LOW-ENERGY ELECTRON-POSITRON COLLIDER TO SEARCH AND STUDY ($\mu^+\mu^-$) BOUND STATE

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Dimuonium

- Dimuonium, bimuonium or true muonium is a lepton atom ($\mu^+\mu^-$).
- From 6 leptonic atoms (e^+e^-), (μ^+e^-), ($\mu^+\mu^-$), (τ^+e^-), ($\tau^+\mu^-$), ($\tau^+\tau^-$) only two (e^+e^-), (μ^+e^-) were observed.
- Dimuonium is pure QED system (no strong interaction, calculable).
- Very compact (large m_μ), more sensitive to new physics than other exotic atoms.

Why dimuonium?

- Observation of the new classical QED object.
- QED test in the new regime.
- Experimental challenge leads to development of new techniques.
- Tests of muon properties are motivated by
  - 3.5σ difference between $(g\text{-}2)_{\mu}$ measurement and SM prediction,
  - discrepancies in the proton charge radius in muonic hydrogen,
  - hints of lepton-universality violation in rare B decays (LHCb), $B^{+} \to K^{+}e^{+}e^{-}$ and $B^{+} \to K^{+}\mu^{+}\mu^{-}$.

Some references

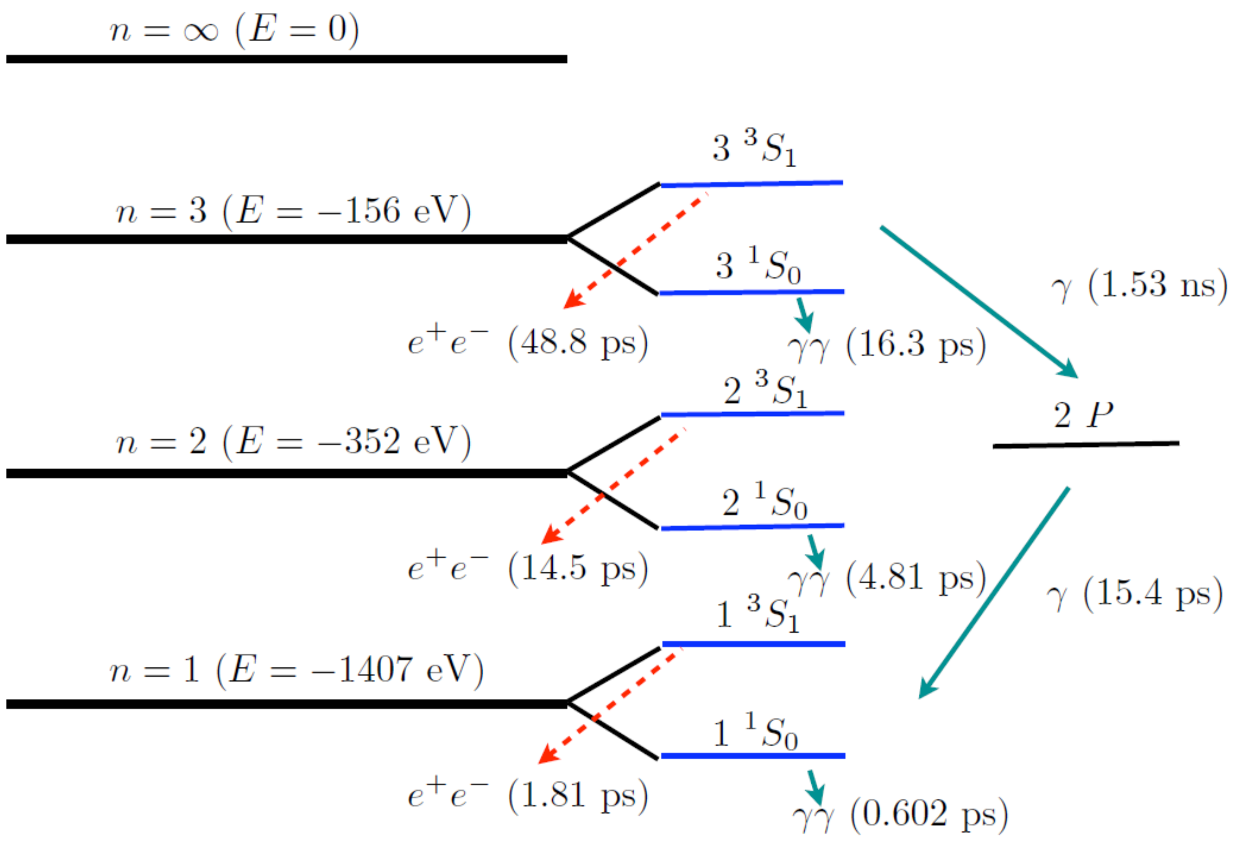
- V.N.Baier and V.S.Synakh, Bimuonium production in electron-positron collisions, SOVIET PHYSICS JETP, **14**, № 5, 1962, pp.1122-1125
  - *Properties of the bound state, probability of observation*
- S.J. Brodsky and R.F. Lebed. Production of the Smallest QED Atom: True Muonium ($\mu^+\mu^-$). Phys. Rev. Lett., 102:213401, 2009
  - *Very large crossing angle in order to eliminate background*
- H. Lamm and R.F. Lebed, True Muonium ($\mu^+\mu^-$) on the Light Front, arXiv 1311.3245v3, 12 Nov 2014
  - *Spectrum*
- H. Lamm, True muonium: the atom that has it all, arXiv 1509.09306v1, 30 Sep 2016
  - *Novel properties*

Dimuonium properties

- Mass
  $$M_{\mu\mu} = 2 \times 105.7 \text{ MeV} - 1.4 \text{keV}$$
- Bohr radius
  $$R_{\mu\mu} = 512 \text{ fm}$$
  $$R_{ee} = 106000 \text{ fm}$$
- Muon lifetime 2.2 μs
- $^3S_1$ states have photon quantum numbers ($J^{PC} = 1^{--}$); therefore could be produced in e^+e^- collisions

Dimuonium energy levels diagram

S.J. Brodsky, R.F. Lebed, Phys. Rev. Lett., 102:213401, 2009



Dimuonium production cross section

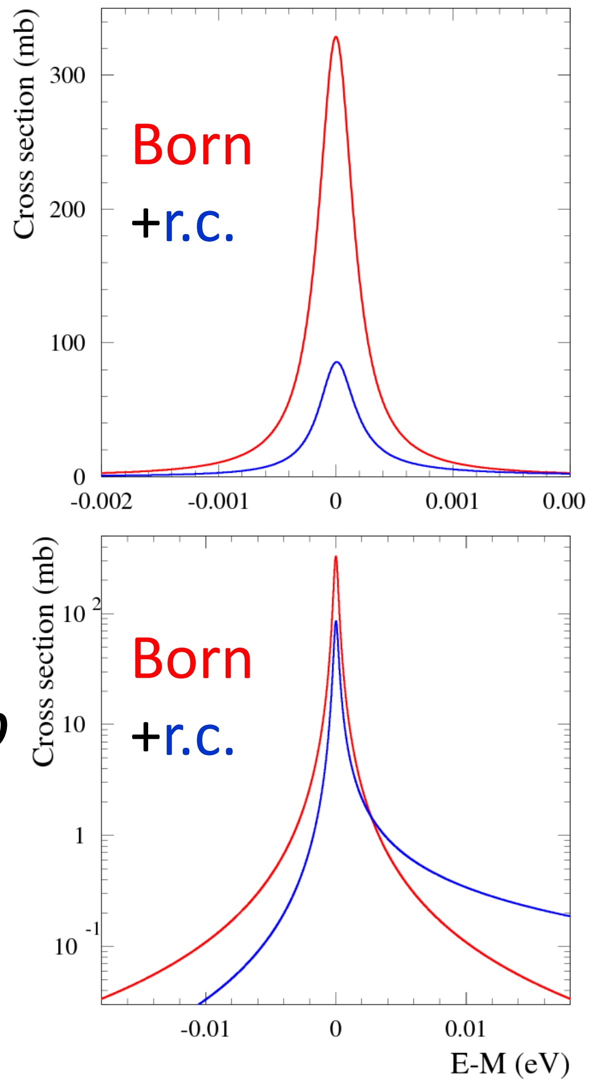
- Production of $n\ {}^3S_1$ in the $e^+e^- \to (\mu^+\mu^-) \to e^+e^-$
- $1\ {}^3S_1$: $\sigma(m_{\mu\mu}) \approx \frac{12\pi}{m_{\mu\mu}^2}\sqrt{\frac{\pi}{8}}\frac{\Gamma_{ee}}{\sigma_M} \approx 0.2\frac{\Gamma_{ee}}{\sigma_M}$

where σ_M is center-of-mass energy spread

- For different collision schemes

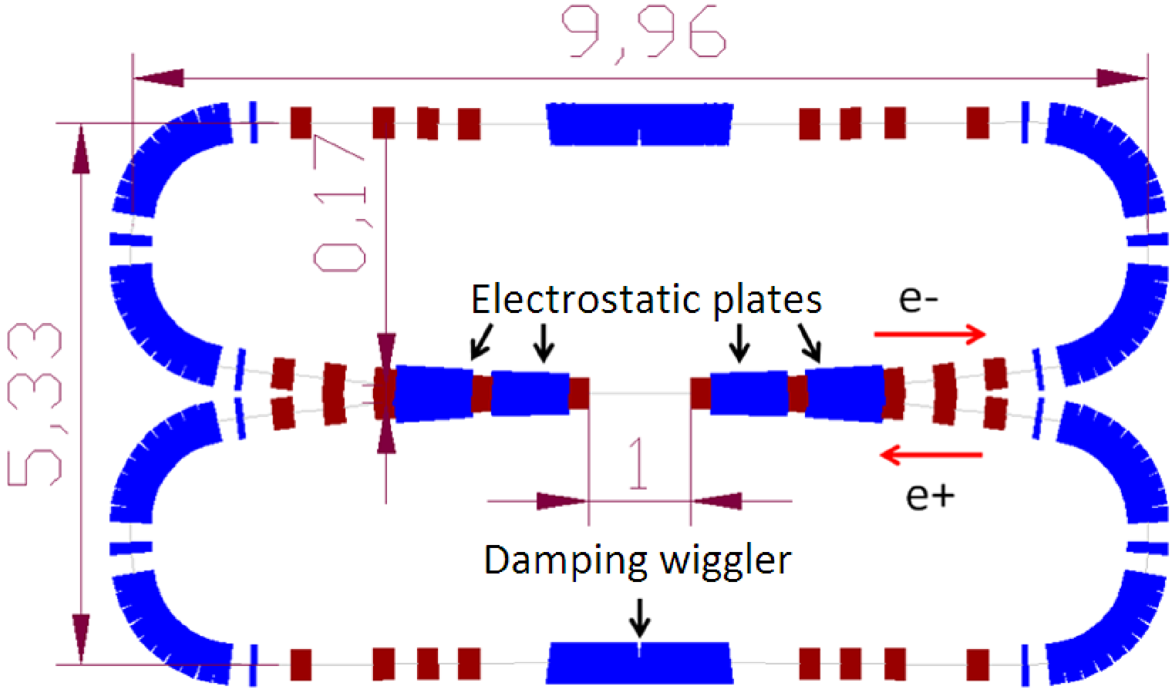
$\frac{\Gamma_{ee}}{\sigma_M} = \frac{0.37\times10^{-6} keV}{(7\div400) keV} \approx (1 \div 50)\times10^{-9}, \sigma(m_{\mu\mu}) = 0.15 \div 7\ nb$

- Background: elastic $e^+e^- \to e^+e^-$ scattering
    - For crossing angle $45° \div 135°$ $\sigma_{Bhabha} = 22000\ nb$
- $Background/signal = (5 \div 210)\times10^3$
- Background suppression is possible if decay point is separated from the origin point (decay path$1\ {}^3S_1$: $c\tau = 540\ \mu m$)



Head-on e+e- collision

E_{beam}=100÷150 MeV
Collision monochromatization a la Reniery:
10 keV invariant mass resolution
$L \approx 10^{30}$ cm^{-2}s^{-1} (~50 $(\mu^+\mu^-)$/hour).



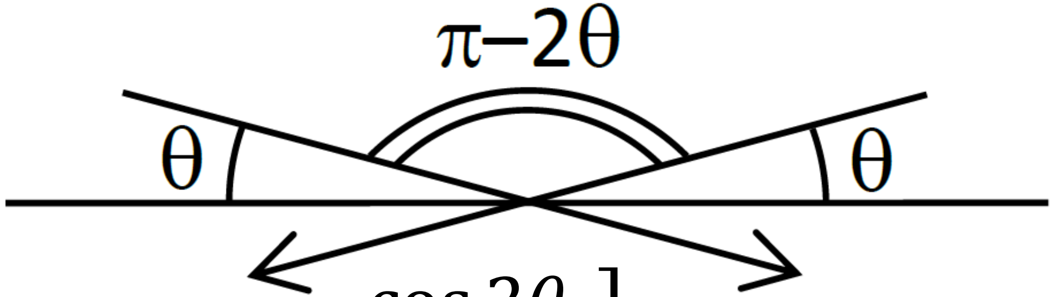
https://eventbooking.stfc.ac.uk/uploads/eefact/mumutron-eefact2016-2.pptx

Observation of the dimuonium
by searching for X-rays from $(\mu^+\mu^-)$
Bohr transitions such as 2P→1S (J.W.Moffat).

Failed due to large background.

Large crossing angle proposed by S.J.Brodsky and R.F.Lebed.

Large angle beam crossing



Invariant mass

$$\langle M \rangle = 2E_0 \cos\theta - \frac{E_0}{2}\cos\theta\left[\sigma_\delta^2 + \sigma_{px}^2 + \sigma_{py}^2 \frac{\cos 2\theta}{(\cos\theta)^2}\right]$$

Invariant mass resolution

$$\sigma_M^2 = 2E_0^2\left[\sigma_\delta^2(\cos\theta)^2 + \sigma_{px}^2(\sin\theta)^2\right]$$

Luminosity ($\varphi = \sigma_z \tan\theta / \sigma_x$)

$$\mathcal{L}_0 = \frac{N_1 N_2}{4\pi\sigma_y\sigma_{\mathrm{x}}\sqrt{1+\varphi^2}} f_0 N_b \approx \frac{N_1 N_2}{4\pi\sigma_y\sigma_z \tan\theta} f_0 N_b$$

Peak production rate

$$\dot{N}_{\mu\mu} \approx \frac{\Gamma_{\mu\mu}\sigma_{\mu\mu}\mathcal{L}_0}{2\sqrt{\pi}\sigma_M}$$

Background

Decay length $\left(\mu^+\mu^-(1\ ^3S_1) \to e^+e^-\right)$

$$OA = l = c\,\tau_{0,\mu\mu}\beta_{\mu\mu}\gamma_{\mu\mu} = c\,\tau_{0,\mu\mu}\tan\theta$$

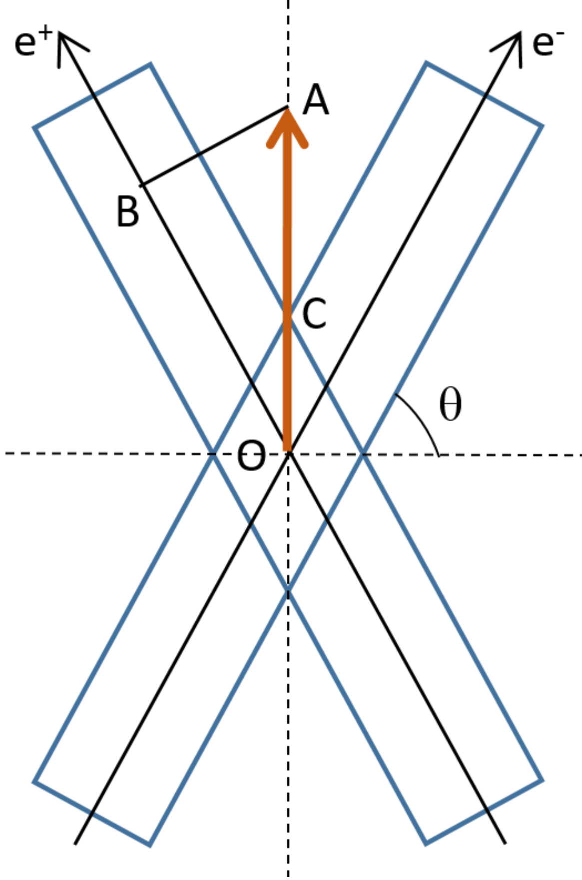
Background: density of beam particles

$$N_1 \propto \exp\left(-n_x^2/2\right)$$

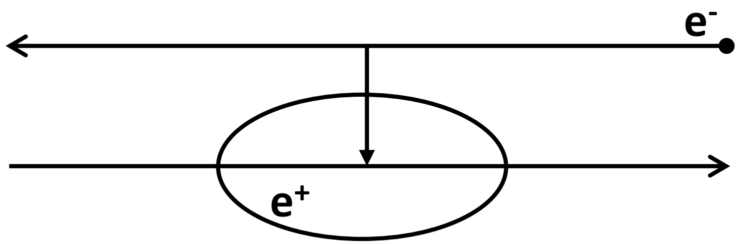
$$n_x = \frac{AB}{\sigma_x} = \frac{l\ \cos\theta}{\sigma_x} = \frac{c\,\tau_{0,\mu\mu}}{\sigma_x}\sin\theta$$

Signal to background ratio

$$\frac{\dot{N}_{\mu\mu}}{\dot{N}_{ee}} \propto \frac{\exp\left[\frac{c^2\tau_{0,\mu\mu}^2}{\sigma_x^2}\sin^2\theta\right]}{\sqrt{\sigma_\delta^2\cos^2\theta + \left(\sigma_x^2/\beta_x^2\right)\sin^2\theta}}$$



Beam-beam effects with large crossing angle



Beam-beam tuneshift

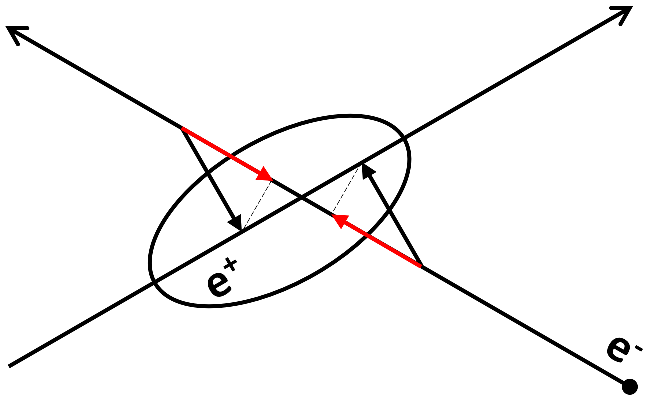
$$\xi_z = -\frac{N\,r_e}{2\pi\gamma}\frac{\alpha}{|\alpha|\sigma_\delta\sigma_z}\frac{\varphi^2}{1+\varphi^2}$$

Hamiltonian

$$\mathcal{H} = -\alpha\frac{p_z^2}{2} - \frac{\nu_s^2}{\alpha R^2}\frac{z^2}{2} - \frac{2\xi_z\nu_s}{\alpha R^2}\frac{z^2}{2}$$

Population limit for $\alpha > 0$

$$N < \frac{2\pi R\,\gamma}{r_e}\frac{\alpha\,\sigma_\delta^2}{2}$$

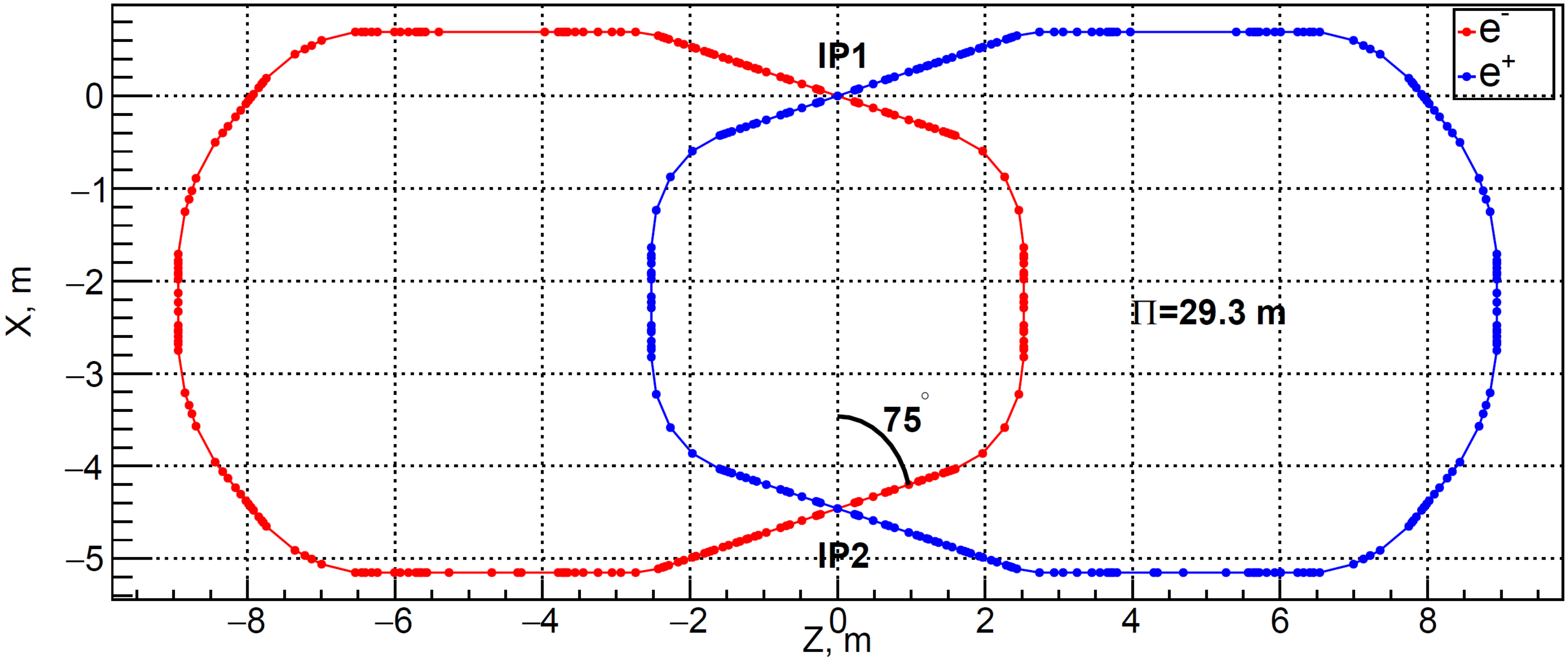


$\alpha < 0$ has been studied at KEKB and at DAΦNE, no large currents, no luminosity due to microwave instability

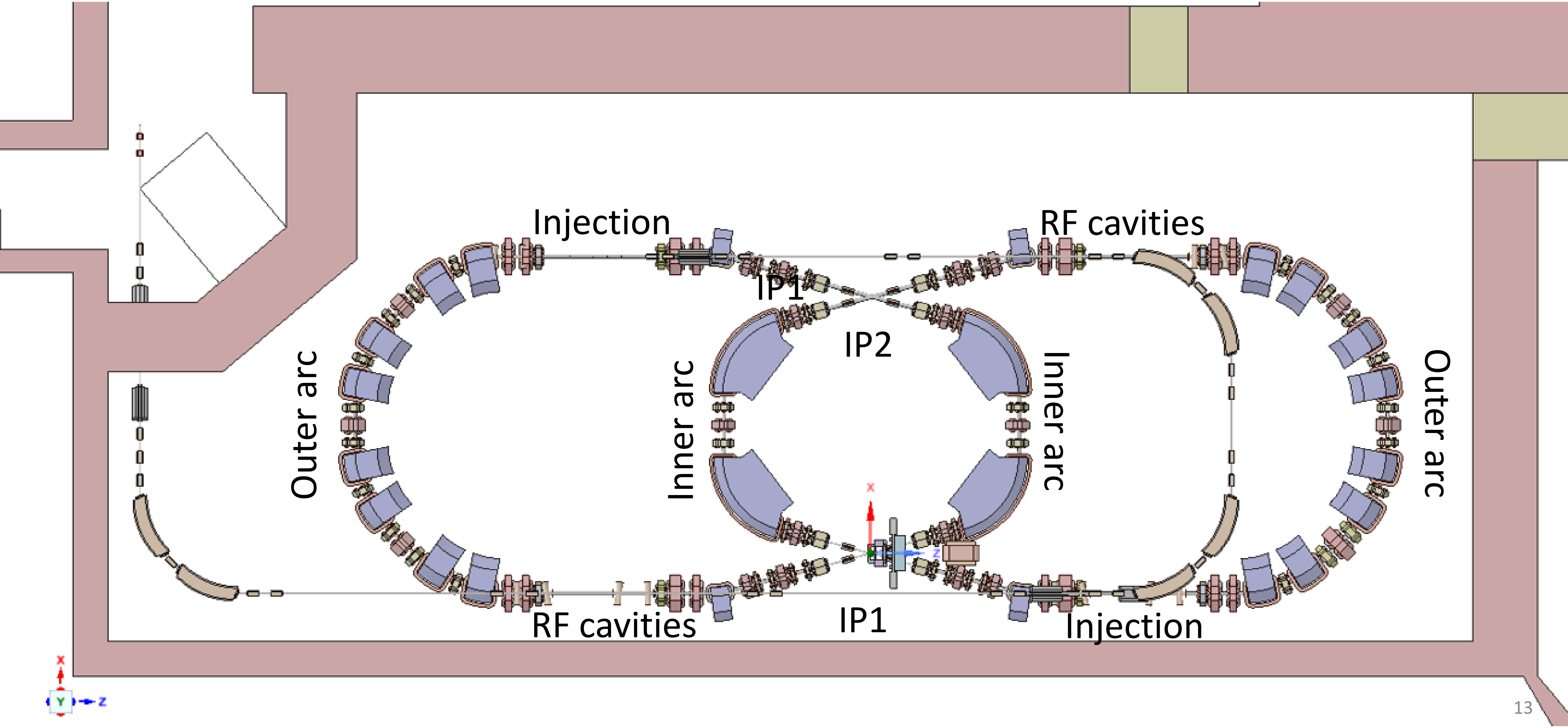
Accelerator requirements

- Large positive momentum compaction (small circumference)
- Large crossing angle with small vertical beta function gives high luminosity (similar to crab waist)
- Large crossing angle 75° provides comfortable beam energy (e^+ production) and decay length
  - beam energy $E_b = 408$ MeV
  - decay length $l\left(\mu^+\mu^-\left(1\ ^3S_1\right)\right) = 2$ mm
- Higher signal to noise ratio requires $\sigma_x < c\ \tau_{0,\mu\mu} = 0.54$ mm
- Horizontal beam divergence contributes significant part in invariant mass resolution; therefore, low horizontal emittance
- Reverse of the beam direction provides 15° crossing angle and allows to study c.m. energy range from η to η′ mesons (550-960 MeV)

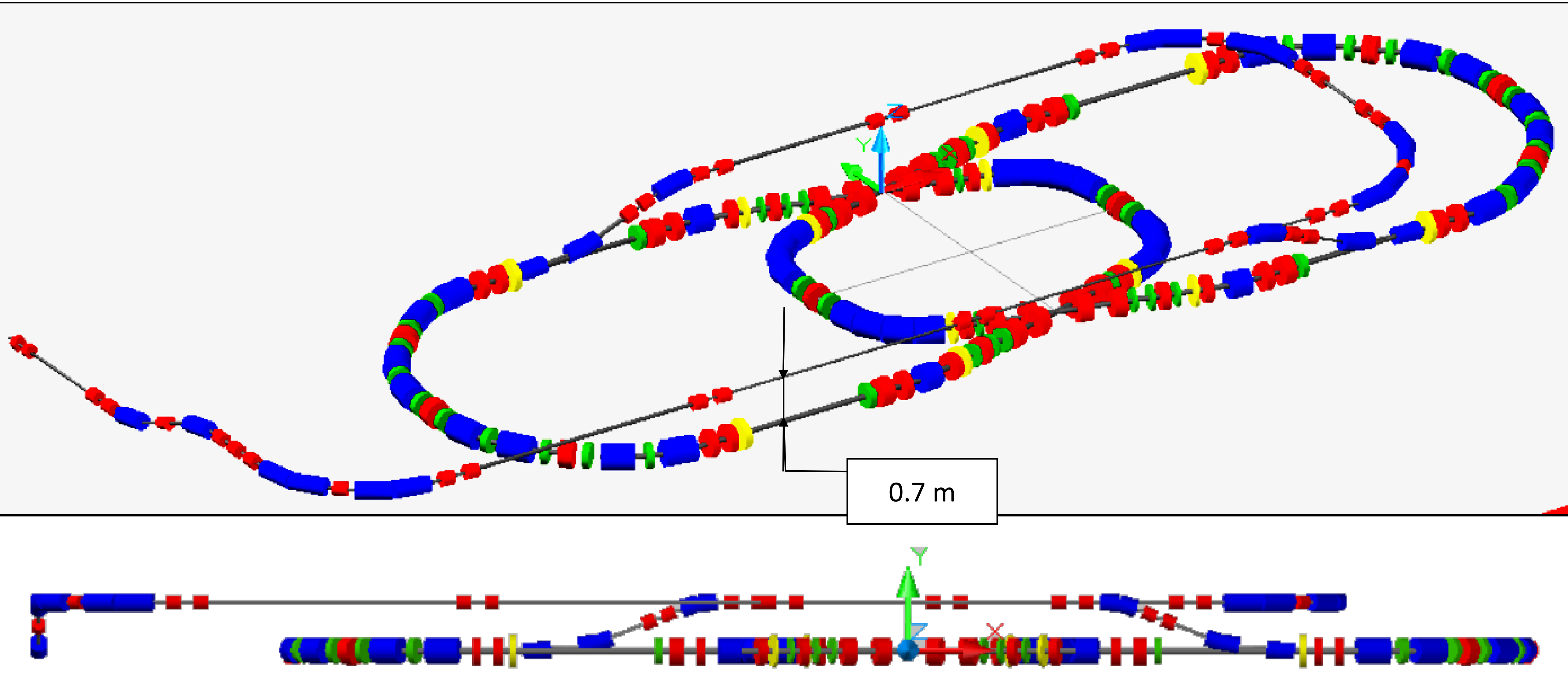
Collider: overview



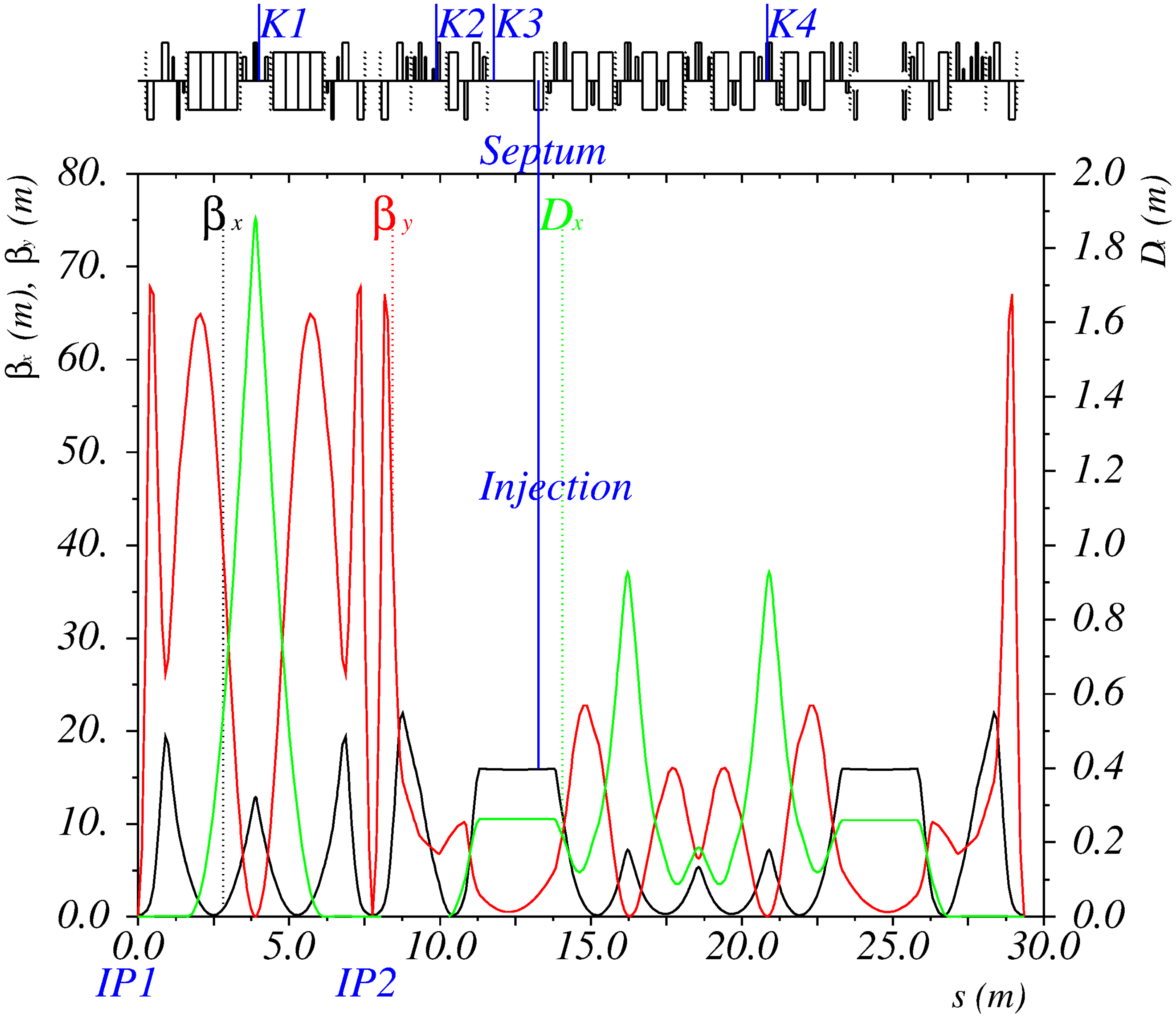
Collider: overview



Injection channels

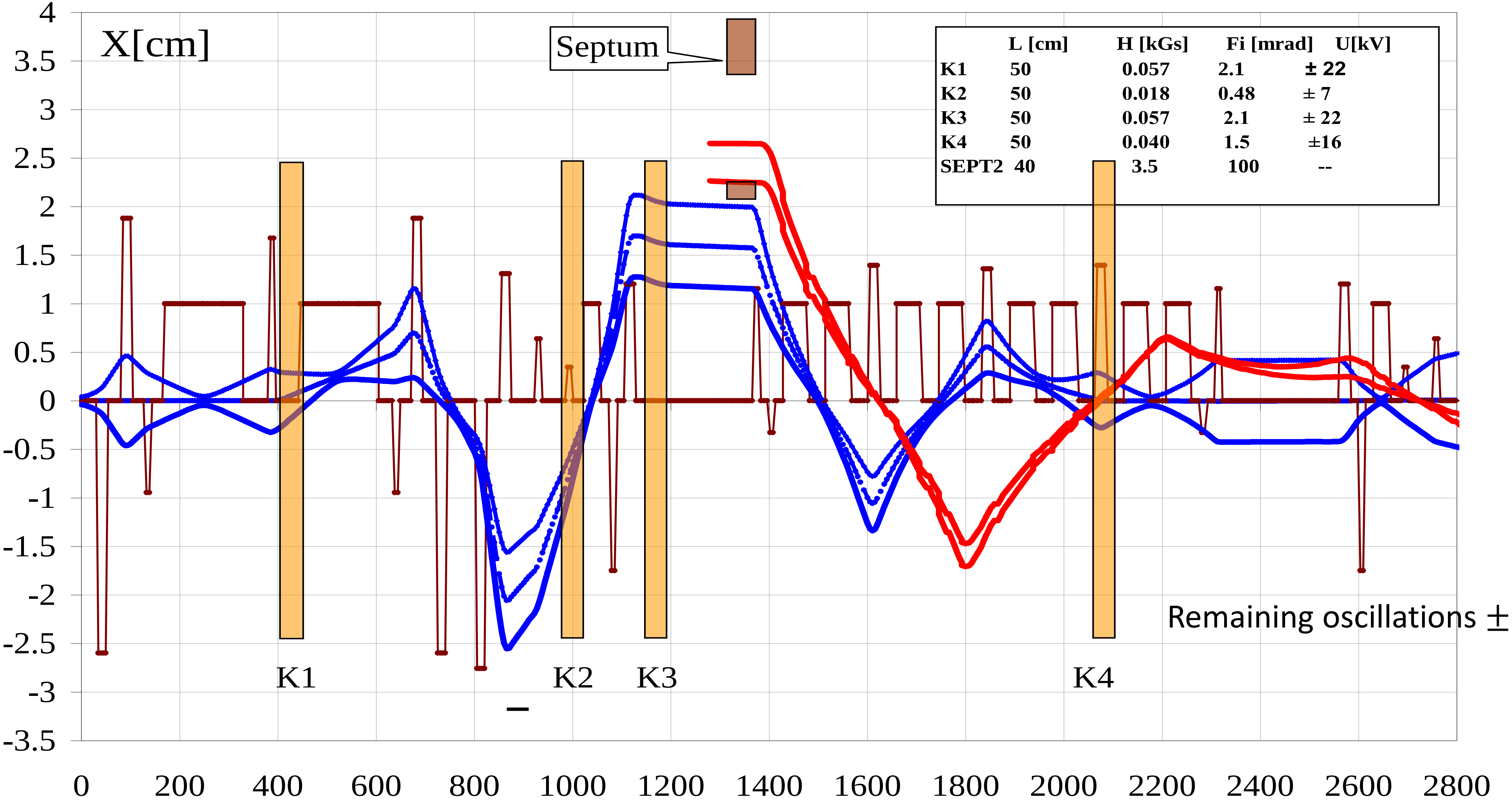


Injection optics



- One turn injection in the horizontal plane
- K1 – K4 – running wave kickers
- Septum – Lambertson injection magnet

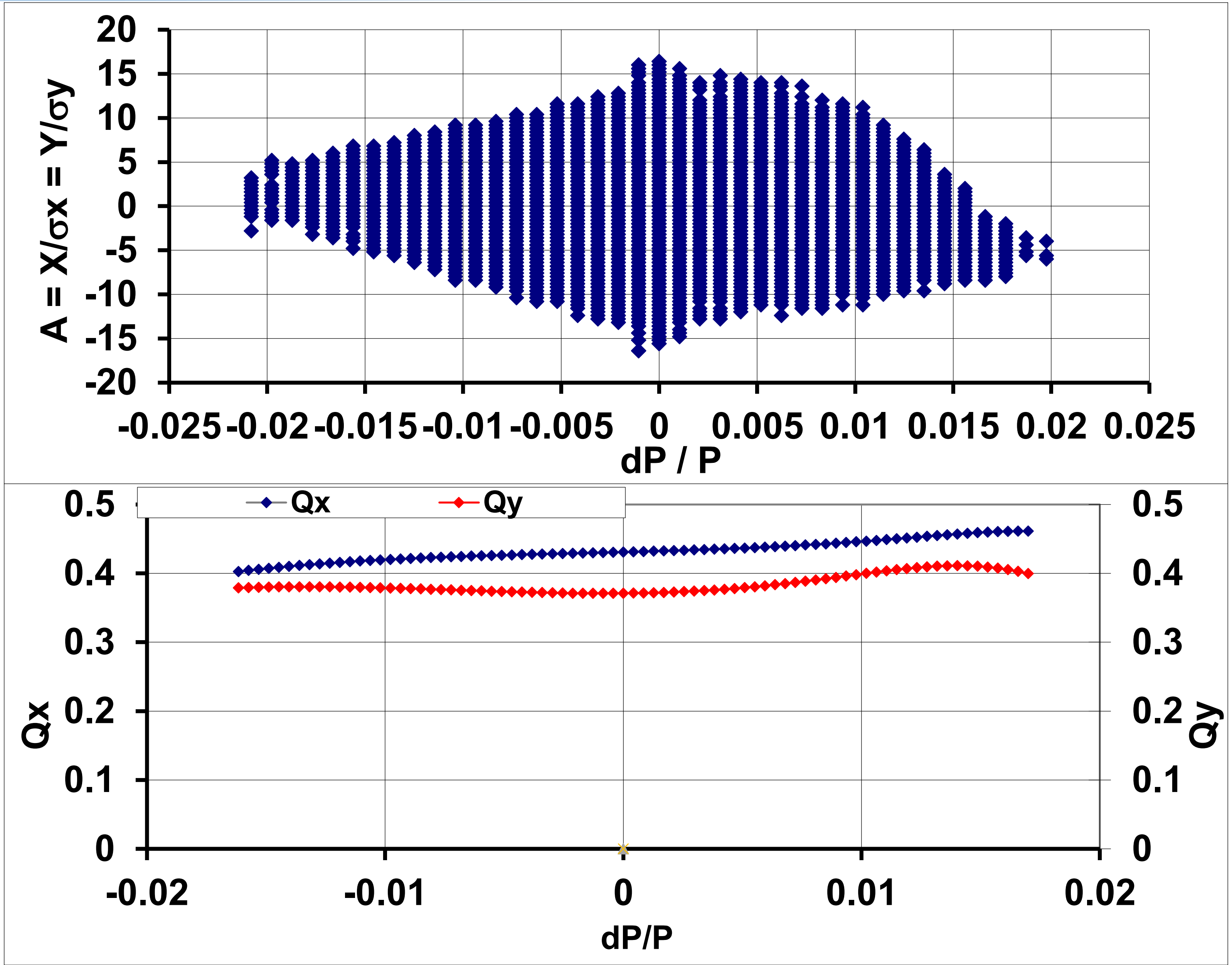
Injection trajectories



	L [cm]	H [kGs]	Fi [mrad]	U[kV]
K1	50	0.057	2.1	± 22
K2	50	0.018	0.48	± 7
K3	50	0.057	2.1	± 22
K4	50	0.040	1.5	±16
SEPT2	40	3.5	100	--

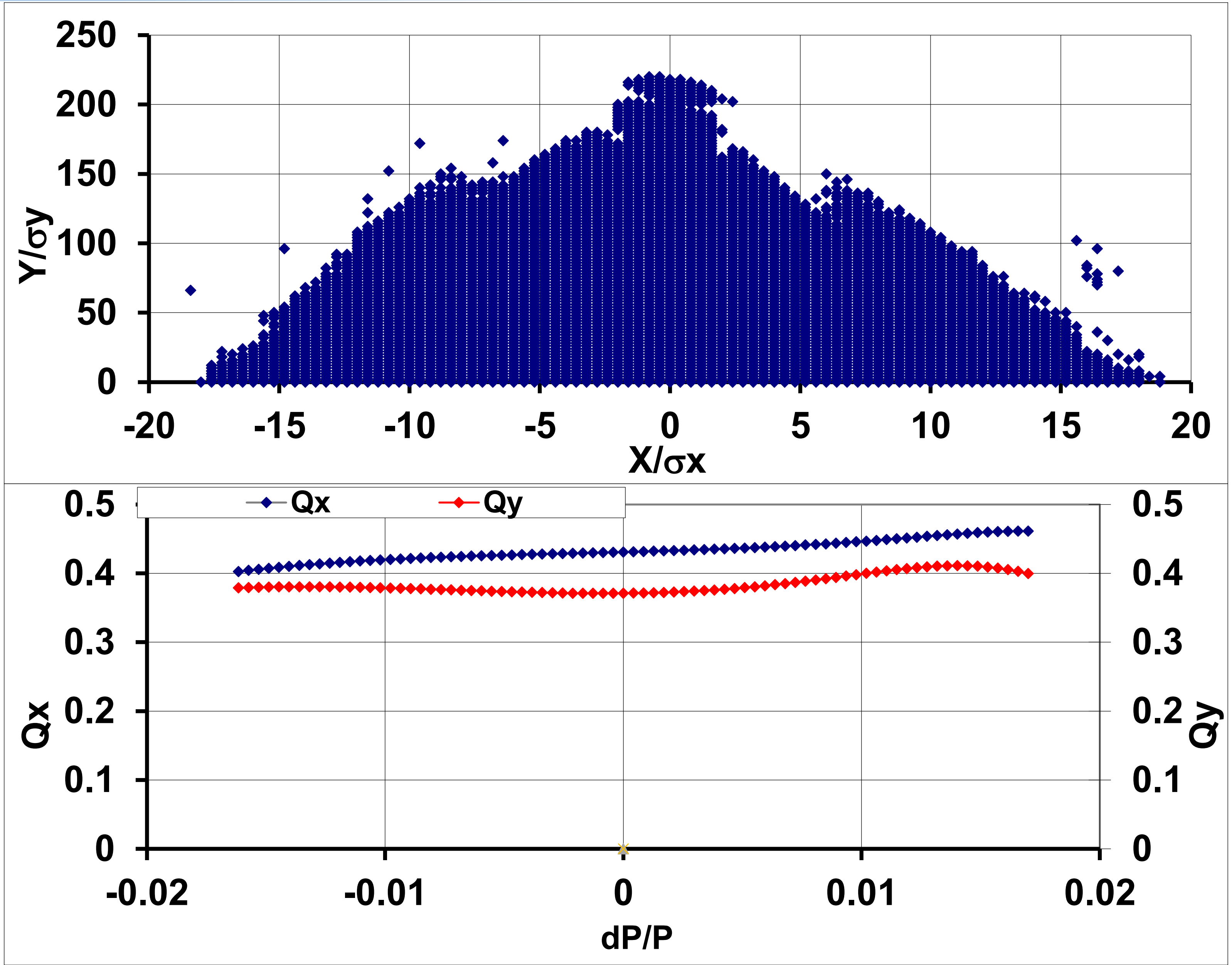
Remaining oscillations $\pm 10\ \sigma_x$

Dynamic aperture and energy acceptance



$\nu_x = 4.43$
$\nu_y = 3.37$

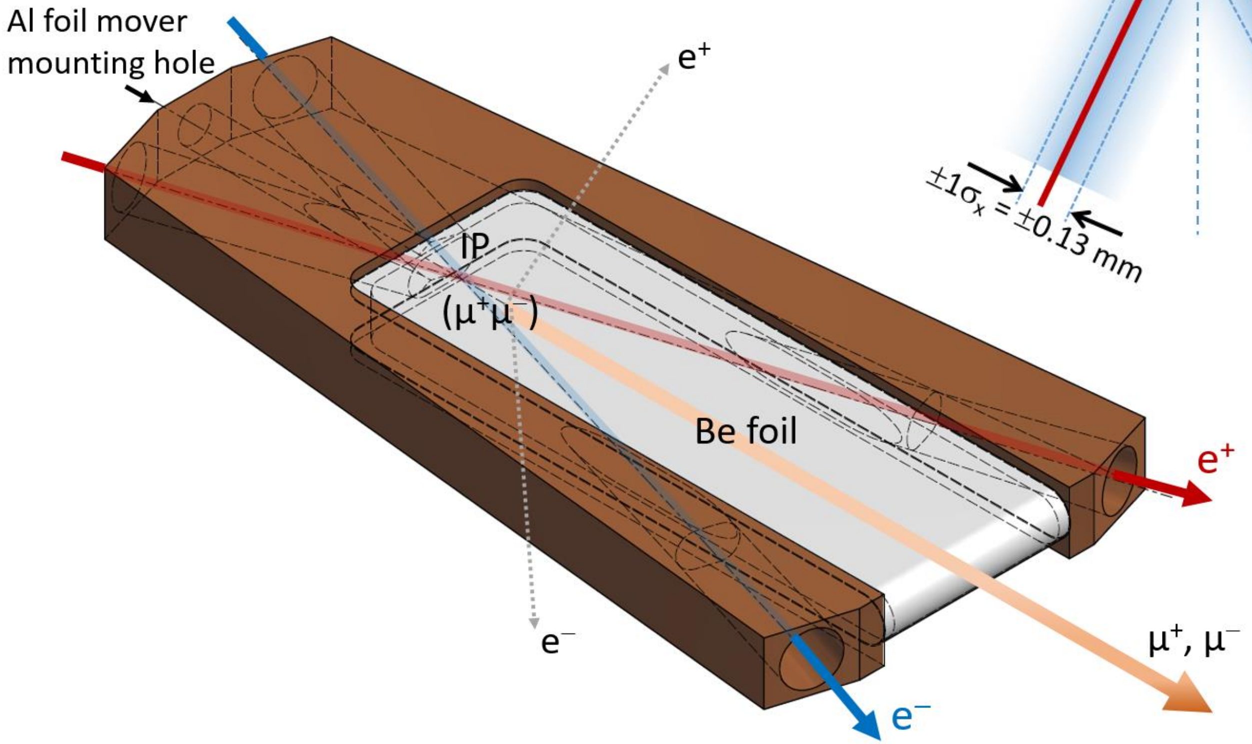
Dynamic aperture and energy acceptance

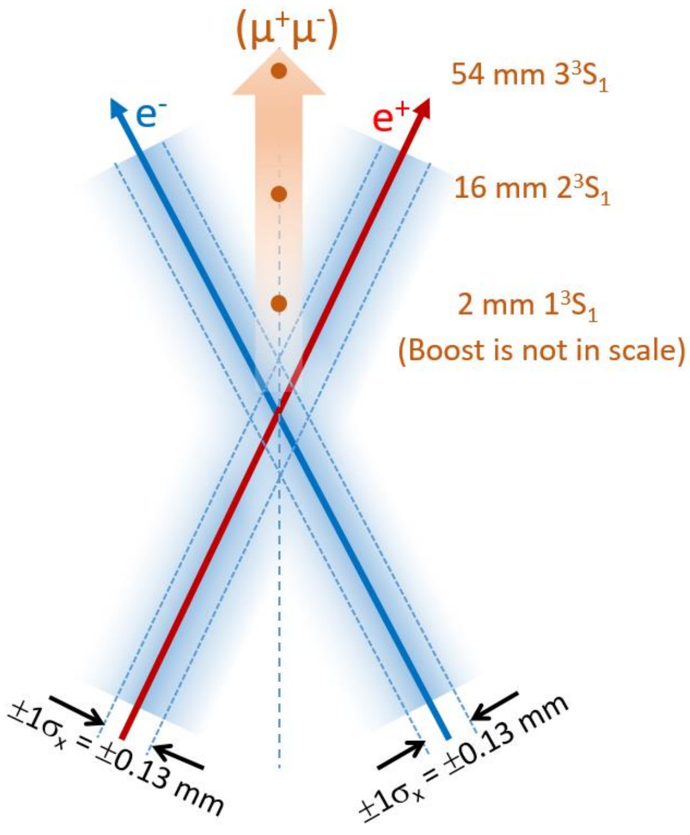


$\nu_x = 4.43$
$\nu_y = 3.37$

Interaction region

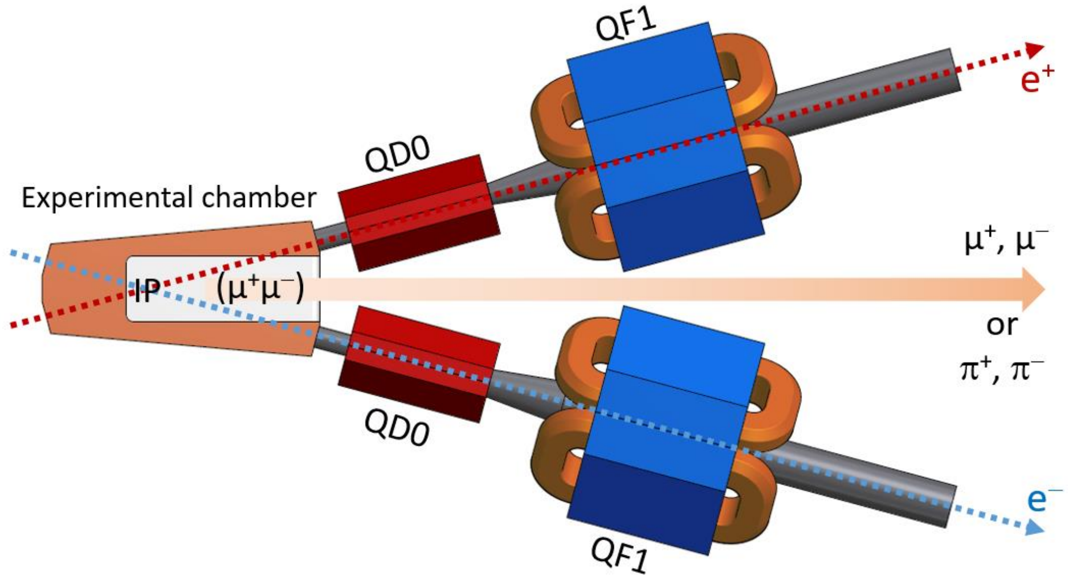
- Experimental chamber: flat box with 0.5-mm-thick beryllium windows on the top and on the bottom allowing passage of e$^{\pm}$ produced by the dimuonium atoms decay.
- Detector: tracking systems around the median plane, magnetic spectrometer

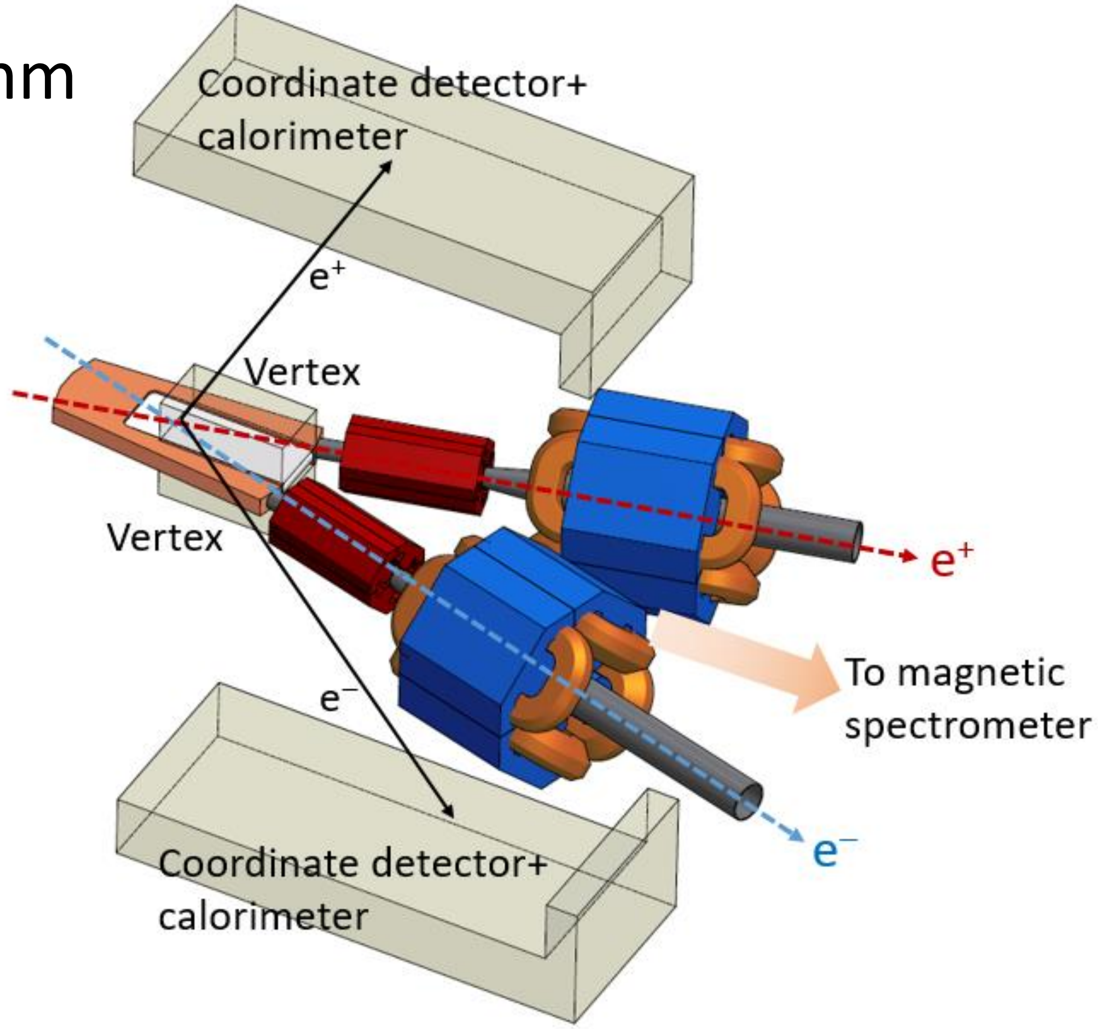




Interaction region

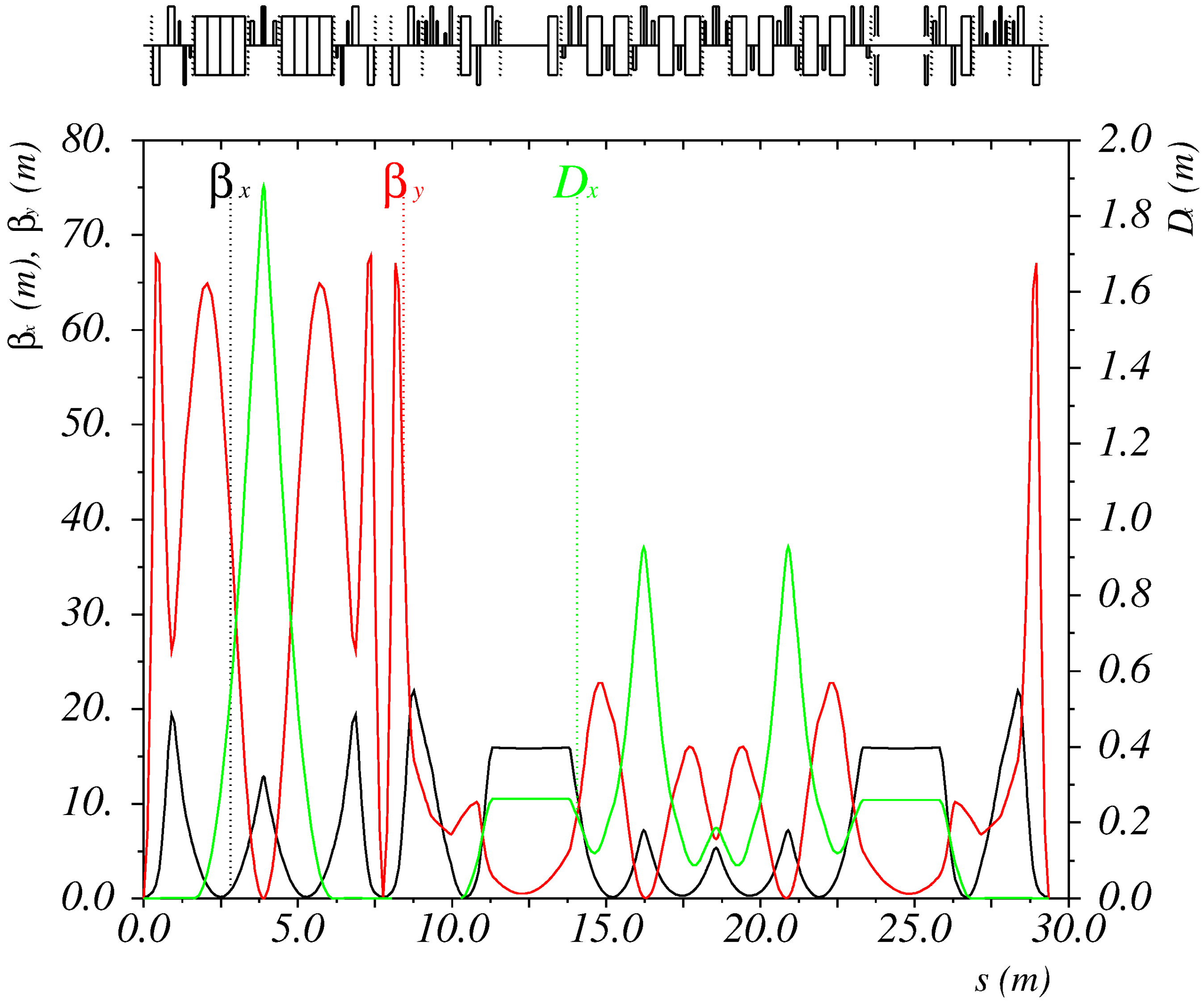
- QD0: permanent magnet, G=-35 T/m, ∅ 30mm
- QD/QF1: electromagnet





Collider: optics

Beam energy	408 MeV
Circumference	29.35 m
Momentum compaction	5.8×10^{-2}
Bunch intensity	3.5×10^{10} / 57 mA
Horizontal emittance	30 nm 65 nm (IBS)
Energy spread	3.7×10^{-4} 8.7×10^{-4} (IBS)
β_x / β_y	150 mm / 2 mm
Luminosity	2.8×10^{30} cm^{-2}s^{-1}, Nb=1 8.3×10^{31} cm^{-2}s^{-1}, Nb=30



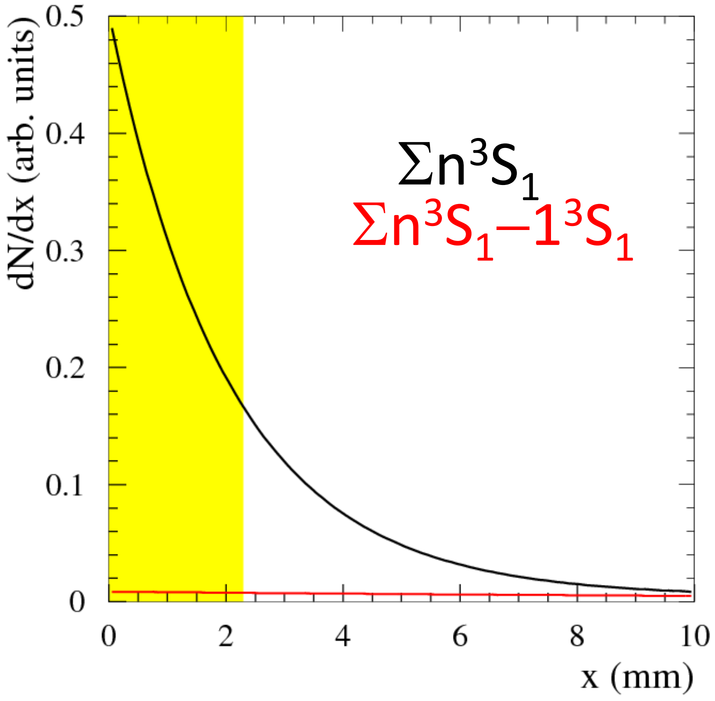
Collider: parameters

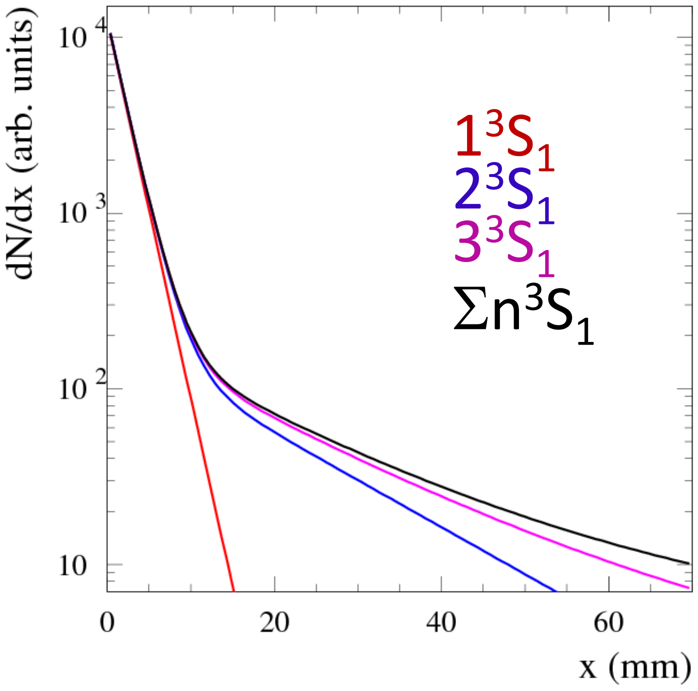
RF frequency	347.29 MHz	Beam energy	408.225 MeV
RF harmonic	34	Invariant mass (M)	211.315 MeV
RF voltage	510 kV	σ_M	383 keV
RF acceptance	2%	σ_M/M	1.8×10^{-3}
Synchrotron tune	1.96×10^{-2}	IP beam divergence	6.4×10^{-4} (hor)
Damping partition	1.6 (hor) 1.4 (lon)	Energy spread	3.7×10^{-4} 8.7×10^{-4} (IBS)
Damping times	25 ms (hor) 40 ms (ver) 28 ms (lon)	Beam-beam tune shift	2×10^{-6} (hor) 1.1×10^{-3} (ver) -2×10^{-3} (lon)
Bunch length	5.1 mm 12 mm (IBS)	IP beam size at IP	97 μm (σ_xIBS) 264 μm ($\sigma_x/\sqrt{2}\cos\theta$)

Dimuonium production and distribution

- Detection efficiency is about 15% (2 IPs)
- $\beta\gamma c\tau = 2.03\ mm$
- $\sigma_x(IP) = \sigma_x/\left(\sqrt{2}\cos\theta\right) = 280\ \mu m$
- Detector vertex resolution is 150 μm
- Total $\sigma_{vtx} = 320$ μm
- 6.25 σ background suppression with vertex position x>2 mm

$\mu^+\mu^-$ rate		1 hour	4 months
$x > 2$ mm	1S/2S/3S	4.7/1.4/0.5	13k/4k/1k





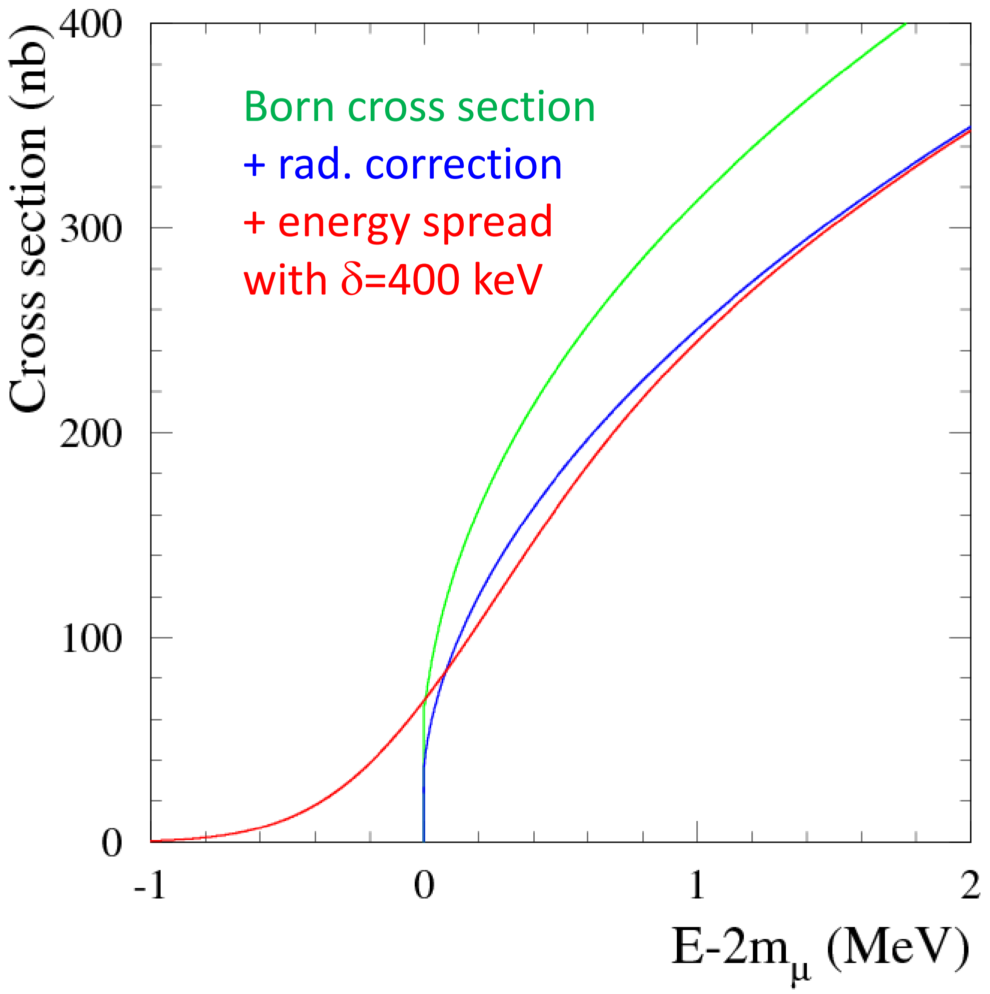
Experiments: what can we measure?

- From the fit of the decay vertex distribution
  - *dimuonium production rate (Γ_{ee}) of 1S (2% for 10^7 s), 2S(15%), 3S(30%)*
  - *dimuonium decay lengths with the same accuracy*
- Dimuonium interaction with a thin foil (30μm Al) allows
  - *measurement of the breakup probability*
  - *measurement 1S-2P transition probabilities*
  - *2P lifetime*
- Laser spectroscopy (?)
  - *ΔE(2S-2P) (laser $\lambda \approx 100\mu$m)*
  - *2P lifetime*

Experiments: $e^+e^- \to \mu^+\mu^-$ near threshold

Coulomb interaction in the final state leads to nonzero cross section at the threshold; therefore,

- Background-free measurement of the cross section near the threshold, requires magnetic spectrometer
- Precision measurement of the SSSG-factor
- C.M. energy and its spread calibration
- The same technique may be used for $e^+e^- \to \pi^+\pi^-$



Experiments: 15° crossing angle

- This region (c.m. 550-960 MeV) of ρ and ω resonances is important for SM $(g\text{-}2)_\mu$ calculation
- $e^+e^- \to \pi^+\pi^-$ cross section measurement with unlimited statistics
- Precision measurements of other hadronic cross sections ($e^+e^- \to \pi^+\pi^-\pi^0, \pi^0\gamma, \eta\gamma, \pi^0\pi^0\gamma, 4\pi, \cdots$)
- Rare processes $e^+e^- \to \eta, \eta'$
- Two-photon processes $\gamma\gamma \to \pi^0, \pi\pi, \eta$
- Measurement of meson-photon transition form factors

Reverse beam: 15° crossing angle

Beam energy	283.59 MeV (η)	495.78 MeV (η')
Invariant mass (M)	547.86 MeV	957.76 MeV
σ_M (σ_M/M)	420 keV (7.7×10^{-4})	580 keV (6.1×10^{-4})
Energy spread	2.8×10^{-4} / 10.6×10^{-4} (IBS)	4.8×10^{-4} / 8.4×10^{-4} (IBS)
IP beam divergence (hor)	8.3×10^{-4}	7.1×10^{-4}
Horizontal emittance	11.4 nm / 105 nm (IBS)	34.8 nm / 75 nm (IBS)
Bunch length	3.7 mm / 14.2 mm (IBS)	6.3 mm / 11 mm (IBS)
Beam-beam ξ (h/v/l)	3×10^{-4} /1.4×10^{-2} /-2×10^{-3}	3×10^{-4} /1.3×10^{-2} /-2×10^{-3}
Synchrotron tune	1.67×10^{-2}	1.71×10^{-2}
Luminosity (Nb=1 / 30)	3.3×10^{31} / 9.9×10^{32}	5.2×10^{31} / 1.5×10^{33}

Conclusion

- Collider to observe and study bound state of ($\mu^+\mu^-$)
  - *two rings, large crossing angle*
  - *circumference 29 m, not expensive to build and operate*
  - *luminosity 8×10^{31} $cm^{-2}s^{-1}$*
- Reverse of the beam allows experiments in 500-1000 MeV central mass energy range
- Geometry is optimized to fit the present hall.
- Dynamic aperture and energy acceptance are sufficient for injection and beam life time.
- Details are in https://doi.org/10.1051/epjconf/201818101032
https://pos.sissa.it/314/810/pdf and https://arxiv.org/abs/1708.05819
- We started manufacturing of the collider components.

We are open for collaboration and experiments proposals