Background to the search for dark photon

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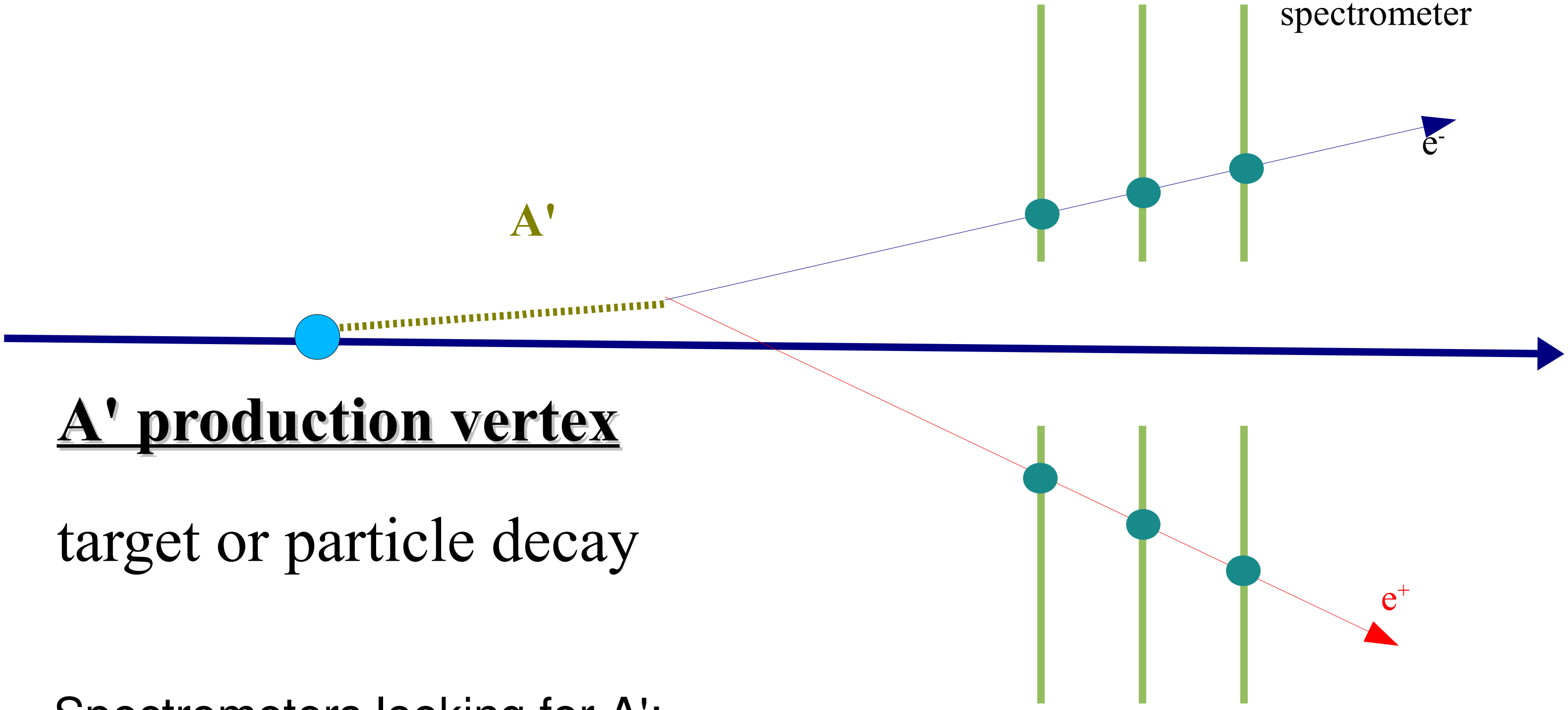
Overview

- Overview of annihilation experiments
- Dark photon production
- Multiphoton annihilation
- Bremsstrahlung
- Radiative
- Conclusions/open questions

Visible dark photons

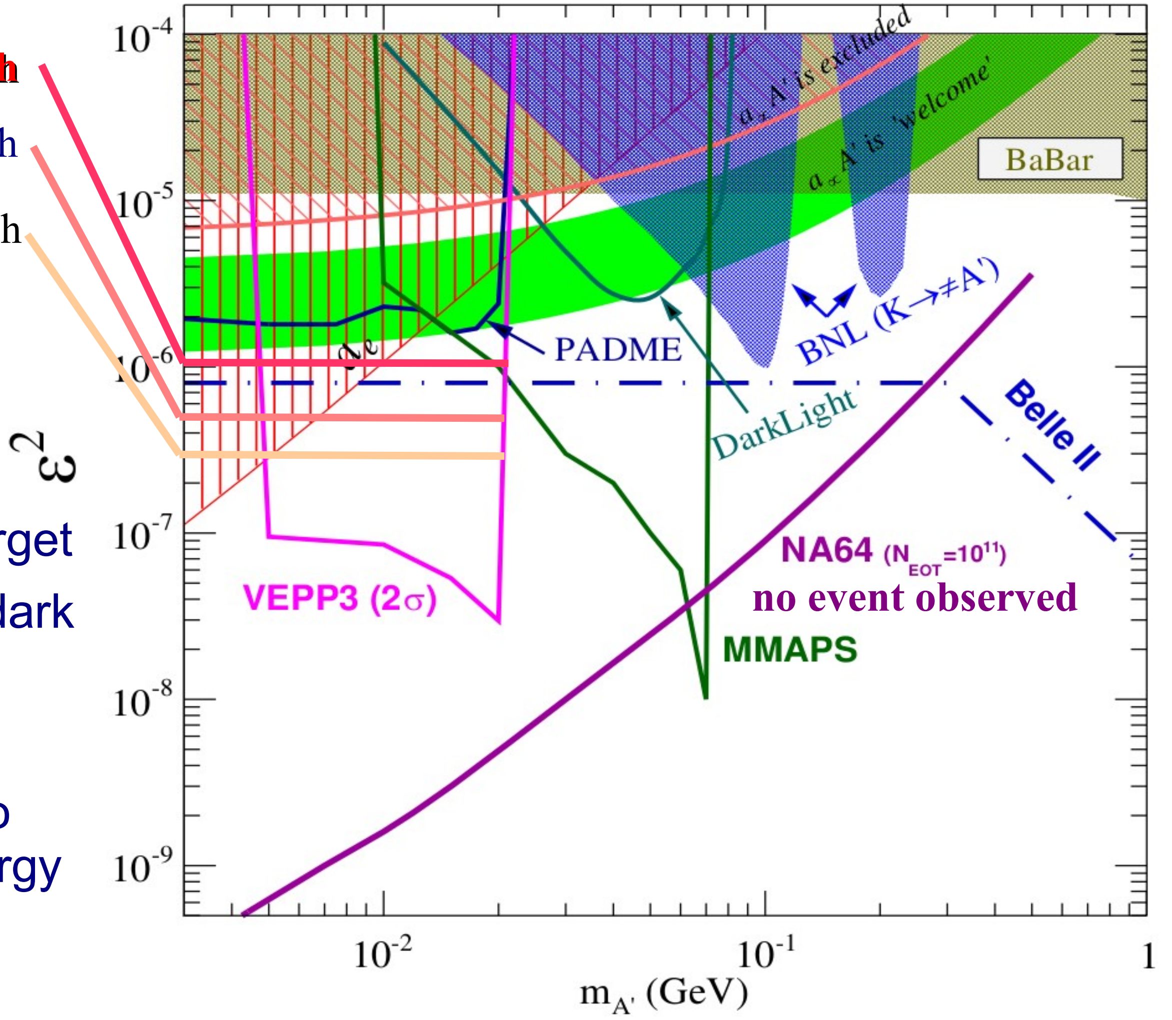


A' production vertex

target or particle decay

Spectrometers looking for A':
- produced in a thin target
- decaying to leptons

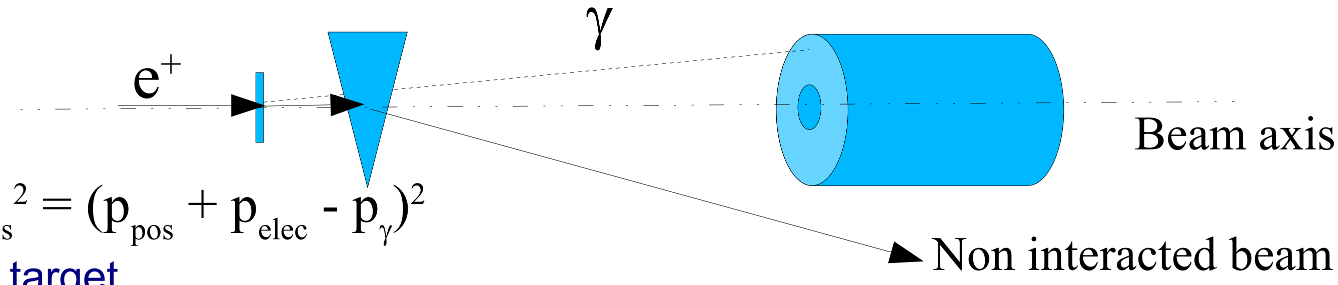
Invisible dark photons



- Addressing the missing mass
  - PADME@Frascati, VEPP3@Novisibirsk, MMAPS@Cornell
  - Positron beam on a thin target
  - Annihilation production of dark photons
- Missing energy
  - NA64: leakage of energy to the dark sector in high energy shower development
- Dark matter scattering
  - BDX

Missing mass technique

Study only the recoil photon

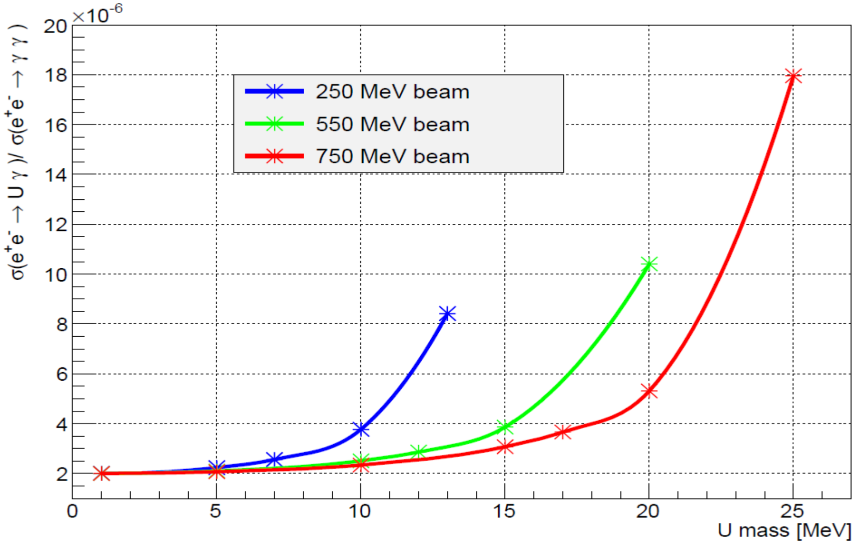


$$M_{miss}^2 = (p_{pos} + p_{elec} - p_\gamma)^2$$

- Positron beam on a thin target
- Positron momentum is determined by the accelerator characteristics
- Missing mass resolution: annihilation point, E_γ, φ_γ

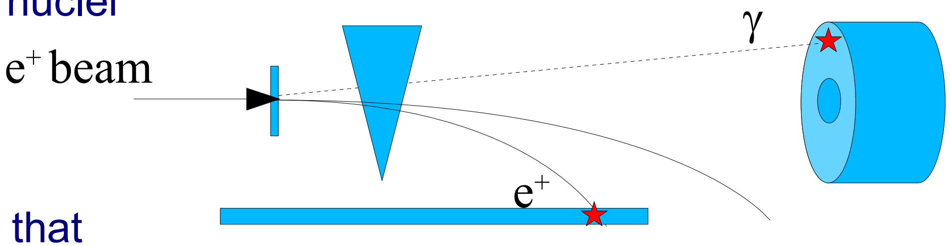
$$\frac{\sigma(e^+e^- \to U\gamma)}{\sigma(e^+e^- \to \gamma\gamma)} = \frac{N(U\gamma)}{N(\gamma\gamma)} * \frac{Acc(\gamma\gamma)}{Acc(U\gamma)} = \epsilon^2 * \delta,$$

Cross section enhancement with the approach of the production threshold

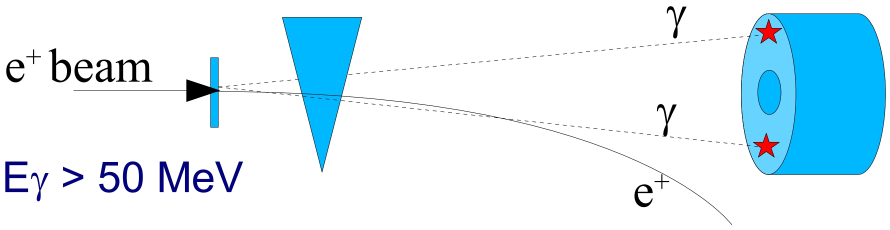


Backgrounds

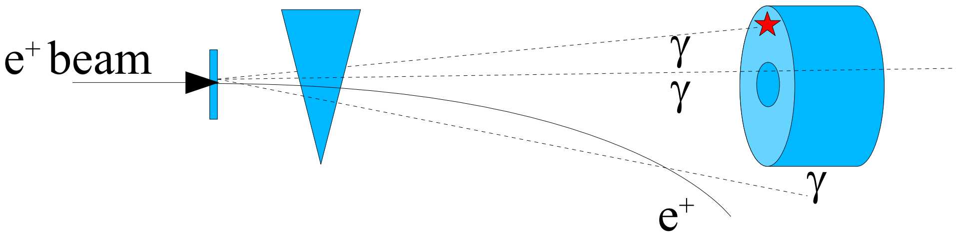
- Bremsstrahlung in the field of the target nuclei
  - Photons mostly @ low energy, background dominates the high missing masses
  - An additional lower energy positron that could be detected due to stronger deflection



- 2 photon annihilation
  - Peaks at $M_{miss} = 0$
  - Quasi symmetric in gamma angles for Eγ > 50 MeV

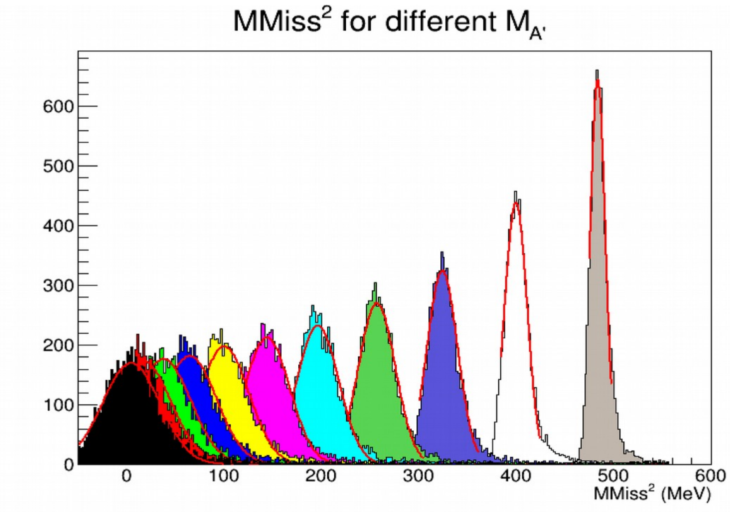


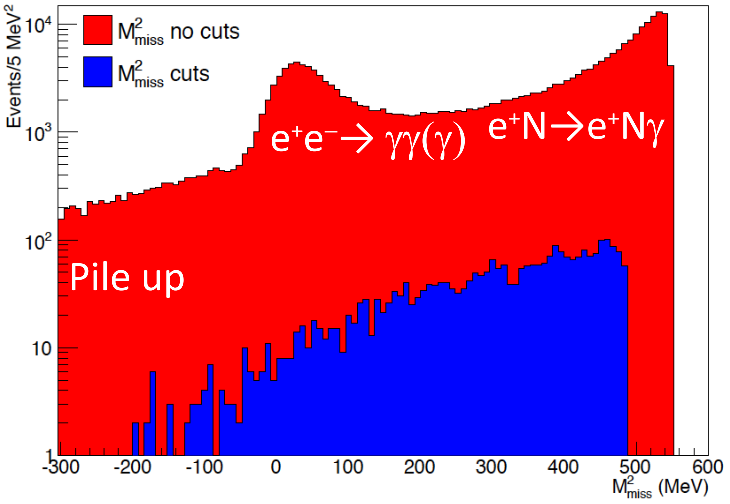
- 3 photon annihilation
  - Symmetry is lost – decrease in the vetoing capabilities
  - Does not peak



- Radiative bhabha scattering
  - Topology close to bremsstrahlung
  - Could have higher energy loss by the incident positron

Measurement strategy





- Background suppression

Background process	Cross section e$^+$@550 MeV beam	Comment
$e^+e^- \rightarrow \gamma\gamma$	1.55 mb	
$e^+ + N \rightarrow e^+ N \gamma$	4000 mb	Eγ > 1MeV, C
$e^+e^- \rightarrow \gamma\gamma\gamma$	0.16 mb	CalcHEP, Eγ > 1MeV
$e^+e^- \rightarrow e^+e^-\gamma$	180 mb	CalcHEP, Eγ > 1MeV

- Not a background free experiment!
- 3g and bremsstrahlung dominate and are of comparable size
- O(10^4 – 10^5) foreseen background events for a given A' mass

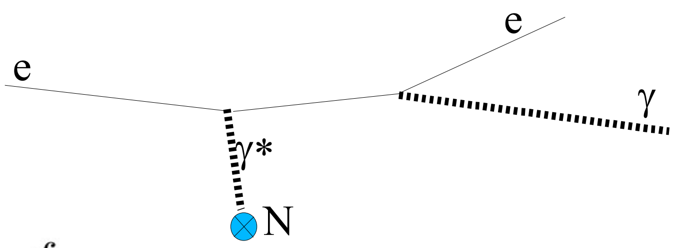
Missing mass searches status

	PADME	MMAPS	VEPP3
Place	LNF	Cornell	Novosibirsk
Beam energy	550 MeV	Up to 5.3 (**6.0**) GeV	500 MeV
$M_{A'}$ limit	23 MeV	74 MeV	22 MeV
Target thickness	2×10^{22} e⁻/cm²	$O(2\times10^{23})$ e⁻/cm²	5×10^{15} e⁻/cm²
Beam intensity	8×10^{-11} mA	2.3×10^{-6} mA	30 mA
$e^+e^- \rightarrow \gamma\gamma$ rate [s^{-1}]	15	2.2×10^6	1.5×10^6
ε^2 limit (plateau)	**10^{-6} (*10^{-7} SES*)**	**$10^{-6} - 10^{-7}$**	**10^{-7}**
Time scale	2017 - 2018	?	2020 (ByPass)
Status	**Approved**	**Funds identification**	**Approved**

Processes and tools

- Types of background
  - Multiphoton annihilation
    $e^+e^- \to \gamma\gamma$, $e^+e^- \to \gamma\gamma\gamma$, $e^+e^- \to \gamma\gamma\gamma\gamma$, ….
  - Bremsstrahlung in the field of the nuclei
  - Photon emission in the field of orbital electrons
- GEANT4
  - Bremsstrahlung, 2 photon annihilation
- CalcHEP
  - Cross-section calculation, 3 photon annihilation
- Different specialized MC generators
  - Babayaga
  - MCJPG

Bremsstrahlung



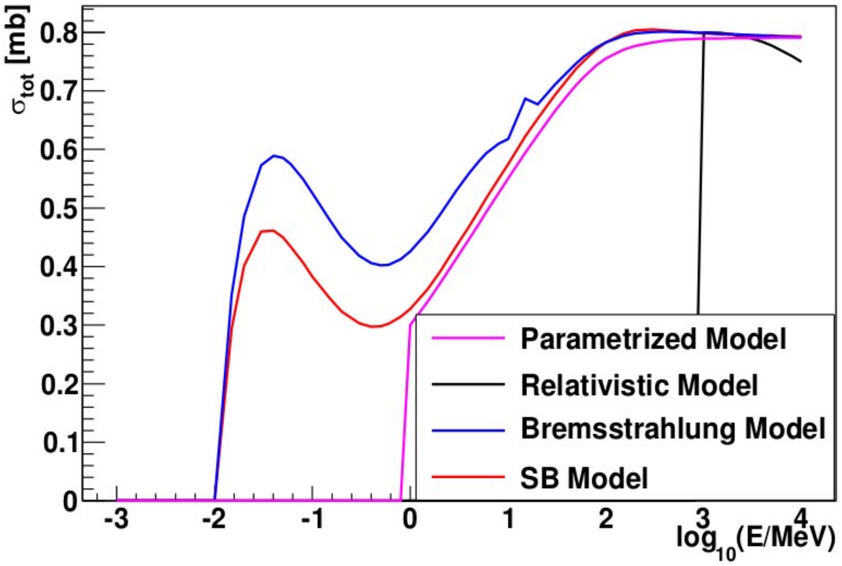
- Usually thoroughly simulated through GEANT4
- Different models exist
  - Parametric – up to version 9.4

$$\sigma(Z,T,k_c) = Z(Z+\xi_\sigma)(1-c_{sigh}Z^{1/4})\left[\ln\frac{T}{k_c}\right]^\alpha \frac{f_s}{N_{Avo}}$$

  - Seltzer-Berger model (default)

$$\frac{d\sigma}{dk} = \frac{d\sigma_n}{dk} + Z\frac{d\sigma_e}{dk}$$

    - Parametrization of tabulated data
    - Takes into account e-N and e-e interactions

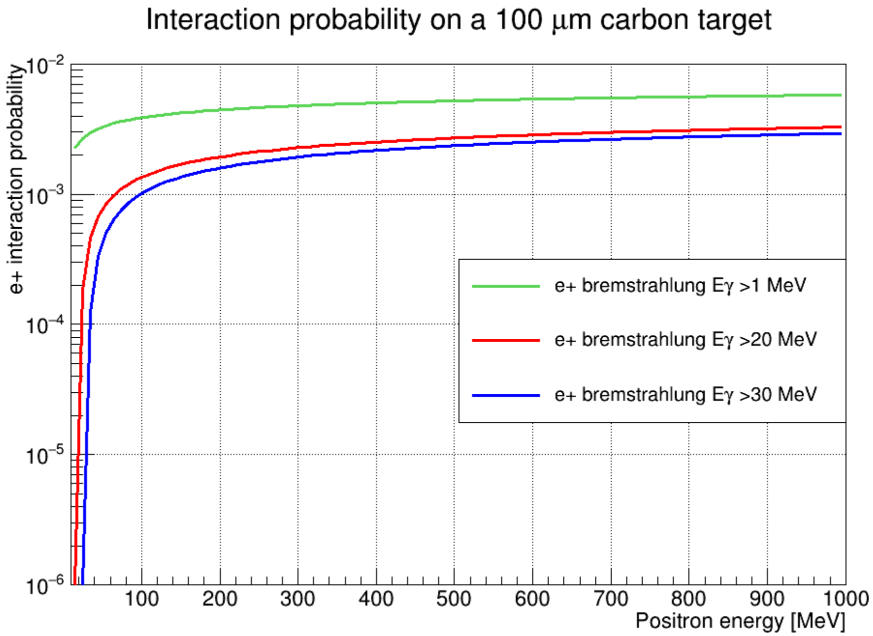


  - Analytic – in the relativistic limit
    - Used for E > 1 GeV

$$\frac{d\sigma}{dk} = \frac{4\alpha r_e^2}{3k}\left[\{y^2+2[1+(1-y)^2]\}[Z^2(F_{el}-f)+ZF_{inel}] + (1-y)\frac{Z^2+Z}{3}\right]$$

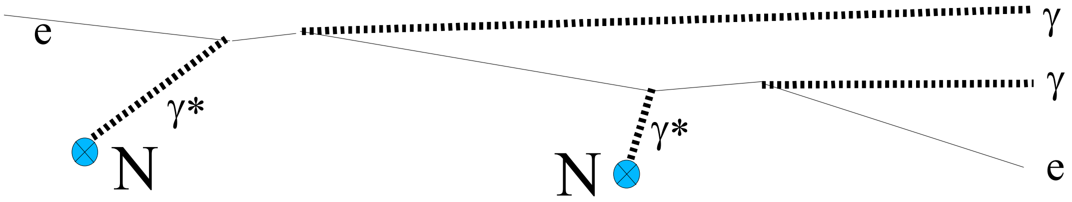
The PADME and VEPP3 case

- Positron energy – 500 – 550 MeV
- The parametrized model seem to be well consistent with the SB model
  - Can be used for quick checks
- Using as a reference PADME
  - 100 um carbon target
- At Eγ << E_{e+} the cross section depends mostly on Eγ
- Bremsstrahlung probability @550 MeV
  - Eγ > 1 MeV: 0.55 %
  - Eγ > 20 MeV: 0.28 %
  - Eγ > 30 MeV: 0.25 %



- Almost every bunch has numerous bremsstrahlung emitted photons
  - Most at small angles with respect to the positron flight direction

Double bremsstrahlung



- Non negligible probability for the two consequent bremsstrahlung by the same electron
  - P(2γ) with Eγ > 20 MeV @ 100 um carbon: $\sim 10^{-5}$
  - Comparable with annihilation probability
- Possible background source
  - An event is rejected as signal only if Eγ + E_{e+} is around the beam energy
    - Maximizes the acceptance for dark photon detection in the presence of pile-up bremsstrahlung

BUT

    - Decreases the vetoing capabilities
- Should be able to perform at least two steps in the target volume

Uncertainties

- The PADME sensitivity estimation relies on the knowledge of the background
  - Statistical uncertainty of the simulated background taken as a reference to determine the 90% (or 68 %) confidence level exclusion limits

$$\sigma_{tot}(N) \sim (\sqrt{N})_{stat} \oplus (\delta_{model} * N)$$

- We use **$\sigma_{tot}(N) / N(\gamma\gamma) / Acc(A')$** to describe the sensitivity
- GEANT4 model uncertainties
  - Parametric: 4-5 % for $E_{e+} > 1$ MeV
  - SB model: 3-5% for $E_{e+} > 50$ MeV
- @ 10^{13} events the number of background events due to bremsstrahlung per given A' mass interval varies from $10^4 - 10^5$ ($\sqrt{N}/N \leq 1\%$)

Already at that level the model uncertainty matters!

and even dominates...

- Is it sufficient to extend the validity of the relativistic limit down to 300 MeV?

Bremsstrahlung: open questions

- Can we use reliably the G4 bremsstrahlung simulation (and how)?

- Step modification to include possibility for double bremsstrahlung in the target? Or shall we introduce a custom double bremsstrahlung generator?

- How to decrease the bremsstrahlung uncertainty and tune the MC in the region 100 MeV < E_{e+} < 1 GeV
  - Additional experimental measurements?
  - Might be possible also at LNF/BTF or elsewhere...

- Shall we employ data driven methods instead of MC ones for reliable bremsstrahlung background estimation?
  - Or a combination of both...

Annihilation

- E_{e+} = 550 MeV, annihilation in flight
- Analytic expression for the cross section – Heitler formula

$$\sigma(Z,E) \;=\; \frac{Z\pi r_e^2}{\gamma+1}\left[\frac{\gamma^2+4\gamma+1}{\gamma^2-1}\ln\left(\gamma+\sqrt{\gamma^2-1}\right)-\frac{\gamma+3}{\sqrt{\gamma^2-1}}\right]$$

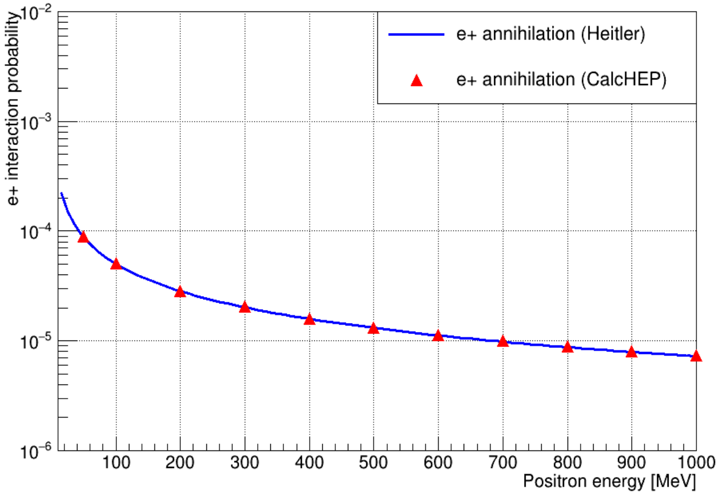
- The simulation is straight forward
  - GEANT4 includes the positron annihilation process
    - Sample the lab frame photon energy using $d\sigma/dE\gamma$
    - Isotropic asimutal angle
  - Can be done with a custom event generator
    - 2-body → 2 body in the CM system, isotropic γ direction
    - Boost to the LAB-frame
- Well understood, background under control due to the strict kinematics

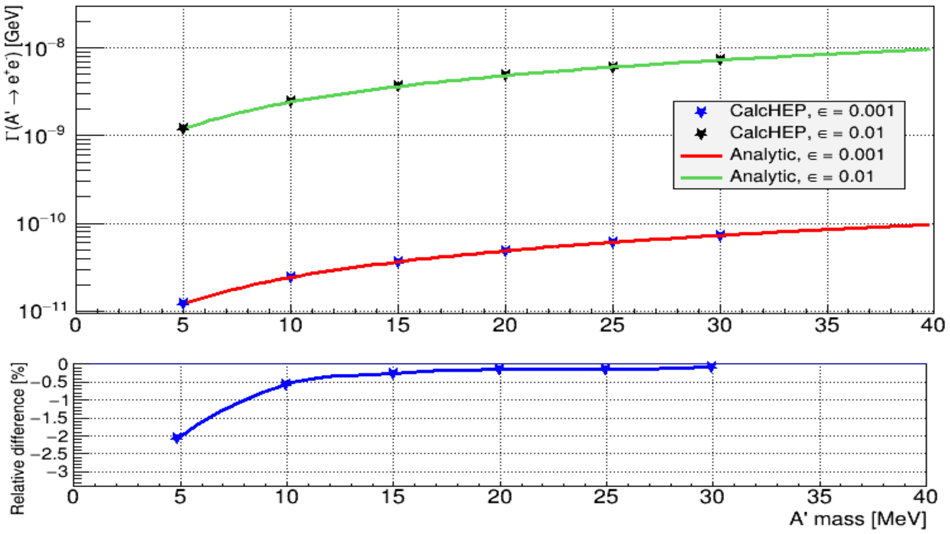
Annihilation: 3 photon

- The process is not included by default in the simulation of positron interactions
- Can be assumed as a radiative correction to the 2γ annihilation
- Different approaches to the treatment – from naive to “proper”

- CalcHEP – *“a package for calculation of Feynman diagrams and integration over multi-particle phase space“*
  - Development/support still active – last version 28.06.2016
  - Easy to use and modify – models, parameters, particle content, etc...

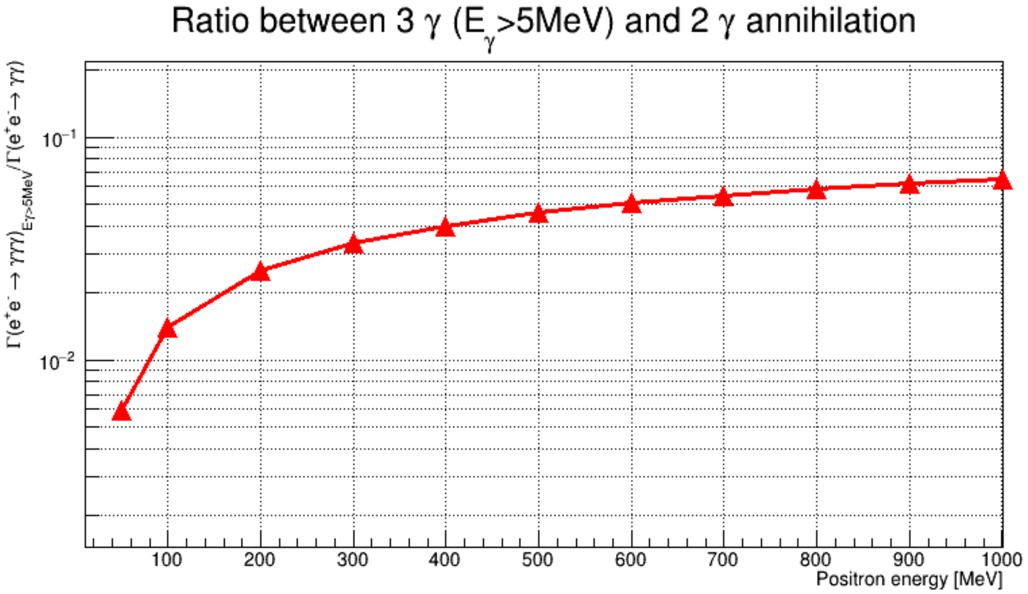
Interaction probability on a 100 μm carbon target





Annihilation: 3 photon

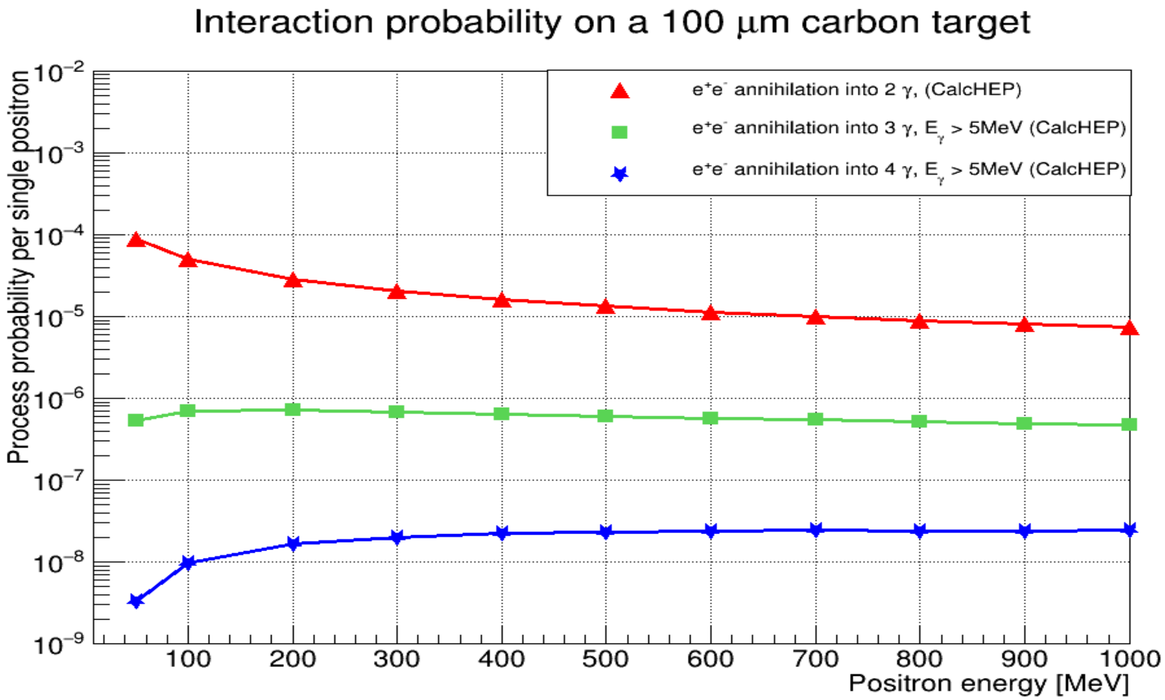
- Thought to be negligible, but in-flight annihilation different from annihilation at rest
- Soft addition photon might be interpreted as initial state radiation (ISR)
- Cross section divergent with $E\gamma \to 0$, a cut at $E\gamma > 5$ MeV
  - 1% of the nominal BTF beam energy for PADME
  - Seem consistent with the miniminal detectable energy in the calorimeter
    - Seeding cell + shower



- 3γ events as much as ~4.5% @550 MeV positron energy
- Should be custom generated and treated separately for background estimation
  - The third photon spoils the symmetry and veto capability of the calorimeter

Annihilation: multi-photon

- We could even go further – $e^+e^- \to N\gamma$



- The low energy part of $e^+e^- \to N\gamma$ is absorbed in the virtual corrections of $e^+e^- \to (N-1)\,\gamma$

$$\Gamma(\text{annihilation}) = \Gamma(e^+e^- \to \gamma\gamma) + \Gamma(e^+e^- \to \gamma\gamma\gamma) + \Gamma(e^+e^- \to \gamma\gamma\gamma\gamma) + \ldots \approx 1.05 \text{ x } \Gamma(e^+e^- \to \gamma\gamma)$$

The N+1 photon annihilation can introduce a sizable correction to the N photon rate

Knowledge at better than % level necessary

Bhabha scattering

- Exists in G4
- Radiative correction to the Bhabha: $e^+e^- \rightarrow e^+e^-\gamma$
  - In principle such a process is already considered in GEANT4 SB bremsstrahlung model – the inelastic cross section $d\sigma_e/dk$ term
    - Is this the whole story?
  - Simulation can be performed through external libraries
    - MCJPG
      - Has to be upgraded since many formulas inside use $m_e=0$ approximation (recall E_{CM}(PADME/VEPP3) ~ 23 MeV)
    - Babayaga
      - No extra work necessary, ready to go
  - Should avoid double counting with GEANT4?
  - Take into account the screening from the atomic nuclei
- The specific treatment of this type of background has been neglected so far
  - Necessary to be tested and verified in consistent way

Conclusions

- Background evaluation is a key ingredient to understand the sensitivity of the dark photon searching experiments
- Different techniques
  - MC based
  - Data driven – electron beam
  - Data driven – fit sidebands
  - A combination of all three
- Just EM processes included but still not all machinary and tools experienced at that low center of mass energy
- How to assure the knowledge of the background contribution at < 1% level?