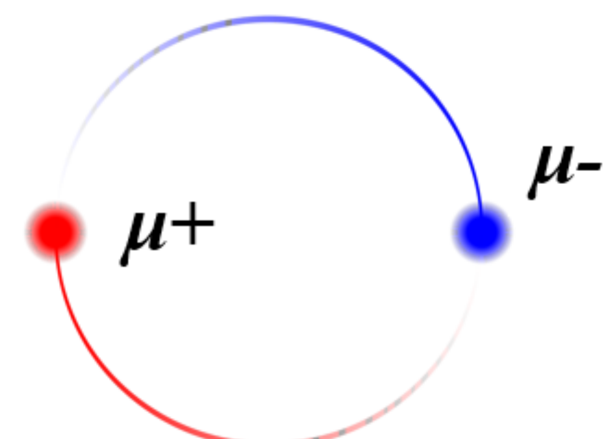
DIMUS:Di-Muononium Spectroscopy Collider



Patrick Fox
(work with Sergo Jindariani and Vladimir Shiltsev)

Muons in Minneapolis

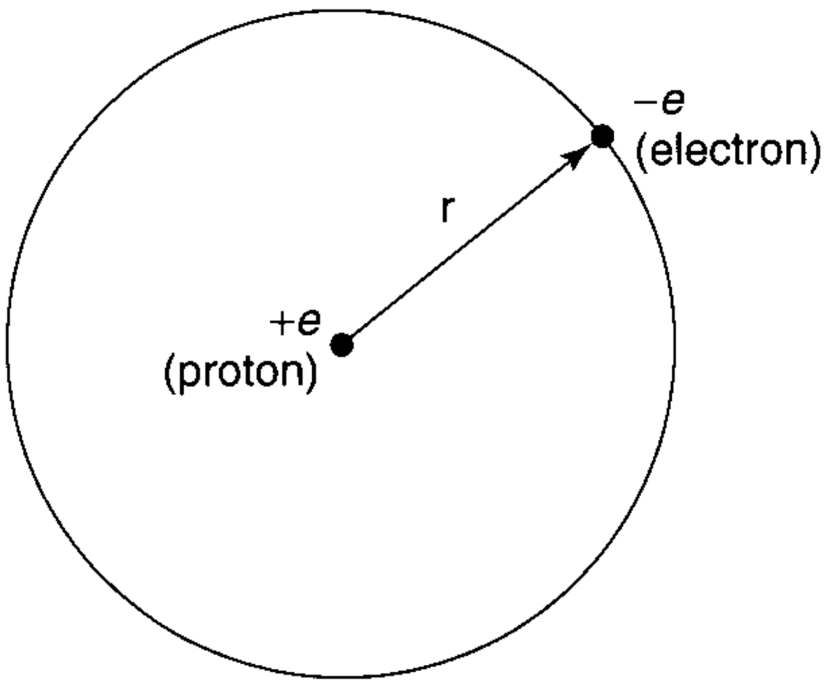
December 8, 2023

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 $(\pi^\pm\mu^\mp)$

Bound States of QED

The Bohr atom



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

$$\psi_{n\ell m}(r,\theta,\varphi) = \sqrt{\left(\frac{2}{na_0^*}\right)^3 \frac{(n-\ell-1)!}{2n(n+\ell)!}} e^{-\rho/2} \rho^\ell L_{n-\ell-1}^{2\ell+1}(\rho) Y_\ell^m(\theta,\varphi)$$

Higher order corrections (fine and hyper-fine) e.g. relativistic, spin-orbit, Lamb shift, spin-spin, lift n^2degeneracy

True muonium/Dimuonium

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

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

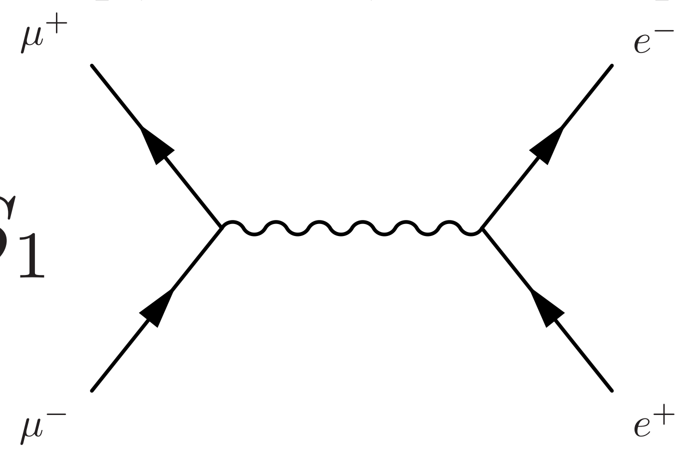
$$r_1(H) = a_0 = 53000\,\mathrm{fm} \quad r_1(e^+e^-) = 2a_0 \quad r_1(\mu^+\mu^-) = 530\,\mathrm{fm}$$

Unlike positronium there are fermionic decays (for S levels)

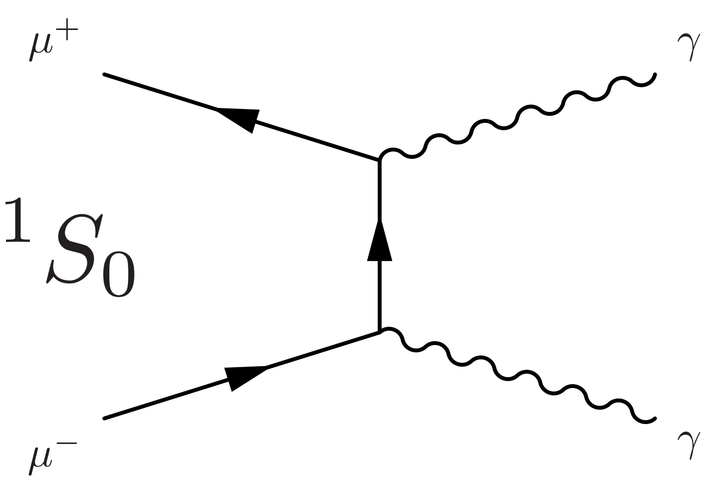
$$\Gamma \propto |\psi(0)|^2$$

$[(e^+e^-) \to 3\gamma]$

O: n^3S_1



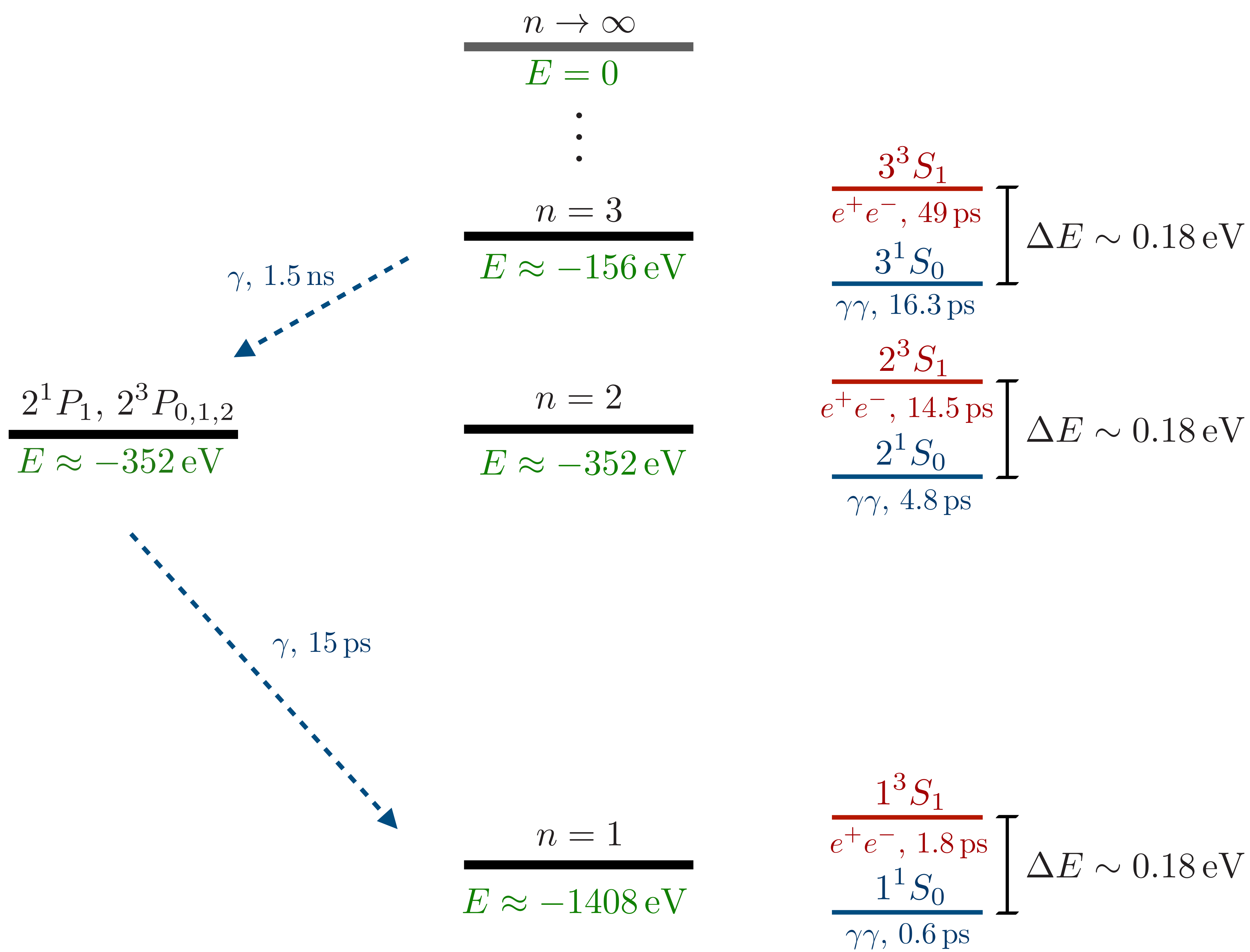
P: n^1S_0



$$\tau = \frac{6n^3}{\alpha^5 m_\mu} \qquad \tau = \frac{2n^3}{\alpha^5 m_\mu}$$

$n^{2s+1}l_J$

Muonium spectrum and decays



$n^{2s+1}l_J$

Possible TM Production Processes

- Storied history: pion collisions, electron beams, photon beams, RHIC…

More recently:

Banburski and Schuster [1206.3961]

- HPS, electron beam on a thin foil, production through 1/3 photon processes. Few hundred events

$$N_{TM} \sim \mathcal{O}(100) \times \left(\frac{I \times T}{450\, nA \times \mathrm{month}} \right)$$

- Eta decays at LHCb

Vidal et al [1904.08458]

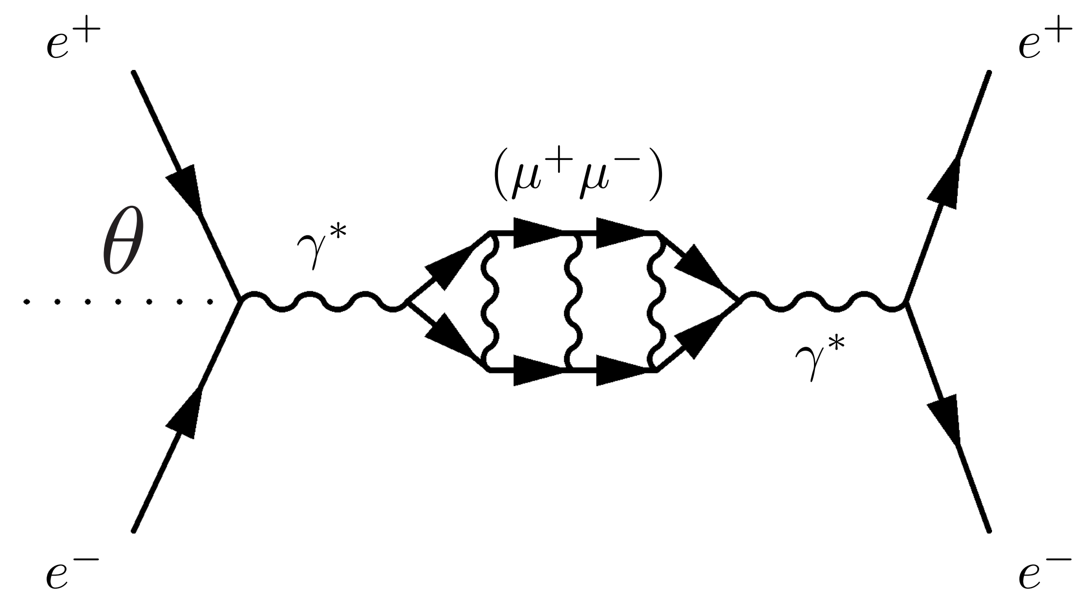
$$\mathrm{BR}(\eta \to \gamma[\mu^+ \mu^-]) \sim 5 \times 10^{-10}$$

Look for displaced electron pair, w/ or w/o a photon
Expect 100-1000 events after Run 3

Another True Muonium Production

Fool's Intersection Storage Ring

Brodsky & Lebed [0904.2225]

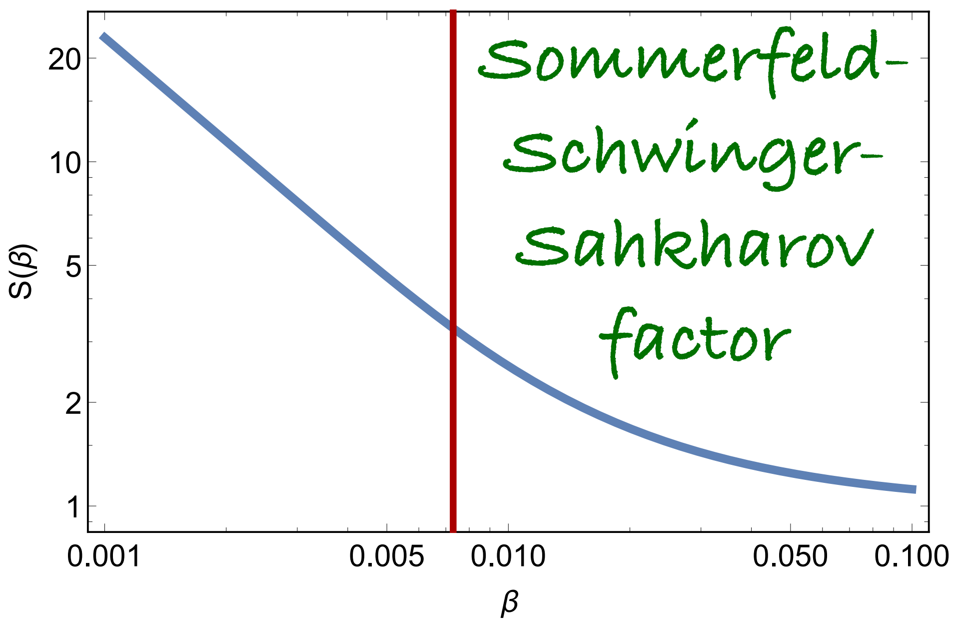


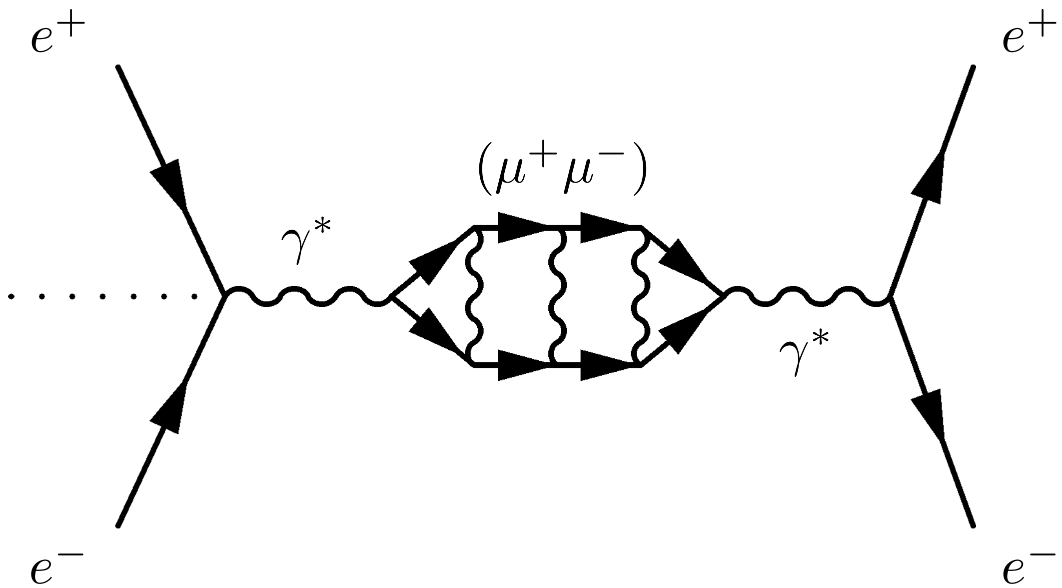
- Produces n^3S_1 states with relative rate n^{-3}
- For symmetric beam energies $p_z = \dfrac{2m_\mu}{\tan\theta}$ and boost $\gamma = \dfrac{1}{\tan\theta}$
- $E_{\text{beam}} = \dfrac{m_\mu}{\sin\theta}$

Boost is critical for separating signal from background (Bhabha)

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

Muonium Production



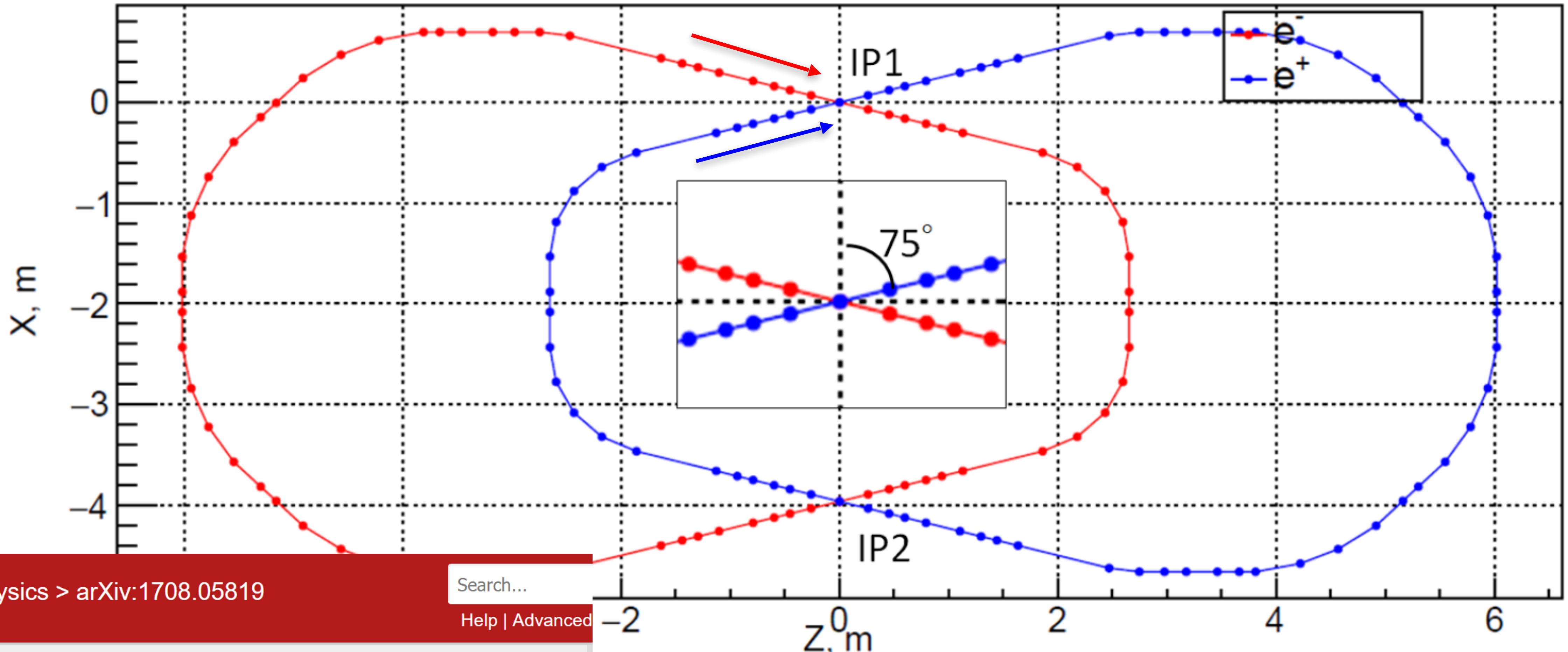


$$\sigma(e^+e^- \to \mu^+\mu^-)\big|_{\beta\approx 0} = \frac{2\pi\alpha^2\beta}{s}\left(1 - \frac{\beta^2}{3}\right) S(\beta)$$

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

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

Novosibirsk “Mu-Mu-Tron” Design



arXiv.org > physics > arXiv:1708.05819

Search...

Help | Advanced

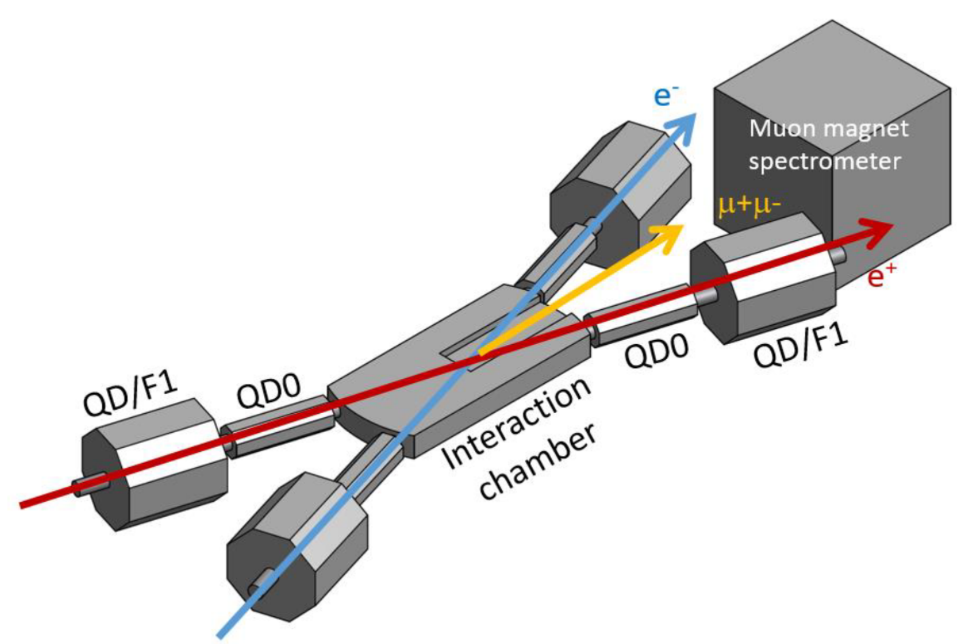
Physics > Accelerator Physics

[Submitted on 19 Aug 2017]

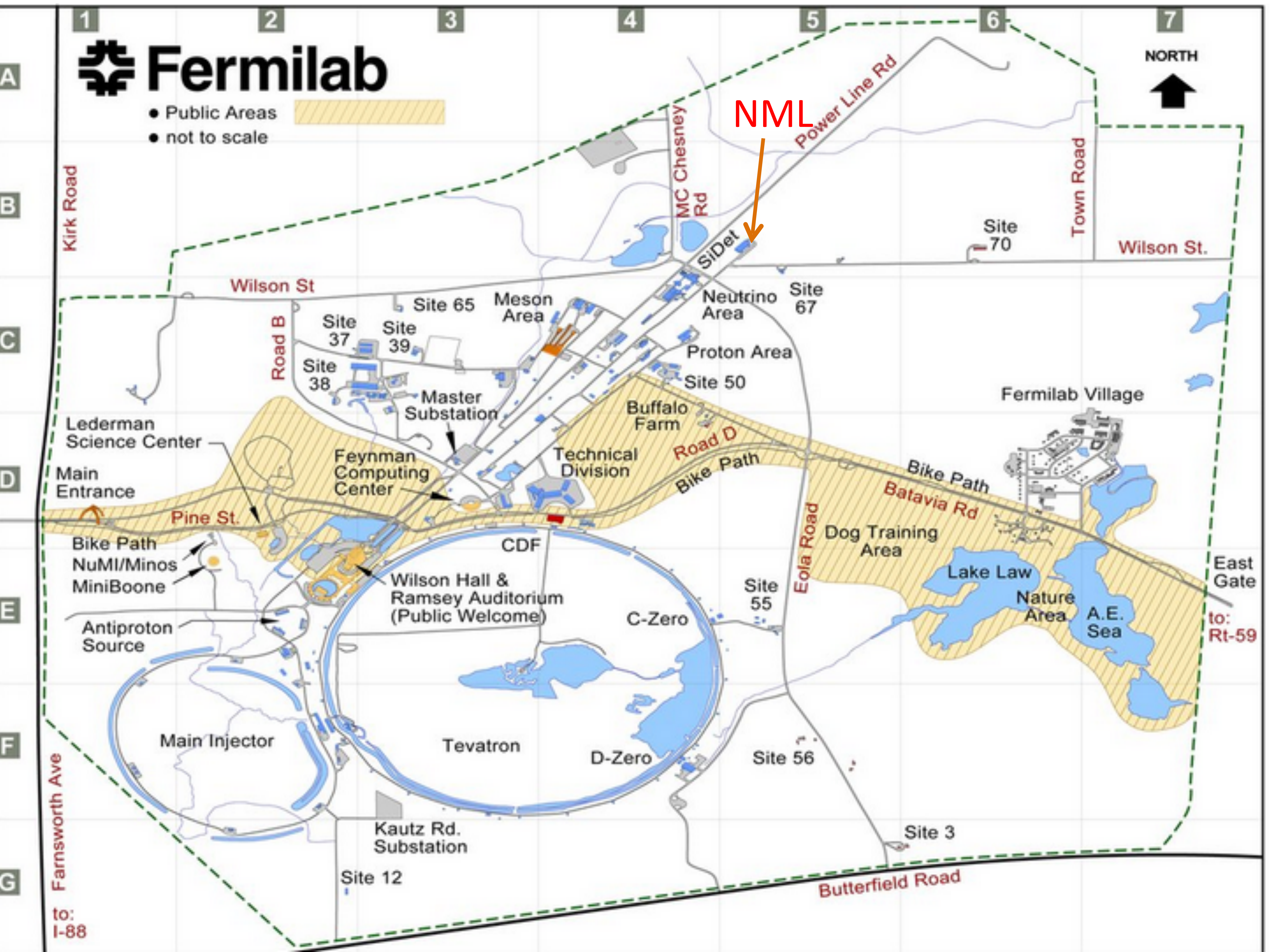
Low-energy electron-positron collider to search and study (μ^+μ^-) bound state

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

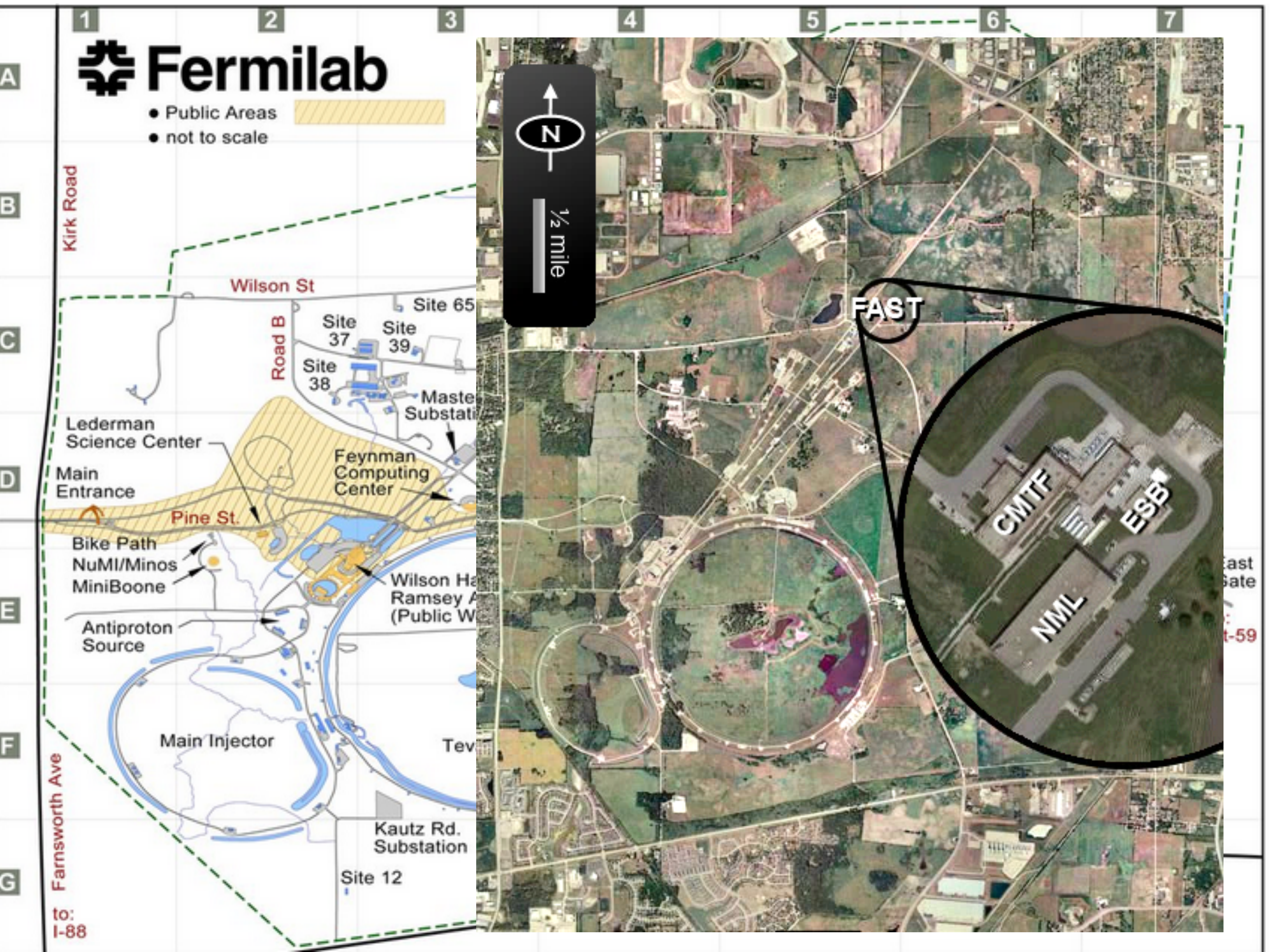
We discuss a low energy e^+e^- collider for production of the not yet observed $(\mu^+\mu^-)$ bound system (dimuonium). Collider with large crossing angle for e^+e^- beams intersection produces dimuonium with non-zero momentum, therefore, its decay point is shifted from the beam collision area providing 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.



Fermilab

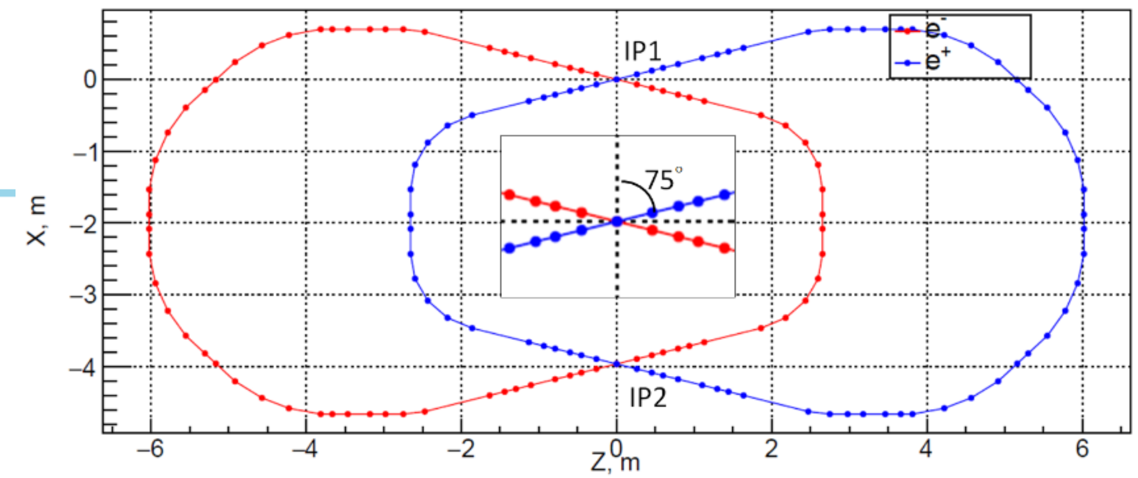


Fermilab
Public Areas
not to scale
NORTH
NML
Power Line Rd
MC Chesney Rd
Town Road
Kirk Road
Wilson St.
Wilson St
Site 70
SiDet
Neutrino Area
Site 67
Site 65
Meson Area
Site 37
Site 39
Site 38
Road B
Proton Area
Site 50
Master Substation
Buffalo Farm
Fermilab Village
Lederman Science Center
Feynman Computing Center
Technical Division
Road D
Bike Path
Batavia Rd
Main Entrance
Pine St.
CDF
Eola Road
Dog Training Area
Bike Path
NuMI/Minos
MiniBoone
Wilson Hall & Ramsey Auditorium (Public Welcome)
Site 55
Lake Law
Nature Area
A.E. Sea
East Gate
to: Rt-59
Antiproton Source
C-Zero
Main Injector
Tevatron
D-Zero
Site 56
Kautz Rd. Substation
Site 3
Site 12
Butterfield Road
Farnsworth Ave
to: I-88

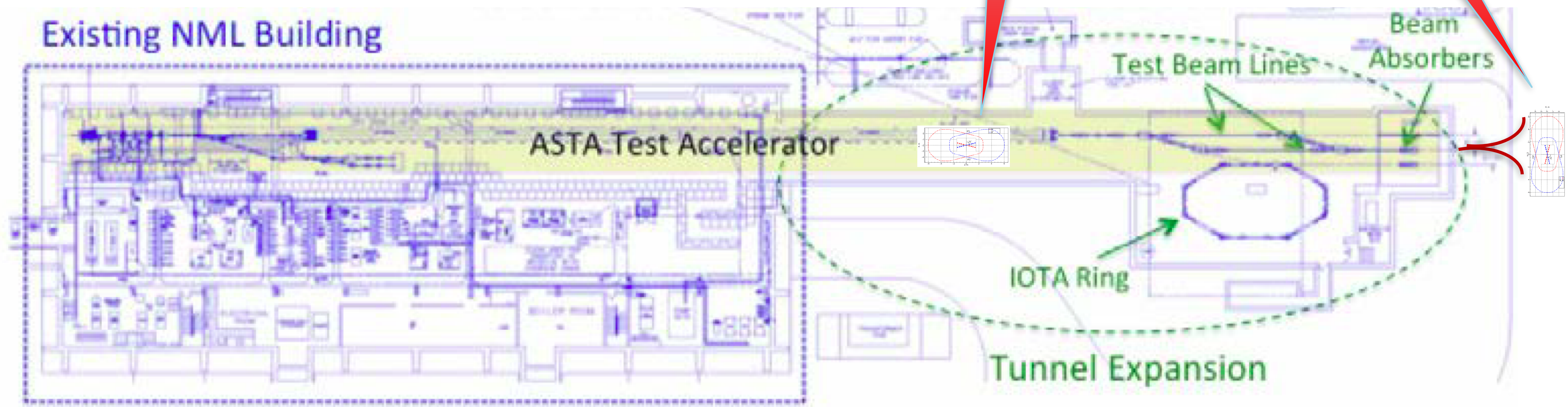


Fermilab
Public Areas
not to scale
Kirk Road
Wilson St
Road B
Site 65
Site 37
Site 39
Site 38
Master Substati
Lederman Science Center
Main Entrance
Feynman Computing Center
Pine St.
Bike Path
NuMI/Minos
MiniBoone
Wilson Ha
Ramsey A
(Public W
Antiproton Source
Main Injector
Tev
Kautz Rd. Substation
Site 12
Farnsworth Ave
to: I-88
N
½ mile
FAST
CMTF
ESB
NML

Placement of the DIMUS Collider



~12m x 6m



DIMUS Collider

For 75° crossing need beam energy of 408 MeV

Require high positron production rate $10^{11}e^{+}/s$

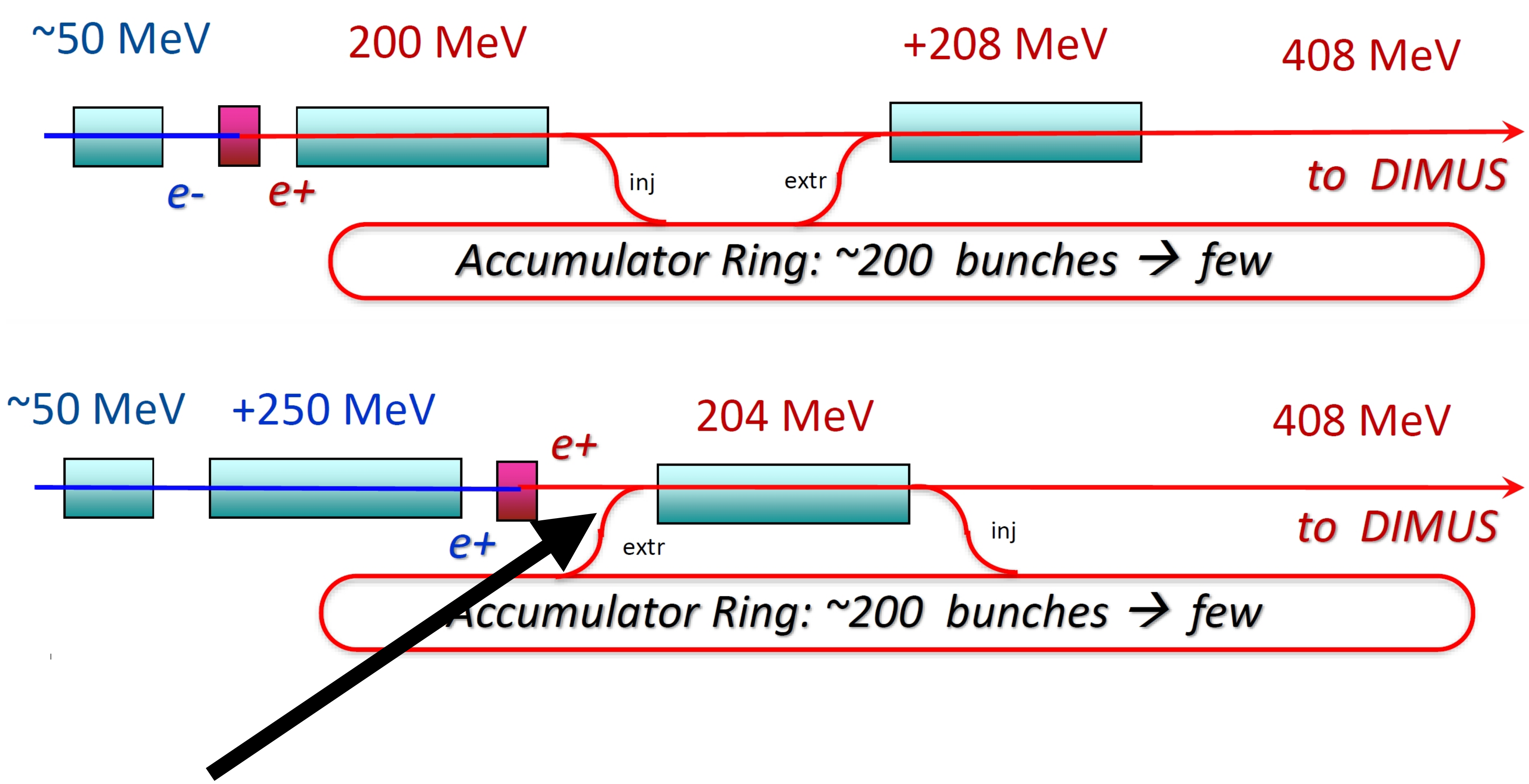
Intra-beam scattering, beam lifetime, non-head-on collisions all leads to technical accelerator challenges…surmountable

FAST has SRF that can deliver $3x10^{14}e^{-}/s$ up to 300 MeV

Need second cryomodule, plenty of space

DIMUS Collider

Positron production: convert e^{-} on a Tungsten target, 2 possible configurations



Injection/extraction requires fast (4ns) kickers, similar to ones developed for ILC

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

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)

Fermilab

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

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

$$X \to SM\ SM$$

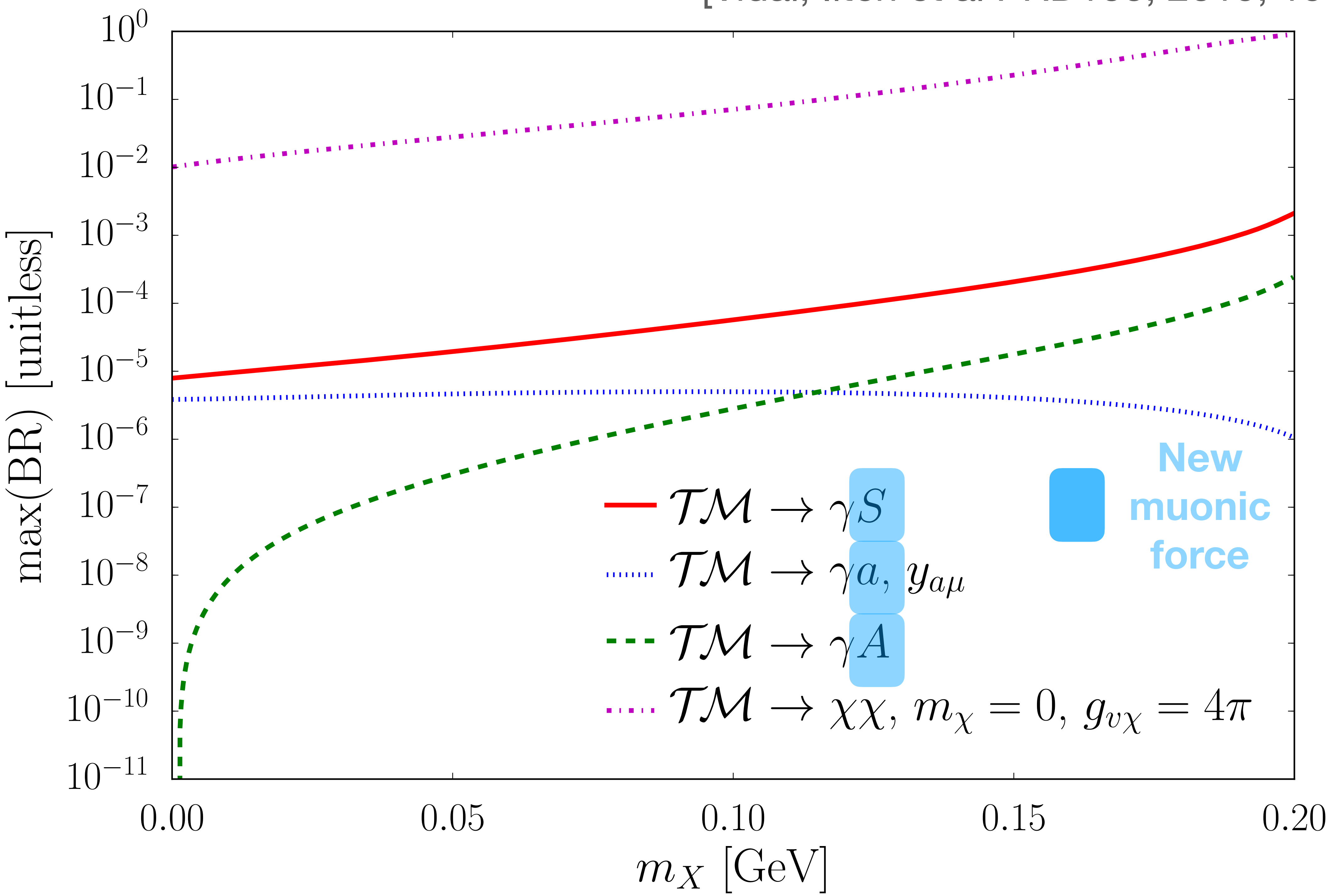
or change energy levels (**spectroscopy)**

2S-2P transition

Strong constraints from other measurements

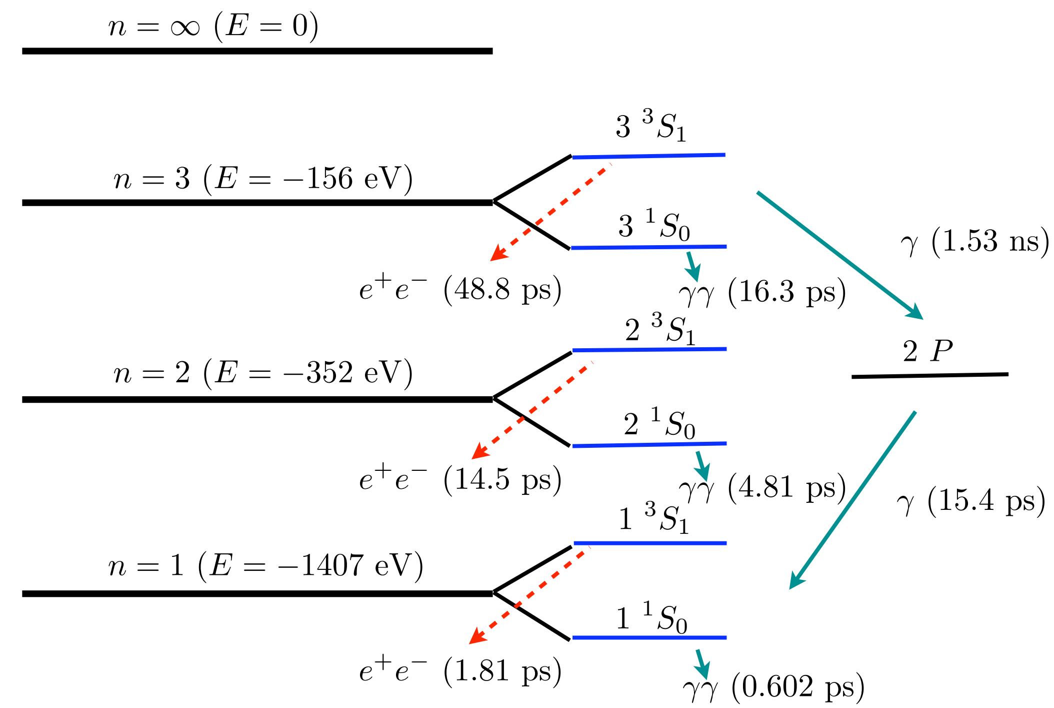
New Decay Modes

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



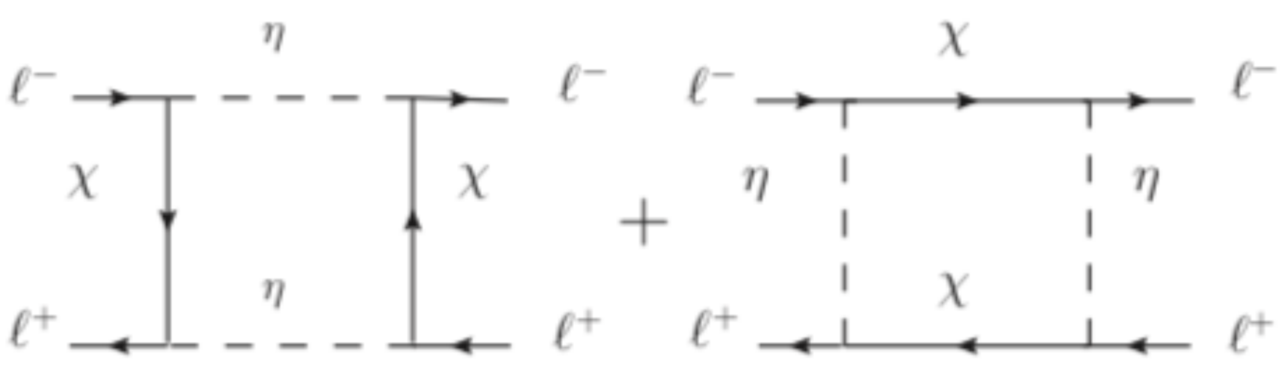
Spectroscopy [Ji,Lamm; 1712.03429]

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

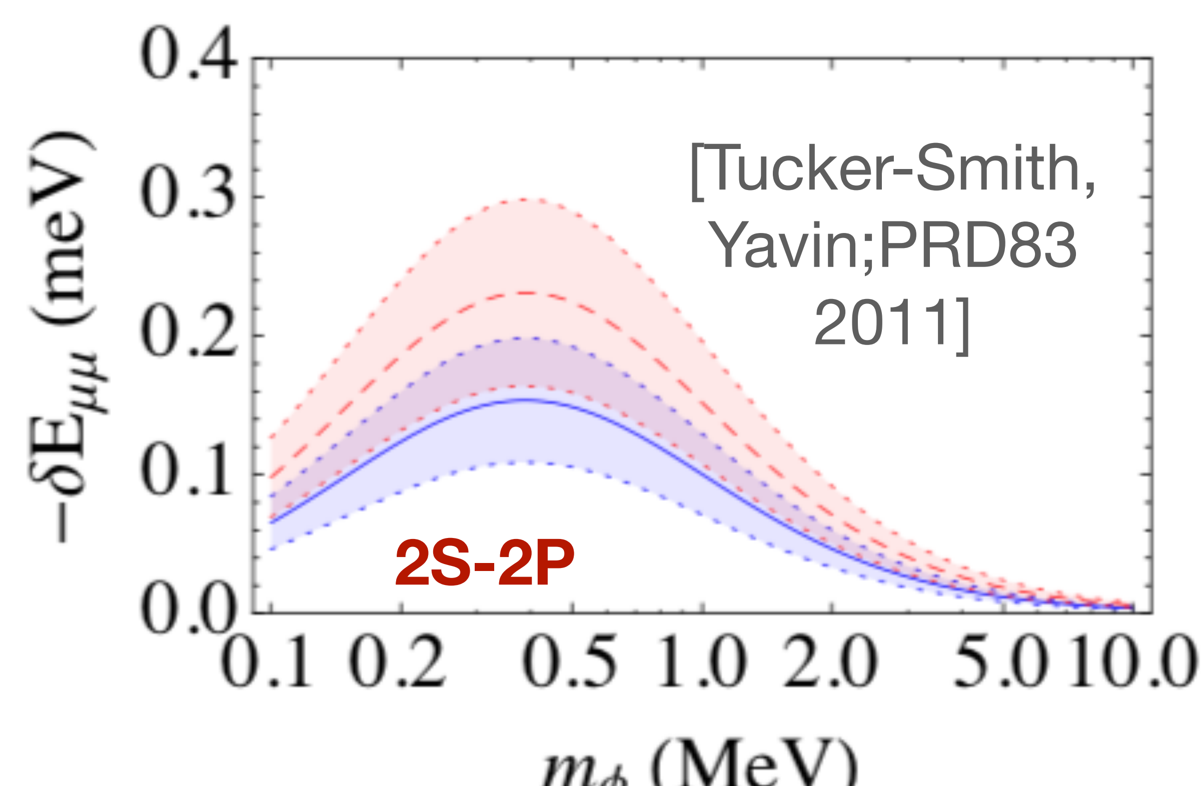


Muonic forces/contact interactions can alter energy levels: Lamb shift, hyperfine, 2P-2S, 2S-1S, etc

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



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



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

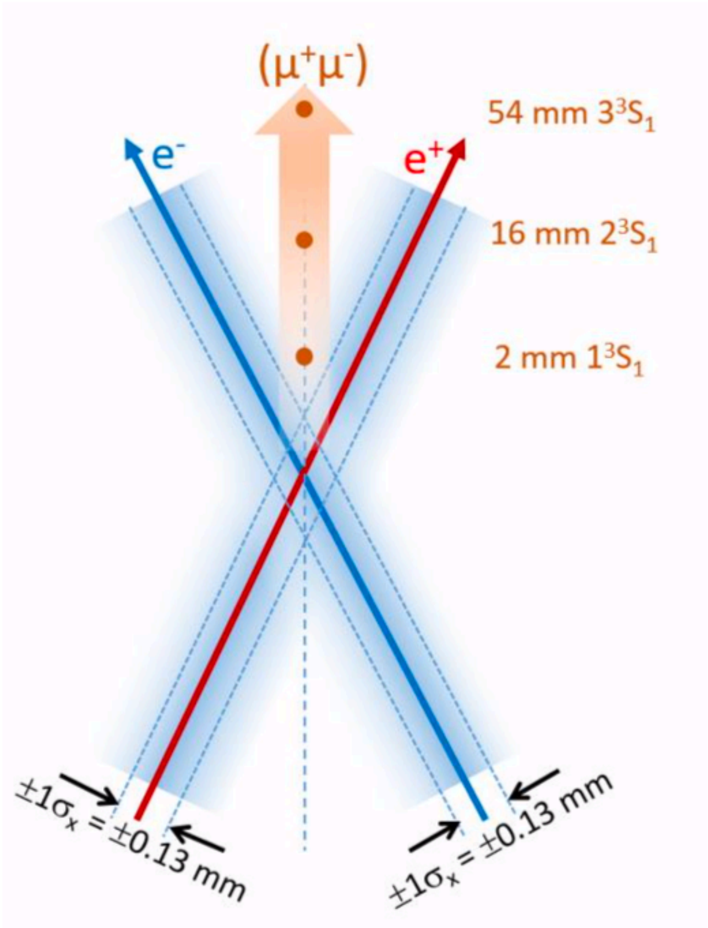
- For Dimuonium: beta* gamma* ctau = 2 mm

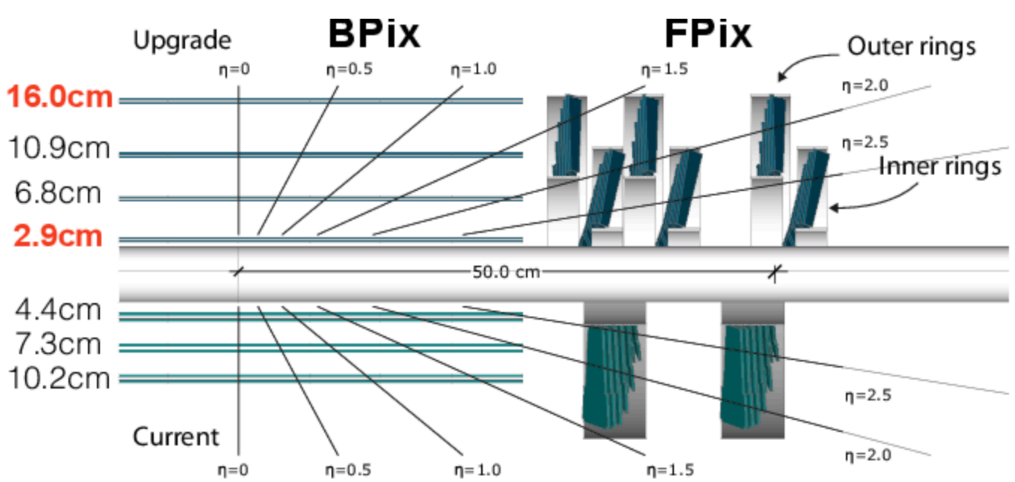
- Interaction region spread ~300 microns
  - Detector resolution can be small (<100 microns)
  - Total vertex resolution <400 microns

- 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?





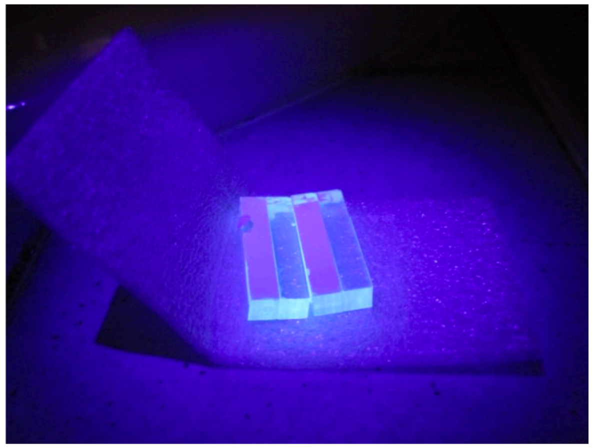
Calorimeter Considerations

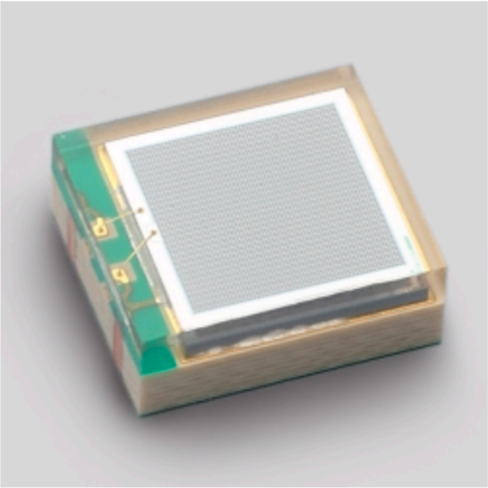
- Electron/positron energy ~ 100 MeV

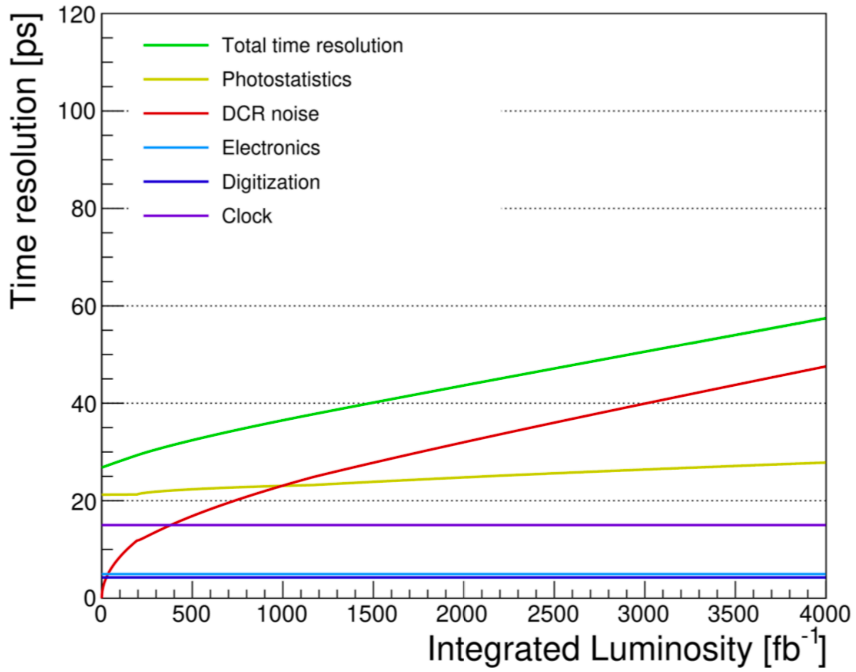
- Only few particles in the event – do not need fine segmentation, but do need good resolution and good coverage/acceptance

- 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

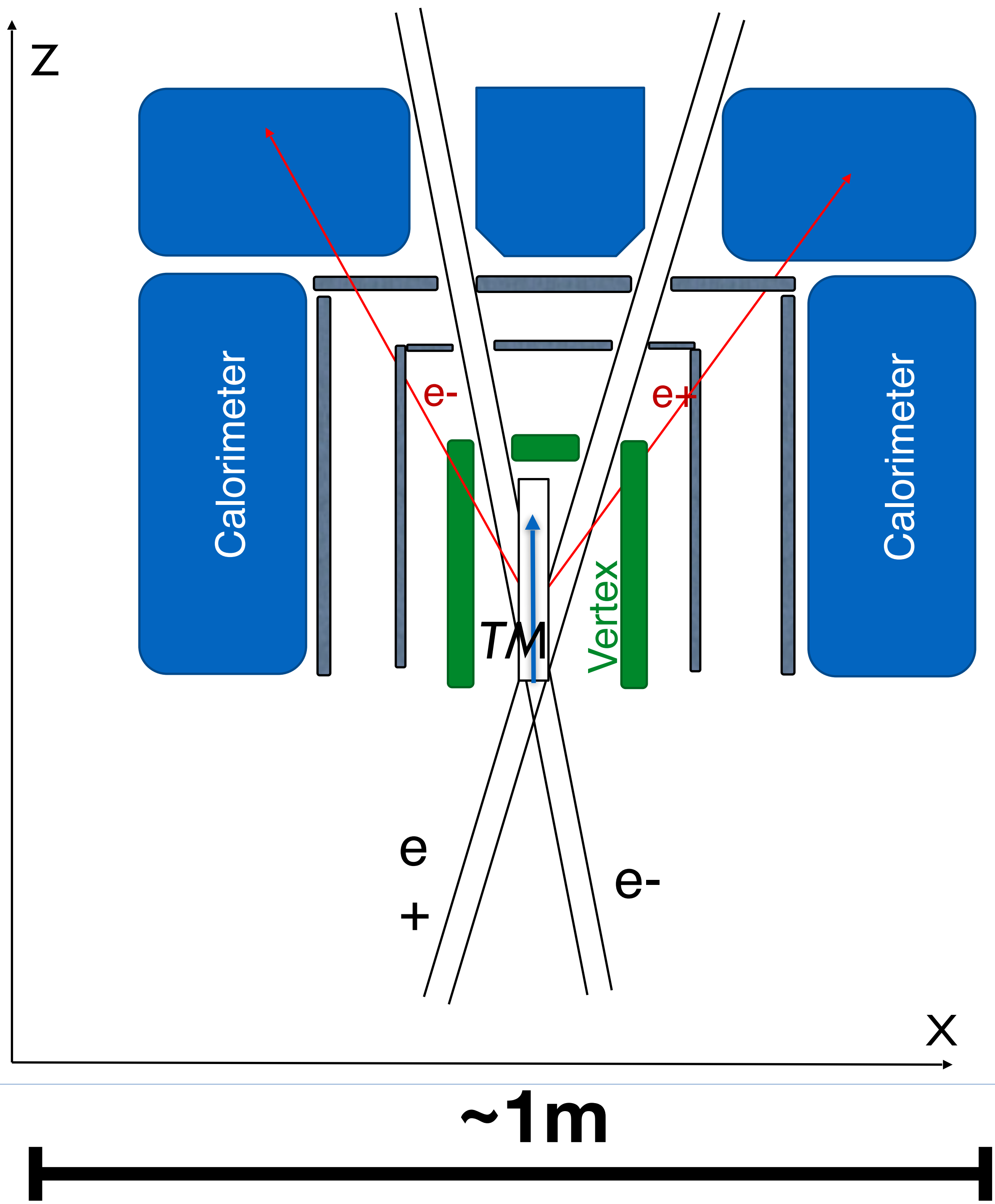
- Precision timing desirable for further BG suppression and spectroscopy measurements?







Detector Sketch



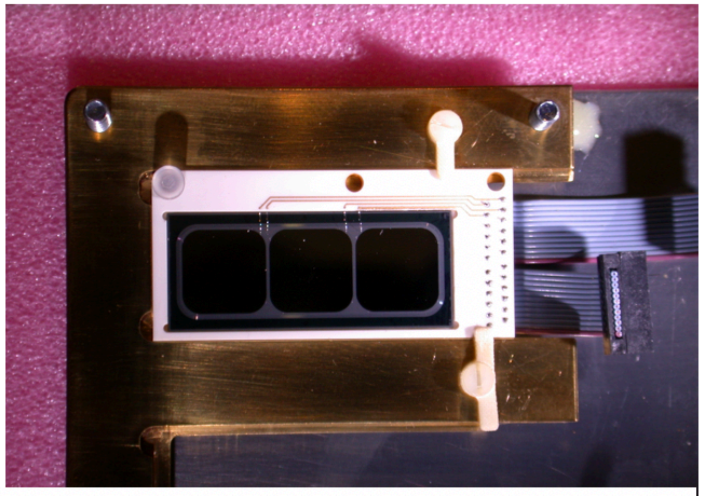
- Vertex: Pixelated silicon vertex detector
- LYSO calorimeter with excellent timing and energy resolution
- Directionality: Additional 2-3 tracking layers between the vertex detector and the calorimeter. Gas based (GEM) or silicon strips
- No magnetic field necessary
- Can probably achieve 50+% acceptance 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.

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.

Thank you!


Muons in Minneapolis Workshop
Fundamental Physics with Muons
University of Minnesota, Twin Cities   Dec 6-8, 2023
Organizers:
Yohei Ema
Saarik Kalia
Zhen Liu
Kunfeng Lyu
Maxim Pospelov
The Simons Foundation
Hot summer in Minneapolis
Photo by Andrey Shkerin

Muons in Minneapolis Workshop

Fundamental Physics with Muons

Organizers:
Yohei Ema
Saarik Kalia
Zhen Liu
Kunfeng Lyu
Maxim Pospelov

THE SIMONS FOUNDATION

Hot summer in Minneapolis

Photo by Andrey Shkerin

Muons in Minneapolis Workshop

Fundamental Physics with Muons

THANK YOU!

Organizers:
Yohei Ema
Saarik Kalia
Zhen Liu
Kunfeng Lyu
Maxim Pospelov

The Simons Foundation

Hot ~~Summer~~ Winter in Minneapolis

Photo by Andrey Shkerin

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.