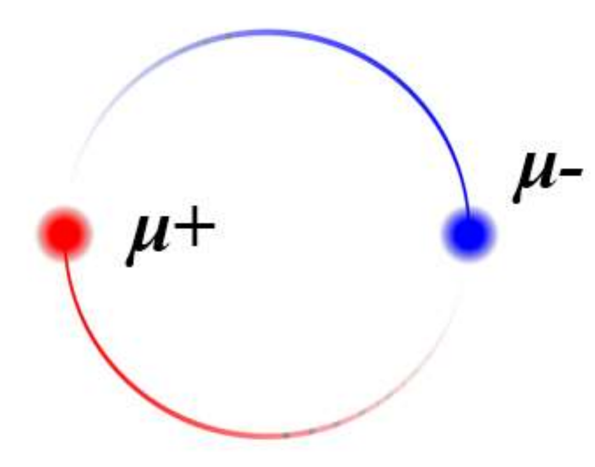

Options for DIMUS: Di-Muon-Spectroscopy Collider

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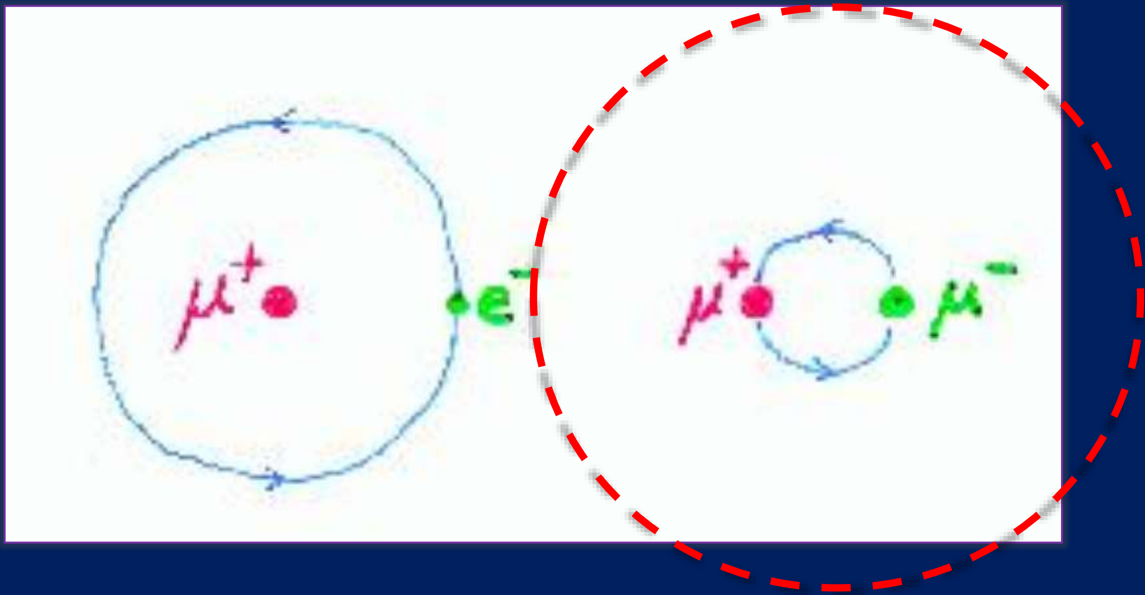
LCWS 2023 Workshop, SLAC

May 18, 2023

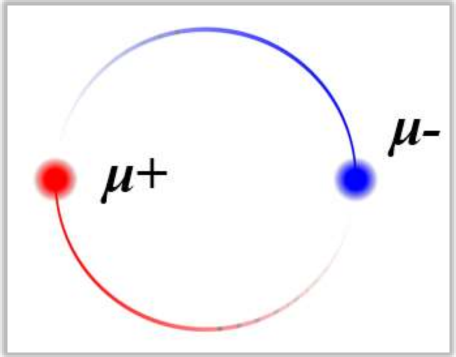
https://arxiv.org/abs/2203.07144

1. The need: Di-Muonium (True Muonium)

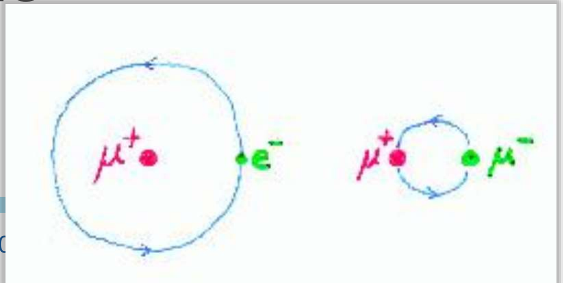


Dimuonium - a bound state of μ+ μ- pair

- Two-lepton system described by QED
- There are 6 leptonic atoms:
  - positronium (*e*+*e*-),
  - muonium (μ +e-), dimuonium (μ+μ -),
  - tauonium(τ+*e*-), tau-muonium (τ+μ-), ditauonium (τ+τ-).
  - **Only positronium and muonium are observed!**
- Dimuonium is more compact system than the positronium and muonium



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



Fundamental Physics

- Observation of dimuonium would be a significant discovery.
- QED tests (dimuonium ≠ positronium x m_e/m_μ)
- Muon sector anomalies:
  - About 4.2 sigma difference between the $(g\text{-}2)_\mu$ SM prediction and measurement (soon)
  - Proton/deuteron radius puzzle
  - Hints of lepton-universality violation in rare *B* decays:

  $B+ \rightarrow K+e+e-$ and $B+ \rightarrow K+\mu+\mu-$ (@SuperKEKB)
- Very complex experimental task → challenge for machine design → challenge for experimentalists → development of new methods

DIMUS Collider

Threshold production: E_cm=211 MeV

- *e+e- →(μ+μ−)[n3S1] → γ∗ → e+e−*

is allowed and has a rate and precision spectroscopy sensitive to vacuum polarization corrections

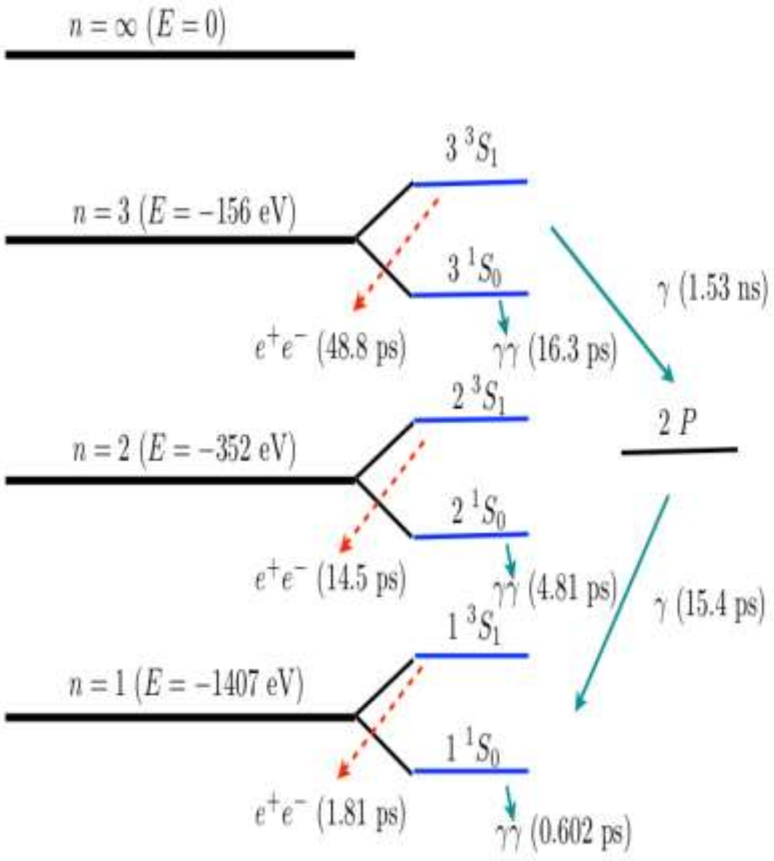
- *(μ+μ−)* has a lifetime of 1.81 ps in the 3S1 state (decaying to e+e−)

✦ Other Physics: High statistics measurements:

- e+e−→ mu+mu−
- e+e−→ pi+pi-

✦ Other hadronic x-sections:

- e+e−→ 3pi
- e+e−→ pi0+gamma
- e+e−→ eta+gamma
- e+e−→ 4pi



G. 1: True muonium level diagram (spacings not to scale).

Signal and Background

- e+e- → TM → e+e-
- The primary background is Bhabha events
- Even for delta(Ee) ~10 keV, the signal cross-section is about 5 nb… Bhabha ~ 22,000 nb → S/B ~1/4,000
- Suppress backgrounds by producing muonium moving

✦ For Dimuonium: beta* gamma* ctau = 2 cm

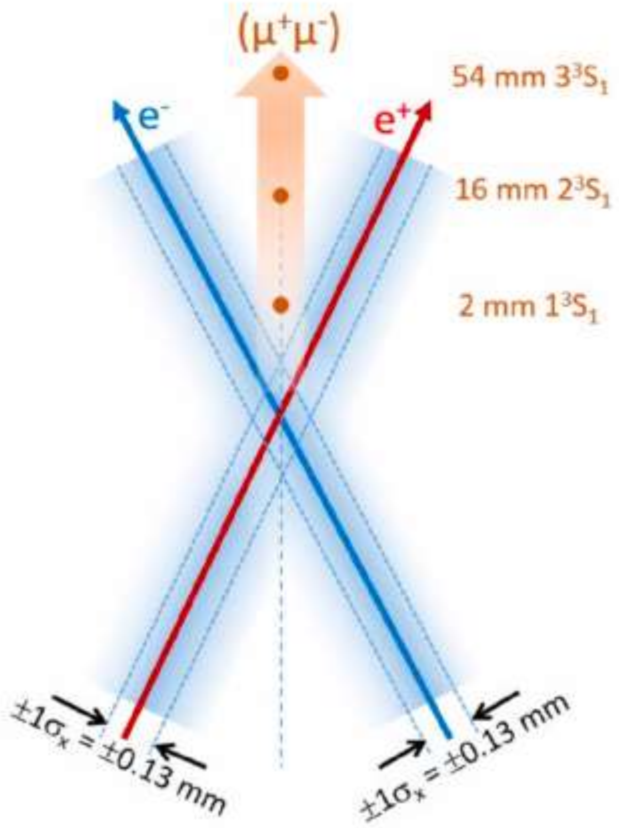
✦ Interaction region spread 300 - 400 microns

  - Detector resolution can be negligible (<100 microns)
  - Total vertex resolution <400 microns

✦ Requiring z > 2 cm would suppress Bhabba events

- Prompt background free after the cut

✦ Extract 1S/2S/3S fractions from the vertex position

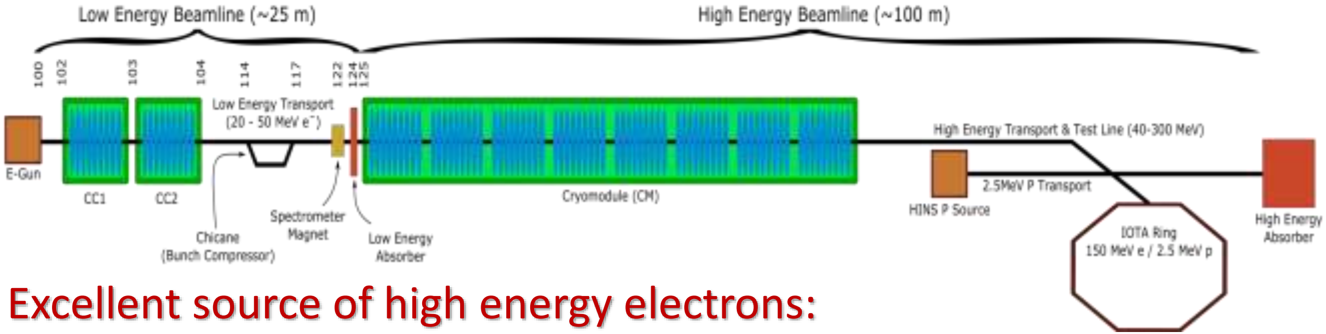


A collider with a large crossing angle (eg 75 deg) was proposed by S.J.Brodsky and R.F.Lebed in Phys. Rev. Lett. 102, 213401 (2009)

2. Possibility : Fermilab FAST/IOTA

IOTA/FAST Facility for Accelerator and Beam Physics R&D

Beams: 5 MeV e-, 50 MeV e-, 100-300 MeV e-, ring and 2.5 MeV p+



Excellent source of high energy electrons:

eg 3000 bunches x 5 Hz x 2e10 = 3e14 *e-/s*

at 1% conversion → 3e12 *e+/s*

DIMUS will probably need much less

eg 200 bunches x 1 Hz x 2e10 = 4e12 *e-/s*

at 1% conversion → 4e10 *e+/s*

Efficient linac – now upto 300 MeV

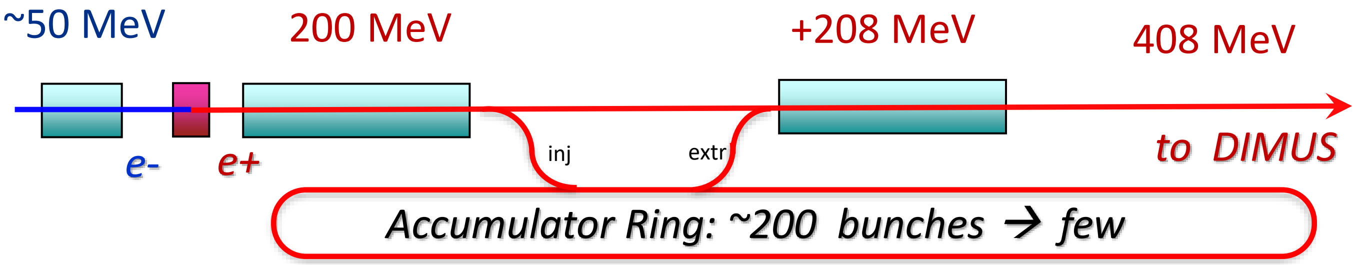
DIMUS will need extra ~108 MeV → total of 408 MeV

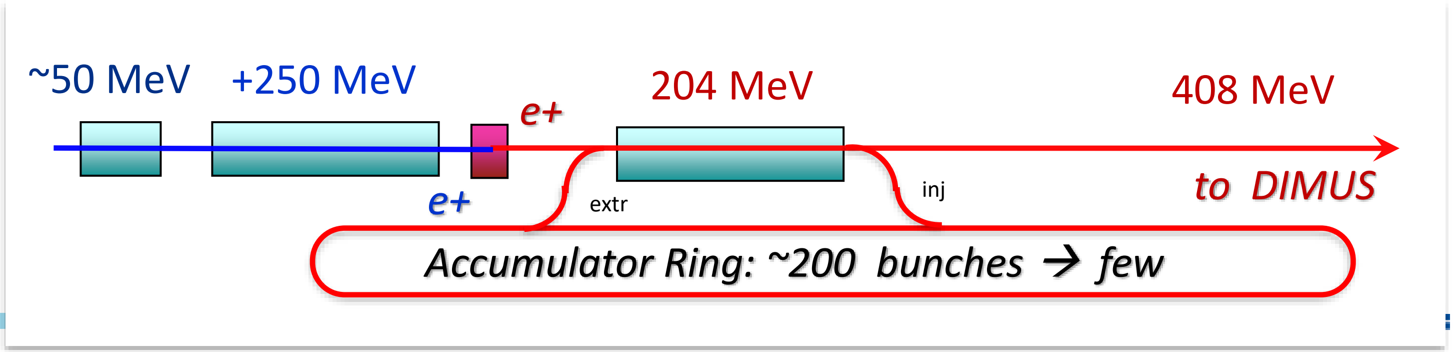
Infrastructure and expertise

IOTA proton injector

Positron Production Options

- Need (at least) two linacs:
  - Accelerate electrons (50… 300 MeV)
  - Convert them on tungsten target
  - Accelerate positrons which then go to a damping ring

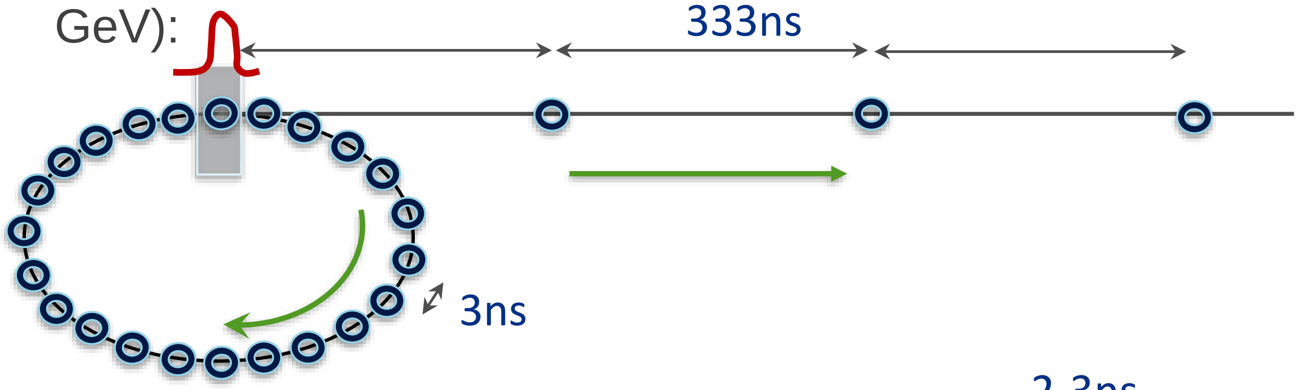




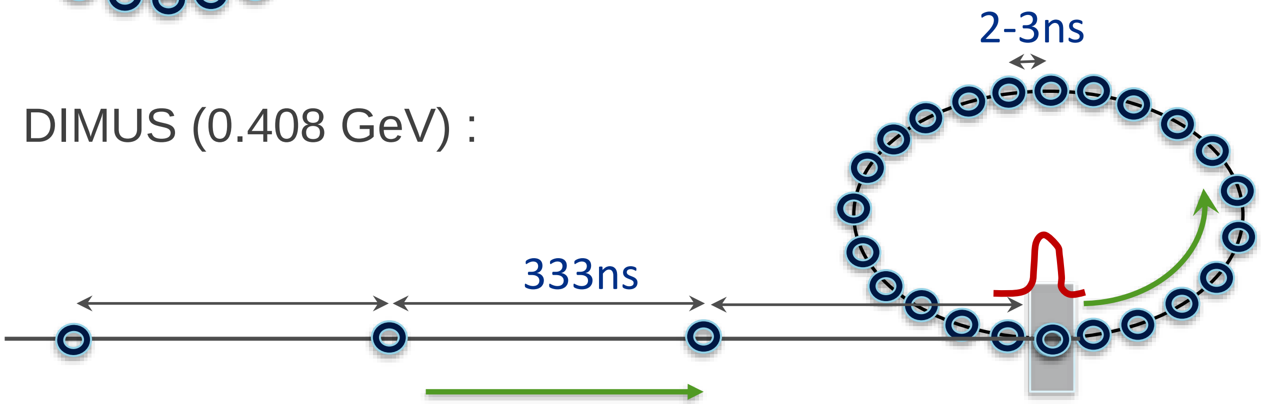
Fermilab

Very Fast Kickers

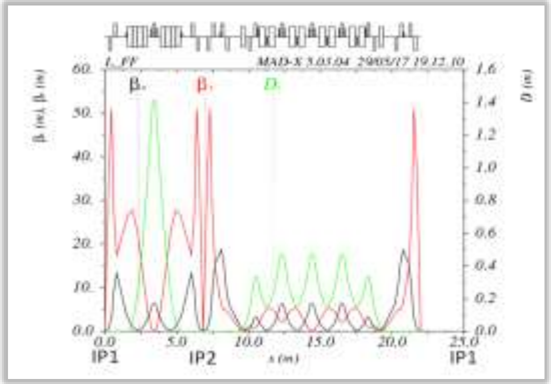
- ILC (5 GeV):

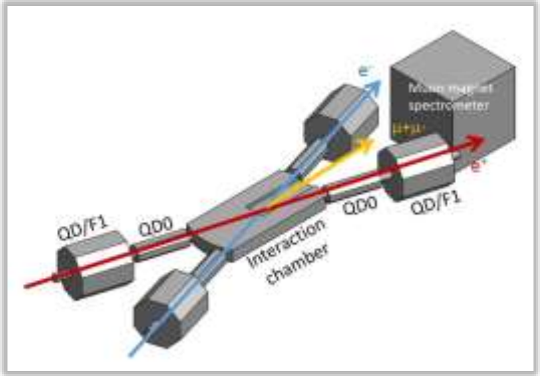


- DIMUS (0.408 GeV) :

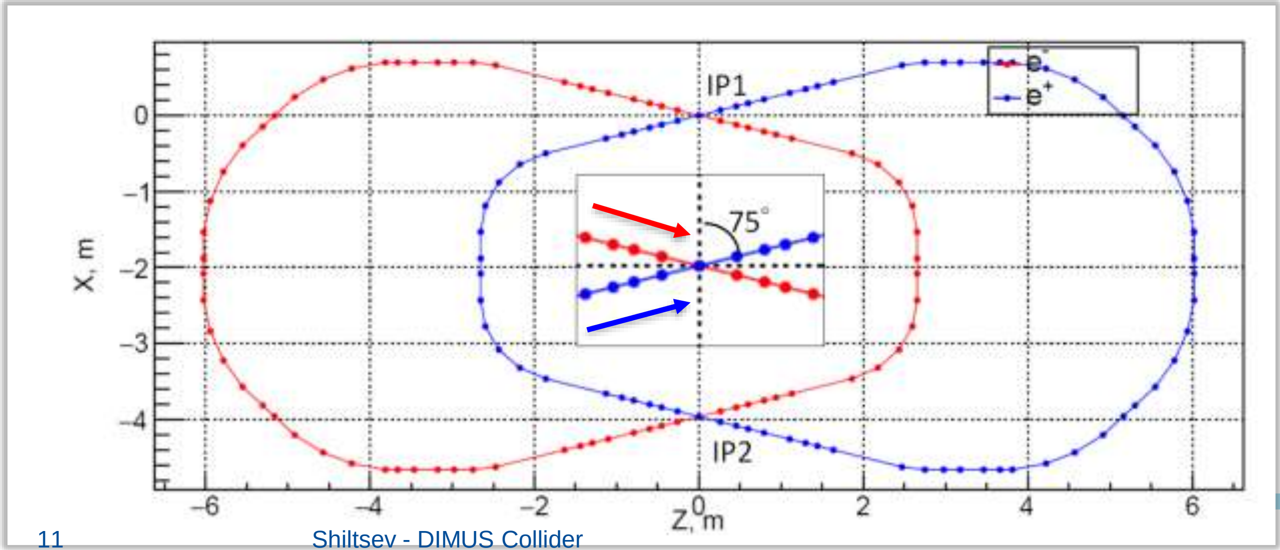


Novosibirsk "Mu-Mu-Tron" Design

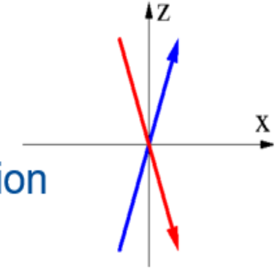




E_{beam} of	408 MeV
E_{CM}	211 MeV
Circumference	23 m
Bunch intensity	3.5×10^{10}/73 mA
Number of bunches	20
σ_x at IP	102 μm
σ_y at IP	0.84 μm
σ_z at IP	11 mm
L_{aver}	8×10^{31} cm^{-2}c^{-1}



Also possible – collisions in "reverse" direction (at 15º)

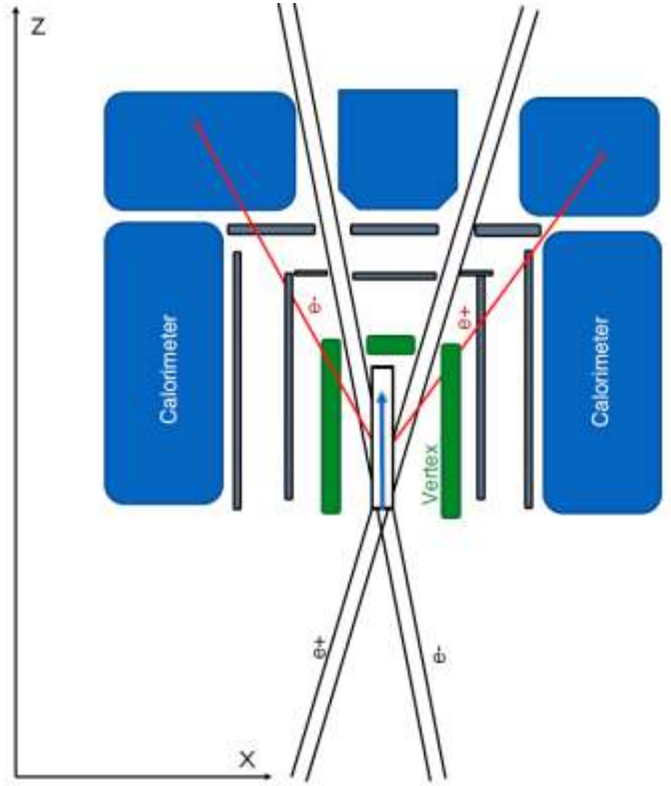


A.Bogomyagkov, et al, arXiv:1708.05819; *EPJ Web. Conf* 181, 01032 (2018)

DIMUS at FAST/IOTA Will Need (New Systems):

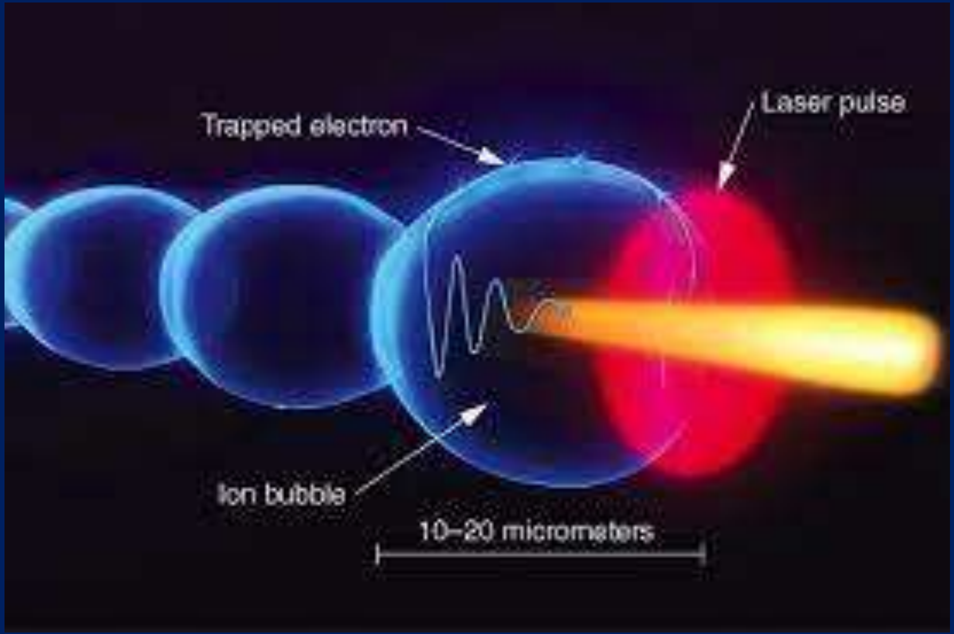
- Second 1.3 GHz SRF CM, so the final energy 408 MeV
  - ~200 *e*- bunches 2e10 each, 333ns apart for *e*+ production
  - 40 *e*- bunches 2e10 each for collider
- Positrons:
  - Conversion/collection/acceleration (200 *e*+ bunches 2e8 each, 333ns apart)
  - *C*=120 m 204 MeV storage ring accumulator (200-204 MeV)
  - Inject 200 *e*+ bunches into accumulator (damping) ring 2 ns apart (400 ns ring)
  - After sub-second damping time combine 200 *e*+ bunches into one with 4e10 *e*+
- Fast extraction/injection kickers 2-3 ns (0-to-0), few kV
- Collider e+e- rings (2 x 408 MeV, 23 m circumference each)
  - Bunches accelerated to 408 MeV injected into 23 m long (~80 ns) DIMUS ring, to be one of ~40 *e*+/*e*- bunches (others intact)
  - *O*(1e32) luminosity and ~0.5M dimuons per year

Detector

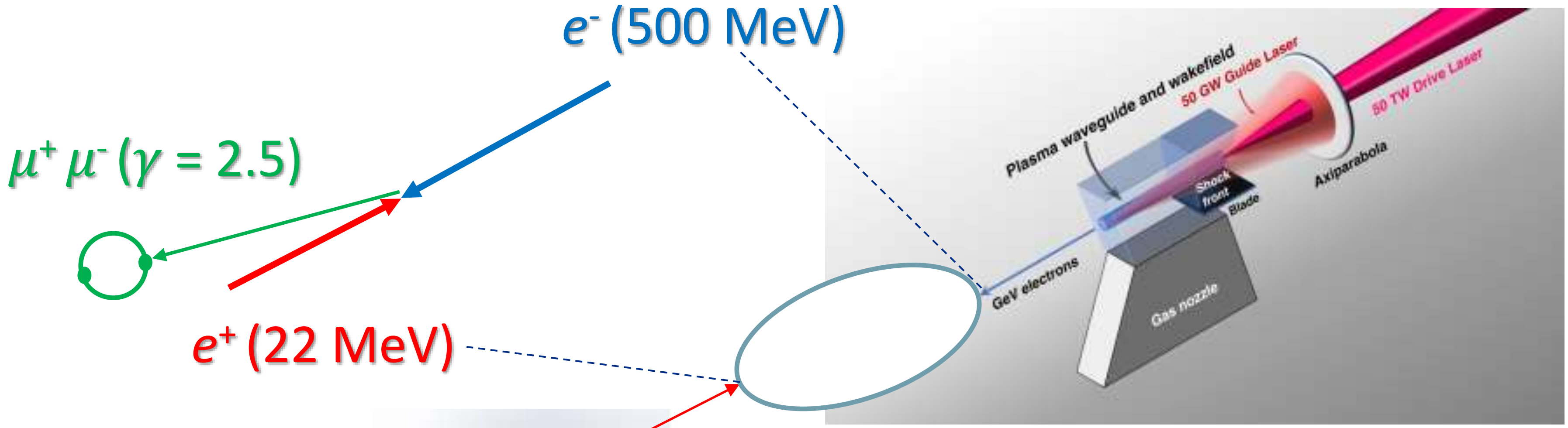


- Vertex: Pixelated silicon vertex detector: <50 microns
- Crystal calorimeter with excellent timing and energy resolution
- Directionality: Additional 2-3 tracking layers between the vertex detector and the calorimeter. Gas based (GEM) or silicon strips
- No magnetic field necessary
- Can probably achieve 50+% acceptance per track, 25% total.
- **500k-1M signal events per year**
- Integrated radiation dose small (?)
- Devil is in the details

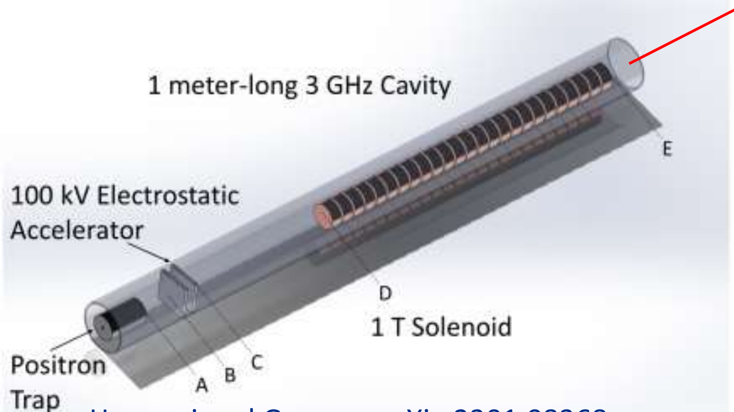
3. Compact : ABC-DIMUS



Asymmetric e+e- DIMUS: Concept



A. Dopp, *Light: Science & Applications* 11, 239 (2022)



Hessami and Gessner, arXiv:2301.08368

Asymmetric Boosted Collisions for Dimuonium (**ABC-DIMUS**)

- See for example "HALHF" https://arxiv.org/pdf/2303.10150.pdf

Boost and Luminosity

Boost

$$\gamma = \frac{1}{2}\left(\frac{2E_p}{\sqrt{s}} + \frac{\sqrt{s}}{2E_p}\right)$$

$\sqrt{s}$ = 211 MeV
E_p = 22 MeV
E_e = 500 MeV
γ = 2.5

Luminosity

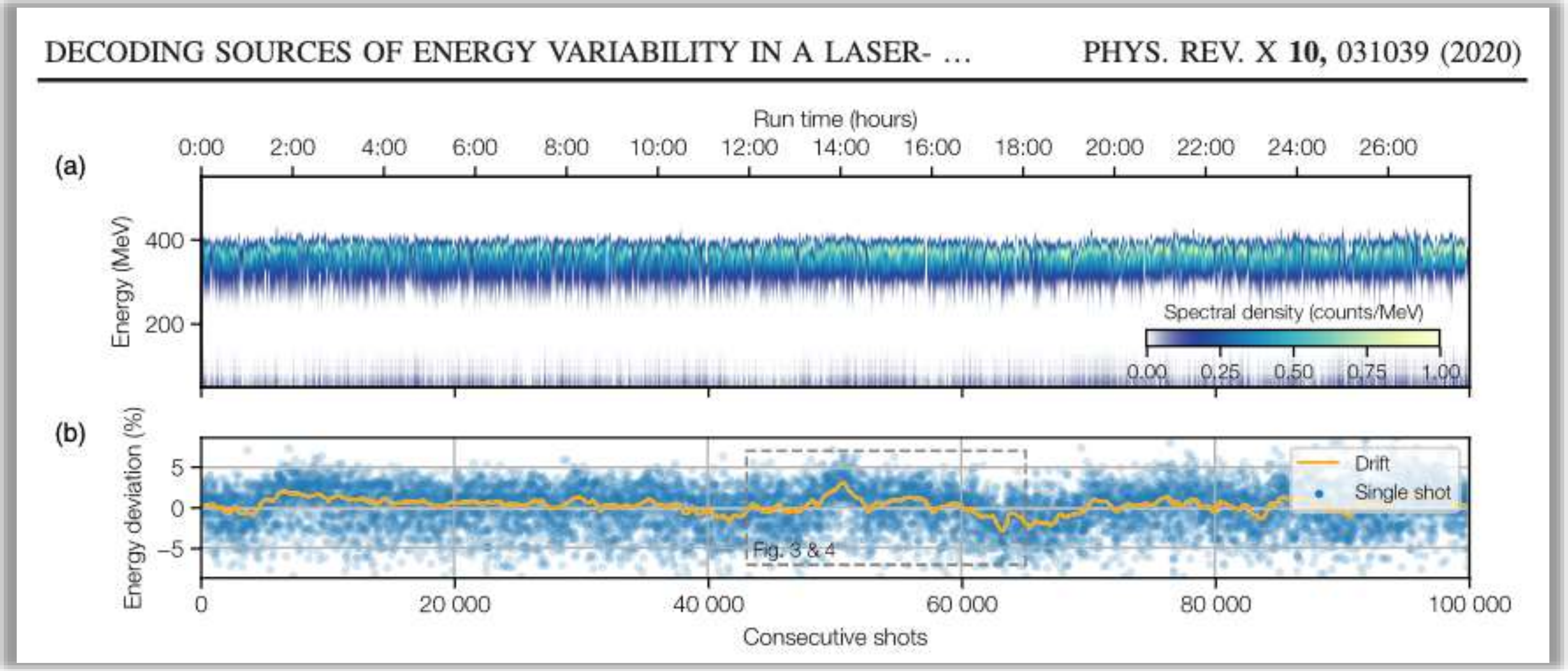
$$\mathcal{L} = \frac{f N^2}{4\pi\sigma_x\sigma_y}$$

f = 10000 Hz
N = 1E9
$\sigma_{x,y}$ = 1 um

} Future fiber laser tech

L = 1E29 $cm^{-2}\,s^{-1}$ ← Ok

Demonstrated State-of-the-art LWFA

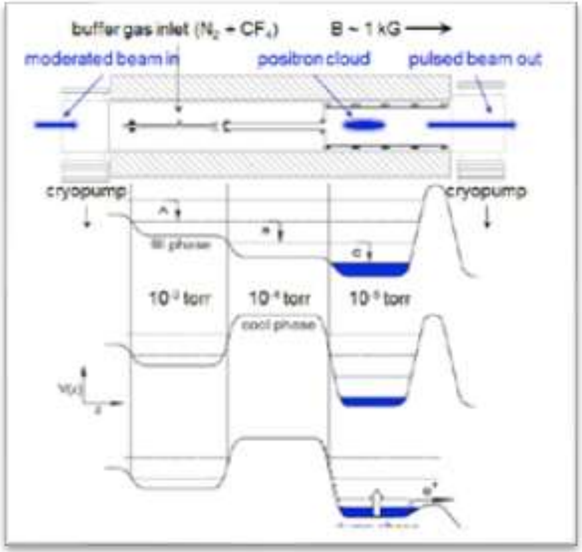


368 MeV and 25 pC at 1 Hz for 24 hours. Better single-shot results exist and work is ongoing to make these systems more robust.

Low Energy Positron Source

GBAR Positron Source

Buffer Gas Trap Schematic



Low energy positron sources are commonly employed in antimatter and material science studies.

Combine Positron Source with Accelerator

(Under study) possibility of accelerating positron beams from the trap:

- https://arxiv.org/abs/2301.08368

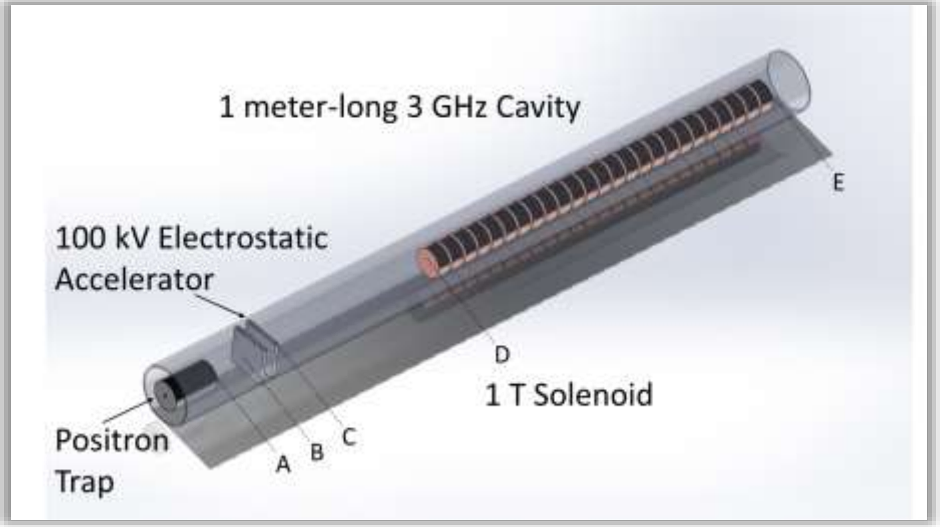
Advantages includes:

- Small thermal emittance ✓
- Compact size/low cost ✓
- Polarized positrons from ^{22}Na ✓

Disadvantages:

- Very-low positron rate ✗
- Low-energy/long bunch ✗

The beam is magnetized.



A Compact Source of Positron Beams with Small Thermal Emittance, R. Hessami and S. Gessner, arXiv 2301.08368 (submitted to PRAB)

This novel, low-cost positron source can enable accelerator physics studies and ultrafast material science research.

Thanks for your attention!

https://arxiv.org/abs/2203.07144

(Some) References:

1. DIMUS @ FNAL – P.Fox, S.Jindariani, V.Shiltsev, arxiv: 2203.07144 (subm. *JINST*)
2. 1st concept – S.J.Brodsky and R.F.Lebed, *Phys. Rev. Lett.* 102, 213401 (2009)
3. Bjorken FISR idea – J. D. Bjorken, *Lect. Notes Phys.* 56, 93 (1976).
4. μμTron – A.Bogomyagkov, et al, arXiv:1708.05819; *EPJ Web.Conf* 181, 01032 (2018)
5. 6 ns kicker – B. Grishanov, et al *NIM-A* 396(1-2) 28-34 (1997)
6. 4 ns kicker – T. Naito, et al, *PRAB* 14(5), 051002 (2011)
7. Positron sources – R.Chehab, 1992 *CAS CERN School*, 2, 643-678 (1994)

Table II

Beam energy, MeV	408
Number of particles/bunch current, mA	$3.5 \times 10^{10}/73$
Energy loss per turn, keV	2.3
Synchrotron frequency	1.71×10^{-2}
Damping time, hor/ver/longl, ms	17.3/27.3/22.1
Hor emittance (without/with IBS), nm	26/90
Energy spread (without/with IBS), $\times 10^4$	4/8.4
Longitudinal size (without/with IBS), mm	5.4/11.6
Invariant mass resolution, keV	390
Hor/ver IP beta function, mm	200/2
Hor/ver beam–beam parameter (ξ_x/ξ_y)	$2 \times 10^{-6}/1.2 \times 10^{-3}$
Longitudinal beam–beam parameter ξ_z	-2×10^{-3}
Luminosity (20 bunches), $cm^{-2}\, s^{-1}$	8×10^{31}