Long-Lived Particles at the LHC with Timing information

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Based on work with Zhen Liu and Liantao Wang, 1805.05957

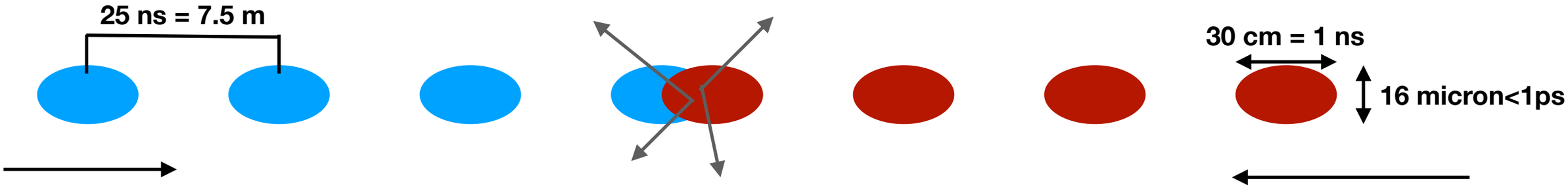
6th PIKIO meeting @University of Notre Dame ,
October 06, 2018

Long-Lived Particles at the LHC with Timing information

- Long-lived particles (skip)
- Timing information at detector
- Long-lived + Timing

Detector with timing information

- Detector needs timing information to record event



- Bunch crossing: 25 ns
- Bunch length: 30 cm~ 1 ns
- Collision is a time extended event.
- Pile-up events: 20~100 per bunch, time spread~190ps
- Detector needs to record time in each 25 ns window, but suffers from pile-up

Detector with timing information

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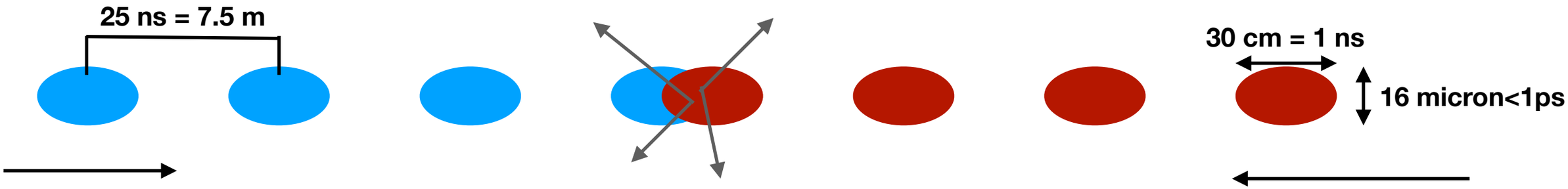

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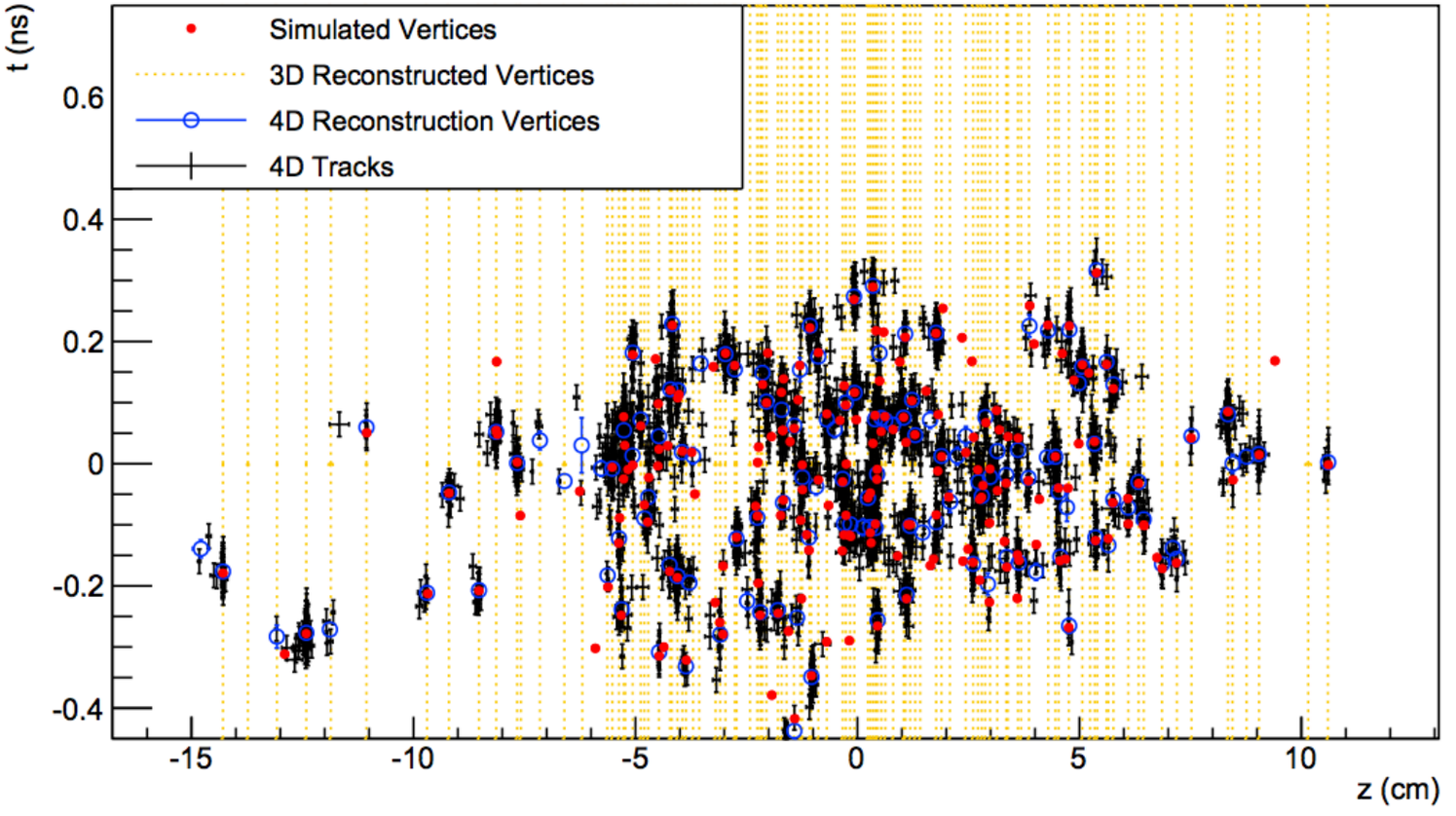
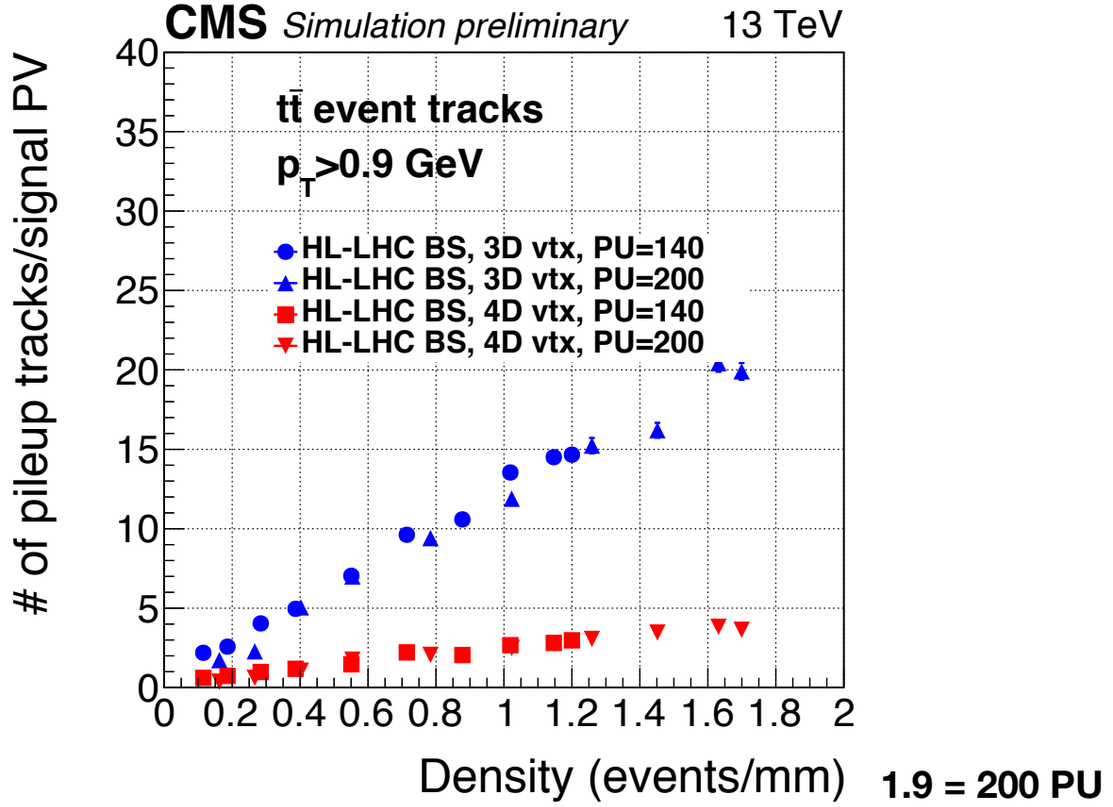
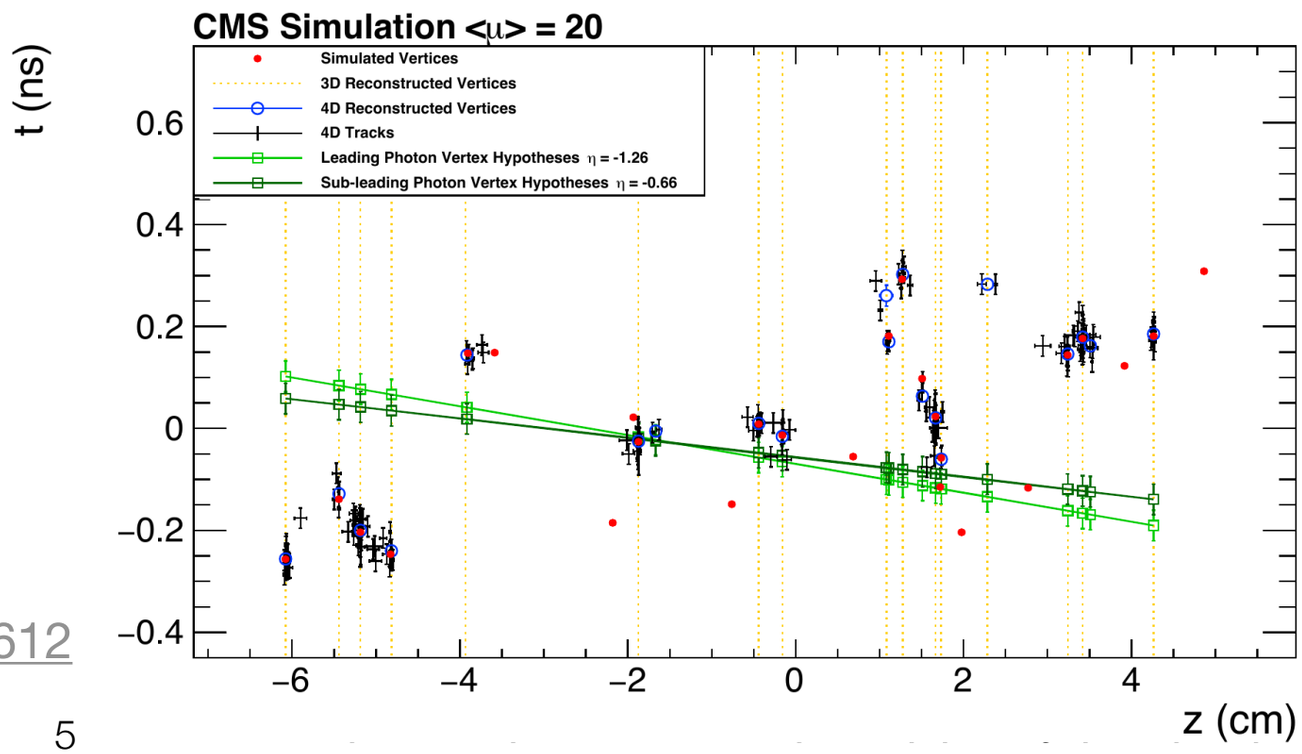


Timing upgrade benefits

- Reduction of pileup tracks
- Suppress pileup jet
- Better missing energy recon.
- B-tagging and tau charged isolation
- Higgs diphoton vertex location





https://cds.cern.ch/record/2296612

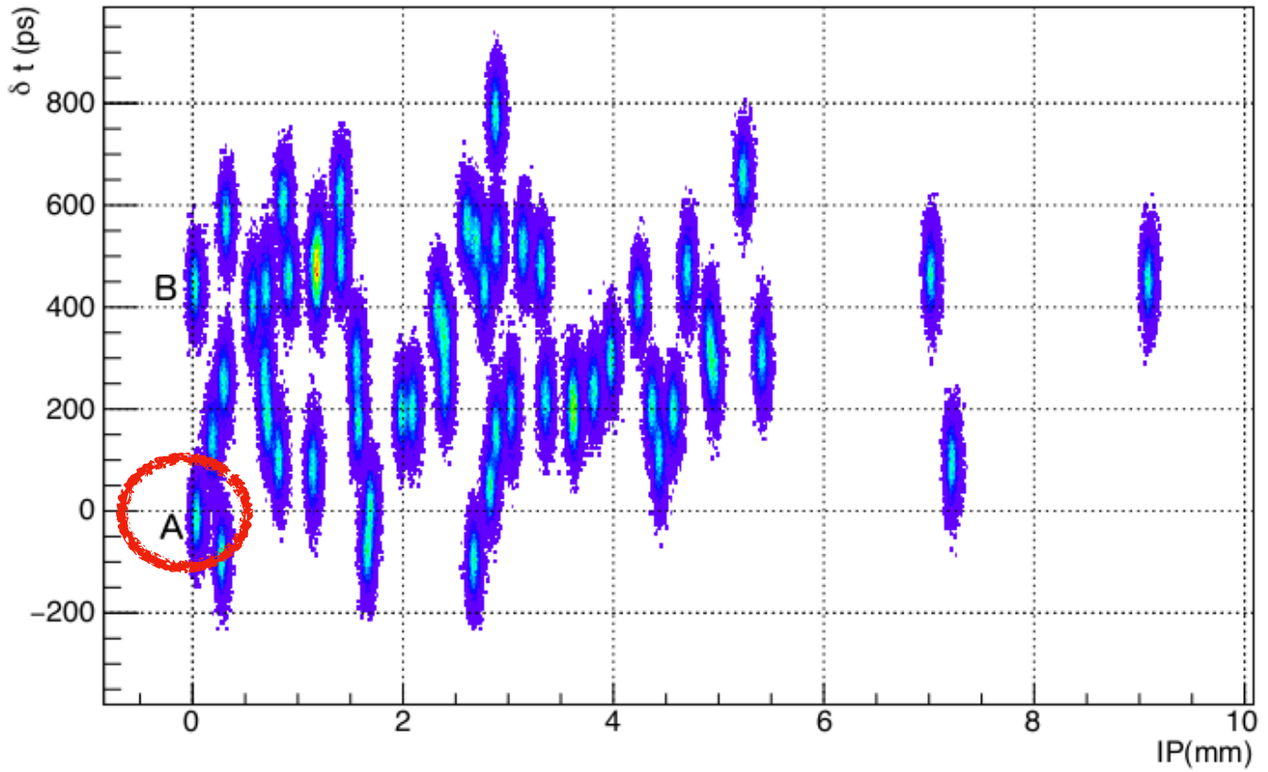
Timing upgrade proposal for ATLAS and LHCb

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

ATLAS: 1804.00622

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

- LHCb: upgrade timing for Vertex Locator (VELO), high granularity ECAL and Torch detector,
  - forward, with ~30ps timing resolution
  - B0->pi+ pi-



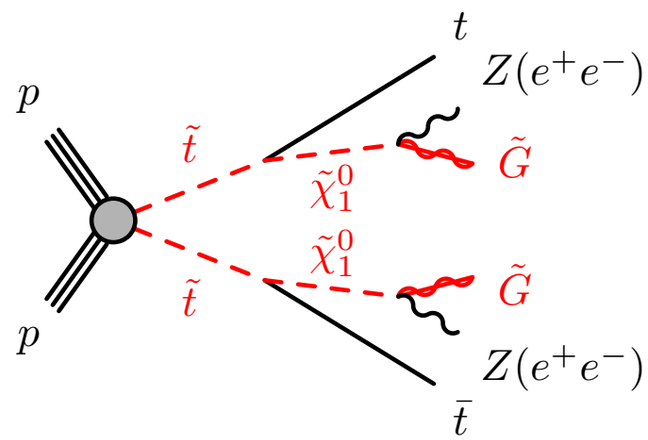
LHCb: 1808.08865

Motivation for our work

- LHC 2 year long shut down from Dec 2018
  - PHASE 2 upgrade: timing detector (~30 ps)
  - How to relate it to new physics?

Motivation for our work

- Previous work
  - Time of flight in (meta-)stable charged particle searches, (CMS: 1305.0491, PAS-EXO-16-036, ATLAS:1604.04520, J. Ellis:ph/0607261)
  - Time delay parameters adopted in non-pointing photon searches (CDF: ph/0407022, physics/0512171, ATLAS:1409.5542)
  - (very loosely) in the stopped particle searches (CMS:1801.00359)
  - Time of flight in neutral particle search for mass determination (CMS MTD Phase 2 upgrade)
  - Backward flying particle from LLP (1706.07407)
- Our work
  - Use timing to suppress SM background in LLP search
  - Fits for generic LLP, e.g. decay to jets



(p_chi0 + p_Z)^2 = 0

Long lived particle (LLP) detection

- Question: if LLP has lifetime 10km, and we have a finite size detector e.g. 10 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. 10 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

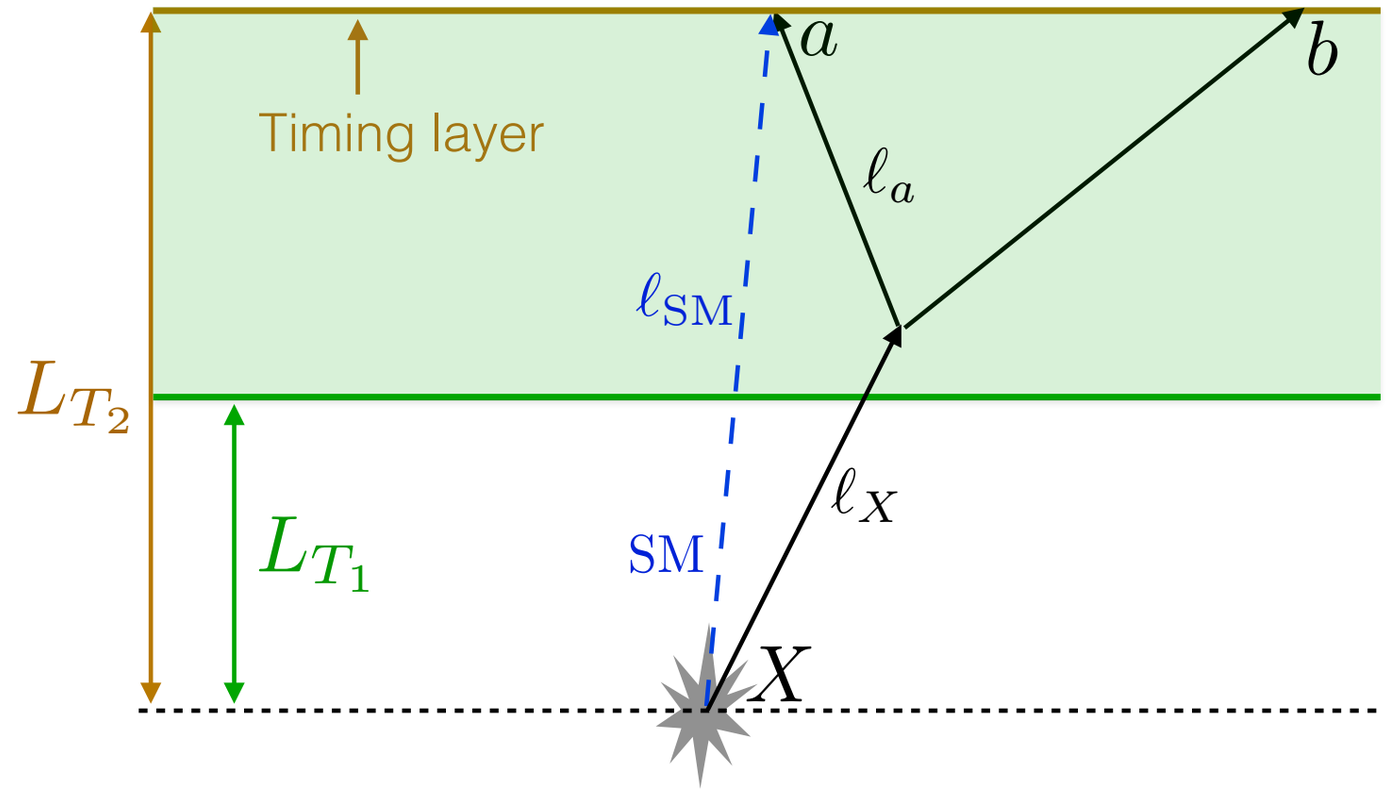
Good news for LHC general purpose detectors!

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 ~ (mh/2)/50GeV, v~0.55
- Time delay ~ 4ns (1/v -1)=3.2ns

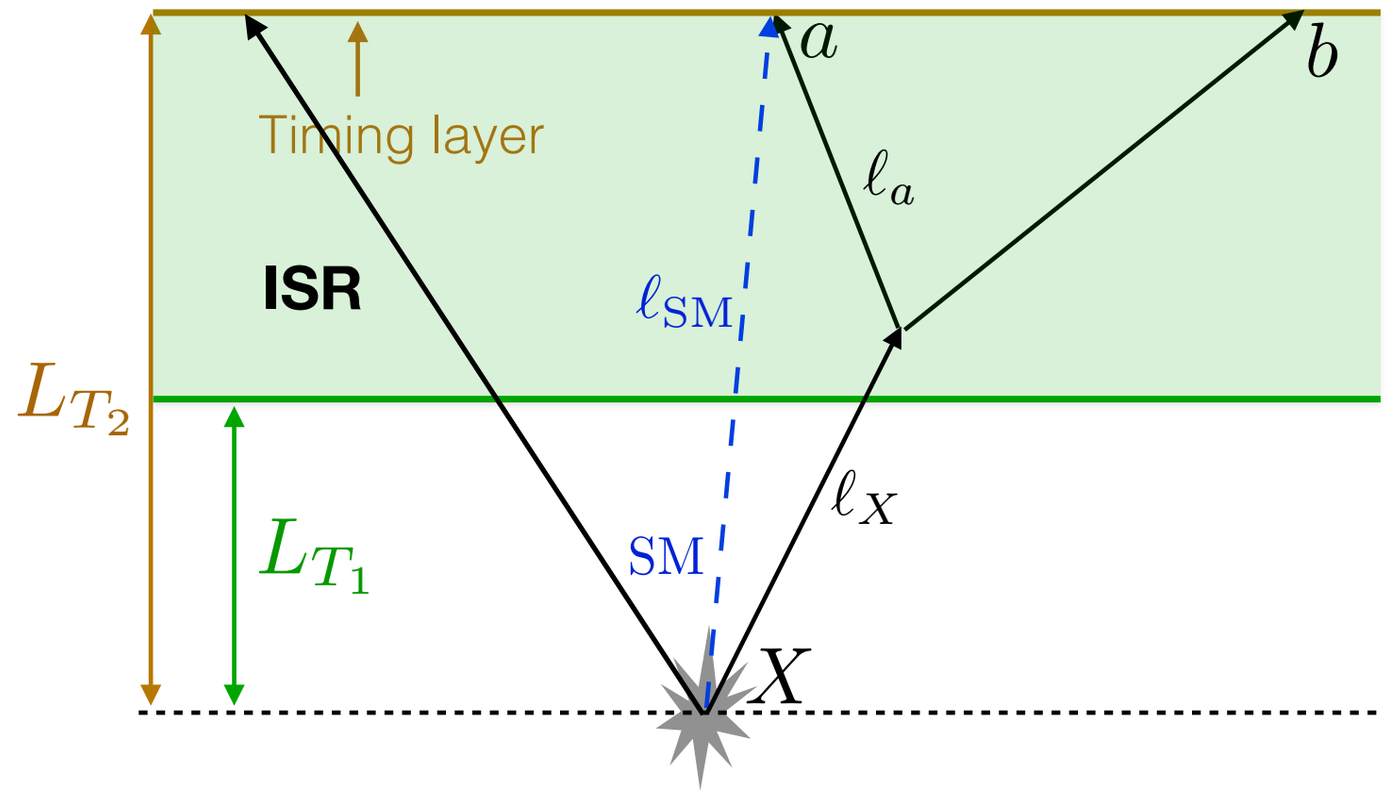


- Proposal: LLP decay before timing layer
  - CMS MTD search: LT1 = 0.2 m, LT2 = 1.2 m (MTD = MIP Timing Detector)
  - ATLAS MS search (hypothetical): LT1 = 4.2 m, LT2 = 10.6m (MS = Muon Spectrometer)

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

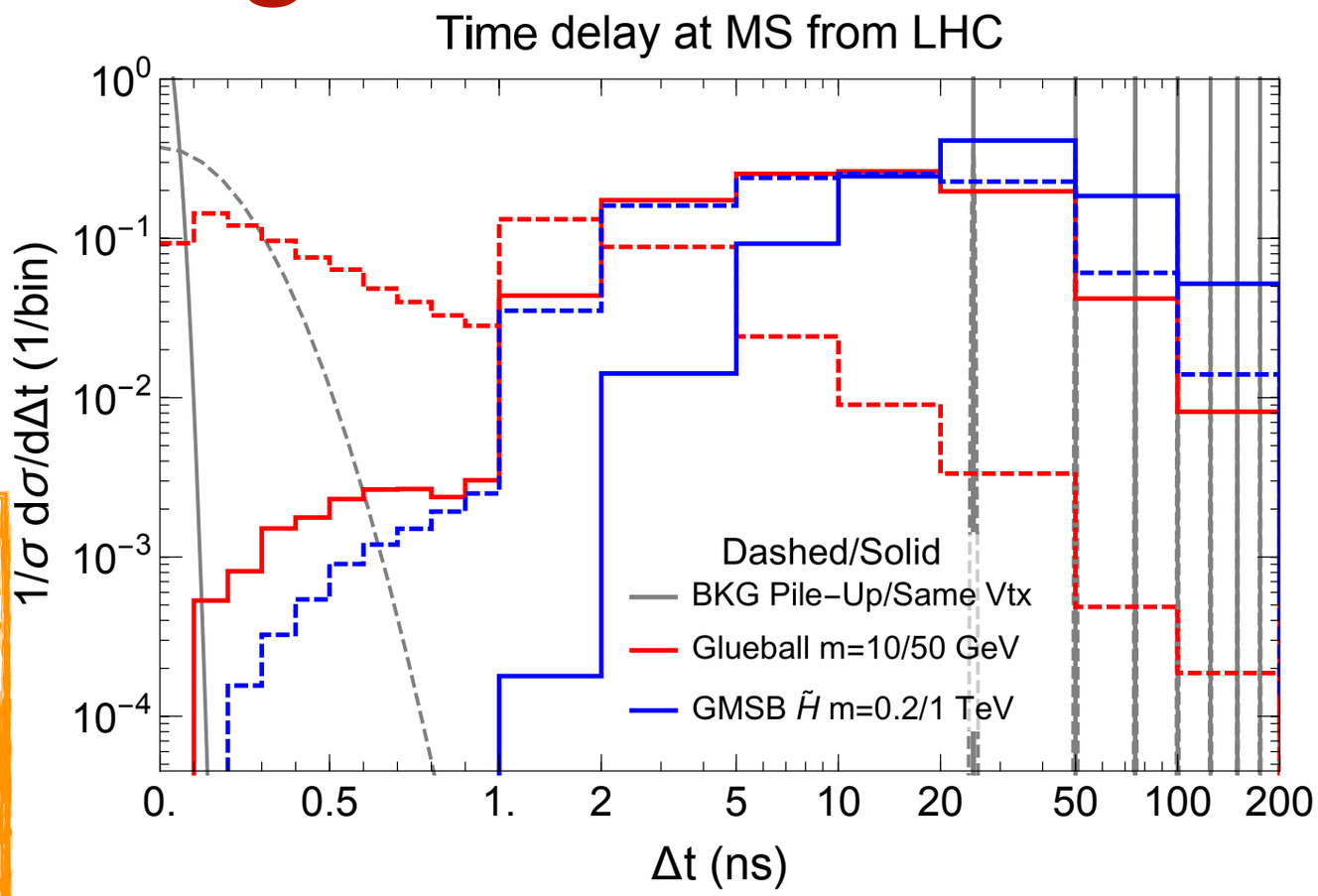
$$\text{SigA}: \; pp \to h + j, \; h \to X + X, \; X \to \text{SM},$$
$$\text{SigB}: pp \to \tilde{\chi}\tilde{\chi} + j, \; \tilde{\chi}_1^0 \to h + \tilde{G} \to \text{SM} + \tilde{G}.$$

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

Motivation for timing cut on LLP

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

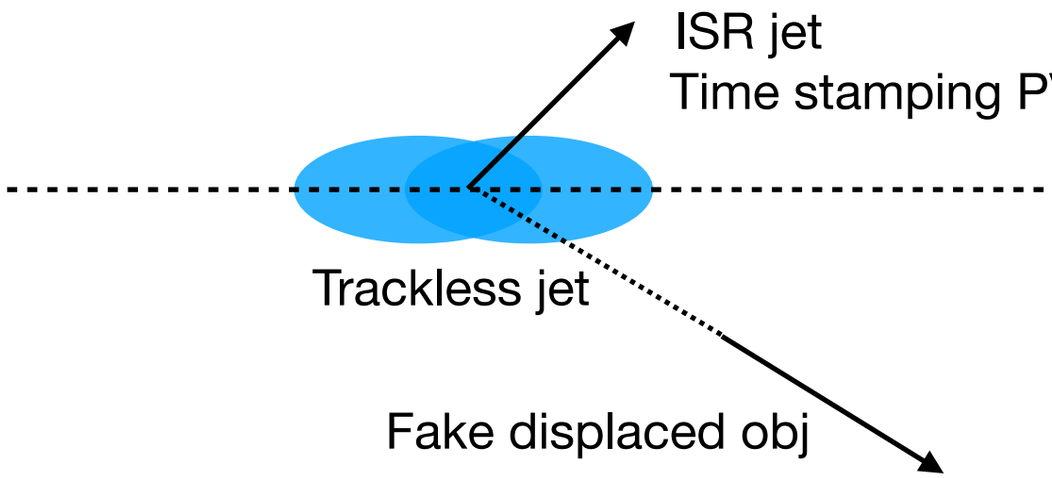
- Use timing cut to suppress background
  - Method: a low pt ISR jet + timing delayed object (no track near PV)
    - Lower pt/MET cut threshold
    - Due to low bkg, use one LLP decay
    - Achieve better sensitivity at large lifetime



- Other SM backgrounds (time uniform):
  - Interactions with materials, cosmic rays, beam halo, satellite beam etc
  - Existing mature veto mechanism (e.g. non-pointing photons, traditional DV search)
- More handles from LLP signal
  - DV, MET at PV, ISR lepton, two delayed objects (if Gaussian fail in the tail)…
  - Help to suppress the bkg

BKG estimation (SV) for LLP with timing

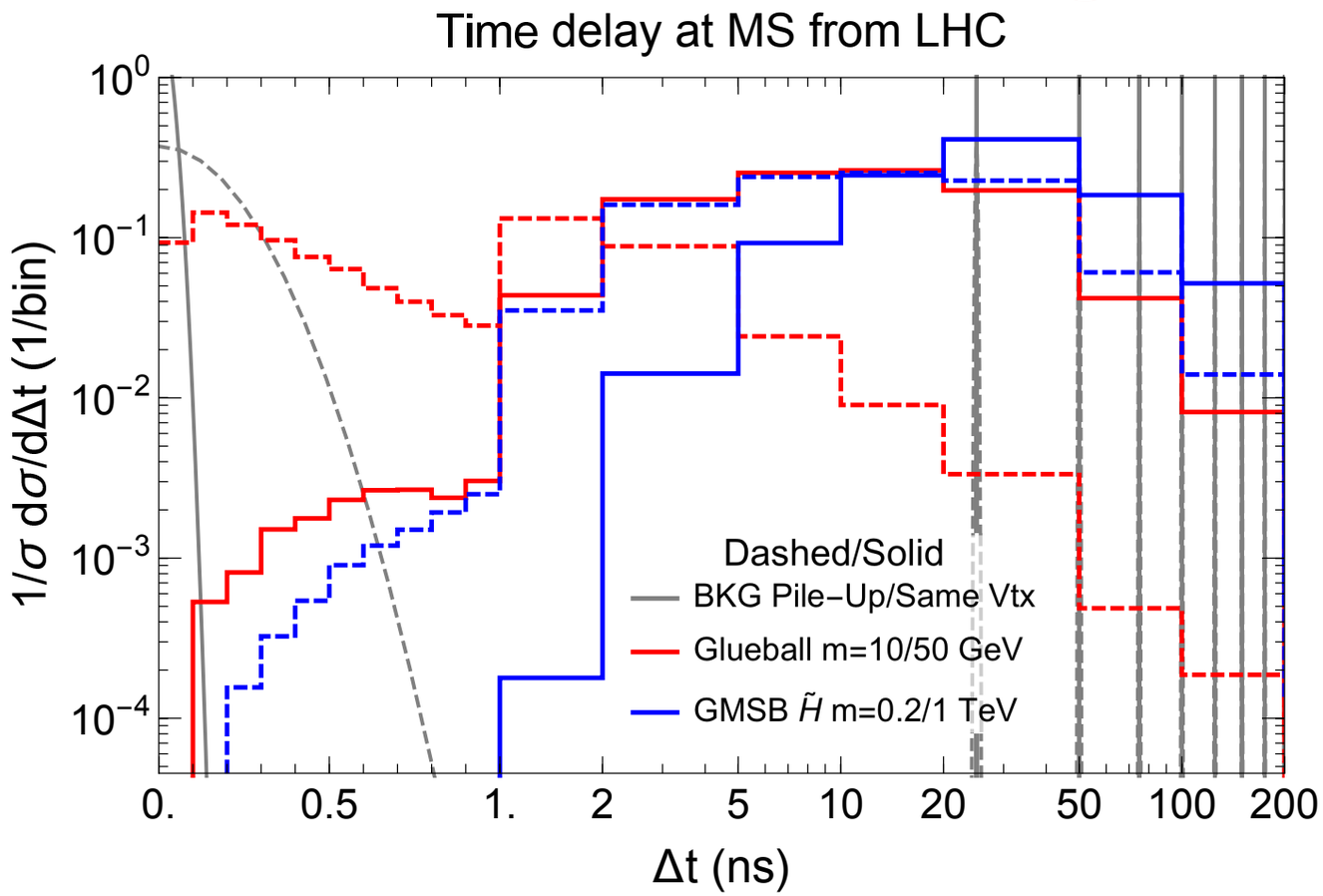
	L_{T_2}	L_{T_1}	Trigger	ϵ_{trig}	ϵ_{sig}	$\epsilon^{j}_{\text{fake}}$	Ref.
MTD	1.17 m	0.2 m	DelayJet	0.5	0.5	10^{-3}	[12]
MS	10.6 m	4.2 m	MS RoI	0.25, 0.5	0.25	5×10^{-9}	[22]



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

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

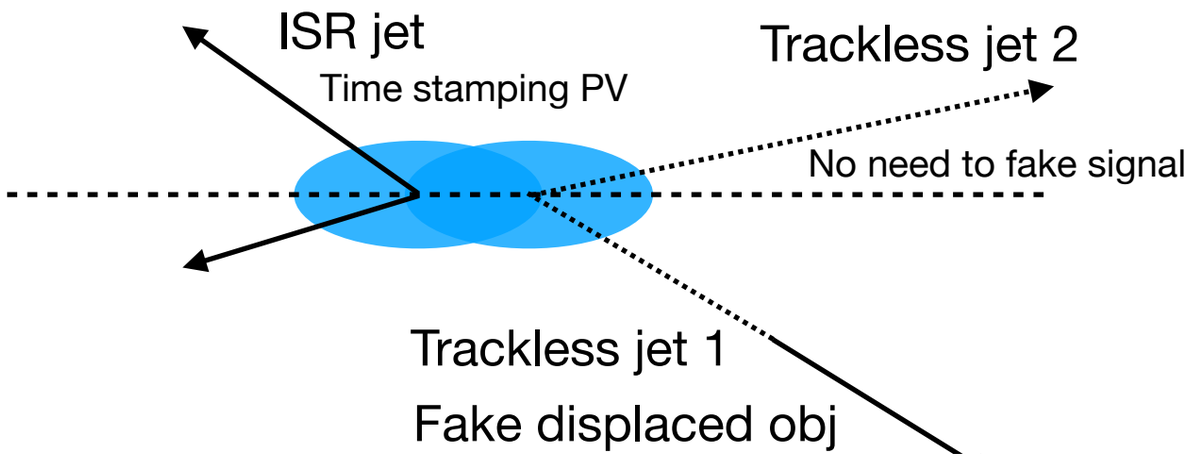
- Hard collision BKG: detector time resolution ~30 ps
  - MTD (30ps) cut: Deltat > 1 ns
  - MS (30ps) cut: Deltat > 0.4 ns
    - BKG(SV) << 1



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

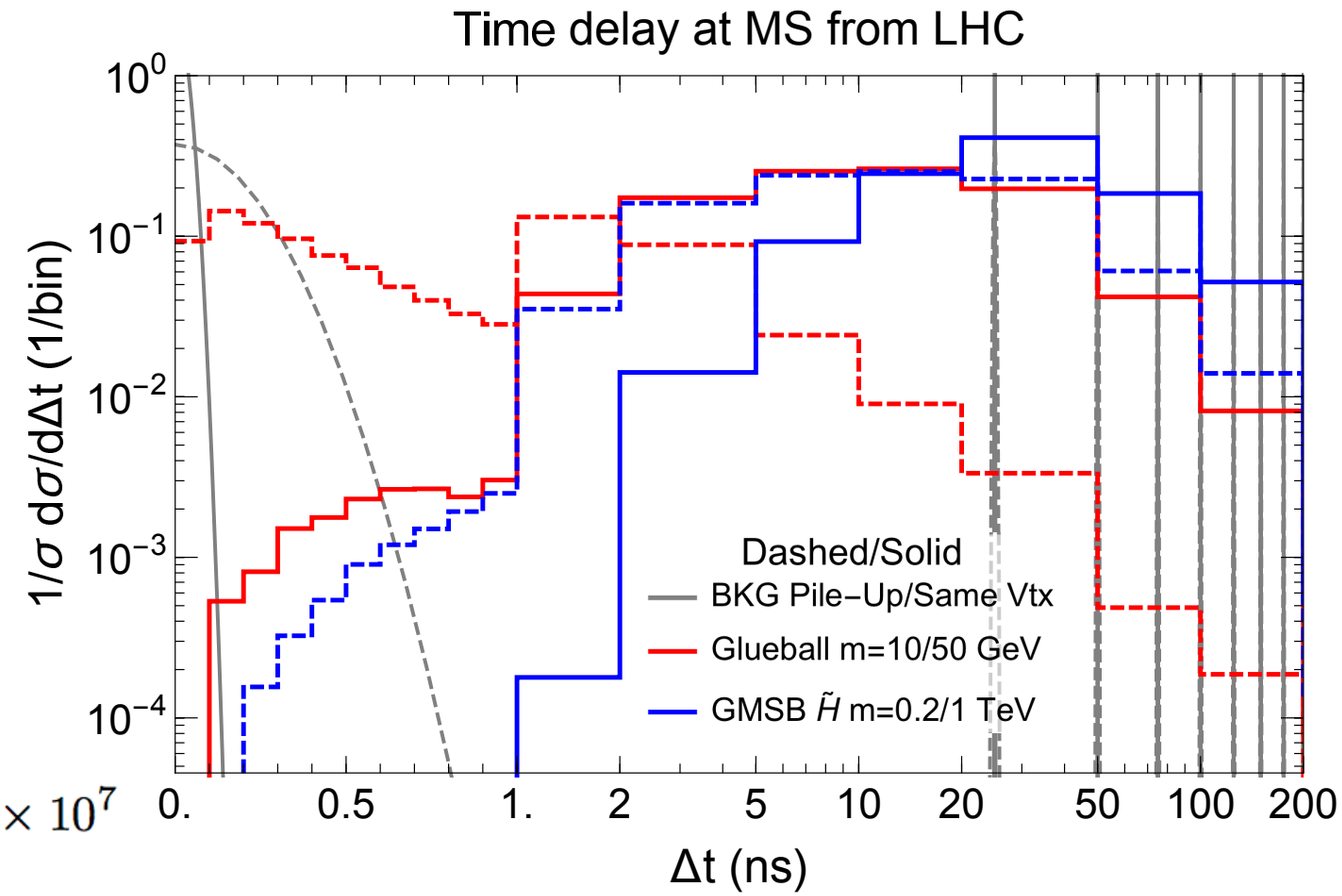
BKG estimation (PU) for LLP with timing

	L_{T_2}	L_{T_1}	Trigger	$\epsilon_{\rm trig}$	$\epsilon_{\rm sig}$	$\epsilon^j_{\rm fake}$	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]



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

$$\text{MS}: \quad N^{\rm PU}_{\rm bkg} = \sigma_{\rm j}\mathcal{L}_{\rm int}\epsilon^{\rm MS}_{\rm trig}\left(\bar{n}_{\rm PU}\frac{\sigma_{\rm j}}{\sigma_{\rm inc}}\epsilon^{j,\rm MS}_{\rm fake}f^j_{\rm nt}\right) \approx 50, \quad (4)$$

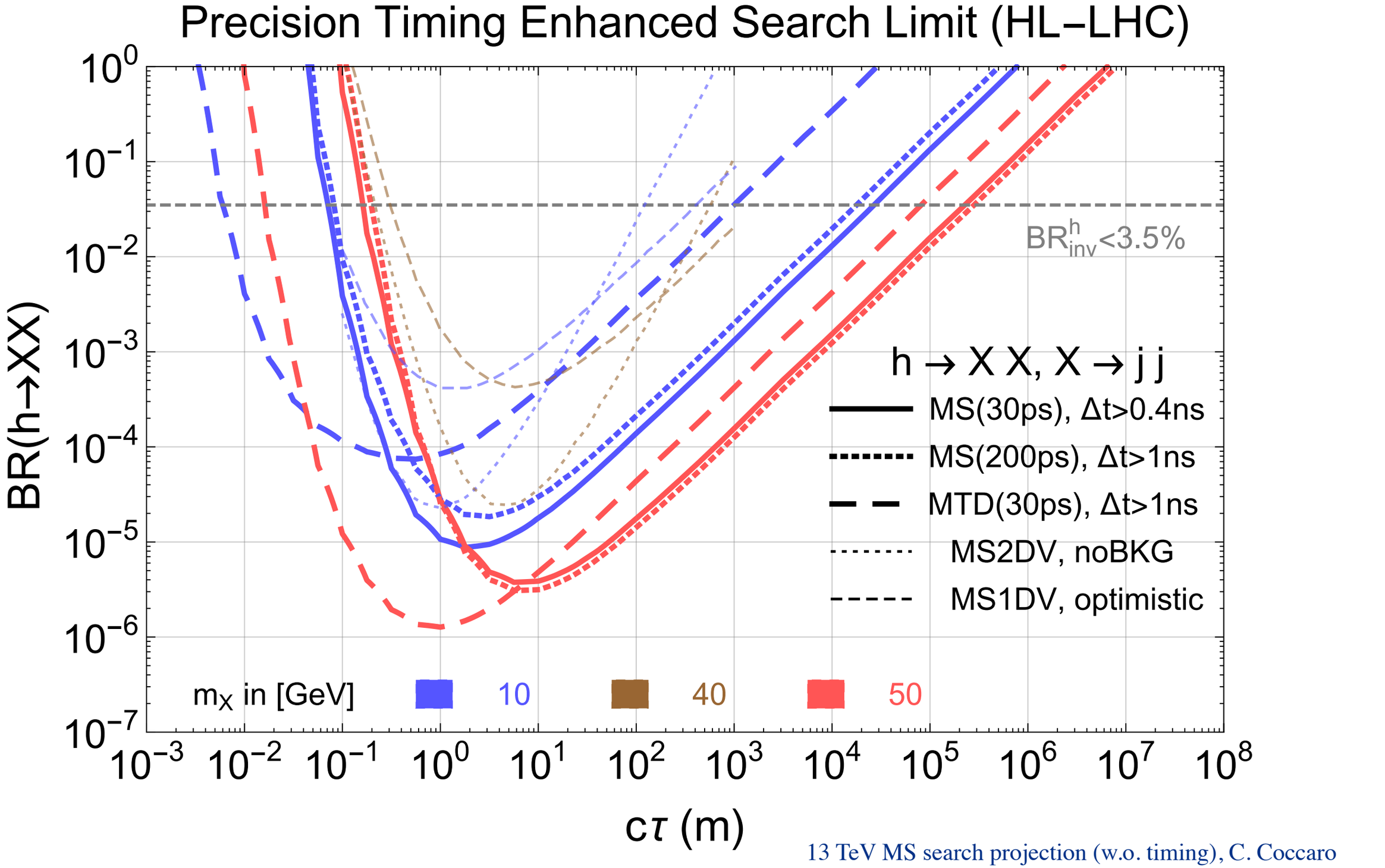


- Pile-up BKG: intrinsic resolution ~190 ps
  - MTD (30ps) cut: Deltat > 1 ns
    - BKG(MTD-PU) ~ 1.3
  - MS (30ps) cut: Deltat > 0.4 ns
    - BKG(MS-PU) ~ 0.86

- 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

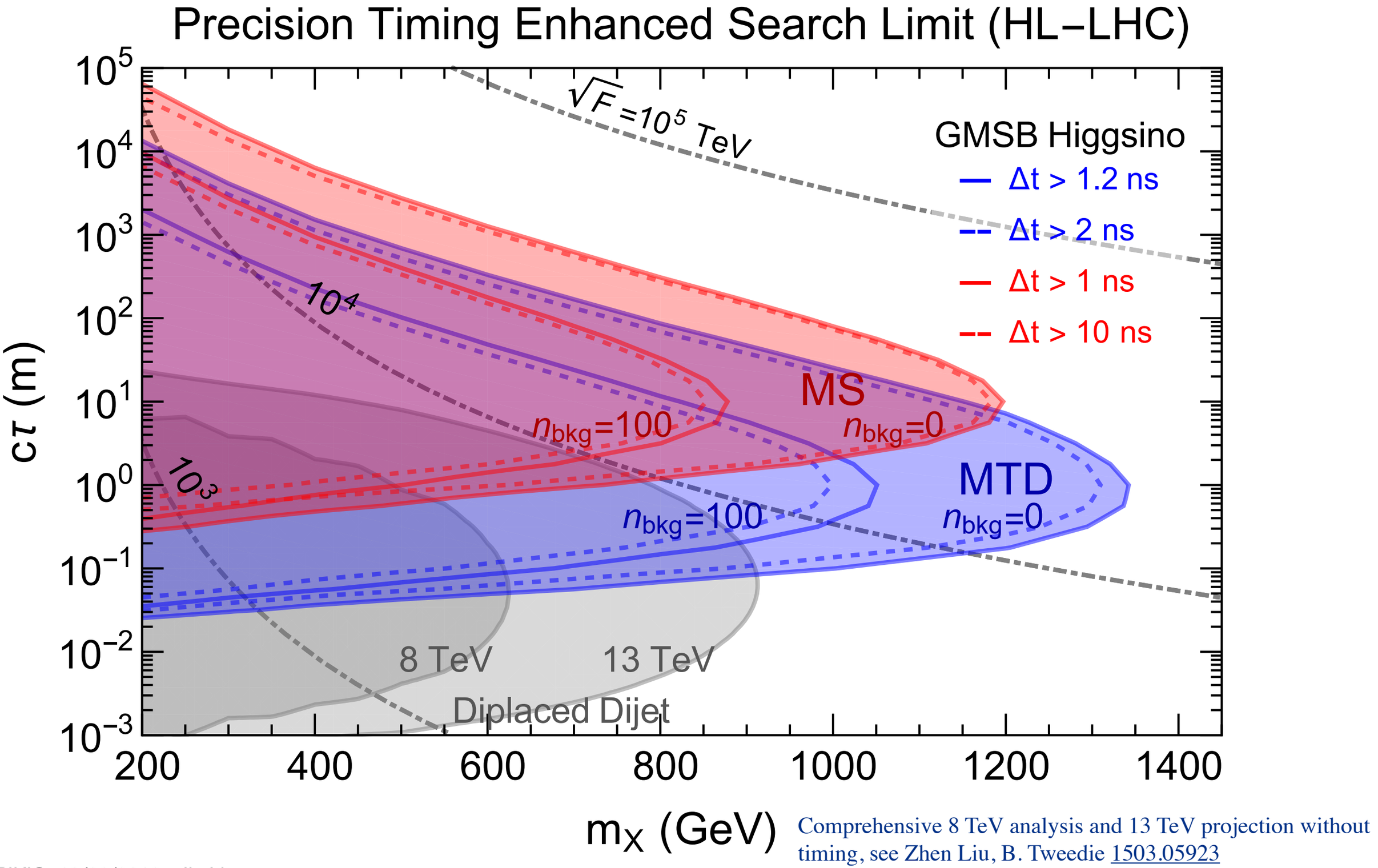
$\mathrm{SigA}: \ pp \to h + j \ , \ h \to X + X, \ X \to \mathrm{SM},$



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

- Timing information helps to suppress BKG
  - Generic feature (slow moving) from heavy LLP
  - Very low requirement (low pt ISR jet)
  - Allow single LLP decay search or even tracks
    - 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

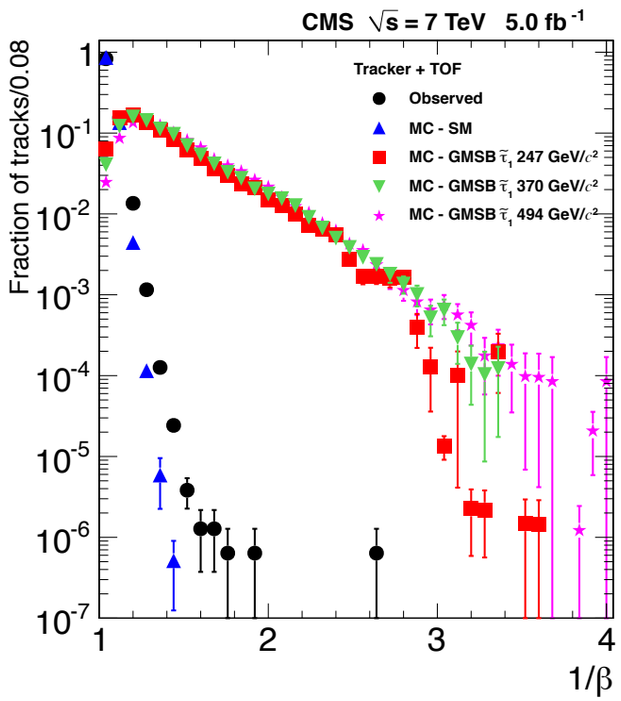
Thank you!

Backup slides

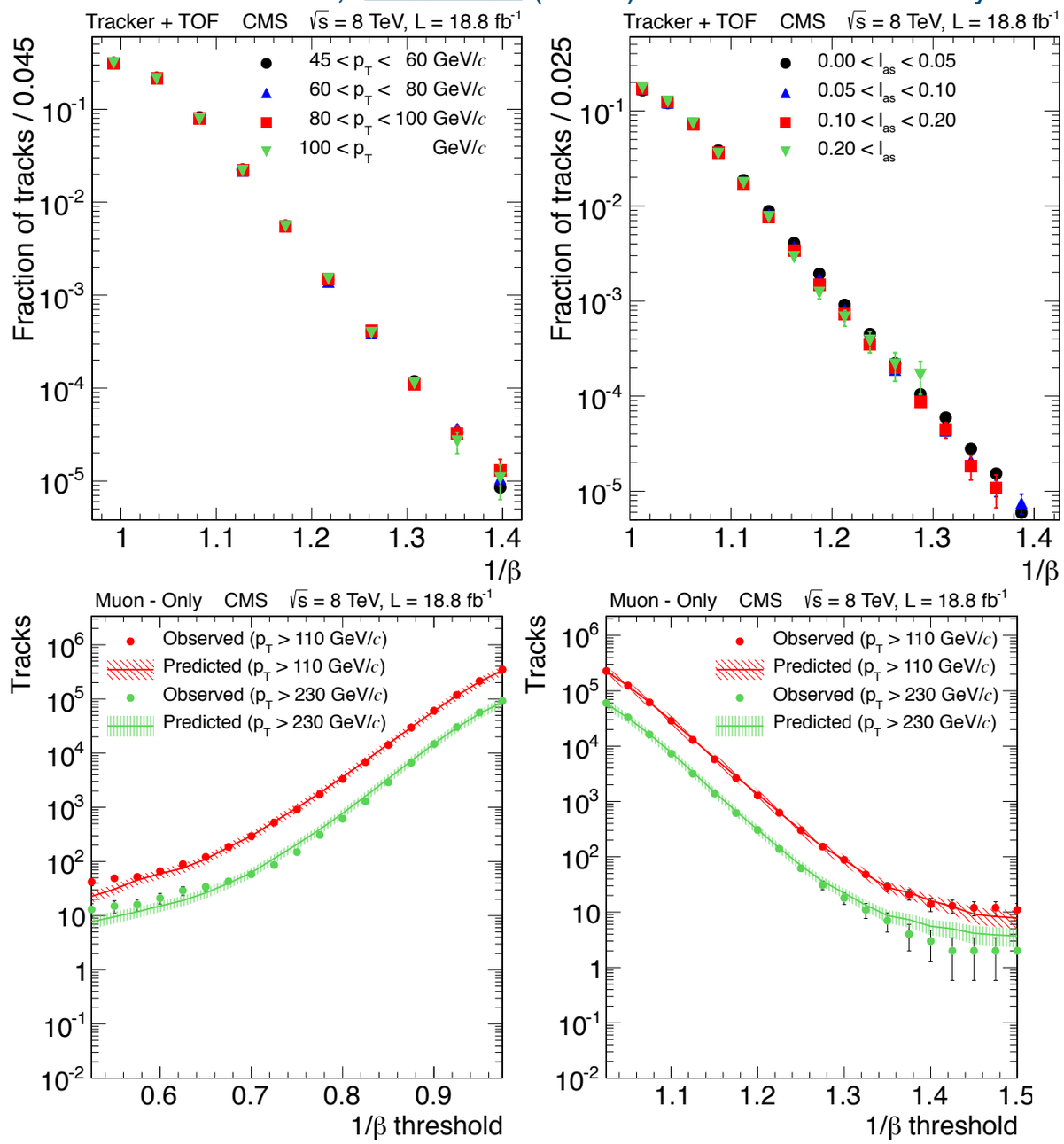
Motivation for LLP search at LHC

- At d>L, LHC and far detector is comparable, but d<L, LHC is exponentially better than MATHUSLA
- LHC BKG suppression:
  - MTD: 10^{-10}, MS: 10^{-5} by timing
- Early measurement for HSCP (non-pointing photon) indicates the SM background behavior agree well with Gaussian up to 10^{-6} (10^{-4}) level (experimental Monte Carlo went to 10^{-9}), where the plot ends (data insufficient);
- More handles to suppress bkg: e.g. MET, double time delay object, displaced parameters (impact parameters)

CMS Heavy stable charged particle (HSCP) track+ToF, 1205.0272 t = L/v



CMS Heavy stable charged particle (HSCP) track+ToF, 1305.0491 (1/v -1). Inner tracker+Muon sys



Discussions

Big Signal selection enhancement
Big trigger efficiency enhancement

Mapping to UV Models

Production \ Decay	$\gamma\gamma(+\text{inv.})$	$\gamma + \text{inv.}$	$jj(+\text{inv.})$	$jj\ell$	$\ell^+\ell^-(+\text{inv.})$	$\ell^+_\alpha \ell^-_{\beta\neq\alpha}(+\text{inv.})$
DPP: sneutrino pair	†	SUSY	SUSY	SUSY	SUSY	SUSY
HP: squark pair, $\tilde{q} \to jX$ or gluino pair $\tilde{g} \to jjX$	†	SUSY	SUSY	SUSY	SUSY	SUSY
HP: slepton pair, $\tilde{\ell} \to \ell X$ or chargino pair, $\tilde{\chi} \to WX$	†	SUSY	SUSY	SUSY	SUSY	SUSY
HIG: $h \to XX$ or $\to XX + \text{inv.}$	Higgs, DM*	†	Higgs, DM*	RHν	Higgs, DM* RHν*	RHν*
HIG: $h \to X + \text{inv.}$	DM*, RHν	†	DM*	RHν	DM*	†
RES: $Z(Z') \to XX$ or $\to XX + \text{inv.}$	Z', DM*	†	Z', DM*	RHν	Z', DM*	†
RES: $Z(Z') \to X + \text{inv.}$	DM	†	DM	RHν	DM	†
CC: $W(W') \to \ell X$	†	†	RHν*	RHν	RHν*	RHν*

Timing most significant because
No tracking & No displaced vertex

X represents the LLP
*model definitely include missing energy;
+signature not appeared in the minimal/simplest model setup;

- Basic Summary of our understanding:
  - For all models, **timing helps** (reduce bkg / allow to loosen cuts)
  - For large fraction of models, **timing @ trigger level helps A-LOT** by enabling LLP-targeted triggers
  - For decays to photons, **timing is critical** because there are no other handles (no tracking, no displaced vertices)

Challenges and opportunities

- CMS MTD will be there + delay jet L1 trigger(?): require non-trivial effort to realize, e.g., low+high level with jet ROI. Once realized, could be universal boost to LLPs at the LHC! (some initial effort at LBNL LLP workshop)

  - MTD chip (4cm x 4cm), single chip trigger needs comparison to reach 30ps, track/ECAL assisted

- ATLAS MS timing layer(?) + Muon RoI trigger: timing layer no proposal yet, but is interesting to study. If not, MS RPC timing (~0.7ns) could be used, still good for heavy LLP.

- More (signal specific) additional handles: combined trigger strategy with timing as new d.o.f.

- ATLAS high granularity timing detector and LHCb Torch detector: look for forward region new physics with timing