Probing dark sector particles in colliders

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Outline

- **Long-lived (LL) dark photons @ LHC**
  - **Timing detector**
  - **LHCb**

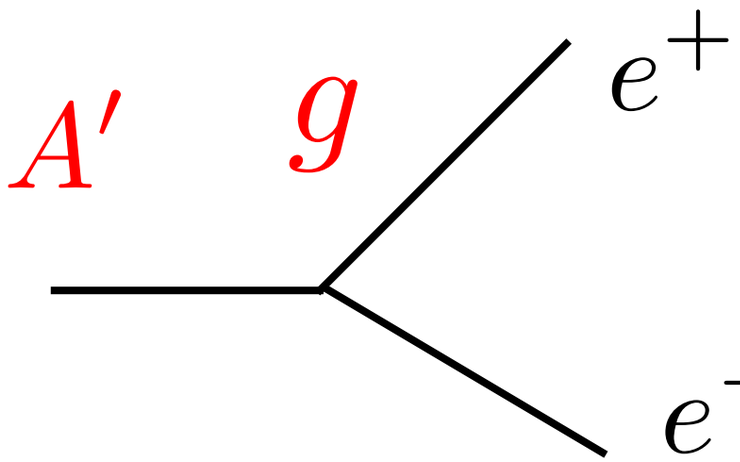
[Du, ZL, Tran, 1908.xxxxx]

- **Millicharged particles @ electron colliders**
  - **Belle II**
  - **STCF**
  - **BESIII**
  - **BaBar**

[Liang, ZL, Ma, Zhang, 1908.xxxxx]

Long-lived (LL) particles @ LHC

LL particles in a variety of BSM models



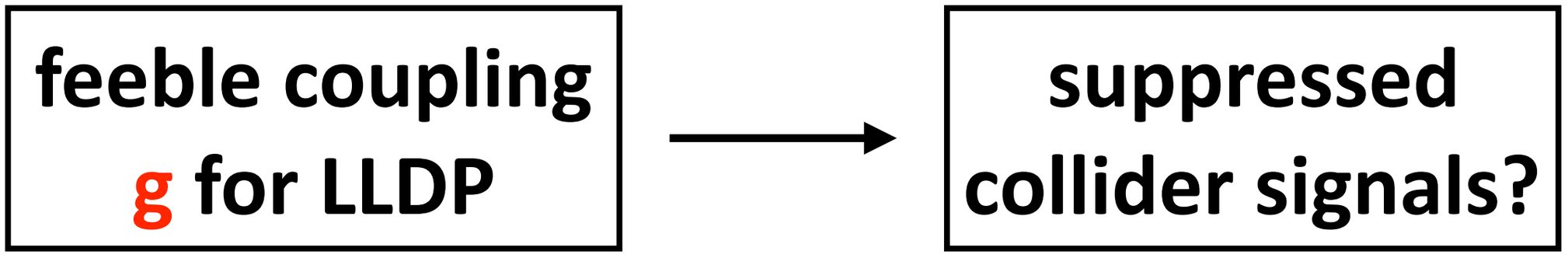
Dark photon (DP)
w/ coupling g to e

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

distance travelled by long-lived dark photon (LLDP)

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

Enhance LLDP production xsec



We construct a model in which LLDP is produced via a different channel from its decay

SM extended by a dark sector w/ two U(1) gauge bosons & one Dirac fermion

[Du, ZL, Tran, 1908.xxxxx]

SM extension with two U(1)

Extending SM w/ 2 U(1) & Stueckelberg terms

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

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

$U(1)_Y$: B_μ in SM

$U(1)_F$: X_μ in hidden sector, $m_1 \sim$ GeV, $\varepsilon_1 \sim 10^{-7}$

$U(1)_W$: C_μ in hidden sector, $m_2 \sim$ TeV, $\varepsilon_2 \sim 10^{-2}$

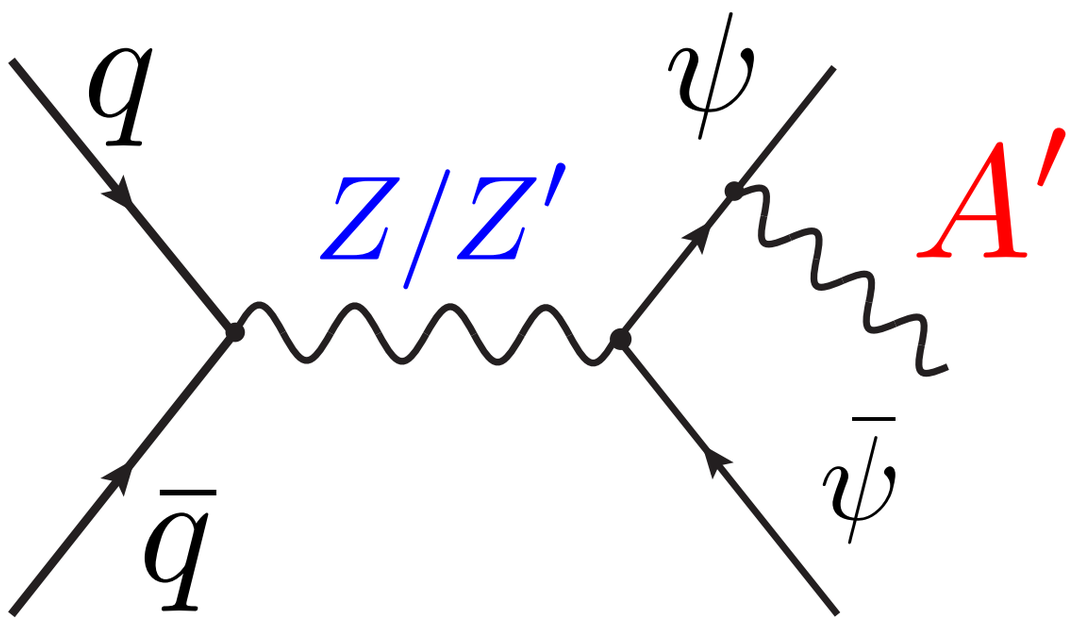
→ **GeV dark photon A' & TeV Z'**

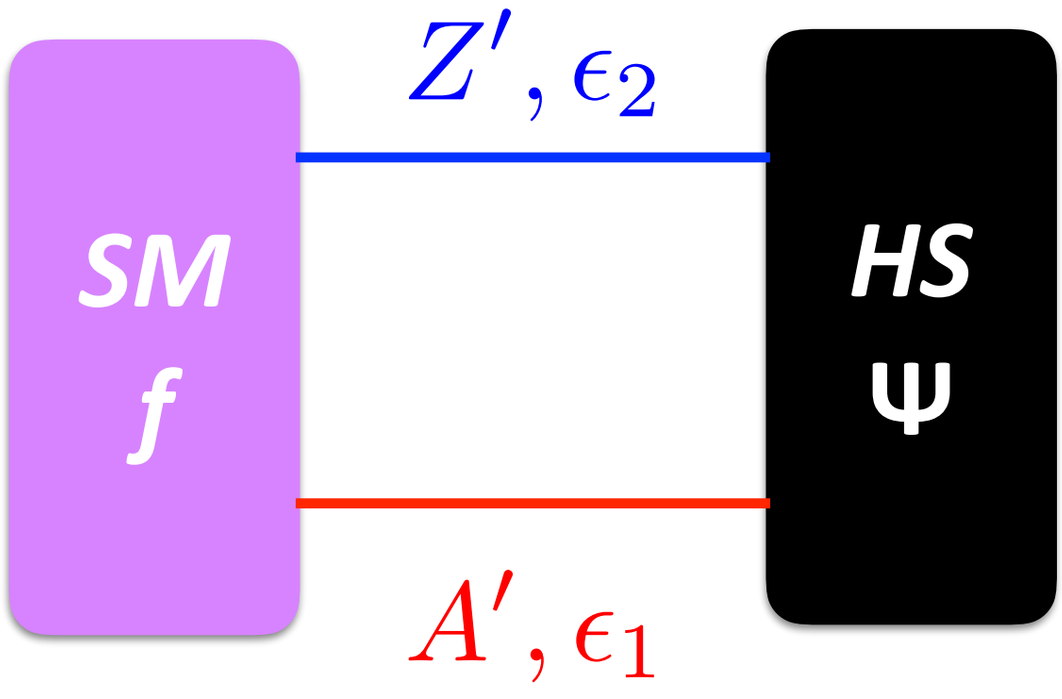
LLDP production @ LHC

hidden sector fermion Ψ charged under 2 U(1)

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

LLDP production via Z/Z' process





Ψ is DM candidate

Mass matrix of neutral gauge bosons

4 by 4 mass square matrix in V = (C, X, B, A³)

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

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

Det(m²)=0 ⇒ massless photon mode

Vector & axial-vector couplings

v & a couplings between bosons & fermions

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

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

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

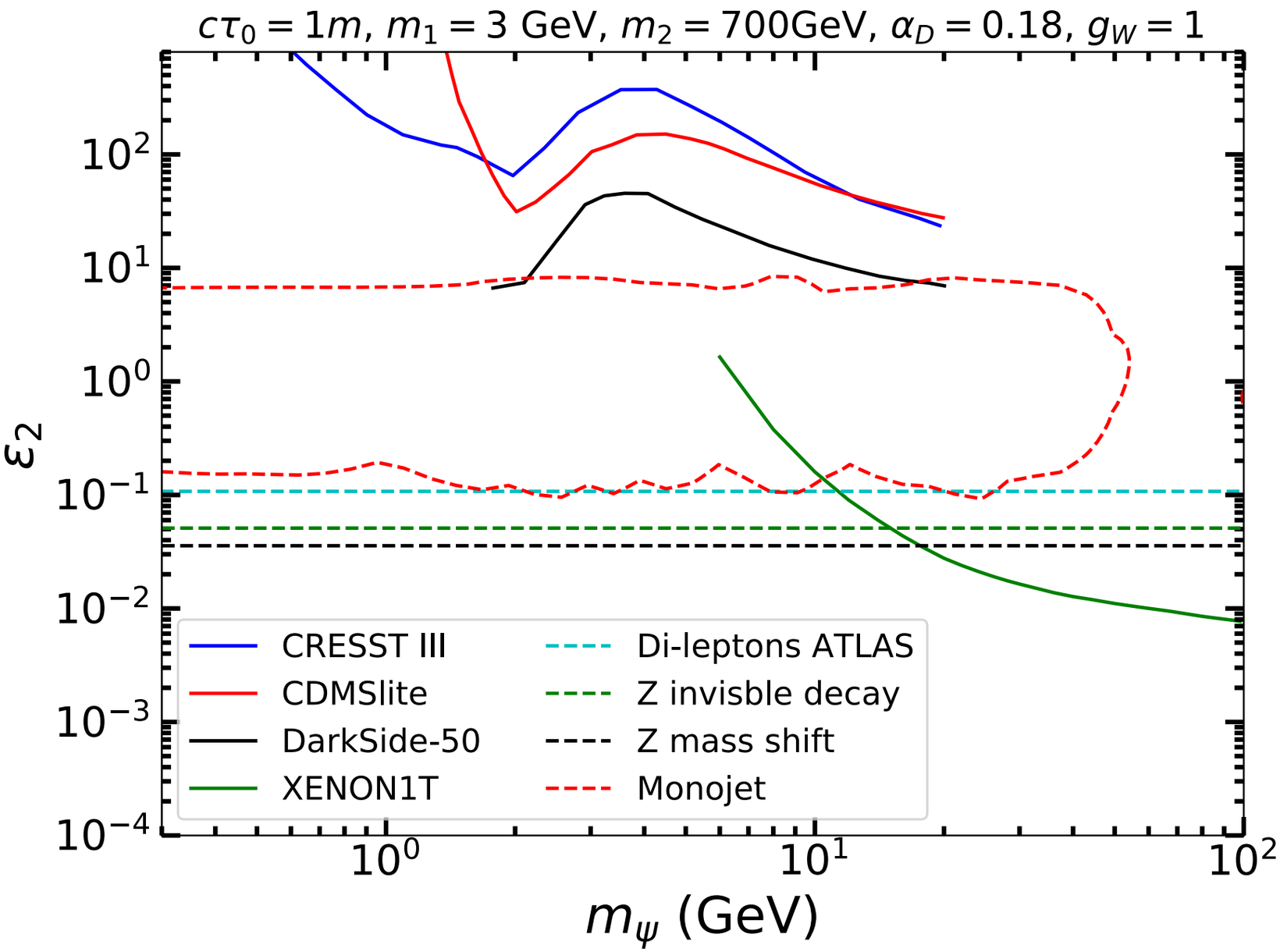
$$v_i^\psi = g_W\mathcal{O}_{1i} + g_F\mathcal{O}_{2i}$$

E = (Z', A', Z, A)

A': dark photon

Z': hypercharge-like

Experimental constraints

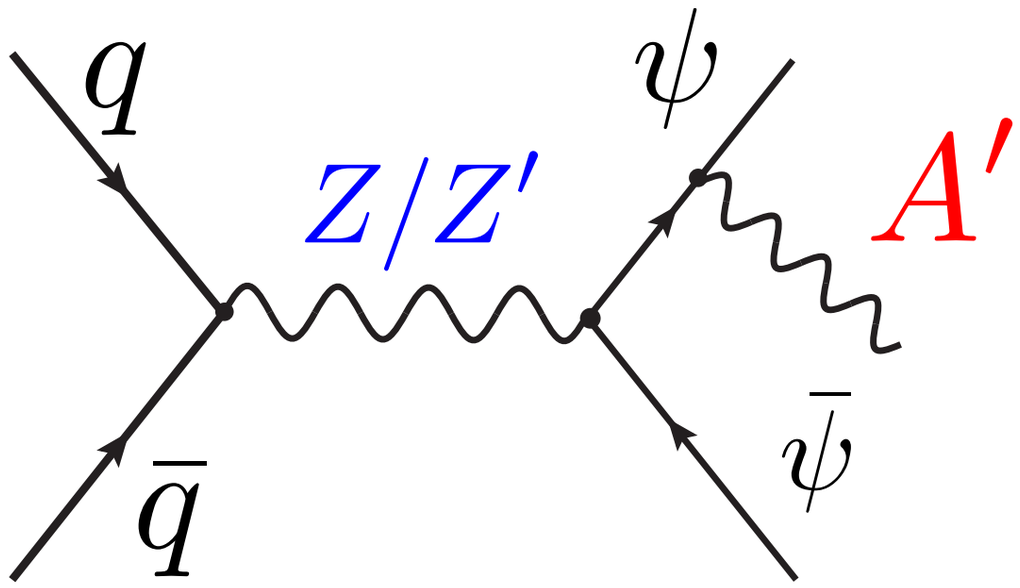


DMDD (solid)

collider (dashed)

DM relic abundance is suppressed in freeze-out

DP radiation in the dark sector

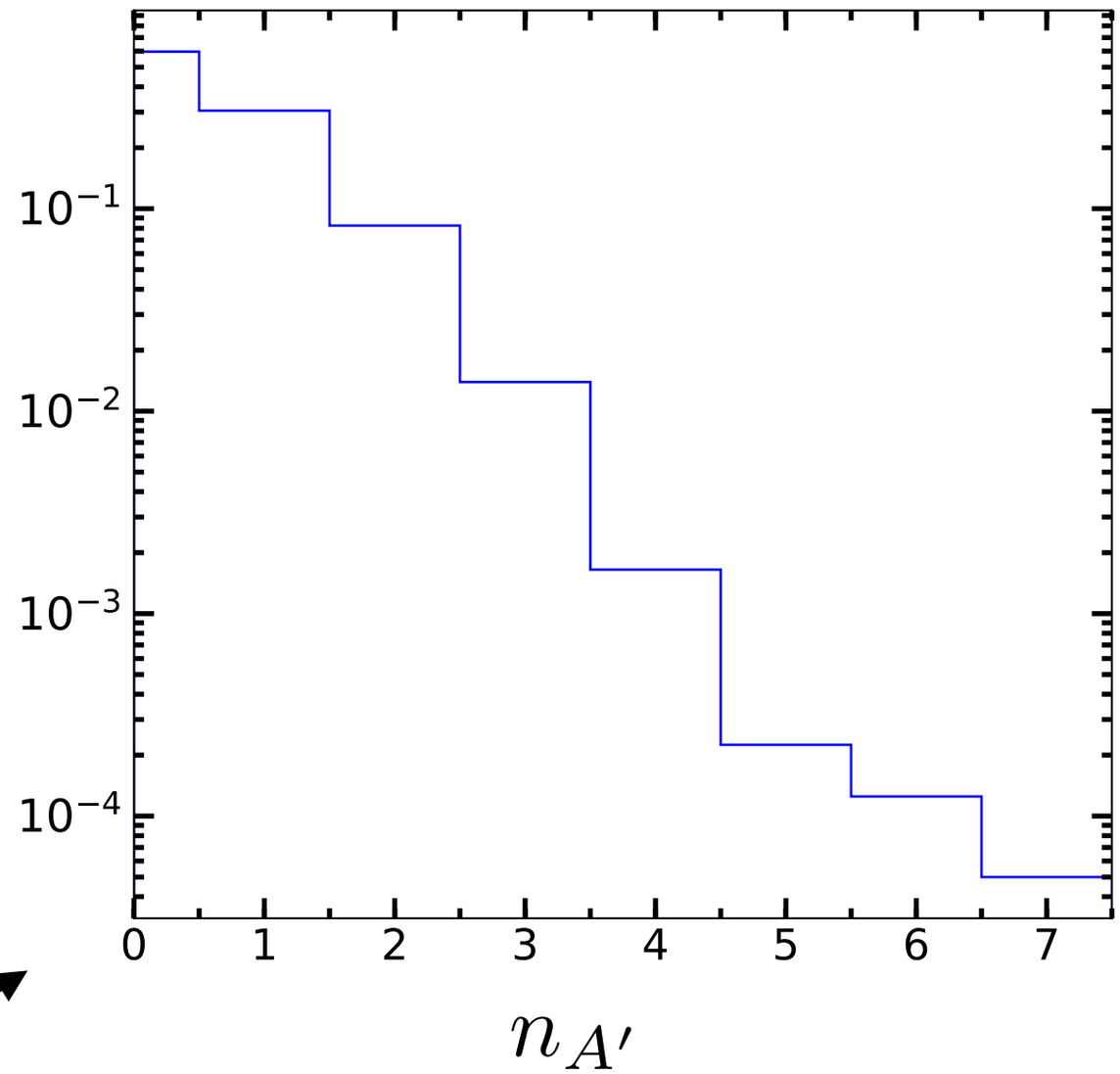


DM: 5 GeV

DP: 3 GeV

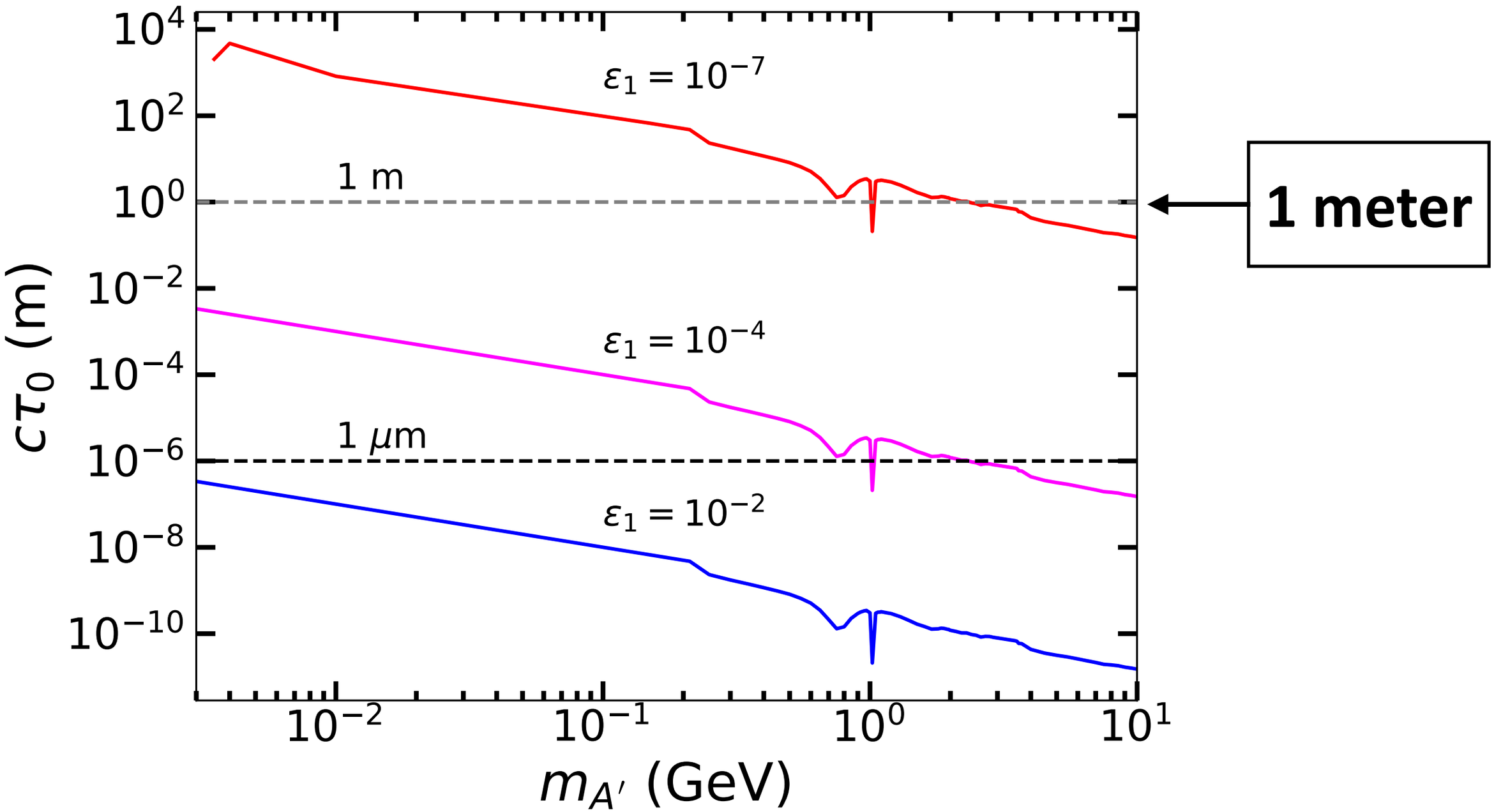
g=1.5

pythia simulation

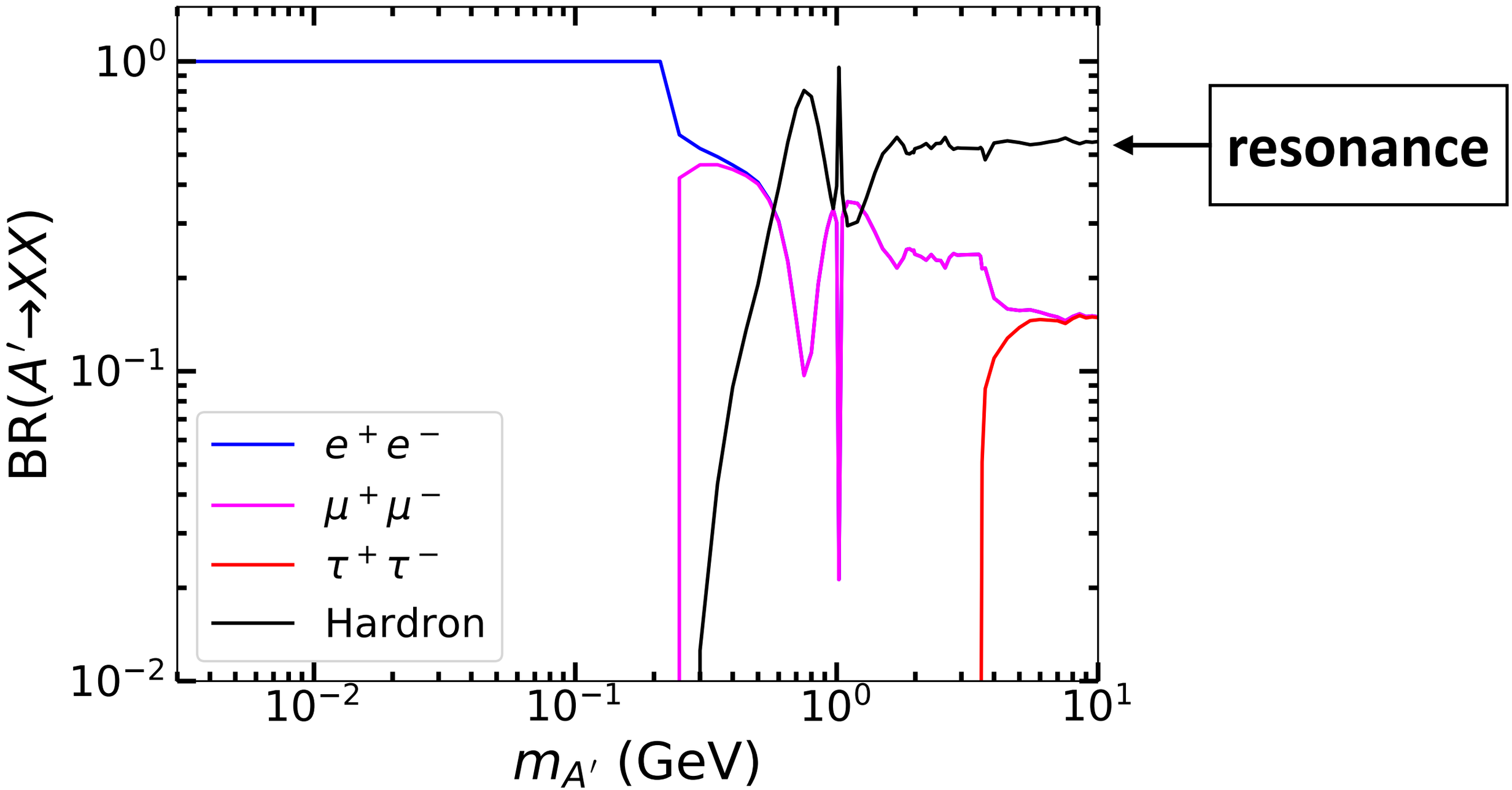


[recent dark radiation analysis: see. e.g. Chen, Ko, Li, Li, Yokoya, 1807.00530]

dark photon lifetime

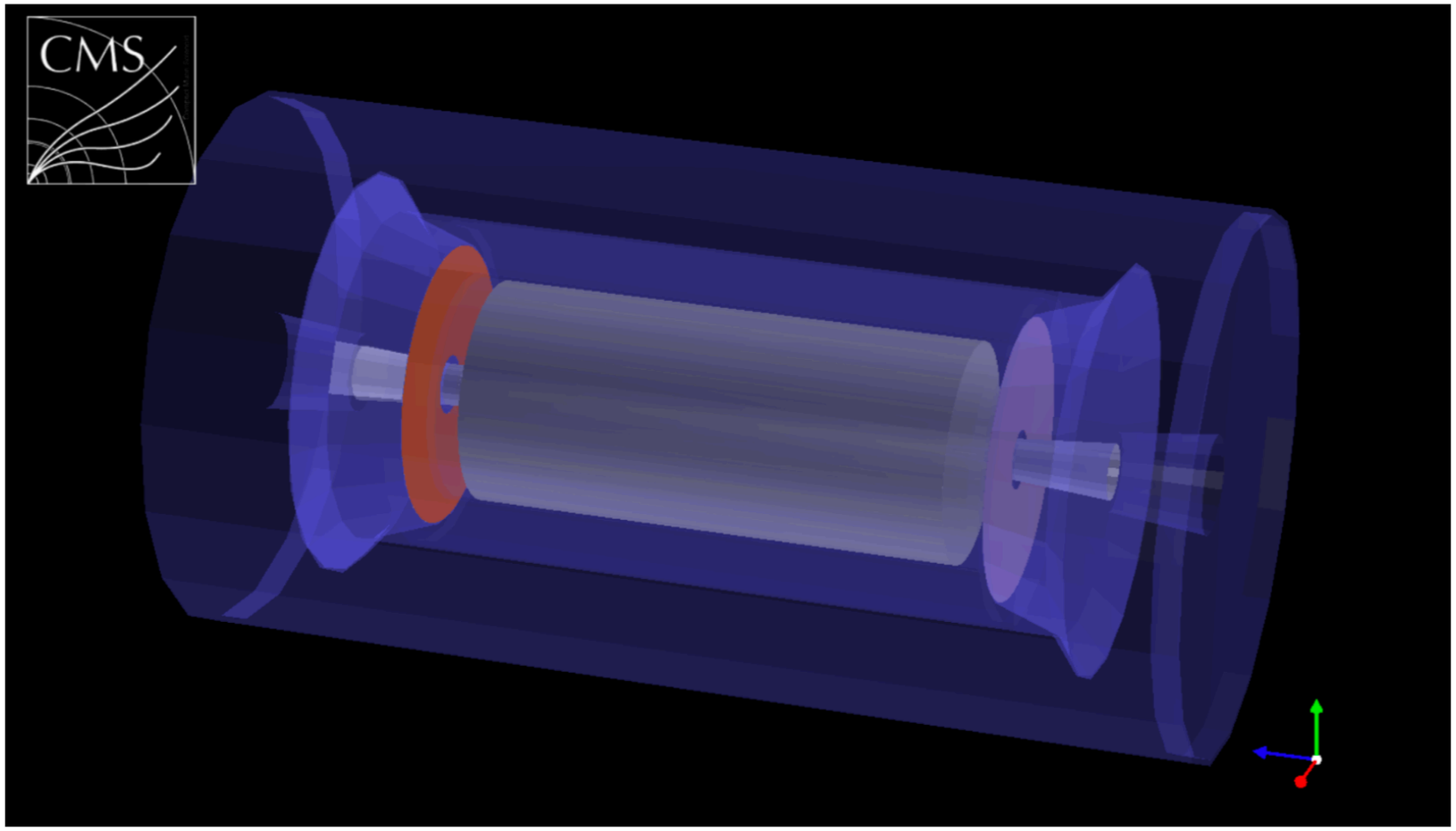


dark photon decay branching ratio



Precision timing detectors in HLLHC

CMS timing detector (phase 2)



between tracker & calorimeter

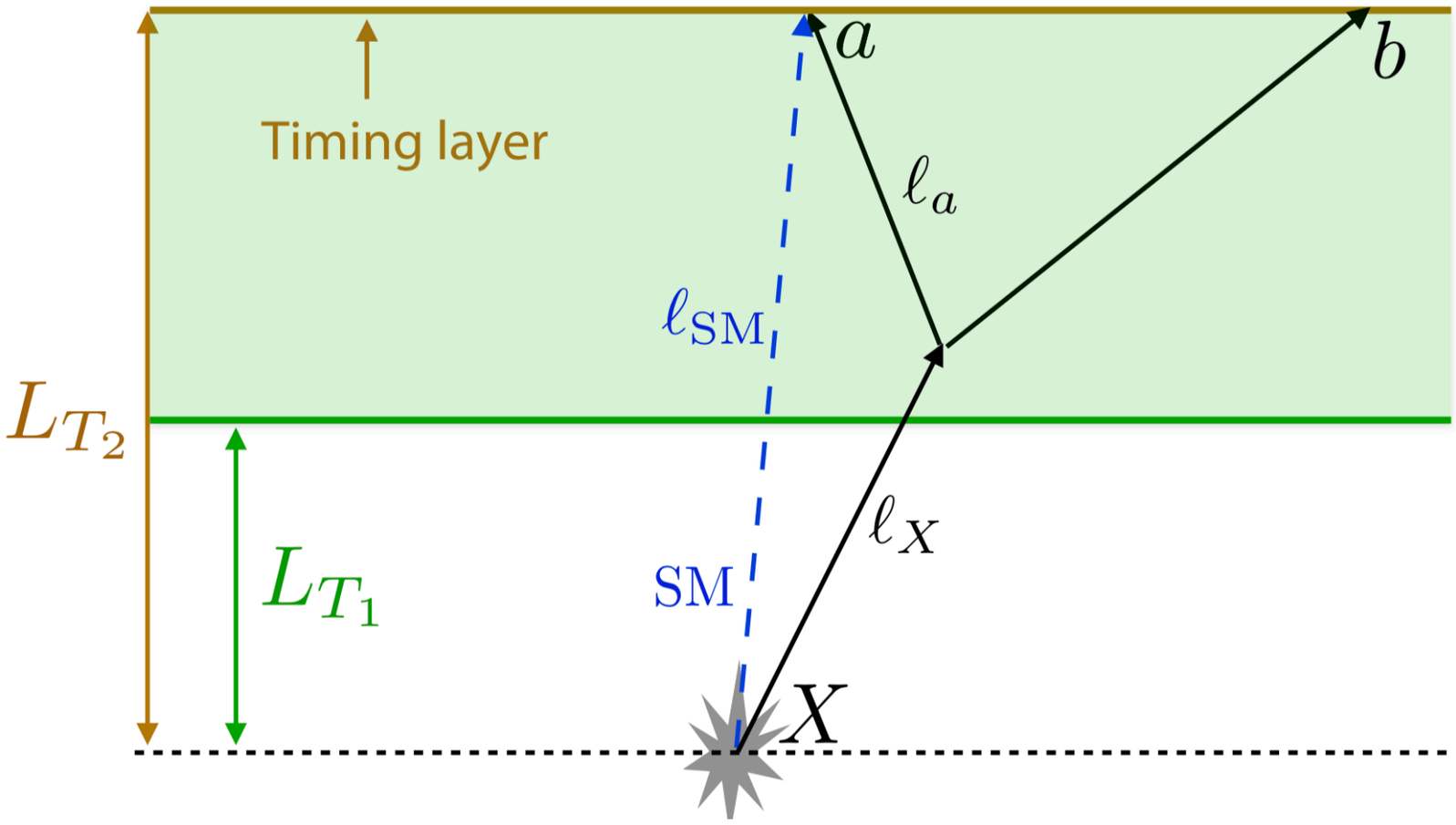
δt = 30 ps; pileup reduction & LLP

see also: ATLAS & LHCb upgrades

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

Time delay for LLP

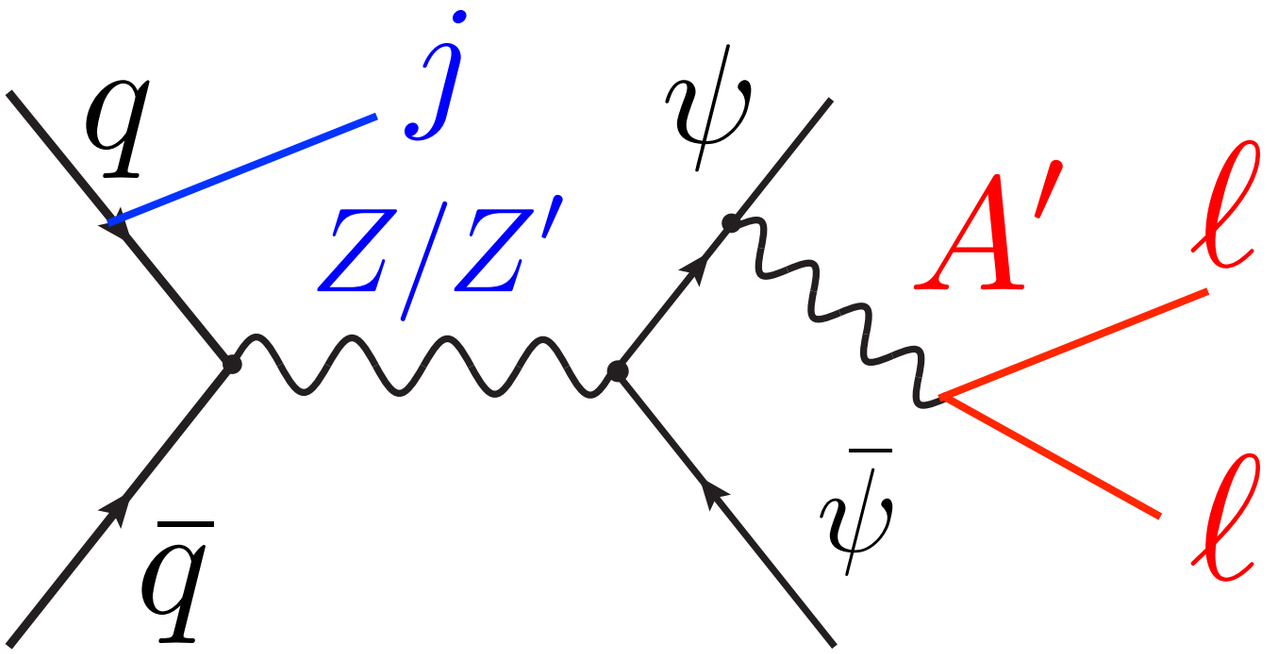
[Liu, Liu, Wang, 1805.05957]

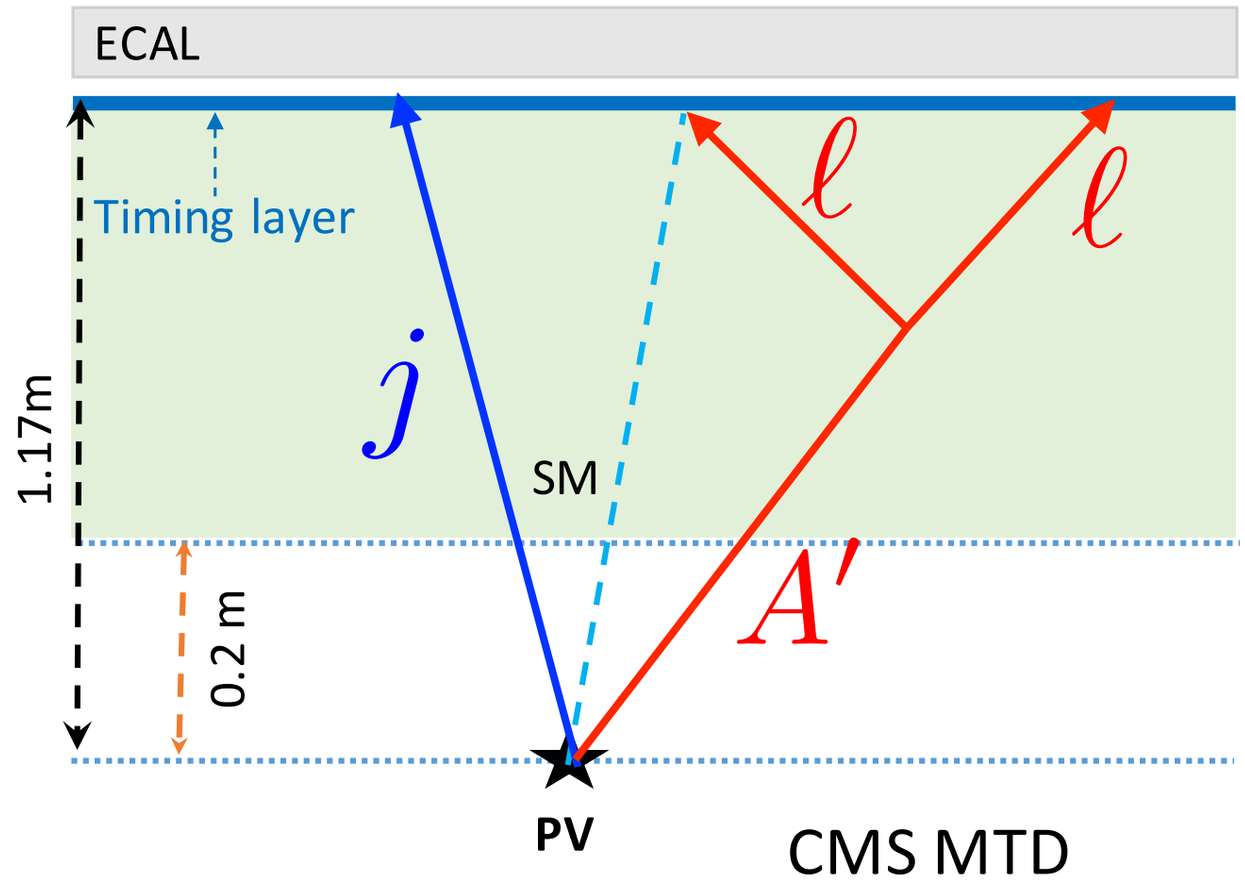


$$\Delta t = \frac{\ell_X}{\beta_X} + \frac{\ell_a}{\beta_a} - \frac{\ell_{\rm SM}}{\beta_{\rm SM}} \qquad \beta_a \simeq \beta_{\rm SM} \simeq 1$$

significant time delay for NR LLP

Detector cuts for LLDP





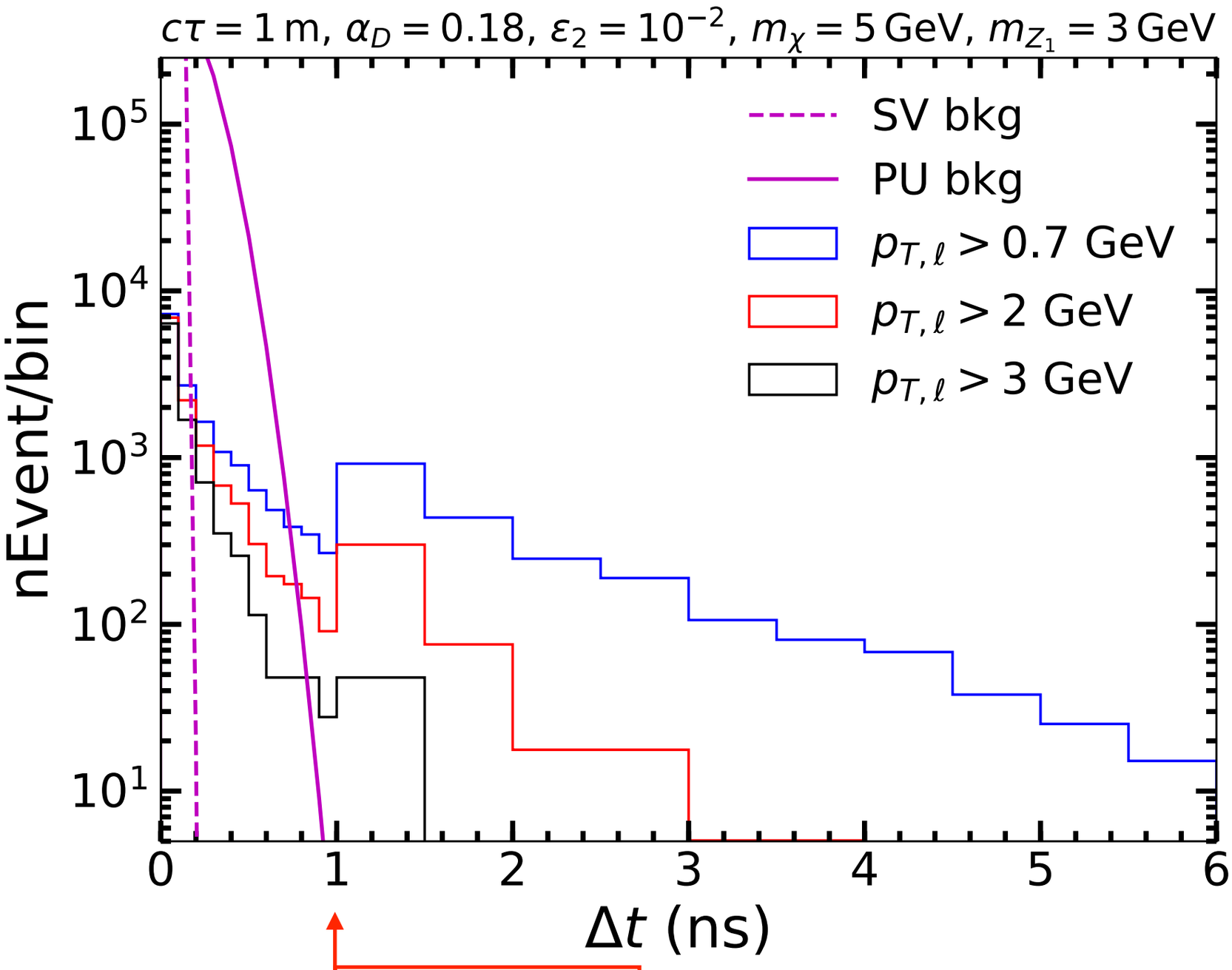
lepton: p_T > 3 GeV

time delay: Δt > 1 ns

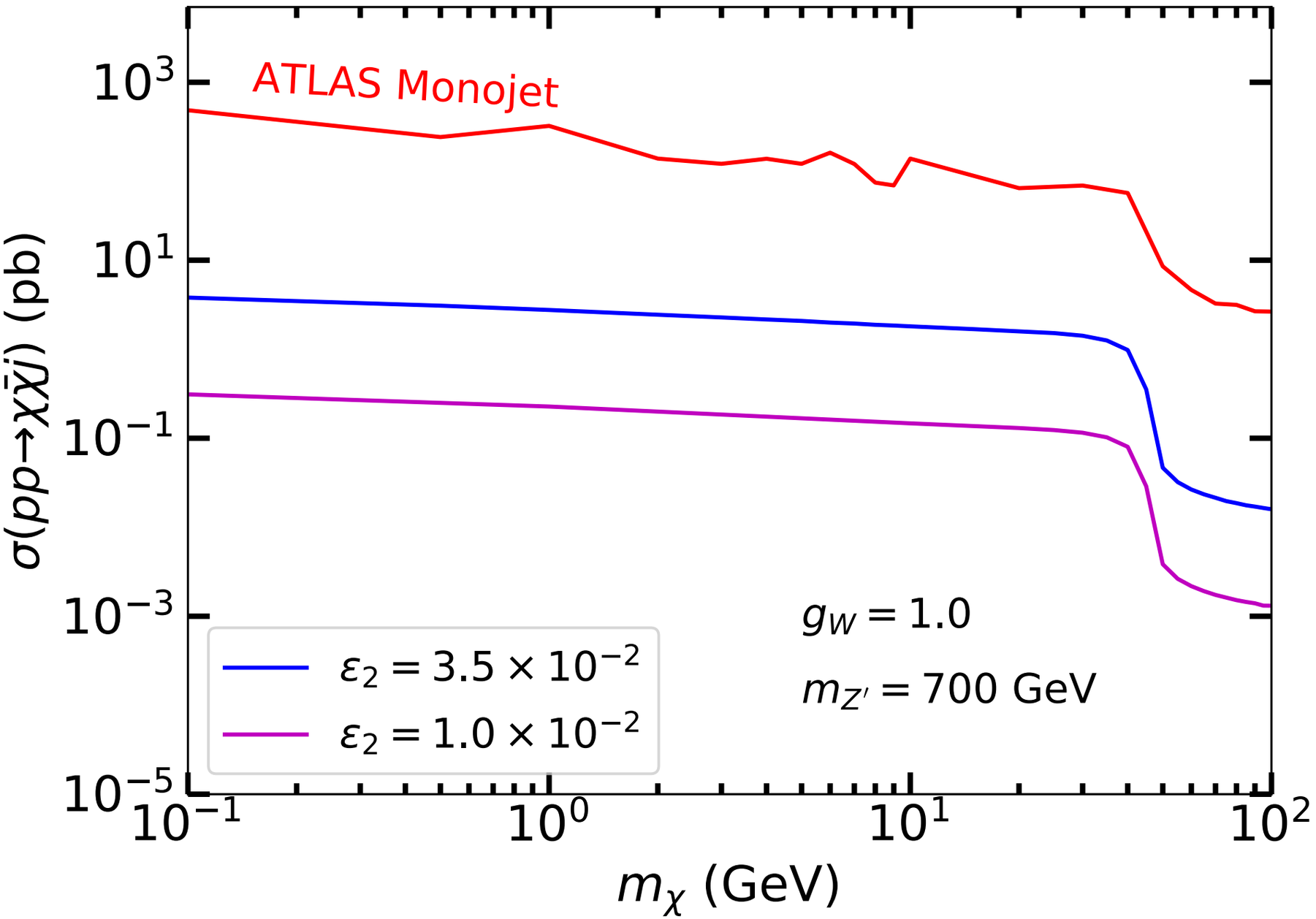
DP: 0.2 m < L_T < 1.17 m & z < 3.04 m

ISR jet: p_T > 30 GeV & |η| < 2.5

Time delay distribution



DM production σ @ LHC



ISR jet

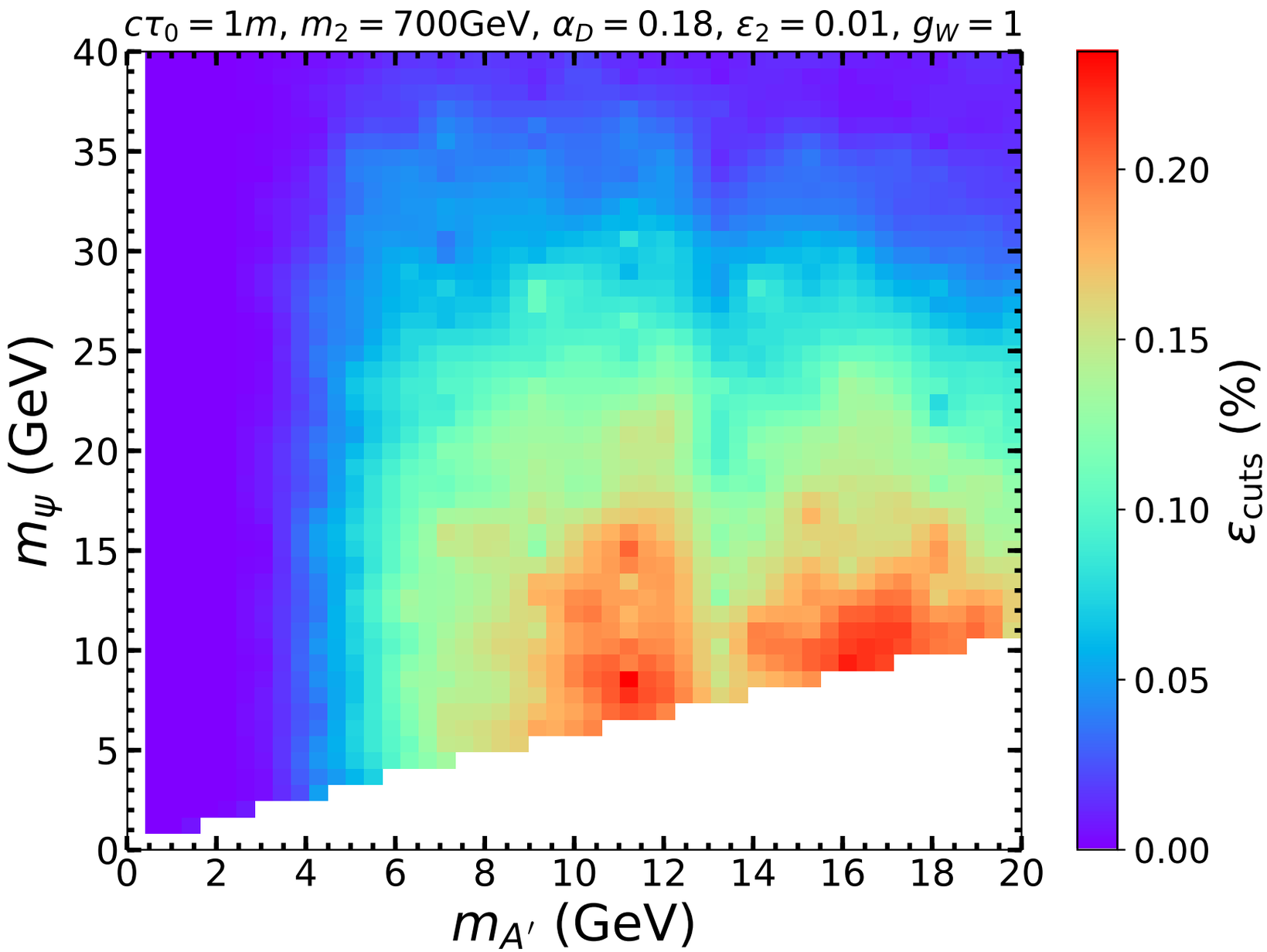
p_T > 30 GeV

|η| < 2.5

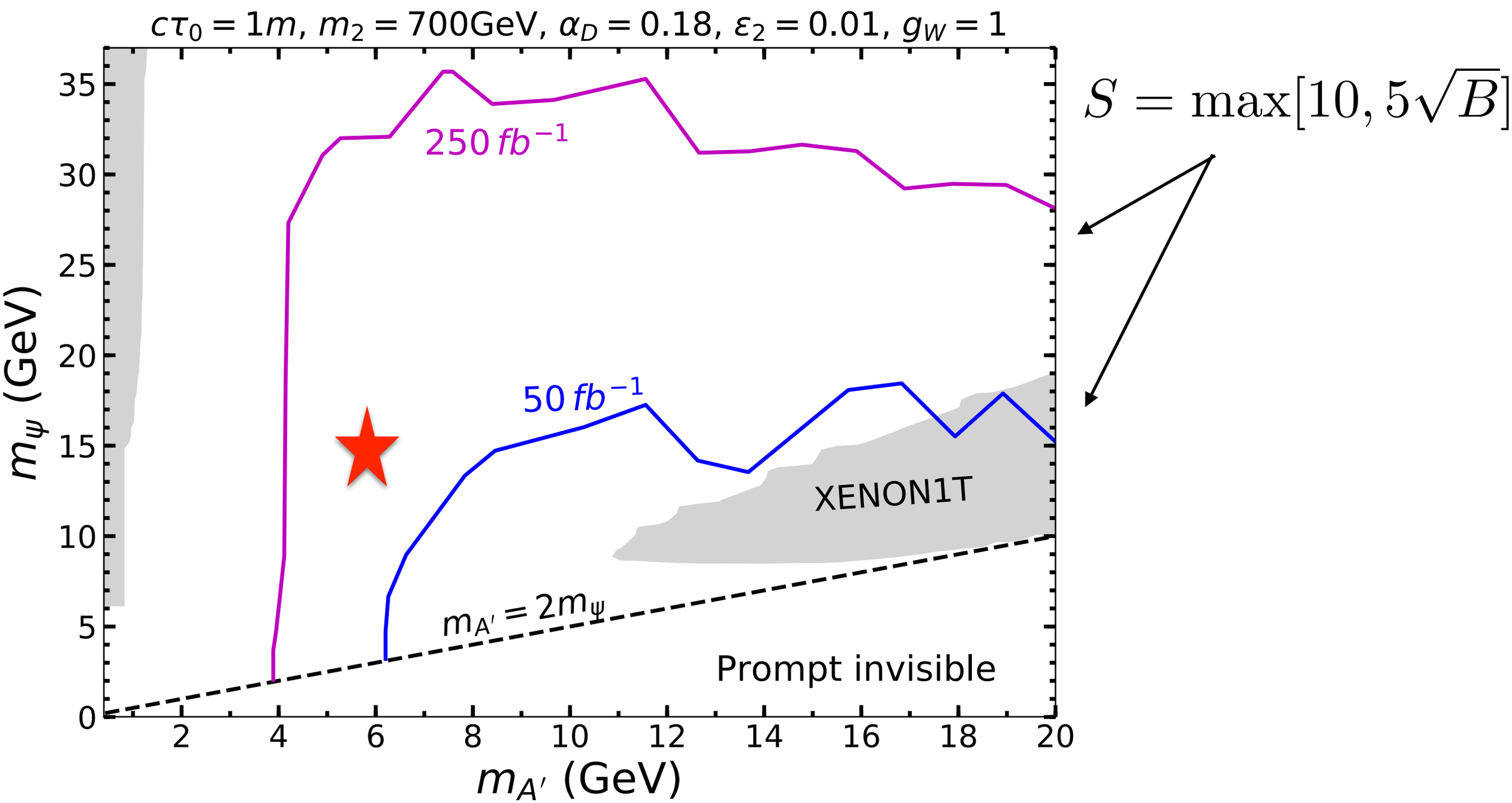
Z-diagram dominates

Detector efficiency

LLDP events under detector cuts per ΨΨ FS

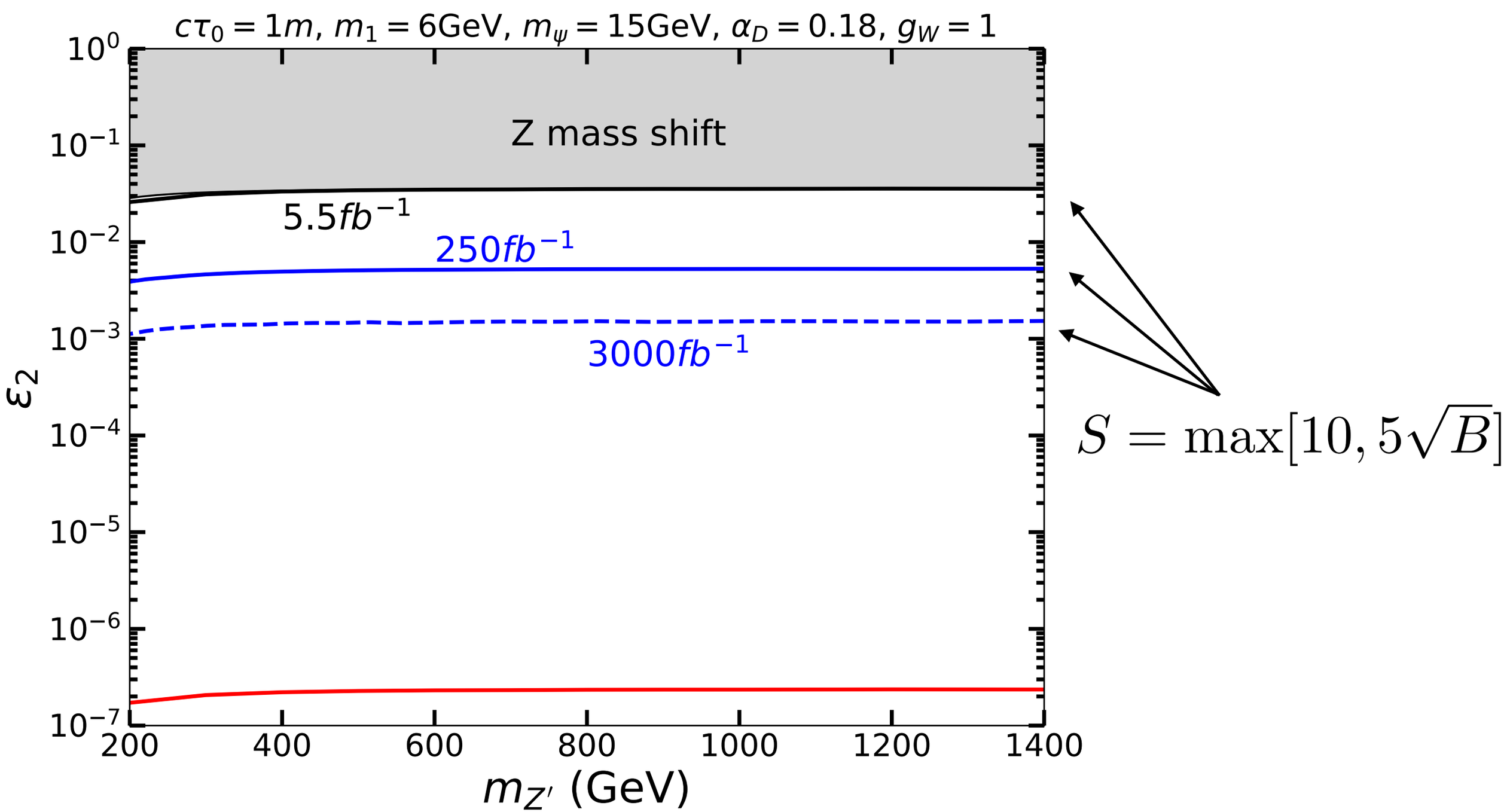


Time delay reach on LLDP



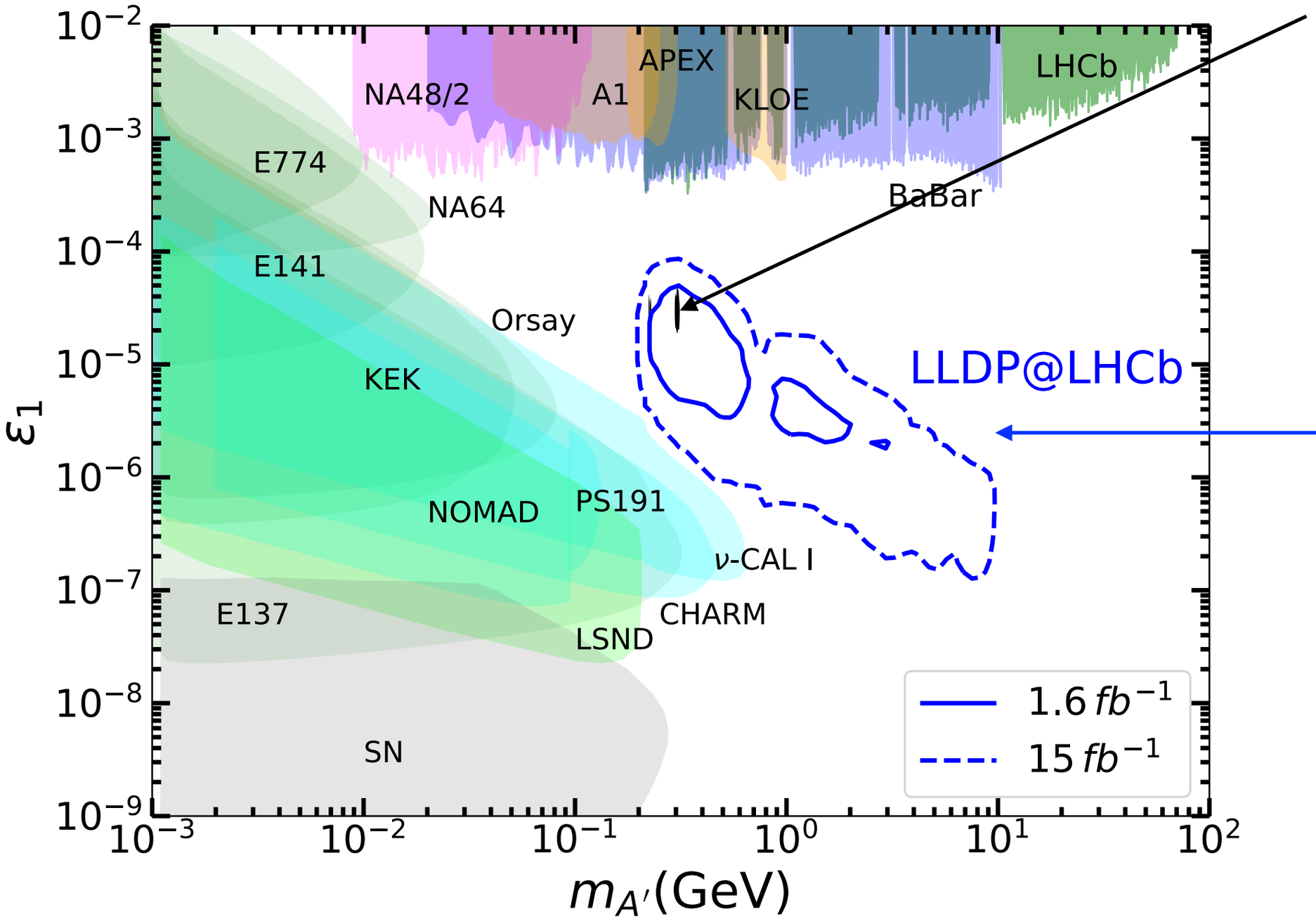
[Du, ZL, Tran, 1908.xxxxx]

Different σ_{prod} versus different ε_2



[Du, ZL, Tran, 1908.xxxxx]

LHCb sensitivity on LLDP



“ordinary” DP below η

our model

$S/\sqrt{B} = 2$

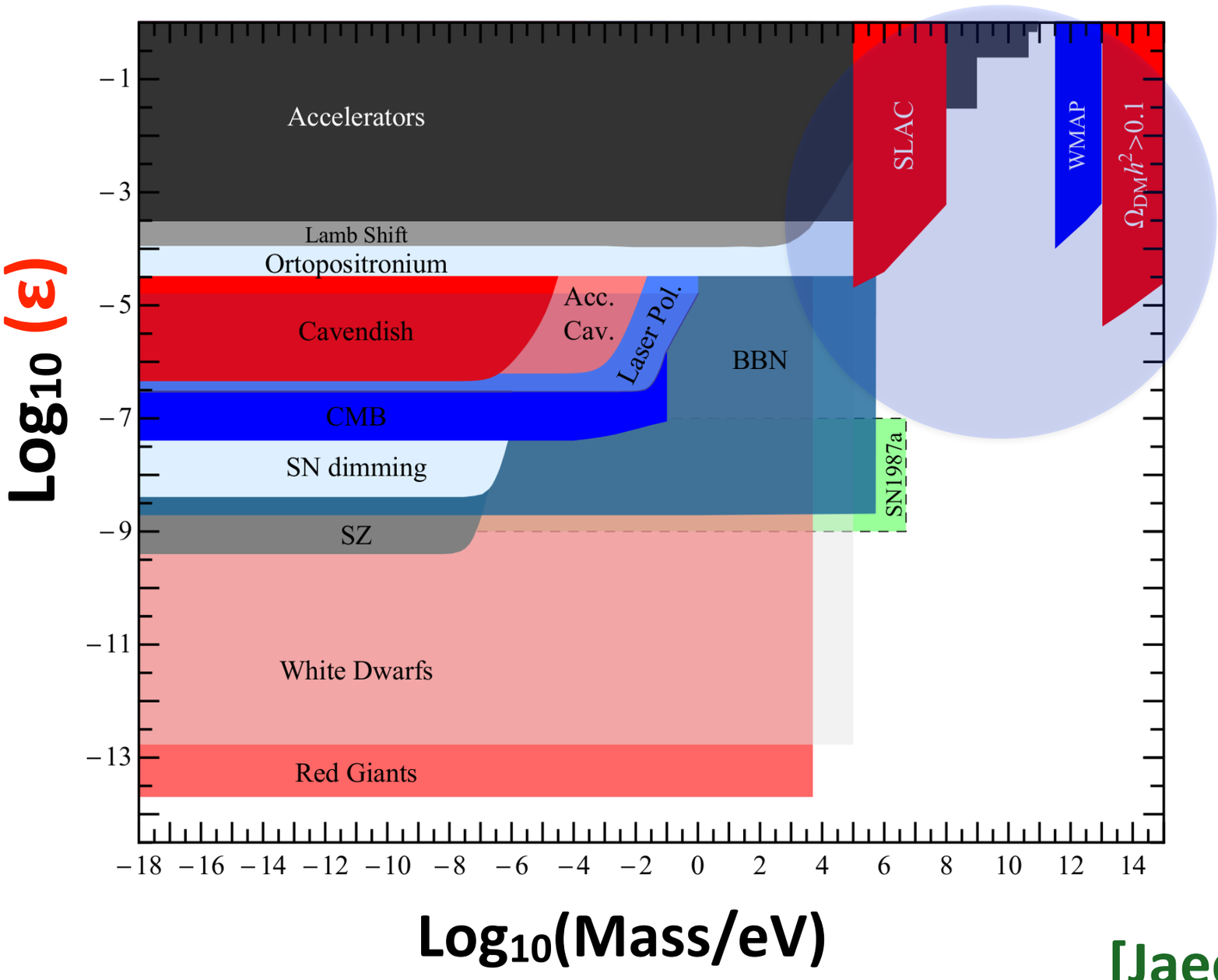
[Du, ZL, Tran, 1908.xxxxx]

Millicharged particles @ electron colliders

- **Belle II**
- **STCF**
- **BESIII**
- **BaBar**

Constraints on millicharge

Millicharged particles have been searched for extensively



poorly constrained

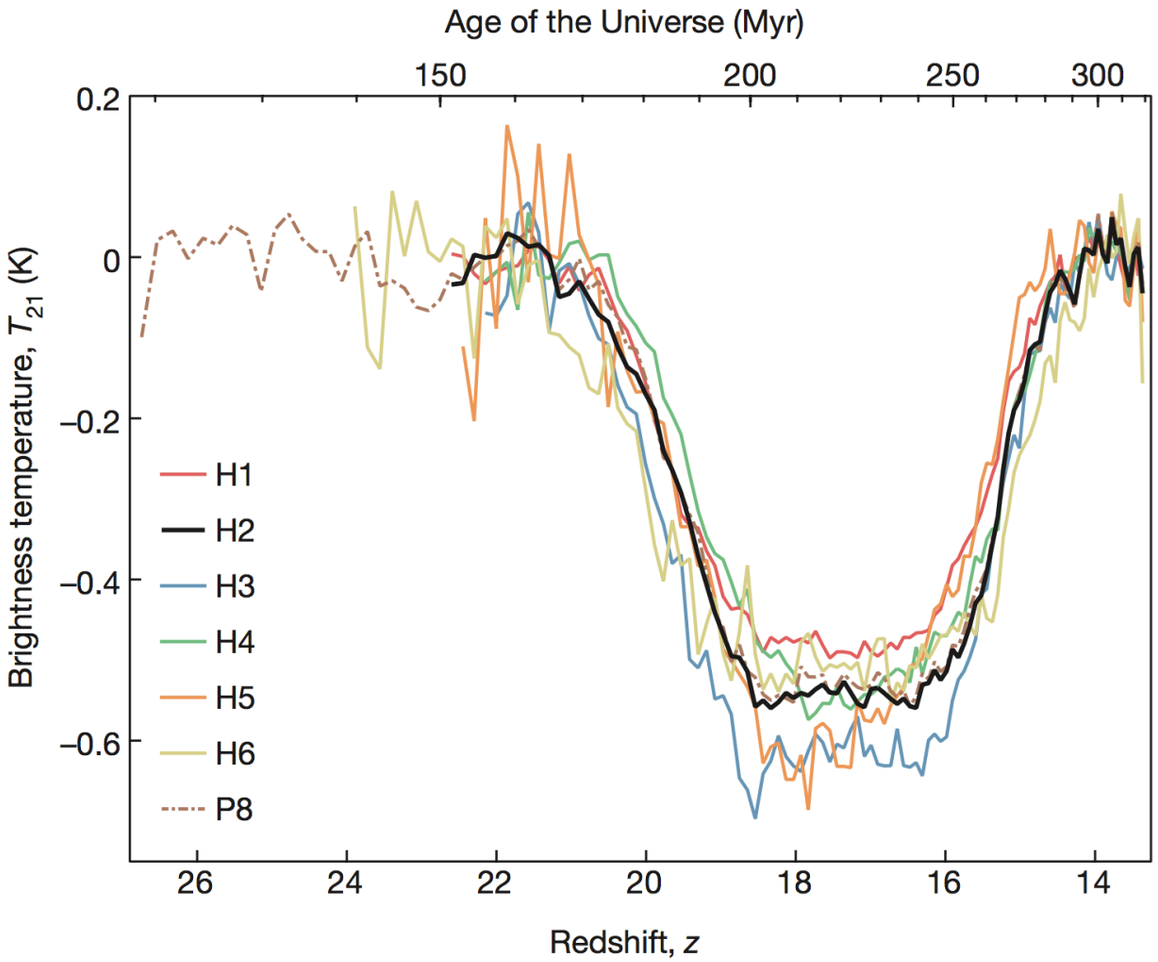
millicharge ε

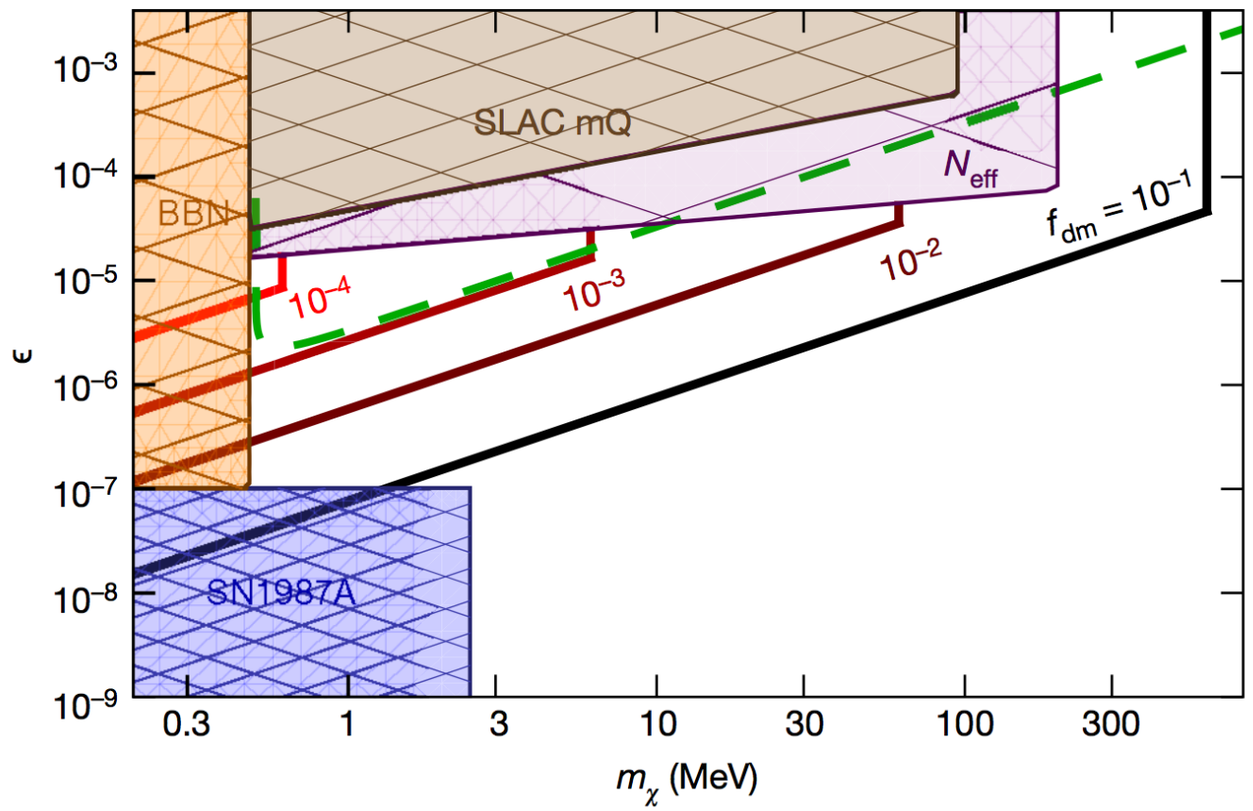
$$\epsilon e A_\mu \bar{\psi} \gamma^\mu \psi$$

[Jaeckel, Ringwald, 1002.0329]

Millicharged DM & 21 cm

21 cm @ EDGES





[Bowman et al., Nature25792 (2018); Barkana, Nature25791 (2018); Munoz, Loeb, Nature 557 (2018) no.7707, 684; + others]

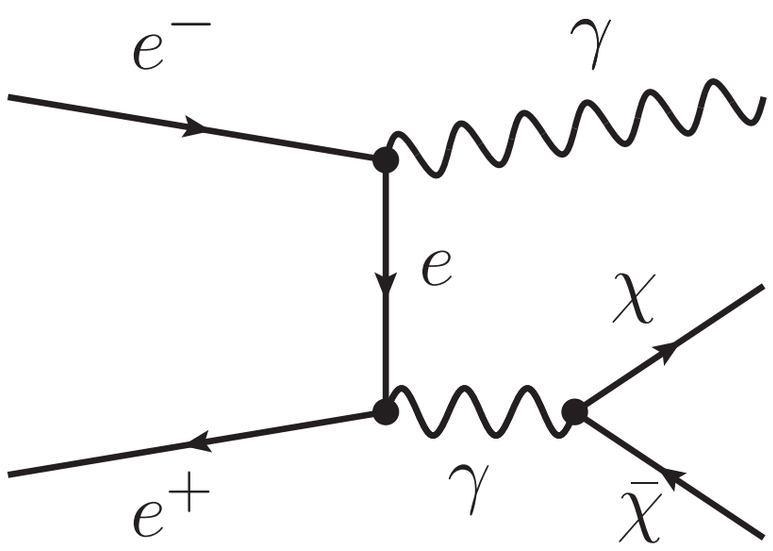
momentum transfer xsec millicharge DM & baryon

$$\bar{\sigma}_{\rm t} = \frac{2\pi c^2 \hbar^2 \alpha^2 \epsilon^2 \xi}{\mu_{\chi,{\rm t}}^2 v^4}$$

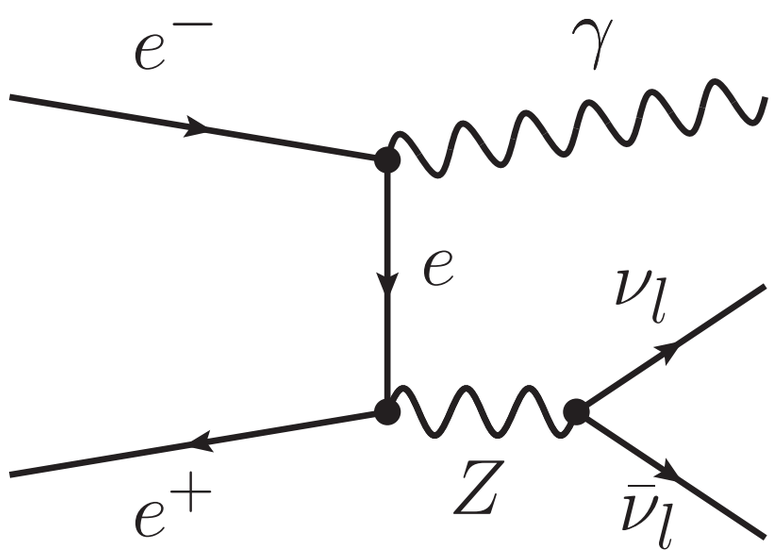
Millicharge @ colliders

very small ionization due to millicharge → **mono-photon @ electron colliders**

[ZL, Zhang, 1808.00983]



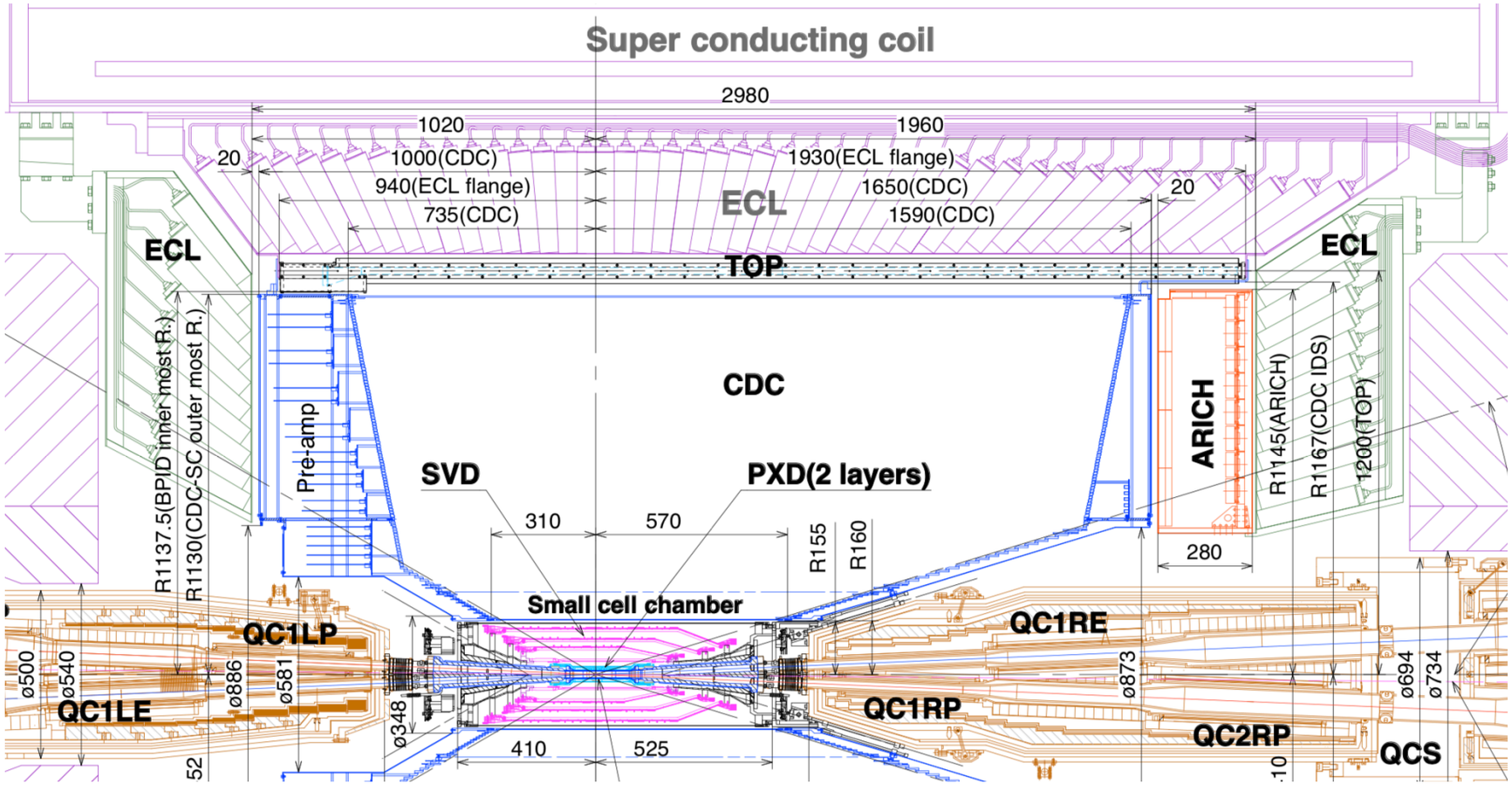
signal process



irreducible background

Belle II

7 GeV electron collides w/ 4 GeV positron



ECL
lab frame

$$12.4^\circ < \theta < 31.4^\circ$$
$$32.2^\circ < \theta < 128.7^\circ$$
$$130.7^\circ < \theta < 155.1^\circ$$

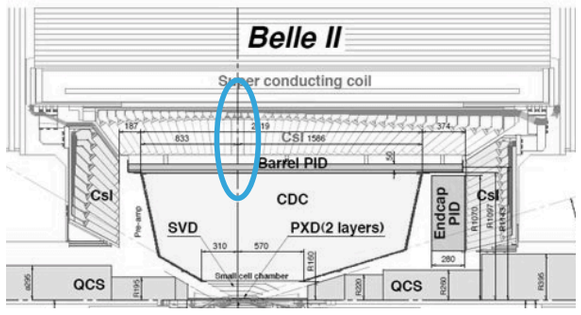
[1808.10567]

reducible BG
- **BG due to ECL gaps**
- **BG due to non-coverage at beam**

Gap and beam BG in Belle II

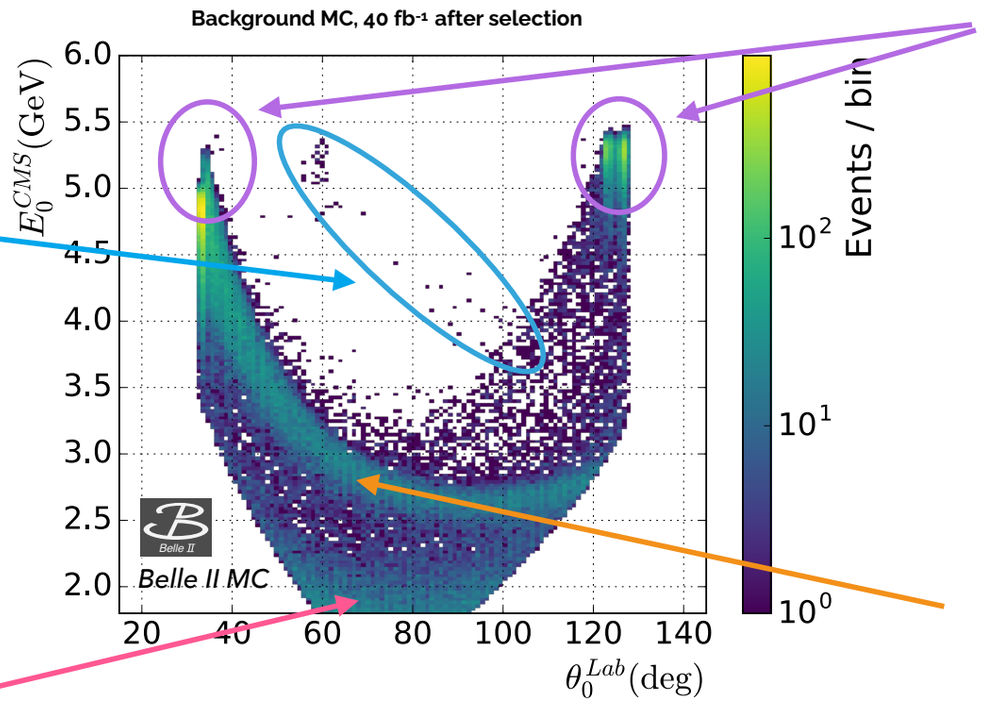
[taken from Ferber's talk]

B: Invisible Dark Photon searches

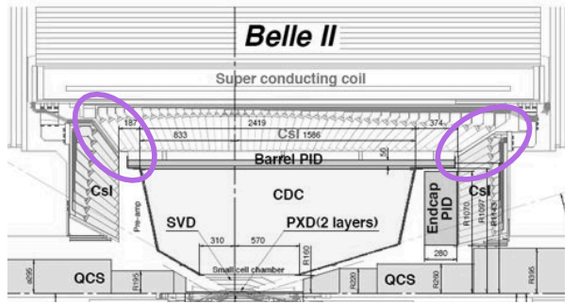


ee→2γ and 3γ
1γ in ECL 90° gap
1γ out of ECL acceptance

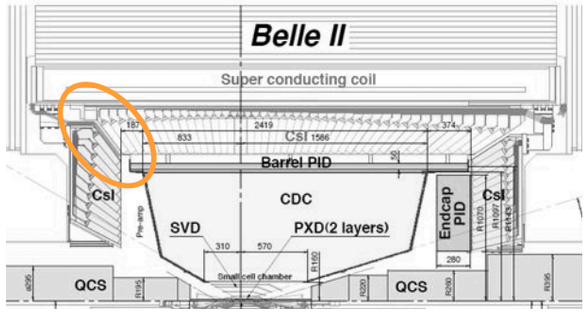
$$E_\gamma = \frac{s - M_{A'}^2}{2\sqrt{s}}$$



ee→eeγ
both electrons
out of tracking acceptance



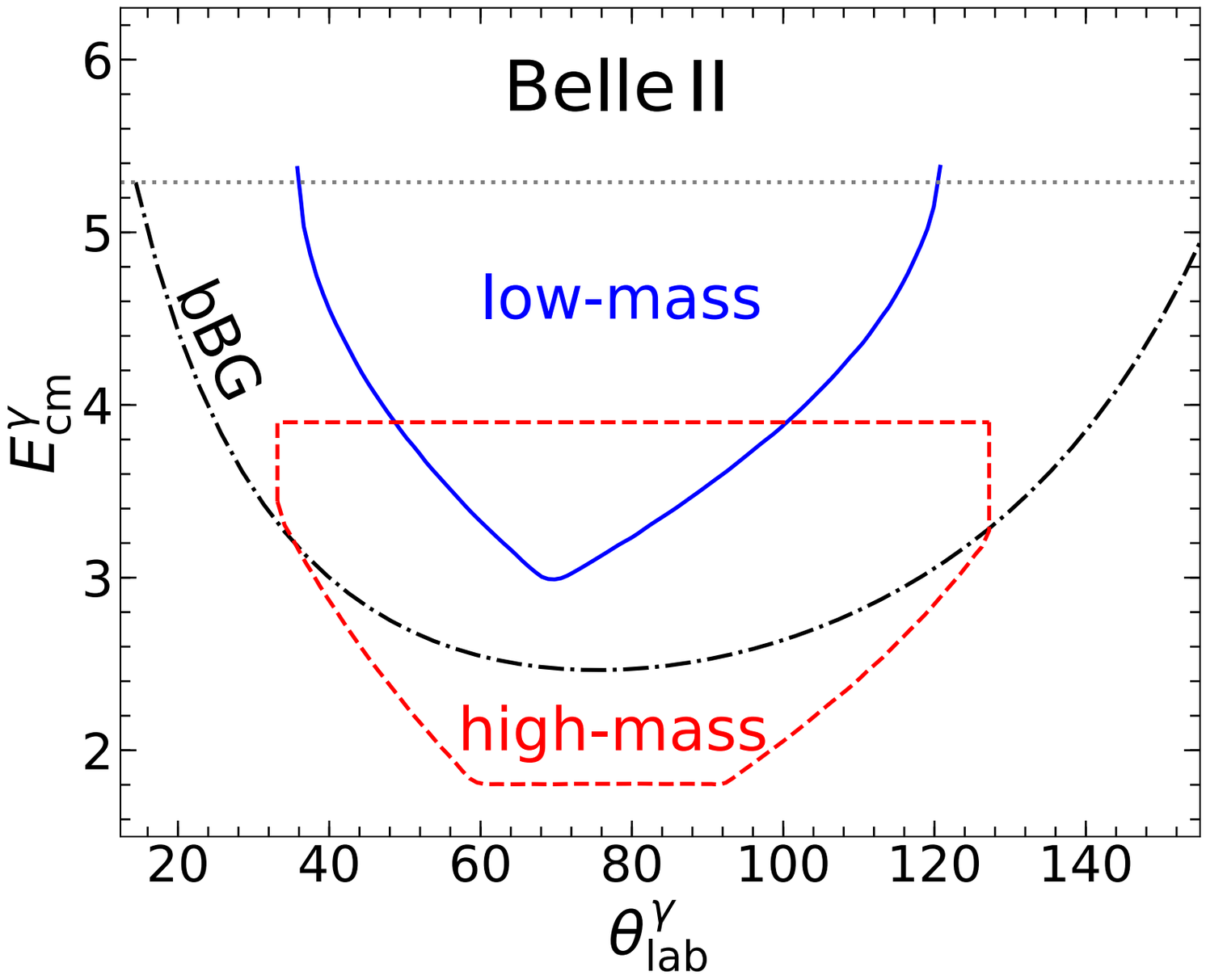
ee→2γ
1γ in ECL BWD or FWD gap



ee→3γ
1γ in ECL BWD gap
1γ out of ECL acceptance

Reducible BG & cuts in Belle II

bBG cut in the CM frame $E_\gamma < \dfrac{\sqrt{s}(Ac_1 - s_1)}{A(c_1 - s_\gamma) - (s_\gamma + s_1)}$



$$A = \frac{s_1 - s_2}{c_1 - c_2}$$

$\theta_1 \& \theta_2$: boundary

large E in gap BG

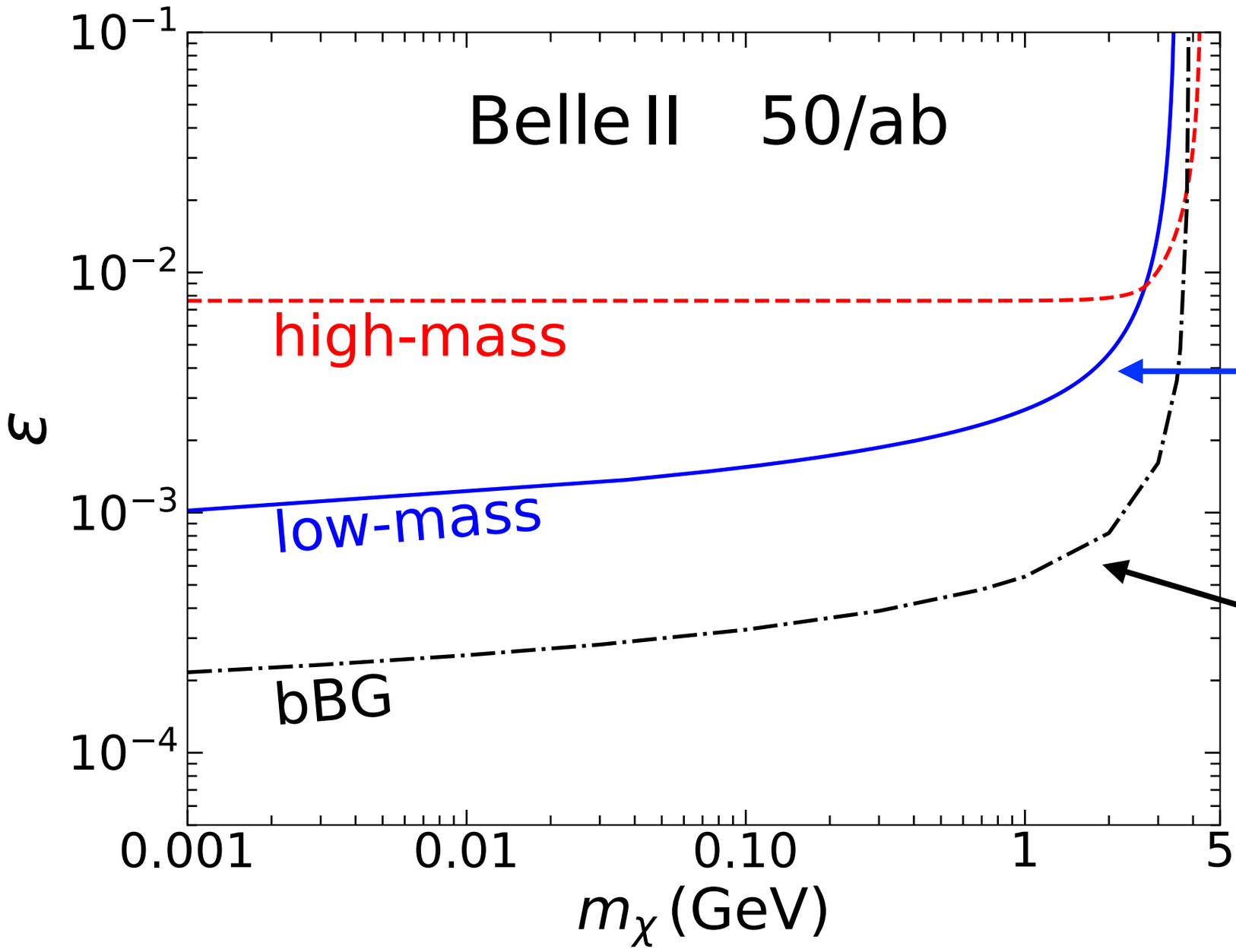
low-mass

high-mass

[1808.10567]

Belle II sensitivity on millicharge

8-yr data w/ diff cuts

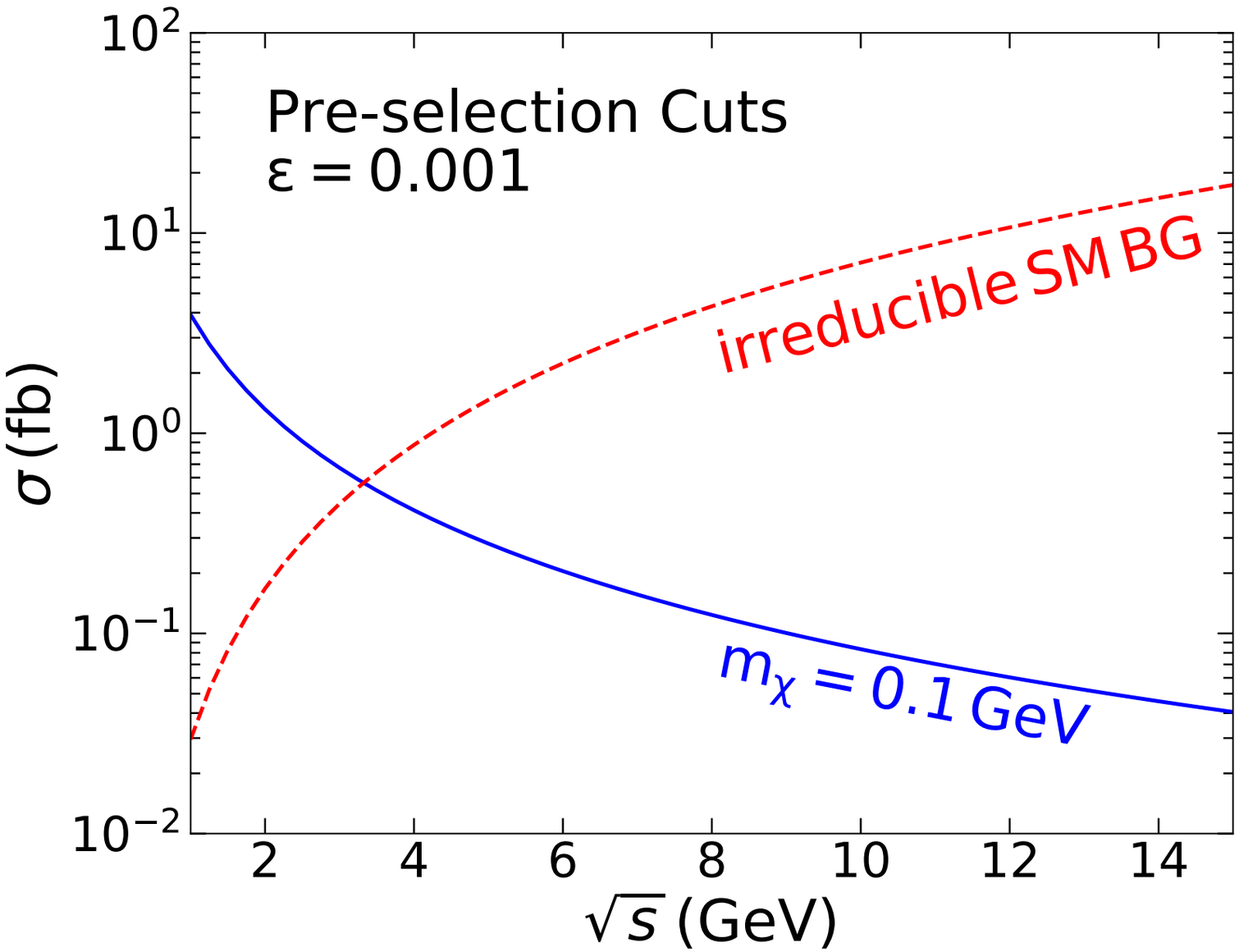


"low-mass" cut is better in low-mass

overestimate bBG

σ vs colliding energy

low-E collider is better for sub-GeV particles



pre-selection

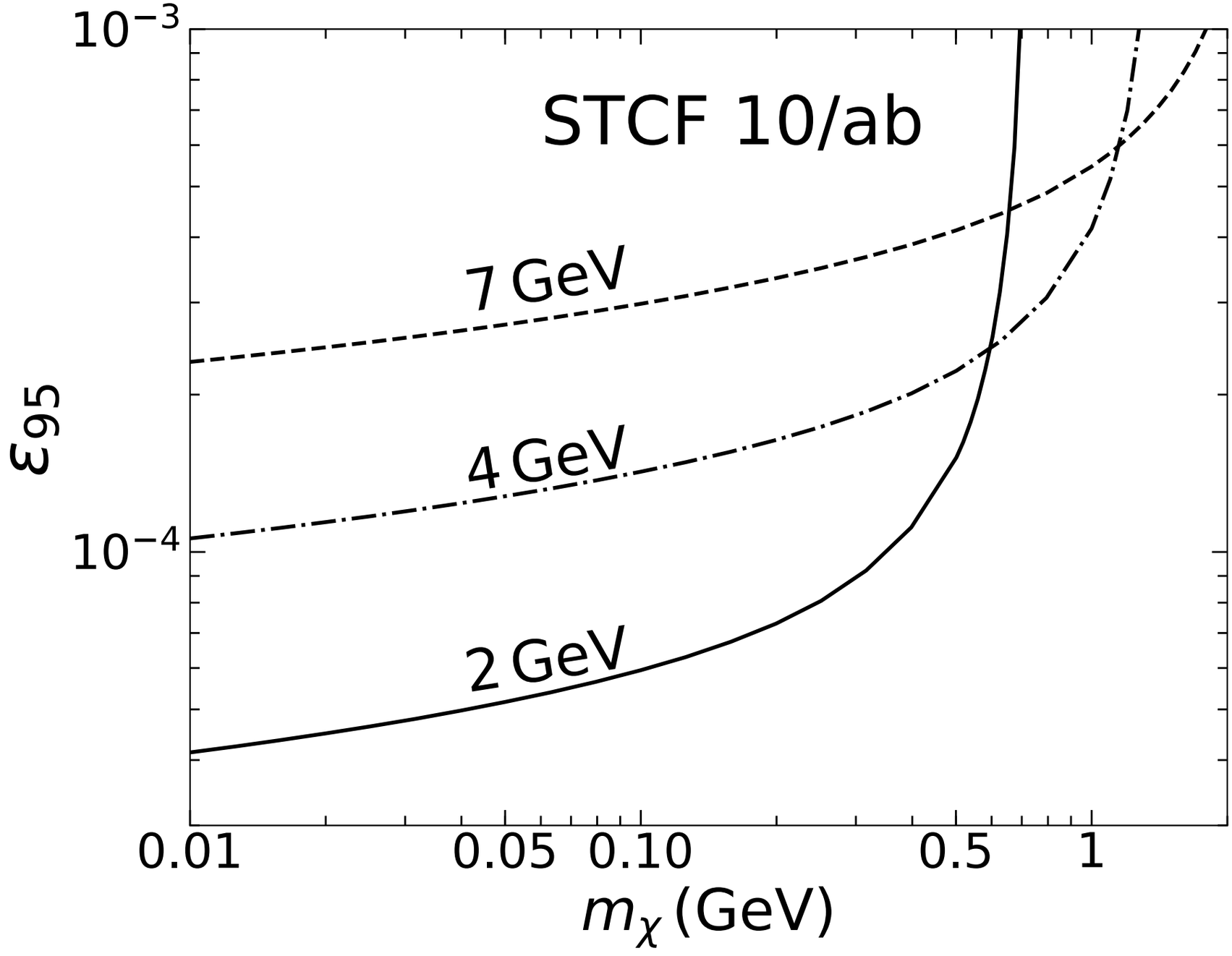
E_γ>25 MeV
$|\cos(\theta_\gamma)|$<0.8

E_γ>50 MeV
0.86<$|\cos(\theta_\gamma)|$<0.92

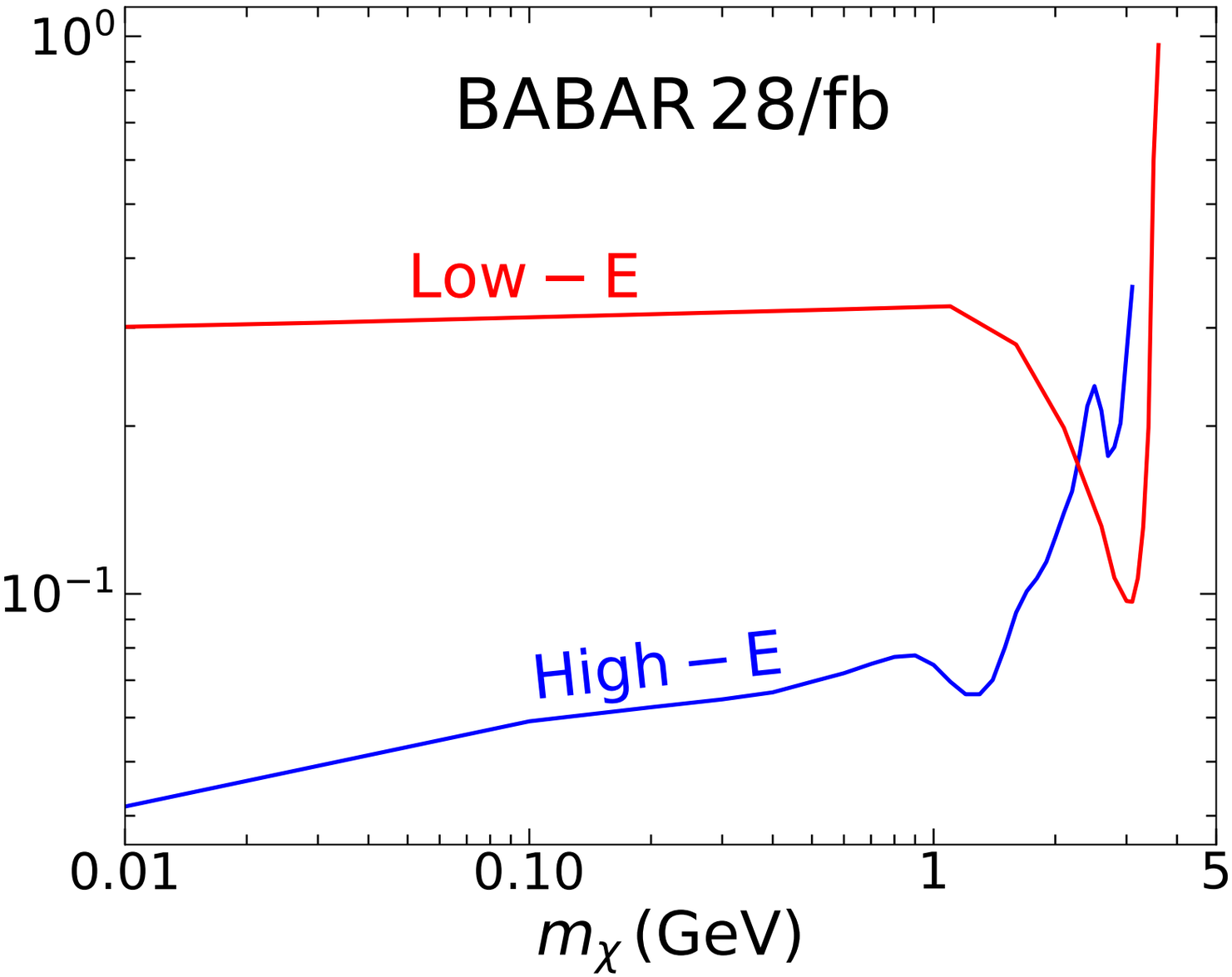
[BESIII, 1707.05178]

Different STCF colliding energies

STCF low-E mode: better for low mass



BaBar sensitivity on millicharge



High-E

$3.2 < E^*_\gamma < 5.5$ GeV

$-0.31 < \cos\theta^*_\gamma < 0.6$

Low-E

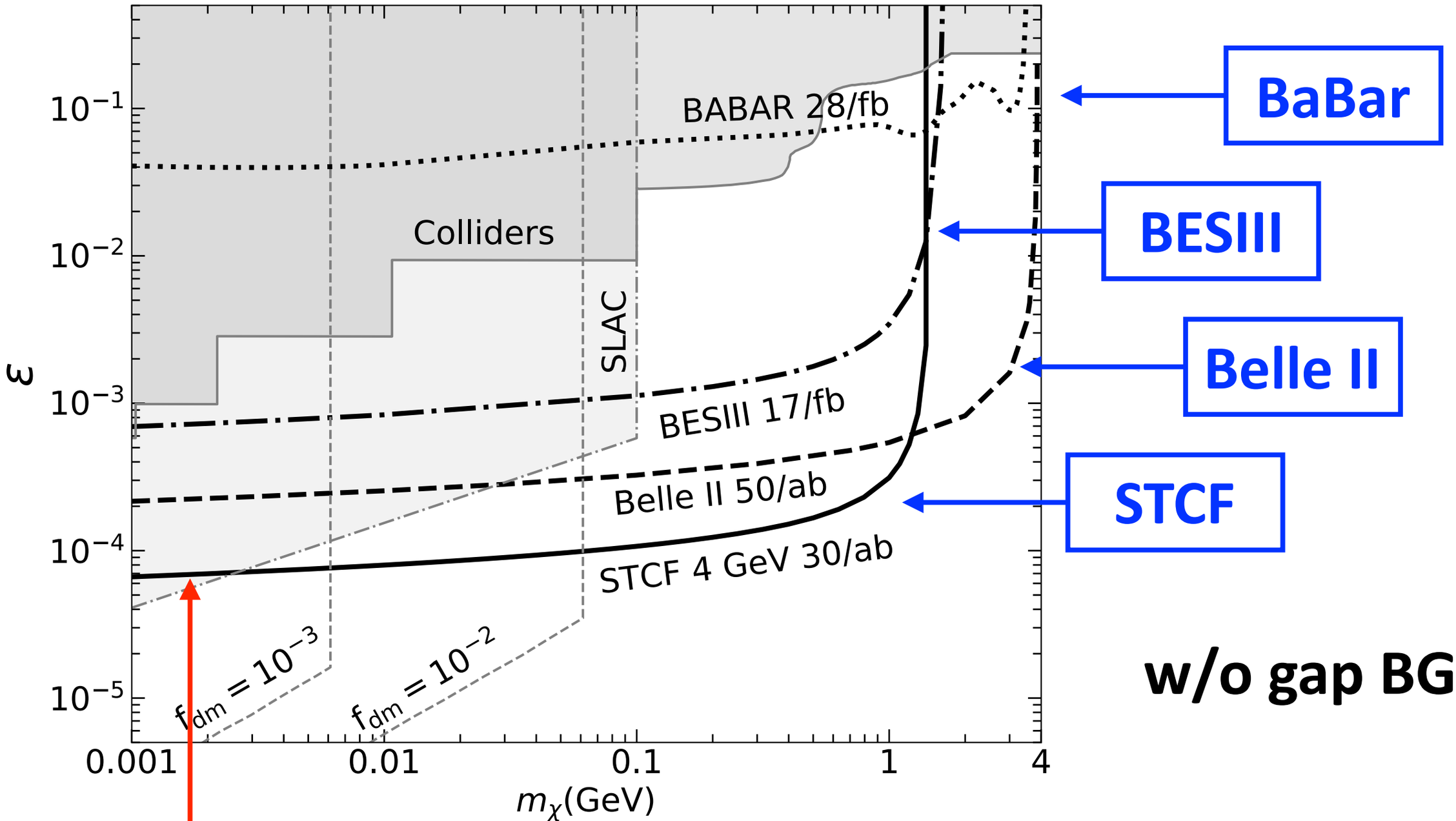
$2.2 < E^*_\gamma < 3.7$ GeV

$-0.46 < \cos\theta^*_\gamma < 0.46$

[BaBar, 0808.0017]

high-E data has better sensitivity to light mass

Collider sensitivity on millicharge



BaBar

BESIII

Belle II

STCF

w/o gap BG

down to 10^{-4}

[Liang, ZL, Ma, Zhang, 1908.xxxxx]

Summary

- **We construct a BSM model in which the long-lived dark photon signal is greatly enhanced**

- **We propose to search for millicharged particles at electron-positron colliders**

- **Belle II, STCF, BESIII and Babar have sensitivity to the parameter space of millicharge that is otherwise unexplored**