A novel method to improve displaced vertex searches

An extended version of the arXiv:2405.16993 preprint

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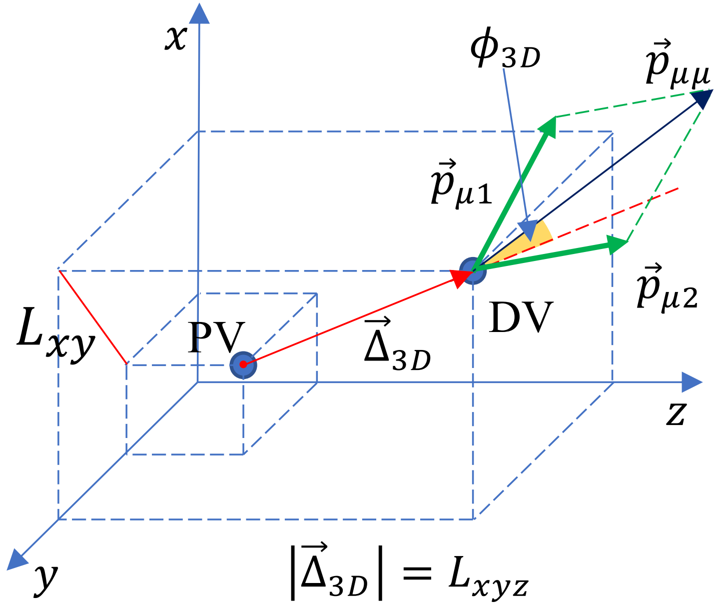
Introduction

- Starting point is all the analysis published by CMS and ATLAS in run1 and run2 on dimuon displaced vertex searches
- There are 5 papers published by CMS and 4 papers by ATLAS
- All of them preselect events using standard kinematics and quality cuts AND few specific cuts on variables useful to discriminate displaced vertices
- The variables used are:
  - Muon impact parameter and its significance (d_0 for the first and second muon)
  - Distance of the Displaced Vertex (DV) to the primary vertex (PV) in the transverse plane and its significance (L_{xy} and $L_{xy}/\sigma_{L_{xy}}$)
  - Angle between the PV-DV direction and the dimuon system direction in the transverse plane (in the plot is shown only the 3D angle ϕ_{3D})



Introduction

- Starting point is all the analysis published by CMS and ATLAS in run1 and run2 on dimuon displaced vertex searches
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Paper	Year	$\sqrt{s}$	$\mathcal{L}$ fb^{-1}	d_0	$\lvert d_0/\sigma_{d_0}\rvert$	χ^2_{vtx} fit	d_{xy}	$d_{xy}/\sigma_{d_{xy}}$	ϕ_{3D}
CMS 1 [7]	2013	7	5.1	-	2	5	-	5	NO
CMS 2 [8]	2015	8	20.5	-	12	5	-	-	2D
ATLAS 1 [9]	2019	13	32.9	-	-	NO	-	-	NO
ATLAS 2 [10]	2020	13	32.8	2	-	5	2	-	NO
ATLAS 3 [11]	2020	13	136	2	-	5	4	-	NO
CMS 3 [12]	2022	13	113	0.1	-	NO	-	-	NO
CMS 4 [13]	2022	13	101	-	2/1	5	-	-	2D
CMS 5 [14]	2023	13	97.6	-	6	10	-	6	2D
ATLAS 4 [15]	2023	13	139	0.1	-	NO	-	-	NO

Table 1: CMS and ATLAS muon inclusive searches (d_0, σ_{d_0}, d_{xy} and $\sigma_{d_{xyz}}$ are measured in mm). 2D in the table indicates that the ϕ_{3D} angle is used in the transverse plane.

Analysis Strategy

- The purpose of this work is to evaluate if what has been done so far by ATLAS and CMS could be improved and the key question becomes:
- Given a narrow resonance which decay to a $\mu^+\mu^-$ pair with a specific lifetime…
- What is the minimal cross-section (times the branching ratio to $\mu^+\mu^-$) σ_D which may produce a discovery at the LHC run 2?

Analysis Strategy

- The purpose of this work is to evaluate if what has been done so far by ATLAS and CMS could be improved and the key question becomes:
- Given a narrow resonance which decay to a $\mu^+\mu^-$ pair with a specific lifetime…
- What is the minimal cross-section (times the branching ratio to $\mu^+\mu^-$) σ_D which may produce a discovery at the LHC run 2?

The general idea is to look for displaced vertices

Analysis Strategy

- To define the discovery cross-section σ_D I need several ingredients…

- A basic detector simulation: DELPHES with the standard CMS card
- A vertex finding algorithm: the DELPHES external package TrackCovariance developed by Franco Bedeschi
- Integrated Luminosity 140 fb^{-1} (full run2 luminosity)
- Base selection cuts:
  - At least 2 muons (opposite sign) with $p_T > 30(10)$ GeV for the most (second) energetic muon
  - $|\eta| < 2.4$ for both muons
  - Relative charge isolation $\frac{\sum p_T}{p_T^\mu} < 0.3$ where the sum is extended to all tracks in a cone with $\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2} < 0.3$

Analysis Strategy

- To define the discovery cross-section σ_D I need several ingredients…

- Discovery criterion: observed effect should have the equivalent of a five standard-deviation discrepancy with the Standard Model
- A model which allow to produce signal events of a BSM resonance which decay to a muon pair and allow to select several decay length: PHYTIA model for a Z' resonance
- A Standard Model generator to produce background events
  - PYTHIA has been used to produce Drell-Yan events $pp \rightarrow \gamma/Z^0 \rightarrow \mu\mu$, di-Top events $pp \rightarrow t\bar{t}$ and Single-Top (s-channel and t-channel) $pp \rightarrow qt$
  - MADGRAPH has been used to produce tW events $pp \rightarrow tW$
- The last ingredient which allows to calculate σ_D as a function of the LLP mean lifetime $\langle\tau\rangle$ is then given by the equation

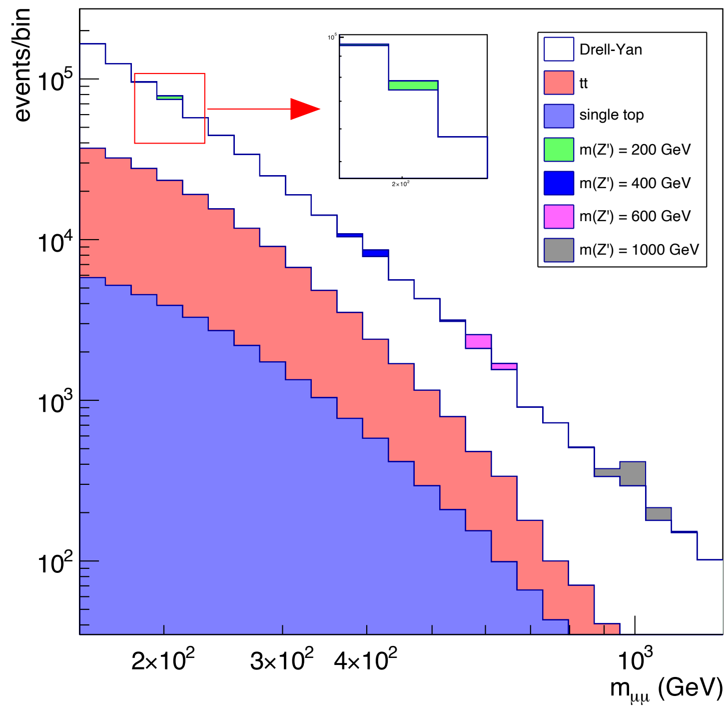
$$\tau = \frac{L}{c\beta\gamma} = \frac{mL_{xyz}}{|\vec{p}|}$$

Final receipt for σ_D

- The discovery cross section σ_D is finally defined as

$$\text{significance} = \frac{N_S - N_B}{\sqrt{N_B}} = \frac{N_{Z'}}{\sqrt{N_B}} = \frac{\mathcal{L}\varepsilon_D\sigma_D}{\sqrt{N_B}} = 5 \Rightarrow \boxed{\sigma_D = \frac{5\sqrt{N_B}}{\mathcal{L}\varepsilon_D}}$$

- Where the factor 5 is the common 5σ discovery condition and ε_D is the selection efficiency obtained for the BSM particle
- Example in figure: the SM dimuon mass distribution is shown in the range [150,1200] GeV
- No DV specific cuts have been used (only the base selection cuts)
- Four Z' with different masses and very short lifetime (Z' is produced at the PV) have been added using the calculated σ_D

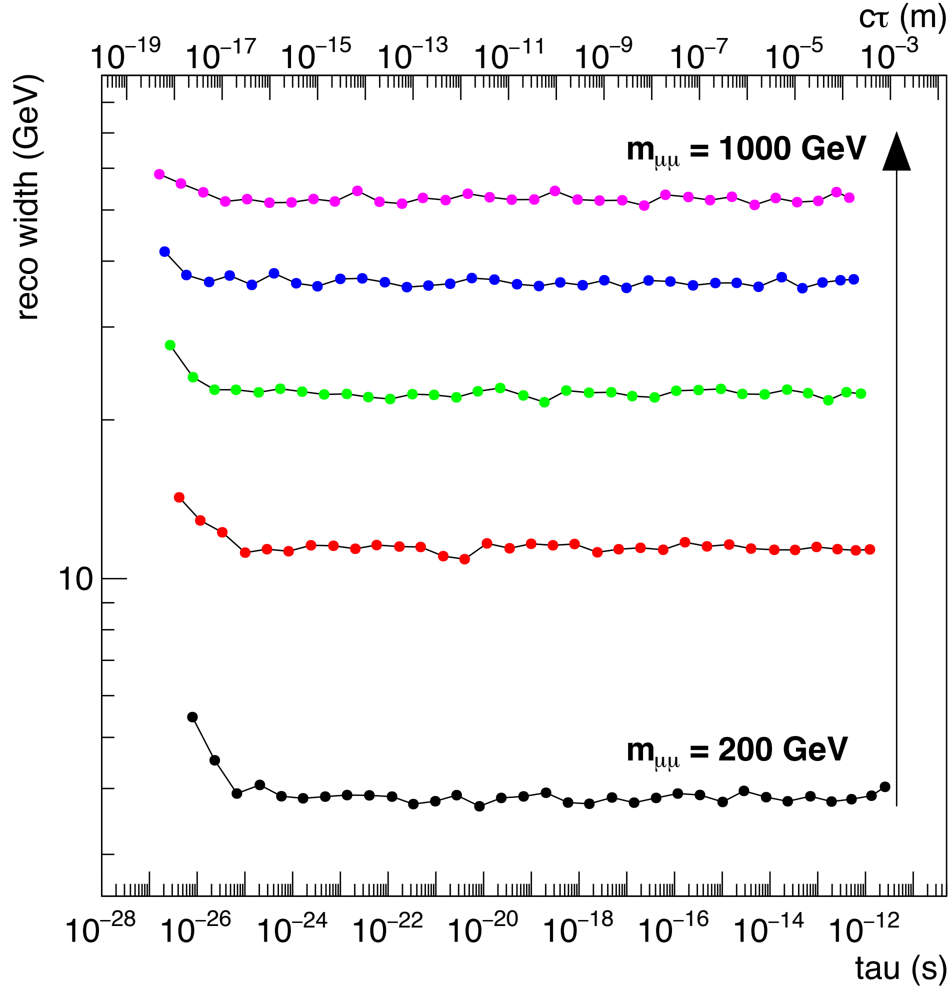


Final recipe for σ_D

- Six discriminant variables (see distribution in backup) have been chosen to select a DV event together with the base selection cuts.
- Each variable has been studied in a wide range of value:
  - $|d_0| > [0.010, 0.100]$ mm
  - $L_{xy} > [0,2]$ mm
  - $L_{xyz} > [0,2]$ mm
  - $|d_0|/\sigma_{d_0} > [0.5,20]$
  - $L_{xy}/\sigma_{L_{xy}} > [0.5,20]$
  - $L_{xyz}/\sigma_{L_{xyz}} > [0.5,20]$
- For a given Z' mass point and selection cut, the number of SM events N_B is obtained from the integral of the dimuon invariant mass distribution in the range $[m - 2\Gamma, m + 2\Gamma]$

Analysis Strategy

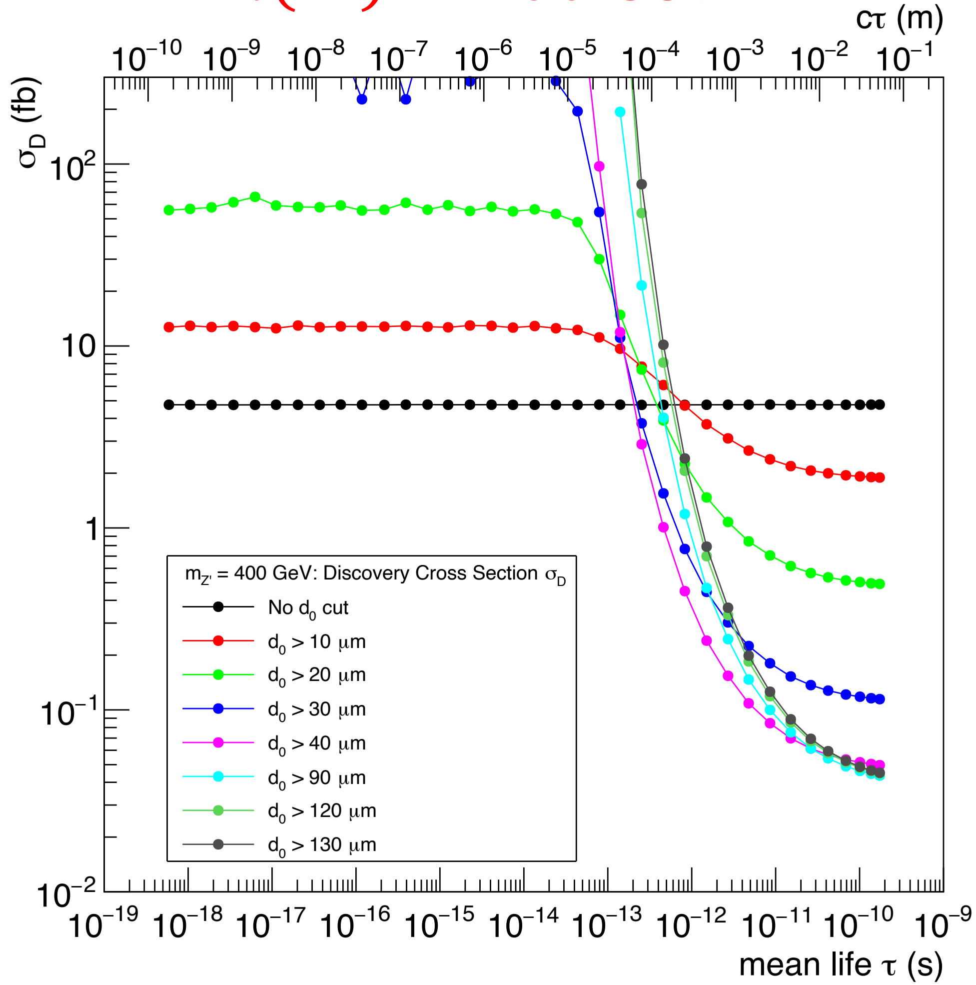
- Five Z' mass points have been generated: 200, 400, 600, 800 and 1000 GeV
- For each mass points, 40 different lifetime have been generated from $\sim 10^{-26}$ to $\sim 10^{-12}$ seconds which corresponds to a mean decay length $c\tau$ from $\sim 10^{-18}$ to $\sim 10^{-3}$ m
- For each mass and lifetime points, the width of the resonance has been measured, fitting with a gaussian the peak of the reconstructed distribution
- The width is constant for $\langle\tau\rangle > 10^{-25}$ s: the dimuon invariant mass resolution is bigger then the real Z' width
- The width varies from 3.8 GeV for $m_{Z'} = 200$ GeV up to 54.4 GeV for $m_{Z'} = 1$ TeV for $\langle\tau\rangle > 10^{25}$ s



Results: d_0 optimization example

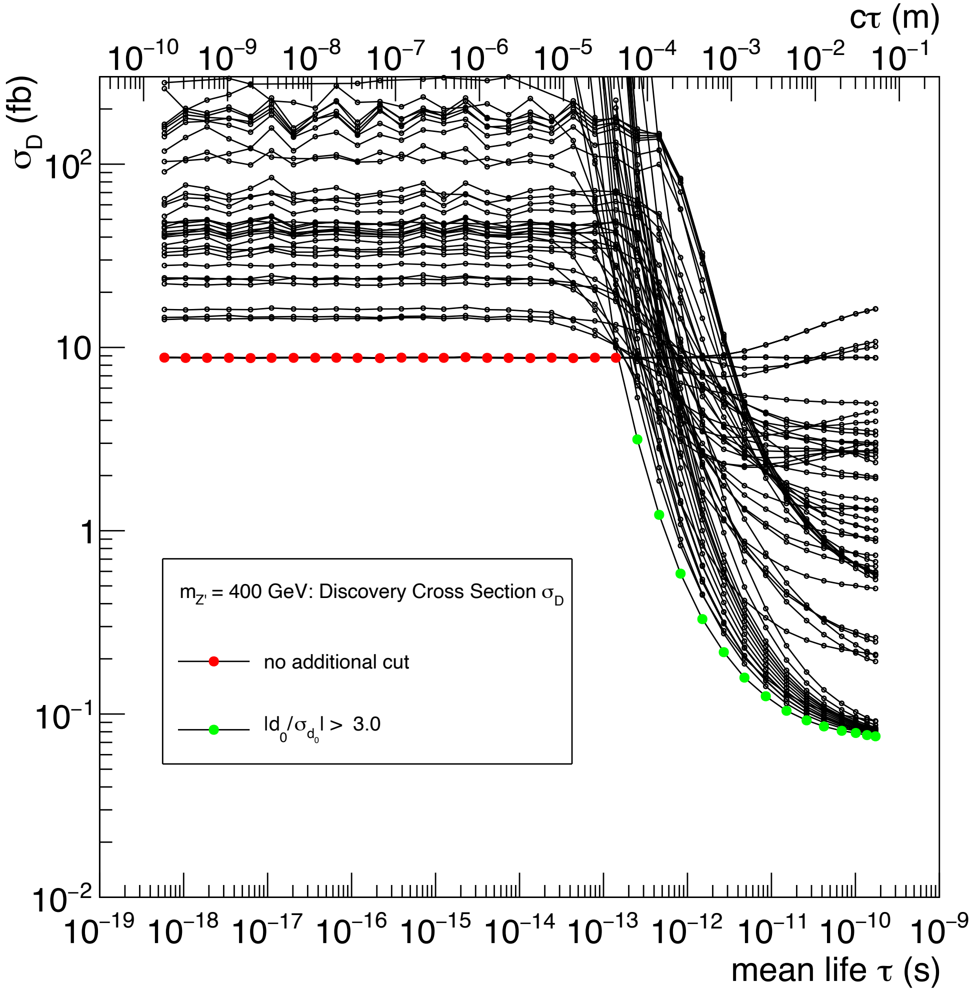
- For each mass points and cut type, a similar plot has been produced (total 5 mass point × 6 cut types = 30 plots)
- The area above each curve represents the combination of Z′ parameters that may lead to a discovery at LHC
- The area below indicates a combination of Z′ parameters which gives too few events to allow for a discovery using the 5σ criterion

$m(Z') = 400$ GeV



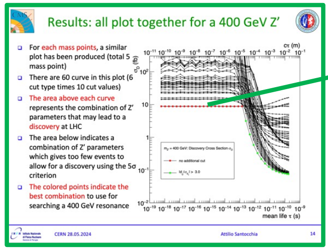
Results: all plot together for a 400 GeV Z'

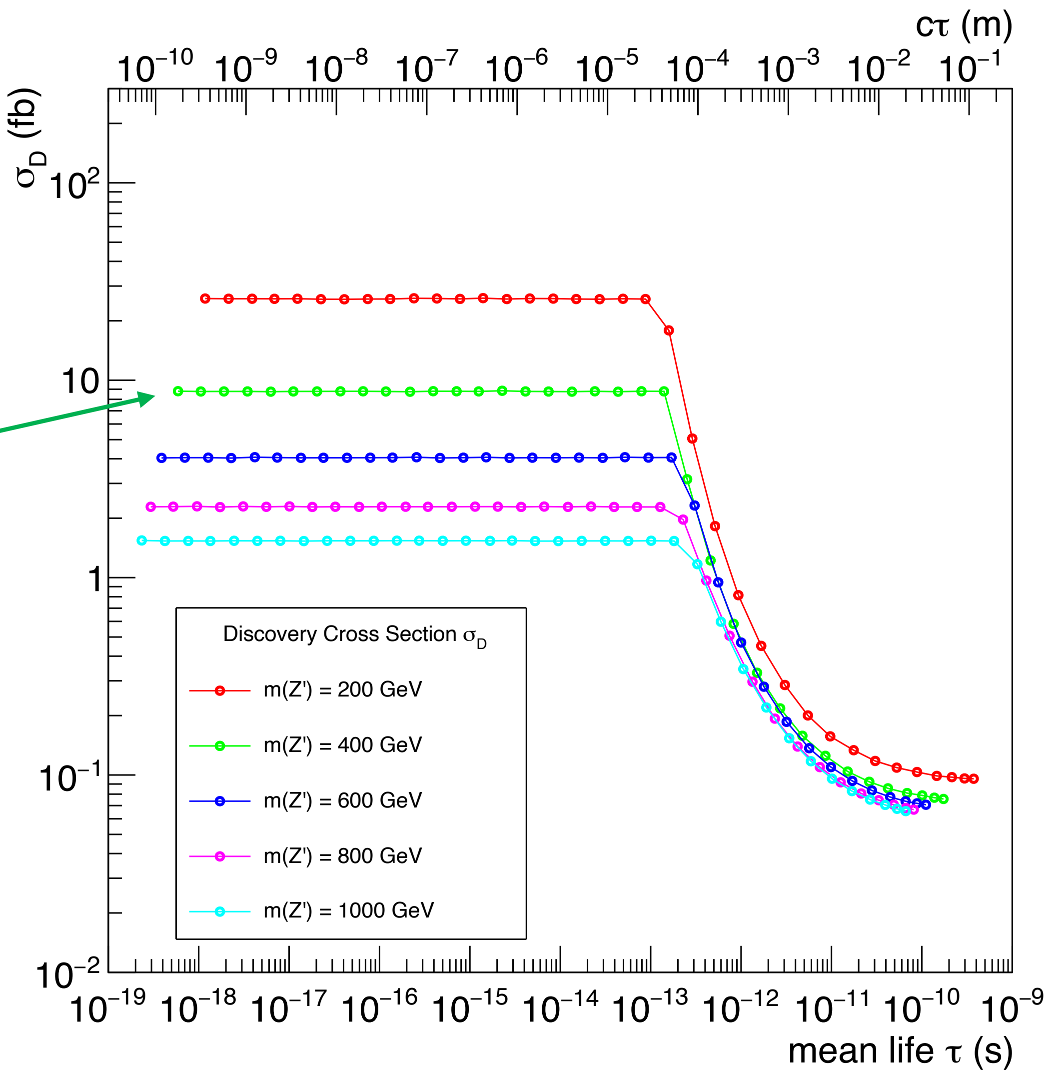
- For each mass points, a similar plot has been produced (total 5 mass point)
- There are 60 curve in this plot (6 cut type times 10 cut values)
- The area above each curve represents the combination of Z' parameters that may lead to a discovery at LHC
- The area below indicates a combination of Z' parameters which gives too few events to allow for a discovery using the 5σ criterion
- The colored points indicate the best combination to use for searching a 400 GeV resonance



Results: Best Discovery Conditions

- Best discovery condition for all 5 mass points
- Each curve is obtained from a plot similar to the one shown in the previous slide ($m_{Z'}$ = 400 GeV… here is the green curve)

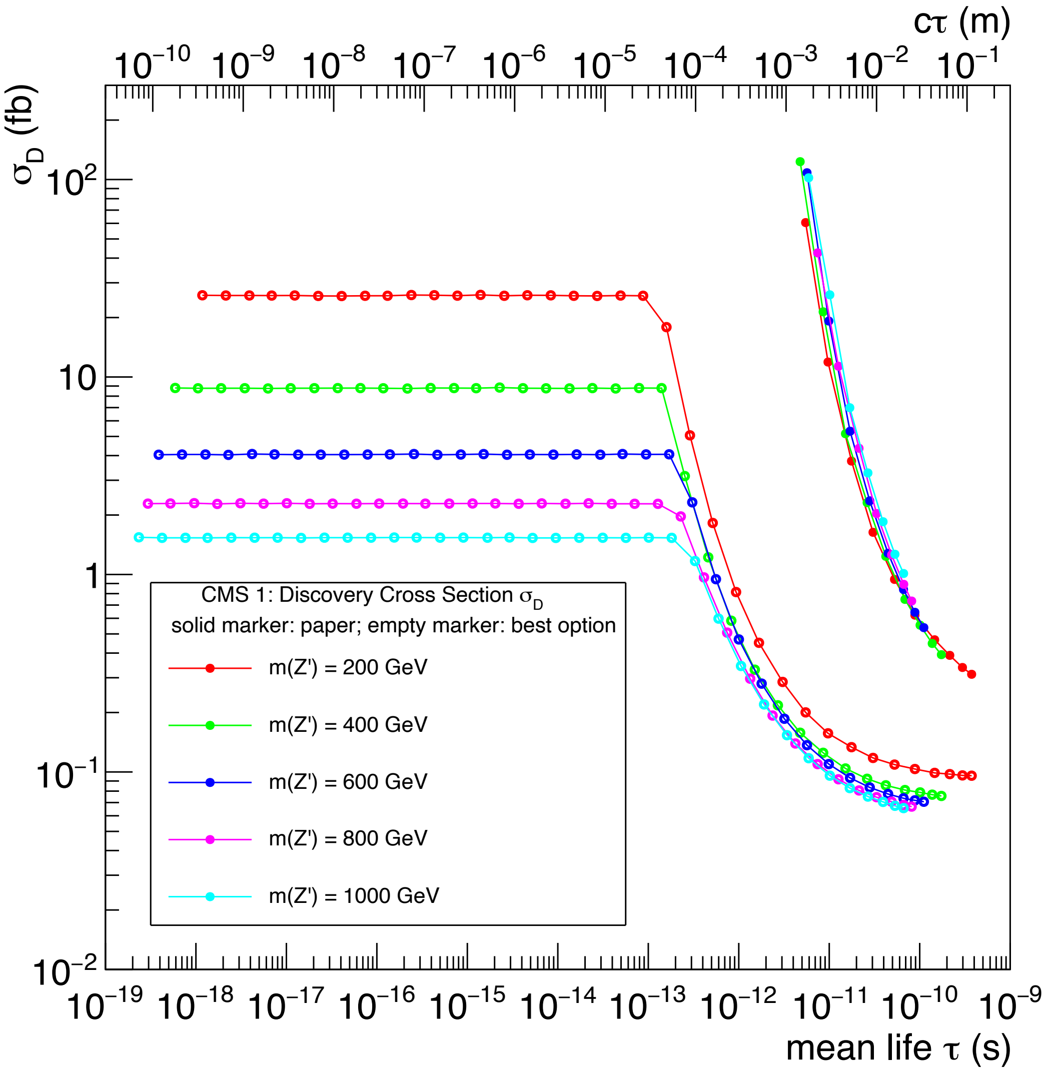




Results: Best Discovery Conditions

- Best discovery condition for all 5 mass points

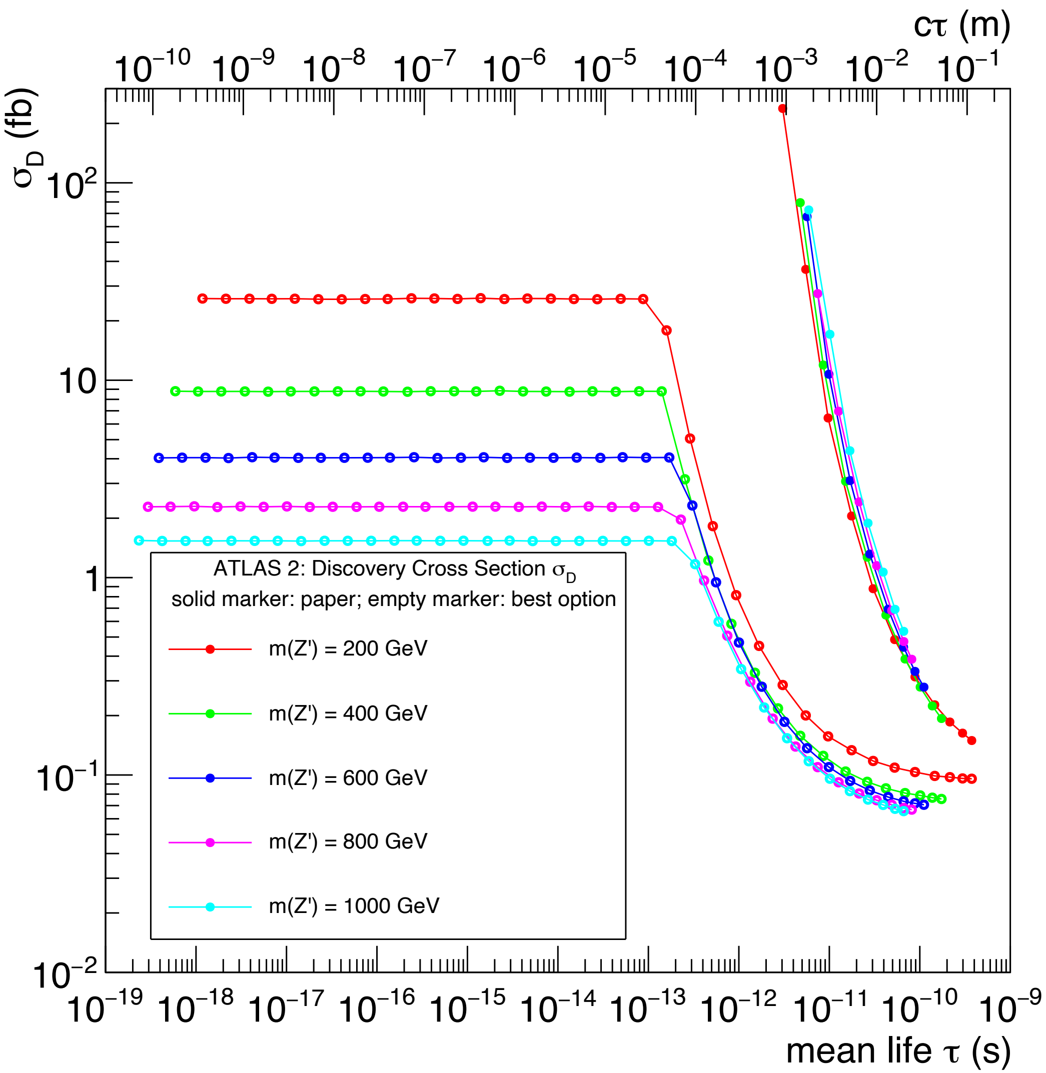
- Comparison with the σ_D using the 1st paper in the table (CMS 1) which use:
  - $|d_0|/\sigma_{d_0} > 2$
  - $L_{xy}/\sigma_{L_{xy}} > 5$



Results: Best Discovery Conditions

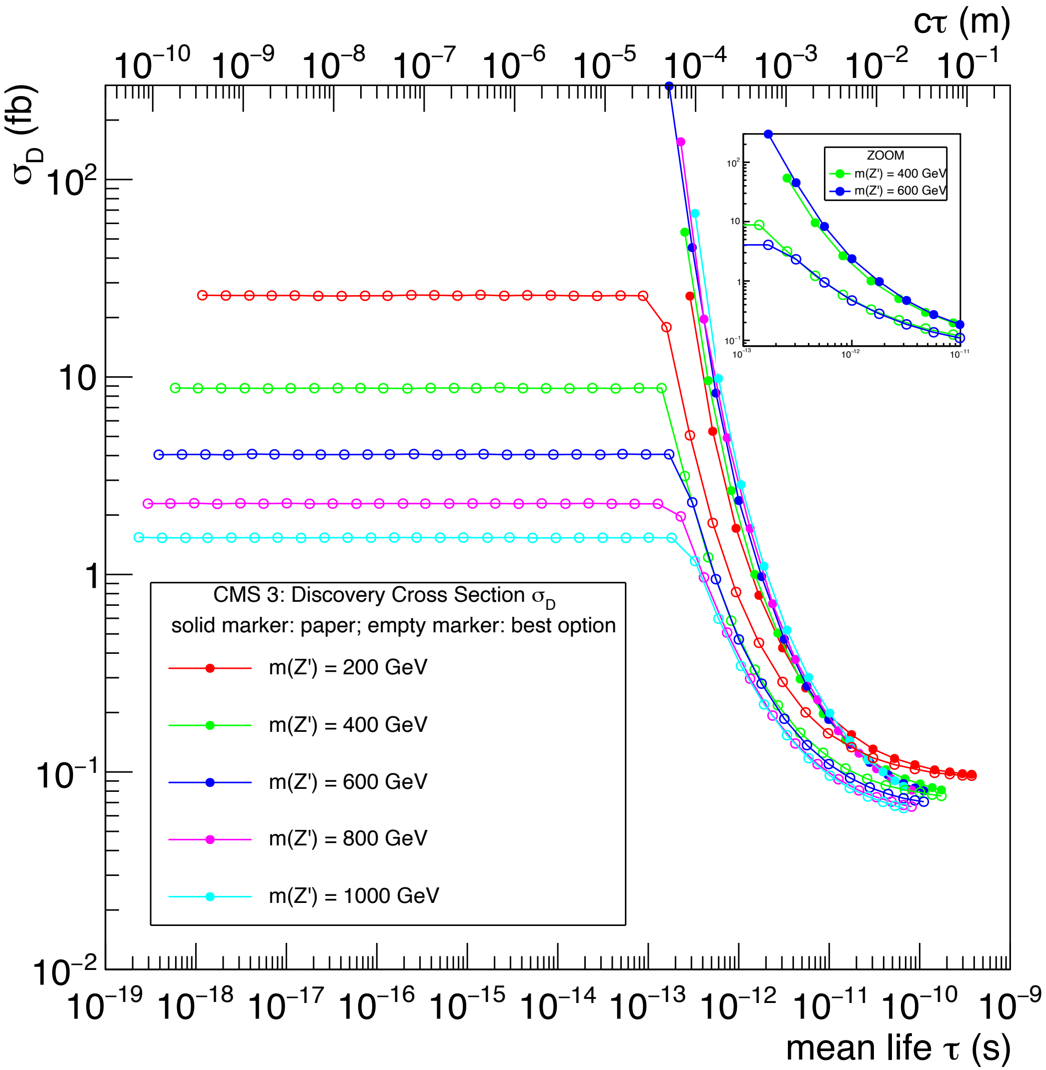
- Best discovery condition for all 5 mass points

- Comparison with the σ_D using the 4th paper (ATLAS 2) in the table which use:
  - $|d_0| > 2$ mm
  - $d_{xy} > 2$ mm



Results: Best Discovery Conditions

- Best discovery condition for all 5 mass points
- Comparison with the σ_D using the 6th paper (CMS 3) in the table which use:
  - $|d_0| > 0.1$ mm
- In principle this choice looks like the best one among the 9 papers analyzed



Result

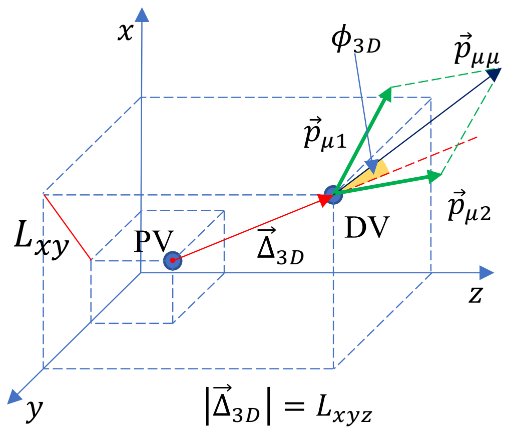
- This approach imply the perfect knowledge of the SM background distribution
- It's an ideal situation…
- But we know that all these variables are not well modelled by our simulation, and we can't rely on MC events to extract the SM background
- The only reasonable approach is to rely on DATA only
- And we have to deal with a lot of systematics effects…

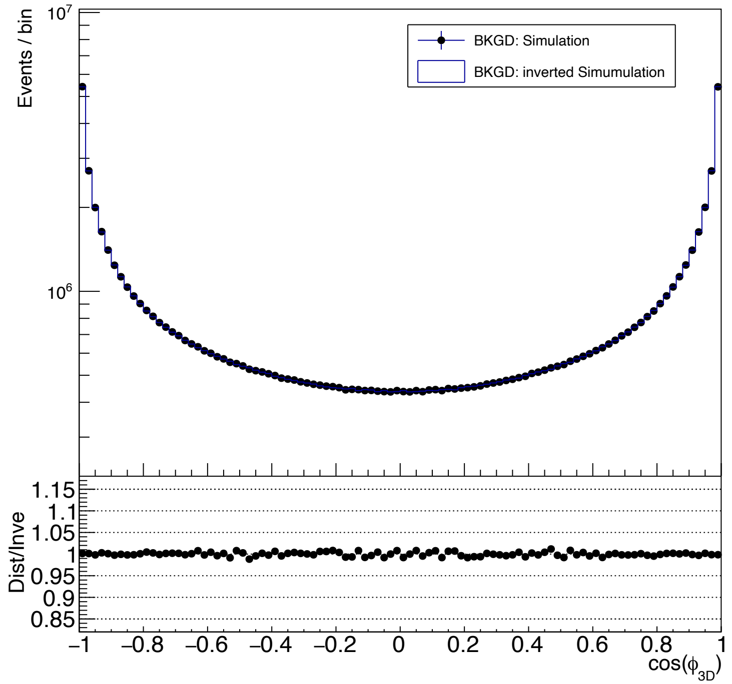
A new approach for Displaced Vertices

- Both ATLAS and CMS focused on improving DV searches far from the PV (trying to cover distances up to few meters)
- PROs:
  - no SM backgrounds… a few events could mean a discovery!
- CONs:
  - Tracking efficiency drops far from the PV
  - New specific Trigger needed
- But what about DVs nearby PV (order up to few mm)?
- PROs:
  - No Trigger or Tracking efficiency problems
  - All tools and algos developed for standard physics could be used
  - No ad-hoc searches published up-to-now
- CONs
  - SM background is not negligible

A new approach for Displaced Vertices

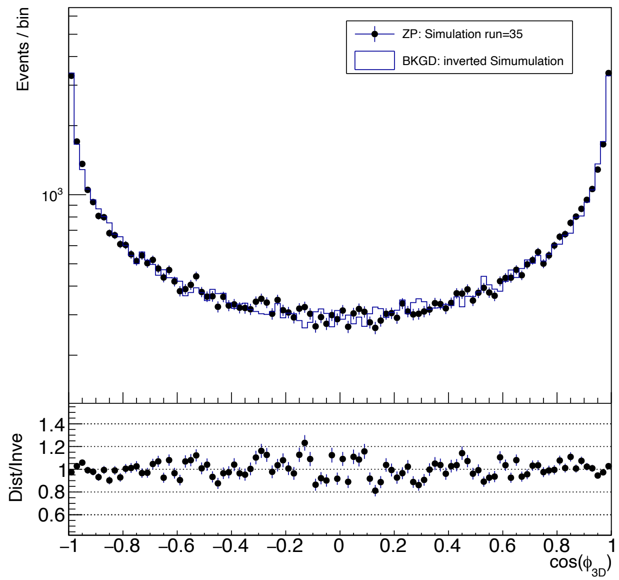
- The new proposed approach will use the ϕ_{3D} angle
- For SM events above the *b* quark mass, all vertices reconstructed from a dimuon pair will coincide with the PV
- The vectors $\vec{\Delta}_{3D}$ and $\vec{p}_{\mu\mu}$ will be largely uncorrelated and the displacement of the DV wrt the PV will be due only to detectors effect
- The distribution of the variable $\cos\phi_{3D}$ will be symmetrical around 0
- The plot shows the $\cos\phi_{3D}$ and the inverted distribution (each bin is swapped with the symmetric bin around $\cos\phi_{3D}$=0) for SM events. The ratio equal to 1 means the distribution is fully symmetric.

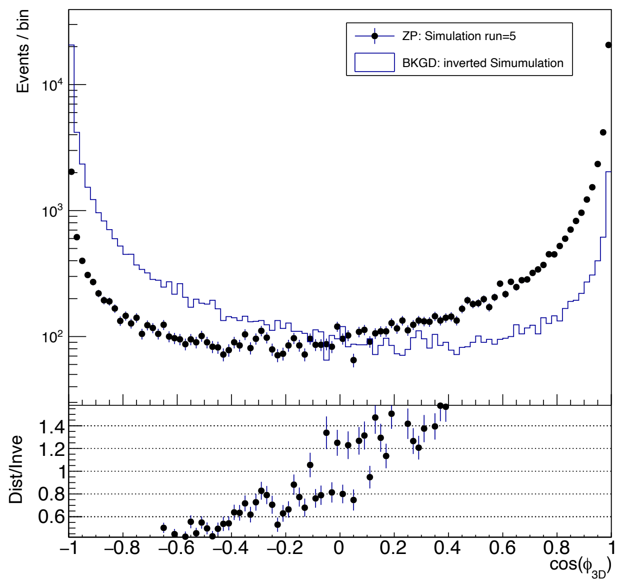




A new approach for Displaced Vertices

- For any particle produced at the PV that decays in a muon pair and the DV is far from the PV, the cos ϕ_{3D} distribution will be completely different
- In an ideal 2 body-decay, the direction of the $\vec{\Delta}_{3D}$ and $\vec{p}_{\mu\mu}$ will be identical, ϕ_{3D}= 0 and cos ϕ_{3D} = 1
- The top figure show a Z' with $\langle\tau\rangle = 4.2 \cdot 10^{-27}$ s and $c\langle\tau\rangle = 1.3 \cdot 10^{-18}$ m. The dimuon vertex coincide with the PV and the situation is identical to SM particles
- The bottom figure show a Z' with $\langle\tau\rangle = 2.6 \cdot 10^{-13}$ s and $c\langle\tau\rangle = 78\ \mu$m. The distribution now is strongly peaked at 1 and the symmetry is lost.

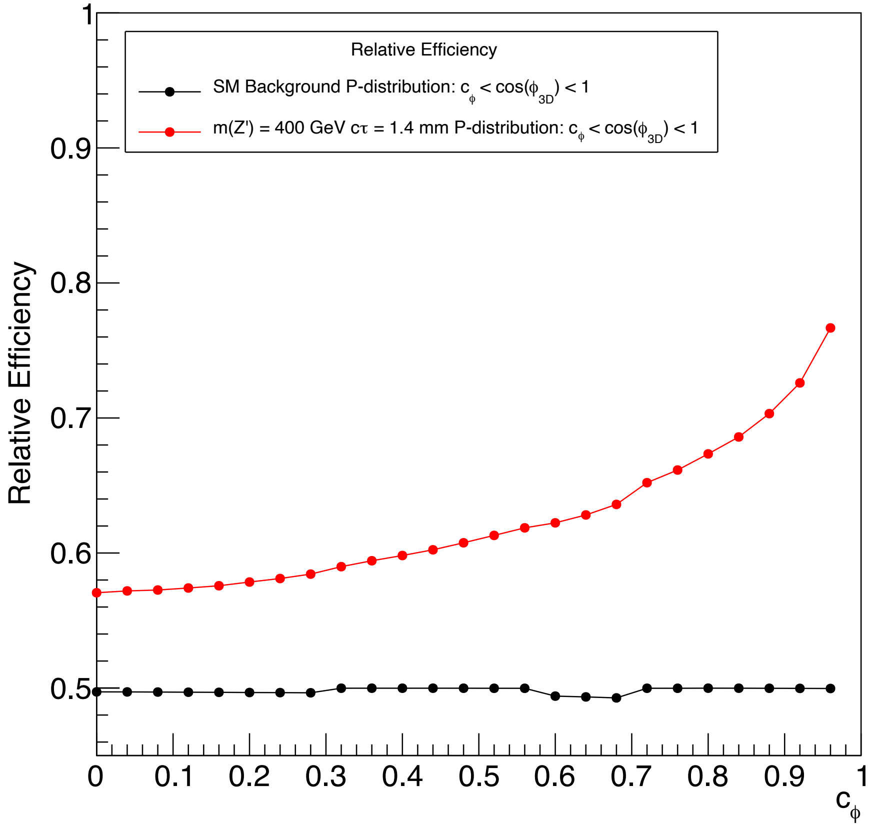




A new approach for Displaced Vertices

- The dimuon invariant mass distribution could be therefore divided in 2 different distributions (**P**lus and **M**inus distributions):
  - The P-distribution $c_\phi < \cos\phi_{3D} < 1$
  - The M-distribution $-1 < \cos\phi_{3D} < -c_\phi$
- Where c_ϕ is any value in the range $c_\phi \in [0,1]$
- For SM events the 2 distributions will be identical (within statistical fluctuations)
- For a BSM resonance which decay to a muon pair far from the PV, most of the events will populate the P-distribution
- Example: a 400 GeV Z' with a $c\langle\tau\rangle$ = 1.4 mm and using $c_\phi = 0.90$ will populate the P-distribution with 72% of the events (only 28% will populate the M-distribution)

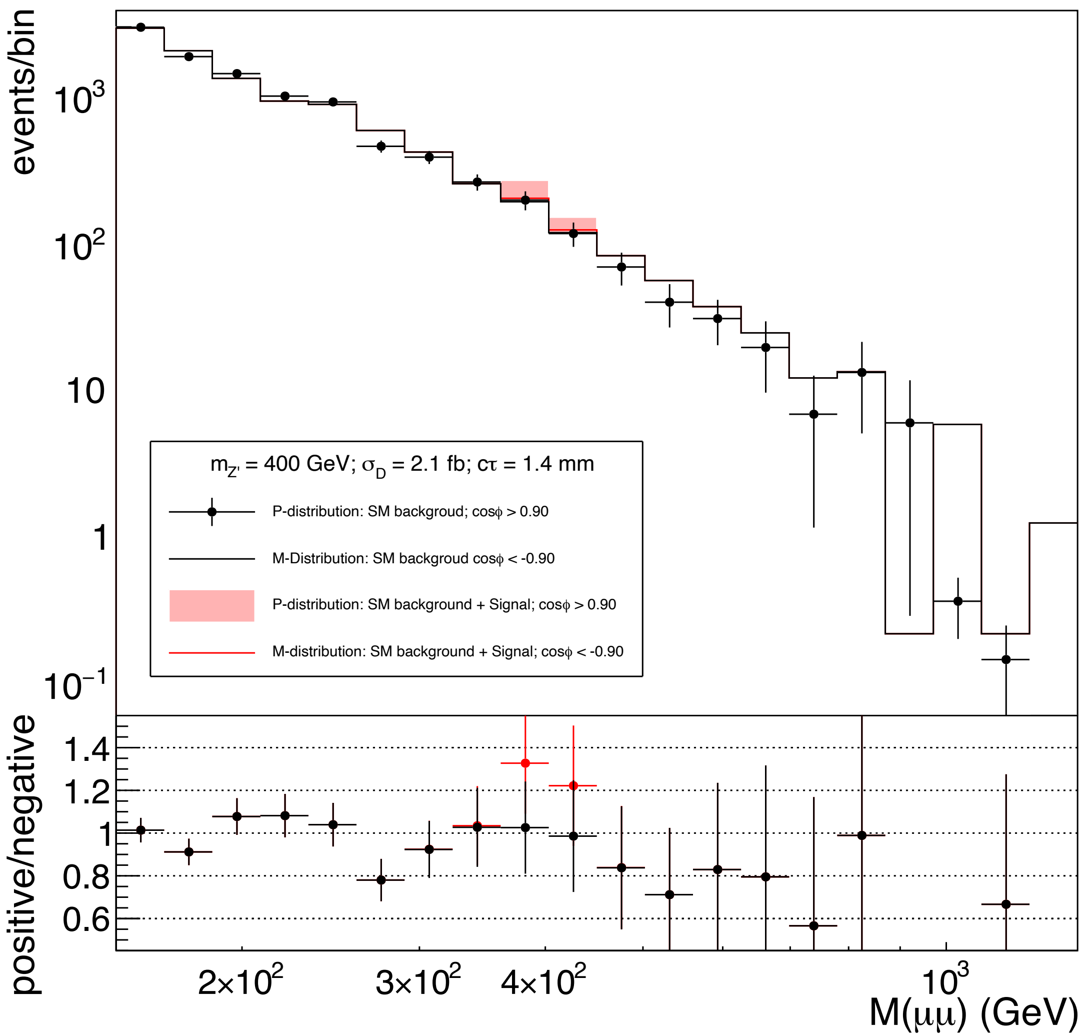
Example: a 400 GeV Z'



A new approach for Displaced Vertices

- Dimuon mass distribution for SM and Z' events
- Cuts:
  - o $c_\phi = 0.90$
  - o $|d_0|/\sigma_{d_0} > 1$
- Black is SM (P- and M- distributions superimposed)
- RED is the Z', $c\langle\tau\rangle$ = 1.4 mm added on top of the SM
- $\sigma_D = 2.1$ fb
- Assuming a gaussian signal and using a profile likelihood ratio as a statistical test the local significance is 5.12

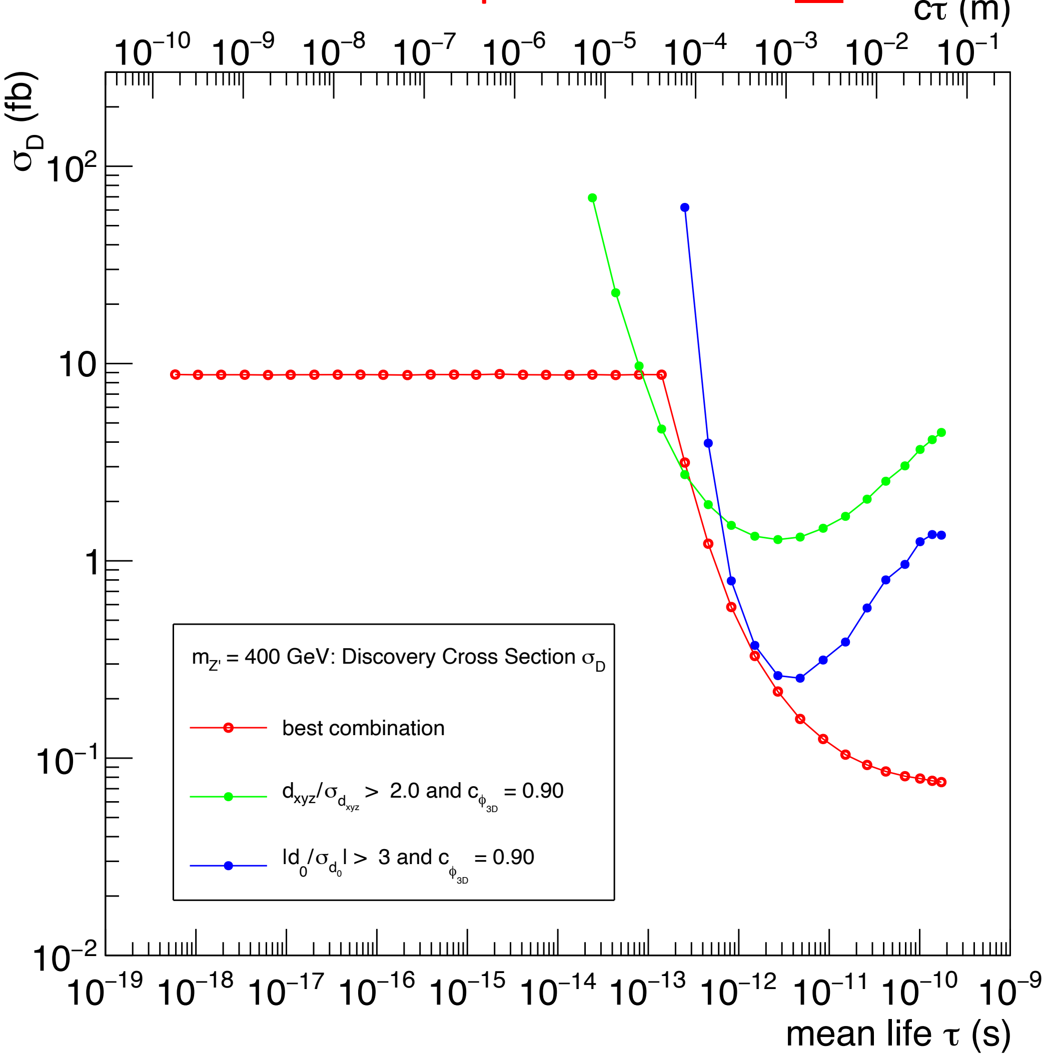
Example: a 400 GeV Z'



A new approach for Displaced Vertices

- Same full study performed on standard dimuon invariant mass distribution
- Same 6 variables, same cut values plus 6 different c_ϕ values in the range [0,0.98]
- Same procedure to extract the discovery cross section σ_D
- Full scan for all possible combinations to extract the best combination (cut type/cut value) for different BSM masses and lifetimes.
- Example: in the range up to 1 mm the P/M approach is comparable to the ideal one

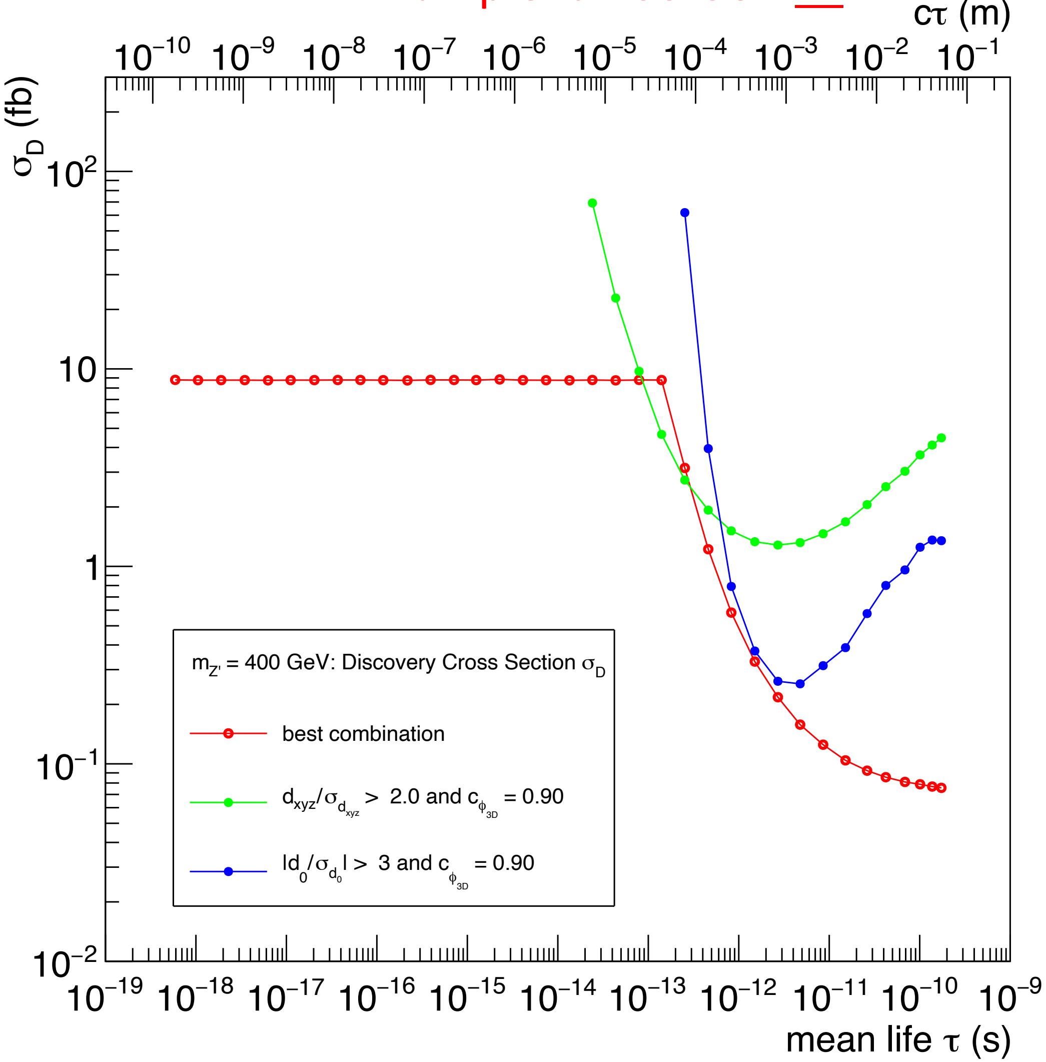
Example: a 400 GeV $\underline{Z'}$



A new approach for Displaced Vertices

- PROs
- P- and M-distributions directly from DATA and no MC needed to search DVs
- Almost all systematic effects cancel out because both P- and M- distributions will be affected at the same level
  - Alignment could produce an overall difference in the P-/M-distributions and it's the only major systematic effect which has to be studied carefully
- CONs
- …
- ???

Example: a 400 GeV Z'



Conclusions

- Searches of LLPs are widely used at LHC experiments for BSM particles discovery.
- A careful study is needed to fully exploit tracker detector potentialities for a DV within few mm from the PV
- Fast (like the one presented today) and full-simulation studies could give several hints on how to optimize these searches…
- However, also full simulation for the variables typically used for such searches are far from being perfect and a robust search will have to be based on data only
- A new approach fully based on data has been proposed which allows reducing at a minimum the systematic uncertainties while keeping at best the capability to detect a BSM resonance which decays nearby the PV.
- This new approach, presented today for a dimuon displaced vertex, could be used for any process where a displaced vertex could be measured.

BackUp

Reference of the 9 papers on displaced muon searches

[7] CMS Search in Leptonic Channels for Heavy Resonances Decaying to Long-Lived Neutral Particles [arXiv:1211.2472]

[8] CMS Search for long-lived particles that decay into final states containing two electrons or two muons in proton-proton collisions at $\sqrt{s} =$ 8 TeV [arXiv:1411.6977]

[9] ATLAS Search for long-lived particles in final states with displaced dimuon vertices in pp collisions at $\sqrt{s}=$ 13 TeV with the ATLAS detector [arXiv:1808.03057]

[10] ATLAS Search for displaced vertices of oppositely charged leptons from decays of long-lived particles in pp collisions at $\sqrt {s}$ =13 TeV with the ATLAS detector [arXiv:1907.10037]

[11] ATLAS Search for long-lived, massive particles in events with a displaced vertex and a muon with large impact parameter in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector [arXiv:2003.11956]

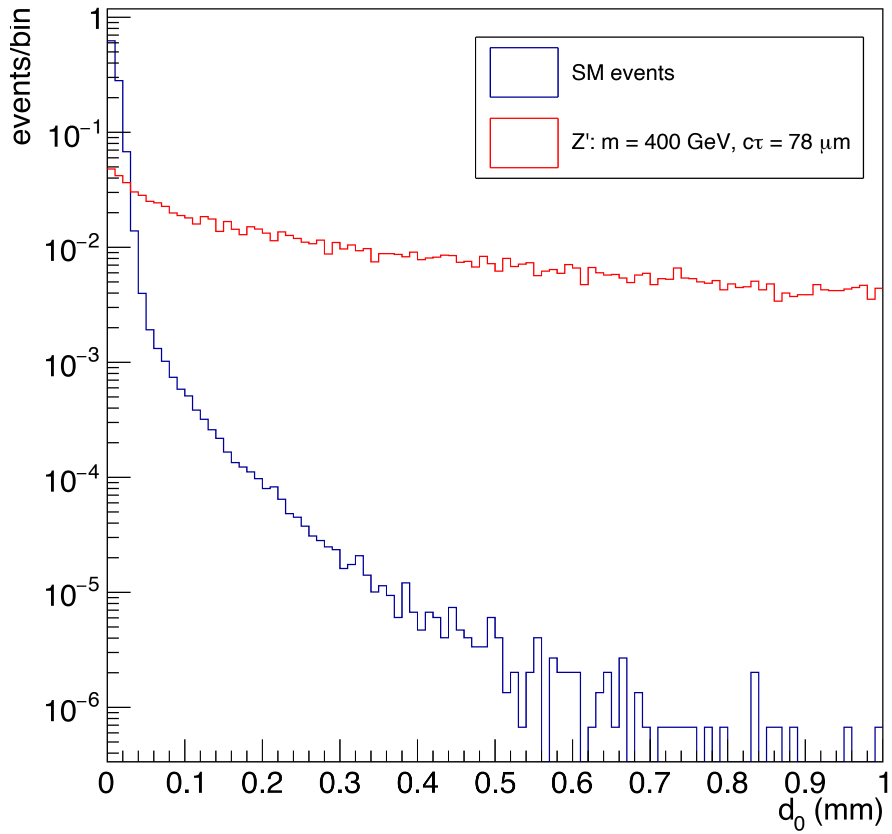
[12] CMS Search for long-lived particles decaying to leptons with large impact parameter in proton-proton collisions at $\sqrt{s}$ = 13 TeV [arXiv:2110.04809]

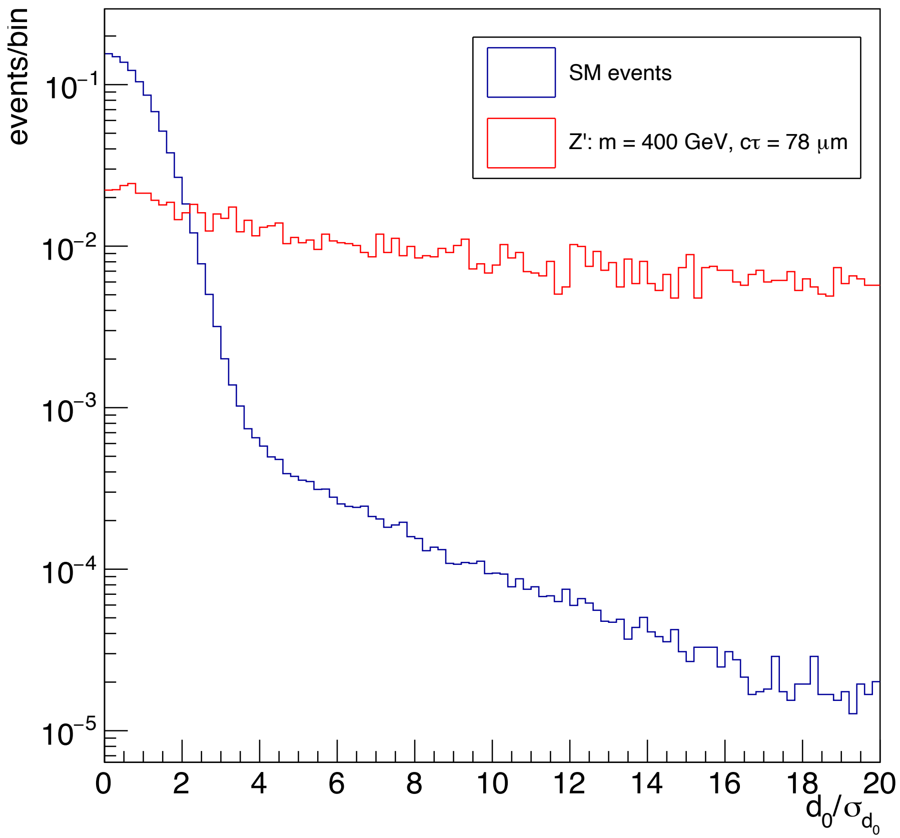
[13] CMS Search for long-lived particles decaying into muon pairs in proton-proton collisions at $ \sqrt{s} $ = 13 TeV collected with a dedicated high-rate data stream [arXiv:2112.13769]

[14] CMS Search for long-lived particles decaying to a pair of muons in proton-proton collisions at $ \sqrt{s} $ = 13 TeV [arXiv:2205.08582]

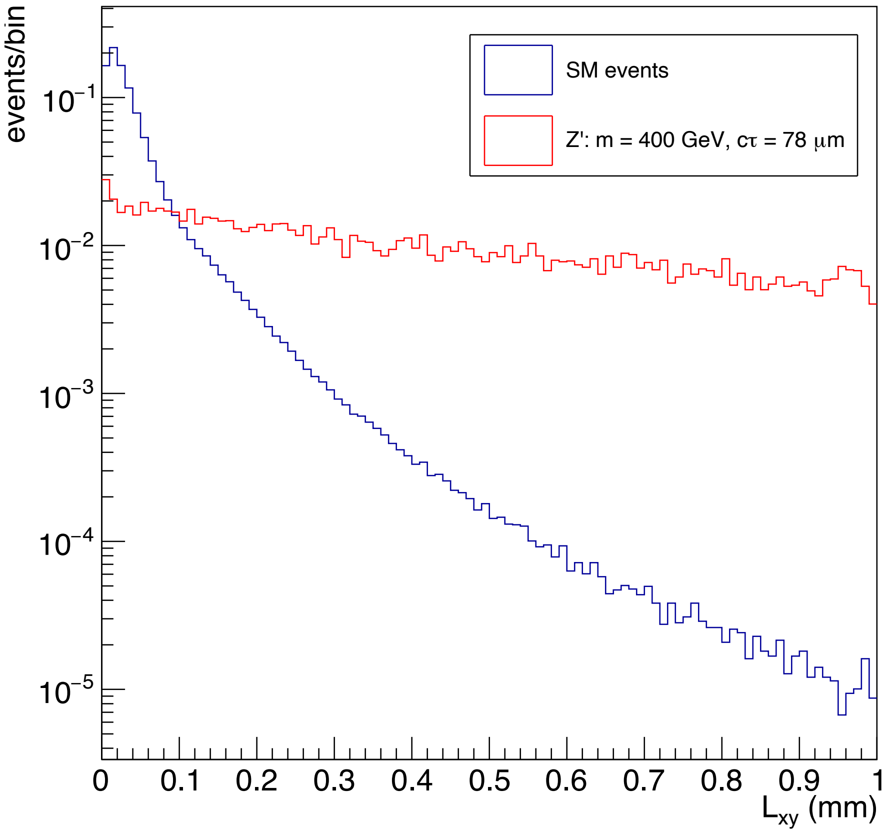
[15] ATLAS Search for heavy neutral leptons in decays of W bosons produced in 13 TeV pp collisions using prompt and displaced signatures with the ATLAS detector [arXiv: 2305.02005]

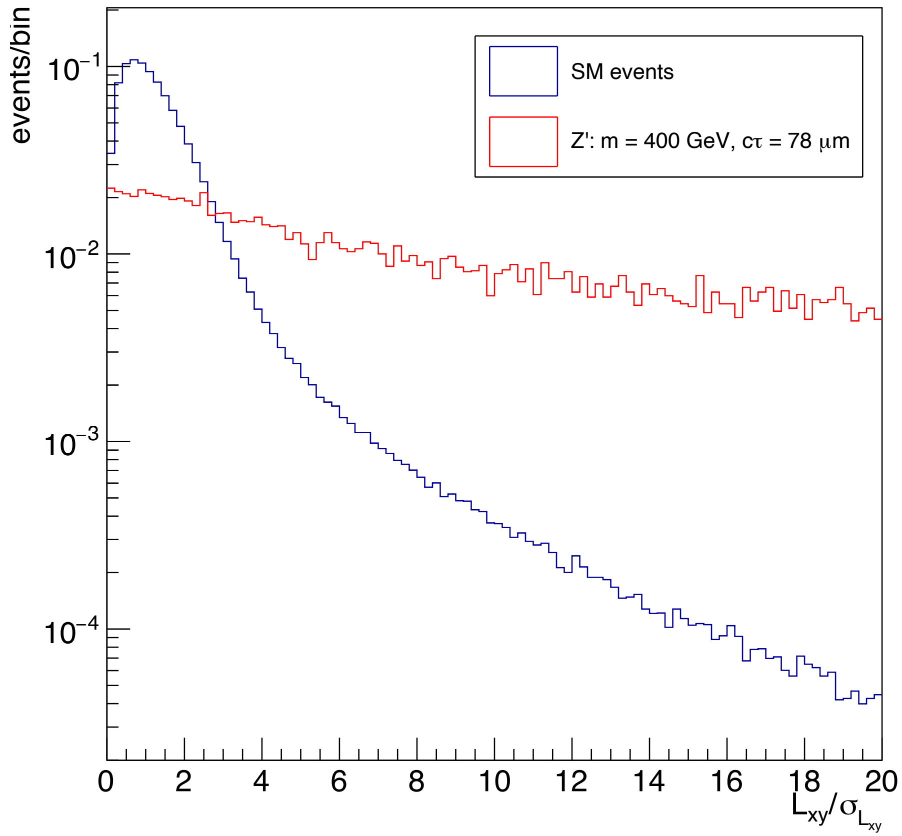
d_0 and d_0/σ_{d_0} Distribution





L_{xy} and $L_{xy}/\sigma_{L_{xy}}$ Distribution





L_{xyz} and $L_{xyz}/\sigma_{L_{xyz}}$ Distribution