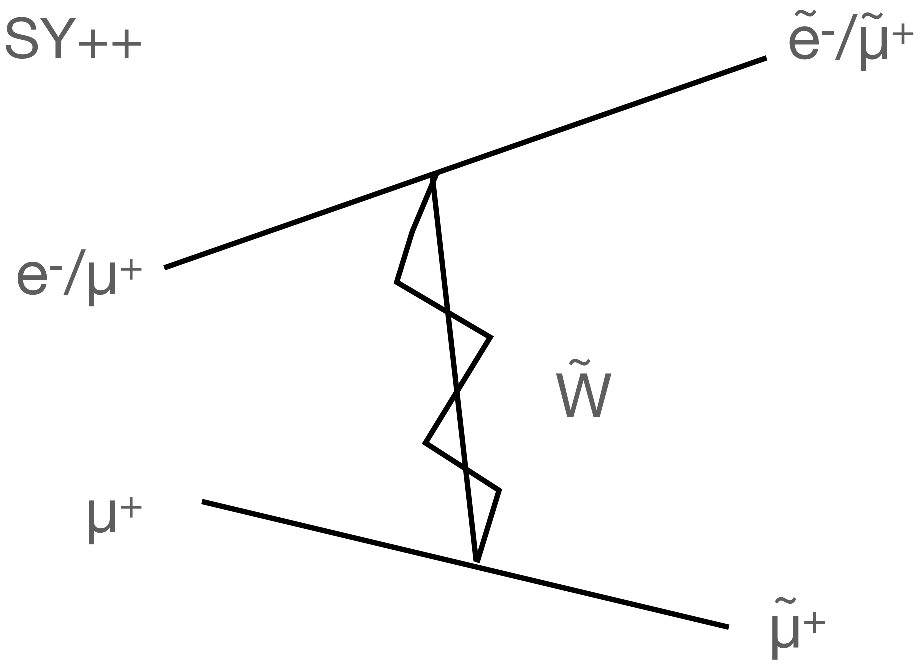
top?



We haven’t studied these, but maybe interesting.

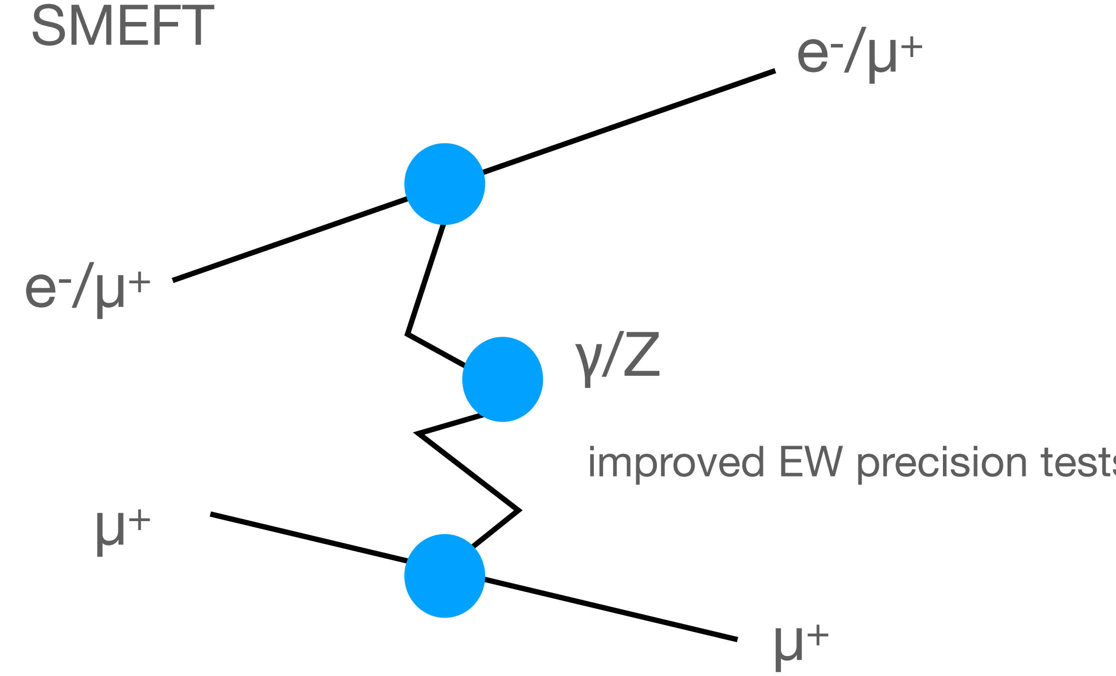
New physics?

SUSY++

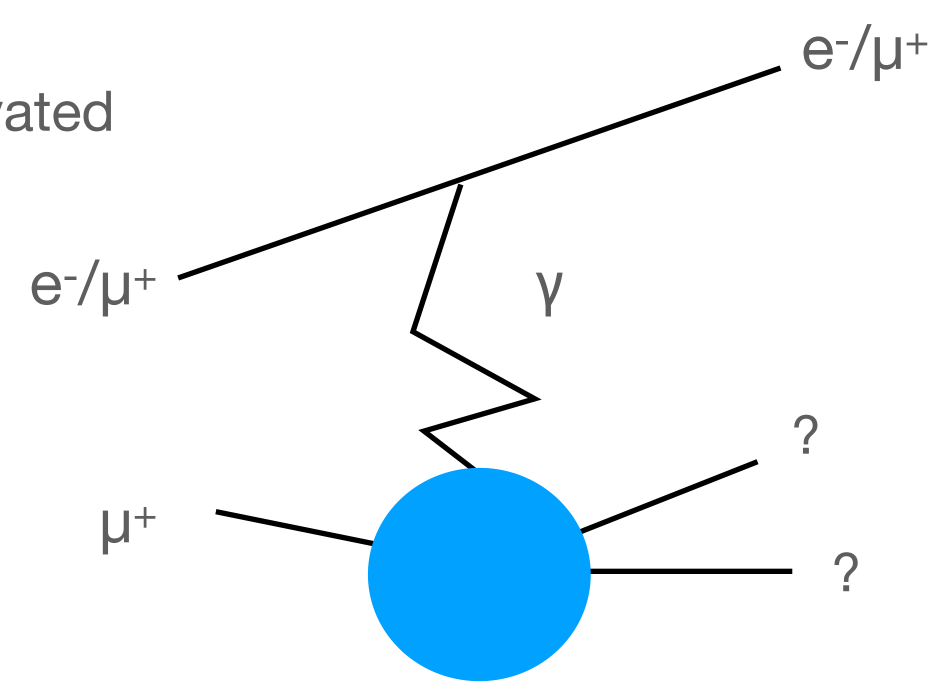


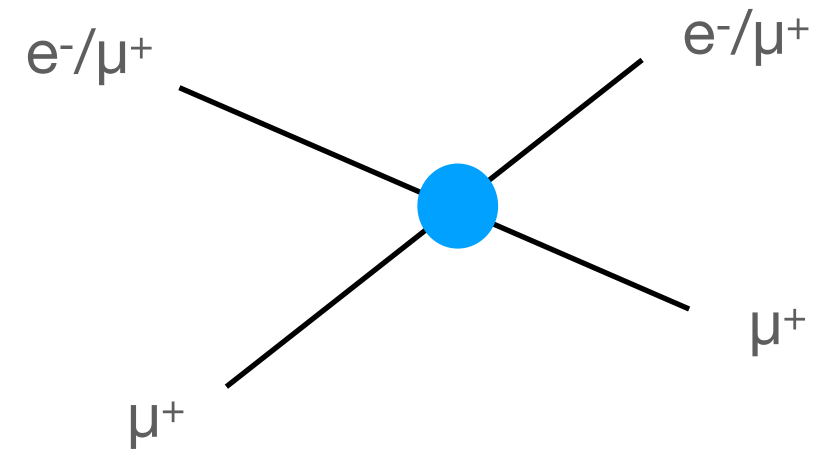
TeV mass new particles

SMEFT



g-2 motivated

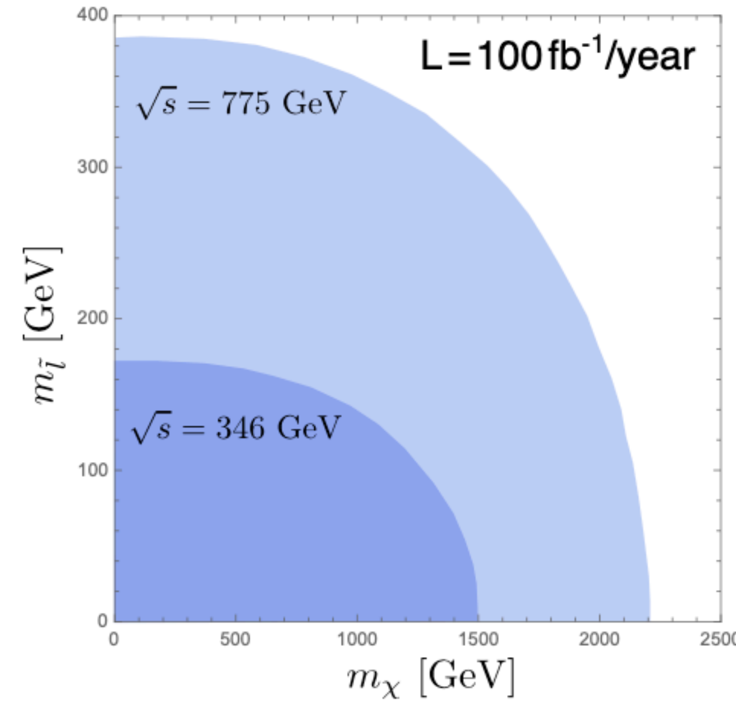


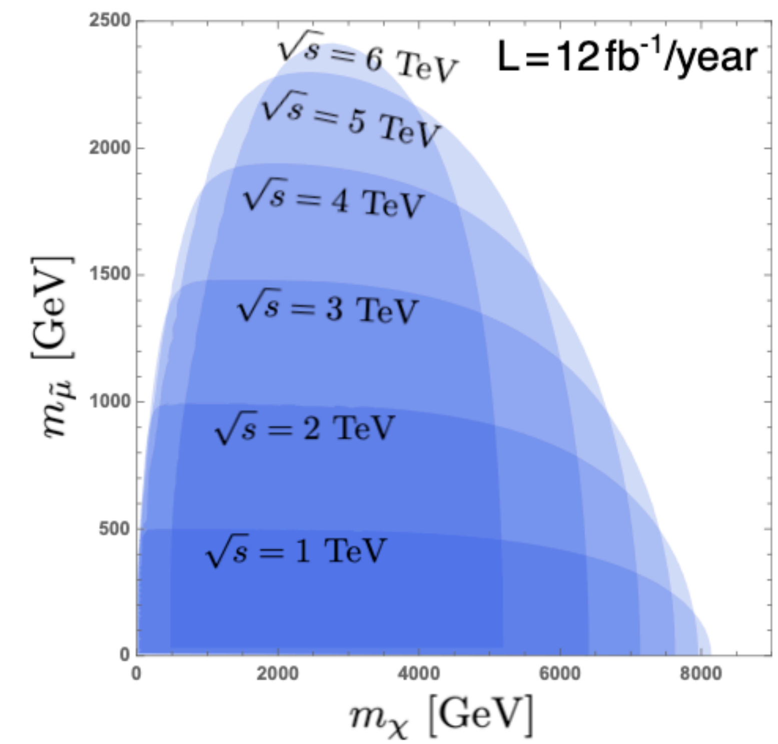


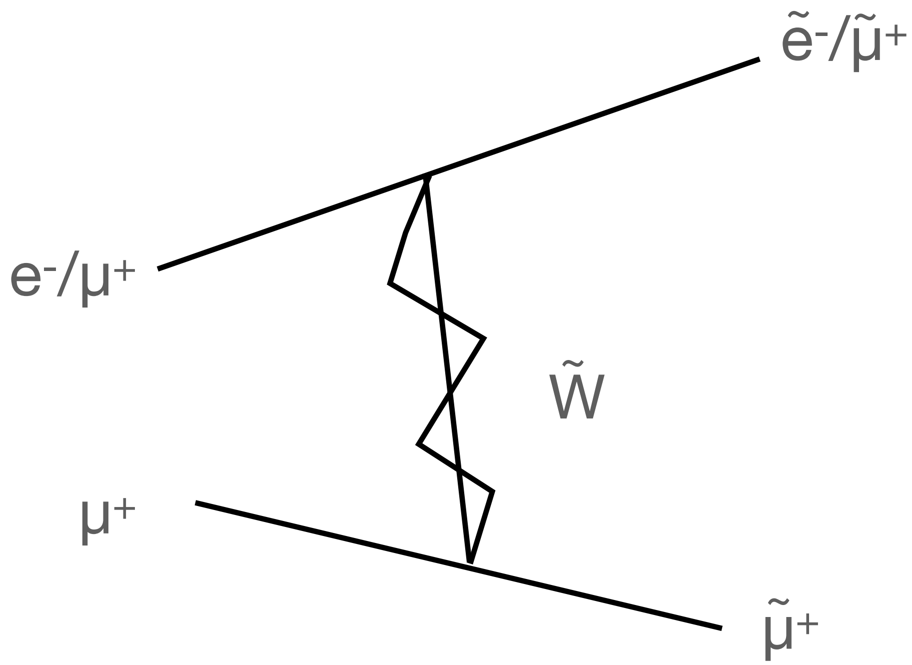
probe 100TeV scale physics!?

Supersymmetry

Regions for N_{event}/year > 100.





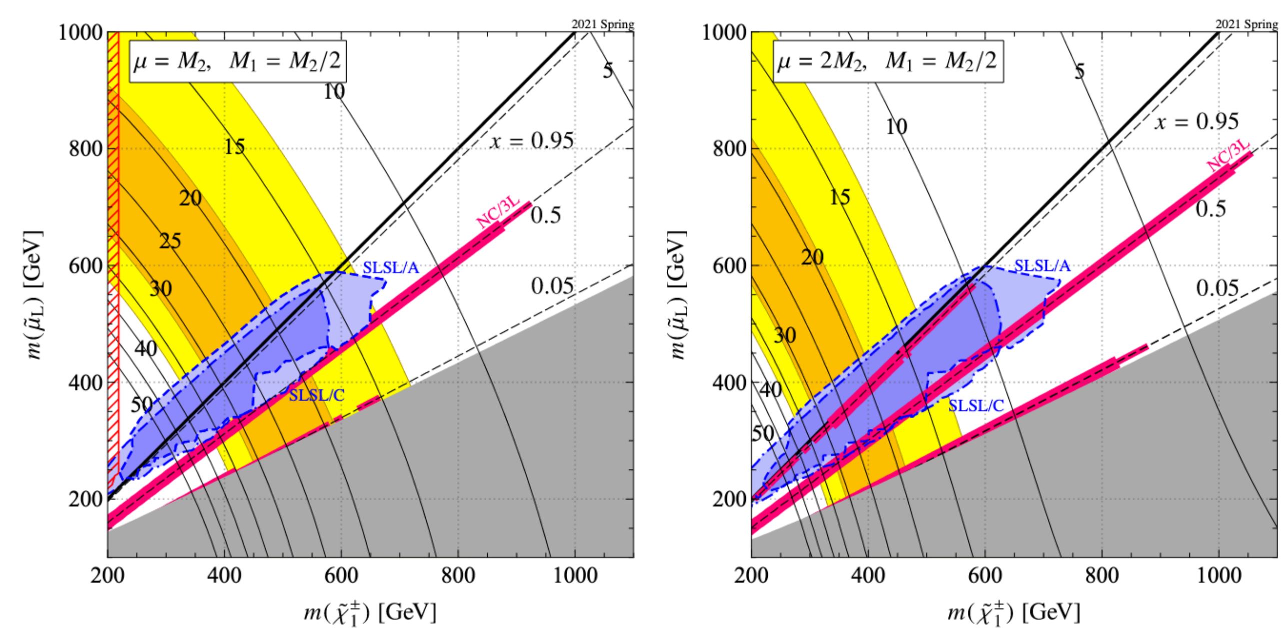


Scalar muons up to TeV even for very heavy gauginos.

Almost completely cover the muon g-2 motivated region.

[Endo, Hamaguchi, Iwamoto, Kitahara '21]

gaugino production in progress…



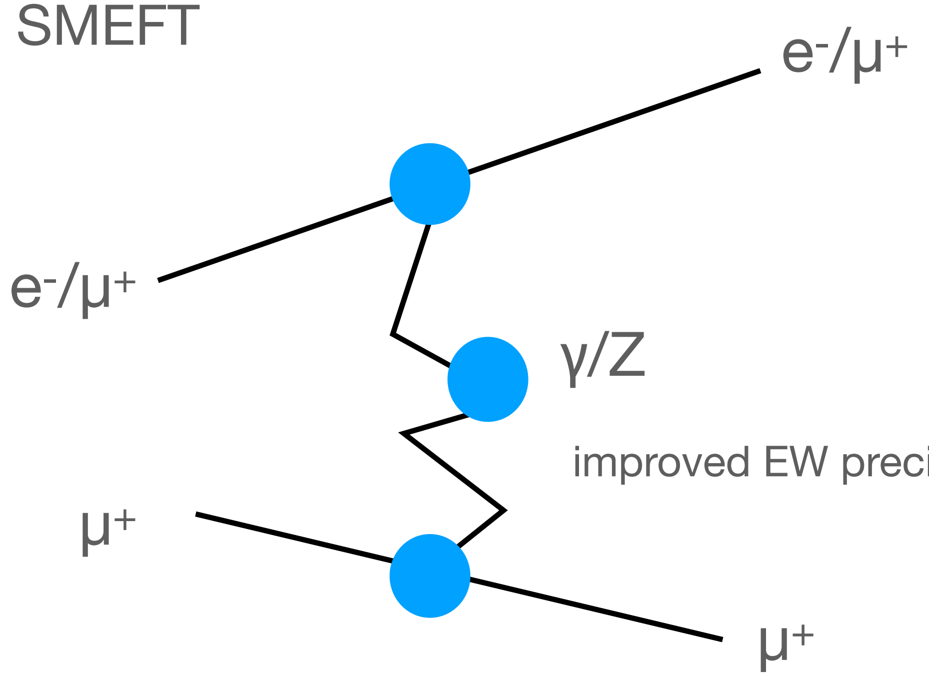
(A) $\mu = M_2,\ M_1 = M_2/2$.

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

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

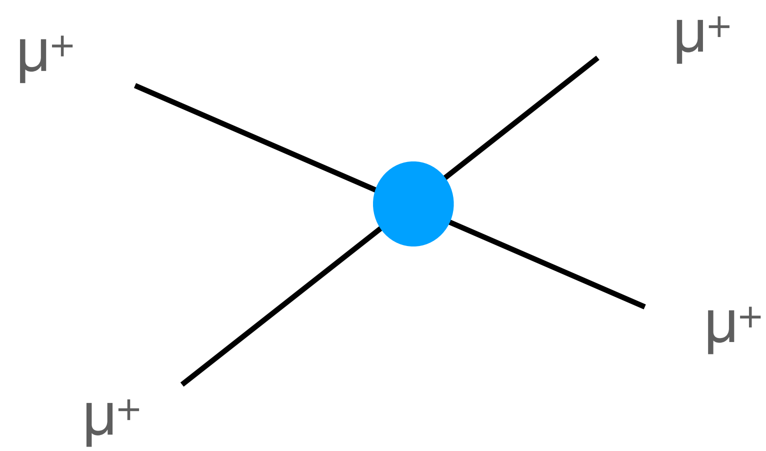


improved EW precision tests

S
T
(H current)(L current)
4-fermi

	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 $15.4^\circ \lesssim \Theta \lesssim 178^\circ$, 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 $62.8^\circ \lesssim \Theta_e \lesssim 178^\circ$.

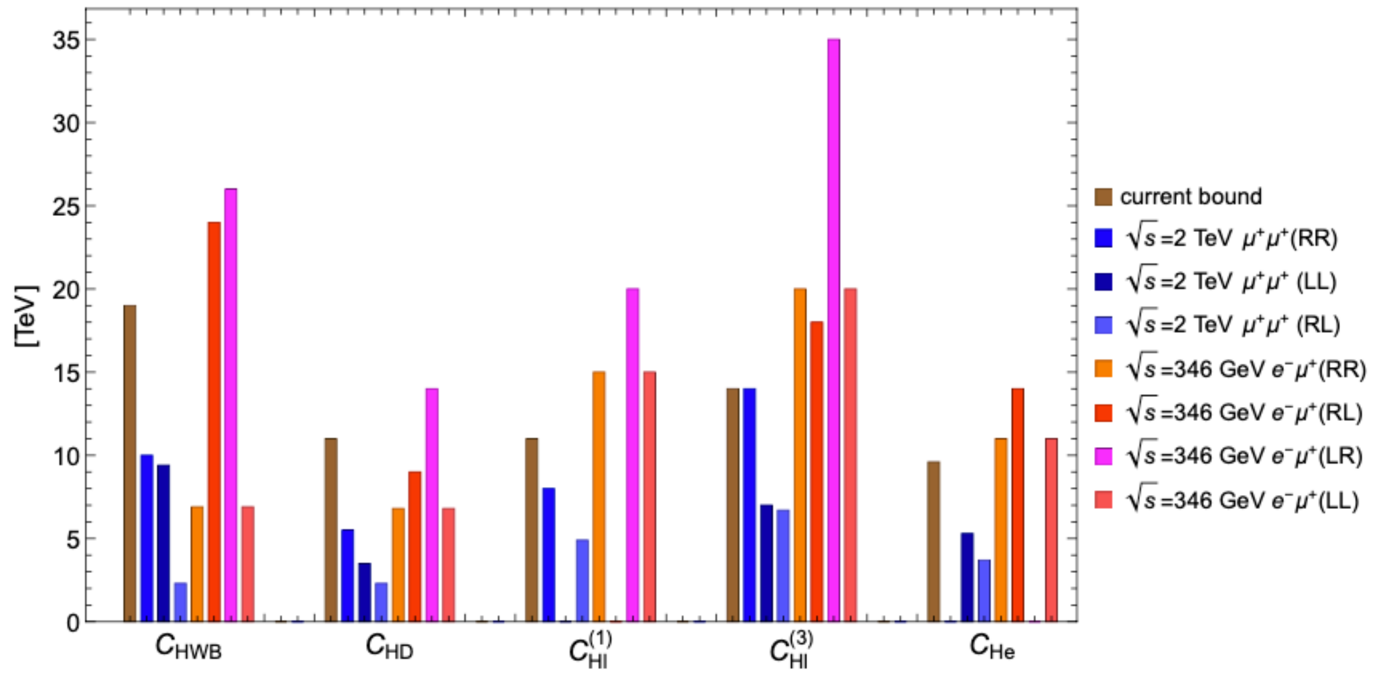


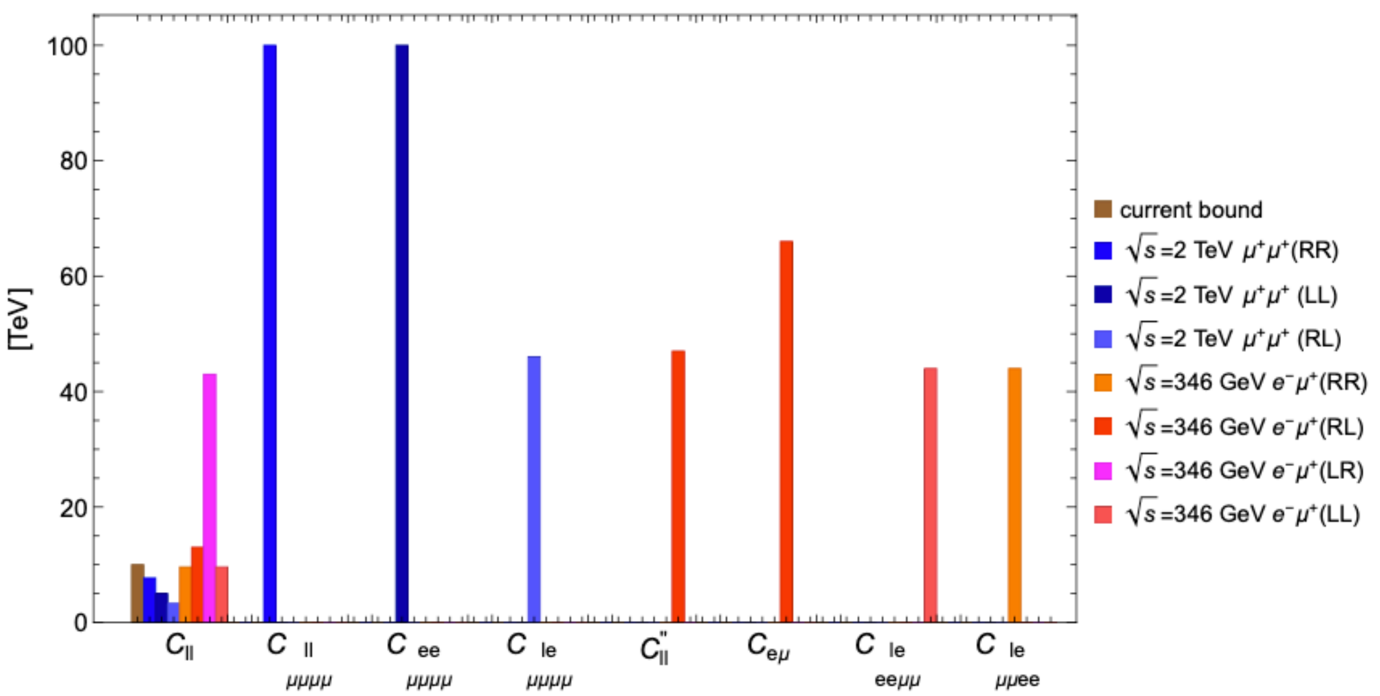
S
T
(H current)(L current)
4-fermi

	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 $\theta_i - 0.5^\circ < \theta < \theta_i + 0.5^\circ$. The considered range of θ_i is $16^\circ \leq \theta_i \leq 164^\circ$.

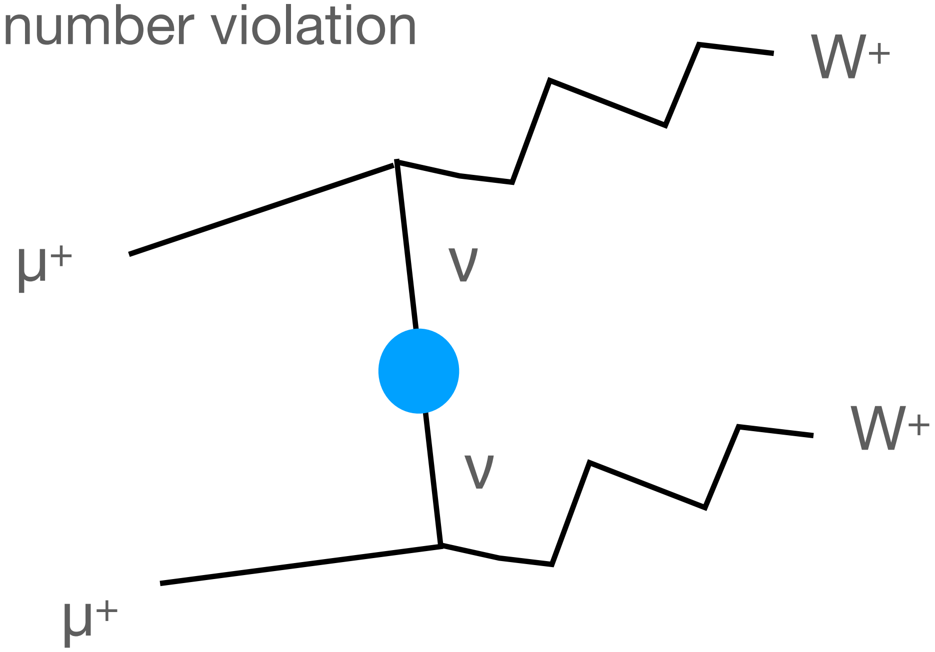
Indirect searches



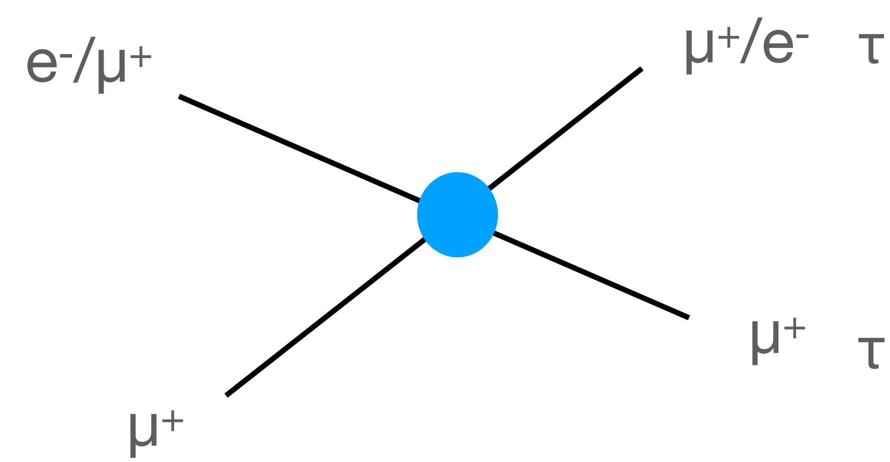


Lepton number/flavor violation?

lepton number violation



lepton flavor violation

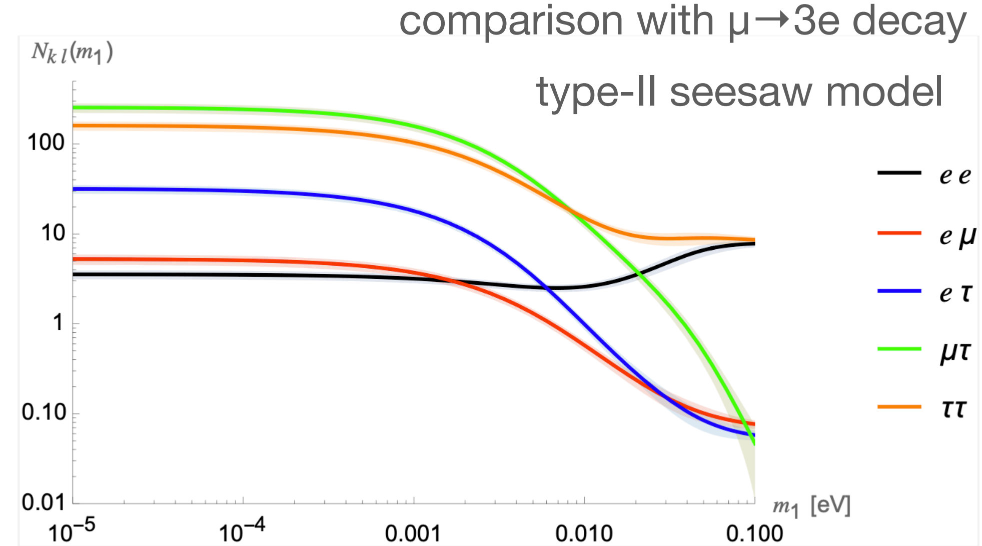


Can be better than rare decays!

(with Fridell and Takai in progress)

comparison with μ→3e decay

type-II seesaw model



I love this collider, but…

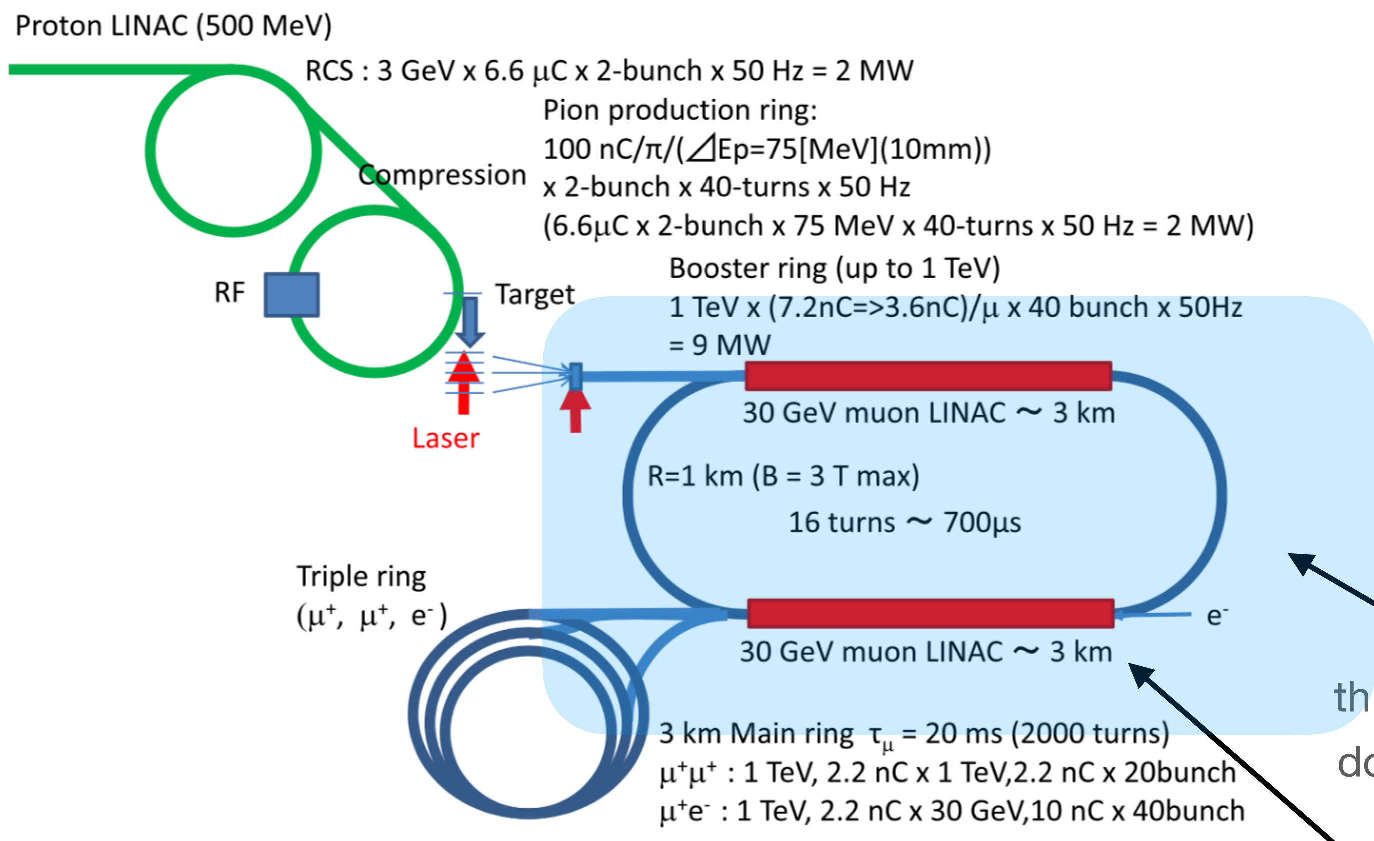


Fig. 1. Conceptual design of the $\mu^+e^-/\mu^+\mu^+$ collider.

this part is very big…

doesn't quite fit the KEK Tsukuba campus.

Also, this straight line is dangerous due to the neutrino radiation from muon decays.

Also, too much power consumption?

In the end, very expensive?

Maybe starting with 100GeV+100GeV (EW precision) + muon/hadron/neutrino program

and progressively goes to W physics, top physics, higgs physics, new particle searches…

Summary

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

We should build a new machine.

personal opinion:

Isn’t it so great to imagine that the human being succeed to accelerate muons and open up new particle-physics era?