Time-delayed leptons from dark photon in extension Stueckelberg model

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ICISE QUY NHON VIETNAM

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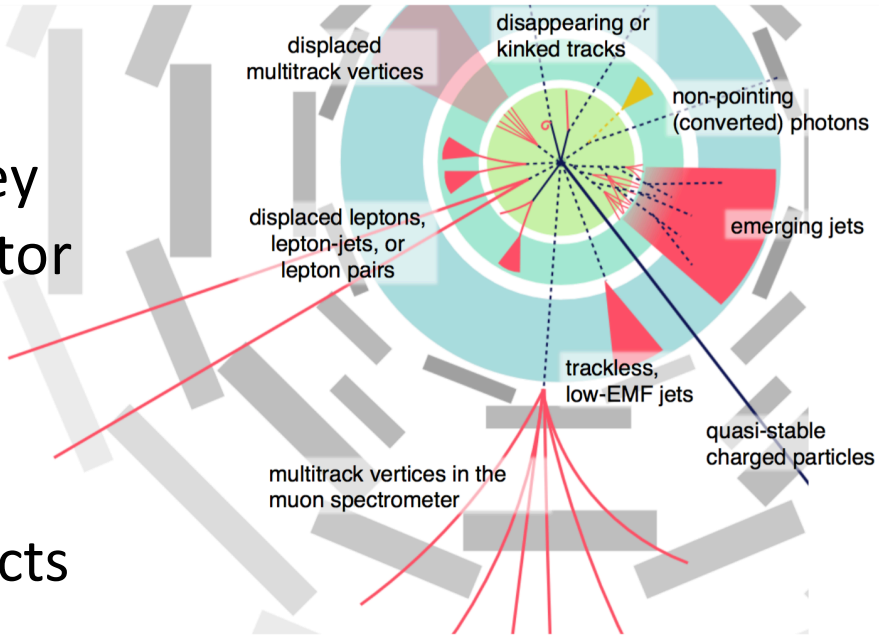
New Physics with Exotic and Long-Lived Particles: A Joint ICISE-CBPF Workshop

LLPs motivation

- LHC is working hard to search for new particles in BSM
- So far, no evidence of new particles is detected.

➢ If new particles are weakly interacting to SM particles or quasi-stable and travelling far away from primary vertex, they may escape the current detector triggers.

➢ Experimental signatures:
  - Displaced objects
  - Non-pointing/kinked objects
  - Heavy Stable Charged Particles
  - Delayed objects

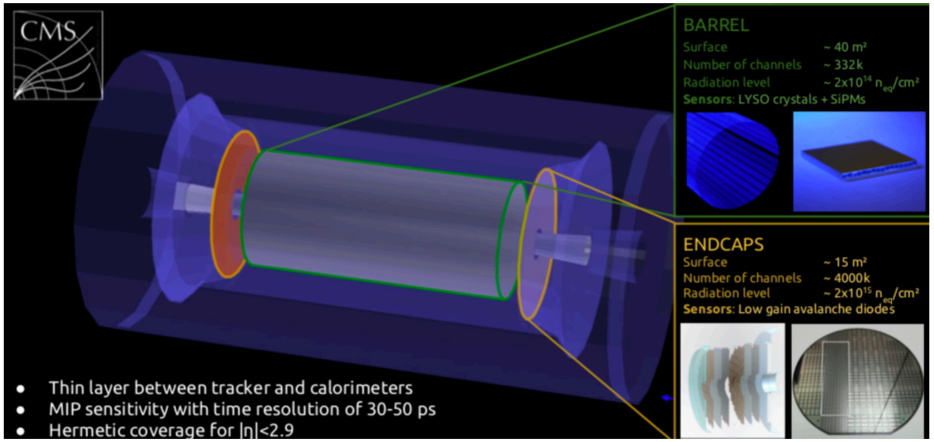


Heather Russell

Timing detector at CMS phase 2 upgrade (CMS MTD)

See Juliette's talk for more.

- A timing detector is proposed to install in front of ECAL, 1.2 m from beam line.
- Resolution: **30 ps**,
- $p_T > \mathbf{0.7}\ \boldsymbol{GeV}$ (Barrel)
- and $p > \mathbf{0.7}\ \boldsymbol{GeV}$ (Endcaps)



CMS technical proposal:
https://cds.cern.ch/record/2296612

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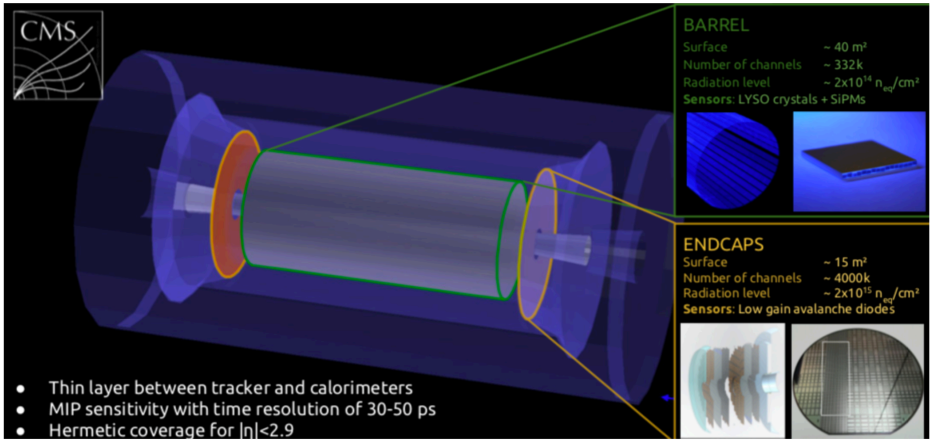

- Using time information to reconstruct 4D vertex.
- **Purpose: reducing pileup** at HL-LHC

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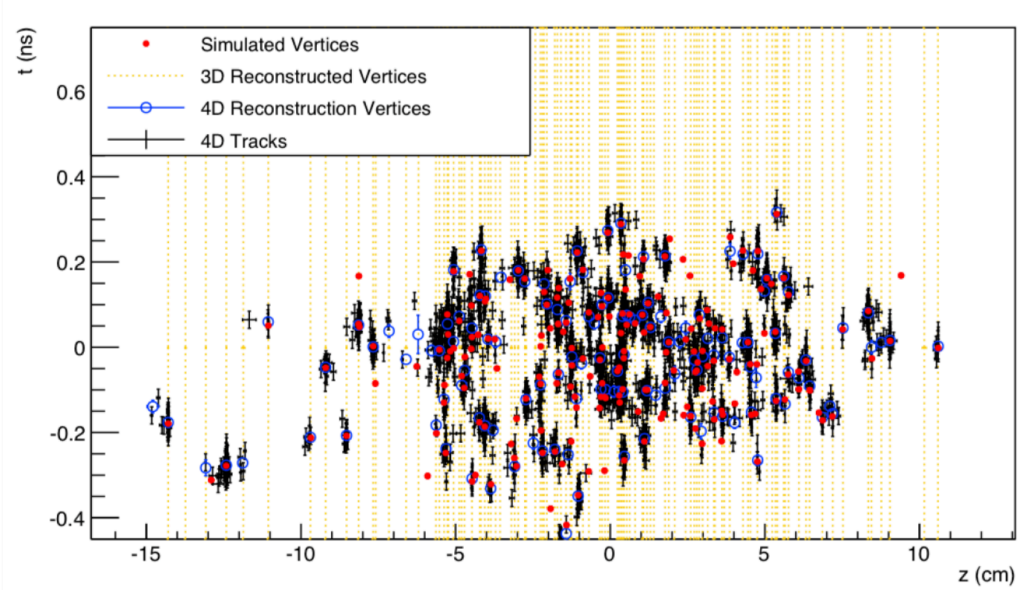


A possible LLP signal using timing

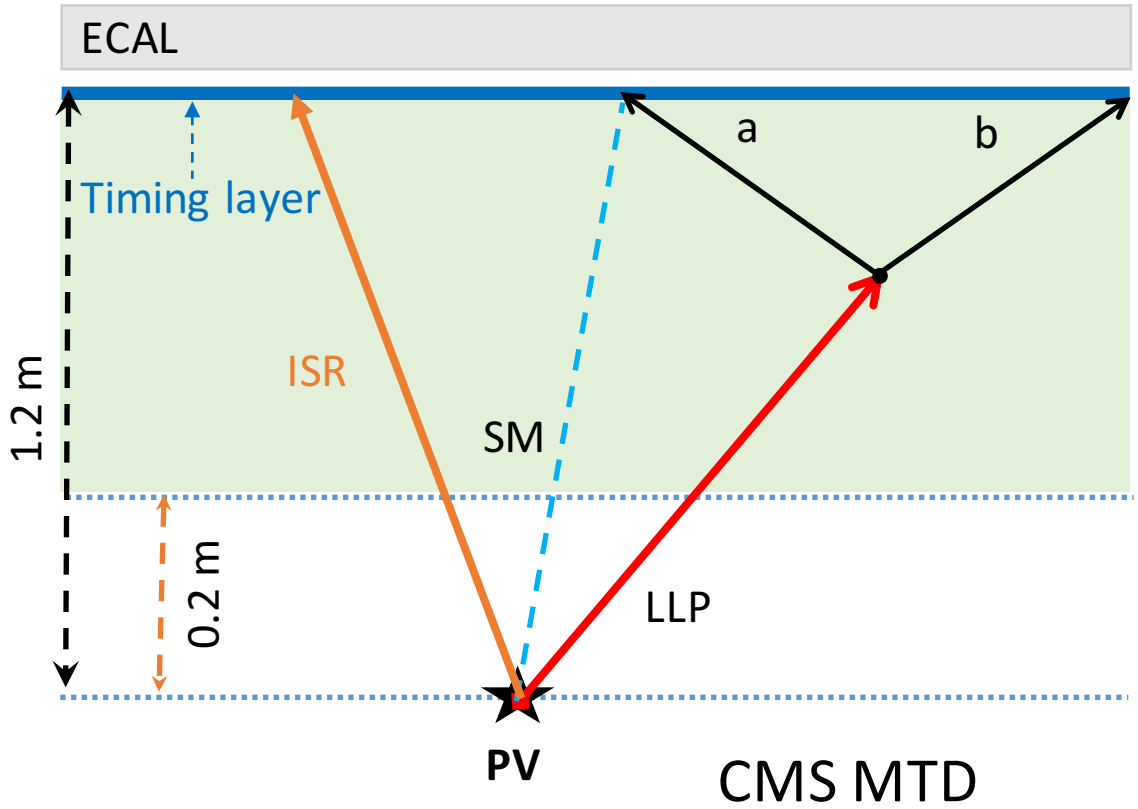
Estimation delayed time:

$$LLP \rightarrow a + b$$

$$\Delta t = \boxed{\frac{l_{LLP}}{\beta_{LLP}} + \frac{l_a}{\beta_a}} - \boxed{\frac{l_{SM}}{\beta_{SM}}}$$

Signal arrival time

SM bkg ref time



J.Liu, Z.Liu, L.T Wang PRL 122 (2019)

J.D Mason arXiv:1905.07772

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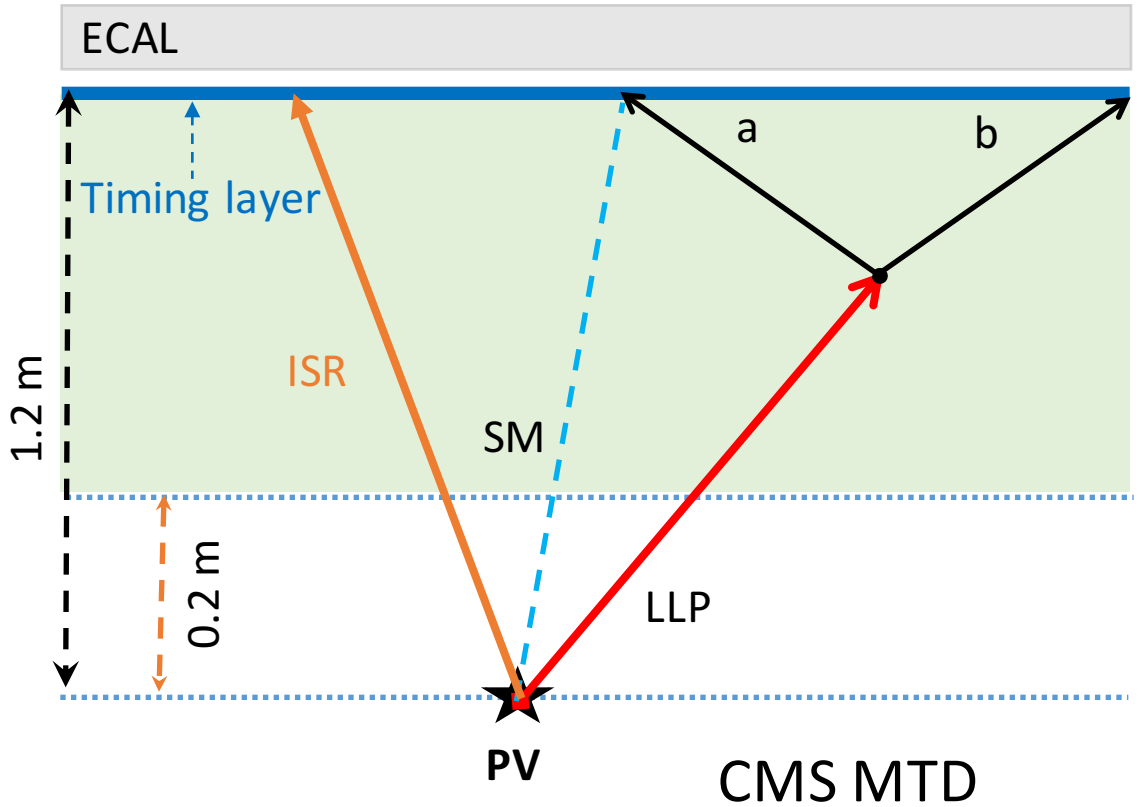

Lower bound for delayed time signal:

$$\boxed{\Delta t \geq l_{LLP}(\beta_{LLP}^{-1} - 1)}$$

J.Liu, Z.Liu, L.T Wang PRL 122 (2019)

J.D Mason arXiv:1905.07772

Example: $h \rightarrow LLP + LLP$ with $m_{LLP} = 50\ GeV$

Result in $\Delta t \approx 3.2\ ns$

The extension Stueckelberg Model

- In general, one can extend minimal Stueckelberg model by adding N number of abelian gauge $U(1)_X$

$$\mathcal{L}_{\text{extSt}} = \left(-\frac{1}{4}B_{\mu\nu}B^{\mu\nu} + g_Y B_\mu J_Y^\mu\right) + \sum_{i=1}^{N_V}\left(-\frac{1}{4}C_{\mu\nu i}C_i^{\mu\nu} + g_i C_{\mu i} J_i^\mu\right)$$
$$-\frac{1}{2}\sum_{j=1}^{N_S}\left(\partial_\mu\sigma_j + m_{0j}B_\mu + \sum_{i=1}^{N_V} m_{ij}C_{\mu i}\right)^2 .$$

- N_V is number of abelian gauge field
- N_S is number of axion

B. Kors and P. Nath 2005
D. Feldman, Z. Liu, P. Nath, B.D. Nelson 2009

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- The minimal Stueckelberg model can be realized when $N_V = 1$, $N_S = 1$.

$$\mathcal{L}_{\rm St} = \left(-\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}C_{\mu\nu 1}C_1^{\mu\nu} + g_Y B_\mu J_Y^\mu + g_{\chi_1} C_{\mu 1} J_\chi^\mu\right) - \frac{1}{2}\left(\partial_\mu\sigma_1 + m_{01}B_\mu + m_{11}C_{\mu 1}\right)^2$$

D. Feldman, Z. Liu, P. Nath, B.D. Nelson 2009
E. C. G. Stueckelberg 1938
V. I. Ogievetskii & I. V. Polubarinov 1962

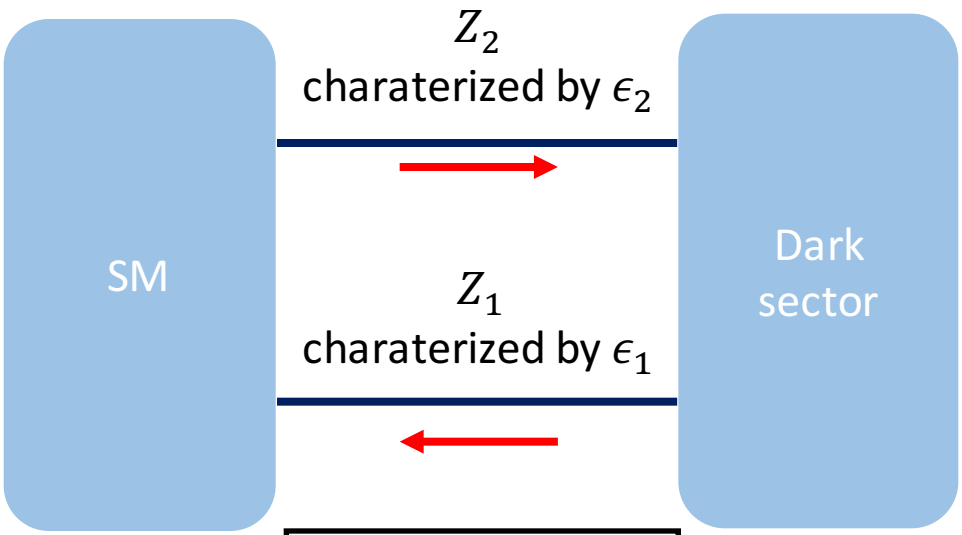
The extension Stueckelberg Model

- The next minimal model is $N_V = 2$ and $N_S = 2$

$$\mathcal{L}_{\rm St} = -\frac{1}{4}\left(B_{\mu\nu}B^{\mu\nu} + C_{\mu\nu 1}C_1^{\mu\nu} + C_{\mu\nu 2}C_2^{\mu\nu}\right) + g_Y B_\mu J_Y^\mu + g_{\chi_1} C_{\mu 1} J_\chi^\mu + g_{\chi_2} C_{\mu 2} J_\chi^\mu$$
$$-\frac{1}{2}\left(\partial_\mu \sigma_1 + \underline{m_{01}} B_\mu + m_1 C_{\mu 1}\right)^2 - \frac{1}{2}\left(\partial_\mu \sigma_2 + \underline{m_{02}} B_\mu + m_2 C_{\mu 2}\right)^2 .$$

$\epsilon_1 m_1$ $\epsilon_2 m_2$

- Where $J_\chi^\mu = \bar{\chi}\gamma^\mu\chi$
- χ is fermionic dark mater
- Z_1 has feeble coupling to SM particles and could be a LLP



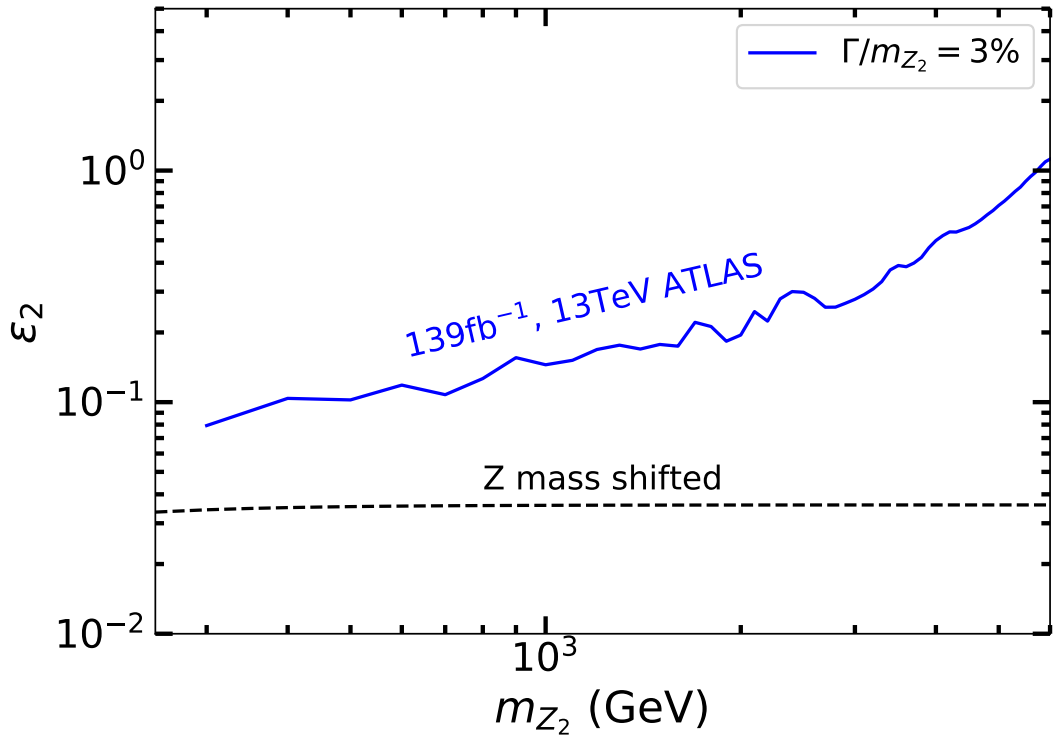
$m_{Z_2} \gg m_{Z_1}$
$\epsilon_2 \gg \epsilon_1$

Current constraints

- We obtain the upper limit on ϵ_2 from Z mass shifted

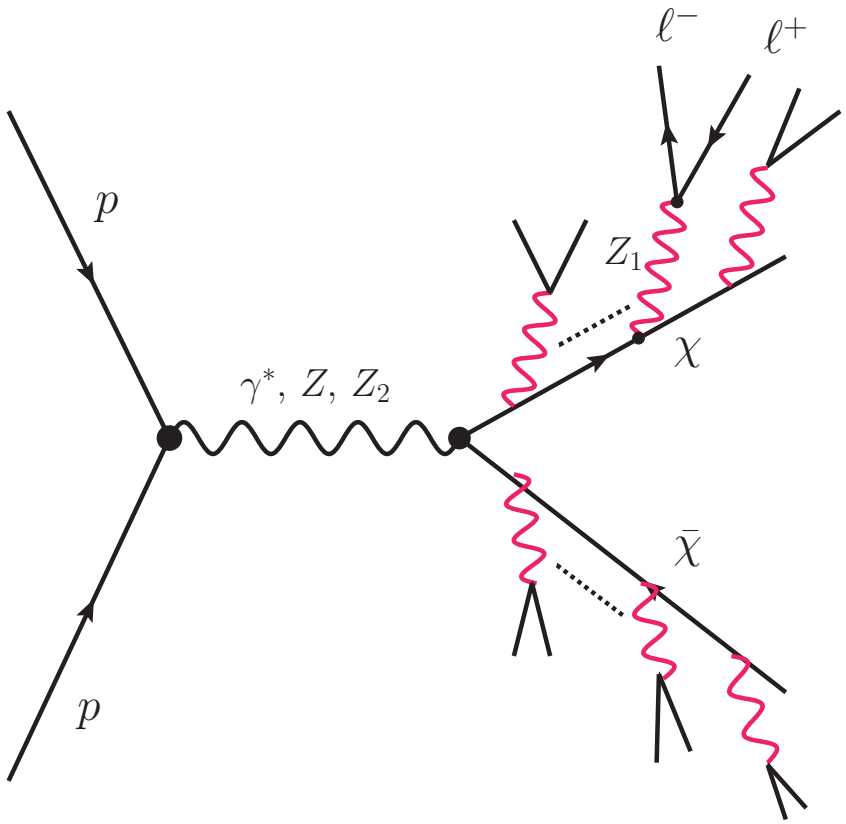
$$|\epsilon_2| \lesssim 0.036\sqrt{1-(M_Z/m_2)^2}$$

- Constraint from di-lepton search at ATLAS is weaker than Z mass shifted

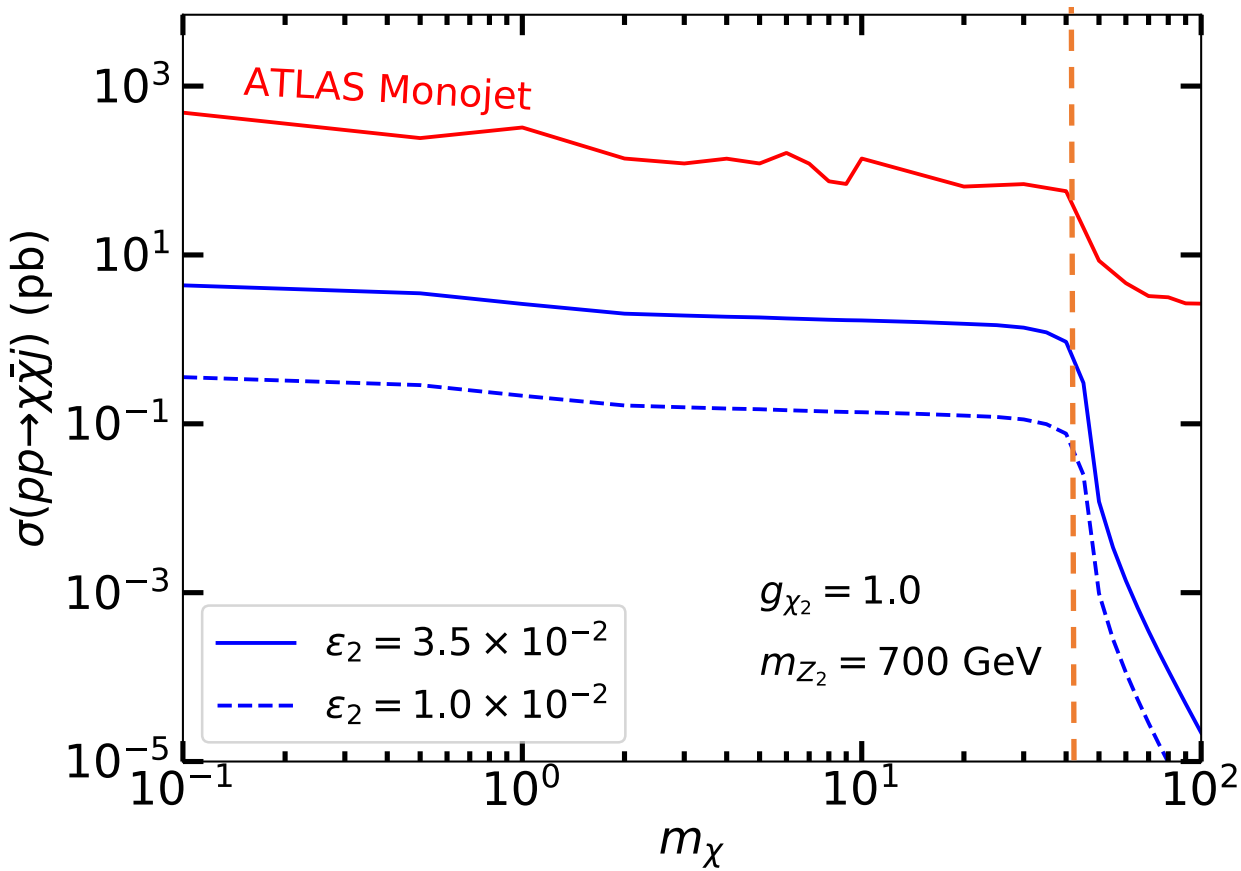


Time-delayed leptons from Dark Photon

- The production of Dark matters is proportional to ϵ_2^2.
- Dark matter radiated off Dark Photon.
- Dark photon decays into SM leptons or jets which may arrive timing detector late.

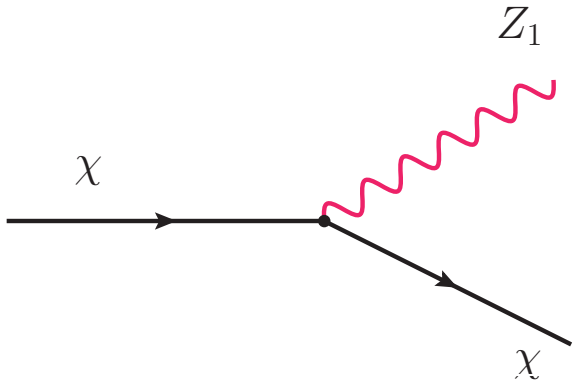


Production of DM at LHC



- Z boson exchange is dominant channel when $m_\chi < 2\, m_Z$.
- $\sigma(pp \to \chi\bar{\chi}\, j\,) \sim \mathrm{O}(\mathbf{100\ fb})$ at LHC 13 TeV

Dark Radiation

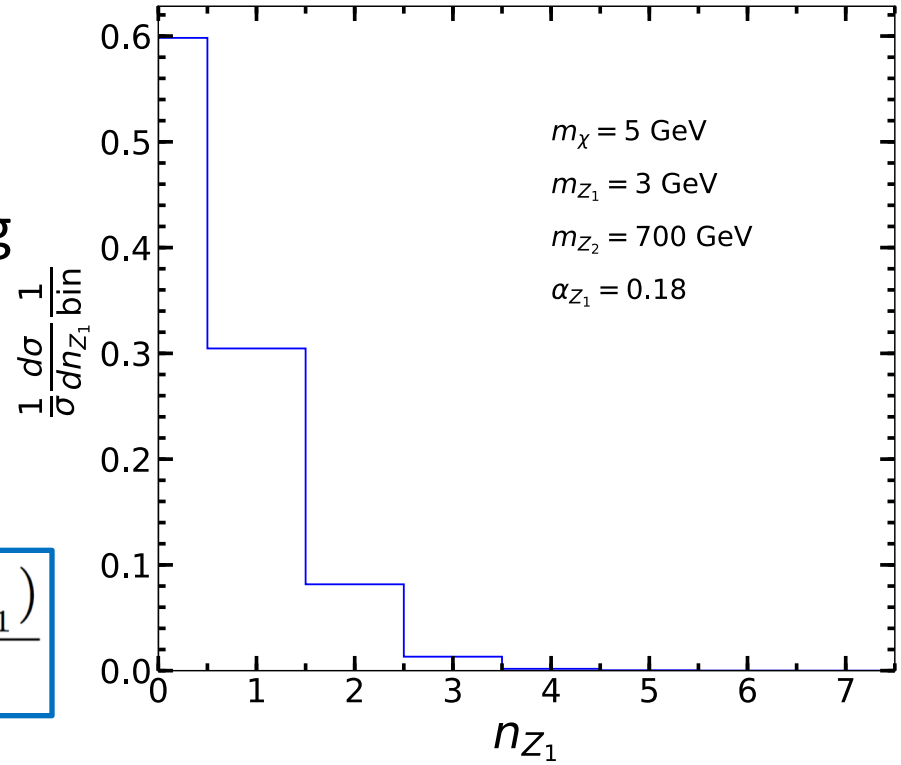


The differential probability for a collinear splitting:

$$\frac{\alpha_{Z_1}}{2\pi} dz \frac{dt}{t} P_{\chi\to\chi Z_1}(z,t)$$

- t = the virtuality of the incoming dark matter particle
- $z = E_{\chi_{in}}/E_{\chi_{out}}$
- The splitting function is

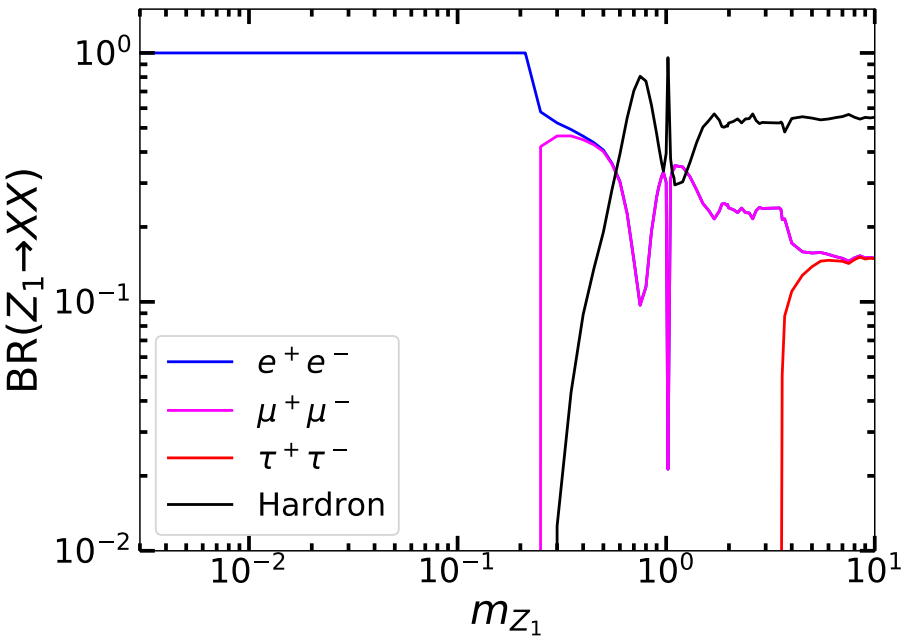
$$P_{\chi\to\chi Z_1}(z,t) = \frac{1+z^2}{1-z} - \frac{2(m_\chi^2 + m_{Z_1}^2)}{t}$$

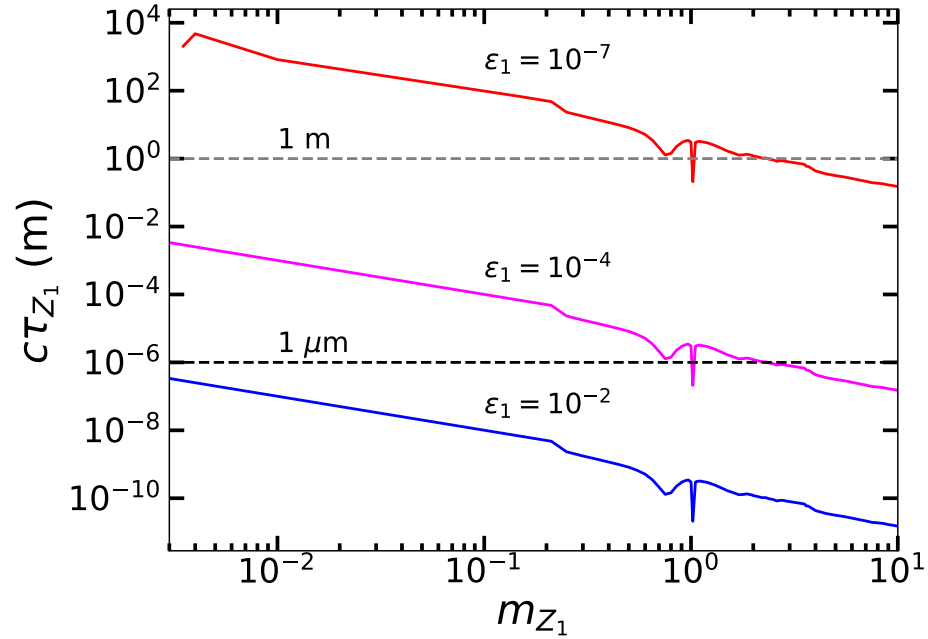


M.Buschmann, J.Kopp, J.Liu and P.A.N.Machado (2015)

M.Kim, H.S.Lee, M.Park and M.Zhang (2016)

Dark photon decay and lifetime

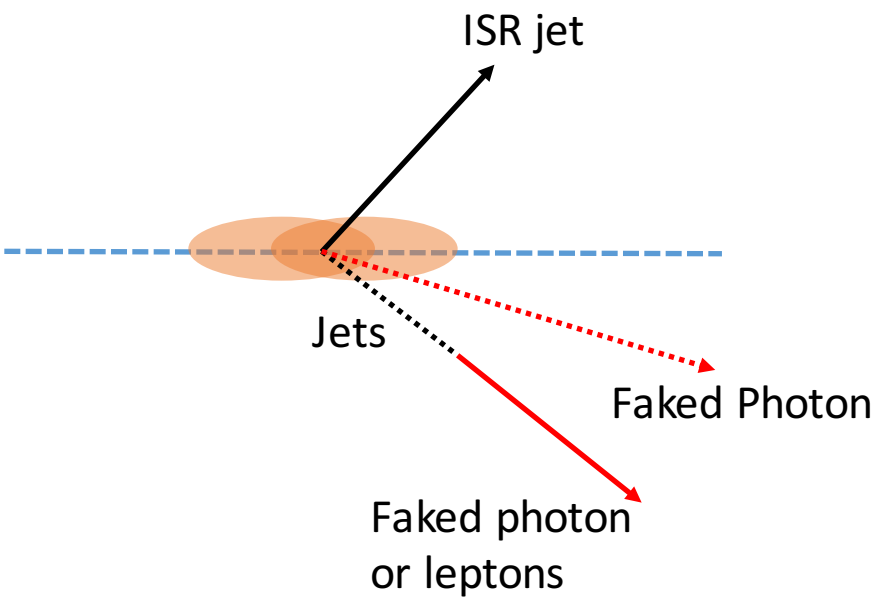




$$c\tau_{Z_1} \approx \mathcal{O}(\mathrm{m}) \times \left(\frac{10^{-7}}{\epsilon_1}\right)^2 \left(\frac{3\,\mathrm{GeV}}{m_{Z_1}}\right)$$

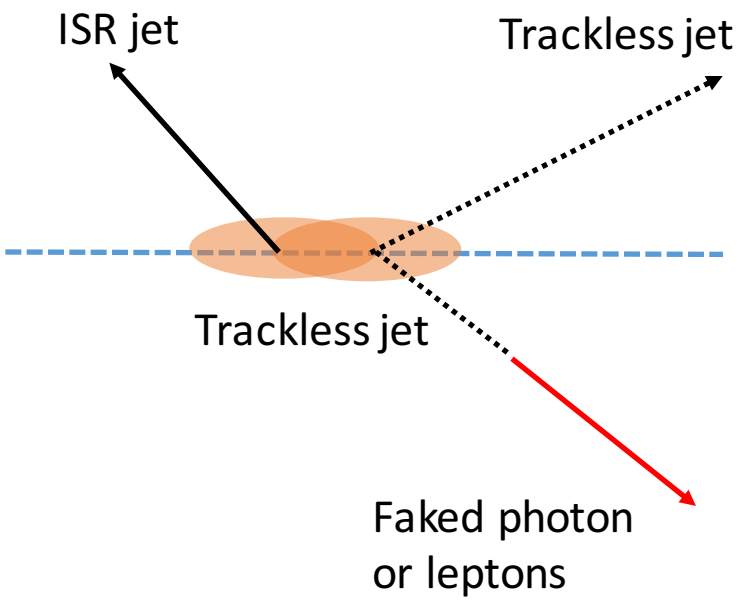
Background

Same hard interaction (SV)



- Time of arrival mis-measurement due to timing resolution: **30 ps**

Pile up (PU)



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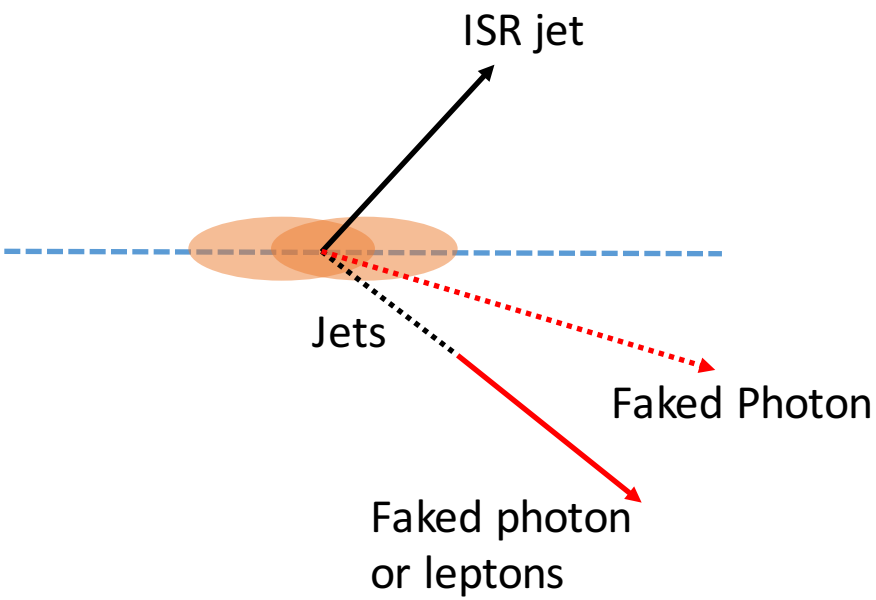

- Time of arrival mis-measurement due to timing resolution: **30 ps**
- Estimation number of this BG:

$$N_{SV} = \sigma_\gamma \mathcal{L} + \sigma_j \mathcal{L} f_\gamma \approx \mathbf{2{\times}10^{11}}$$

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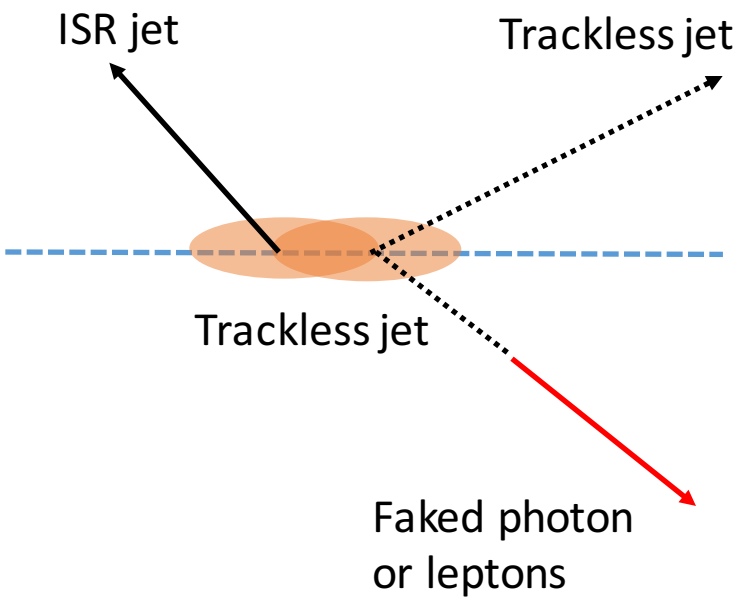

- Time of arrival mis-measurement due to the spread of the proton bunch: **190 ps**
- Estimation number of this BG:

$$N_{PU} = \sigma_j \mathcal{L} f_j f_\gamma (n_{PU} \sigma_j / \sigma_{inc}) \approx \mathbf{1{\times}10^{7}}$$

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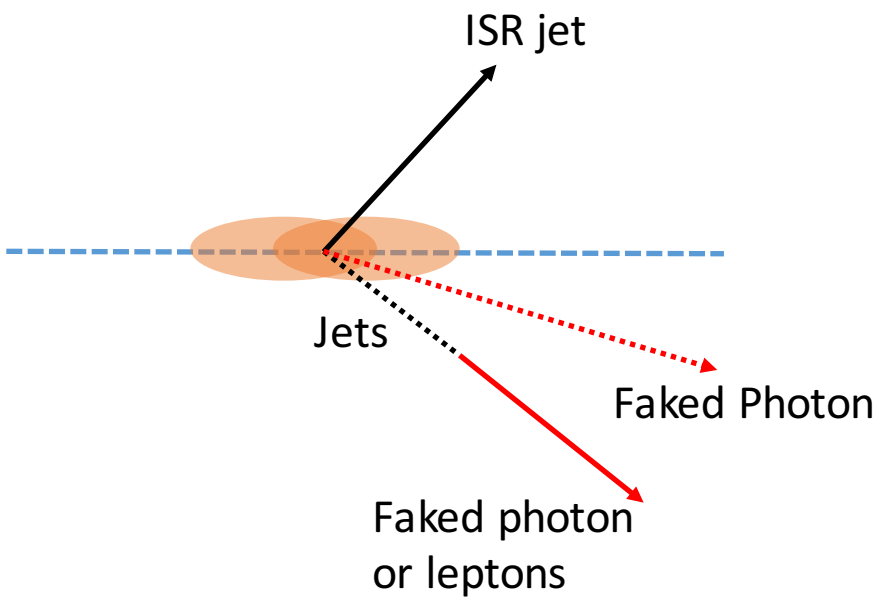

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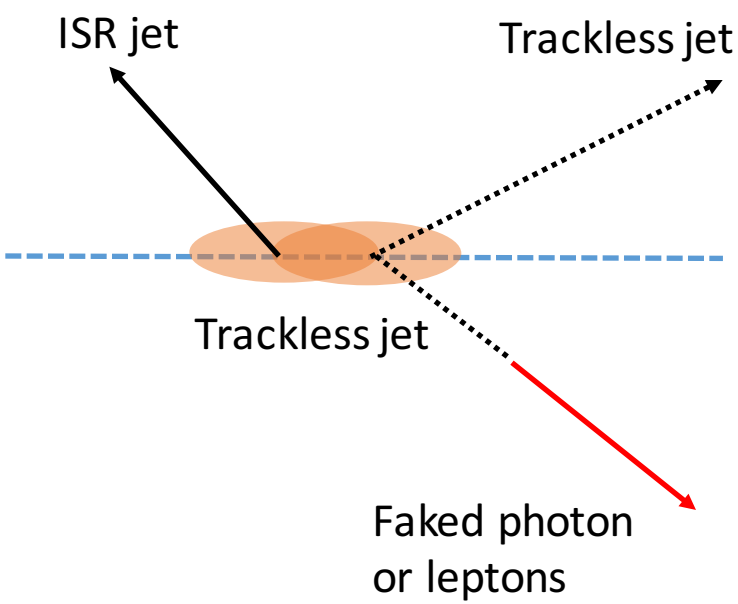

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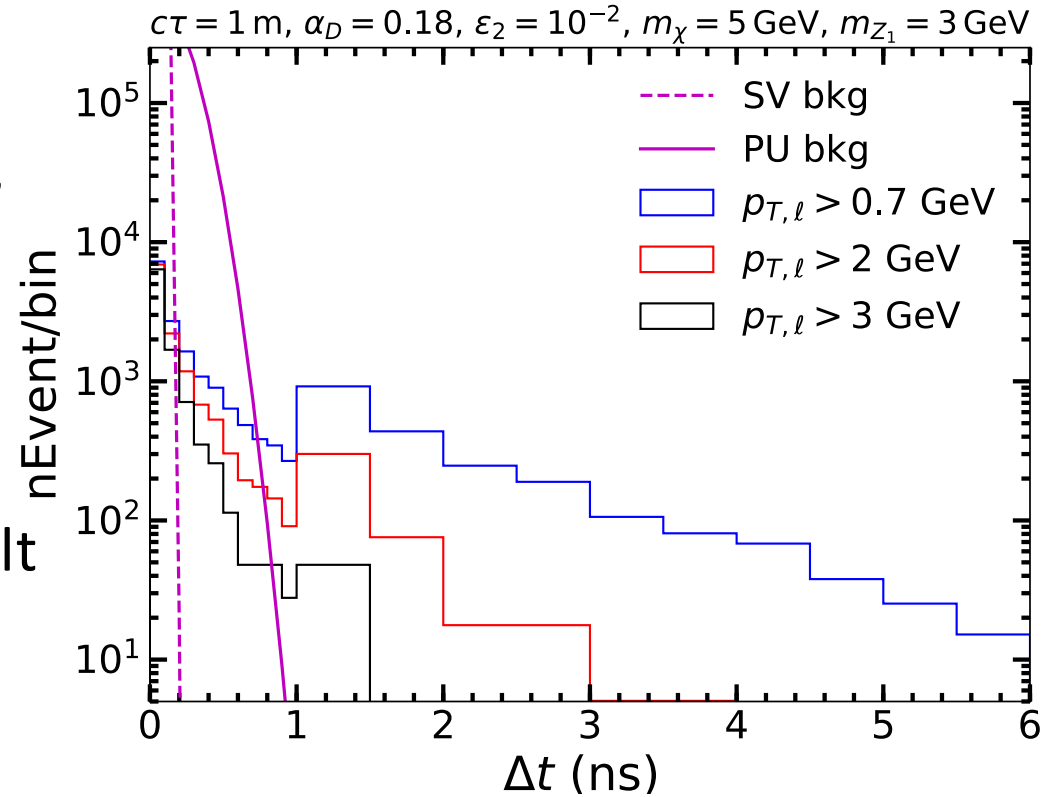
❖ Other BGs come from cosmic ray, core and satellite bunch and beam halo. See Juliette's talk.

arXiv:1906.06441

Results

- After timing cut $\Delta t > 1\ ns$, the number of BG: $N_{SV} \approx 0$ and $N_{PU} \approx 0.7$

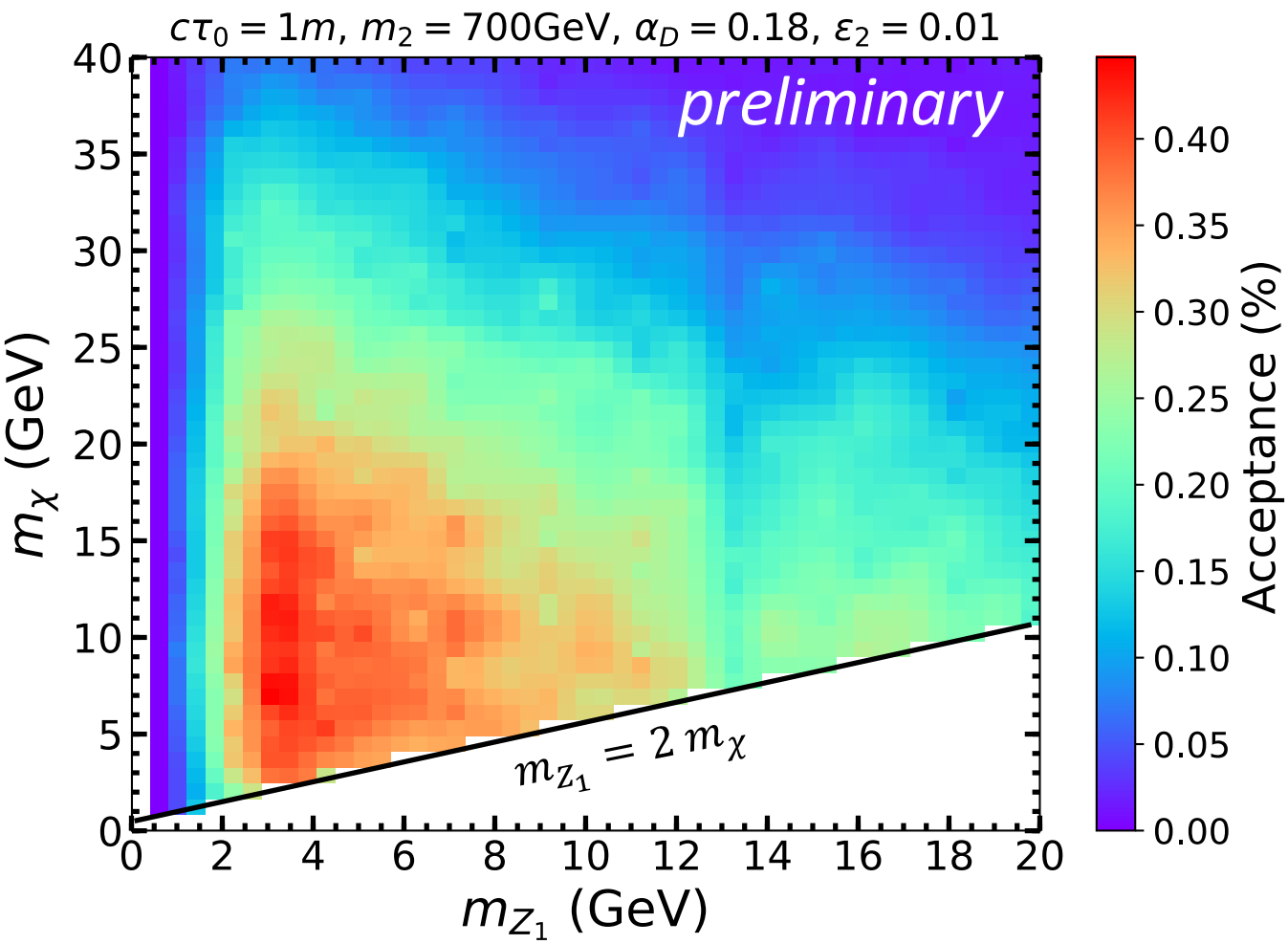
- Higher transverse momentum of lepton, result in smaller number signal time-delayed.



Cuts	BP	bkg
$p_{T,j} > 30$ GeV & $\lvert\eta(j)\rvert < 2.5$	113514	–
$0.2\text{m} < L_T^{Z_1} \leq 1.17\text{m}$	28267.3	–
$z_{Z_1} \leq 3.04\text{m}$	19744.2	–
$p_{T,\ell} > 0.7\ (2.0)\ (3.0)$ GeV	17922.82 (12845.32) (9715.45)	–
$\Delta t > 1$ ns	2207.82 (431.96) (47.99)	SV: 0; PU: 0.7

Results

CMS MTD, $p_{T,l} > 0.7\ GeV,\ \Delta t > 1ns$



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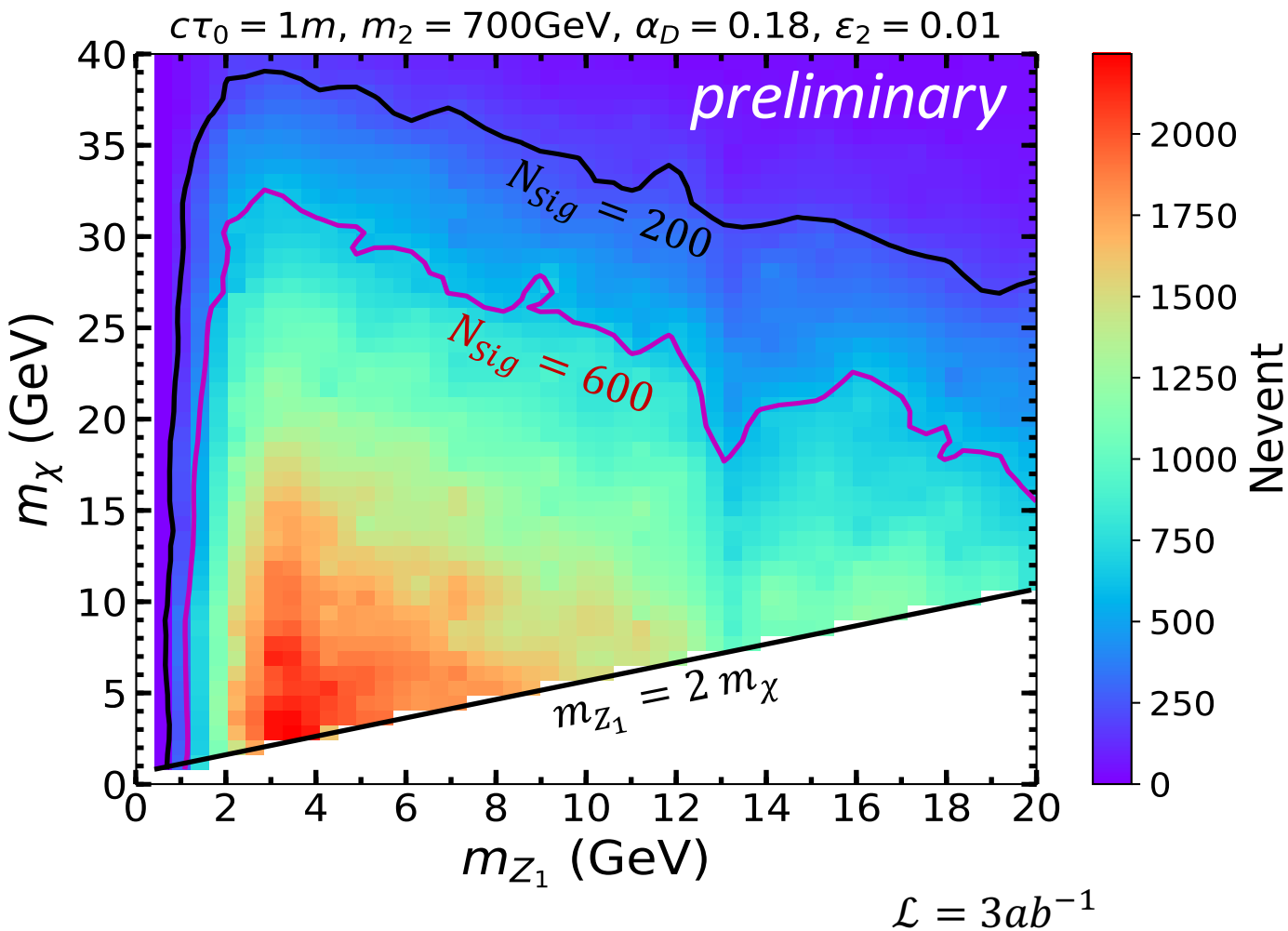

$\mathcal{L} = 3ab^{-1}$

Conclusion

- The timing information is a promised direction searching for LLP.
- Dark photon in extension Stueckelberg Model weakly interact with SM and can be a LLP.
- With low p_T threshold and good timing resolution at CMS MTD, one can search for the time-delayed LLP signal from Dark photon.

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