Long-lived dark photon at the LHC

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- The long-lived dark photon (LLDP) model
- Current experimental constraints
- Timing detector
- LHCb sensitivity
- Conclusion

Motivation

- LHC is working hard to search for new particle BSM
- So far, no evidence for new particle.

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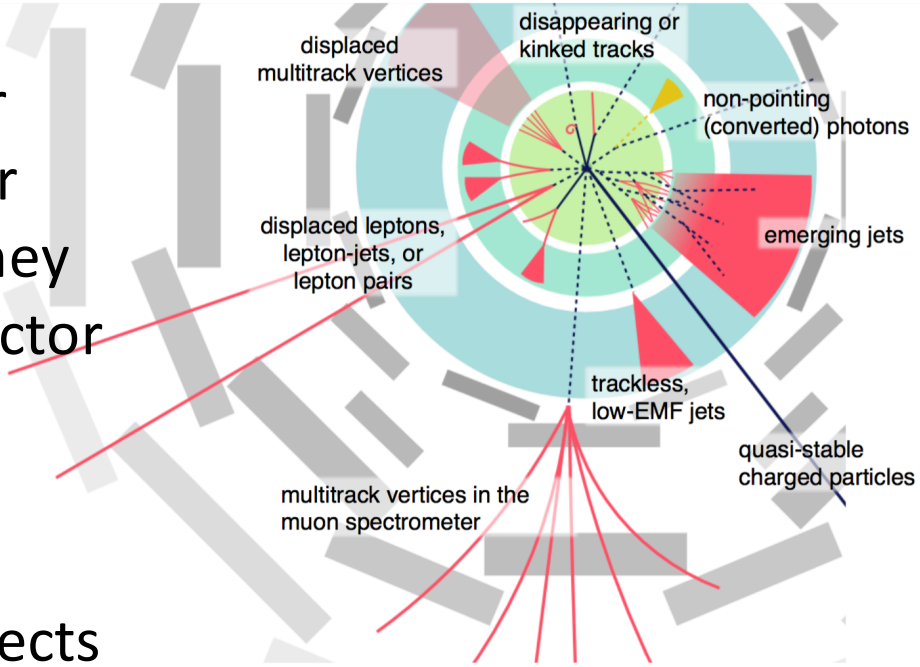
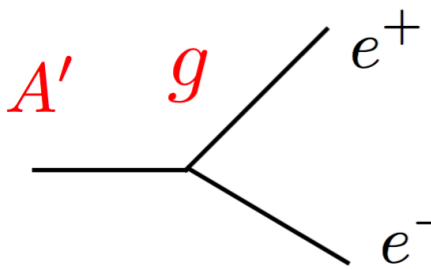
➢ Experimental signatures:
  - Displaced objects
  - Non-pointing/kinked objects
  - Heavy Stable Charged Particles
  - Delayed objects



Heather Russell

Motivation

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)

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

Taken from Liu's talk

Motivation

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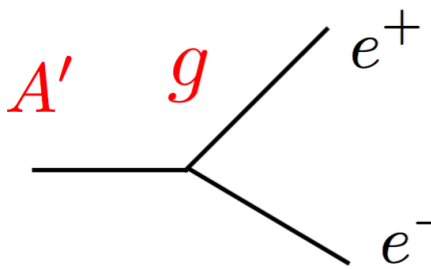

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feeble coupling g for LLDP → **suppressed collider signals?**

Taken from Liu's talk

Our LLDP Model

- We construct a model in which LLDP is produced via a different channel from its decay
- SM extended by a hidden sector (HS) with 2 U(1) gauge bosons X and C, and 1 Dirac fermion ψ

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

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

- Both 2 extra gauge bosons obtain mass via Stueckelberg mechanism

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

- A vector current interaction between the Dirac fermion and the gauge bosons in the hidden sector

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

Our LLDP Model

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

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

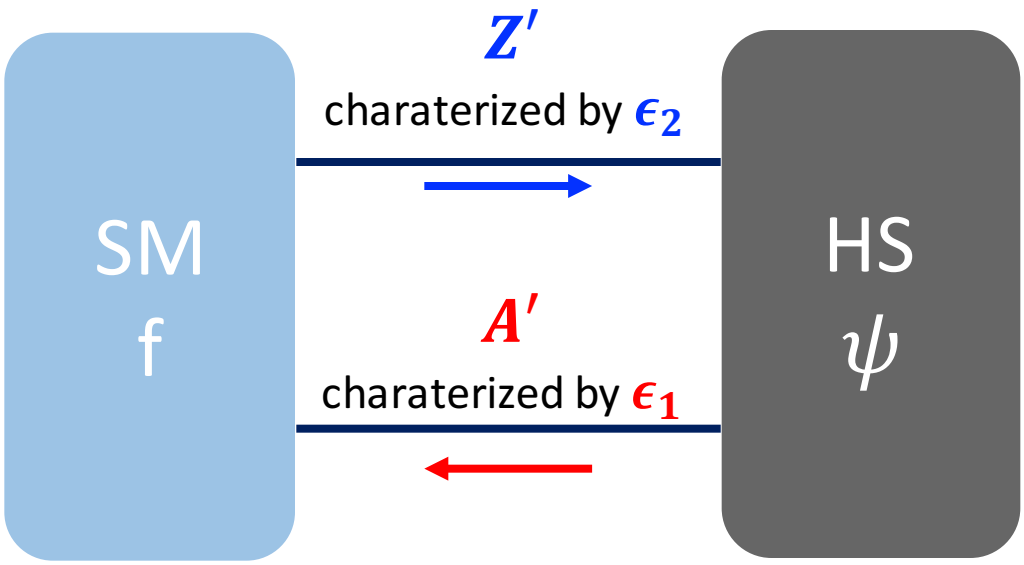
mass eigenstates E = (Z', A', Z, A) via $V_i = O_{ij} E_j$

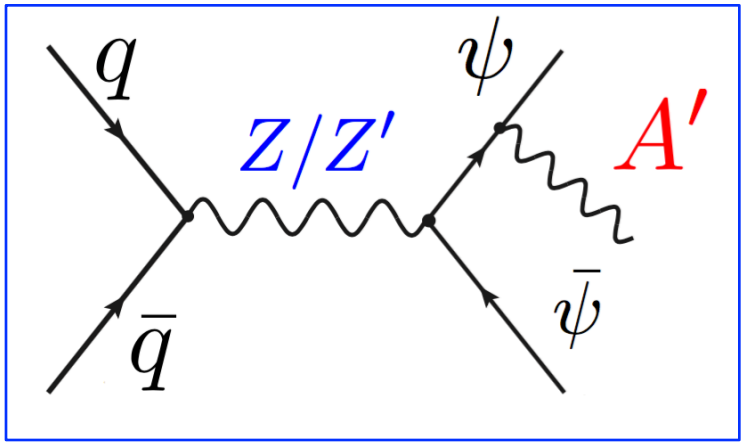
Det(m^2)=0 ⇒ massless photon mode

ϵ_1=0=ϵ_2 ⇒ HS decouples from SM

Taken from Liu's talk

LLDP production at the LHC

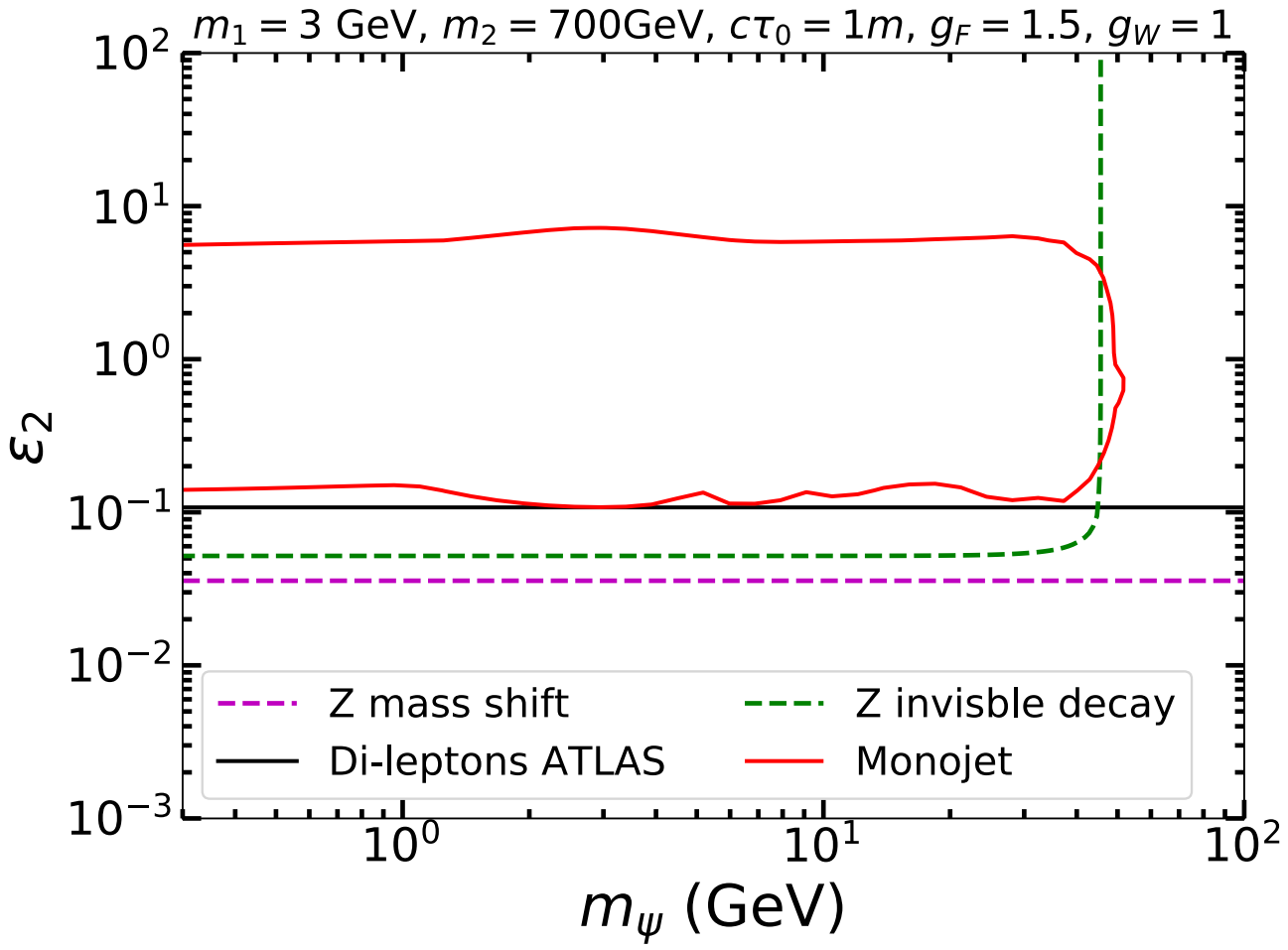




$m_{Z'} \sim O(1)$ TeV and $\epsilon_2 \sim 10^{-2}$
$m_{A'} \sim O(1)$ GeV and $\epsilon_1 \sim 10^{-7}$

→ GeV-scale LLDP and TeV Z'

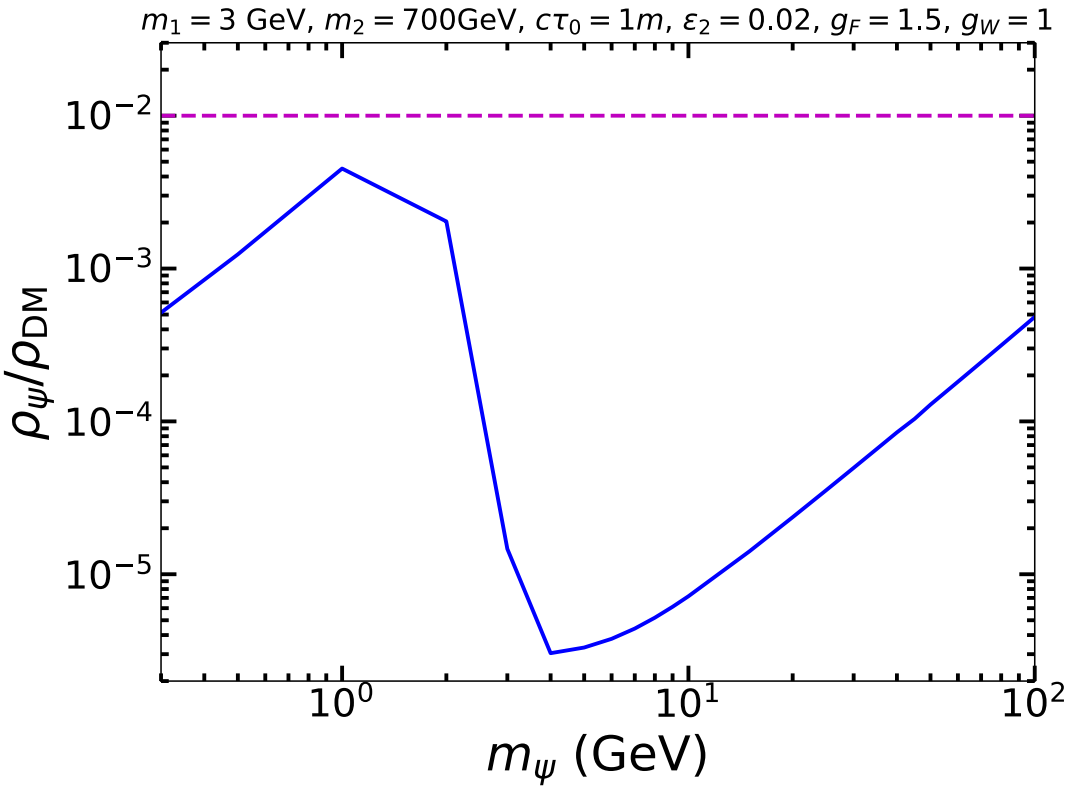
Experimental constraints

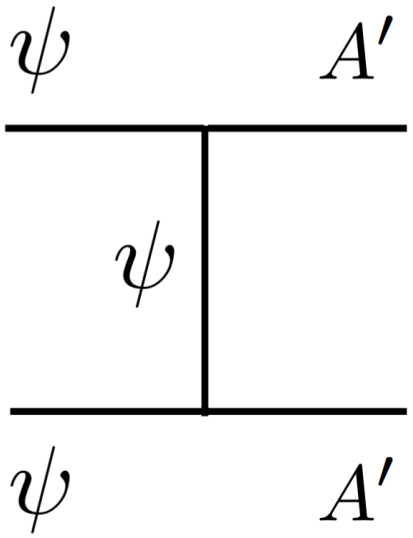


- The most stringent constraint on ϵ_2 is from Z mass shift

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

Experimental constraints (DM)



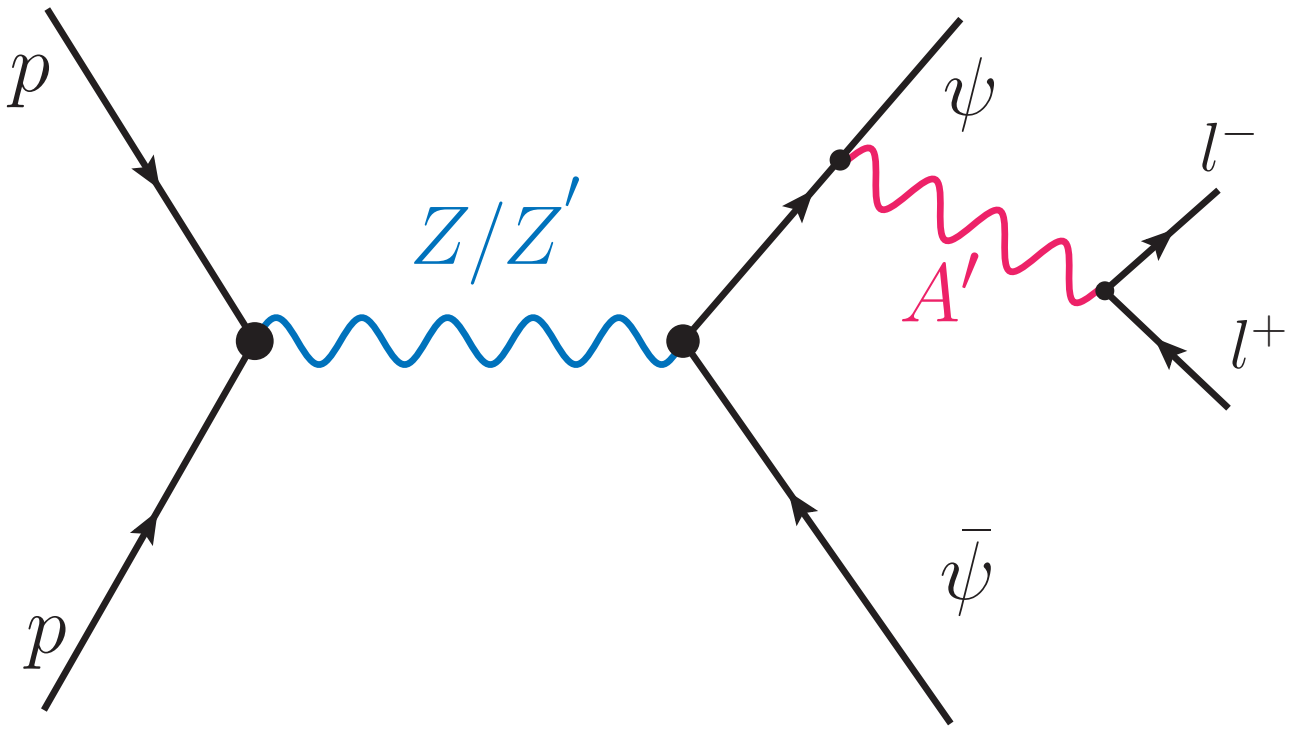


About 1% of DM can be charged

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

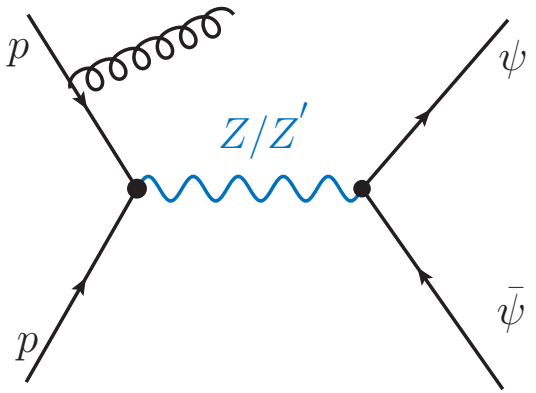
With $\epsilon_2 \sim 10^{-2}$, ψ DM cannot reach underground lab
-> **No constraint from DMDD**

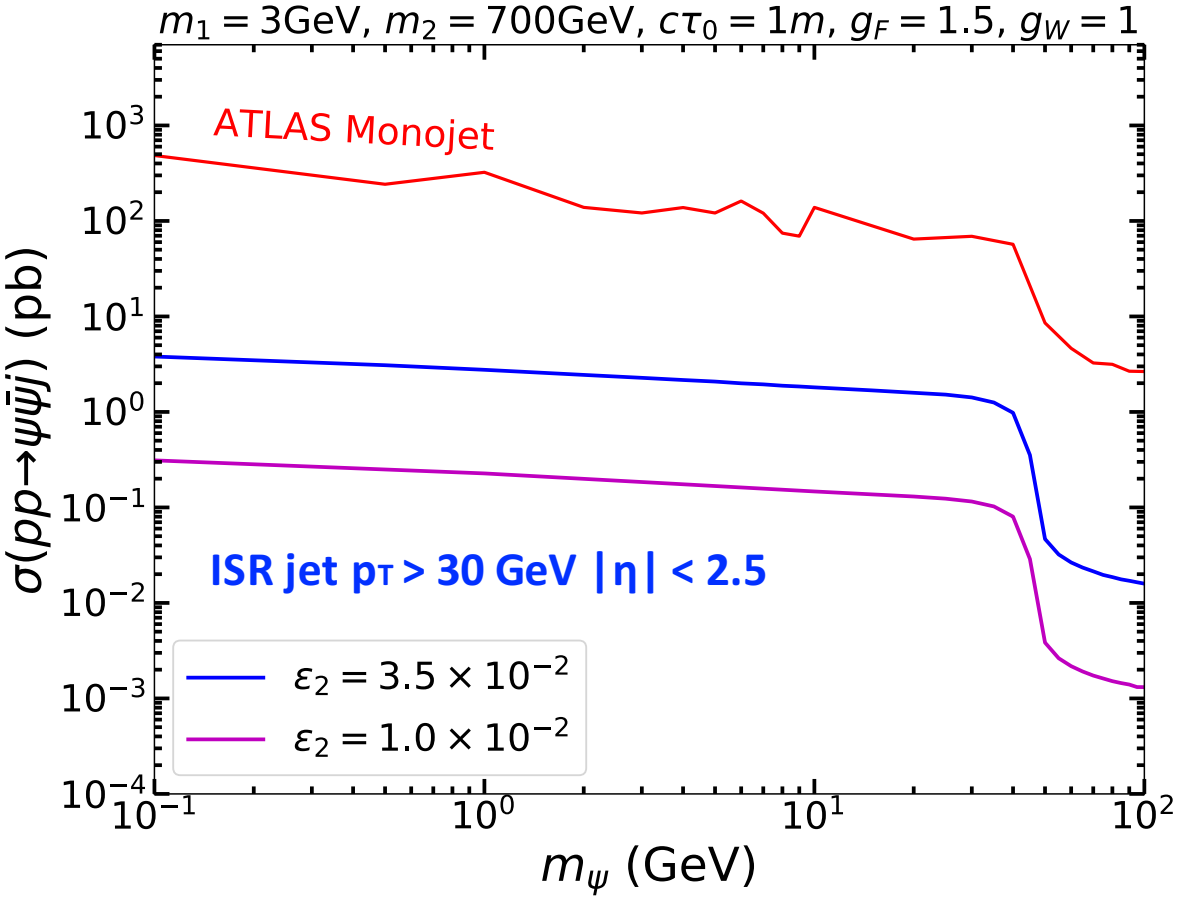
Our LLDP signal diagram



- ✓ A dark matter pair is produced via Z/Z' process .
- ✓ The DMs radiate off LLDP.
- ✓ The LLDP decays into SM leptons or jets

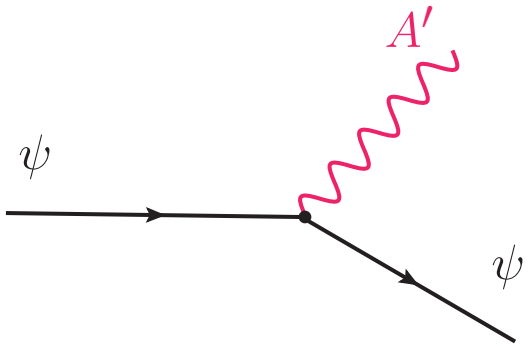
Production of DMs at LHC





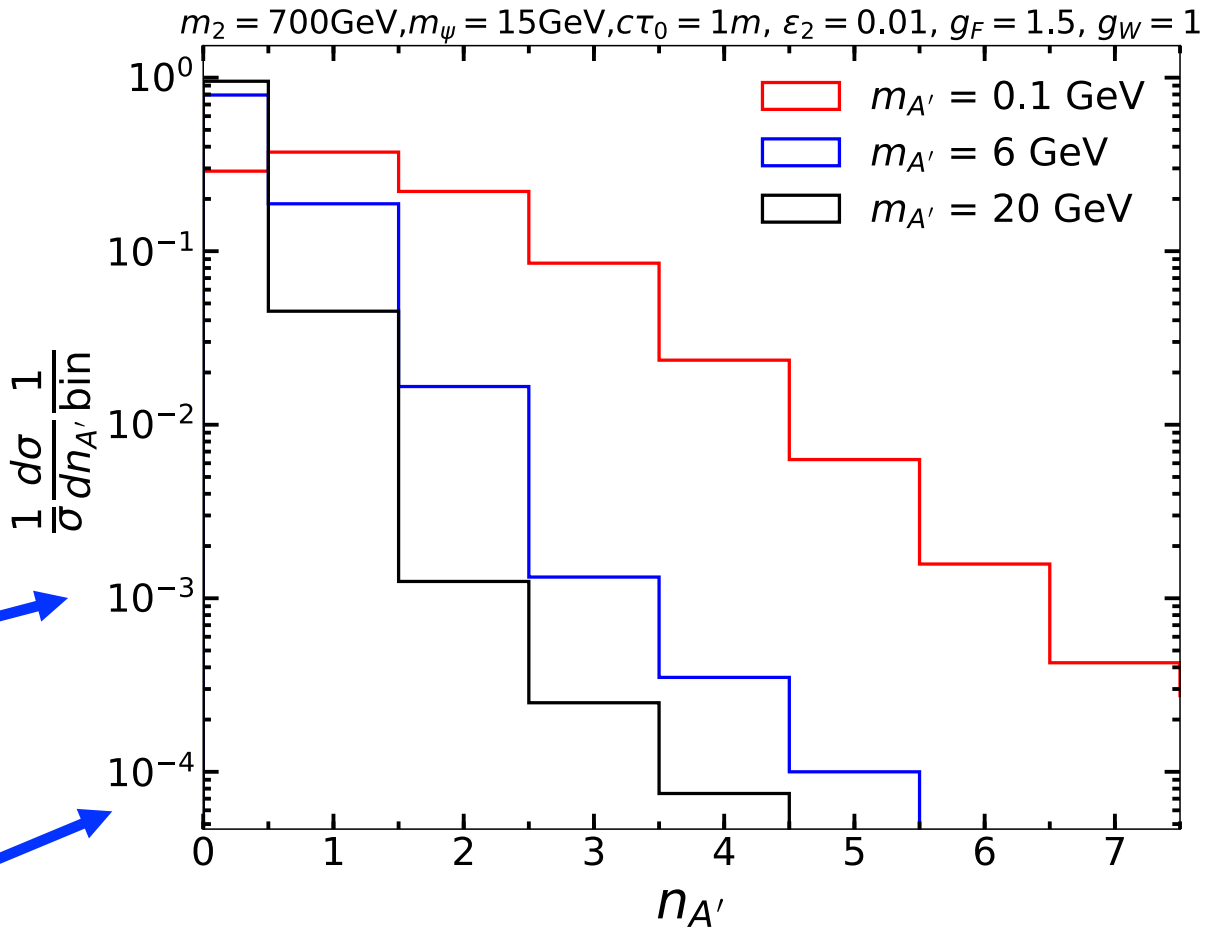
- Z boson exchange is dominant channel when $m_\psi < m_Z/2$.
- $\sigma(pp \to \psi\bar{\psi}\, j\,) \sim \mathrm{O}(\mathbf{1\ pb})$ at LHC 13 TeV

Dark Radiation



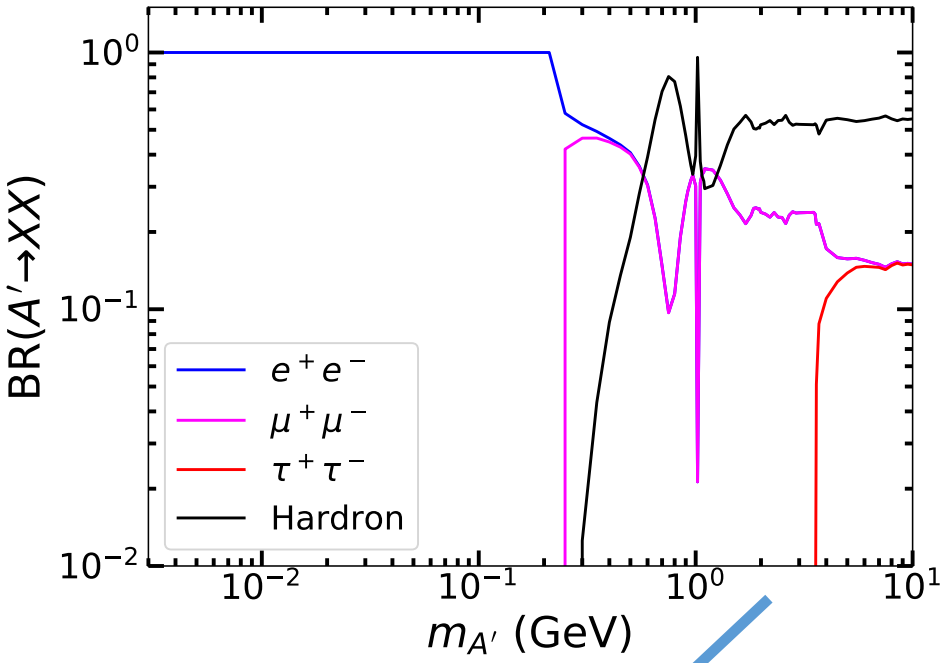
$$m_\psi = 15\ GeV$$
$$\alpha_F = {g_F^2}/{4\pi} \approx 0.18$$

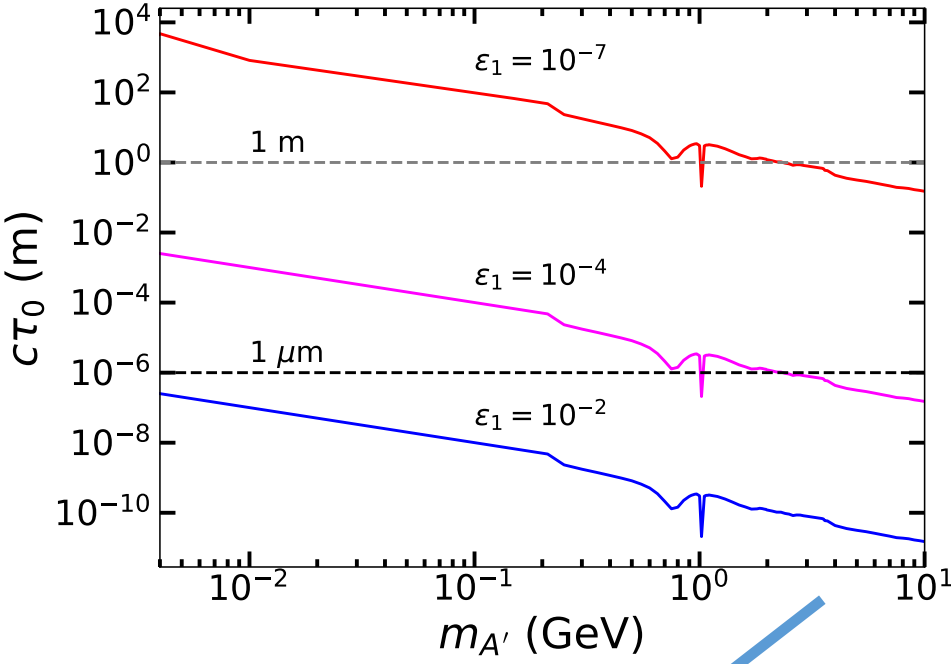
Pythia 8.2 simulation



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

Dark photon BR and lifetime





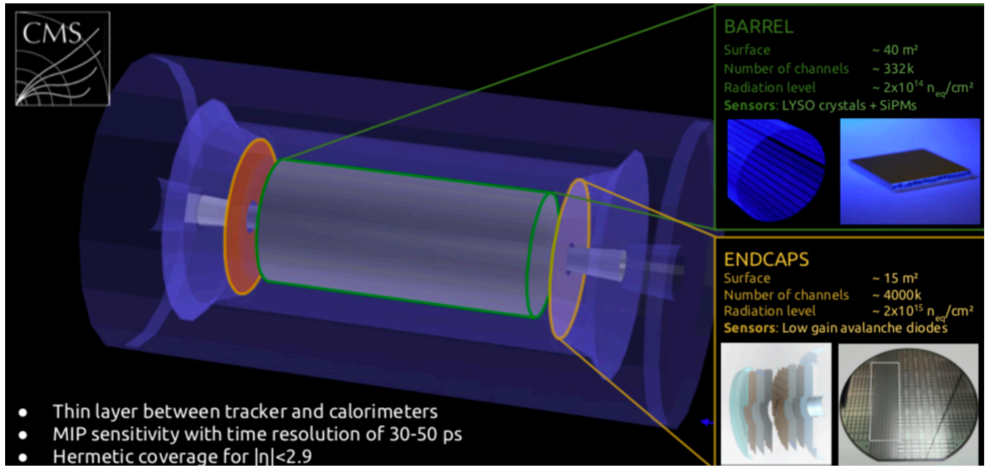
For $m_{A'} \sim O(1-10)$GeV
-> About 50% DP decays into leptons

$$c\tau_0 \approx O(1\,m) \times \left[\frac{10^{-7}}{\epsilon_1}\right]^2 \times \left[\frac{3\,GeV}{m_{A'}}\right]$$

Timing detector @CMS phase 2 upgrade

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

- Between tracker & calorimeter
- Resolution: **30 ps**,
- $p_T > \mathbf{0.7}\ \boldsymbol{GeV}$ (Barrel)
- and $p > \mathbf{0.7}\ \boldsymbol{GeV}$ (Endcaps)



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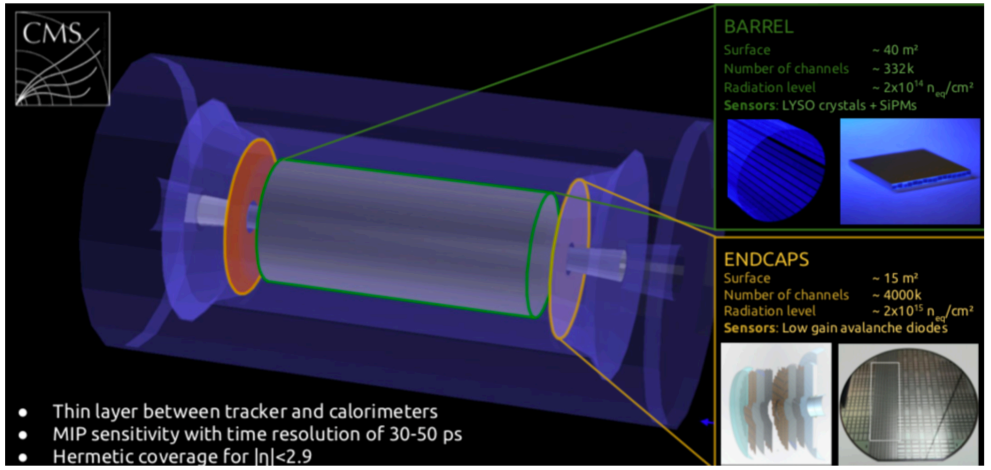
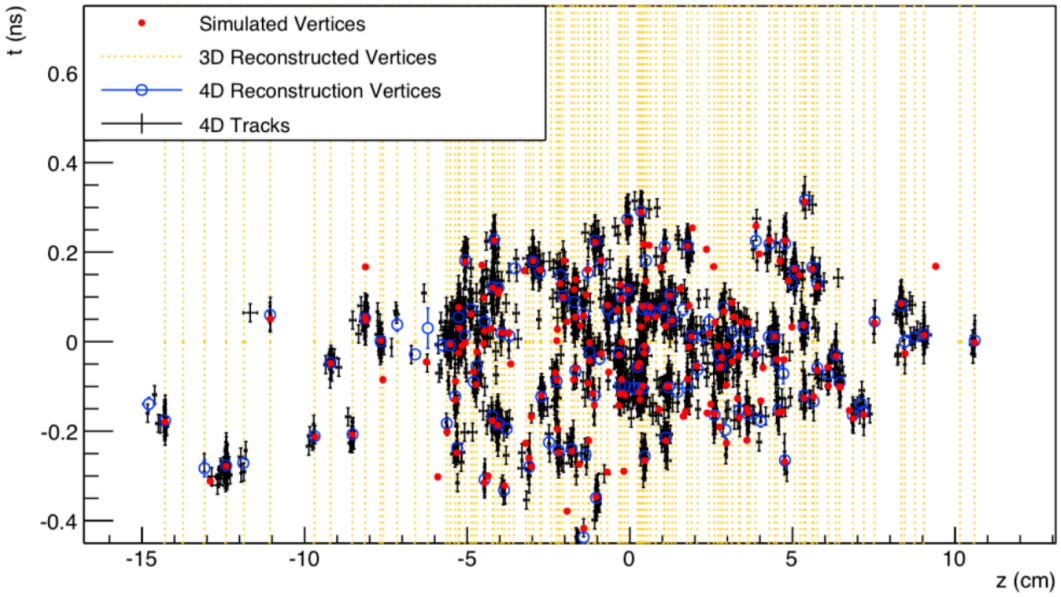
- Using time information to reconstruct 4D vertex.
- **Purpose: pile-up reduction @HL-LHC**
- **Available for BSM searches**





see also: ATLAS & LHCb upgrades

A possible LLP signal using timing info

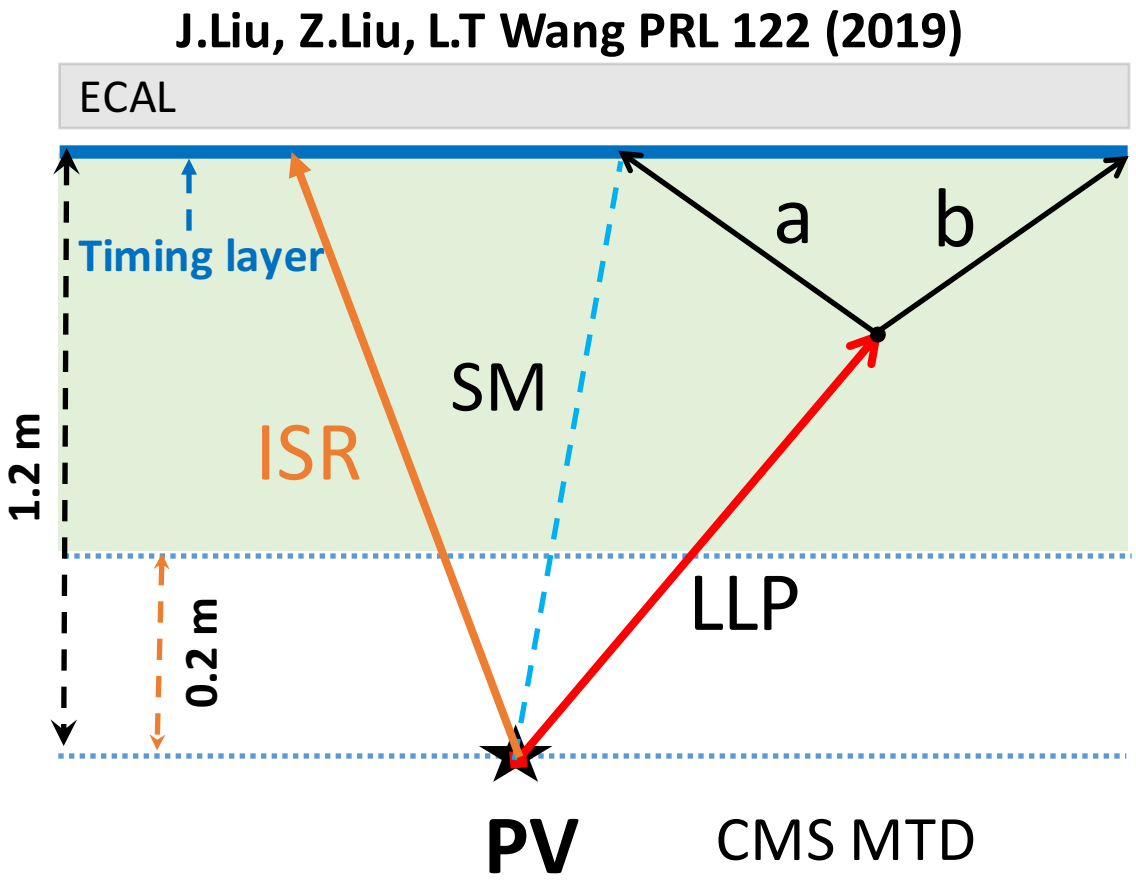
Estimation delayed time:

$$LLP \rightarrow a + b$$

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

Signal arrival time

SM bkg ref time



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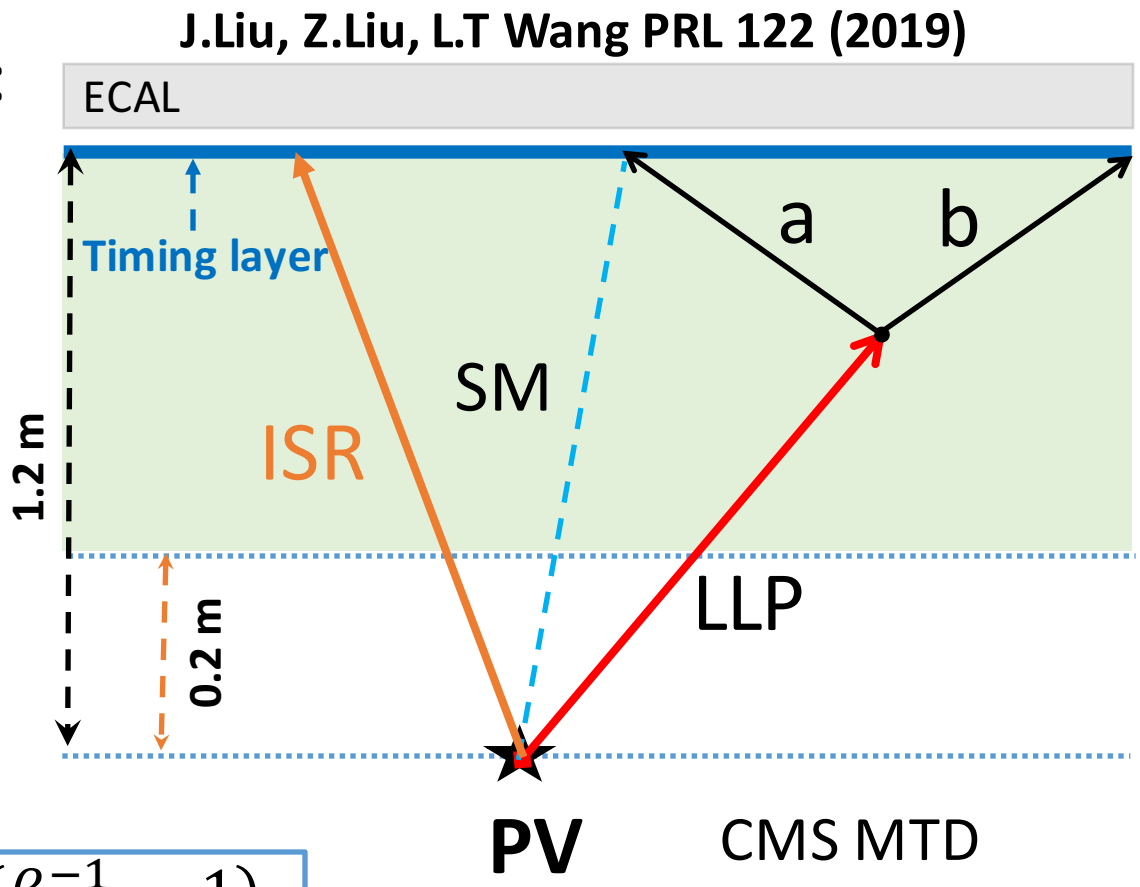
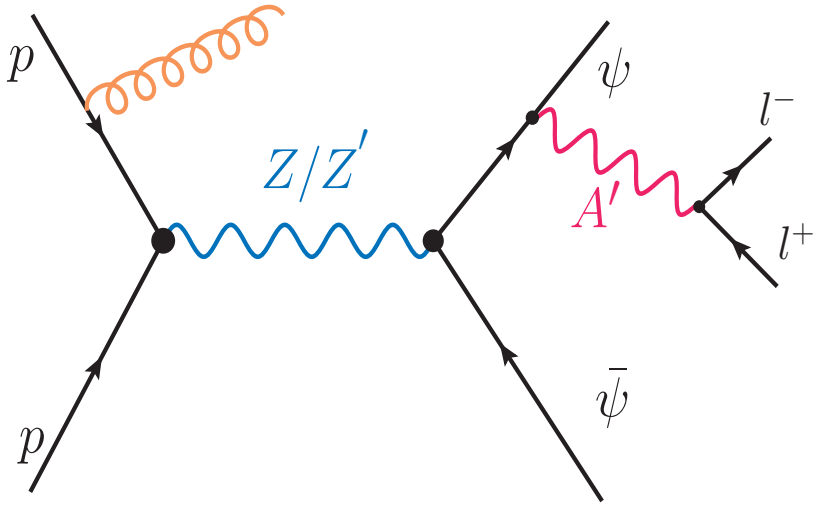


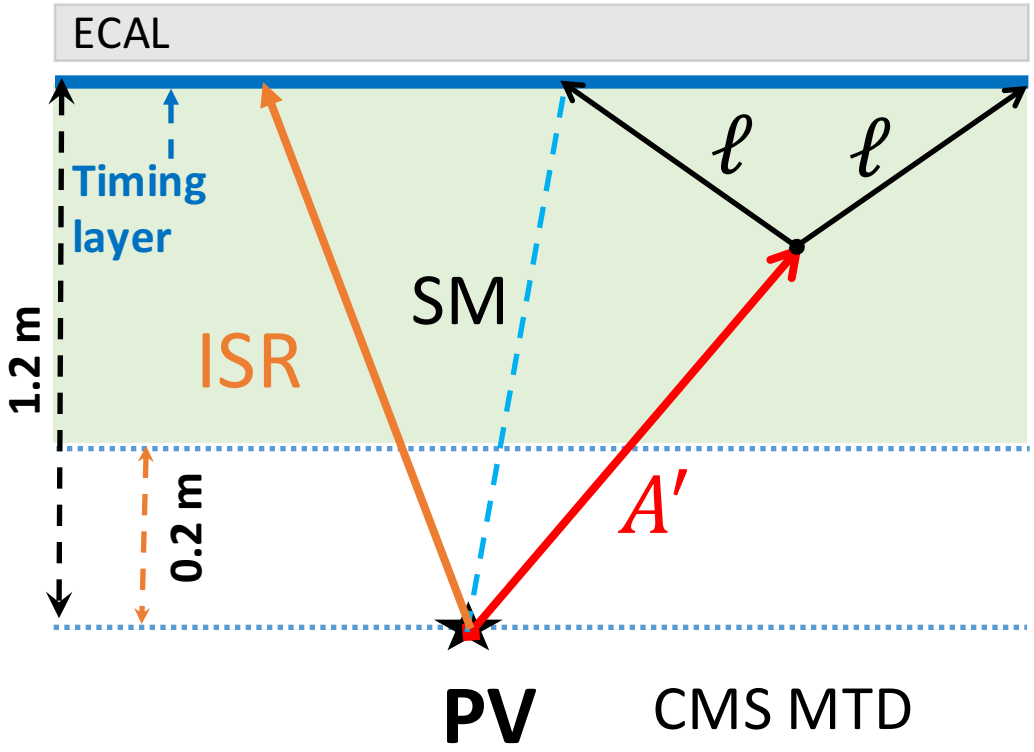
Lower bound: $\Delta t \geq l_{LLP}(\beta_{LLP}^{-1} - 1)$

Example: $h \rightarrow LLP + LLP$

with $m_{LLP} = 50\ GeV \rightarrow \Delta t \approx 3.2\ ns$

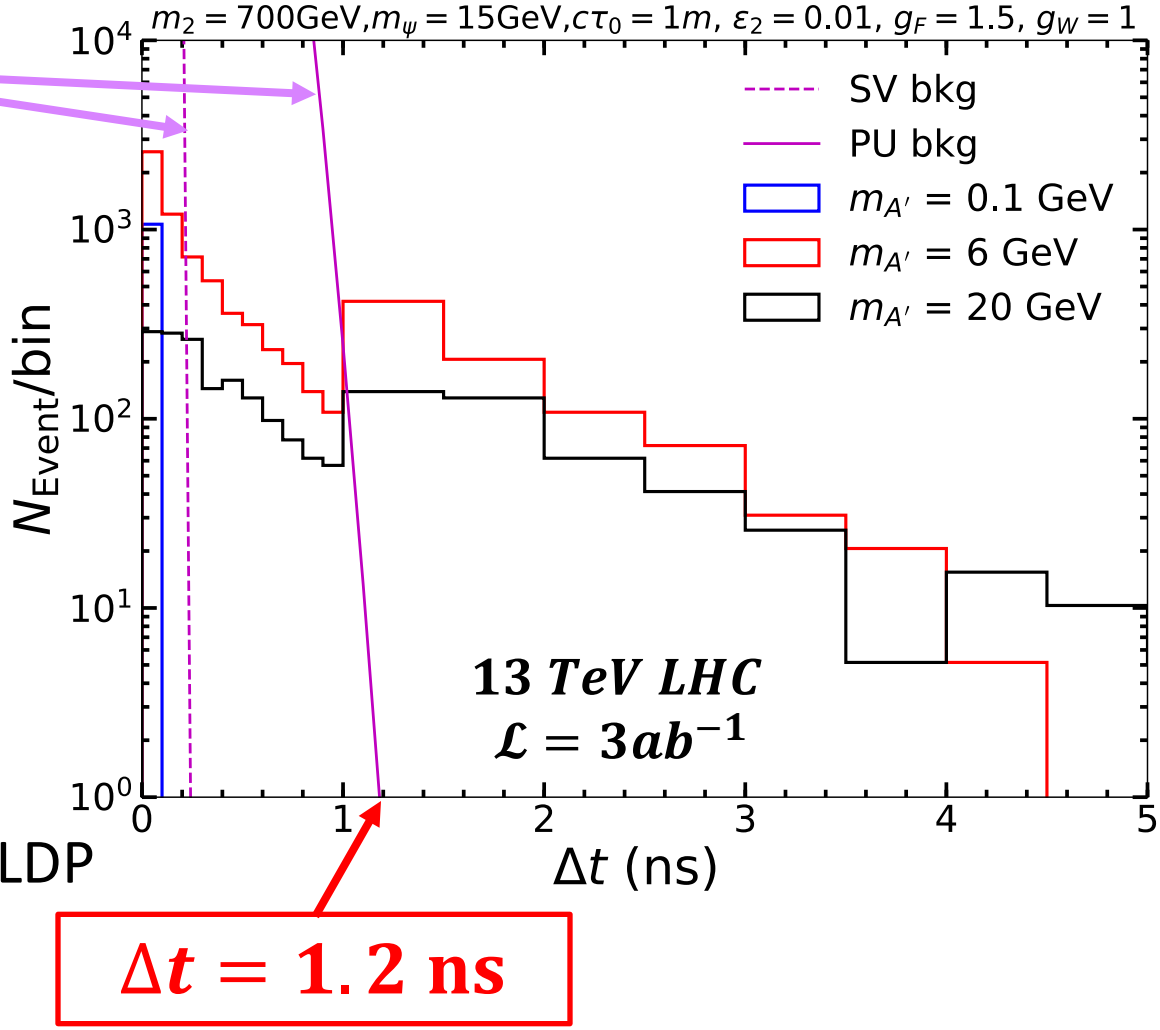
Our LLDP time delay signal





Time delay Δt distribution

Background



- Bkgs are negligible for Δt > 1.2 ns
- Time delay is less sensitive to low mass LLDP

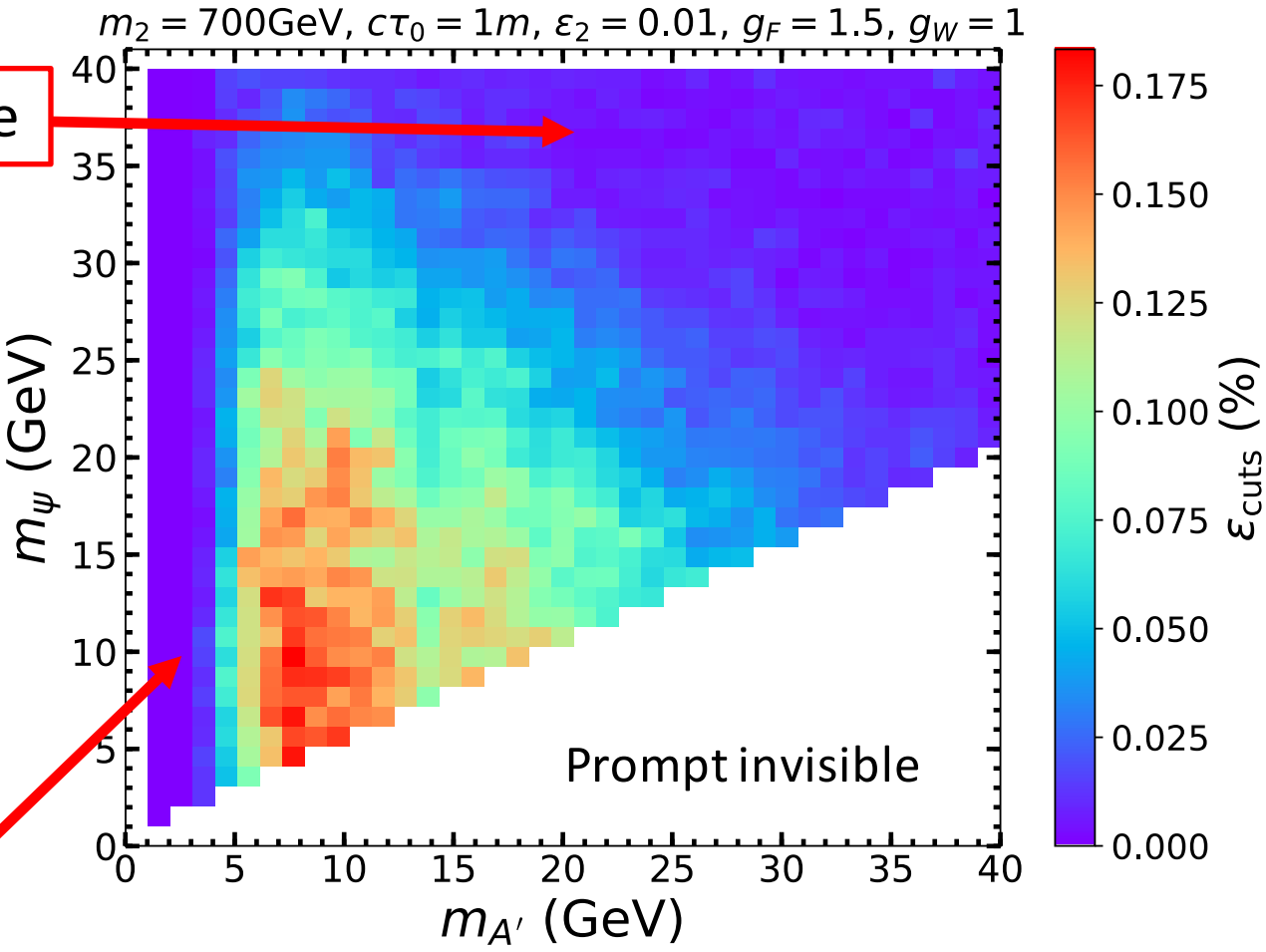
Detector efficiency

Event selection:
DP: 0.2m< L_T <1.17m & z < 3.04m
ISR jet: p_T > 30 GeV &$|\eta|$ < 2.5
Lepton: p_T > 3 GeV
Time delay: **Δt > 1.2 ns**

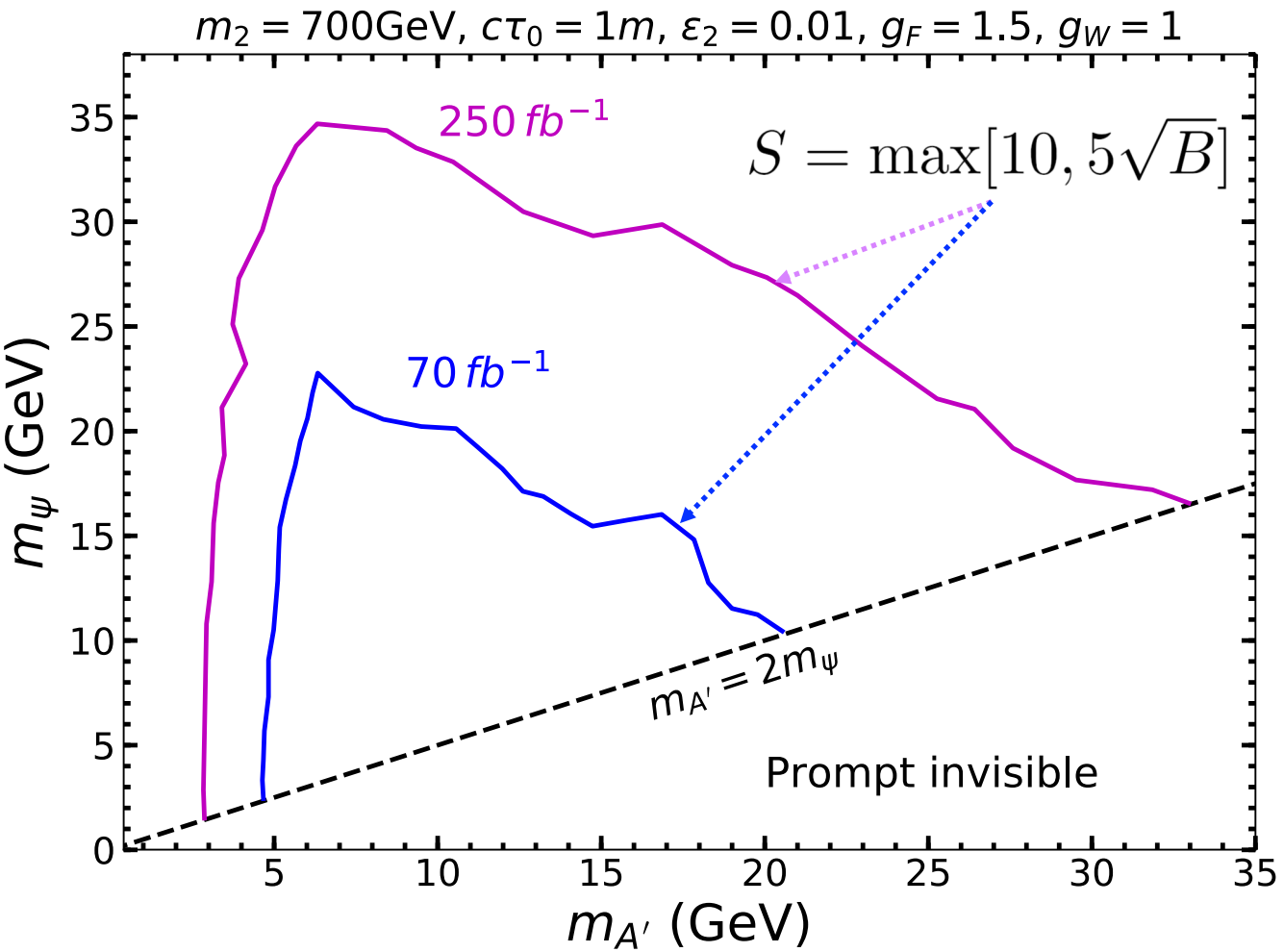
LLDP events under detector cuts per $\psi\psi$

Low dark radiation rate

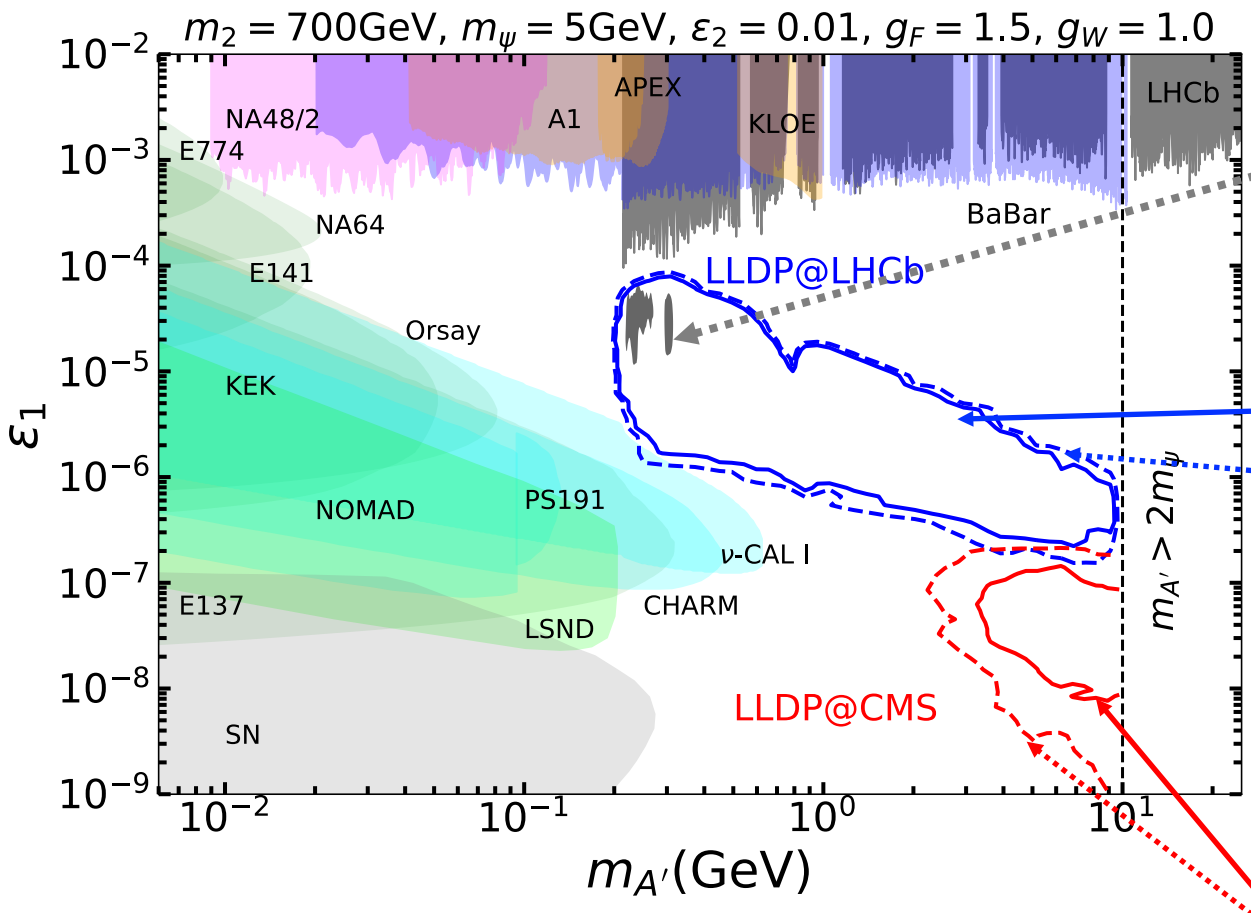
Low p_T lepton & small time delay



Time delay reach on LLDP



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 $6mm < L_T\ (A') < 22mm$

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 long-lived dark photon signal is greatly enhanced.
- We examine the model by taken into account various experimental constraints.
- We compute the sensitivities to the long-lived dark photons from the precision timing detector and LHCb.

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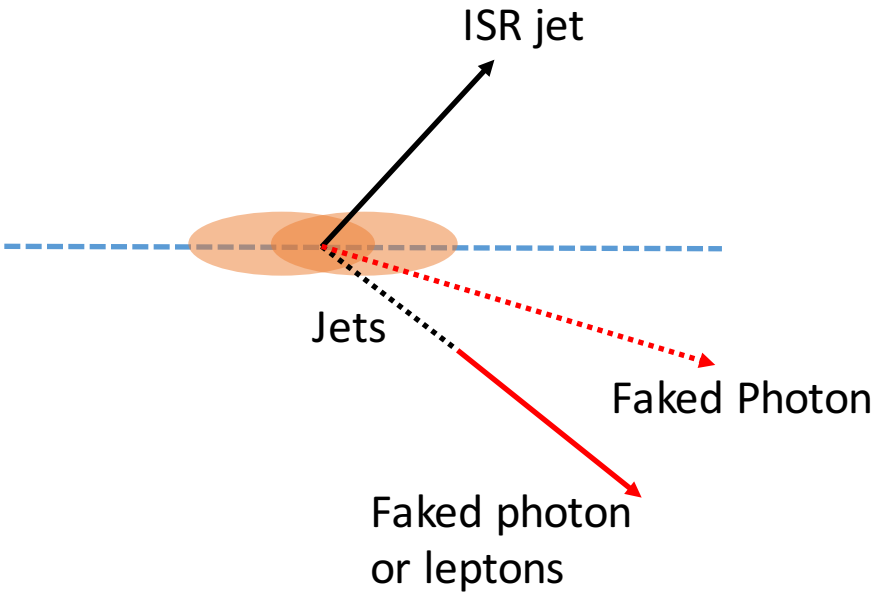
Thank You

Back up

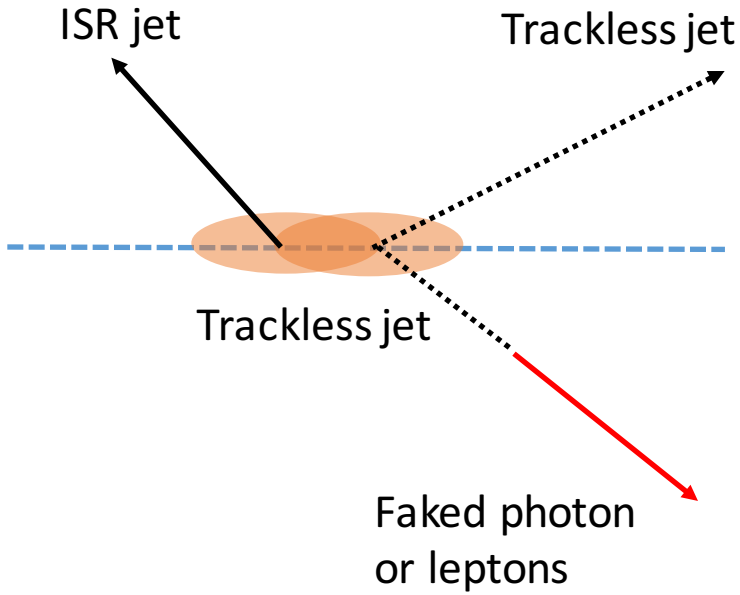
Background

Same hard interaction (SV)



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

Pile up (PU)



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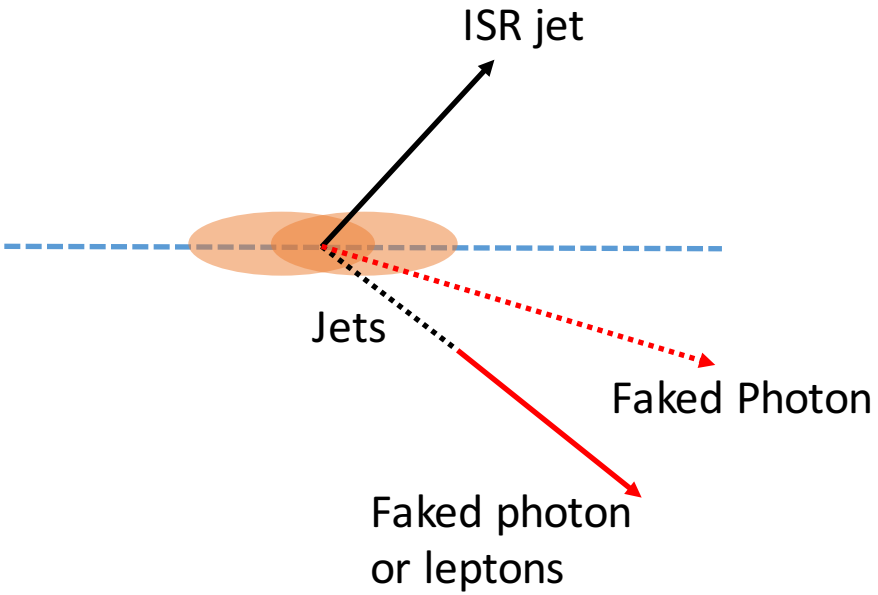

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$$N_{SV} = \sigma_\gamma \mathcal{L} + \sigma_j \mathcal{L} f_\gamma \approx \mathbf{1.2{\times}10^{15}}$$

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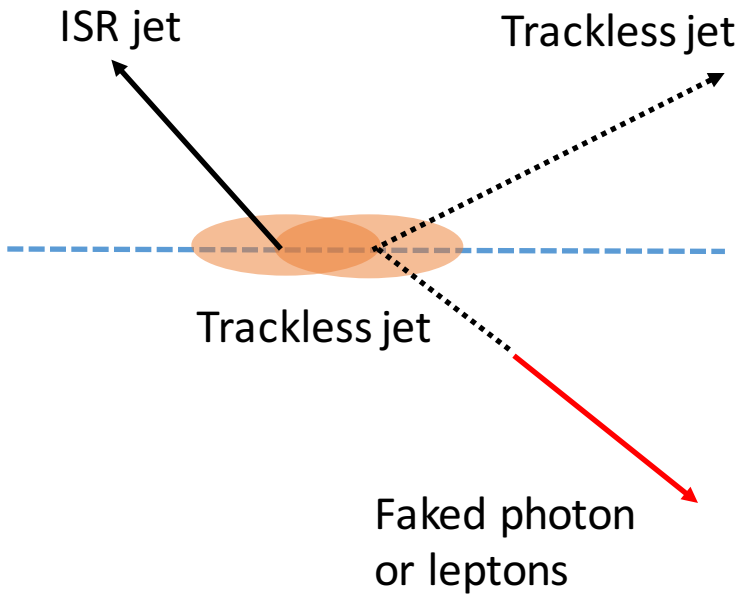

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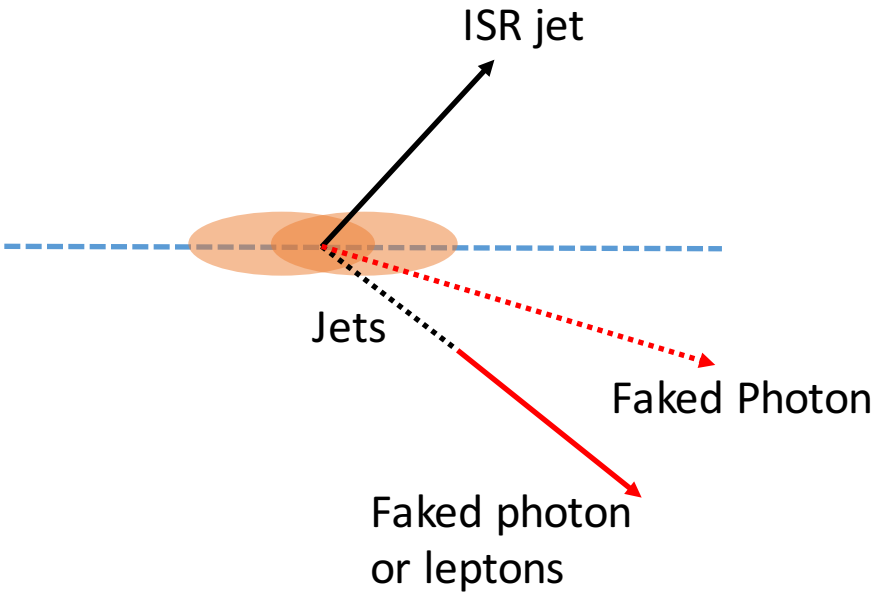

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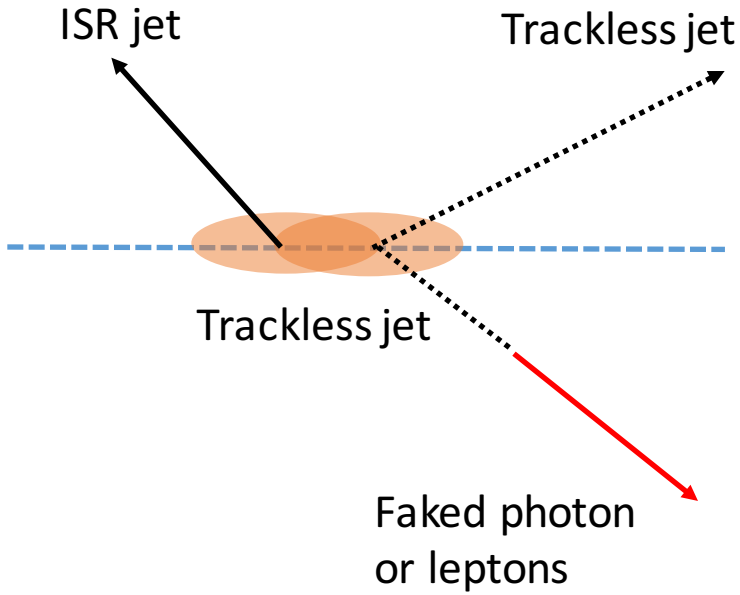

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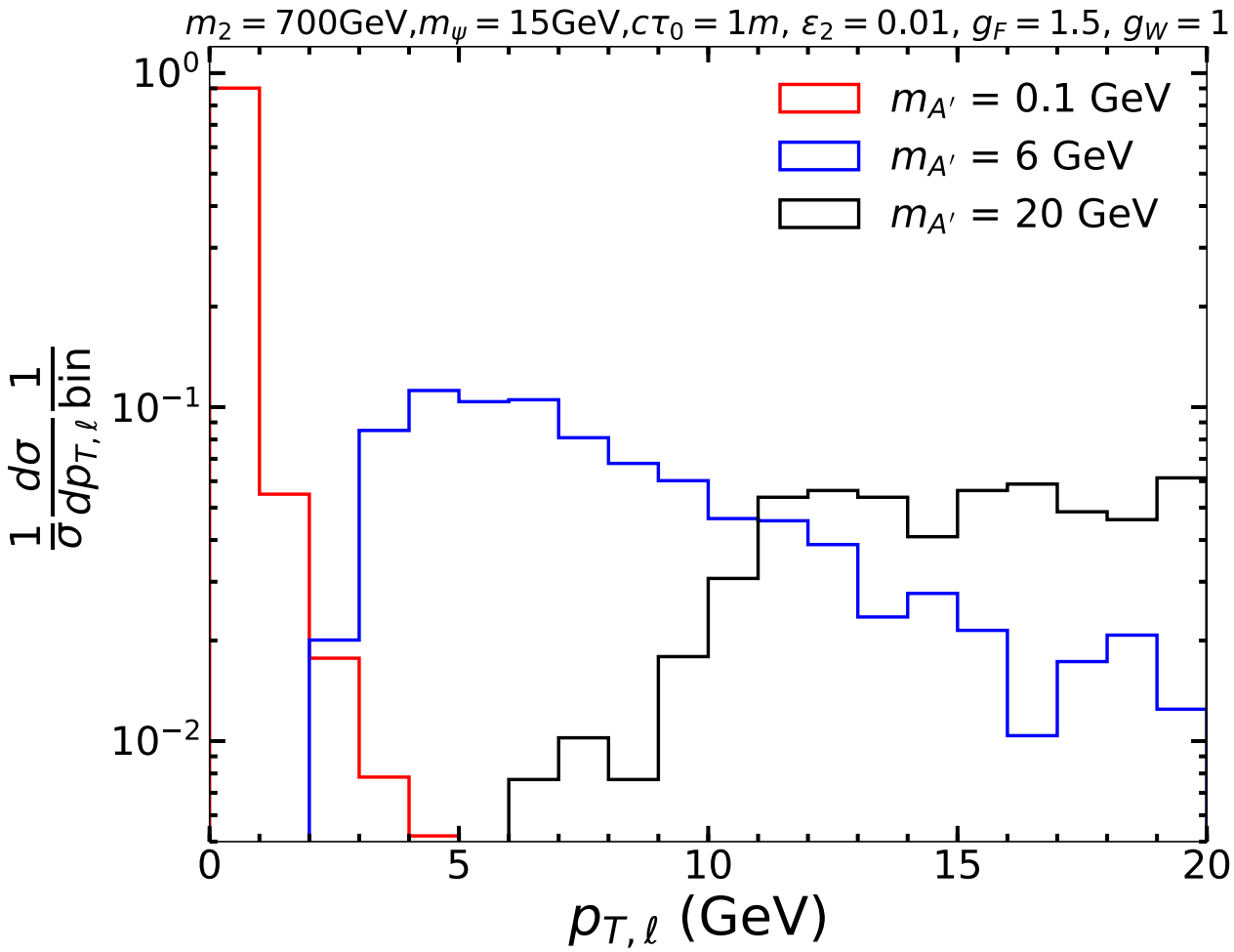
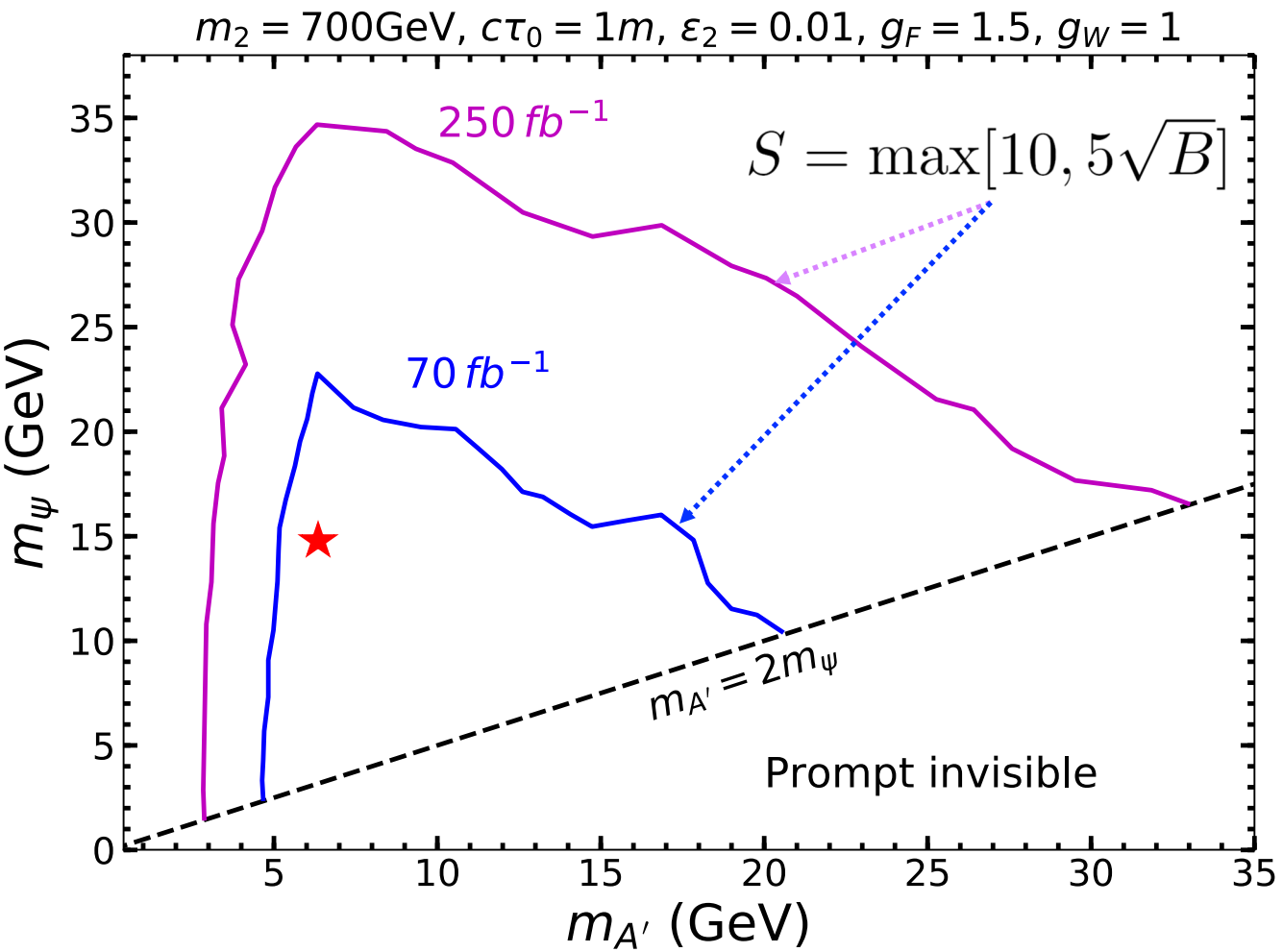
❖ Other BGs could come from cosmic ray, core and satellite bunch and beam halo.

arXiv:1906.06441

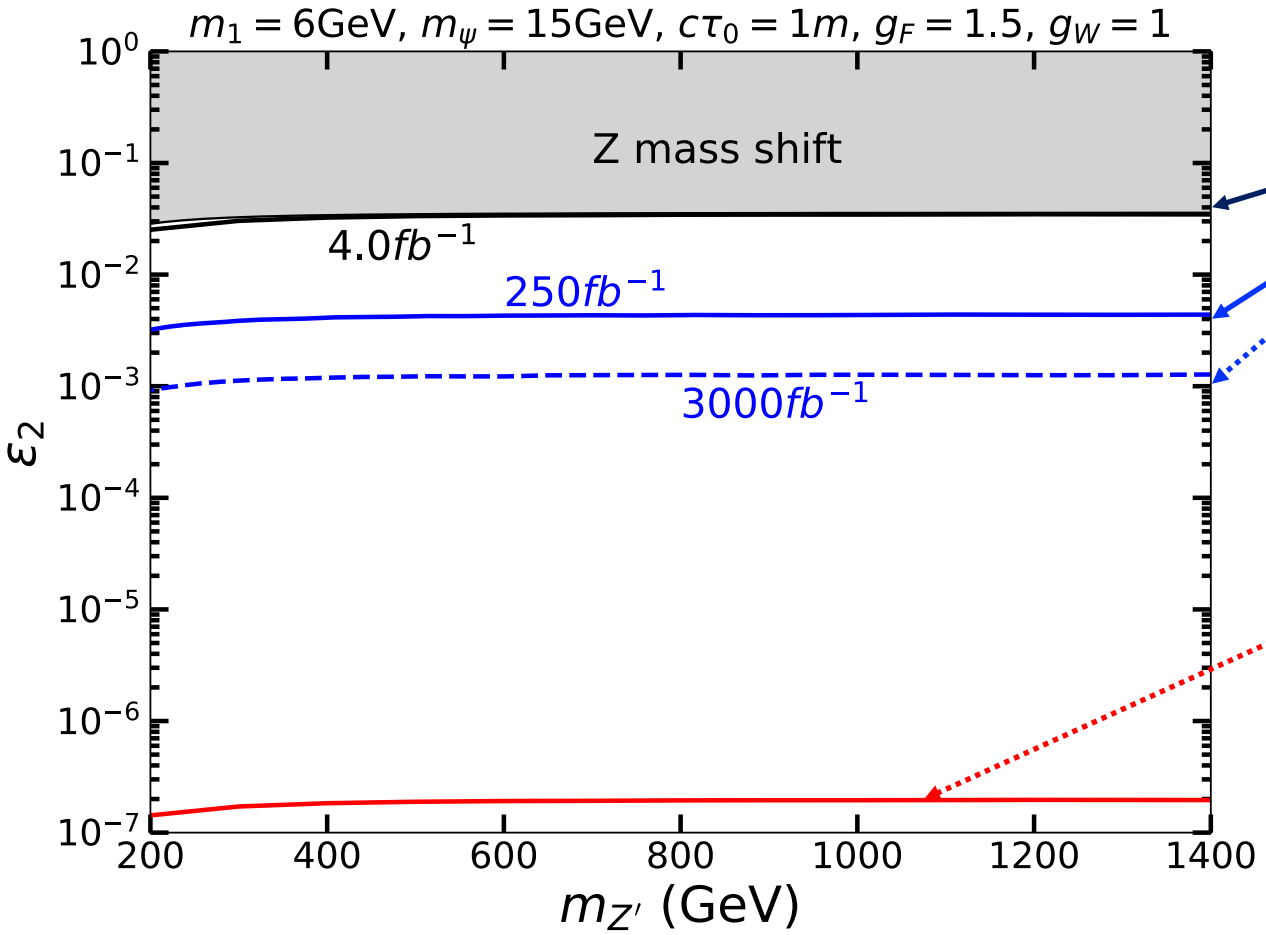
Lepton p_T distribution



Time delay reach on LLDP (1)



Time delay reach on LLDP (2)



$$S = \max[10, 5\sqrt{B}]$$

Boundary contour where our model is less significant than 'ordinary' DP model.