# Long-Lived Particles searches at the LHC with Timing information

Jia Liu

The Enrico Fermi Institute, University of Chicago

With Zhen Liu and Liantao Wang, 1805.05957

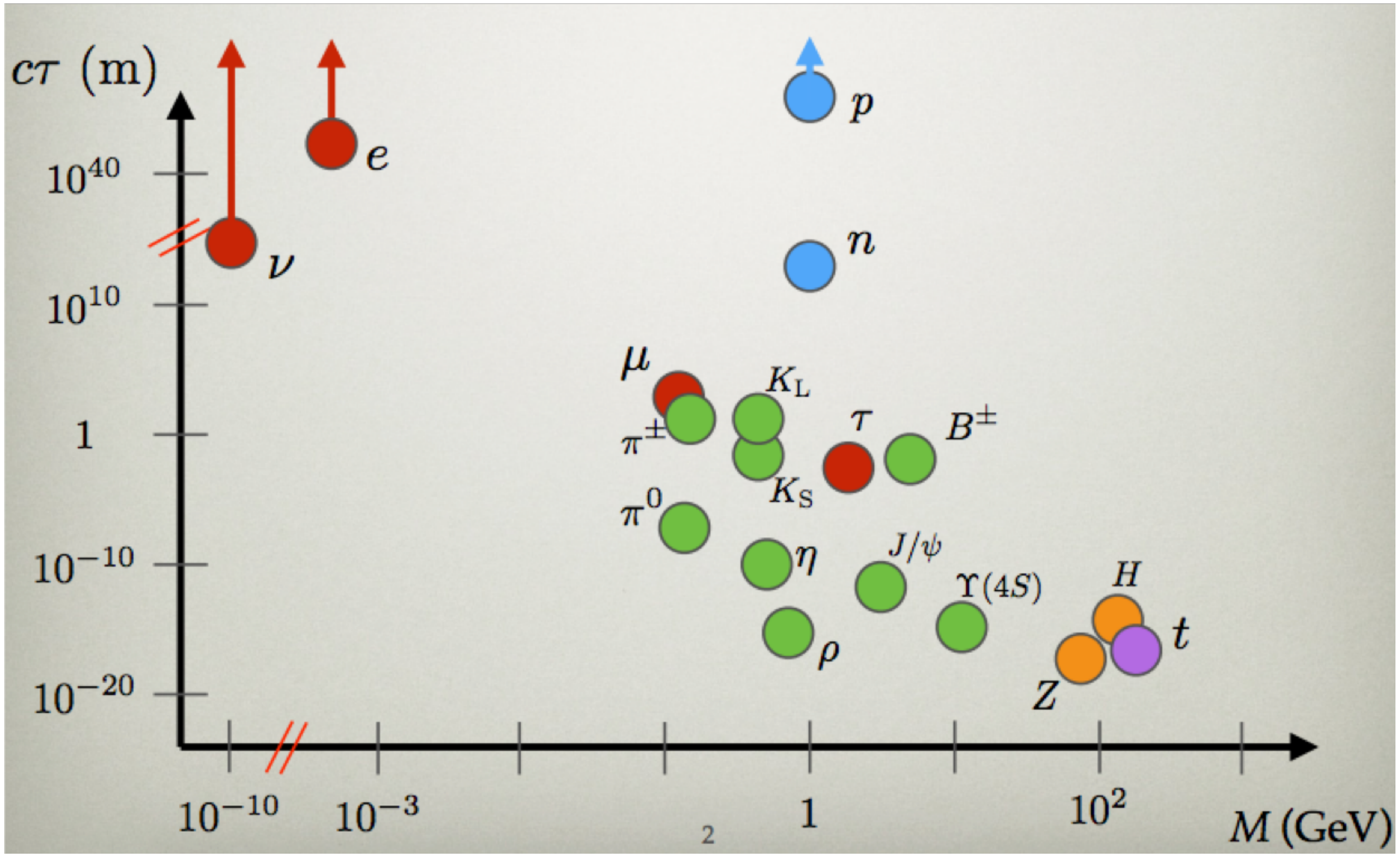
Phys.Rev.Lett. 122 (2019), 131801

SUSY 2019 @ Texas A&M University – Corpus Christi

2019-05-22

# Why looking for long-lived particles?

- 0. Long-lived particles from SM




Credit: B. Shuve

- Suppression from heavy mass scale: muon/charged pion
- Approximate symmetry & near degenerate state: $K_L$ to three pions

# Why looking for long-lived particles?

- 1. Long-lived particles from beyond SM, e.g. SUSY

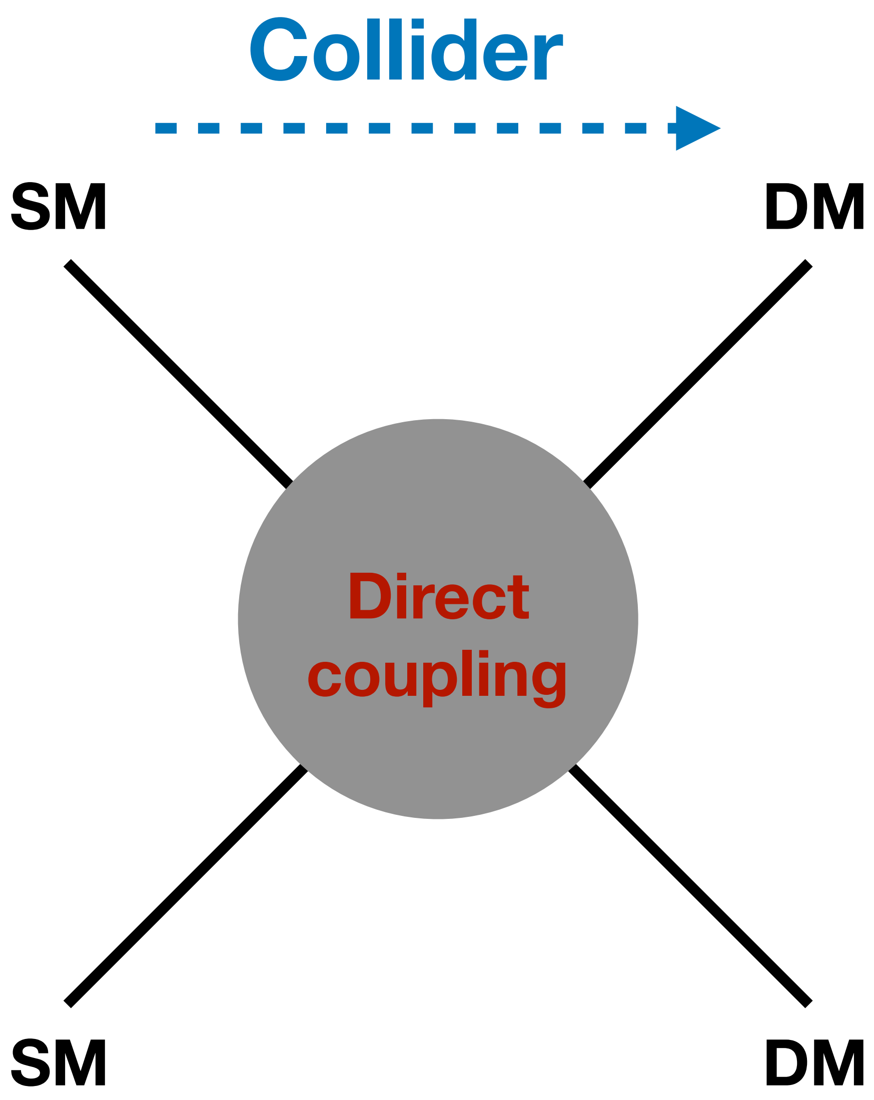
- Feeble couplings: R-parity violating Supersymmetry, sterile neutrinos, portal models

- Suppression from heavy mass scale: gauge mediated spontaneous breaking Supersymmetry

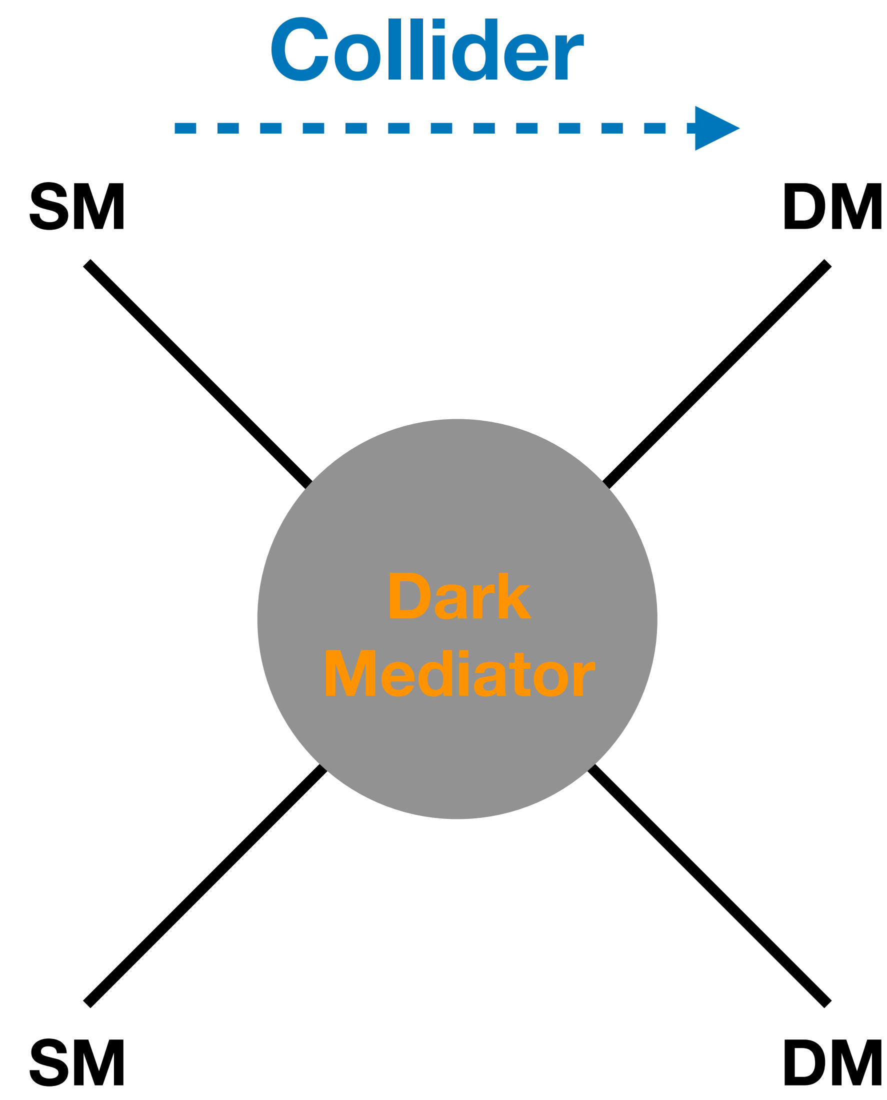
- Near degenerate state: higgsino-like chargino/neutralino, or anomaly-mediated spontaneous breaking Supersymmetry

# Why looking for long-lived particles at Collider?

- 2. Long-lived particle examples from dark sector




**WIMP**




**Hidden sector DM**

# Why looking for long-lived particles at Collider?

- 2. Long-lived particle examples from dark sector

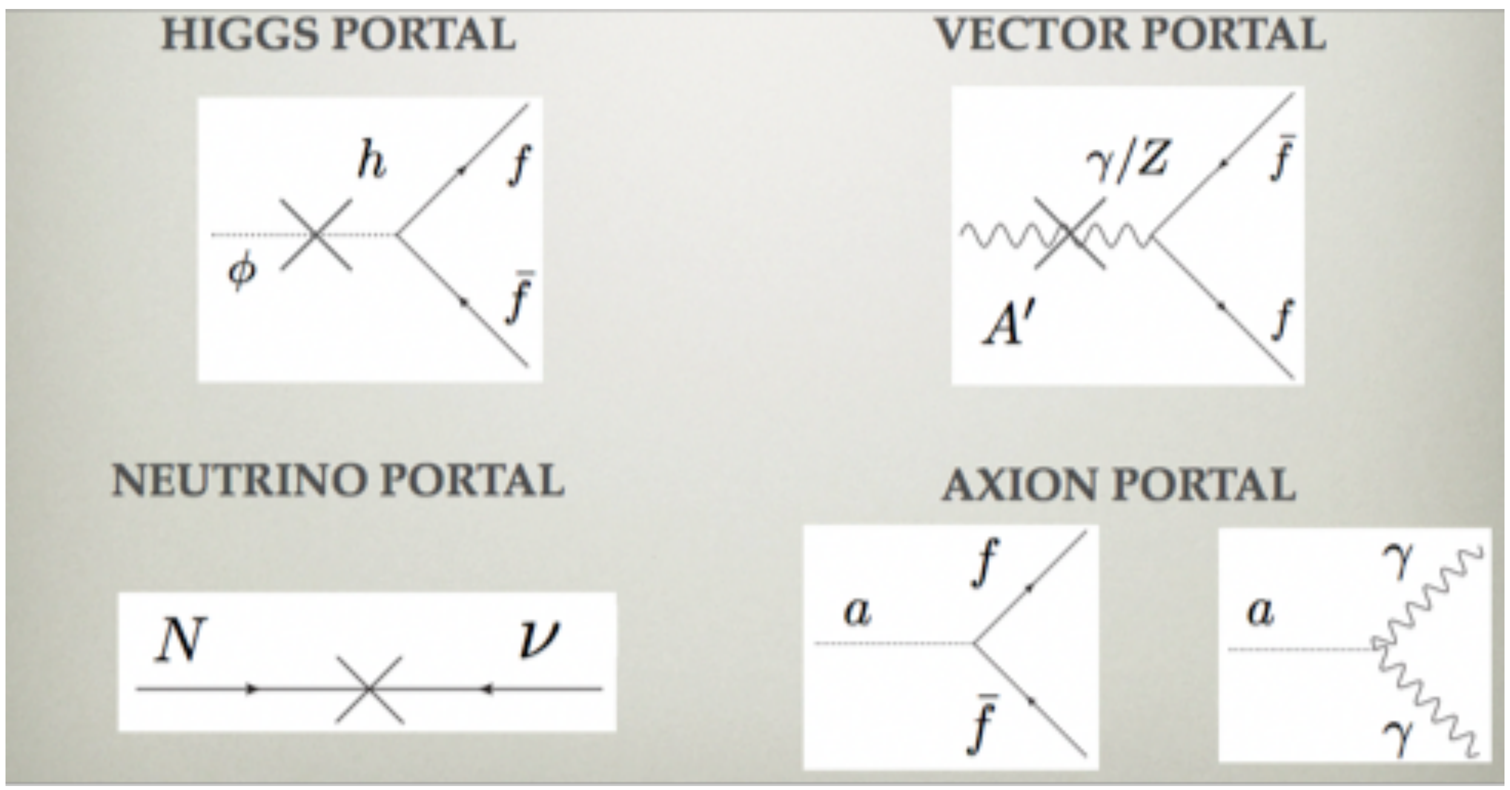
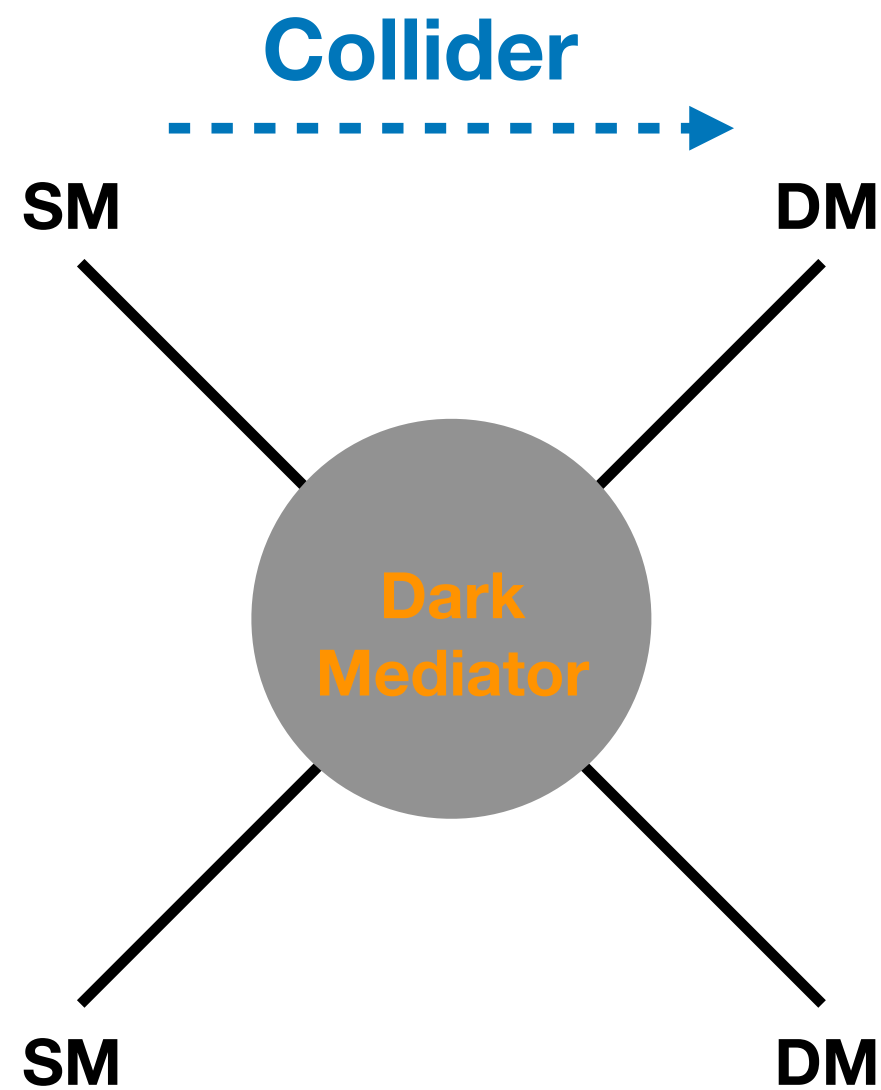


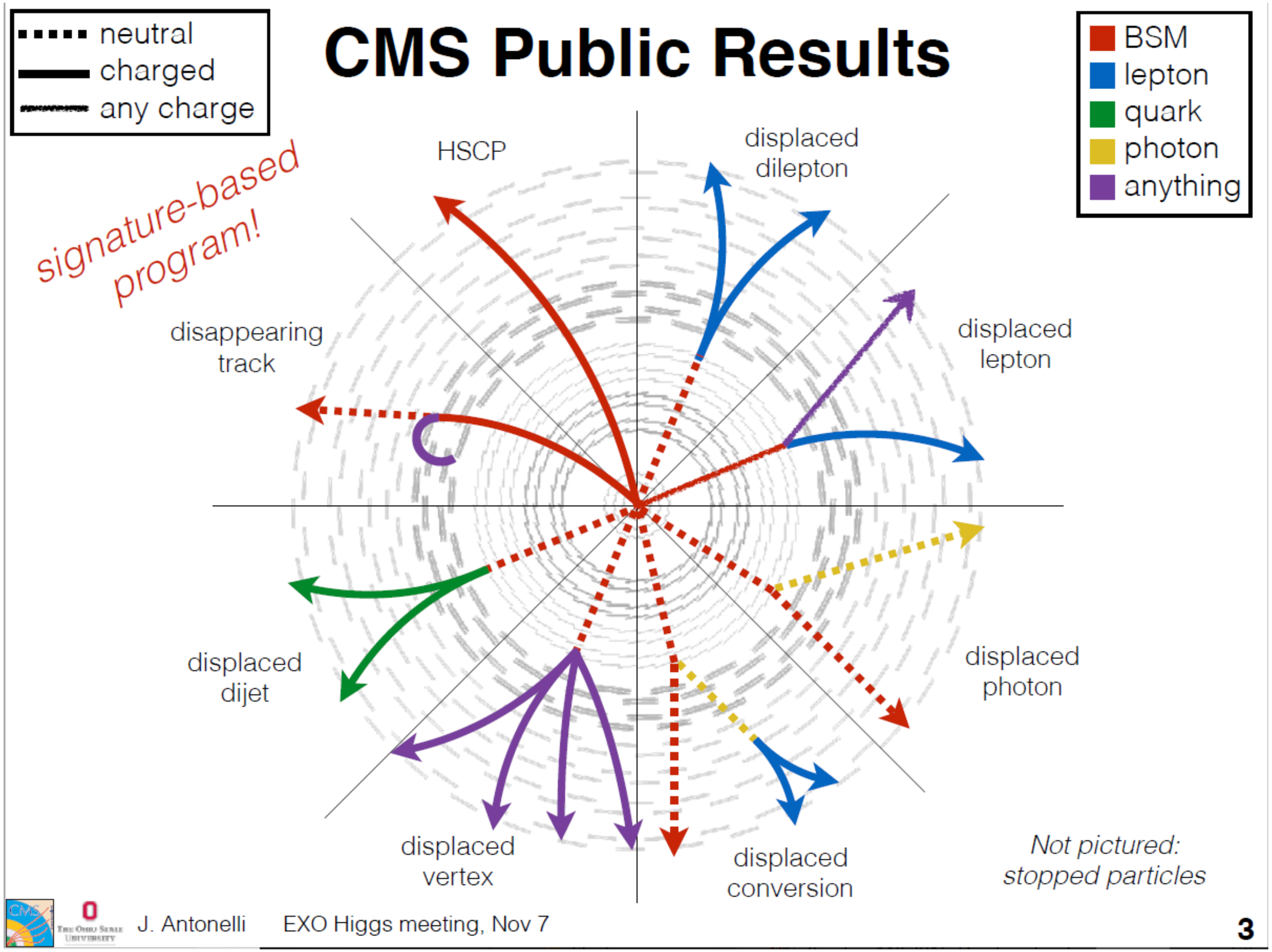

Fig. credit B. Shuve




Hidden sector DM

# How to search for long-lived particles?

- Spatial discrimination: mostly related with displaced-vertex, and track-based



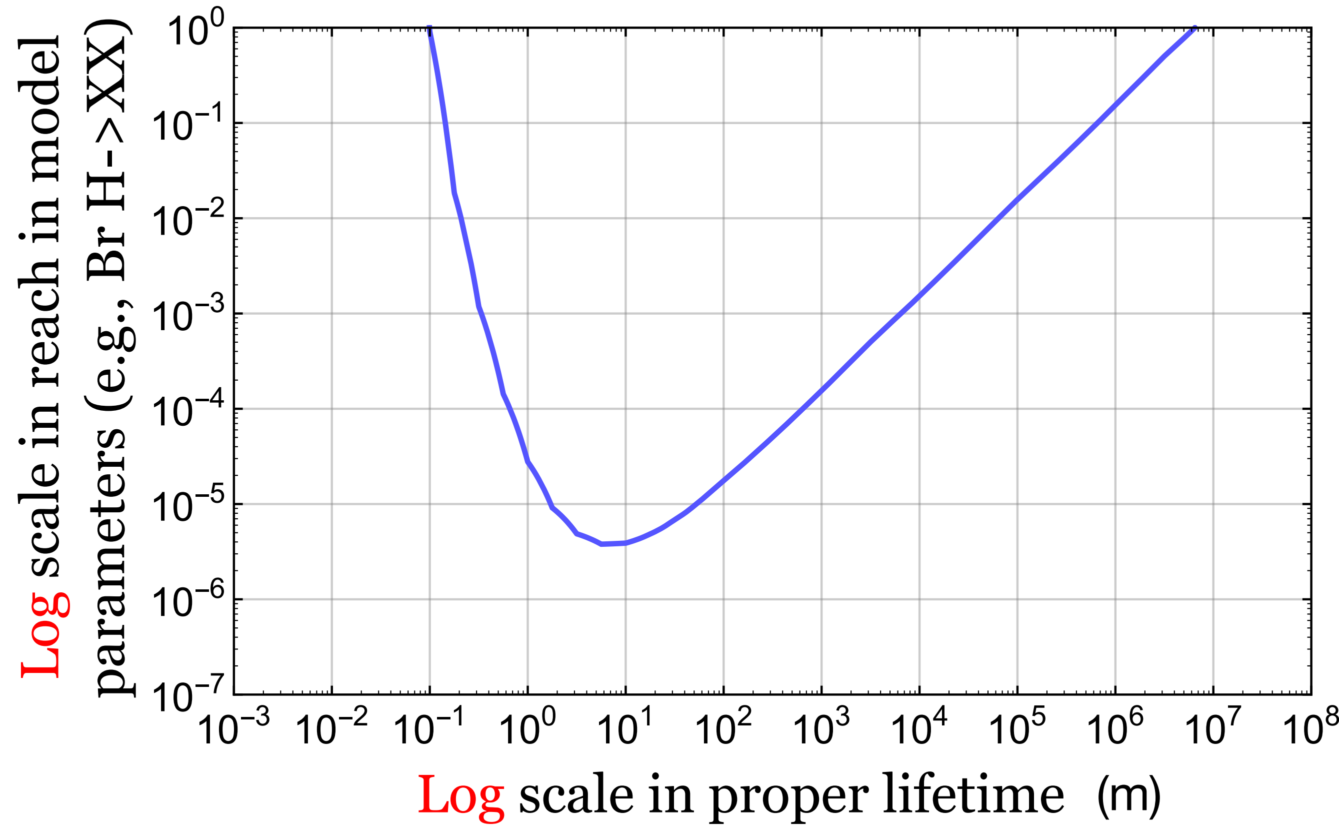
# LLP searches at the LHC

- LLP has strong theoretical motivation.
  - New proposals made for far detectors.
- We focus here on new approaches for searches at existing detectors, i.e., ATLAS and CMS.
  - Larger geometrical acceptance, but also large background.
  - Ample room for new ideas.

# LLP basics: Geometrical acceptance

- $P_{in}$: Geometrical acceptance

$$P_{\text{in}} = \frac{1}{4\pi}\int_{\Delta\Omega} d\Omega \int_{L_1}^{L_2} dL \frac{1}{d} e^{-L/d}$$
$$\approx \frac{\Delta\Omega}{4\pi} \; e^{-L_1/d} \; \frac{L_2 - L_1}{d}$$




- The detector length $L_2$ - $L_1$
- d: expected decay length of LLP in lab frame

$$d = c\tau\gamma\beta$$

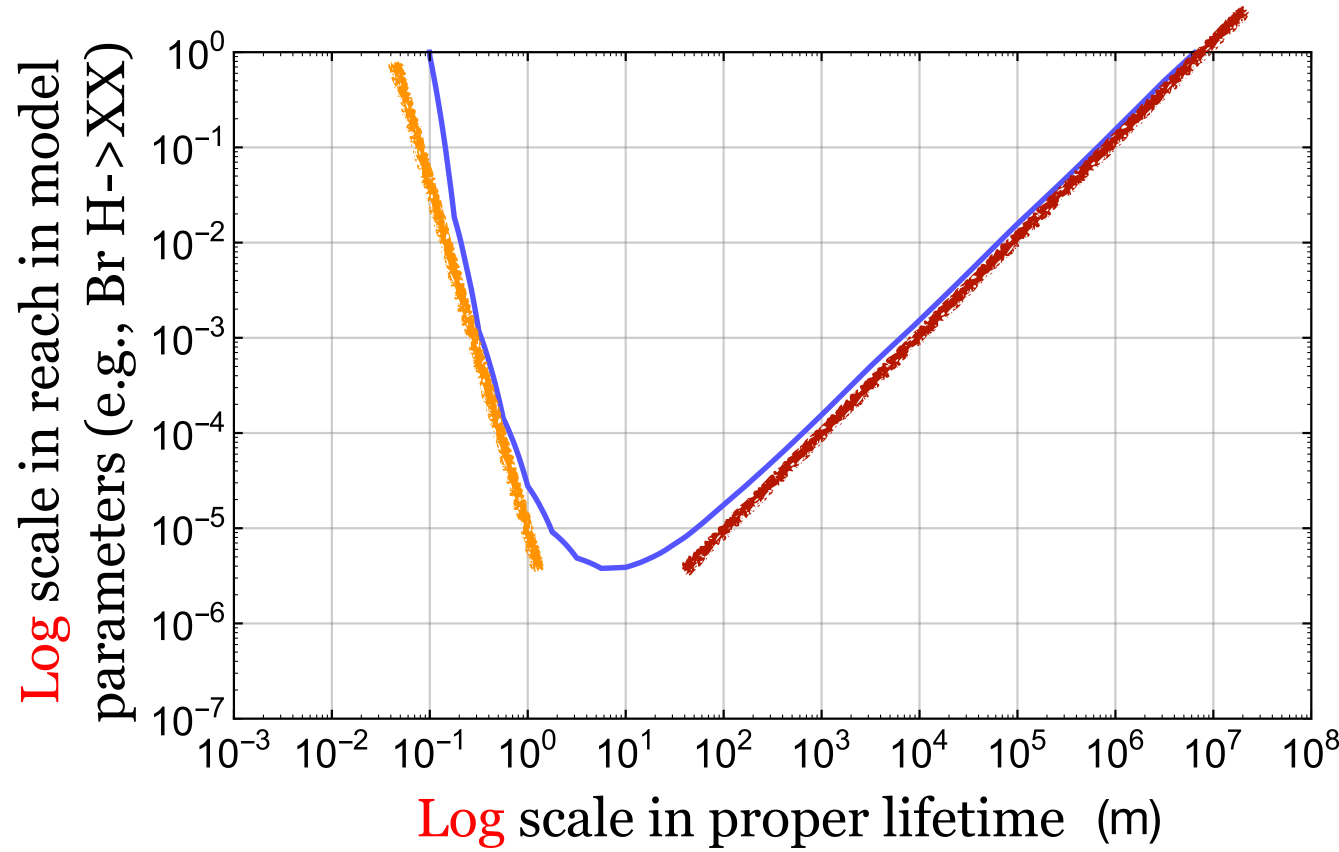
# LLP basics: Geometrical acceptance

- $P_{in}$: Geometrical acceptance

$$P_{\text{in}} = \frac{1}{4\pi}\int_{\Delta\Omega} d\Omega \int_{L_1}^{L_2} dL \frac{1}{d} e^{-L/d}$$

$$\approx \frac{\Delta\Omega}{4\pi} e^{-L_1/d} \frac{L_2 - L_1}{d}$$

**Solid angle** **Detector length**



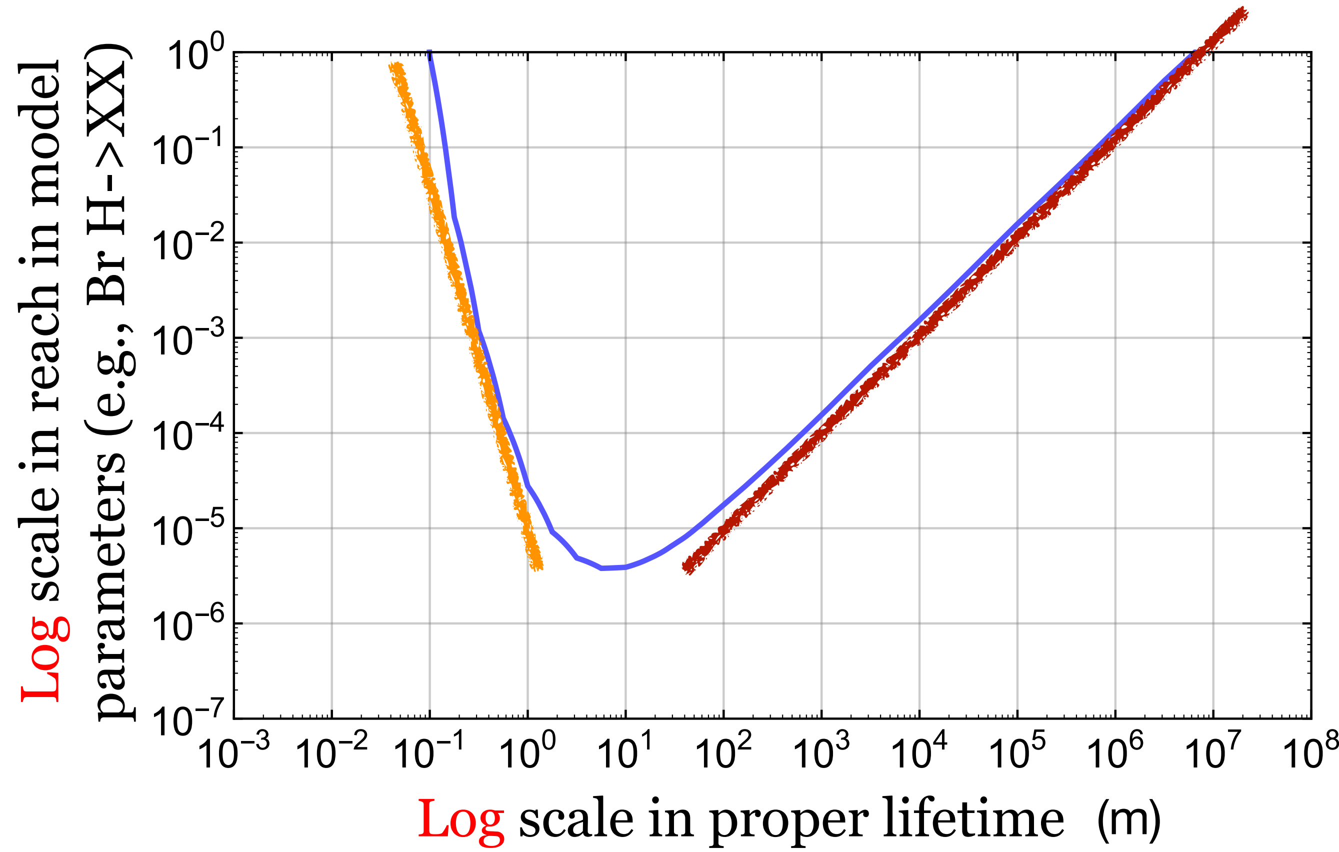

- The detector length $L_2$ - $L_1$
- *d*: expected decay length of LLP in lab frame $d = c\tau\gamma\beta$

# LLP basics: Geometrical acceptance

- $P_{in}$: Geometrical acceptance

$$P_{\rm in} = \frac{1}{4\pi}\int_{\Delta\Omega} d\Omega \int_{L_1}^{L_2} dL \frac{1}{d} e^{-L/d}$$
$$\approx \frac{\Delta\Omega}{4\pi} e^{-L_1/d} \frac{L_2 - L_1}{d}$$

**Solid angle** **Detector length**




- The detector length $L_2$ - $L_1$
- *d*: expected decay length of LLP in lab frame

**We need**

- Closer to IP ( for smaller lifetime)
- Longer detector (for larger lifetime),
- The larger solid angle (any lifetime)

# LLP basics: Geometrical acceptance

| | ATLAS/CMS |
|---|---|
| • Closer to IP ( for smaller lifetime) | • Inner detector, DV searches… |
| • Longer detector (for larger lifetime) | • ~ meter(s) |
| • The larger solid angle (any lifetime) | • ~ 4 π |

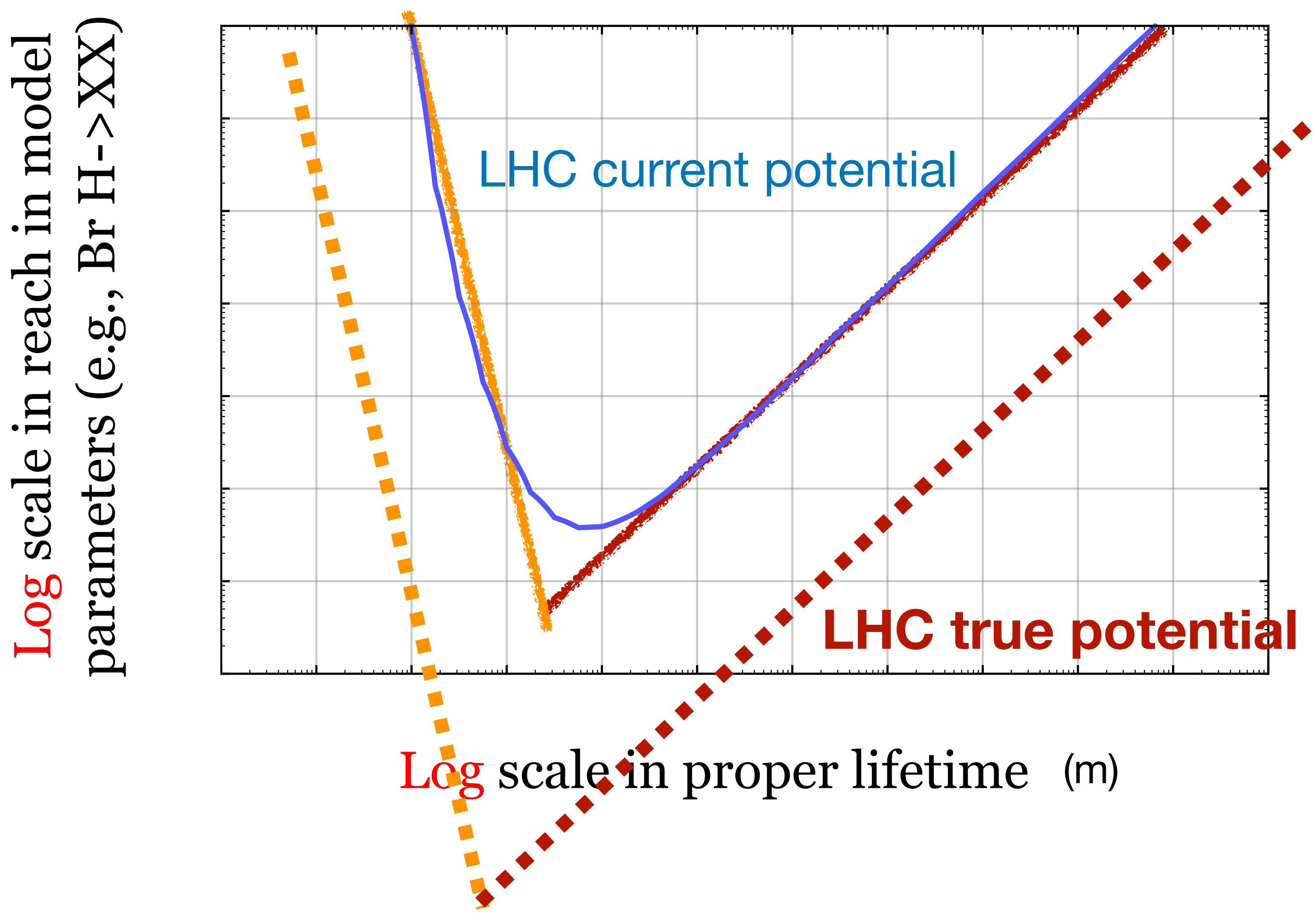
# Challenges

$$n_{sig} = N_{prod} \times P_{in} \times \epsilon_{trig} \times \epsilon_{sig} \times \epsilon_{bkg}^{penalty}$$

geometrical acceptance | trigger | signal efficiency | bkgd fake rate

LHC already maximizes $P_{in}$ in all aspects except longer detector length

Optimizing the efficiency factors to realize the full power of LHC



# Timing upgrade proposals at LHC

LHCC-P-009

- CMS: MIP Timing Detector (MTD) in central region, High Granularity Calorimeter (HGCAL) in endcap region.

CMS-TDR-019

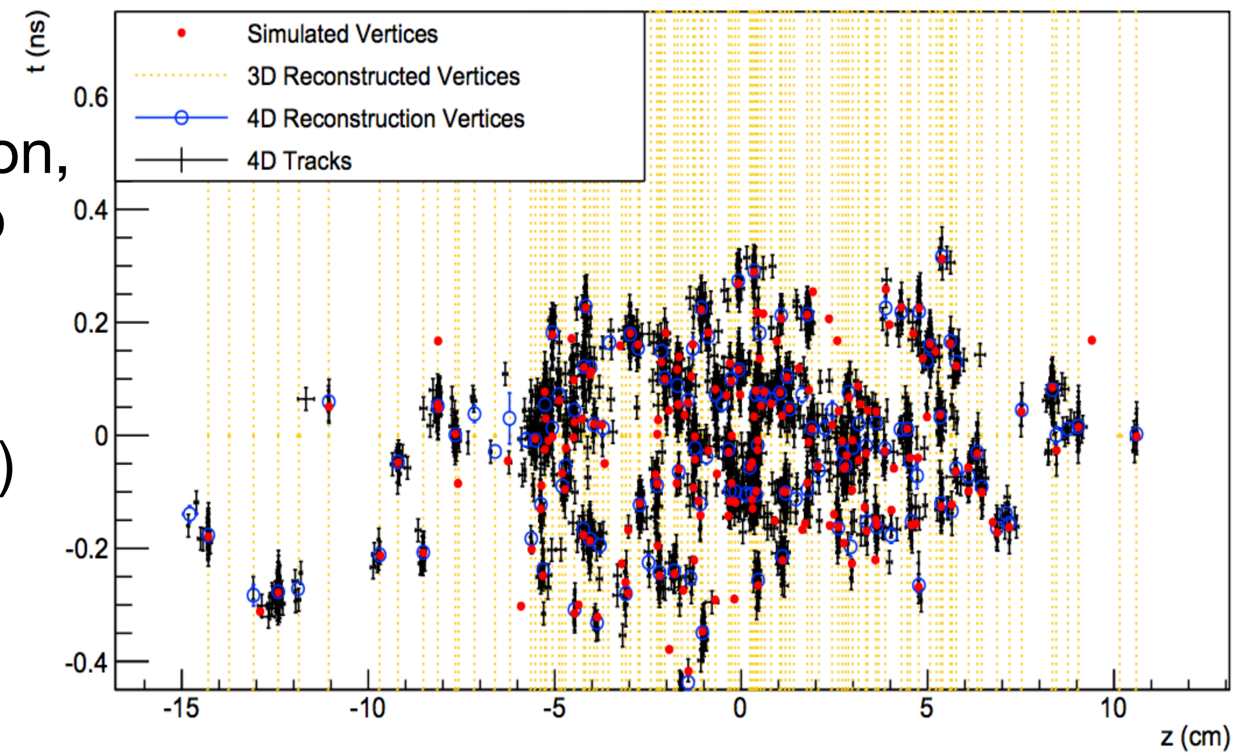
**30 ps resolution!**

- ATLAS: High Granularity Timing Detector (HGTD)

1804.00622

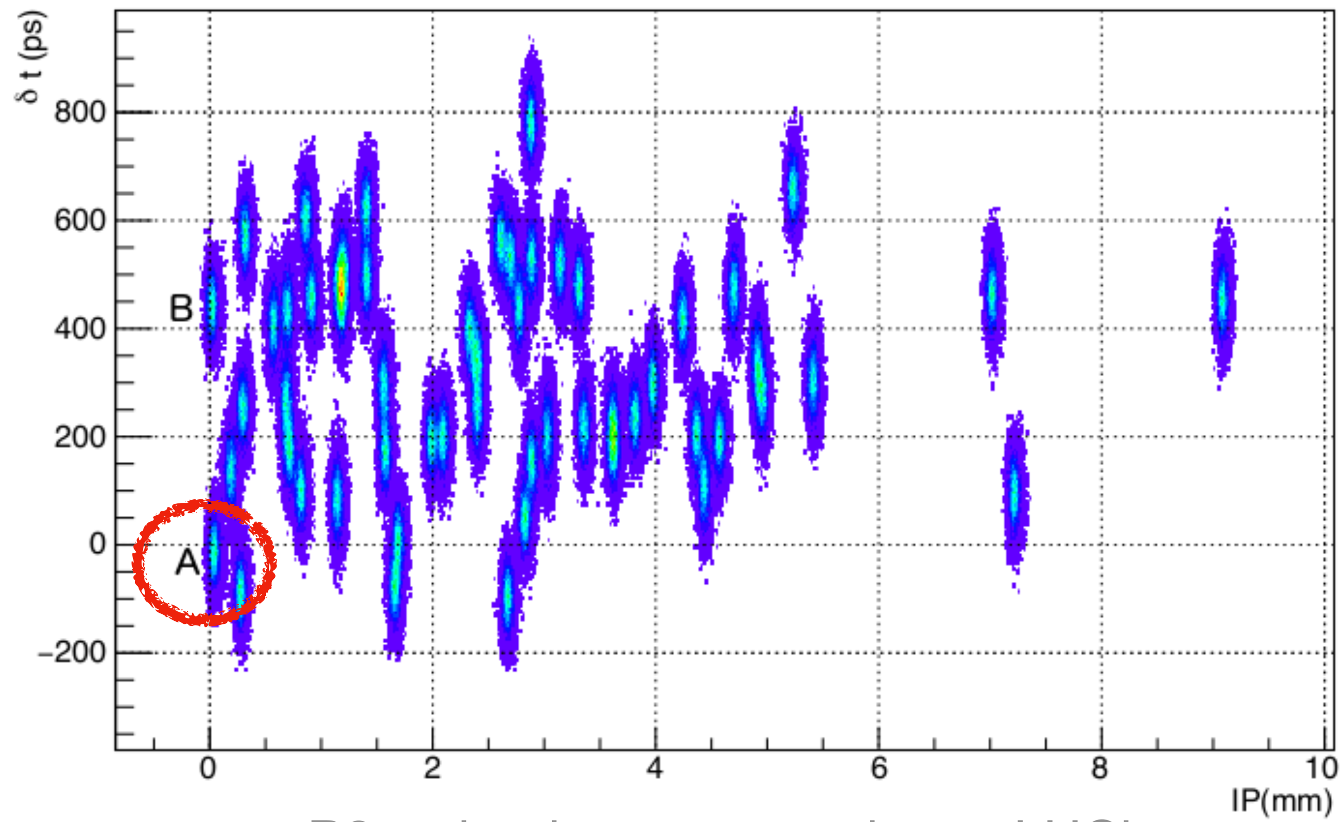
- LHCb: Vertex Locator (VELO), high granularity ECAL and Torch detector

LHCb: 1808.08865, B0->pi+ pi-




PV reconstruction at LHC

- Good potential to benefit new physics searches! (Rest of this talk)






B0->pi+ pi- reconstruction at LHCb

# Time delay from LLP and detection proposal

- Long-lived particle X decay, X-> a b

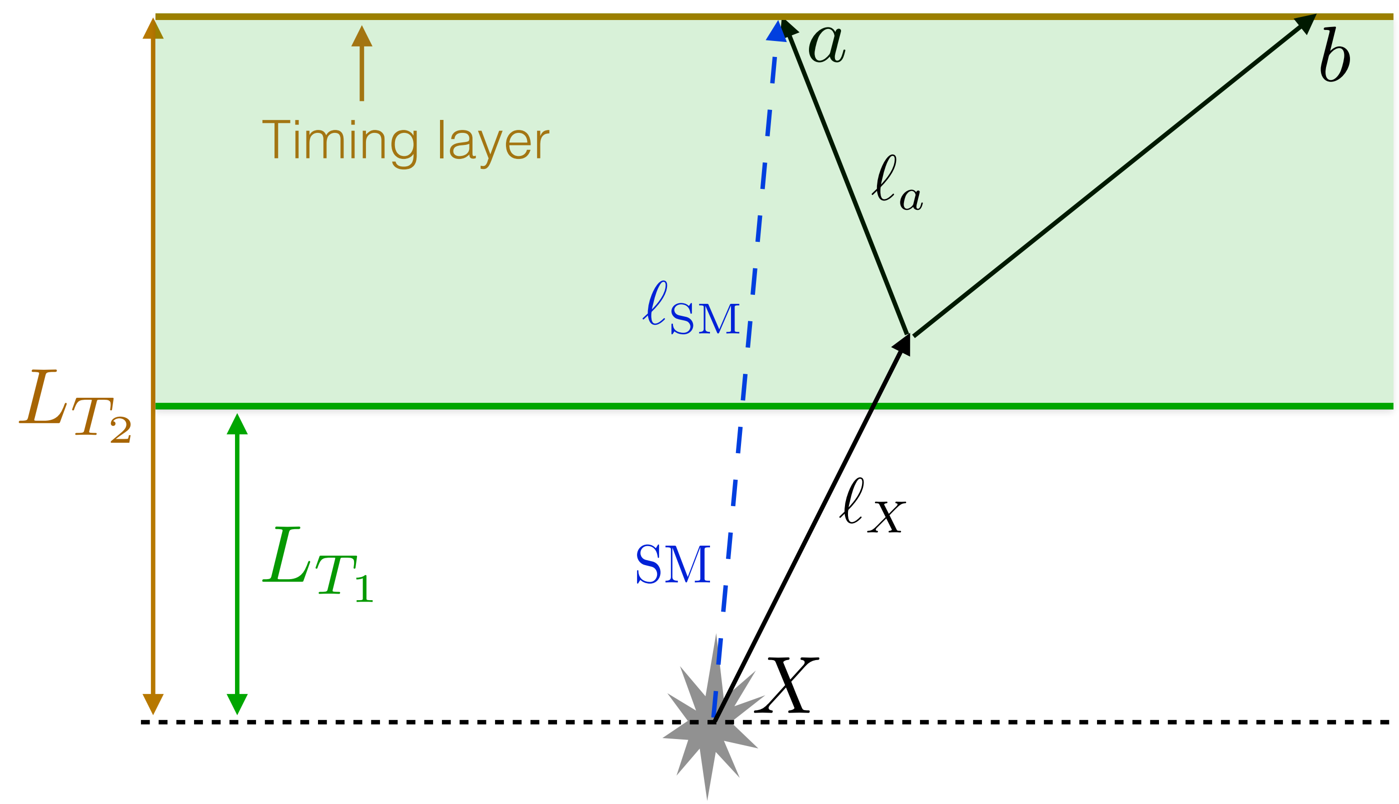
$$\Delta t = \frac{\ell_X}{\beta_X} + \frac{\ell_a}{\beta_a} - \frac{\ell_{\rm SM}}{\beta_{\rm SM}}$$

Signal arrival time - SM bkg ref time

$$\beta_X \lesssim O(1) \qquad \beta_a \simeq \beta_{\rm SM} \simeq 1$$

- Lower bound from slow X

$$\Delta t \geq \frac{\ell_X}{\beta_X} - \frac{\ell_X}{1} = \ell_X(\beta_X^{-1} - 1)$$




JL, Z. Liu, L.T. Wang, 1805.05957

# Time delay from LLP and detection proposal

- Long-lived particle X decay, X-> a b

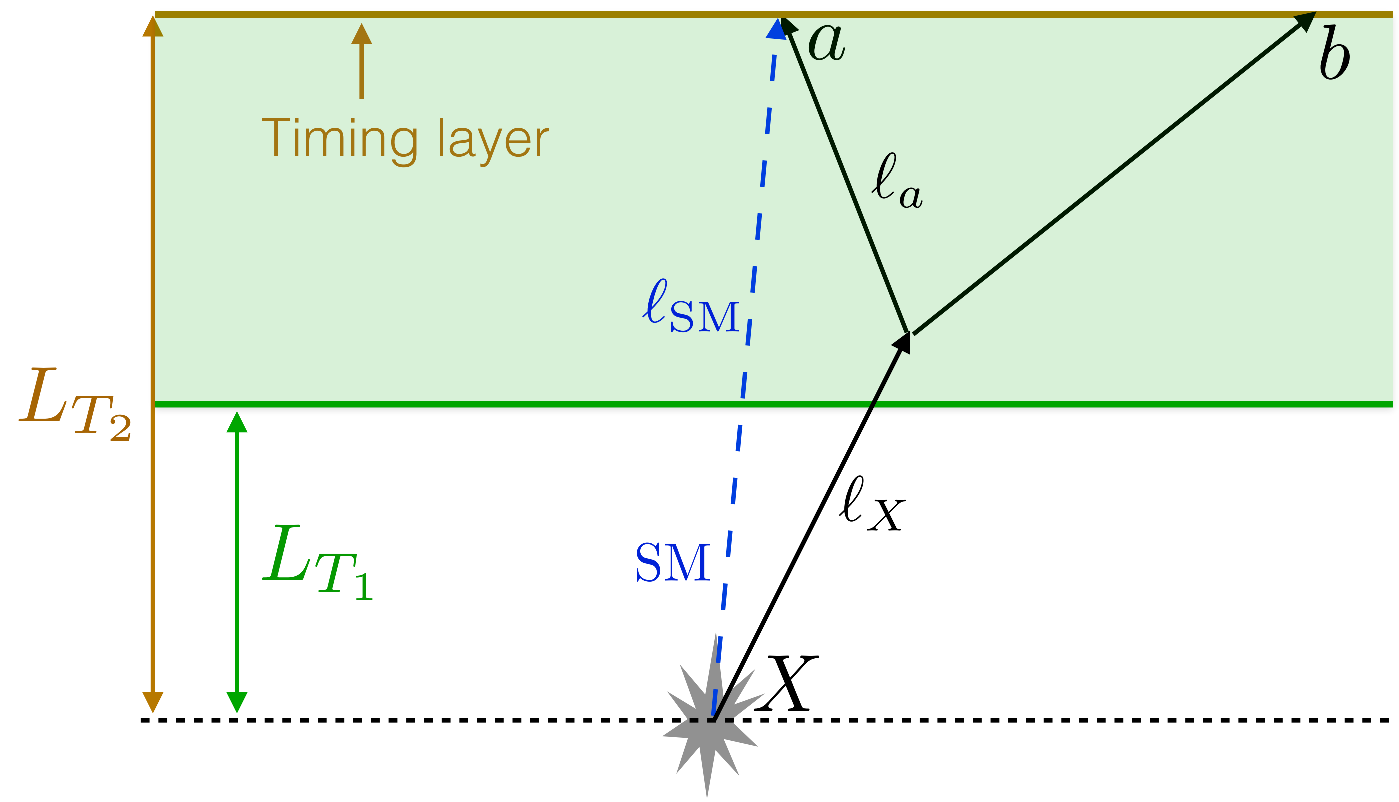
$$\Delta t = \frac{\ell_X}{\beta_X} + \frac{\ell_a}{\beta_a} - \frac{\ell_{\rm SM}}{\beta_{\rm SM}}$$

Signal arrival time - SM bkg ref time

$$\beta_X \lesssim O(1) \qquad \beta_a \simeq \beta_{\rm SM} \simeq 1$$

- Lower bound from slow X

$$\Delta t \geq \frac{\ell_X}{\beta_X} - \frac{\ell_X}{1} = \ell_X(\beta_X^{-1} - 1)$$

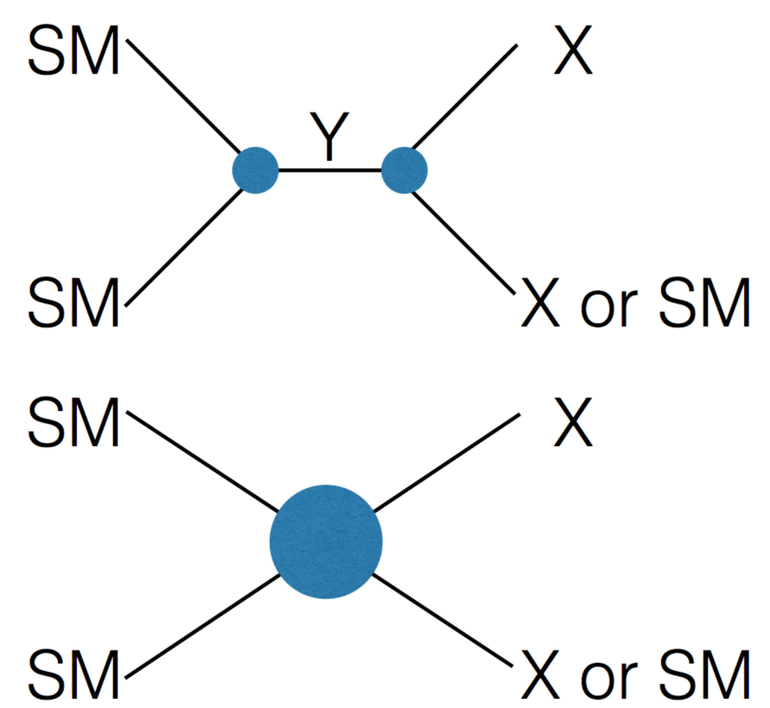



JL, Z. Liu, L.T. Wang, 1805.05957

- For CMS MTD size, $l_X$ ~ 1.2 m ~ 4 ns
    - LLPs (mass > 10 GeV) typically move much slower than speed of light
    - LLPs have O(ns) time delay
- SM bkg time delay: Phase-2 time resolution 30 ps, Pile-up intrinsic resolution 190 ps
- LLPs are significantly delayed comparing with SM backgrounds!!!

# Signal models

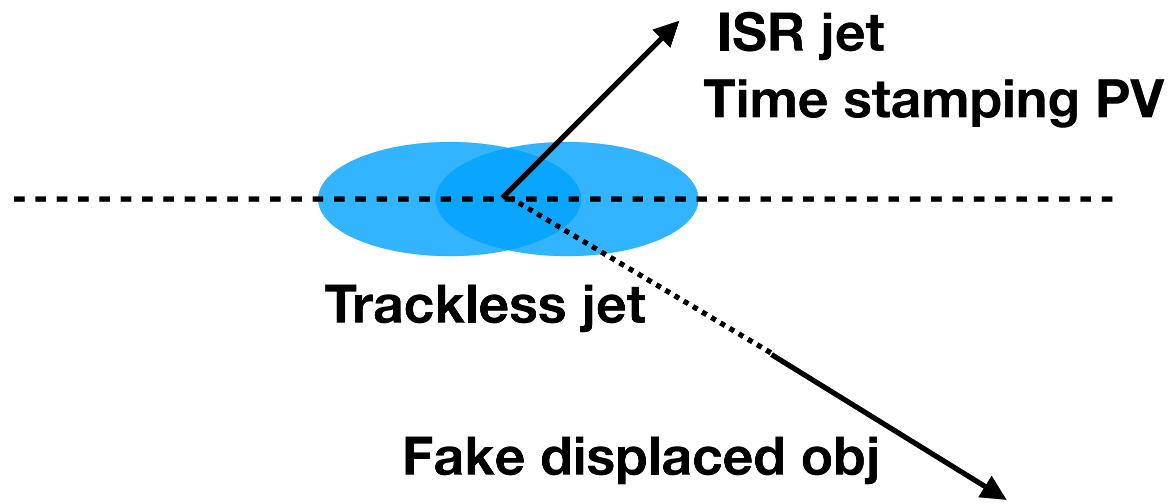
- Physics model:
  - SigA (resonant Higgs): SM Higgs decay to two LLPs
  - SigB (pair prod): GMSB SUSY long lived neutralino



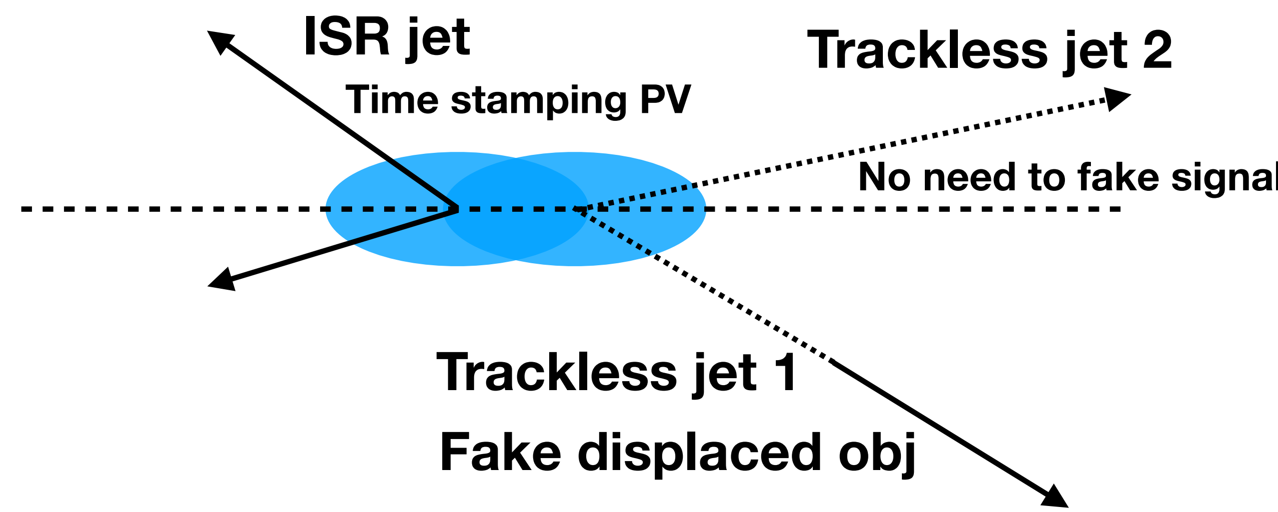

$$\text{SigA}: \; pp \to h + j, \; h \to X + X, \; X \to \text{SM},$$
$$\text{SigB}: pp \to \tilde{\chi}\tilde{\chi} + j, \; \tilde{\chi}_1^0 \to h + \tilde{G} \to \text{SM} + \tilde{G}.$$

# Background

## Same vertex hard interaction




## Pile up




Time delay from
resolution of timing detector

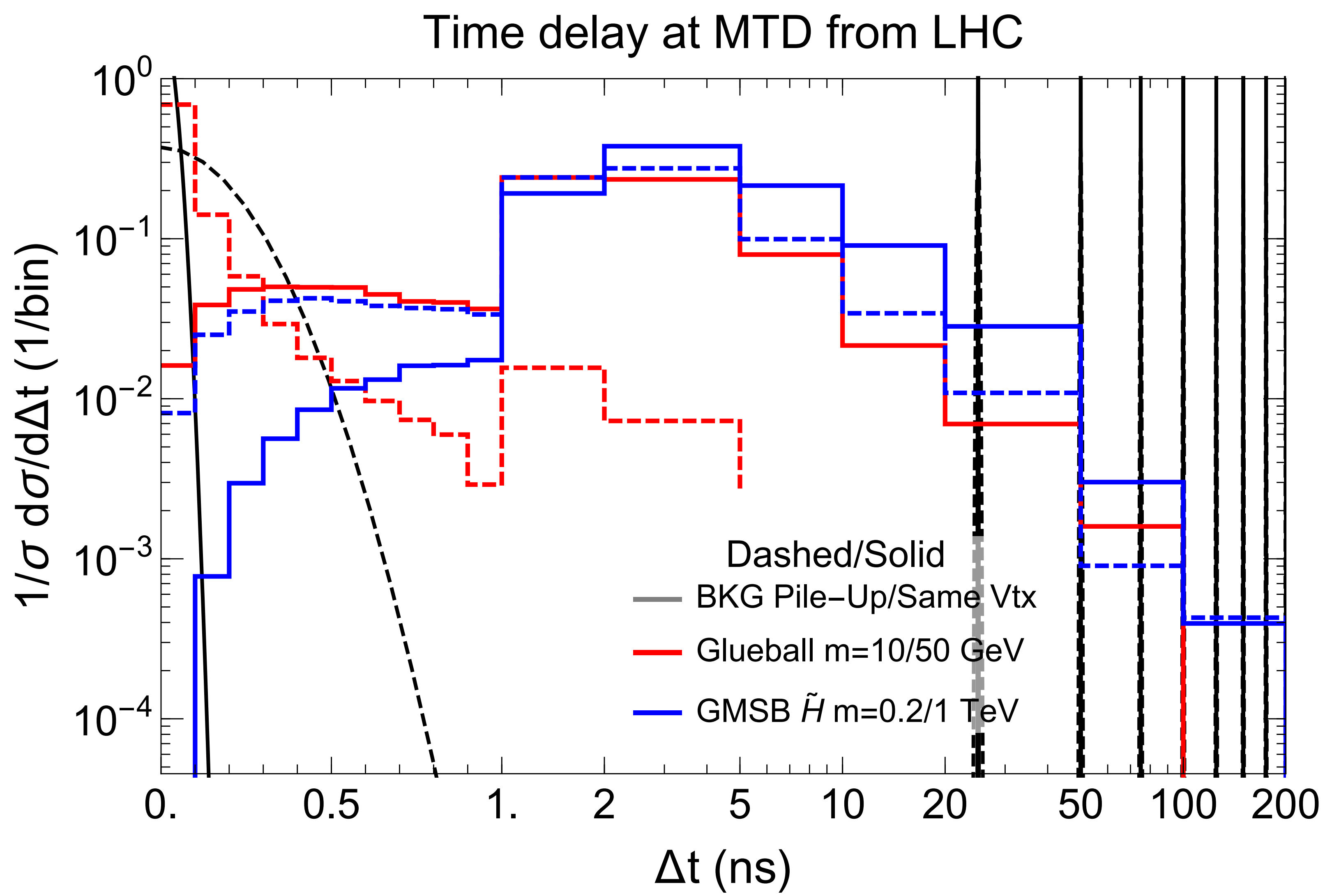
$\sim$ **30 ps**

Time delay from
spread of the proton bunch

$\sim$ **190 ps**

Other backgrounds: Interaction with material, Cosmic rays, Beam halo, Satellite bunches. Many already have mature veto mechanism; need to revisit to see the impact on timing.

# Time delay distributions

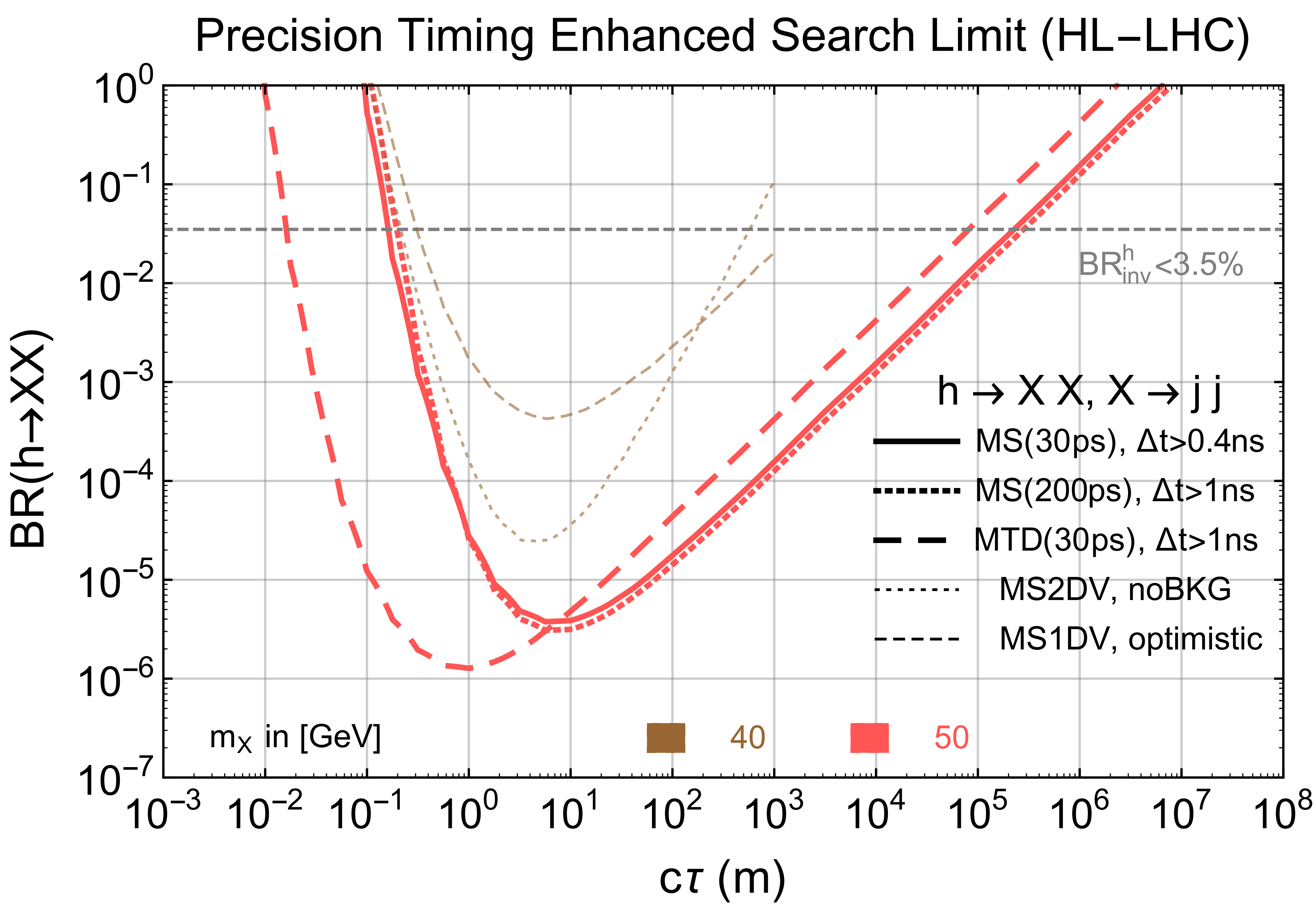



- SM background time spread (Gaussian):
  - Hard collision: ~30 ps
  - Pile-up: ~190 ps

- Use timing cut to suppress SM background
  - Lower pt/MET threshold

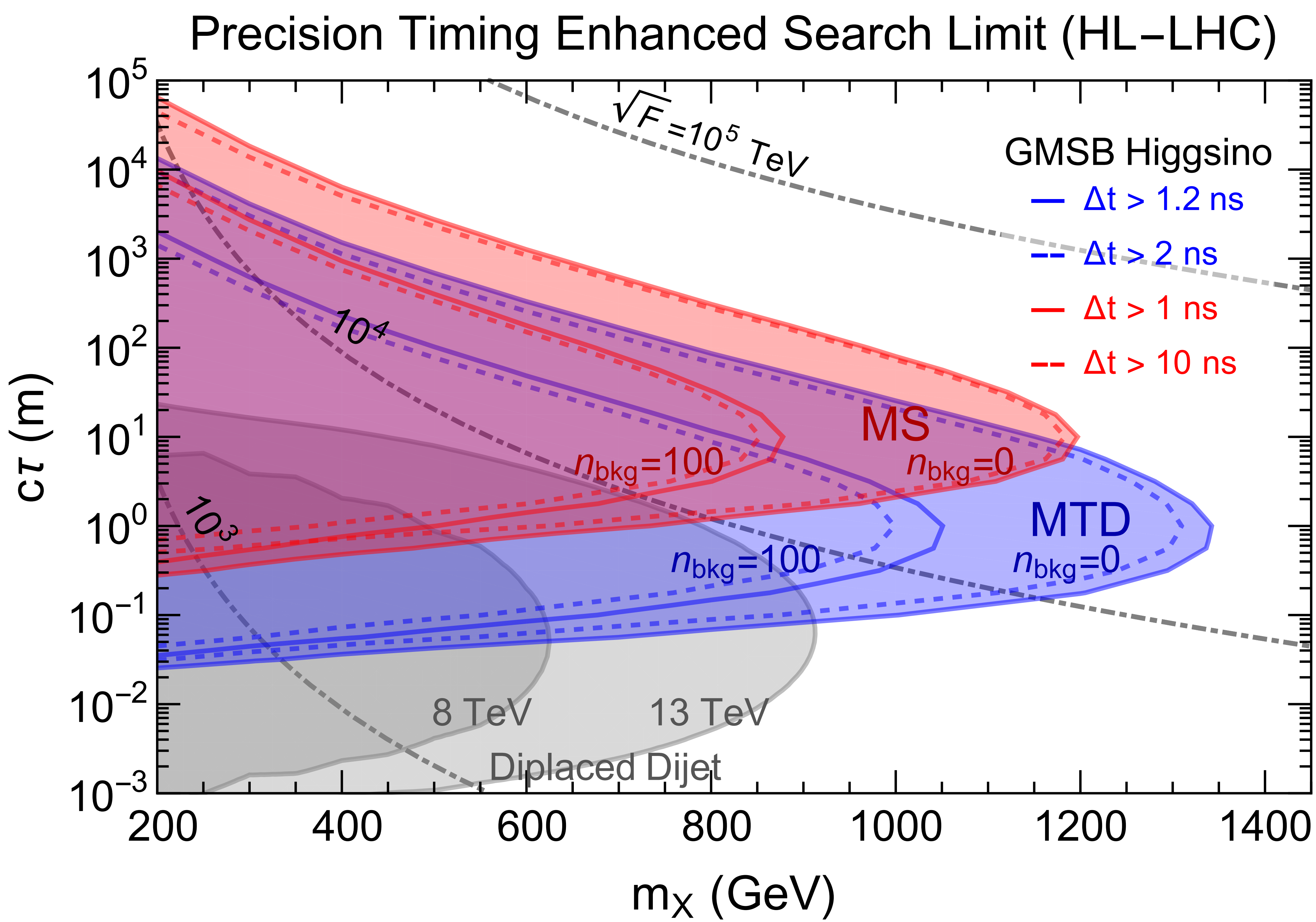
# LLP sensitivity for resonance production

$$\mathrm{SigA}: \; pp \to h + j \;, \; h \to X + X, \; X \to \mathrm{SM},$$



# LLP sensitivity for resonance production

$$\mathrm{SigB}: pp \to \tilde{\chi}\tilde{\chi} + j,\ \tilde{\chi}_1^0 \to h + \tilde{G} \to \mathrm{SM} + \tilde{G}$$

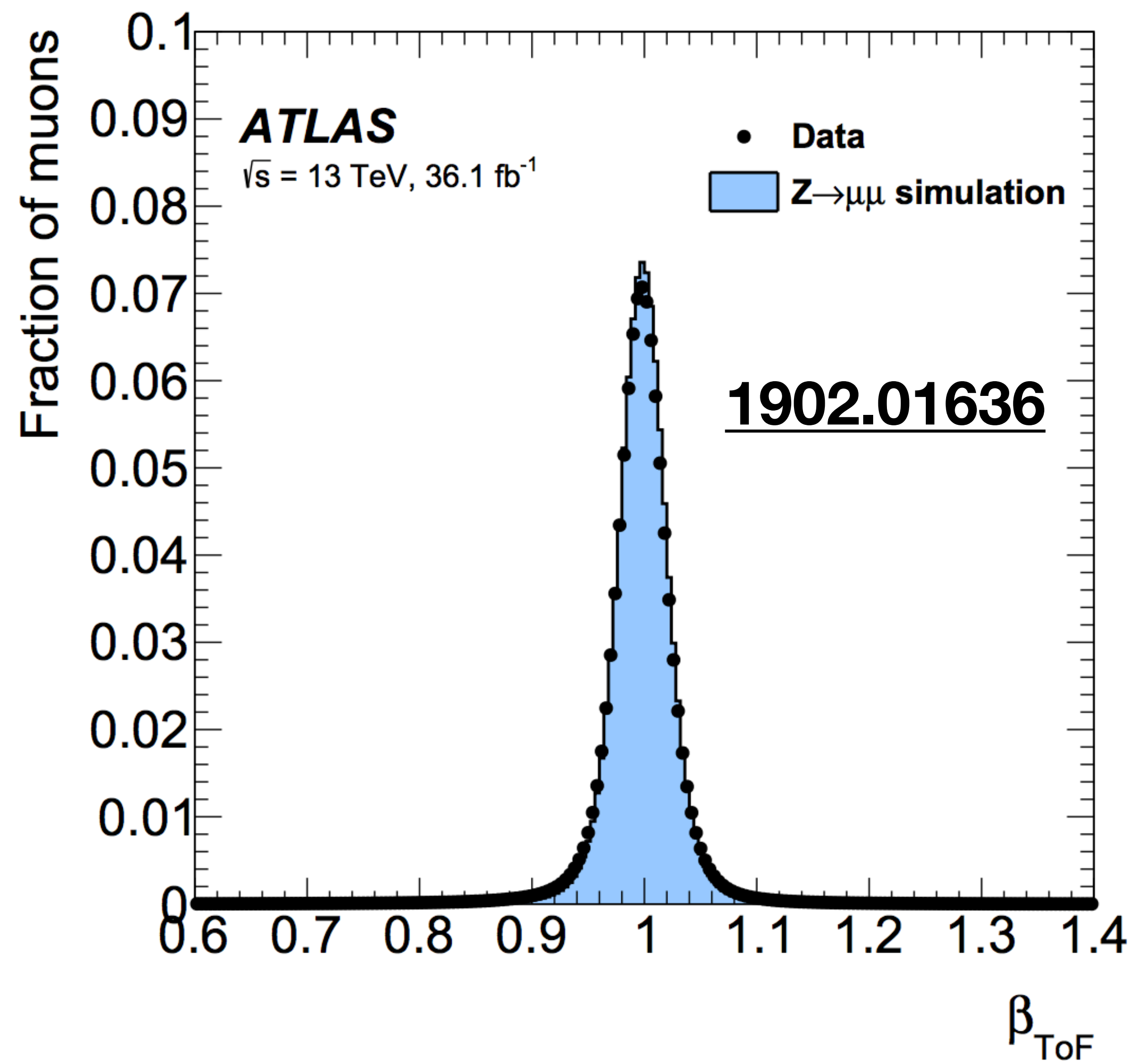





Jia Liu

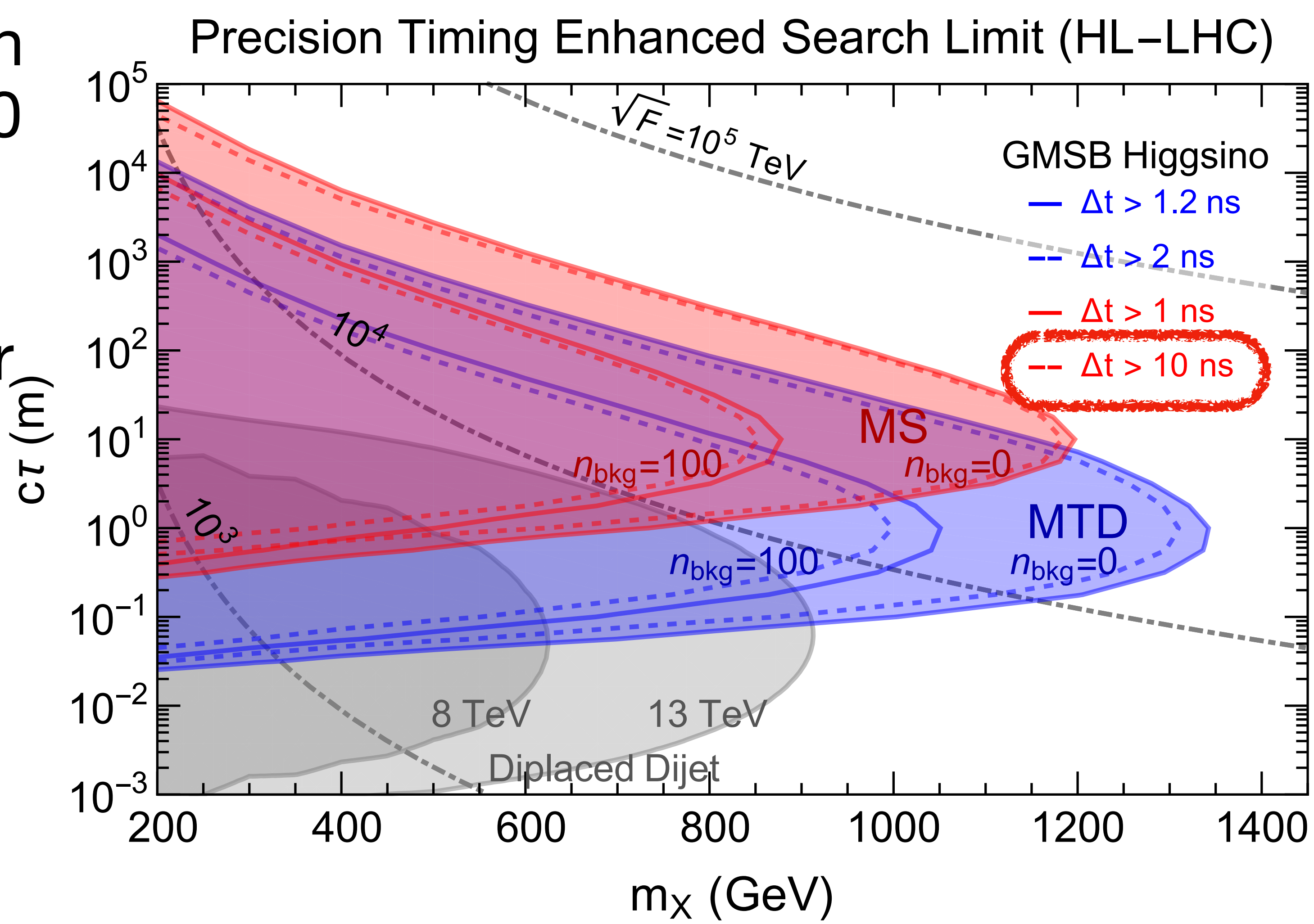
# Challenges and opportunities

- To enable 30 ps resolution, require timestamp by ISR object or other prompt product (squark -> q neutralino)
  - Fine for central timing detector (large solid angle)
  - Bad for forward timing detector (small solid angle)
- Without timestamp - directly cut on large time delay, due to pile-up 190 ps resolution
  - Fine for large LLP mass, bad for small LLP mass
  - e.g. ATLAS MS: tile calorimeter timing resolution is 1.3–1.7 ns, RPCs 1.8 ns



# Challenges and opportunities

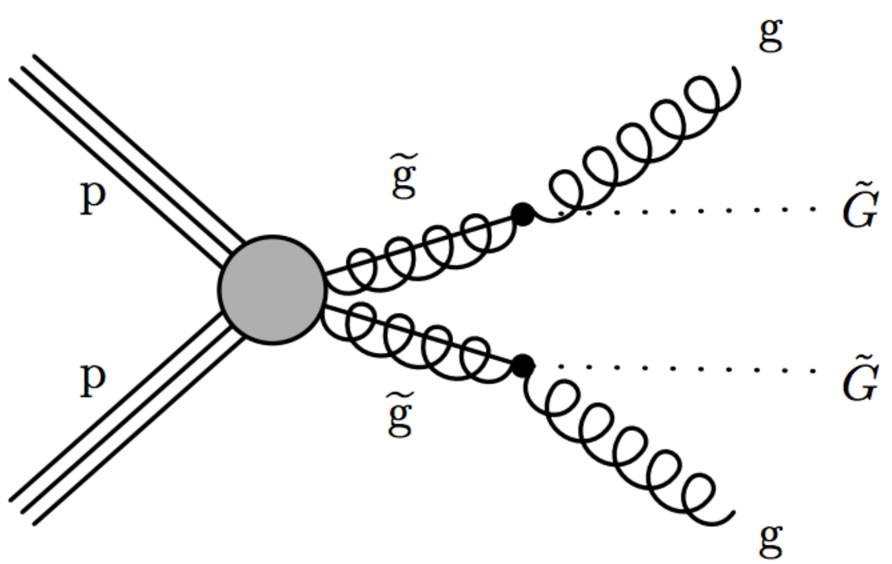
- To enable 30 ps resolution, require timestamp by ISR object or other prompt product (squark -> q neutralino)
  - Fine for central timing detector (large solid angle)
  - Bad for forward timing detector (small solid angle)
- Without timestamp - directly cut on large time delay, due to pile-up 190 ps resolution
  - Fine for large LLP mass, bad for small LLP mass
  - e.g. ATLAS MS: tile calorimeter timing resolution is 1.3–1.7 ns, RPCs 1.8 ns. Good enough for 10 ns timing cut.

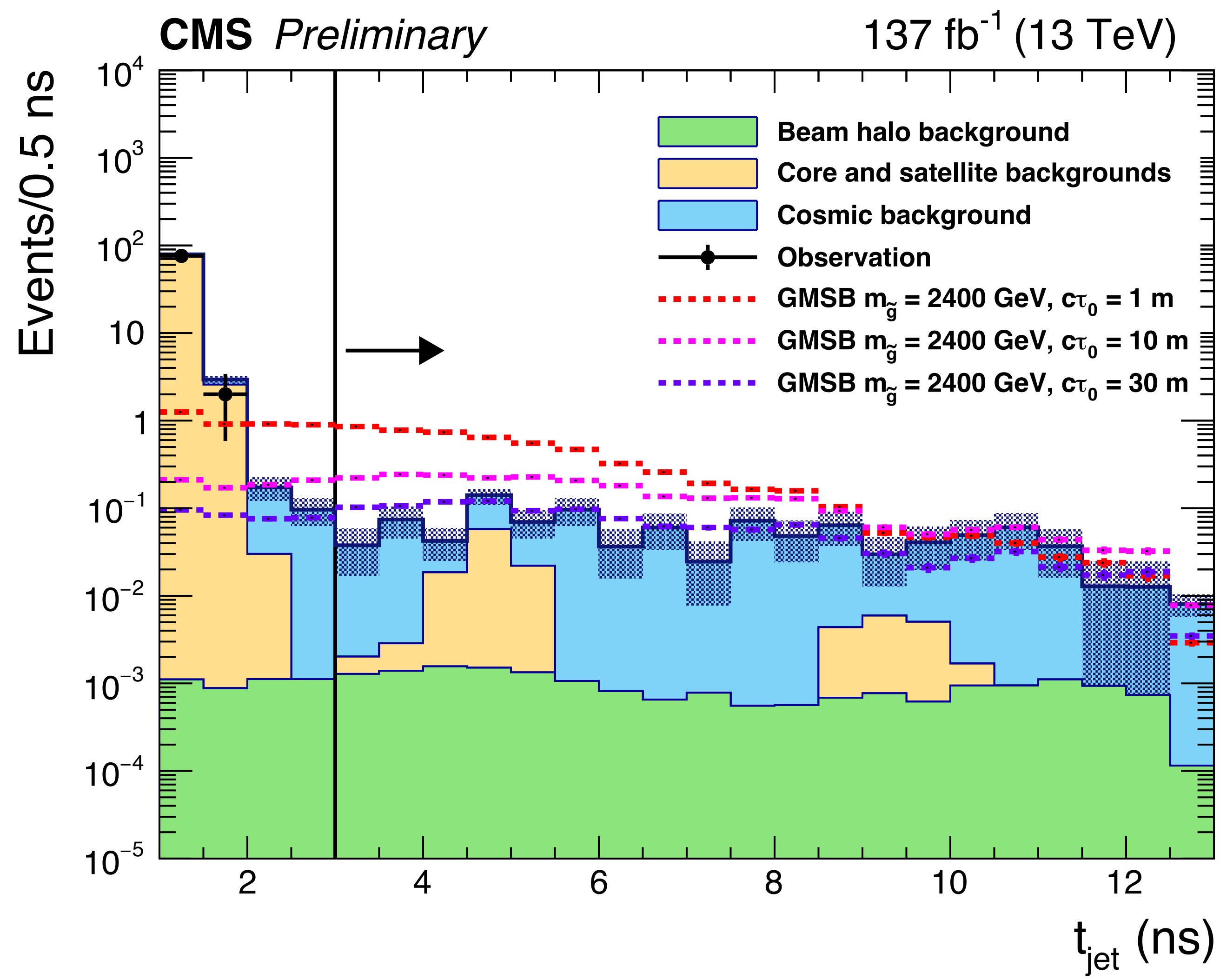


# Challenges and opportunities

- Other SM backgrounds: Interactions with materials, cosmic rays, beam halo, satellite beam etc
    - Existing mature veto mechanism
    - More handles in bkg rejection: MET at PV, ISR lepton, two delayed objects…
- Feedback from CMS collaboration
    - CMS EXO-19-001 applies the timing techniques
    - the first application of ECAL timing (~200 ps) to searching for displaced jets from neutral long-lived particles.
    - The above backgrounds are manageable!

# CMS EXO-19-001 background study



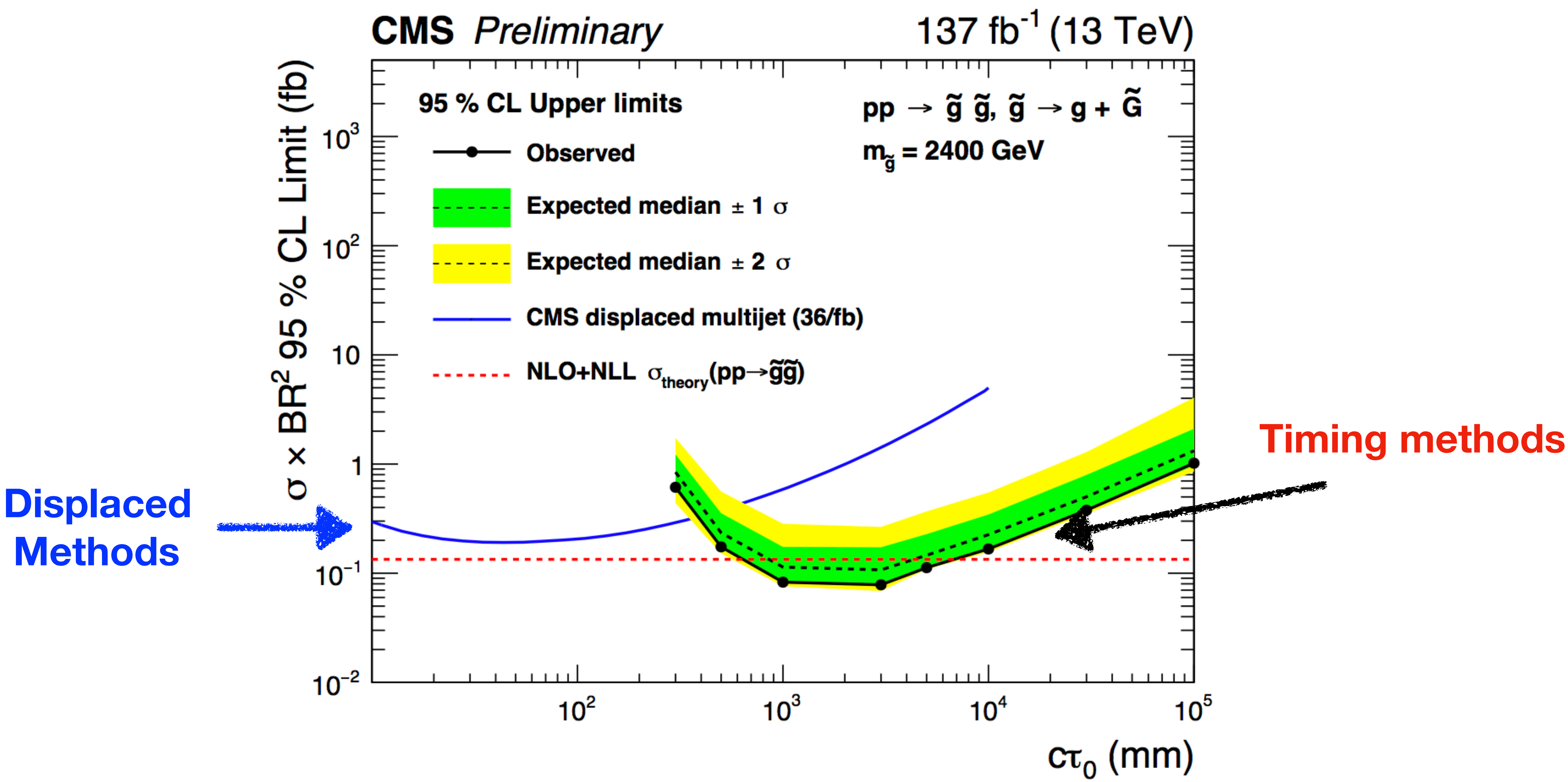




***Timedelay is useful!***

| Background | Prediction |
|---|---|
| Beam halo | $0.02^{+0.06}_{-0.02}$ (stat) $^{+0.05}_{-0.01}$ (syst) |
| Core and satellite bunches | $0.11^{+0.09}_{-0.05}$ (stat) $^{+0.02}_{-0.02}$ (syst) |
| Cosmics | $1.0^{+1.8}_{-1.0}$ (stat) $^{+1.8}_{-1.0}$ (syst) |

- Beam halo small
- Core and satellite bunches small but one shall try to improve by precision timing
- Cosmics small (for this analysis, no need to do cosmic veto further but there are many ways) and scale with time but not luminosity

# CMS EXO-19-001 applies the timing techniques



# Summary

- LHC has great detectors for long-lived particle searches
- Timing information helps to suppress BKG
  - Generic feature (slow moving) for heavy LLP
  - Powerful enough to allow search for single LLP decay
- LLPs (even in the extremely long-lifetime limit) could be optimally searched at the LHC main detectors
- All existing LLP searches can be re-optimized using timing information
- Precision timing is a new dimension of particle physics information available for BSM searches. Further exploration is well motivated, exciting and will significantly enhance discovery potential universally for LLPs

**Thank you!**