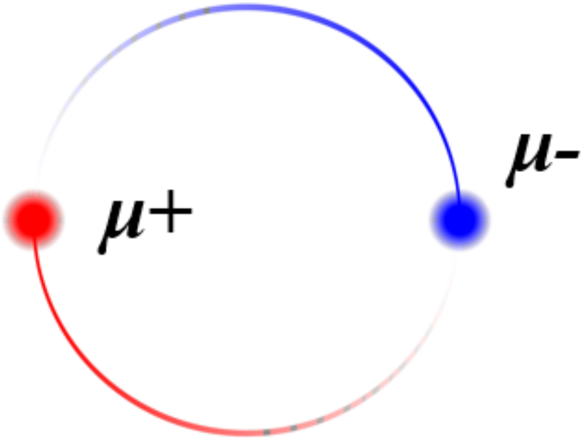
DIMUS:Di-Muononium Spectroscopy Collider



Patrick Fox (with Sergo Jindariani and Vladimir Shiltsev)

Muon Properties and Related Topics III, Snowmass

February 4, 2022

Bound States of QED

- Hydrogen atom $(p^+ e^-)$
- Positronium $(e^+ e^-)$
- Muonium $(\mu^\pm e^\mp)$
- "True" Muonium/Dimuonium $(\mu^+ \mu^-)$
- More exotic di-leptonic resonances $(\tau^\pm \ell^\mp)$,$(\tau^+ \tau^-)$
- "Molecular systems" $(e^+ e^-)(e^+ e^-)$
- Other atoms $(\pi^\pm \mu^\mp)$

Bohr atom $E_n = -\frac{\alpha^2 \mu}{2n^2}$ $r_n = \frac{n^2}{\alpha \mu}$

Higher order corrections (fine and hyper-fine) e.g. relativistic, spin-orbit, Lamb shift, spin-spin, lift degeneracy

True muonium

Rescale positronium. Mass is $2m_\mu - E_1$

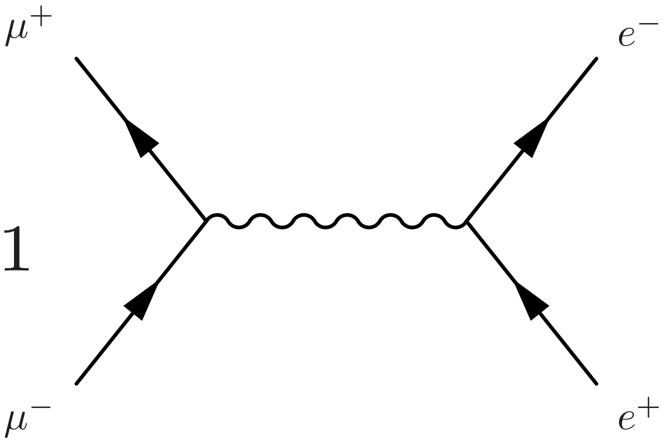
$$E_1(H) = -13.6\,\mathrm{eV} \quad E_1(e^+e^-) = -6.8\,\mathrm{eV} \quad E_1(\mu^+\mu^-) = -1407\,\mathrm{eV}$$

$$r_1(H) = a_0 = 53000\,\mathrm{fm} \quad r_1(e^+e^-) = 2a_0 \quad r_1(\mu^+\mu^-) = 530\,\mathrm{fm}$$

Unlike positronium there are fermionic decays (for S levels)

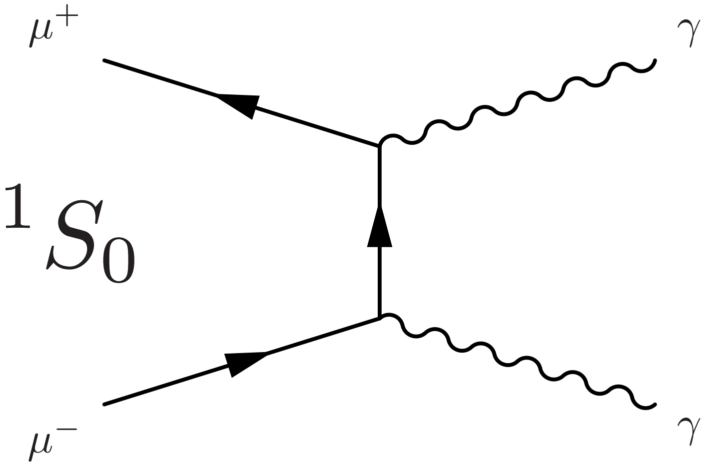
$$\Gamma \propto |\psi(0)|^2$$

n^3S_1



$$\tau = \frac{6n^3}{\alpha^5 m_\mu}$$

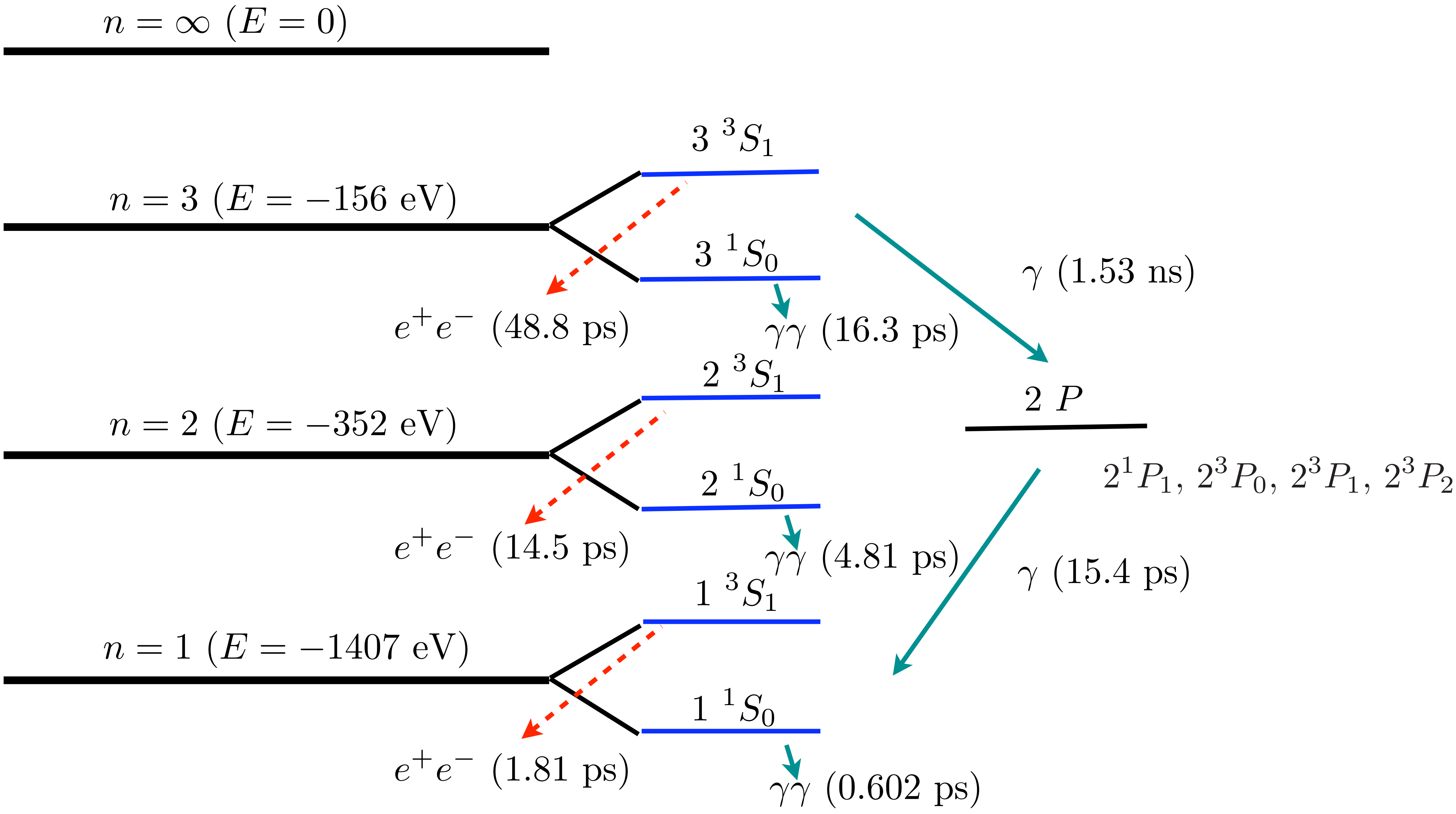
n^1S_0



$$\tau = \frac{2n^3}{\alpha^5 m_\mu}$$

$n^{2s+1}l_J$

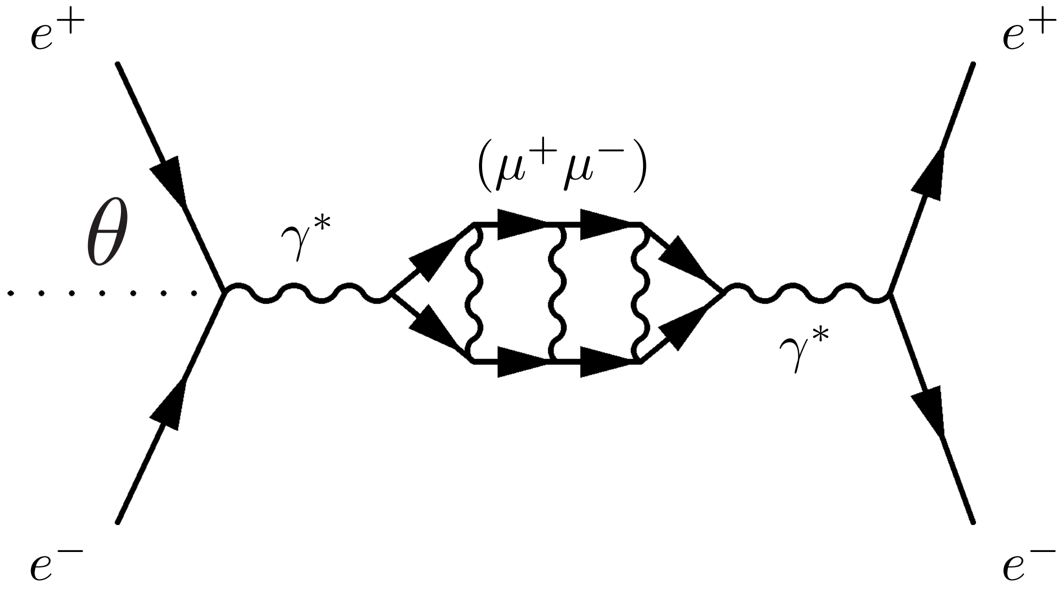
Muonium decays



[Brodsky, Lebed PRL102, 2009]

Decays/transitions short compared to muon lifetime (~2 microsec)

Muonium Production



Fool’s Intersection Storage Ring

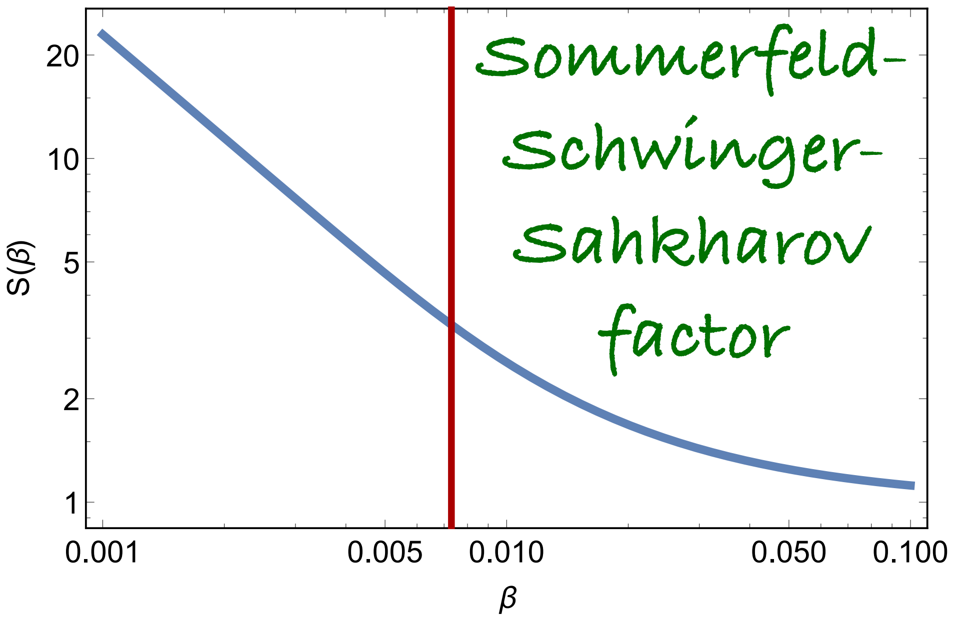
Alternative schemes included production in meson decays (eg LHCb), or radiative production (TM+gamma)

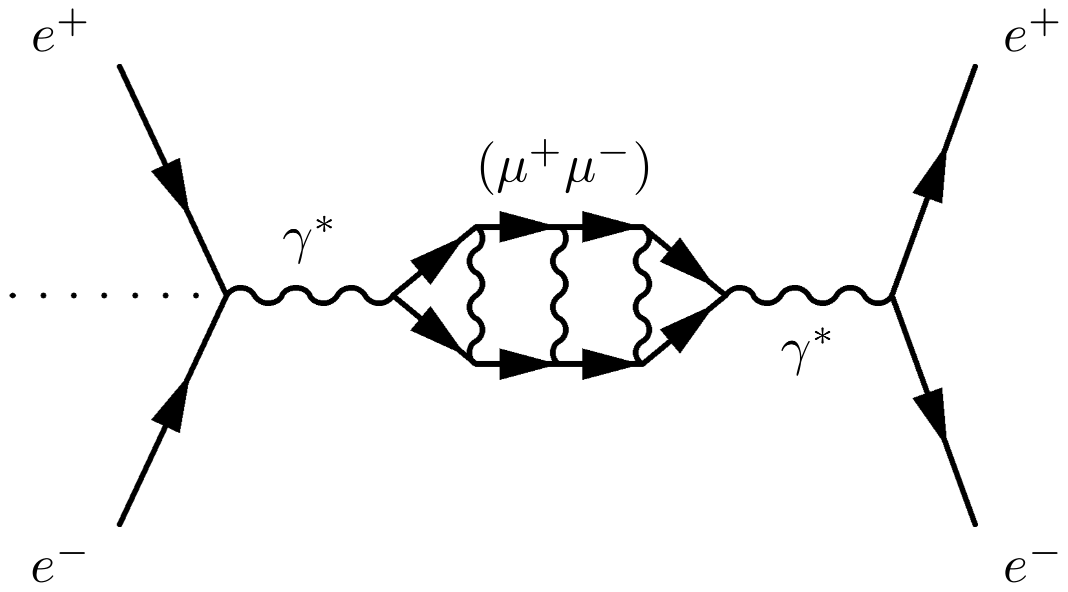
- Produces n^3S_1 states with relative rate n^{-3}
- For symmetric beam energies $p_z = \frac{2m_\mu}{\tan\theta}$ and boost $\gamma = \frac{1}{\tan\theta}$

Boost is critical for separating signal from background (Bhabha)

$$c\tau(^3S_1) \approx 0.5\,\mathrm{mm}$$

Muonium Production



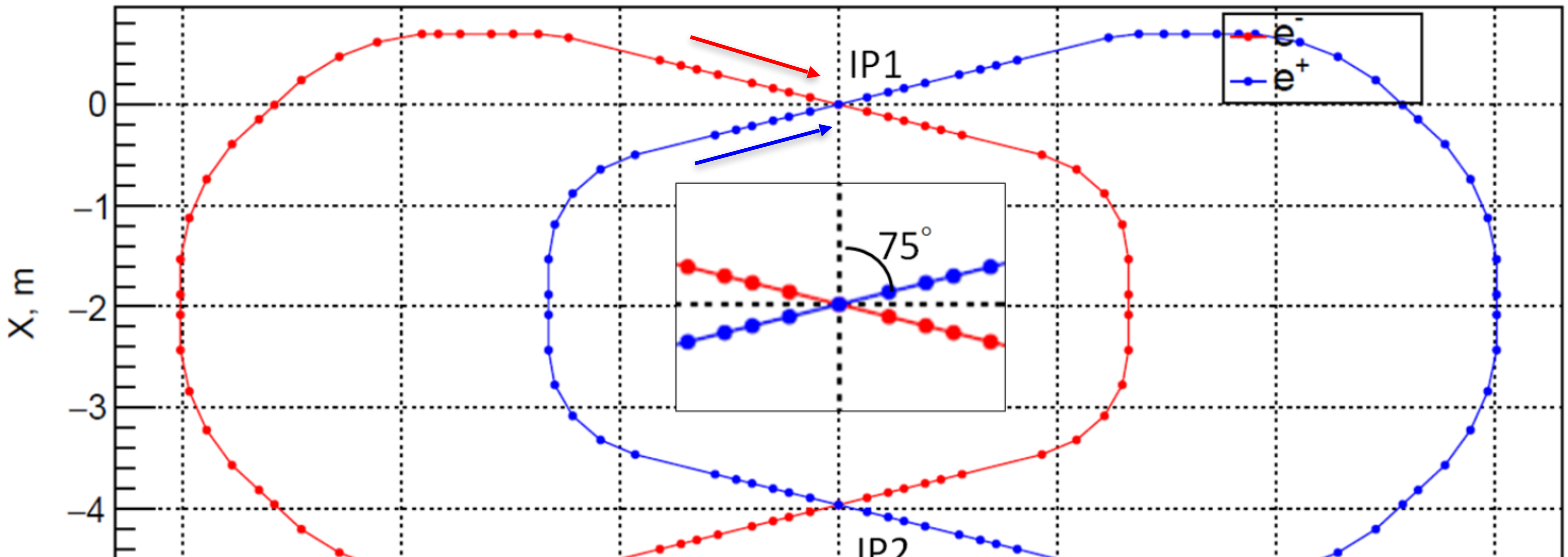


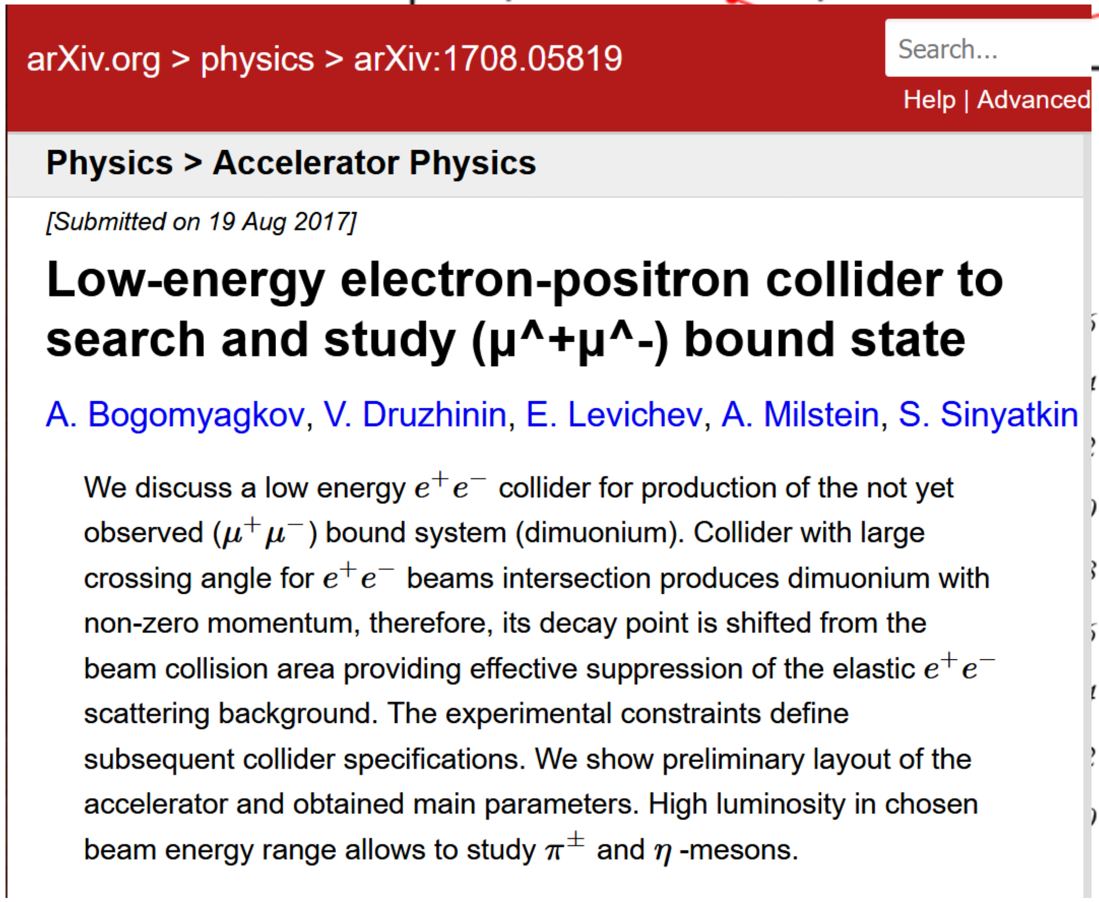
$$\sigma(e^+e^- \to \mu^+\mu^-)\big|_{\beta\approx 0} = \frac{2\pi\alpha^2\beta}{s}\left(1-\frac{\beta^2}{3}\right)S(\beta)$$

$$\sigma_{b.s} = \left(\frac{\pi^2\alpha^3}{2m_\mu^2}\right)\left(\frac{\alpha^2 m_\mu}{4\Delta E_e}\right) \sim \left(\frac{1\mathrm{MeV}}{\Delta E_e}\right)10^{-34}\mathrm{cm}^2$$

$$\frac{\sigma_{b.s}}{\sigma_{Bhabha}} \sim \left(\frac{3\pi\alpha}{2}\right)\left(\frac{\alpha^2 m_\mu}{4\Delta E_e}\right) \sim \left(\frac{1\mathrm{MeV}}{\Delta E_e}\right)10^{-4}$$

Novosibirsk “Mu-Mu-Tron” Design





arXiv.org > physics > arXiv:1708.05819

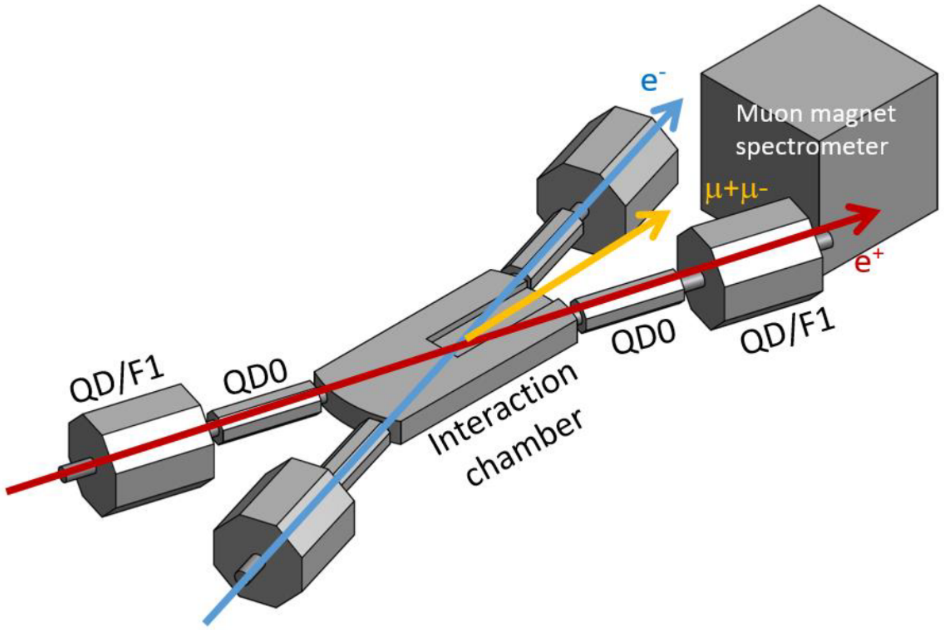
Physics > Accelerator Physics

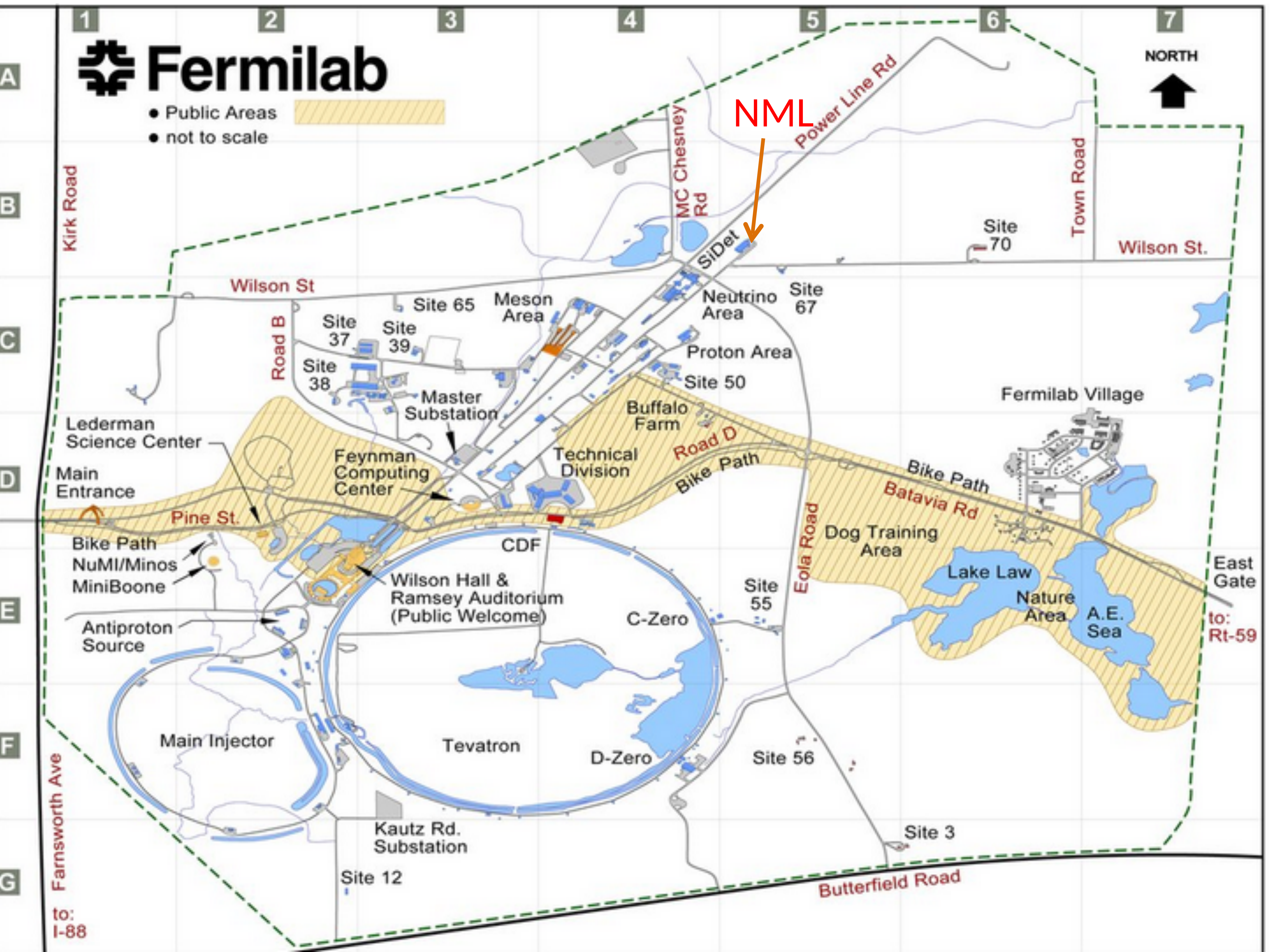
[Submitted on 19 Aug 2017]

Low-energy electron-positron collider to search and study (μ^+μ^-) bound state

A. Bogomyagkov, V. Druzhinin, E. Levichev, A. Milstein, S. Sinyatkin

We discuss a low energy e^+e^- collider for production of the not yet observed $(\mu^+\mu^-)$ bound system (dimuonium). Collider with large crossing angle for e^+e^- beams intersection produces dimuonium with non-zero momentum, therefore, its decay point is shifted from the beam collision area providing effective suppression of the elastic e^+e^- scattering background. The experimental constraints define subsequent collider specifications. We show preliminary layout of the accelerator and obtained main parameters. High luminosity in chosen beam energy range allows to study $\pi^\pm$ and η -mesons.

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Kirk Road
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Wilson St.
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Site 65
Meson Area
Neutrino Area
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Road B
Site 37
Site 39
Site 38
Proton Area
Site 50
Master Substation
Fermilab Village
Buffalo Farm
Lederman Science Center
Road D
Technical Division
Feynman Computing Center
Bike Path
Bike Path
Batavia Rd
Main Entrance
Pine St.
Eola Road
Dog Training Area
CDF
Bike Path
NuMI/Minos
MiniBoone
Wilson Hall & Ramsey Auditorium (Public Welcome)
Lake Law
East Gate
Site 55
Nature Area
A.E. Sea
Antiproton Source
C-Zero
to: Rt-59
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Kautz Rd. Substation
Site 3
Site 12
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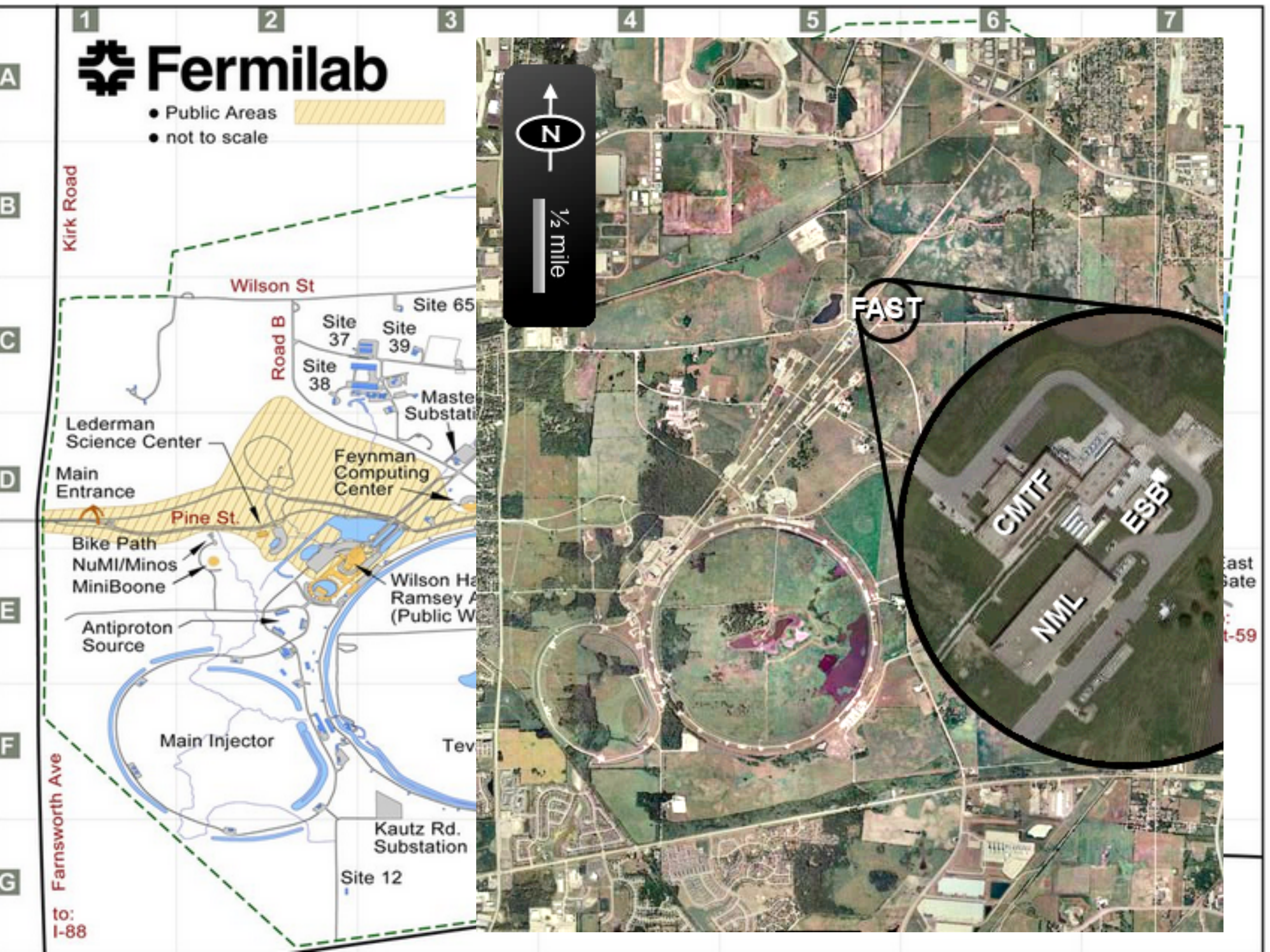
to: I-88


Fermilab
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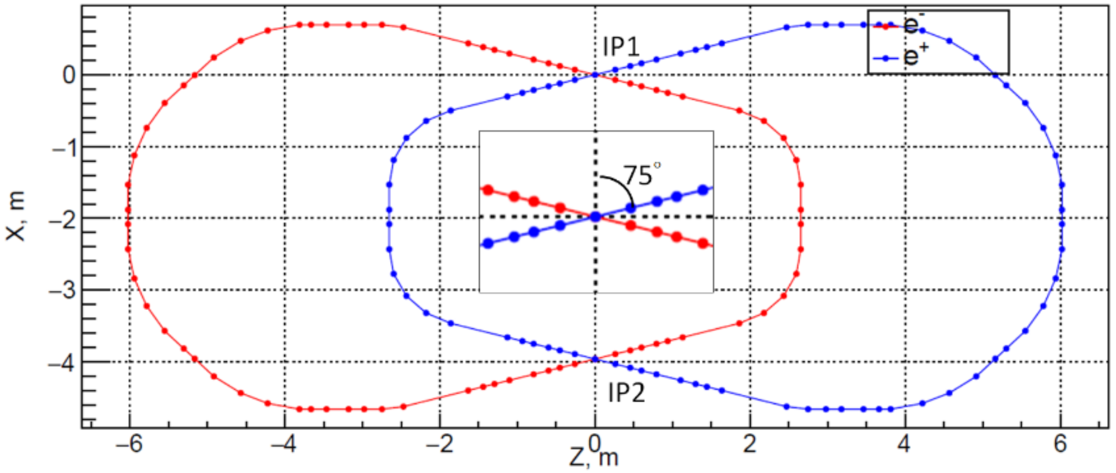
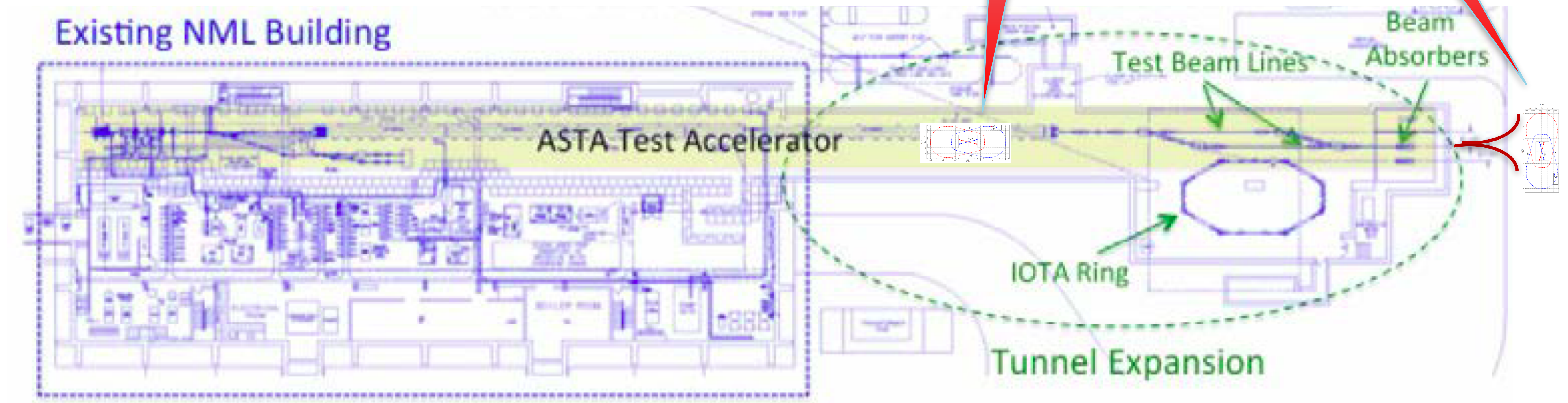
Placement of the DIMUS Collider

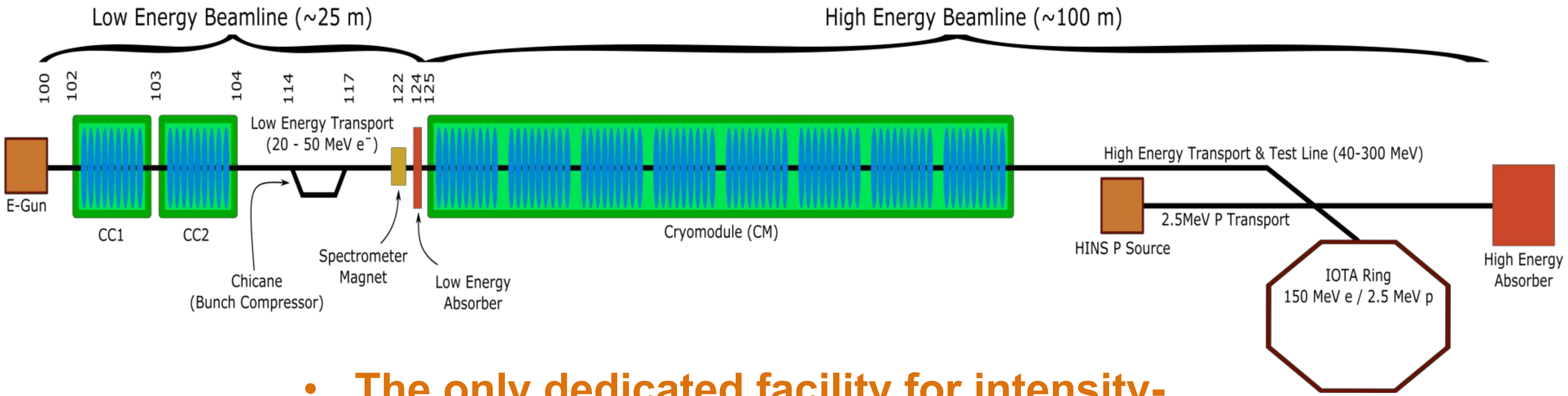


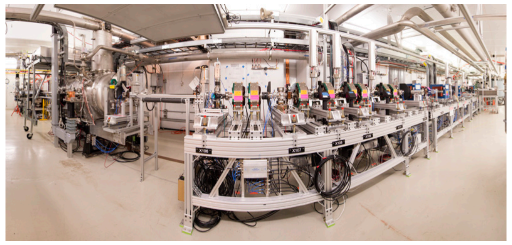
~12m x 6m



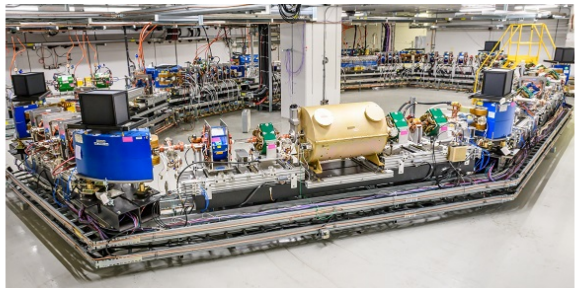
IOTA/FAST Facility for Accelerator and Beam Physics R&D

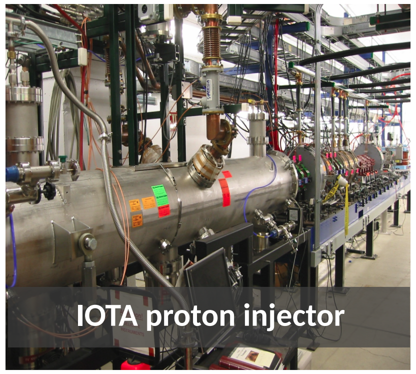
- **IOTA/FAST: 5 MeV e-, 50 MeV e-, 100-300 MeV e-, ring and 2.5 MeV p+**

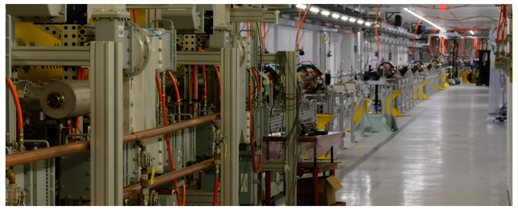




- **The only dedicated facility for intensity-frontier accelerator R&D; ranked as top facility ("Tier 1") for acc. & beam physics thrust by recent GARD review (Jul 2018)**
- ~30 Collaborating institutions
- Nat. Lab Partnerships: ANL, BNL, LANL, LBNL, ORNL, SLAC, TJNAF
- Many opportunities for R&D with cross-office benefit in DOE/SC







DiMuonSpectroscopy (DiMuS) at NML : Opportunities

- 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:
  - wide & (important) long tunnel, cryo, power, HCW, etc
  - knowledgeable people

To Covert NML into Collider Facility One Needs:

- Collider *e+e-* Rings (2 x 408 MeV)

- Second CM, so the final energy 408 MeV

- Positrons:
  - Conversion/collection system
  - Acceleration
  - Storage ring accumulator

- Fast injection kickers

The Second CryoModule

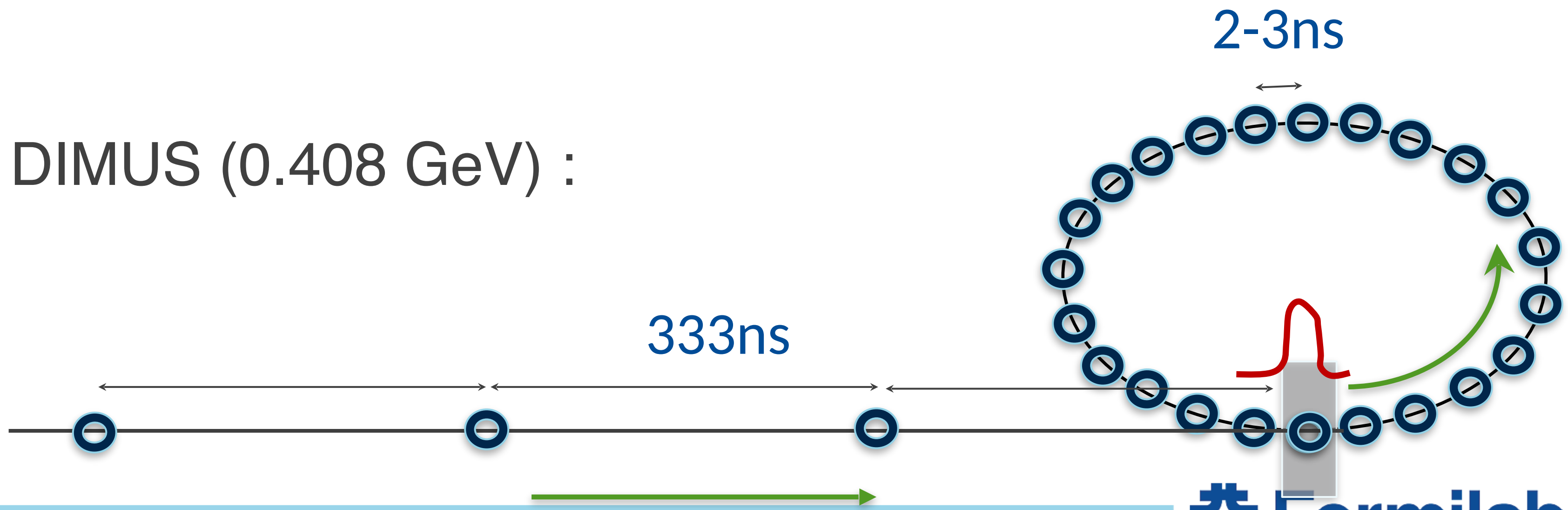
- *will be good for 250-320 MeV*
- *DIMUS might need only 208 MeV*

Positron Production - Several Options Exist

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

Will require fast kickers (similar to ILC)

- DIMUS (0.408 GeV) :



DiMuS at NML : Summary

- They can be created in *e+e-* collision with large longitudinal momentum (as they quickly decay)
  - e.g. 408 MeV/beam at 75^o
- FAST/NML is perfectly suitable for DIMUS:
  - SRF accelerators, plenty of *e-*, wide/long tunnels
  - potential for *O*(1e32) luminosity and ~0.5M dimuons per year
- Requires:
  - second SRF CM, positron production and accumulation system, collider rings, detector(s)

After production

If muonium transits material it can be destroyed

$$\sigma_{dissoc.} \approx 13Z^2\mathrm{barn}$$

If muonium exposed to intense laser it can be put into P-state

If transits regions with strong B-field, level mixing can also populate other states

Spectroscopy: measure Lamb shift, hyperfine etc
Decay lifetimes and branching ratios

New Physics

Ongoing anomalies in muon sector: g-2, muonic Hydrogen, R_K
New physics coupled to muons?

Great probe of short distances, no nuclear effects to contend with

New forces can change size of muonium, altering production/ **decay**

$$(\mu^+\mu^-) \to V^*_{NP} \to e^+e^-$$

and provide new **decay** channels

$$(\mu^+\mu^-) \to \gamma X \qquad (\mu^+\mu^-) \to XX$$

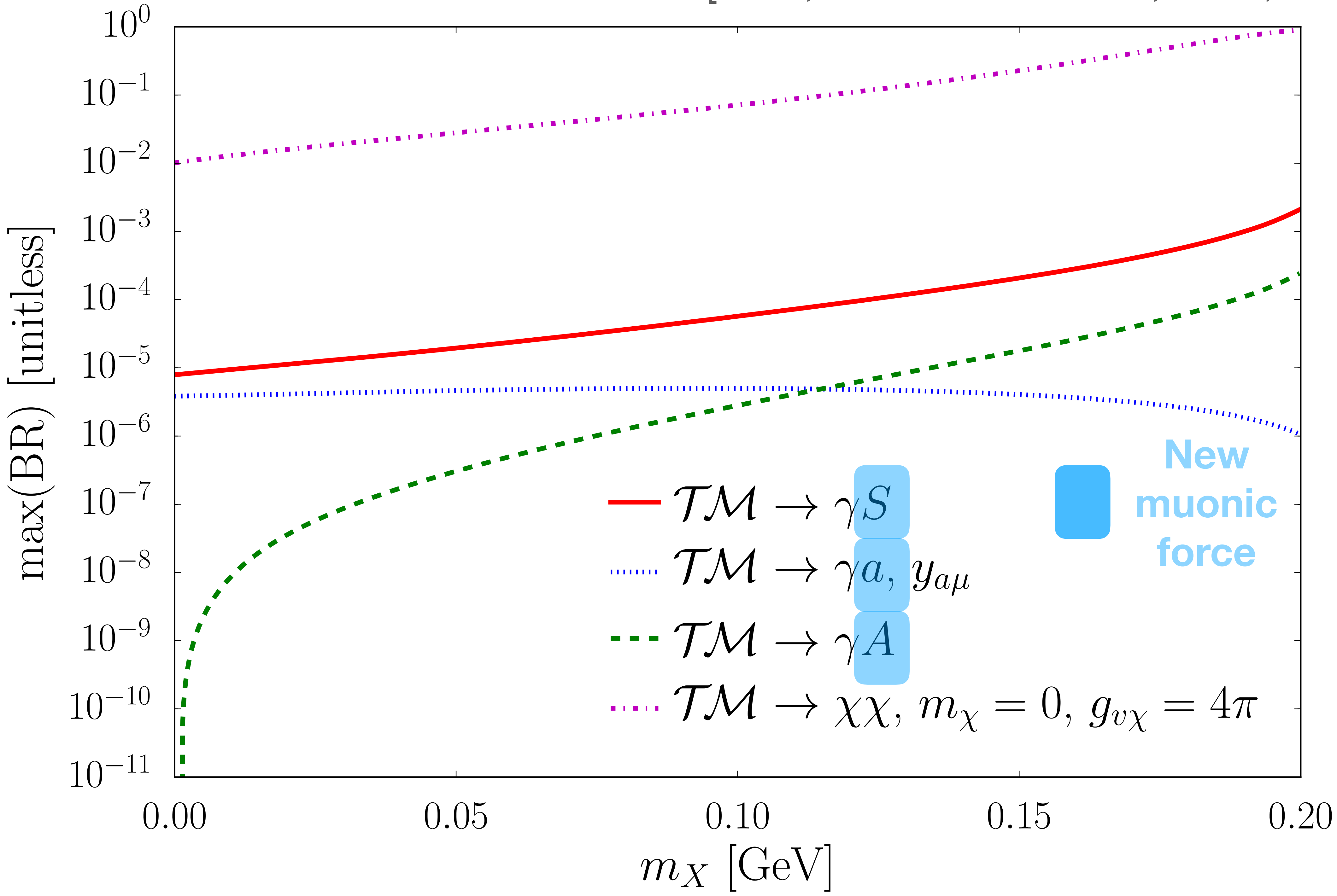
$$X \to SM\ SM$$

or change energy levels (**spectroscopy)**

2S-2P transition

Strong constraints from other measurements

New Decay Modes

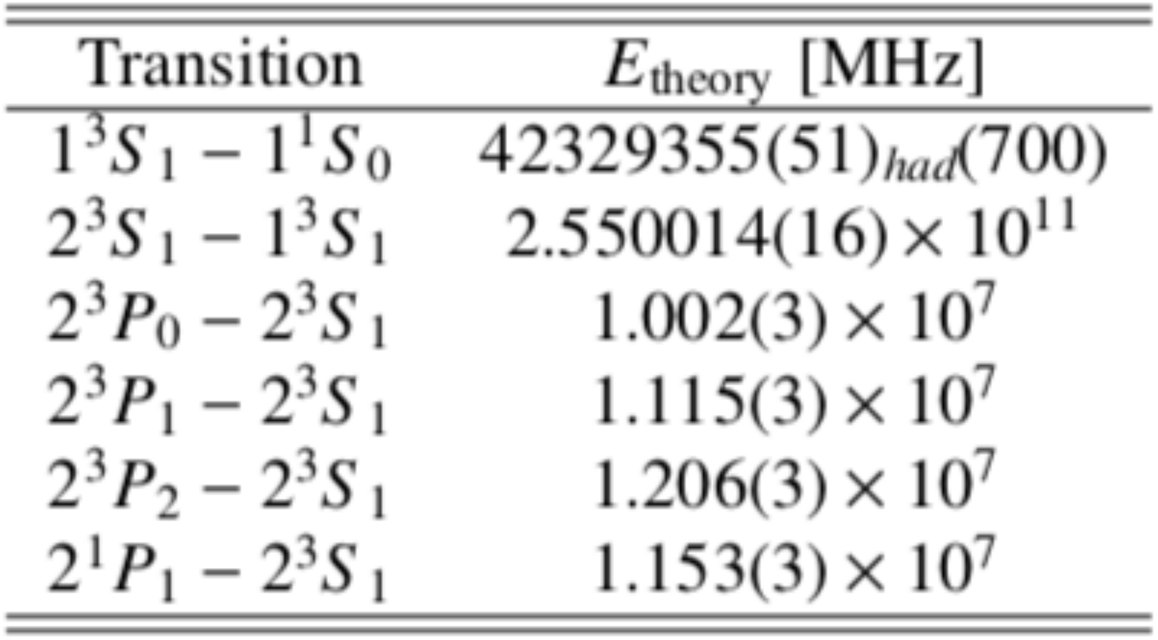


[Vidal, Ilten et al PRD100, 2019; 1904.08458]

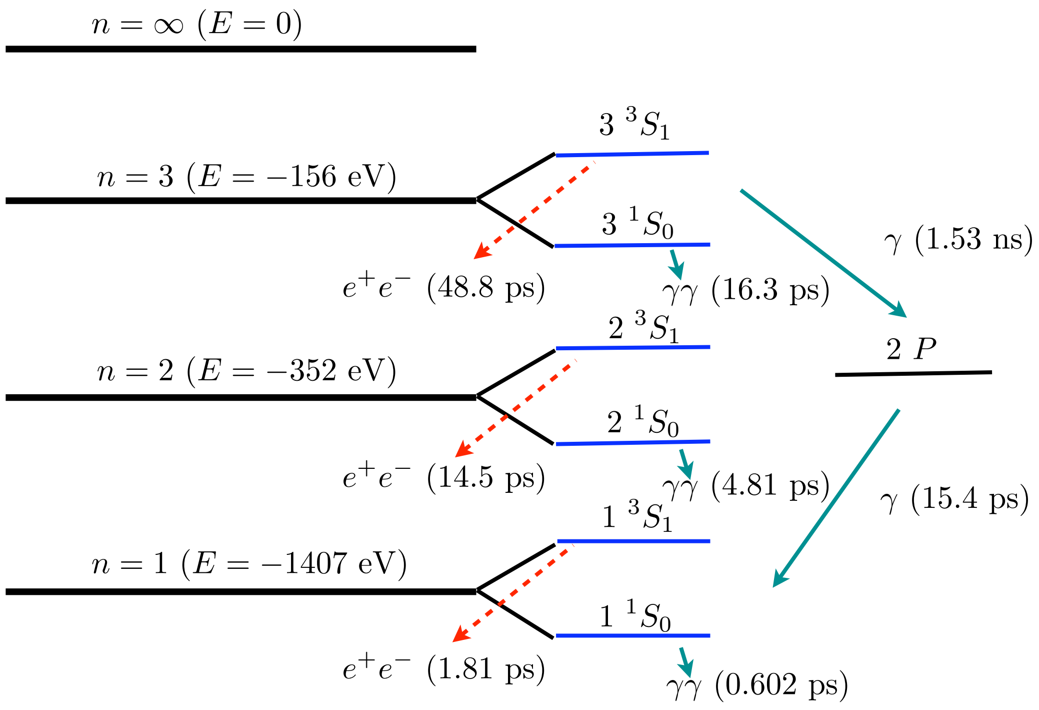
🟦 **New muonic force**

Spectroscopy

[Ji,Lamm; 1712.03429]

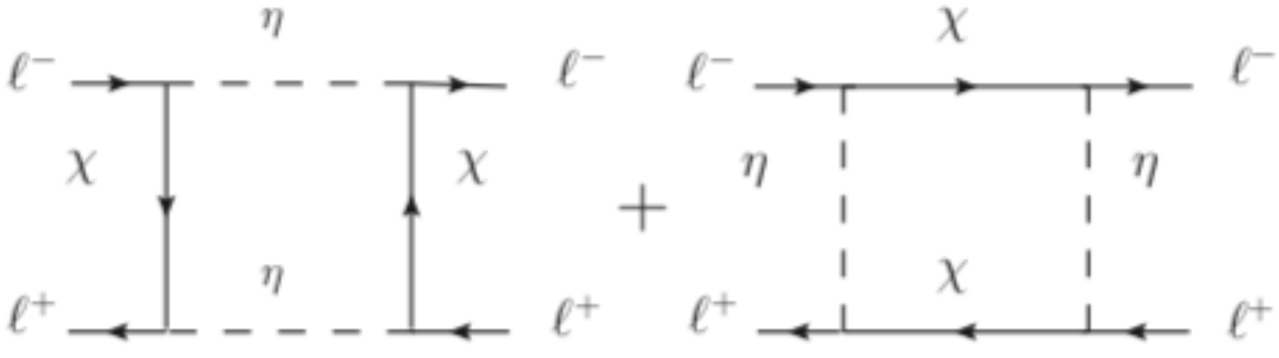


Transition	E_{theory} [MHz]
$1^3S_1 - 1^1S_0$	$42329355(51)_{had}(700)$
$2^3S_1 - 1^3S_1$	$2.550014(16) \times 10^{11}$
$2^3P_0 - 2^3S_1$	$1.002(3) \times 10^7$
$2^3P_1 - 2^3S_1$	$1.115(3) \times 10^7$
$2^3P_2 - 2^3S_1$	$1.206(3) \times 10^7$
$2^1P_1 - 2^3S_1$	$1.153(3) \times 10^7$

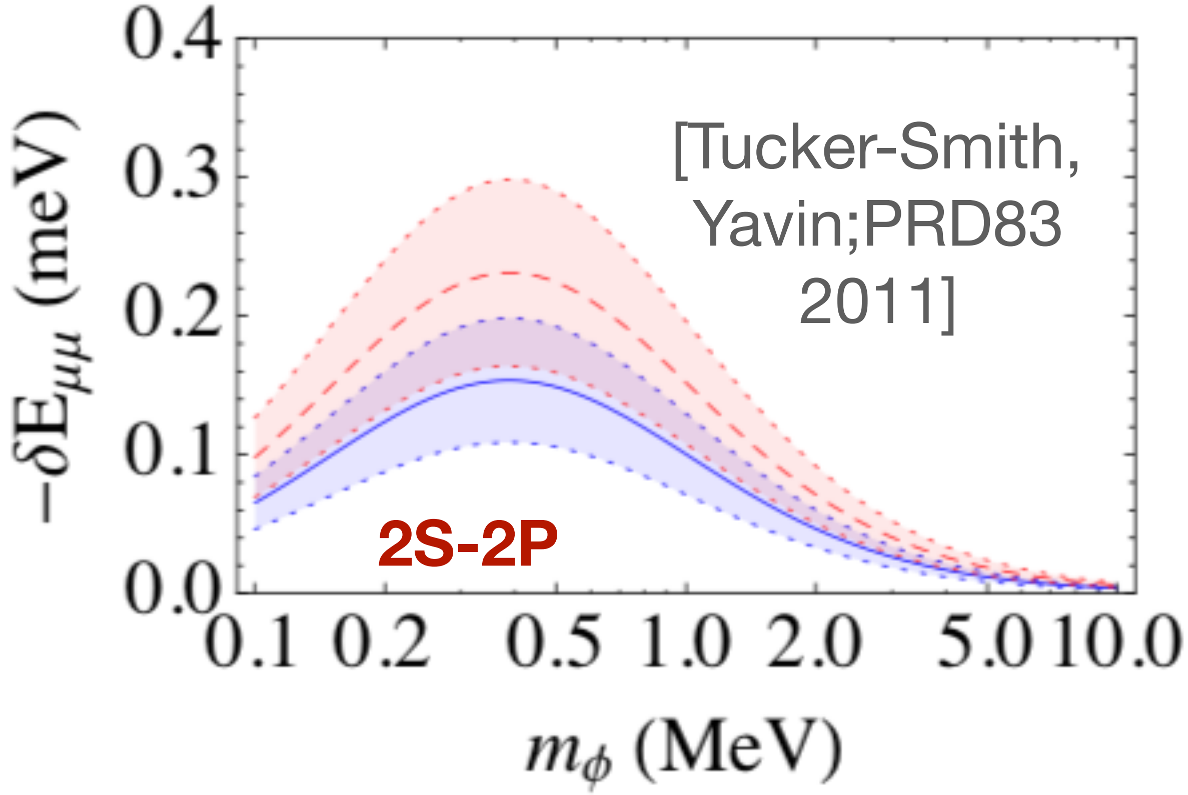


Muonic forces/contact interactions can alter energy levels: Lamb shift, hyperfine, 2P-2S, 2S-1S, etc

QED prediction known to $\mathcal{O}(m_\mu \alpha^5)$ BSM ~100 MHz



$$\Delta E^{\mu^+\mu^-}_{\text{hfs}} = -1.47 \text{ MHz} \times y^4 \left(\frac{100 \text{ GeV}}{m_\chi}\right)^2 ,$$



[Tucker-Smith, Yavin;PRD83 2011]

Detection

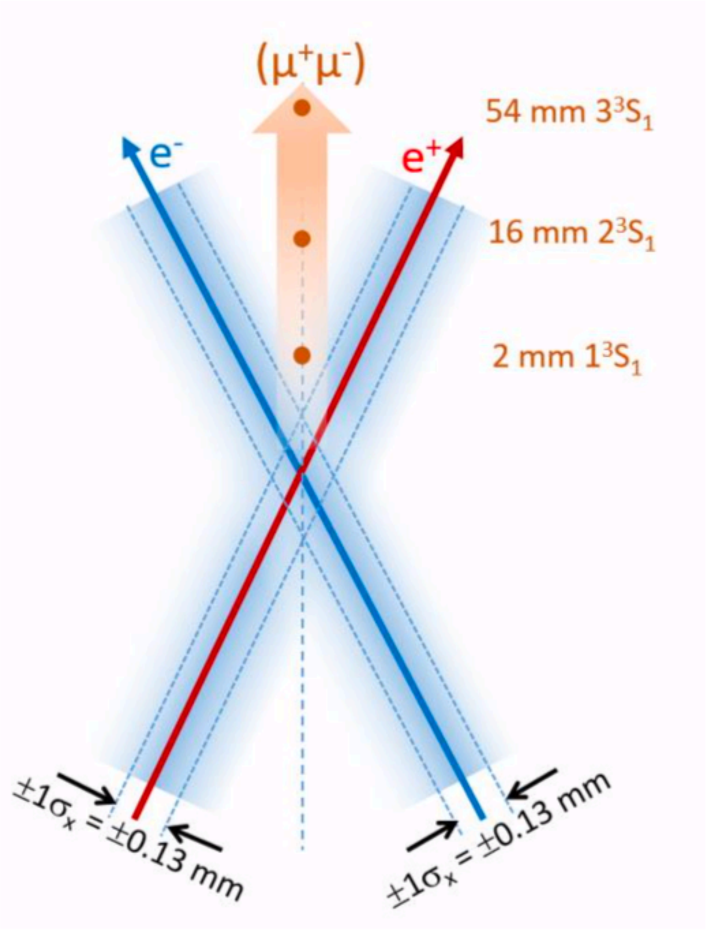
- **Detector requirements can depend on the physics goals**
- Can we observe True Muonium (TM) ?
- Can we perform spectroscopy analysis of TM ?
- Are there exotic decays of TM we should look for?
- Can we do other physics with this setup?

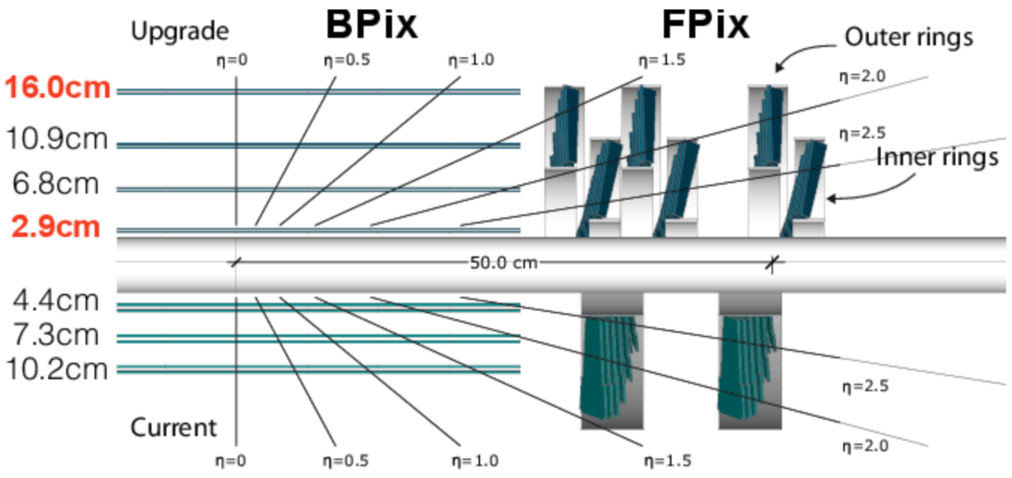
The Challenge:

- e+e- → TM → e+e-
- The primary background is Bhabha events
- For delta(E_e) ~10 keV, the signal x-section is ~5 nb
- Bhabha ~ 22,000 nb —> S/B ~1/4,000

Tracker Considerations

- For Dimuonium: beta* gamma* ctau = 2 mm
- Interaction region spread ~300
  - Detector resolution can be small (<100 microns)
  - Total vertex resolution <400 microns
- Requiring z > 2 mm would suppress Bhabba events
  - Prompt background free after the cut
- Extract 1S/2S/3S fractions from the vertex position
- Need a vertex detector:
  - Pixelated silicon
    - – CMS Phase-0 had 100-150 micron pitch pixels and allowed z resolution of <100 microns in r-z and <30 microns transverse plane. Good enough!
  - Drift chamber? Straw tracker?





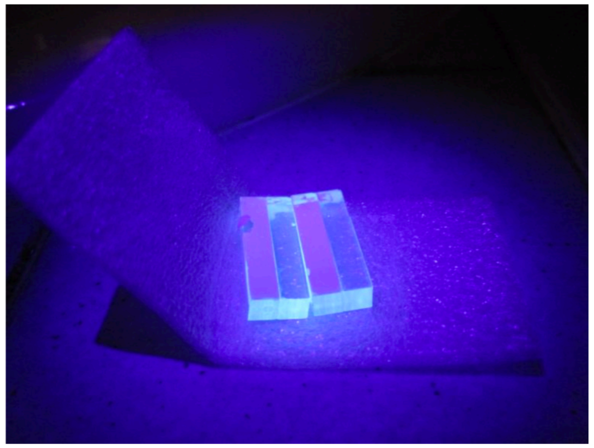
Calorimeter Considerations

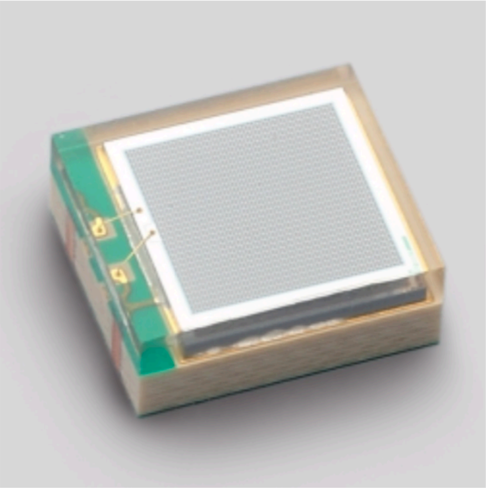
- Electron/positron energy ~ 100 MeV

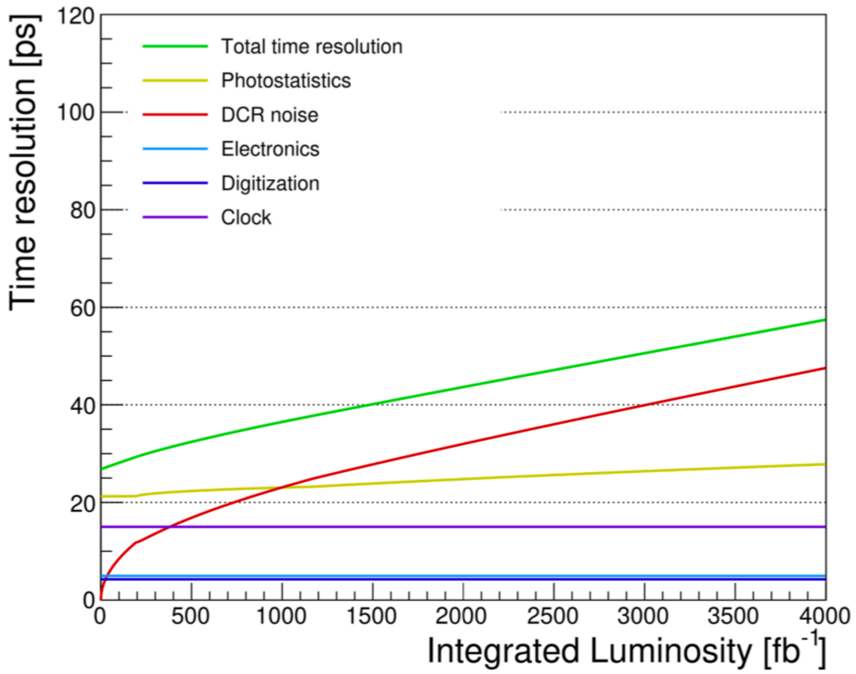
- Only few particles in the event – do not need fine segmentation, but do need good resolution and good coverage/acceptance

- A decently large crystal would contain the electron/positron and the right choice of crystal would give a lot of light
    - LYSO crystal read out by SiPM
    - PbWO4 cheaper but probably not bright enough
    - Plastic is not going to work

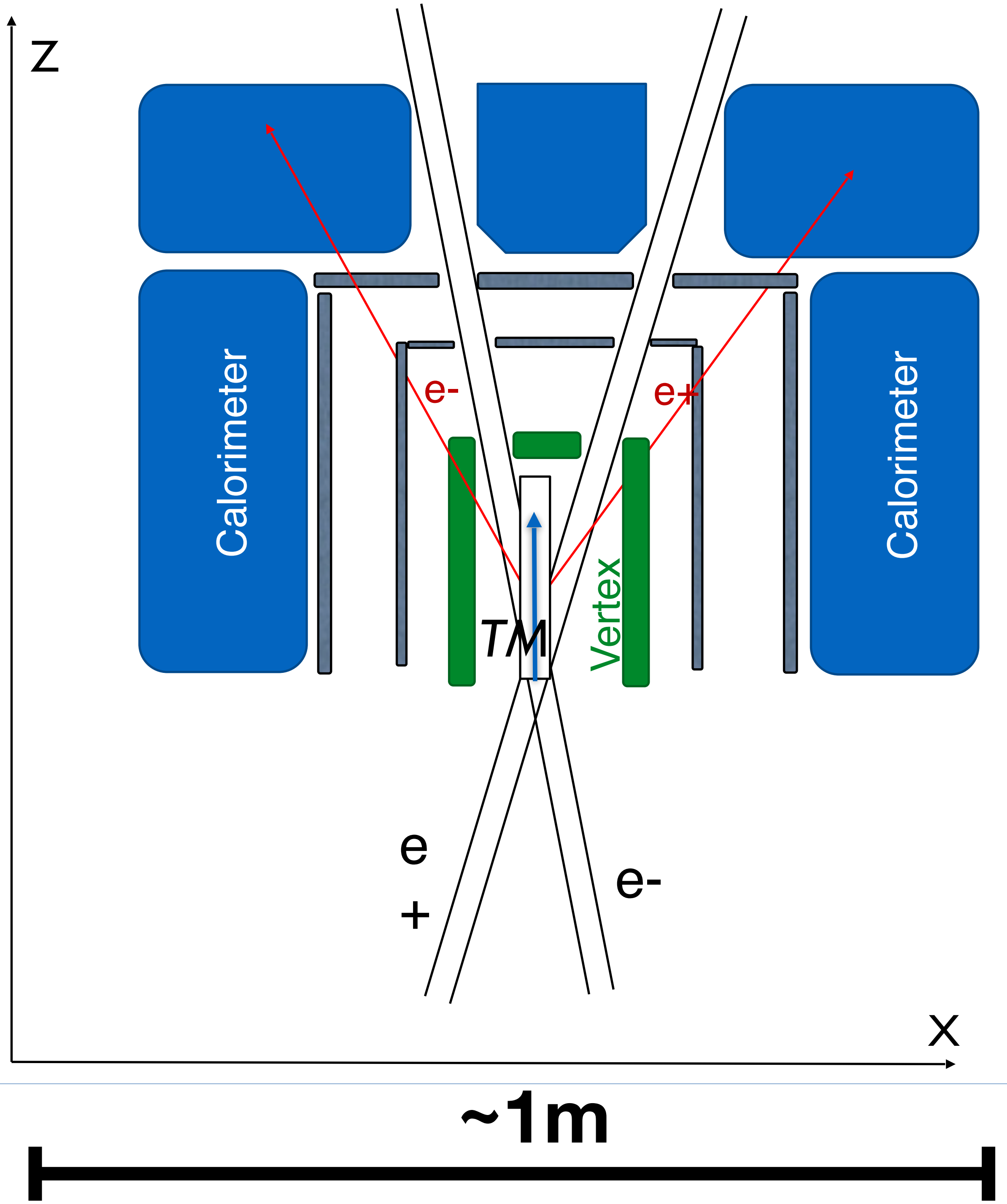
- Precision timing desirable for further BG suppression and spectroscopy measurements?







Detector Sketch



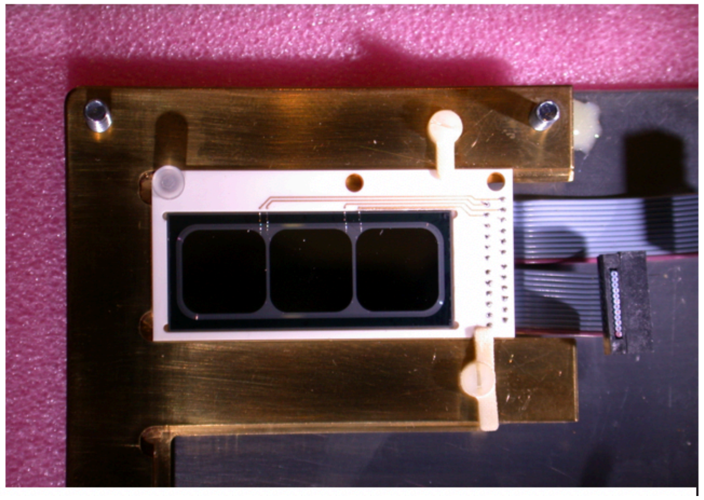
- Vertex: Pixelated silicon vertex detector
- LYSO calorimeter with excellent timing and energy resolution
- Directionality: Additional 2-3 tracking layers between the vertex detector and the calorimeter. Gas based (GEM) or silicon strips
- No magnetic field necessary
- Can probably achieve 50+% acceptance per track, 25% total.
- **100k-0.5M signal events per year**
- Integrated radiation dose small
- Devil is in the details…

X-ray Photon Detection

- Transition between the TM states happens with the emission of photons in the 100 eV – 10 KeV range.
- Can you infer this from the energy resolution of the electron/positron?
  - deltaE/E ~ 10 keV/ 100 MeV $<10^{-4}$, very hard even at the higher end of the spectrum
- Direct detection of KeV photons
  - Examples DEAR, SIDDHARTA experiments at DAFNE (kaon spectroscopy, ~6 KeV x-ray photons)
  - SDD a possibility. Beam backgrounds?
- What about Laser spectroscopy?

Detector	Si(Li)	CCD	SDD
Area [mm2]	200	724	100
Thickness [mm]	5	0.03	0.30
Δ E (FWHM) [eV]	410	170	185
Δ t (FWHM) [ns]	290	-	430

200 SDDs with 1cm^2 per SDD



Conclusions

- Dimuonium is a bound state of QED, never seen before!
- Provides a precision laboratory to test QED and muons
- Existing anomalies: g-2, proton radius, R_D, R_K
- FISR produces relativistic dimuonium in 3S1 states
- Proposal for DIMUS at NML/FAST, modest upgrades (eg 2nd cryo-module, fast kicker, positrons)
- Detection of TM in e+e- final state needs vertex detector, high resolution, good timing calorimeter
- Opportunity for detailed study of its properties — production rate, decays, transitions. Constraints on new physics.

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Thank you!

Beam energy	408	MeV
C.m.e. $\sqrt{s}$	211	MeV
C.m.e. spread	0.4	MeV
Crossing angle	75	deg.
Circumference	23	m
Beta-functions at IP (y, x)	20/0.2	cm
Bunch length	1.2	cm
Bunch spacing	1.9	ns
Beam sizes at IP (y, x)	0.7/130	μm
Number of bunches	40	
Number of e^+/e^- per bunch	$4{\cdot}10^{10}$	
Beam lifetime	≥ 30	sec
Max e^+ production rate	$4\cdot\ 10^{10}$	e^+/s
Peak luminosity	$1.6 \cdot 10^{32}$	cm^{-2}s^{-1}

TABLE I. Main parameters of the DIMUS collider at Fermilab's NML/FAST.