Sensitivity study of the $K^+ \to \mu^+ \nu A'$ with $A' \to e^+ e^-$ decay

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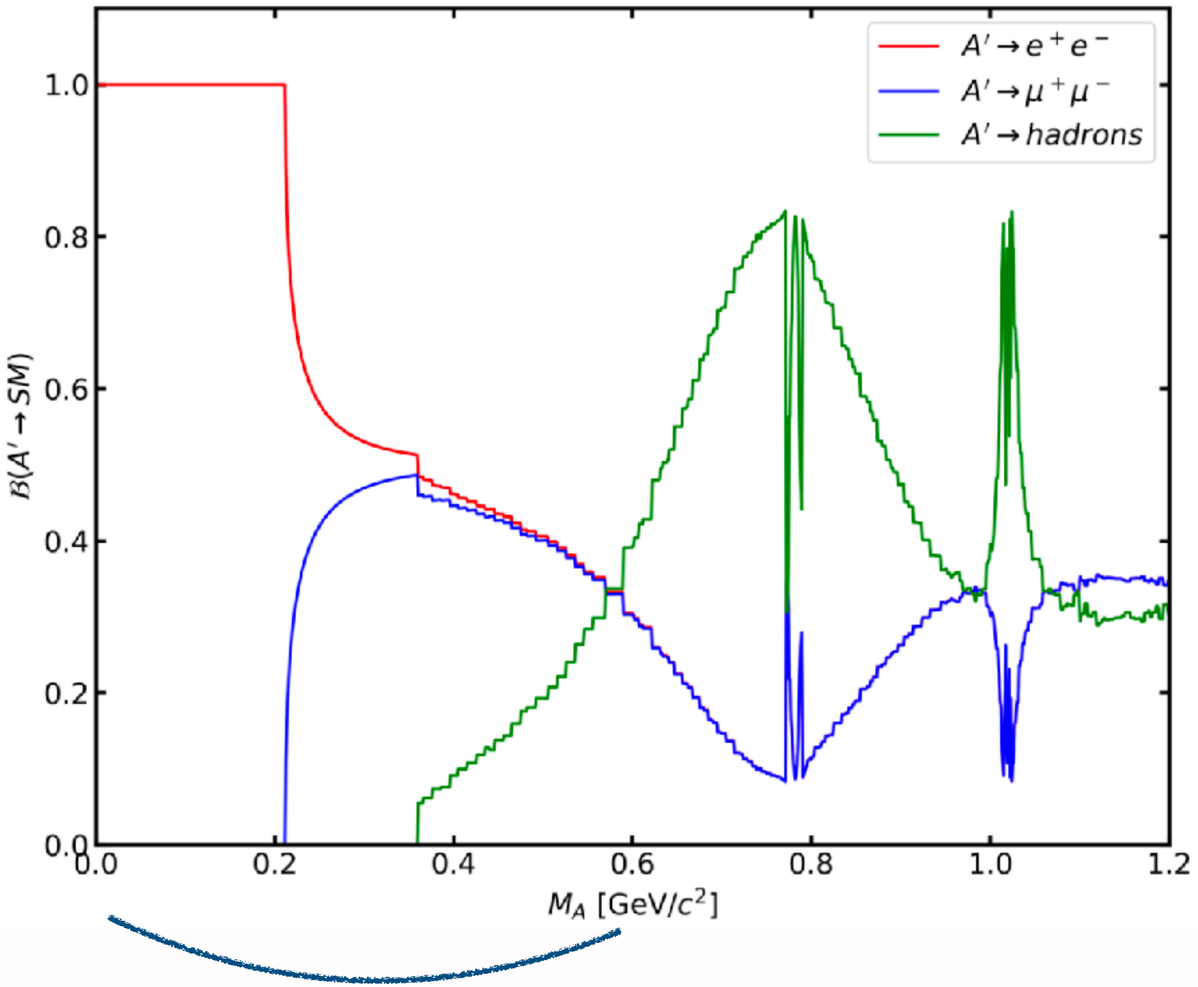
Dark photon: a detailed view

- New vector field $F'_{\mu\nu}$ symmetric under a new U(1) symmetry feebly interacting with the SM fields
- A minimal extension to the SM: kinetic mixing with the SM hypercharge

$$-\frac{\epsilon}{2}F'^{\mu\nu}B_{\mu\nu}$$

M(A′) and ε are free parameters



Decay width dominated by lepton antilepton final states for M(A′)< 700 MeV

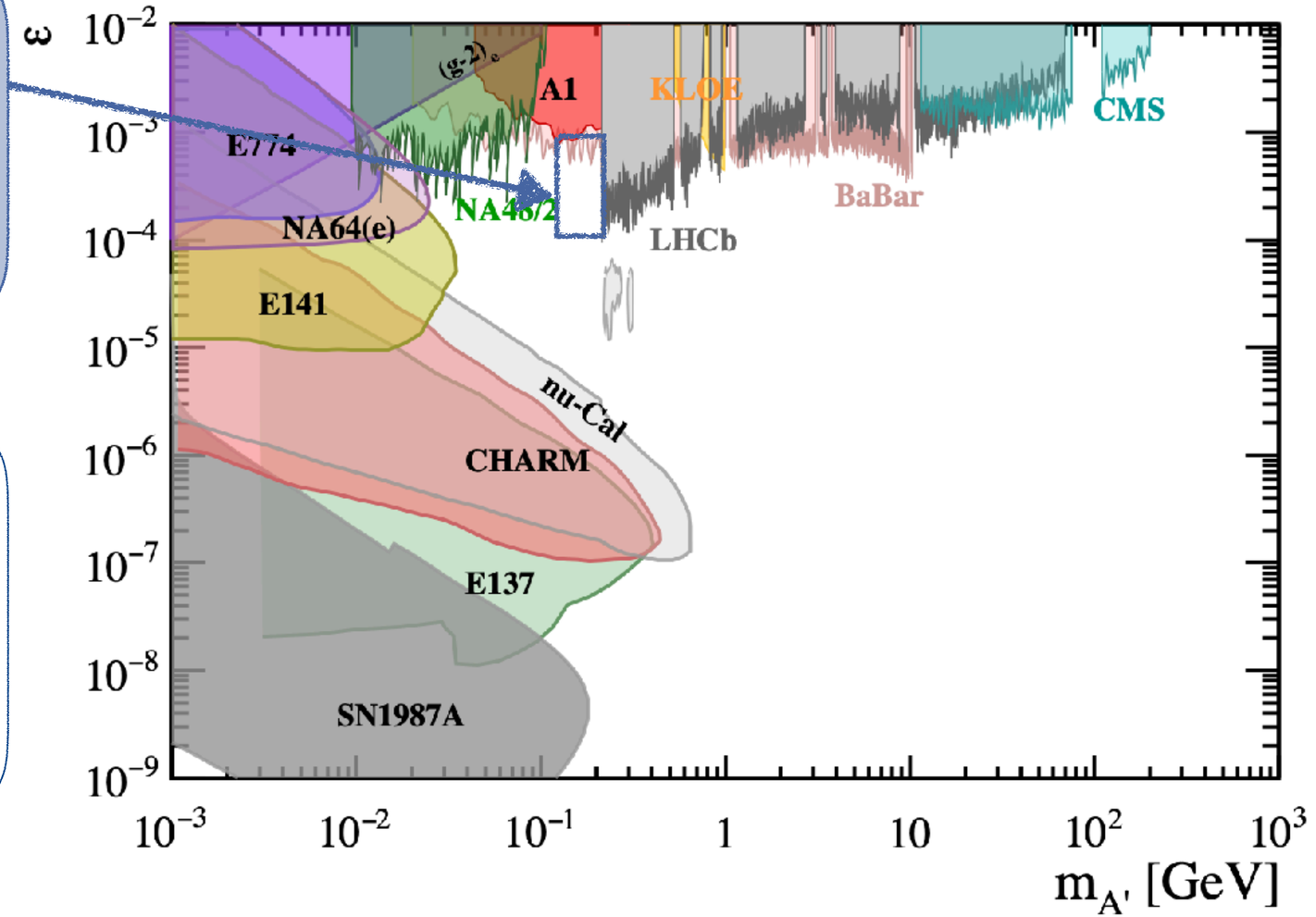
Search motivation

Are we truly sensitive in this portion of the phase space (?)

Can we assume that the decay $A' \to e^+e^-$ is prompt without losing in acceptance (?)

2 competing effects

- For large values of ϵ, the momentum of the DP is higher to compensate for a shorter lifetime
- At smaller values of ϵ, the rest lifetime of the DP is longer



Dark photon search in $K^+ \to \mu^+ \nu A' (A' \to e^+ e^-)$

➡ Search for **prompt** dark photon decay $A' \to e^+ e^-$ from $K^+ \to \mu^+ \nu A'$

$$K^+ \to \mu^+ \nu A'$$
$$A' \to e^+ e^-$$

If the decay is prompt the two vertices coincide

$$K^+ \to \mu^+ \nu e^+ e^-$$

Has the same signature as the DP prompt decay channel

$$B(K^+ \to \mu^+ \nu e^+ e^- \,|\, m_{e^+e^-} > 140\, MeV/c^2) = (7.06 \pm 0.31) \times 10^{-8}$$

Value set in order to avoid the $K^+ \to \mu^+ \nu \pi^0_D$ decay background

Selection criteria

Vertex selection

- Exactly one good vertex
  - ➡ Q=+1, Vertex $\chi^2 < 25$
  - ➡ CDA vex-beam axis < 30 mm
  - ➡ Vertex-beam axis distance < 40 mm
  - ➡ Tracks $\chi^2 < 40$
  - ➡ 105 m < Z_{vtx} < 180 m
  - ➡ $|t_{trk} - t_{trig}| < 2.5$ ns
  - ➡ Track separation at Straw planes > 15 mm
  - ➡ Track separation at LKr front plane > 200 mm

Track selection

- Track momenta in the range 6-65 GeV/c
- Geometrical acceptance with STRAW1-4 LKr NewCHOD

PID

- E/p (<0.2 μ^+, between 0.9 and 1.1 for $e^{\pm}$)
- μ^+ associated outer MUV3 candidate within 5 ns

VETO

- LKr veto
- LAV veto

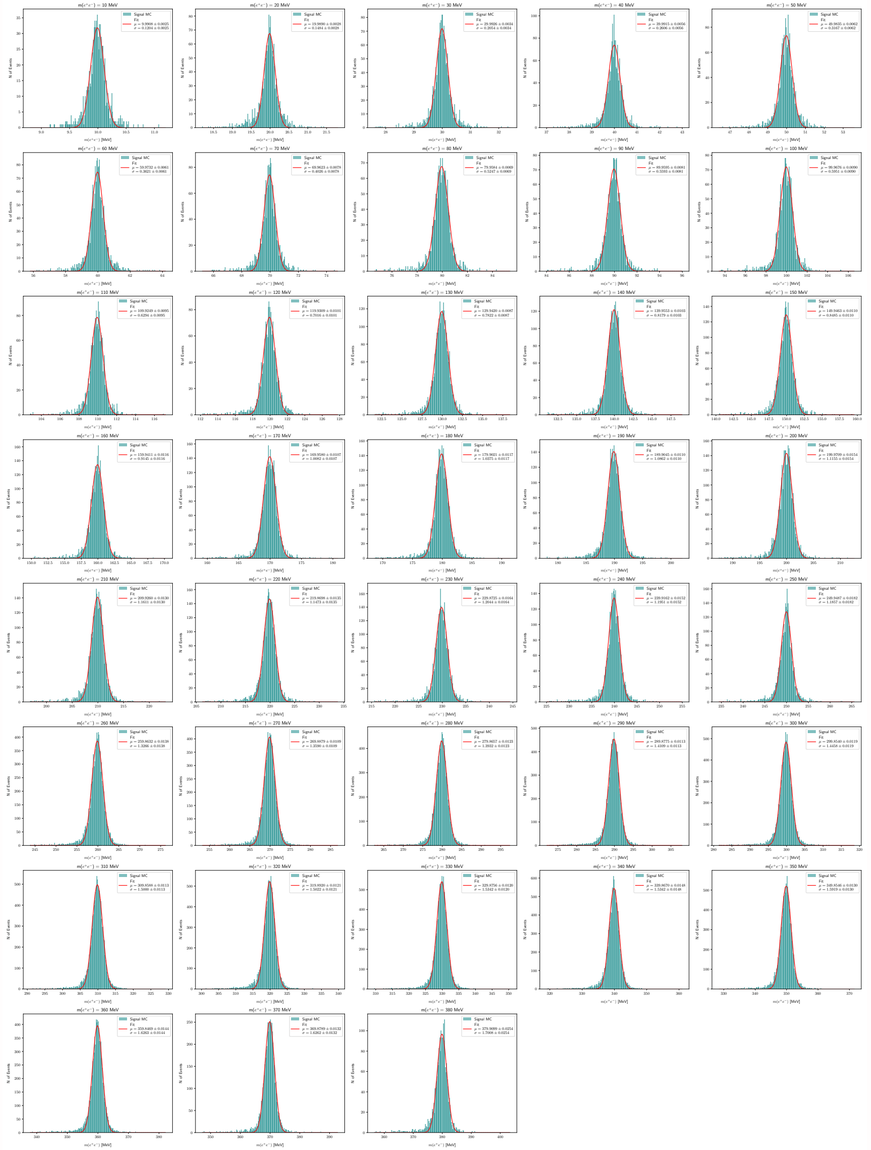
Kinematic cuts

➡ Cut on the resonances mass at $\pm 1.5\,\sigma_m$

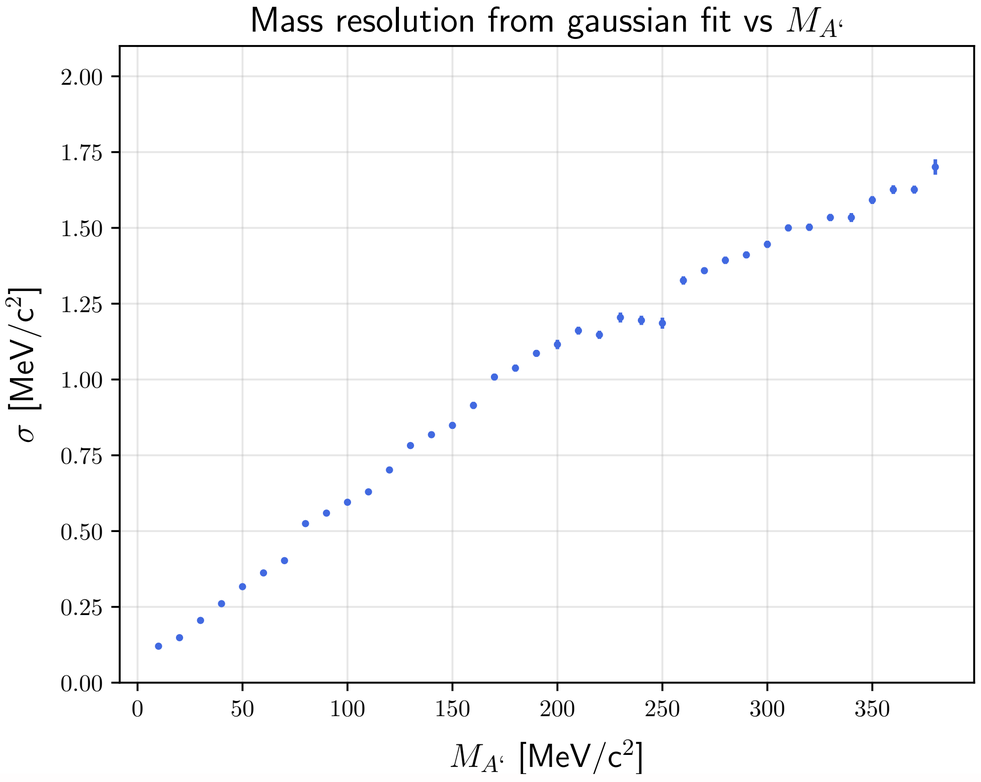
Normalisation

- The plan is to use the $K^+ \to \pi^+ e^+ e^-$ decay or maybe the $K^+ \to \mu^+ \nu \pi^0_D$

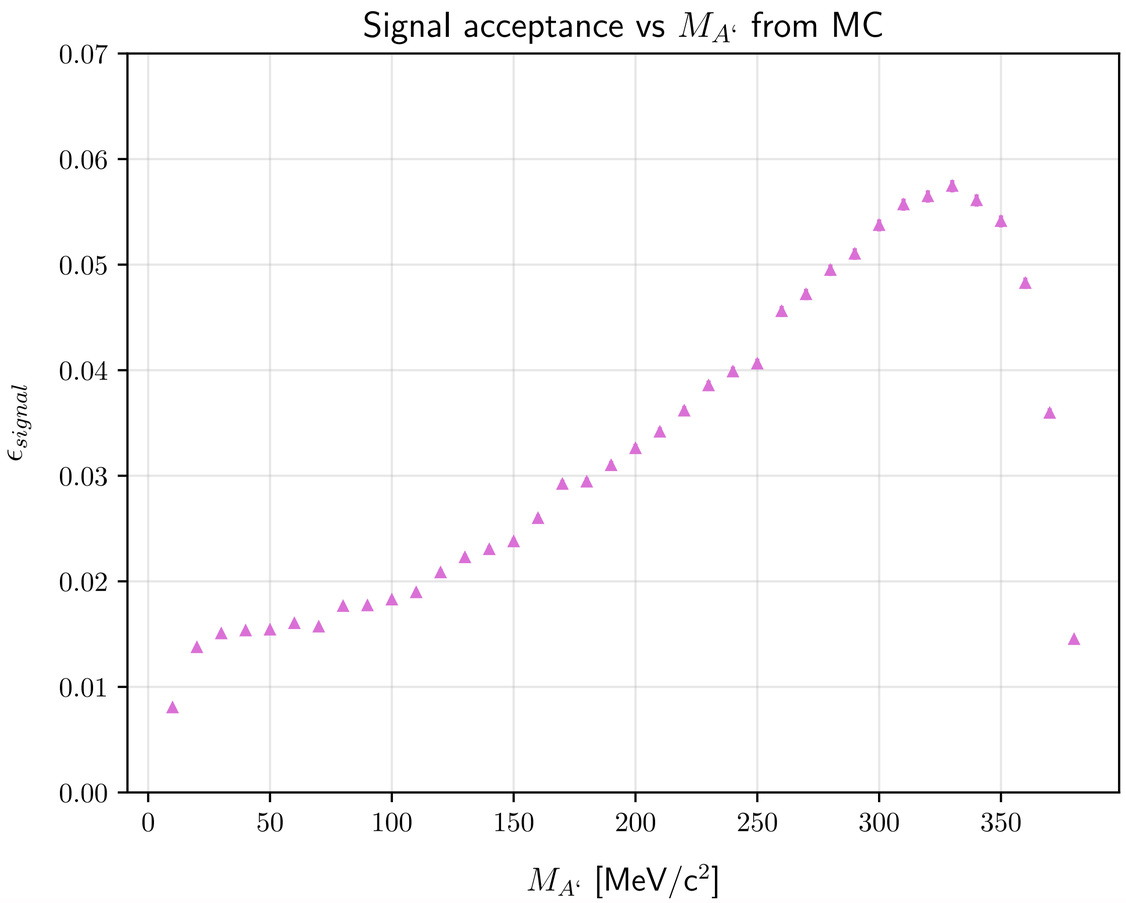
Mass resolution

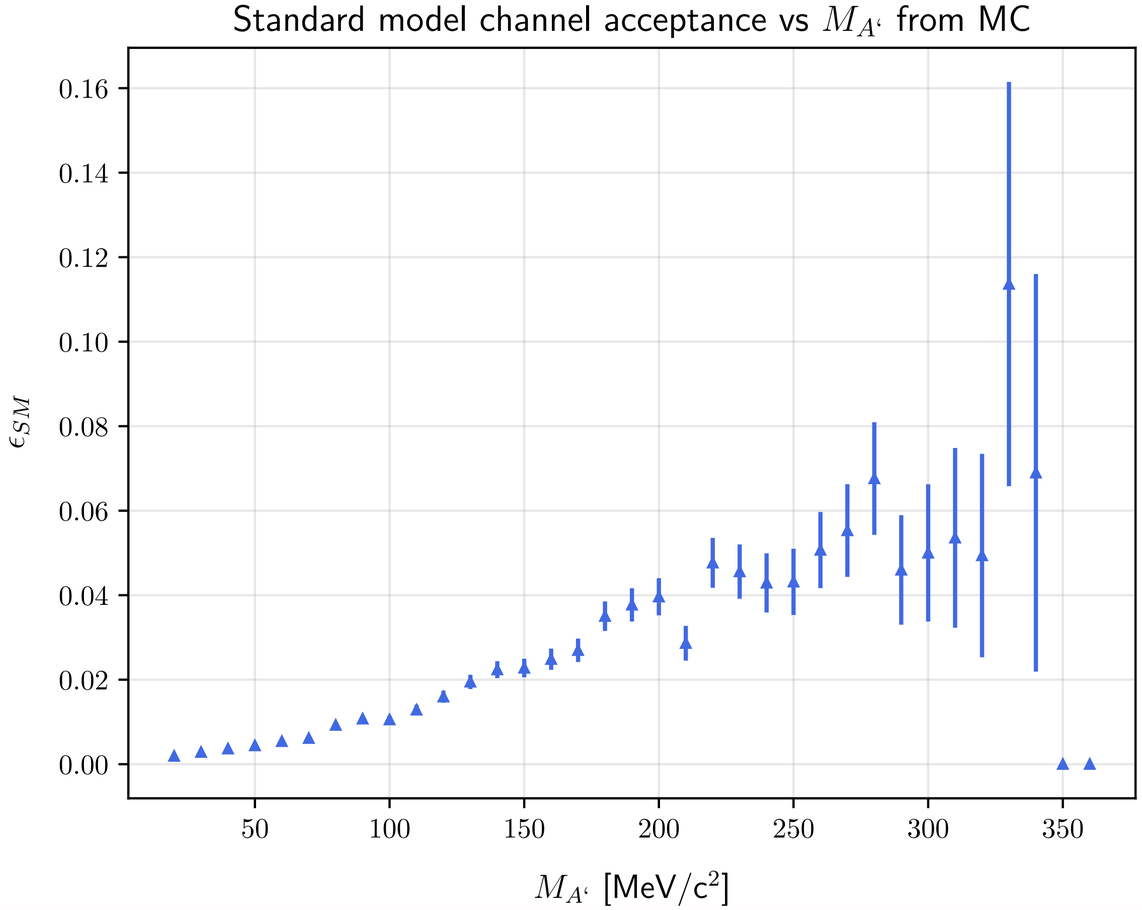


- The range of the dark photon sample was chosen between 10 MeV/c^2 and 380 MeV/c^2 with steps of 10 MeV/c^2
- The mass resolution was calculated using the KmunuA' MC and the resolution is extracted from a fit on the $m_{e^+e^-}$ reconstructed invariant mass



Acceptance DP vs SM





In the mass window of interest (140-210 MeV/c^2) the acceptance is of the order of 2.5 %

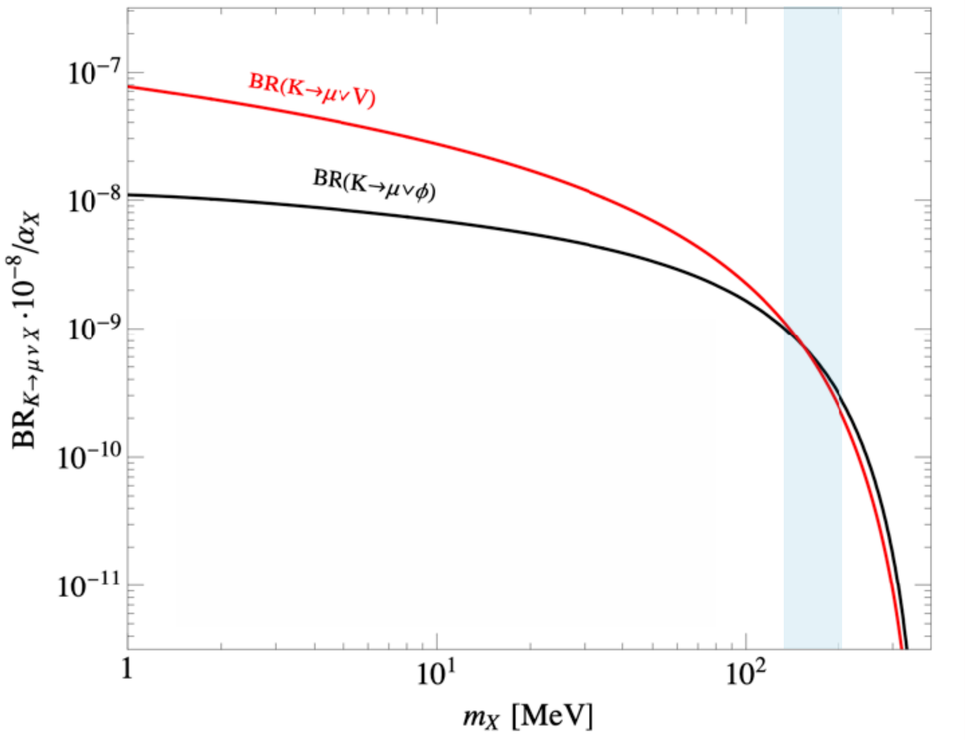
Towards the upper limit

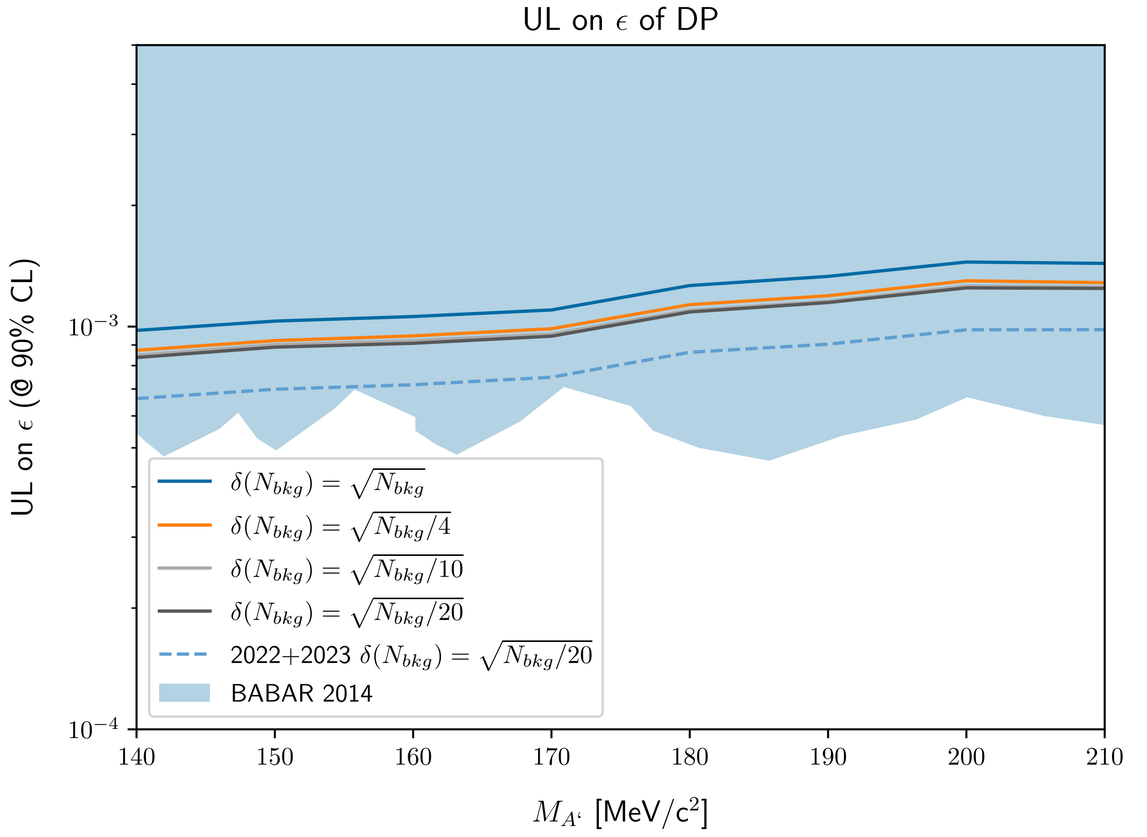
Do not look at data – just use Kmunuee MC with overlay (v3.7.3, v3.9.9 reco)

- Use $N_K = 2 \times 10^{12}$ (considering the idea to run on 2022-2023 data $N_K = 5 \times 10^{12}$)
- Count number of candidates in each search window (defined by $\pm 1.5\sigma_m$ from NA62)
- Assign N_{obs} = N_{bkg} (taking into account the scale factor MC/data)
- Feed into standard CLs_limit code in NA62FW to get expected upper limits on number of dark photon candidates.
- Use acceptance and N_K: to derive Br_{SES}.
- From limits in N_s and SES derive the expected upper limits on $Br(K^+ \to \mu^+ \nu A')$
- Convert to limits on dark photon mixing parameter ε

UL on ϵ

The mass window of interest is 140-210 MeV/c^2





$$\alpha_X = \epsilon^2 \alpha_{em}$$

Next steps

- The approach to follow should be the **data driven** background estimation (fit the data around $M_{A'}$ with a polynomial function)
- The selection needs to be refined to maximise the **acceptance**
- We really need to understand if can be **competitive** with other experiments (APEX/BABAR for example)
- Is the prompt approach fruitful?
- Do we need to consider the displaced vertex?

Thanks for the attention

Spares

$K^+ \to \mu^+ \nu A'$

3-body decay

$$E_{A'} = \frac{M_K^2 + m_{A'}^2 - m_{\mu\nu}^2}{2M_K}$$

LAB frame

$\gamma_K = 150$

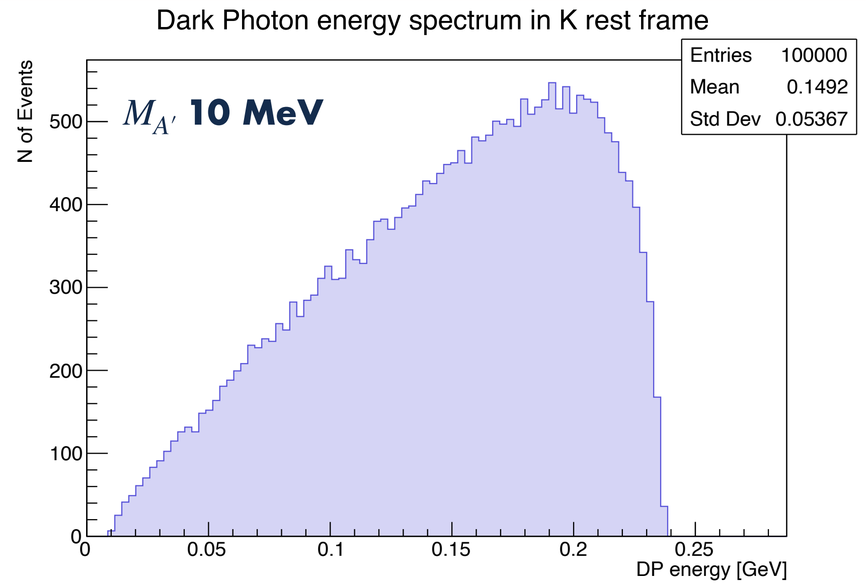
$\vec{P}_K$

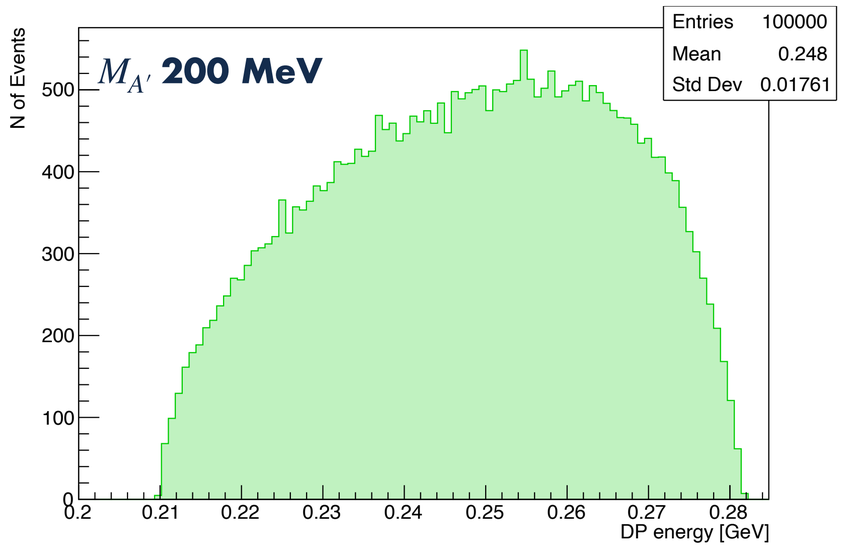
$\vec{P}_{A'}$

$$\gamma_{A'} = \frac{\gamma_K (E^*_{A'} - p^*_{A'})}{m_{A'}}$$

$\vec{P}_{A'}$

$$\gamma_{A'} = \frac{\gamma_K (E^*_{A'} + p^*_{A'})}{m_{A'}}$$





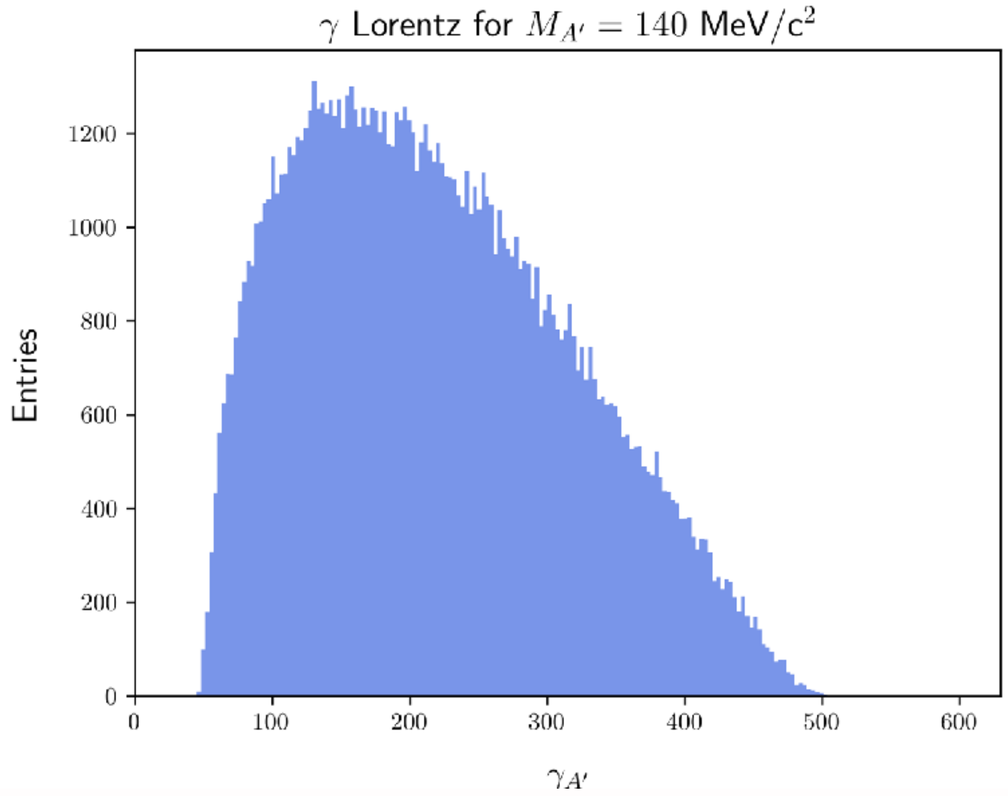
Prompt assumption

The idea is to start from the prompt search, so we need to understand if this assumption is true

$$c\,\gamma_{A'}\,\tau_{A'} = \ell_{A'}$$

$$\Gamma(A' \to \ell^+\ell^-) = \frac{1}{3}\alpha\epsilon^2 m_{A'}\sqrt{1-\frac{4m_\ell^2}{m_{A'}^2}}\left(1+\frac{2m_\ell^2}{m_{A'}^2}\right)$$

$$\tau_{A'} = \frac{\hbar}{\Gamma_{A'}}$$



If we suppose that we want to achieve a limit on ϵ of the order 10^{-4} in the mass range $140\,MeV/c^2 < M_{A'} < 210\,MeV/c^2$

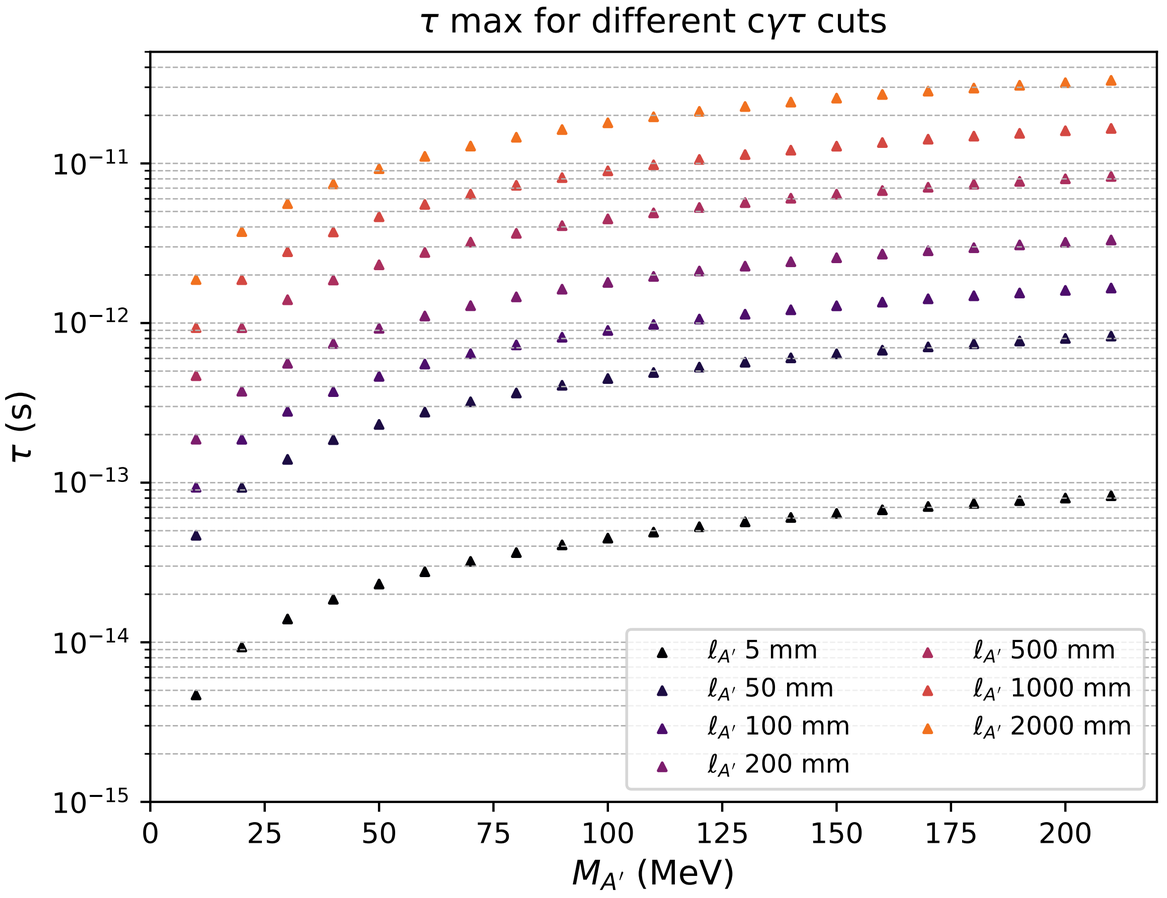
$$\ell_{A'} \approx 16\,mm\left(\frac{\gamma_{A'}}{10^2}\right)\left(\frac{10^{-8}}{\epsilon^2}\right)\left(\frac{50\,MeV}{M_{A'}}\right) \longrightarrow \ell_{A'}^{max}(140\,MeV/c^2) \approx 3\,cm$$

A quick look at the $\tau_{A'}$

LAB frame

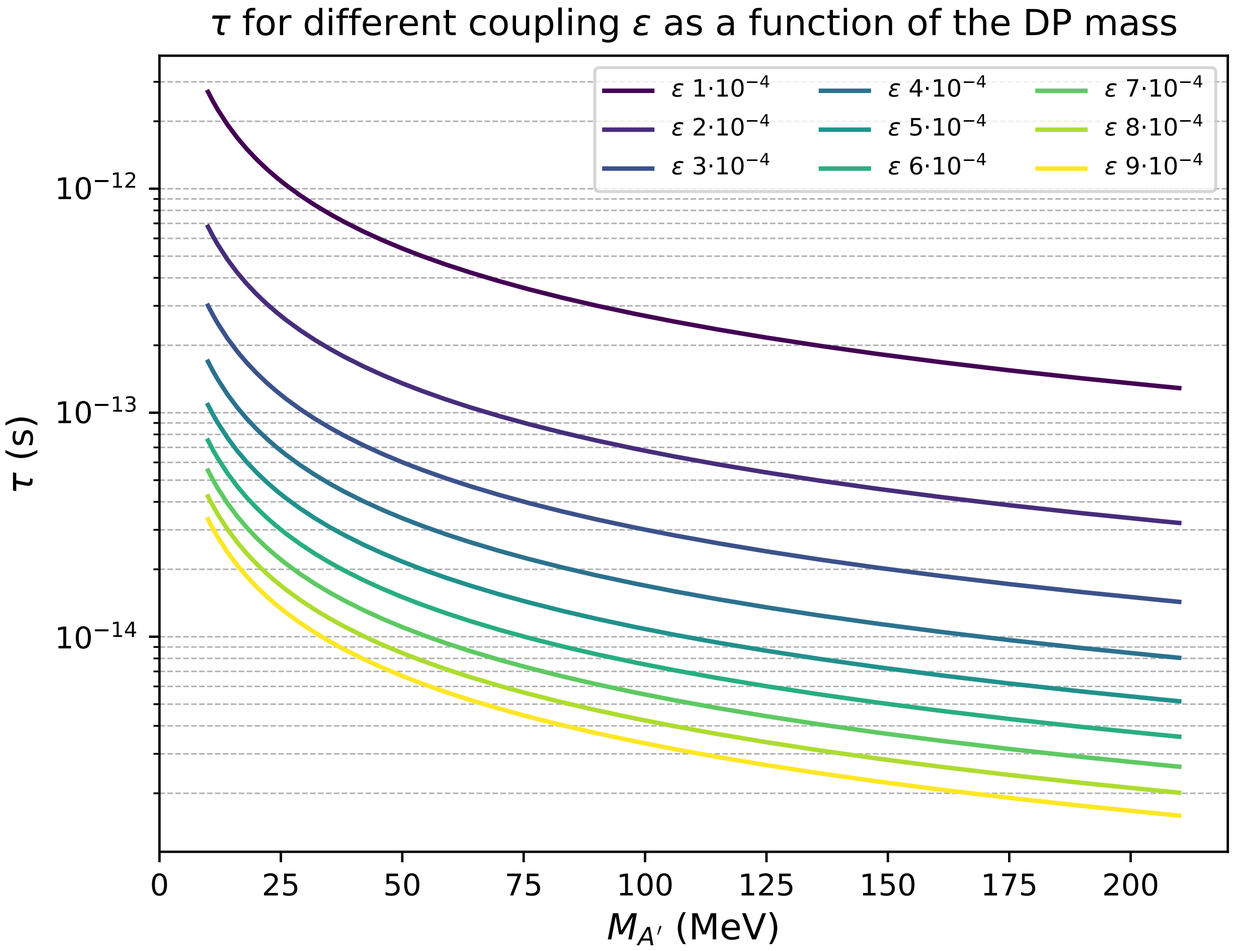
$$c\,\gamma_{A'}\,\tau_{A'} = \ell_{A'}$$

- If on average A' travels $\ell_{A'}$ in the lab frame, then its mean lifetime is $\tau_{A'}$.
- If the maximum distance between the vertex of A' and that of K^+ to which I am sensitive is d_{max}, this means that I can distinguish two regimes:
  - $\ell_{A'} > d_{max}$ **displaced**
  - $\ell_{A'} < d_{max}$ **prompt**
- The regimes can be translated in terms of lifetime:
  - $\tau_{A'} < \tau_{max}$ **prompt**
  - $\tau_{A'} > \tau_{max}$ **displaced**



Introduciamo l'accoppiamento

A quick look at the $\tau_{A'}$



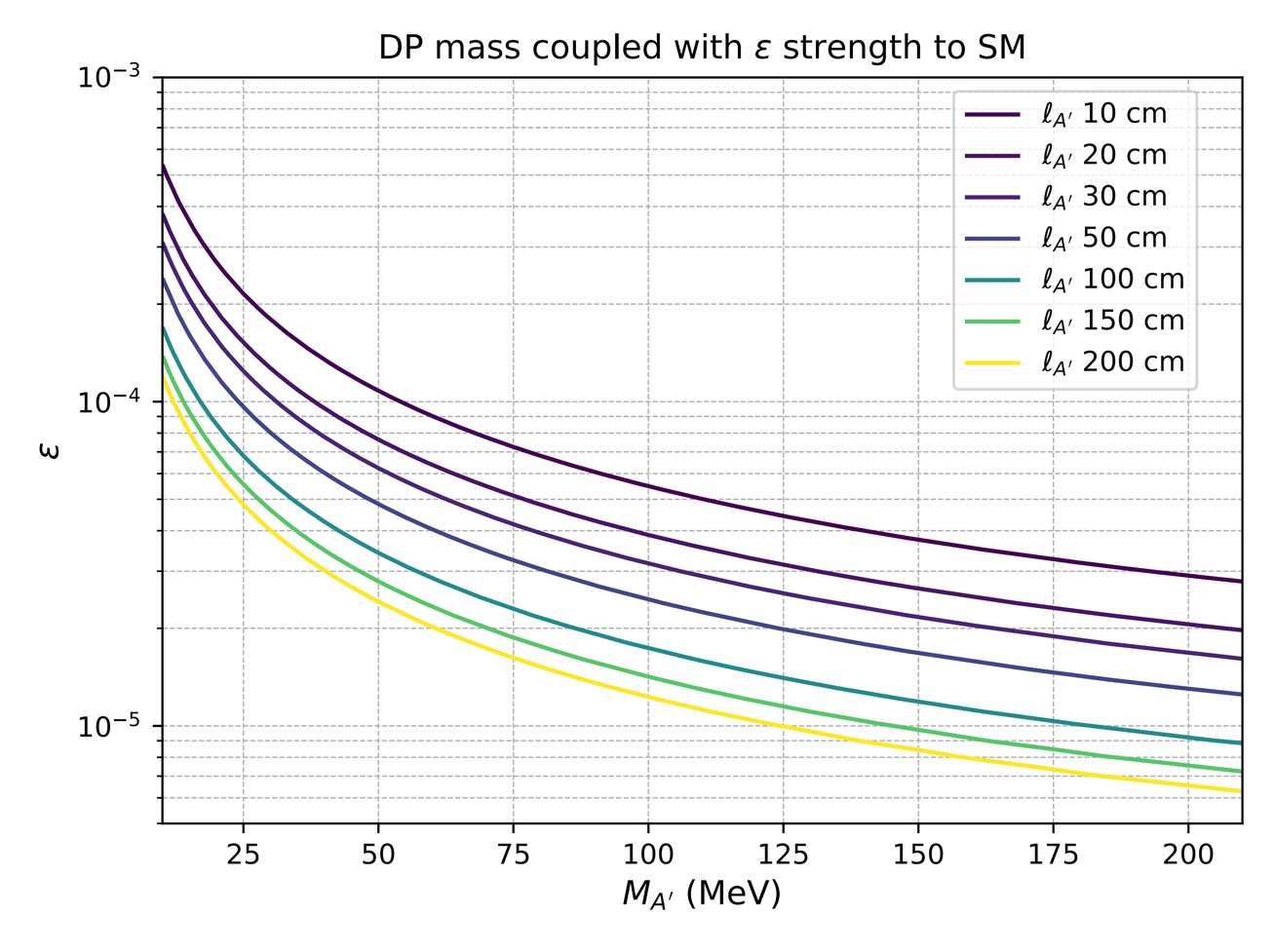
Assuming the only allowed decay mode is A′ → e+e−

$$\Gamma(A' \to \ell^+\ell^-) = \frac{1}{3}\alpha\epsilon^2 m_{A'}\sqrt{1-\frac{4m_\ell^2}{m_{A'}^2}}\left(1+\frac{2m_\ell^2}{m_{A'}^2}\right)$$

Mean flight distance in the LAB frame

$$\ell_{A'} \simeq 16\,mm\left(\frac{\gamma_{boost}}{10^2}\right)\left(\frac{10^{-8}}{\epsilon^2}\right)\left(\frac{50\,MeV}{M_{A'}}\right)$$

$\tau_{A'}$: level curves



$$\Gamma(A' \to \ell^+\ell^-) = \frac{1}{3}\alpha\epsilon^2 m_{A'}\sqrt{1-\frac{4m_\ell^2}{m_{A'}^2}}\left(1+\frac{2m_\ell^2}{m_{A'}^2}\right)$$

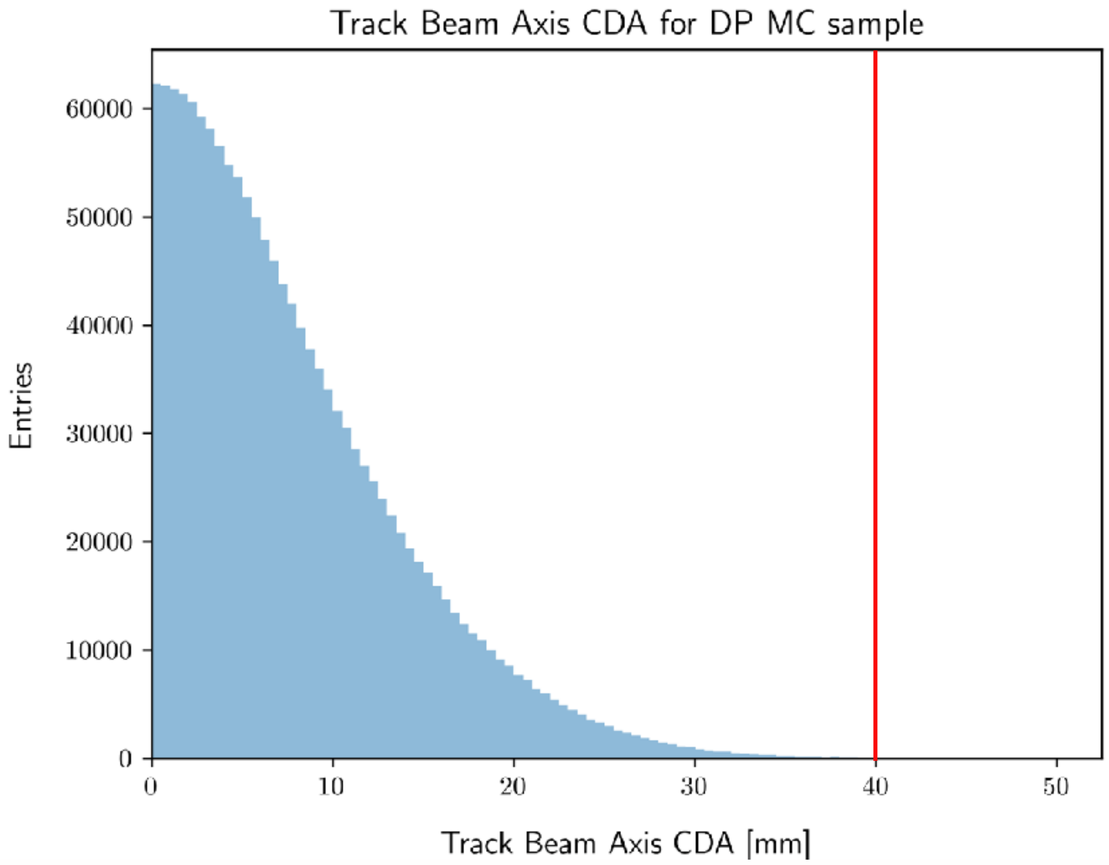
$$\tau_{A'} = \frac{\hbar}{\Gamma_{A'}}$$

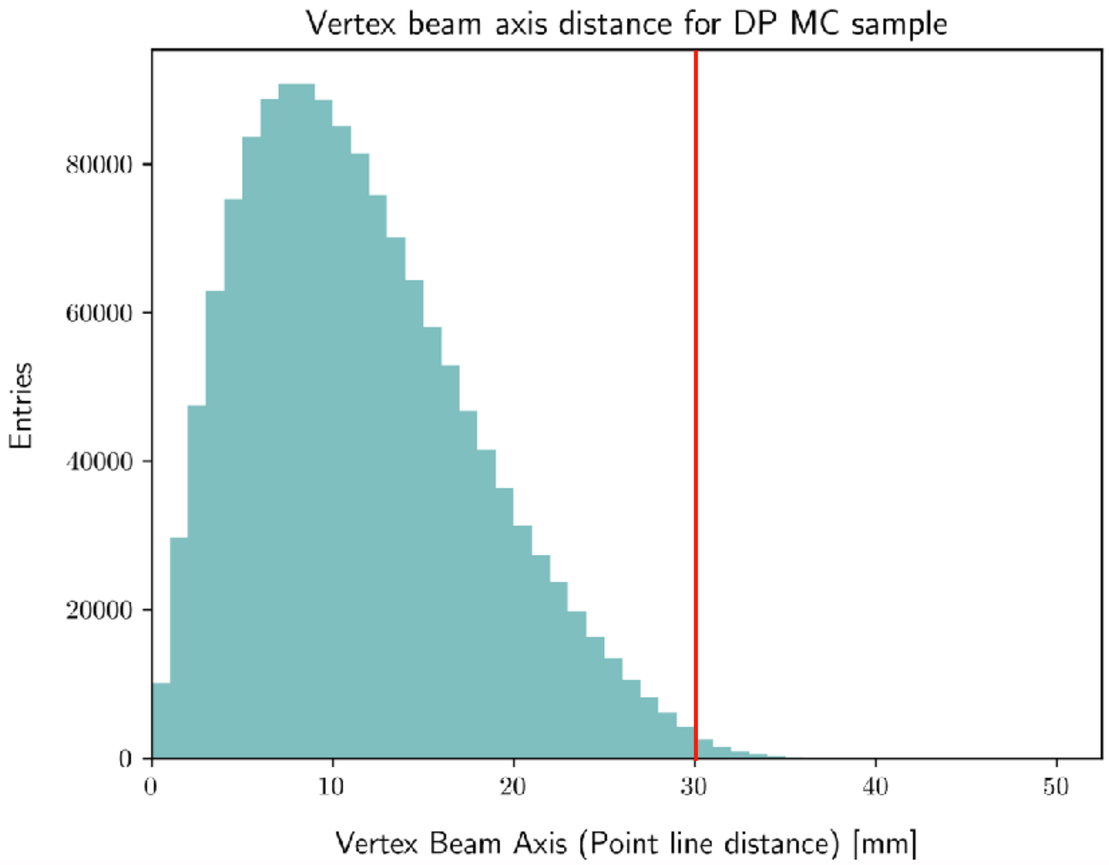
$$c\,\gamma_{A'}\,\tau_{A'} = d_{lab}$$

$$d_{lab} = f(\epsilon, M_{A'})$$

- Construct a grid in the $\epsilon, M_{A'}$ phase space
- Construct the contour lines at fixed values of d_{lab}
- $\gamma_{A'}$ is a function of the DP mass

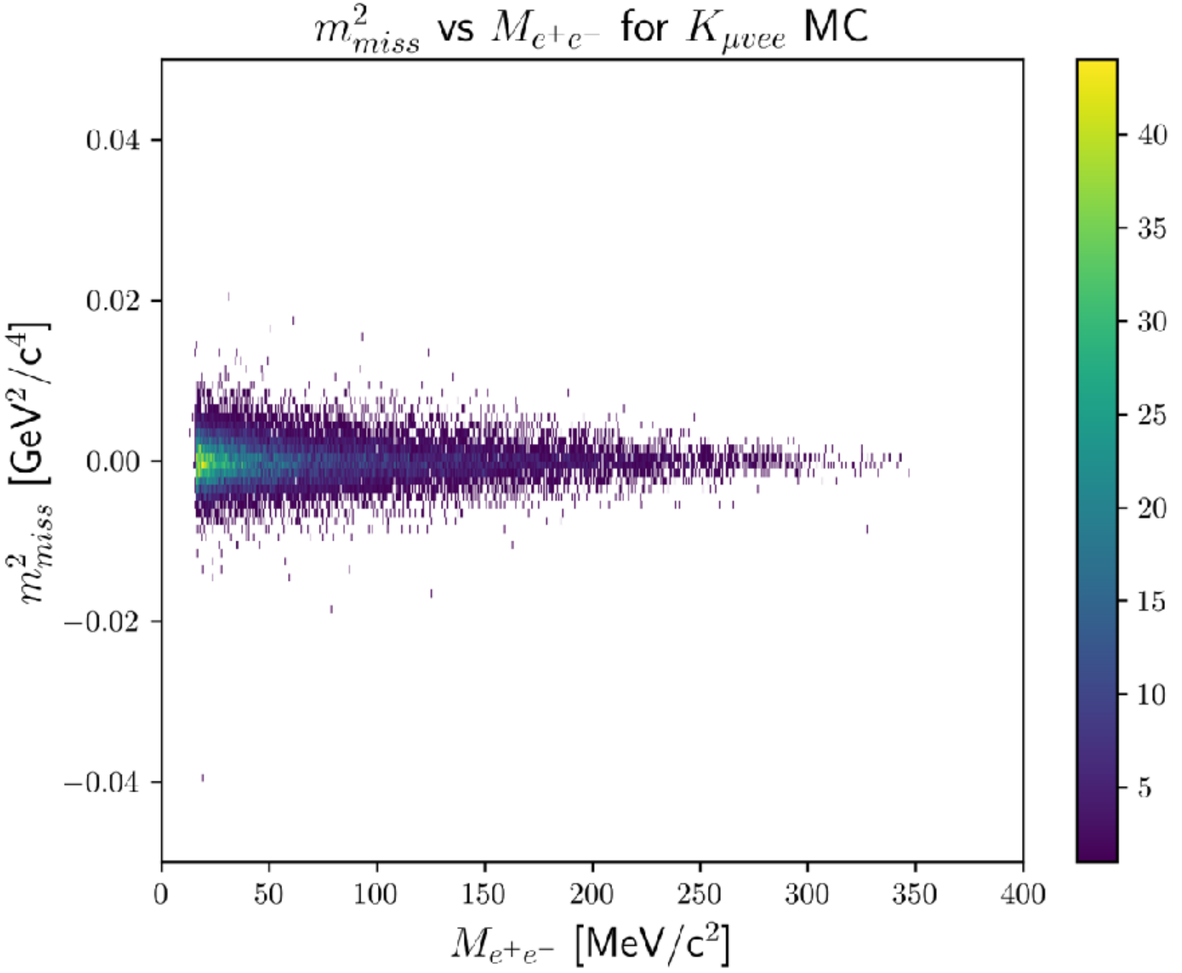
Distribution before cut

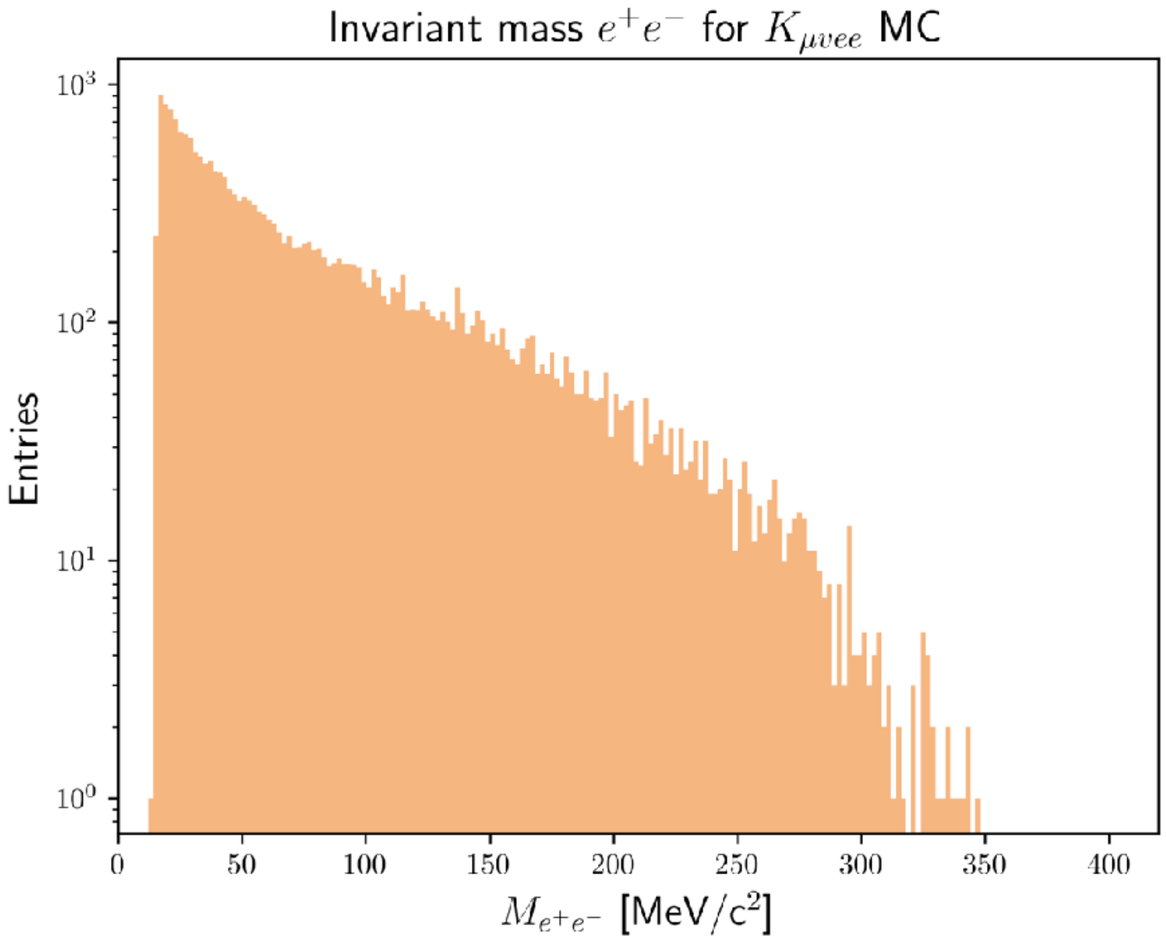




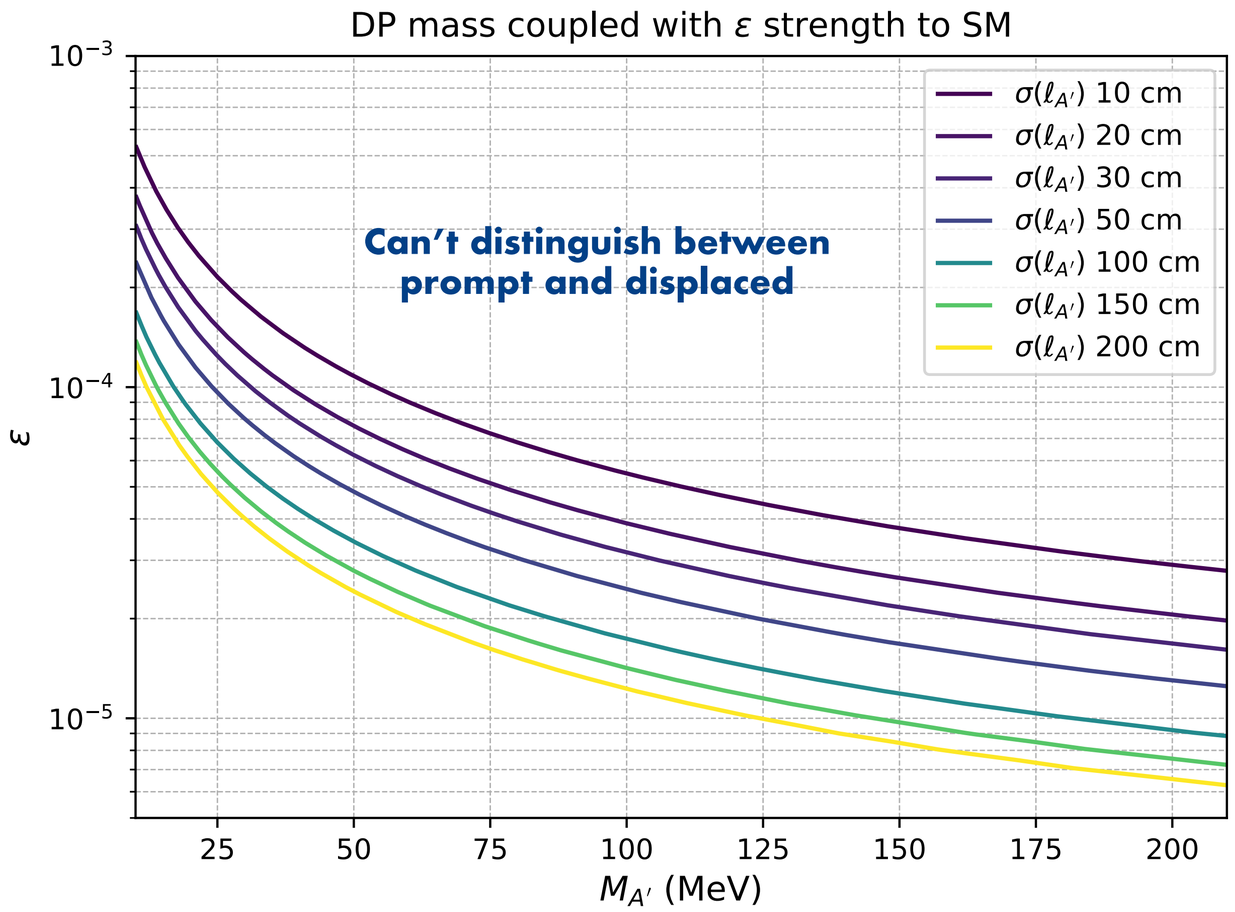
Kinematic distribution after the selection for the SM

SM sample before the kinematic cut





$\tau_{A'}$: level curves

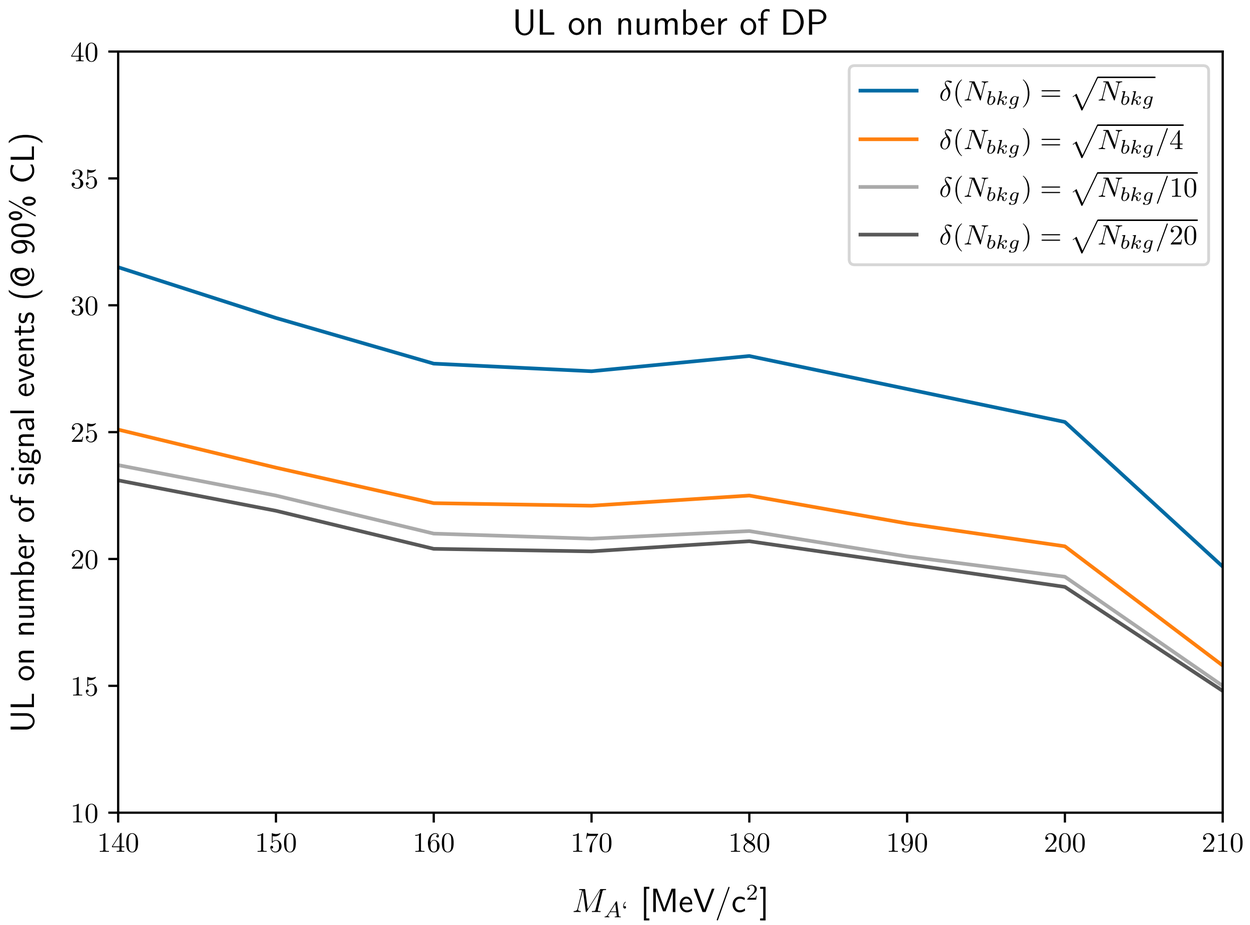


- If my resolution is $\sigma(\ell_{A'})$ the upper region of the phase space is the one in which I cannot distinguish between the prompt and the displaced decay
- Is important to understand which is my acceptance in the upper region as the lifetime varies

A study on the acceptance for different lifetime hypothesis and in the mass range should be performed

UL on Number of DP

The mass window of interest is 140-210 MeV/c^2



CLs method implemented in the framework with

$$N_{obs} = N_{bkg}$$

The uncertainty assigned to the bkg is varied in order to reproduce the "real" situation in which the bkg evaluation is data driven

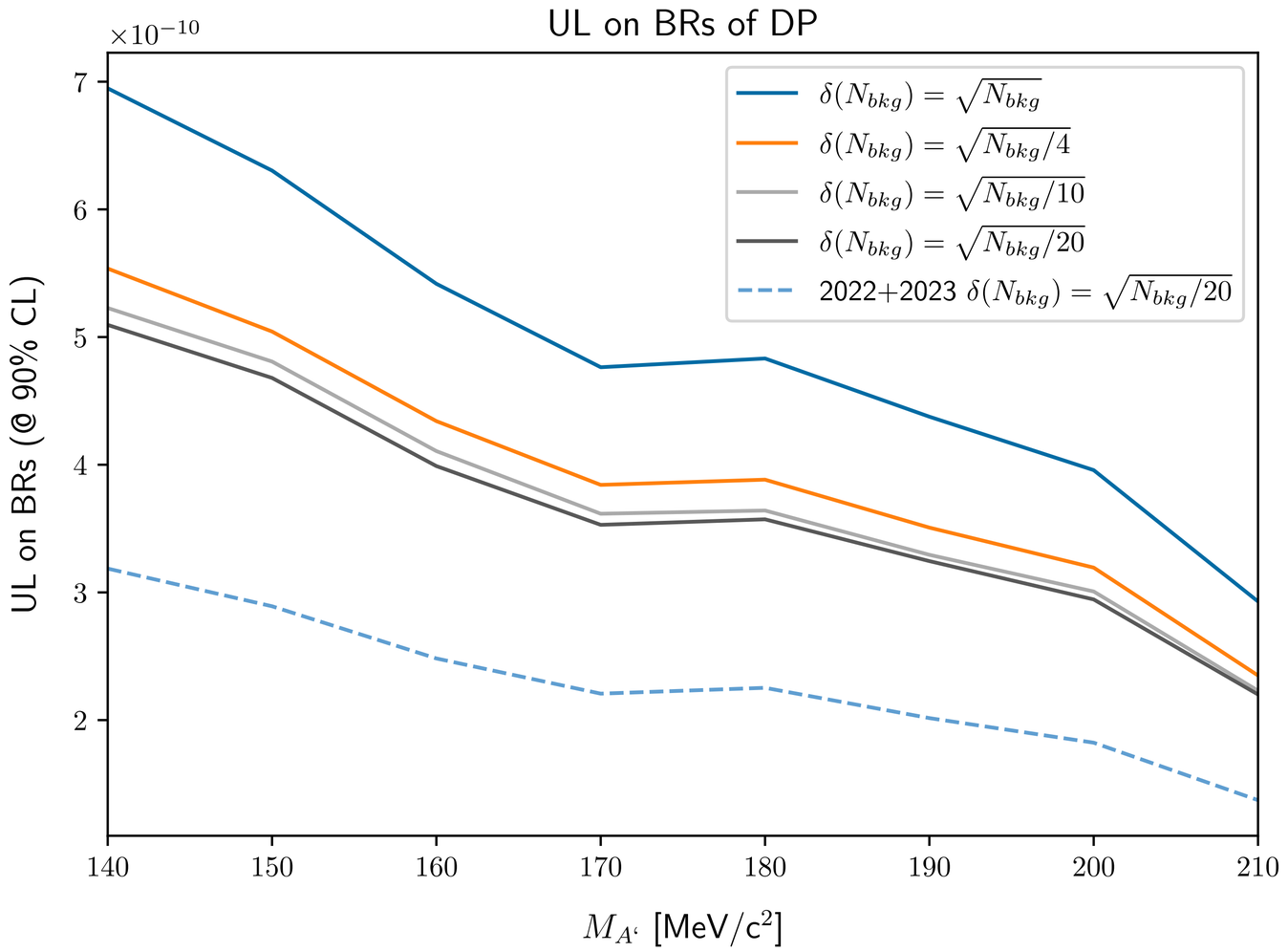
$$\delta(N_{obs}) = \sqrt{N_{obs}}$$

$$\delta(N_{bkg}) = \sqrt{N_{bkg}/k}$$

The scaling MC/data used to obtain N_{bkg}

UL on Br

The mass window of interest is 140-210 MeV/c^2



$$UL(Br_{K^+\to\mu^+\nu A'}) = \frac{UL(N_{DP})}{N_K\, Acc_{DP}}$$

Dark photon search in $K^+ \to \mu^+ \nu A' (A' \to e^+ e^-)$

$K^+ \to \mu^+ \nu A'$ ($A' \to e^+ e^-$) with Run1 data

- **New idea: use $K^+ \to \mu^+ \nu A'$ instead!**
  - $K^+ \to \mu^+ \nu \gamma$: Biggest BR of K^+ decay mode with a real photon
  - we gain one order of magnitude in ε^2 "for free" (BR ~ $10^{-3} \times \varepsilon^2$)
  - we could use also the μe trigger, increasing further the dataset by a factor ~ 2 (for Run1)
- **From very rough evaluations:**
  - Expected SES from Run1 ~ $O(10^{-11})$
  - Irreducible background: $K^+ \to \mu^- \nu e^+ e^-$, BR ~ 10^{-7}
    (but with peak search it's reduced by $O(10^{-2})$ due to mass window cut)

$$\frac{S}{\sqrt{B}} \approx 1 \rightarrow \varepsilon^2 \approx \frac{1}{3\,Acc_{sig}} \sqrt{\frac{Acc_{bkg}}{N_K}}$$

Using $N_K \sim 10^{12}$, $Acc_{sig} \sim 10\%$, $Acc_{bkg} \sim 10\% \times 10^{-2}$ we get **$\varepsilon^2 \sim 3 \times 10^{-7}$ [i.e. $\varepsilon \sim 5 \times 10^{-4}$]**

→ we should be already competitive with Run1 data!

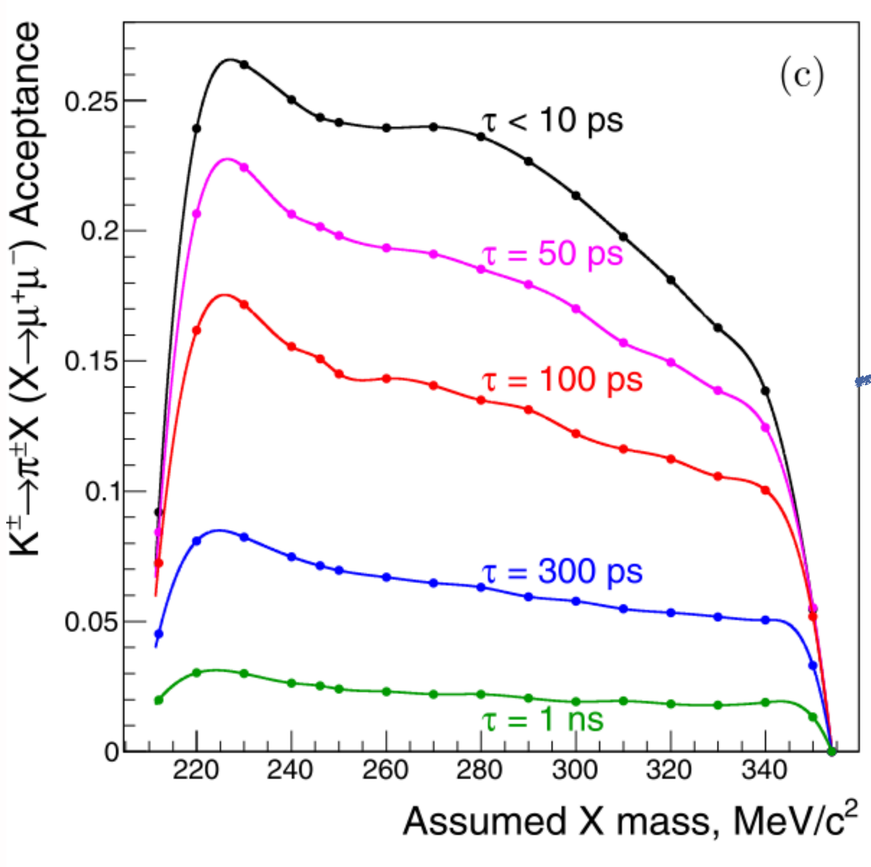
- **Proper feasibility study should be done!**
  - Signal and background acceptances
  - Expected ULs as a function of m(A')
  - Do we need to consider displaced e^+e^- vertices?

$K^+ \to \pi^+\mu^+\mu^-$ with NA48/2

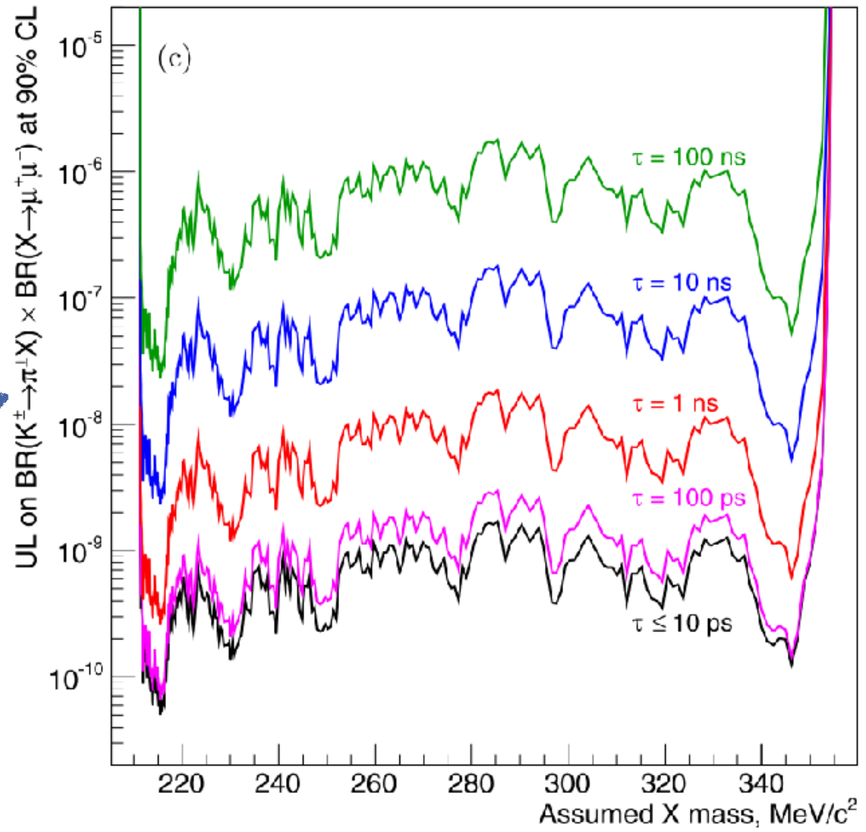
Within the 50 cm resolution on the longitudinal vertex position, $K^\pm \to \pi^\mp\mu^\pm\mu^\pm$ and $K^\pm \to \pi^\pm\mu^+\mu^-$ decays (denoted $K^{\rm LNV}_{\pi\mu\mu}$ and $K^{\rm LNC}_{\pi\mu\mu}$ below) mediated by short-lived (lifetime $\tau \lesssim 10$ ps) particles are indistinguishable from three-track decays.

N.B. K^+ 60 GeV/c

DCH different resolution

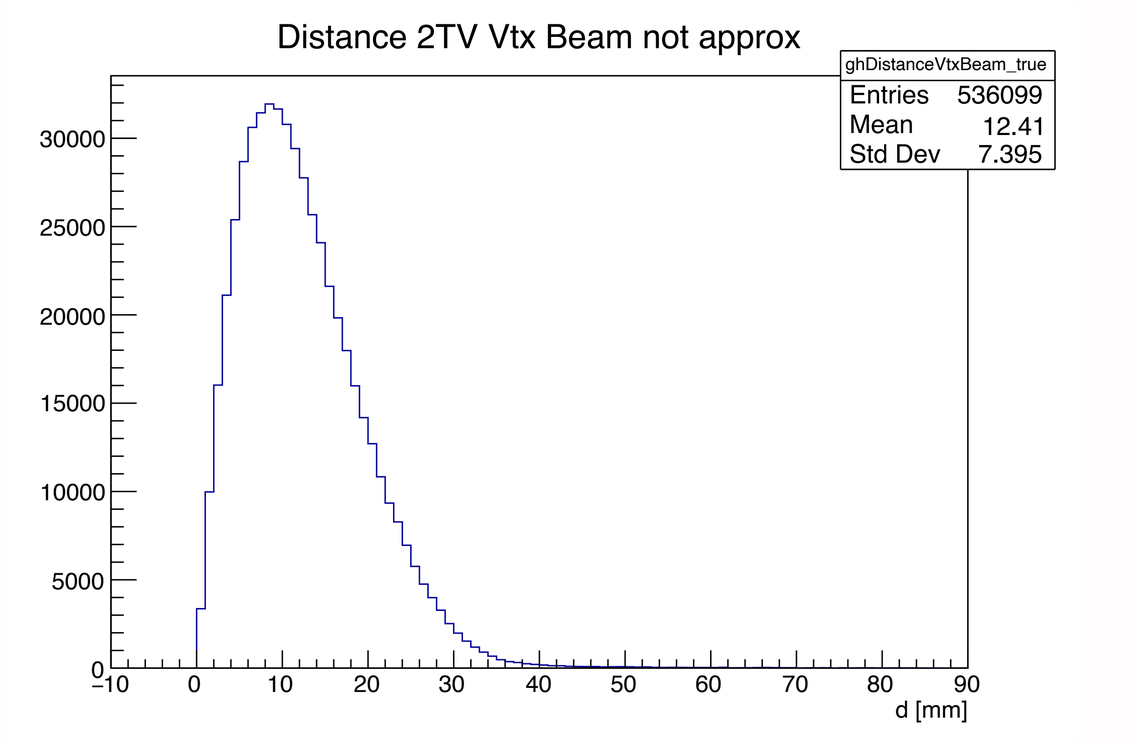


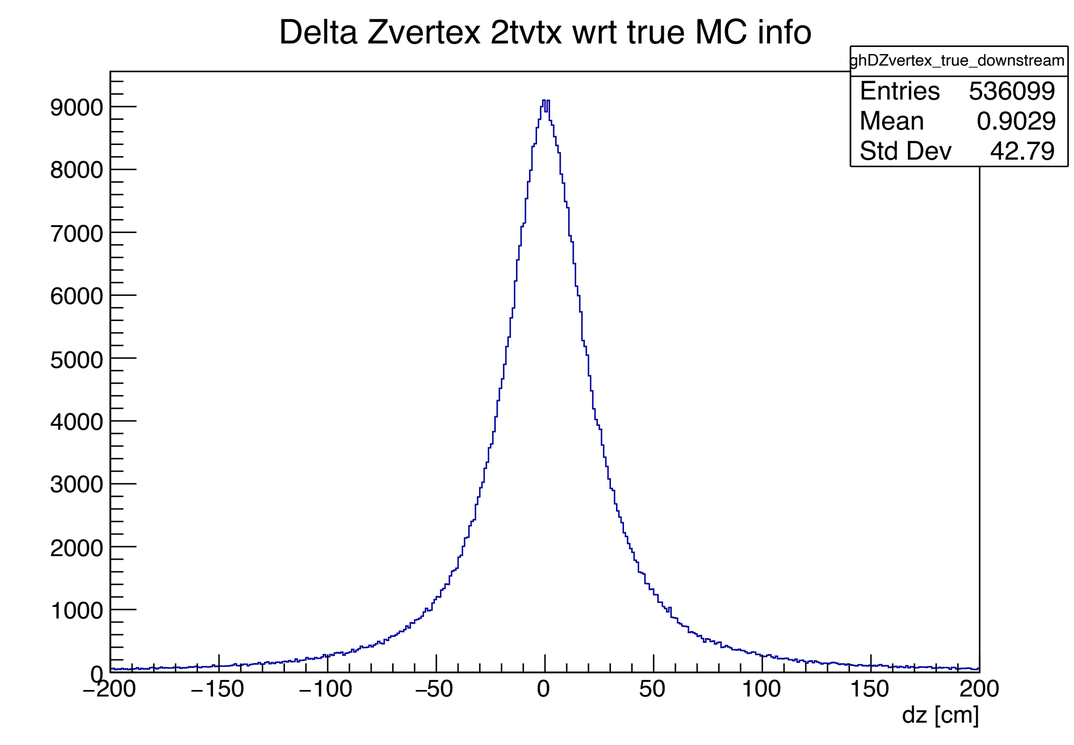
The better is the acceptance the more stringent is the U.L.



Vertex study

MC prompt: 2TV





MC prompt: 2TV vs 3TV