# BTF at LNF and the dark photon paradigm

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Proposal to search for a dark photon in $e^+$ on target collisions at DAΦNE linac.

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**Abstract**

Photon-like particles are predicted in many extensions of the Standard Model. They have interactions behaviour similar to the photon, are vector bosons, and can be produced together with the photons. The present paper proposes a search for such type of particles exploiting the beam test facility at Laboratori Nazionali di Frascati, INFN. With present beam parameters a sensitivity in the coupling constant down to $10^{-6}$ is achievable in one year running for mass region from 2.5 MeV< $M_U$ <20 MeV.

***LNF seminar***

**25 February 2014**

# Outline

- Motivation
- BTF @ LNF
- Idea
- Production
- Experimental setup
- Simulation & Reco
- Expected sensitivity
- Conclusions

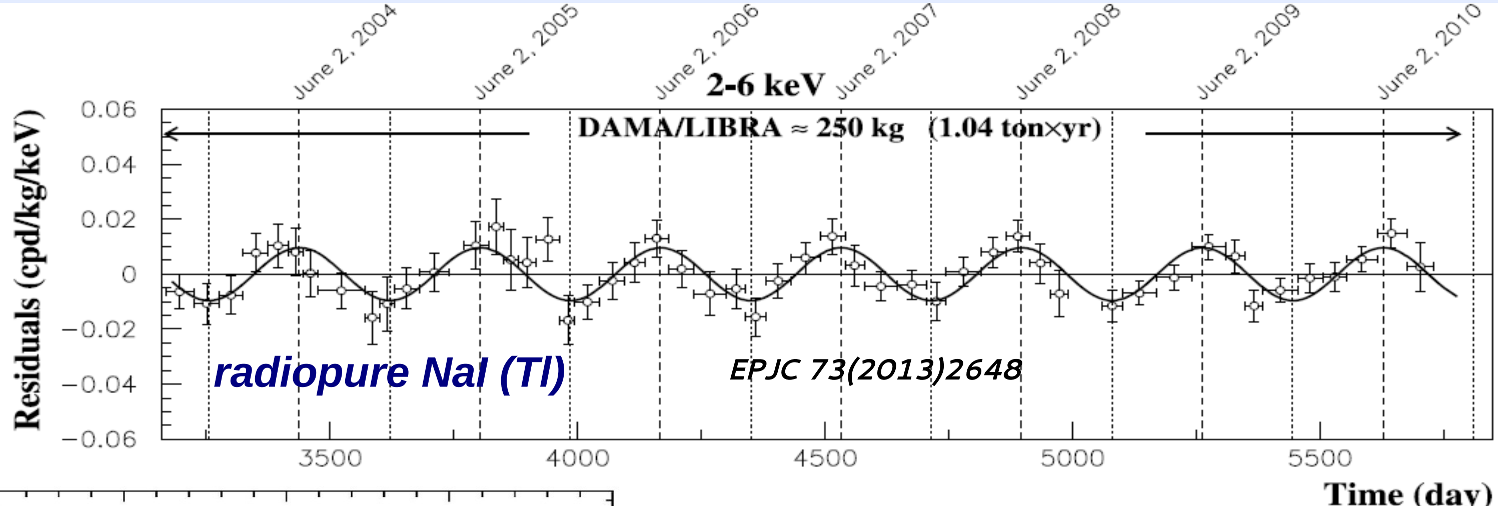
# Motivation: New Physics

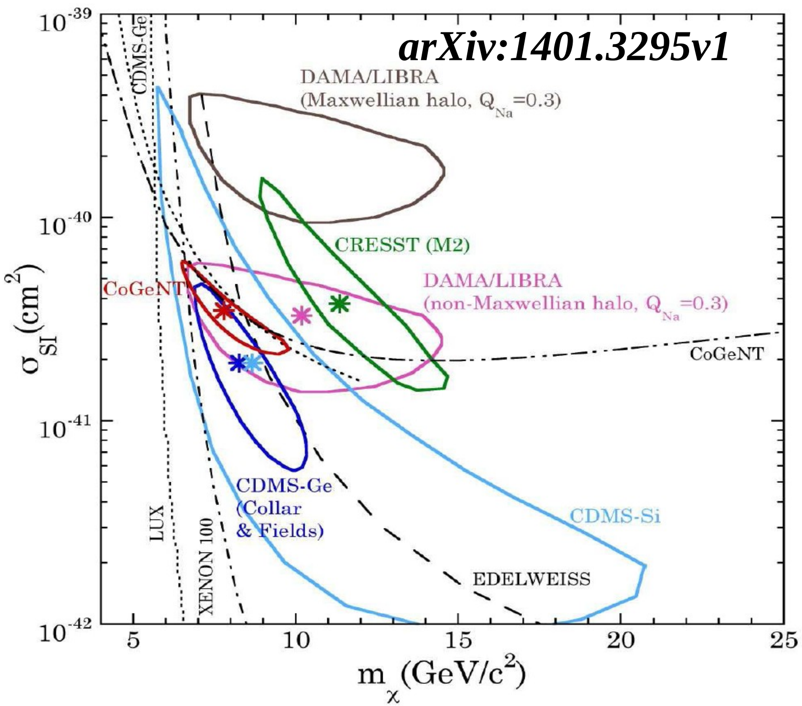
- Standard Model is complete: 2012 LHC - Higgs boson
- Unknowns:
  - Matter-antimatter asymmetry
  - Dark matter
  - Dark Energy
- Still some places of discrepancies between theory and experiment

- The Standard Model is a low energy approximation of a more fundamental theory.

***But which theory?***

# Direct search experiment

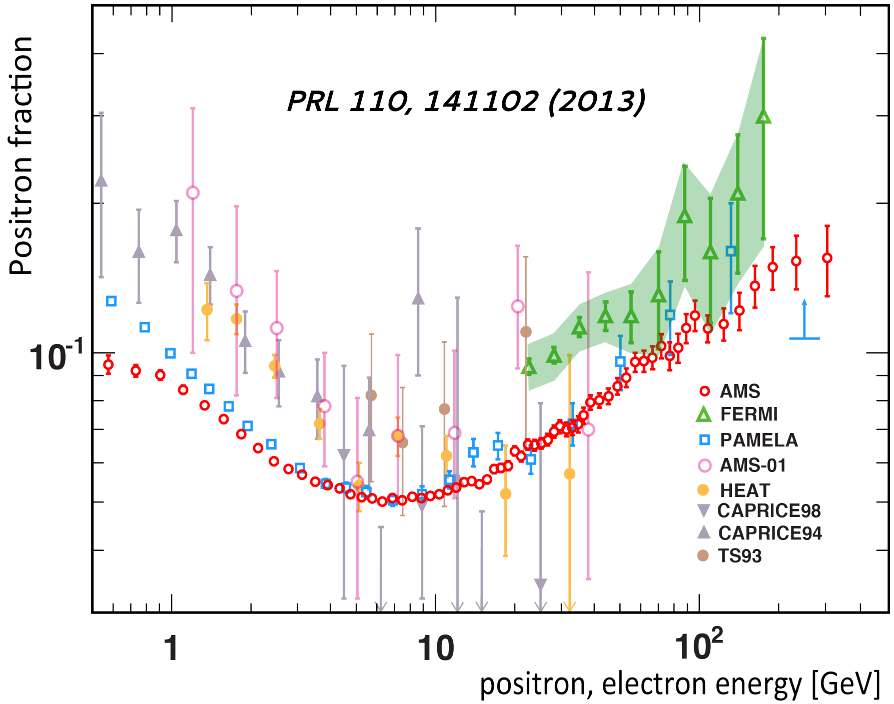


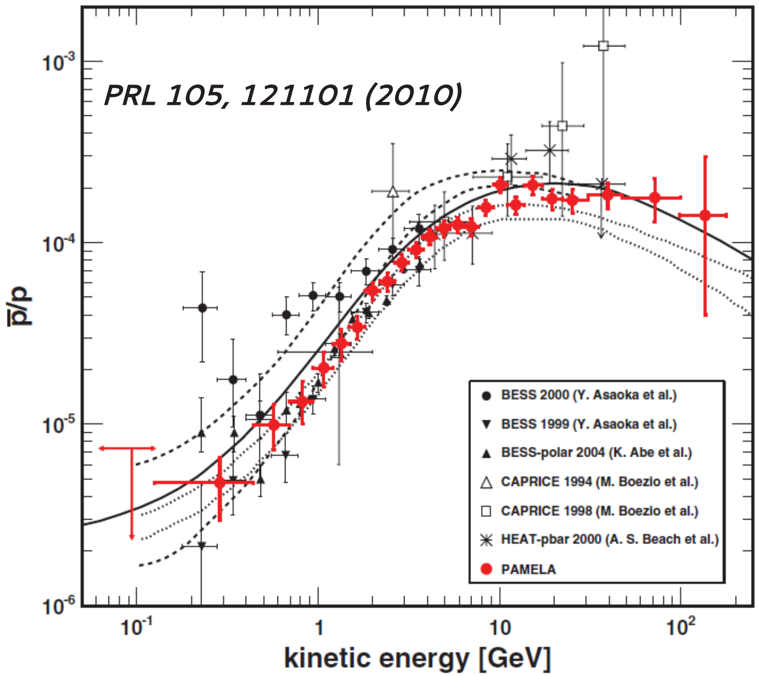




- DAMA/LIBRA results unexplained: 9.2 σ
- Used to be alone, now few other indications emerged
- Seem to be possible to build a consistent picture
- If the explanation is Dark Matter, it should be relative light: ~10 GeV

# Particle astrophysics

Antiparticles in the cosmic rays

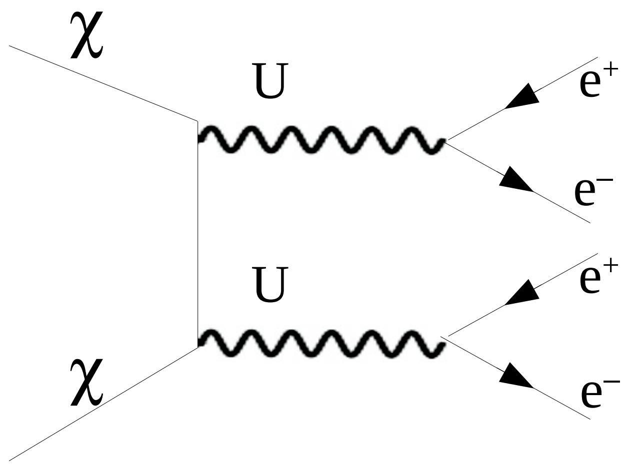


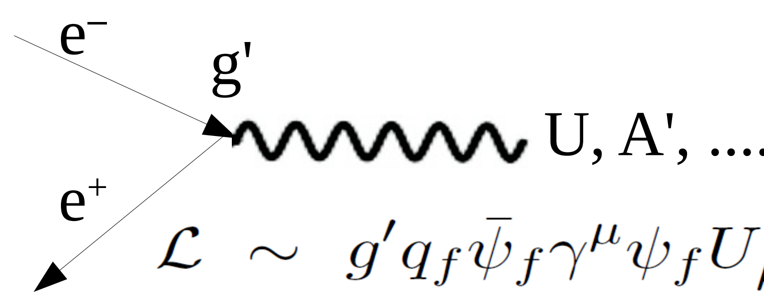




- Positron excess: PAMELA, FERMI, AMS02
- No significant excess in antiprotons
  - Consistent with pure secondary production
- Leptofilic annihilation?

# Hint for dark matter?

Dark matter annihilation through

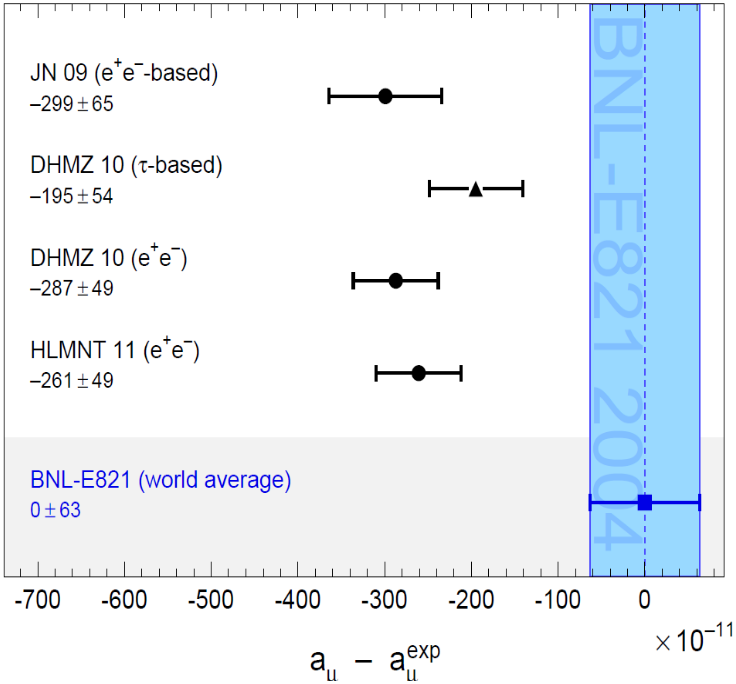


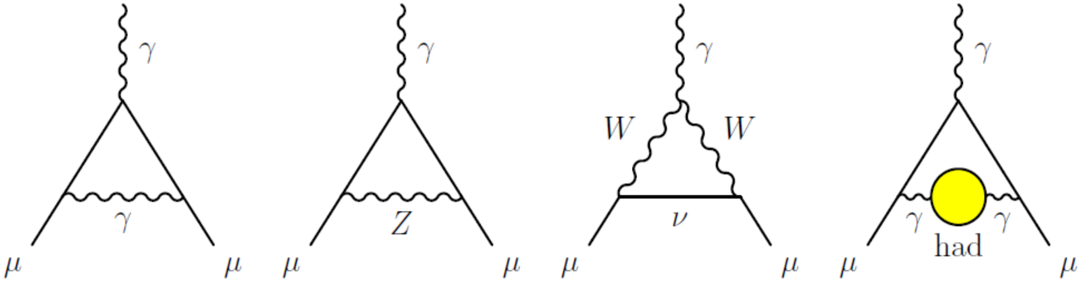




$$\mathcal{L} \sim g' q_f \bar{\psi}_f \gamma^\mu \psi_f U'_\mu$$

- If Dark Matter is the explanation to the positron excess, then the mediator should be light ( < $2 * M_{proton}$)
- Coupling constant to DM could be arbitrary (even O(1))
- The Lagrangian term can arise through
  - fermions being charged (mili) under this new gauge symmetry ($q_f \to 0$ for some flavours)
  - Kinetic mixing between ordinary photon and DM one
  - **Using simply an effective description:** $g' \cdot q'_e = \varepsilon$, $\alpha' = \alpha * \varepsilon^2$

# g-2



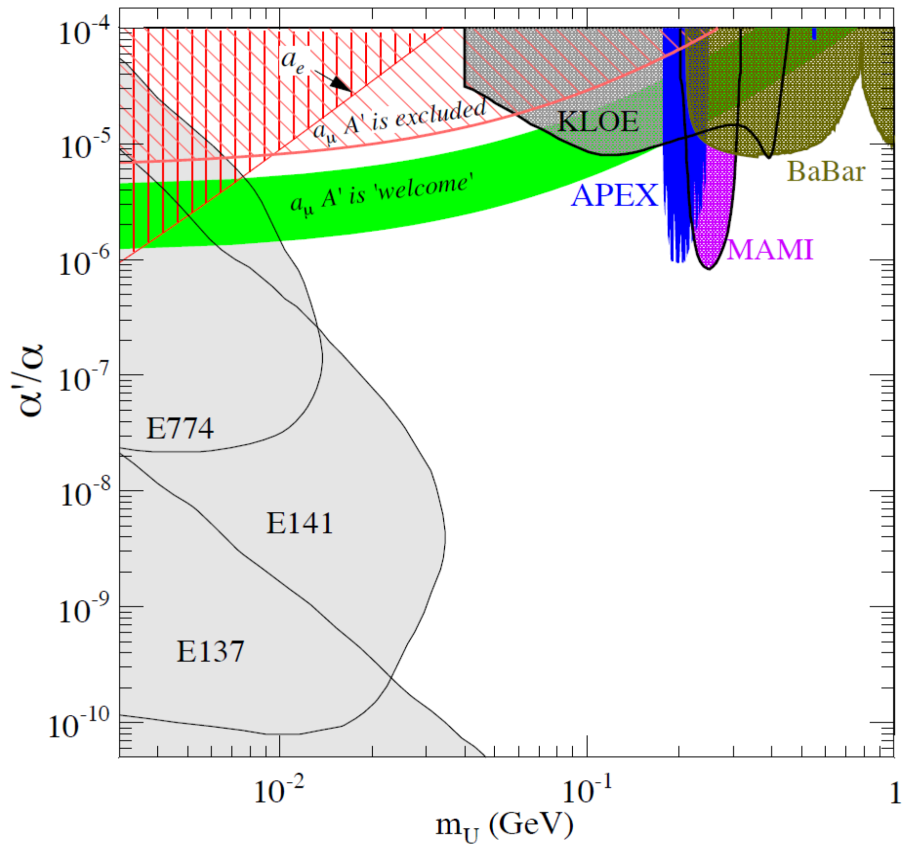

- About 3 σ discrepancy between theory and experiment (3.6 σ, if taking into account only $e^+e^- \to$ hadrons)

$$a_\mu^{\text{dark photon}} = \frac{\alpha}{2\pi}\varepsilon^2 F(m_V/m_\mu)\,, \tag{17}$$

where $F(x) = \int_0^1 2z(1-z)^2/[(1-z)^2 + x^2 z]\,dz$. For values of $\varepsilon \sim 1$–$2 \cdot 10^{-3}$ and $m_V \sim 10$–$100\,\text{MeV}$, the dark photon, which was originally motivated by cosmology, can provide a viable solution to the muon $g-2$ discrepancy. Searches for the dark

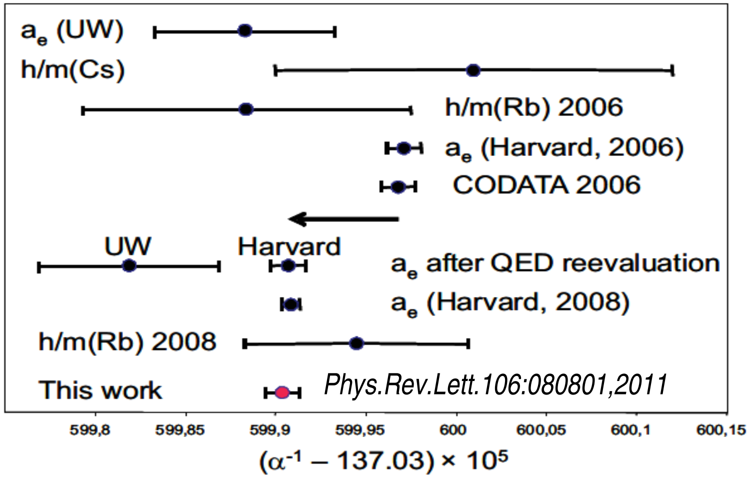
# Heavy/Dark photon/boson

- The most attractive explanation of the phenomena is the simplest one – with a single object
- If this is the U-boson, it should be sufficiently light – 10-100MeV
- Searches
  - Beam dump experiments
    - A'-strahlung production
    - Every observed event is signal
  - Fixed target
    - peaks in the e+e- invariant mass spectrum
  - Meson decays
    - Peaks in $M_{e+e-}$ or $M_{\mu+\mu-}$



# Present limits

- There is no direct present limit in the U→invisible decay – from $a = \frac{g-2}{2}$
- The discrepancy is not in $g_\mu$-2 itself, it's in the consistency of $g_e$ & $g_\mu$
- Alternative inputs can be used to extract info from $g_e$ - α



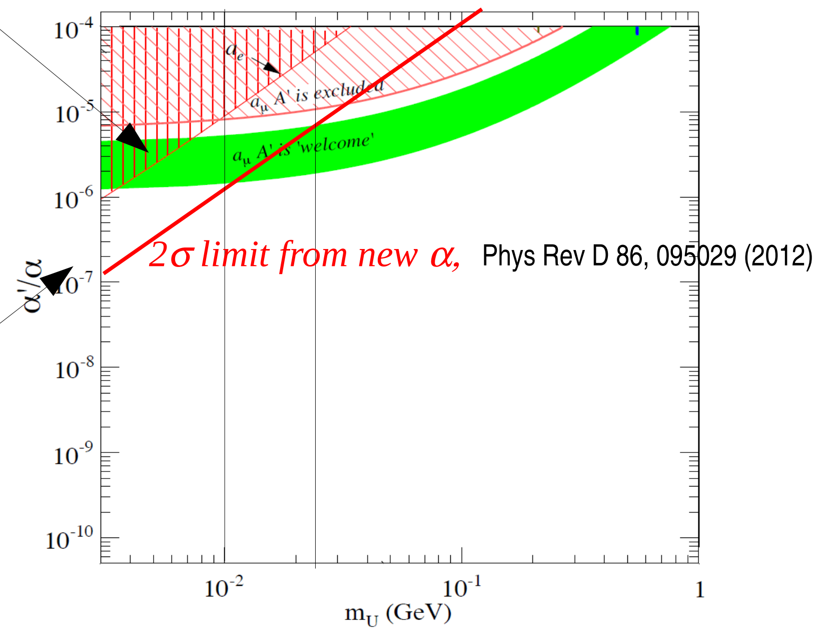

$\alpha^{-1}$ = 137 .035 999 037 (91)

$$|a_e^{th} - a_e^{exp}| = (1.06 \pm 0.82) \times 10^{-12}$$

- Anomalous magnetic moment limits
  - $\alpha_{EM}$ usually a determined from $g_e$-2 - *input*
  - Used further to constrain $g_\mu$-2
  - Dark photon contribution:

$$\delta a = \frac{\alpha_{EM}\,\epsilon^2}{2\pi} * f,\ f = \begin{cases} 1, \text{ for } m_l >> M_U \\ 2m_l^2/(3M_U^2), \text{ for } m_l << M_U \end{cases}$$

Phys.Rev.D80:095002,2009




**However this is based on a single measurement with drastically improved precision**

# U boson searches

- Searching a U-boson in a kinematically constraint event and using full reconstruction
- Basic process: positron on a fixed target

$$e^+ + e^- \rightarrow \gamma + U \begin{cases} \gamma + E_{miss} & \text{(invisible channel)} \\ \gamma + e^+e^- & \text{(visible channel)} \end{cases}$$

- Normalizing to the concurrent process - annihilation

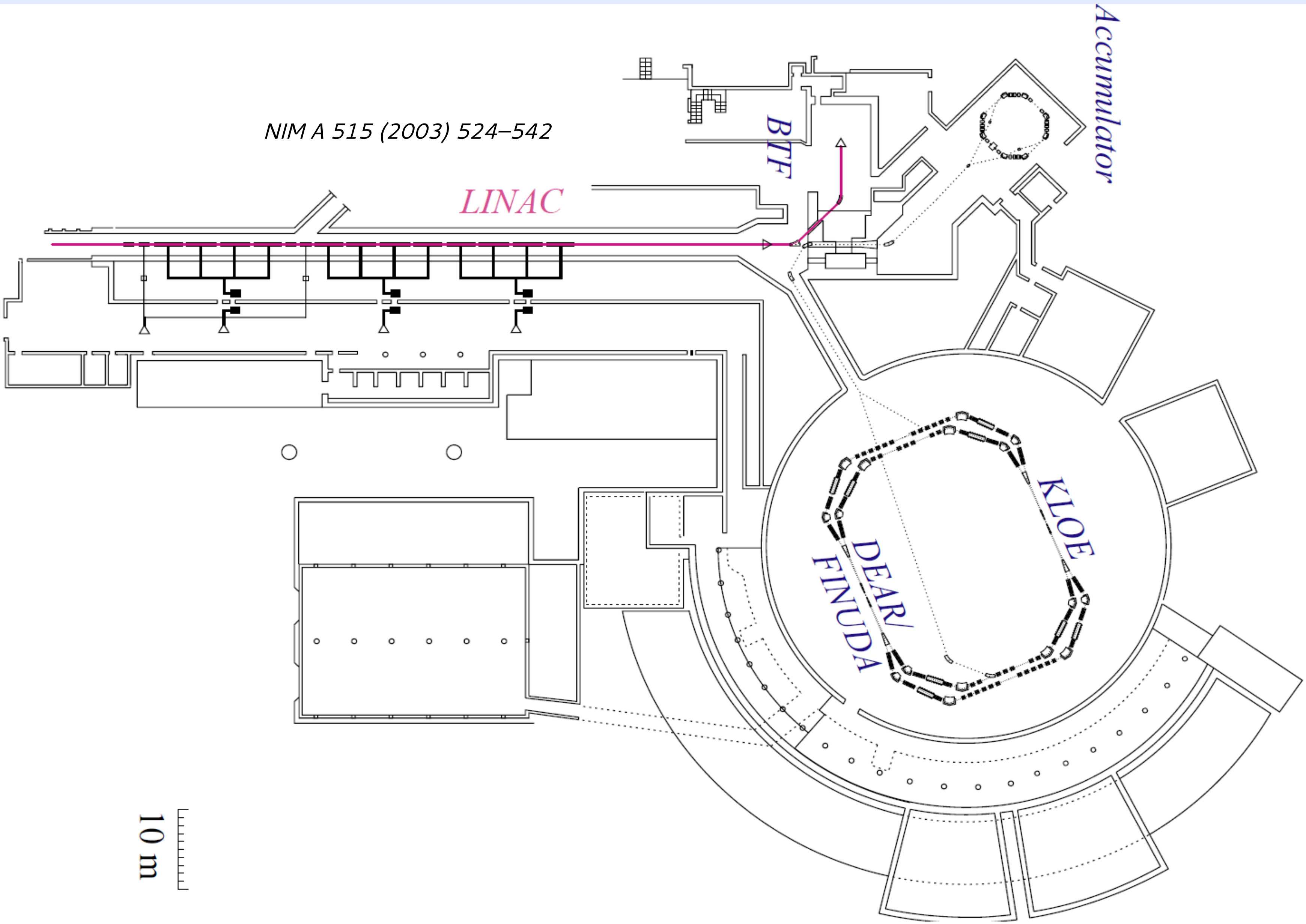
$$\frac{\sigma(e^+e^- \rightarrow \gamma U)}{\sigma(e^+e^- \rightarrow \gamma\gamma)} = \frac{N(\gamma U)}{N(\gamma\gamma)} * \frac{Acc(\gamma\gamma)}{Acc(\gamma U)} = \varepsilon^2 * \delta$$

  - $N(\gamma U)$, $N(\gamma\gamma)$ - number of registered events
  - $Acc(\gamma U)$, $Acc(\gamma\gamma)$ - detection efficiency
  - $\delta$ – cross section enhancement factor (see further)

**Is it possible such a search to be conducted here at LNF?**

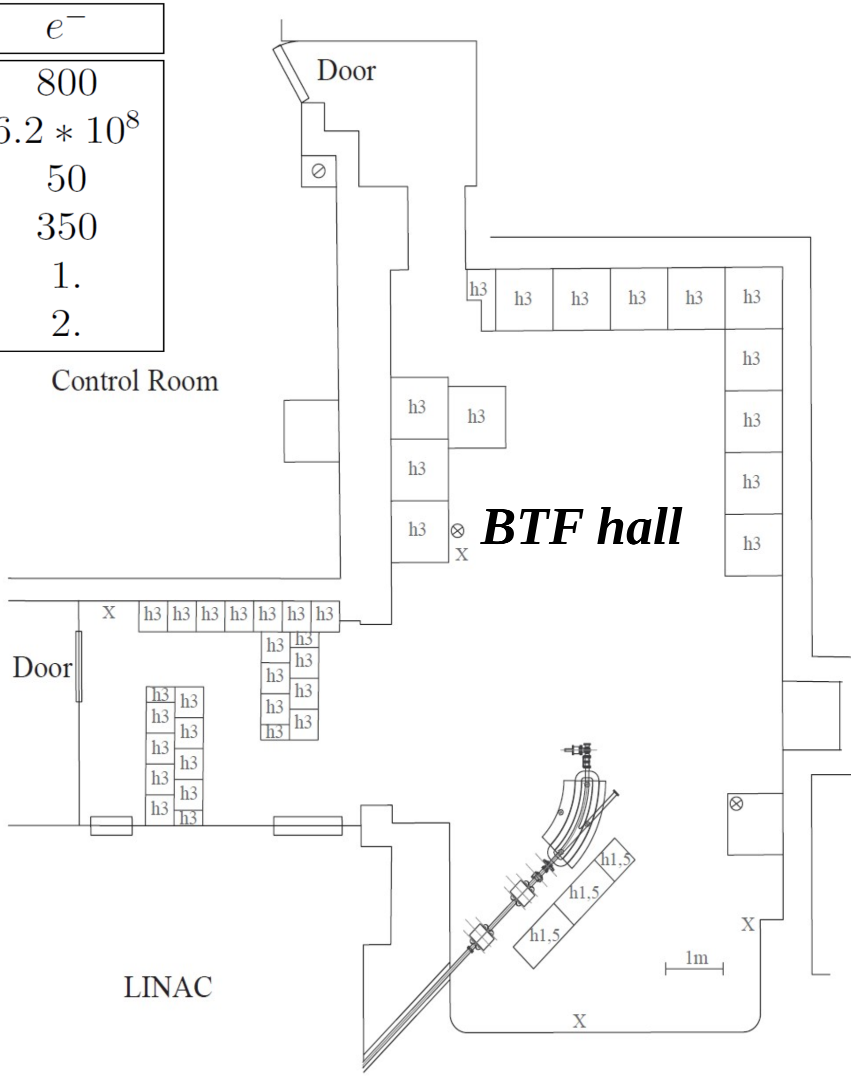
# BTF @ LNF

NIM A 515 (2003) 524–542



# BTF @ LNF

| | $e^+$ | $e^-$ |
|---|---|---|
| Maximal beam energy [MeV] | 550 | 800 |
| Beam rate [particles/burst] | $6.2 * 10^8$ | $6.2 * 10^8$ |
| Number of bursts per second | 50 | 50 |
| Max. averaged current during a burst [mA] | 85 | 350 |
| Typical emittance (mm mrad) | 1.5 | 1. |
| Beam spot size ($\sigma$ in mm) | 2. | 2. |



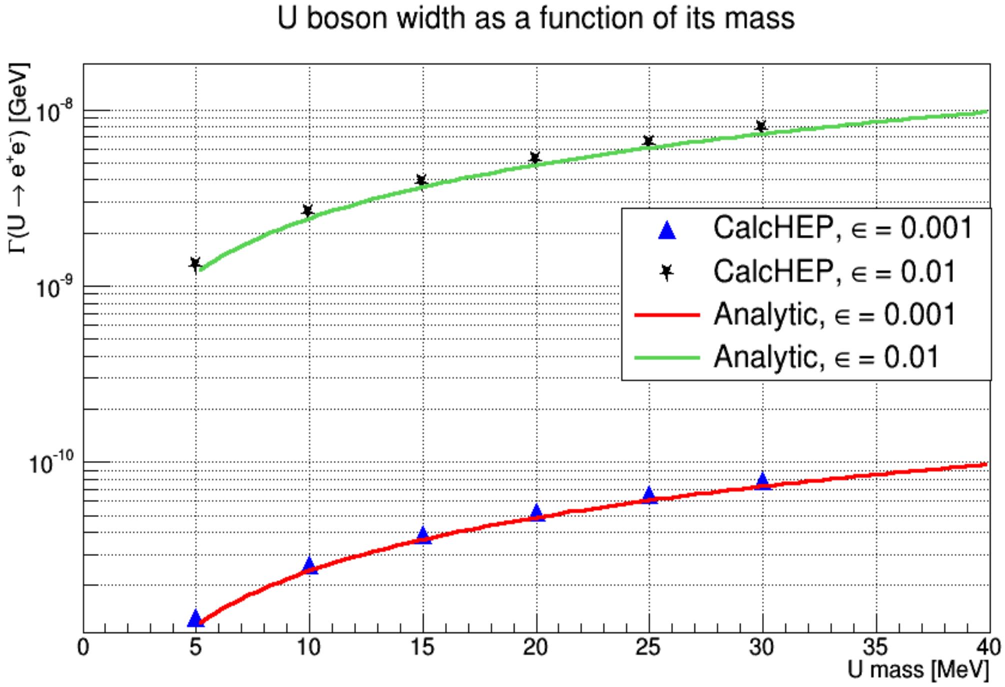

- Variable beam energy (from ~250 MeV to $E_{MAX}$)
- Possibility for single particle beam
  - However we need statistics...
- Planned upgrades:
  - **Maximal beam energy (1GeV for e-)**
  - **Beam intensity (up to $10^{10}$/bunch)**
  - **Bursts per second**
  - **Burst length (at least 40 ns)**
- The accessible region is limited by the maximal beam energy
  - Around 22 MeV for 500 MeV $e^+$ beam

# Heavy/Dark photon/boson

- After production, U boson may decay into $e^+e^-$

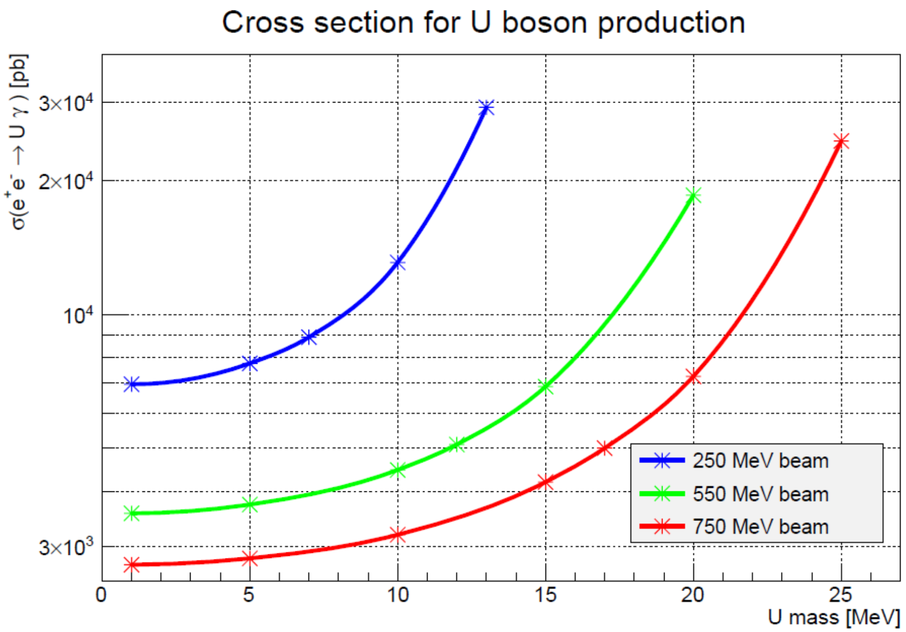
$$\Gamma_U = \Gamma_{U \to e+e-} = \frac{1}{3}\alpha\epsilon^2 M_U \sqrt{1 - \frac{4me^2}{M_U^2}} \left(1 + \frac{2me^2}{M_U^2}\right)$$

Simple model implemented in CalcHEP, used for the further studies

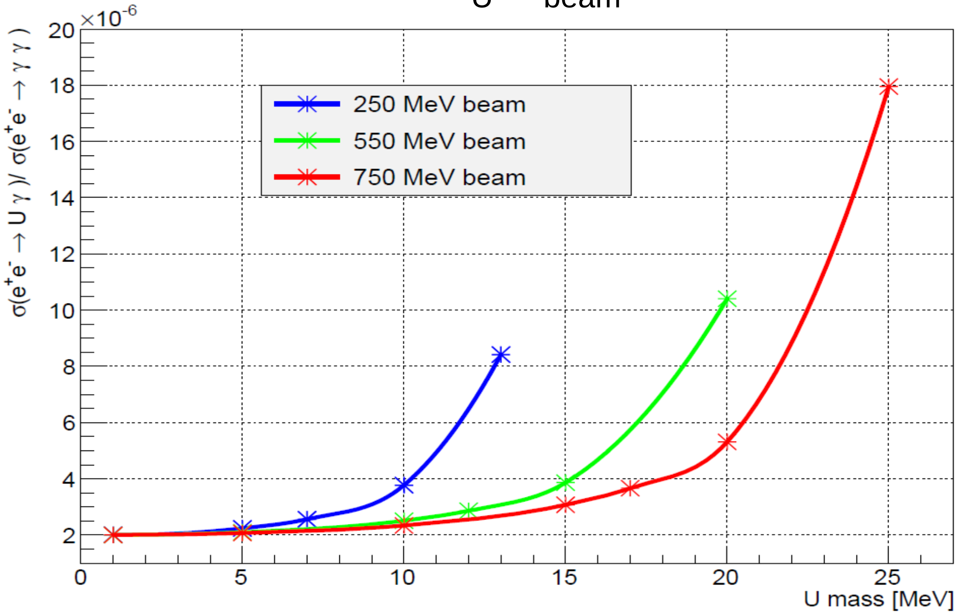


# U-boson production

**For ε = $10^{-3}$**



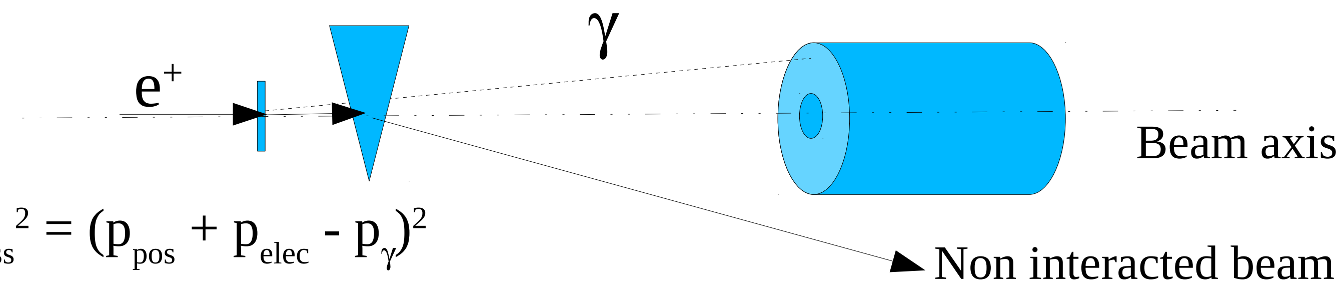

$\delta = \delta(M_U, E_{beam})$




- Increasing of the cross section with the approach of the kinematics limit – resonant production of U
  - Speculation on the possibility to scan the region 10MeV - 23 MeV by varying the beam energy?

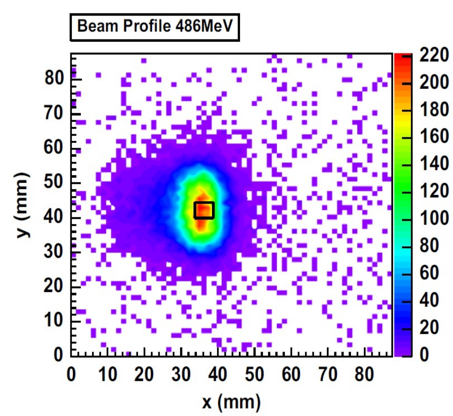
# Basic idea: U@BTF

## Focusing on the invisible channel

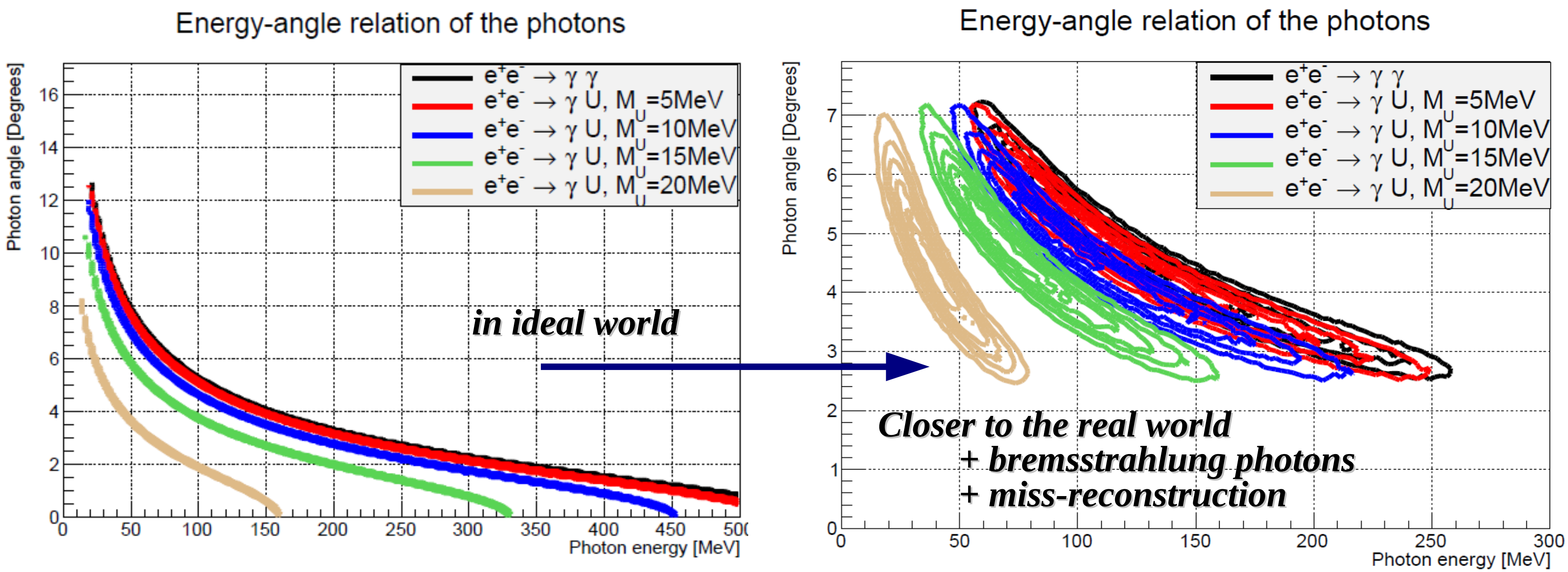



$$M_{miss}^{\;2} = (p_{pos} + p_{elec} - p_{\gamma})^2$$

- Electron is at rest
- Positron momentum is determined by the accelerator characteristics – 1% resolution
- Basic contribution to the missing mass resolution – reconstruction of the photon 4-momentum
  - Interaction point inside the target – beam transverse size is small, but the time stability is not sufficient
  - Cluster position in the calorimeter
  - Energy resolution of the calorimeter



# Event reconstruction



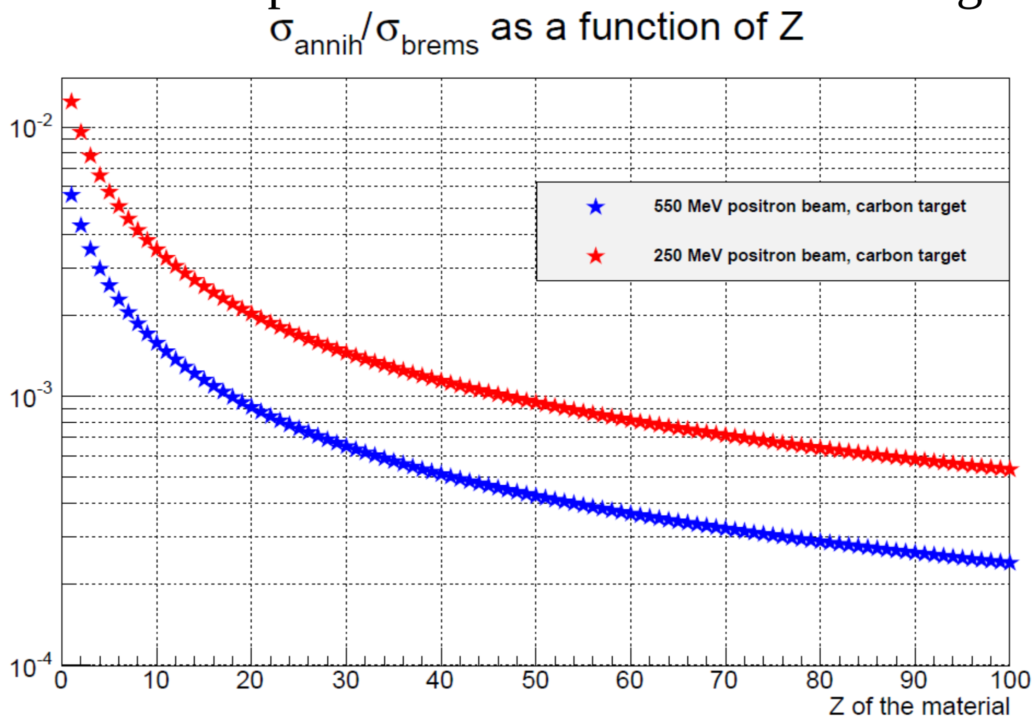

$MeV^2/c^4$

- Clear 2 body correlation
- Background minimization
  - Best possible resolution on energy/angle measurement
  - **Dominant process in e+/e- interactions with matter is bremsstrahlung**
  - Photons vetoing
  - Minimize the interaction remnants + vetoing

# Target

Active target for burst by burst beam profiling

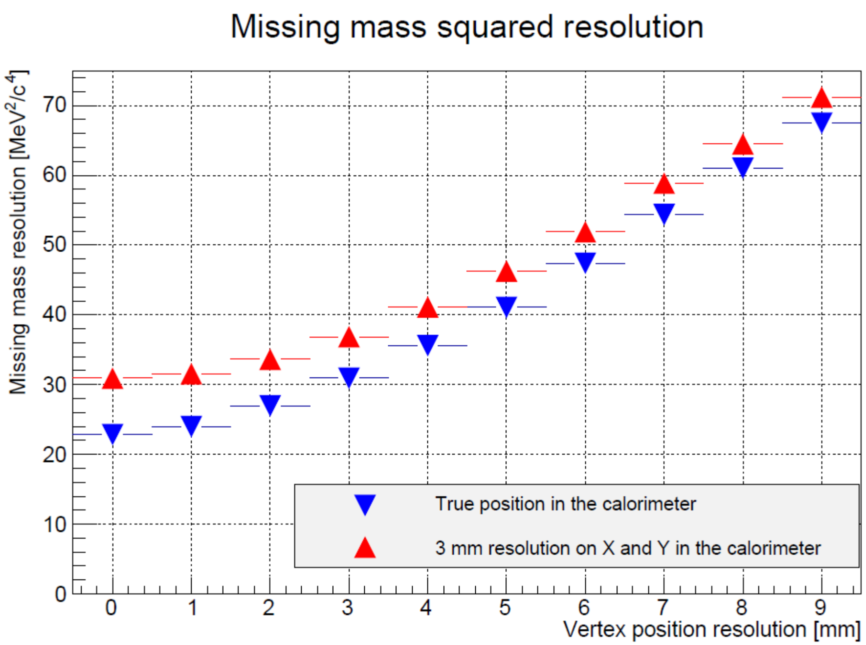
Main interaction process of e+/e- - bremsstrahlung

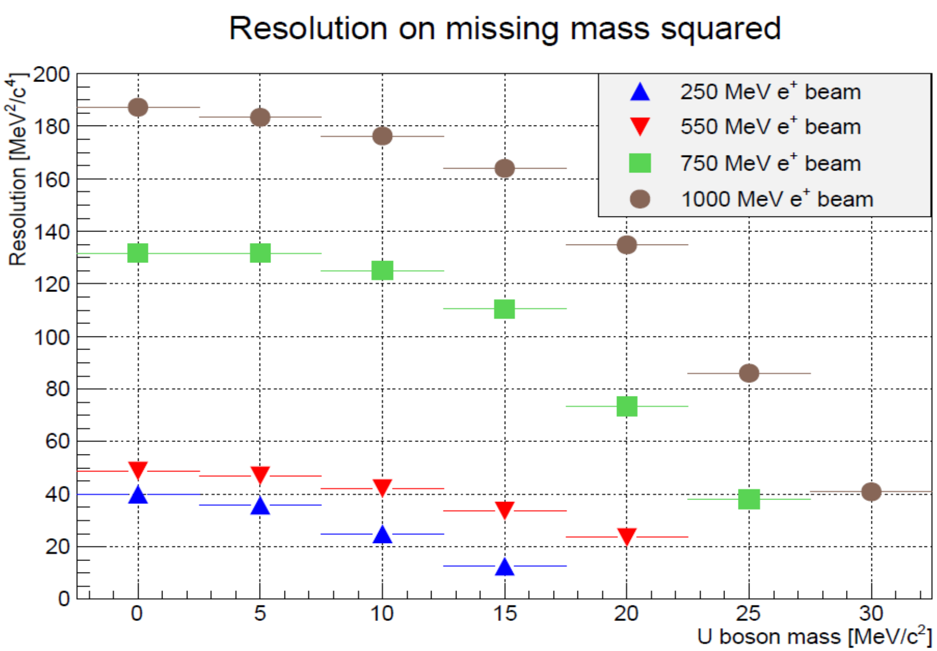



- Target with minimal Z
- Target with minimal thickness to suppress number of secondary interactions, contributing to the beam position/momentum spread

CARBON

# Missing mass resolution: target

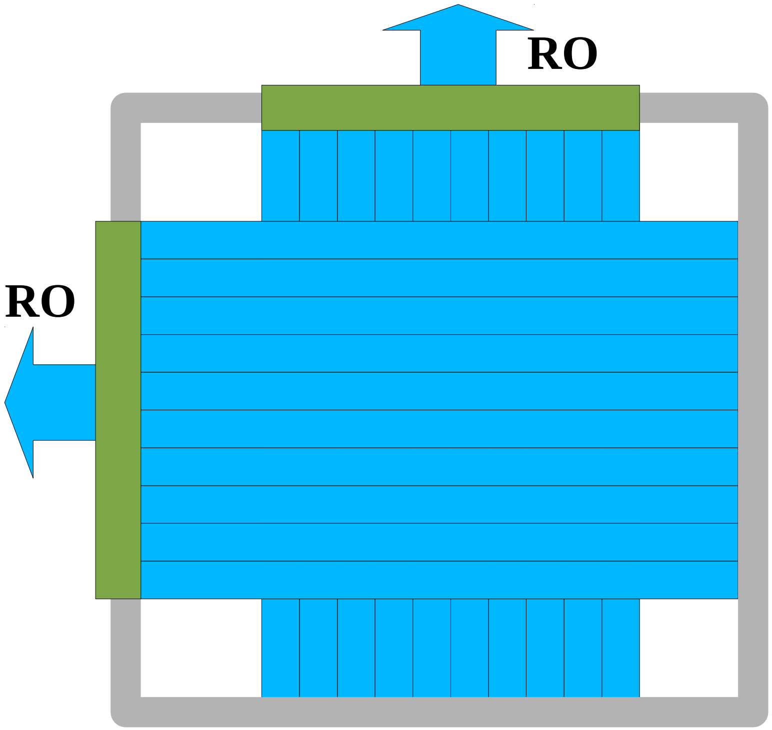


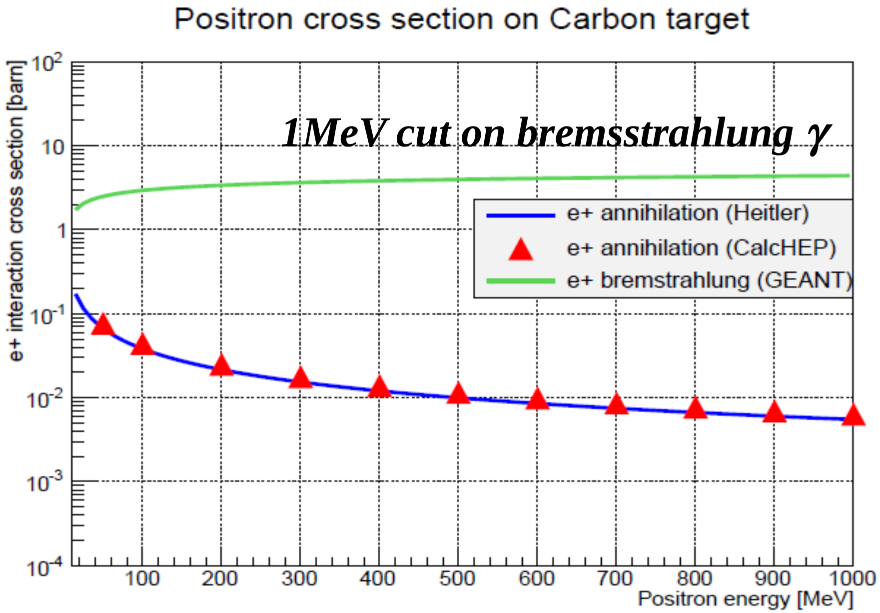




- Toy studies on kinematics
- Target optimization to minimize the scattering of the beam inside while keeping the annihilation probability relatively high

$10^4 - 10^5$ positrons/burst, 50um target thickness

# Target




- U boson may also be produced in a higher cross section U-strahlung process: $e^+ + N \rightarrow e^+ + N + U$
- Accessible if the experiment is sensitive to $U \rightarrow e^+e^-$

- 10 diamond strips of 2 mm x 50 mm with 25um thickness
  - Horizontal and vertical mounted on a vacuum flange
  - Readout with SiPM (Čerenkov light) or using it as a standard ionization chamber
- Information for beam position and intensity (normalization crosscheck)

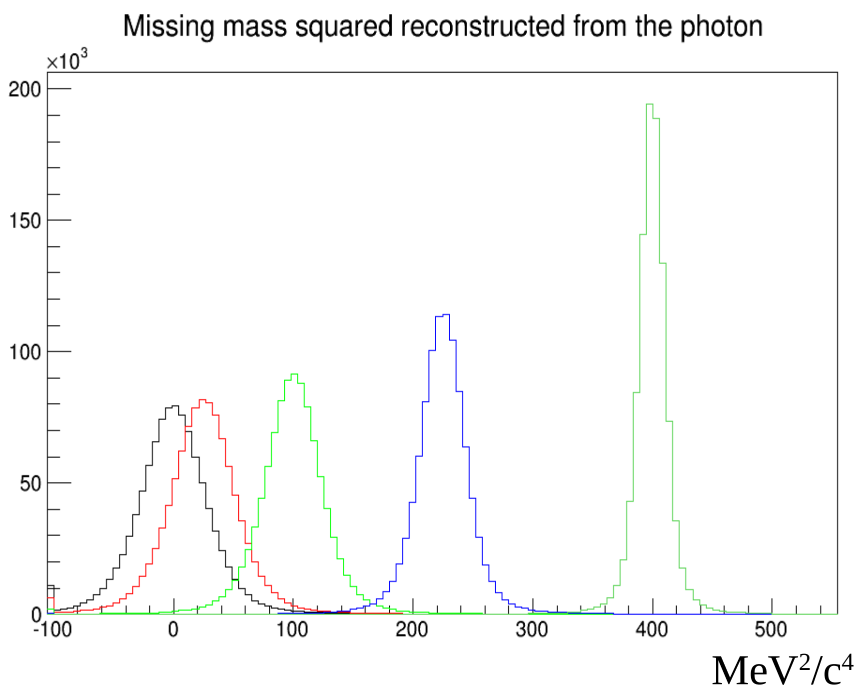
# Production possibilities

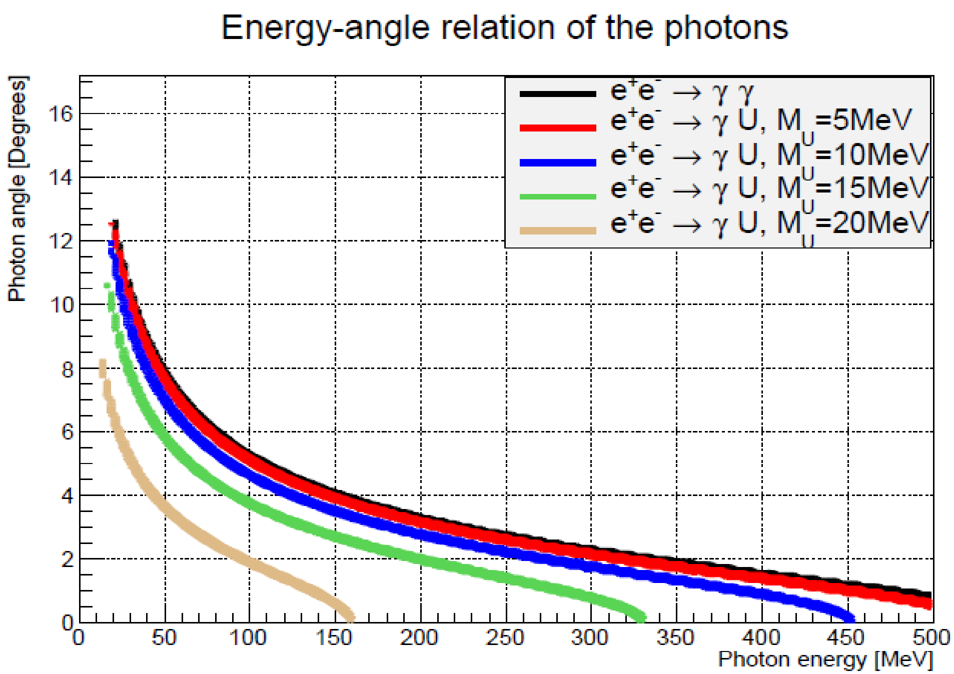
- Benchmark BTF operation:
  - 1 year of continuous running
  - 60% efficiency (data taking)
  - 50 bursts/s
  - $10^4$ positrons/burst
  - Total of ~$10^{13}$ positrons on target
  - > 100 U bosons produced in $e^+e^- \to \gamma U$, for any $M_U$, assuming $\varepsilon \sim 10^{-3}$!
  - U bosons produced also in a higher cross section U-strahlung
    - Possibly accessible through $U \to e^+e^-$ decay reconstruction
- If exists and couples to electrons the U-boson can be produced in a very thin target at BTF, provided $\varepsilon \sim X{*}10^{-4}$ or higher

**But can those events be detected by a suitable experimental setup?**

**Spare**

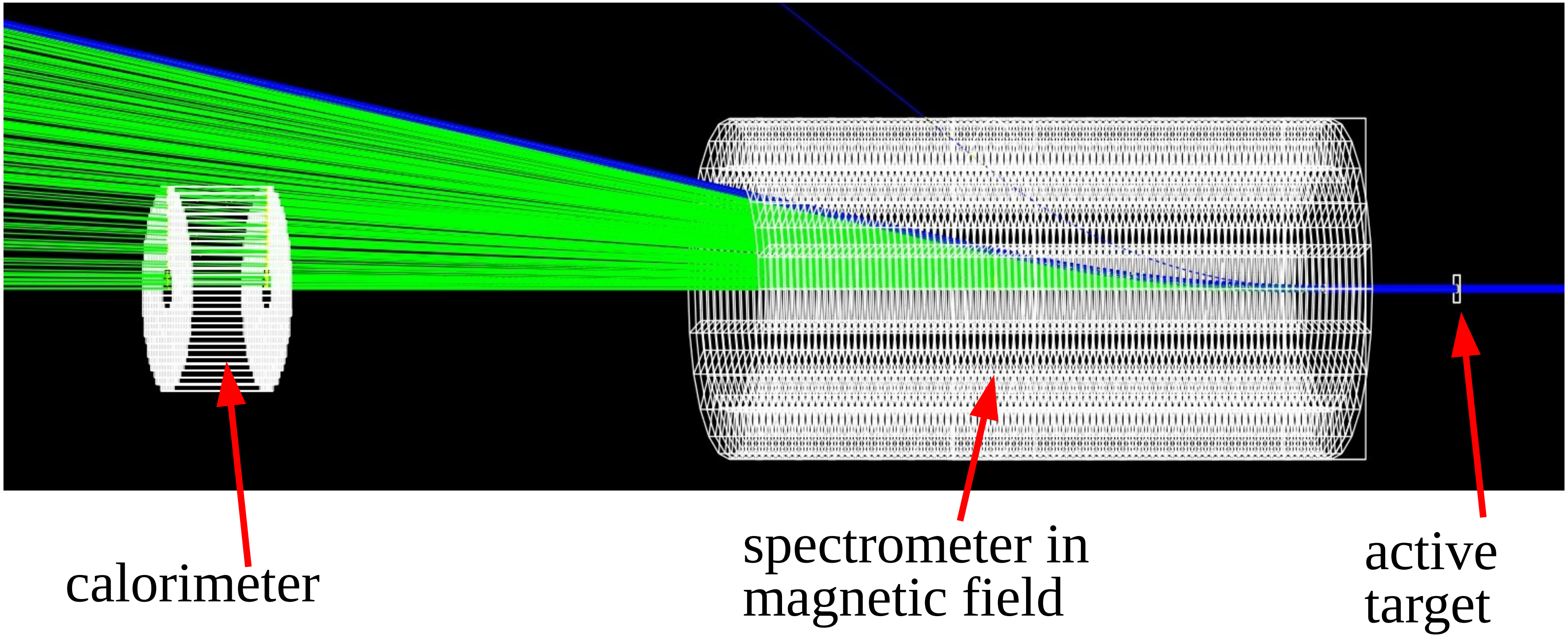
# Event reconstruction




- The resolution depends on the U-boson mass
- The photon energy is dependent on the photon angle (2 body kinematics)

# Heavy/Dark photon/boson




- Possible simultaneous registration of both visible and invisible channel
- The magnetic field serves for both:
  - Deflecting the primary positron beam out of the ECAL acceptance
  - Measurement of the momenta of charged particles