Long-lived dark photons at the LHC

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Papers

- Enhanced Long-Lived Dark Photon Signals at the LHC
  Mingxuan Du, ZL, Van Que Tran
  JHEP 05 (2020) 055 • e-Print: 1912.00422 [hep-ph]

- Enhanced long-lived dark photon signals at lifetime frontier detectors
  Mingxuan Du, Rundong Fang, ZL, Van Que Tran
  Phys.Rev.D 105 (2022) 5, 055012 • e-Print: 2111.15503 [hep-ph]

- FACET: A new long-lived particle detector in the very forward region of the CMS experiment
  S. Cerci et al.,
  JHEP 06 (2022) 110 • e-Print: 2201.00019 [hep-ex]

Outline

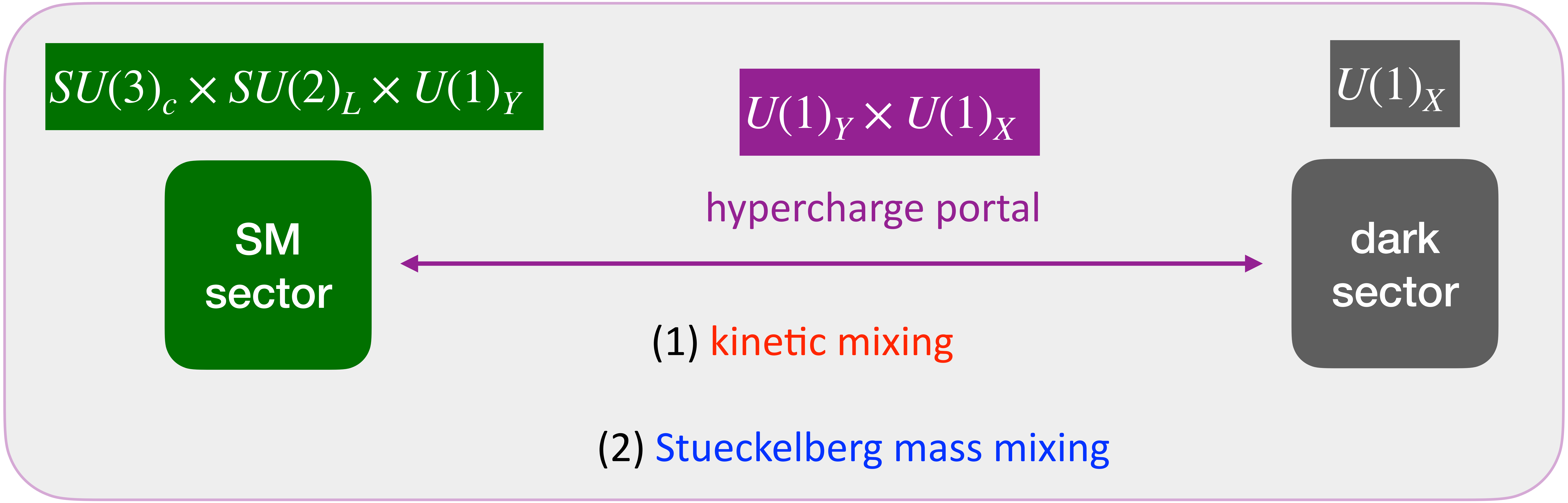
1. Dark photon models & constraints
2. Our new (long-lived) dark photon models
3. Long-lived dark photon signals at the LHC

1 Dark photon models & constraints

Hypercharge portal models $\Longrightarrow$ dark photon

[Holdom 1986] [Foot & He 1991] [Kors & Nath 2004] [Feldman, ZL, Nath, hep-ph/0702123, 372 cites]

Hypercharge portal models $\Longrightarrow$ dark photon



[Holdom 1986] [Foot & He 1991] [Kors & Nath 2004] [Feldman, ZL, Nath, hep-ph/0702123, 372 cites]

Kinetic mixing & mass mixing

$SU(3)_c \times SU(2)_L \times U(1)_Y \times U(1)_X$

[Feldman, ZL, Nath, hep-ph/0702123, 372 cites]

$$\mathscr{L} = -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}X_{\mu\nu}X^{\mu\nu} + g_D X_\mu \bar{\chi}\gamma^\mu \chi - \frac{\tilde{\delta}}{2} B_{\mu\nu} X^{\mu\nu} - \frac{M_1^2}{2}(\partial_\mu \sigma + X_\mu + \tilde{\epsilon} B_\mu)^2$$

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kinetic mixing

mass mixing

kinetic mixing $\tilde{\delta}$ & mass mixing $\tilde{\epsilon}$ are degenerate (w/o χ): only $\epsilon \sim (\tilde{\epsilon} - \tilde{\delta})$ is physical

dark photon & millicharged particles

$$\mathscr{L} = -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}X_{\mu\nu}X^{\mu\nu} + g_D X_\mu \bar{\chi}\gamma^\mu \chi - \frac{\tilde{\delta}}{2} B_{\mu\nu} X^{\mu\nu} - \frac{M_1^2}{2}(\partial_\mu \sigma + X_\mu + \tilde{\epsilon} B_\mu)^2$$

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[see also Fabbrichesi+, 2005.01515, Dark Photon Review]

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- $X_\mu \Longrightarrow A'_\mu$ (dark photon), if $M_1 \ll M_Z$

  $\epsilon e Q_f A'_\mu \bar{f}\gamma^\mu f$ (SM sector) and $g_D A'_\mu \bar{\chi}\gamma^\mu \chi$ (dark sector)

[Feldman, ZL, Nath, hep-ph/0702123, 372 cites]

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[Feldman, ZL, Nath, hep-ph/0702123, 372 cites]

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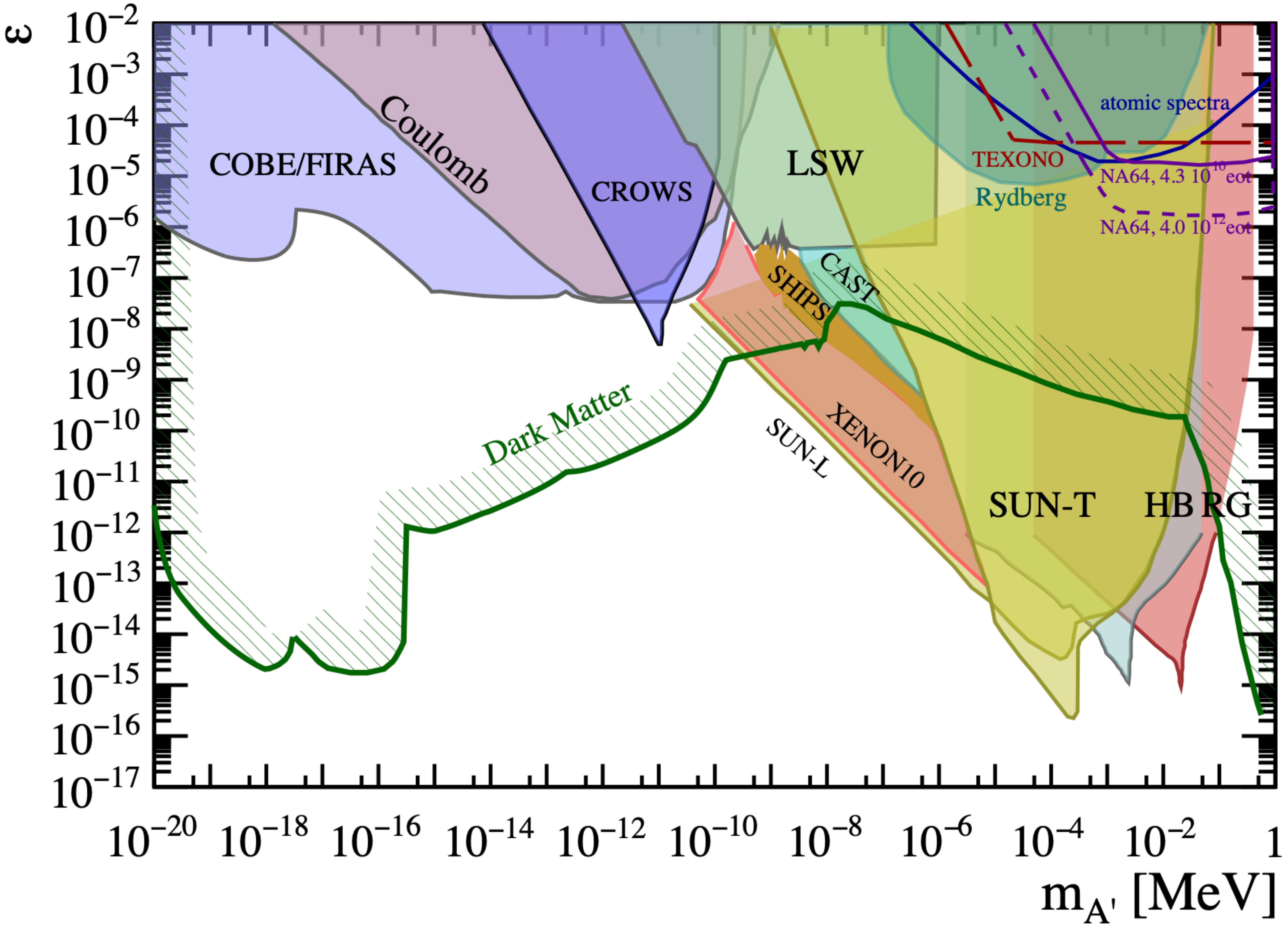
If A'_μ or Z'_μ is massive, χ is millicharged ($\epsilon e A_\mu \bar{\chi}\gamma^\mu \chi$) only when $\tilde{\epsilon} \neq 0$

[Feldman, ZL, Nath, hep-ph/0702123, 372 cites]

[see also Fabbrichesi+, 2005.01515, Dark Photon Review]

Limits on dark photon with mass below 1 MeV

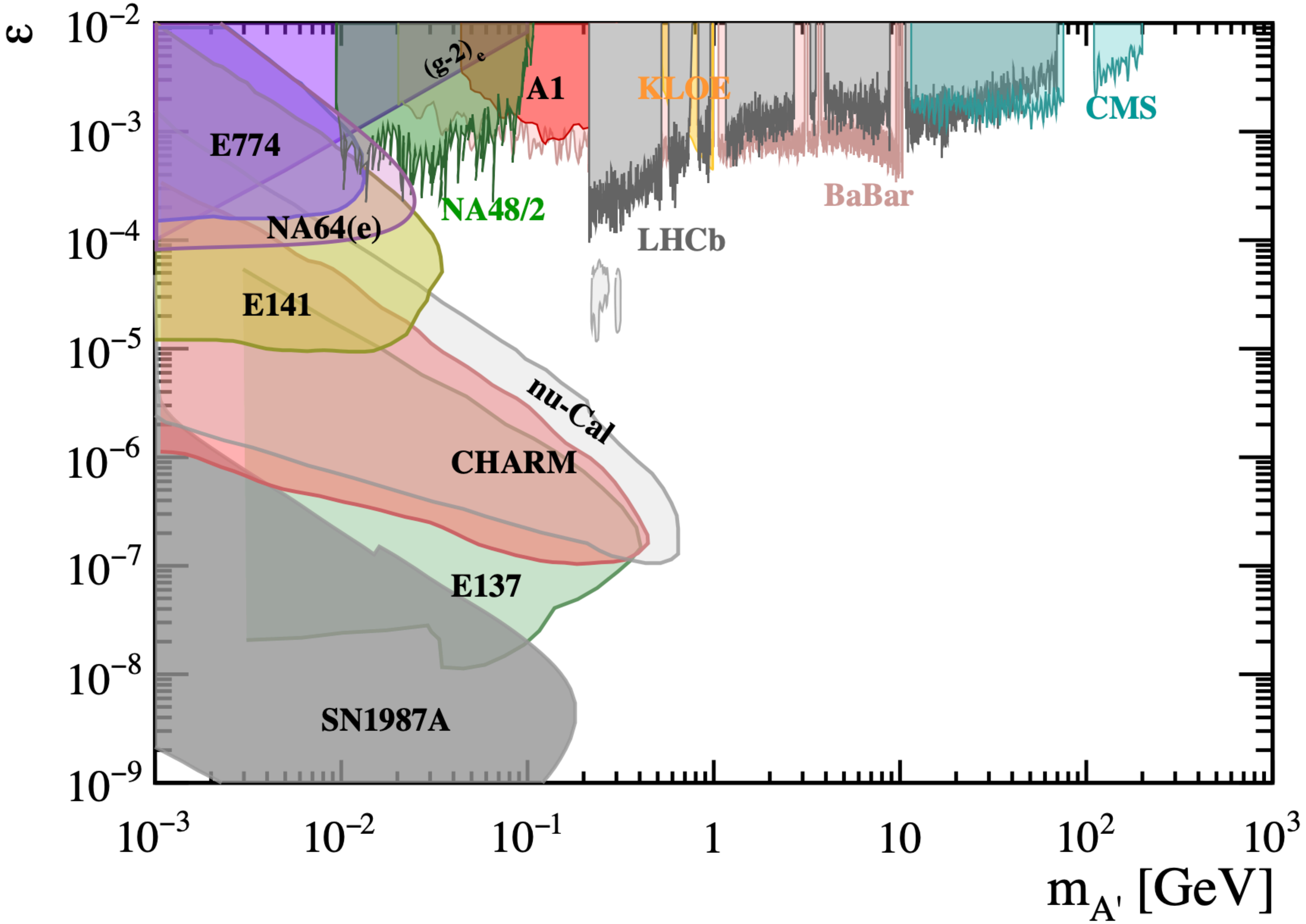


[Fabbrichesi+, 2005.01515, Dark Photon Review]

$\epsilon e Q_f A'_\mu \bar{f} \gamma^\mu f$

astro/cosmo probes

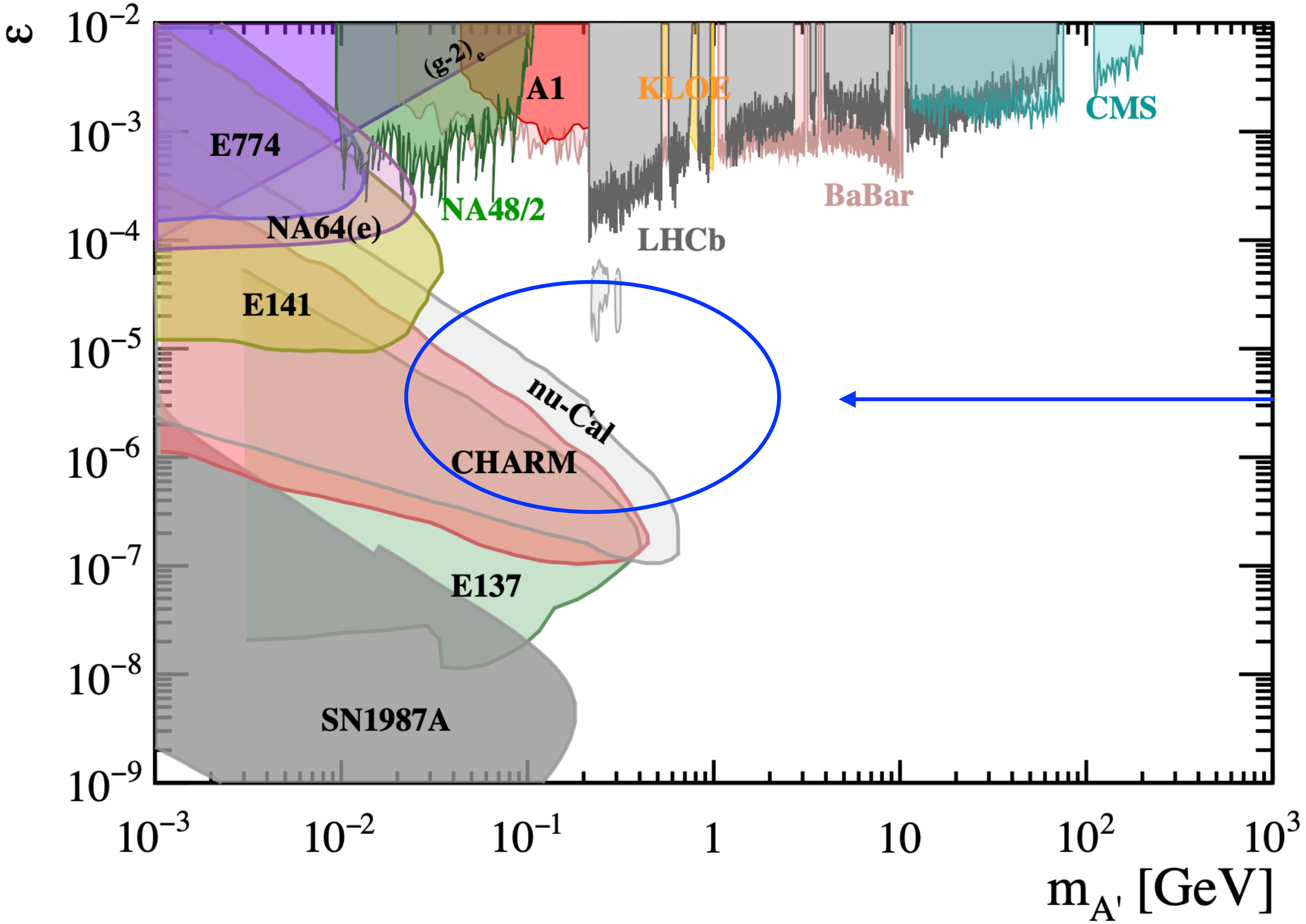
Limits on dark photon with mass above 1 MeV



[Fabbrichesi+, 2005.01515, Dark Photon Review]

accelerator probes

Limits on dark photon with mass above 1 MeV



Long-lived dark photon (LLDP)

accelerator probes

[Fabbrichesi+, 2005.01515, Dark Photon Review]

Long-lived particles at accelerators

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dark photon interaction with SM particles $\epsilon e Q_f A'_\mu \bar{f} \gamma^\mu f$

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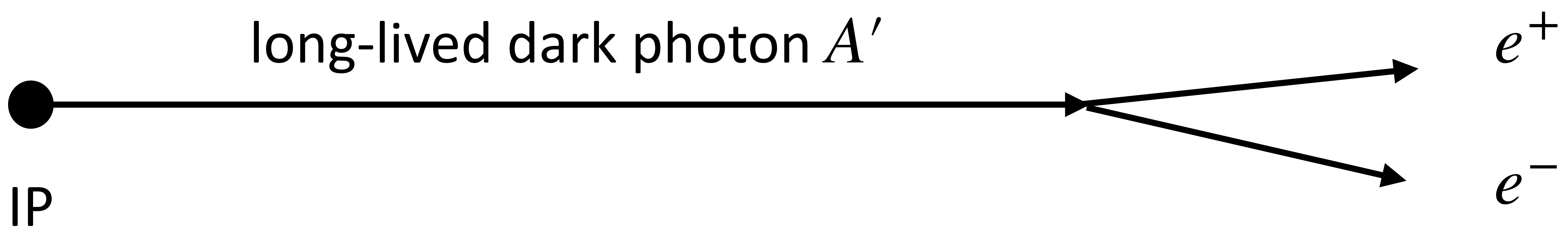

decay length:
($A' \to e^+ e^-$ only)

$$L_{A'} = \gamma v \tau \simeq 100 \text{ meter} \left[\frac{10^{-6}}{e\epsilon Q_f}\right]^2 \left[\frac{E_{A'}}{100 \text{ GeV}}\right] \left[\frac{0.1 \text{ GeV}}{M_{A'}}\right]^2$$

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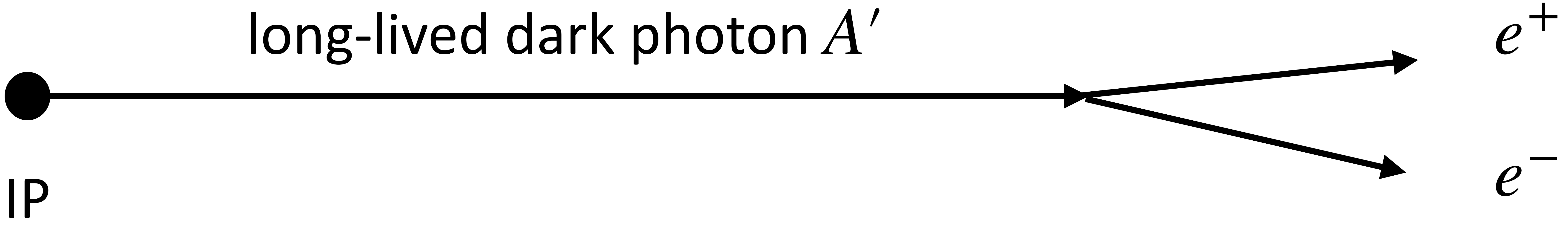

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long decay length $\Longrightarrow$ small coupling

2 Our new (long-lived) dark photon models

Long-lived dark photon signals

LLDP $\Longrightarrow$ small coupling $\Longrightarrow$ suppressed collider signals

[1503.06770]

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Go beyond the simple one U(1) picture

BSM theories can predict multiple U(1)'s, e.g. $SO(32)$ string theory [1503.06770]

Extend SM with 2 U(1)'s $SU(3)_c \times SU(2)_L \times U(1)_Y \times U(1)_X \times U(1)_C$

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Dirac fermion ψ charged under both U(1)'s $(g_F X_\mu + g_W C_\mu)\bar{\psi}\gamma^\mu\psi$

Two U(1)'s in the dark sector

$$SU(3)_c \times SU(2)_L \times U(1)_Y \times U(1)_X \times U(1)_C$$

[Du, ZL, Tran, 1912.00422]

Two U(1)'s in the dark sector

$$\mathscr{L}_F = -\frac{1}{4}X_{\mu\nu}^2 - \frac{1}{2}(\partial_\mu\sigma_1 + m_1\epsilon_1 B_\mu + m_1 X_\mu)^2$$

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$m_1 \sim \text{GeV} \Longrightarrow$ dark photon

$\epsilon_1 \sim 10^{-6} \Longrightarrow$ long-lived

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$$SU(3)_c \times SU(2)_L \times U(1)_Y \times U(1)_X \times U(1)_C$$

$m_2 \sim \text{TeV} \Longrightarrow Z'$

$\epsilon_2 \sim 10^{-2} \Longrightarrow$ production

$$\mathcal{L}_W = -\frac{1}{4}C_{\mu\nu}^2 - \frac{1}{2}(\partial_\mu\sigma_2 + m_2\epsilon_2 B_\mu + m_2 C_\mu)^2$$

[Du, ZL, Tran, 1912.00422]

mass matrix of neutral gauge bosons

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

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

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mass eigenstates: $E = (Z', A', Z, A)$ via $V_i = O_{ij}E_j$

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determinant = 0 $\Longrightarrow$ massless photon

[Du, ZL, Tran, 1912.00422]

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[Du, ZL, Tran, 1912.00422] $\epsilon_1 = 0 = \epsilon_2 \Longrightarrow$ decouple

vector and axial-vector couplings of neutral bosons

vector and axial-vector couplings between bosons & fermions

$$\bar{f}\gamma_\mu(v_i^f - \gamma_5 a_i^f)fE_i^\mu + v_i^\psi \bar{\psi}\gamma_\mu\psi E_i^\mu$$

[Du, ZL, Tran, 1912.00422]

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$$v_i^f = (g\mathcal{O}_{4i} - g'\mathcal{O}_{3i})T_f^3/2 + g'\mathcal{O}_{3i}Q_f$$

SM fermion v

$$a_i^f = (g\mathcal{O}_{4i} - g'\mathcal{O}_{3i})T_f^3/2$$

SM fermion a

[Du, ZL, Tran, 1912.00422]

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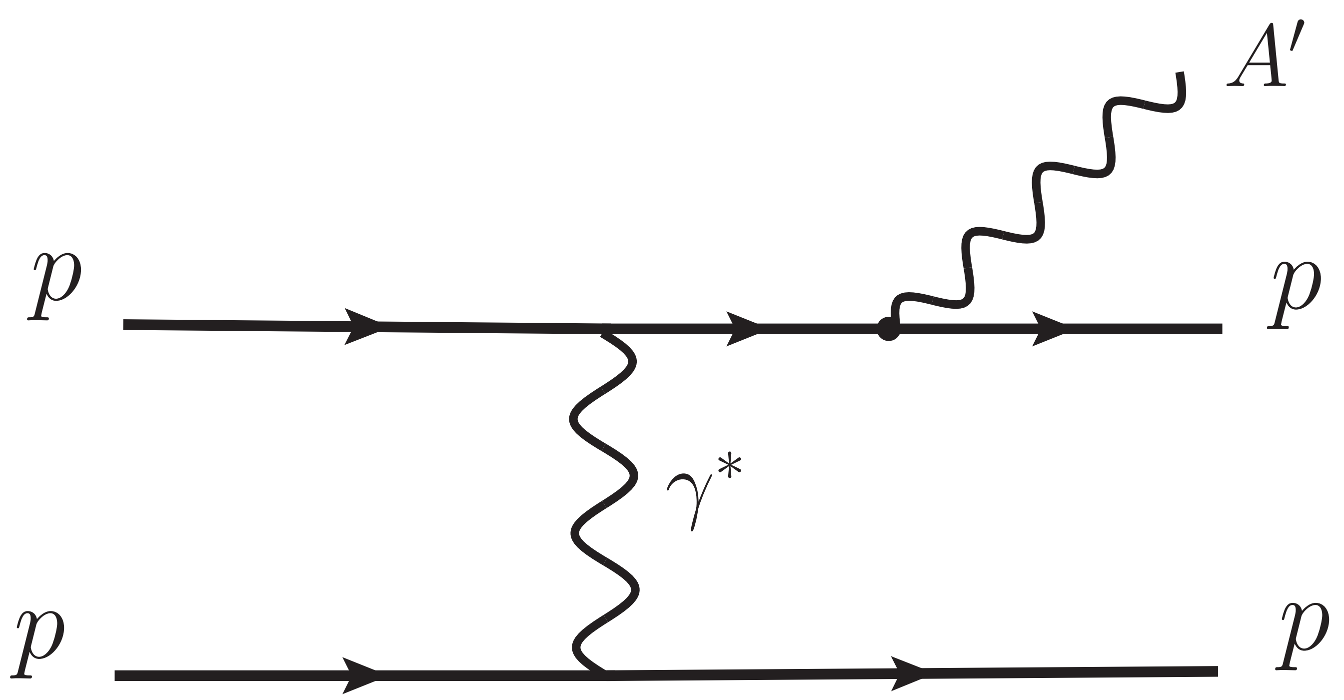
SM fermion a

$$v_i^\psi = g_W\mathcal{O}_{1i} + g_F\mathcal{O}_{2i}$$

dark sector

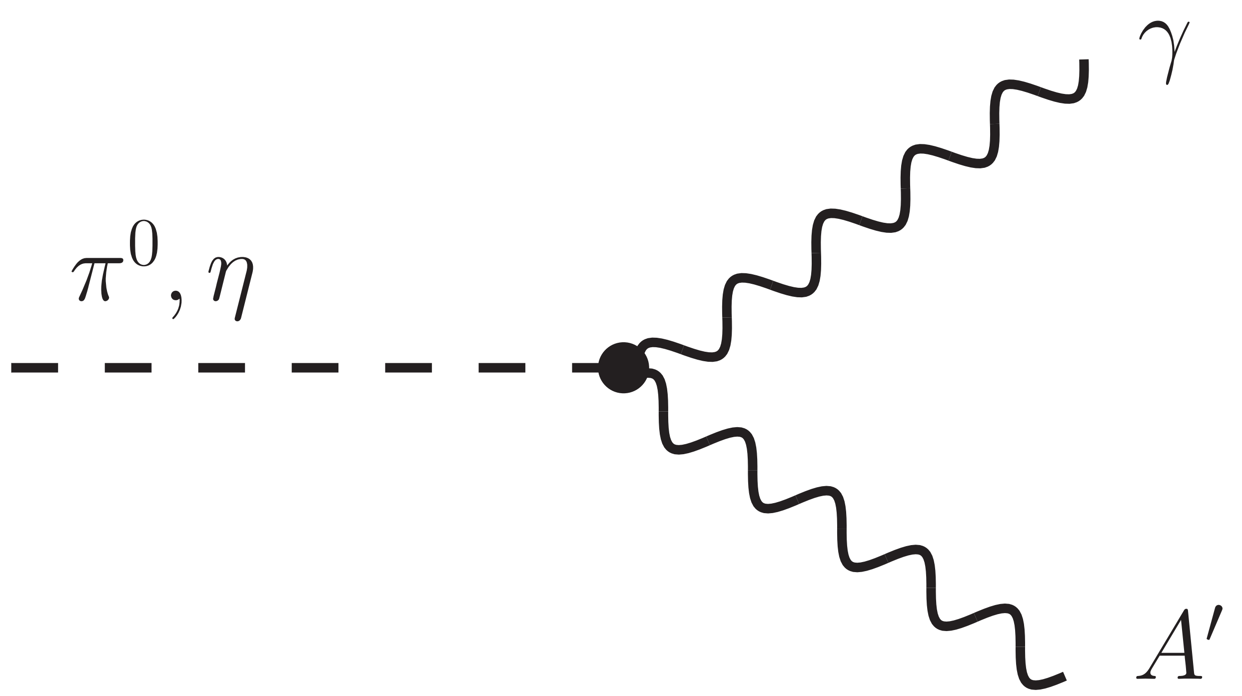
[Du, ZL, Tran, 1912.00422]

three dark photon production channels at the LHC

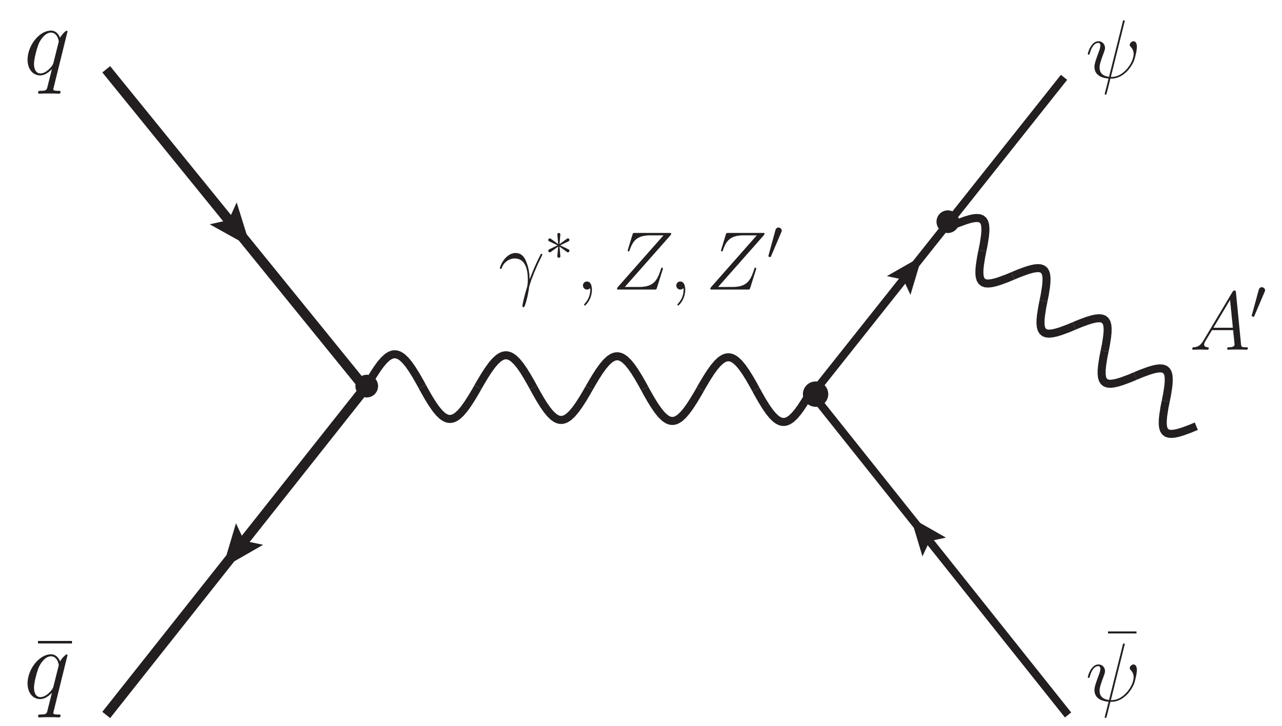


proton bremsstrahlung

[see e.g., Feng+ 1708.09389]



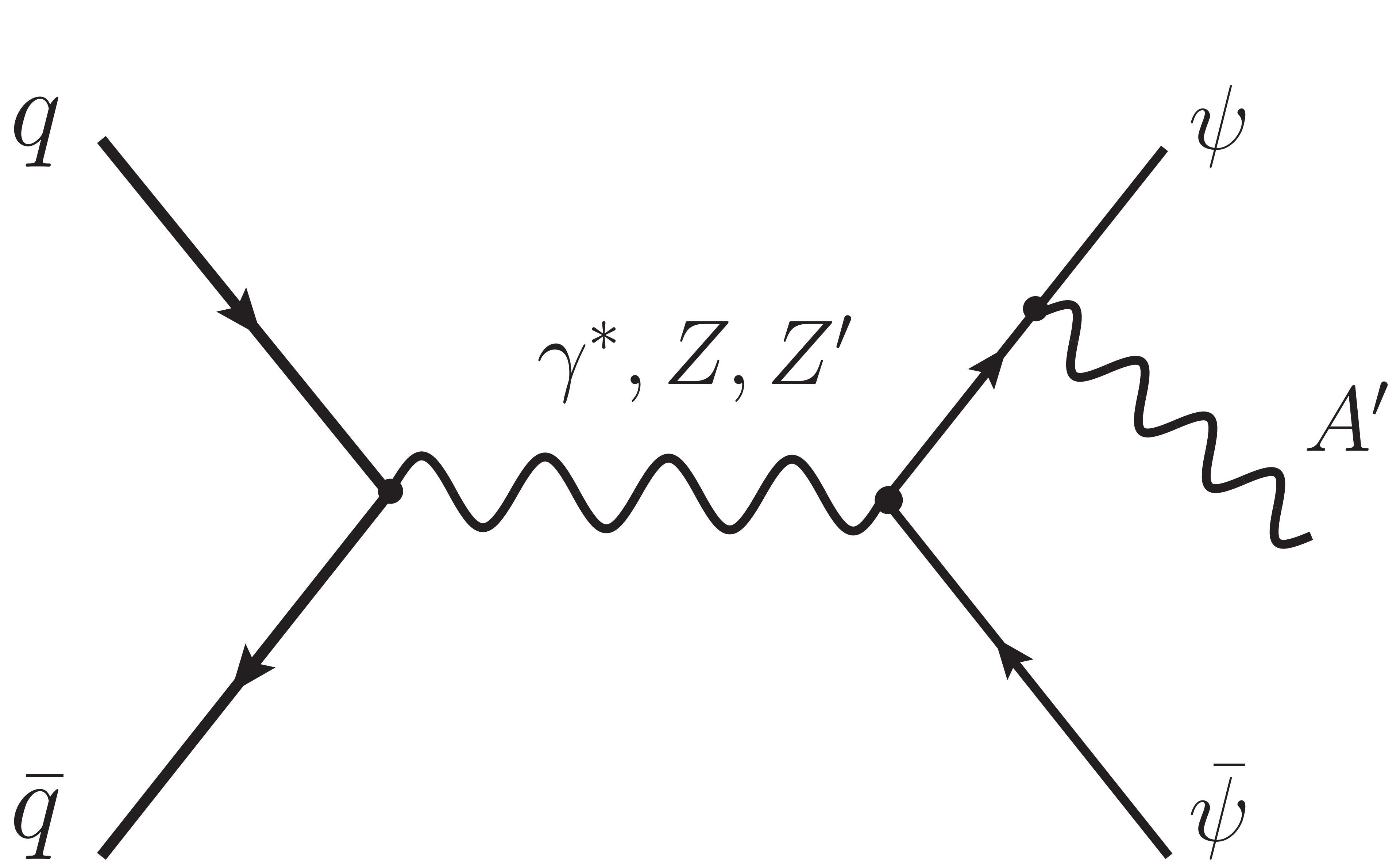
meson decay

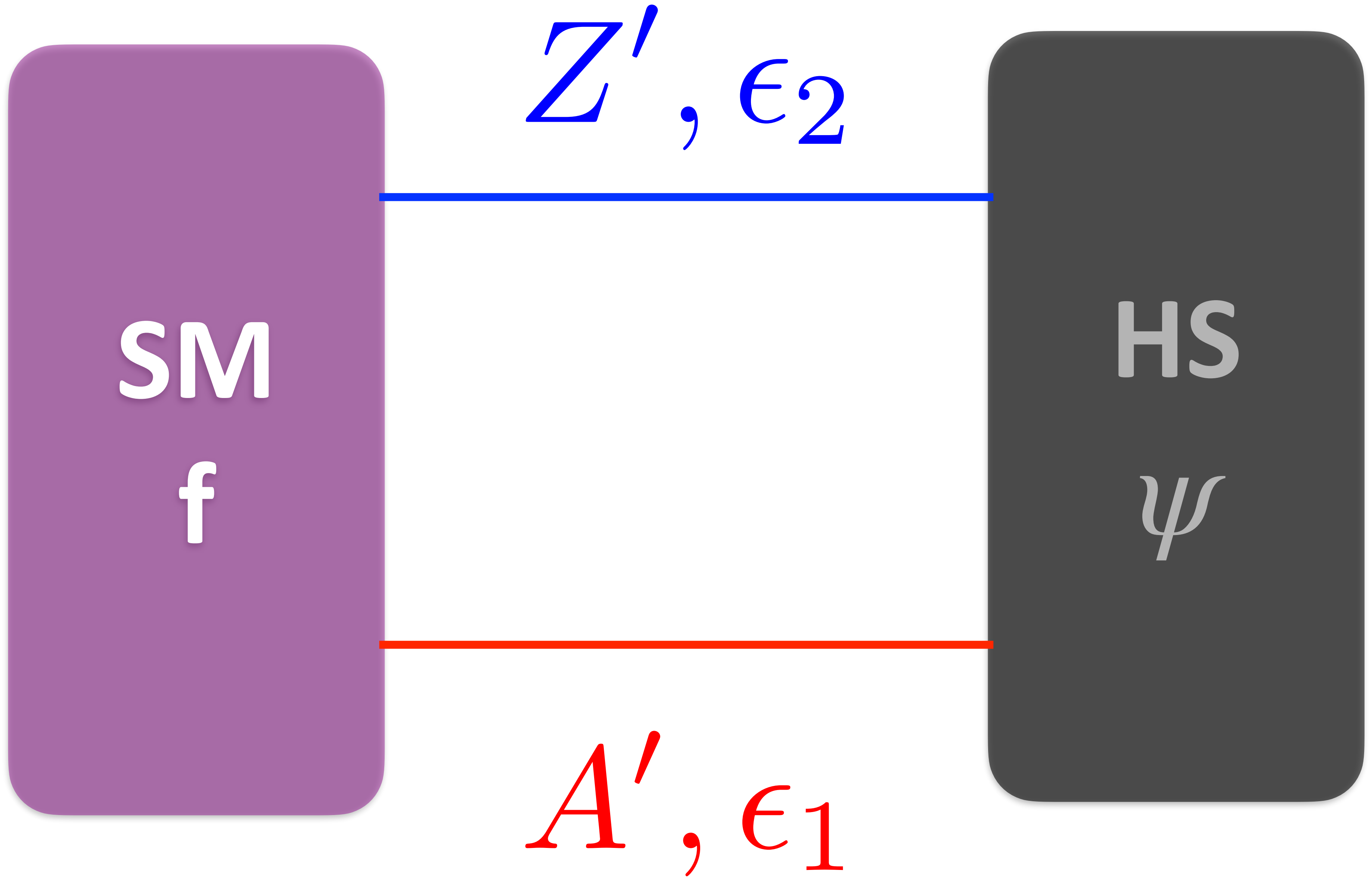


hidden radiation

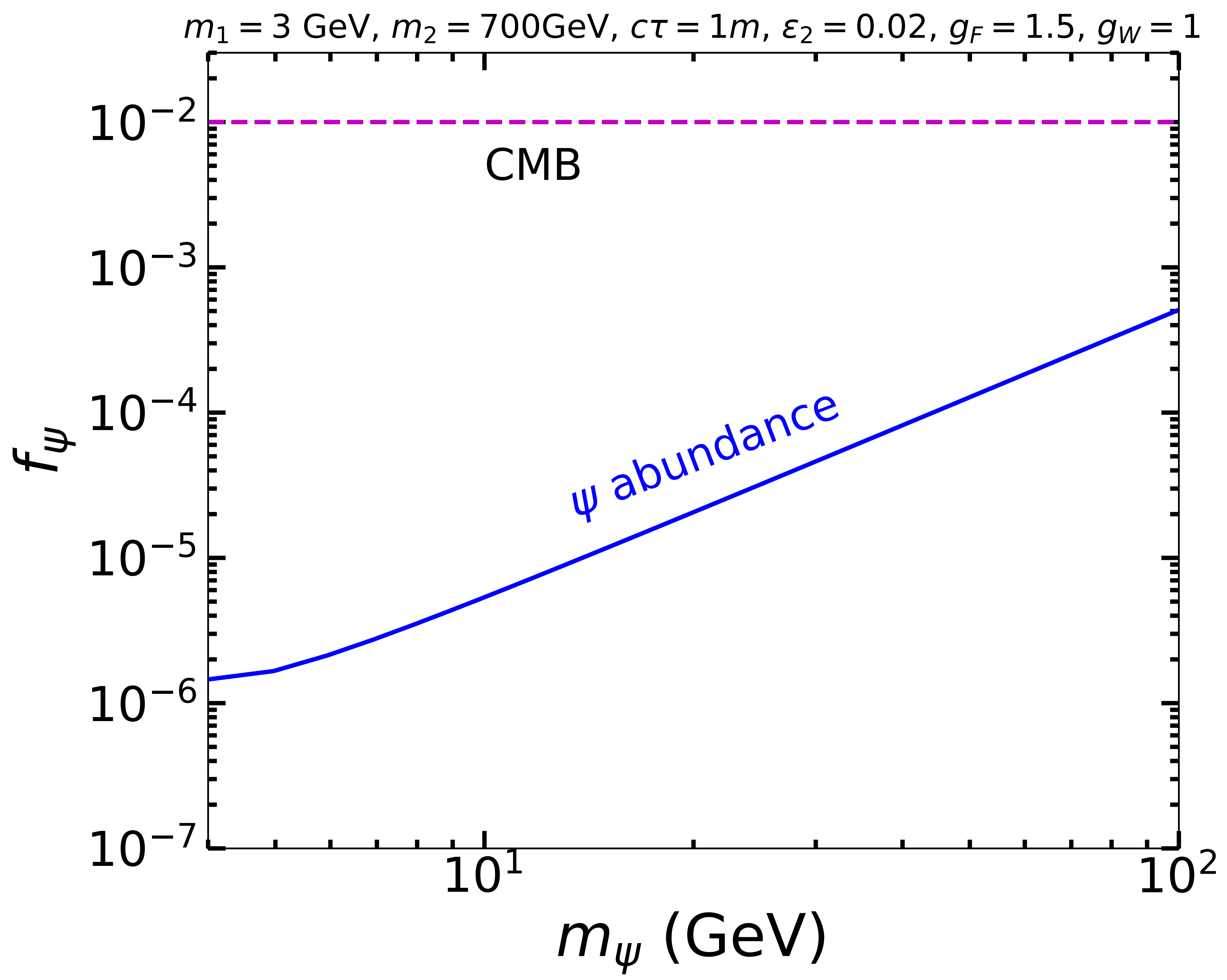
[Du, ZL, Tran, 1912.00422]

hidden radiation channel

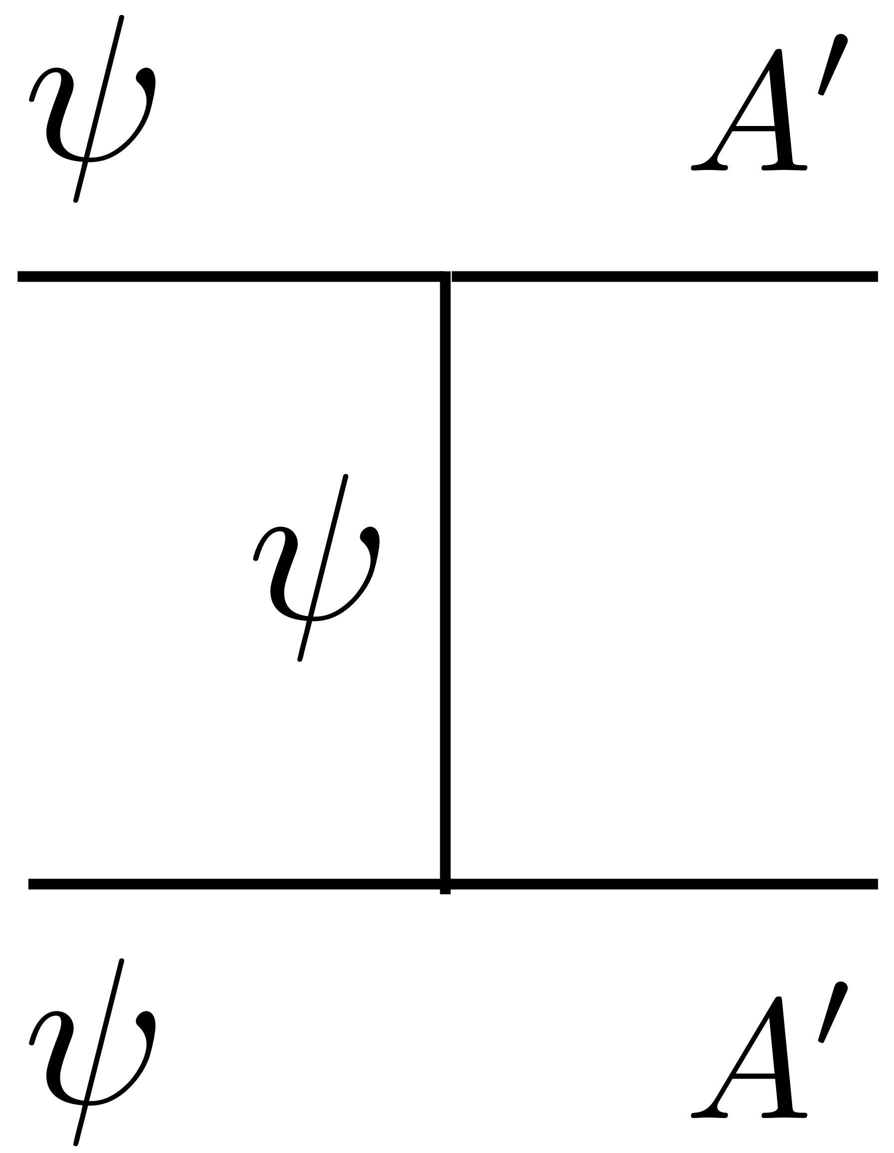




millicharged dark matter constraints

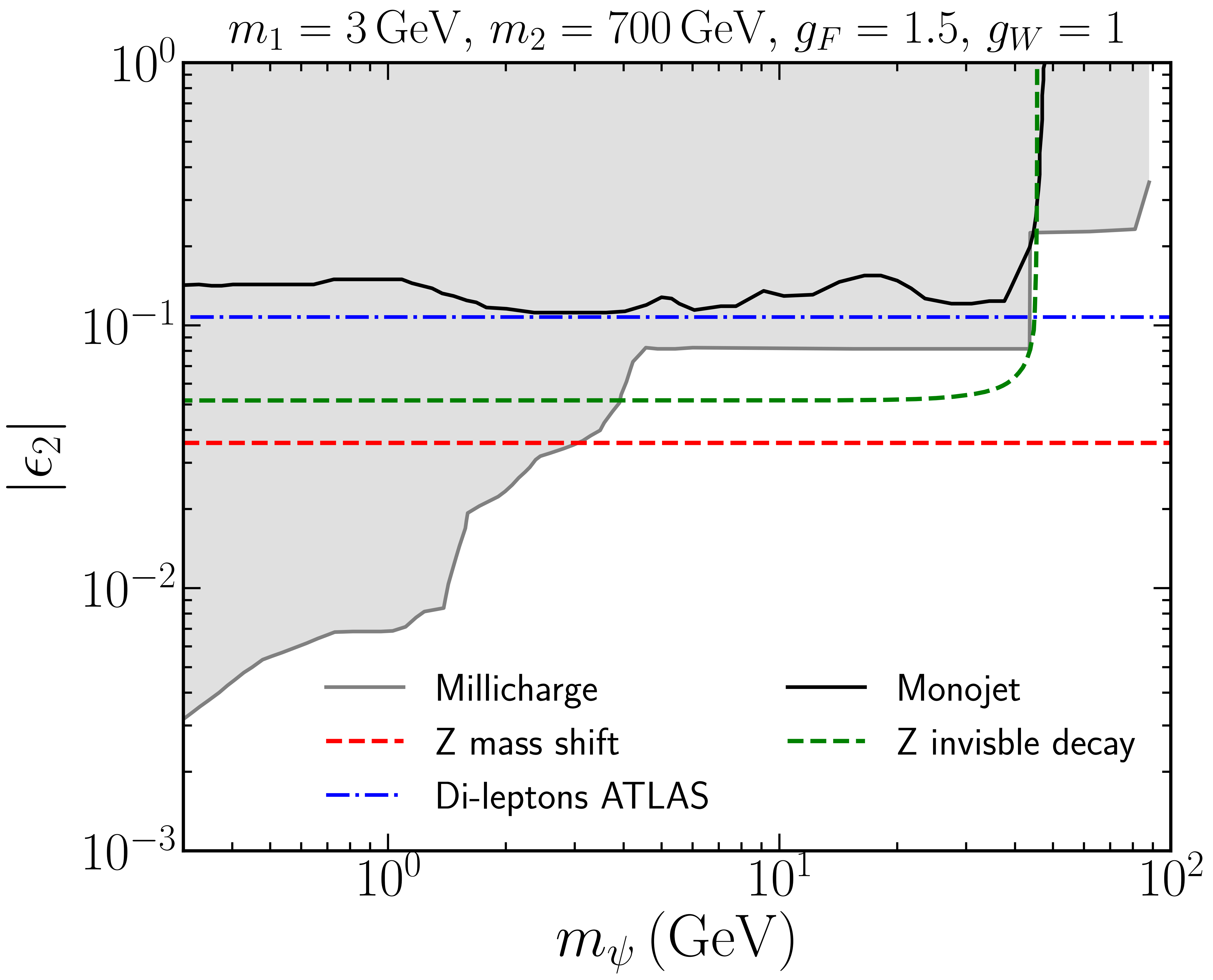


millicharged DM abundance < 0.4%



[see. e.g. Kovetz+ 1807.11482, Boddy+ 1808.00001, Puttter+ 1805.11616]

experimental constraints



More recent constraints on millicharged particles from SENSEI, BEBC, Super-K etc

[2305.04964]

[2011.08153]

[2211.11469]

[Du, Fang, ZL, Tran, PRD, 2111.15503]

3 Long-lived dark photon signals @ the LHC

lifetime frontier detectors

3 types detectors: (1) far forward, (2) far transverse, (3) near timing

Detector	η	Distance from IP (m)	Decay volume (m^3)	LHC runs
FACET [3,4]	[6, 7.2]	100 (upstream)	12.3	Run 4 (2027)
FASER [5–9]	>9	480 (downstream)	0.047	Run 3 (2022)
FASER2 [9,10]	>6.87	480 (downstream)	15.7	HL-LHC
AL3X [11]	[0.9, 3.7]	5.25 (upstream)	915.2	Run 5 (2032)
MoEDAL-MAPP [12]	$\sim$3.1	55 (upstream)	$\sim$150	Run 3 (2022)
CODEX-b [18,19]	[0.14, 0.55]	26 (transverse)	10^3	Run 4 (2027)
MATHUSLA [13–17]	[0.64, 1.43]	60 (transverse)	2.5×10^5	HL-LHC
ANUBIS [20]	[0.06, 0.21]	24 (transverse)	$\sim 1.3 \times 10^4$	HL-LHC
CMS-MTD [21]	[−3, 3]	1.17 (barrel), 3.04 (endcaps)	25.4	HL-LHC
ATLAS-HGTD [22]	[2.4, 4]	3.5 (endcaps)	8.7	HL-LHC
LHCb-TORCH [23,24]	[1.6, 4.9]	9.5 (beam direction)	$\cdots$	HL-LHC

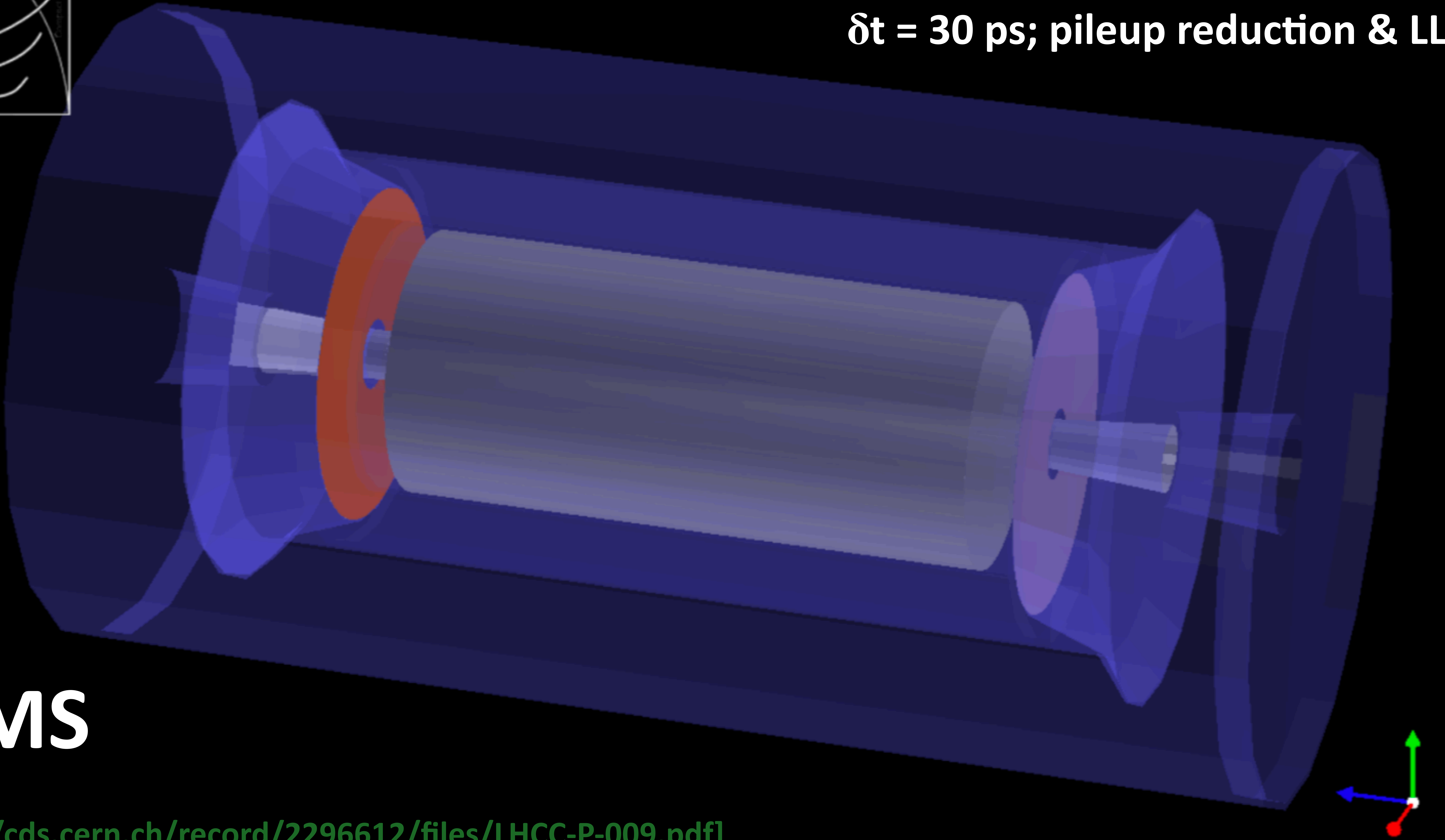
[Du, Fang, ZL, Tran, PRD, 2111.15503]

Timing detectors at ATLAS/CMS/LHCb

- CMS-TMD
- ATLAS-HGTD
- LHC-TORCH

between tracker & calorimeter

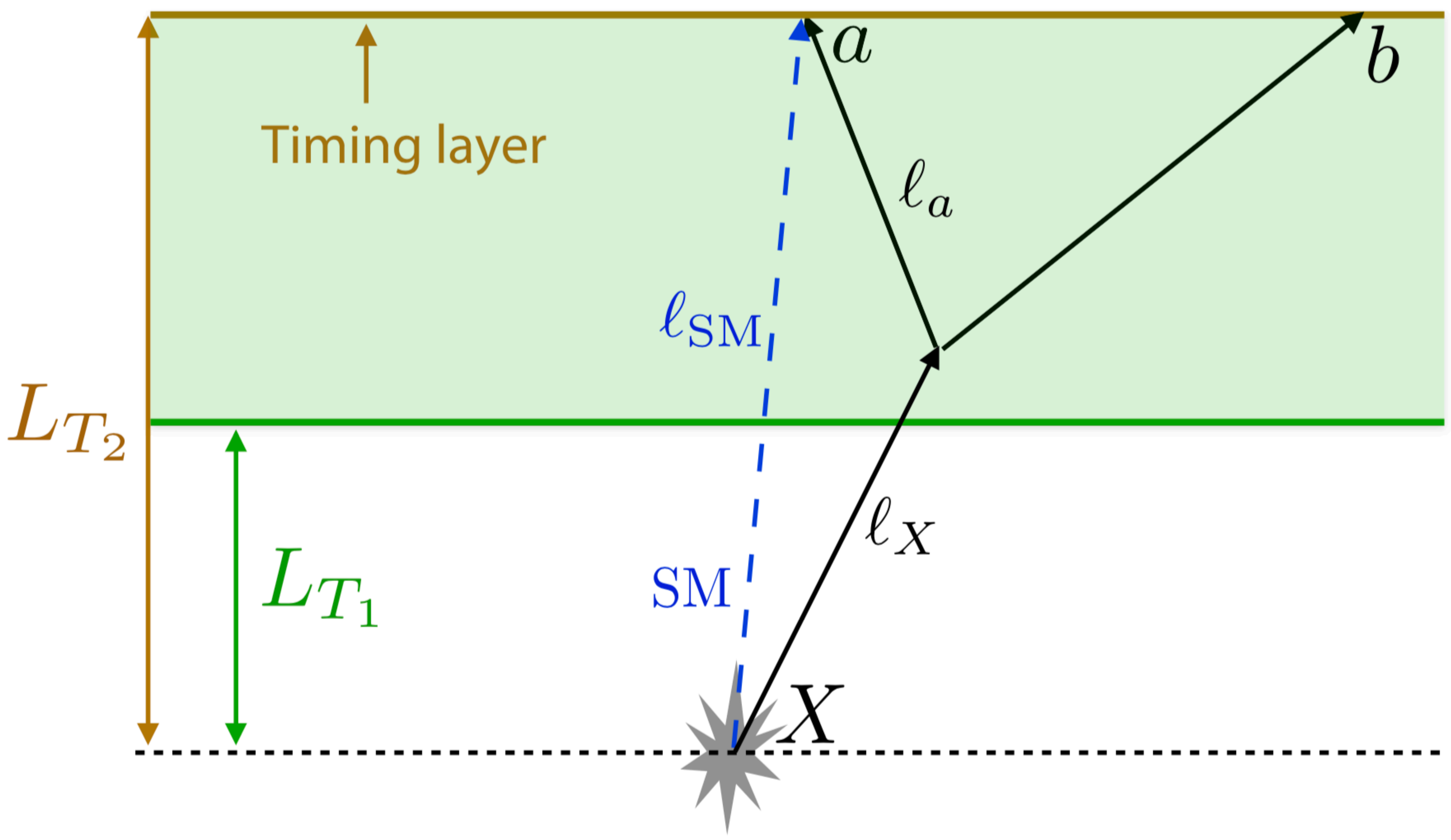
δt = 30 ps; pileup reduction & LLP



CMS

[https://cds.cern.ch/record/2296612/files/LHCC-P-009.pdf]

Time delay for NR long-lived particles



time delay for NR LLP

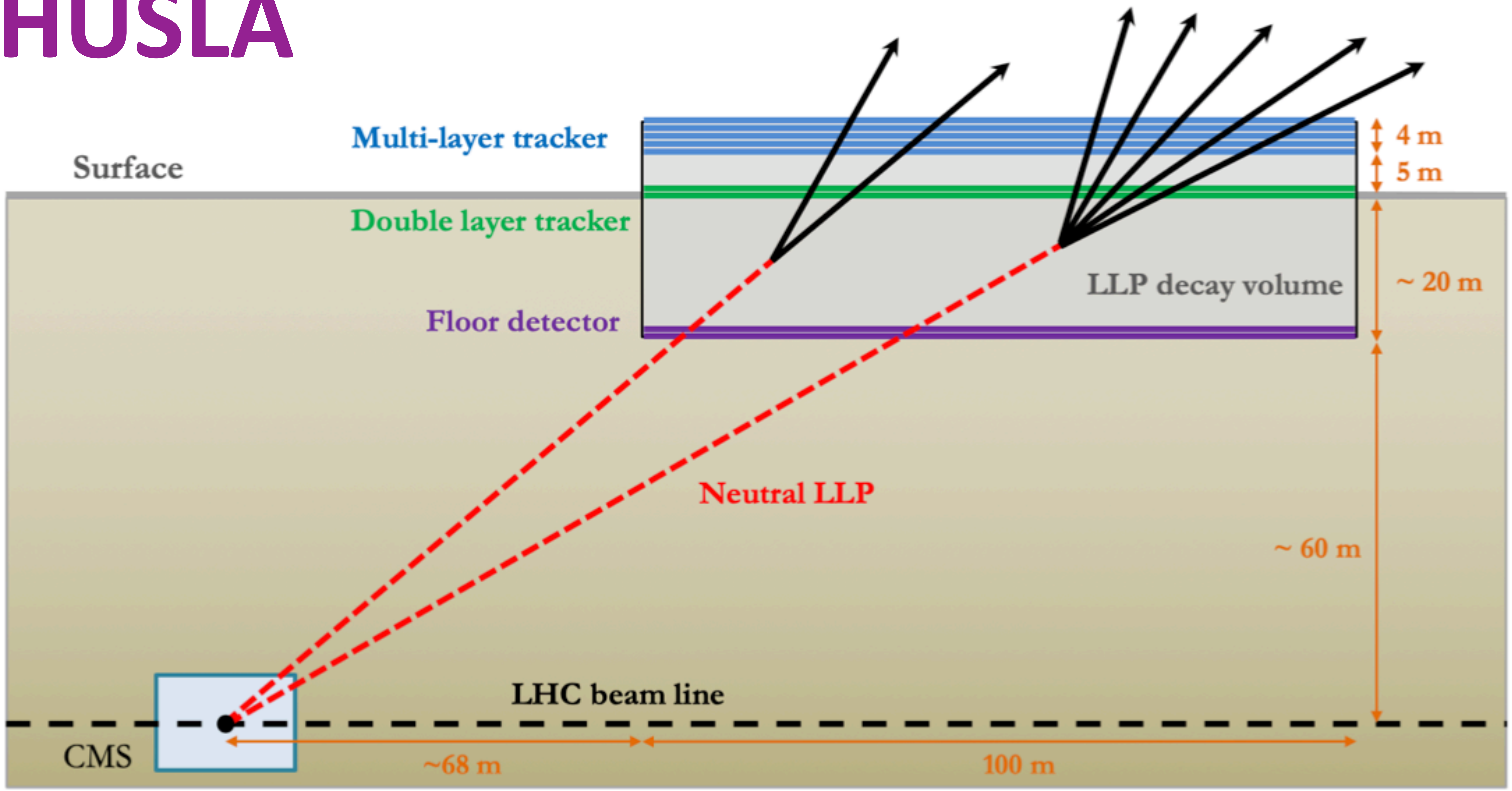
$$\Delta t = \frac{\ell_X}{\beta_X} + \frac{\ell_a}{\beta_a} - \frac{\ell_{SM}}{\beta_{SM}}$$

[Liu, Liu, Wang, 1805.05957]

Transverse detectors

- CODEX-b
- MATHUSLA
- ANUBIS

MATHUSLA

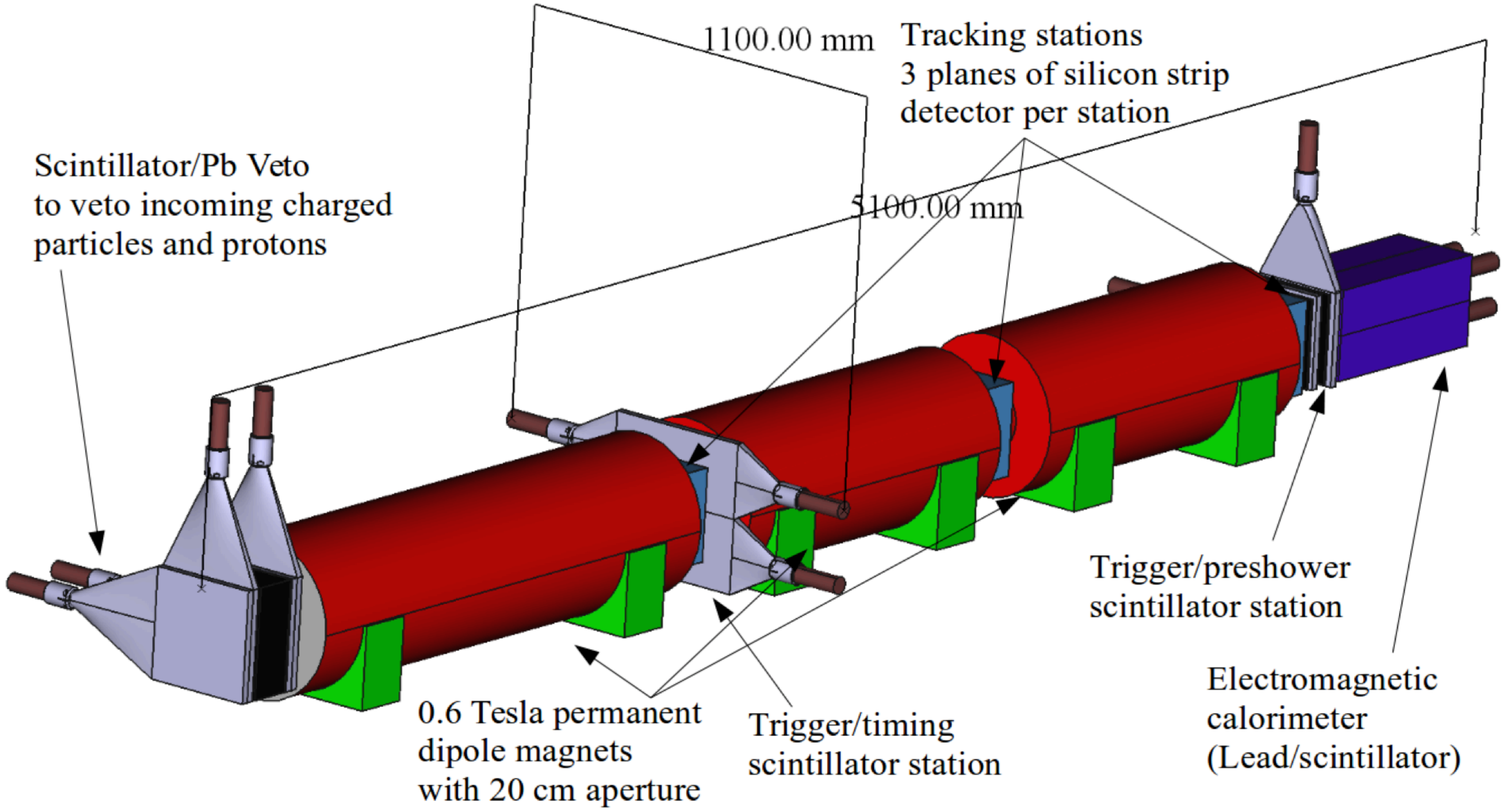


[MATHUSLA, 2009.01693]

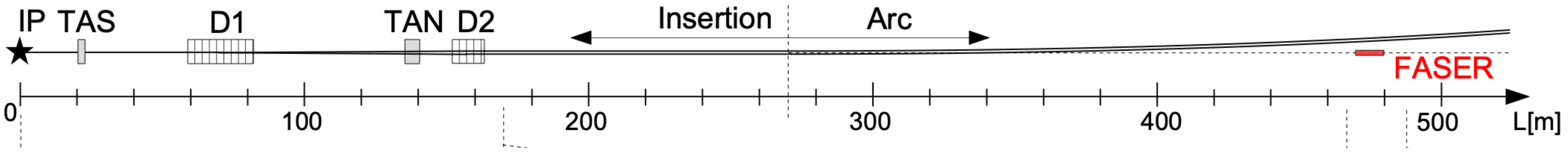
Far detectors

- FASER and FASER2
- FACET

FASER



[FASER 1901.00468]



[see 2308.05587 for FASER's new results]

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FACET: a new long-lived particle detector in the very forward region of the CMS experiment

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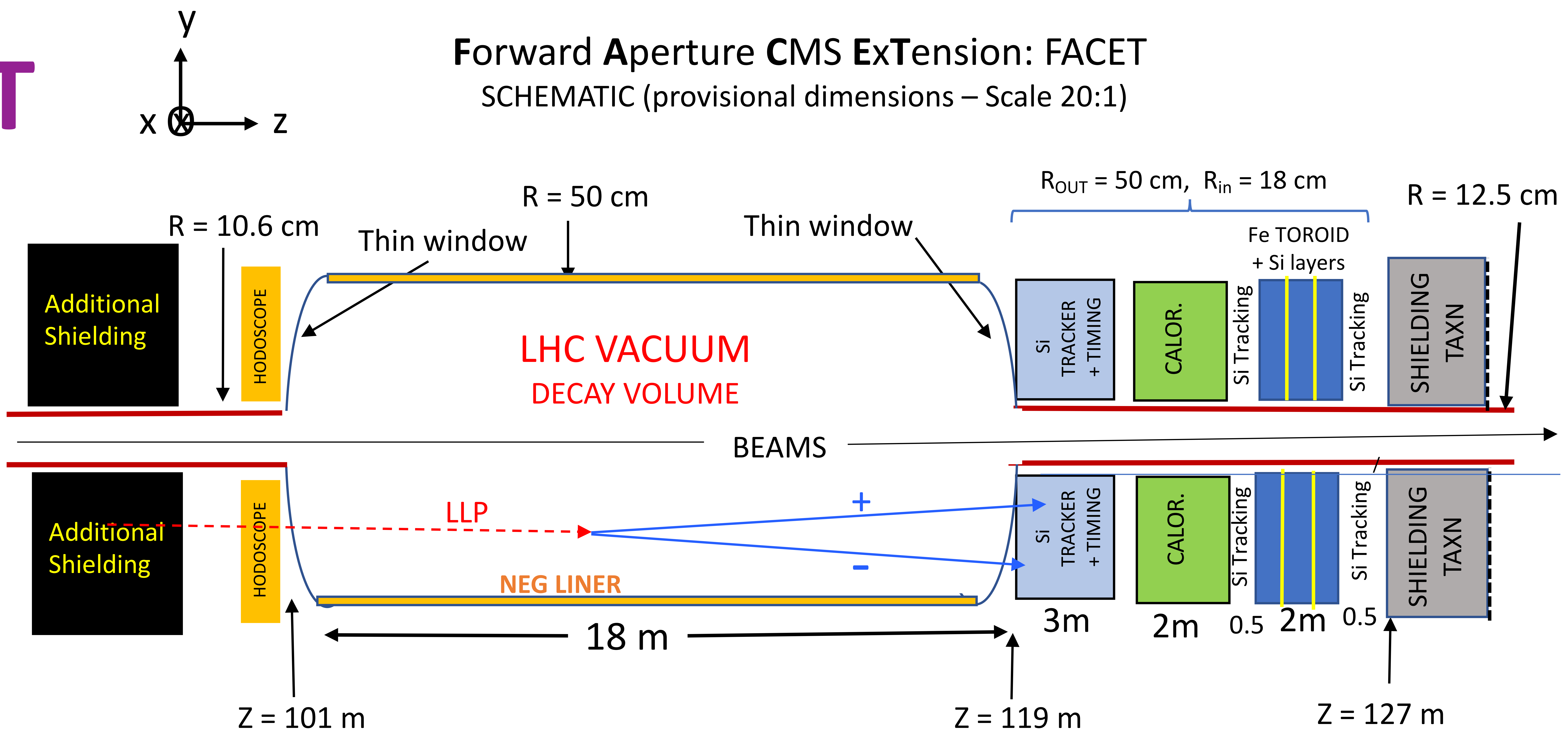
FACET



100 meter from CMS

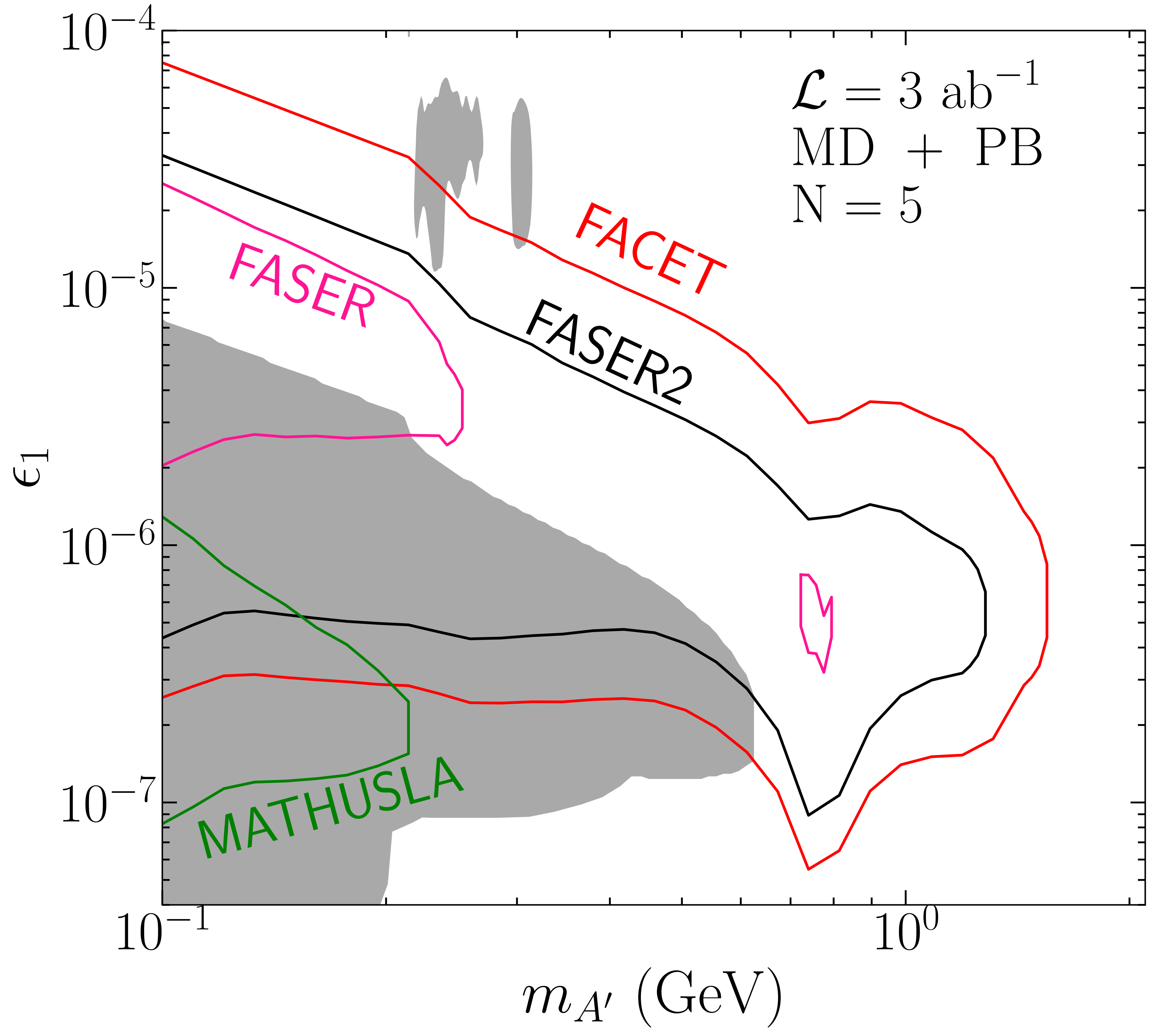
R = 50 cm pipe (vacuum)

[FACET, JHEP, 2201.00019]

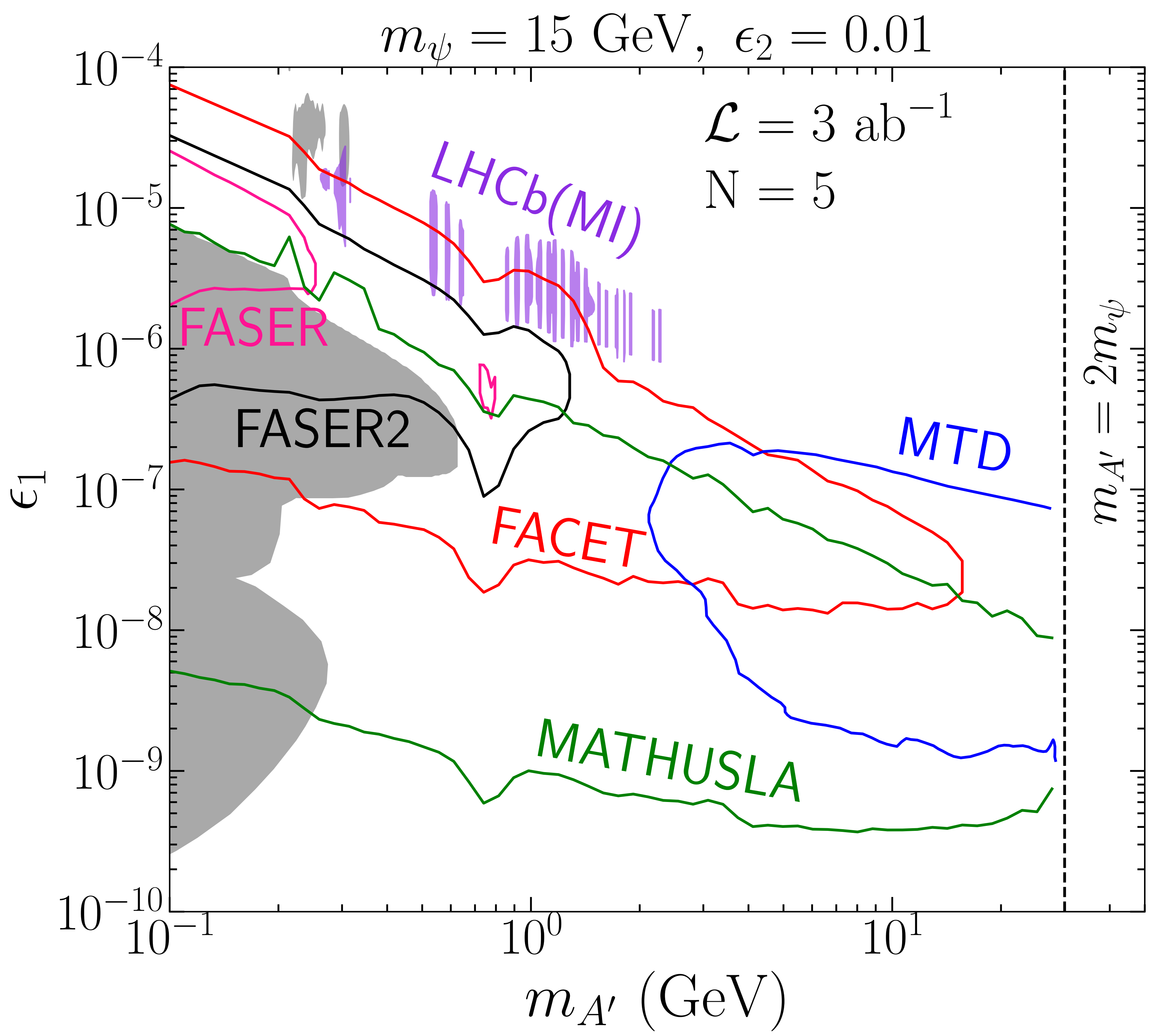
[see Albrow's talk for variants]

Sensitivities from lifetime frontier detectors

Minimal DP

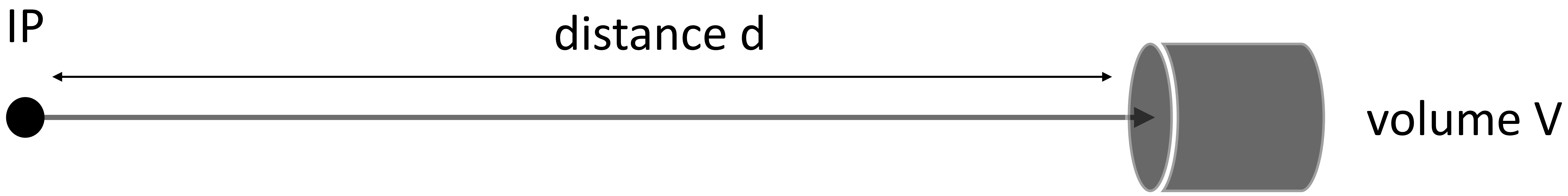


New DP model



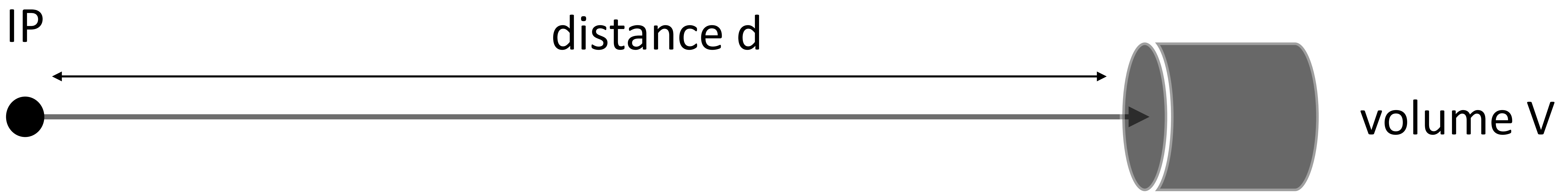
[Du, Fang, ZL, Tran, 2111.15503]

Sensitivities from different detectors on LLDP



[Du, Fang, ZL, Tran, PRD, 2111.15503]

Sensitivities from different detectors on LLDP



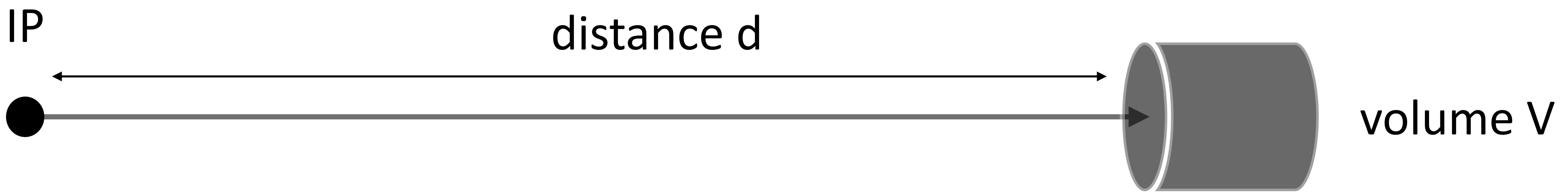
probability of decaying at distance L:

(suppressed at large L, but NOT at small L)

$$\frac{dP}{dL} = \frac{1}{L_{A'}} \exp\left(-\frac{L}{L_{A'}}\right)$$

[Du, Fang, ZL, Tran, PRD, 2111.15503]

Sensitivities from different detectors on LLDP



probability of decaying at distance L:

(suppressed at large L, but NOT at small L)

$$\frac{dP}{dL} = \frac{1}{L_{A'}} \exp\left(-\frac{L}{L_{A'}}\right)$$

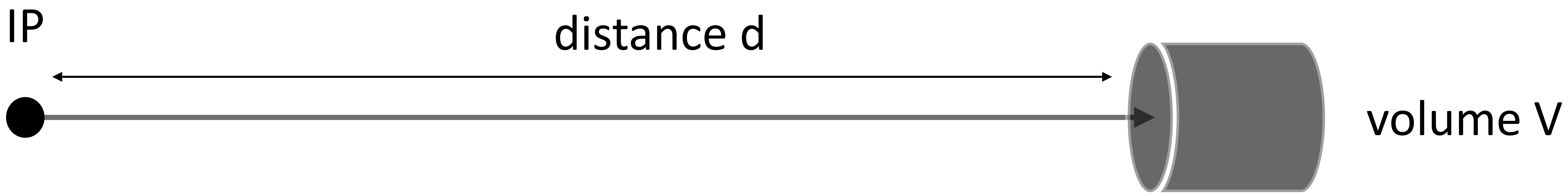
ratio between 2 far detectors

(assuming isotropic)

$$\frac{N_1}{N_2} = \frac{V_1}{V_2}\left[\frac{d_2}{d_1}\right]^2 \exp\left[-\frac{d_1 - d_2}{L_{A'}}\right]$$

[Du, Fang, ZL, Tran, PRD, 2111.15503]

Sensitivities from different detectors on LLDP



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ratio between 2 far detectors
(assuming isotropic)

$$\frac{N_1}{N_2} = \frac{V_1}{V_2}\left[\frac{d_2}{d_1}\right]^2 \exp\left[-\frac{d_1 - d_2}{L_{A'}}\right]$$

larger & closer to IP is better
(geometrical, w/o BG)

$$\frac{N_{\rm FACET}}{N_{\rm FASER(2)}} \simeq 7 \times 10^3\,(20)\ \exp\left[\frac{380\,\rm m}{L_{A'}}\right]$$

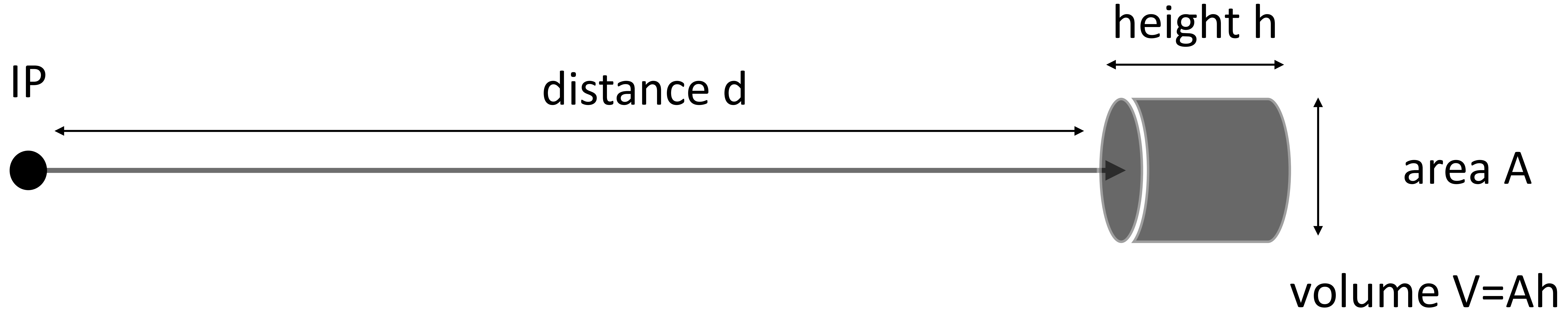
[Du, Fang, ZL, Tran, PRD, 2111.15503]

Summary

- Minimal dark photon models have suppressed long-lived dark photon signals at the LHC
- We build a new model by extending the SM with two U(1) gauge fields in the dark sector, where the dark photon is produced via another gauge boson and is not suppressed
- We study a new dark photon production channel at the LHC: hidden radiation, in additional to the proton bremsstrahlung and meson decay channels
- Far detectors (FASER & FACET) and timing detectors (CMS, ATLAS, LHCb) are sensitive to long-lived dark photons with small and large masses, respectively

additional slides

LLDP decays inside a far detector



probability of decaying at distance L: $$\frac{dP}{dL} = \frac{1}{L_{A'}} \exp\left(-\frac{L}{L_{A'}}\right)$$

probability of decaying in $(d, d+h)$: $$P = \frac{h}{L_{A'}} \exp\left(-\frac{d}{L_{A'}}\right)$$

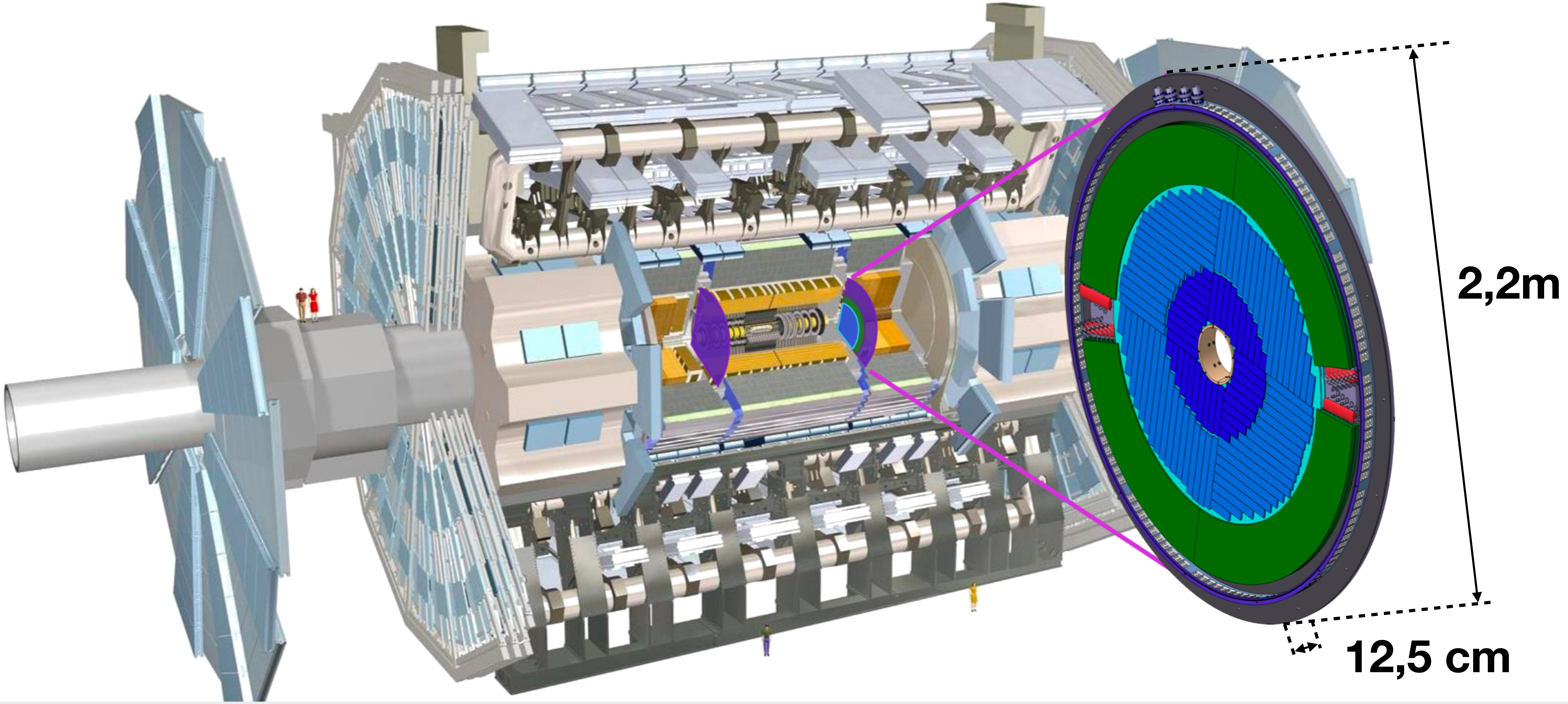
(for $h \ll d$)

LLDP decays inside volume V $$N \simeq N_{\rm IP} \frac{A}{4\pi d^2} P = N_{\rm IP} \frac{1}{4\pi} \frac{V}{d^3} \exp\left[-\frac{d}{L_{A'}}\right] \frac{d}{L_{A'}}$$

High-Granularity Timing Detector

- ATLAS upgrade detector for the high luminosity - LHC
- uses LGAD sensors to measure time with **σ_t~30-50ps per track** until end of HL-LHC
- covers range **$2.4 \leq |\eta| \leq 4.0$**
- two disks positioned at z = ±3.5m from the interaction point

[taken from Leopold's talk]



LHCb-TORCH

[CERN-LHCC-2017-003]

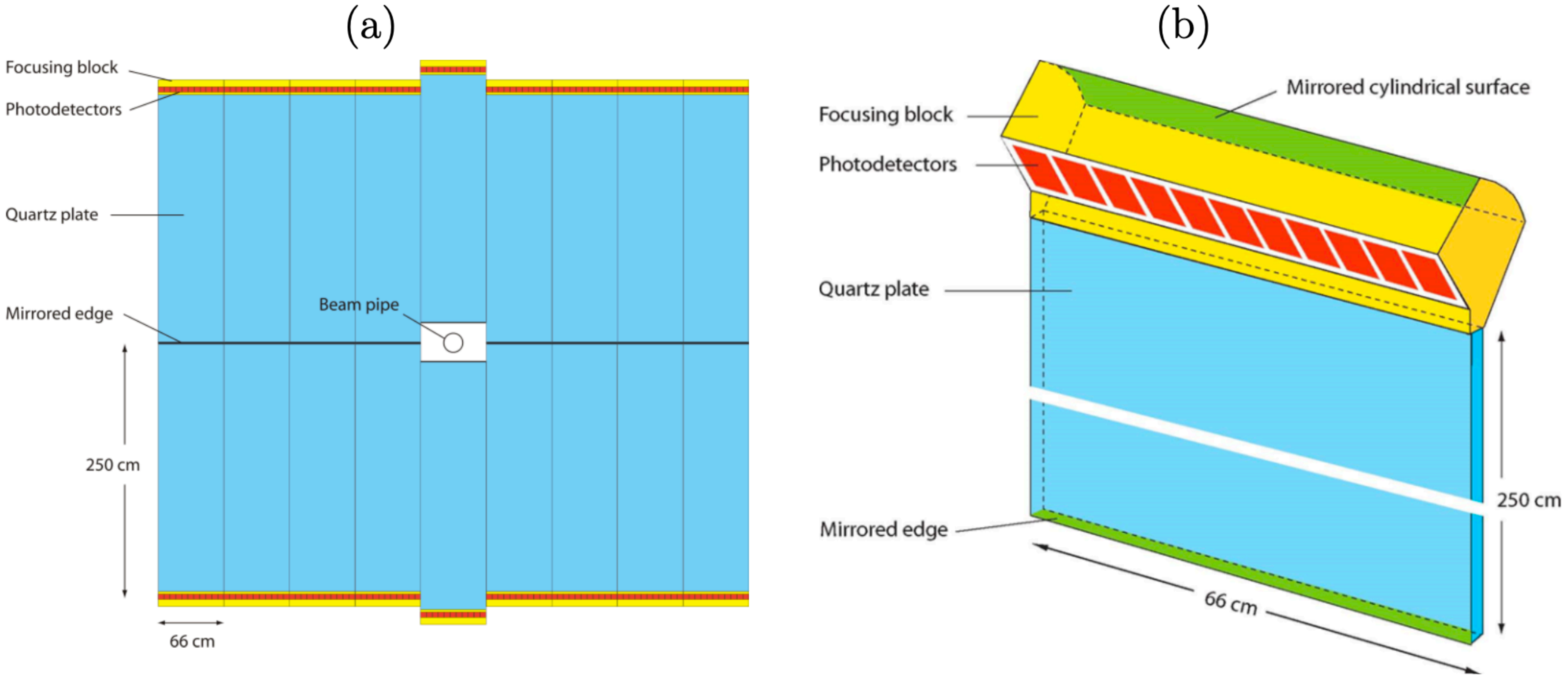


Figure 4.9: Schematic of TORCH detector for LHCb: (a) Front-on view of full detector; (b) View of single module showing focusing block and photodetector plane.

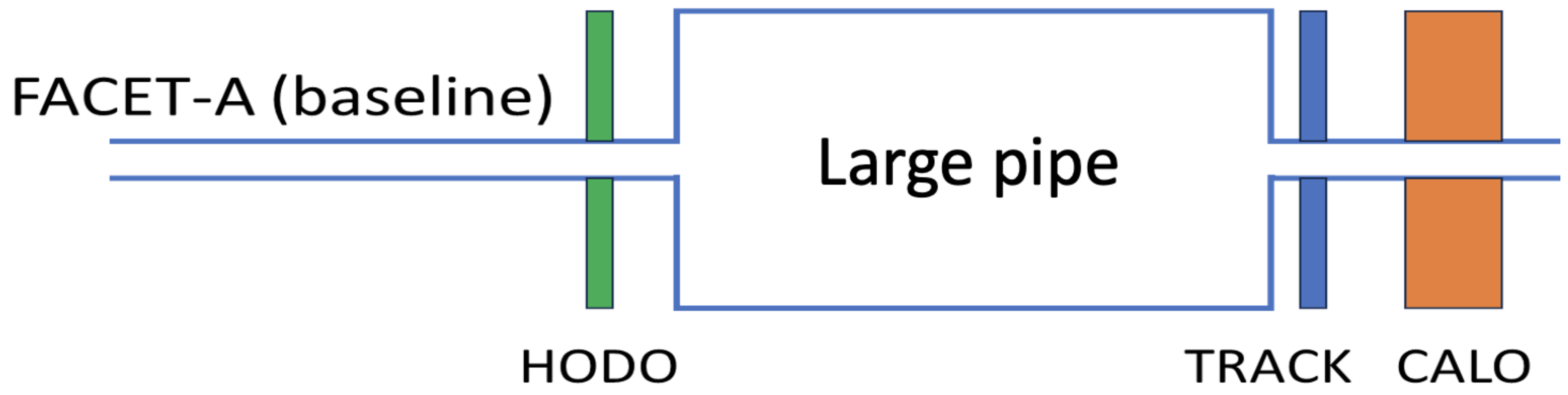
The precision of each track in the TORCH system is 15 ps

Mike Albrow 20231025

FACET FUTURE OPTIONS

Contributions mainly:
Mike Albrow
Deniz Sunar Cerci
Salim Cerci
Suat Ozkorucuklu
Aldo Penzo
Burak Hacisahinoglu
Orhan Aydilek
+

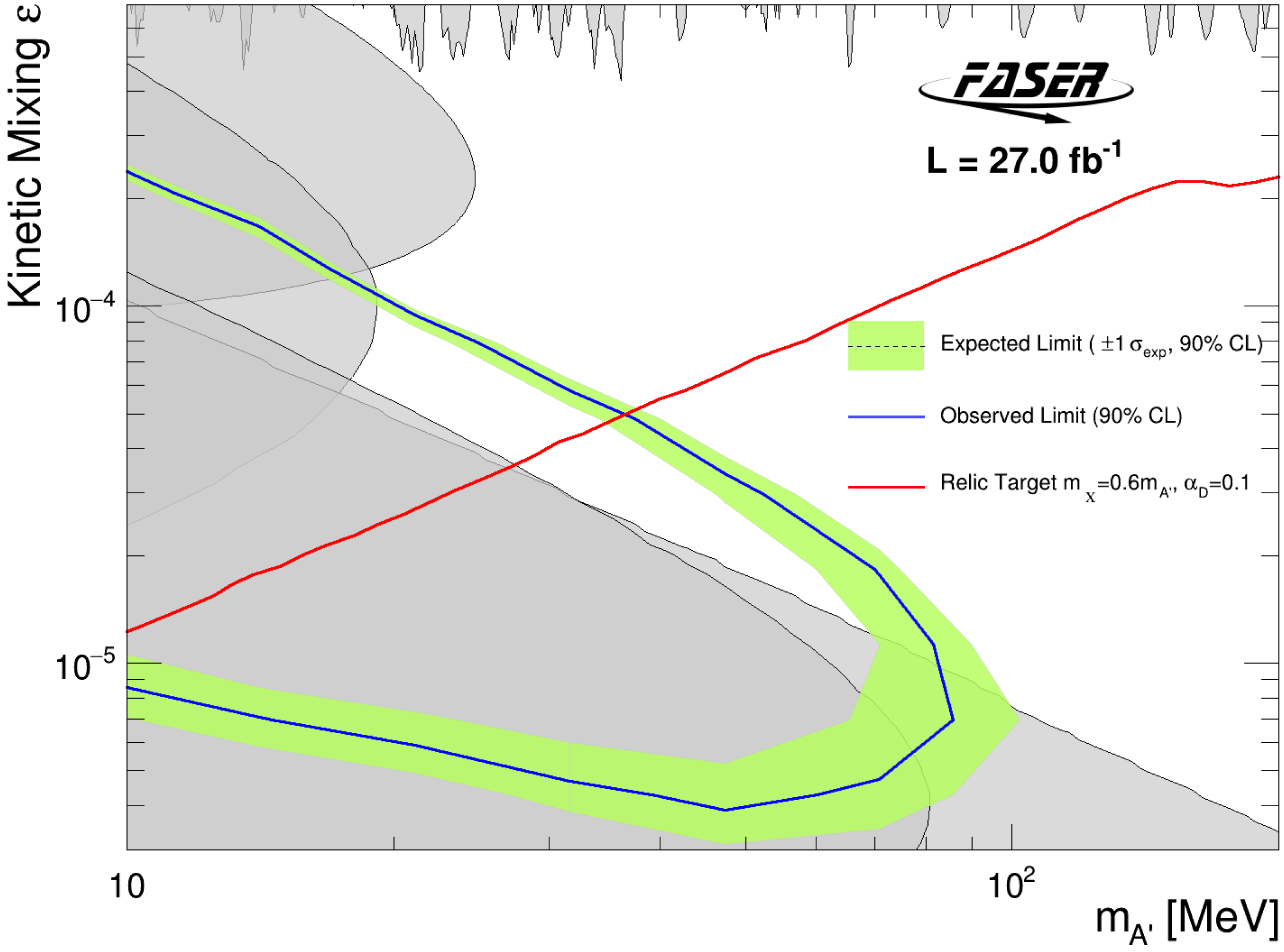
FACET – A (baseline) with ***large*** pipe as JHEP paper
but with beam pipe optimized for background reduction:



(Too late for Run4: Plan for Run 5 subject to feasibility from more studies)
FACET – B (variant) with ***standard*** pipe, detectors as FACET-A (full azimuth):
(Possible for Run4 – but would need modifications to LHC, e.g pipe supports)
FACET – C (variant) ***above standard*** pipe :
(smaller acceptance, no mods to LHC, easiest option. Area shown nominal example)

FACET

[Albrow's talk]



FASER

[2308.05587]