Enhanced Long-Lived Dark Photon signal @ LHC

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- Enhanced LLDP signal @ timing detectors
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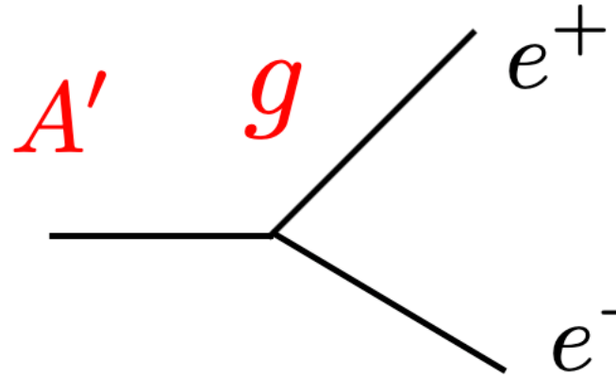
Motivation

Long-lived particles (LLP) present in a lot of BSM models



Dark photon (DP)

w/ coupling g to e

$$g A'_\mu \bar{e} \gamma^\mu e$$

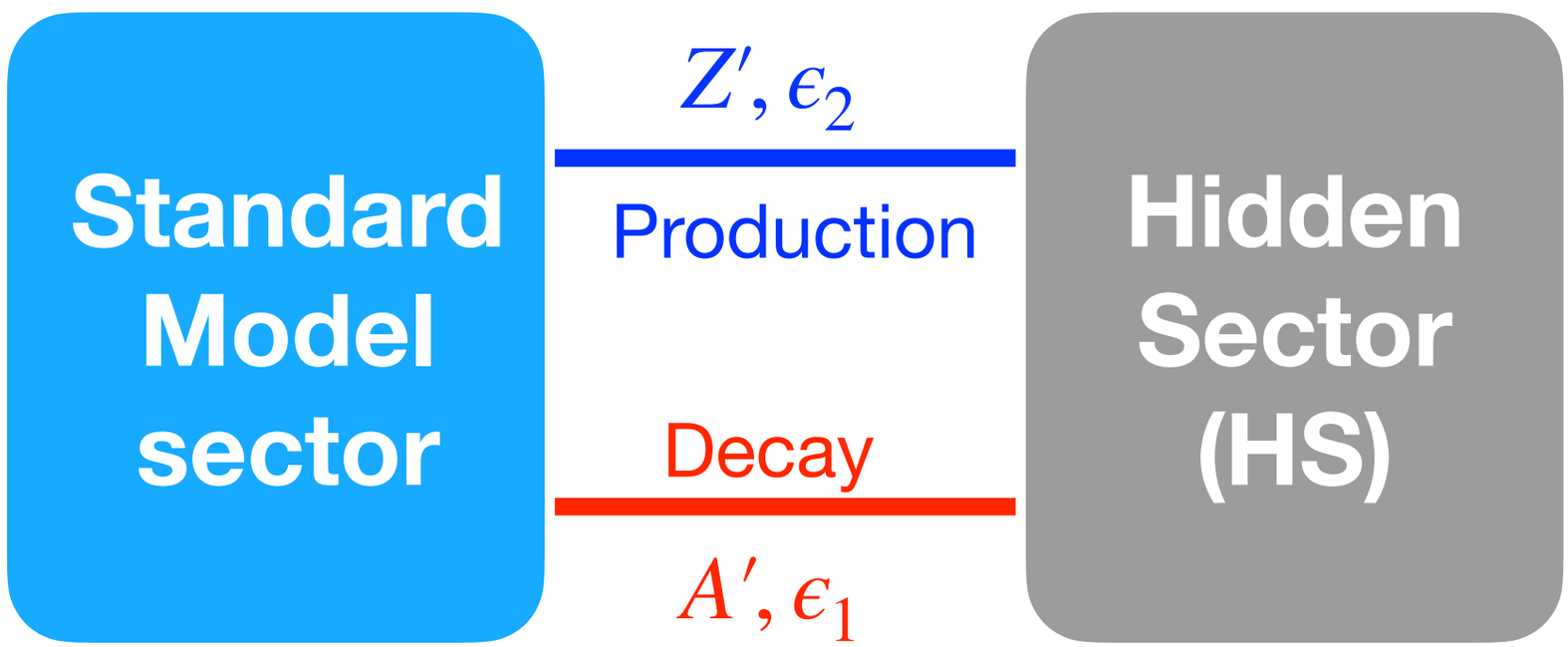
distance travelled by long-lived dark photon (LLDP)

$$d = \gamma v \tau \simeq 1 \text{ meter} \left[\frac{10^{-6}}{g}\right]^2 \left[\frac{E_{A'}}{100 \text{ GeV}}\right] \left[\frac{\text{GeV}}{M_{A'}}\right]^2$$

Suppressed ? **Boosted** **Collider**

To enhance LLDP signals@LHC

Make the LLDP production process different with its decay process



If $\epsilon_2 \gg \epsilon_1 \sim 10^{-6}$, A' is LLDP and its signal can be enhanced

Stueckelberg w/ 2 U(1) extension

- SM extended by a hidden sector (HS) with **two** U(1) gauge bosons X and C

Hidden $U(1)_F$

$$-4\mathcal{L}_F = X_{\mu\nu}^2 + 2(\partial_\mu \sigma_1 + m_1 \epsilon_1 B_\mu + m_1 X_\mu)^2$$

$$-4\mathcal{L}_W = C_{\mu\nu}^2 + 2(\partial_\mu \sigma_2 + m_2 \epsilon_2 B_\mu + m_2 C_\mu)^2$$

Hidden $U(1)_W$

SM $U(1)_Y$

- Both 2 extra gauge bosons obtain mass via **Stueckelberg** mechanism

E. C. G. Stueckelberg 1938
D. Feldman, Z. Liu,P. Nath, B.D.Nelson 2009
Kors & Nath, hep-ph/0402047
V. I. Ogievetskii & I. V. Polubarinov 1962

- Dirac fermion ψ $(g_F X_\mu + g_W C_\mu)\bar{\psi}\gamma^\mu\psi$

Mass matrix of neutral gauge bosons

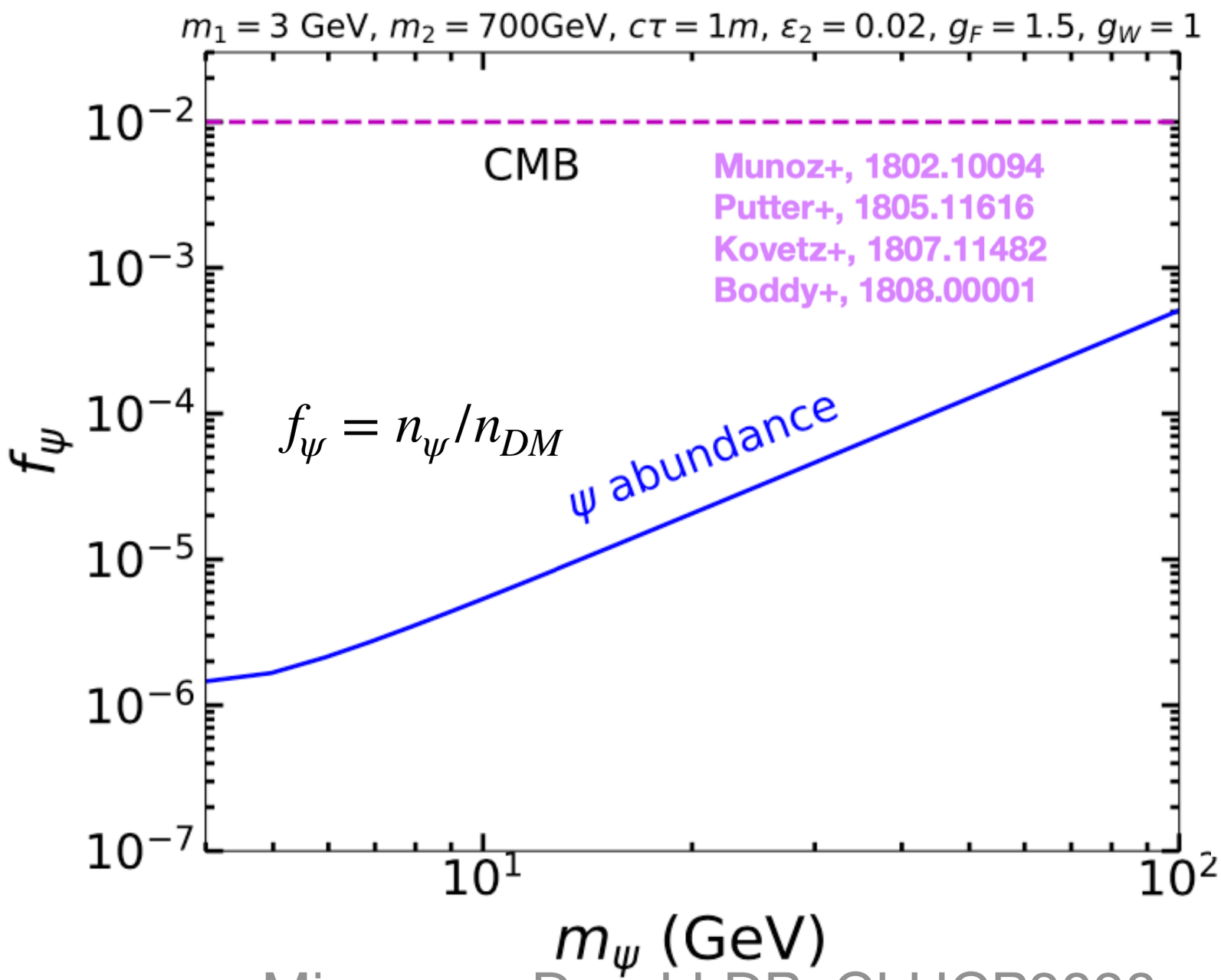
4 by 4 mass square matrix in $V = (C, X, B, A^3)$

$$m^2 = \begin{pmatrix} m_2^2 & 0 & m_2^2\epsilon_2 & 0 \\ 0 & m_1^2 & m_1^2\epsilon_1 & 0 \\ m_2^2\epsilon_2 & m_1^2\epsilon_1 & m_1^2\epsilon_1^2 + m_2^2\epsilon_2^2 + \frac{g'^2v^2}{4} & -\frac{g'gv^2}{4} \\ 0 & 0 & -\frac{g'gv^2}{4} & \frac{g^2v^2}{4} \end{pmatrix}$$

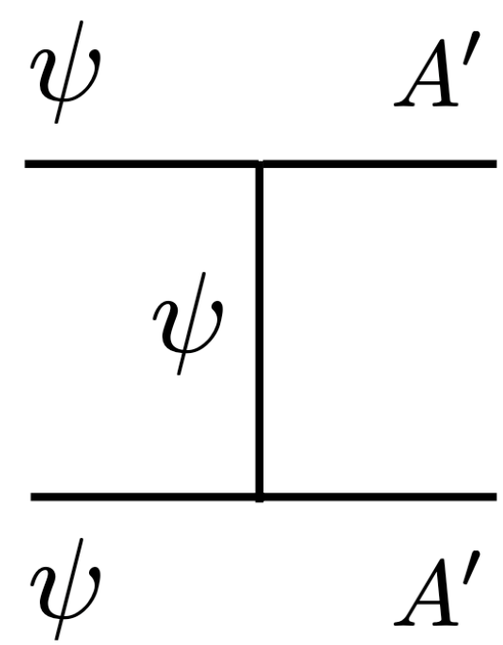
Mass eigenstates $E = (Z', A', Z, A)$ via $E = VO$ where $O^T m^2 O$ is diagonal

ψ couples w/ A due to the neutral gauge bosons mixing; ψ is millicharged

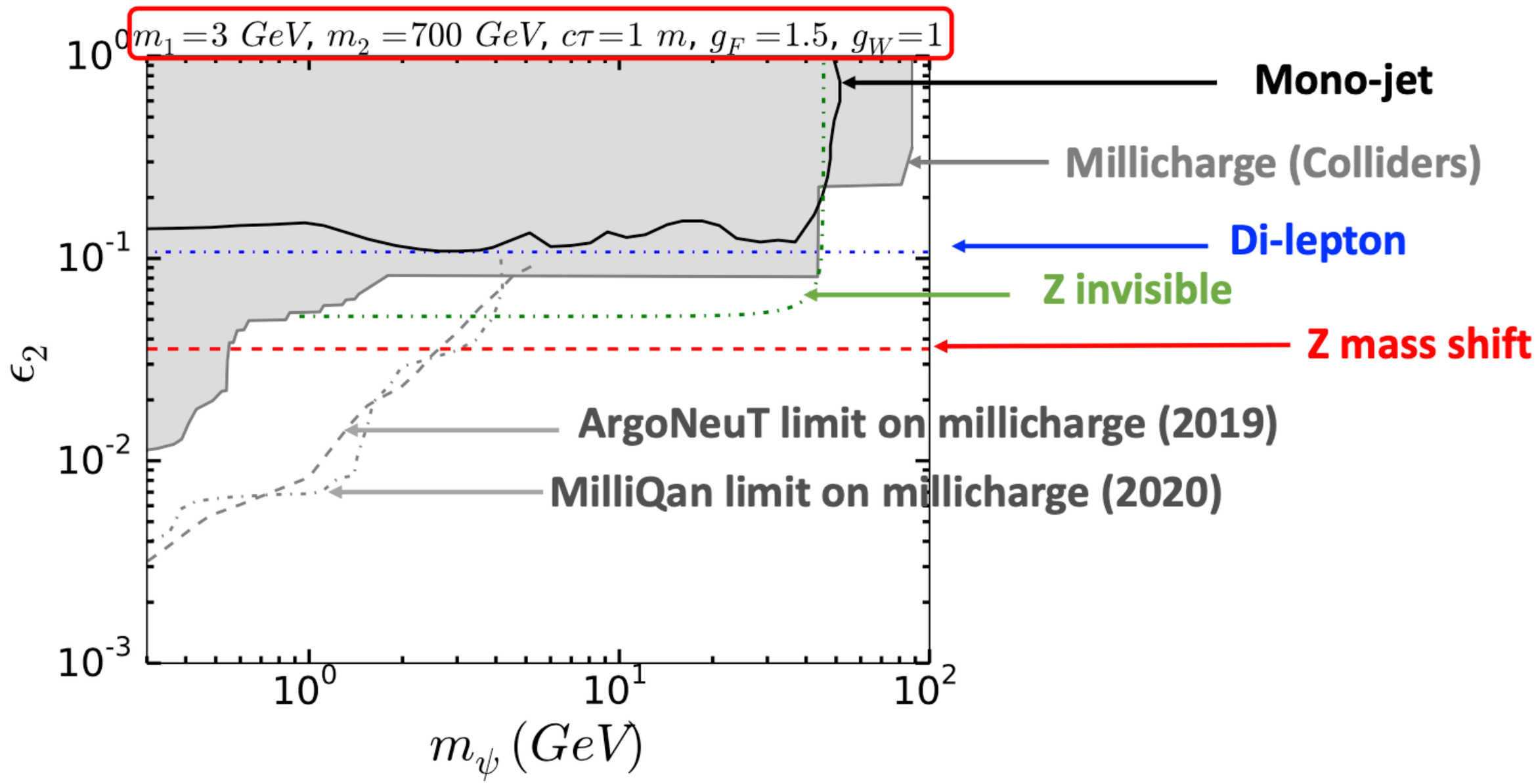
CMB constraint



$\sim 1\,\%$ of DM can be charged

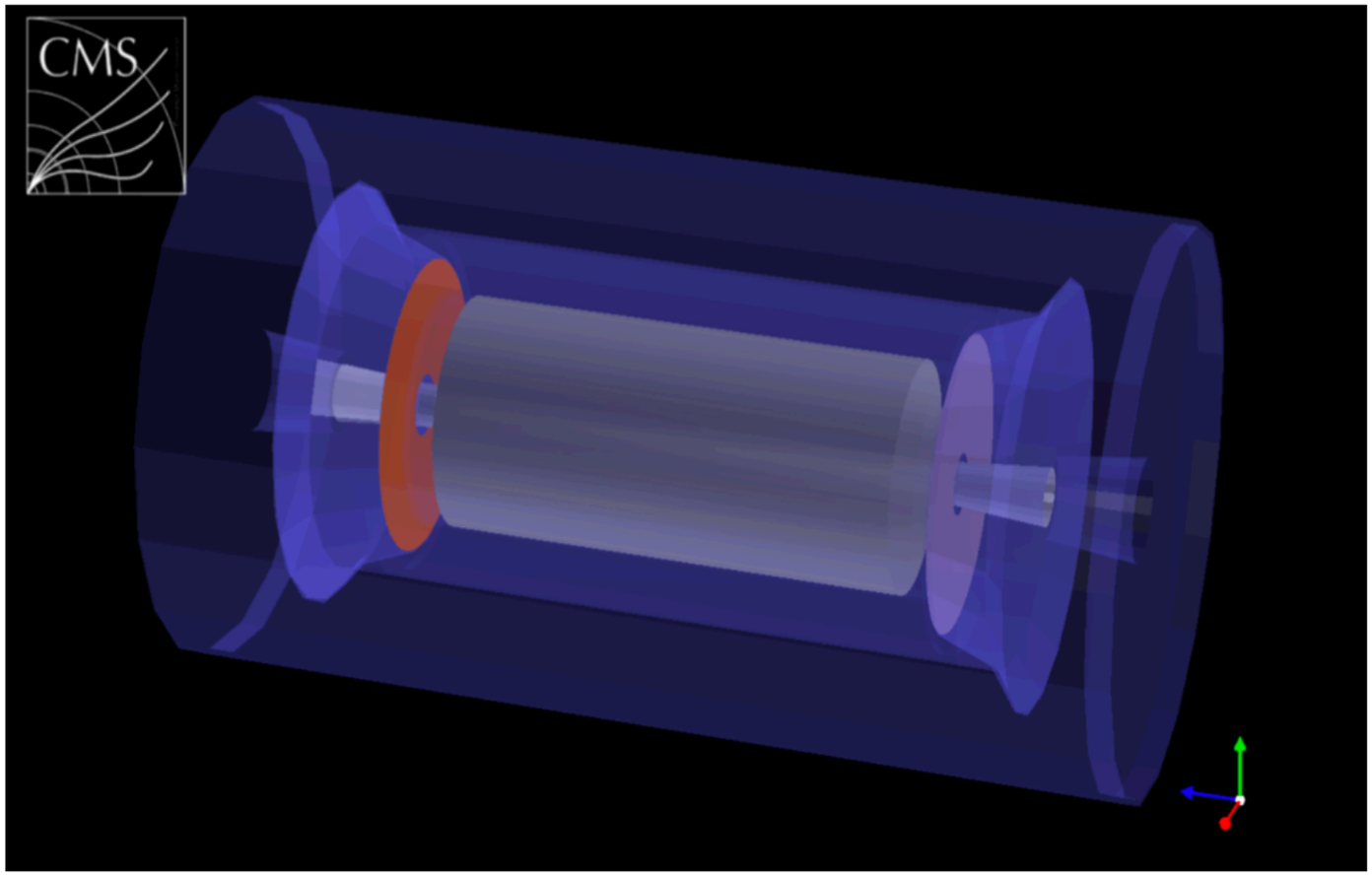


Experimental constraints



Timing Detector

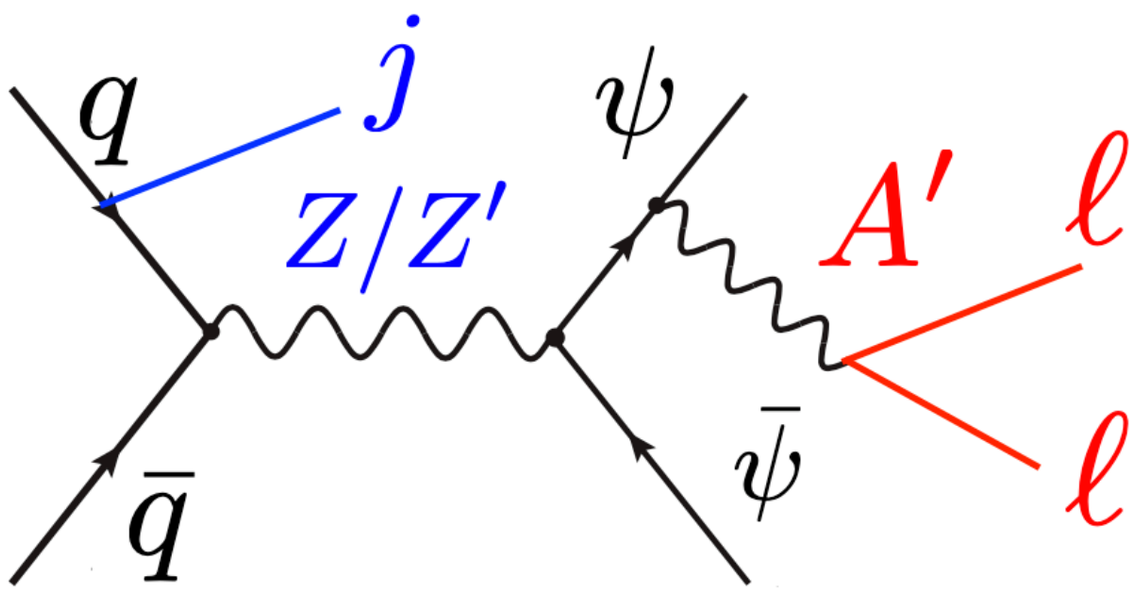
CMS timing detector (phase 2)

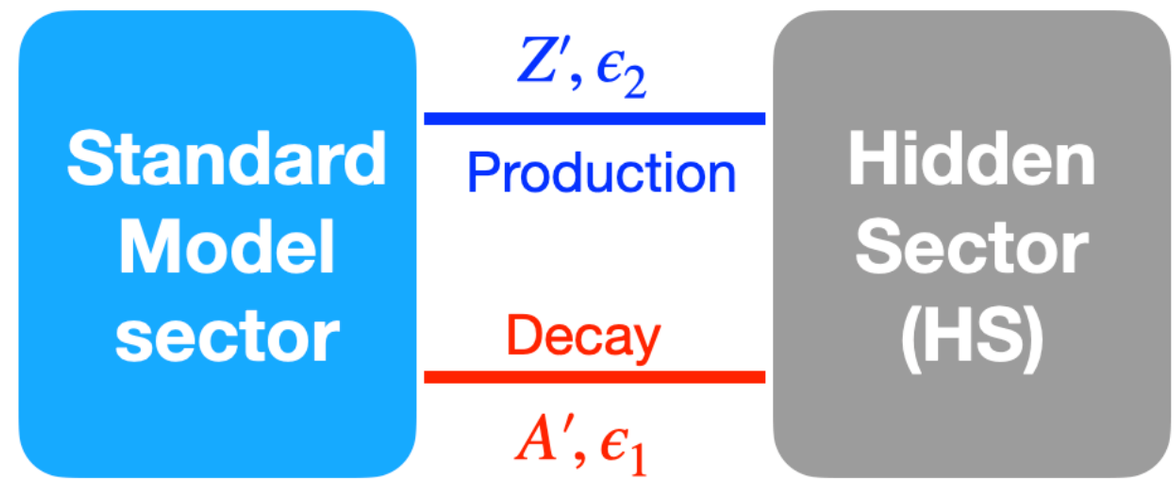


- between the tracker and calorimeter
- $\delta t = 30\text{ps}$
- $1.17\text{m} \sim \text{O}(\text{ns})$ away from the beam axis

hsps://cds.cern.ch/record/2296612/files/LHCC-P-009.pdf

LLDP @ LHC



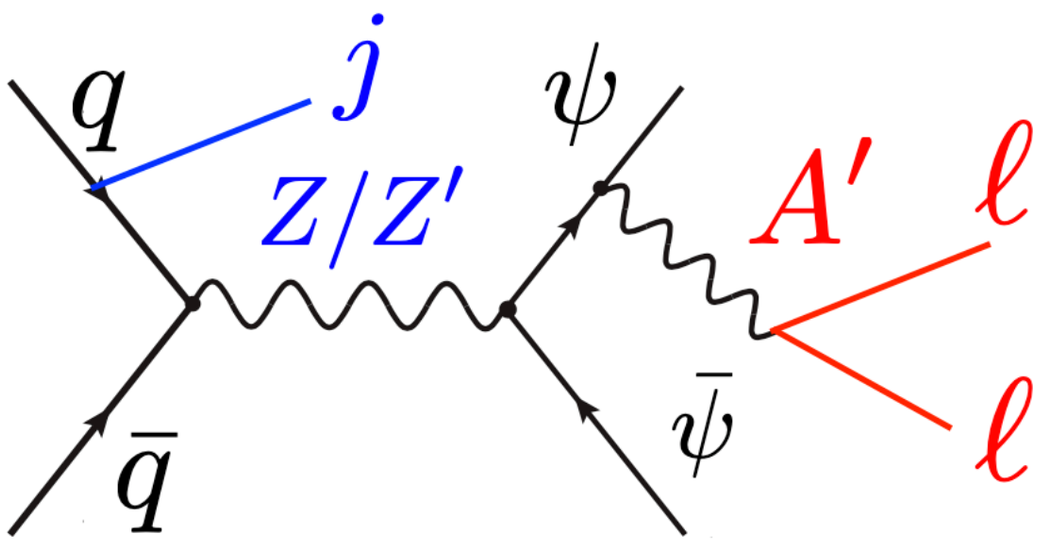


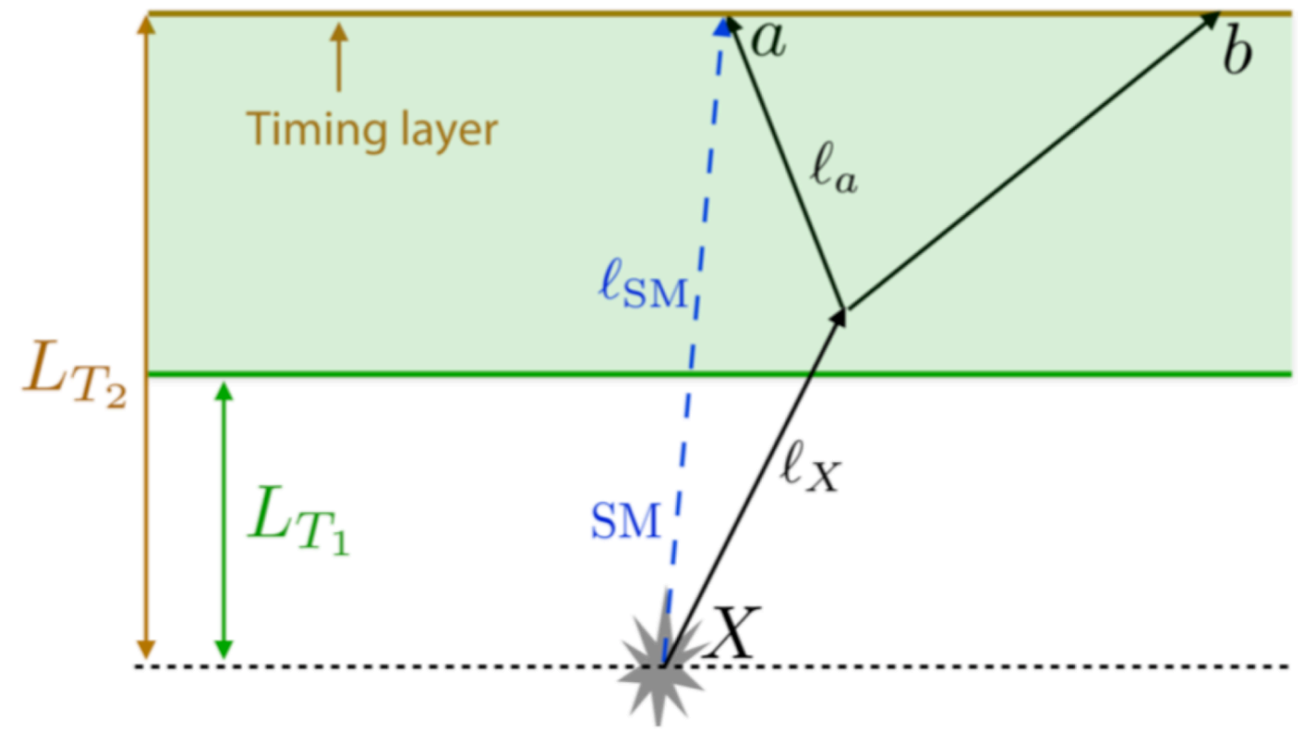
$m_{Z'} \sim O(1)\text{TeV}$ and $\epsilon_2 \sim 10^{-2}$

$m_{A'} \sim O(1)\text{GeV}$ and $\epsilon_1 \sim 10^{-7}$

GeV LLDP w/ $\tau \sim 1\text{m}$

Time delay for LLP





$$\Delta t = \frac{\ell_X}{\beta_X} + \frac{\ell_a}{\beta_a} - \frac{\ell_{\rm SM}}{\beta_{\rm SM}} \qquad \beta_a \simeq \beta_{\rm SM} \simeq 1$$

Liu, Liu, Wang, 1805.05957

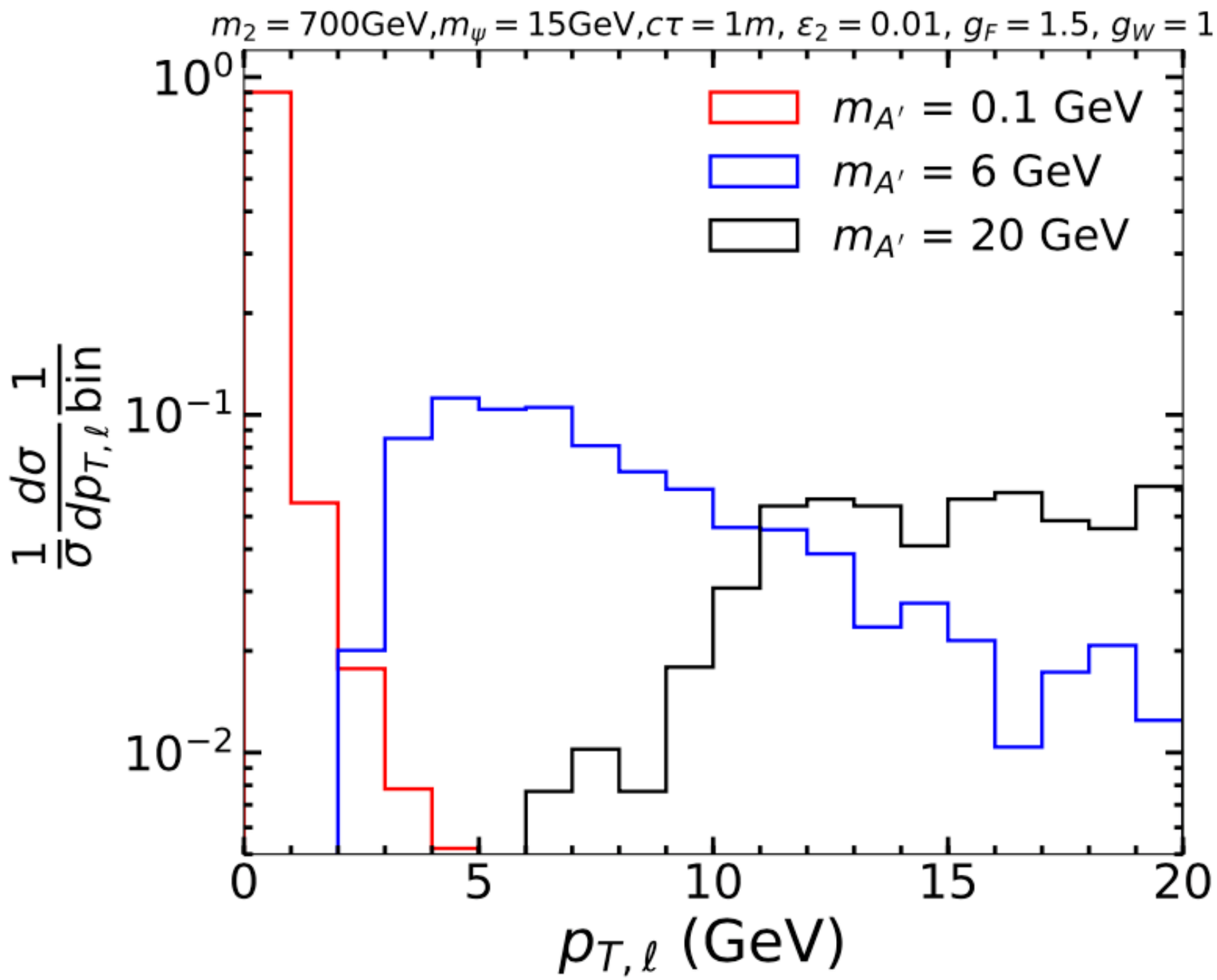
lepton: p_T > 3 GeV

time delay: Δt > 1.2 ns

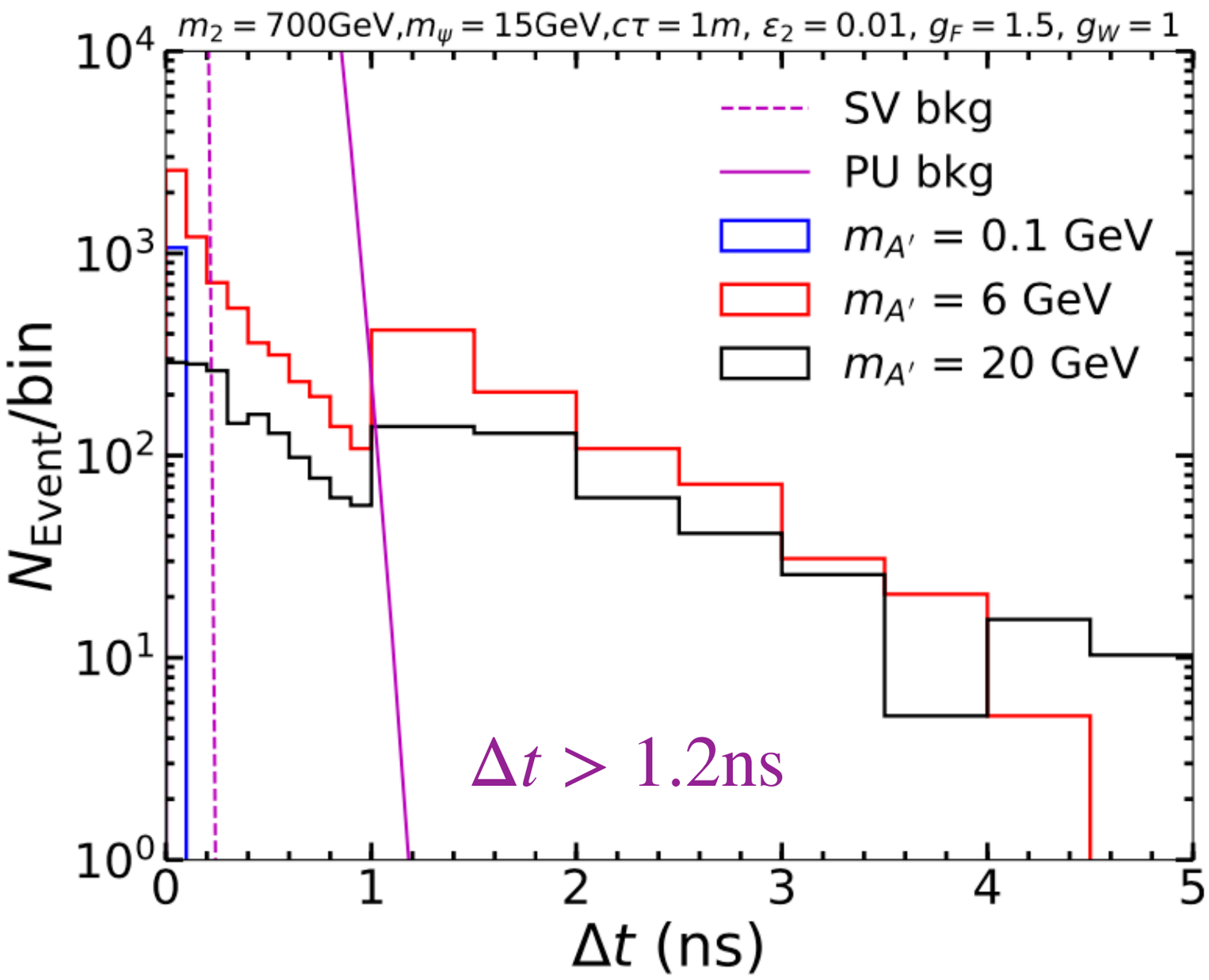
DP: 0.2 m < L_T < 1.17 m & z < 3.04 m

ISR jet: p_T > 30 GeV & |η| < 2.5

Lepton pT distribution

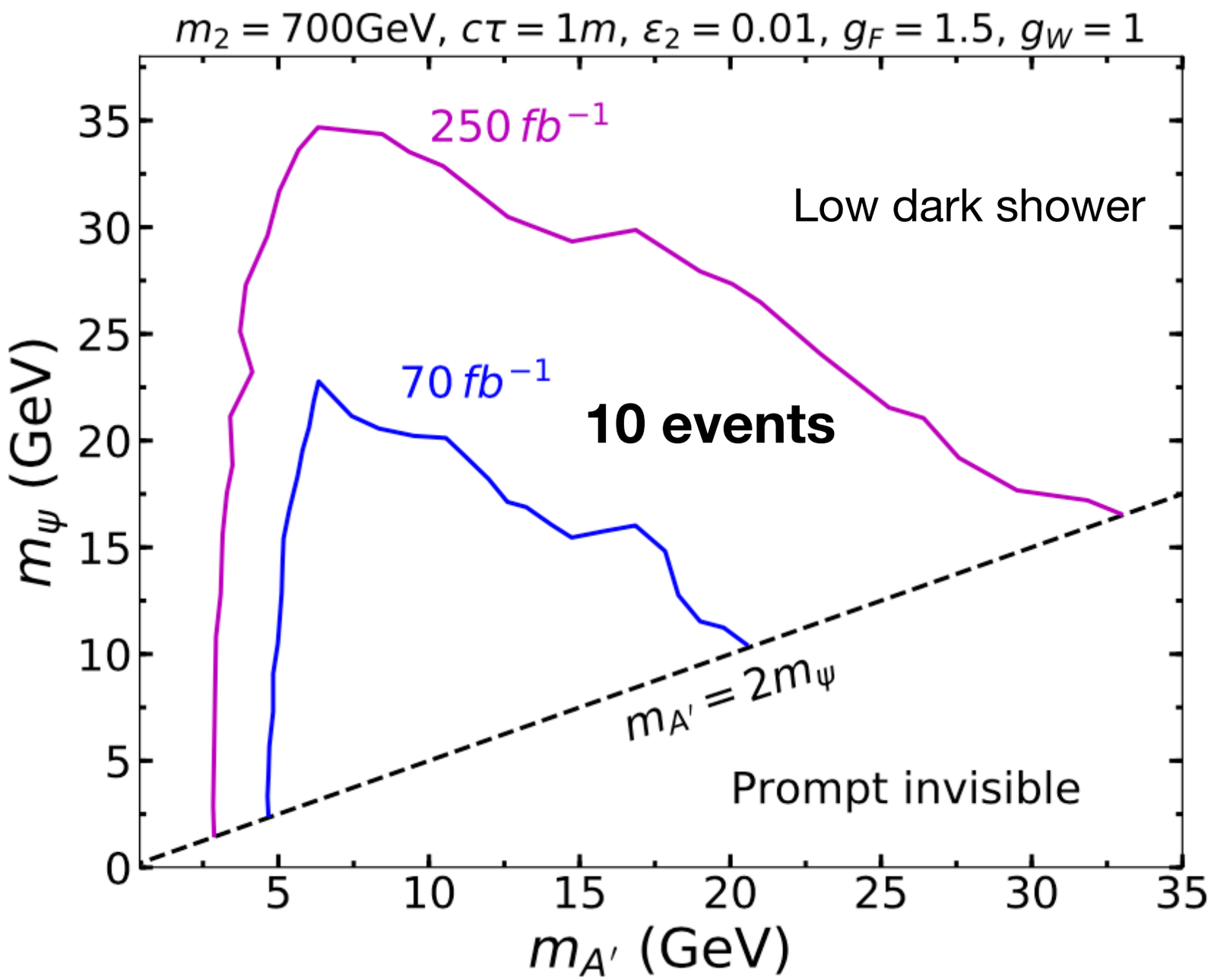


Time delay distribution



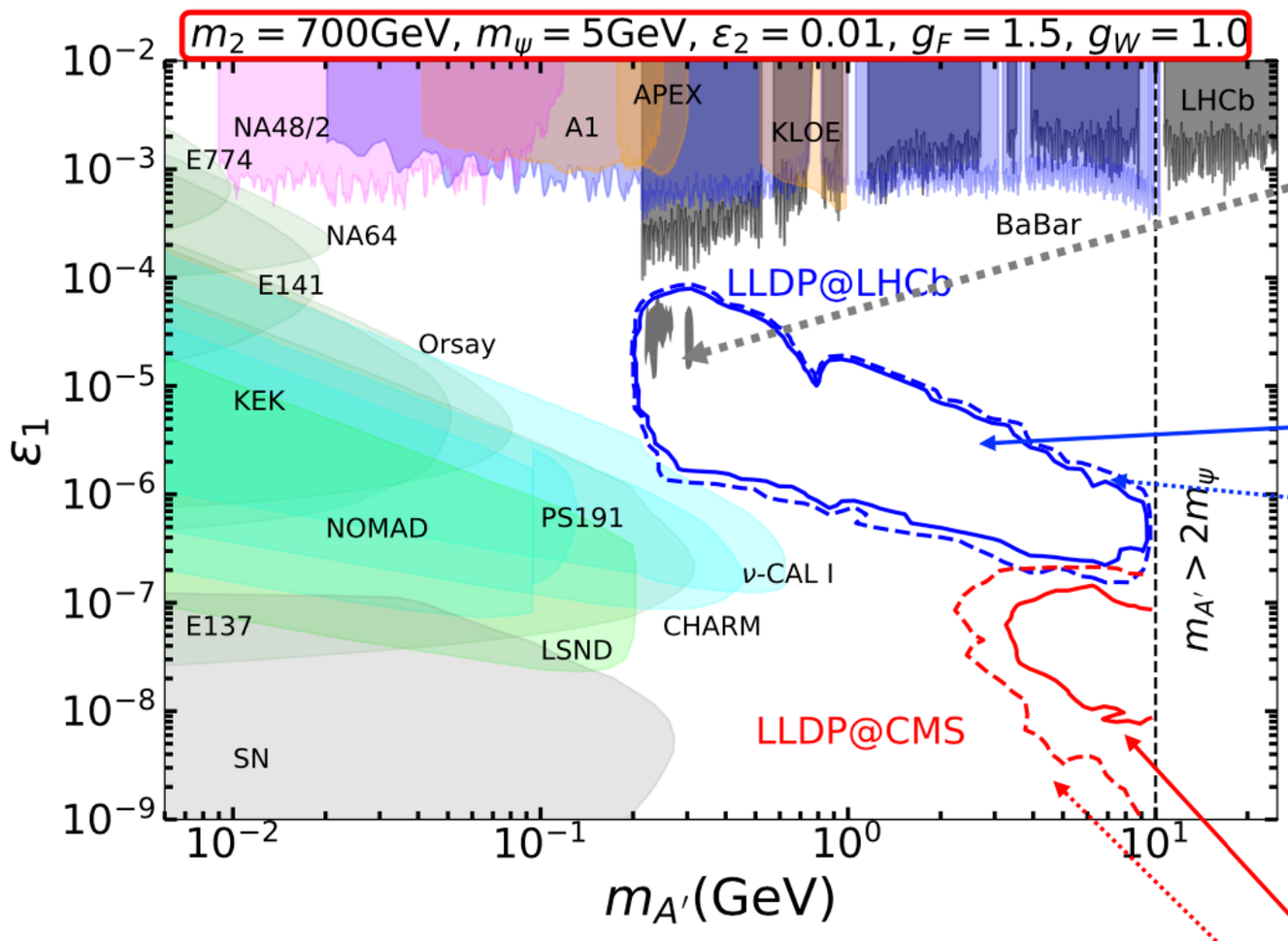
- SV: same vertex, due to time resolution: 30ps
- PU: pile-up, due to the spread of proton bunch

Timing detector sensitivity on LLDP



pT cut

LHCb sensitivity on LLDP



LHCb 1910.06926

"Ordinary" LLDP
L= 5.5/fb

Our model:
L = 5.5/fb (now)
L =15/fb (run 3)

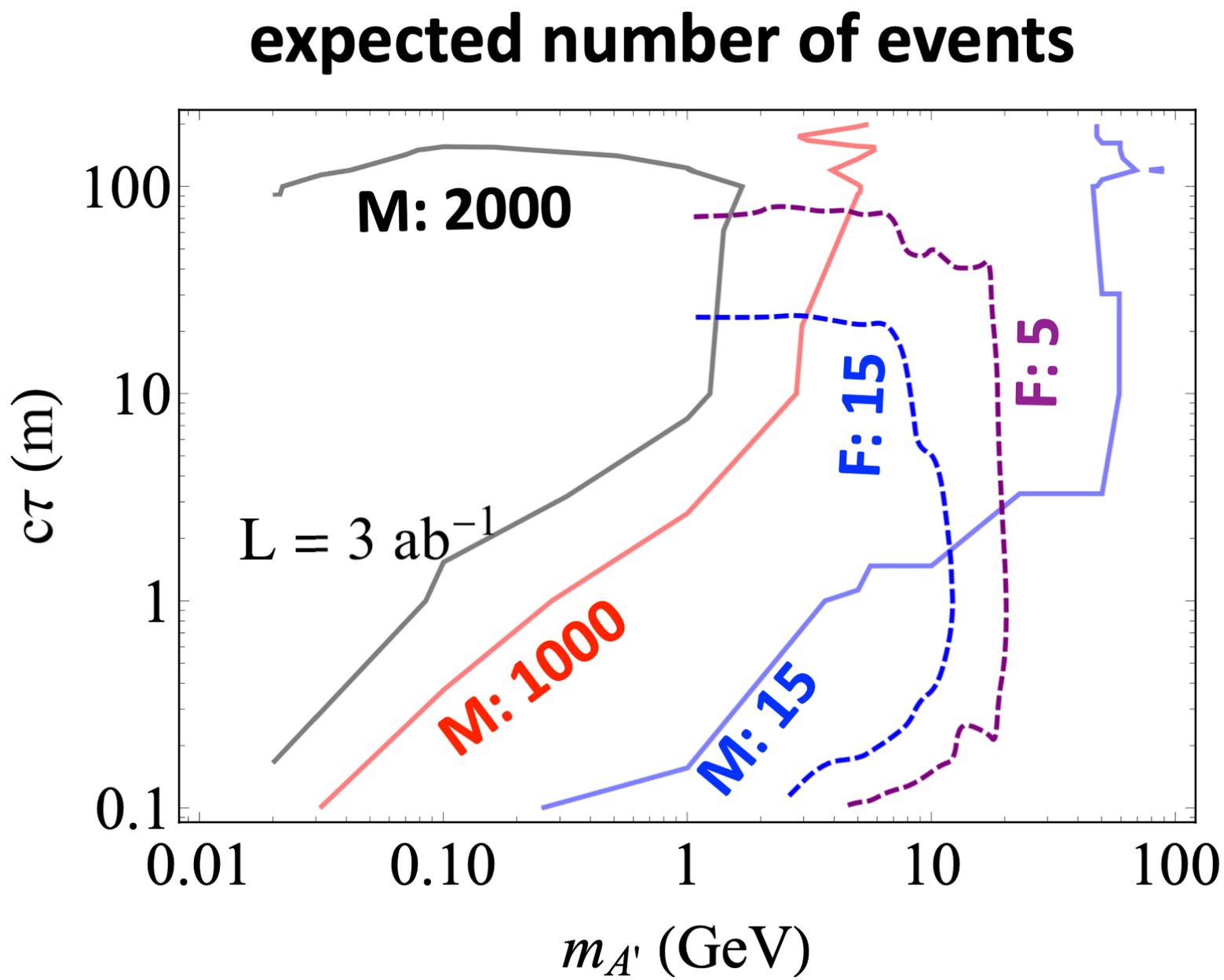
$$\frac{S}{\sqrt{B}} = 2.71$$

Time delay@CMS
L = 250/fb
L =3000/fb

LHCb: $A' \to \mu^+\mu^-$
with $6mm < L_T\ (A') < 22mm$

Lifetime frontier detectors

- MATHUSLA (MAssive Timing Hodoscope for Ultra-Stable neutraL pArticles) $\sim 150\text{m}$
- FMS (Forward Multi-particle Spectrometer) $\sim 100\text{m}$



Conclusion

- “Ordinary” long-lived dark photon has a small LHC signal due to the extremely weak coupling
- We construct a BSM model in which the LLDP signal is greatly enhanced
- We analyzed various experimental constraints on the LLDP model
- Sensitivity to the LLDPs from the precision timing detector and LHCb are computed
- It can be searched in the LHC lifetime frontier, such as FMS, MATHUSLA … (work in progress)

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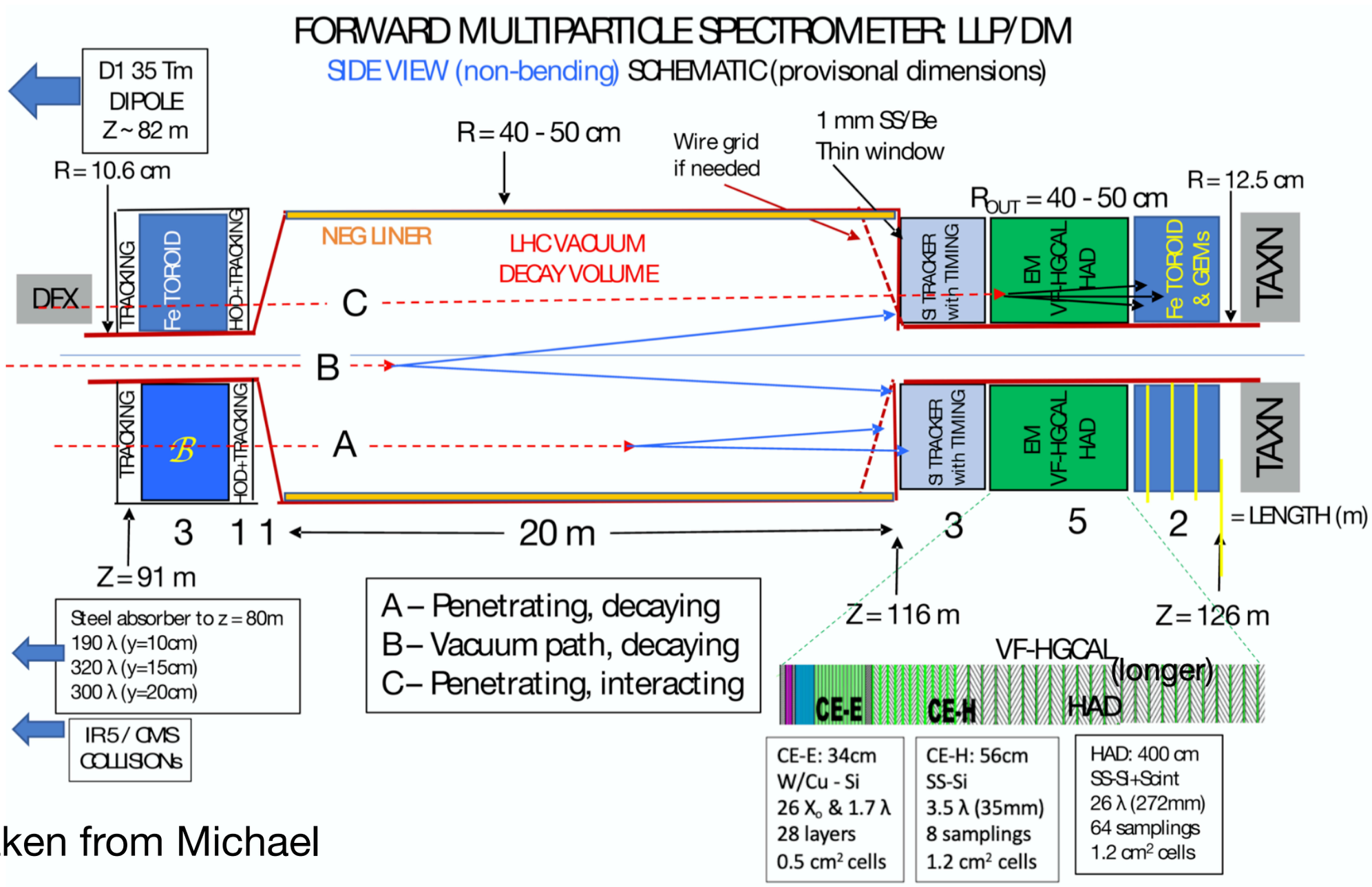
Thank you !

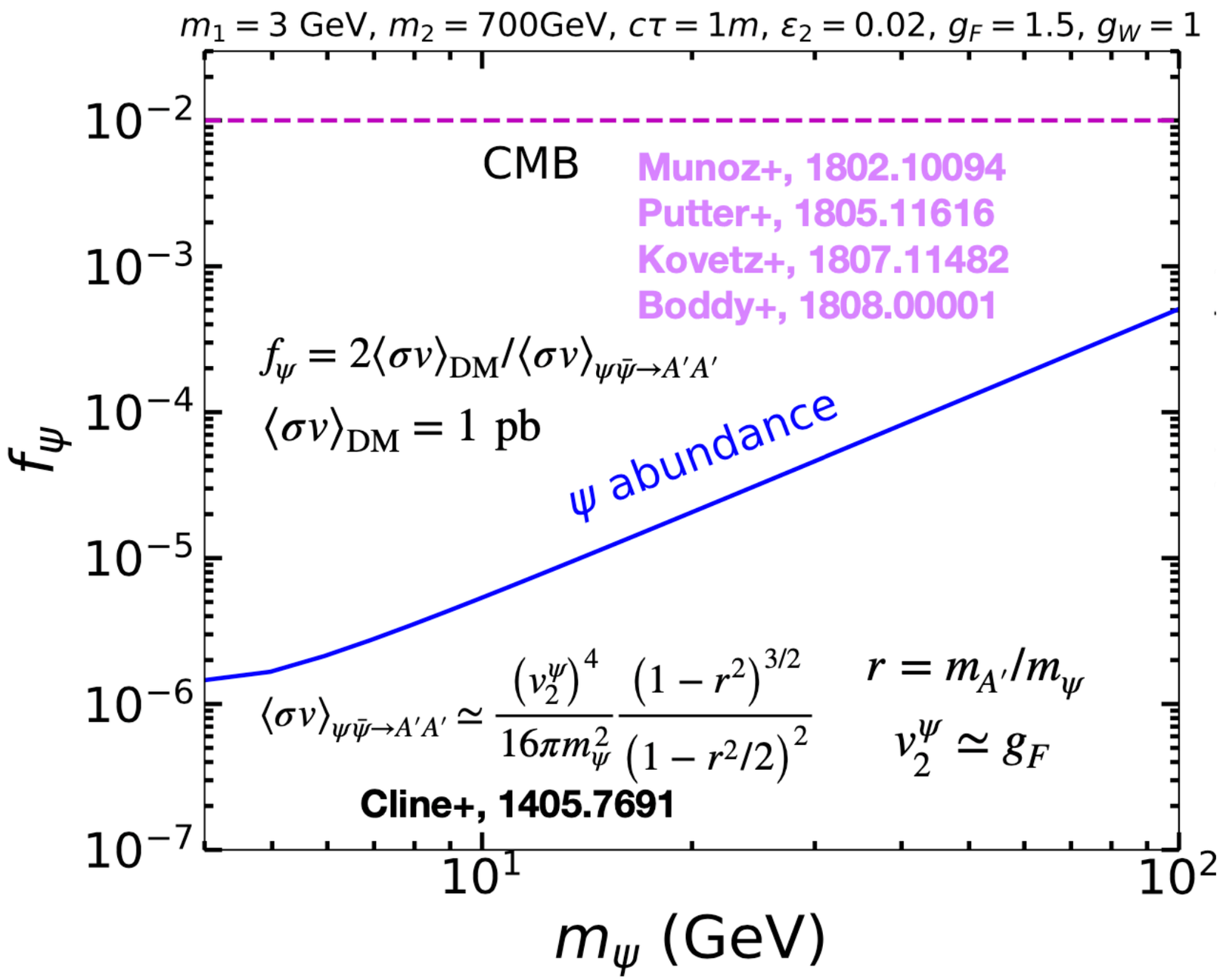
Backups

FMS detector



Taken from Michael

CMB constraint



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