Prospects for True Muonium $(\mu^+\mu^-)$ observation at existing beamlines and colliders

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Leptonic -onium states & True Muonium

- ”Onium” ($f\bar{f}$) purely leptonic states: positronium (e^+e^-), **true muonium ($\mu^+\mu^-$)**, true tauonium ($\tau^+\tau^-$)
  $\rightarrow$ Positronium is extensively studied - also produced every time a e^+ source (Na-22) is used

- True muonium (TM) and true tauonium never observed
  $\rightarrow$ Same properties of dark photons (spin 1) and ALPs (spin 0)
- Possible to search for new physics and, in parallel, discover TM, ”cross-motivating” both studies

- **”Dream” experiment: Precision TM spectroscopy (as for muonium)**
  $\rightarrow$ access to vacuum polarization and new-physics, à la g-2 [1]

Production methods: classification

- Tried to classify proposed production methods in terms of feasibility: inspirehep.net/dimuonium|true muonium

- Employs an existing beamline or collider?
  - $\rightarrow$ Yes, with relatively large significance (~ 1 paper)
    - $\eta \rightarrow TM\gamma$ at LHCb with Run3 data [..]
  - $\rightarrow$ Yes, but with small significance (~ 12 papers)
  - $\rightarrow$ No, needs new facilities (~ 8 papers)

- Tried to bridge the gap in the green section by proposing two new methods
  - $\rightarrow$ Resonant $e^+e^- \rightarrow TM \rightarrow e^+e^-$ at H4 (+1 paper)
  - $\rightarrow$ $\gamma\gamma$ fusion $e^+e^- \rightarrow TM \rightarrow e^+e^-$ at Belle-II (+1 paper)

Prospects in the near future

- $\eta \to TM\gamma$ $(BR \sim 5 \times 10^{-10})$ @ LHCb with Run3 data [2]

  $\rightarrow$ Work by Vidal et al. in 2019: Possibility of observation in next years ?

- $e^+e^- \to TM \to e^+e^-$ at SPS-H4 (our work): PRD 110, 092015

  $\rightarrow$ Rare events **displaced-vertex** search with ~ 0 bkg: requires **3 months** dedicated **positron** beam time with a 12m long multi-target assembly

  $\rightarrow$ **Design of target assembly, detectors, background rejection strategy, complete simulation**, after preliminary work by P. Crivelli et al. [3]

  $\rightarrow$ **Our target optimization inserted in the NA64 e^+ phase-2 prospects**, in Physics Beyond Colliders report for ESPPU [..]

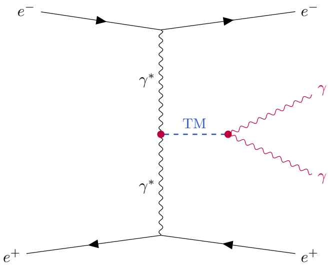
  $\rightarrow$ In the same report a TM factory at future FCC-ee injectors is proposed

  - Large $(10^3 - 10^4$ TM/day) rates thanks to excellent σ_E^{beam}, allowing spectroscopy

- TM at Belle-II with 2020-22 data (our work): **see next slides**

True Muonium with photon-photon fusion

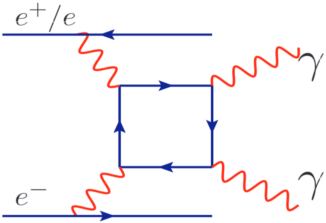
- **Belle-II can produce TM via $\gamma\gamma$ fusion:** $e^+e^- \to e^+e^-\gamma^*\gamma^* \to e^+e^-$TM
- para-TM (spin-0) is created: decays to two photons: TM $\to \gamma\gamma$
- Collinear photon scattering $\to$ leptons at low angles
- Signature: no leptons but two isolated photons with $m_{\gamma\gamma} \sim 0.211$ GeV

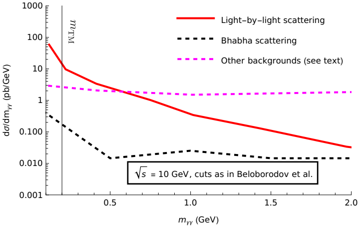


- In order to apply the collinear photon approximation in the analysis we cut $Q^2_{max} < m^2_{TM}/10$ (not necessary in the data)
- Complementary phase-space with visible leptons also sensitive to TM (see next slides)

Background and generator-level simulation

- Dominant background: light-by-light (LBL) scattering $\gamma\gamma \to \gamma\gamma$
  $\to$ Subdominant: $e^+e^- \to \gamma\gamma\gamma\gamma$, double radiative Bhabha ($e^+e^- \to e^+e^-\gamma\gamma$)
- Photon-coupled ALPs and para-TM have same quantum numbers $\to$ In narrow-width approximation they are equivalent if $\Gamma_{ALP} = \Gamma_{TM}$
- Simulation using SUPERCHIC generator: LbL bkg & ALP signal
- Analytical and SUPERCHIC XS values match at 3%
- σ_S ~30.6 fb, $\sigma_B \sim 2000$ fb in a 50 MeV signal window

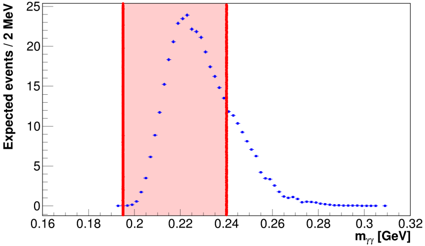


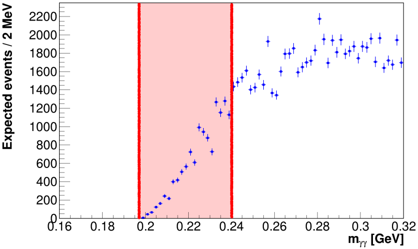


Reco-level simulation

- Acceptance, resolution, efficiencies, trigger and isolation cuts included
  $\rightarrow$ Threshold-like shapes due to competing trigger cuts and Q^2 cuts

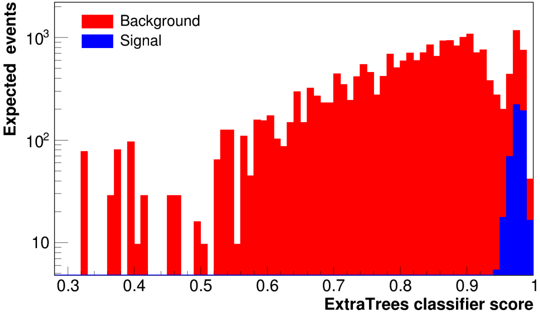
- With 363 fb^{-1} (2020-22), mass-cuts significance: $S(\sim 300)/\sqrt{B(\sim 13\text{k})} \sim 2.7\sigma$
- S/B$\sim$ 2% $\rightarrow$ Systematic effects degrade significance
  $\rightarrow$ For both reasons further discrimination required, see next slides





Background suppression

- **ExtraTrees classifier** (BDT-like but simpler and more randomized) trained on ALP samples with flat mass distribution as **signal** to avoid mass sculpting + half of **bkg** sample
- Large signal/background separation using kinematical features



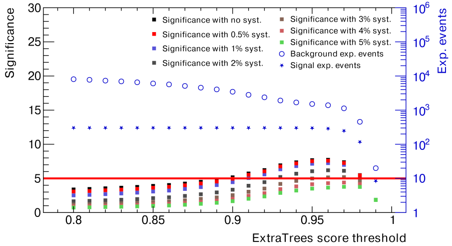
- Performances tested on original m_{TM} signal sample + other half of bkg sample

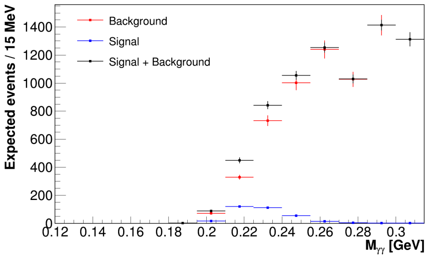
- Cut on the classifier score to be optimized (see next slide)

Significance

- Discovery significance $> 5\sigma$ achieved for systematics on bkg $\leq$ 3%

- Total background in the signal region to be well under control
- Employed conservative Q^2_{max} cut to ensure collinearity $\rightarrow$ could go better in data if also the remaining phase-space is simulated

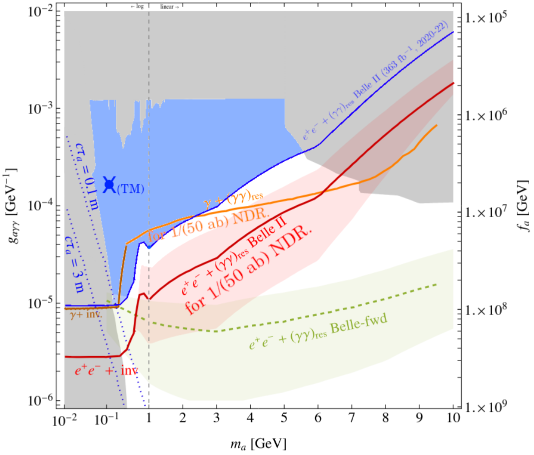




Summary and other possibilities

- TM observable with Belle-II 2020-22 data with collinear $\gamma\gamma$ fusion :)

  $\rightarrow$ arXiv:2501.17753, recently accepted in Physics Review D



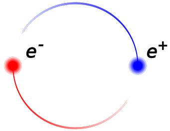
- Other channel: visible e^+e^- + $\gamma\gamma$ final states (see doi.org/10.1007/JHEP12(2024)099 for ALPs, lumi-scaled by us)

- Discovery level significance also in this channel $\rightarrow$ possibility to combine both

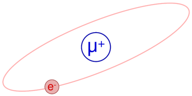
↓ Backup ↓

Atoms & other QED bound states

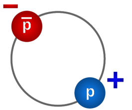
- Most common bound states: nuclei, atoms & gravitation-bound systems



- Atoms are bound by quantum electrodynamics (QED)
  $\rightarrow$ precise predictions available



- Many other QED bound states, can be divided in:
  $\rightarrow$ purely leptonic & semi-leptonic: e^+e^-, μ^+e^-, μ^-p, ...
  $\rightarrow$ purely hadronic: K^-p, π^-p, p^-p^+, ...



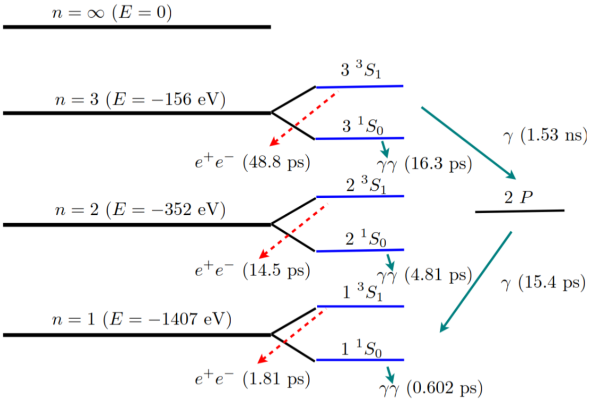
- Purely leptonic states allow high-precision spectroscopy:
  $\rightarrow$ muonium (μ^+e^-) at PSI

True Muonium levels

- Ortho-TM: Spin 1: $e^+e^- \leftrightarrow TM$
- Para-TM: Spin 0: $\gamma\gamma \leftrightarrow TM$
- Lifetimes scaling as n^3 with the energy level n
- Ion. energy: 1.4 keV

$$\tau(nS_{s=1} \to e^+e^-) = \frac{6\hbar n^3}{\alpha^5 m_\mu c^2} \sim n^3 \times 1.8\,\mathrm{ps}$$

$$\tau(nS_{s=0} \to \gamma\gamma) = \frac{1}{3}\tau(nS_{s=1} \to e^+e^-)\,.$$



- Lifetimes in ps region, like B/D mesons

Production methods: $e^+e^- \to TM(X)$

- $e^+e^- \to TM \to e^+e^-$ on resonance (displaced vertices search)
  - $\to$ at new dedicated colliders:
    - $\to$ $n = 1$ boosted TM with $\theta_{coll} = 30^\circ$ and $O(1)$ GeV beams [4] [5]
    - $\to$ $n > 1$ TM with 105 MeV e^+/e^- beams (our previous work) [6]
  - $\to$ SPS-H4 with $\sim 43.7\ e^+$ beams $\sqrt{s} \approx 2m_\mu$, available at CERN
    - $\to$ **Our work**, after preliminary studies by Crivelli et al. [3]

- Out-of-resonance production at existing e^+e^- colliders:
  - $\to$ $e^+e^- \to TM\gamma$ at $\sqrt{s} = O(1)$ GeV $\to \sigma \sim O(10^{-1})$ fb [7]
  - $\to$ Photon-photon fusion at $\sqrt{s} = O(10)$ GeV $\to \sigma \sim O(50)$ fb
    - $\to$ Belle-II with already collected dataset (our work) [m]

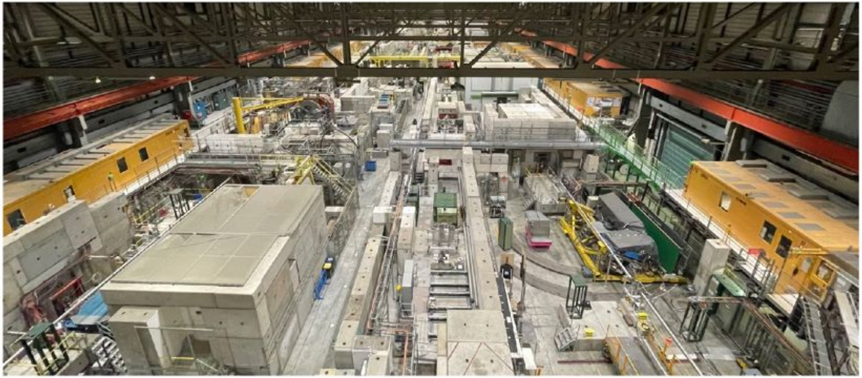
Other production methods

- From meson decays:
  - $\rightarrow$ $\eta \rightarrow TM\gamma$ ($BR \sim 5 \times 10^{-10}$) @ LHCb [8] [9] [10] [11]
  - $\rightarrow$ $K_L \rightarrow TM\gamma$ ($BR \sim 7 \times 10^{-13}$) @ neutral kaons beamlines [12]

- Other possibilities:
  - $\rightarrow$ Bremmstrhalung-like and triplet-like processes $eZ \rightarrow e\,TM\,Z$ with $O(10)$ GeV beams, $\sigma \sim O(10^{-2})$ fb [13] [14]
  - $\rightarrow$ Photon-photon fusion in relativistic heavy ion collisions [15]
  - $\rightarrow$ Interactions of ultra-slow μ^+ and μ^-
    - $\rightarrow$ μ^- beam on μ^+e^- / μ^+ beam on μ^-p [16], maybe at J-PARC (Only method allowing spectroscopy)

True muonium at SPS-H4: Pillars

- $e^+e^- \to TM \to e^+e^-$ with 43.6 GeV e^+ beam $\to \sqrt{s} = \sqrt{2m_e E} = 2m_\mu$
- TM dissociates in matter with huge XS $\to$ multiple thin lithium targets
- Displaced vertex search, rejecting Bhabha scattering background
- Our work: arXiv:2409.11342, accepted by Physics Review D

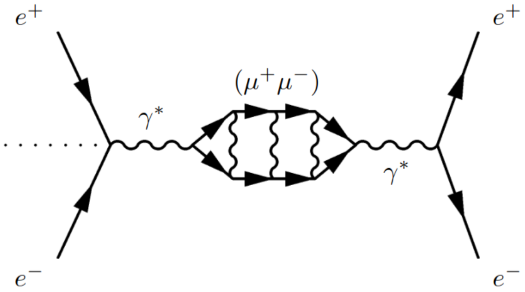


True muonium resonant production: Theory

- Peak cross-section: $\sigma_P = \frac{3}{2}\pi\alpha \cdot \sigma^{rel}_{e^+e^- \to \mu^+\mu^-} = \frac{2\pi^2\alpha^3}{s}$ = 66.6 nb
- Probability to produce the spin 1 n-th state: $n^{-3} \to p_{1S}$ = 83 %
- Need $\sqrt{s} \in [2m_\mu, 2m_\mu - \delta E]$ where $\delta E = 1.4$ keV (ion. energy)

$\to$ XS reduced by integrating the $\sqrt{s}$ distribution in the energy window

$\to$ At H4 energy spread in a $\pm 1.2\%$ window. Including ISR: $\sigma_{eff} = 29$ pb

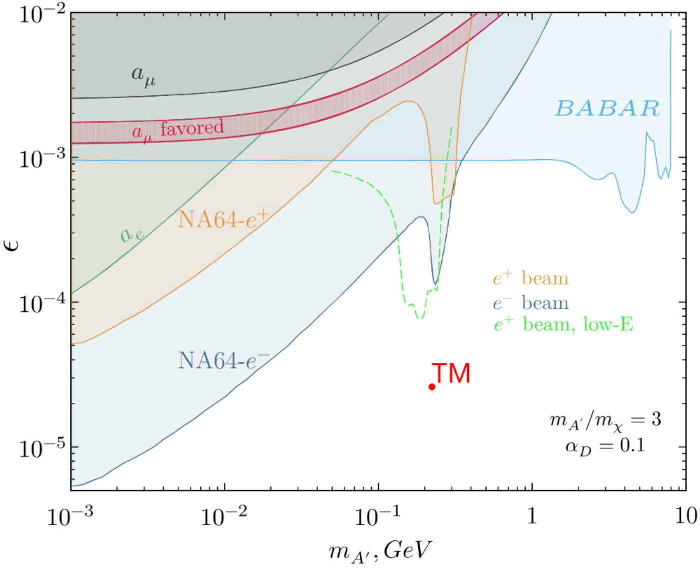


$\to$ Similar to dark photon production

$\to$ $\Gamma^{1S}_{TM} = 3.6 \times 10^{-10}$ MeV = $\frac{1}{3}\alpha\epsilon^2 m_{TM}$

$\to$ Coupling: $\epsilon = 2.6 \times 10^{-5}$

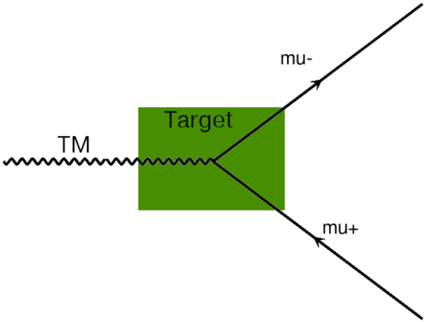
Limits for dark photons in the TM region



- Similar to dark photon production
- $\Gamma^{1S}_{TM} = 3.6 \times 10^{-10}$ MeV= $= \frac{1}{3}\alpha\epsilon^2 m_{TM}$
- Coupling: $\epsilon = 2.6 \times 10^{-5}$
- TM / dark photon differences due to TM behaviour in matter

Dissociation in matter

- Due to nuclei electrical fields TM can be ionized very easily: $TM \to \mu^+\mu^-$
- Huge dissociation cross-section: $\sigma_D = 13Z^2$ b
- Most important limit to TM discovery so far and biggest difference with dark photons
- Low probability to flip spin instead of dissociating: $\sigma_{flip} = O(1)$ mb

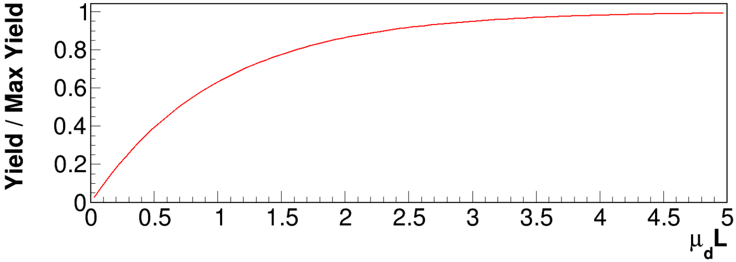


Expected yield on target: theory

- Defining an inverse dissociation length: $\mu_d = \rho N_A / A \cdot 13 Z^2 b$
- Evaluating the expected yield per e^+ on a target with thickness L
- TM at a depth z must survive for a length $(L - z)$:

$\rightarrow \frac{dTM}{de^+ dN_{\text{target}}} = \rho N_A Z / A \sigma_{eff} \int_0^L dz e^{-\mu_d (L-z)} = \frac{\sigma_{eff}}{13 Z \,\mathrm{b}} (1 - e^{-\mu_d L})$

- $L = 2\mu_d^{-1} \rightarrow > 80\%$ of the maximum yield is achieved

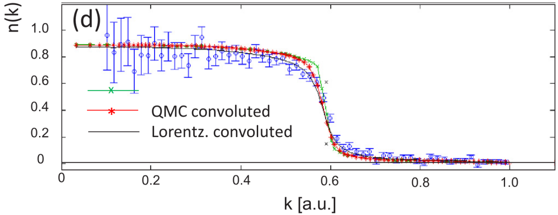


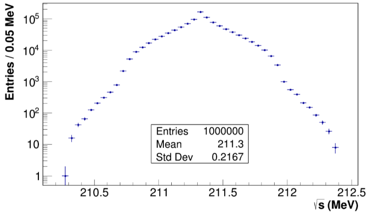
Target choice

- Yield proportional to $1/Z \rightarrow$ Low Z target
- TM yields saturates for high target thickness
  - $\rightarrow$ Thick targets only increase backgrounds
  - $\rightarrow$ Need very thin target $L \sim 2\mu_d^{-1}$
- A single thin target limits discovery potential
  - $\rightarrow$ Target assembly made by **multiple** 4mm ($\sim 2\mu_d^{-1}$) **lithium foils** (Z=3)
- Very reactive with air and moisture
  - $\rightarrow$ Challenging to handle but feasible

Evaluating σ_{eff}: Electron motion

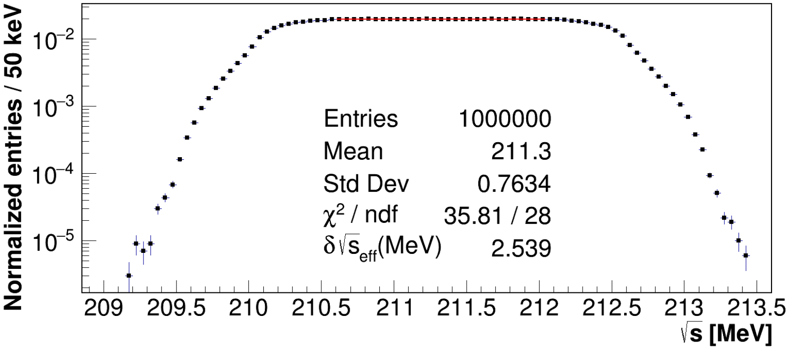
- Electron motion can be important at fixed target e^+e^- [17]
- Full $\sqrt{s}$ formula: $\sqrt{2m_e^2 + 2E_-E_+ - 2E_+k_- \cos\theta_-}$
- Polycrystalline material $\rightarrow \cos\theta_-$ uniform
- Electron momentum (k) distribution from Compton profile data [18]
- Resulting spread in $\sqrt{s}$: ~ 200 keV $\rightarrow \sigma^{ele}_{\sqrt{s}}/m_{TM} \sim 10^{-3}$ (very small ✓)





Evaluating σ_{eff}: Beam energy spread (BES)

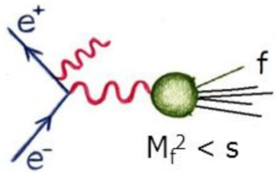
- H4 momentum selection: $\pm 1.2\%$ (uniform spread) [19]
- BES convoluted with electron motion and fitted in the uniform region
- At m_{TM} the $\sqrt{s}$ distribution is uniform $\rightarrow \delta\sqrt{s}_{eff} = 2.54$ MeV
  $\rightarrow \sigma_{eff} \sim \delta E/\delta\sqrt{s}_{eff} \cdot \sigma_P = 1.4$ keV$/2.54$ MeV $\cdot\, 66.6$ nb $= 36.7$ pb
- One effect missing $\rightarrow$ Initial State Radiation $\rightarrow$ Final XS: 29 pb

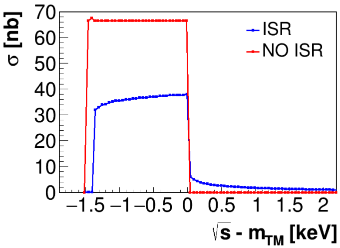


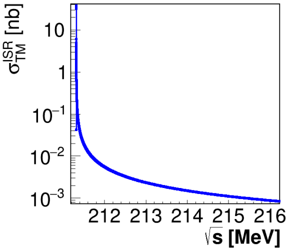
Evaluating σ_{eff}: Initial State Radiation (ISR)

- Evaluating the combined effect of ISR and BES is not trivial
  $\rightarrow$ A fraction x of initial $\sqrt{s}$ is kept after ISR, but $\sqrt{s}$ fluctuates
- Representing $\sigma_{TM}(\sqrt{s})$ as a rectangle of width δE and height σ_P
- Ingredients: $f_{ISR}(x, \sqrt{s})$ (QED radiator) & $G(\sqrt{s})$ (BES p.d.f.)

$\rightarrow$ $\sigma_{\text{TM,eff.}} = \int ds'\, \mathcal{G}_{\text{BES}}(\sqrt{s'}) \underbrace{\int dx\, f_{\text{ISR}}(x; \sqrt{s'})\sigma_{\text{TM}}(x\sqrt{s'})}_{\sigma^{ISR}_{TM}(\sqrt{s'})}$ = 29 pb

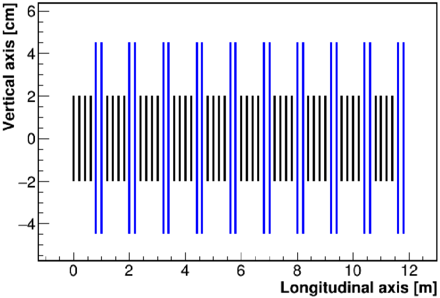






Expected yield and target assembly

- Inputs: σ_{eff} = 29 pb, $L = 4$ mm, $\mu_d = 1.86$ mm, $Z = 3$
- Result: $\frac{dTM}{de^+ dN_{\text{target}}} = \frac{\sigma_{eff}}{13Z\,\text{b}}(1 - e^{-\mu_d L})$ = 6.6×10^{-13}
- Goal: ~ 5 events for $10^{12} e^+$ with $\sim$ 20% eff. $\rightarrow$ 40 targets (=10 cells)
- Displaced vertex search ($\beta\gamma c\tau = 11.3$ cm) $\rightarrow$ 20 cm distance between targets to avoid dissociations + 2-layer silicon trackers every 4 targets



$\rightarrow$ **1 cell = 4 targets + 2 Si trackers**

$\rightarrow$ #targets per cell limited by multiple scattering (all in vacuum)

$\rightarrow$ #cells limited by space before Goliath (checked from a LEMMA TB [20])

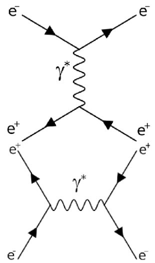
$\rightarrow$ Energy loss in the whole target: $\sim$20 MeV $\rightarrow$ negligible $\sqrt{s}$ fluctuation

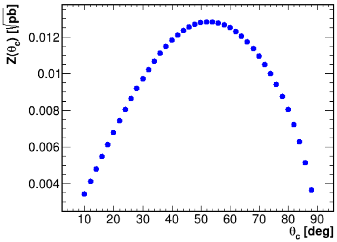
Background: preliminary discussion

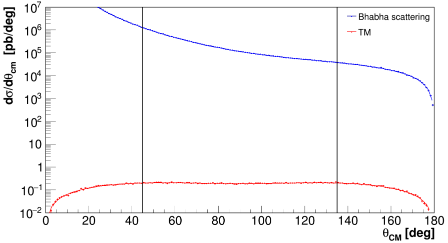
- e^+ on target interact e.m. with e^-, p and weakly with e^-, p, n
- e^+e^- **Bhabha**, e^+p Moller scattering ($\sim 1/s = m_e/m_p \sim 1/2000$ smaller)
- Weak XS of the same order of $\bar{\nu}N \to \mu^+X$: 3 fb / E_{e+}[GeV] $\to$ O(0.1) pb
- Bhabha ($e^+e^- \to e^+e^-$), **except for the displaced vertices and $\theta_{\mathbf{cm}}$ distribution**, shows **identical** features as $TM \to e^+e^-$
  $\to$ Used to estimate signal acceptance and design the detector
  $\to$ Dominant background, but minor ones are anyway included in MC
- Strategy: identify Bhabha/TM events $\to$ cut in θ_{CM} $\to$ look at vtx z

Angular acceptance

- Bhabha: $\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{8E^2}\left(\underbrace{\frac{1+\cos^2\vartheta}{2}}_{\text{s-channel}} + \underbrace{\frac{1+\cos^4\frac{\vartheta}{2}}{\sin^4\frac{\vartheta}{2}}}_{\text{t-channel}} - \underbrace{\frac{2\cos^4\frac{\vartheta}{2}}{\sin^2\frac{\vartheta}{2}}}_{\text{s-t interf.}}\right)$
- TM decay: $\frac{dN}{d\Omega} = \underbrace{\frac{1+\cos^2\vartheta}{2}}_{\text{s-channel}} \rightarrow$ Cutting $\bar{\theta} < \theta_{CM} < \pi - \bar{\theta}$
- Maximize $S/\sqrt{B} \rightarrow \bar{\theta} = 53°$. Increase very low TM yield $\rightarrow \bar{\theta} = 45°$





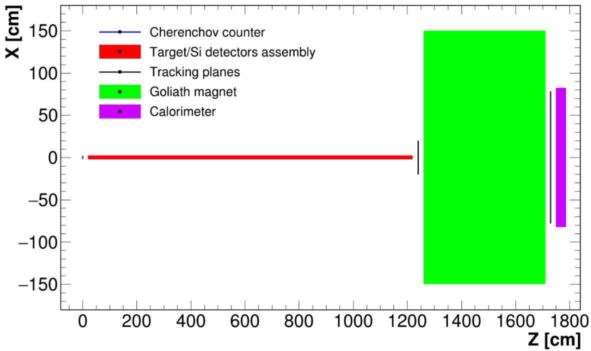


- $\epsilon_{TM}^{acc.} = 61\%$
- $\sigma_{Bh.} = 21\mu b$
- θ_{lab} b/w 2.7-16.6 mrad
- E_{lab} b/w 6.4-37.3 GeV

Detectors

- Goal: 100 % acceptance for $TM \to e^+e^-$ after θ_{CM} cut
- Employing the Goliath magnet (1.2T) as a key element of the setup

1. Gas Cherenchov to reject hadron contamination
2. Targets + Si TRK, measuring #part., θ_{lab}, vtx of each cell
3. Trackers ($\sigma_x \sim 5$ mm) before/after Goliath for γ-rejection + measuring #part., charge from all cells
4. ECAL to reject photons and measuring energies



Silicon detectors requirements

- 4.5×4.5 cm^2 area taking into account beam spot and tracks angle
- Requirements (from MC): $\sigma_{x,y} = 5\ \mu m$ and 0.3% X_0 per-layer

- Very thin monolithic pixel sensors like ALICE ITS-3

- 405 cm^2 in total $\rightarrow$ scaling **naively** cost with area $\rightarrow \sim$ 20 kCHF

Tracking planes

- Goliath magnet: Vertical B=1.2 T over $\Delta z = 2$ m, with geometrical apertures $\Delta x \sim 2$ m, $\Delta y \sim 1$ m and 4.5m total external length [21]

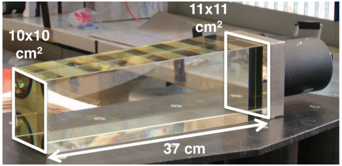
- Beam-momentum particles curve by 16.4 mrad $\rightarrow \Delta x = 7.4$ cm
- Trackers before/after Goliath (σ_x = 5 mm) $\rightarrow > 20\ \sigma\ e^+/e^-$ separation
- Low-p particles instead curve by 0.5 m (fitting magnet aperture ✓)

- Tracker areas: 40×40 cm^2 (1st), 55×156 cm^2 (2nd)
- Cost-effective solution: scintillating bars (at least for the 2nd tracker)

Photon rejection & ECAL

- Hard Bremmstrhalung photons could be dangerous $\rightarrow \gamma$ tagging
  $\rightarrow$ γ conversions in 1st tracker $\rightarrow e^+/e^-$ pair vetoed by 2nd tracker
  $\rightarrow$ γ conversions in 2st tracker $\rightarrow$ no track matching
  $\rightarrow$ γ only in **ECAL** $\rightarrow$ no track matching
- ECAL also needed to constrain total energy to beam momentum
  $\rightarrow$ ECAL resolution: $\sigma_E/E = 5\%/\sqrt{E[\text{GeV}]} \oplus 10\%/E[\text{GeV}] \oplus 1\%$
- Large ECAL area: $> 55 \times 156$ cm^2 (at least matching 2nd tracker)

- Cost-effective solution: 16×6 NA62 LAV-like lead glass blocks [22]



Simulation and trigger

- Geant4 proof-of-concept simulation to evaluate bkg rejection
- 10^{14} POT simulated with mono-energetic pencil beam
- Only 1 cell simulated (4 targets + 2 Si detectors), acceptable because:
  $\rightarrow$ Analysis cuts designed to select clean 2-body processes + displaced vtx
  $\rightarrow$ e^+/e^- from Bhabha and TM decays only cross a few cells
  $\rightarrow$ Each cell has a 1% X_0 material budget $\rightarrow$ small effect on signal efficiency
  $\rightarrow$ Interactions of bkg e^+/e^- in next cells don't spoil vtx $\rightarrow$ small bkg increase
- Virtual detector (VD) downstream to simulate trackers+calorimeter

- Trigger applied during simulation:
  $\rightarrow$ $= 1$ positive and $= 1$ negative tracks on VD + any number of neutrals
  $\rightarrow$ Both tracks with 2 $< \theta_{lab} <$20 mrad and 3 $< E <$42 GeV

Smearing, reconstruction and kinematics selection

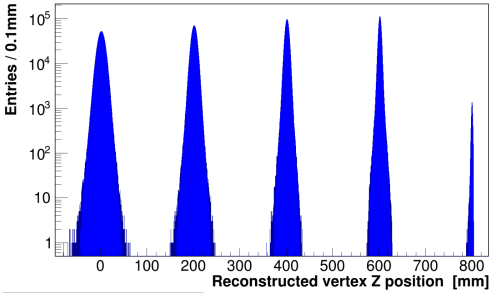
- Energies and silicon detector positions smeared
- θ_{lab} angles reconstructed using Si trackers positions
- Extrapolating z at the target as $\sqrt{x^2 + y^2} / \tan(\theta_{lab})$

- Kinematics-based selection applied:
  - $\rightarrow$ $= 2$ tracks in each silicon detector (clean Bhaha/TM event)
  - $\rightarrow$ $|E_+ + E_- - E_{beam}| < 2$ GeV (no energy loss)
  - $\rightarrow$ Combined mass of track pair within 15 MeV of m_{TM} (no energy loss)
  - $\rightarrow$ $|p^x_+ - p^x_-| < 8$ MeV & $|p^y_+ - p^y_-| < 8$ MeV (limits mult. scattering)
  - $\rightarrow$ $|\theta_{cm} - \pi/4| < \pi/2$ (Bhabha scattering reduction)

- Vertex z evaluated very simply as $z = (z_+ + z_-)/2$

Efficiency and vertex selection

- Efficiency of reconstruction and kinematics-based selection for $|\theta_{cm} - \pi/4| < \pi/2$ Bhabha events : $\epsilon_{reco} = 77.4\%$
- Angular acceptance of TM in the $|\theta_{cm} - \pi/4| < \pi/2$ region: $\epsilon_{\theta_{cm}} = 61\%$
- Select regions in z with 0 bkg in MC $\rightarrow \frac{\#BKG}{\#e^+} = N_{\text{cells}} POT_{MC}^{-1} = 10^{-13}$
- z-selection efficiency: $\epsilon_z = 42.5\% \rightarrow$ Total eff.: $\epsilon_{1S}\epsilon_{reco}\epsilon_{\theta_{cm}}\epsilon_z = 16.2\%$

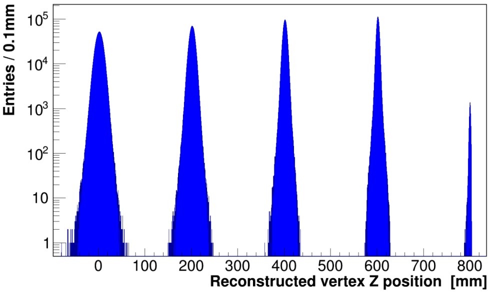


Target z [mm]	z_{min} [mm]	z_{max} [mm]	Partial ϵ_v
0	70	150	27.3%
200	250	356	39.1%
400	438	571	49.4%
600	631	782	56.0%

- Last peak due to hits in the 1st silicon detector $\rightarrow$ fake vtx

Vertex selection, efficiency and significance

- $10^{14} e^+$ simulated in GEANT4 on 1 cell to estimate bkg rejection
- Quality + Angular cuts to reduce Bhabha ($e^+e^- \to e^+e^-$) + other bkgs
- Select regions in z with 0 bkg in MC $\to \frac{\#BKG}{\#e^+} = N_{\text{cells}} POT_{MC}^{-1} = 10^{-13}$
- Efficiency estimated with Bhahba + exp. integral in z regions: 16.2%



- With 3k spills/day, 3 months run and 10^7 e^+/spill:
  S=12, B=0.3 $\to$ 8 σ significance
- Good start, clearly if needed more refined simulations should be made

Significance and positron rates

- Including total. eff. $\epsilon = 16.2\% \to$ TM yield $\frac{\#TM}{\#e^+} = 4.35 \times 10^{-12}$
- Average SPS spill rate: 3000/day. Rate $\#e^+$/spill to be discussed
  - $\to$ At LEMMA TB 5×10^6 e^+/spill at 44 GeV without exploiting max. intensity
  - $\to$ NA64 quoted $5 - 7 \times 10^6$ at 100 GeV, but at 44 GeV we expect higher rates
  - $\to$ Two scenarios for e^+/spill: conservative (5×10^6), optimistic (10^7)
  - $\to$ In 3 months run: $\#e^+ = 1.35(2.7) \times 10^{12}$ being conservative (optimistic)
- Signal ev.: 5.8 (11.6), Bkg ev.: 0.13 (0.26), **Significance: 5.8 (8.2)** σ
- Expected bkg could be overestimated, due to limited MC statistics
- Good start, clearly if needed more refined simulations should be made

TM from 43.6 GeV positron beam: outlook

At SPS-H4 with current rates:

- Target made by 40 lithium foils (4mm) with Si trk
- 2 scintillating tracker planes + ECAL after target
- Space needed: 12m before Goliath + ~ 2 m after
- Discovery potential in a 3 months run
- In parallel dark photon searches could be made

In the future:

- Our target optimization inserted in the NA64 e^+ phase-2 prospects
  $\rightarrow$ See Physics Beyond Colliders report for ESPPU [arXiv:2505.00947v1]
- In the same report a TM factory at FCC-ee injectors is proposed, exploiting the excellent energy resolution
  $\rightarrow$ Large $(10^3 - 10^4$ TM/day) rates, potentially allowing spectroscopy