Experiment on study of dimuonium properties in Novosibirsk

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Origin the project

➤ In BINP (Novosibirsk) the project of the Super charm-tau factory (CTF) is currently developed.

➤ CTF is a high luminosity ($L \approx 10^{35}$ cm^{-2}s^{-1}) machine operating in the energy range $2E_{beam}$=2-5 GeV.

➤ This is a long-term (~10 years) project using many new accelerator technologies.

➤ At the first stage it is planned to build a short-term, low-cost, low-energy machine to test and study these technologies.

➤ In addition to purely accelerator studies, it is important to formulate interesting physical tasks for this machine, i.e. production and study dimuonium.

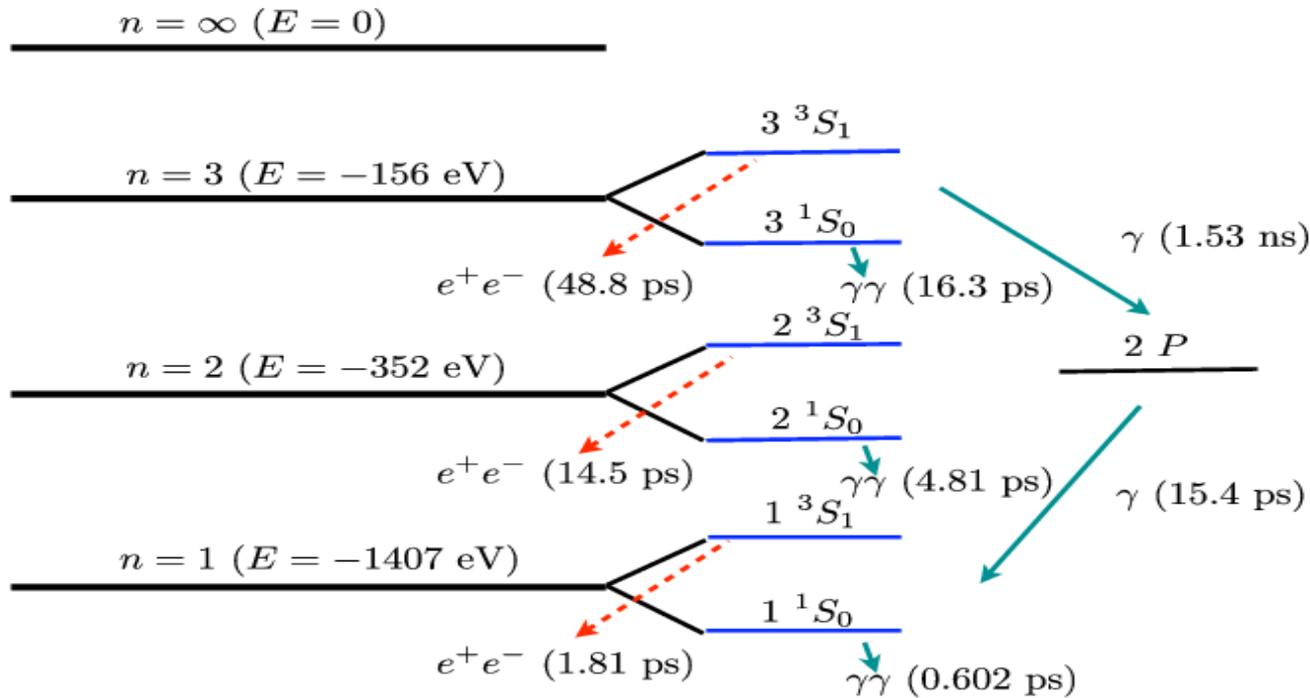➤ The machine is named μμ-tron.

Dimuonium

- Dimuonium is a bound state of $\mu^+\mu^-$ pair
- Two-lepton system described by QED
- There are 6 leptonic atoms: positronium (e^+e^-), muonium (μ^+e^-), dimuonium ($\mu^+\mu^-$) , tauonium (τ^+e^-), tau-muonium($\tau^+\mu^-$) , ditauonium ($\tau^+\tau^-$). Only positronium and muonium are observed.
- Dimuonium is more compact system than the pasitronium and muonium

$R_{\mu\mu} \approx (1/100)R_{\mu e} \approx (1/200)R_{ee}$.

Why is dimuonium interesting?

■ Observation of dimuonium would be a significant discovery.

■ Very complex experimental task → challenge for experimentalist → development of new methods

■ QED tests (dimuonium ≠ positronium × m_e/m_μ)

■ Muon sector anomalies

✓ About 3.5σ difference between the $(g-2)_\mu$ SM prediction and measurement

✓ Proton/deuteron radius puzzle

✓ Hints of lepton-universality violation in rare B decays: $B^+ \rightarrow K^+ e^+ e^-$ and $B^+ \rightarrow K^+ \mu^+ \mu^-$

Dimuonium properties

The $^3S_1$ states have photon quantum numbers ($J^{PC}=1^{--}$) and can be produced in e^+e^- collisions

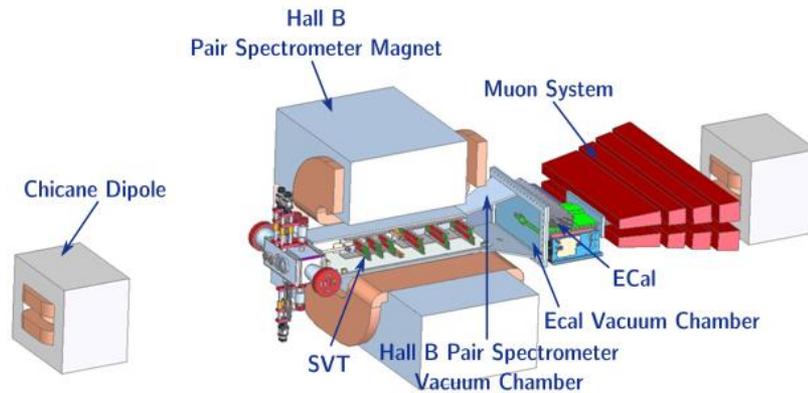$^3S_1$ $J^{PC}=1^{--}$ $^3P_0$ $J^{PC}=0^{++}$ $^1P_1$ $J^{PC}=1^{+-}$
$^1S_0$ $J^{PC}=0^{-+}$ $^3P_1$ $J^{PC}=1^{++}$
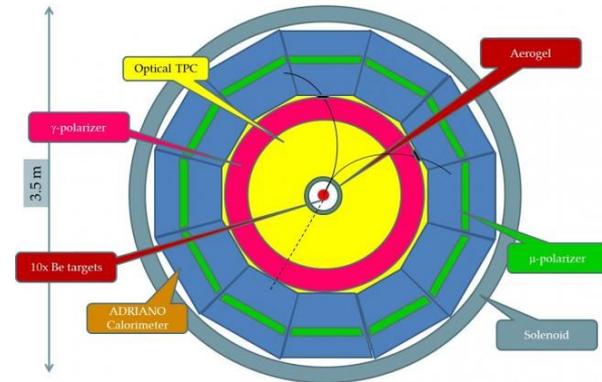 $^3P_2$ $J^{PC}=2^{++}$

V.N.Baier and V.S.Synakh, Bimuonium production in electron-positron collisions, SOVIET PHYSICS JETP **14**, 1122 (1962)

Experiments on dimuonium search

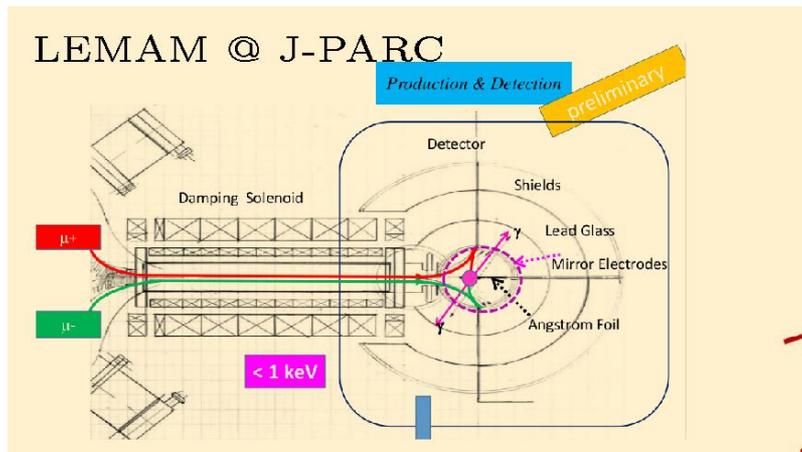HPS @ JLAB $e^- Z \rightarrow e^- (\mu^+\mu^-) Z$

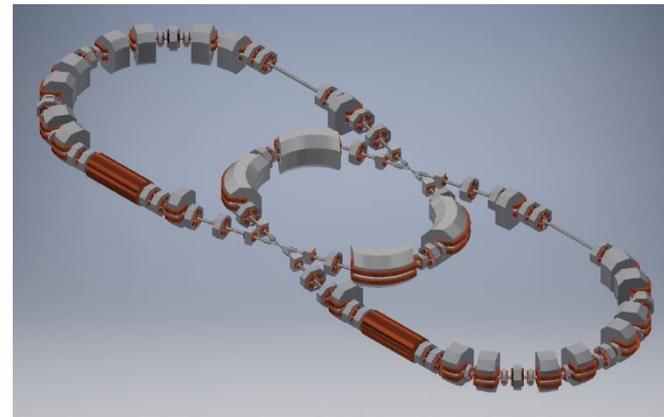

REDTOP @ FERMILAB $\eta \rightarrow \gamma(\mu^+\mu^-)$

Collision of cold μ^+ and μ^-

$\mu\mu$-tron @ BINP $e^- e^+ \rightarrow (\mu^+\mu^-)$

Dimuonium production cross section

The n^3S_1 states can be produced in the reaction $e^+e^- \rightarrow (\mu^+\mu^-) \rightarrow e^+e^-$.

$$\sigma_B(E) \approx \frac{12\pi}{E} \frac{m_{\mu\mu}^2 \Gamma_{ee}^2}{\left(E^2 - m_{\mu\mu}^2\right)^2 + m_{\mu\mu}^2 \Gamma^2}$$

$$\sigma(E) = \int_0^1 \sigma_B\left(E\sqrt{1-x}\right) W(E, x) dx$$
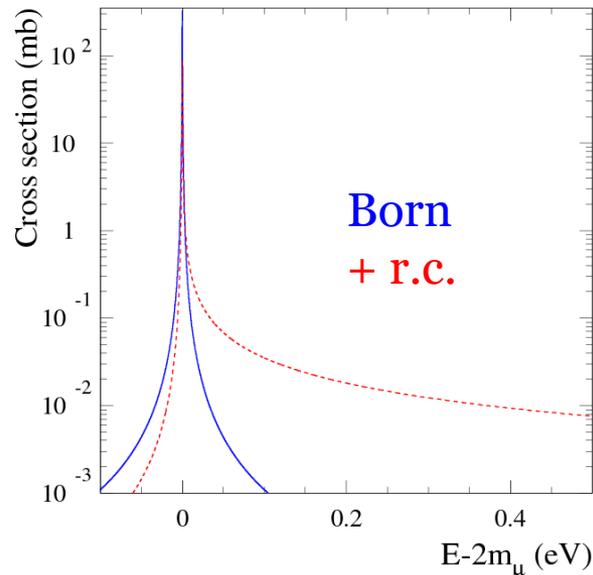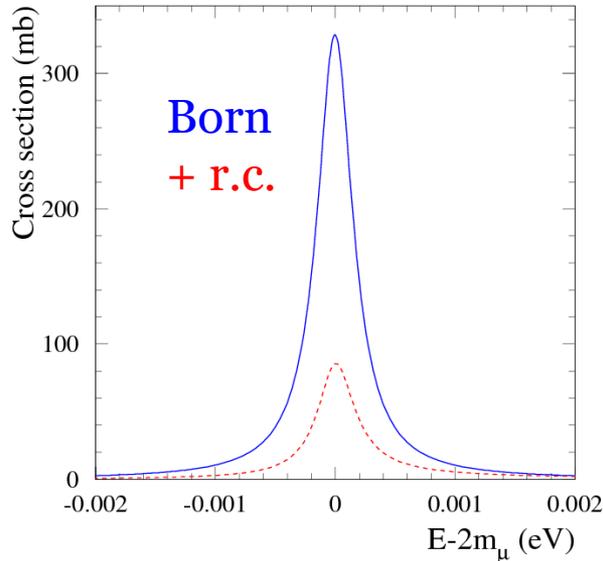
$$\sigma_{vis}(E_0) = \int \sigma(E) \exp\left(-\frac{(E-E_0)^2}{\delta^2}\right) dE \approx A \frac{\Gamma_{ee}}{\delta}$$

δ is the energy spread in the e^+e^- c.m. frame.

For different collision schemes:

$\Gamma_{ee}/\delta = 0.37 \times 10^{-6}$ keV/(7-400) keV $\approx (1-50) \times 10^{-9}$
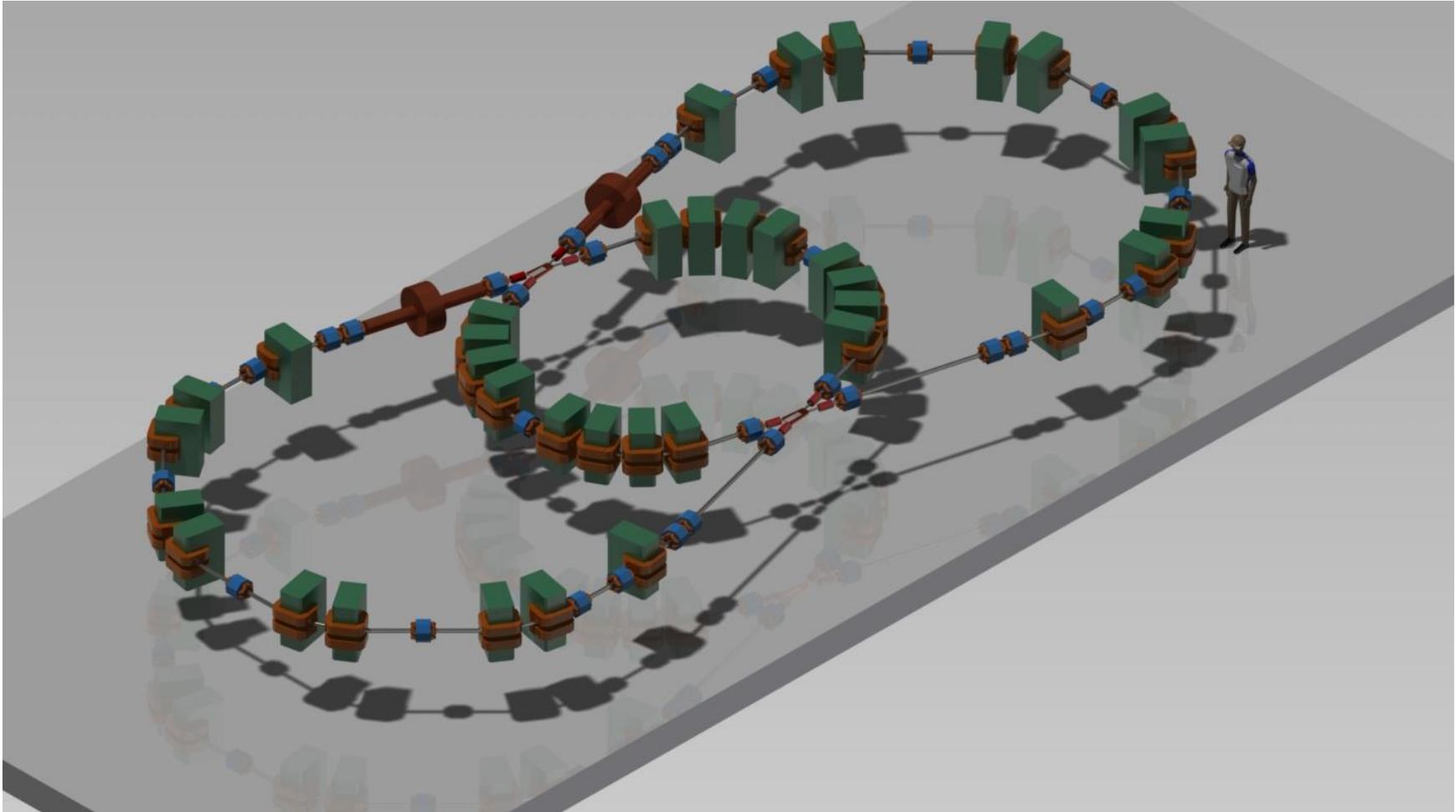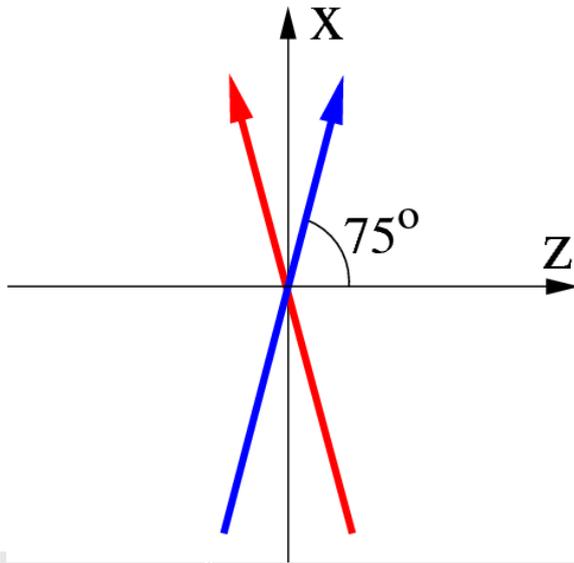
For 1^3S_1 state $\sigma_{vis}(m_{\mu\mu}) = 0.15 - 6.9$ nb

Background

❑ The physical background source is the elastic $e^+e^- \to e^+e^-$ (Bhabha) scattering

❑ For $45° < \theta < 135°$ σ_{bkg}=22000 нб

❑ The background-to-signal ratio is $(3\text{-}150) \times 10^3$

❑ Even at the collider with monohromatization (δ=7 keV) the background-to-signal ratio is too big, about 3000.

❑ Further background suppression is possible if the dimuoniom is produced moving (for 1^3S_1 $c\tau$=540 μm)

❑ In this case a condition on the dimuonium flight length can be used to reject Bhabha events.

A collider with a large crossing angle was proposed by S.J.Brodsky and R.F.Lebed in Phys. Rev. Lett. 102, 213401 (2009)

μμ-tron view

µµ-tron parameters
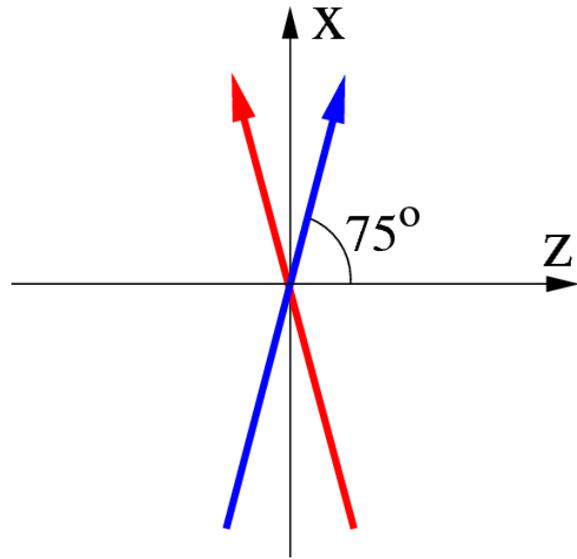

A large beam crossing angle allows

✓ to form a dimuonium beam directed along the x axis,
✓ to increase the decay length $l=\beta\gamma c\tau$,
✓ and hence to suppress background,
✓ to use existing e+/e- source

E_{beam} of	408 MeV
E_{CM}	211 MeV
Circumference	23 m
Bunch intensity	$3.5\times10^{10}/73$ mA
Number of bunches	20
σ_x at IP	102 µm
σ_y at IP	0.84 µm
σ_z at IP	11 mm
L_{aver}	8×10^{31} cm^{-2}c^{-1}

Important µµ-tron task is to study and test many accelerator technologies used in the CTF project

μμ-tron parameters

E_{beam}	408 MeV
σ_E/E_{beam}	7.8×10^{-4}
$\Delta\alpha$	6.8×10^{-4}
σ_x at IP	102 μm
σ_y at IP	0.84 μm
σ_z at IP	11 mm
Luminosity	8×10^{31} cm^{-2}c^{-1}

✓ Center-of-mass energy $E = 2E_{beam}\cos\alpha = 211$ MeV

✓ $\delta = 2E_{beam}\sqrt{(\sigma_E/E_{beam})^2\cos^2\alpha + \Delta\alpha^2\sin^2\alpha} = 398$ кэВ

✓ β=0.966, γ=3.86, l= βγcτ=2.02n³ mm for n³S₁

✓ Interaction region size:

σ_x(IR) = σ_x /(√2cos α)=280 μm, σ_y(IR) = σ_y/√2 = 0.6 μm, σ_z(IR) ≈ σ_x /(√2sin α) = 75 μm

Interaction region

Experimental chamber: 0.2-mm-thick beryllium window to decrease multiple scattering of $e^{\pm}$ from the dimuonium decay and $\mu^+\mu^-$ pair from the process $e^+e^- \rightarrow \mu^+\mu^-$

Detector of electron pair
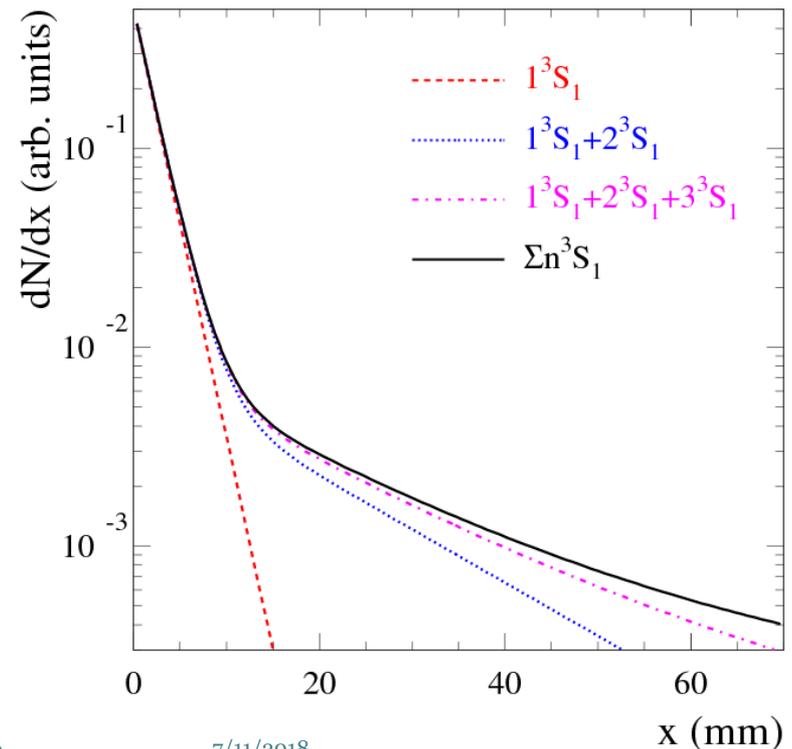
Detector of electron pair

- ✓ Vertex detector (5 layers with resolution of 100 μm)
  Drift chamber with hexagonal cell
- ✓ Two-coordinate GEM based detectors
- ✓ Scintillator hodoscope with time resolution better than 300 ps.
- ✓ Sandwich-calorimeter: lead+plastic scintillator with light output by a wavelength-shifter fiber and Si PM.
- ✓ Detection efficiency is 15% for two tracks detected in the calorimeter
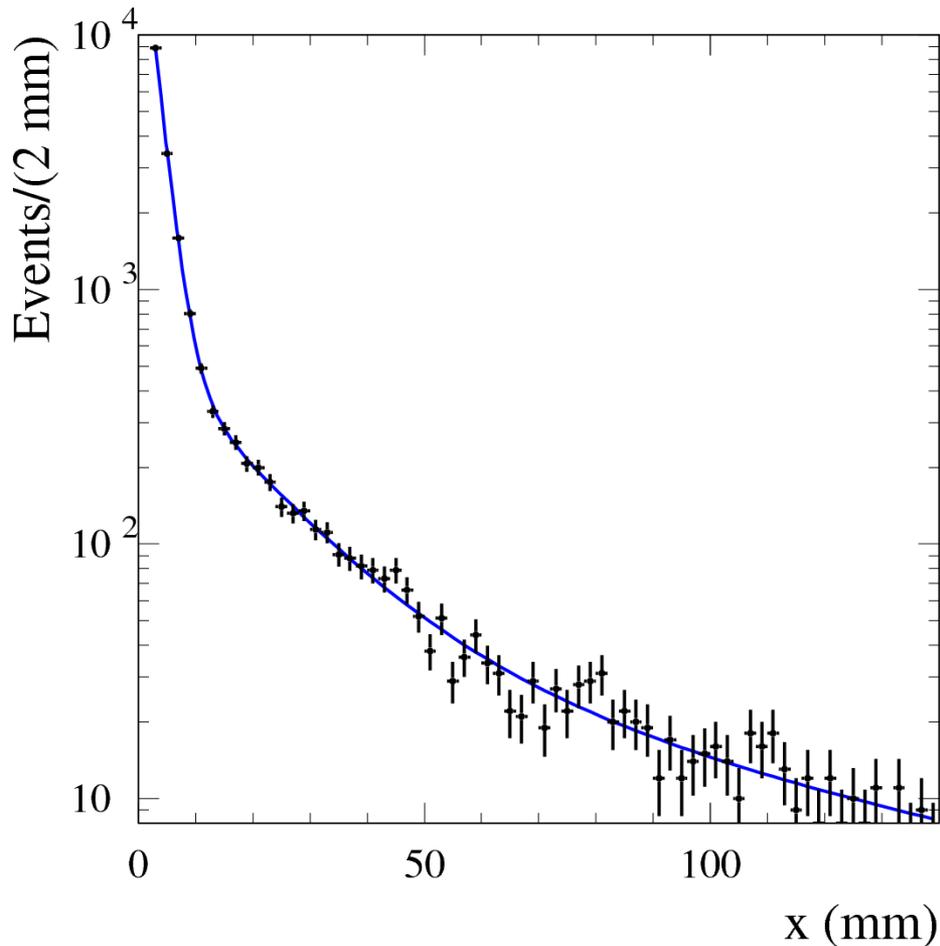
Detection of dimuonia

Events	hour	Four months
x>2.0 mm (1S/2S/3S)	4.7/1.4/0.5	13k/3.9k/1.3k

Detection efficiency — 15%

- $\beta\gamma c\tau \ (1^3S_1) = 2.02$ mm
- $\sigma_x(\text{IP}) = 280$ μm
- Detector resolution is better than 300 μm
- Total resolution on the vertex x-coordinate $\sigma_{vtx} = 400$ μm
- For suppression of Bhabha events it is required that $x_{vtx} > 5\sigma_{vtx} = 2$ mm
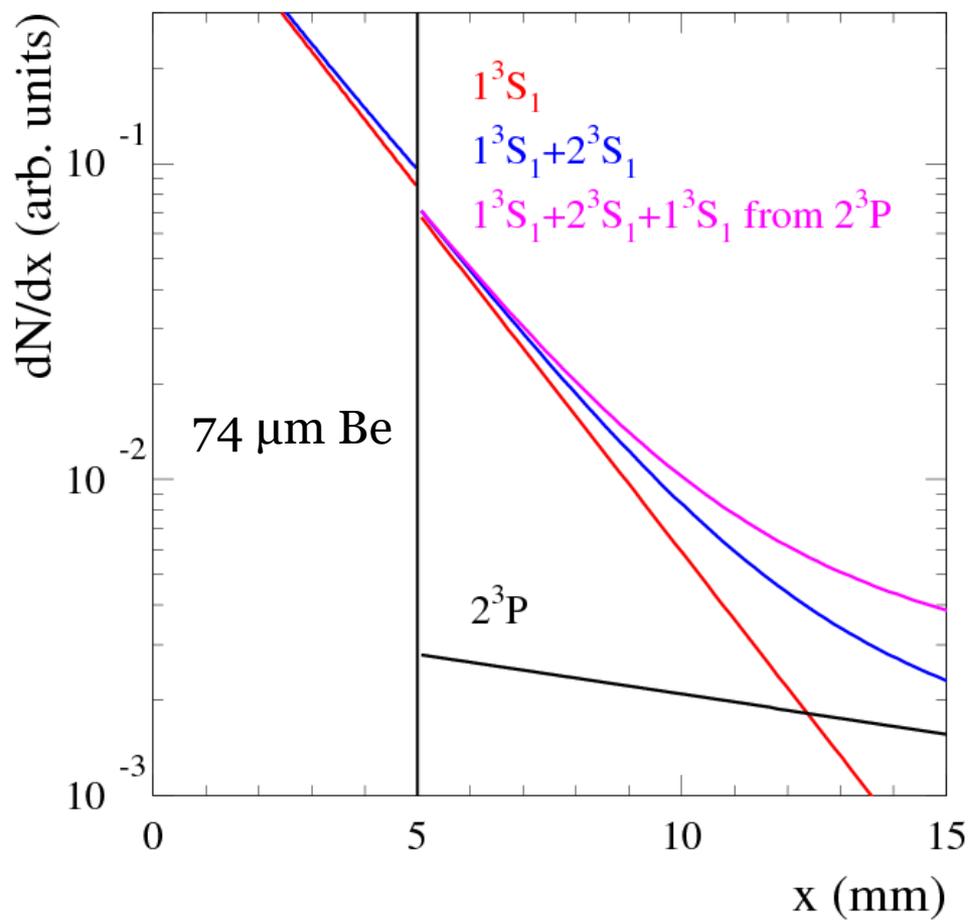
Dimuonium. Life time

	true	fit
$N_{1S} \times 10^{-3}$	118.1	118.9±1.7
L_{1S}, µм	2020	2008±36
$N_{2S}/N_{1S} \times 10^3$	125	123±14
L_{2S} (мм)	16.2	15.7±1.9
$N_{3S}/N_{1S} \times 10^3$	37	41±15
L_{3S} (мм)	54.5	54±14

x (mm)

10^7 s, two interaction regions

✓ From L_{1S} the life time or total width Γ are determined
✓ From N_{1S} - the product $\Gamma \times B^2_{ee}$.
✓ Difference of B_{ee} from 0.997 → search for invisible decays
✓ The radiative corrections modify Γ at the 1% level.
✓ For these measurement the energy spread δ and γ-factor must be known with an accuracy of about 10^{-3}.
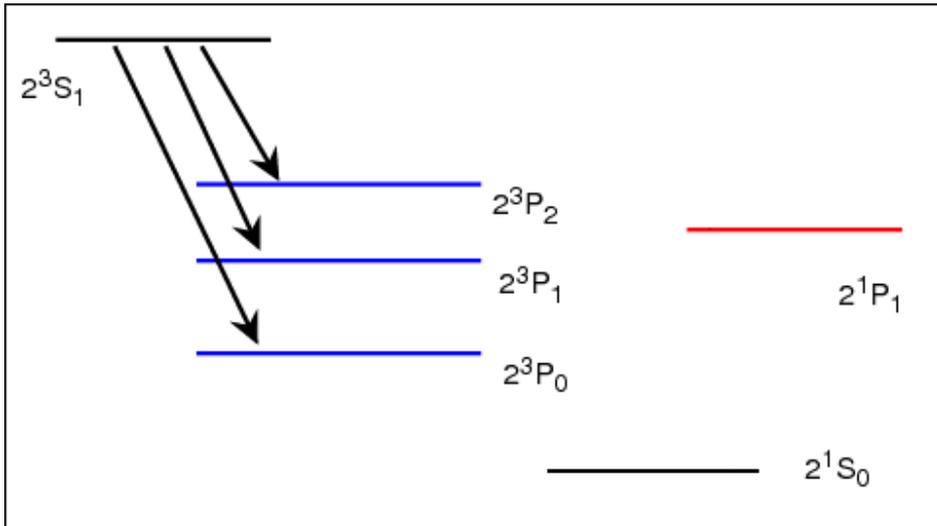
Dimuonium. Interaction with material.

1^3S_1
$1^3S_1 + 2^3S_1$
$1^3S_1 + 2^3S_1 + 1^3S_1$ from 2^3P

74 μm Be

2^3P

The processes of dimuonium interaction with nuclei
- Dissociation $(\mu^+\mu^-) \rightarrow \mu^+ \mu^-$
- Exitation S ‹-› P

From the x_{vtx} distributions measured with different foil widths and positions the cross sections for these processes can be obtained.

2^3P-states transit to 1^3S_1-state with emission of photon with an energy of 1 keV in the rest frame. In lab frame 30% photons emitted into the 10∘ cone relative to the x axis (5-7 keV)
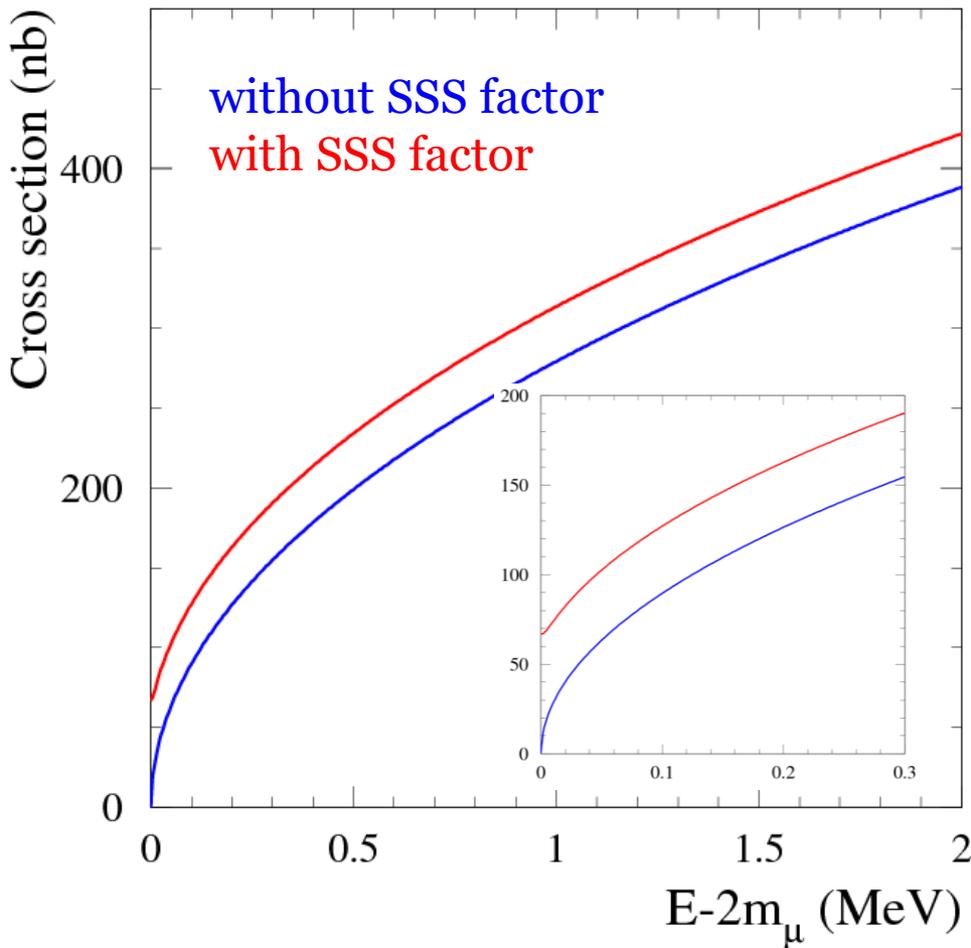
Dimuonium. Laser spectroscopy

Transitions inside the fine structure

❑ Wavelengths are 79, 114, 173 μm in the rest frame
❑ Using Doppler shift leads to λ=10 μm − 1 mm
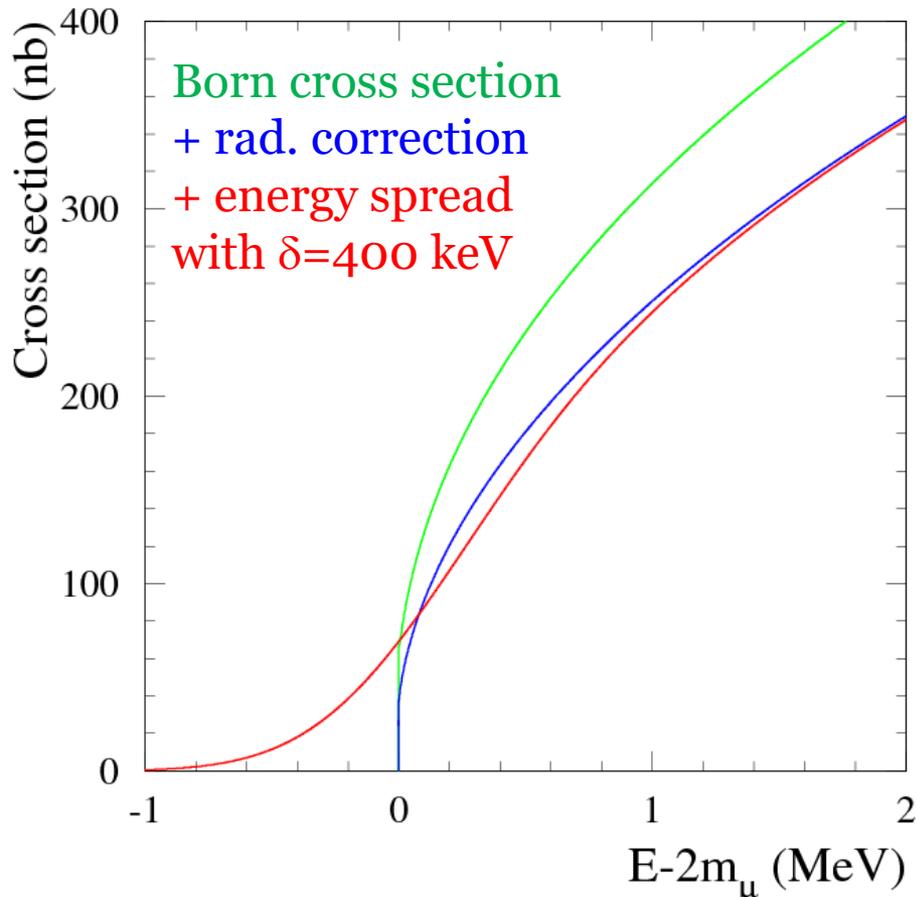❑ Very large power (~MW) is needed
❑ Under study

e⁺e⁻→ μ⁺μ⁻ near threshold

$$\sigma_B(E) = \frac{2\pi\alpha^2\beta}{E^2}\left(1 - \frac{\beta^3}{3}\right)C(\beta),$$

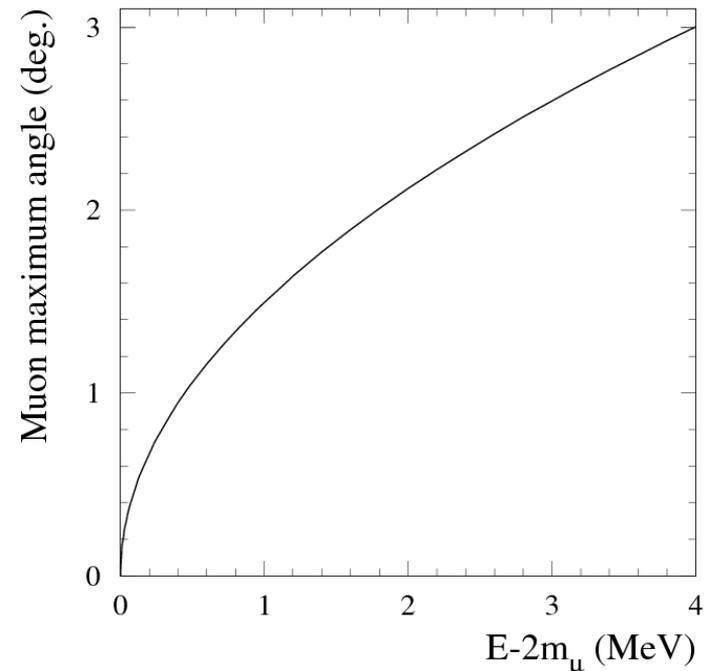$$C(\beta) = \frac{y}{1-\exp(-y)}, \quad y = \frac{\pi\alpha}{\beta}$$

$$\sigma_B(2m_\mu) = \frac{2\pi^2\alpha^3}{4m_\mu^2}$$

The Coulomb interaction in the final state leads to nonzero cross section at the e⁺e⁻→ μ⁺μ⁻ threshold.

without SSS factor
with SSS factor

Процесс e⁺e⁻→ μ⁺μ⁻

Born cross section
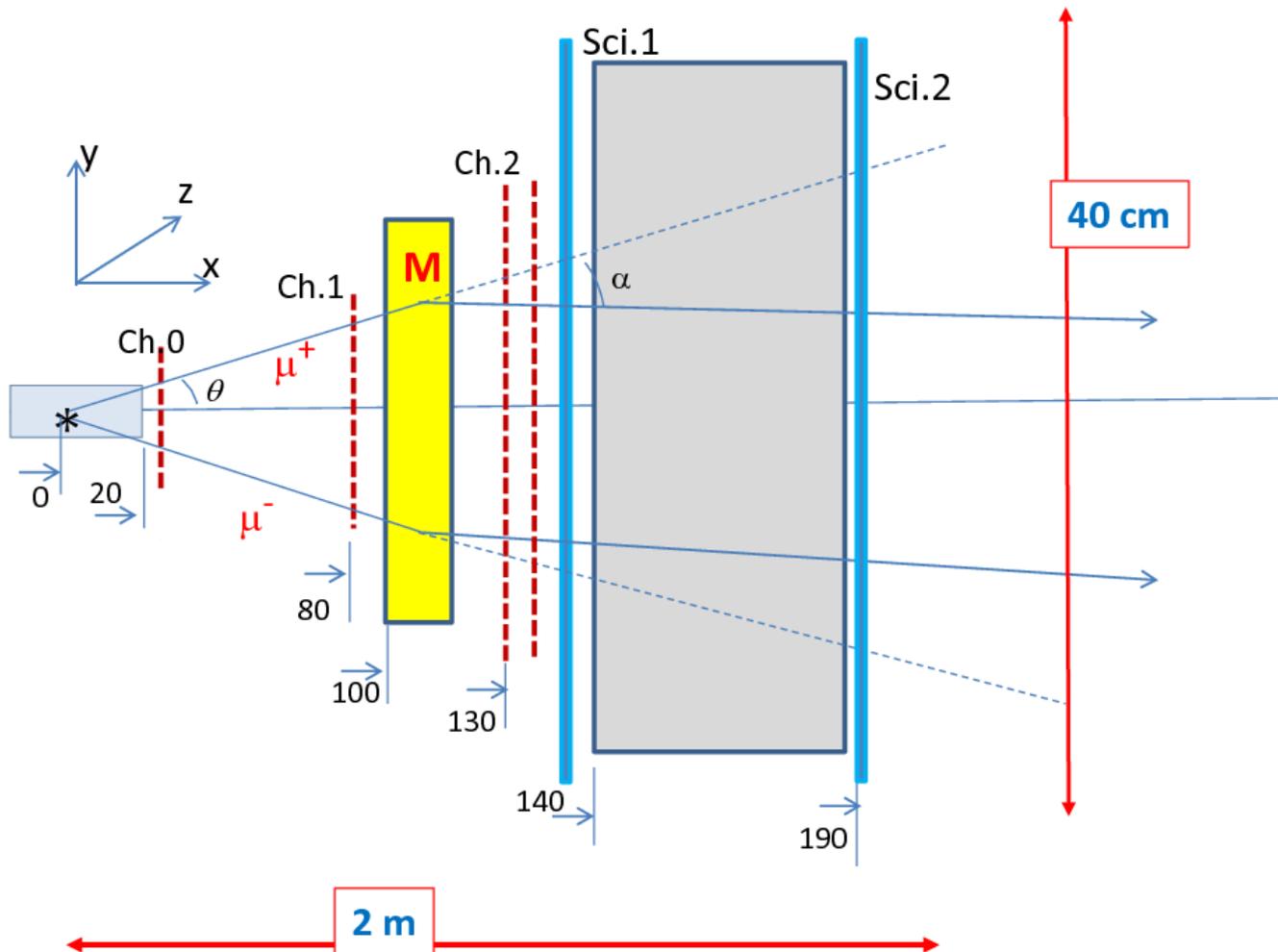+ rad. correction
+ energy spread
with δ=400 keV

- ✓ Muon pairs at threshold are produced with a frequency of 5 Hz.
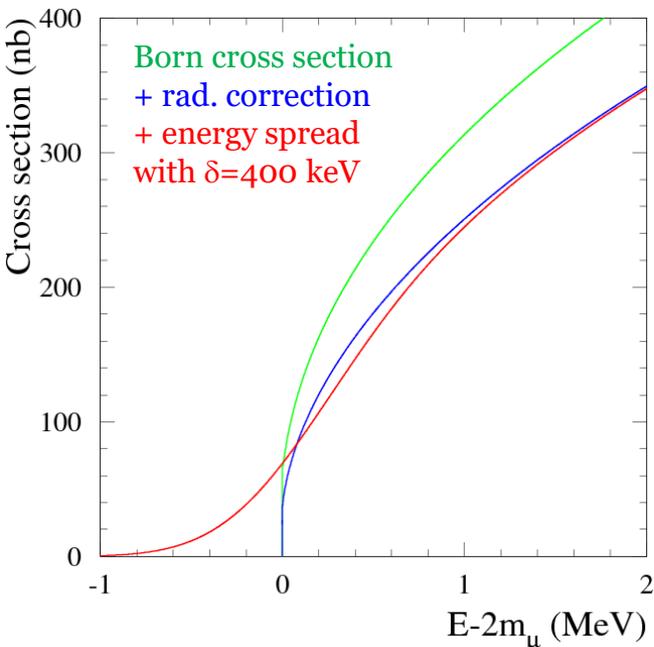- ✓ Muons moves in a narrow cone along the x axis.

Relatively small detector (magnetic spectrometer) installed perpendicular the x axis provides background-free detection of muon pair with an efficiency close to 100%

Muon-pair spectrometer

Muon-pair spectrometer

Born cross section
+ rad. correction
+ energy spread
with δ=400 keV

Cross section (nb) vs $E - 2m_\mu$ (MeV)
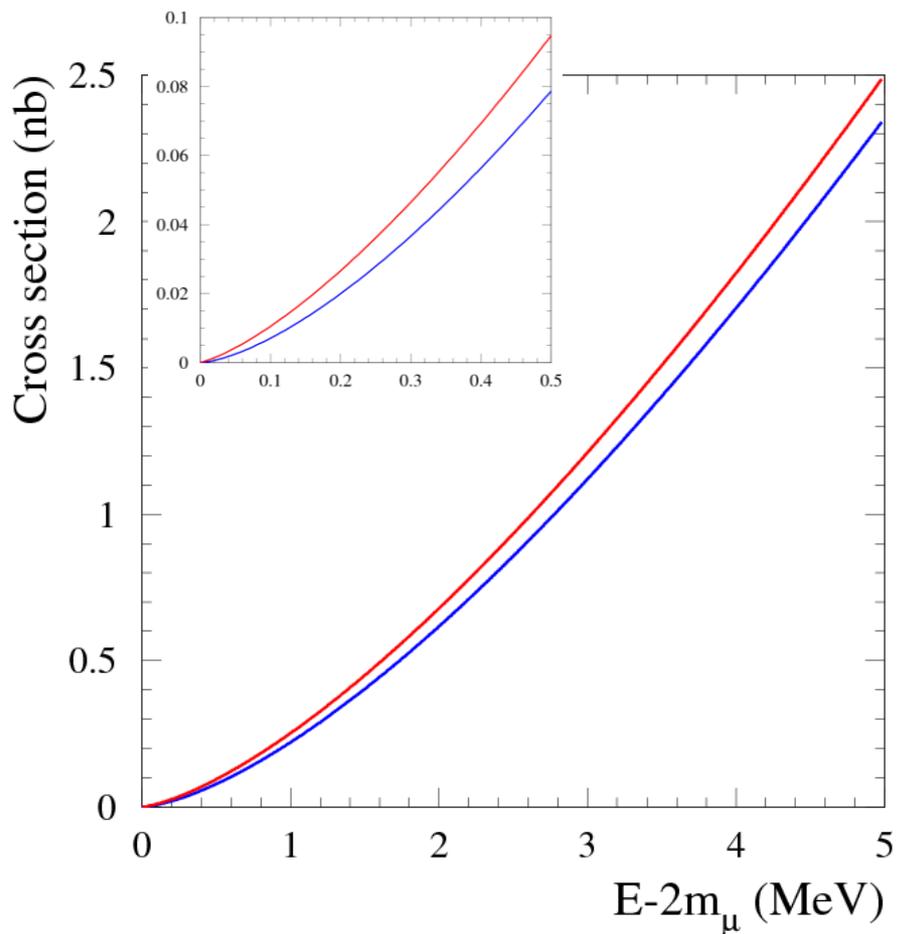
Determination of collider parameters:

❑ Special energy scan (data taking at $T = E - 2m_\mu =$ -0.5, 0, 2 MeV, 1 hour/point) allows to perform
   - ✓ c.m. energy calibration with an accuracy of 4 keV
   - ✓ c.m. energy spread measurement with an accuracy of about 2 keV

❑ Data taking at the $e^+e^- \to \mu^+\mu^-$ threshold
   - ✓ Energy control on the dimuon rate
   - ✓ Energy-spread control using muon angular and momentum distributions
   - ✓ x-direction control

❑ E_{beam} is measured using the method of Compton backscattering of laser photons on beam

The first experiment at μμ-tron will be the precision measurement of the $e^+e^- \to \mu^+\mu^-$ cross section and extraction of the SSS-factor.
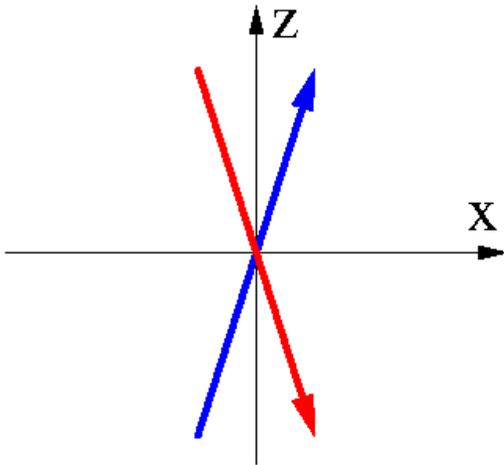
$e^+e^- \rightarrow \pi^+\pi^-$ at threshold

➢ The same spectrometer can be used for the precise measurement of the $e^+e^- \rightarrow \pi^+\pi^-$ cross section near its threshold.

➢ For this measurement the beam collision angle should be changed from 75° to 70°.

➢The Coulomb interaction increases the cross section by 20% (13%) at T=0.5 (1.0) MeV.

➢Measurement of the effect of final-state strong interaction

15° collision configuration.

✓ Covers the c.m. energy region from 500 MeV to 1000 MeV
✓ This region of the ρ and ω resonances is important for the SM $(g-2)_\mu$ calculation
✓ Luminosity (10^{33} cm^{-2}s^{-1}) is higher than that at VEPP-2000 by 2 orders of magnitude

✓Measurement of $e^+e^- \to \pi^+\pi^-$ with unlimited statistics.
✓ Measurement of other hadronic cross sections ($e^+e^- \to 3\pi$, $\pi^o\gamma$, $\eta\gamma$, $\pi^o\pi^o\gamma$, 4π, ...) and rare processes, e.g. $e^+e^- \to \eta$, η'.
✓ Two-photon processes $\gamma\gamma \to \pi^o$, $\pi\pi$, η. Measurement of meson-photon transition form factors
✓ A large universal detector is needed which is hard to be installed at so small machine.

Summary

- Collider to observe and study dimuonium
  - two rings
  - large crossing angle
  - circumference of 23 m
  - not expensive to build and operate
  - luminosity 8×10^{31} cm^{-2}s^{-1}
- Reverse of the beam allows to perform experiments in the 500-1000 MeV energy range
- Details are in https://arxiv.org/abs/1708.05819
- Currently we are preparing technical design and plan to make a decision by the end of the year

We are open for collaboration and experiments proposals