Timing BSM signals

Zhen Liu (Fermilab)

Searching for long-lived particles at the LHC:

Third workshop of the LHC LLP Community

May. 18th , 2018

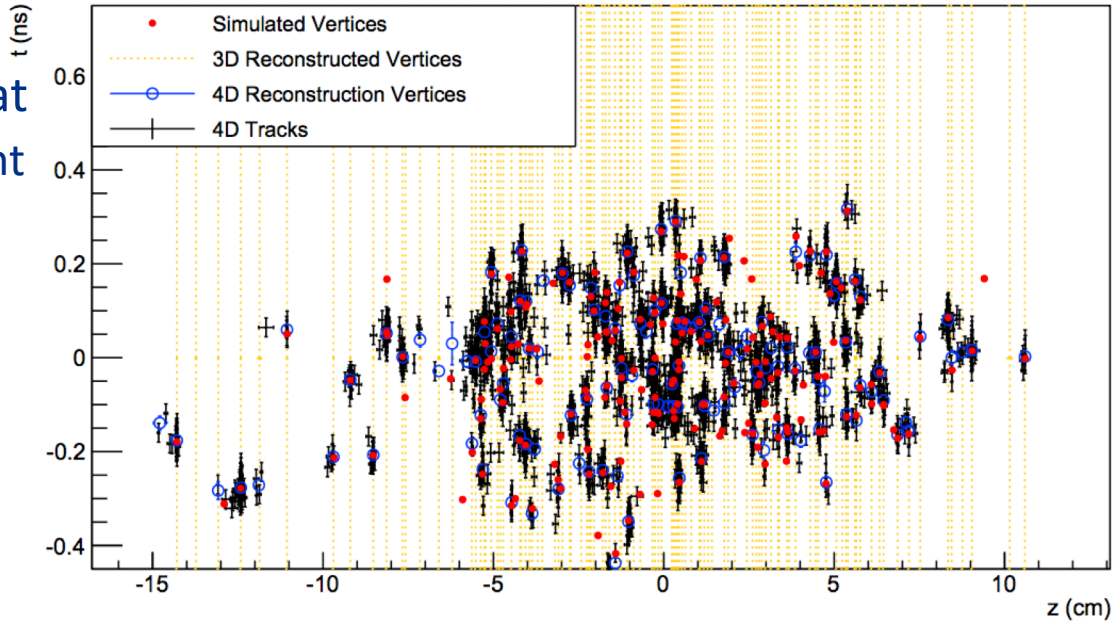
Based on work with Jia Liu and Lian-Tao Wang, 1805.05957

Precision timing--a new dimension

Precision timing information now compliments spatial information, and its bears great potential to fully realize LHC's physics reach in LLP.

For long-lived particles (whose lifetime is macroscopic >~ mm), they generically move slower and their long-lived nature substantiates their slowness in motion at colliders.

- 30 picosecond timing resolution at CMS after phase2 upgrade (in front of ECal, 1.2 m from beam);
- Proposed to enable 4d construction of vertices:
  - reducing the pile up level;
  - Reducing pile-up track mis-association in to the primary interaction;

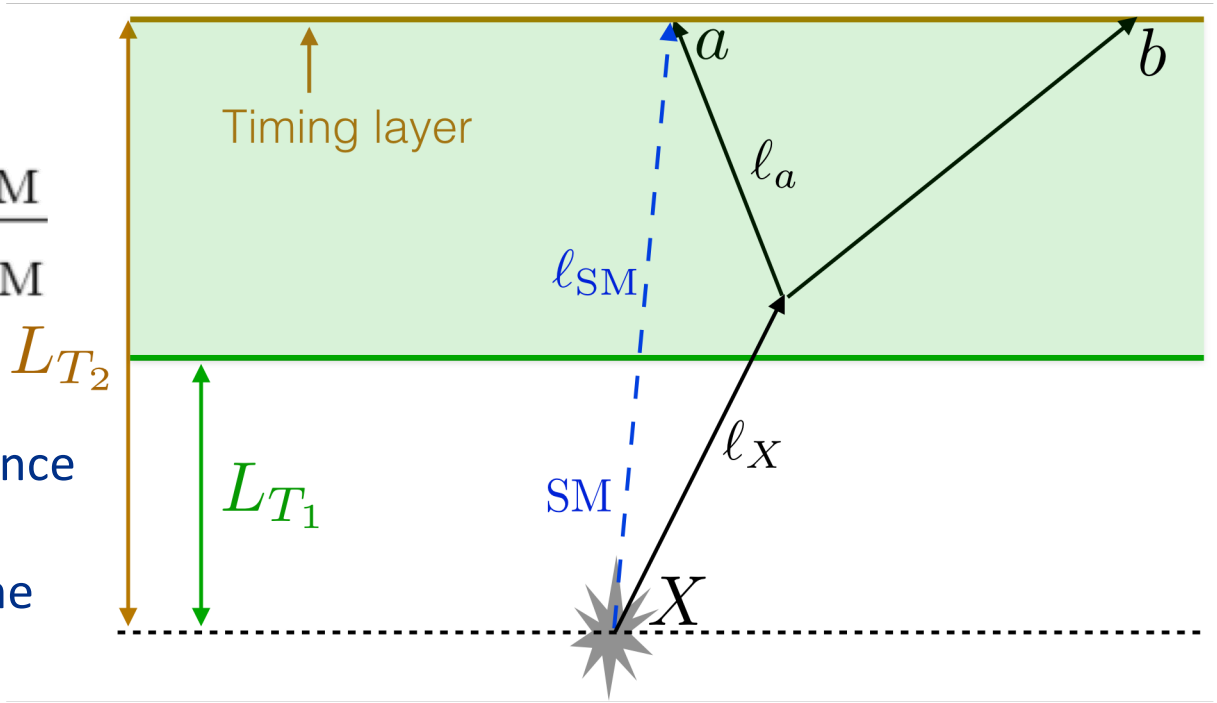


Timing BSM

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

signal arrival time

SM reference particles arrival time



For CMS timing layer (1.2 m, t0=4 nanoseconds)*, 30 picosecond timing resolution indicates sensitivity to BSM signal having >1% velocity (boost factor $\gamma < 7$) /path difference w.r.t. SM particles!

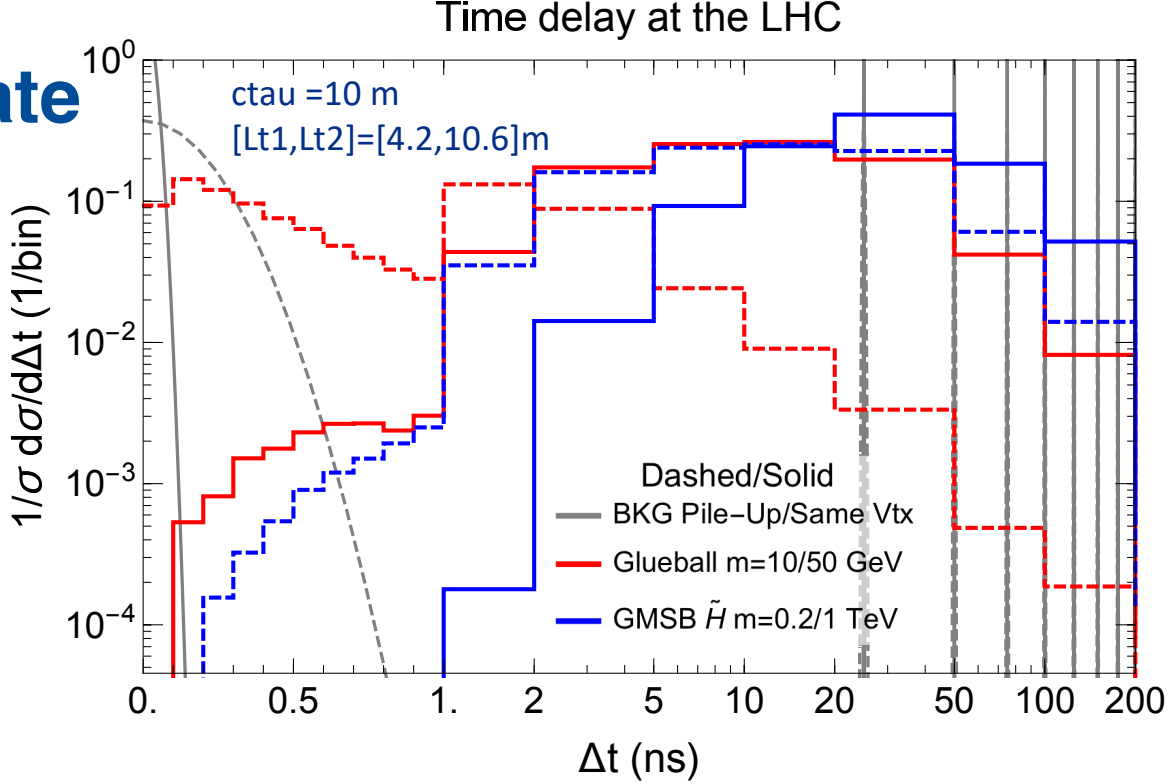
LLP (with mass > 10s of GeV) typically all have much slower motion!

*for pseudorapidity 0; higher rapidity enlarges the timing difference;
*SM particles essentially all travel at speed of light;

LLPs arrive (very) late

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

We also consider a possible timing layer outside Muon spectrometer, making use of the large LHC detector volume.



Signals:

- Red: Higgs decaying into glueballs (neutral naturalness)
  Representative as particles produced with typical pT;
- Blue: Higgsinos (GMSB SUSY)
  Representative as particles pair produced at the LHC;

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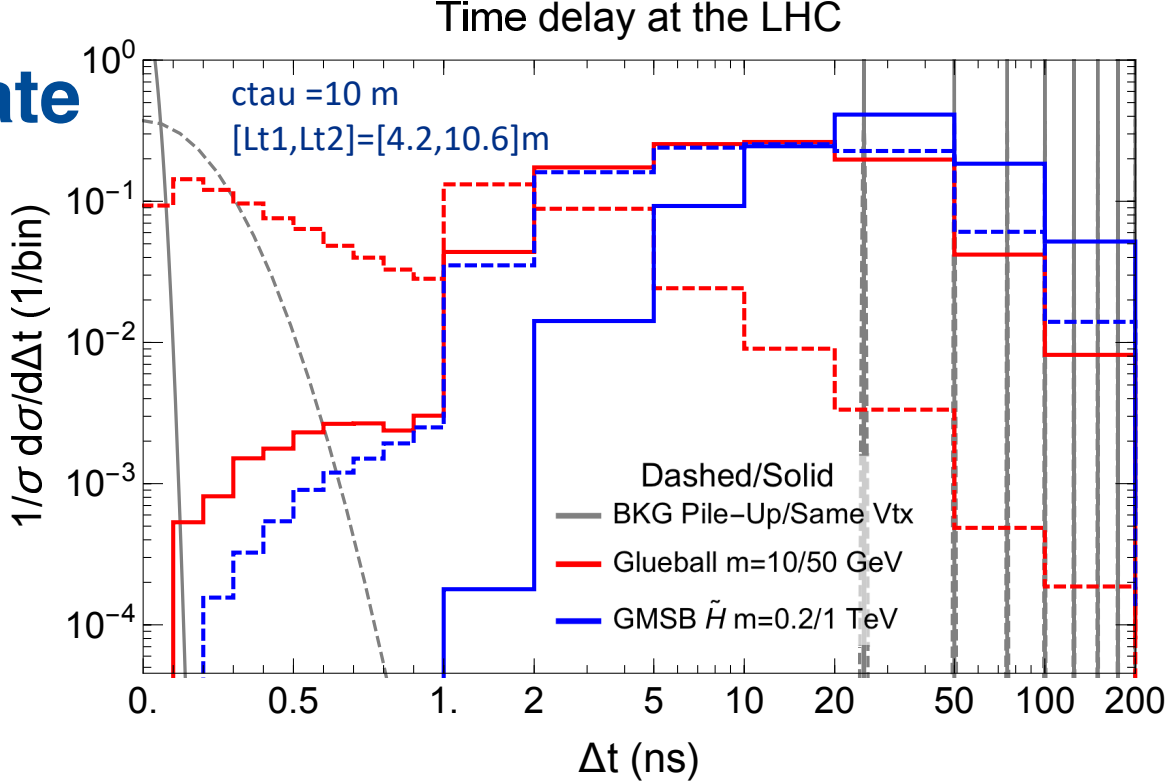

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Backgrounds:

- Gray (Dashed): Pile-up with natural spread of 190 ps (beam property)
- Gray (Solid): Hard collision spread due to uncertainties in timing

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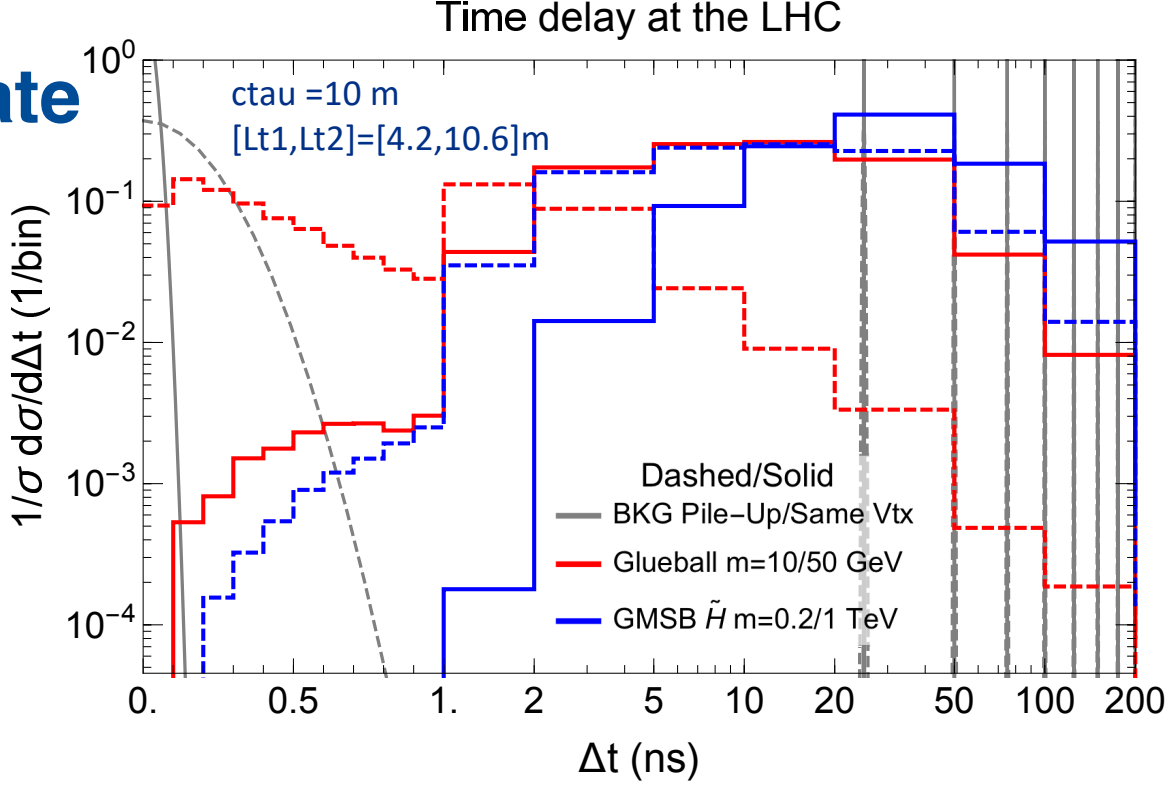

Other backgrounds:

- Interaction with material
- Cosmic rays
- Beam halo

…

All have mature veto mechanism; need to revisit to see the impact of timing

Late comers will be spotted easily:

	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}	[11]
MS	10.6 m	4.2 m	MS RoI	0.25, 0.5	0.25	10^{-7}	[20]

CMS timing module

ATLAS MS LLP search (without timing)

Designed 2 generic search: no restriction on the signal, as long as they can deposit energy (30 GeV pT min)*

Multijet and pile-up background can be effectively rejected use timing*

*challenges will be discussed later, let's first see the potential

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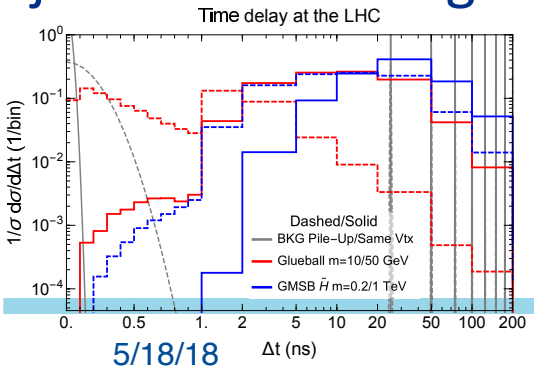

Same-vertex hard scattering background, time spread 30 ps (precision timing)

$$\text{EC}: \quad N^{\text{SV}}_{\text{bkg}} = \sigma^{\text{multi}}_{\text{j}} \mathcal{L}_{\text{int}} \epsilon_{\text{trig}} \epsilon^{j}_{\text{fake}} \approx 5.6 \times 10^{9}$$

$$\text{MS}: \quad N^{\text{SV}}_{\text{bkg}} = \sigma^{\text{multi}}_{\text{j}} \mathcal{L}_{\text{int}} \epsilon_{\text{trig}} \epsilon^{j}_{\text{fake}} \approx 2.8 \times 10^{5}$$

Pile-Up background, time spread 190 ps (beam property)

$$\text{EC}: \quad N^{\text{PU}}_{\text{bkg}} = \sigma_{\text{j}} \mathcal{L}_{\text{int}} \epsilon_{\text{trig}} \left(\bar{n}_{\text{PU}} \frac{\sigma_{\text{j}}}{\sigma_{\text{inc}}} \epsilon_{\text{fake}} f^{j}_{\text{nt}} \right) \approx 2.6 \times 10^{4},$$

$$\text{MS}: \quad N^{\text{PU}}_{\text{bkg}} = \sigma_{\text{j}} \mathcal{L}_{\text{int}} \epsilon_{\text{trig}} \left(\bar{n}_{\text{PU}} \frac{\sigma_{\text{j}}}{\sigma_{\text{inc}}} \epsilon_{\text{fake}} f^{j}_{\text{nt}} \right) \approx 1.3, \qquad (5)$$

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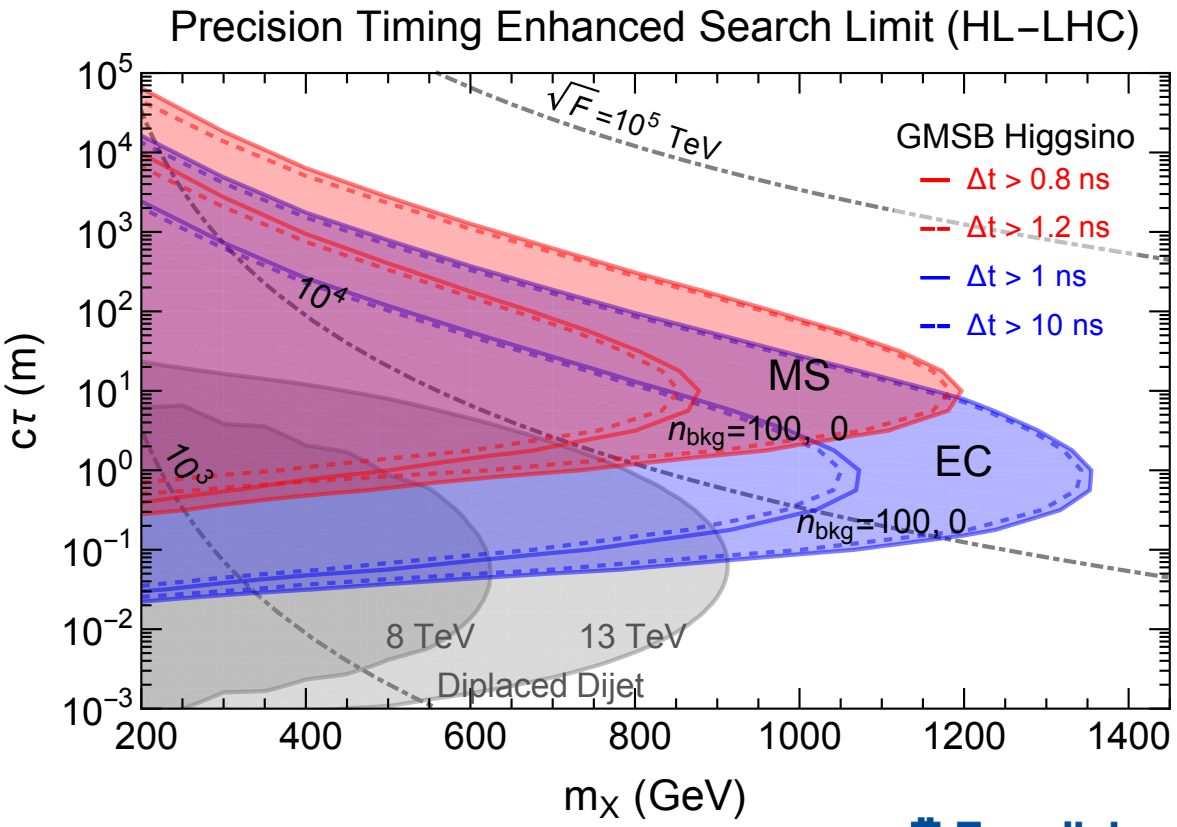
CMS timing module

ATLAS MS LLP search

(without timing)

- EC: >0.8 ns or >1.2 ns timing cut (<25 ns always there)
- MS: 1 ns or 10 ns timing cut (0.2 ns or 2 ns resolution sufficient)
- Significant improvement!
- Little difference for signal as they are very slow
- large tolerance room if background non-gaussian;



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For comprehensive 8 TeV analysis, see **ZL**, B. Tweedie **1503.05923**

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CMS timing module

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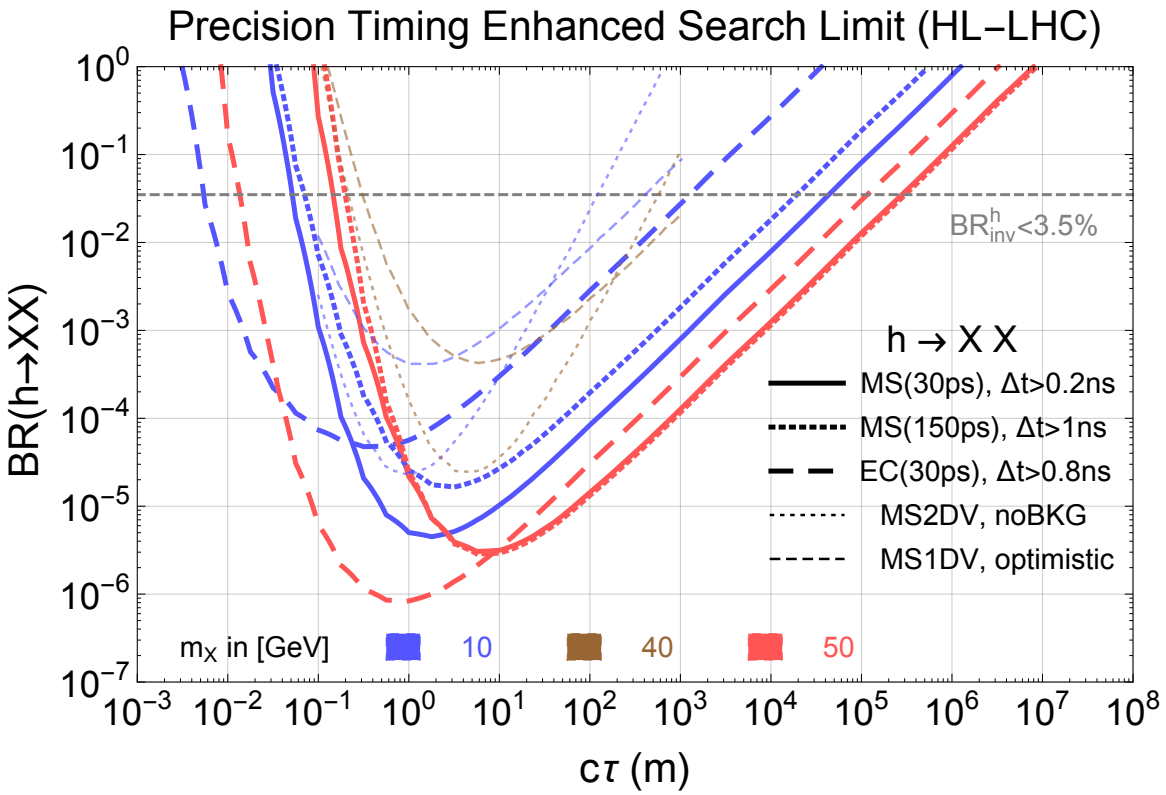
- EC: >0.8 ns timing cut (<25 ns always there)
- MS: 0.2 ns or 1 ns timing cut (30 ps or 0.2 ns resolution sufficient)
- Significant improvement!
- 10 GeV benchmark point sensitive to the timing cut, as they are more boosted and having less time delay.



8 TeV results from C. Csaki, E. Kuflik, S. Lombardo, O. Slone, 1508.01522

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

Challenges (opportunities)

- Timing reducing background to 10^-10 level. 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); Would be an interesting SM property measurement;
- For EC search, timing layer will be there. Delayed jet (anything) trigger would require non-trivial effort to realize, low+high level with jet ROI; Once realized, could be universal boost to LLPs at the LHC!
- For MS search, a feasibility study on new timing layer options like this, balancing technology, design, cost, and physics goals would be a natural future step. As we have shown, except for the light LLP (~10 GeV), the large delay does not require 10s ps timing precision. Sub (even) nanosecond for the MS is sufficient;
- There are many more handles on the signal selection and background rejection can be used;

Summary and outlook

- LHC great detector for LLP searches, a rich program is still under development;

- All traditional LLP searches could be augmented by the timing information (re-optimization);
- We consider two benchmark new searches: one is ECal based with delayed jet trigger, one is MS based with new timing layer;
- New searches can capture general features of the LLP in a very robust way by exploiting their delayed feature;

- **Precision timing is a new dimension of particle physics information available for BSM searches**

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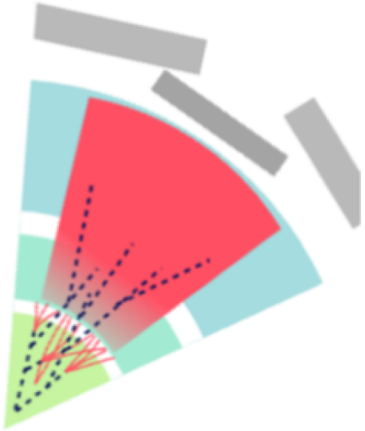
Thank you!

Backup

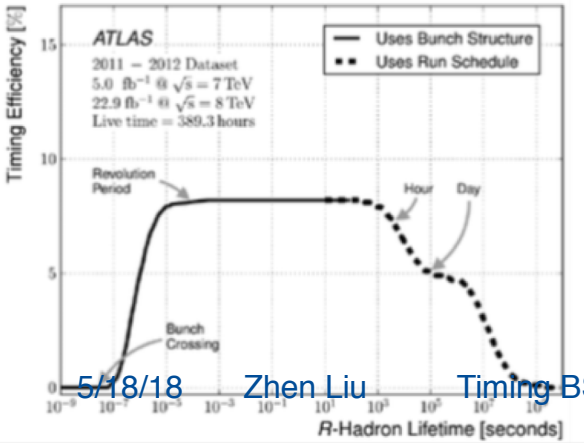
LLPs decaying to hadrons:

- signature could be displaced multi-track vertex
  + resolved jets (CMS, LHCb), or single boosted jet (ATLAS)
- a jet with no tracks & low EMF
  - ATLAS can trigger on this signature
- multi-track vertex in the muon system



Emerging jets

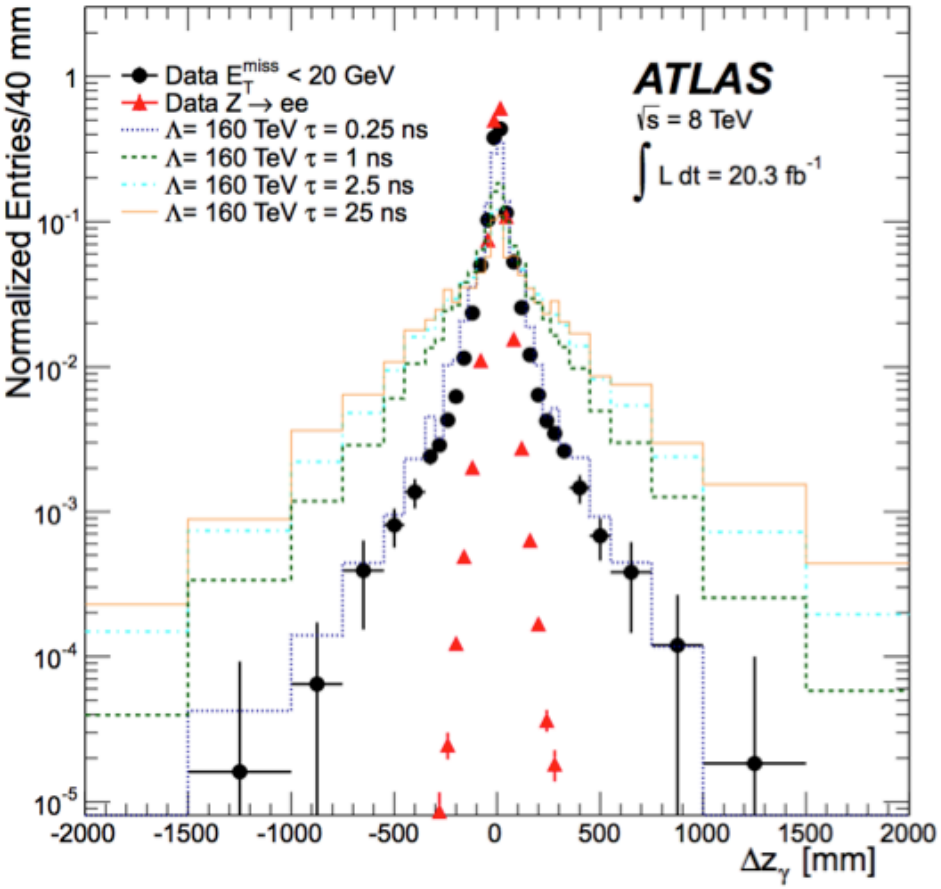
- multiple displaced vertices

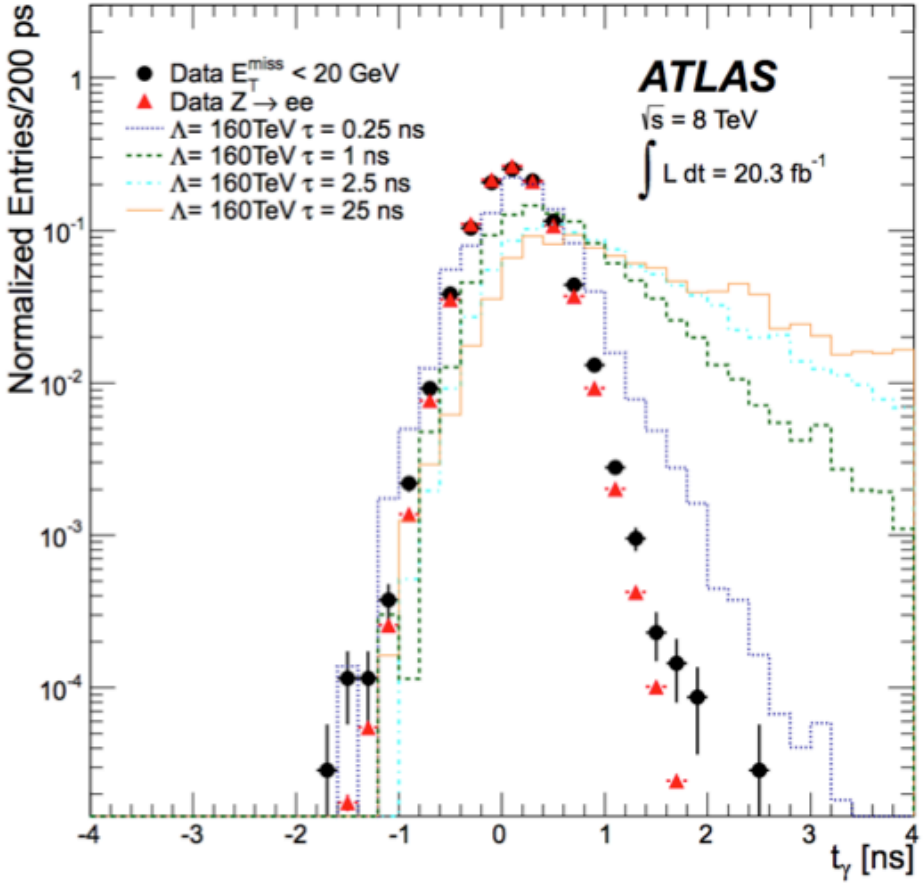


(very) late decays in the calorimeter

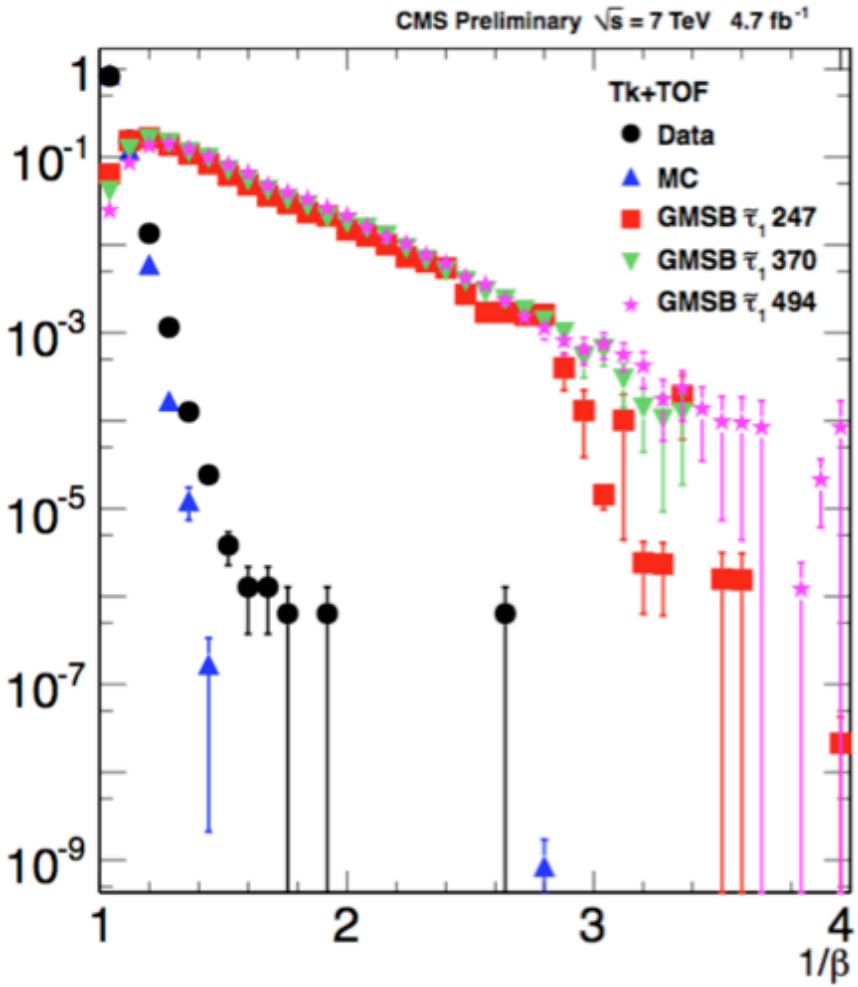
- ATLAS and CMS look for jets in empty bunch crossings (neither beam in the detector)

ATLAS non-pointing photon





CMS Heavy stable charged particle (HSCP) track+ToF



MS Volume

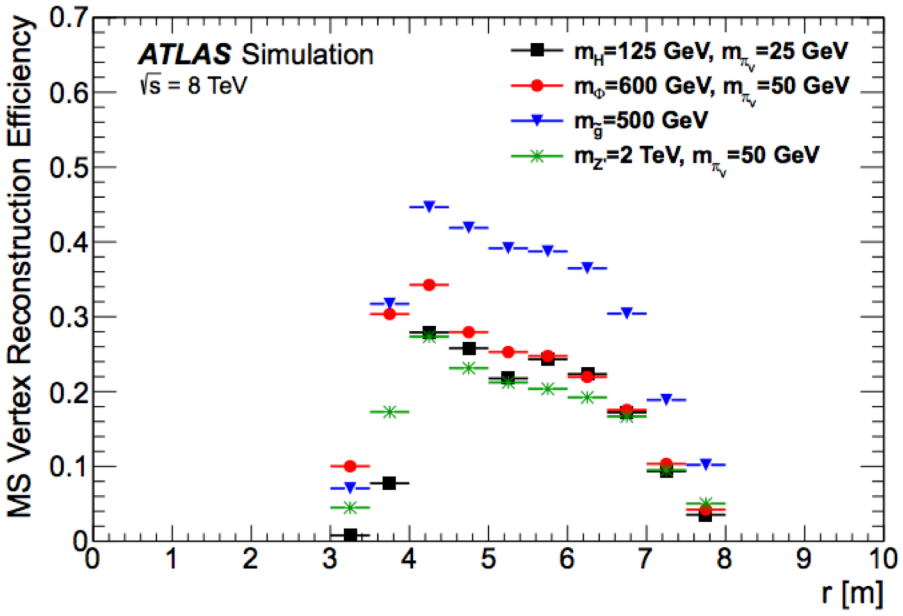


FIG. 7. Barrel MS vertex reconstruction efficiency as a function of the radial decay position of the long-lived particle for scalar boson, Stealth SUSY, and Z' benchmark samples.

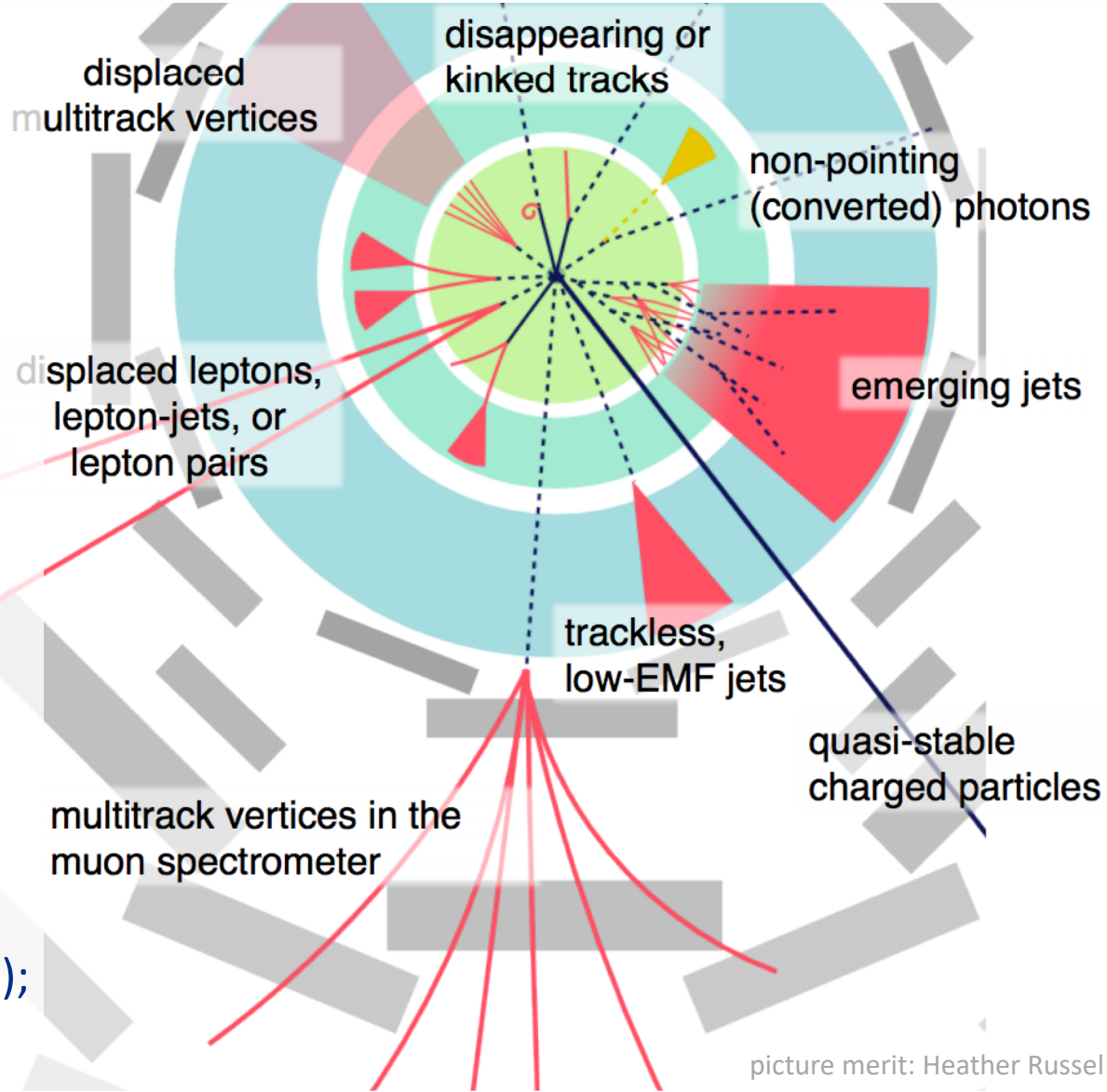
- Effective decay volume 4-7 m 4-10 m.
- New layer and upgrades might relax/extend the MS Vertexing length.
- We took the full volume in our study.
- If stick to 4-7 m, the efficiency will reduce by roughly a factor of 2.

Long-lived particles

current status and challenges also mentioned in many other talks in this workshop

These nonconventional and rich BSM signatures receives a lot of attention as:

- Theoretically well motivated: SUSY (RPV, GMSB, Split, compressed, etc.), neutral naturalness, hidden valley, dark shower… etc;
- Experimentally challenging but bearing great potential for discovery:
  - New signatures could have been missed by conventional searches;
  - Low (zero) background analysis once carried out);



picture merit: Heather Russel