μTRISTAN

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

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

talk@ILC IDT-WG3, April 20, 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).

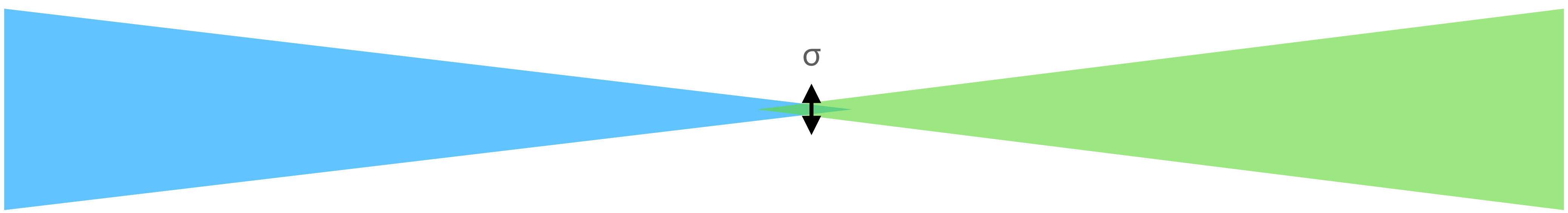
We cannot stop here.

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

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

Luminosity

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



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

As a reference,

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

$\sigma=1\mu m$

$f_{rep}=1MHz$

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

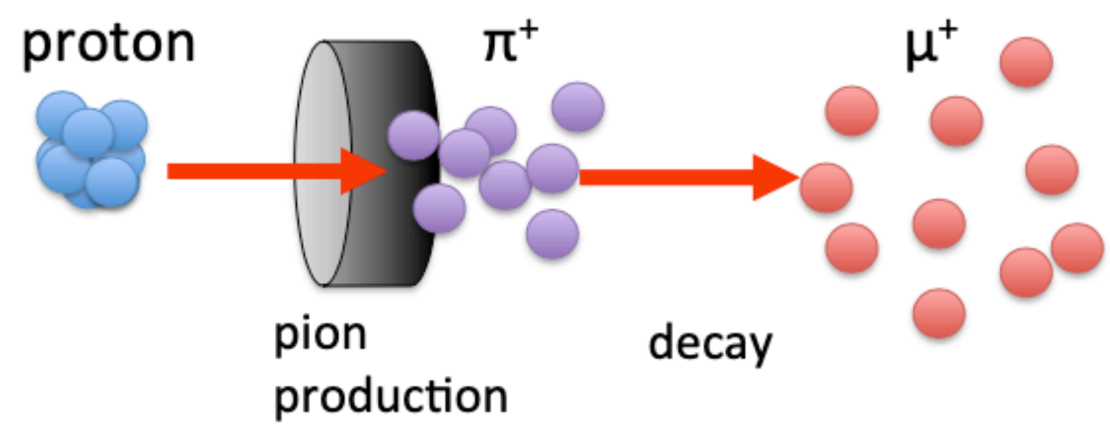
We want ab^{-1} level luminosity for physics (HL-LHC, ILC)

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

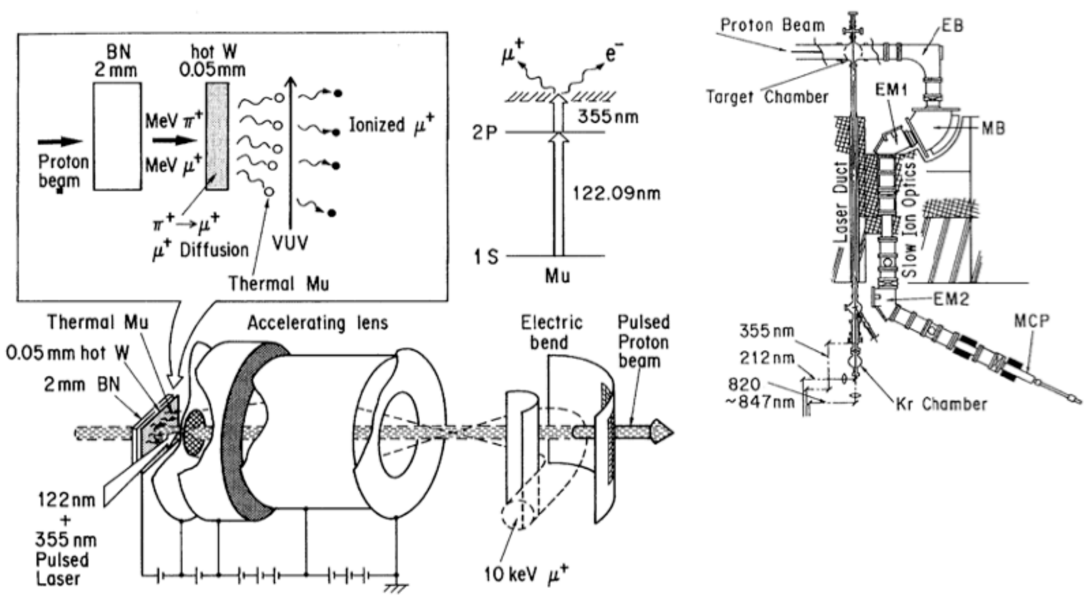
Strong focusing
Muon loss
BG π contamination

Taken from Mibe-san's lecture slide

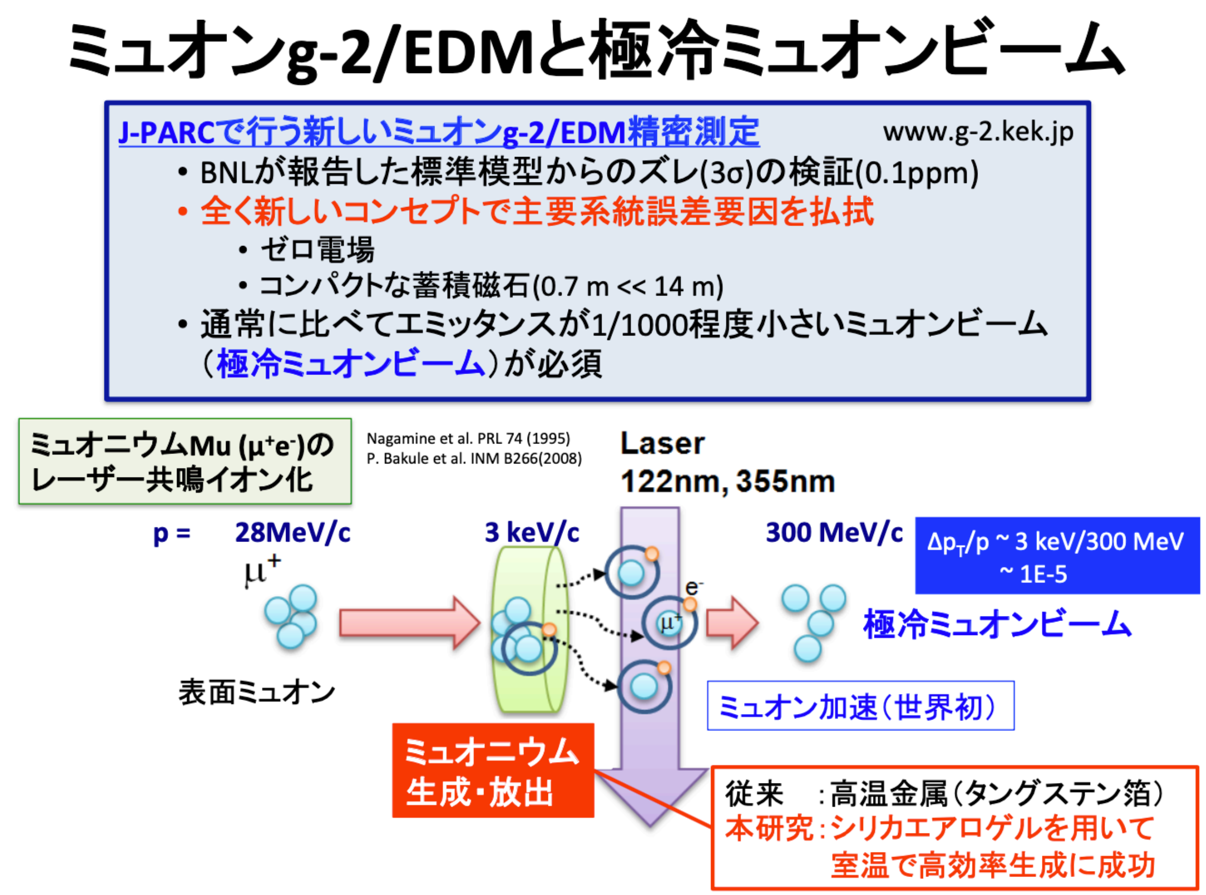
Muon cooling

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

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



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



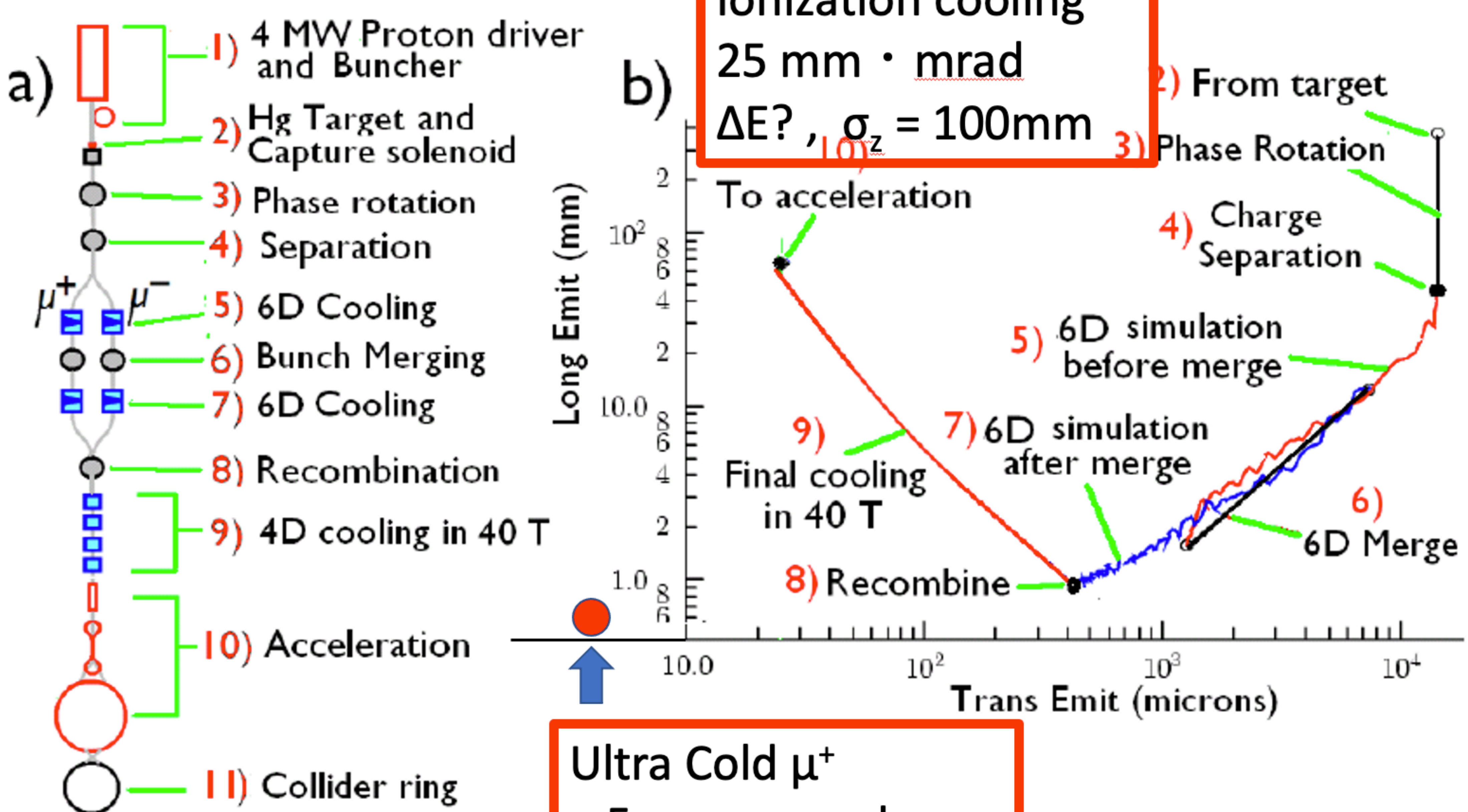
Mibe-san's slide

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

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

Emittance : Ionization cooling vs Ultra Cold

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



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

μTRISTAN

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

PTEP

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μTRISTAN

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

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

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

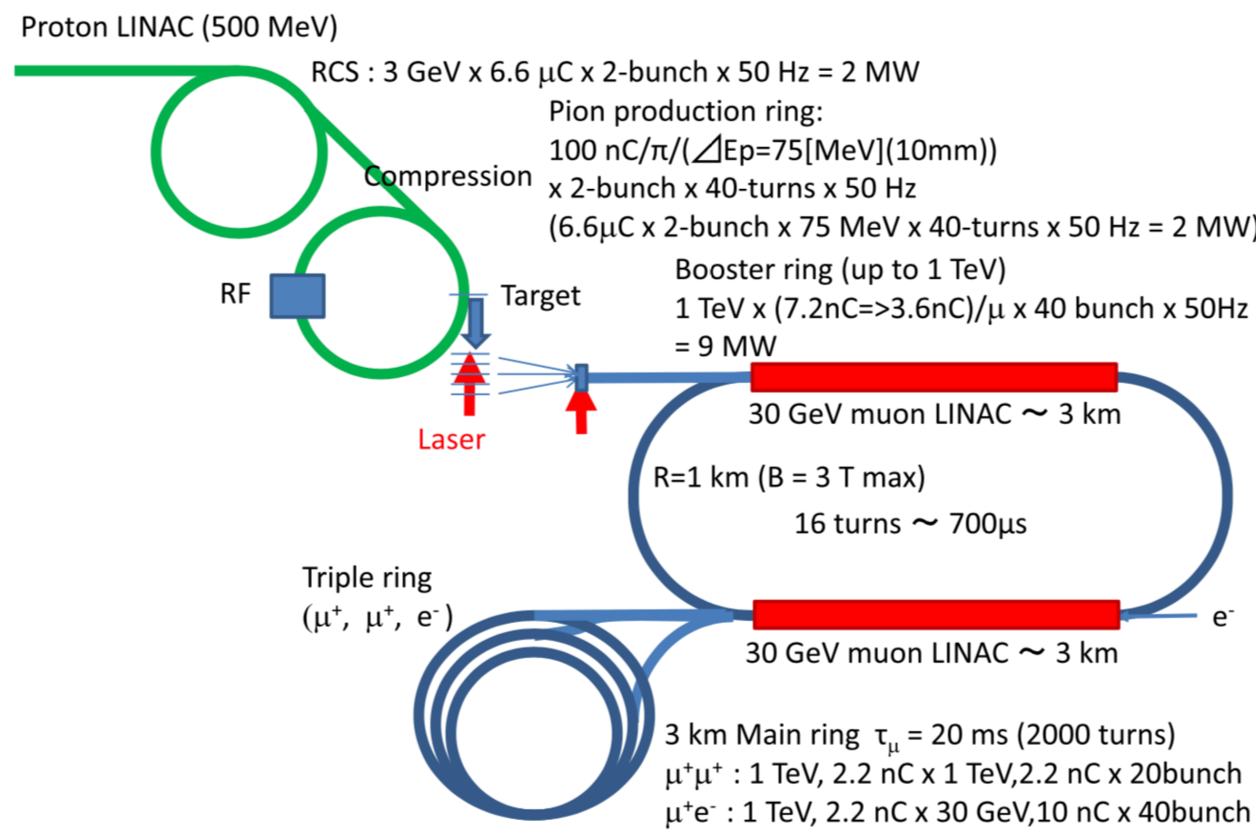


Fig. 1. Conceptual design of the $\mu^+e^-/\mu^+\mu^+$ collider.

How many cold muons?

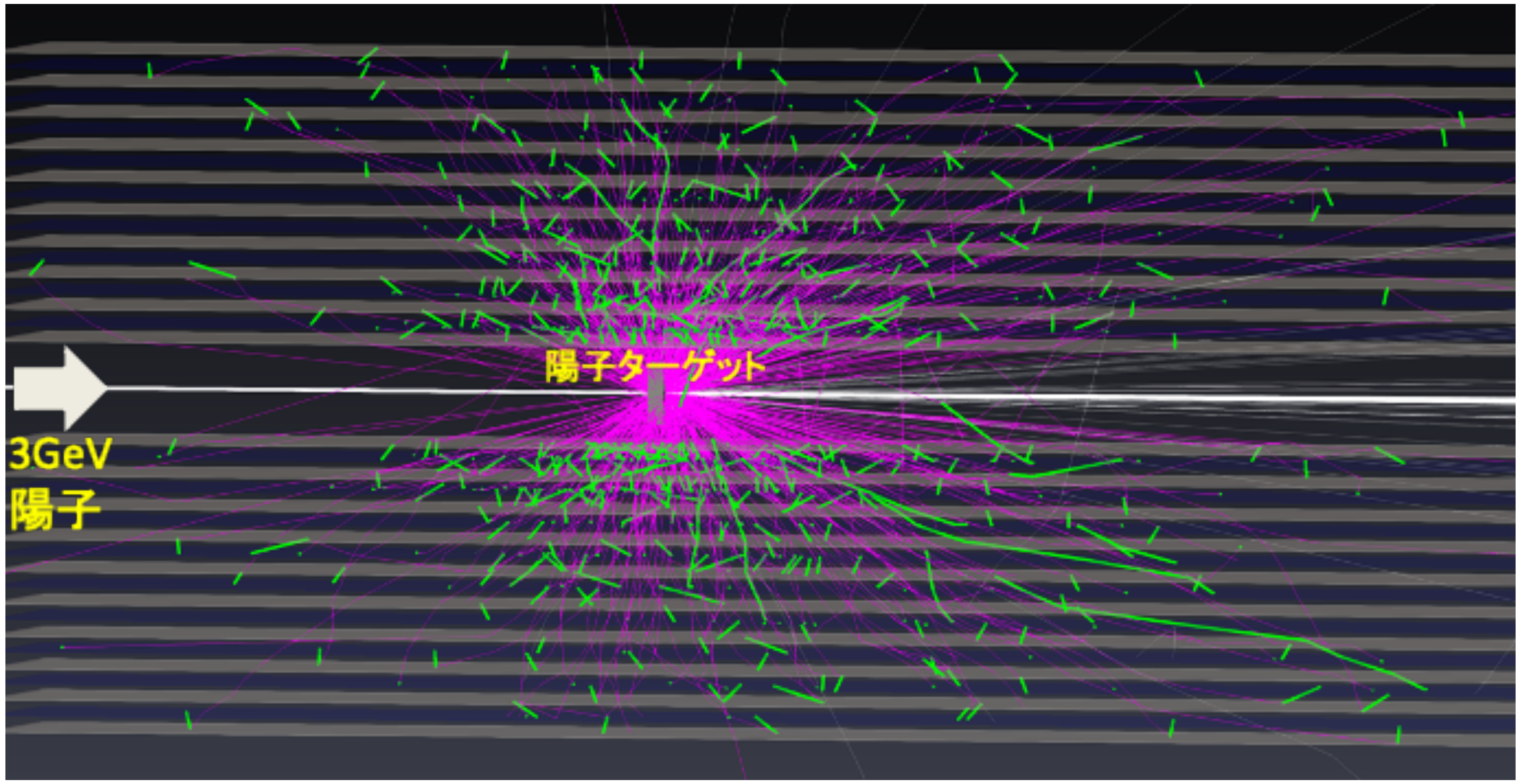
1/(20ms) where 20ms is the lifetime of the 1TeV muon

J-PARC like proton driver:	6.6 μC * 50 Hz * 2 bunches = 4.1 x 10^{15} protons/s			realistic
pion production target:	40 hits/bunch	0.016 π^+/proton	2.6 x 10^{15} π^+/s	maybe realistic
pion stopping target:	0.5 stopping efficiency * 0.07 muons/π^+		9 x 10^{13} μ^+/s	maybe challenging

10^5 larger than J-PARC MLF.

Super muon factory!

simulation: (in progress)



pink: pion
green: muon

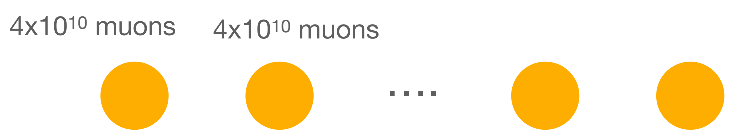
Luminosity?

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

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

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

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



40 bunches

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

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

$\sigma \sim$ 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.

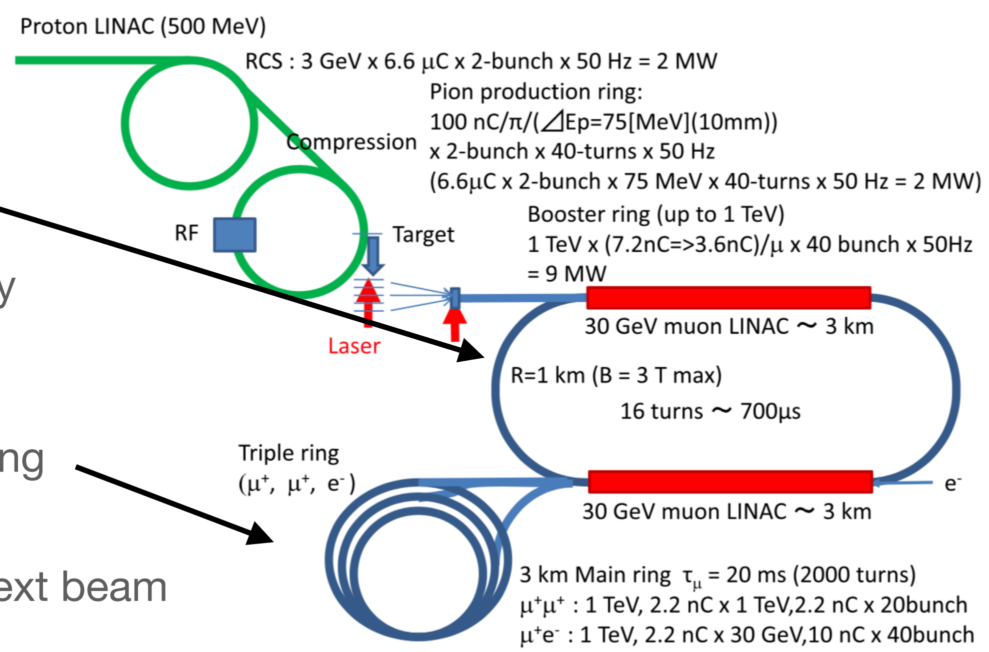


Fig. 1. Conceptual design of the $\mu^+e^-/\mu^+\mu^+$ collider.

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

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

(β^* may be much smaller?)

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

not bad.

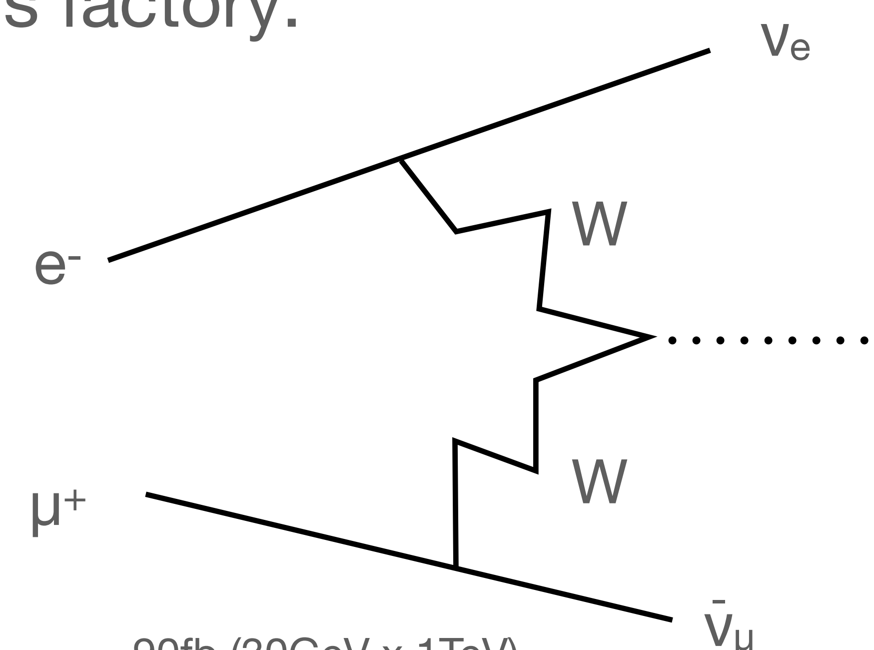
Luminosity

Our estimates are actually pretty much conservative.

	LHC	HL-LHC	MAP			LEMMA	μ^+TRISTAN		/ERL
			Higgs				μ^+e^-	$\mu^+\mu^+$	μ^+e^-
ビームエネルギー (GeV)	7000	7000	63	200	1500	3000	1000 x 30	1000	1000 x 60
重心系エネルギー (GeV)	14000	14000	126	400	3000	6000	350	2000	500
リングの円周(m)	26659	26659	350	1000	6000	6000	3000	3000	3000
偏向磁場 (T)	8.65	8.65	3	5	5	15	10	10	10
総供給粒子数($\times 10^9$/s)			20000	20000	20000	90	40000	10000	10000
バンチ辺りの粒子数($\times 10^9$)	100	220	2000	2000	2000	6	20 x 60	20	20 x 60
バンチ辺りの電荷(nC)	16.02	35.244	320.4	320.4	320.4	0.9612	2.4 x 9.6	3.204	2.4 x 9.6
バンチ数	2835	2736	1	1	1	1	80	40	80
規格化エミッタンス(μm rad	3.75	2.5	25	25	25	0.04	4	4	4
衝突点エミッタンス(nm rad)	0.056	0.0375	41.67	13.125	1.75	0.0014	0.4	0.4	0.4
エネルギー分散 (%)	0.1	0.1	0.1	0.1	0.1	3	0.1	0.1	0.1
衝突点 $\beta*$ x,y (mm)	500	150	94	26	3	0.2	30 x 7	15 x 1	15 x 1
バンチ長 σz(mm)	75	75	94	26	3	0.1	5	1	1
衝突点ビームサイズx,y(μm	0.016	0.016	196	26	3.2	0.017	12 x 1	8.6 x 0.4	8.6 x 0.4
崩壊までのターン数			450	700	785	3114	2000	2000	2000
衝突頻度 (kHz)	11	11	857	300	50	50	100	100	100
衝突点の数	1	1	2	2	2	1	1	1	1
ルミノシティ増大係数	1	1	1	1	1	1	1	1	1
ルミノシティ ($\times 10^{34}$ cm^{-2} s	0.992	210.93	0.012	0.1	4.4	5.1	0.96	0.44	3.6
積分ルミノシティ (ab^{-1}/year	0.214	45.56	0.003	0.0216	0.95	1.1016	0.20736	0.09504	0.7776
Higgsの生成断面積 (fb)			1600				100	54	240
Higgs粒子の生成数/year			4147				20736	5132	186624

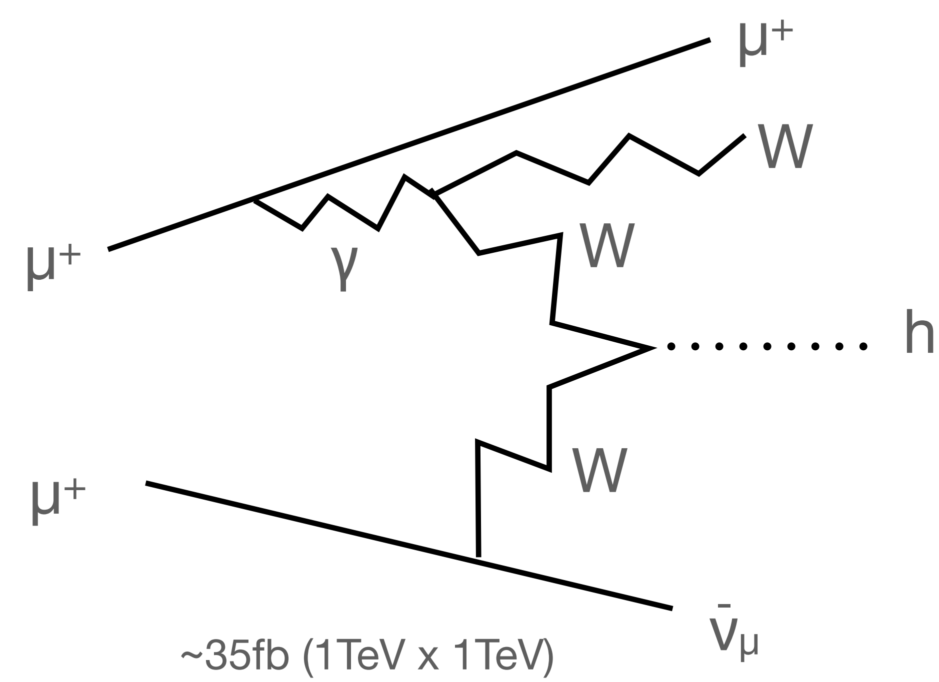
What can we do at μTRISTAN?

Higgs factory:



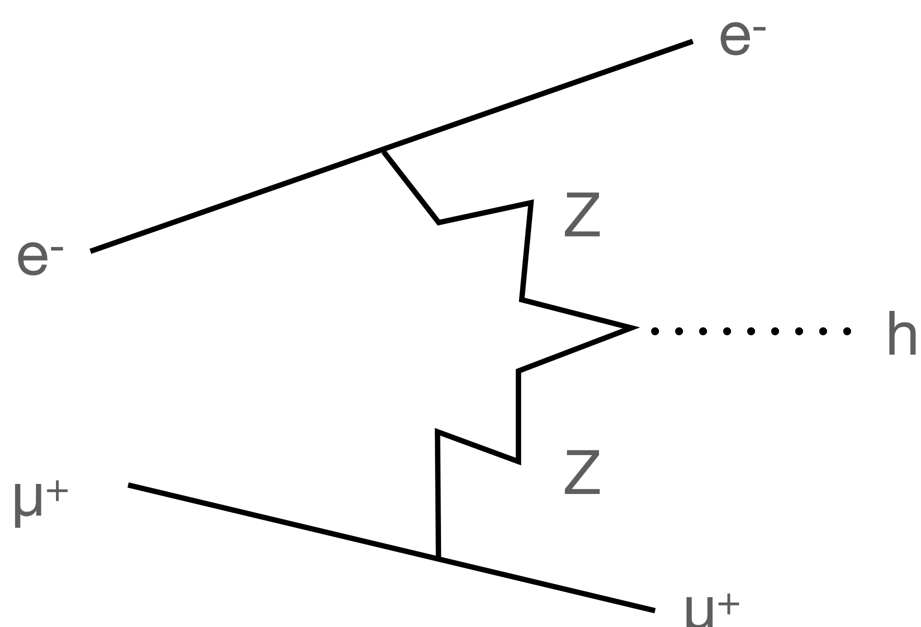
~90fb (30GeV x 1TeV)

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



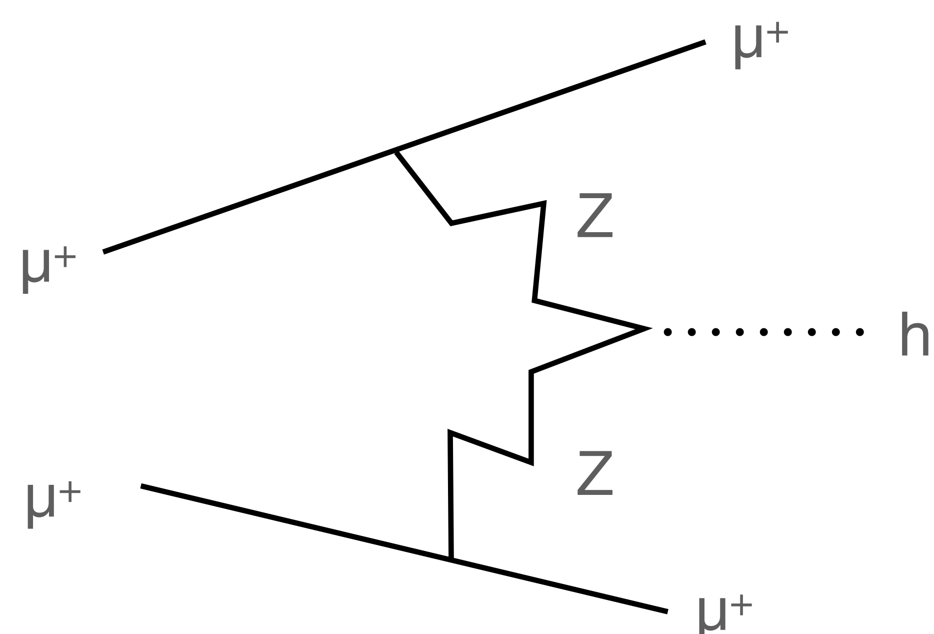
~35fb (1TeV x 1TeV)

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



~4fb (30GeV x 1TeV)

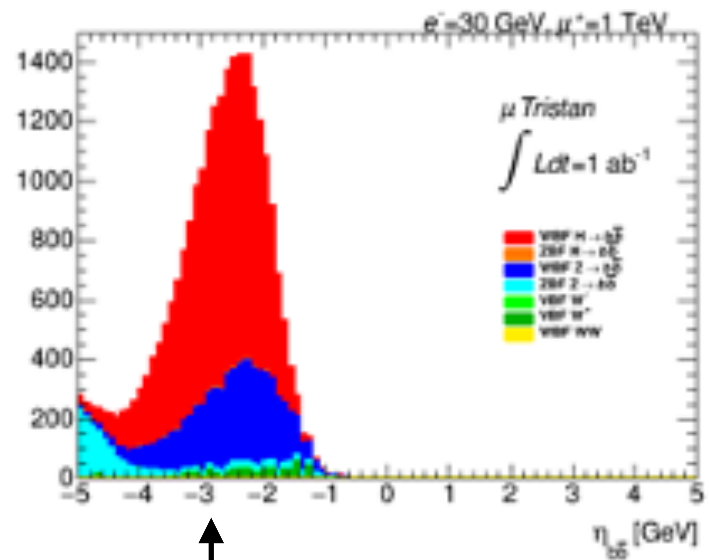
~10^3 Higgs bosons (1ab^{-1})



~54fb (1TeV x 1TeV)

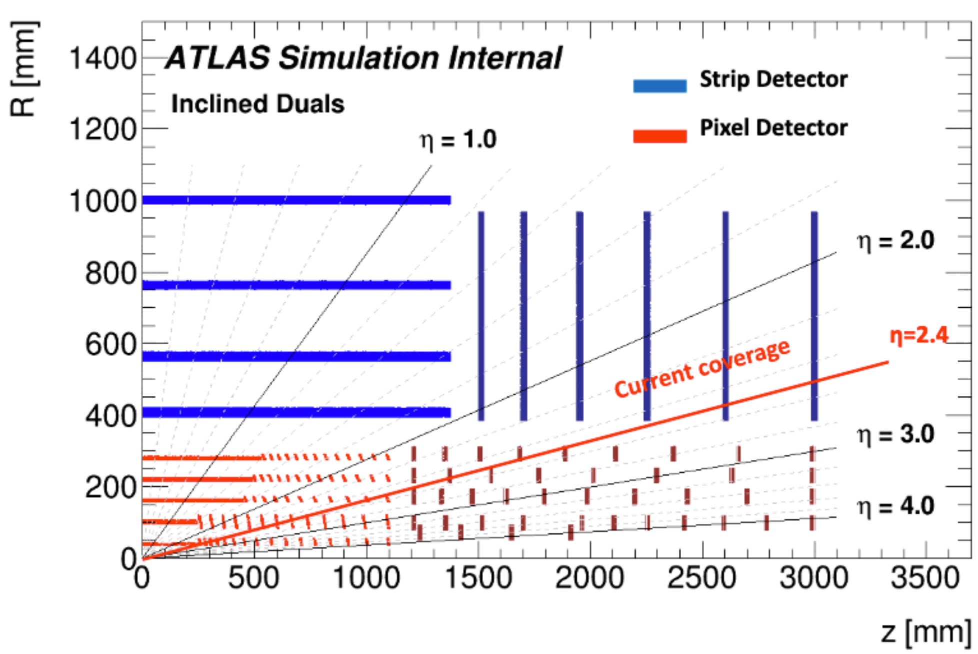
~$10^{4\text{-}5}$ Higgs bosons (1ab^{-1})

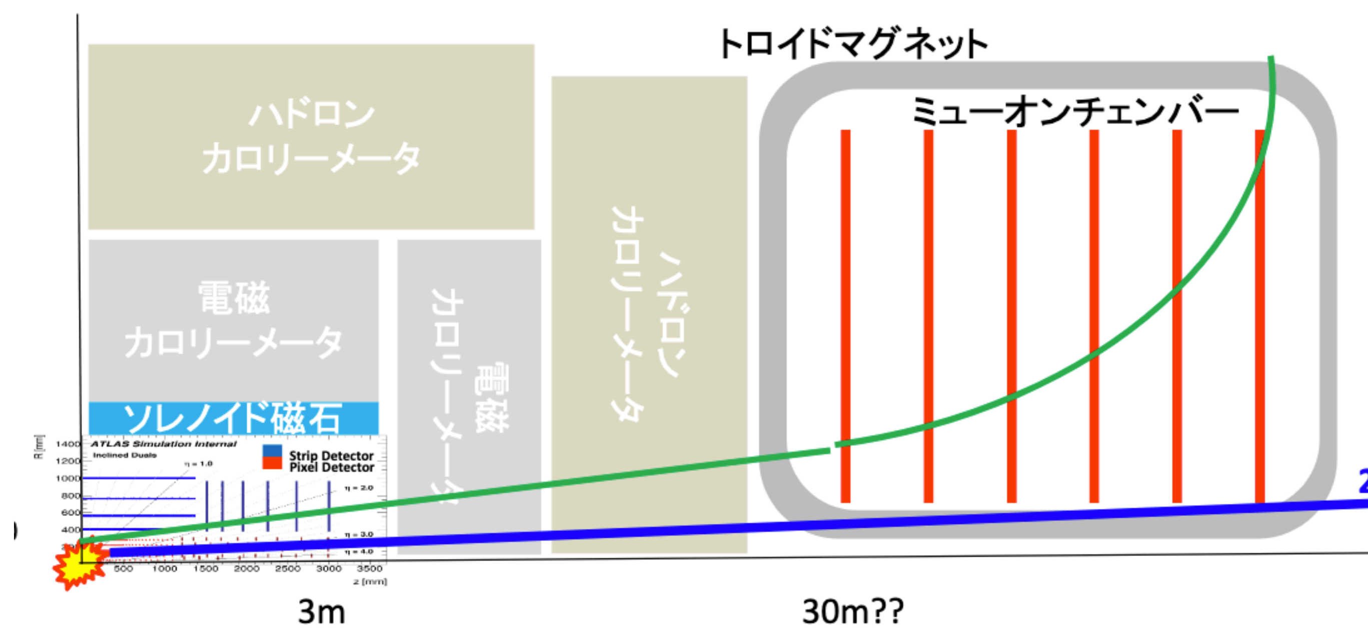
μ+e-: Very asymmetric



All the particles go to the direction of the muon.

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

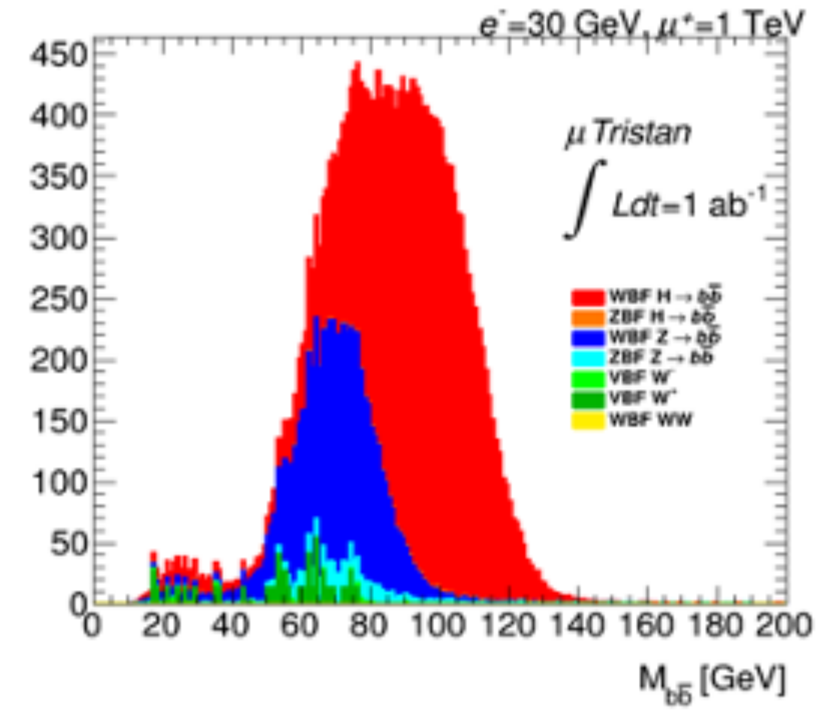




Higgs coupling

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

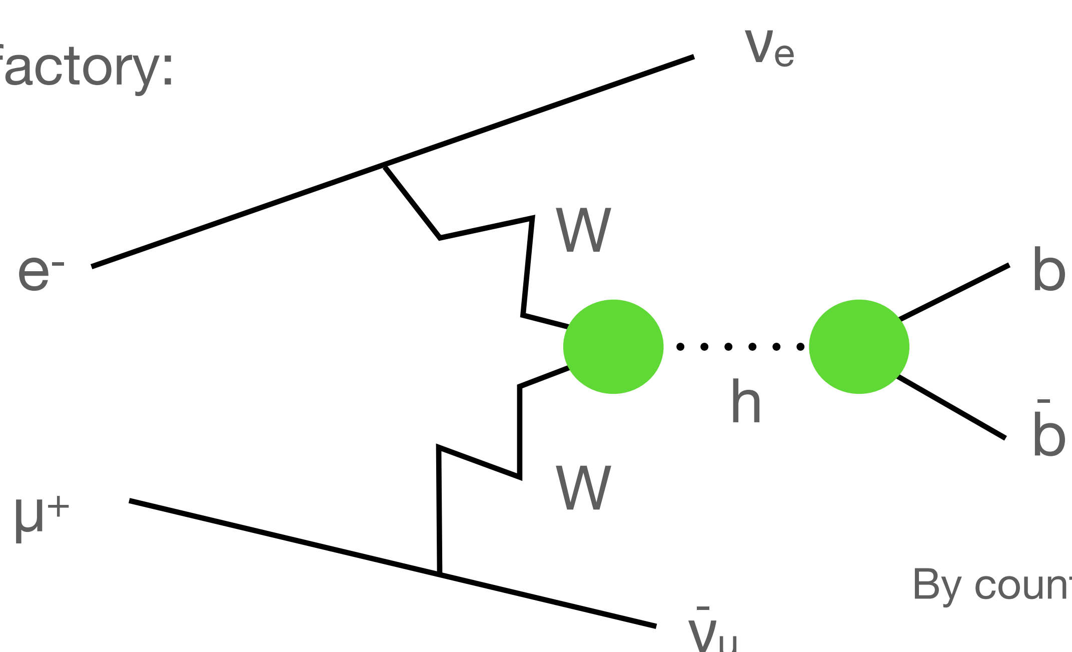
simulation with the ATLAS detector for HL-LHC



acceptance ~ 23%

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

Higgs factory:



~90fb

~10^5 Higgs bosons

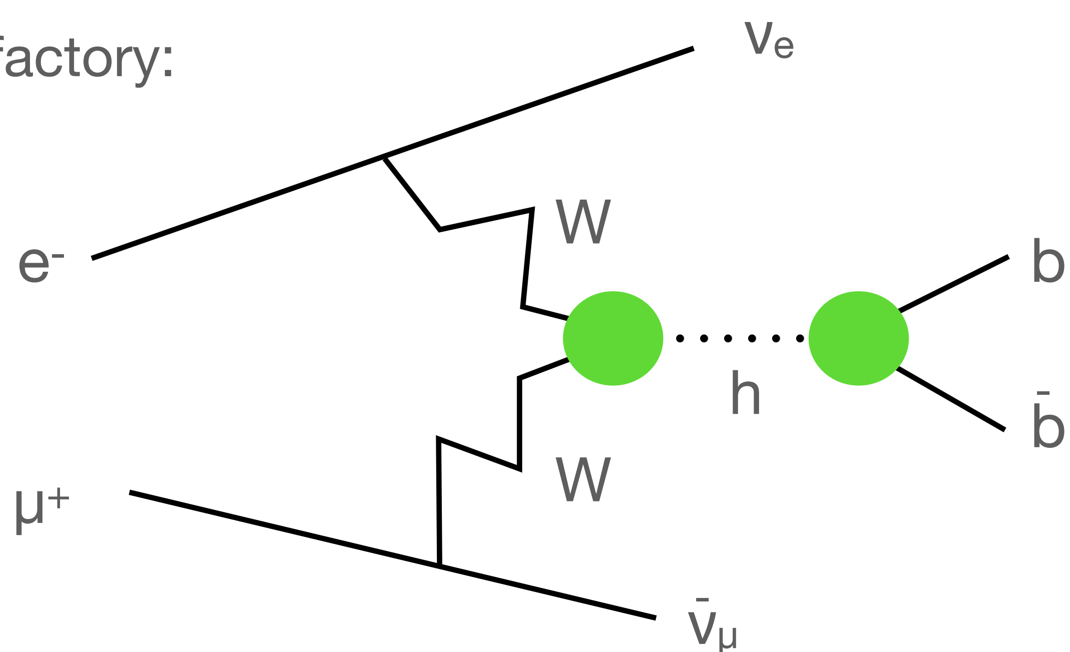
By counting the number of events and compare with the SM prediction

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

sub percent level measurements.

Higher energy? μTevatron?

Higgs factory:



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

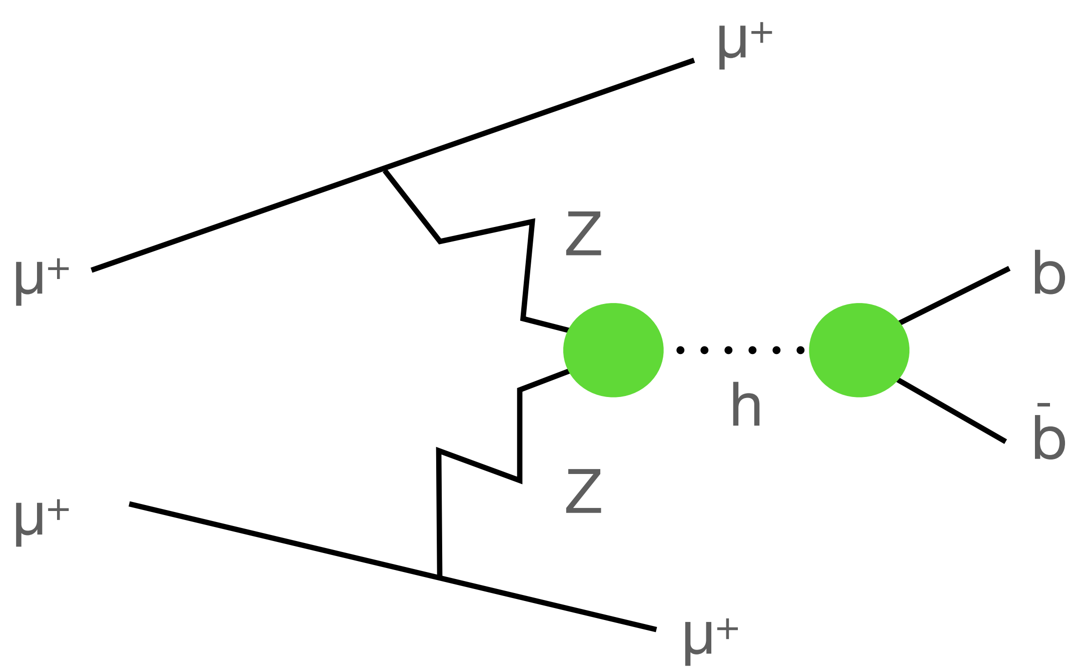
$\sqrt{s}$ = 775 GeV

~472fb (50GeV x 3TeV)

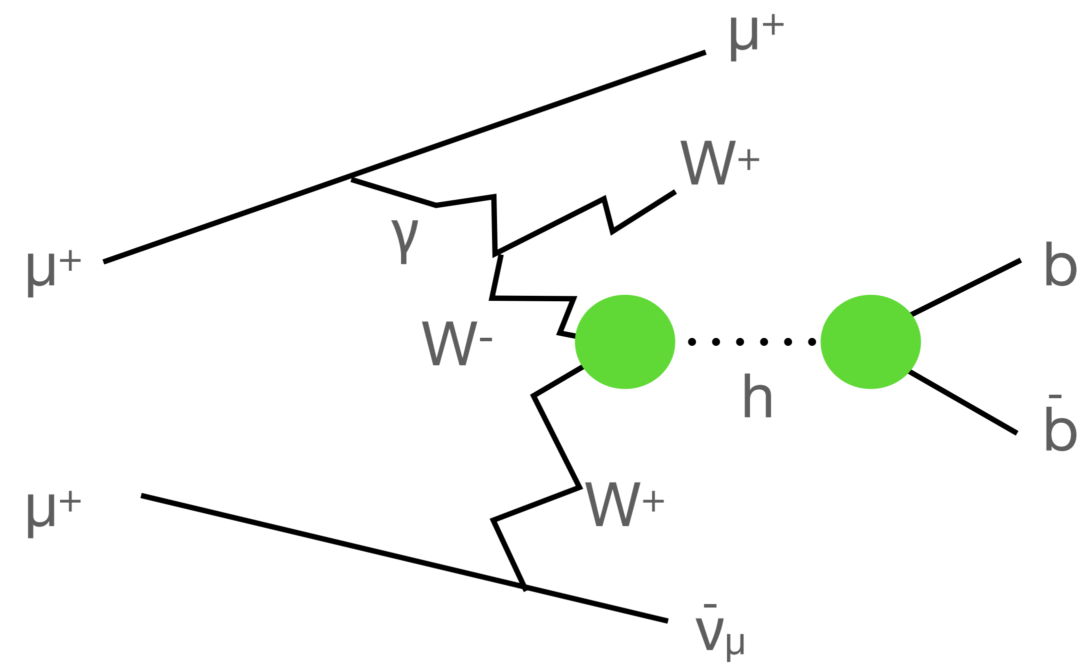
~5x10^5 Higgs bosons (ab^{-1})

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

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



~54fb@2TeV final state all visible



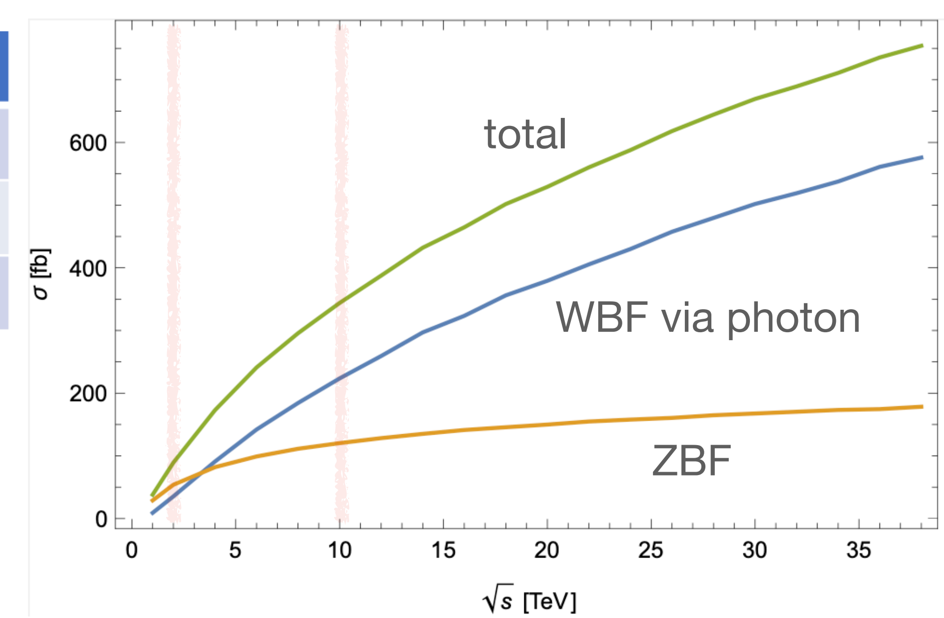
~35fb@2TeV

gets more important at high energy

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

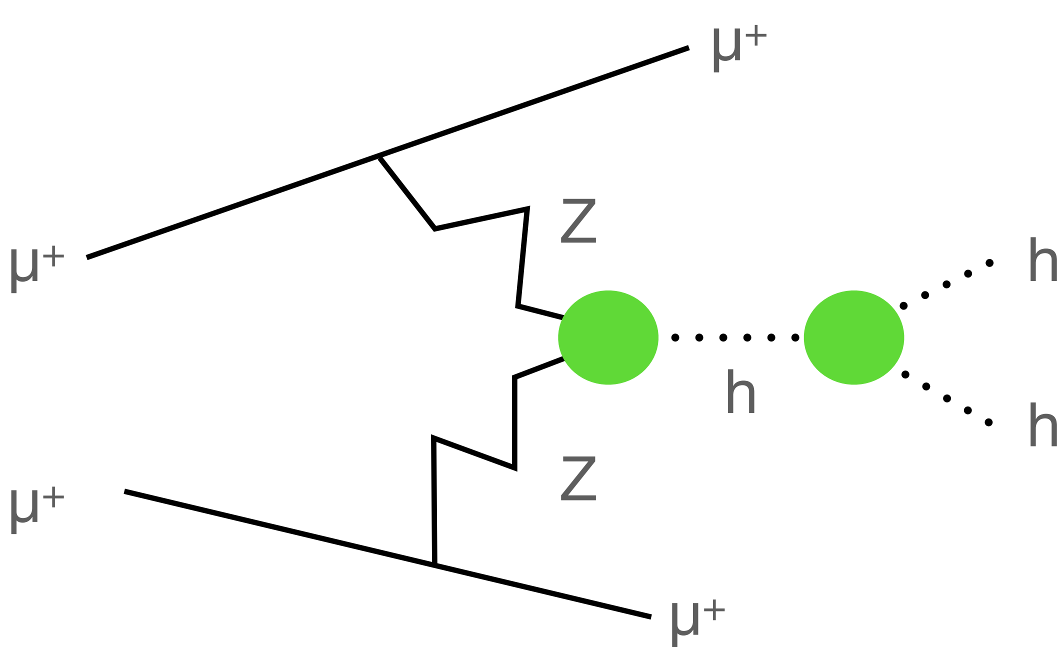
about a factor of two smaller than $\mu^+\mu^-$

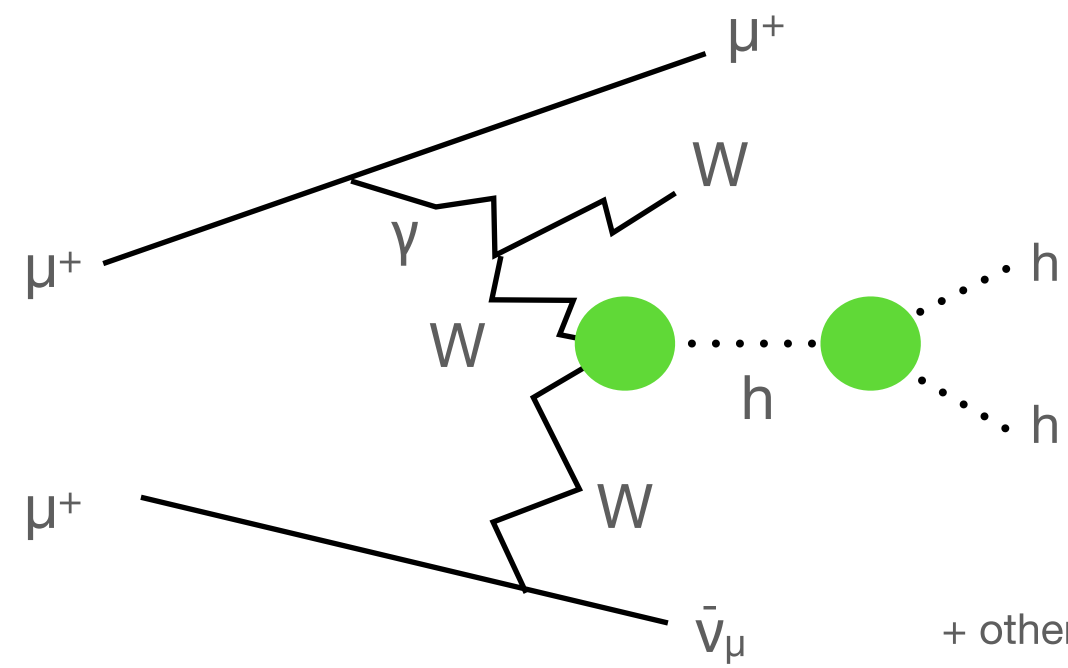
(not too bad?)



maybe we should plan 5-10TeV colliders.

Higgs production@μ⁺μ⁺





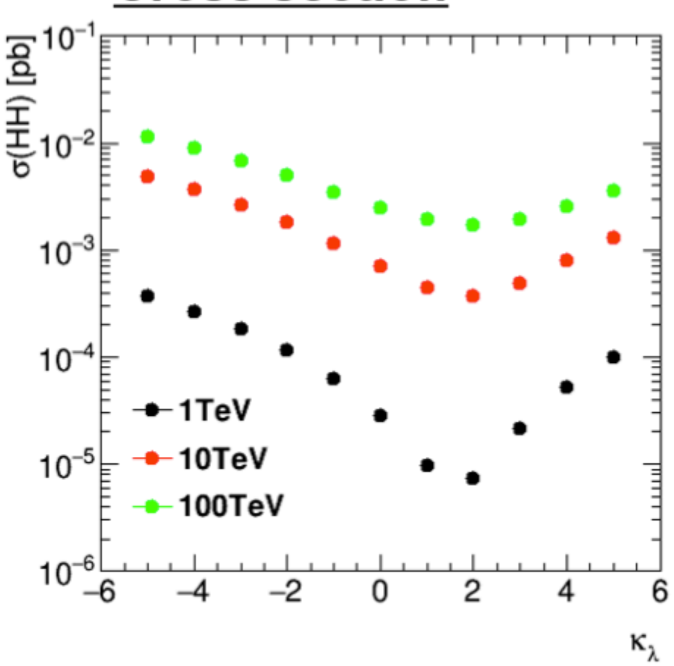
+ others

about 1/3 of μ⁺μ⁻

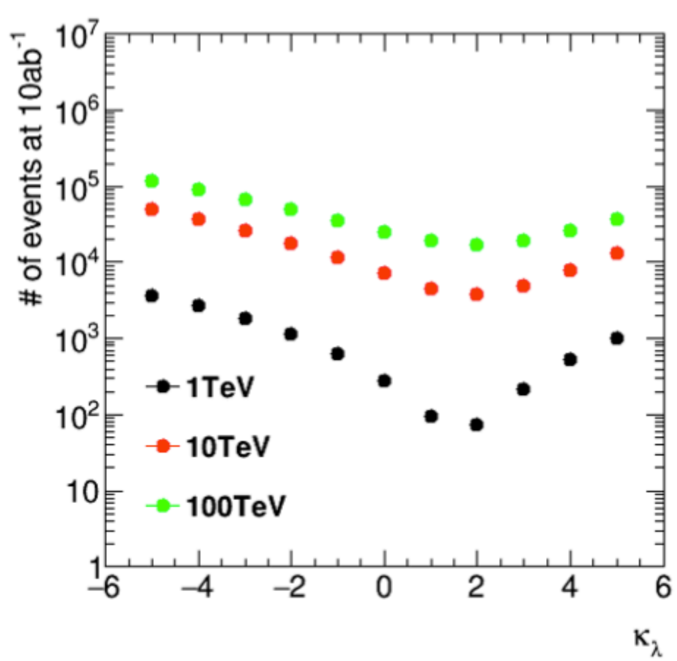
$\sqrt{s}$ [TeV]	ZBF [fb]	Photon emission [fb]
2	0.075	0.010
10	0.62	0.30
20	1.1	0.75

ZBF:

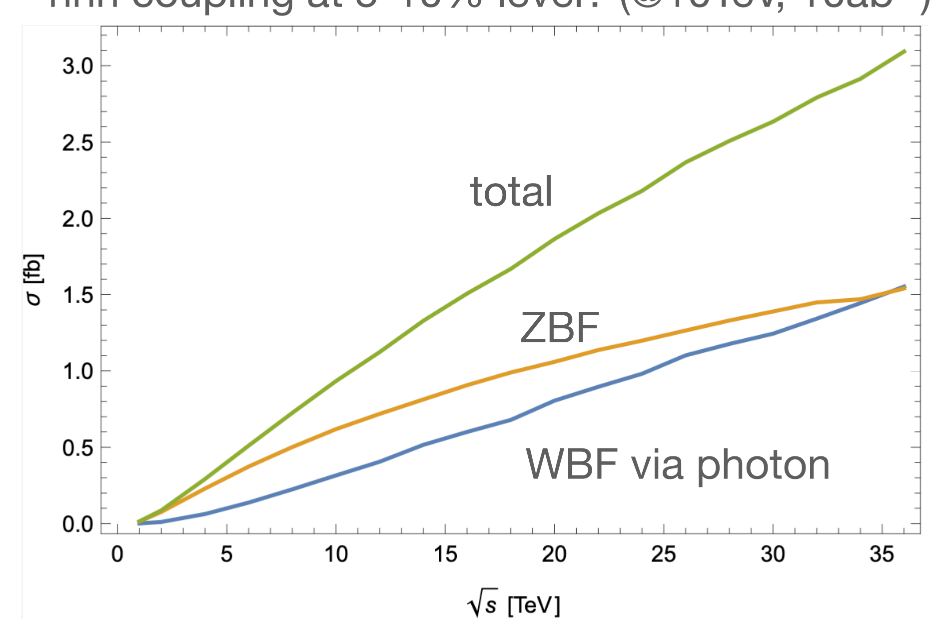
Cross section



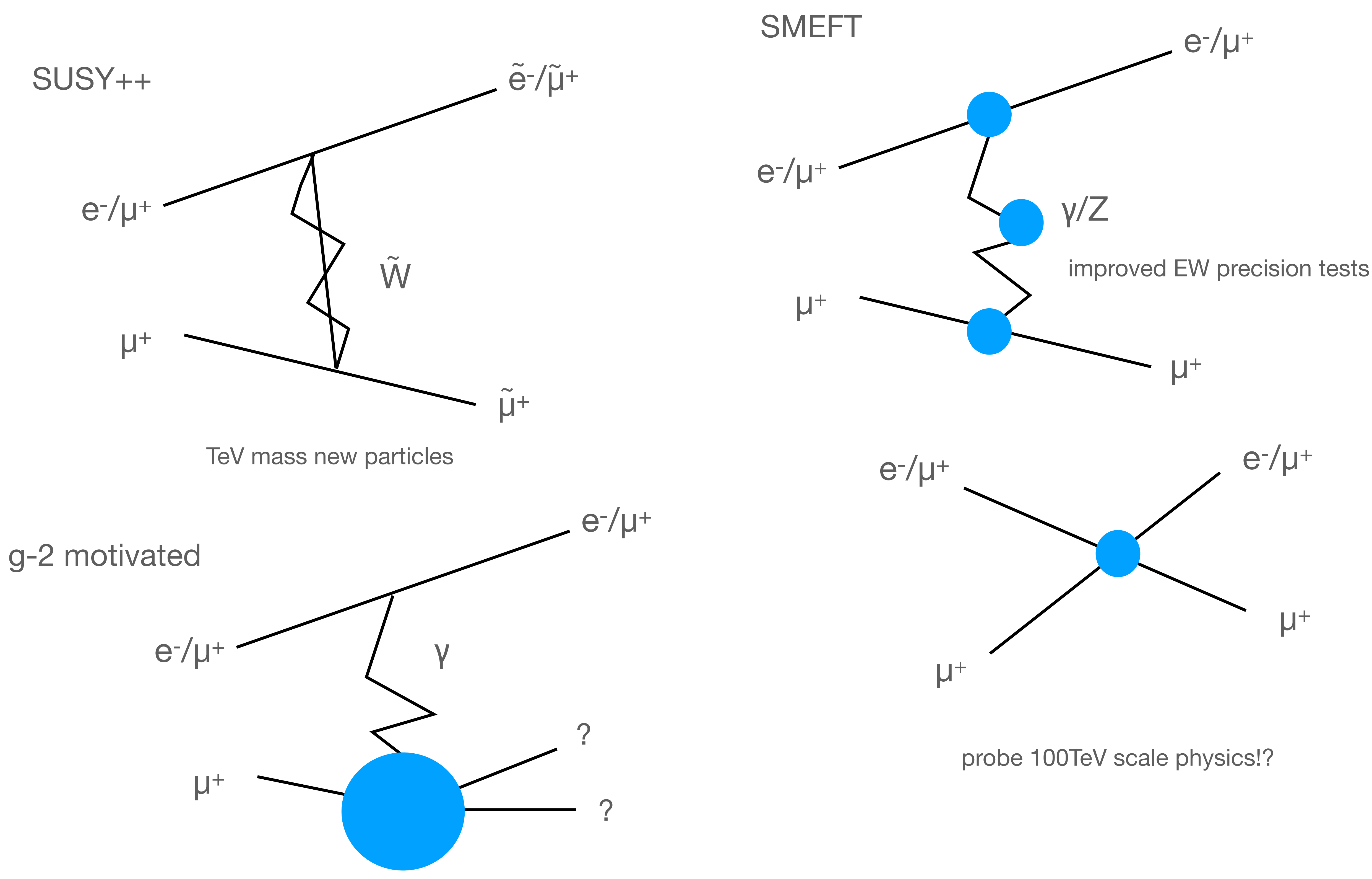
# of Events in 10ab⁻¹



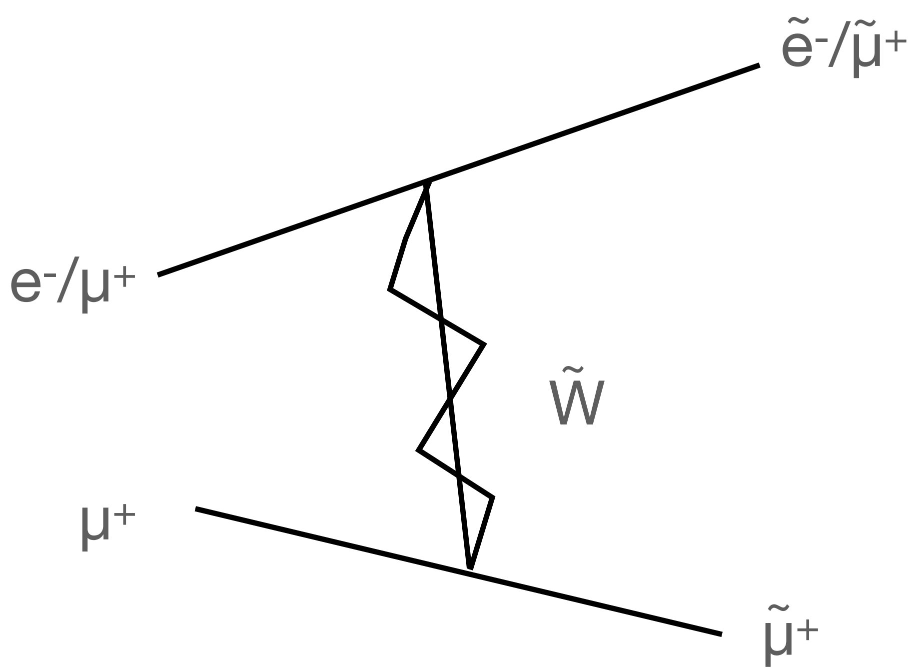
hhh coupling at 5-10% level? (@10TeV, 10ab⁻¹)



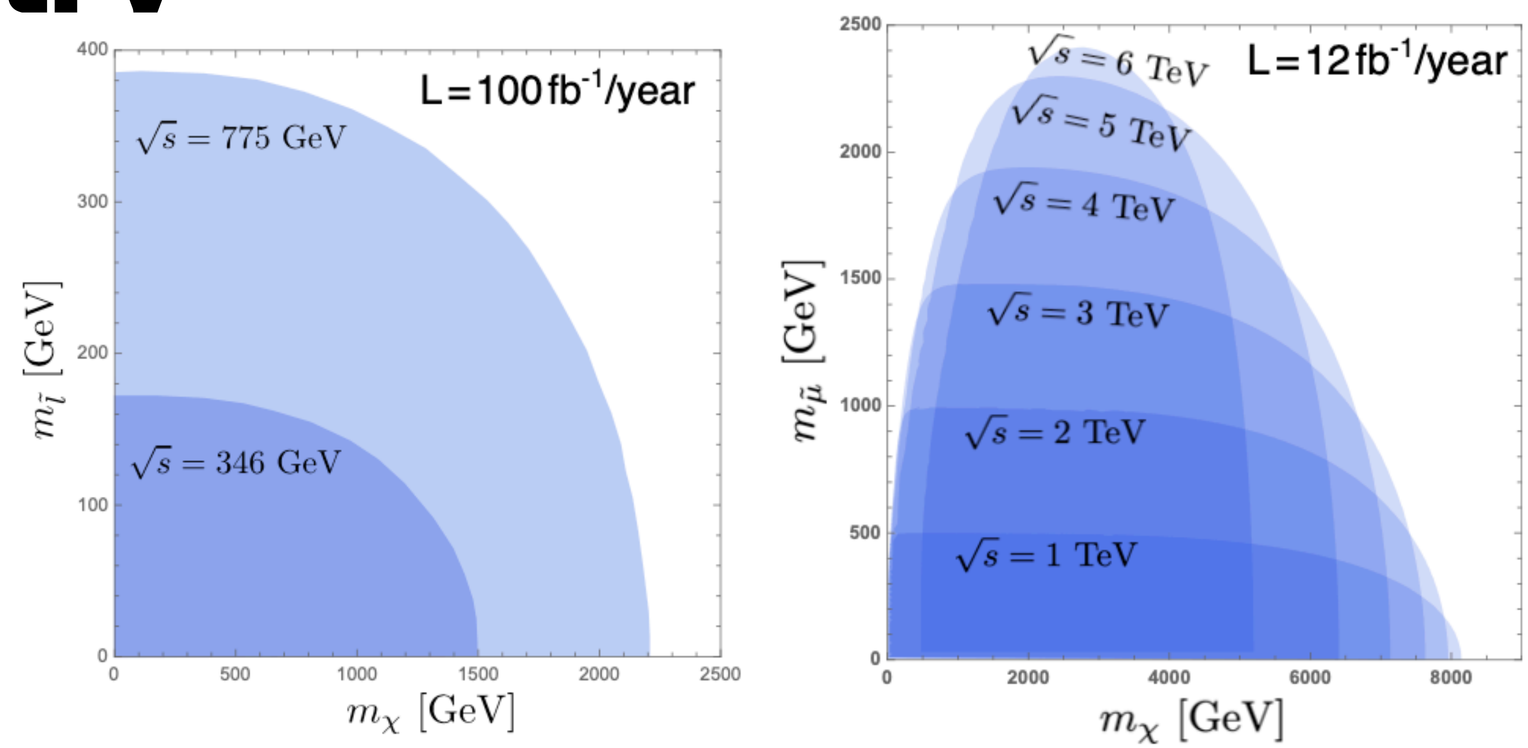
New physics?


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

Supersymmetrv



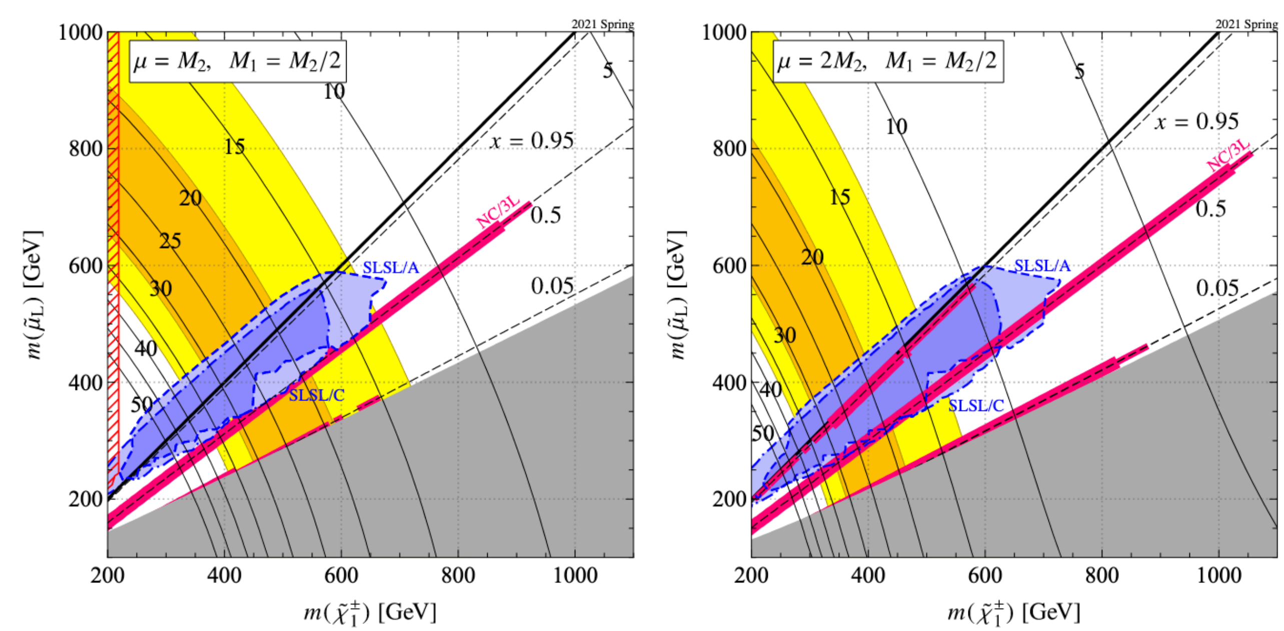
Regions for N_{event}/year > 100.



Scalar muons up to TeV even for very heavy gauginos.

Almost completely cover the muon g-2 motivated region.

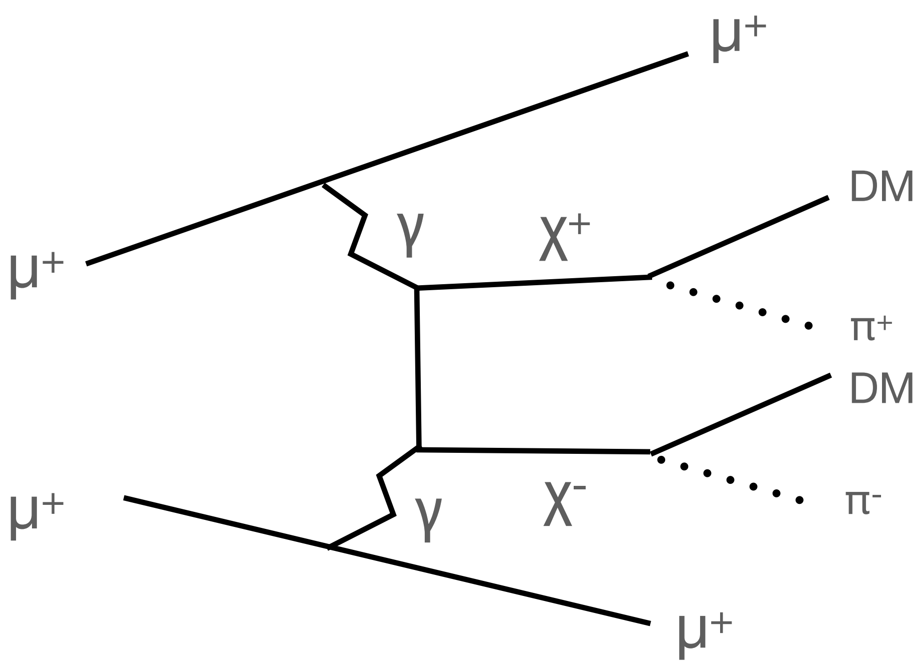
[Endo, Hamaguchi, Iwamoto, Kitahara '21]



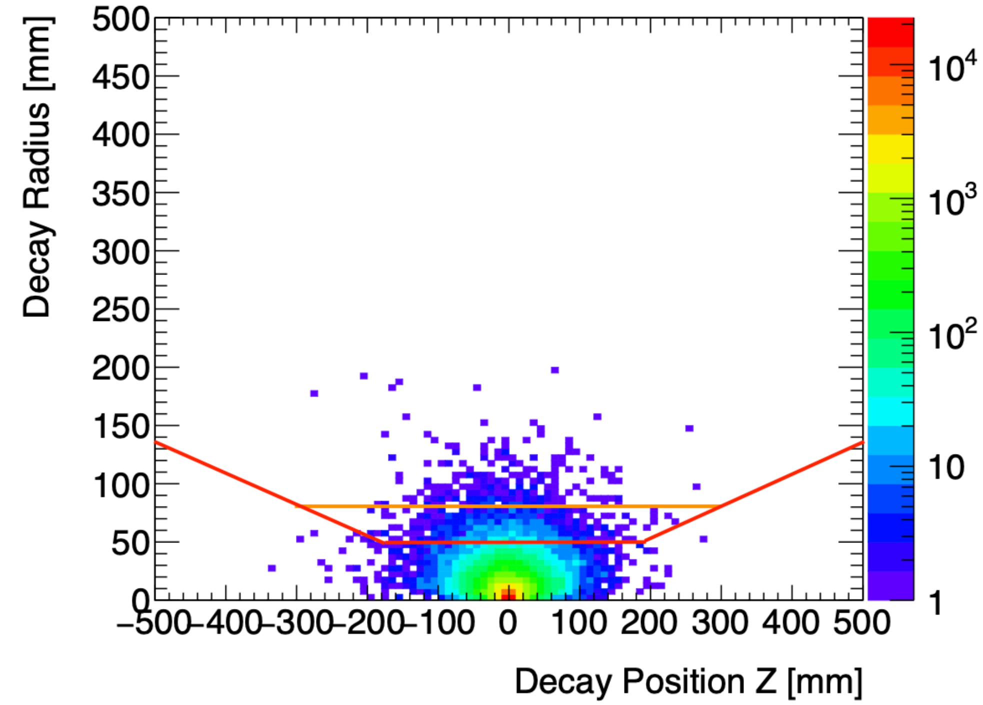
(A) $\mu = M_2$, $M_1 = M_2/2$. (B) $\mu = 2M_2$, $M_1 = M_2/2$.

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

DM search



√s = 10 TeV, 質量 1 TeV Higgsino の崩壊マップ



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

$|\eta| < 2.0$
を再構成できると仮定

# of expected events @ 1 ab^{-1}

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

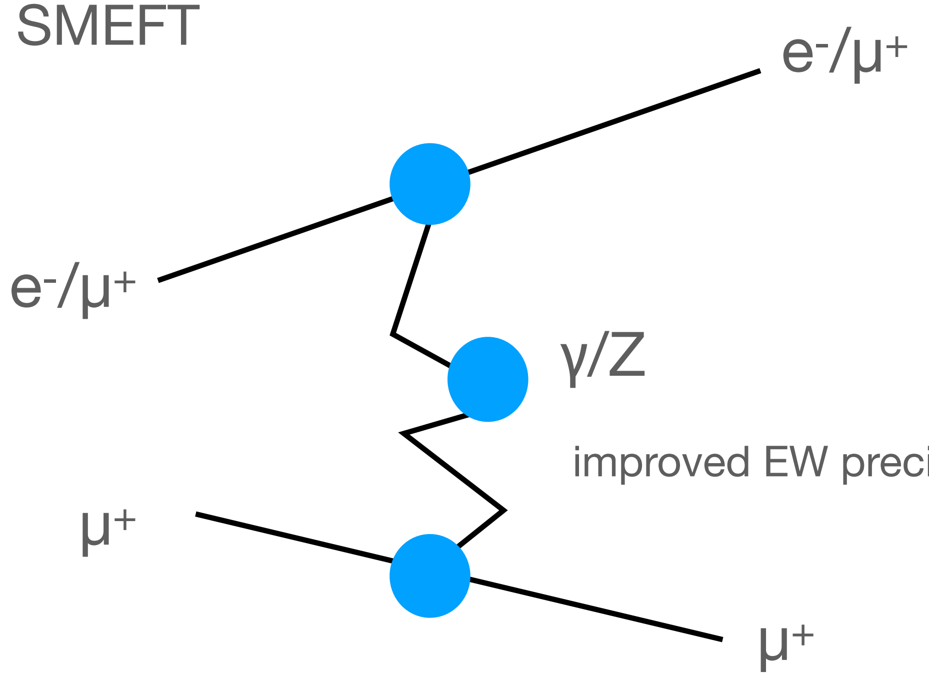
assumed a muon system which can detect forward muons (|η|<6)

Looks like 1TeV Higgsino is within the reach.

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

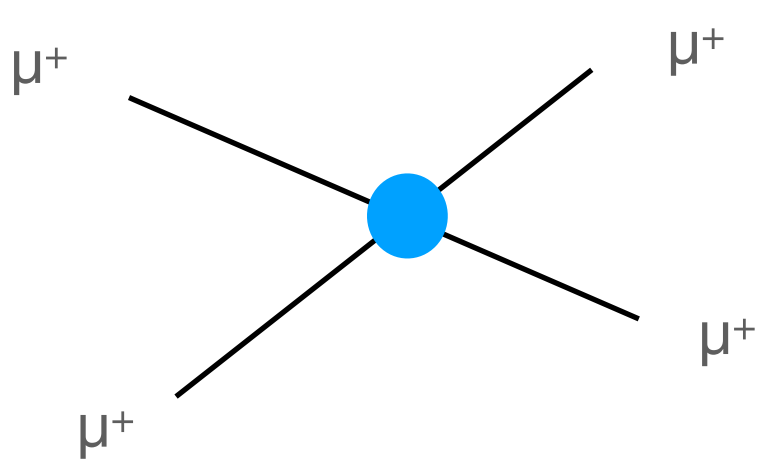


improved EW precision tests

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 $15.4° \lesssim \Theta \lesssim 178°$, corresponding to $\eta_{max} = 2$ for the muon beam side and $\eta_{max} = 4$ for the electron beam side. As a result, the angle range of the electron is $62.8° \lesssim \Theta_e \lesssim 178°$.



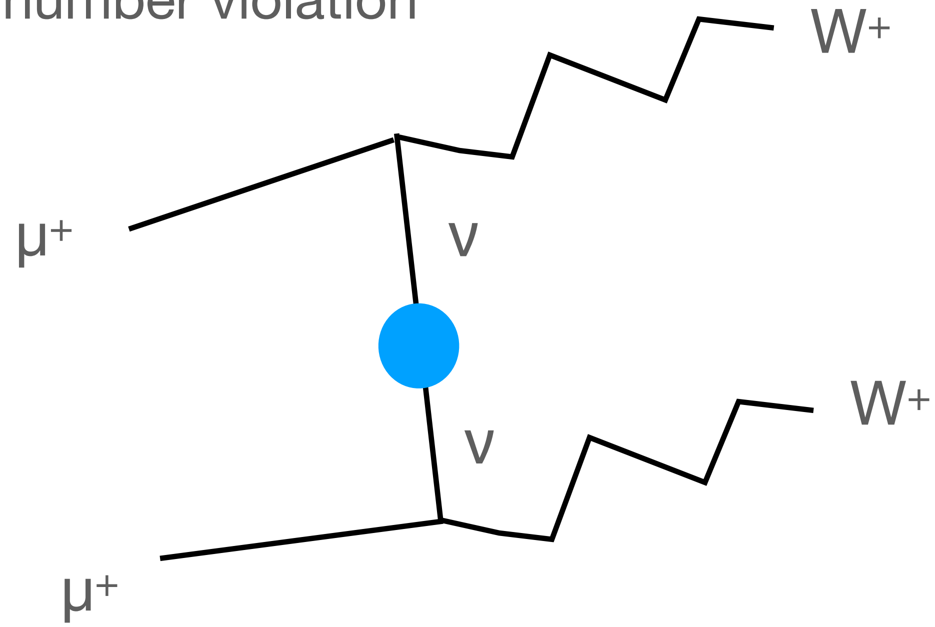
S
T
(H current)(L current)
4-fermi

	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

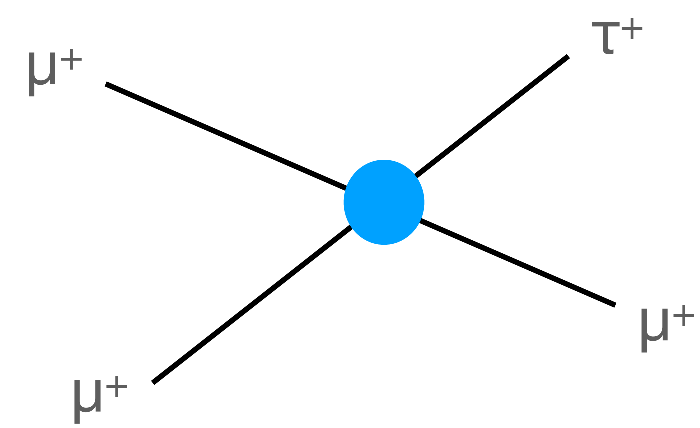
Table 1: Constraints on SMEFT operators at 2-sigma level. $\sqrt{s} = 2$ TeV. The bin size for θ is taken as 1° and each bin covers the range $\theta_i - 0.5° < \theta < \theta_i + 0.5°$. The considered range of θ_i is $16° \leq \theta_i \leq 164°$.

Lepton number/flavor violation?

lepton number violation



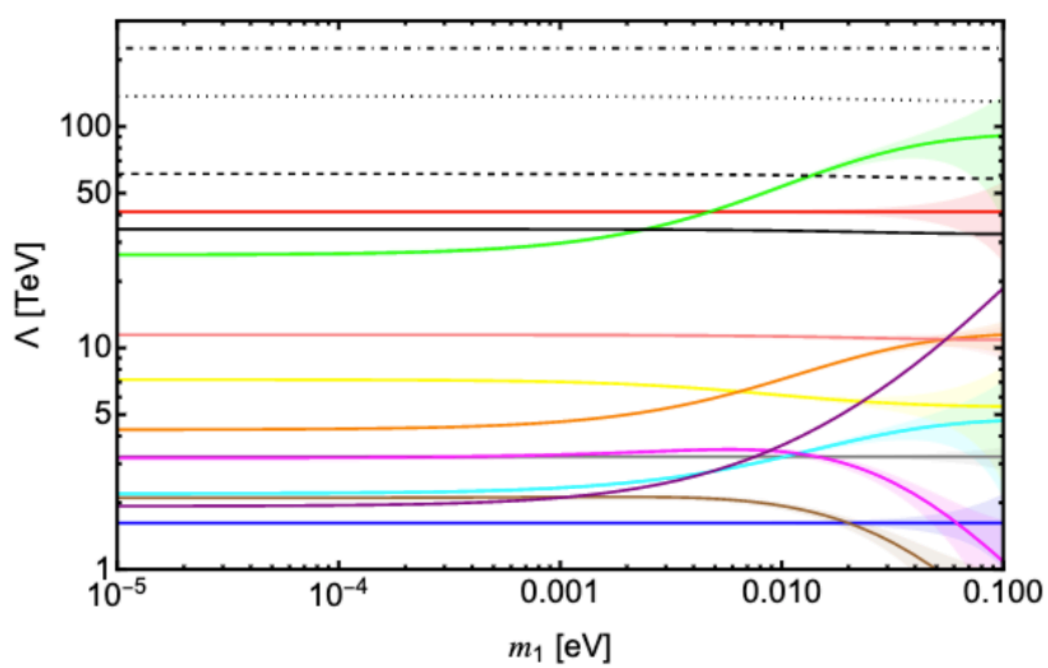
lepton flavor violation

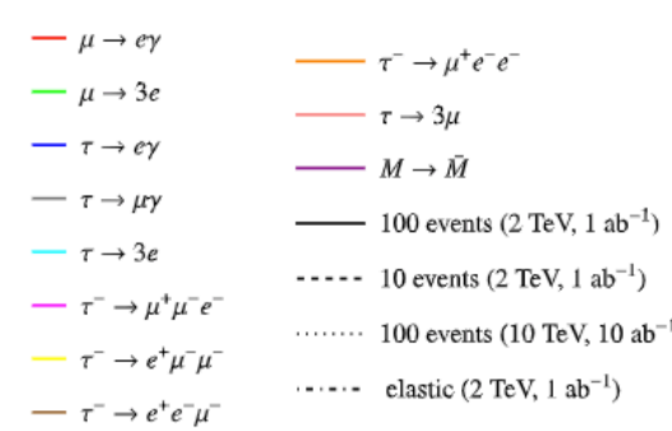


Can be better than rare decays!

(with Fridell and Takai in progress)

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





Summary

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

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

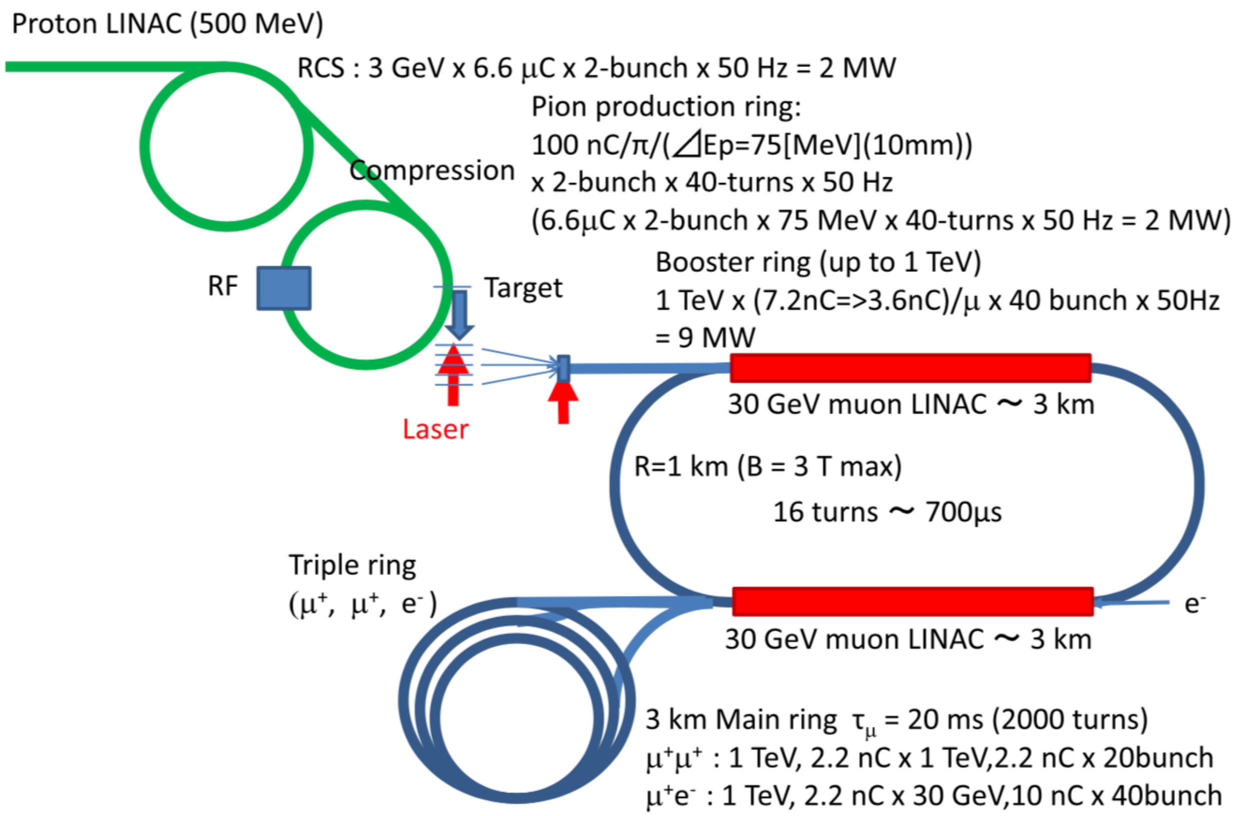


Fig. 1. Conceptual design of the $\mu^+e^-/\mu^+\mu^+$ collider.