Standard Model (SM) and physics beyond SM

The standard model (SM) has been established as a good effective theory.

Lots of phenomena can be explained consistently by the SM.

Some problems in SM:

- Neutrino masses
- Dark matter
- muon g-2 anomaly(?)
- Fine-tuning problem of the Higgs mass

What is the UV physics or unknown sector??

One of the most important questions for the current particle physics

How to uncover BSM

There are some experimental ways to approach this question.

(i) Go to higher energy

Production of new particles

(ii) Precision measurement of couplings to Higgs

Couplings to the Higgs boson are completely predicted within the SM

→ Deviation from the SM values indicates new physics!

The Higgs is relevant to

origin of EWSB, SUSY, right handed neutrinos, SM singlet scalars, Z’,...

Future lepton colliders

- ILC, CLIC ($e^+ e^-$ collider)

Good colliders for Higgs coupling measurements (if they are built)

- Muon colliders ($\mu^+ \mu^-$ colliders) Recently attracting attention

Precision measurements are possible

because it's a lepton collider

High energy (TeV or O(10) TeV) beam can be realized

because of less synchrotron energy than electrons

Important properties for colliders

The cross-section of a process: $\boldsymbol{\sigma}$

The number of the events of the process is

$$N_{\mathbf{event}} = \sigma \cdot \mathcal{L} \cdot t_{\mathbf{run}}$$ ($t_{\mathbf{run}}$: running time of the collider)

where the luminosity is given by

\# of particles

How frequently collisions occur

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

Beam size

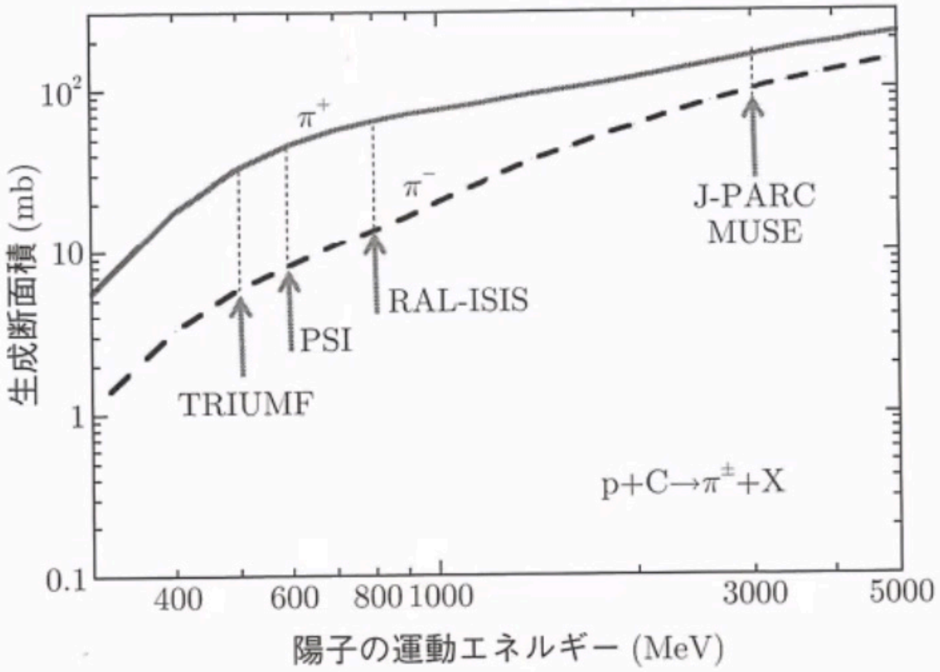
The statistical error of the cross-section measurement is

$$\Delta_{\mathbf{stat.}}\sigma \propto \frac{1}{\sqrt{N_{\mathbf{event}}}}$$

The # of particles and the smallness of beam size are important.

Current difficulties in $\mu^+ \mu^-$ colliders

Problems in μ^- beam



- Production of large amount of μ^-

High energy protons are necessary to produce π^-

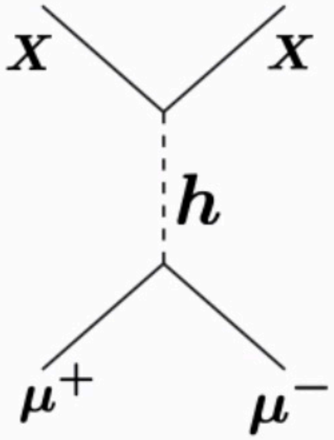
- Cooling of μ^-

To make beam size small, cooling is necessary.

There isn't good established technology for cooling of μ^-.

A considered possibility: muon collider $\sqrt{s} = 125\ \mathrm{GeV}$ as a Higgs factory

Large cross section of O(10) pb $\quad y_\mu \left. \dfrac{1}{s - m_H^2 + i m_H \Gamma_H} \right|_{s=m_H^2}$

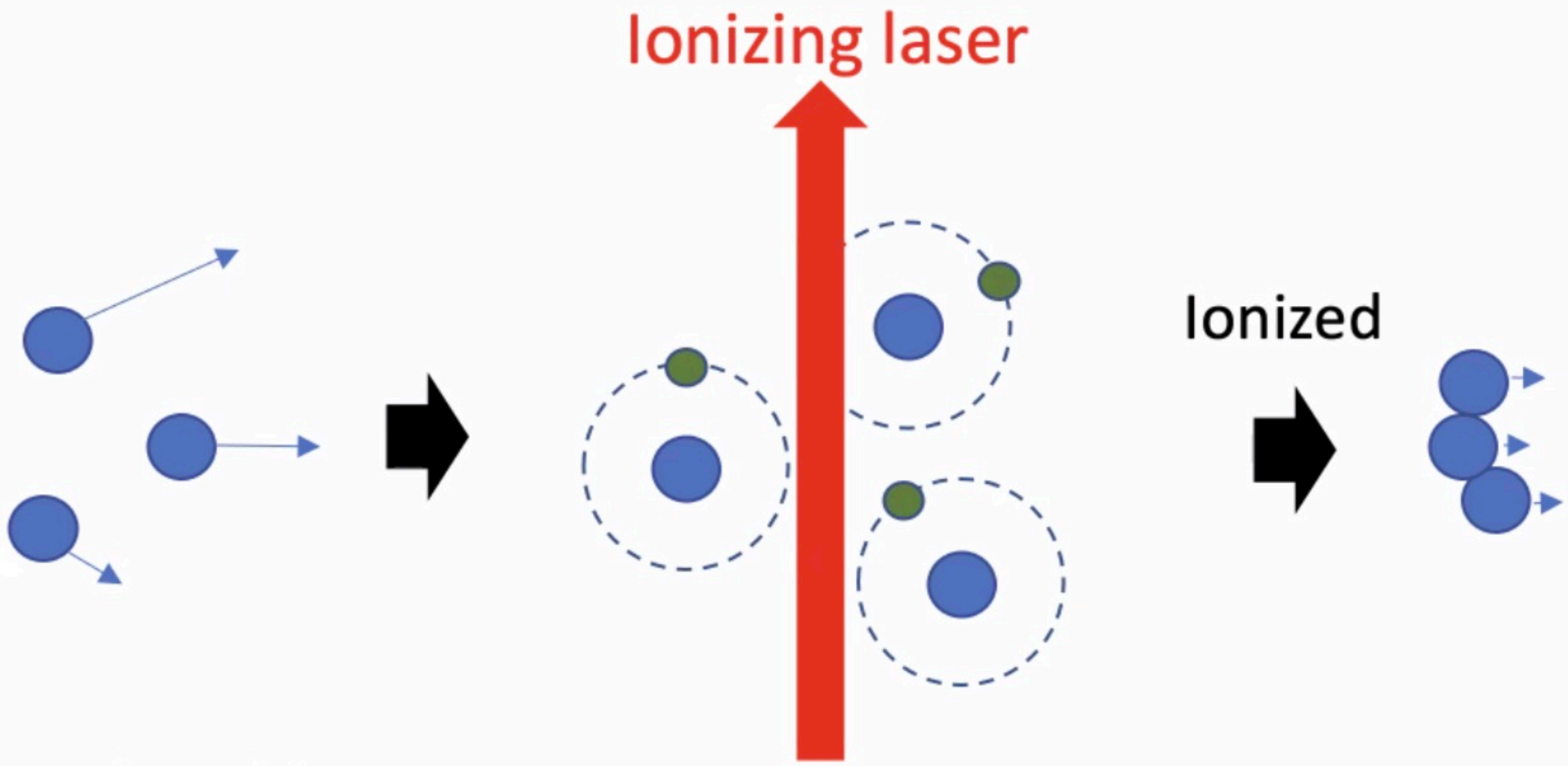


Actually difficult to fully utilize this large cross section due to momentum spread of beam $\Delta\sqrt{s}_{\mathrm{beam}}/m_H (\sim 10^{-3}) \gg \Gamma_H/m_H \simeq 3 \times 10^{-5}$

Technology for cooling μ^+ exists!

Muon g-2 experiment planned at J-PARC

The key technology is cooling of μ^+, which is available today!



μ^+ produced from π^+ decay

$\mu^+ e^-$ bound state (muonium)

Ultracold μ^+

Used as a high-quality μ^+ beam by accelerating ultracold muons to 300 MeV in g-2 exp.

Proposal of new collider experiments

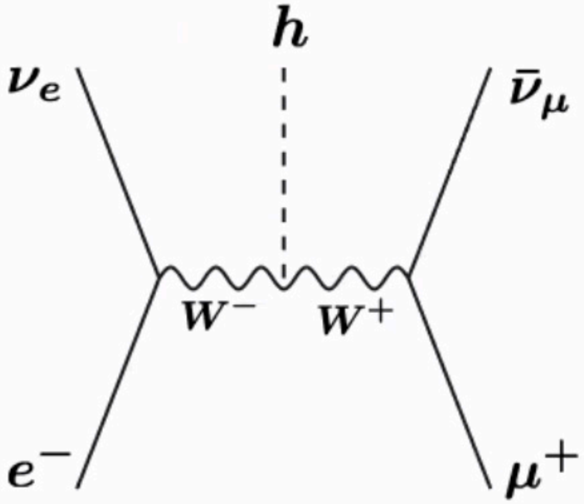
We propose collider experiments using high-quality μ^+ beam and accelerating it to TeV scale!

Using the 3 km ring, we can realize

- $\mu^+ e^-$ collider Higgs factory

$$E_{\mu^+} = 1\ \mathrm{TeV},\ E_{e^-} = 30\ \mathrm{GeV}$$ (TRISTAN energy)

$$\longrightarrow \sqrt{s} = 346\ \mathrm{GeV}$$



- $\mu^+\mu^+$ collider New physics search

$$E_{\mu^+} = 1\ \mathrm{TeV},\ E_{\mu^+} = 1\ \mathrm{TeV}$$

$$\longrightarrow \sqrt{s} = 2\ \mathrm{TeV}$$

μTRISTAN!

Estimated impact of μTRISTAN

- μ^+e^- collider

$$\mathcal{L}_{\mu^+e^-} = 4.6 \times 10^{33}\ \mathrm{cm^{-2}s^{-1}} \longrightarrow \int \mathcal{L}_{\mu^+e^-} dt = 1.0\ \mathrm{ab^{-1}}$$ (Ten-year running)

Case of $\sqrt{s} = 346\ \mathrm{GeV}$

Higgs coupling measurement with sub per-cent $\left|\frac{\Delta g_{hWW}}{g_{hWW}^{\mathrm{SM}}} + \frac{\Delta g_{hbb}}{g_{hbb}^{\mathrm{SM}}}\right| \lesssim 3.1 \times 10^{-3}$

Case of $\sqrt{s} = 775\ \mathrm{GeV}$

Measurement of Higgs trilinear self-coupling with 20 %

- $\mu^+\mu^+$ collider

$$\mathcal{L}_{\mu^+\mu^+} = 5.7 \times 10^{32}\ \mathrm{cm^{-2}s^{-1}} \longrightarrow \int \mathcal{L}_{\mu^+e^-} dt = 130\ \mathrm{fb^{-1}}$$

Scalar lepton search up to TeV scale

Constraint on a new physics scale up to O(100) TeV

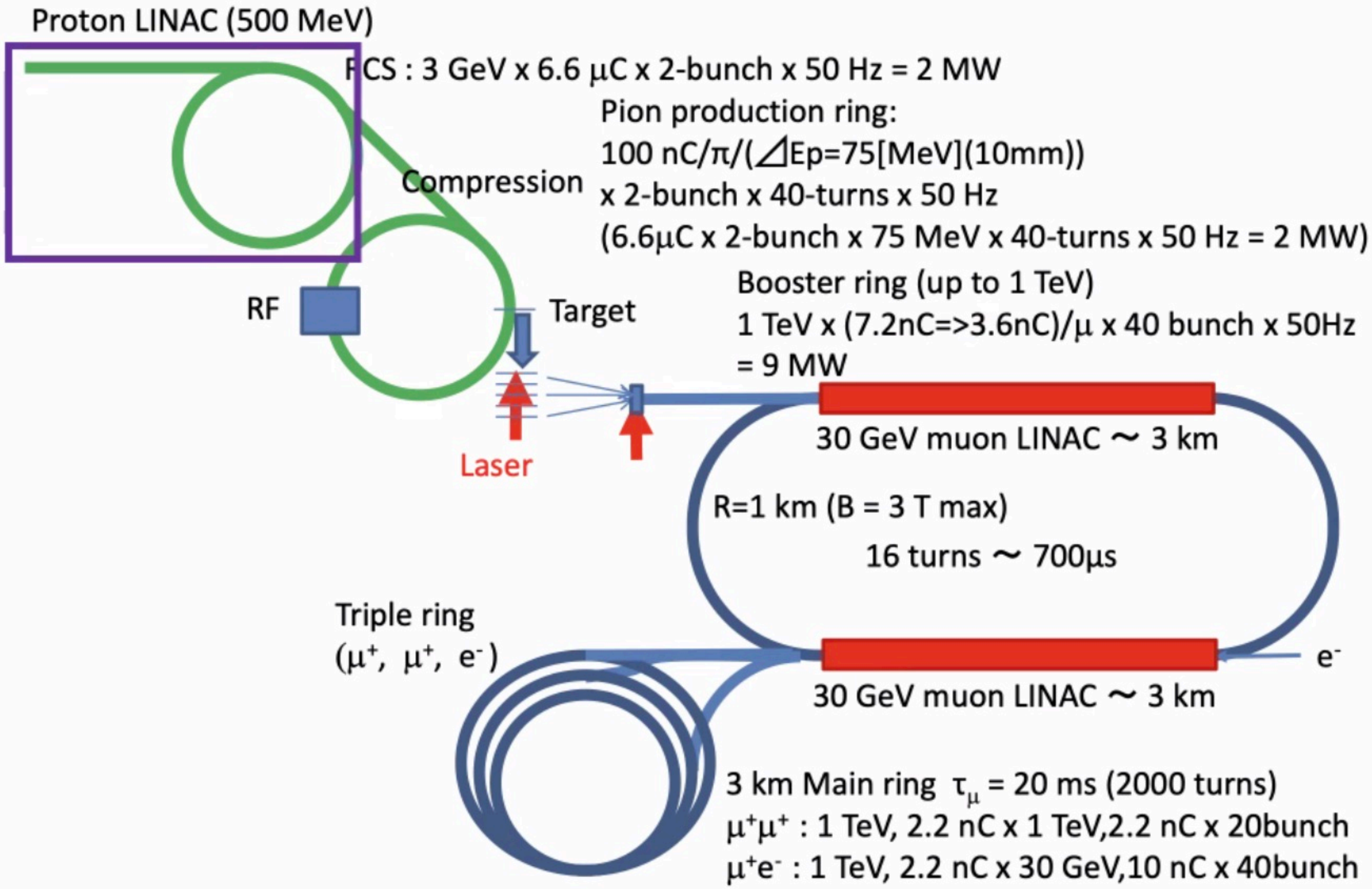
Contents

✓ Introduction

- Collider design and estimate of luminosity
- Higgs boson physics at μTRISTAN
- New physics search at μTRISTAN
- Conclusions

Proton acceleration (Proton LINAC & RCS)

$$p(3\,\mathrm{GeV})$$



RCS : 3 GeV x 6.6 μC x 2-bunch x 50 Hz = 2 MW

Pion production ring:
100 nC/π/(⊿Ep=75[MeV](10mm))
x 2-bunch x 40-turns x 50 Hz
(6.6μC x 2-bunch x 75 MeV x 40-turns x 50 Hz = 2 MW)

Booster ring (up to 1 TeV)
1 TeV x (7.2nC=>3.6nC)/μ x 40 bunch x 50Hz
= 9 MW

30 GeV muon LINAC ～ 3 km

R=1 km (B = 3 T max)
16 turns ～ 700μs

Triple ring
(μ^+, μ^+, e^-)

30 GeV muon LINAC ～ 3 km

3 km Main ring τ_μ = 20 ms (2000 turns)
$\mu^+\mu^+$: 1 TeV, 2.2 nC x 1 TeV,2.2 nC x 20bunch
μ^+e^- : 1 TeV, 2.2 nC x 30 GeV,10 nC x 40bunch

Proton acceleration (Proton LINAC & RCS) → Pion production (Pion production ring)

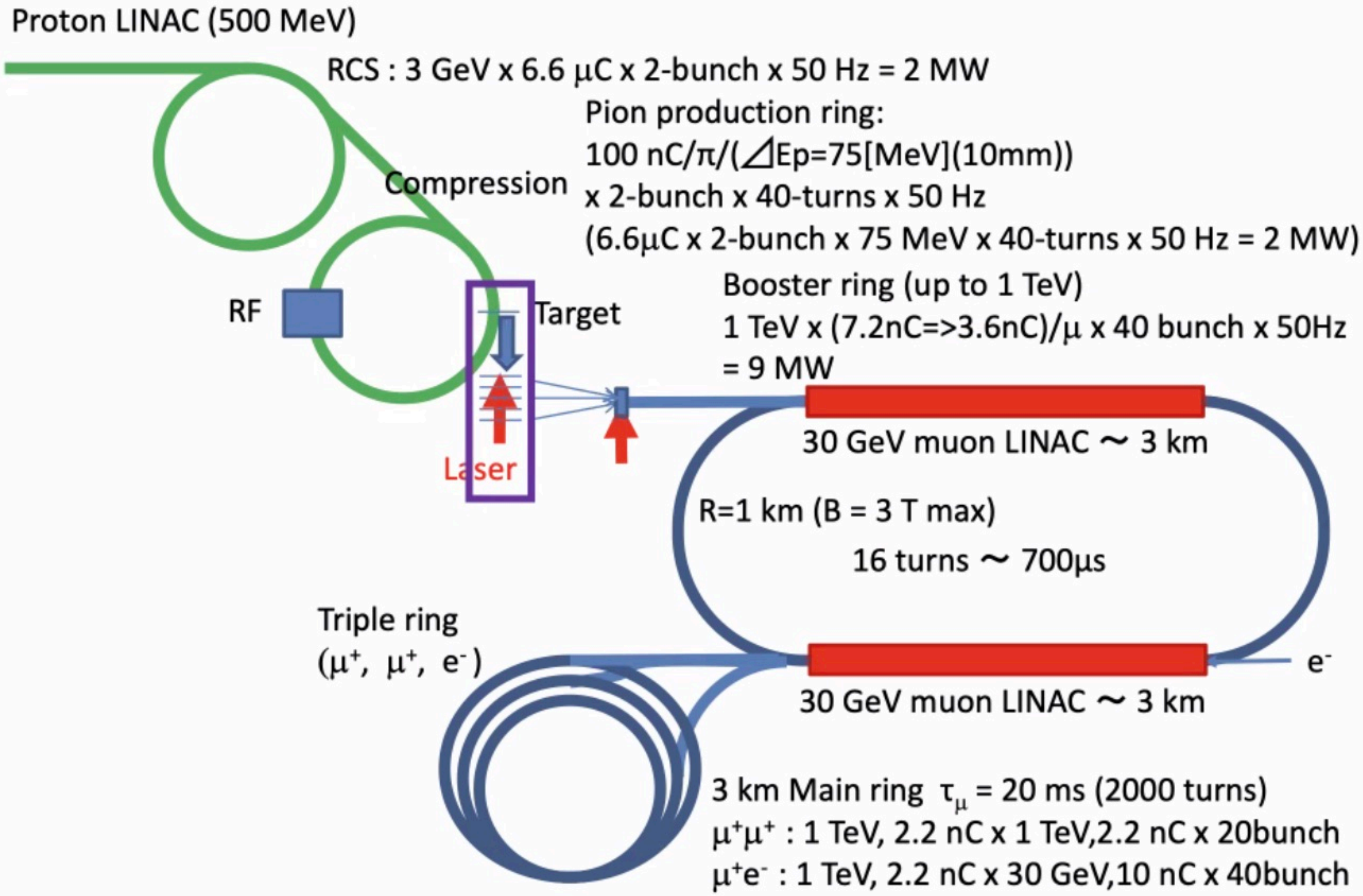
$\boldsymbol{p}(3\,\mathrm{GeV})$ $\qquad$ $\boldsymbol{p}(3\,\mathrm{GeV}) + \boldsymbol{C} \rightarrow \boldsymbol{\pi}^{+} + \boldsymbol{X}$

→ Ultra-cold muon production

$\boldsymbol{\pi}^{+} \rightarrow \boldsymbol{\mu}^{+} + \boldsymbol{\nu}_{\boldsymbol{\mu}}$ Ultra-cold muon

Ionized by laser

Muonium $(\boldsymbol{\mu}^{+}\boldsymbol{e}^{-})$ formation in silica aerogel



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(μ⁺, μ⁺, e⁻)

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Proton acceleration (Proton LINAC & RCS) → Pion production (Pion production ring)

$p(3\,\mathrm{GeV})$

$p(3\,\mathrm{GeV}) + C \to \pi^+ + X$

→ Ultra-cold muon production → Muon acceleration (Booster ring) → Collide (Main ring)

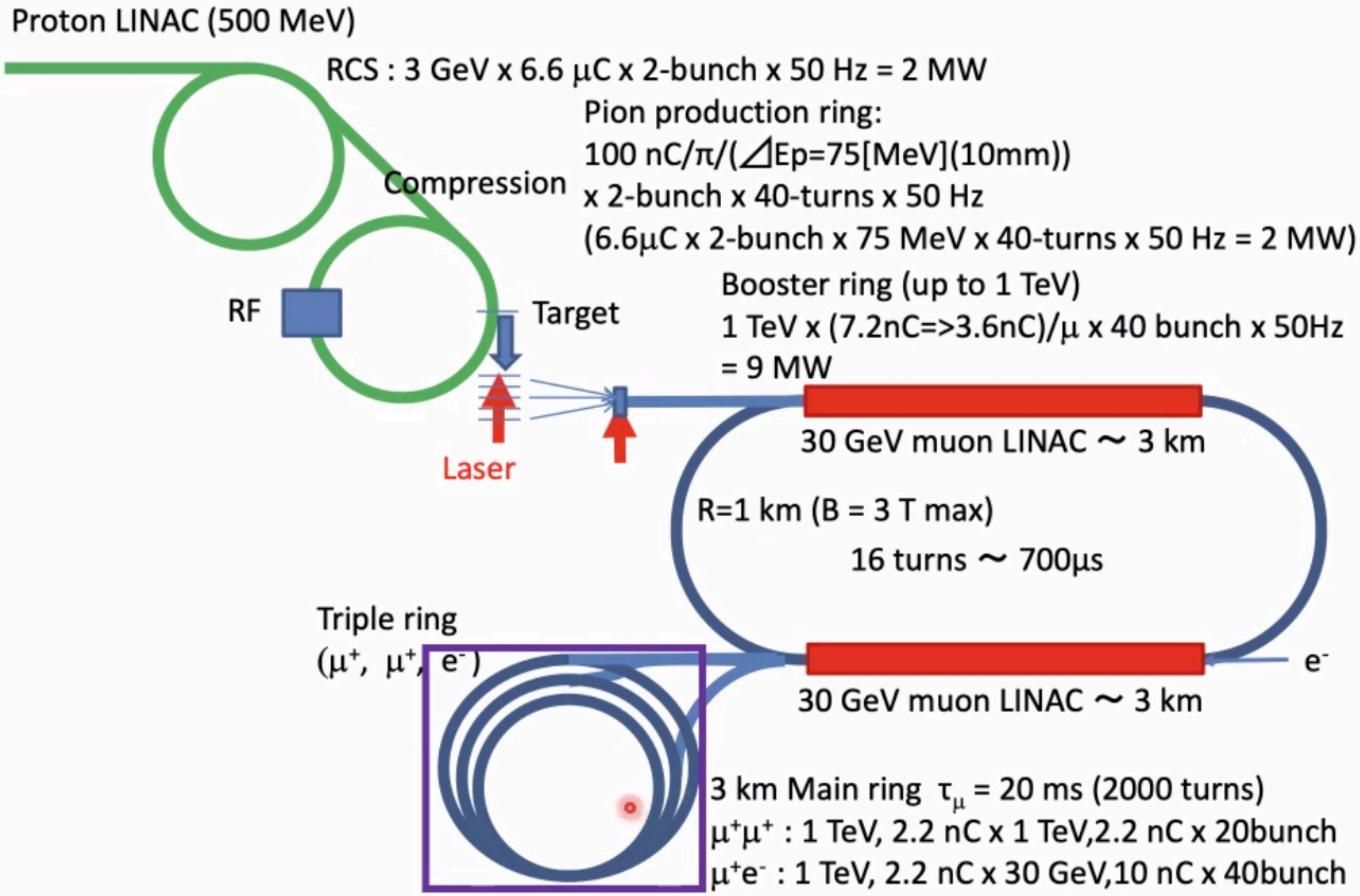
$\pi^+ \to \mu^+ + \nu_\mu$ ↘ Muonium $(\mu^+ e^-)$ formation in silica aerogel ↗ Ionized by laser ↗ Ultra-cold muon

$\mu^+(1\,\mathrm{TeV})$

$[\mu^+(1\,\mathrm{TeV}), e^-(30\,\mathrm{GeV})]$

or

$[\mu^+(1\,\mathrm{TeV}), \mu^+(1\,\mathrm{TeV})]$



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μ^+e^- : 1 TeV, 2.2 nC x 30 GeV,10 nC x 40bunch

$\tau_{\mu(1\,\mathrm{TeV})} = 20$ ms

New beam injected every 20 ms.

Proton acceleration (Proton LINAC & RCS) ⟶ Pion production (Pion production ring)

$p(3\,\mathrm{GeV})$ $\qquad$ $p(3\,\mathrm{GeV}) + C \rightarrow \pi^+ + X$

⟶ Ultra-cold muon production ⟶ Muon acceleration (Booster ring) ⟶ Collide (Main ring)

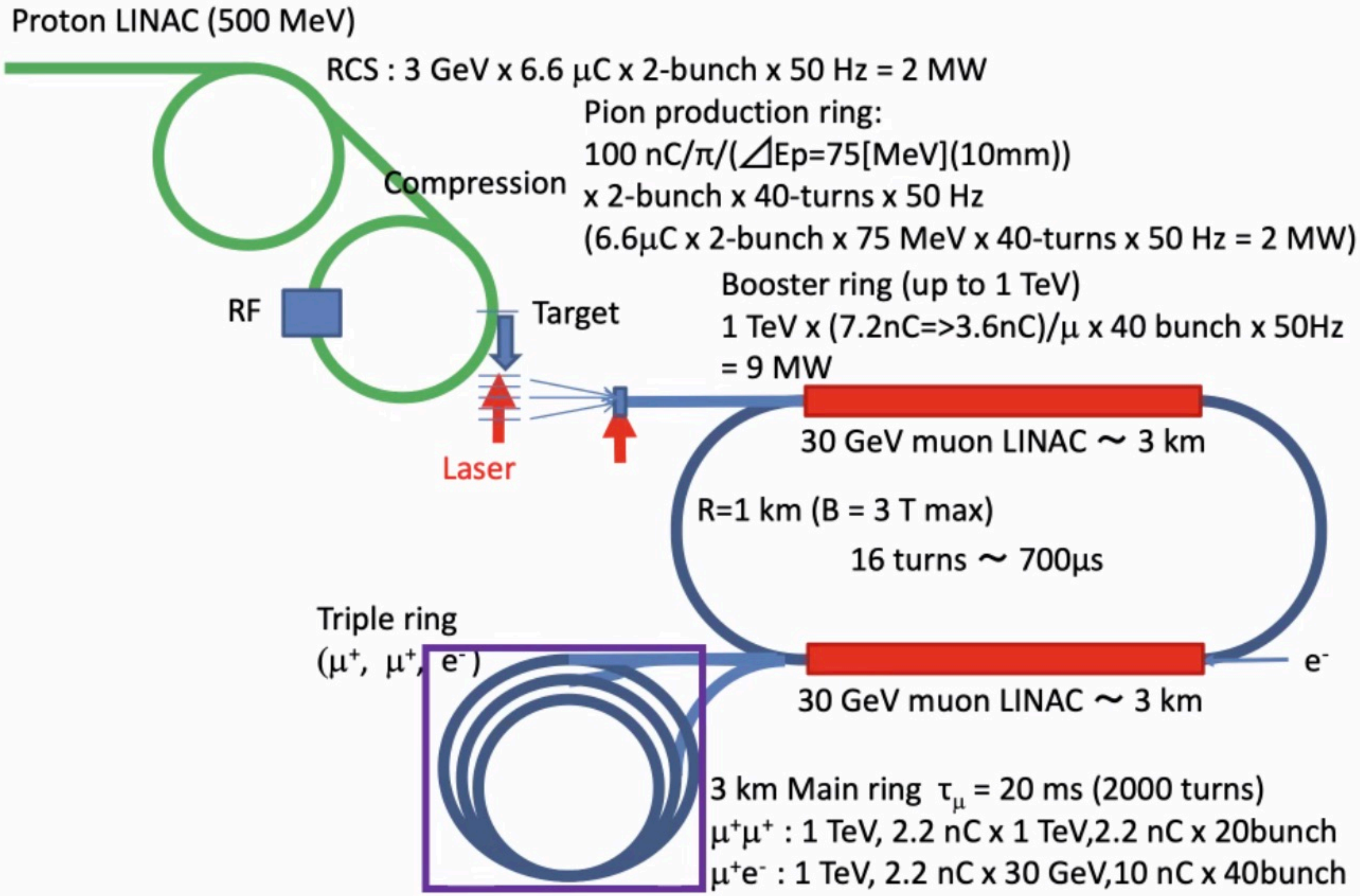
$\mu^+(\mathbf{1\,TeV})$

$[\mu^+(\mathbf{1\,TeV}), e^-(\mathbf{30\,GeV})]$

or

$[\mu^+(\mathbf{1\,TeV}), \mu^+(\mathbf{1\,TeV})]$

$\pi^+ \rightarrow \mu^+ + \nu_\mu$ ↘ Muonium $(\mu^+ e^-)$ formation in silica aerogel ↗ Ionized by laser ↗ Ultra-cold muon



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$\tau_{\mu(\mathbf{1\,TeV})} = \mathbf{20}$ ms

New beam injected every 20 ms.

The number of ultra-cold muons

The number of muons is crucial for high luminosity

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

Our estimate of the number of available ultra-cold muons is

$$9.0 \times 10^{13}/\mathrm{sec.}$$

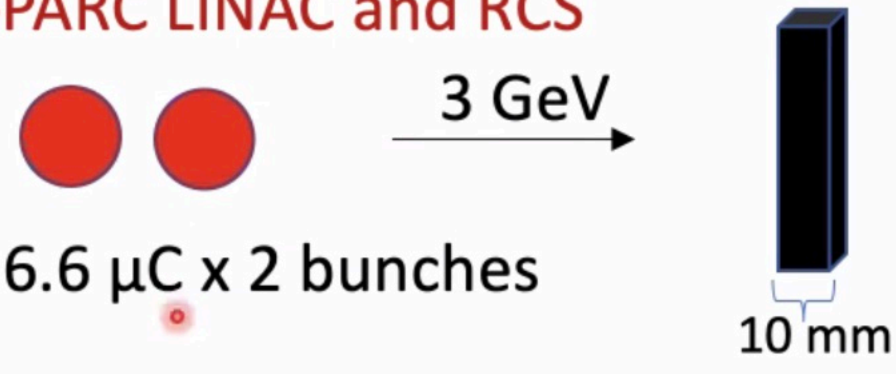
[or $14\,\mu\mathrm{C}/\mathrm{sec.}$]

on which our estimate of the luminosity is based.

Let's see how we get this number.

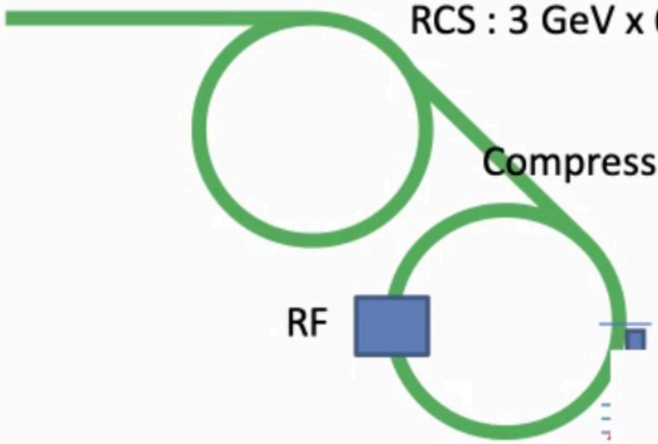
We thank Takayuki Yamazaki, Cedric Zhang, and Shusei Kamioka for providing us with the information of the muon yield on which our estimates are based.

Similar to J-PARC LINAC and RCS



6.6 μC x 2 bunches

Hit 40 times



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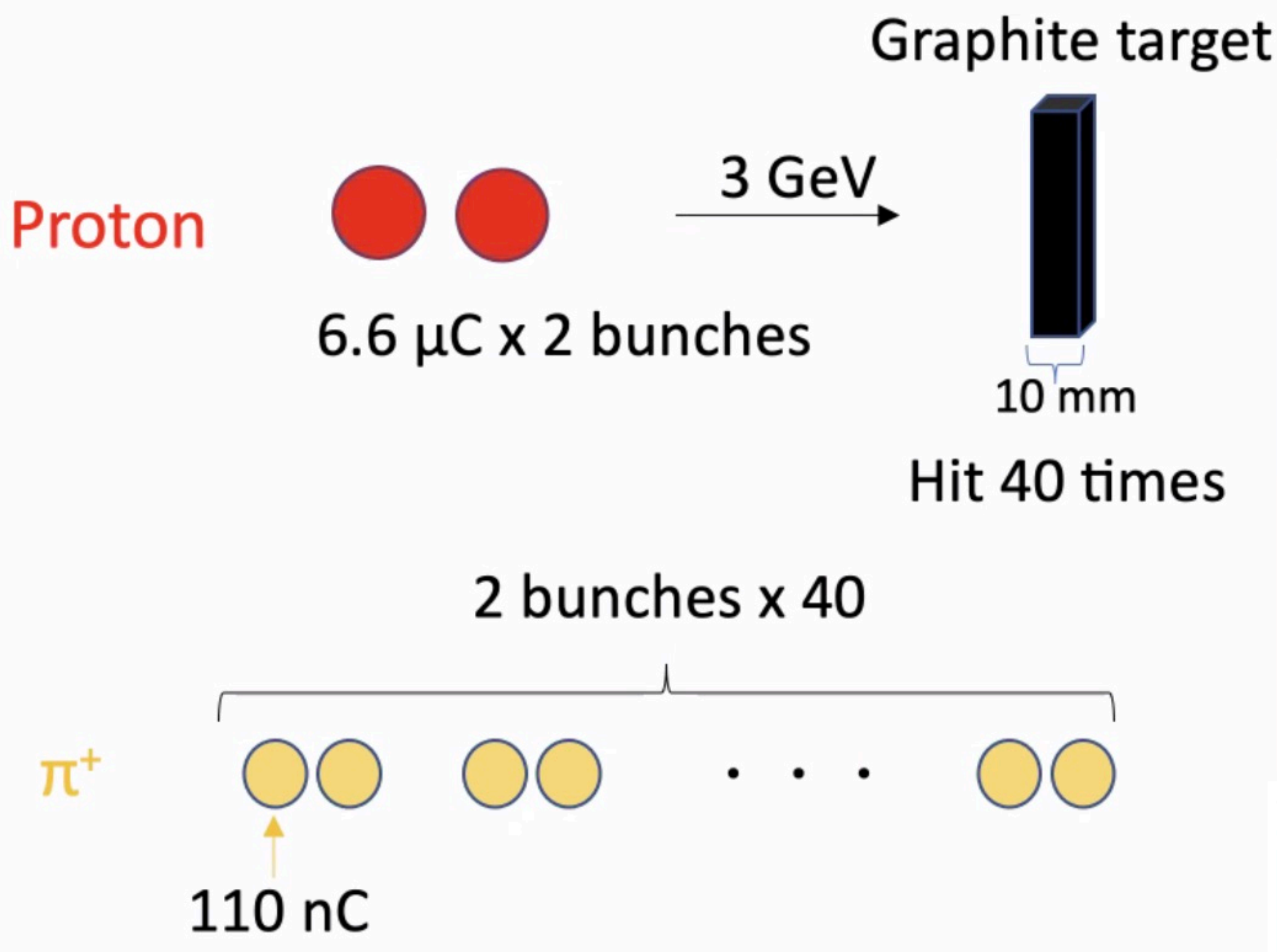
x 2-bunch x 40-turns x 50 Hz
(6.6μC x 2-bunch x 75 MeV x 40



Proton

6.6 μC x 2 bunches

3 GeV

Graphite target

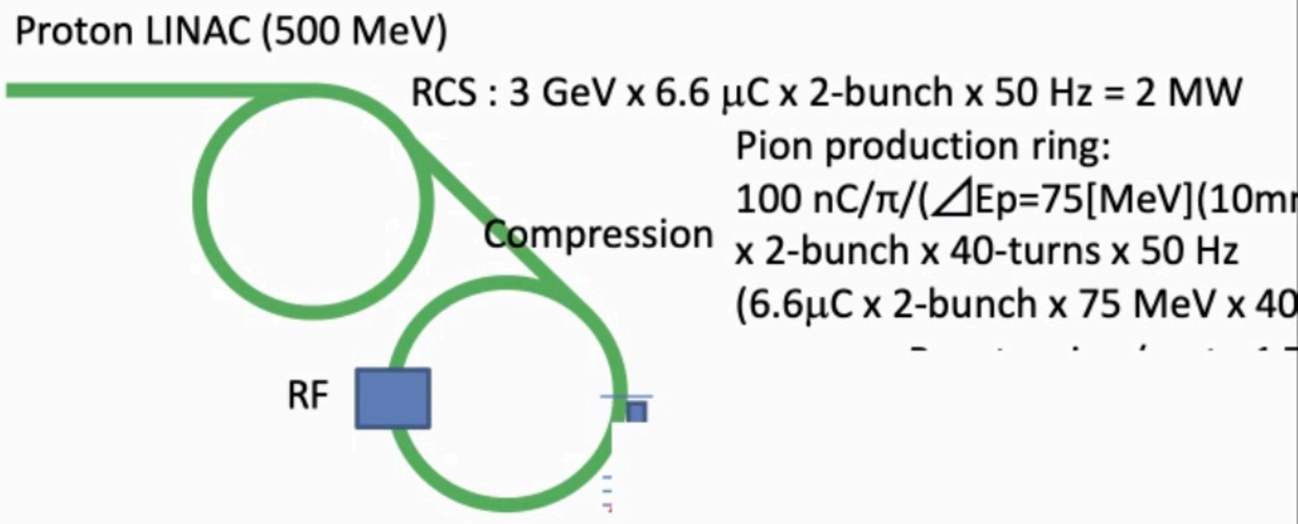
10 mm

Hit 40 times

2 bunches x 40

π⁺

110 nC



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(6.6μC x 2-bunch x 75 MeV x 40

Compression

RF

π⁺ production rate

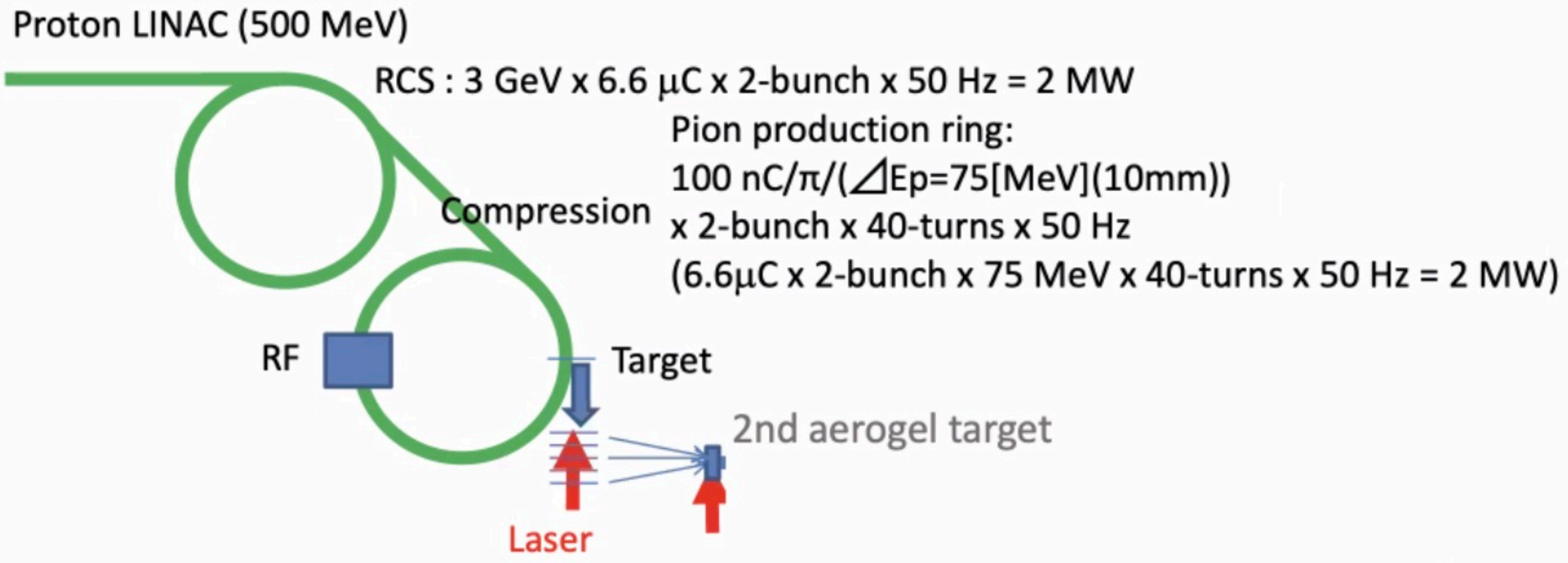
$$n_{\pi^+}/n_p = \sigma n dx = 0.016$$

where

Production cross-section $\sigma = 150\ \mathrm{mb}$

Number density of graphite $n = 1.1 \times 10^{23}\ \mathrm{cm}^{-3}$

Thickness of the graphite target $dx = 10\ \mathrm{mm}$



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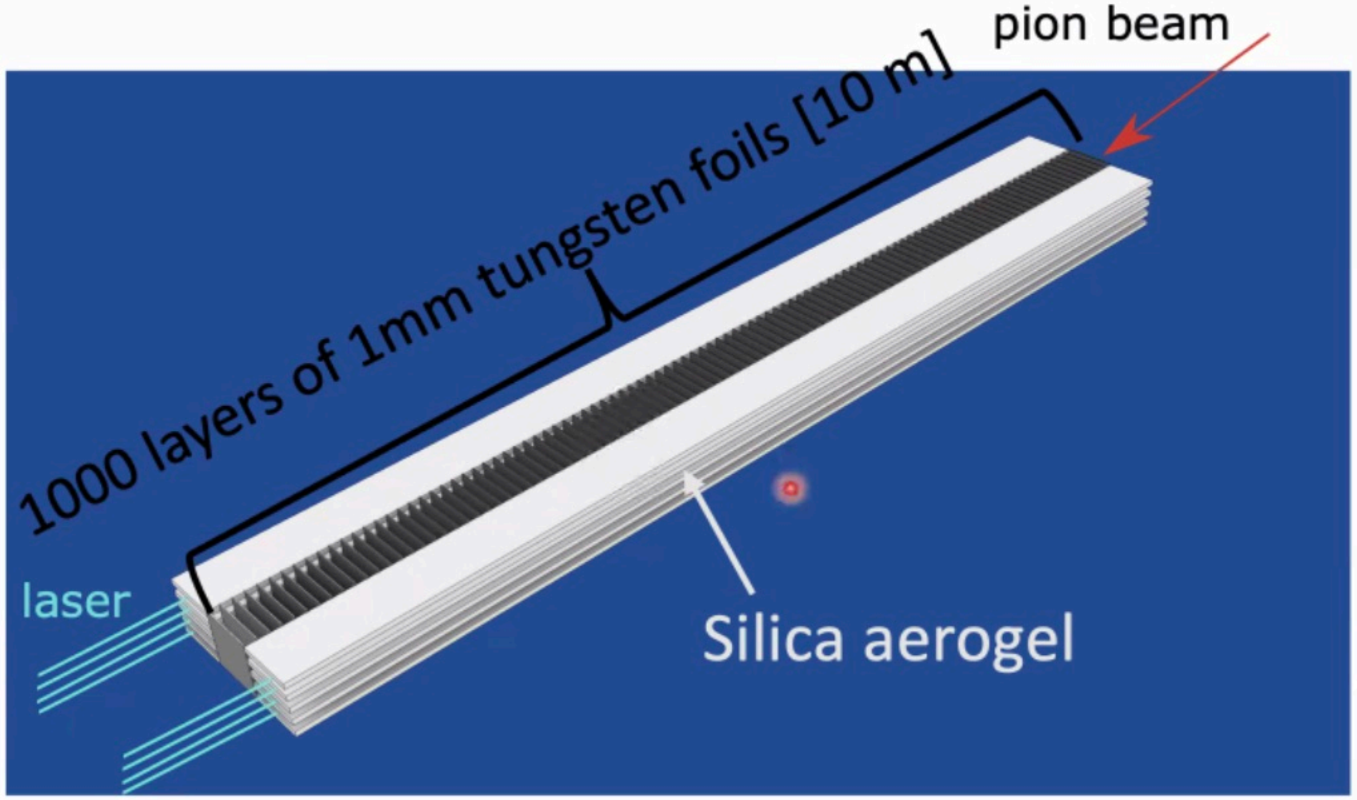


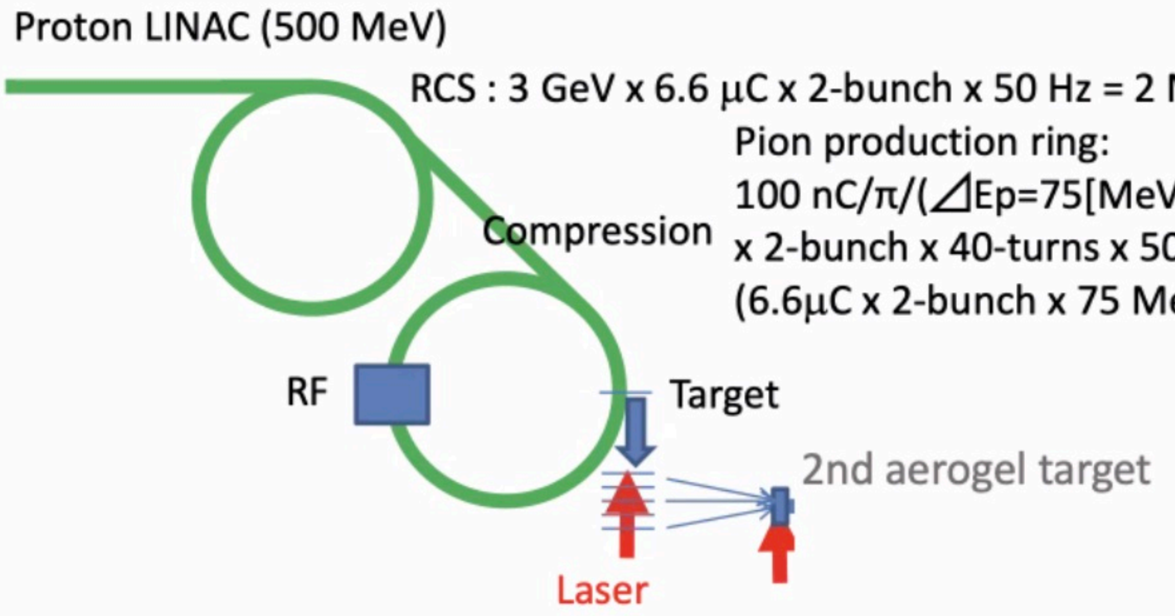
1. Pions are stopped and decay into muons.
2. Muons are transported into the aerogel target and form muoniums ($\mu^+ e^-$ bound state).
3. Neutral muoniums are thermally diffused from the target and ionized by laser.

Ultra-cold muons!

↓

Muons spread over 10 m are transported to the second aerogel target of a few cm.

We finally obtain the ultra-cold muons which can be accelerated.



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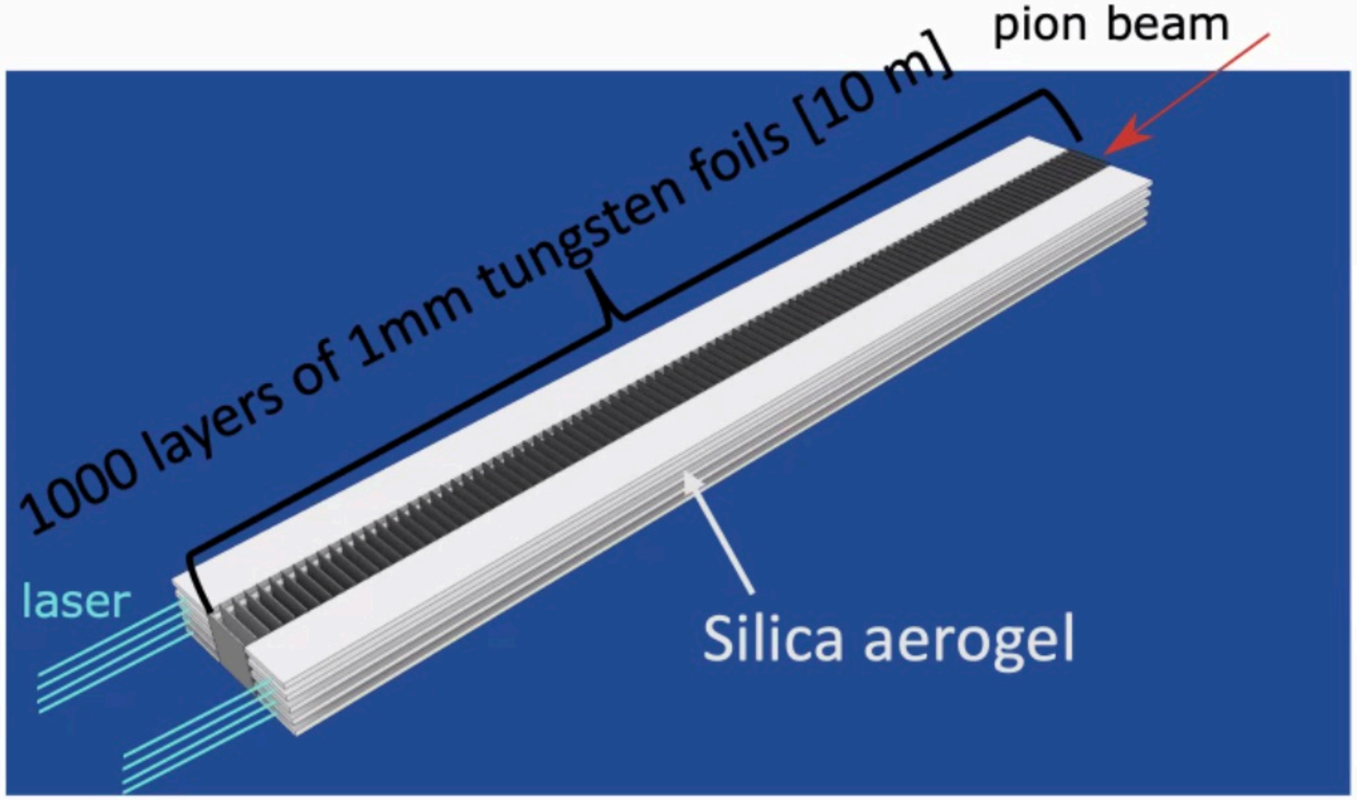


Pion transportation to the target: 50 %
(pion lifetime & pion loss by interactions w/ materials)

1. Pions are stopped and decay into muons.
2. Muons are transported into the aerogel target and form muoniums ($\mu^+ e^-$ bound state).

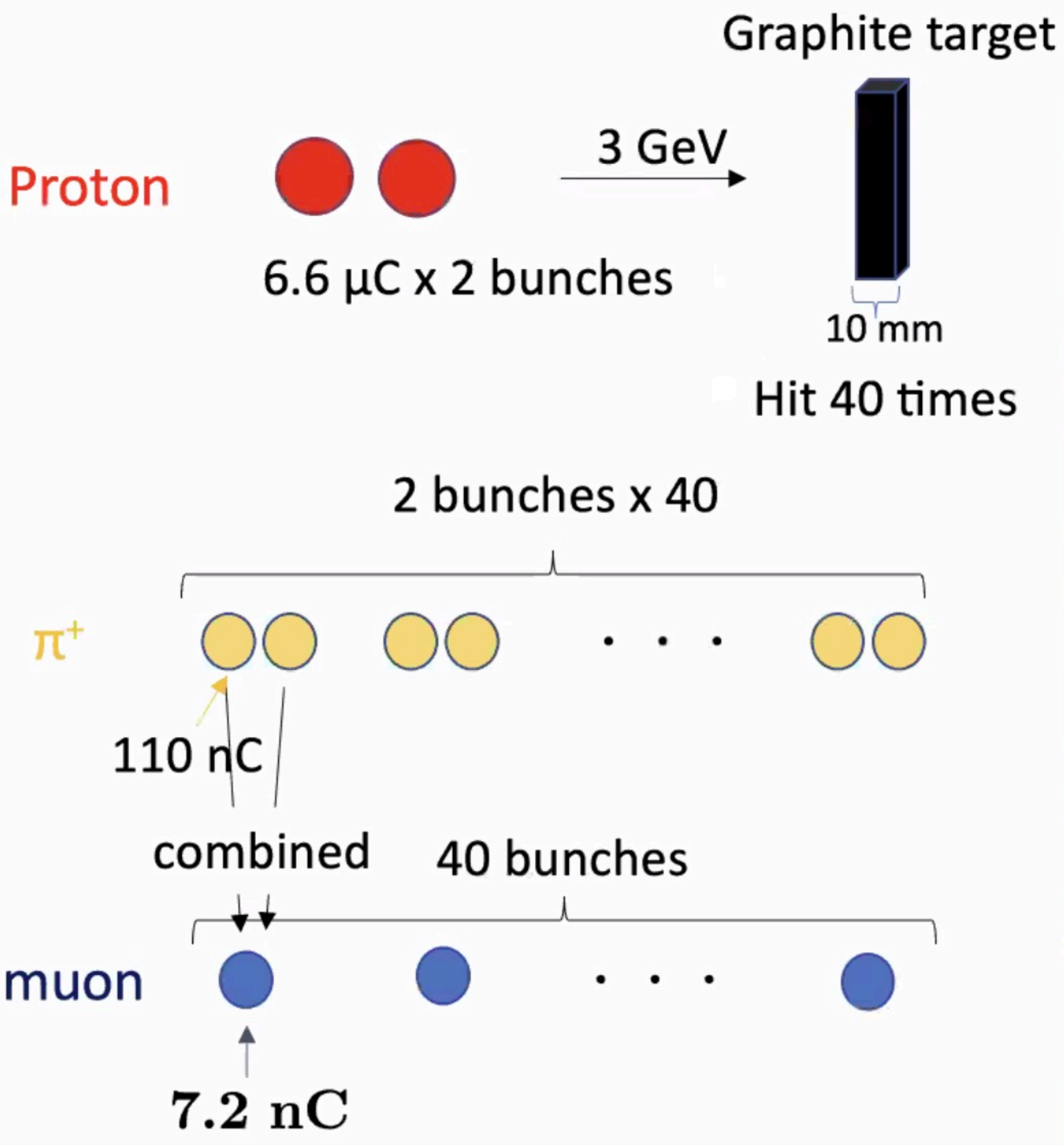
Muonium formation: 52 %

3. Neutral muoniums are thermally diffused from the target and ionized by laser.

Muonium emission to vacuum: 60 %
Remaining muoniums w/o decay: 60 %
Laser ionization: 73 %

↓

Muons spread over 10 m are transported to the second aerogel target of a few cm.
efficiency: 50 % *a very thin target is used
We finally obtain the ultra-cold muons which can be accelerated.



Graphite target

Proton

3 GeV

6.6 μC x 2 bunches

10 mm

Hit 40 times

2 bunches x 40

π^+

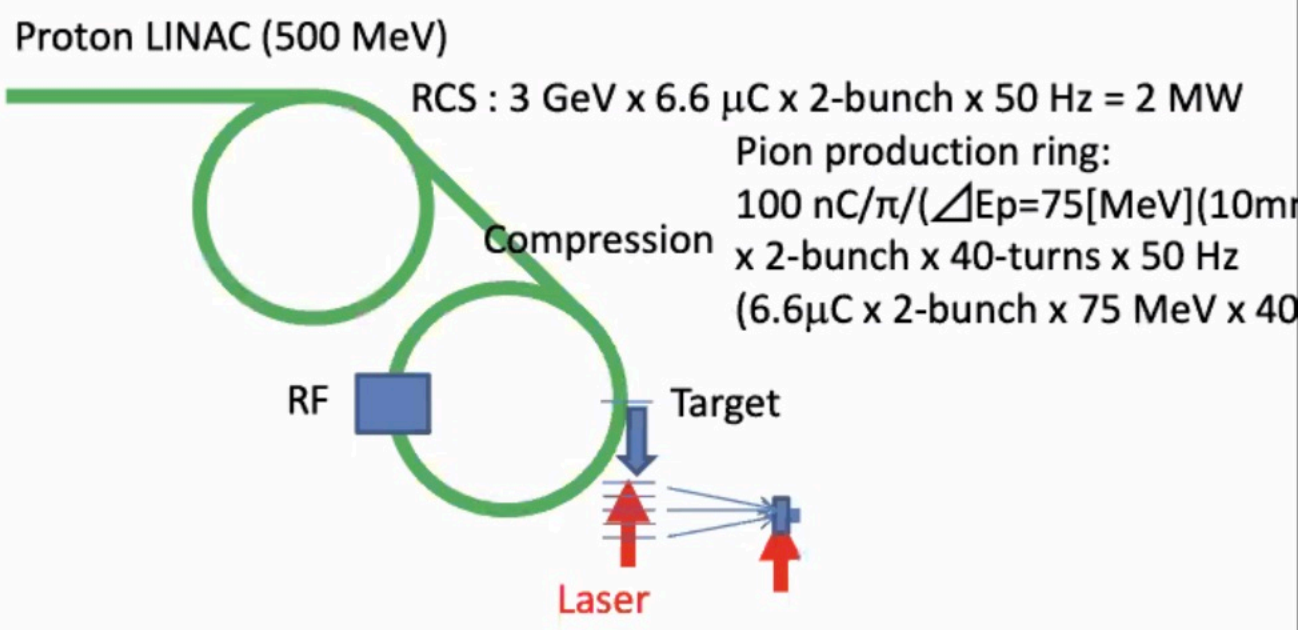
110 nC

combined

40 bunches

muon

$\mathbf{7.2\ nC}$



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(6.6μC x 2-bunch x 75 MeV x 40

Compression

RF

Target

Laser

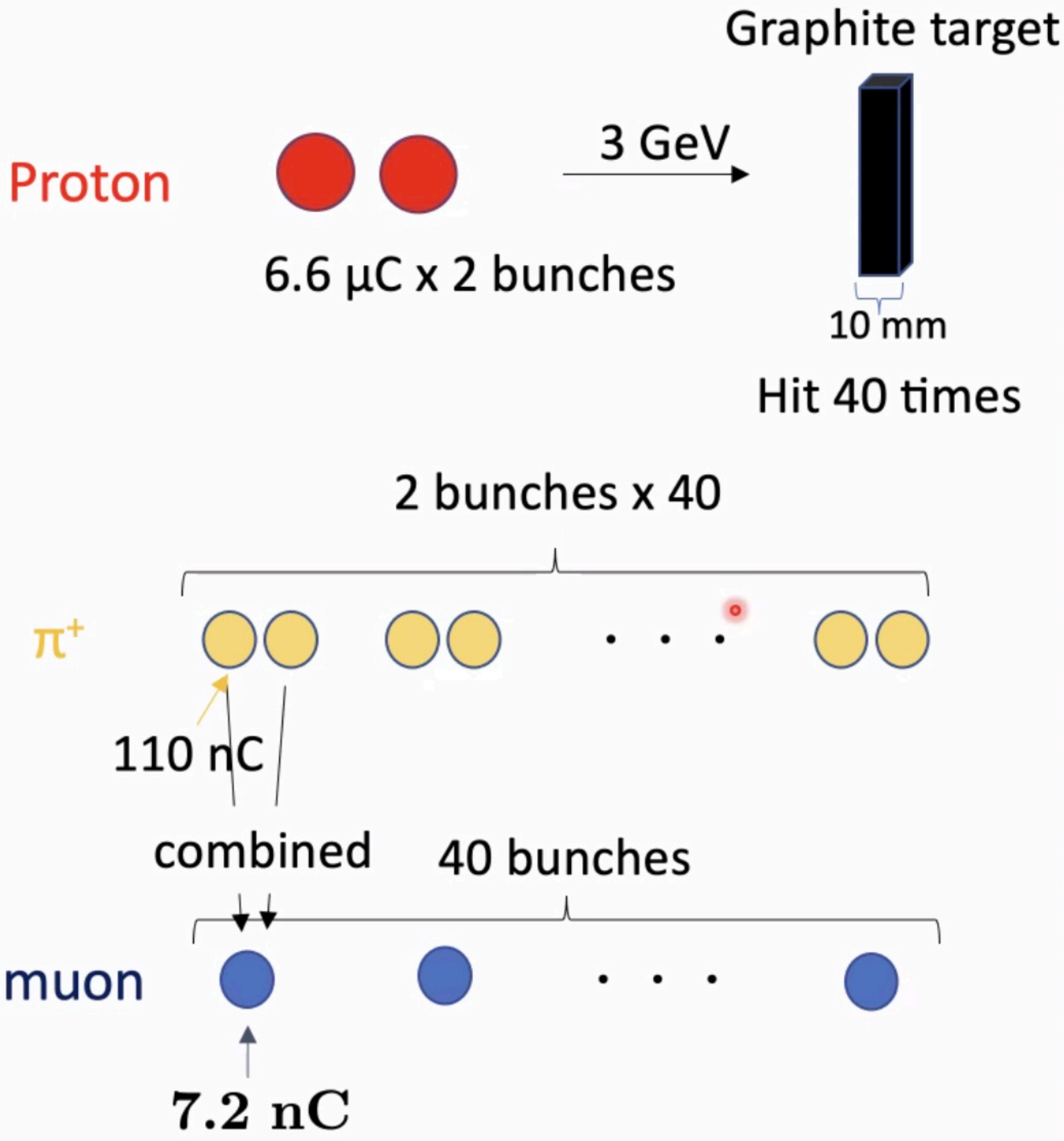
This process is completed for 20 ms.

of the ultra-cold muons that are accelerated:

$$\mathbf{7.2\ nC \times 40/(20\ ms) = 9.0 \times 10^{13}/s}$$

The rate of ultra-cold μ^+ to π^+: 3.4 %

$$[= \mathbf{0.50 \times 0.52 \times 0.60 \times 0.60 \times 0.73 \times 0.50}]$$



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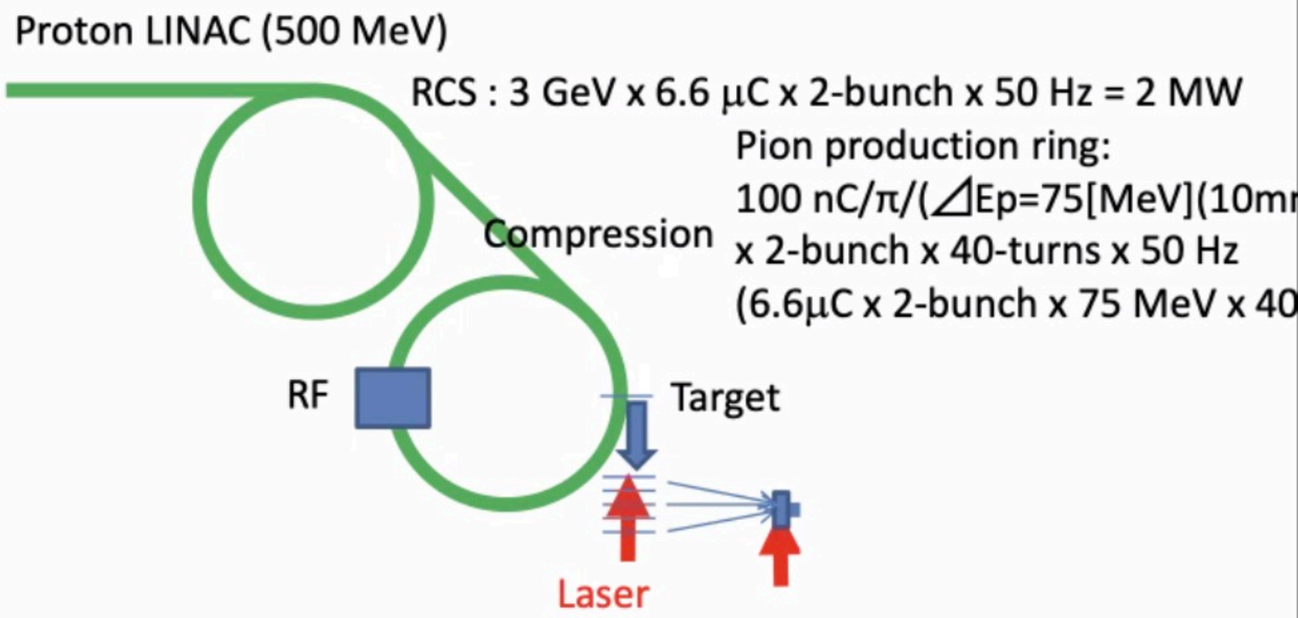

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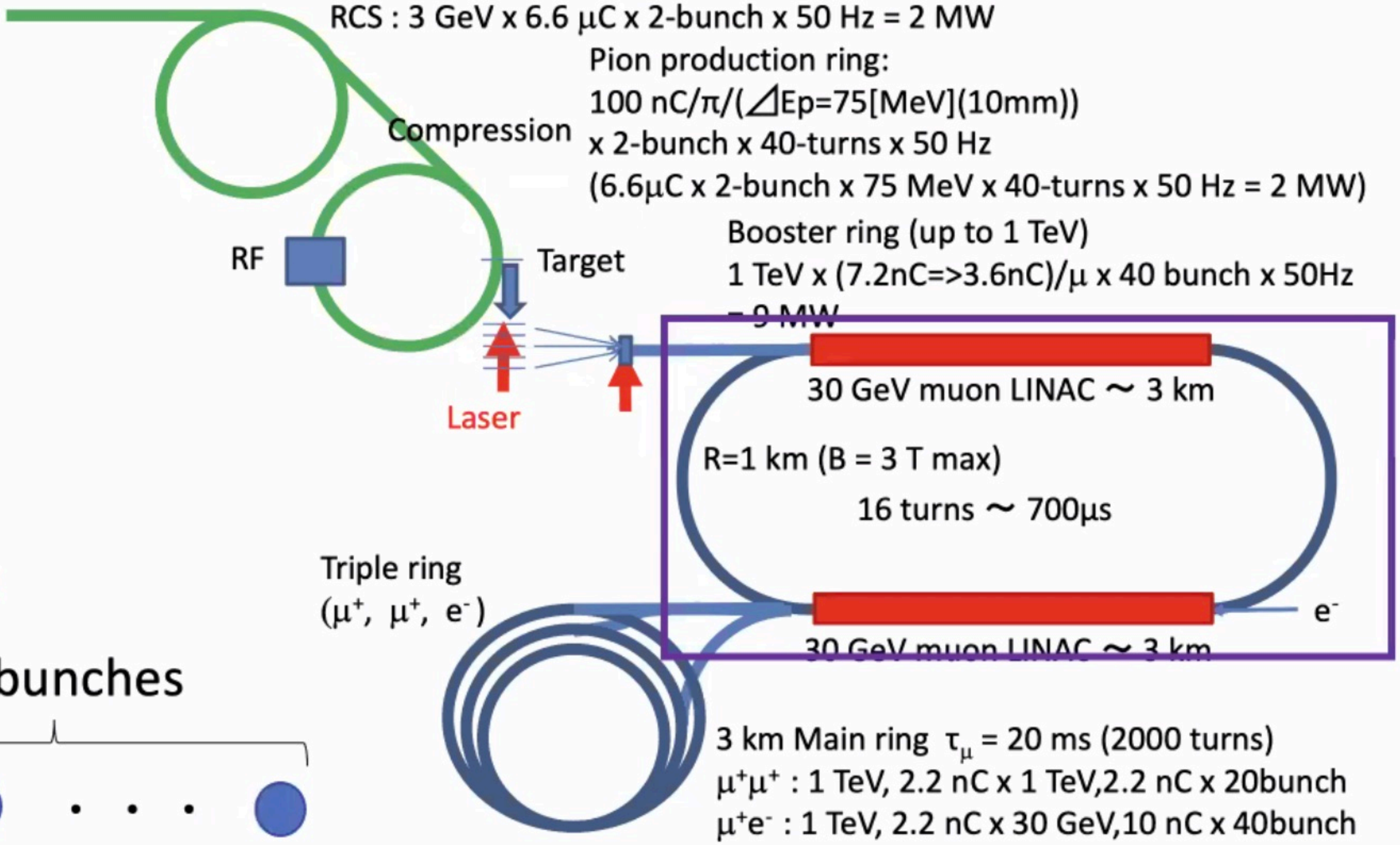
Booster ring

40 bunches

muon : transported to the booster ring

7.2 nC



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Laser

Booster ring (up to 1 TeV)
1 TeV x (7.2nC=>3.6nC)/μ x 40 bunch x 50Hz
= 9 MW

30 GeV muon LINAC ∼ 3 km

R=1 km (B = 3 T max)

16 turns ∼ 700μs

Triple ring
(μ^+, μ^+, e^-)

e^-

30 GeV muon LINAC ∼ 3 km

3 km Main ring τ_μ = 20 ms (2000 turns)
$\mu^+\mu^+$: 1 TeV, 2.2 nC x 1 TeV,2.2 nC x 20bunch
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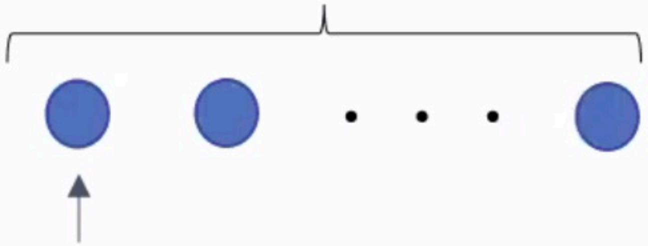
After acceleration

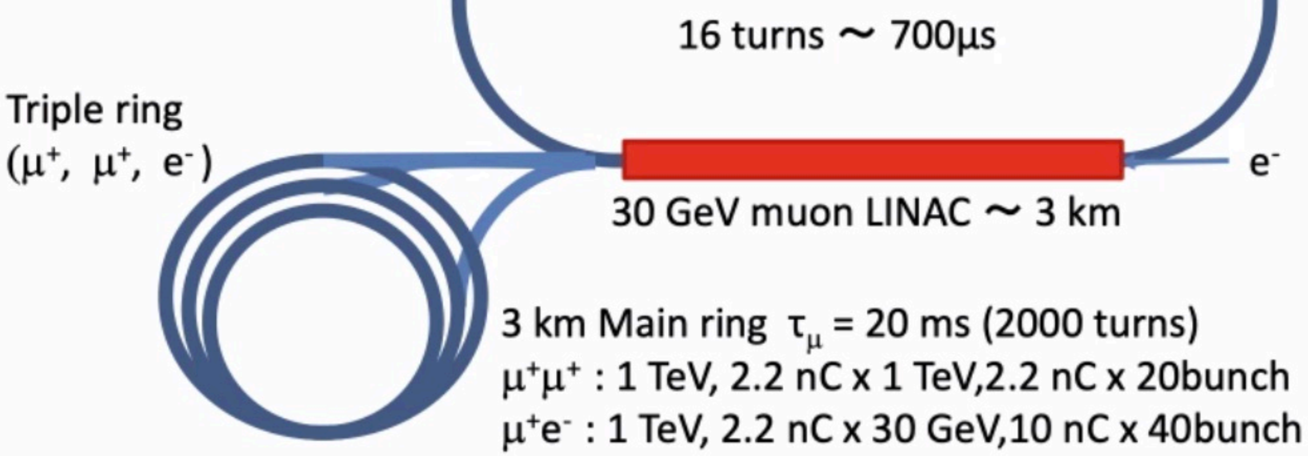
40 bunches



muon
(1 TeV)

3.6 nC decay during the acceleration

Main ring



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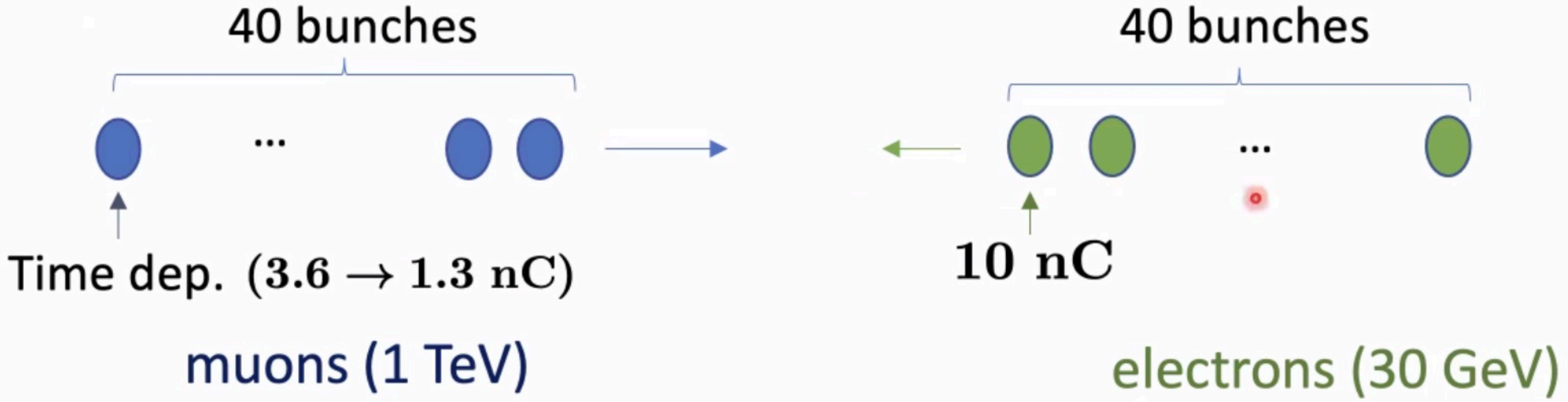
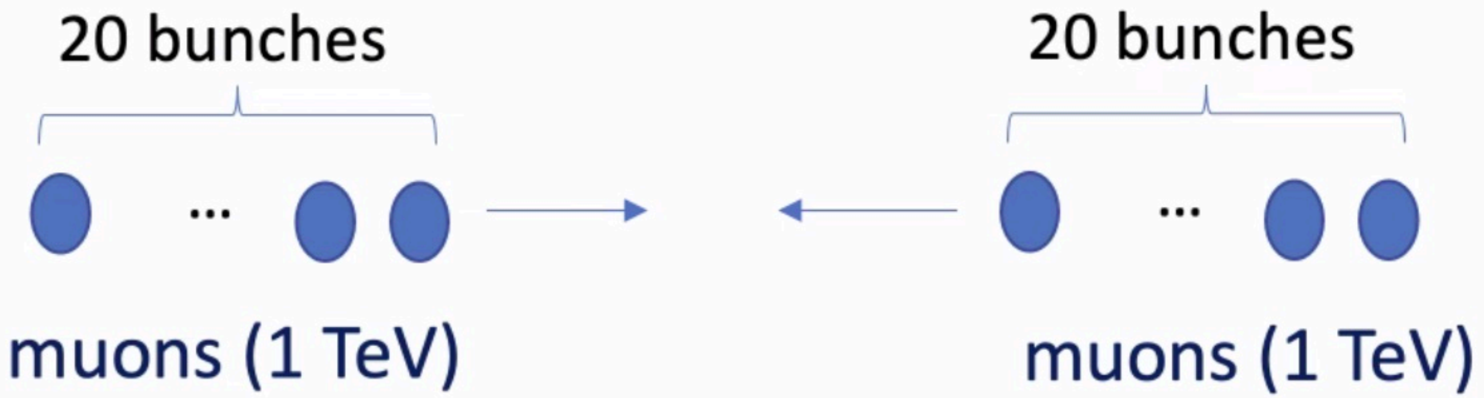
- μ^+e^- collider



- $\mu^+\mu^+$ collider



Luminosity

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

Collision frequency (per detector):

$$f_{\mathrm{rep}}^{(\mu^+e^-)} = 3.0\times 10^8\ \mathrm{m\,s^{-1}}/(3\ \mathrm{km})\times 40 = 4\ \mathrm{MHz}$$

Speed of beam (=c) circumference # of bunches

$$f_{\mathrm{rep}}^{(\mu^+\mu^+)} = 3.0\times 10^8\ \mathrm{m\,s^{-1}}/(3\ \mathrm{km})\times 20 = 2\ \mathrm{MHz}$$

Beam size:

Thanks to ultra-cold muon

$$\sigma_x = 3.6\ \mu\mathrm{m} \qquad \sigma_y = 1.7\ \mu\mathrm{m}$$

$$\text{where}\quad \sigma_i = \sqrt{\epsilon_i\beta_i}\,,\quad \epsilon_i = \frac{4\ \mathrm{mm\,mrad}}{\beta\gamma},\ \begin{cases}\beta_x = 30\ \mathrm{mm}\\ \beta_y = 7\ \mathrm{mm}\end{cases}$$

beta function

Time average of product of beam particle numbers: $\overline{N_{\mathrm{beam1}} N_{\mathrm{beam2}}}$

Our estimate:

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

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

Integrated luminosity

Assuming 10-year running w/ duty factor of 70 %

$$\int \mathcal{L}_{\mu^+ e^-} dt = 1.0\ \mathrm{ab}^{-1}$$

$$\int \mathcal{L}_{\mu^+ \mu^+} dt = 130\ \mathrm{fb}^{-1}$$

Polarization

Polarization: important to enhance various cross sections

We assume $\boldsymbol{P_{\mu^+} = \pm 0.8,\ P_{e^-} = \pm 0.7}$

- Muon polarization

  μ^+ produced from π^+ is 100 % polarized $|+\rangle_{\mu^+}$

  Initial muonium states: $|+\rangle_{\mu^+}|+\rangle_{e^-}$ and $|+\rangle_{\mu^+}|-\rangle_{e^-}$

- Electron polarization

  The targeted polarization at SuperKEKB $\boldsymbol{P_{e^-} = \pm 0.7}$

Polarization

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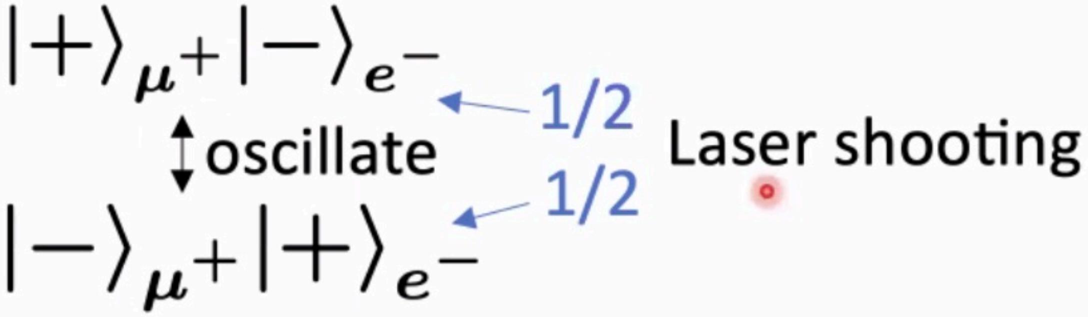

$$|+\rangle_{\mu^+}|-\rangle_{e^-} \updownarrow \text{oscillate}\ |-\rangle_{\mu^+}|+\rangle_{e^-}$$

  Polarization is kept by 50 %.

  Muonium formation at two times reduces the polarization to 25 %.

- Electron polarization

  The targeted polarization at SuperKEKB $\boldsymbol{P_{e^-} = \pm 0.7}$

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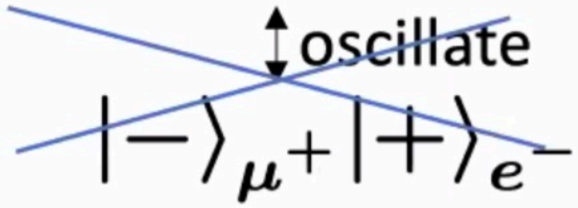


~~$\updownarrow$ oscillate~~

~~$|-\rangle_{\mu^+}|+\rangle_{e^-}$~~

  Under the magnetic field of 0.3 T,
  we can fairly maintain polarization.

  cf. CDR for g-2 experiments at J-PARC

- Electron polarization

  The targeted polarization at SuperKEKB $P_{e^-} = \pm 0.7$

Magnet

Dipole magnet with the magnetic field of 10 T

⟶ Main ring 3 km for $(E_{\mu^+}, E_{e^-}) = (\mathbf{1\ TeV}, \mathbf{30\ GeV})$

9 km for $(E_{\mu^+}, E_{e^-}) = (\mathbf{3\ TeV}, \mathbf{50\ GeV})$

cf. High-luminosity LHC: 11 T

If dipole magnet with the magnetic field of 16 T becomes available

⟶ Main ring 6 km for $(E_{\mu^+}, E_{e^-}) = (\mathbf{3\ TeV}, \mathbf{50\ GeV})$

MadGraph5
J. Alwall et al.

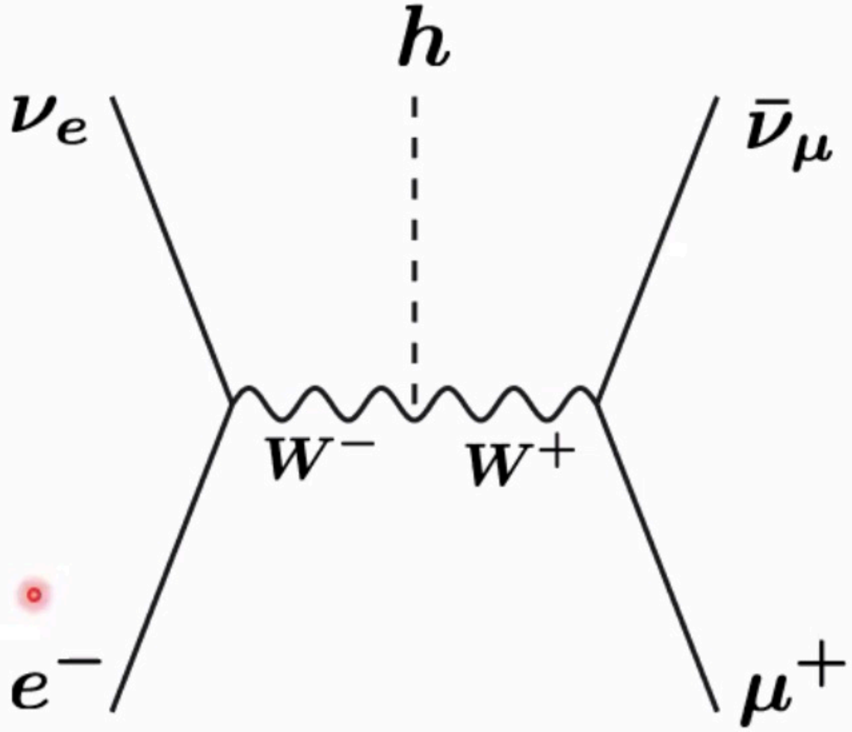
Higgs production

Main Higgs production: W boson fusion (WBF)

$\sqrt{s} = 346\ \mathrm{GeV} \quad (E_{\mu^+} = 1\ \mathrm{TeV},\ E_{e^-} = 30\ \mathrm{GeV})$

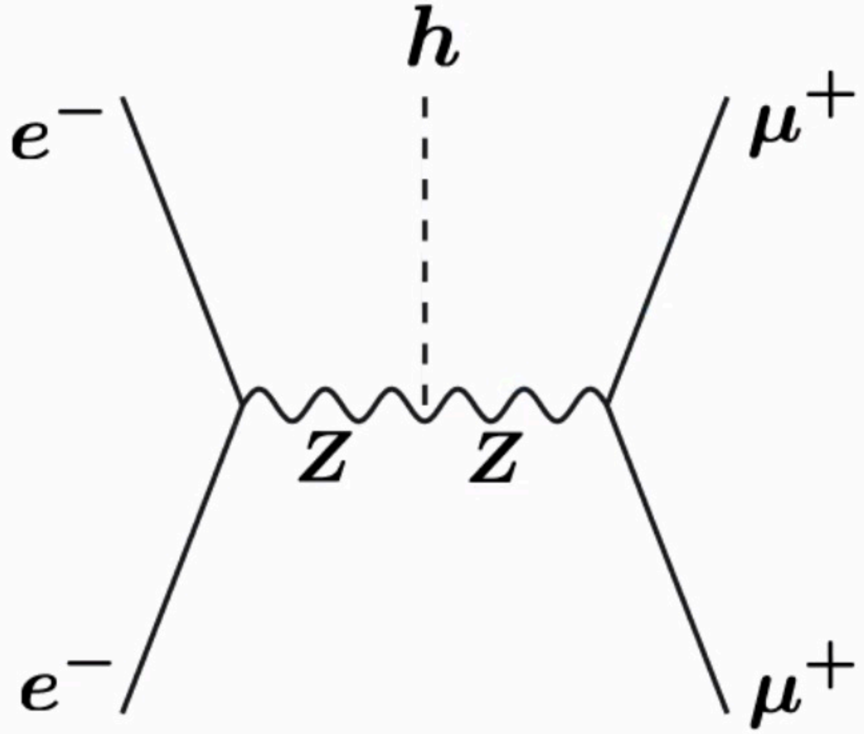
$(P_{\mu^+}, P_{e-}) = (0.8, -0.7)$

$\sigma_{\mathrm{WBF}} \approx 91\,\mathrm{fb}$



Z boson fusion (ZBF)

$\sigma_{\mathrm{ZBF}} \approx 4\,\mathrm{fb}$



Coupling measurement

Focus on the WBF channel

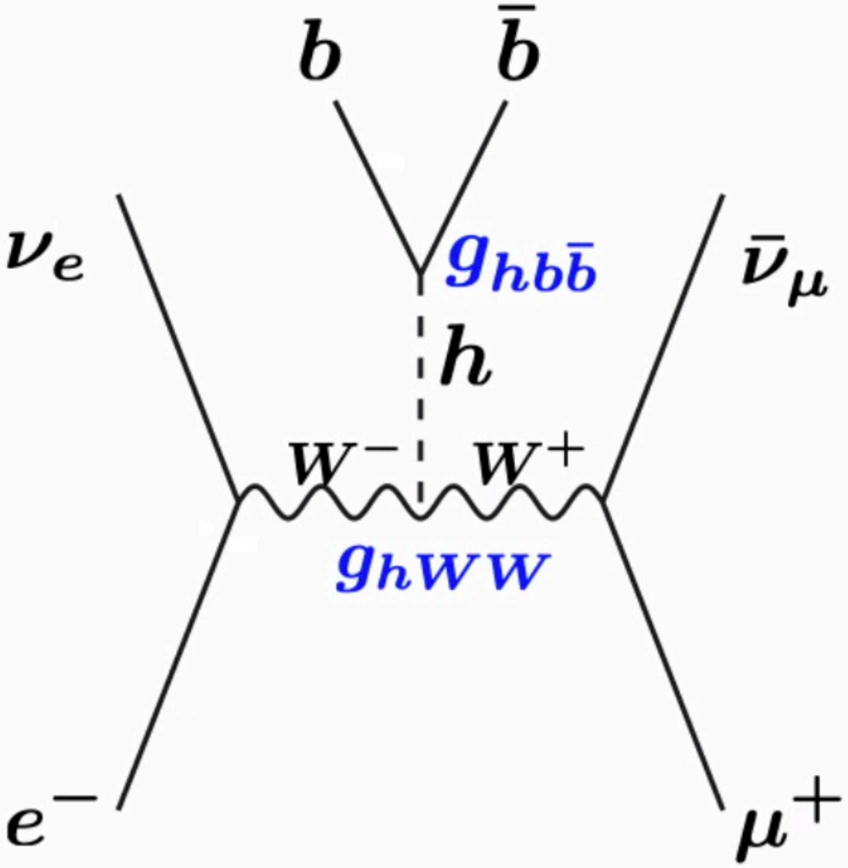
Higgs mainly decays into b$\bar{b}$

(Branching ratio 58.2 % in SM)

$$\sigma_{\mathrm{SM}} = \sigma^{\mathrm{SM}}_{\mathrm{WBF}} \frac{\Gamma^{\mathrm{SM}}_{H\to b\bar{b}}}{\Gamma^{\mathrm{SM}}_{H}}$$

$$\xrightarrow{\text{can be modified}} \quad \sigma = \frac{\kappa_W^2 \kappa_b^2}{\kappa_H^2} \sigma_{\mathrm{SM}}$$

$$\kappa_W = 1 + \Delta\kappa_W \text{ etc.}$$



$$g_{hWW} = \kappa_W g^{\mathrm{SM}}_{hWW}$$

$$g_{hb\bar{b}} = \kappa_b g^{\mathrm{SM}}_{hb\bar{b}}$$

$$\Gamma_H = \kappa_H^2 \Gamma^{\mathrm{SM}}_H$$

Coupling measurement

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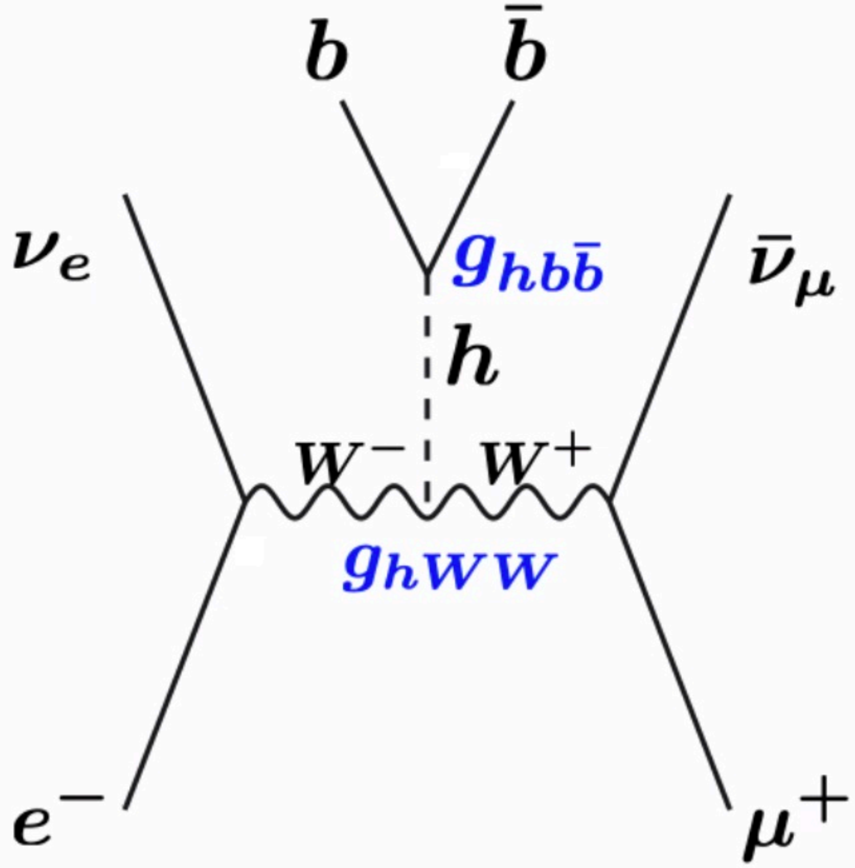

We obtain a constraint

$$|\Delta\kappa_W + \Delta\kappa_b - \Delta\kappa_H|$$

$$\lesssim \frac{1}{2}\frac{\Delta_{\mathrm{stat}}\sigma}{\sigma} \approx \frac{1}{2}\frac{1}{\sqrt{N(\mathrm{WBF}) \times \mathrm{Br} \times \mathrm{efficiency}}}$$

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

Sub per-cent measurement *Statistical error only

Higher energy case

$$\sqrt{s} = 775 \text{ GeV} \quad (E_{\mu^+} = 3 \text{ TeV},\ E_{e^-} = 50 \text{ GeV})$$

$$(P_{\mu^+}, P_{e-}) = (0.8, -0.7)$$

- WBF process $\sigma_{\mathrm{WBF}} \approx 472\,\mathrm{fb}$

S. Di Vita et al.
1711.03978

κ_λ : Higgs trilinear self-coupling

$$|\Delta\kappa_W + \Delta\kappa_b - \Delta\kappa_H + 0.006\Delta\kappa_\lambda|$$

$$\lesssim 1.3 \times 10^{-3} \times \left(\frac{\text{integrated luminosity}}{1.0\ \text{ab}^{-1}}\right)^{-1/2} \left(\frac{\text{efficiency}}{0.5}\right)^{-1/2}$$

$\longrightarrow$ $|\Delta\kappa_\lambda| \lesssim 20\ \%$ when other Δκ's are assumed to be zero.

- Higgs pair creation

$$N(\text{two Higgs}) = 89 \times \left(\frac{\text{integrated luminosity}}{1.0\ \text{ab}^{-1}}\right)^{-1/2}$$

$\longrightarrow$ $|\Delta\kappa_\lambda| \lesssim 10 - 100\ \%$

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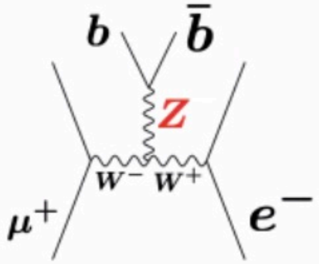
Efficiency

The efficiency to detect the events is important.

Main issues

- Background events

Electron number=+1, Muon number=-1 ⟶ Small number of background events



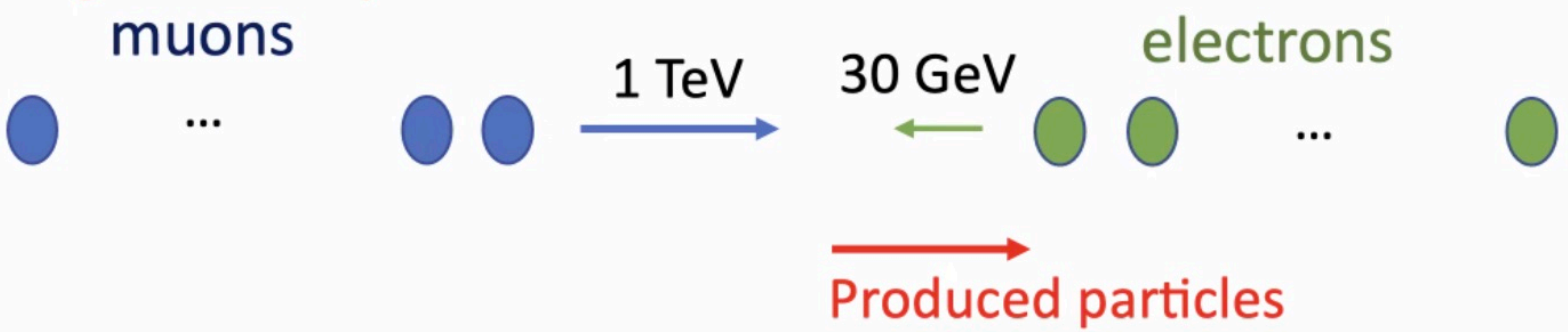
The invariant mass analysis of b-jets would significantly suppress the BG events.

cf. 1403.7734 C. Durig, K. Fujii, J. List, J. Tian

parallel BG events are cut by 90 - 95 % for ILC 250 and 500 GeV

- Coverage of detector in a small angle region

Energies are asymmetric


muons

…

1 TeV

30 GeV

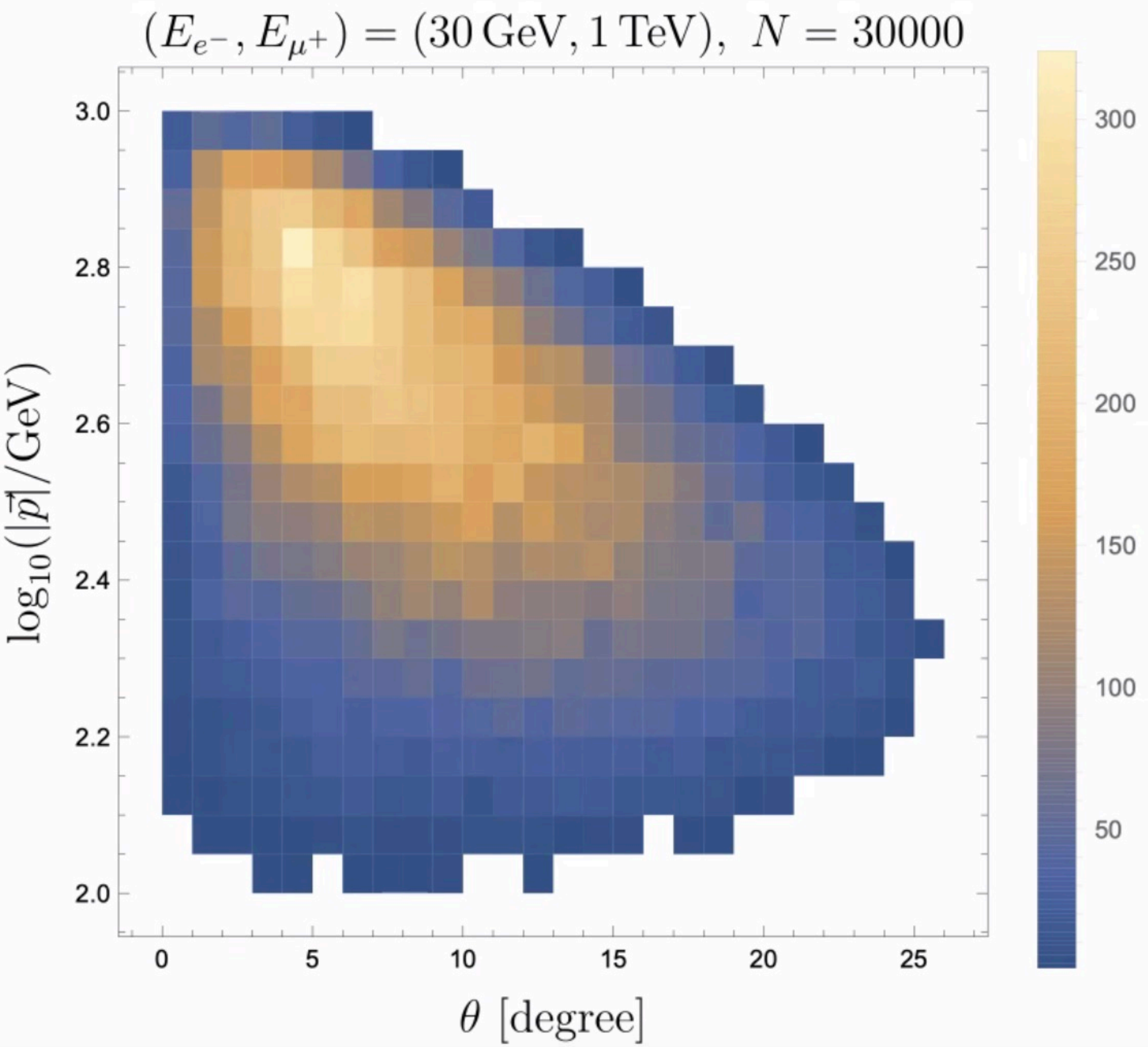
electrons

…

Produced particles

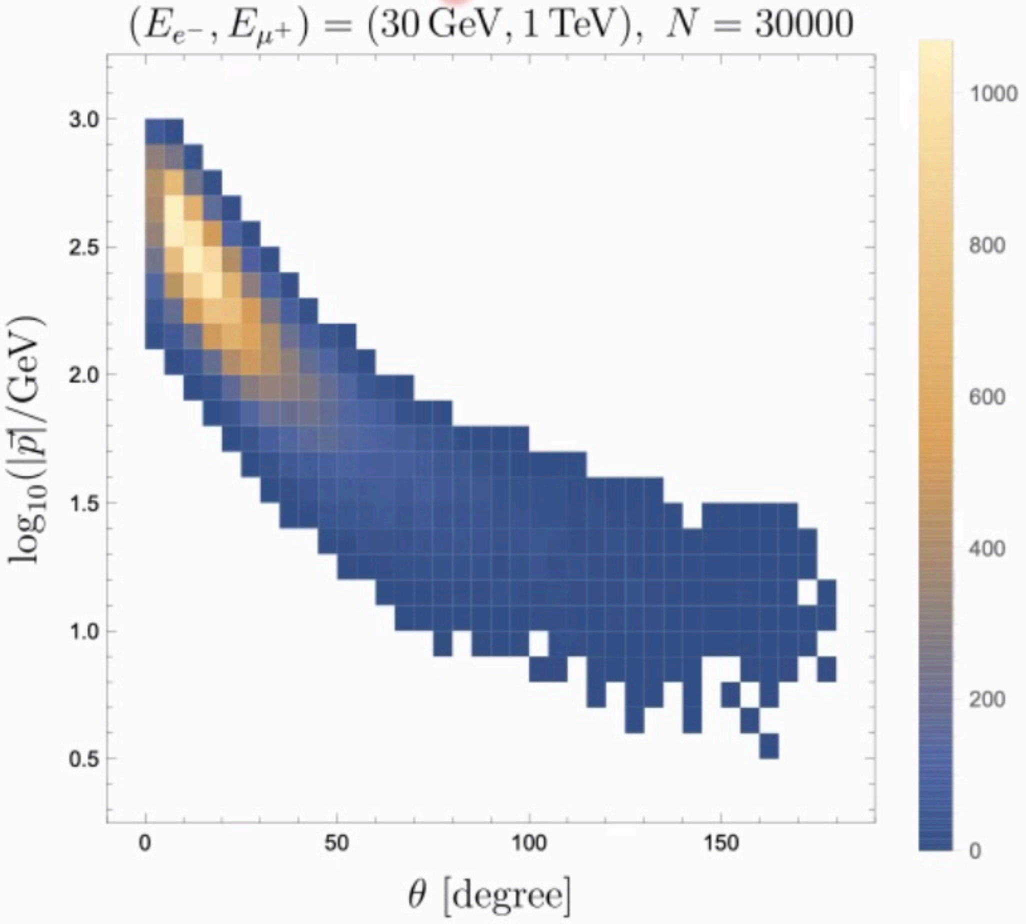
Kinematics of produced Higgs boson

Angle & spatial momentum of produced Higgs boson

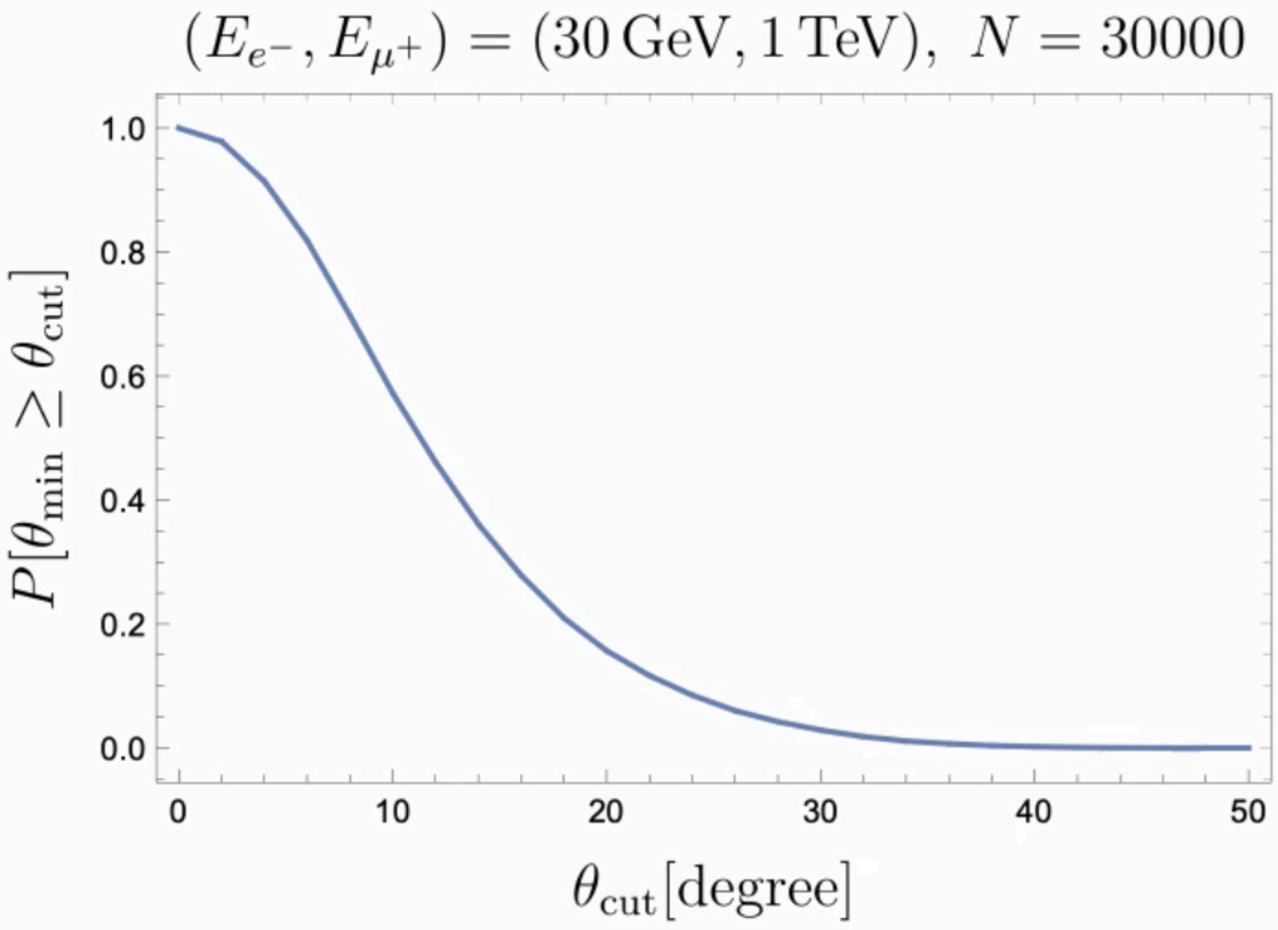


Kinematics of bottom quark

Angle & spatial momentum of bottom quark from Higgs decay



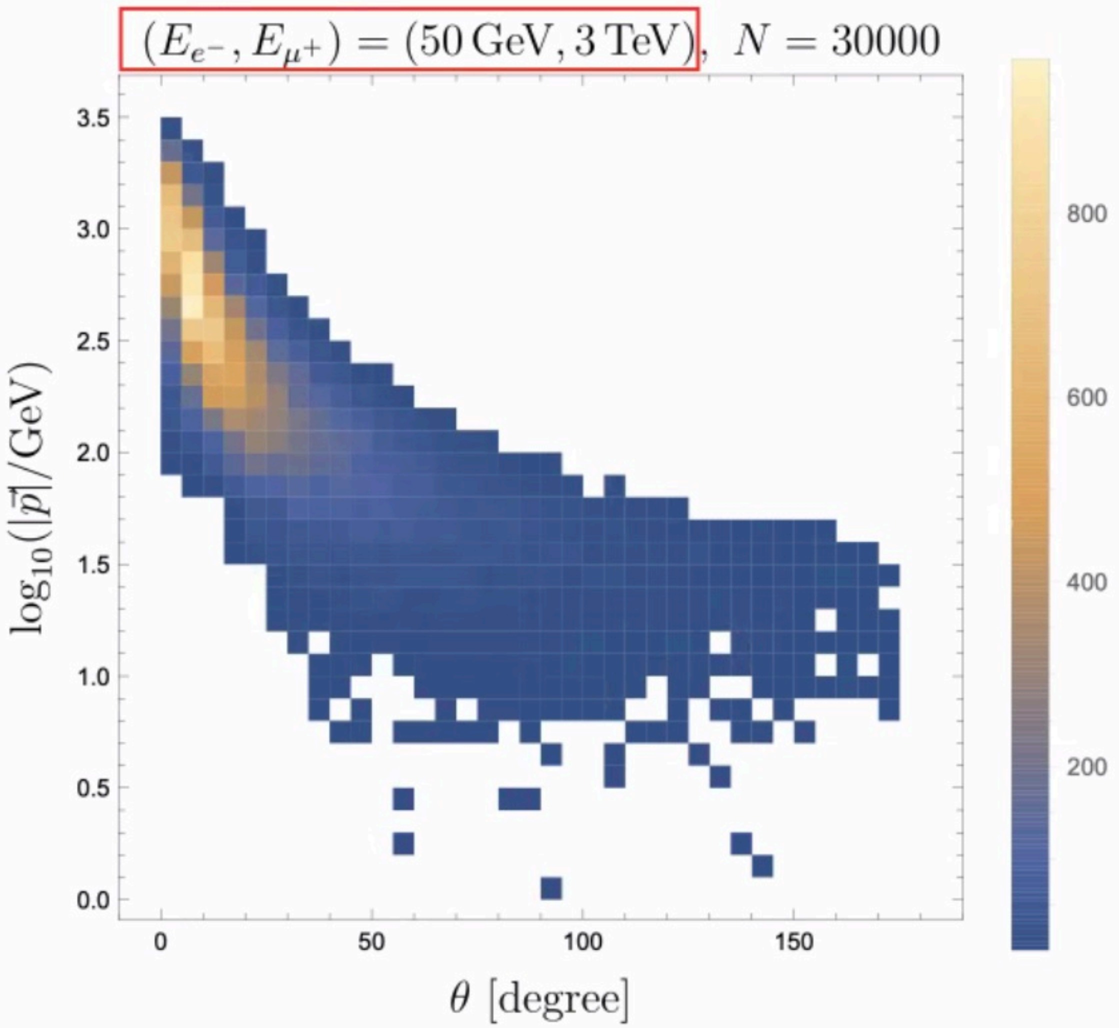
Fraction of events w/ $\boldsymbol{\theta_{\mathrm{min}} = \min(\theta_b, \bar{\theta}_b) \geq \theta_{\mathrm{cut}}}$



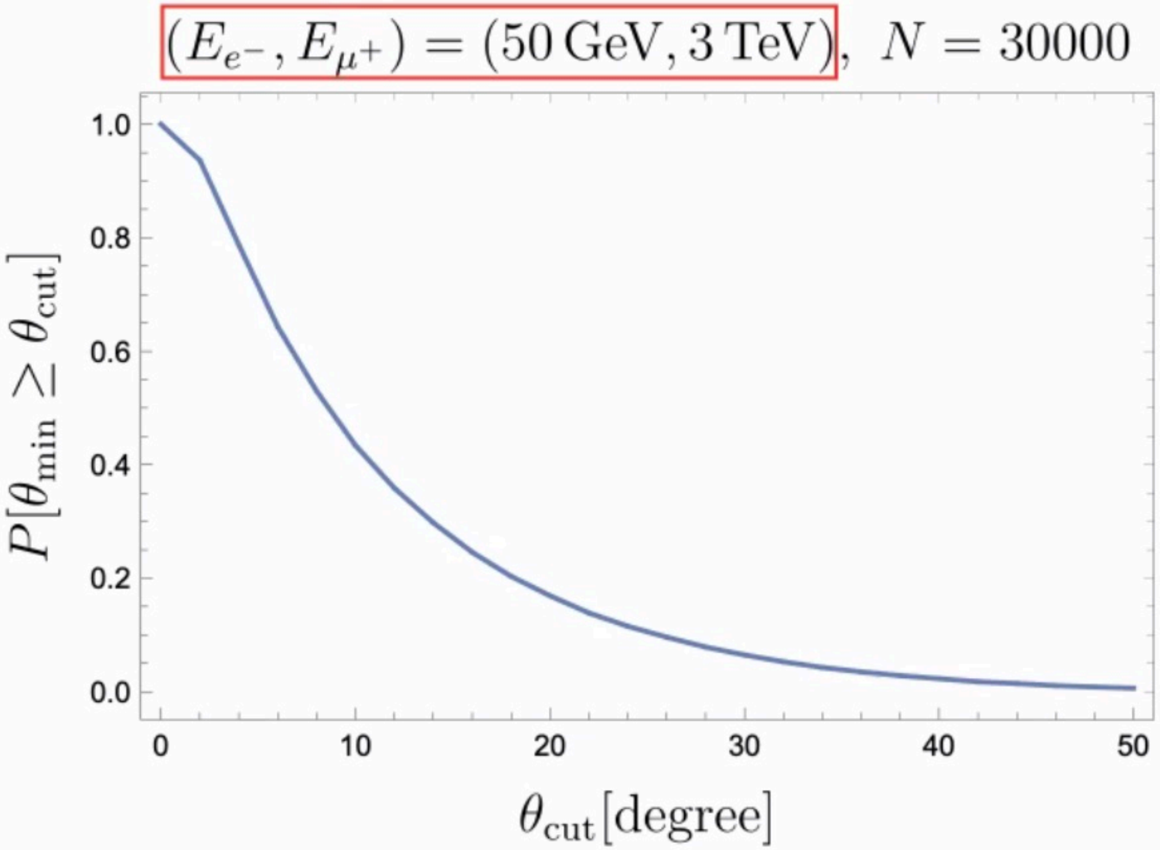
Efficiency depends on how small angle region can be covered.

Kinematics in higher energy case

Angle & spatial momentum of bottom quark from Higgs decay



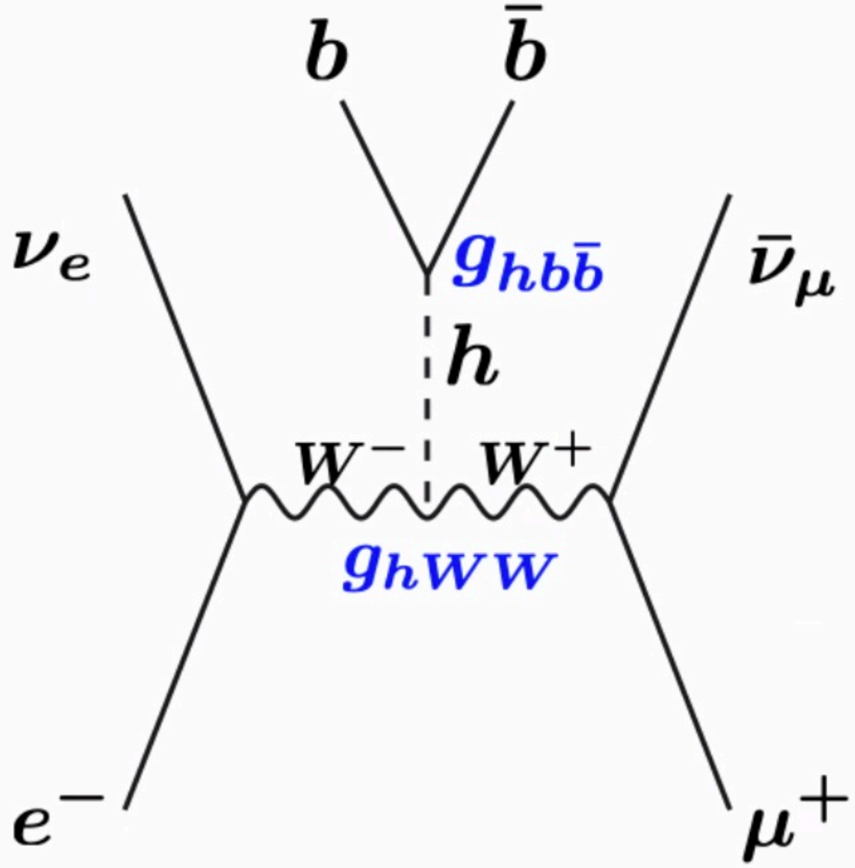
Fraction of events w/ $\boldsymbol{\theta_{\mathrm{min}} = \mathrm{min}(\theta_b, \bar{\theta}_b) \geq \theta_{\mathrm{cut}}}$



Coupling measurement

$$\sigma = \frac{\kappa_W^2 \kappa_b^2}{\kappa_H^2}\sigma_{\mathrm{SM}}$$

$\kappa_W = 1 + \Delta\kappa_W$ etc.



We obtain a constraint

$$|\Delta\kappa_W + \Delta\kappa_b - \Delta\kappa_H|$$

$$\lesssim \frac{1}{2}\frac{\Delta_{\mathrm{stat}}\sigma}{\sigma} \approx \frac{1}{2}\frac{1}{\sqrt{N(\mathrm{WBF}) \times \mathrm{Br} \times \mathrm{efficiency}}}$$

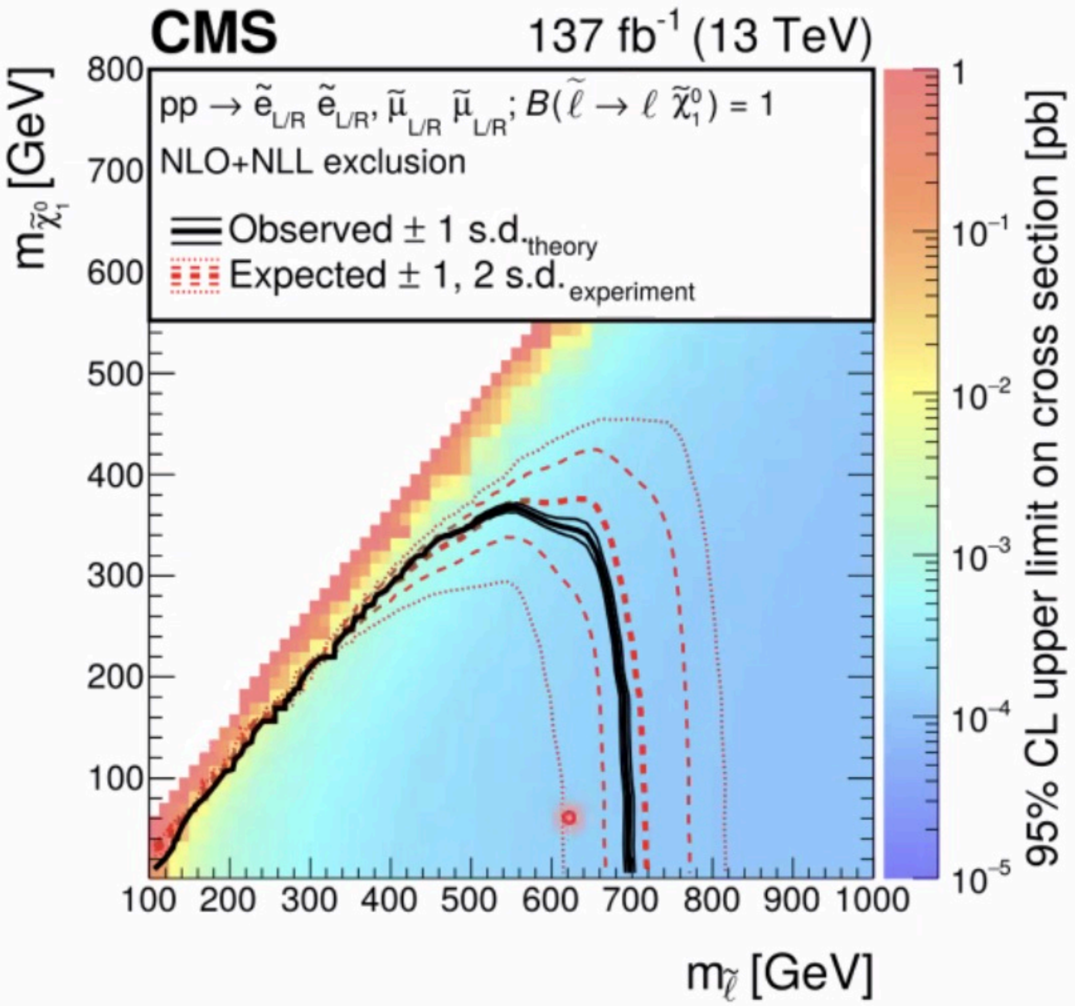
$$= 3.1 \times 10^{-3} \times \left(\frac{\text{integrated luminosity}}{1.0\ \mathrm{ab}^{-1}}\right)^{-1/2}\left(\frac{\text{efficiency}}{0.5}\right)^{-1/2}$$

Sub per-cent measurement *Statistical error only

Supersymmetry

SUSY: Candidate of new physics that may solve some problems in SM

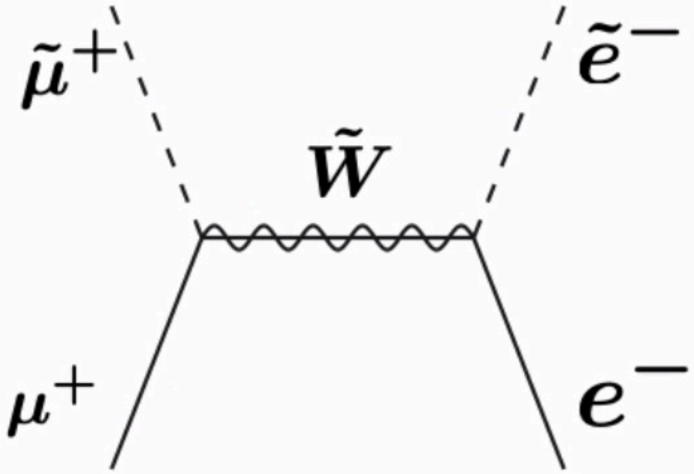
2012.08600 Current scalar lepton search at LHC



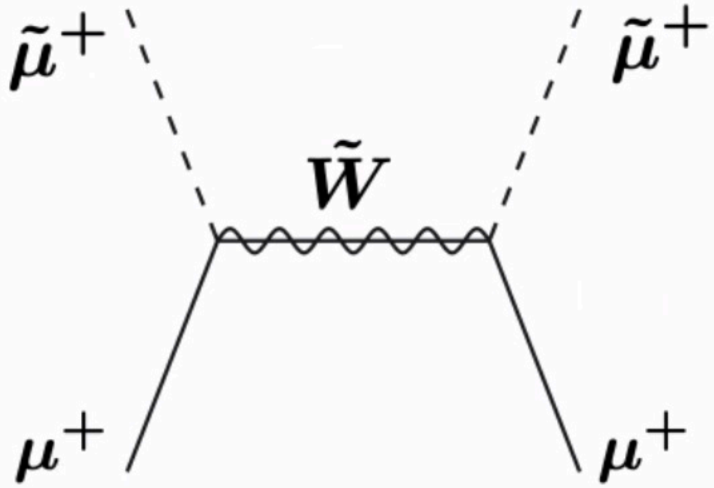
$m_{\tilde{\ell}} \lesssim 700\ \mathrm{GeV}$ is excluded.

Scalar lepton production at μTRISATN

- μ^+e^- collider



- $\mu^+\mu^+$ collider

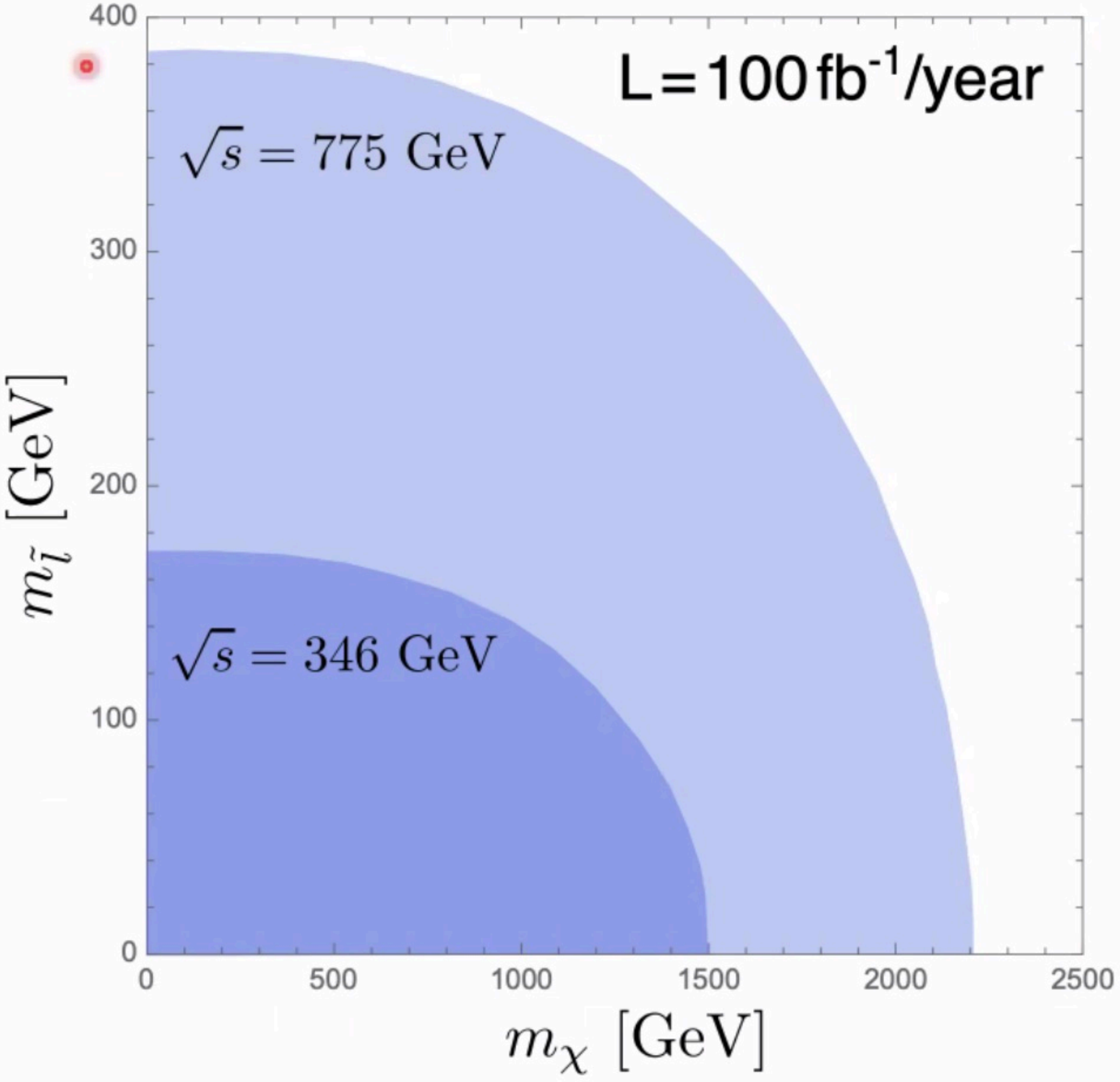


We only consider the diagram where the Wino $\tilde{W}$ is exchanged for simplicity.

superpartner of $SU(2)_L$ gauge boson

Constraint at $\mu^+ e^-$ collider

Mass parameter region where # of the events exceeds 100.

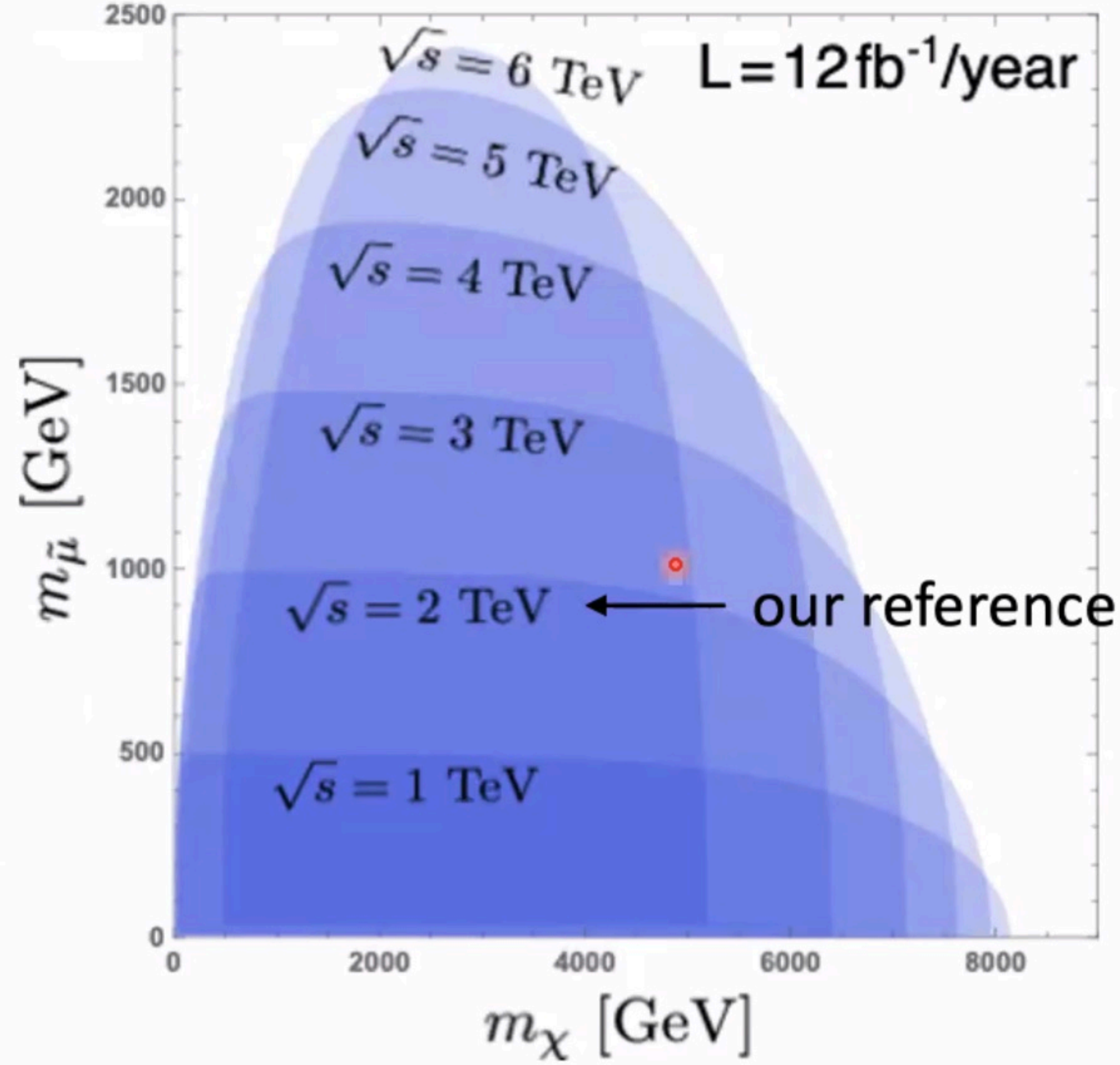


$m_{\tilde{e}} = m_{\tilde{\mu}}$ assumed

Although reach is not so high, we may cover different regions from the LHC.

Constraint at $\mu^+\mu^+$ collider

Mass parameter region where # of the events exceeds 100.



our reference energy

$m_{\tilde{\mu}} \lesssim 1$ TeV can be detected.

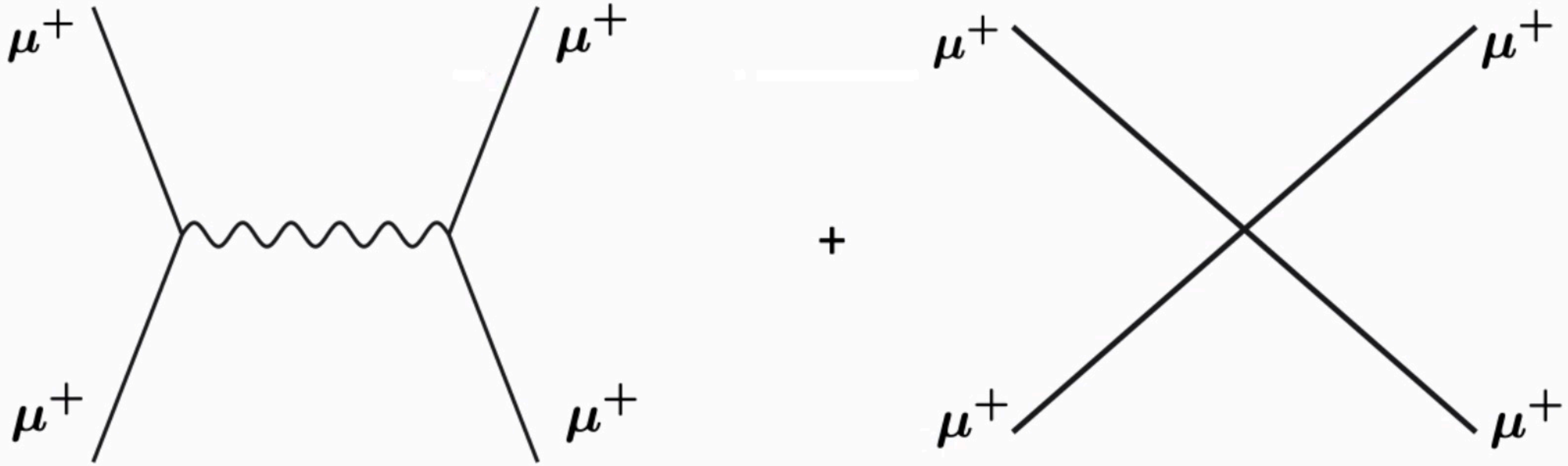
Interesting region in terms of muon g-2 anomaly

Constraint on dimension-6 operators

On-going

SMEFT: a general framework to study modification due to UV physics

Møller scattering



$$\mathcal{L}_{\mathbf{dim6}} = \frac{\mathbf{1}}{\mathbf{\Lambda^2}}(\bar{\mu}_L\gamma_\mu\mu_L)(\bar{\mu}_L\gamma^\mu\mu_L) + \dots$$

We may detect up to $\Lambda \lesssim \mathcal{O}(100)\ \mathrm{TeV}$.

Conclusions

- We proposed new collider experiments, μ^+e^- collider and $\mu^+\mu^+$ collider, utilizing established technology for providing high-quality μ^+ beam.

- We estimated the luminosity of these colliders.

First study of realistic luminosity of the colliders using muon beam

$$\mathcal{L}_{\mu^+e^-} = 4.6 \times 10^{33}\ \mathrm{cm}^{-2}\mathrm{s}^{-1} \longrightarrow \int \mathcal{L}_{\mu^+e^-}dt = 1.0\ \mathrm{ab}^{-1}$$

$$\mathcal{L}_{\mu^+\mu^+} = 5.7 \times 10^{32}\ \mathrm{cm}^{-2}\mathrm{s}^{-1} \longrightarrow \int \mathcal{L}_{\mu^+e^-}dt = 130\ \mathrm{fb}^{-1}$$

Realistic values that can be achieved with *the existing technology*

Conclusions

μ^+e^- collider Good Higgs boson factory

$\sqrt{s} = 346\ \mathrm{GeV}$ case

$$|\Delta\kappa_W + \Delta\kappa_b - \Delta\kappa_H| \lesssim 3.1 \times 10^{-3} \times \left(\frac{\text{integrated luminosity}}{1.0\ \mathrm{ab}^{-1}}\right)^{-1/2} \left(\frac{\text{efficiency}}{0.5}\right)^{-1/2}$$

$\sqrt{s} = 775\ \mathrm{GeV}$ case

$$|\Delta\kappa_W + \Delta\kappa_b - \Delta\kappa_H + 0.006\Delta\kappa_\lambda|$$

$$\lesssim 1.3 \times 10^{-3} \times \left(\frac{\text{integrated luminosity}}{1.0\ \mathrm{ab}^{-1}}\right)^{-1/2} \left(\frac{\text{efficiency}}{0.5}\right)^{-1/2}$$

↓

$$|\Delta\kappa_\lambda| \lesssim 20\ \%$$

$|\Delta\kappa_\lambda| \lesssim 10 - 100\ \%$ from di-Higgs production

Conclusions

$\mu^+\mu^+$ collider New physics search

$$\sqrt{s} = 2\ \mathrm{TeV}$$

Search for scalar muon and Wino up to O(TeV)

Constraint on a new physics scale up to O(100) TeV

Issues to be studied

- More detailed study of luminosity (e.g. efficiency of each step)
- Possible polarization and its relation to beam emittance
- Detector design and detector simulation

⟷ Higgs precision measurement

- Place to construct

Booster ring ~1-10 mSv/year?
Main ring < μSv/year

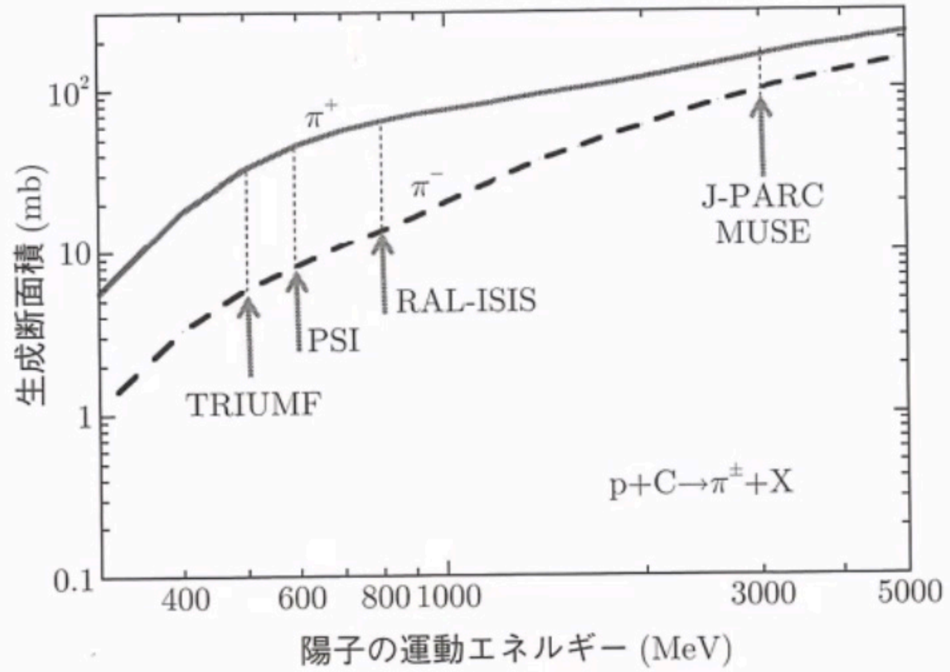
- Other Higgs coupling measurements by using other processes

Another production via ZBF $e^- \mu^+ \to e^- \mu^+ h$

Decay modes $h \to \tau\bar{\tau}, c\bar{c}, ZZ^*, WW^*, \ldots$

There would be a lot of interesting studies.

Current difficulties in $\mu^+ \mu^-$ colliders



Problems in μ^- beam

- Production of large amount of μ^-

High energy protons are necessary to produce π^-

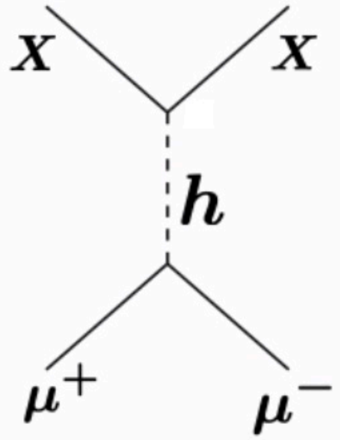
- Cooling of μ^-

To make beam size small, cooling is necessary.

There isn't good established technology for cooling of μ^-.

A considered possibility: muon collider $\sqrt{s} = 125\ \mathrm{GeV}$ as a Higgs factory

Large cross section of O(10) pb $\quad y_\mu \frac{1}{s - m_H^2 + i m_H \Gamma_H}\Big|_{s=m_H^2}$



Actually difficult to fully utilize this large cross section due to momentum spread of beam $\Delta\sqrt{s}_{\mathrm{beam}}/m_H (\sim 10^{-3}) \gg \Gamma_H/m_H \simeq 3 \times 10^{-5}$

Proposal of new collider experiments

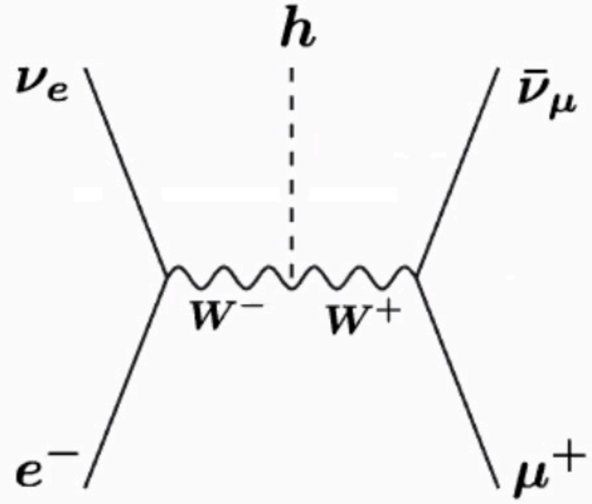
We propose collider experiments using high-quality μ^+ beam and accelerating it to TeV scale!

Using the 3 km ring, we can realize

- μ^+e^- collider Higgs factory

$$E_{\mu^+} = 1\ \mathrm{TeV},\ E_{e^-} = 30\ \mathrm{GeV}$$ (TRISTAN energy)

$$\longrightarrow \sqrt{s} = 346\ \mathrm{GeV}$$



- $\mu^+\mu^+$ collider New physics search

$$E_{\mu^+} = 1\ \mathrm{TeV},\ E_{\mu^+} = 1\ \mathrm{TeV}$$

$$\longrightarrow \sqrt{s} = 2\ \mathrm{TeV}$$

μTRISTAN!

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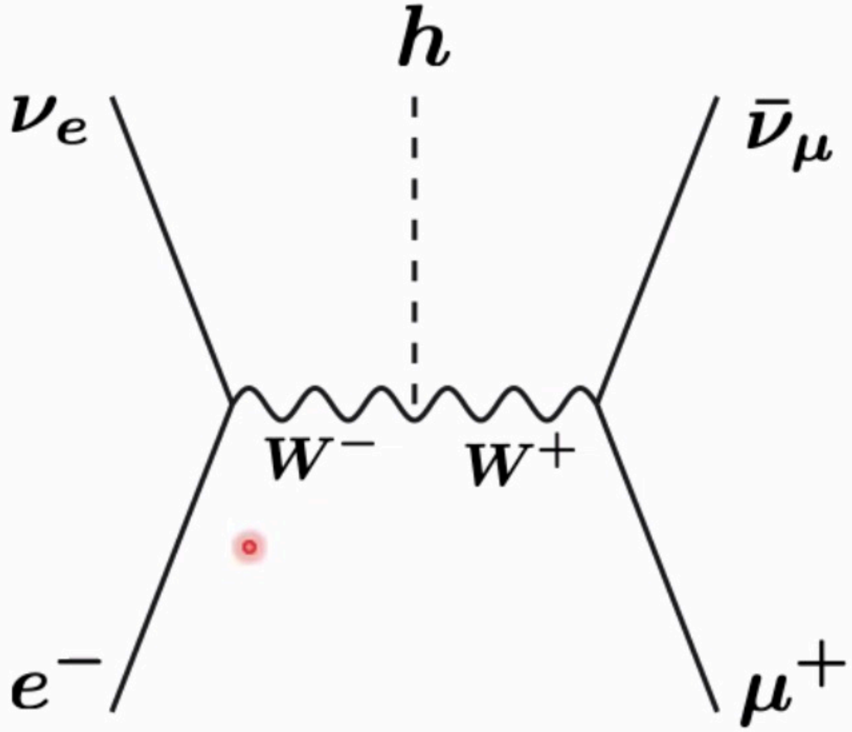

Z boson fusion (ZBF)

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