Long-Lived Particles at the LHC with Timing information

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Based on work with Zhen Liu and Liantao Wang, 1805.05957

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Long lived particle (LLP) at LHC

- Long live the particle! And why.
  - Feeble couplings, e.g. various portals in dark sector, RPV-SUSY
  - Suppression from heavy mass scale, e.g. GMSB, muon/charged pion
    - Near degenerate state, e.g. higgsino-like chargino/neutralino, or AMSB
      - SM meson particles long-lived comparing with fundamental heavy particles, similar in dark sector?
- For LHC searches
  - Prompt searches dominate, but increasing interests in LLP

Long lived particle (LLP) detection

- Question: if LLP has lifetime 10km, and we have a finite size detector e.g. 20 m. Where to put the detector?

Motivation for LLP search at LHC

- Question: if LLP has lifetime 10km, and we have a finite size detector e.g. 20 m. Where to put the detector?

$$N_{\rm obs} \approx N^{\rm sig}_{\rm prod} P_{\rm in}$$

- Pin: The probability to fall in the detector

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

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

$$= \frac{\Delta\Omega}{4\pi}\left(e^{-L_1/d} - e^{-L_2/d}\right)$$

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

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

LHC: ~ 1

~1

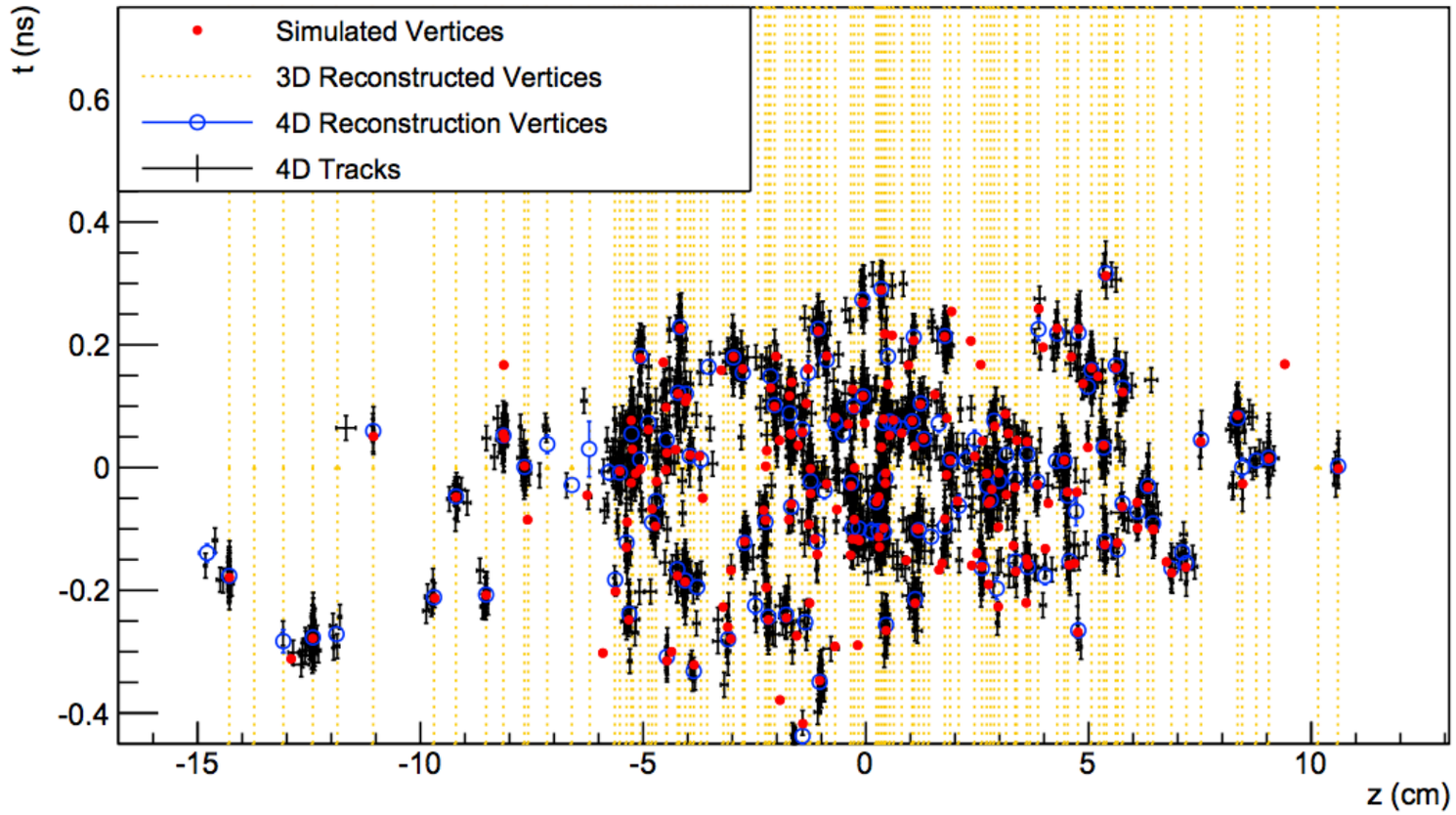
size/d

L1, L2 << d
better close due to solid angle

Good news for LHC general purpose detectors!

Timing detector at LHC

- CMS Phase-2 upgrade: adding timing layer in front of ECal, 1.2 m from beam
  - With 30 ps timing resolution, enable 4d reconstruction
  - Aim for reducing pile-up



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

- ATLAS is also considering adding a High Granularity Timing Detector (HGTD) at |z|=3.5m and 2.4<|eta|<4

1804.00622

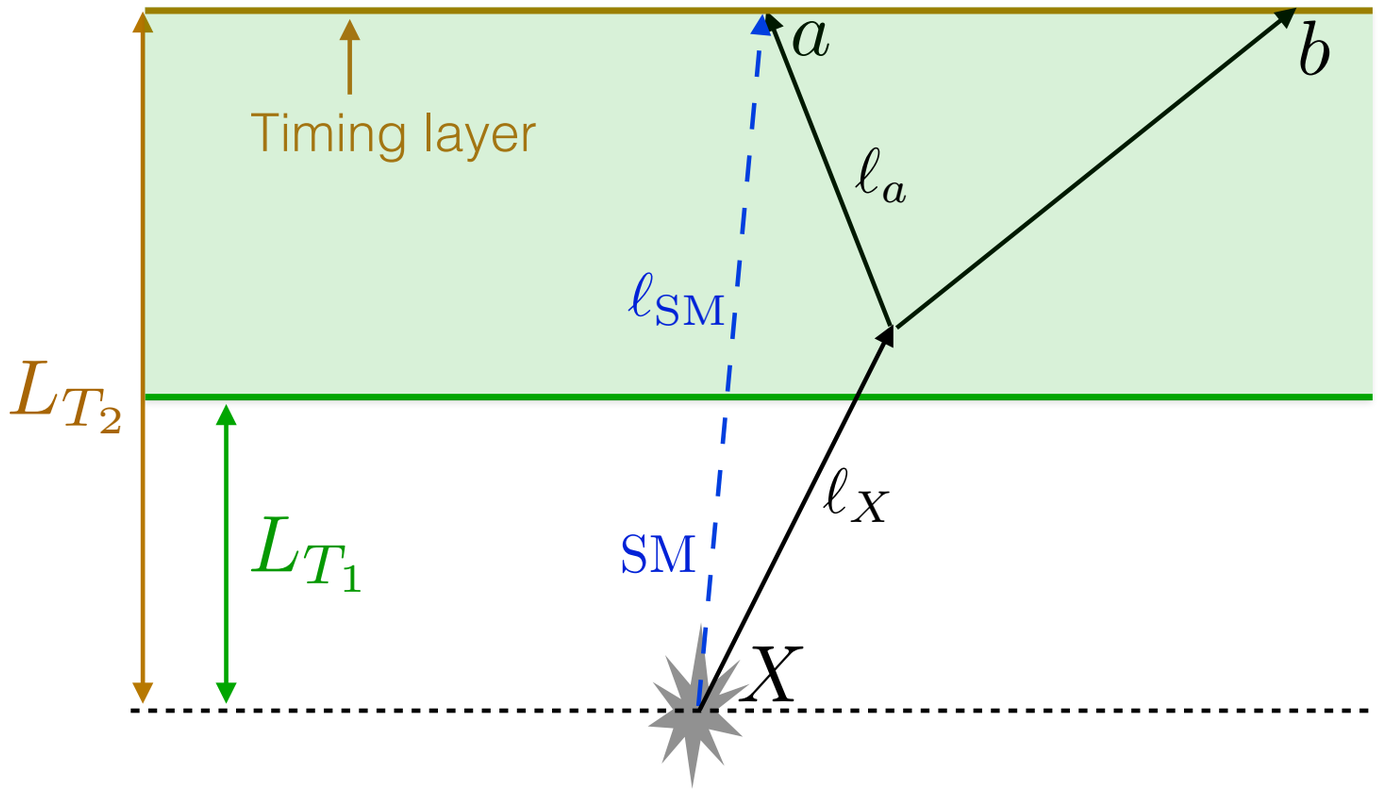
  - With ~30 ps timing resolution, enable 4d reconstruction for reducing pile-up

Time delay from LLP and detection proposal

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

$$\beta_a \simeq \beta_{\rm SM} \simeq 1$$

- CMS timing layer: 1.2 m~ 4ns
- h-> X X, with mX = 50 GeV
- X boost ~ 60/50, v~0.55
- Time delay ~ 4ns (1/v -1)=3.2ns

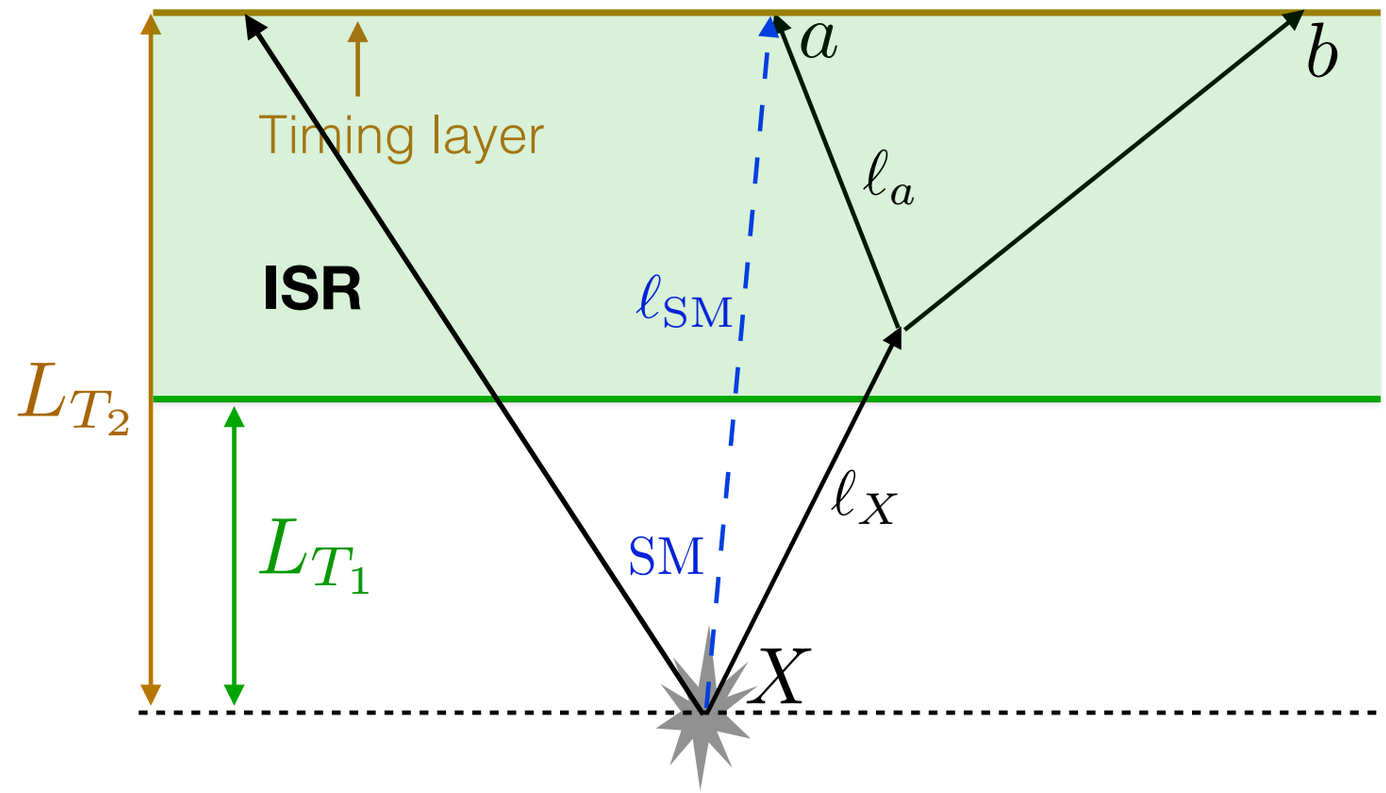


- Proposal: LLP decay before timing layer
  - CMS MTD search: LT1 = 0.2 m, LT2 = 1.2 m (MTD = Mip Timing Detector)
  - ATLAS MS search (hypothetical): LT1 = 4.2 m, LT2 = 10.6m (MS = Muon Spectrometer)

LLP signal and physics model

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

$$\beta_a \simeq \beta_{\rm SM} \simeq 1$$

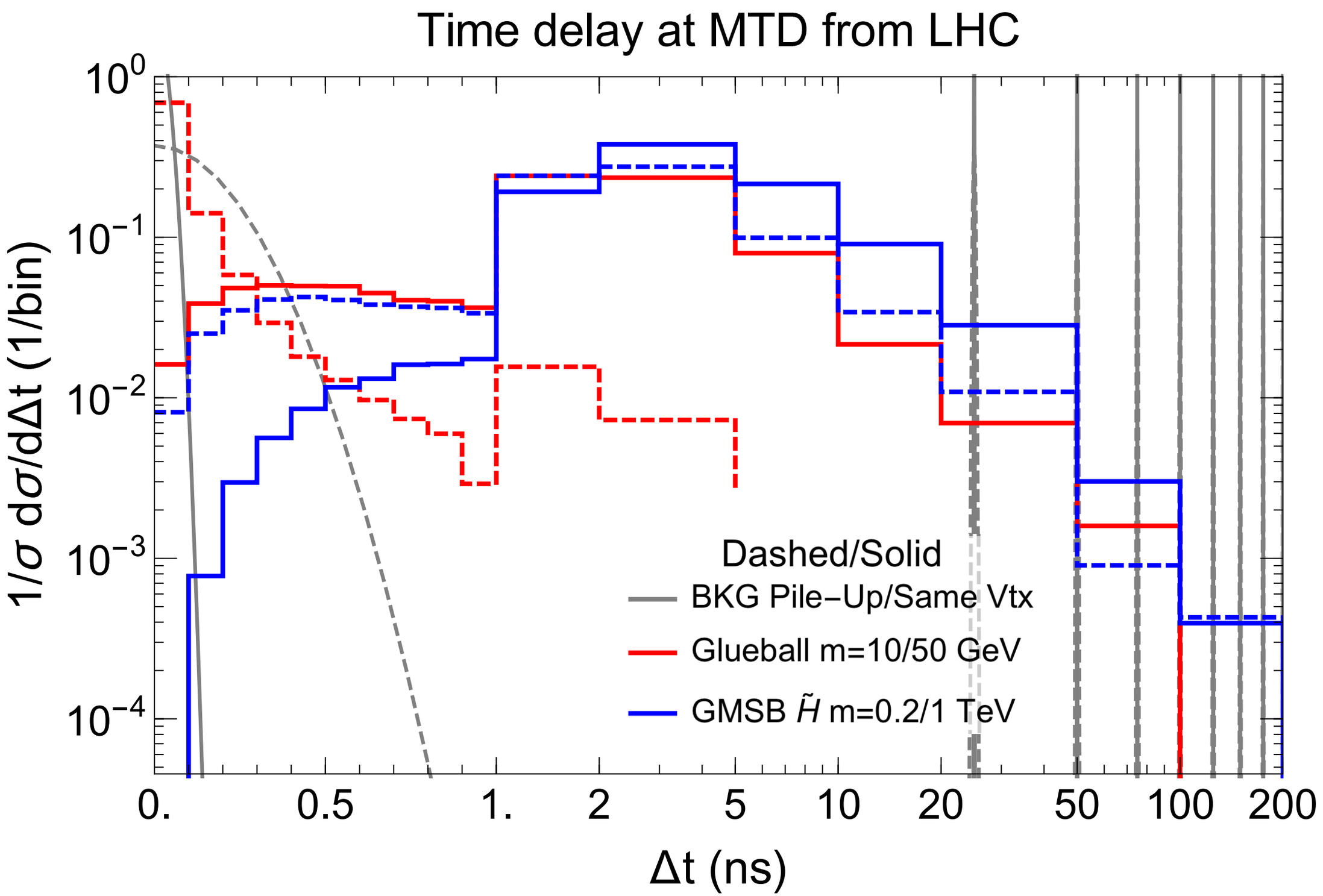


- Physics model:
  - SigA (resonance): SM Higgs decay to two LLPs, e.g. glueball
  - SigB (pair prod): GMSB SUSY long lived neutralino

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

- Time stamping the primary vertex
  - ISR object (jet, lepton, photon)
  - Prompt decay object (squark)

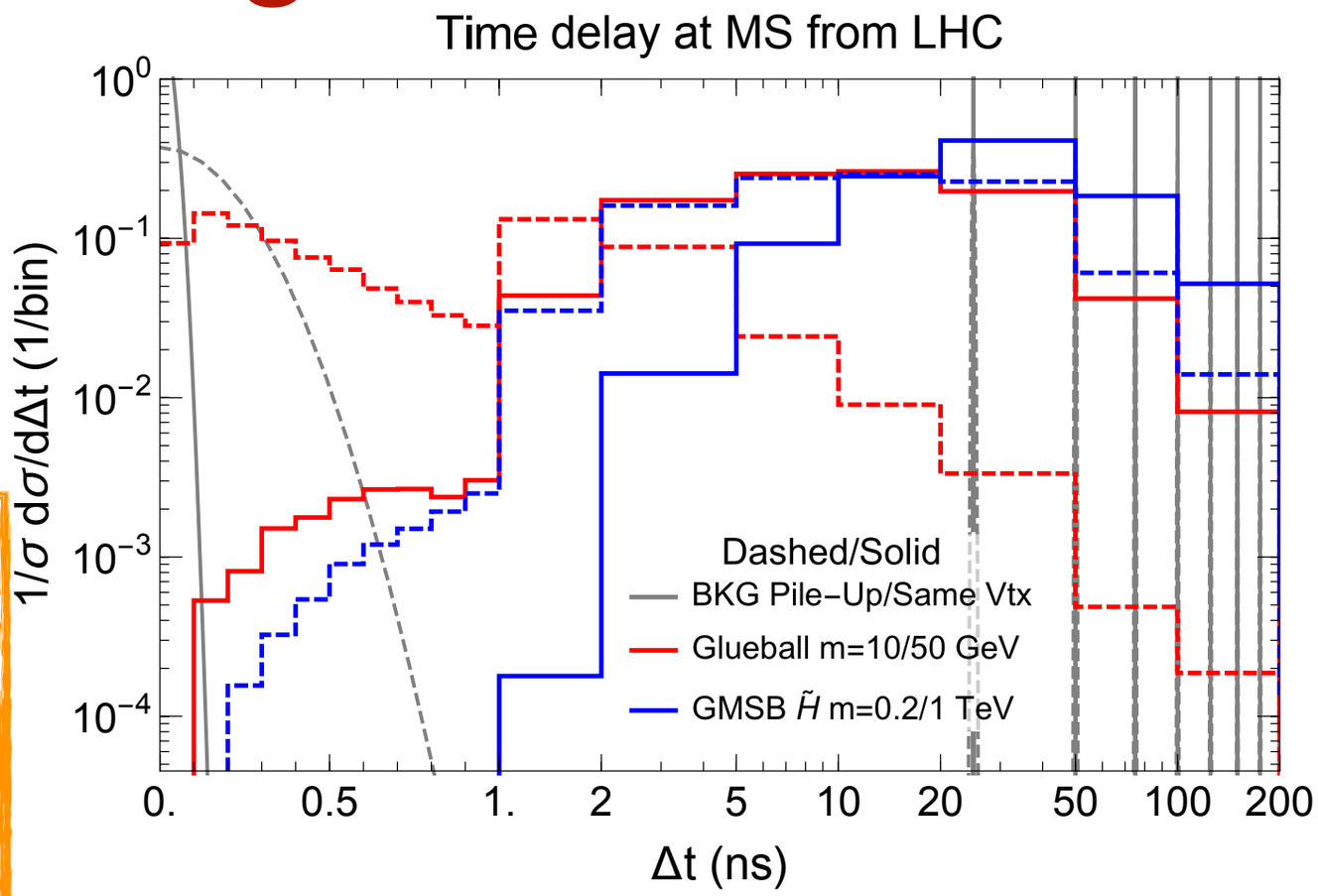
LLP signal and time delay distribution



Motivation for timing cut on LLP

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

- Use timing cut to suppress background
  - Method: a low pt ISR jet + timing delayed object (no track near PV)
    - Lower pt/MET cut threshold
    - Due to low bkg, use one LLP decay
    - Achieve better sensitivity at large lifetime



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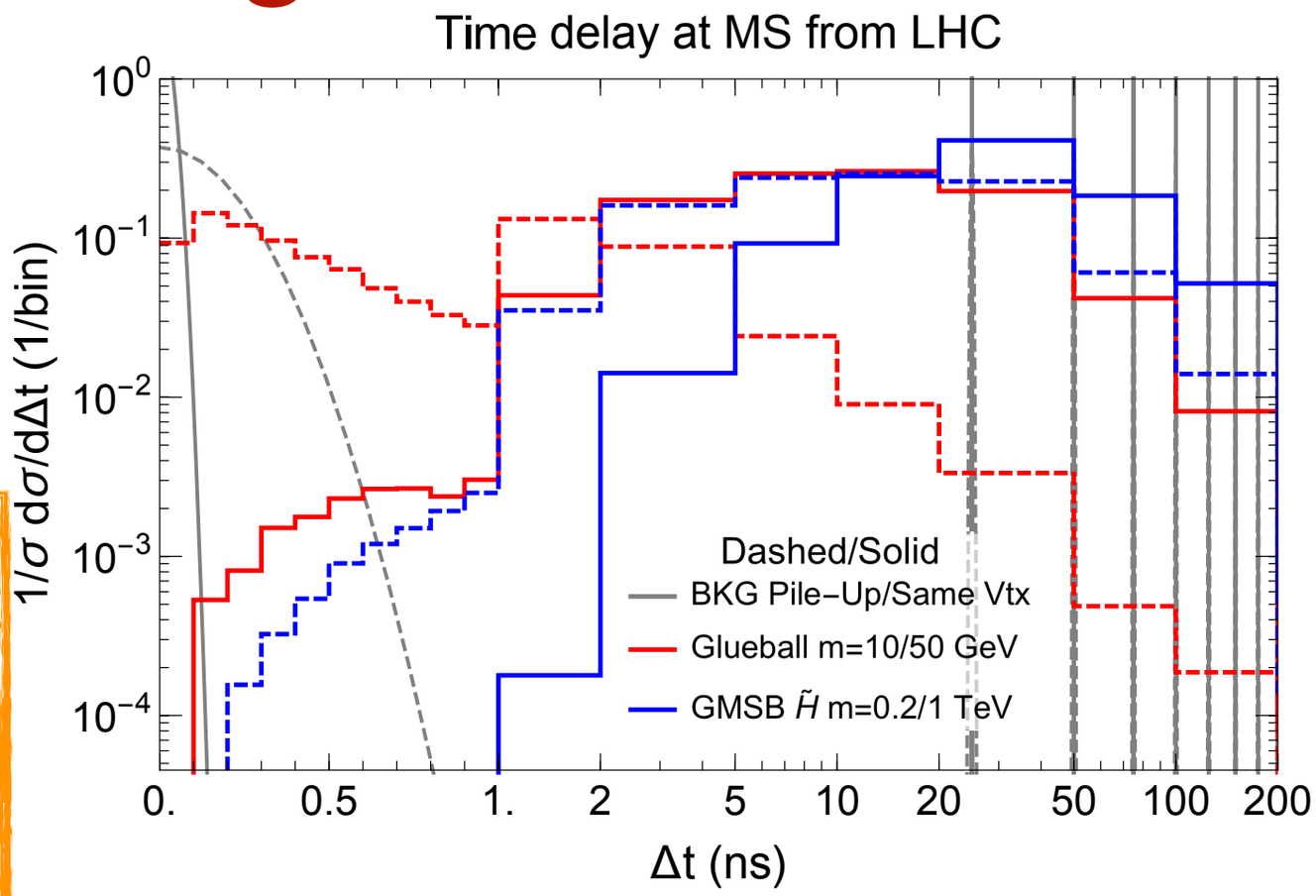
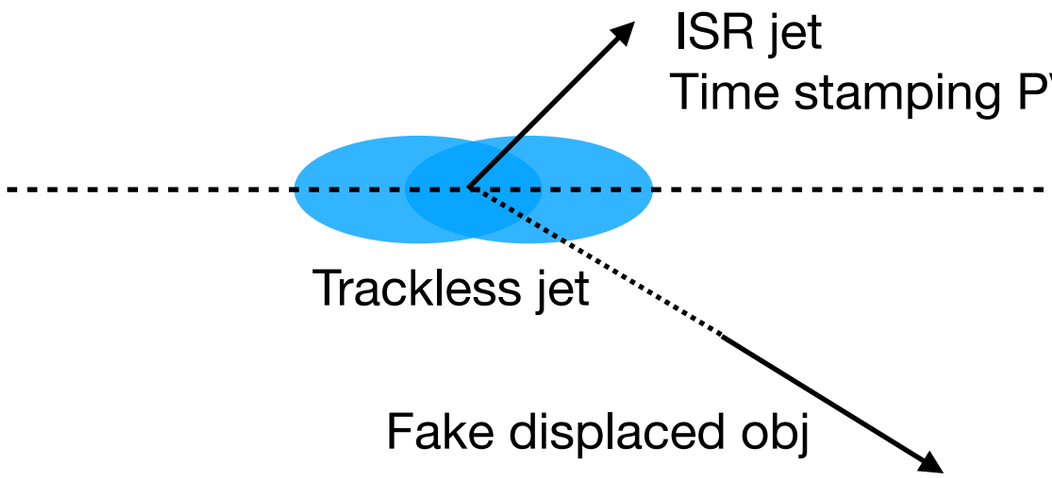


- Other SM backgrounds:
  - Interactions with materials, cosmic rays, beam halo, satellite beam etc
  - Existing mature veto mechanism
- More handles from LLP signal
  - MET at PV, ISR lepton, two delayed objects…
  - Help to suppress the bkg

BKG estimation (SV) for LLP with timing

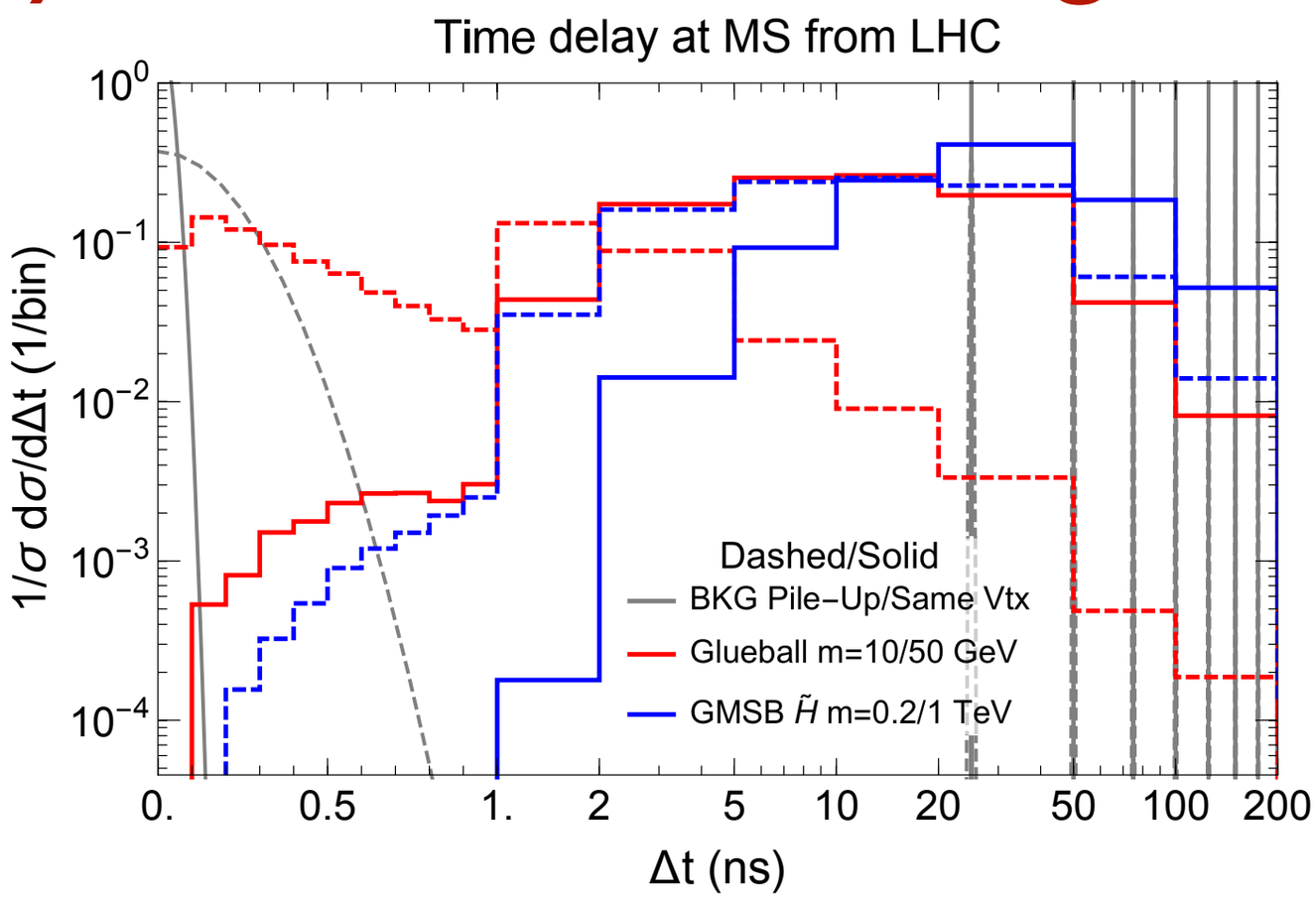
	L_{T_2}	L_{T_1}	Trigger	ϵ_{trig}	ϵ_{sig}	$\epsilon^{j}_{\text{fake}}$	Ref.
MTD	1.17 m	0.2 m	DelayJet	0.5	0.5	10^{-3}	[12]
MS	10.6 m	4.2 m	MS RoI	0.25, 0.5	0.25	5×10^{-9}	[22]



$$\text{MTD}: \quad N^{\text{SV}}_{\text{bkg}} = \sigma_{\text{j}} \mathcal{L}_{\text{int}} \epsilon^{\text{MTD}}_{\text{trig}} \epsilon^{j,\text{MTD}}_{\text{fake}} \approx 1 \times 10^{11}$$

$$\text{MS}: \quad N^{\text{SV}}_{\text{bkg}} = \sigma_{\text{j}} \mathcal{L}_{\text{int}} \epsilon^{\text{MS}}_{\text{trig}} \epsilon^{j,\text{MS}}_{\text{fake}} \approx 4 \times 10^{5},$$

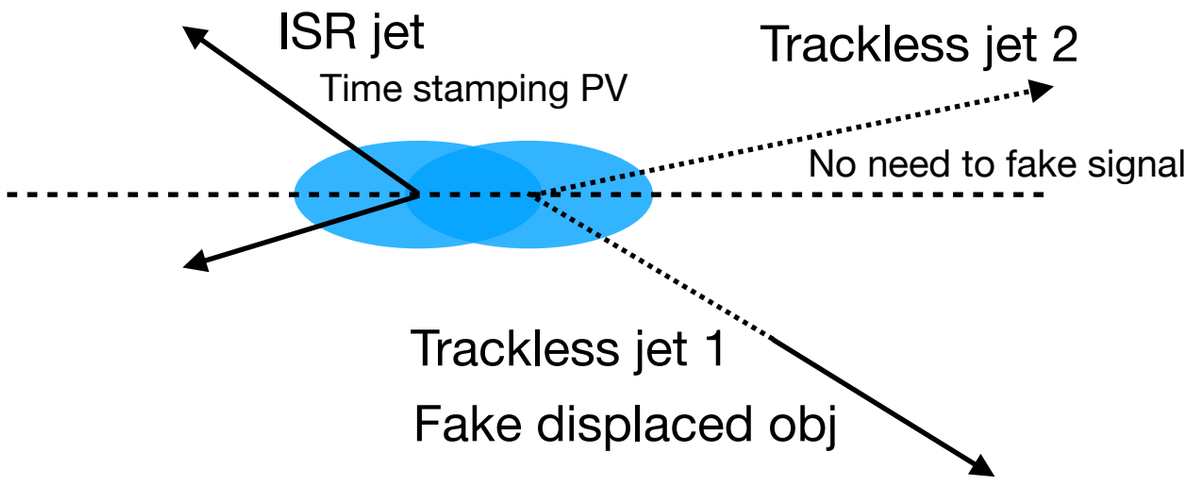
- Hard collision BKG: detector time resolution ~30 ps
  - MTD (30ps) cut: Deltat > 1 ns
  - MS (30ps) cut: Deltat > 0.4 ns
    - BKG(SV) << 1



- The detector time resolution for MS can be downgraded to hundreds of ps
  - MS (200ps) cut: Deltat > 1ns
    - BKG(MS-SV) ~ 0.11

BKG estimation (PU) for LLP with timing

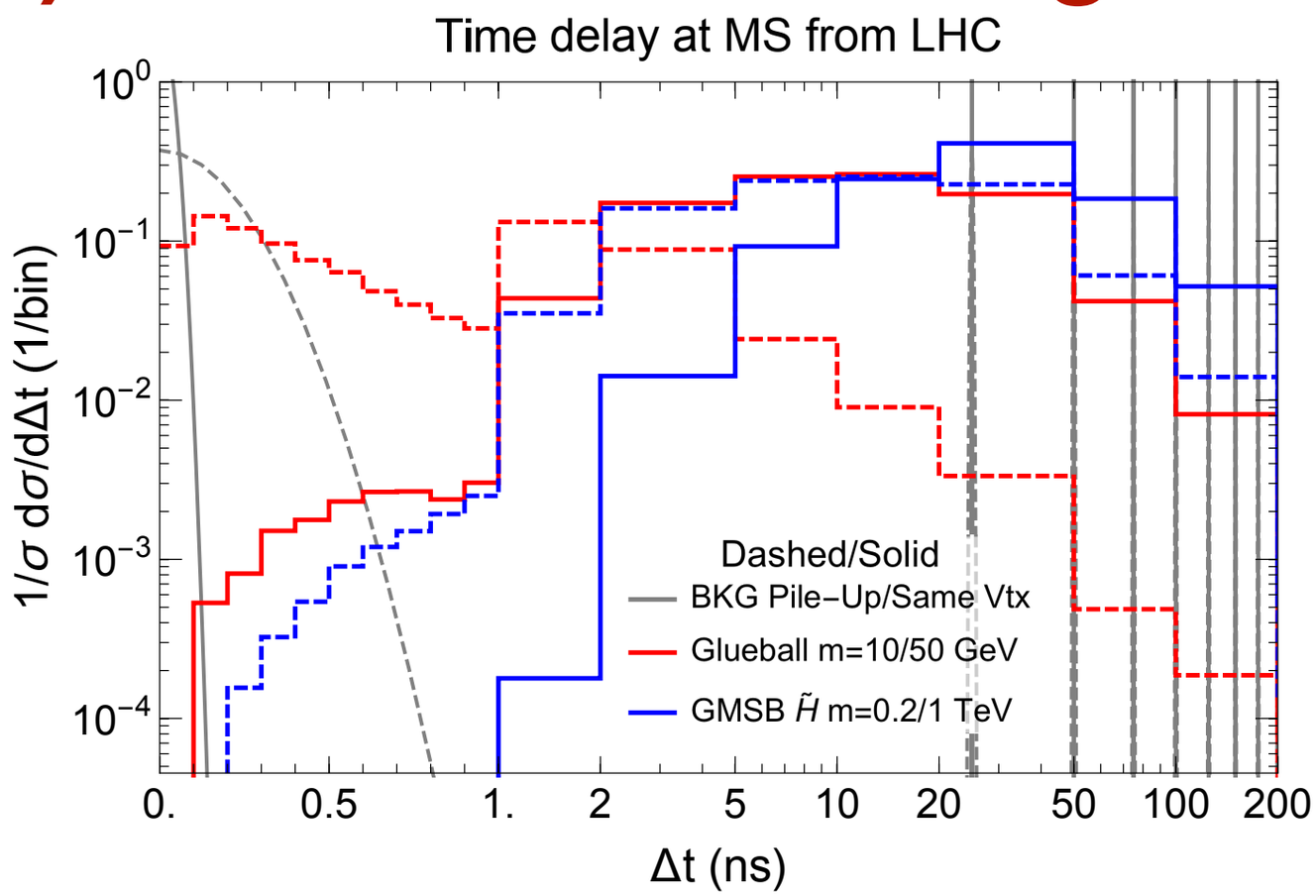
	L_{T_2}	L_{T_1}	Trigger	ϵ_{trig}	ϵ_{sig}	$\epsilon^{j}_{\text{fake}}$	Ref.
EC	1.17 m	0.2 m	DelayJet	0.5	0.5	10^{-3}	[12]
MS	10.6 m	4.2 m	MS RoI	0.25, 0.5	0.25	5×10^{-9}	[24]



$$\text{EC}: \quad N^{\text{PU}}_{\text{bkg}} = \sigma_{\text{j}} \mathcal{L}_{\text{int}} \epsilon^{\text{EC}}_{\text{trig}} \left(\bar{n}_{\text{PU}} \frac{\sigma_{\text{j}}}{\sigma_{\text{inc}}} \epsilon^{j,\text{EC}}_{\text{fake}} f^{j}_{\text{nt}} \right) \approx 2 \times 10^{7},$$

$$\text{MS}: \quad N^{\text{PU}}_{\text{bkg}} = \sigma_{\text{j}} \mathcal{L}_{\text{int}} \epsilon^{\text{MS}}_{\text{trig}} \left(\bar{n}_{\text{PU}} \frac{\sigma_{\text{j}}}{\sigma_{\text{inc}}} \epsilon^{j,\text{MS}}_{\text{fake}} f^{j}_{\text{nt}} \right) \approx 50, \quad (5)$$

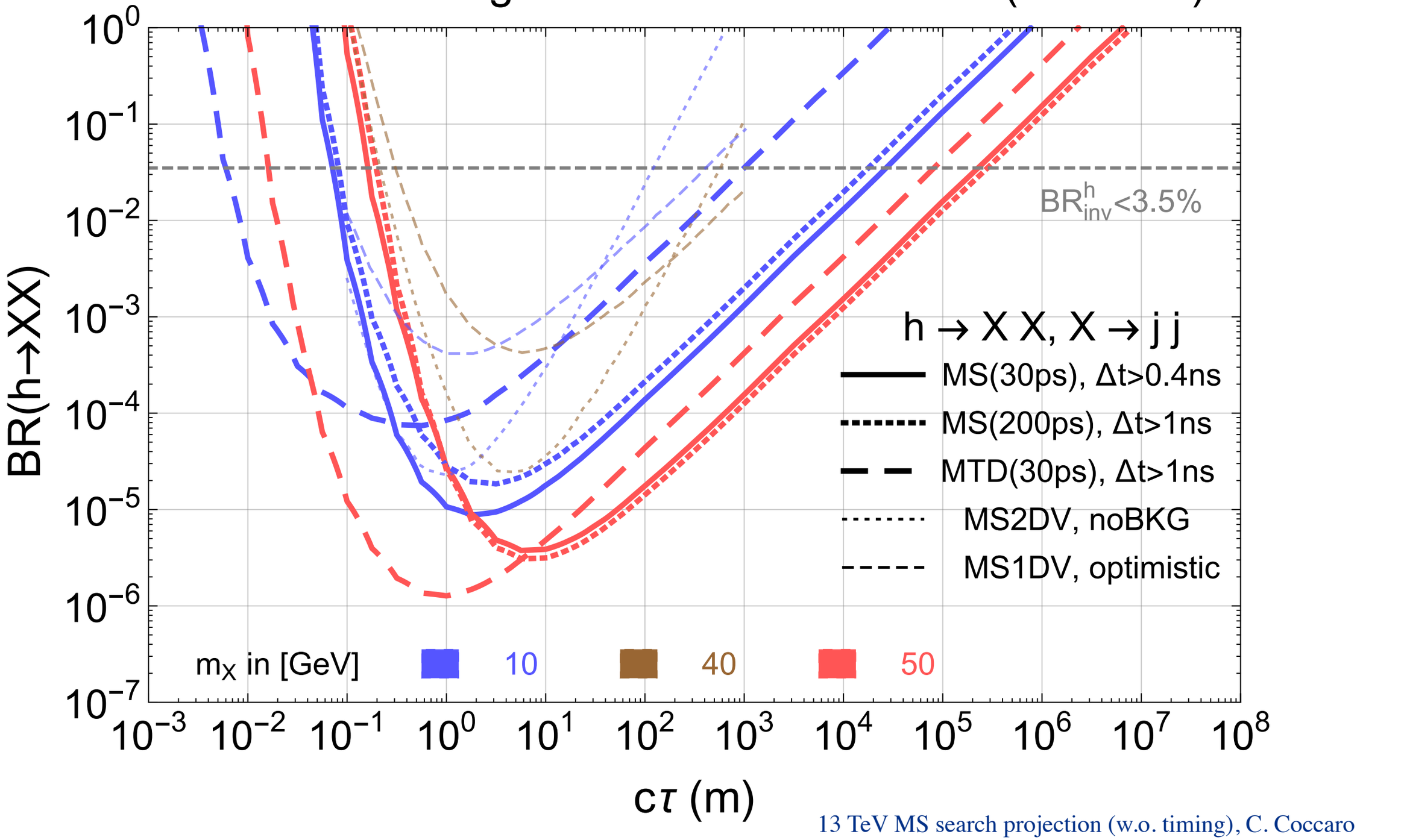
- Pile-up BKG: intrinsic resolution ~190 ps
  - MTD (30ps) cut: Deltat > 1 ns
    - BKG(EC-PU) ~ 1.3
  - MS (30ps) cut: Deltat > 0.4 ns
    - BKG(MS-PU) ~ 0.86



- The detector time resolution for MS can be downgraded to hundreds of ps
  - MS (200ps) cut: Deltat > 1ns
    - BKG(MS-PU) << 1

LLP sensitivity for resonance production

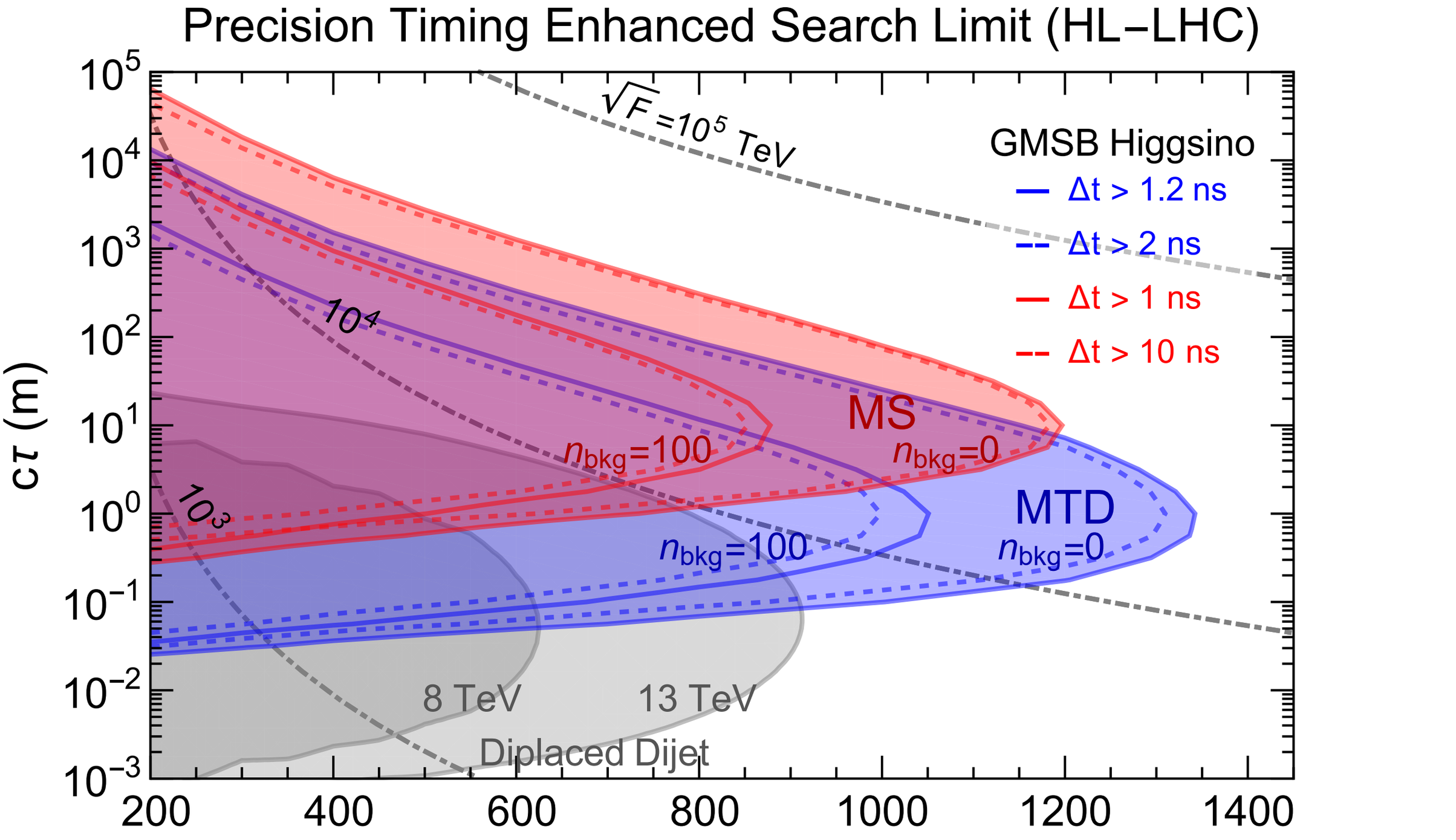
SigA : $pp \to h + j\ ,\ h \to X + X,\ X \to \mathrm{SM},$



13 TeV MS search projection (w.o. timing), C. Coccaro
D. Curtin, H. Lubatti, H. Russell, J. Shelton 1605.02742

LLP sensitivity for pair production

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



Comprehensive 8 TeV analysis and 13 TeV projection without timing, see Zhen Liu, B. Tweedie 1503.05923

Summary and outlook

- Timing information helps to suppress BKG
  - Free information (slow moving) from heavy LLP
  - Very generic signature (low pt ISR jet)
  - Allow single LLP decay
    - Sensitivity reach is good at large lifetime
    - O(100) ps time resolution is good enough for MS searches
- All traditional LLP search can be augmented by timing information (re-optimization)
- Precision timing is a new dimension of particle physics information available for BSM searches

Thank you!