Fermilab U.S. DEPARTMENT OF ENERGY Office of Science

DIMUS Detector Challenges and Considerations

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Potential Fermilab Muon Campus and Storage Ring Experiments Workshop

27 May 2021

Physics Questions?

- I am not an expert in this area
- Presented are general thoughts to facilitate discussions, not an attempt of a detector design
- Building up on presentations by Vladimir and Paddy

- **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?

True Muonium States

https://arxiv.org/abs/0904.2225

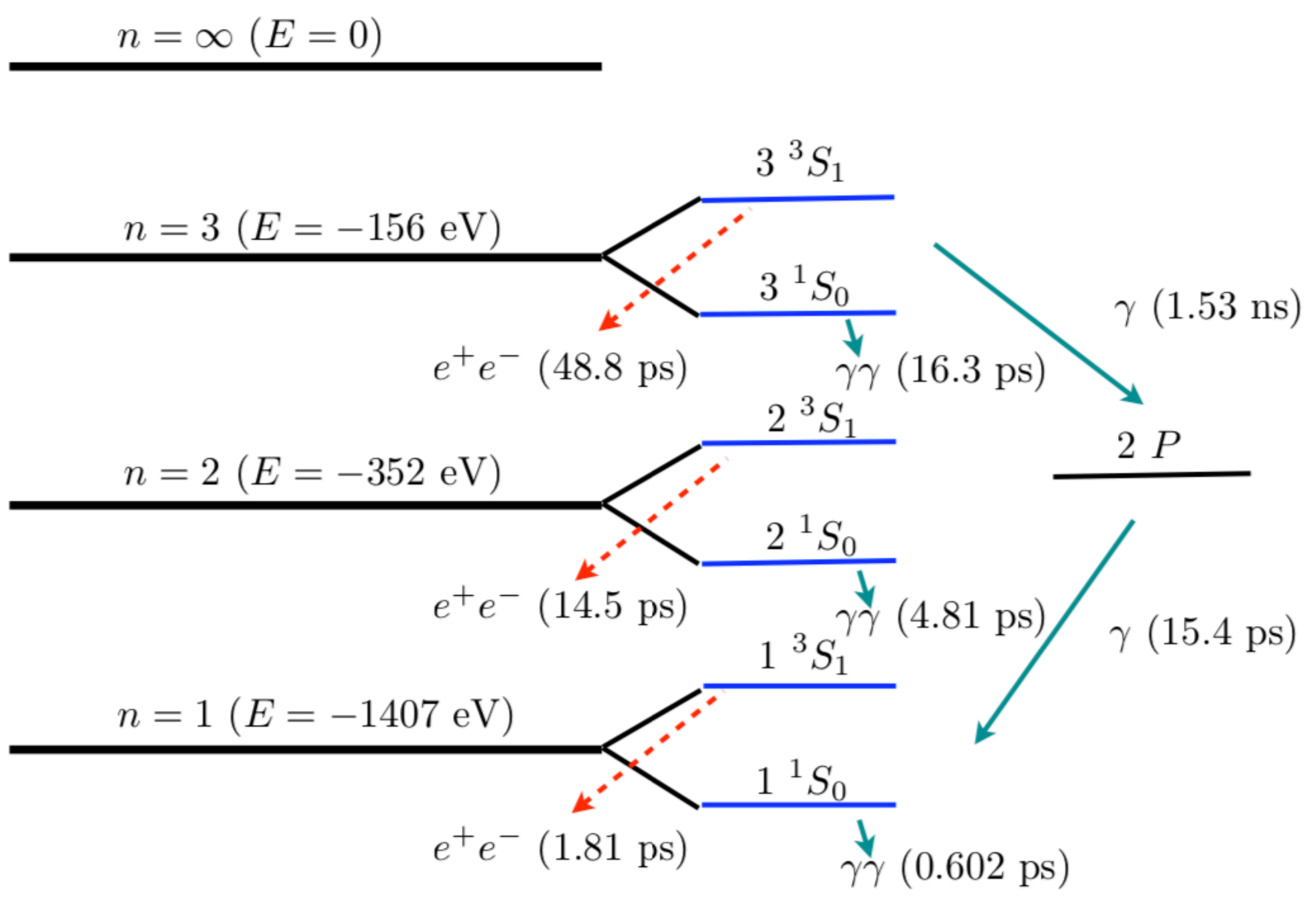


FIG. 1: True muonium level diagram (spacings not to scale).

- e+e-→(μ+μ–)[n^3S_1] → 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 $^3S_1$ state (decaying to e+e–)

LHCb Projections

https://arxiv.org/pdf/1904.08458.pdf

- spin-singlet true muonium states exist, but their dominant decay are to γγ, which is challenging to reconstruct
- Focus on spin-triplet

$$\eta \to \gamma \mathcal{TM},\ \mathcal{TM} \to e^+e^-$$

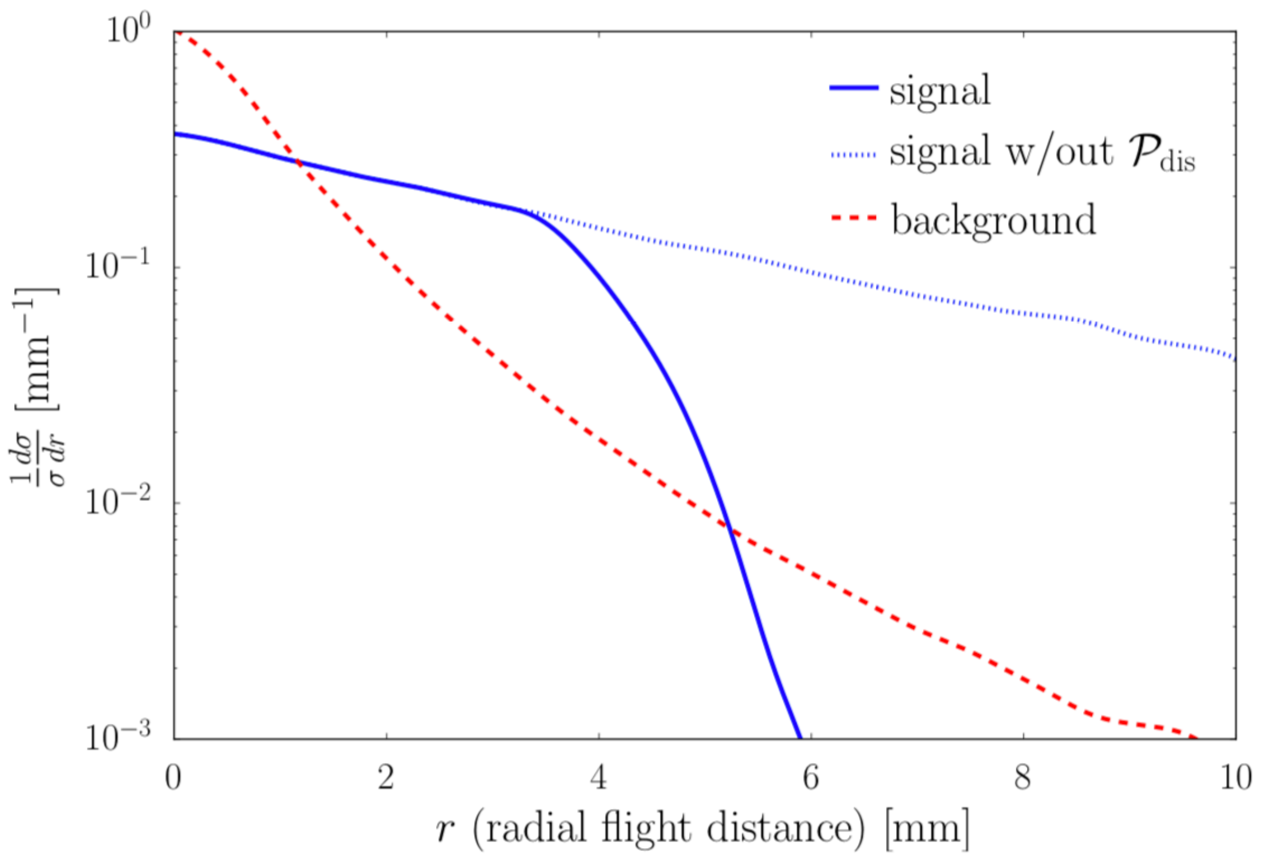
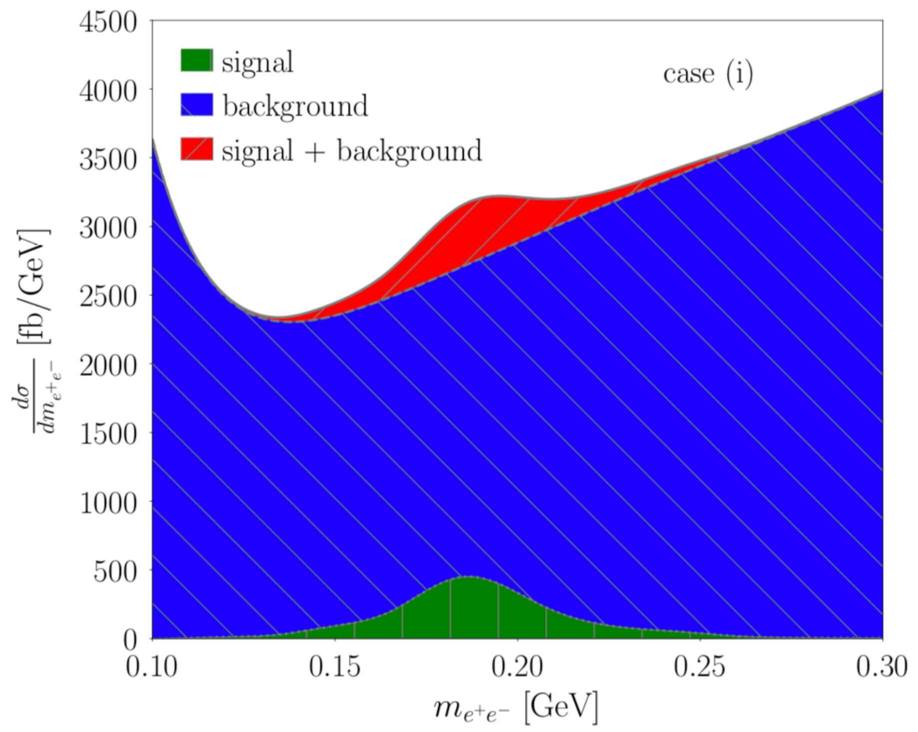
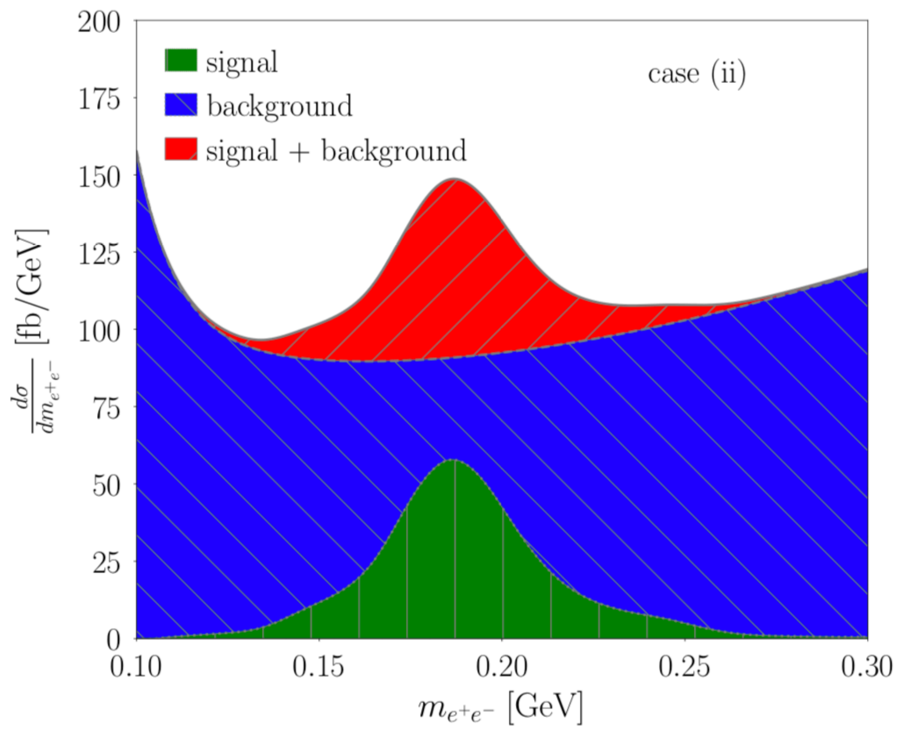


FIG. 2: Normalized radial flight distance distributions for the $\mathcal{TM} \to e^+e^-$ signal (blue solid) with dissociation, (blue dotted) without dissociation, and (red dashed) the e^+e^- background from B-hadron decays.

✦ Looking for:

- Displaced e+e- vertex
- Displaced e+e- vertex + a soft photon from eta decay





- In these conditions, a 5σ observation would be possible with an integrated luminosity of 15 fb^{-1} in case (i) and of 30 fb^{-1} in case (ii).
- Dark photon searches - HPS? Belle-II? Redtop?

Signal and Background

- e+e- → TM → e+e-
- The primary background is Bhabha events

- Even for delta(E_e) ~10 keV, the signal cross-section is about 5 nb
- Bhabha ~ 22,000 nb
- S/B ~1/4,000

- Need to suppress backgrounds

- Produce muonium moving and require displacement

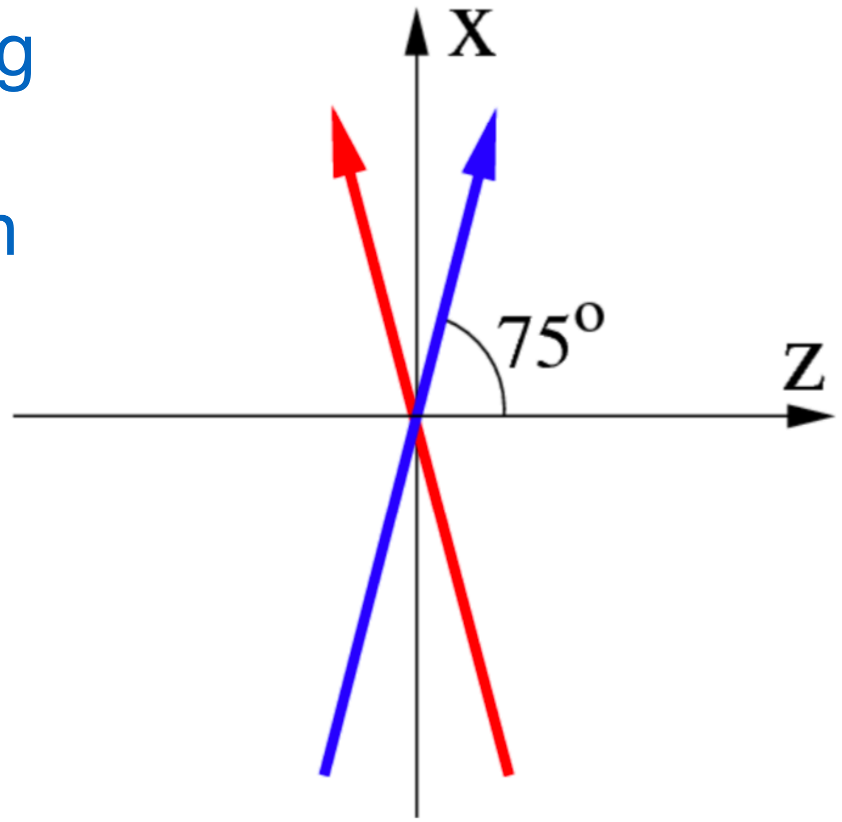
- Angular distribution of TM vs Bhabha (?)

- Timing information (?)

Large Crossing Angle

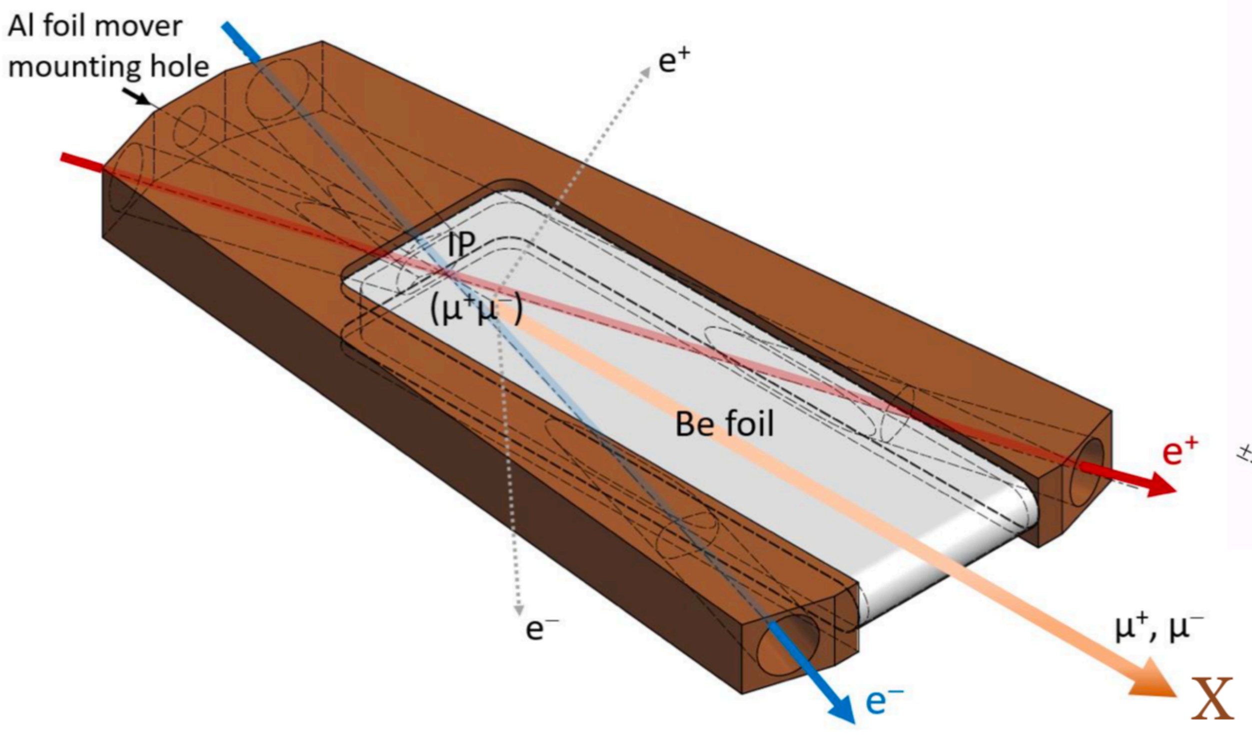
Novosibirsk Design
https://arxiv.org/abs/1708.05819

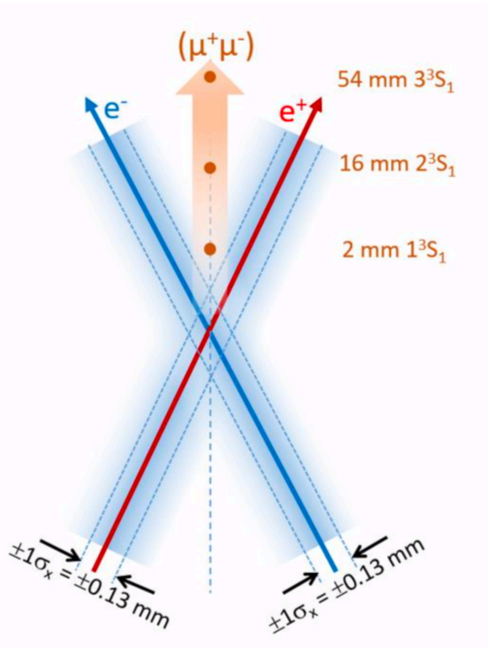
A collider with a large crossing angle was proposed by S.J.Brodsky and R.F.Lebed in Phys. Rev. Lett. 102, 213401 (2009)



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}

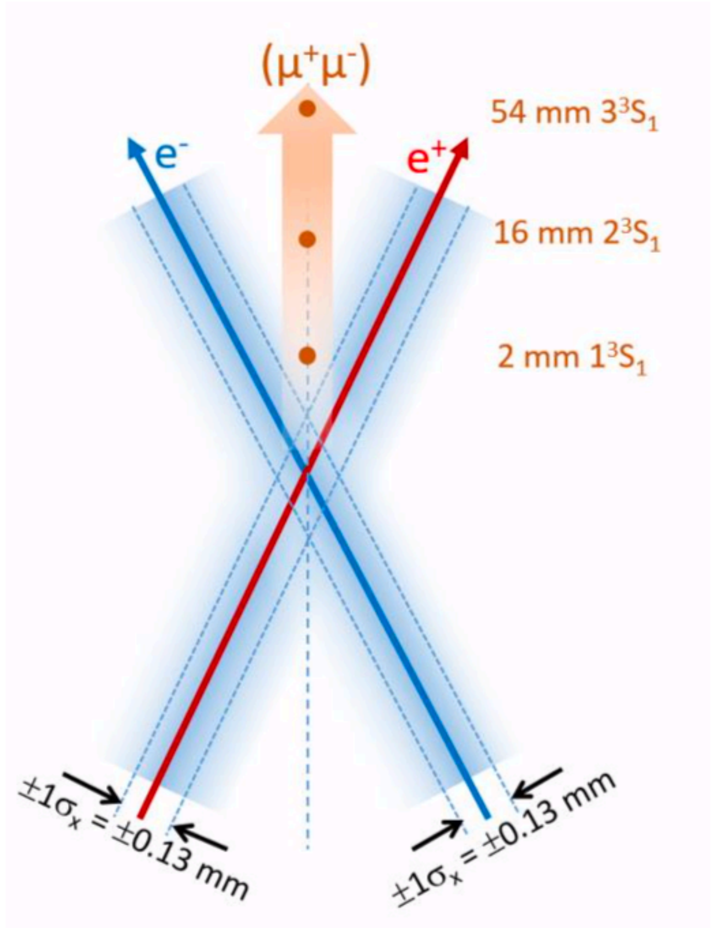
Interaction region

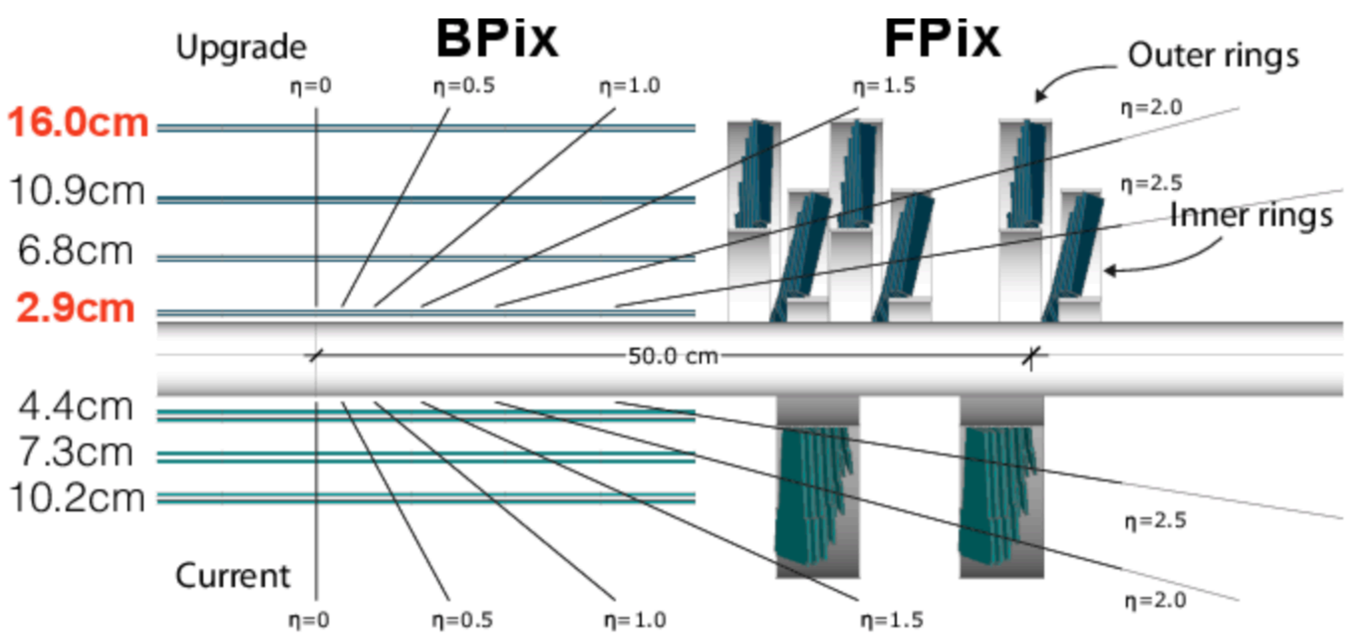




Tracker Considerations

- 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
- 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
  - Drift chamber? Straw tracker?





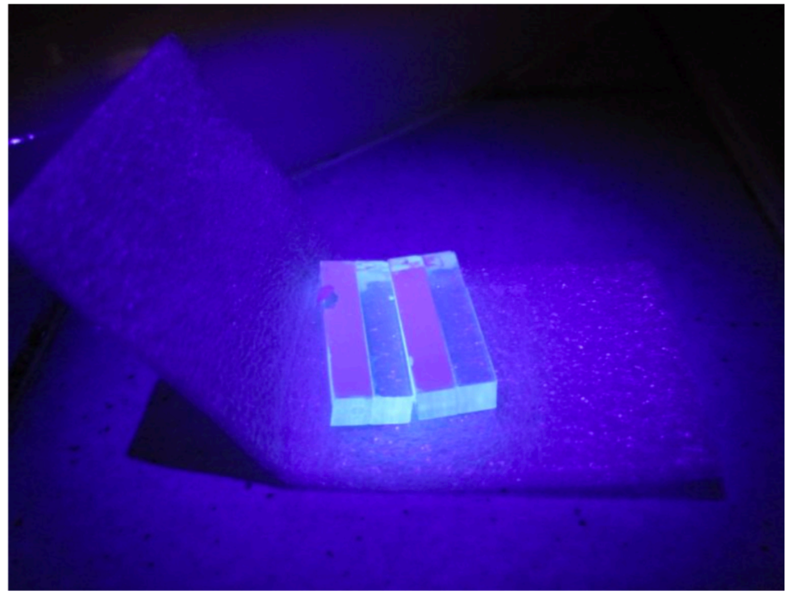
Calorimeter Considerations

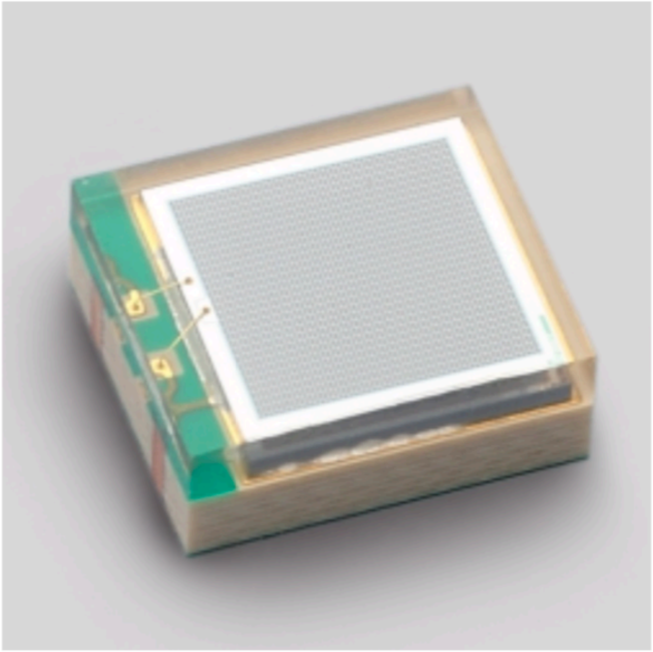
- Electron/positron energy ~ 100 MeV

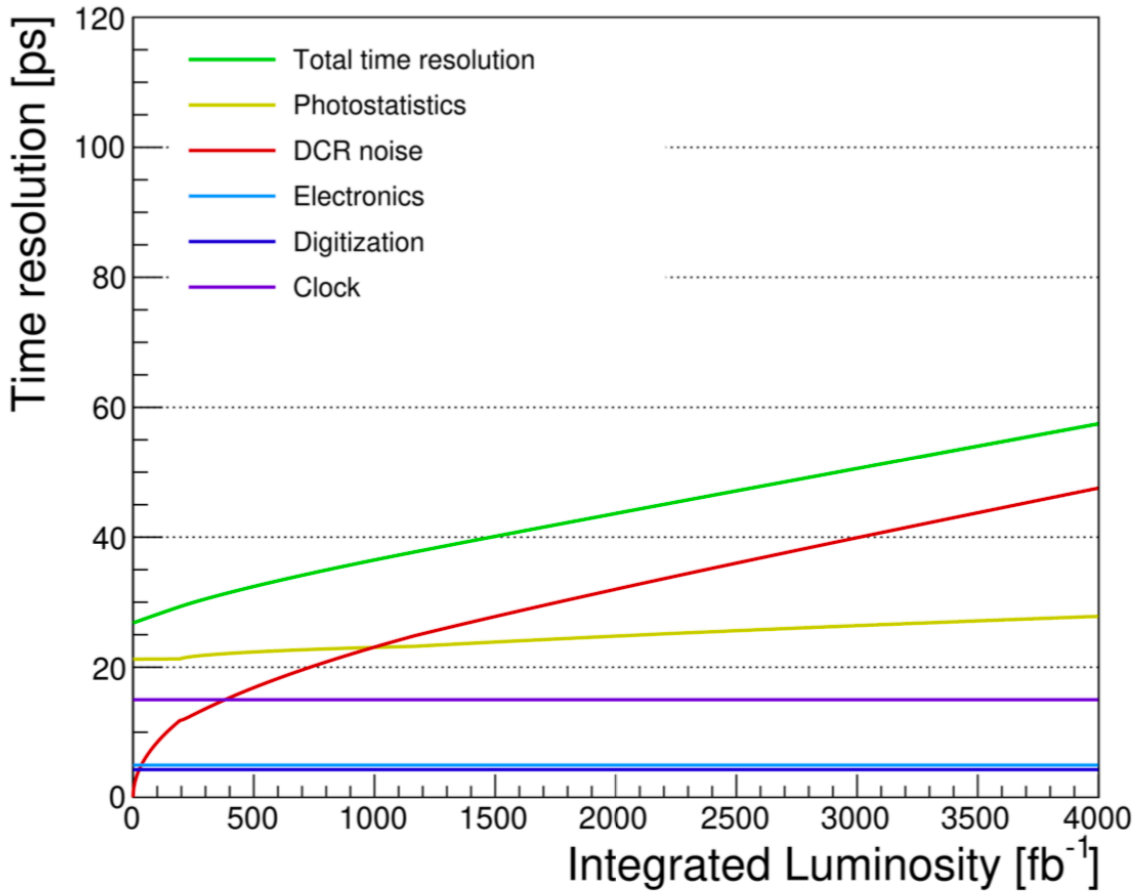
- Only few particles in the event – do not need fine segmentation, but do need good resolution and good coverage/acceptance

- A decently large crystal would contain the electron/positron and the right choice of crystal would give a lot of light
  - E.g. , PbWO4, LYSO crystal read out by SiPM
  - Plastic scintillator? (cheap but perhaps not bright enough)

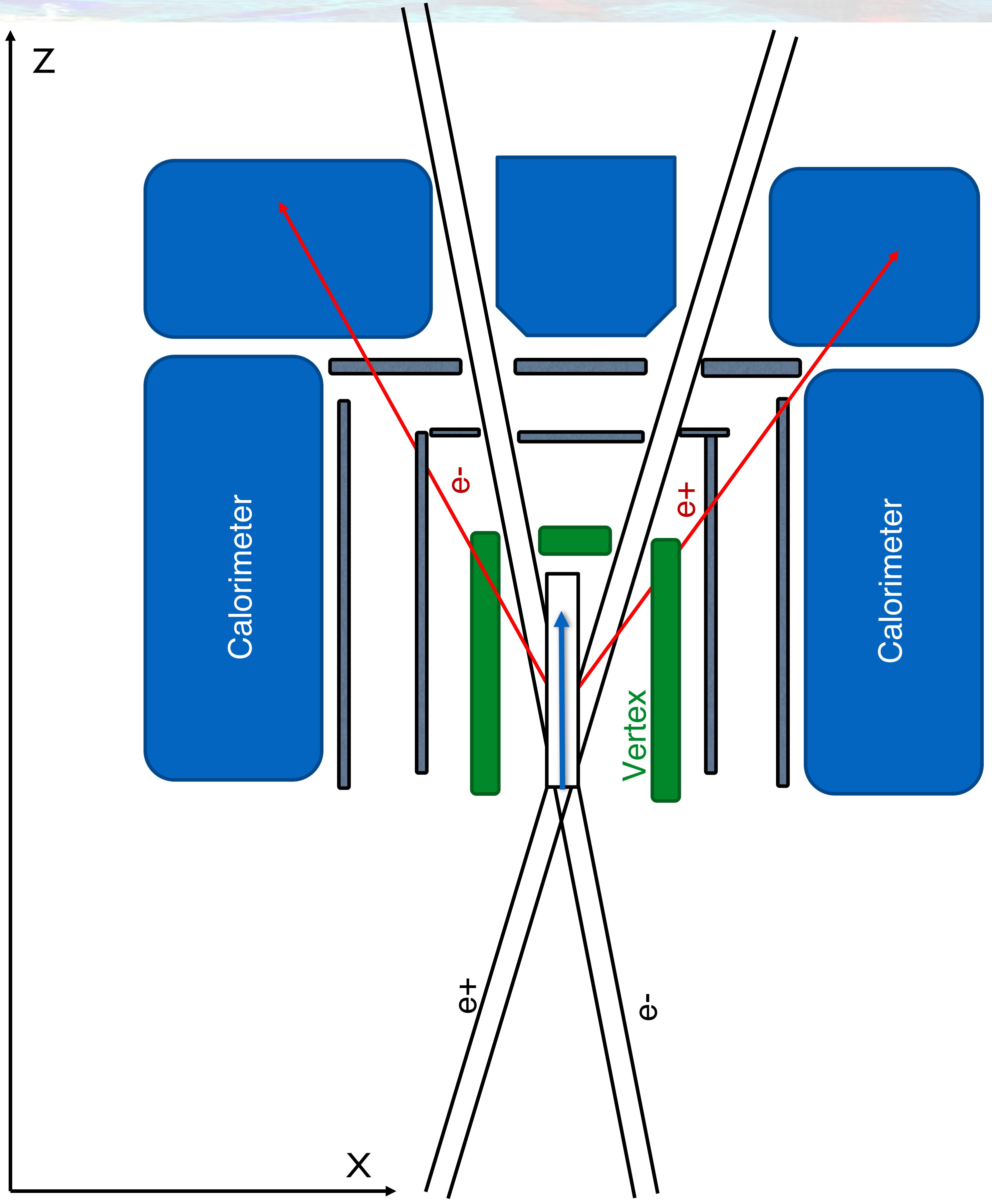
- Precision timing desirable for further BG suppression and spectroscopy measurements?







Detector Sketch



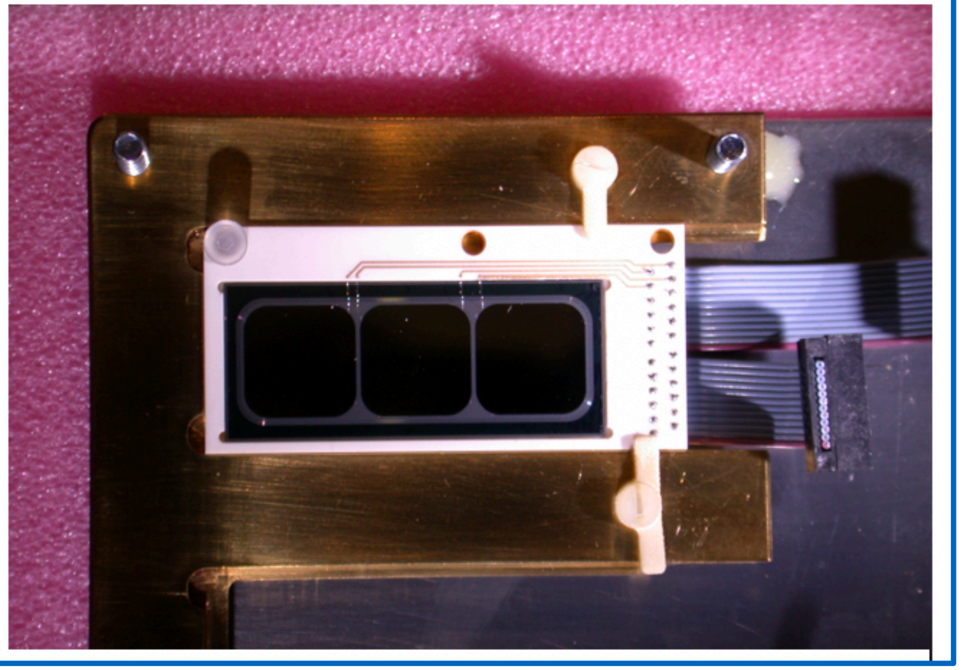
- Vertex: Pixelated silicon vertex detector
- Crystal calorimeter with excellent timing and energy resolution
- Directionality: Additional 2-3 tracking layers between the vertex detector and the calorimeter. Gas based (GEM) or silicon strips
- No magnetic field necessary
- Can probably achieve 50+% acceptance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

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} , hard to achieve 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)
- Dimuonium Laser spectroscopy?

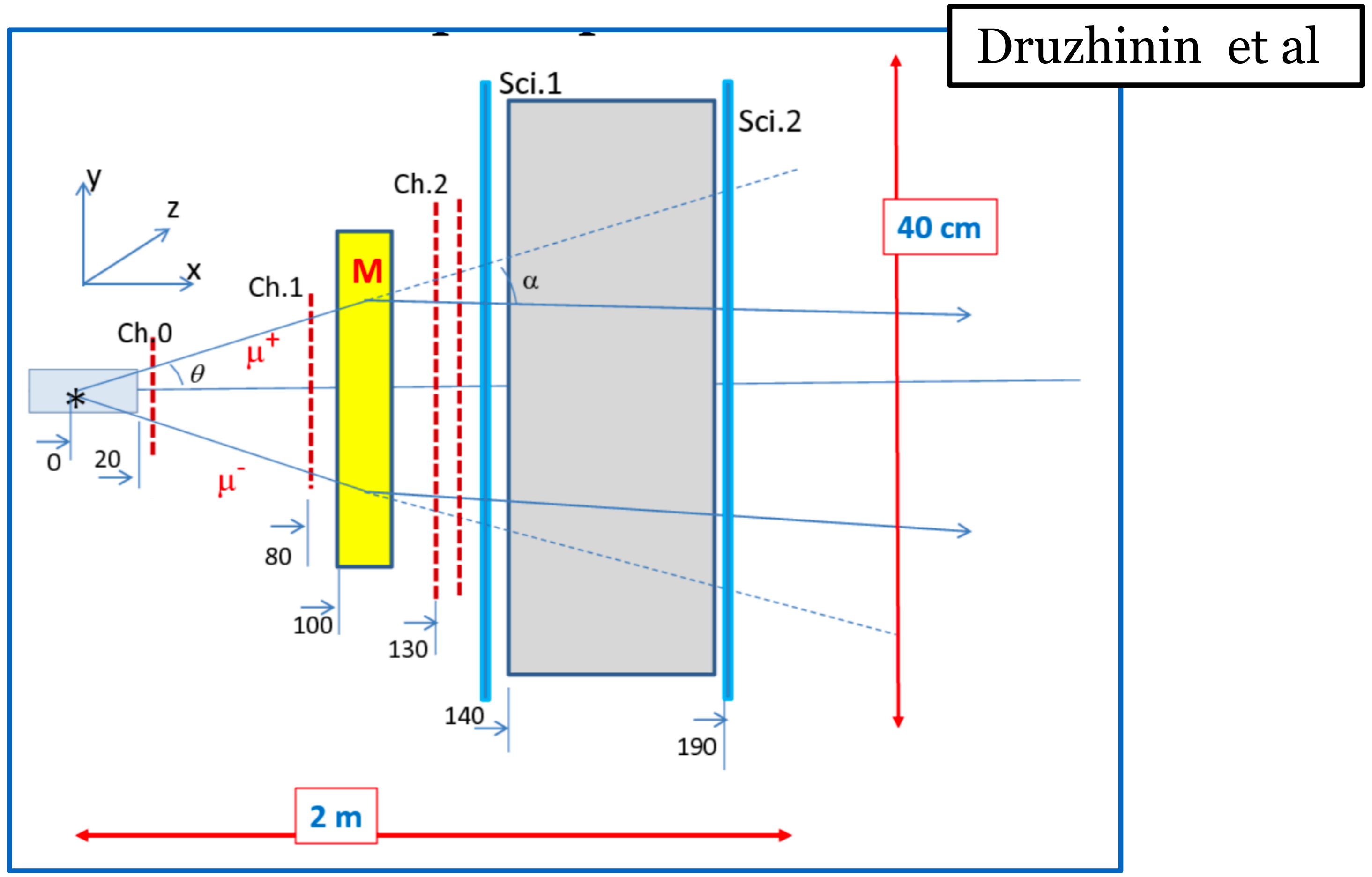
Detector	Si(Li)	CCD	SDD
Area [mm2]	200	724	100
Thickness [mm]	5	0.03	0.30
Δ E (FWHM) [eV]	410	170	185
Δ t (FWHM) [ns]	290	-	430

SDDs with 1cm^2 per SDD



Other processes?

- In principle, such an e+e- collider can provide access to a number of other physics measurements



- 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
  - etc

- Magnetic spectrometer installed perpendicular the beam direction can provide background-free detection of muon pair with very high efficiency
  - Some shielding needed to eliminate any hadronic activity in the muon system
- For hadronic processes a more complete detector is needed
  - Space constraints should be carefully considered and evaluated

Summary

- Presented very rough considerations for designing a TM detector for a large-angle experiment
- Detection of e+e- pairs from the TM decay should not be a problem
- Main features – vertex detector for Bhabba background rejection and high resolution and good timing calorimeter
- Spectroscopy:
  - Requires excellent electron energy resolution (or)
  - Direct photon detection but studies are needed to determine applicability for this particular case (or)
  - Other ideas…
- A broader program would require a multi-purpose detector, including more complete tracking and calorimeter systems