The 4th NPKI Workshop, "Searching for New Physics on the Horizon"

New Ideas and Opportunities for Long-Lived Particles

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May.14th 2019

What is LLP?

Long-lived particles in the standard model:

- approximate symmetries;
- kinematic suppressions;

For BSM particles:

- Prompt particles being actively probed;
- Detector Stable particles are probed as missing energy or EM charged stable particles.

First pixel layer (first layer of detector)

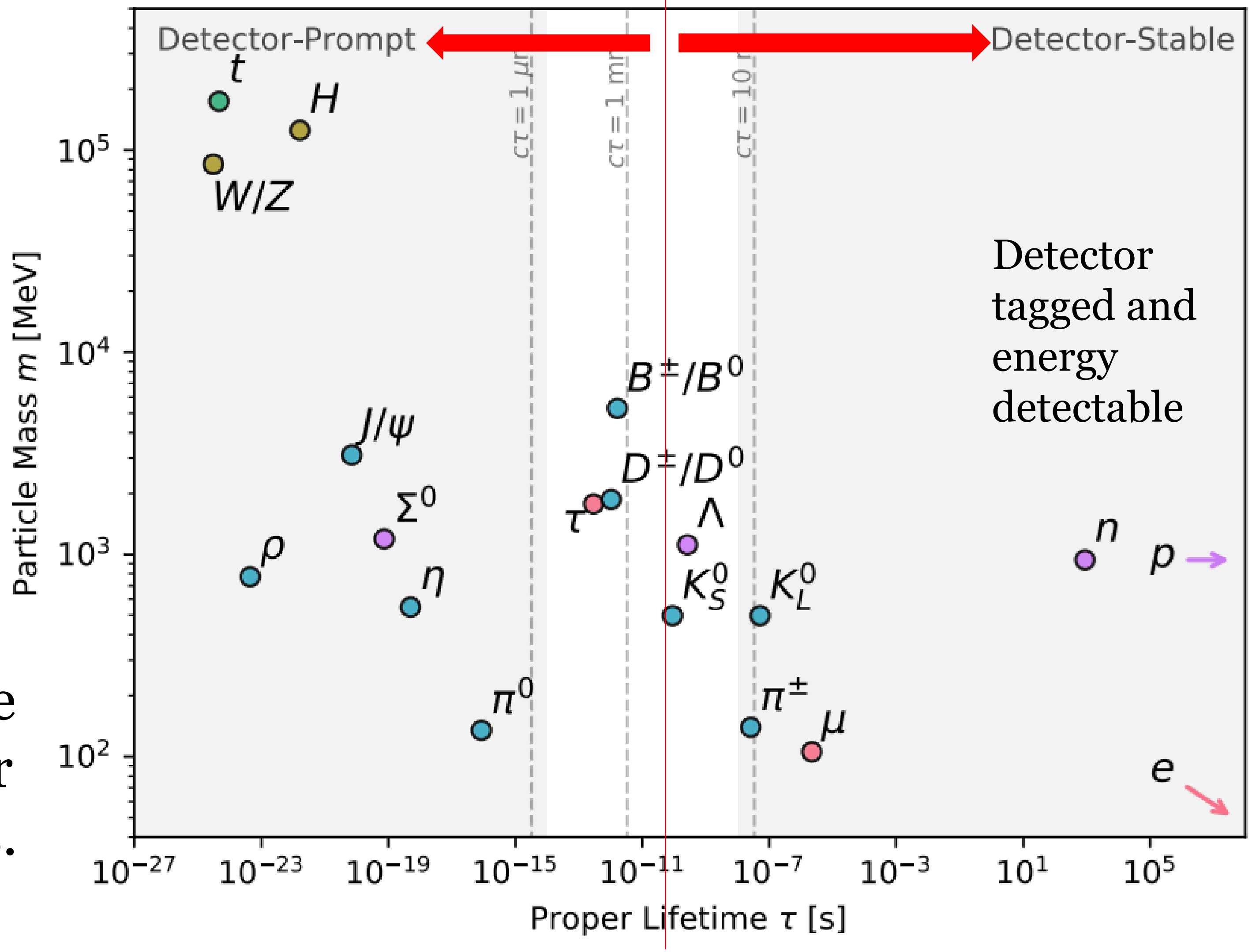
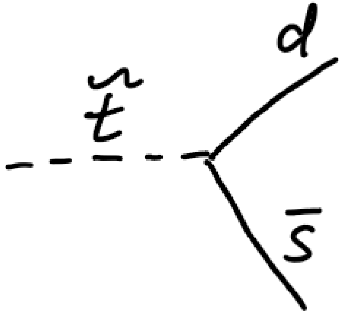


Fig. credit: L. Lee @ ATLAS

Why Long-Lived BSM Particles? Supersymmetry

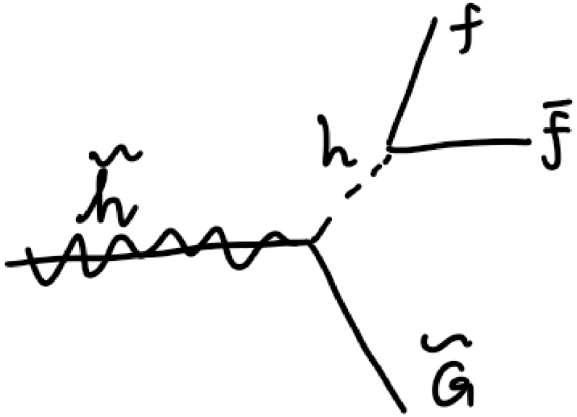
- R-Parity-Violating, small B/L-violating couplings

$$c\tau_{RPV} \sim 1 \text{ m} \left(\frac{100 \text{ GeV}}{\widetilde{m}}\right)\left(\frac{10^{-8}}{\lambda_{RPV}}\right)^2$$



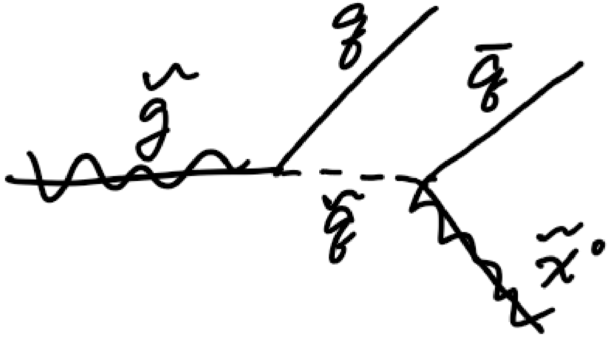
- Gauge mediation—suppressed couplings via SUSY breaking scale

$$c\tau_{\text{GMSB}} \sim 10 \text{ m} \left(\frac{100 \text{ GeV}}{\widetilde{m}}\right)^5\left(\frac{\sqrt{F}}{100 \text{ TeV}}\right)^4$$

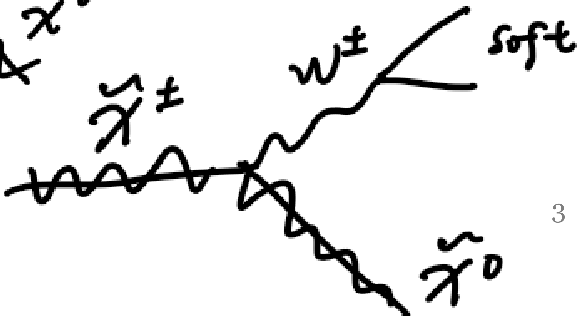


- Mini-split spectrum—suppressed couplings through "decoupled" heavy particles

$$c\tau_{\text{milli-split}} \sim 1 \text{ mm} \left(\frac{\text{TeV}}{m_{\tilde{g}}}\right)^5\left(\frac{m_{\tilde{q}}}{\text{PeV}}\right)^4$$



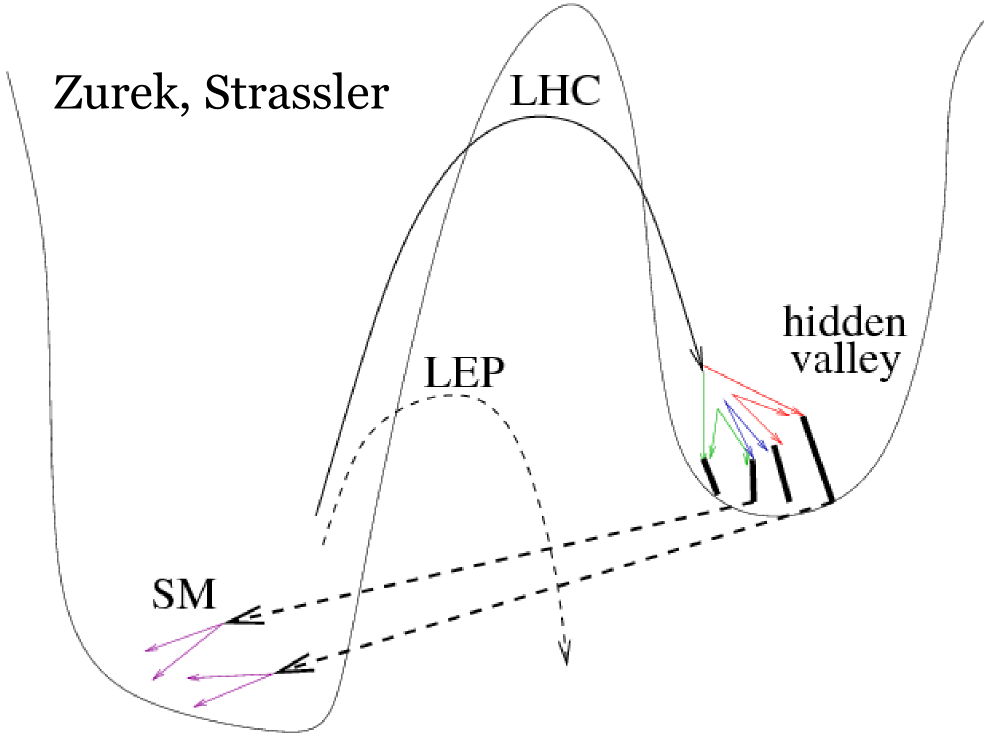
- Pure Wino/Higgsino–nearly degenerated, disappearing track

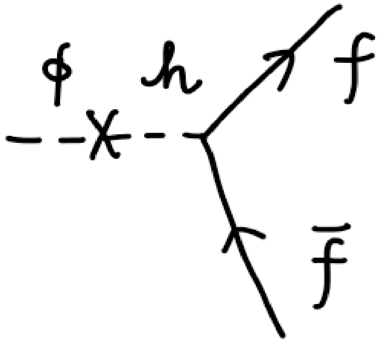


Why Long-Lived BSM Particles? Hidden Valley

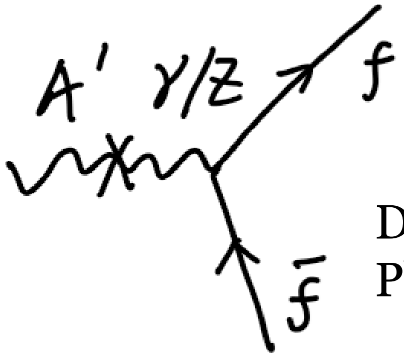
Hidden sector feeble couplings to SM via various portals, suppressed by the smallness of the couplings

Zurek, Strassler

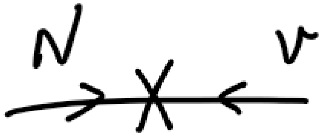




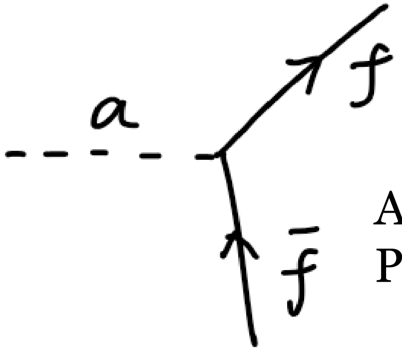
Higgs portal



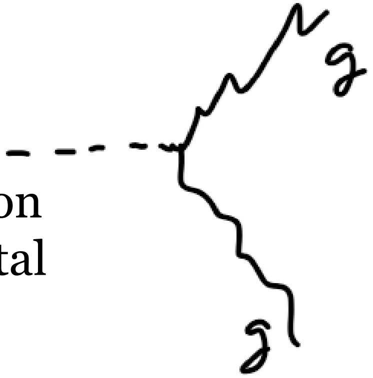
Dark Photon/Z



Neutrino Portal



Axion Portal



LLP: A rich & challenging program

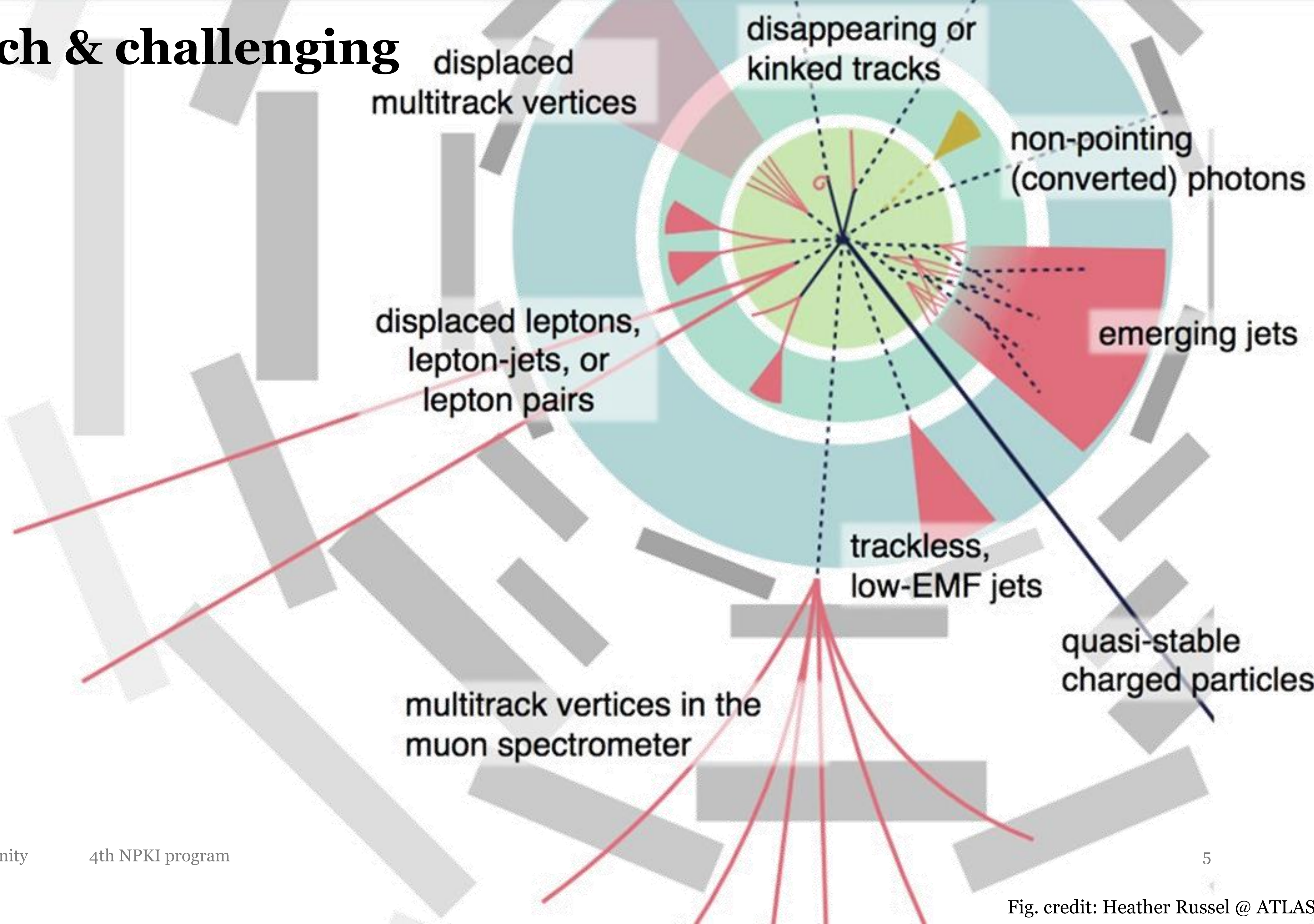


Fig. credit: Heather Russel @ ATLAS

LLP: A rich & challenging program

LHC detectors designed for prompt signals.
For Long-Lived Particles (LLPs):

☹trigger
☹reconstruction
☹non-standard background
☺standard model background

Huge uncharted well-motivated territories to explore!

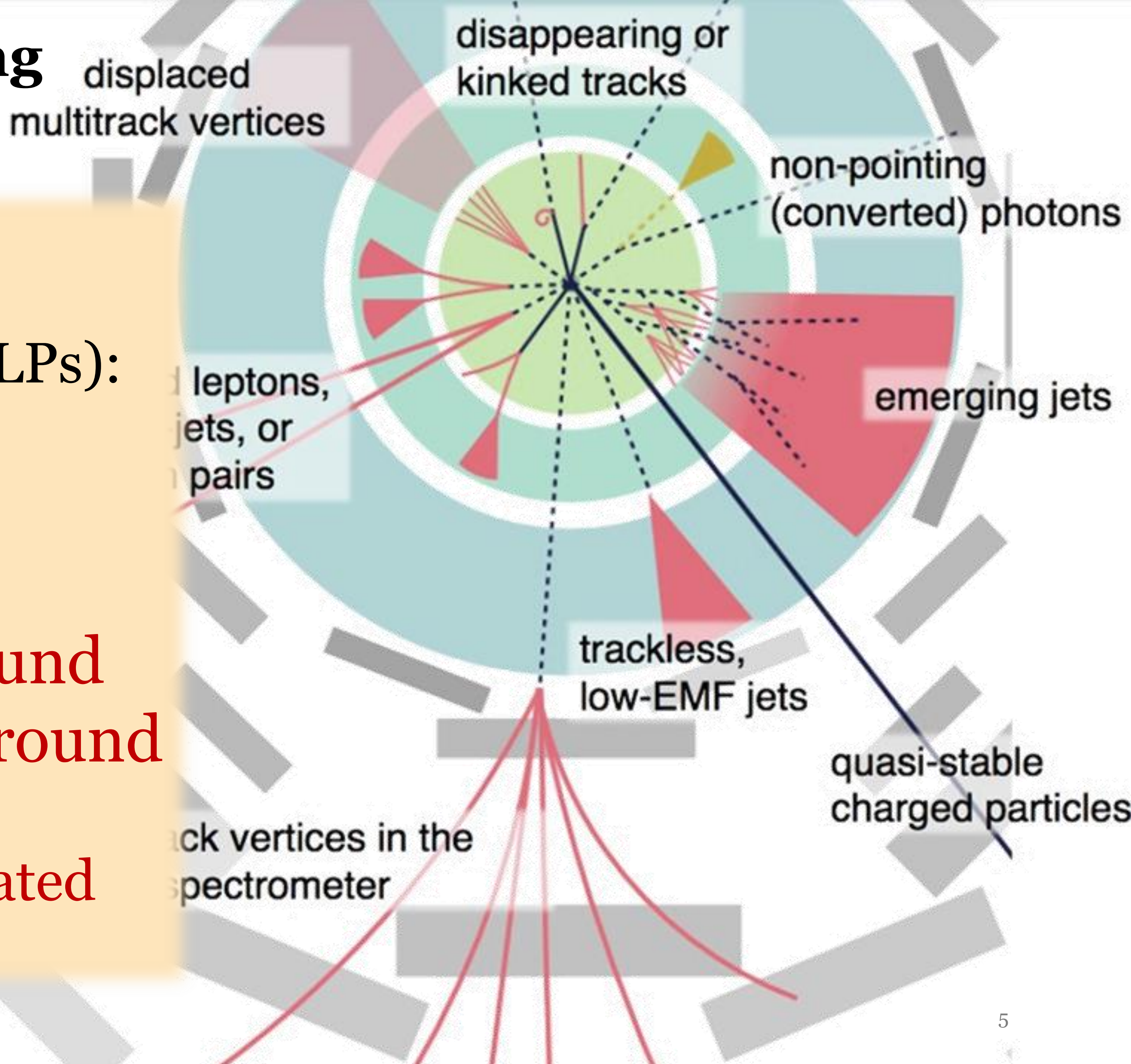
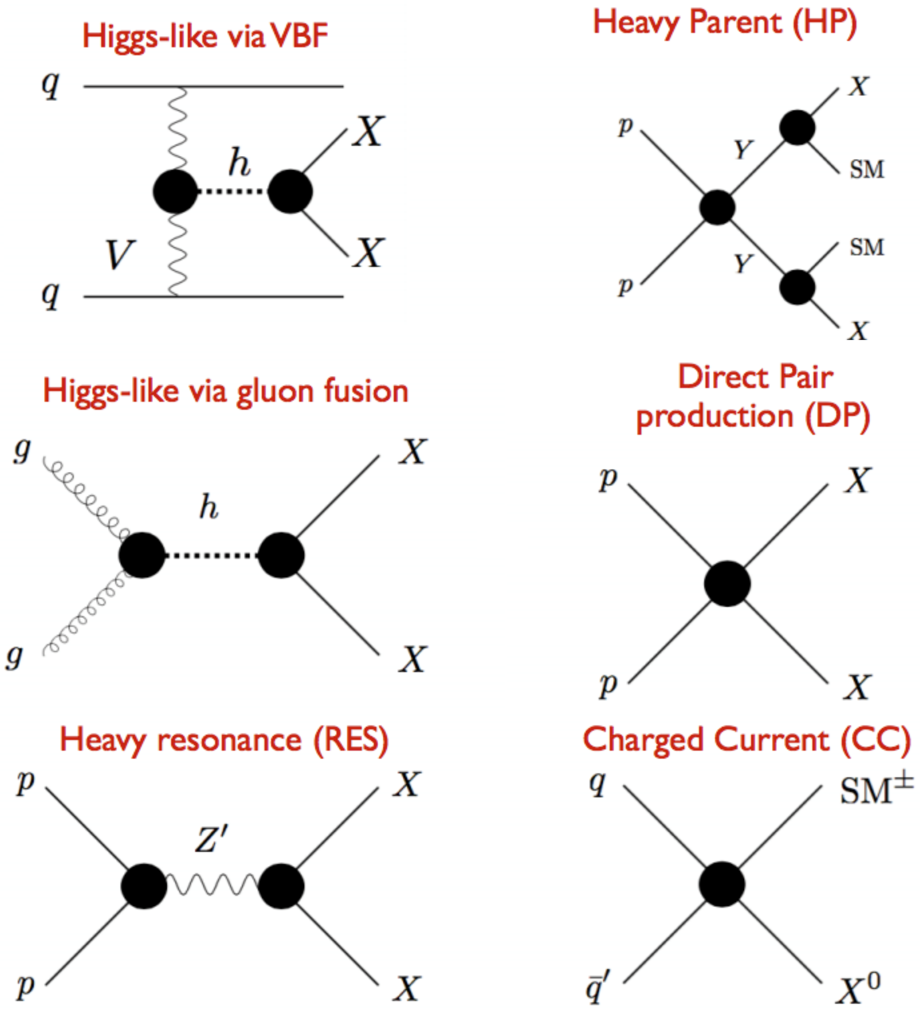


Fig. credit: Heather Russel @ ATLAS

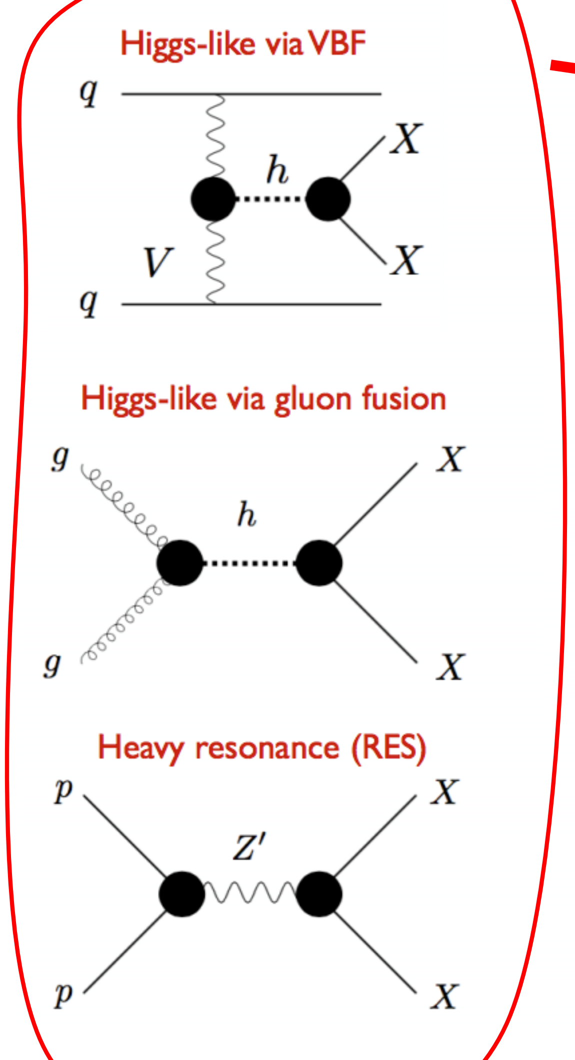
LLP: A rich & challenging program

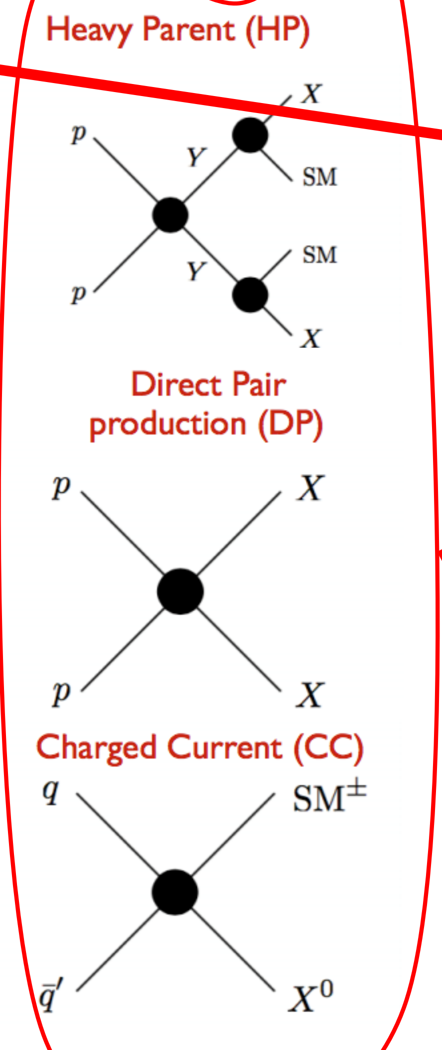


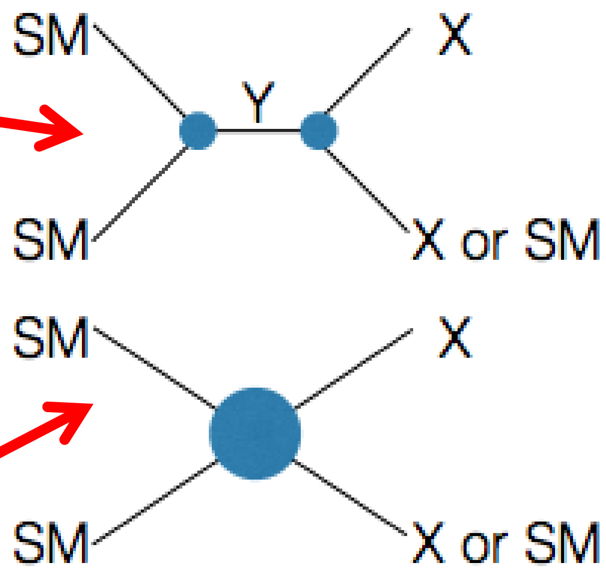
LLP community report
[1903.04497](https://arxiv.org/abs/1903.04497)

- Factorize production and decay;
- Production affects kinematics of LLP and trigger consideration (except for LLP triggers, which are rare currently);
- Decay affects search strategy in picking up the LLPs, convoluting with lab frame geometries;

LLP: A rich & challenging program







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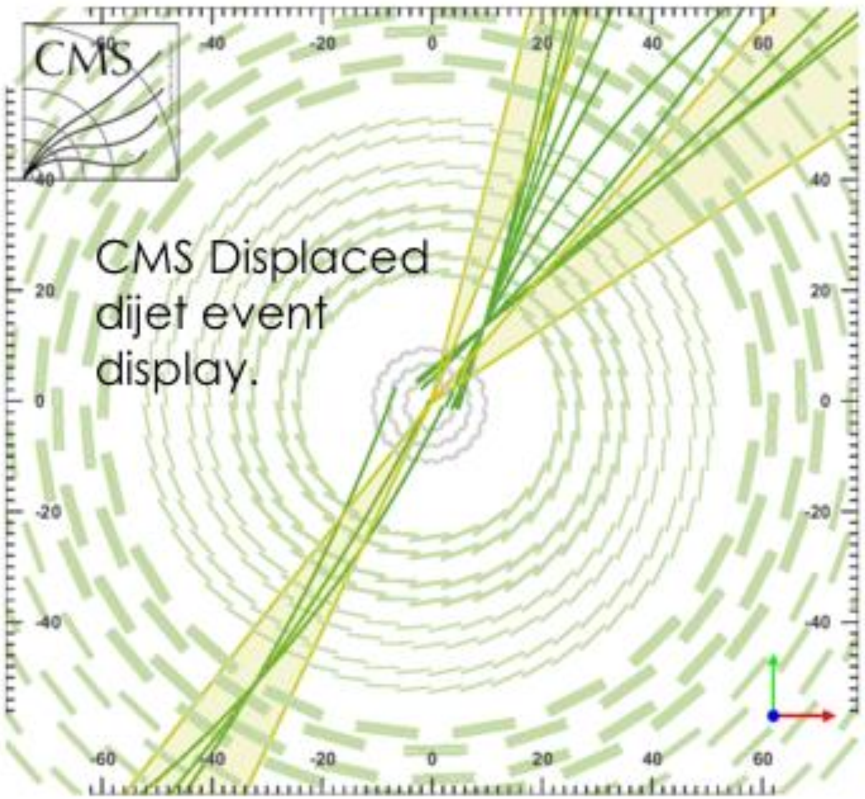
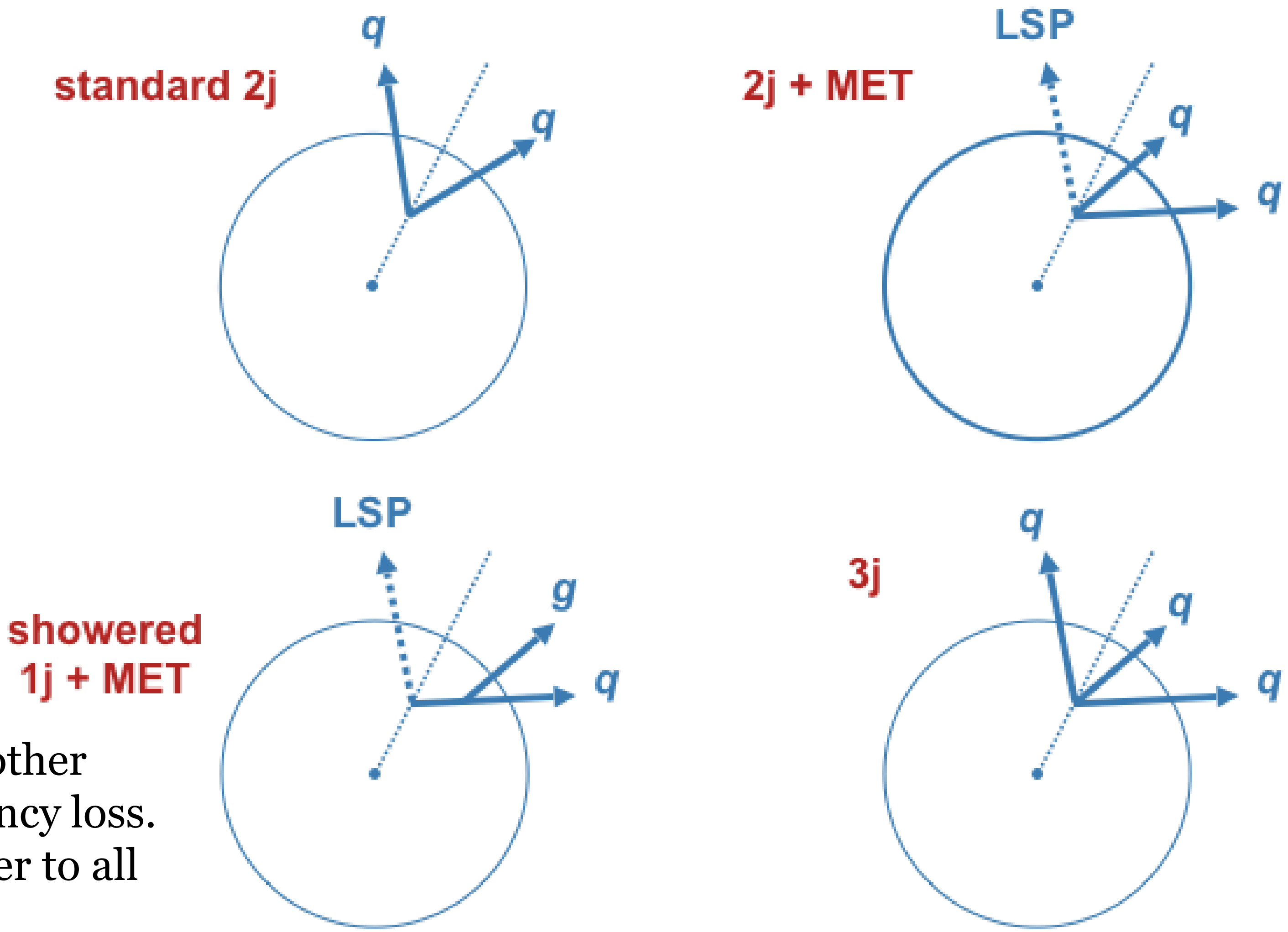
LHC coverage enlarged: CMS Dijet





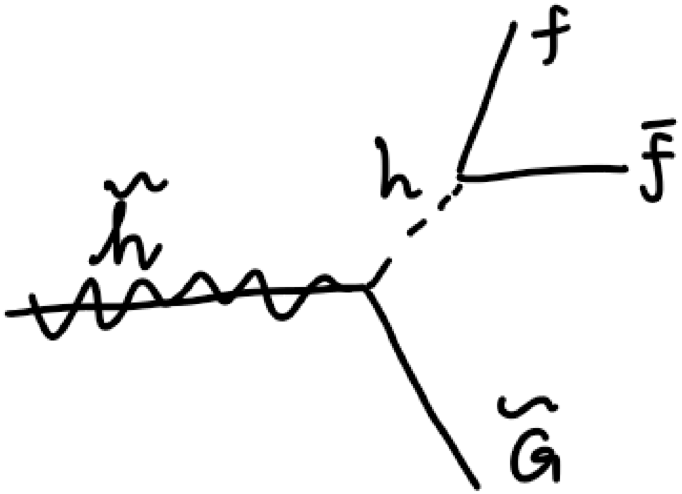
- LLP searches usually are also sensitive to other decay topologies without/with little efficiency loss.
- We emphasis this point and show the power to all SUSY LLPs in our study.

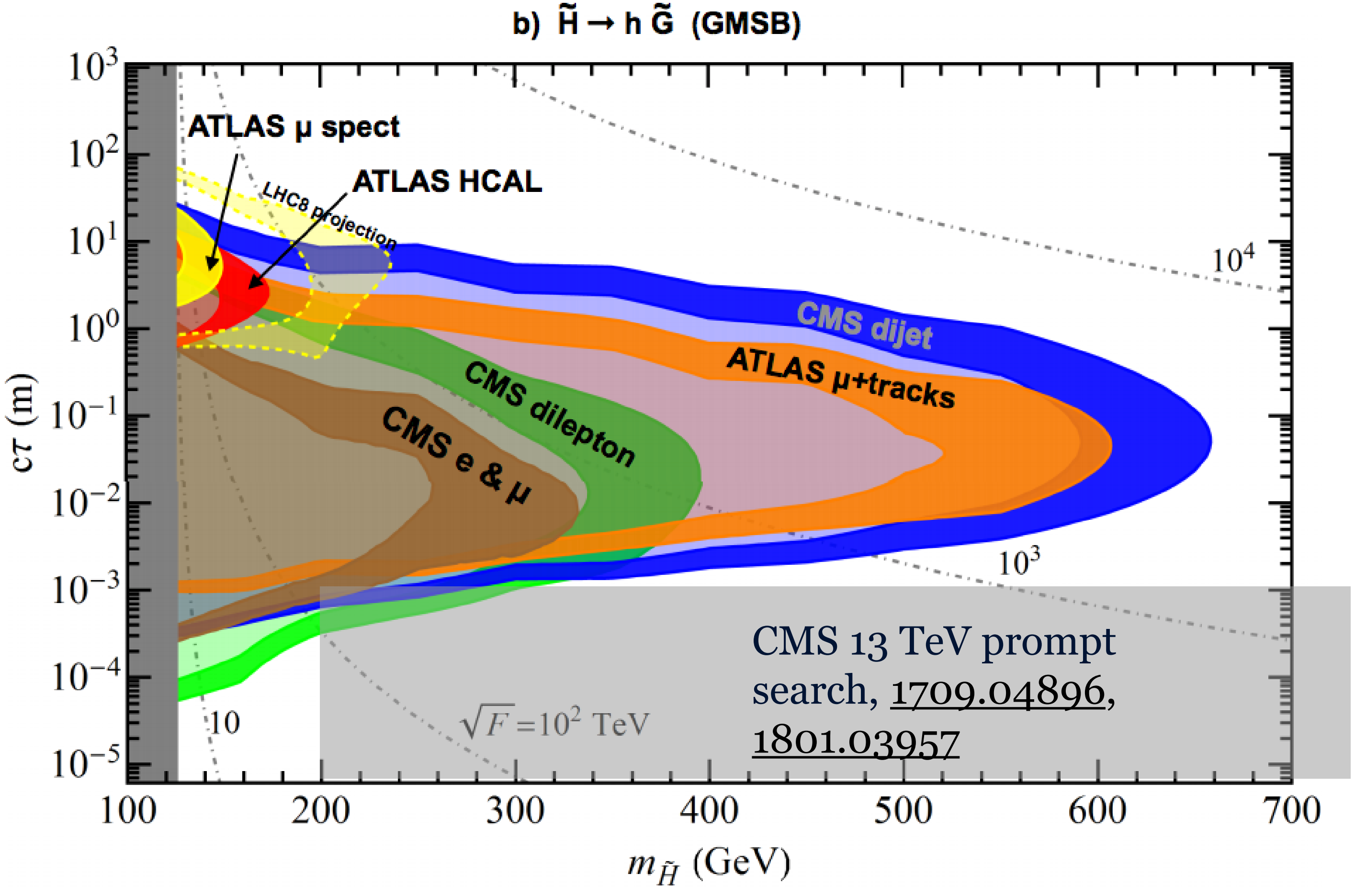
ZL, B.Tweedie, 1503.05923

Gauge Mediated SUSY Breaking (Higgsino)

GMSB Higgsino ➞ Higgs + Gravitino

- Displaced searches (dijet, μ+tracks, $e + \mu$, HCAL, dilepton, μ spectrometer) covers mid-lifetime
- Very sensitive 13 TeV prompt searches cover short lifetime.

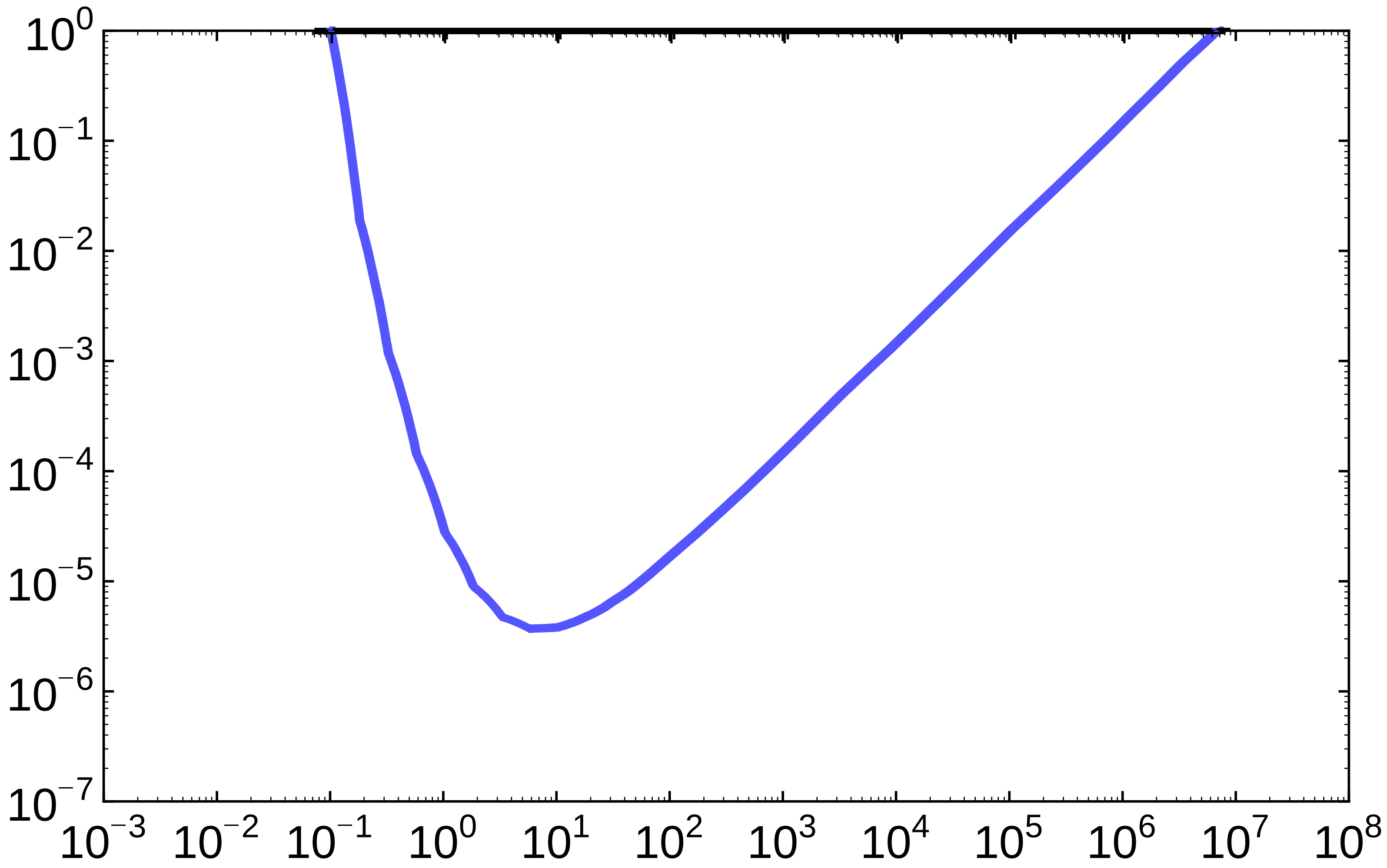




ZL, B.Tweedie, 1503.05923

Universal features of LLPs: a typical reach plot

Log scale in sensitivity in model parameters or observable rate (e.g., Br H->XX)



Better sensitivity

Log scale in proper lifetime

Universal features of LLPs: understanding shapes

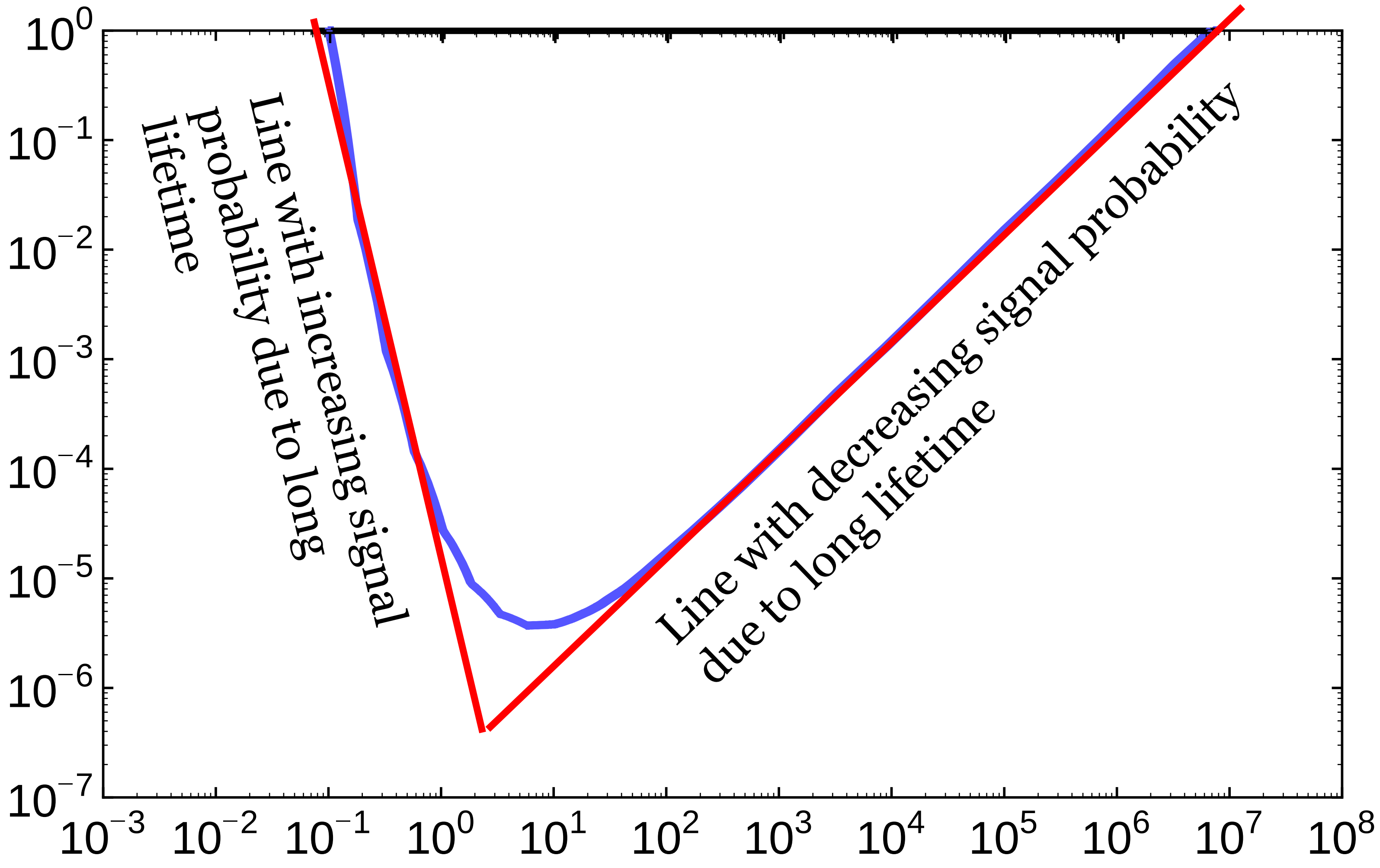
Log scale in sensitivity in model parameters or observable rate (e.g., Br H->XX)

Geometrical acceptance P_{in}

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

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

Better sensitivity



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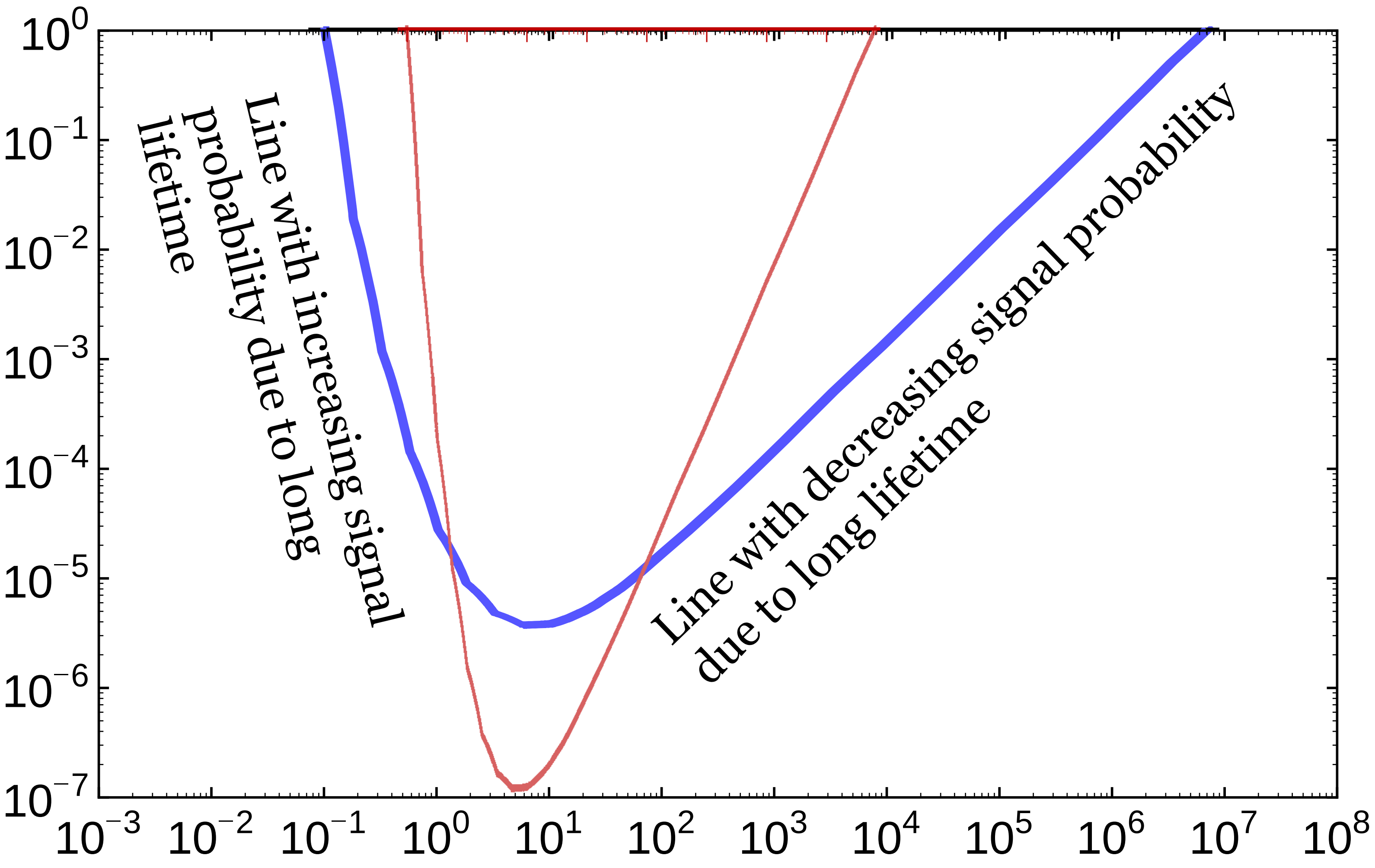
$$\approx \frac{\Delta\Omega}{4\pi} \; e^{-L_1/d} \; \frac{L_2 - L_1}{d}$$

$d = c\tau\gamma\beta$

Double LLPs: $P_{\rm in}^2$

Better sensitivity



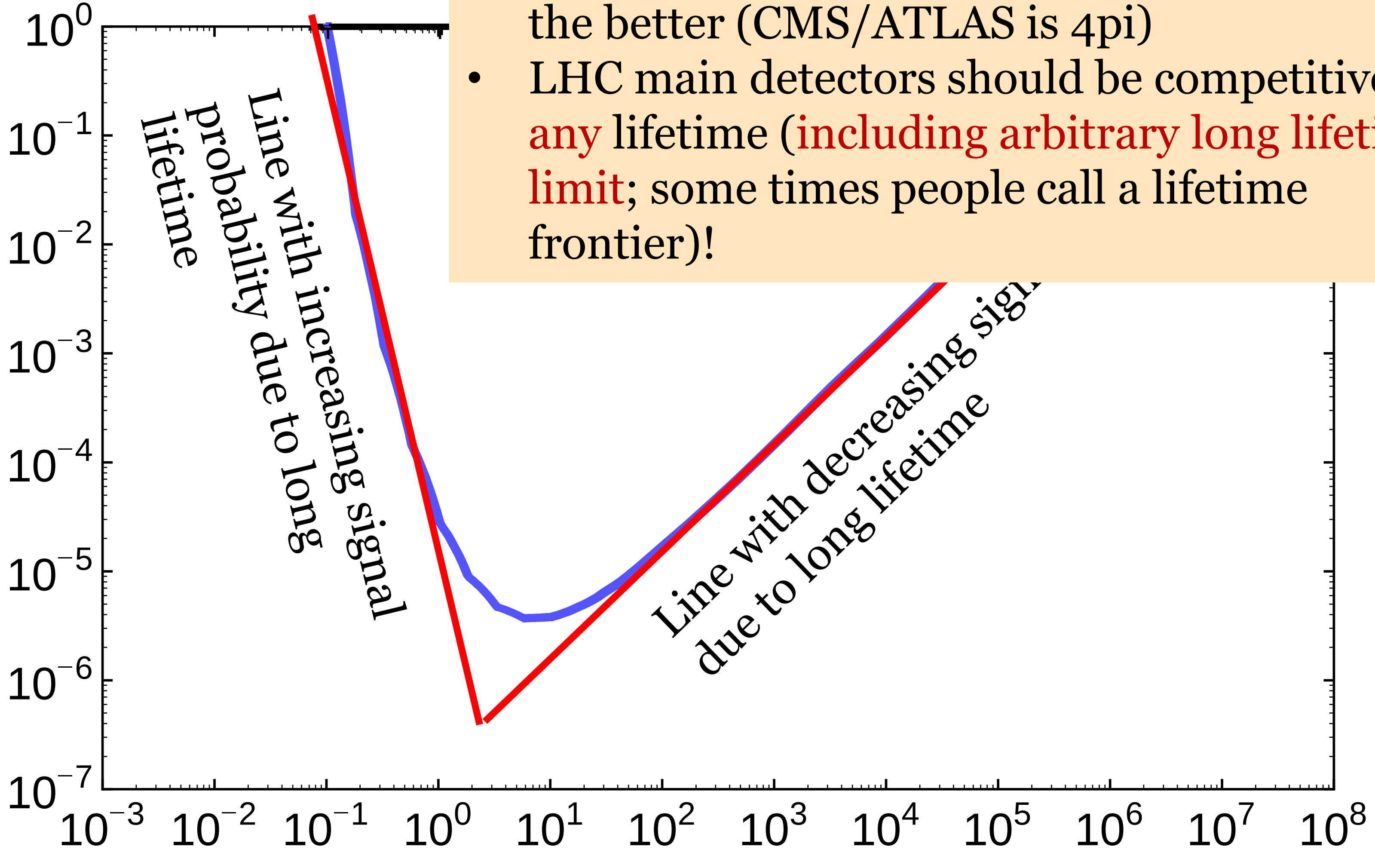
Log scale in proper lifetime

Countering one's intuition

- For short lifetime: the closer the better;
- For long lifetime: the larger decay volume the better (CMS/ATLAS is 6-10 m)
- For any lifetime: angular coverage the large the better (CMS/ATLAS is 4pi)
- LHC main detectors should be competitive in any lifetime (including arbitrary long lifetime limit; some times people call a lifetime frontier)!

Log scale in sensitivity in model parameters or observable rate (e.g., Br H->XX)

Better sensitivity

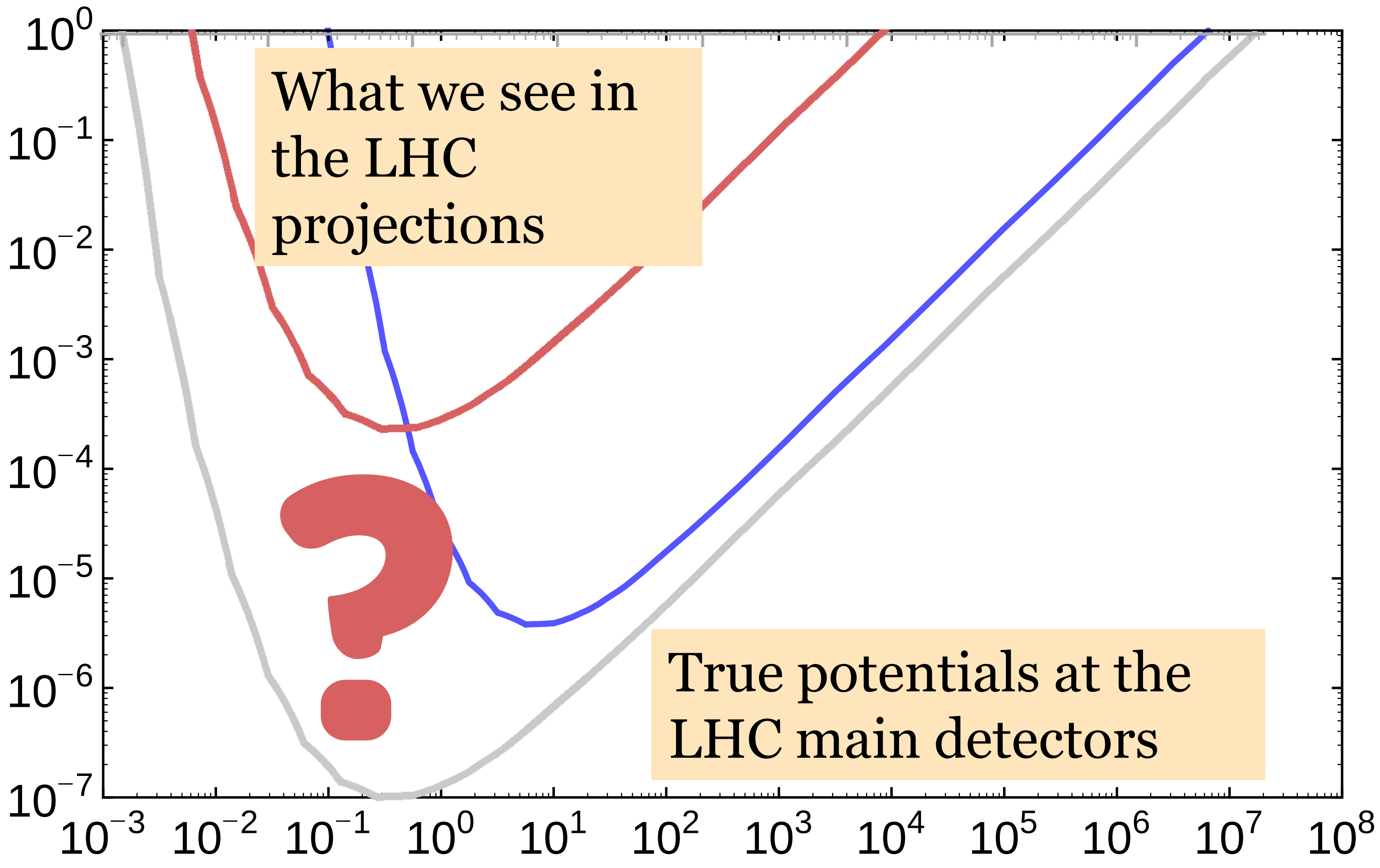


Log scale in proper lifetime

Rebuilding intuition: True Potential of main detectors

Log scale in sensitivity in model parameters or observable rate (e.g., Br H->XX)

Better sensitivity



Log scale in proper lifetime (m)

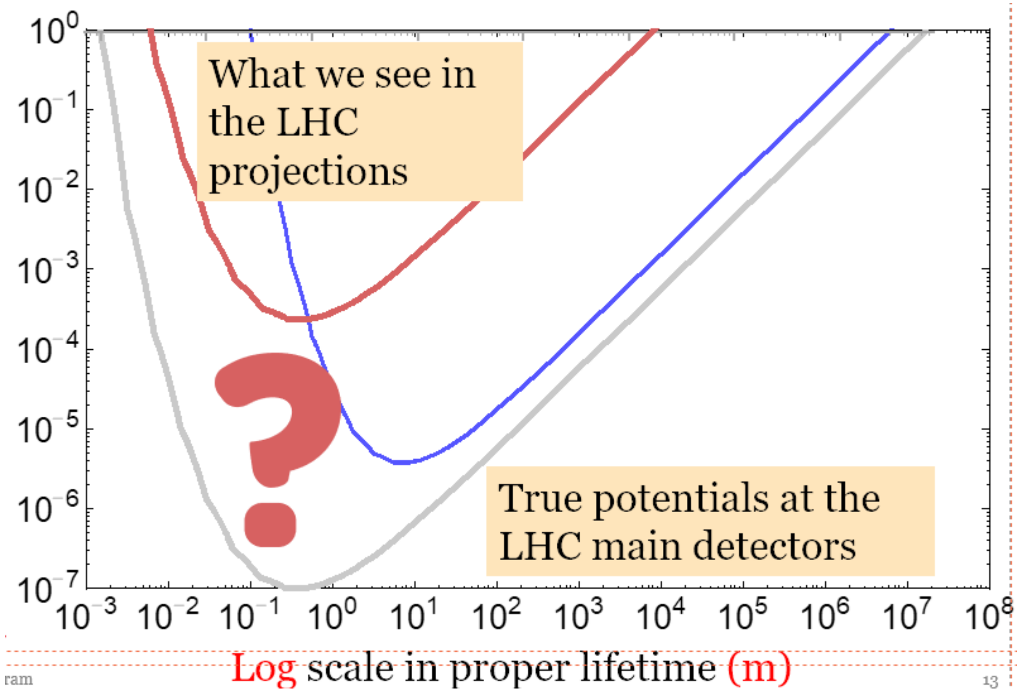
Reexamining intuition: Identifying the challenge

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

O(1%) 1-100%

20-50% for dedicated LLP trigger

Energy threshold, reconstruction efficiency, etc.



Reexamining intuition: Identifying the challenge

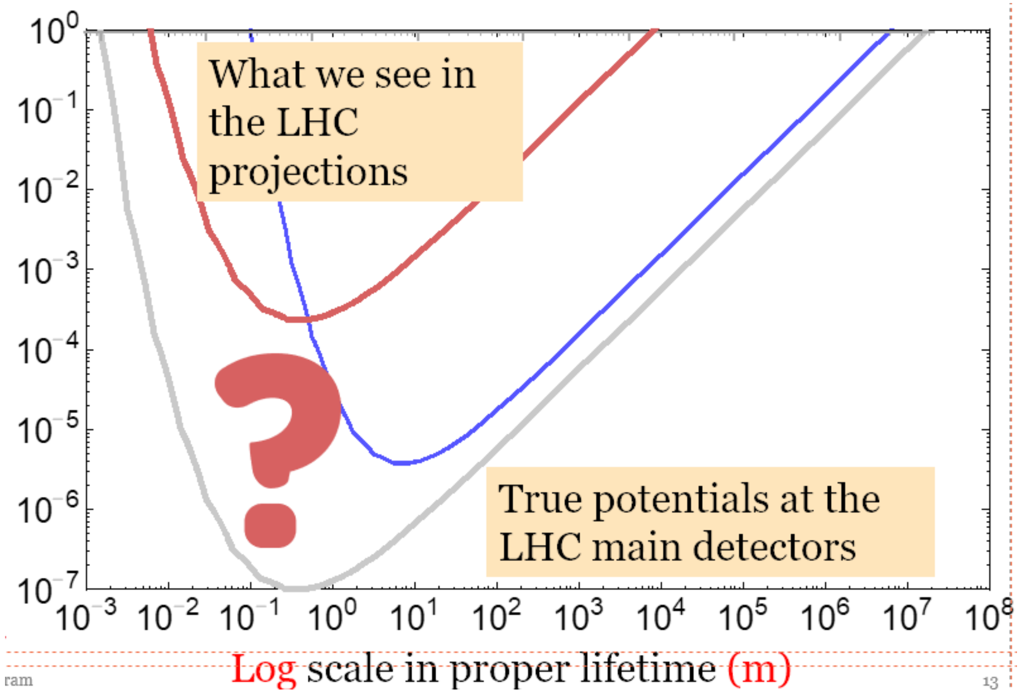
e.g.,
C. Csaki, E. Kuflik, S. Lombardo, O. Slone, 1508.01522 shows Higgs to LLPs typical trigger efficiency <1%;
ZL, B.Tweedie, 1503.05923, O(100 GeV) LLPs have typical efficiency ~1%;

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

O(1%) 1-100%

20-50% for dedicated LLP trigger

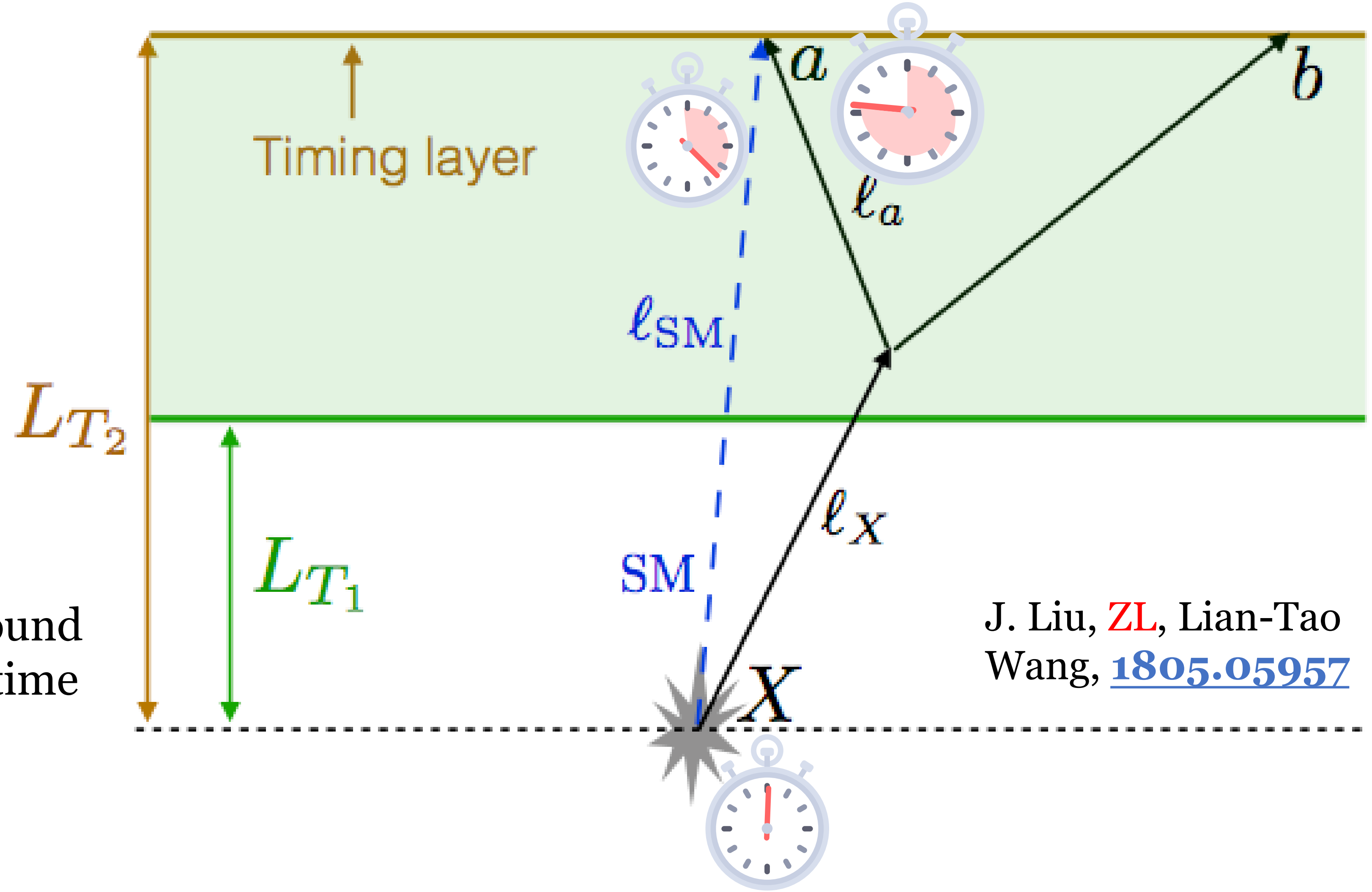
Energy threshold, reconstruction efficiency, etc.



Overcoming the difficulties: Timing LLPs

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

signal arrival time — background arrival time



J. Liu, ZL, Lian-Tao Wang, 1805.05957

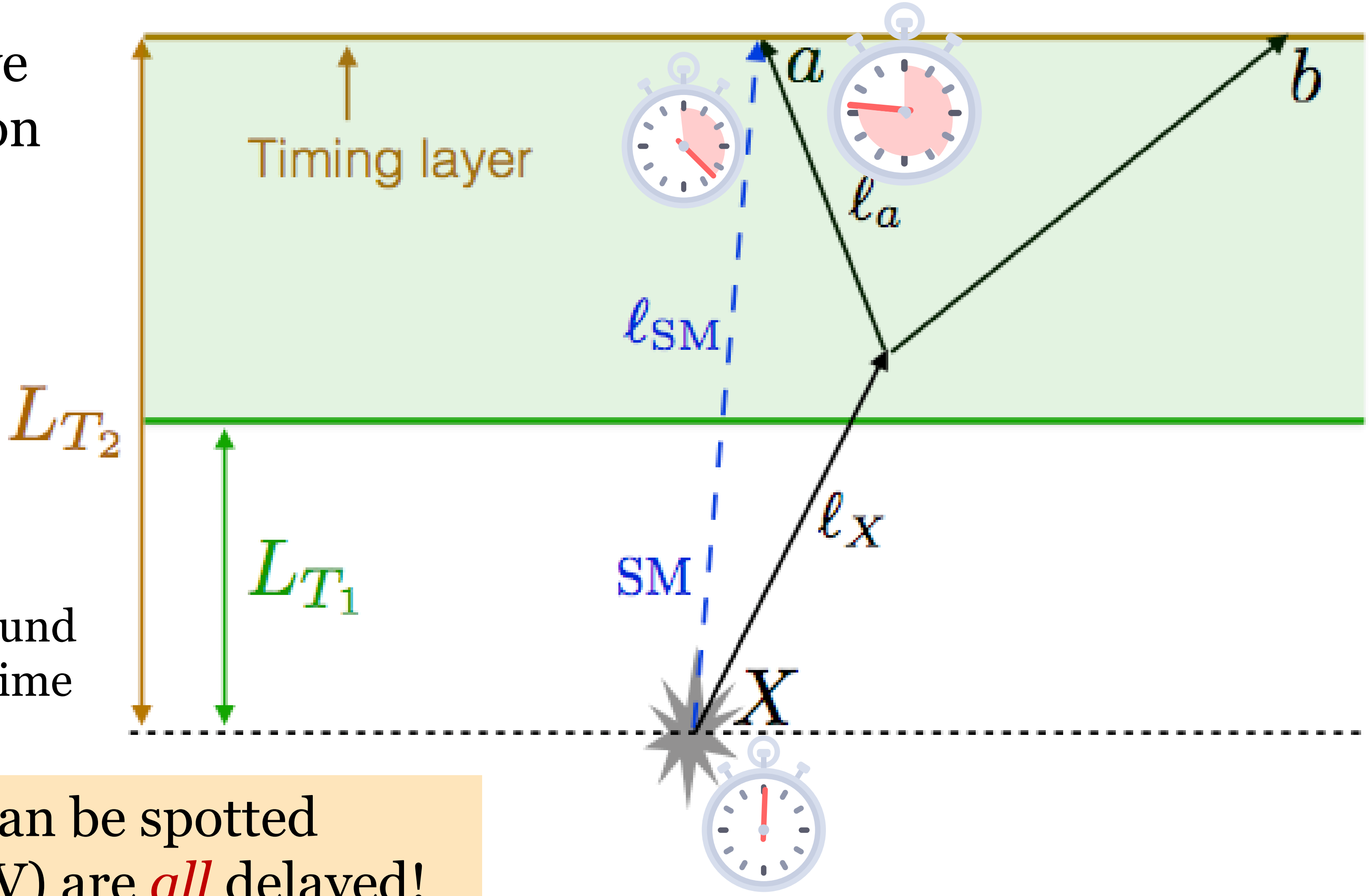
*for pseudorapidity 0; higher rapidity enlarges the timing difference;
*SM particles essentially all travel at speed of light;

Time-delay: universal feature of LLPs

ATLAS, CMS, LHCb all have upgrade plans with precision timing (mainly for pile-up suppression) of order ~30 picoseconds

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

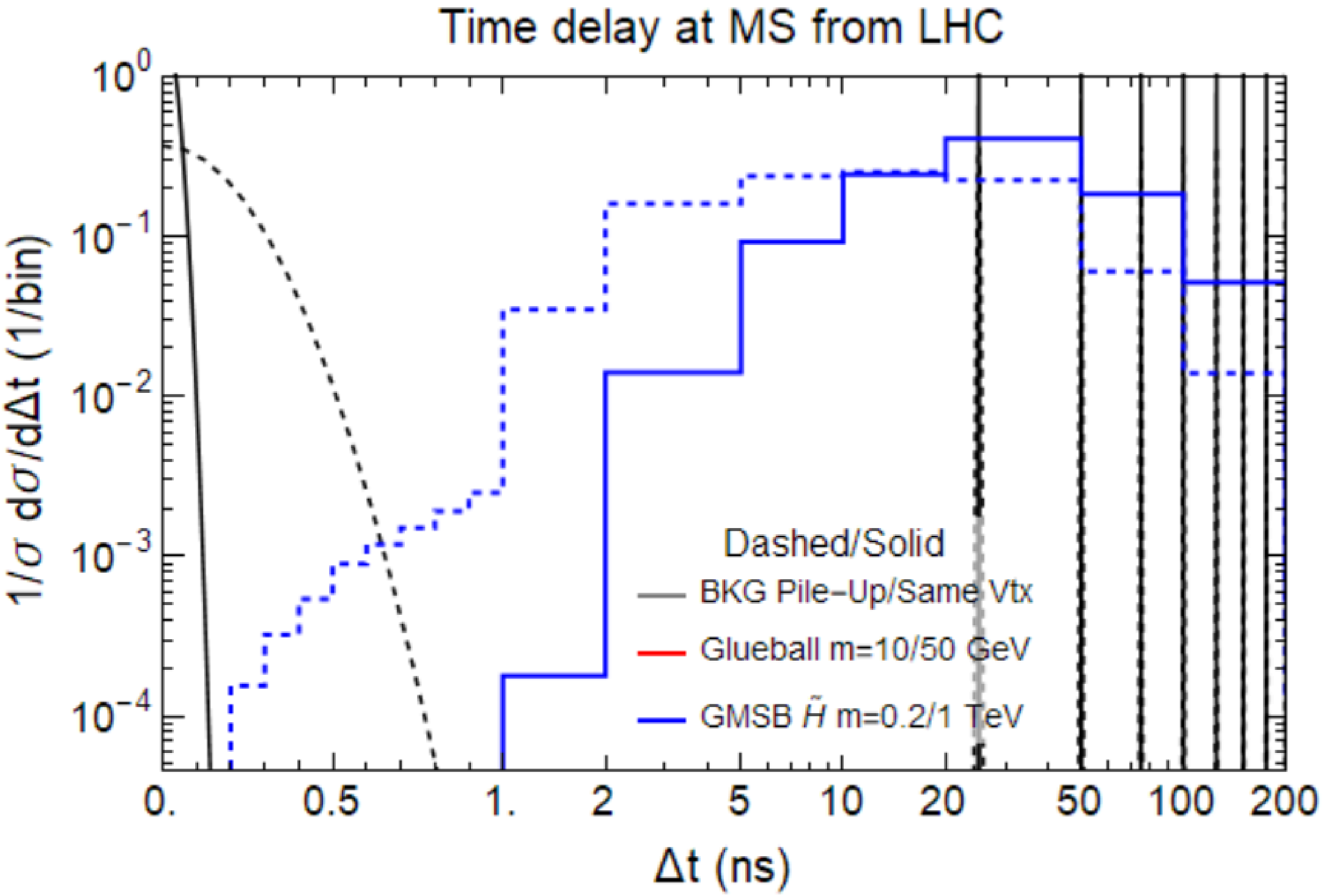
signal arrival time — background arrival time

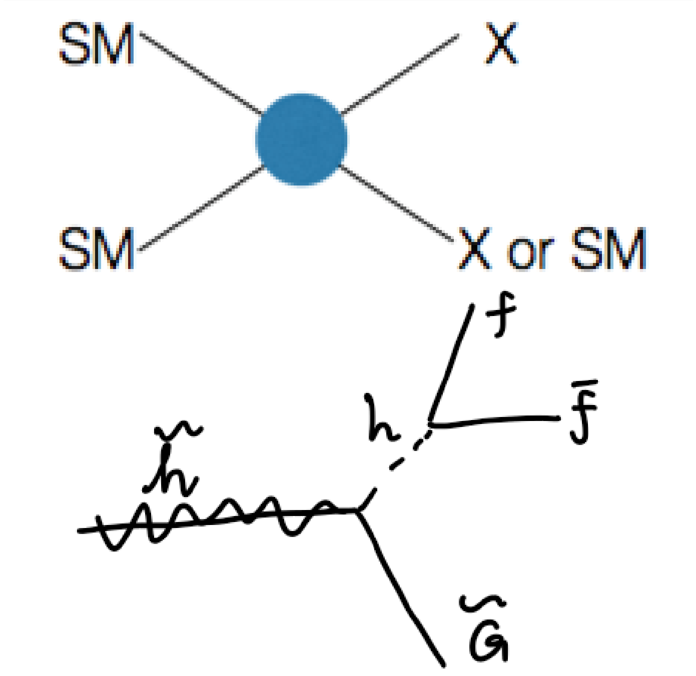


1% delay ($\beta = 0.99; \gamma < 7$) can be spotted
LLP (with mass > 10s of GeV) are *all* delayed!

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

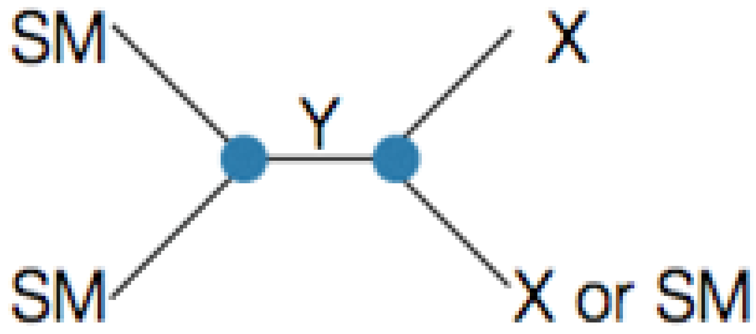
Late comers will be spotted easily: Higgsinos

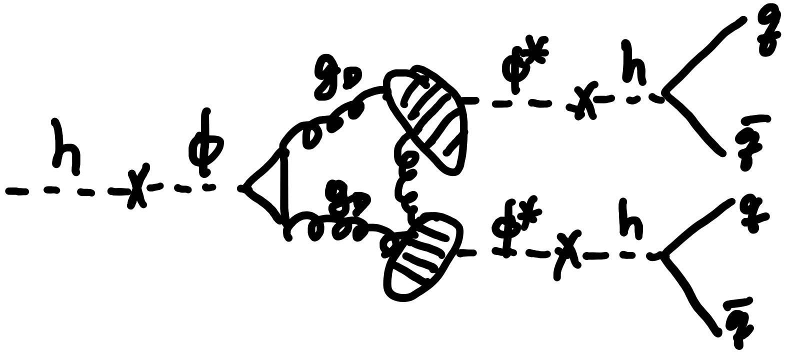




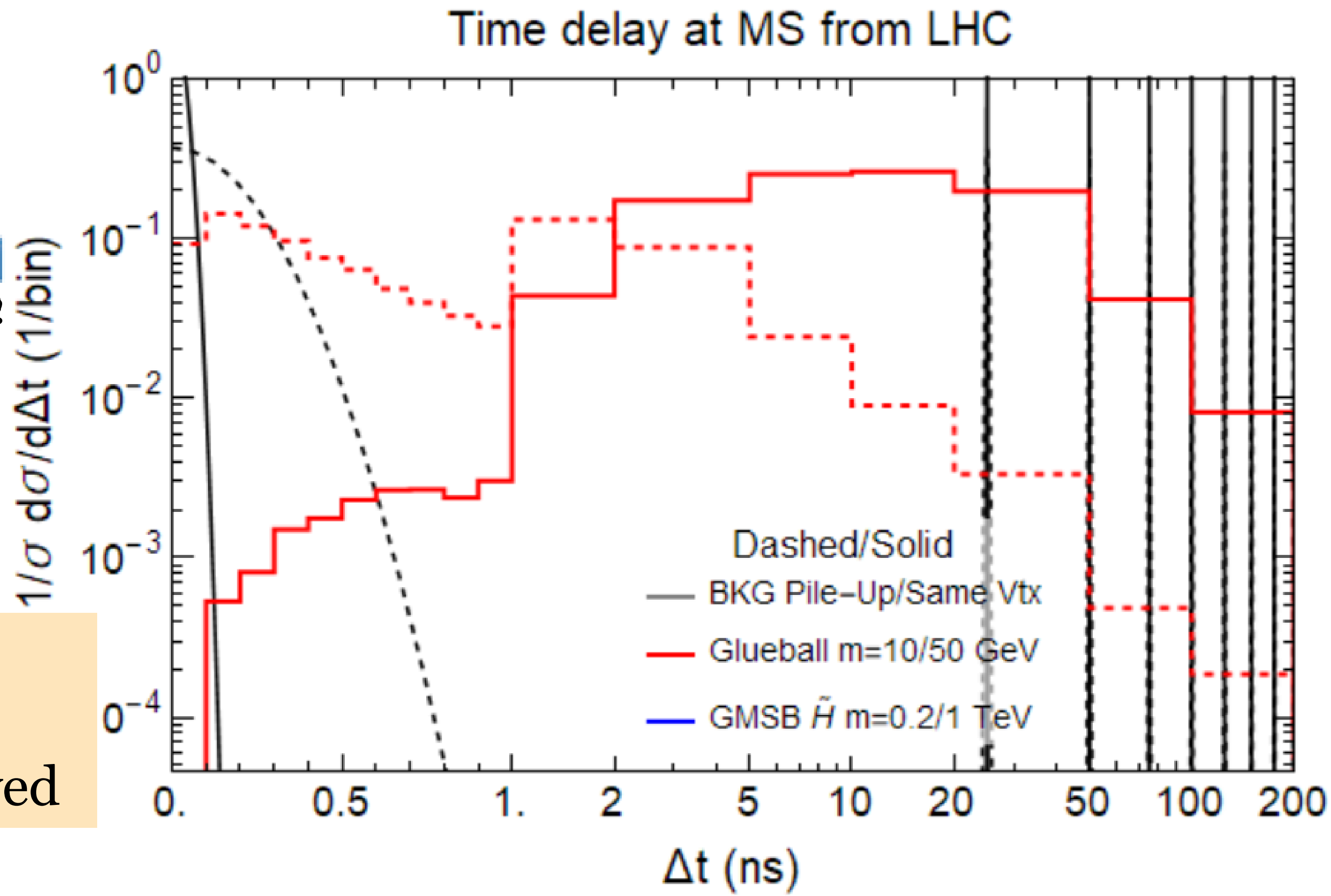
Representative of LLP pair production:
All severely delayed

Late comers will be spotted easily: Higgs decays

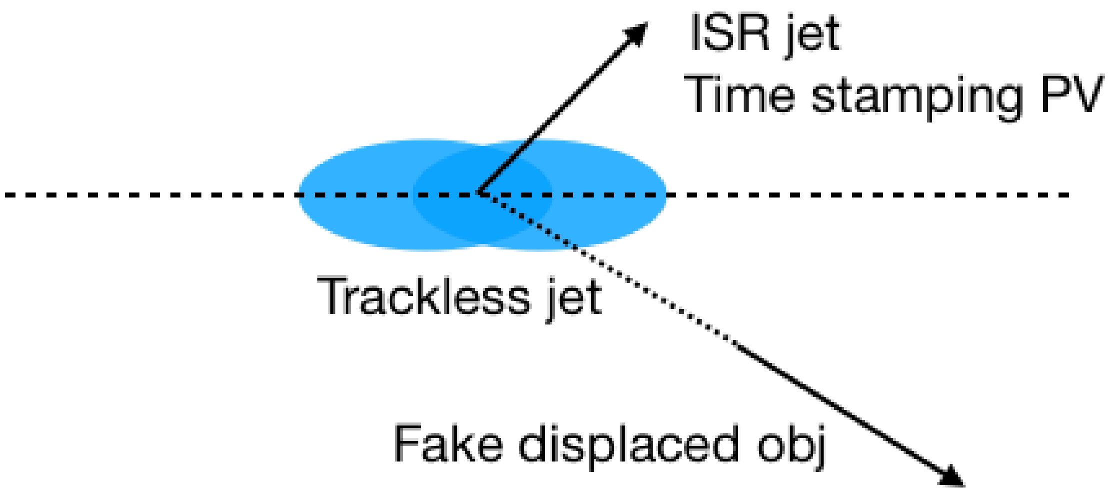


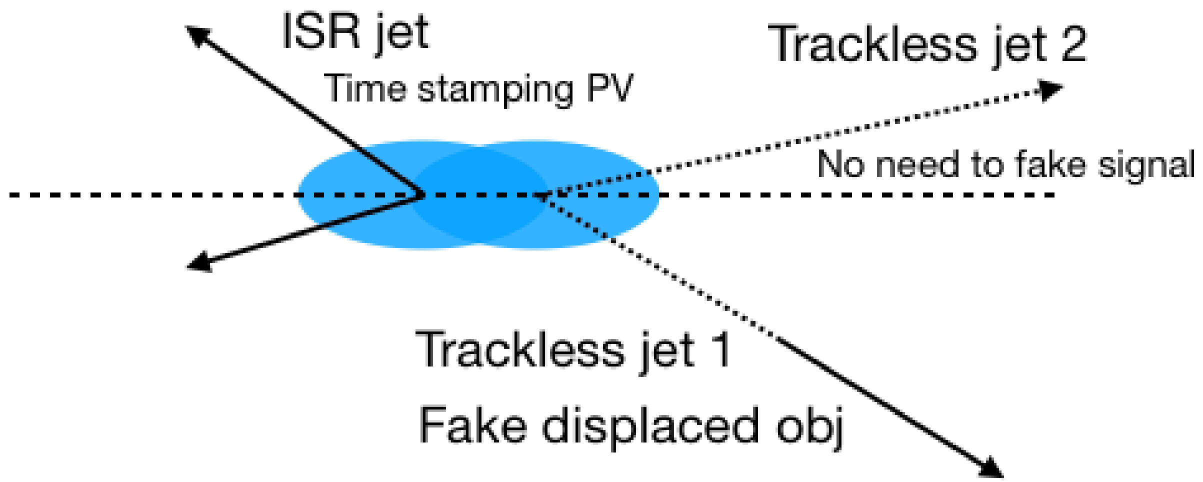


Representative of LLP from resonance decays: Light ones are less delayed



Time-delay: backgrounds



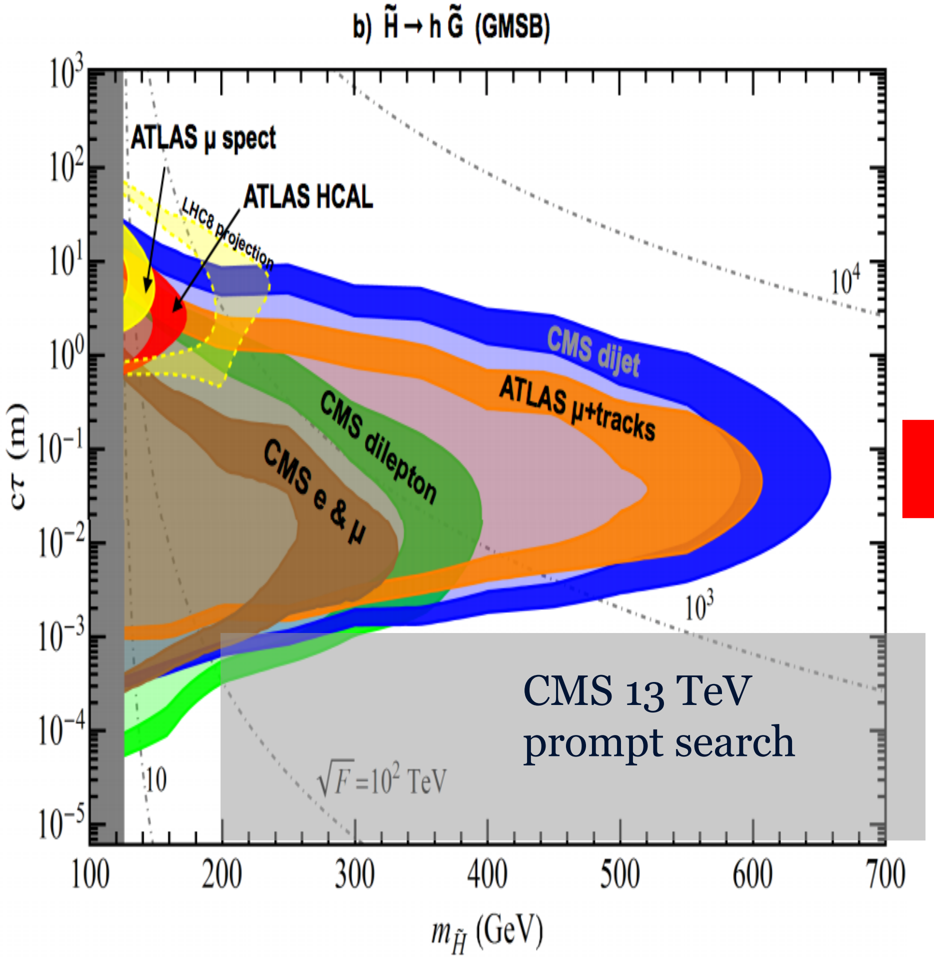


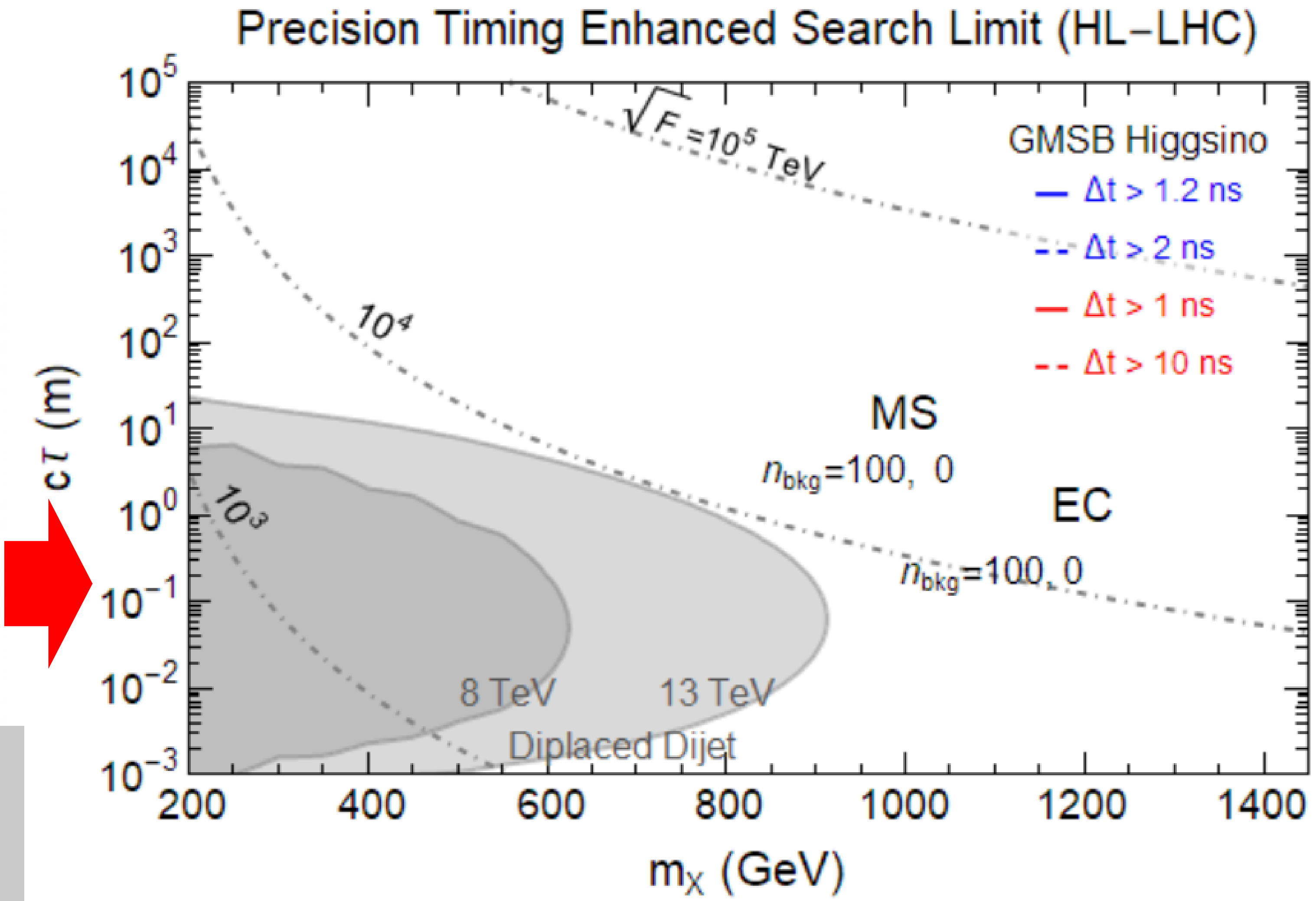
Same-vertex hard scattering background, time spread 30 ps (precision timing resolution)

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

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

Late comers will be spotted easily: Higgsinos





Liu, Tweedie, 15’

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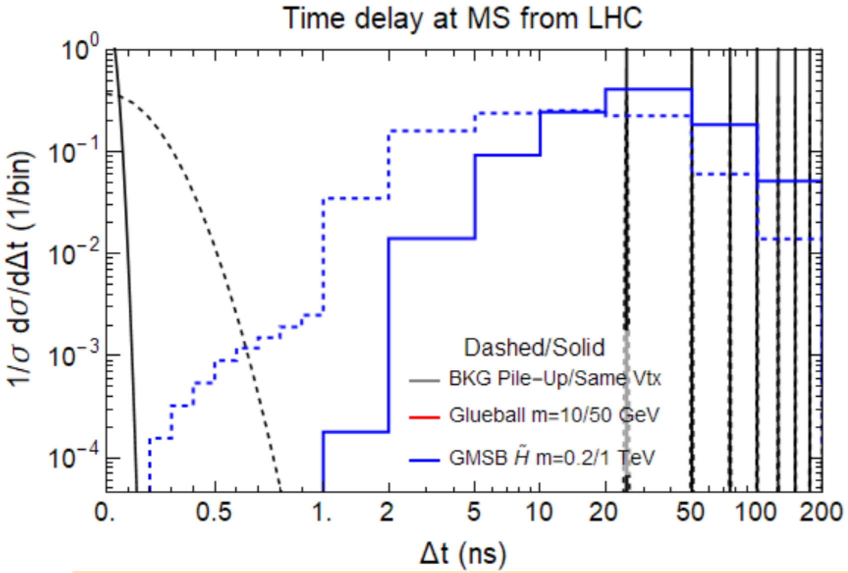
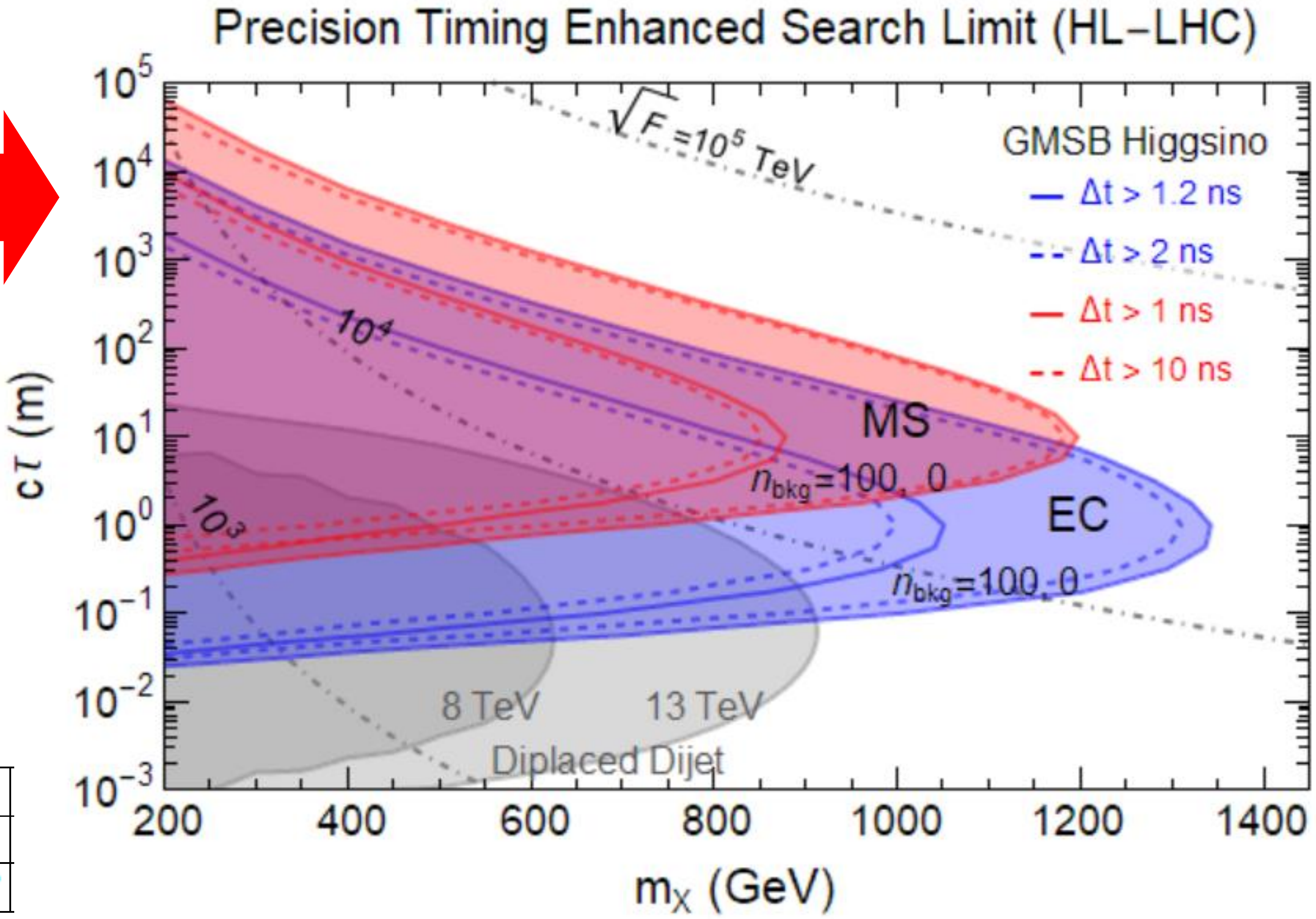


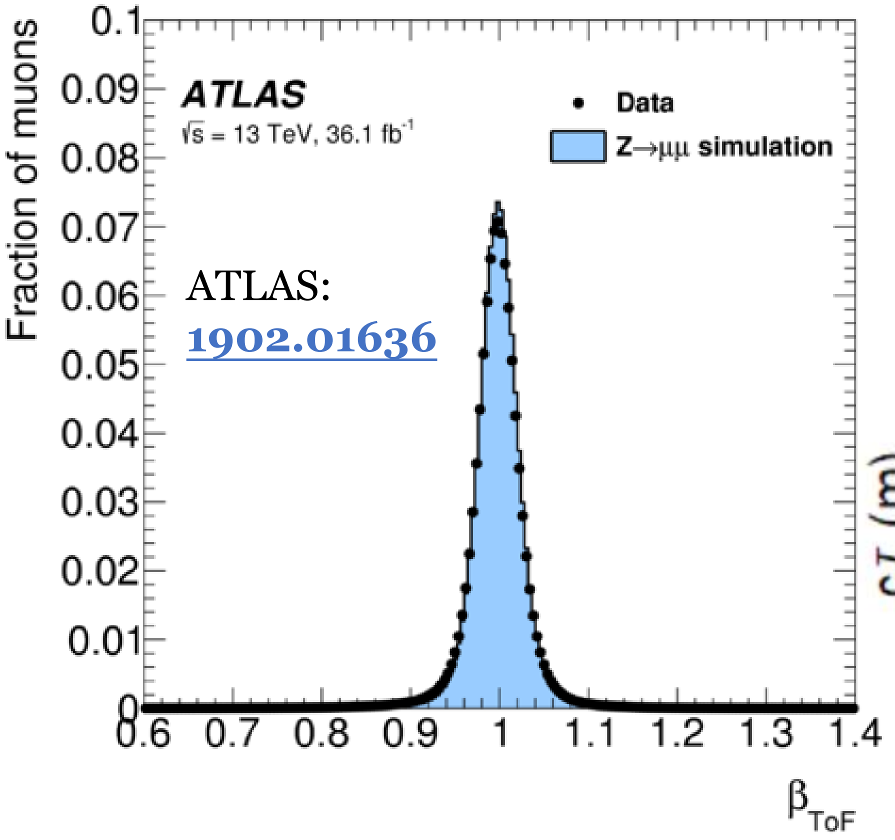


- MTD: >1.2 ns or >2 ns timing cut (<25 ns always there)
- MS: 1 ns or 10 ns timing cut (0.2 ns or 2 ns resolution sufficient)
- Significant improvement!

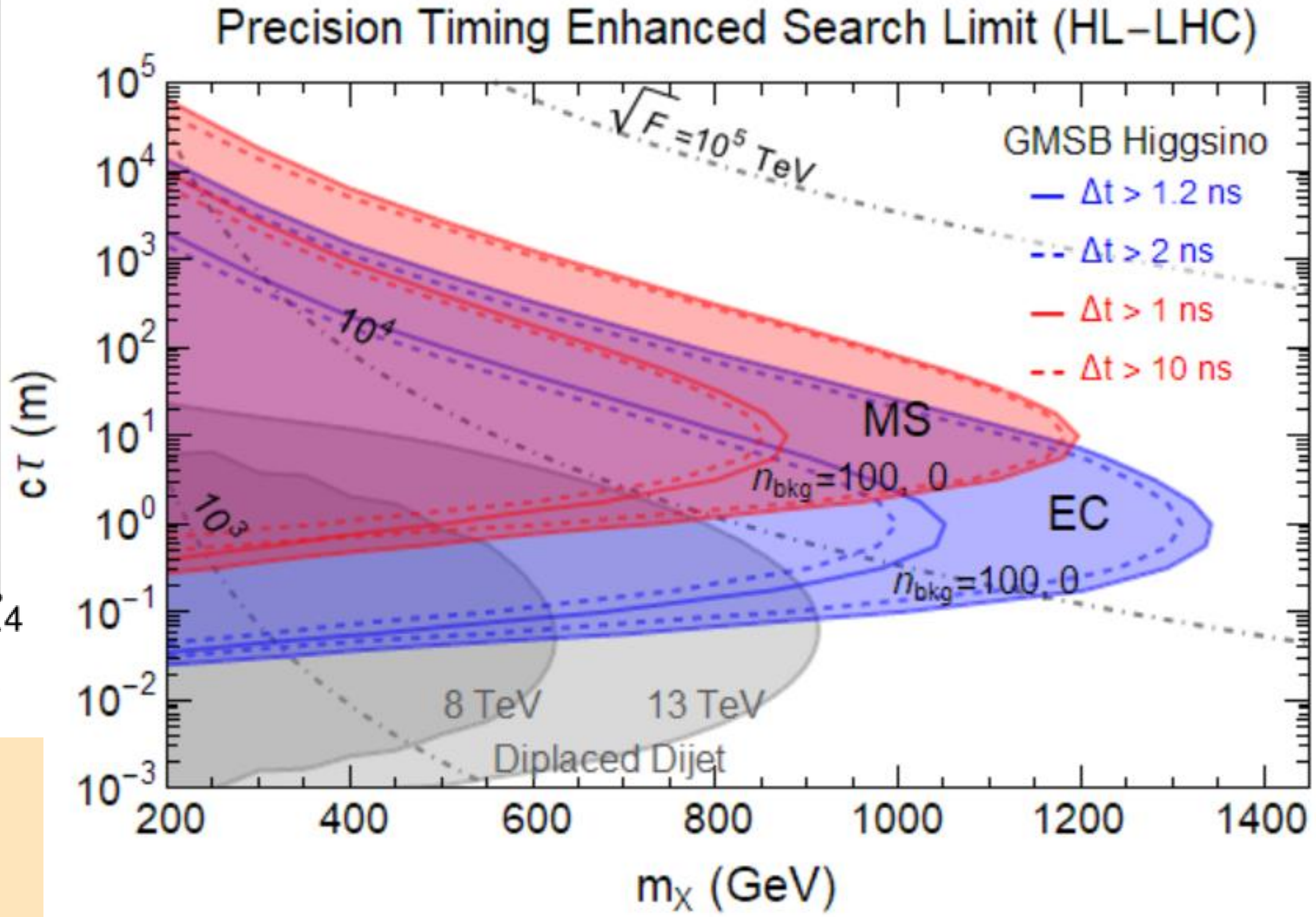
	L_{T_2}	L_{T_1}	Trigger	$\epsilon_{\rm trig}$	$\epsilon_{\rm sig}$	$\epsilon^j_{\rm fake}$
MTD	1.17 m	0.2 m	DelayJet	0.5	0.5	10^{-3}
MS	10.6 m	4.2 m	MS RoI	0.25, 0.5	0.25	5×10^{-9}

Liu, Liu, Wang, 18'

Late comers will be spotted easily: Higgsinos



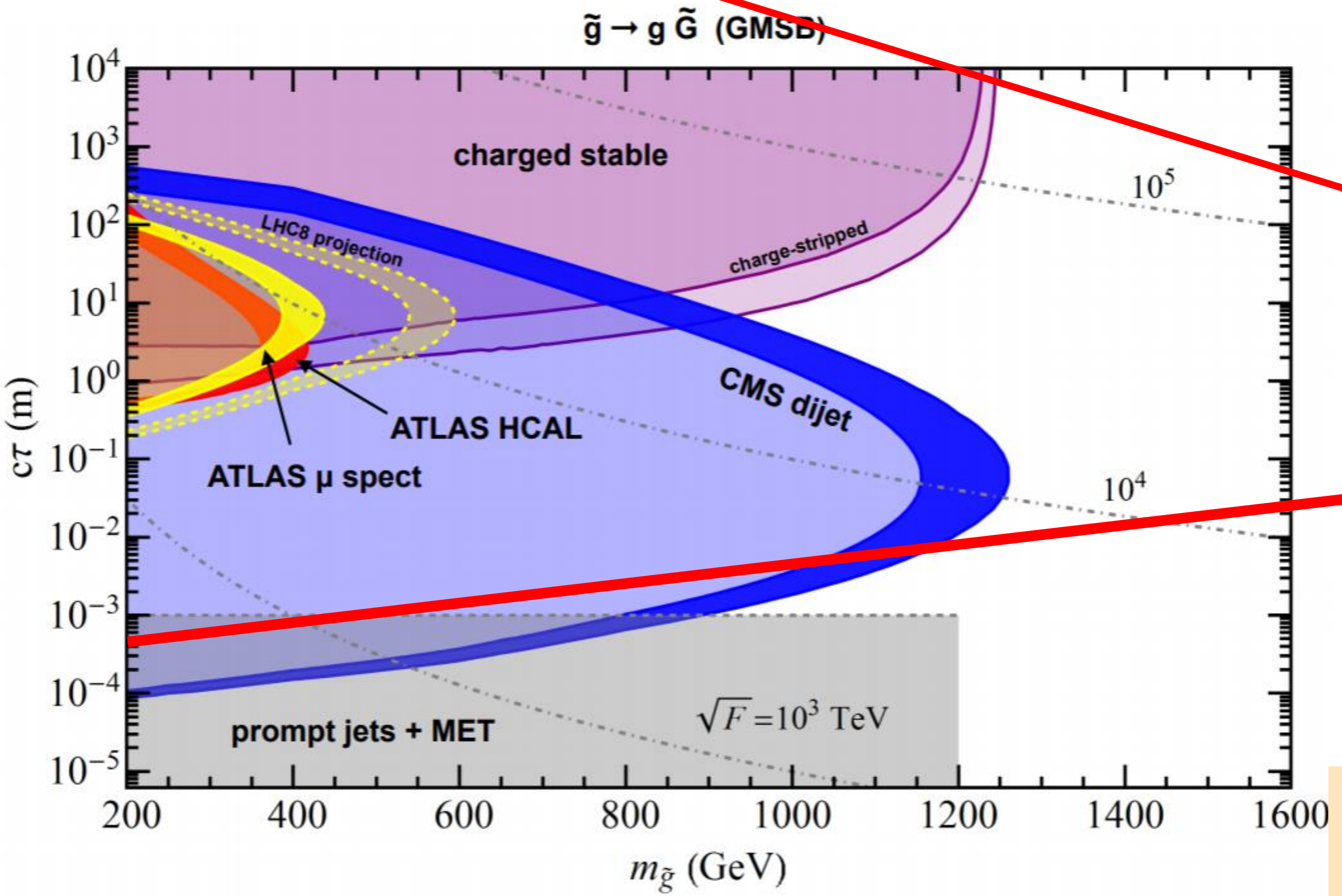
ATLAS: [1902.01636]

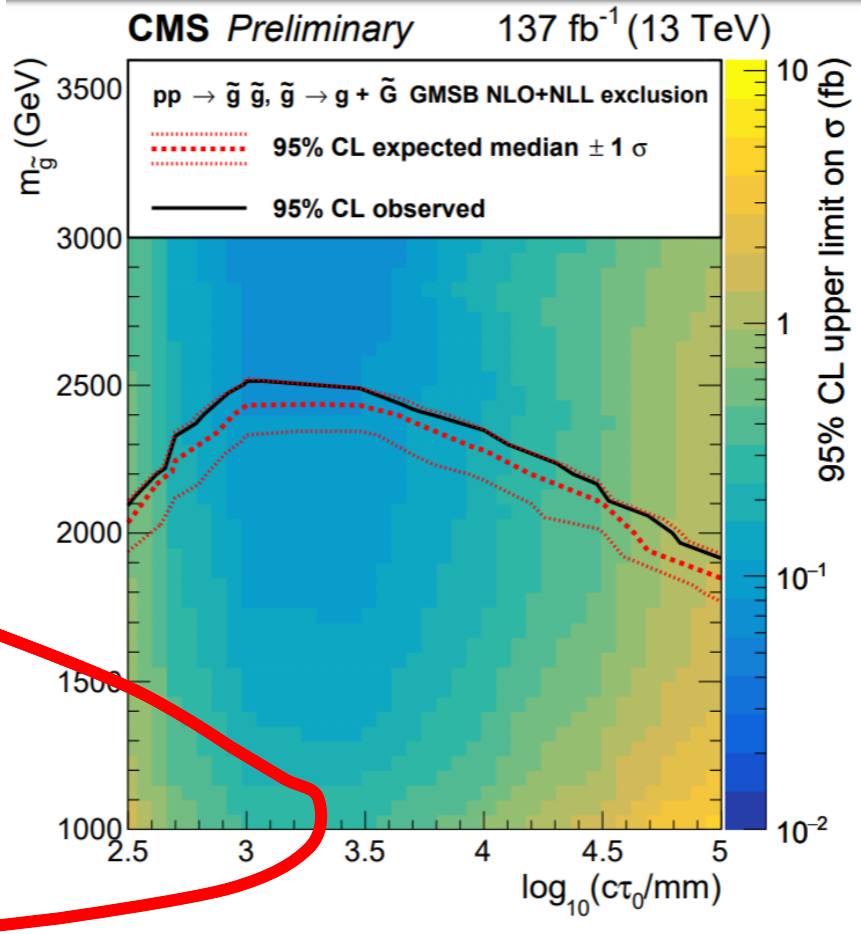


- MS: 1 ns or 10 ns timing cut (0.2 ns or 2 ns resolution sufficient)
- And we already have such resolution from the HSCP studies

Liu, Liu, Wang, 18’

New searches and new results!

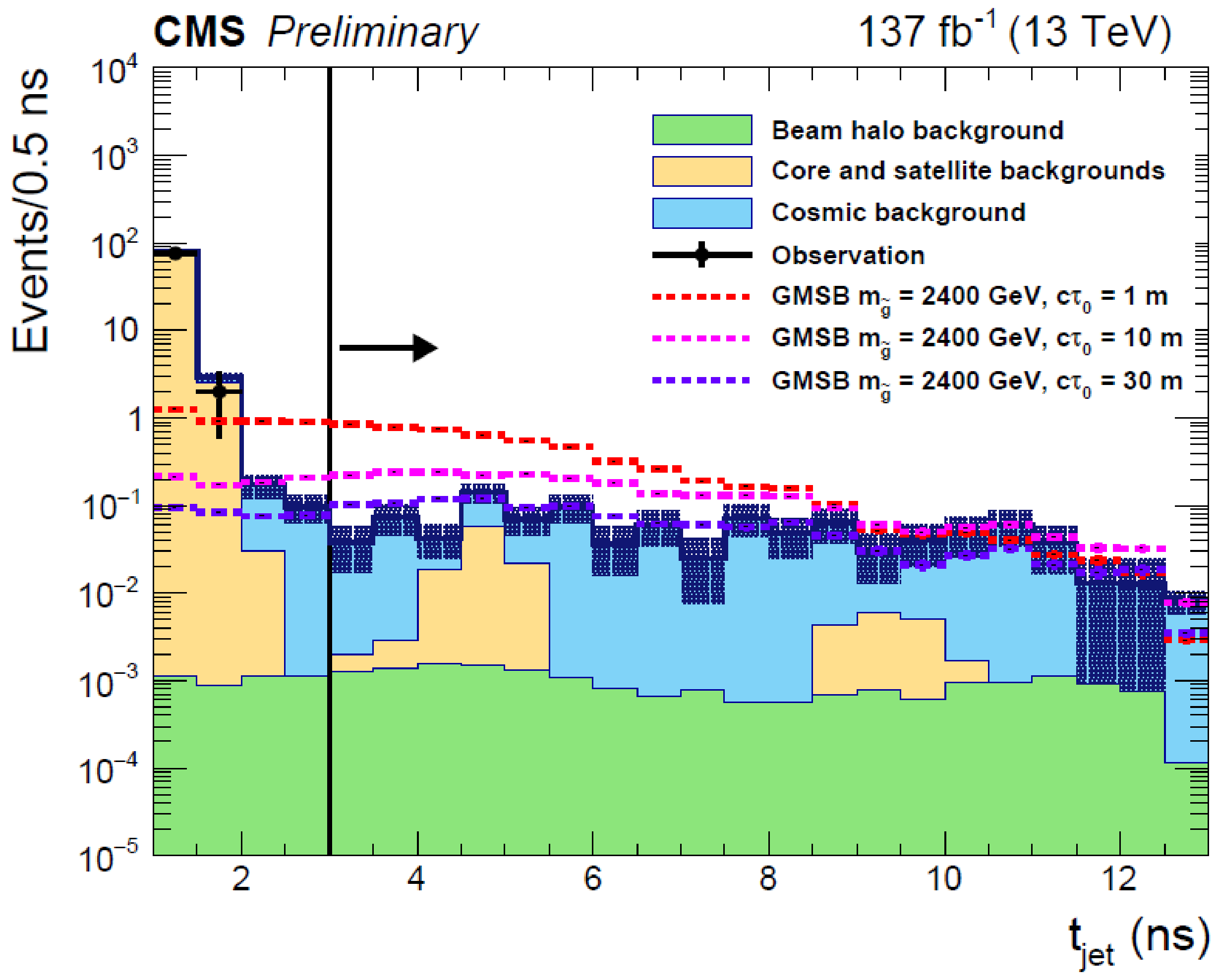


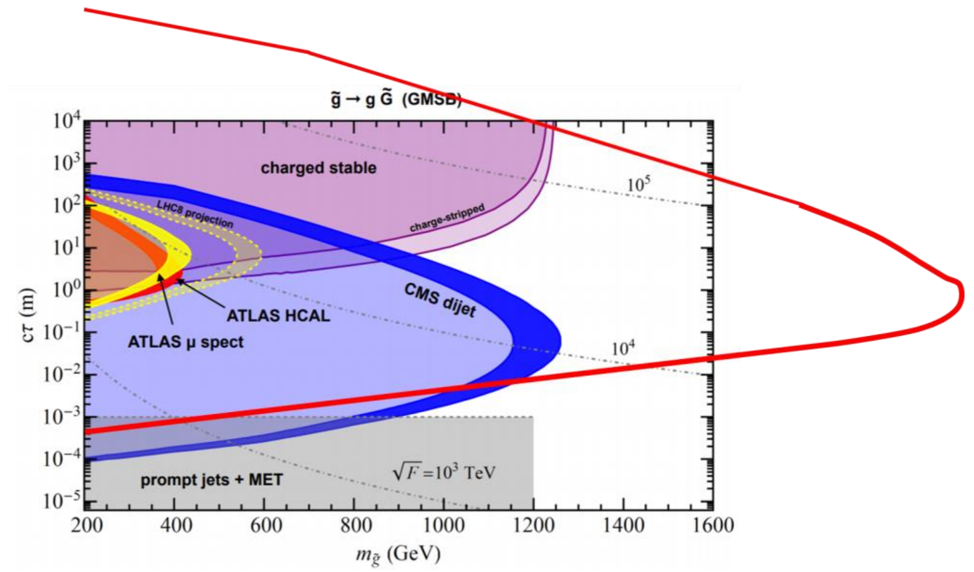


Used traditional 300 GeV MET trigger but rely on the time delays of the trackless jet, start probing new regime!

There is also new significant 13 TeV improvement from the displaced jet searches

New searches and new insights!

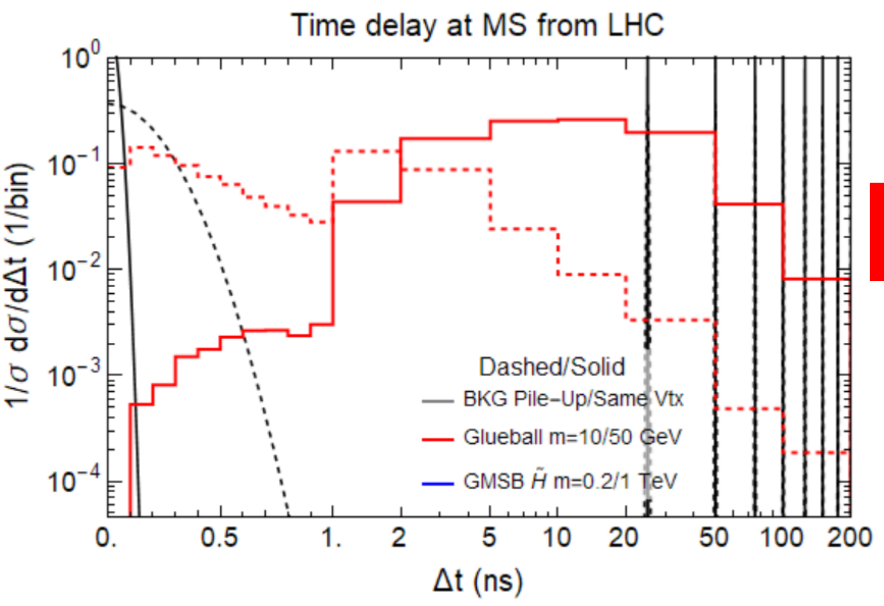


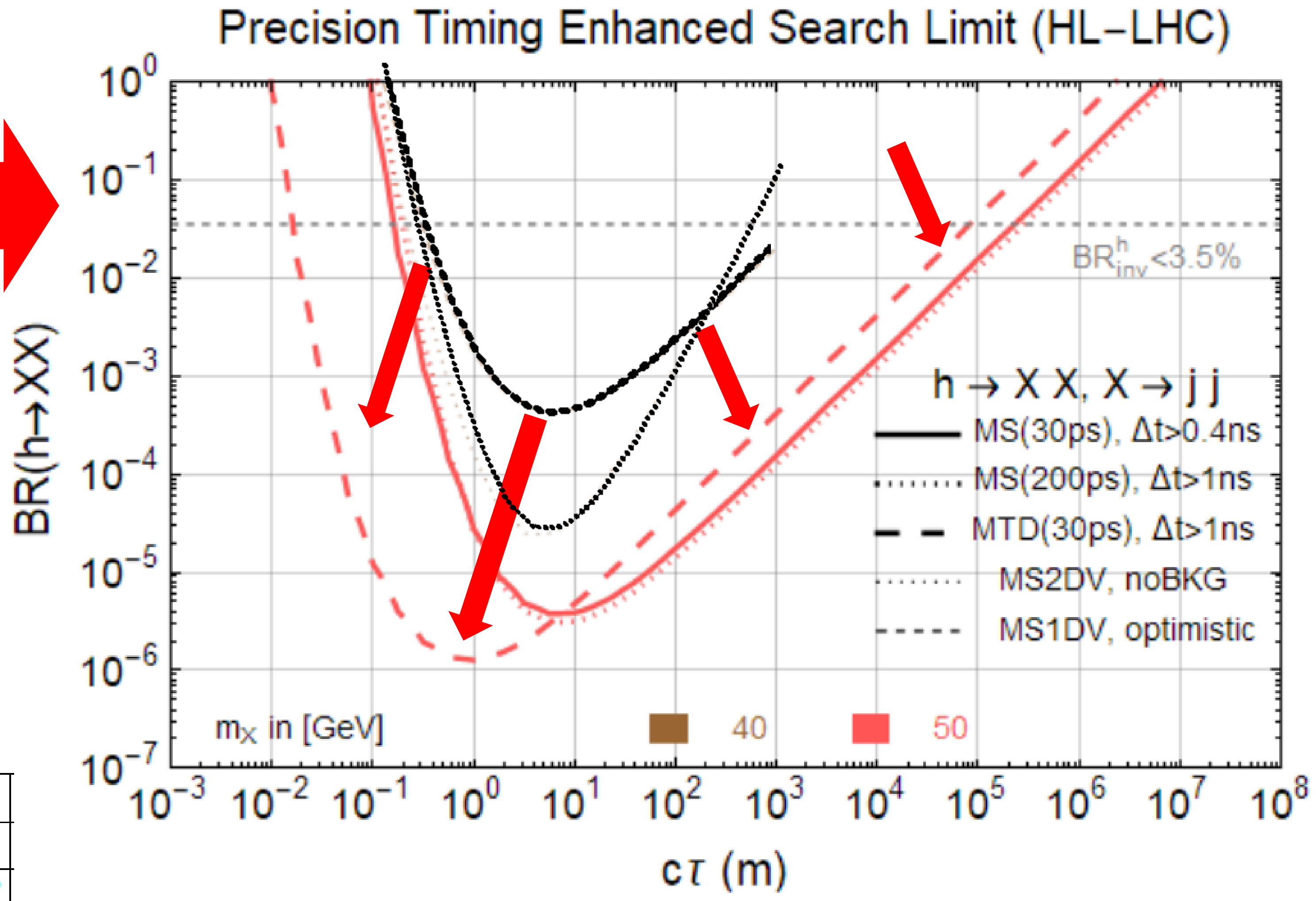


Background	Prediction
Beam halo	$0.02^{+0.06}_{-0.02}$ (stat) $^{+0.05}_{-0.01}$ (syst)
Core and satellite bunches	$0.11^{+0.09}_{-0.05}$ (stat) $^{+0.02}_{-0.02}$ (syst)
Cosmics	$1.0^{+1.8}_{-1.0}$ (stat) $^{+1.8}_{-1.0}$ (syst)

Timedelay useful!
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 yet but there are many ways) and scale with time but not luminosity

Late comers will be spotted easily: Higgs decays





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MTD	1.17 m	0.2 m	DelayJet	0.5	0.5	10^{-3}
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Liu, Liu, Wang, 18'

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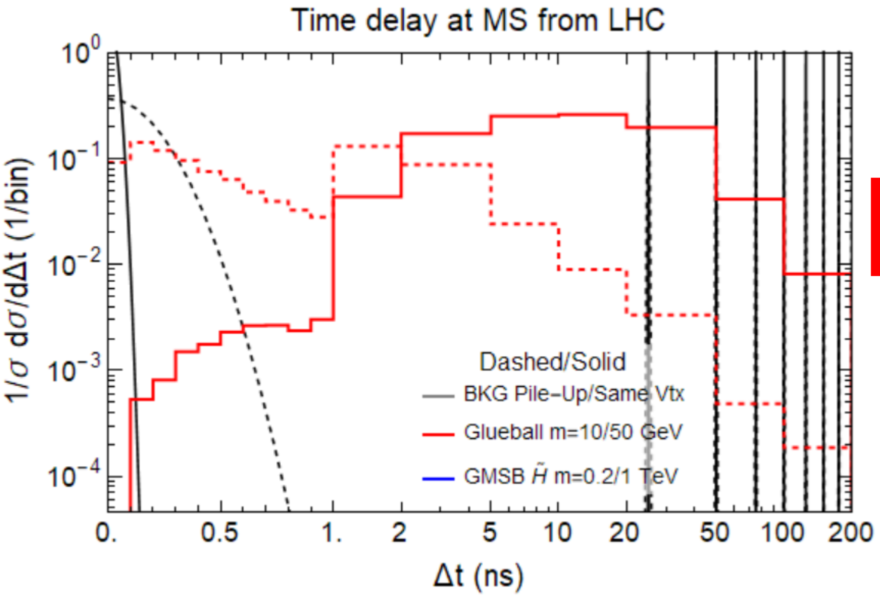
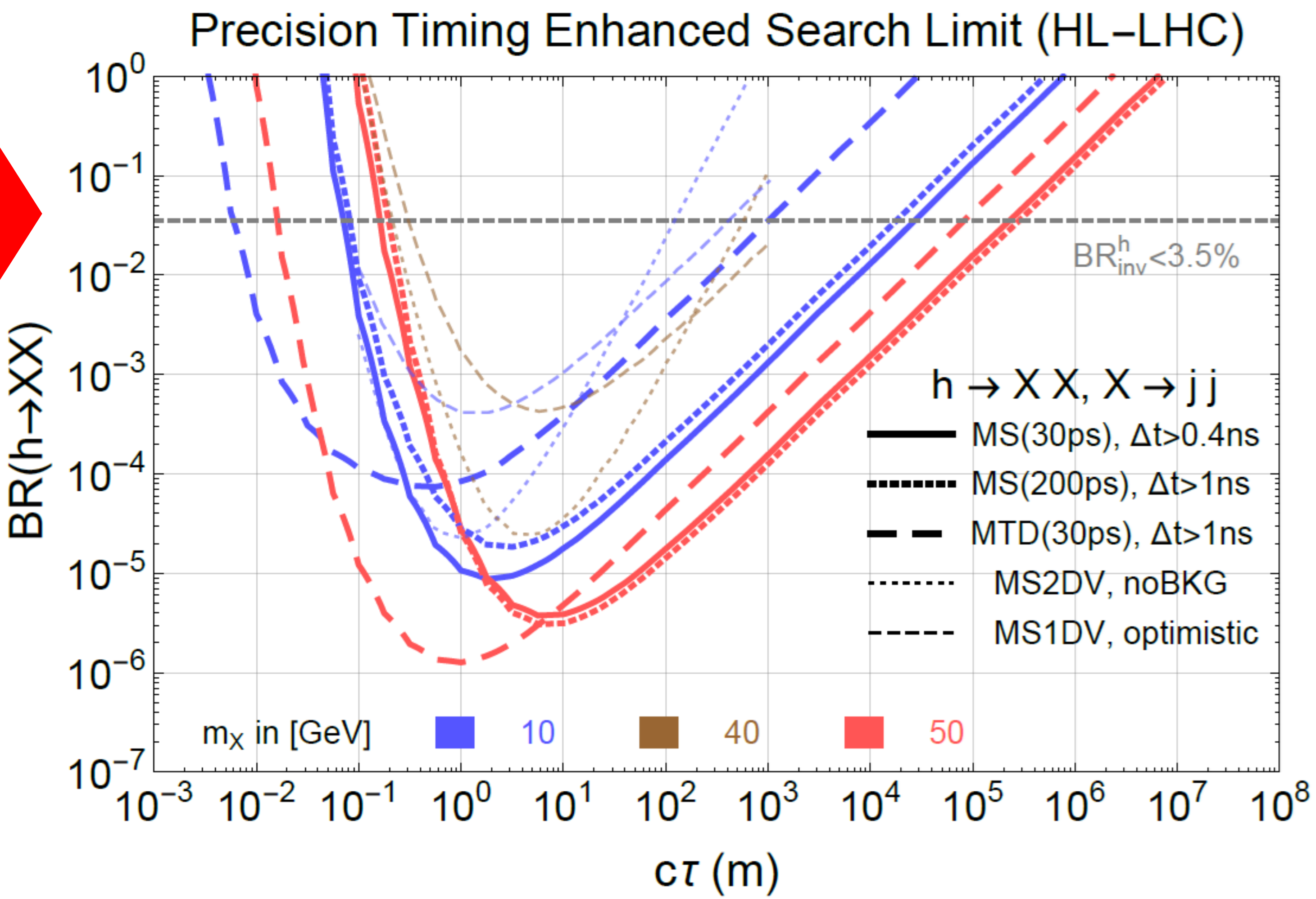


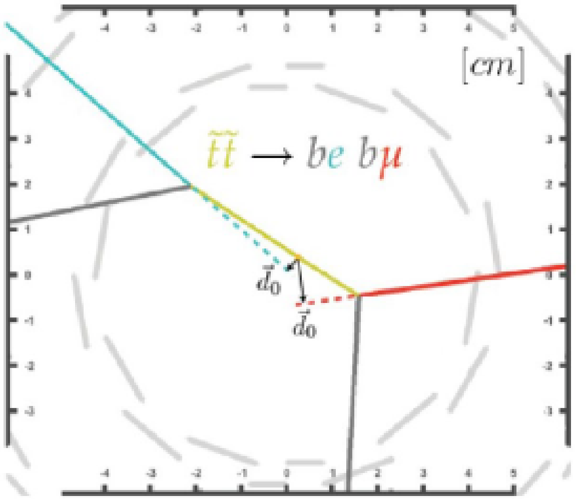


10 GeV benchmark point sensitive to the timing cut, as they are more boosted and having less time delay.

See also in Aurelio Juste's talk

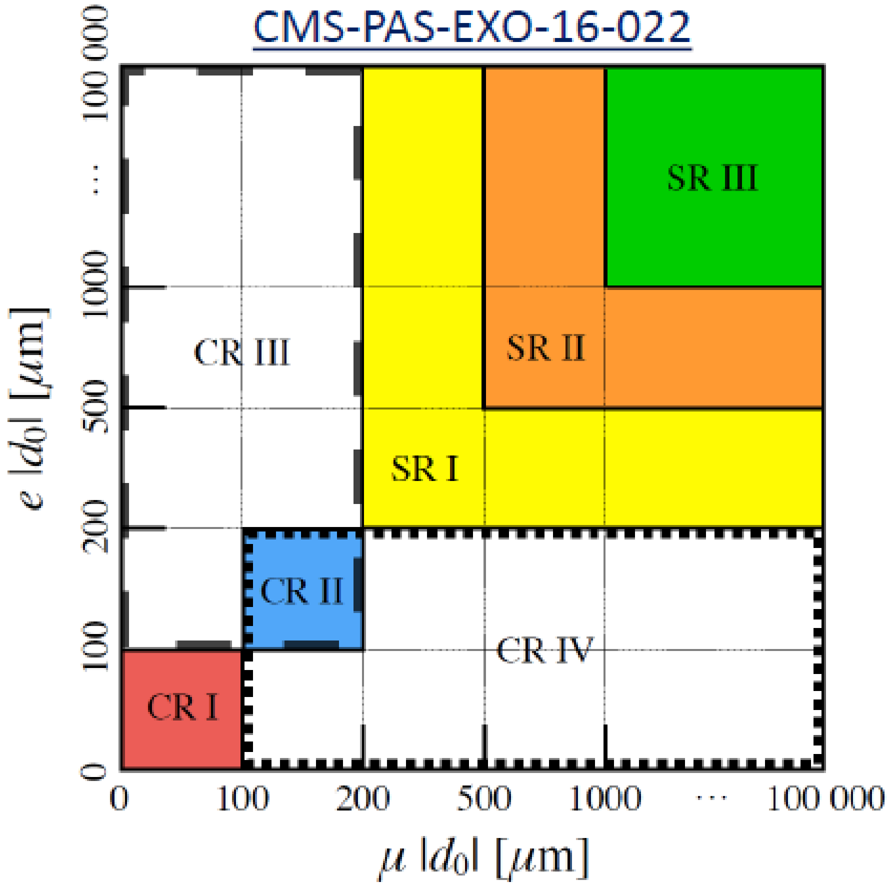
Liu, Liu, Wang, 18'

More ideas: displaced lepton



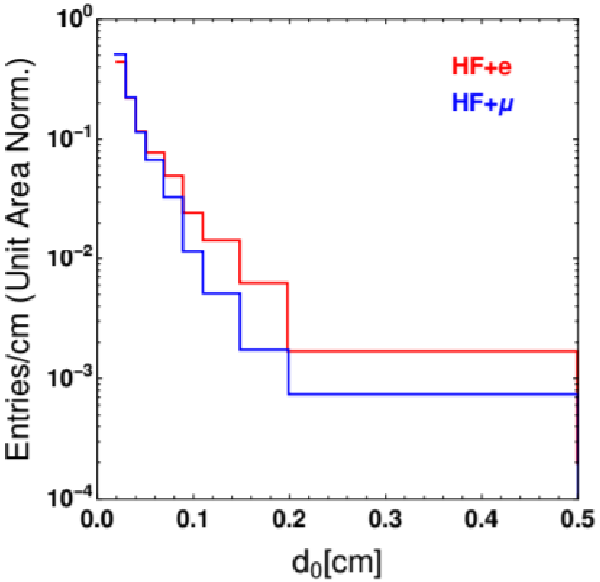
← Single displaced leptons not from the same vertex; focused on e-mu state

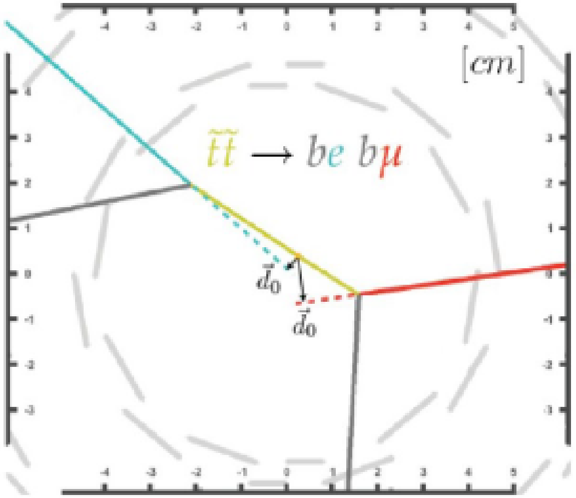
CMS-PAS-EXO-16-022



ZL, J. Liu, L.-T. Wang, X. Wang, 1904.01020

More ideas: displaced lepton





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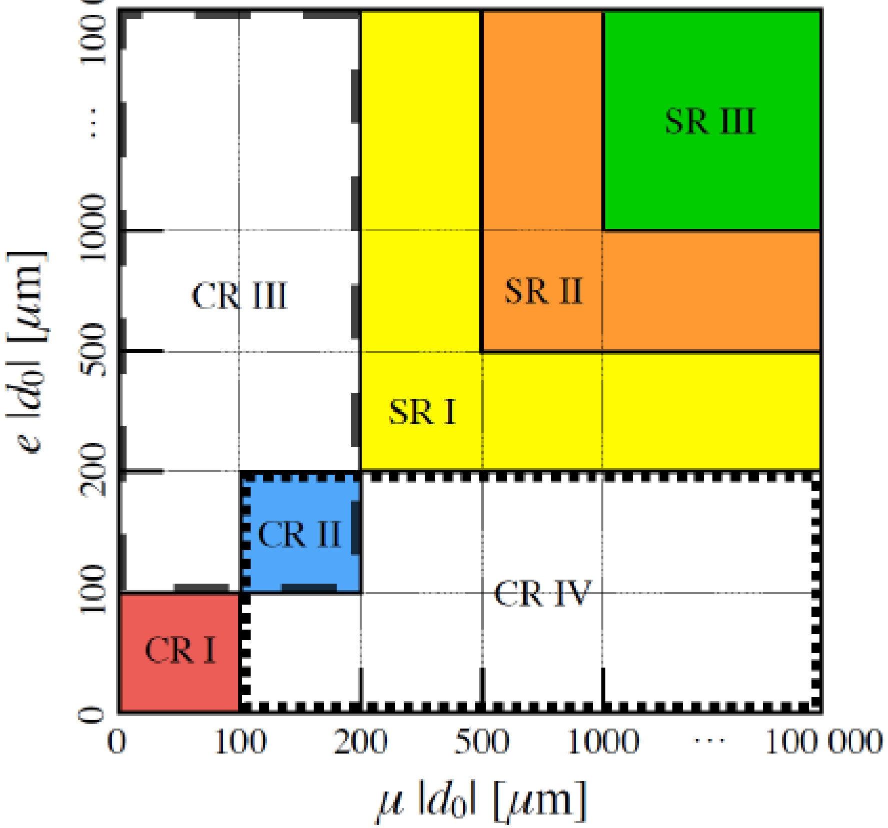
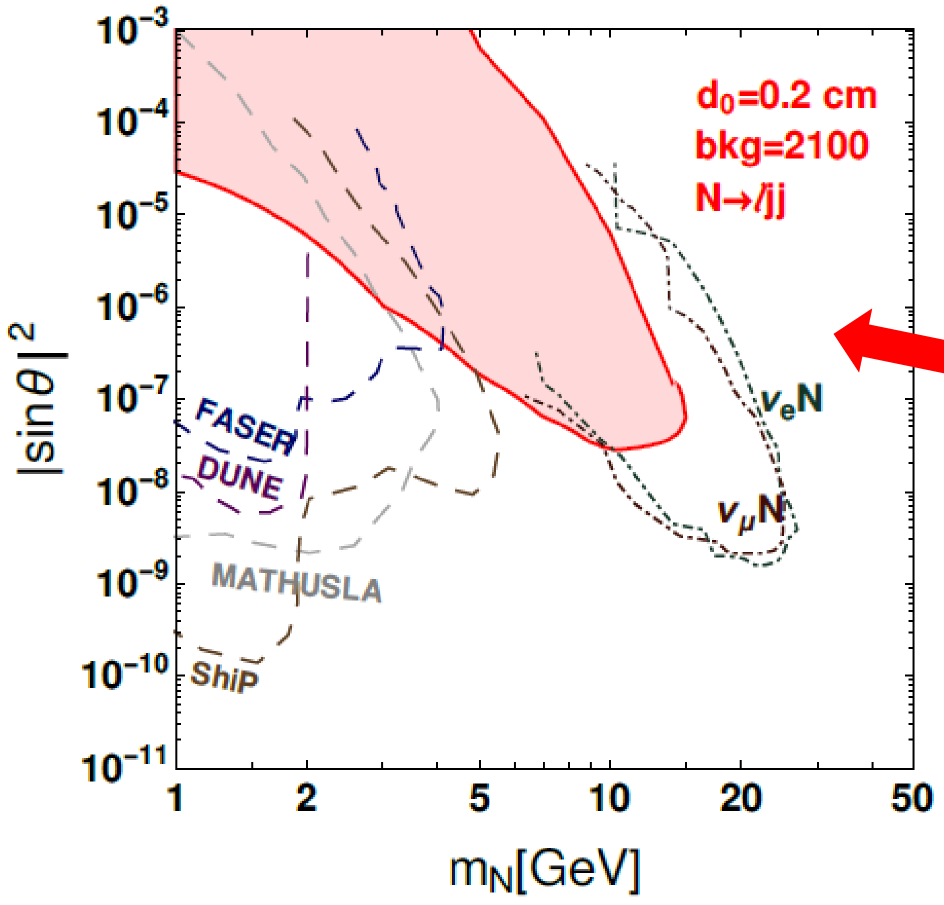
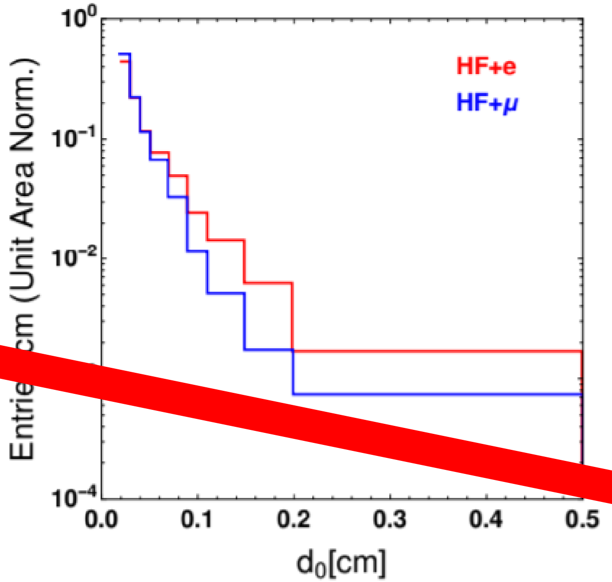
CMS-PAS-EXO-16-022

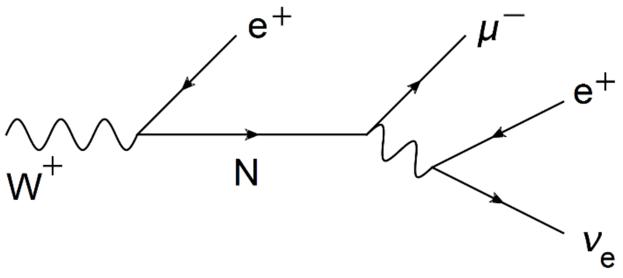


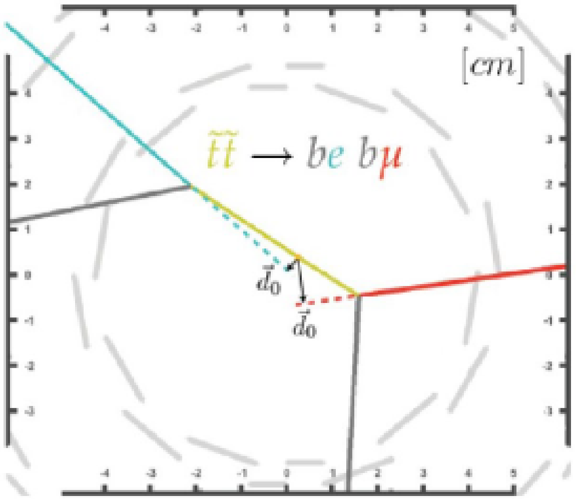
ZL, J. Liu, L.-T. Wang, X. Wang, 1904.01020

More ideas: displaced lepton









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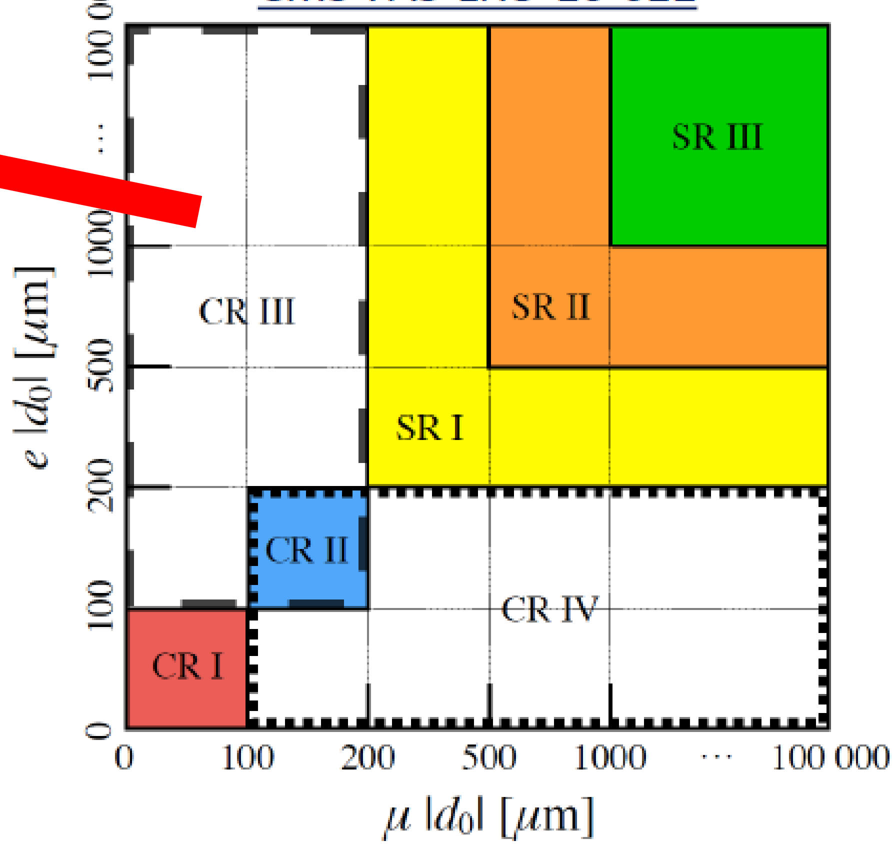
CMS-PAS-EXO-16-022

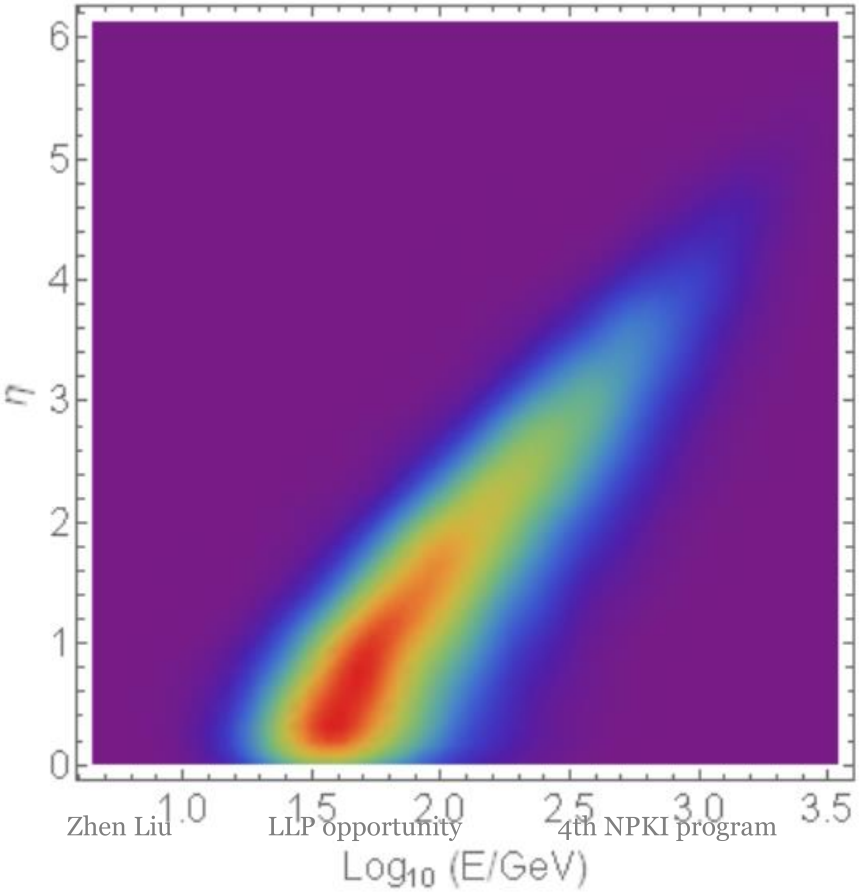


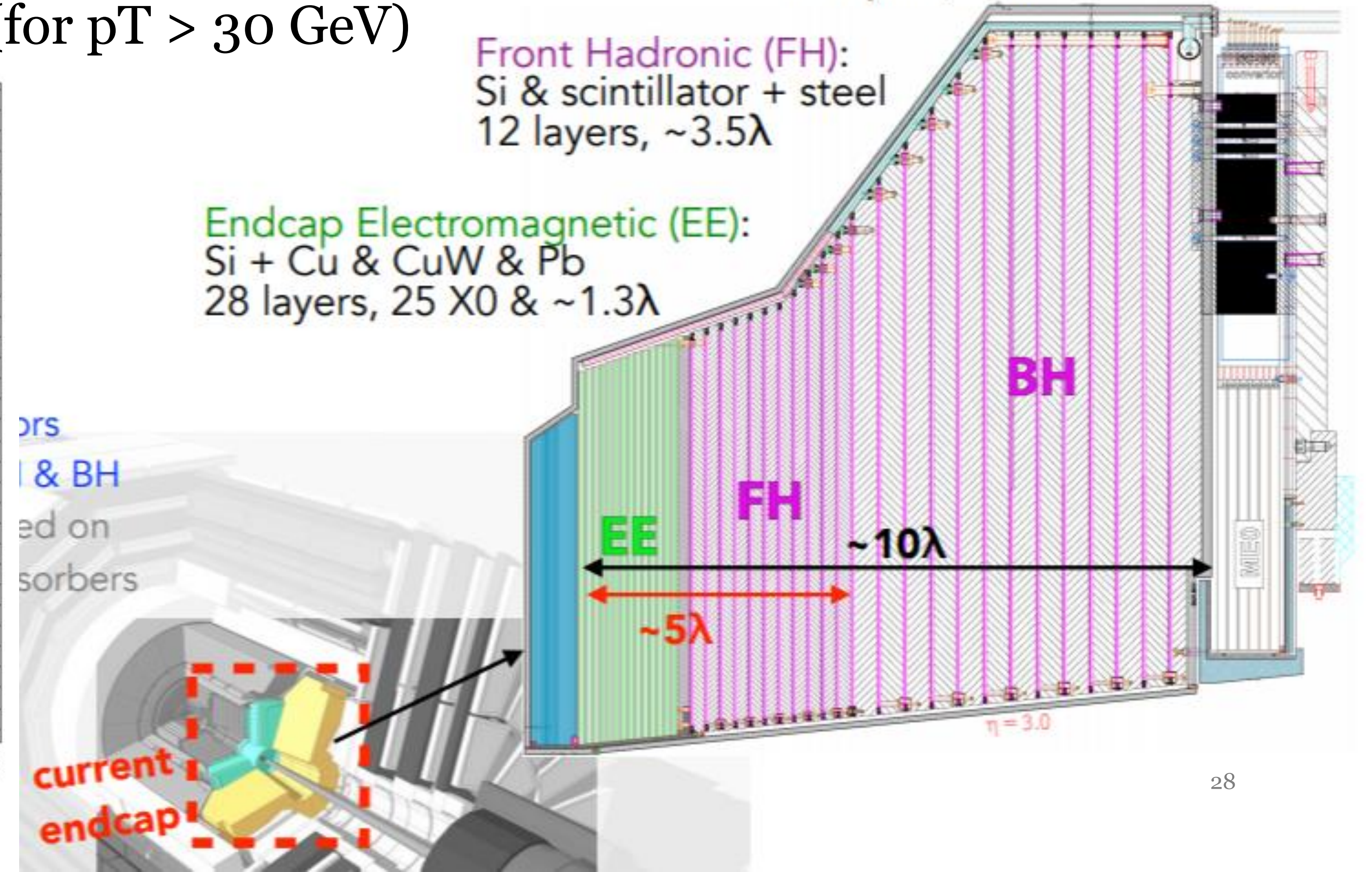
Digging hard and use the control region studies to propose new searches on sterile neutrinos.

ZL, J. Liu, L.-T. Wang, X. Wang, 1904.01020

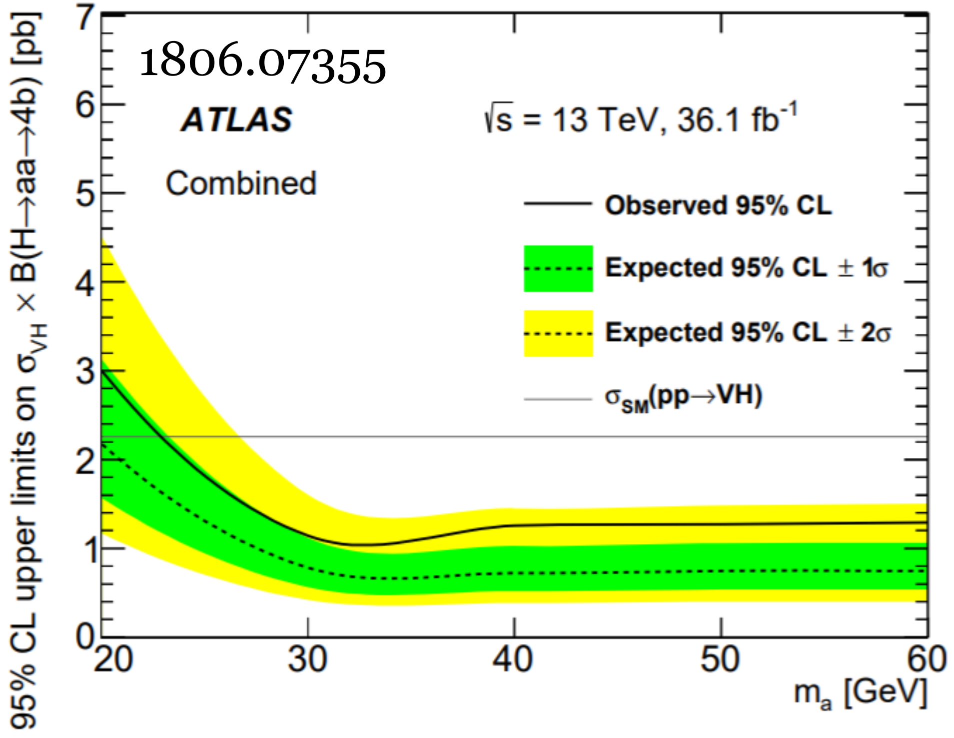
More ideas: High granularity detectors

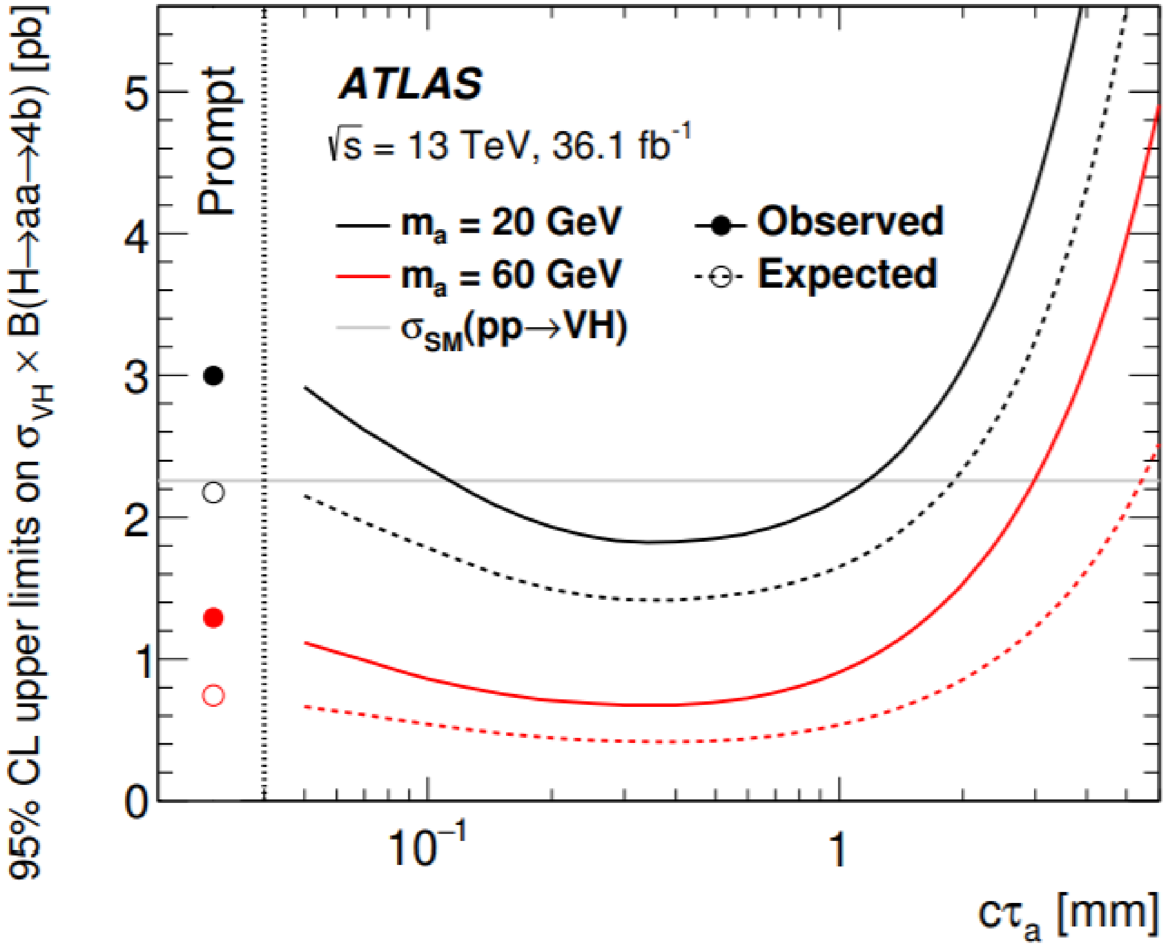
HL upgrade:
Directional resolution milli milliradian,
Temporal resolution 30 ps (for pT > 30 GeV)





More ideas: Prompt→ LLP





Hard to estimate prompt sensitivity for LLPs.

Higgs exotic decays H->(bb)(bb) made a first step, reinterpreted prompt results to LLPs:

- Prompt limits dies-off above a few mm;
- Long-lived limits is better than prompt limit in a prompt search;

Higgs cross section working group (WG3)

Summary and outlook

- LHC great detector for LLP searches, a rich program is still under development;
- Our recast study shows the broad coverage of existing LLP searches;
- Counter your intuition: LLPs (even in the extremely long-lifetime limit) should/could be optimally searched at the LHC main detectors!
- All *traditional* LLP searches could be augmented by the timing information (re-optimization);
- New searches can capture general features of the LLP in a very robust way by exploiting their timedelay feature;
- 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.
- More than timing: many teams start working on this already, including theorists, and CMS/ATLAS/LHCb experimentalists: timing in muon spectrometer, timing in calorimeter, LLPs in high granularity calorimeter (HGCal), displaced tracks trigger, LHCb triggerless readout for LLPs, etc., at both trigger and analysis level.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DUTY FREE

Classification: Production, Decay and Models

Neutral Long-lived particles

LLP decay modes

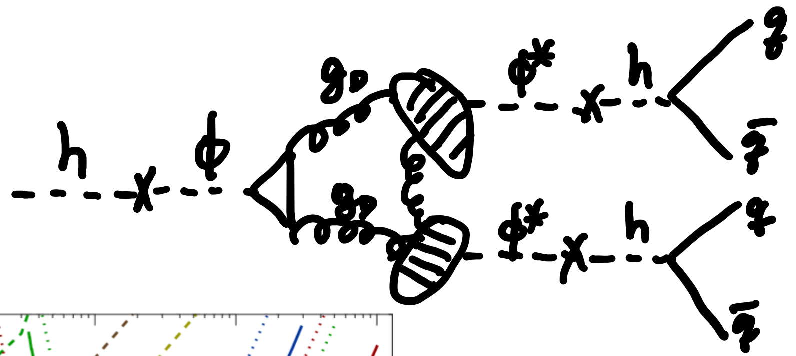
Production \ Decay	$\gamma\gamma(+\text{inv.})$	$\gamma + \text{inv.}$	$jj(+\text{inv.})$	$jj\ell$	$\ell^+\ell^-(+\text{inv.})$	$\ell^+_\alpha \ell^-_{\beta\neq\alpha}(+\text{inv.})$
DPP: sneutrino pair	†	SUSY	SUSY	SUSY	SUSY	SUSY
HP: squark pair, $\tilde{q} \to jX$ or gluino pair $\tilde{g} \to jjX$	†	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*

Canonical production modes: DPP, HP, HIG, RES, CC

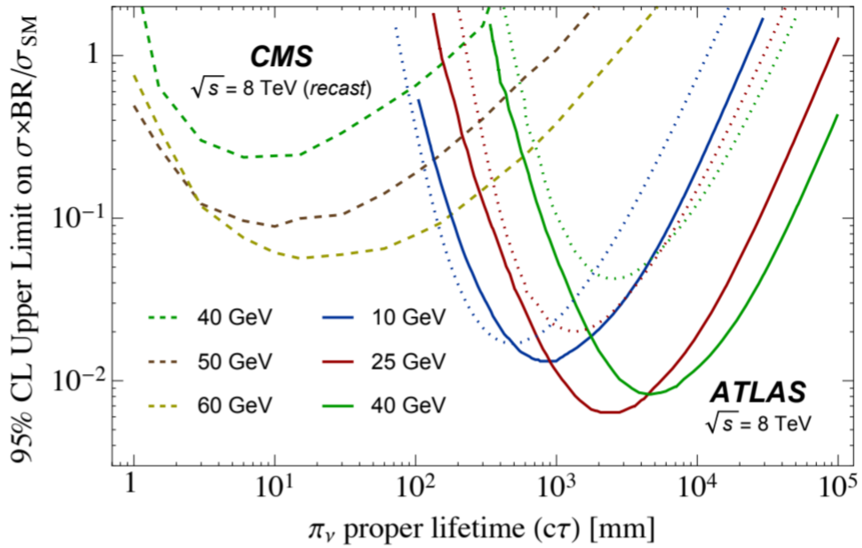
Mapping to UV Models

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

A benchmark: Higgs decays into LLPs



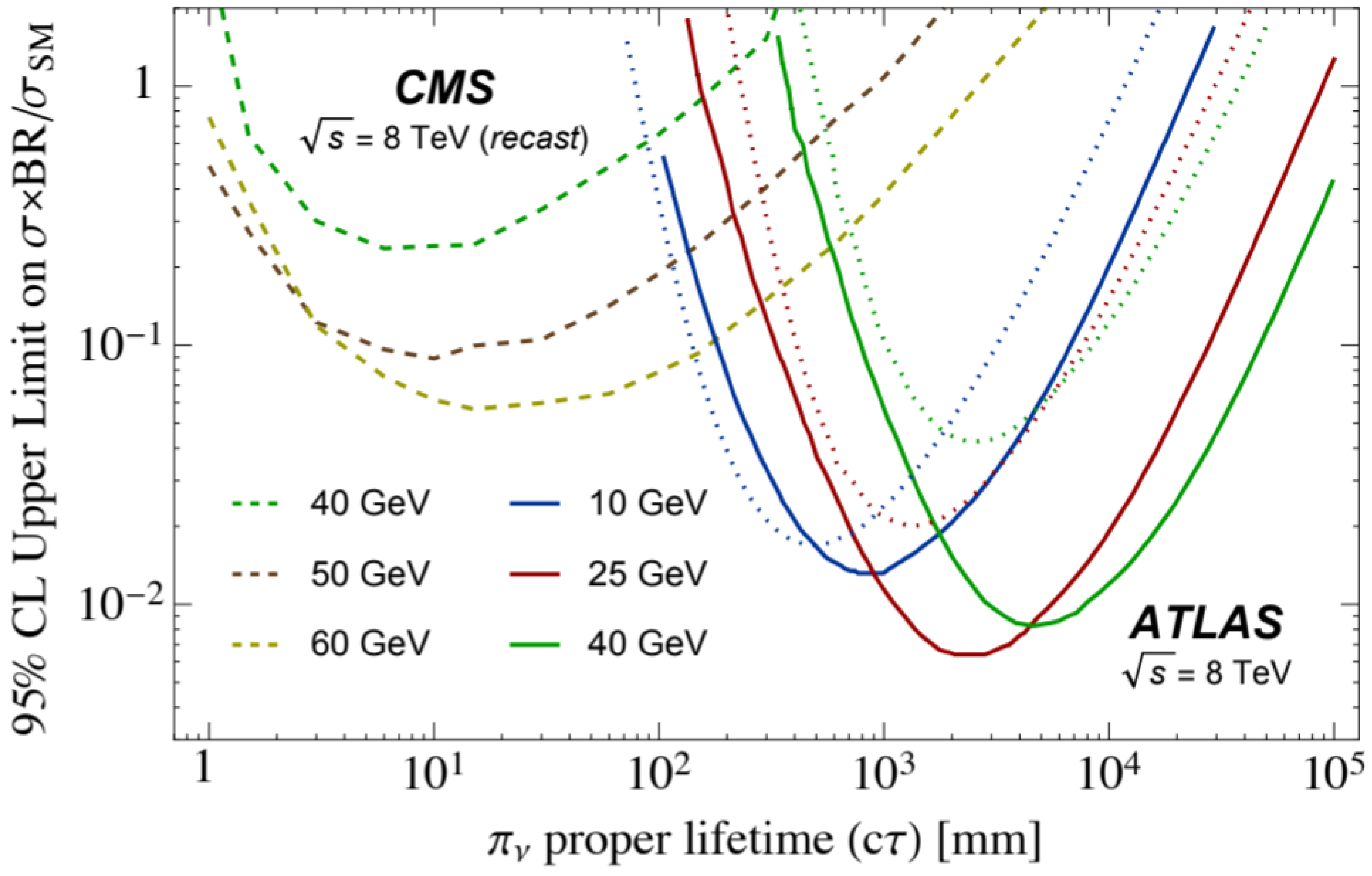
- Only %-level trigger efficiency;
- for longer lifetimes (>10 cm), except for VBF (and maybe trackless jet), the above will all fail, having even lower trigger efficiency.
- One would rely on jet+MET, HT, etc., using hard ISRs for general signals, which will have even big trigger efficiency loss.



C. Csaki, E. Kuflik, S. Lombardo, O. Slone, 1508.01522

Trigger	m_{π_v} (GeV)	$c\tau = 1$ mm				$c\tau = 10$ mm				$c\tau = 100$ mm			
		ϵ_{ggF}	ϵ_{VBF}	ϵ_{VH}	ϵ_{Total}	ϵ_{ggF}	ϵ_{VBF}	ϵ_{VH}	ϵ_{Total}	ϵ_{ggF}	ϵ_{VBF}	ϵ_{VH}	ϵ_{Total}
Displaced jet	10	0.03%	1.3%	1.1%	**0.2%**	1.0 %	30.0%	25.1%	**3.9%**	1.0%	42.0%	34.7%	**5.1%**
	25	0.01%	0.8%	0.7%	**0.09%**	0.7%	20.4%	16.9%	**2.7%**	1.5%	45.3%	37.3%	**5.9%**
	40	0.02%	1.0 %	0.9%	**0.1%**	0.6%	19.7%	16.4%	**2.5%**	1.4%	44.6%	36.3%	**5.7%**
Inclusive VBF	10	1.9%	15.5%	0.8%	**2.8%**	1.8%	15.5%	0.7%	**2.8%**	1.6%	15.1%	0.6%	**2.6%**
	25	1.7%	15.3%	0.7%	**2.7%**	1.7%	15.3%	0.7%	**2.7%**	1.6%	15.2%	0.6%	**2.6%**
	40	1.6%	15.2%	0.7%	**2.6%**	1.6%	15.2%	0.7%	**2.6%**	1.6%	15.2%	0.6%	**2.6%**
VBF, $h \to b\bar{b}$	10	5.8%	20.3%	13.1%	**7.2%**	5.8%	20.2%	13.0%	**7.2%**	3.5%	13.3%	8.1%	**4.4%**
	25	4.6%	16.6%	10.9%	**5.8%**	4.7%	16.7%	10.9%	**5.9%**	4.2%	15.2%	9.7%	**5.3%**
	40	4.0%	14.2%	9.2%	**5.0%**	4.0%	14.2%	9.2%	**5.0%**	3.8%	13.9%	8.9%	**4.8%**
Isolated Lepton	10	3.6%	3.7%	14.7%	**4.1%**	1.0%	1.0%	12.5%	**1.5%**	0.1%	0.2%	11.8%	**0.6%**
	25	1.0%	1.5%	13.0%	**1.6%**	0.3%	0.4%	11.9%	**0.8%**	0.05%	0.07%	11.7%	**0.6%**
	40	1.0%	1.4%	12.6%	**1.6%**	0.3%	0.4%	11.9%	**0.8%**	0.05%	0.07%	11.6%	**0.6%**
Trackless jet	10	0.02%	0.04%	0.04%	**0.02%**	0.8%	1.5%	1.3%	**0.9%**	2.0%	2.4%	2.2%	**2.0%**
	25	0.02%	0.04%	0.06%	**0.02%**	0.5%	1.0%	0.8%	**0.6%**	3.6%	5.9%	5.0%	**3.8%**
	40	0.01%	0.02%	0.03%	**0.01%**	0.1%	0.2%	0.2%	**0.1%**	2.1%	4.1%	3.3%	**2.3%**

A benchmark: Higgs decays into LLPs



C. Csaki, E. Kuflik, S. Lombardo, O. Slone, [1508.01522]

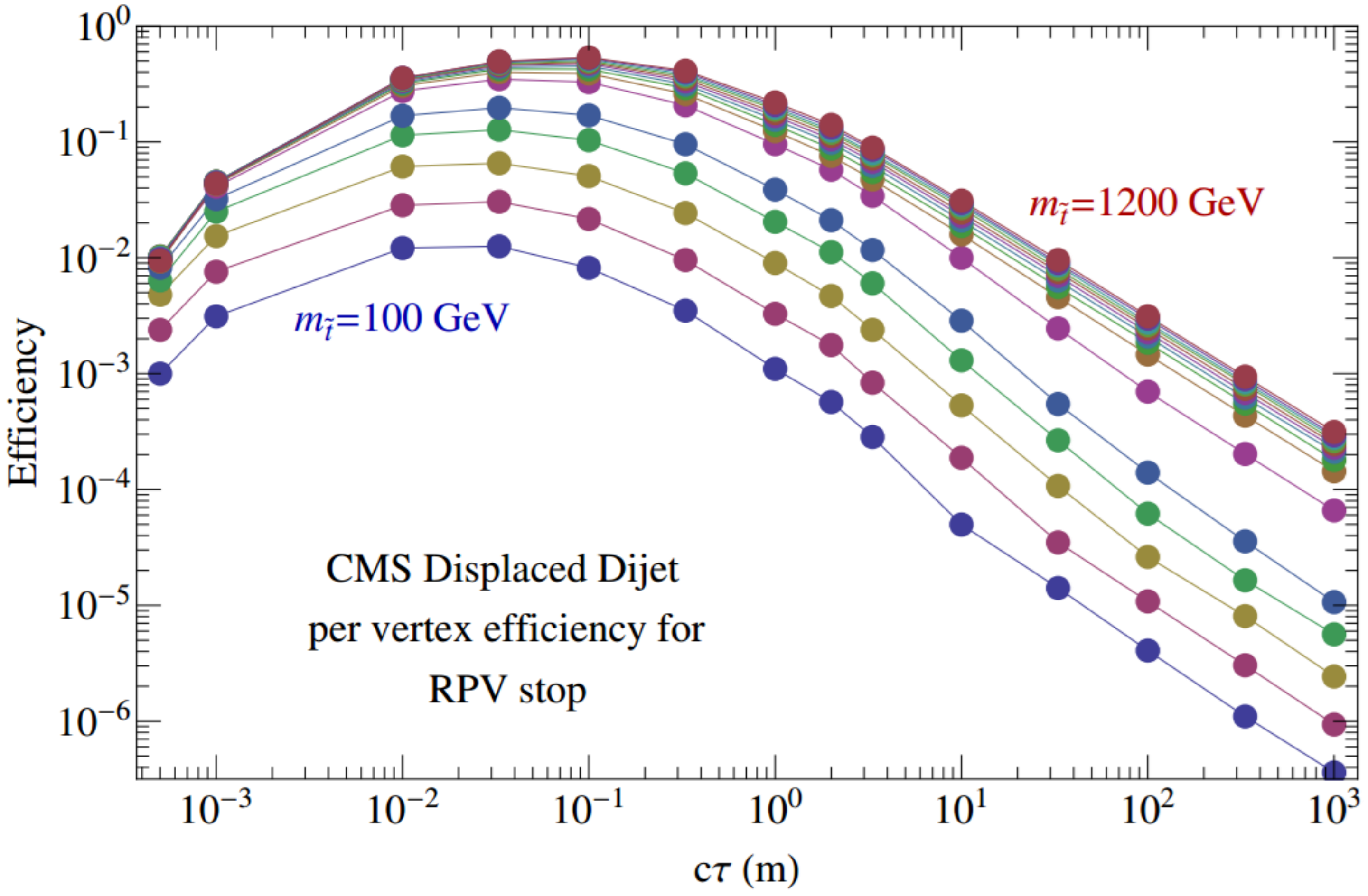
- ATLAS Muon spectrometer searches Higgs trigger efficiency (pioneers of LLP trigger)
- having 1K background at 8 TeV or O(100K) at HL-LHC background for single displaced LLP, requires double tagged LLPs to suppress the background

- CMS Displaced vertices search having low trigger efficiency;
- CMS Displaced vertices search low reconstruction efficiency;
- O(few) background for single tagged LLP, scaling better for higher lifetime

(A)Typical Efficiency Map

Efficiency map for RPV stop decays into light jet pairs in the CMS displaced dijet analysis.

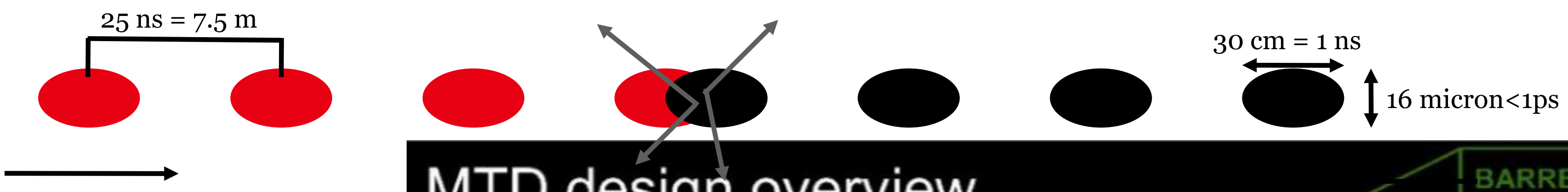
- Lines at increase of 100 GeV
- Low mass suffers more for cuts on jet energy
- High mass approaches constant efficiency shape
- Low efficiency at low lifetime (cut to remove SM)
- (Shift in peak due to Lorentz Factor)



ZL, B. Tweedie, 1503.05923

Detector with timing information

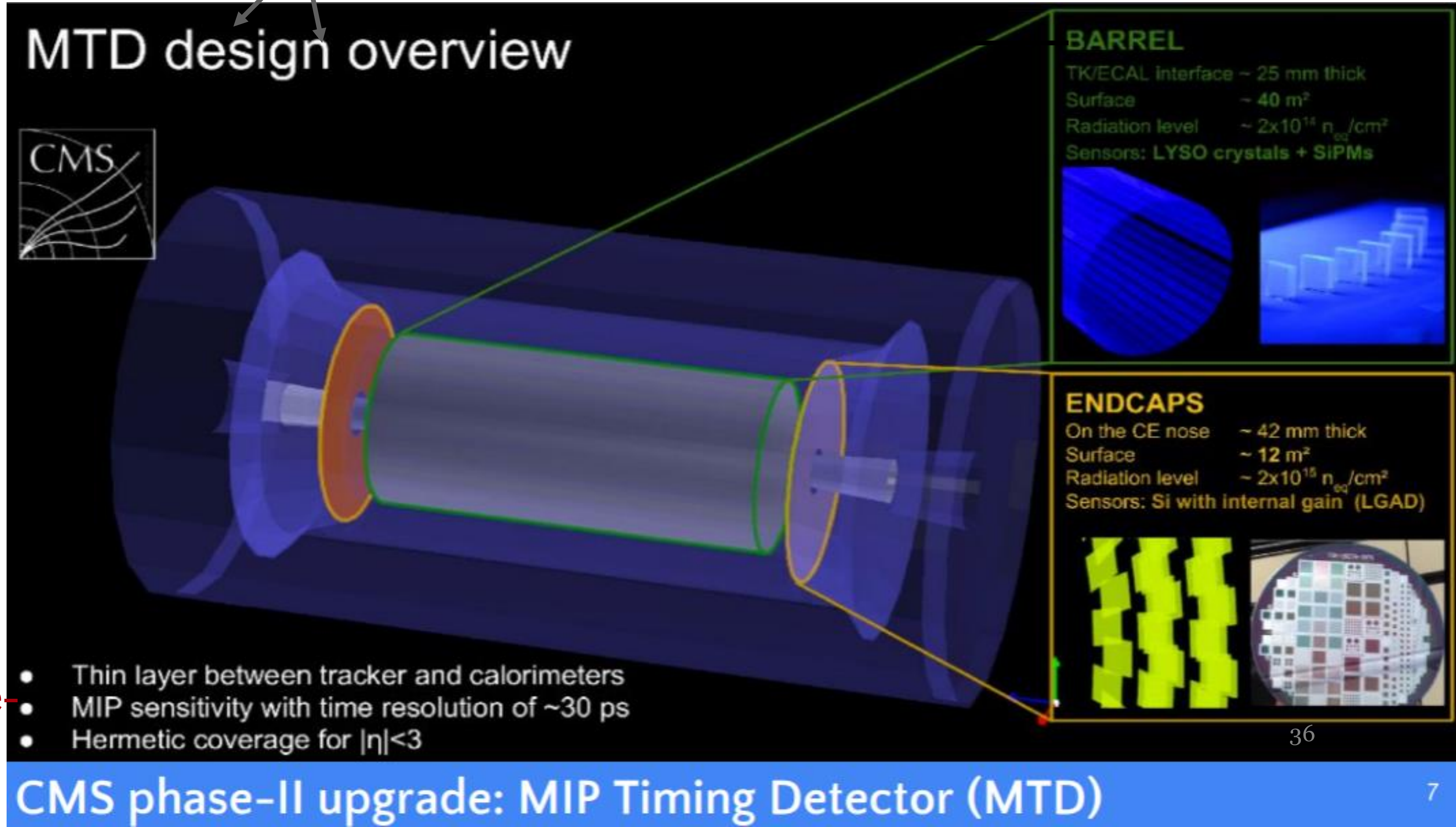
- Detector needs timing information to record event



CMS Phase-II upgrade:
MIP Timing Detector(MTD) both barrel and endcap

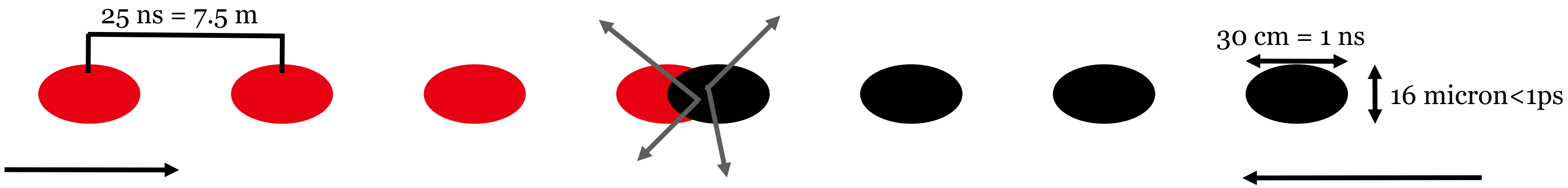
With 30 ps timing resolution, enable 4d reconstruction

Aim for reducing pile-up



Detector with timing information

- Detector needs timing information to record event



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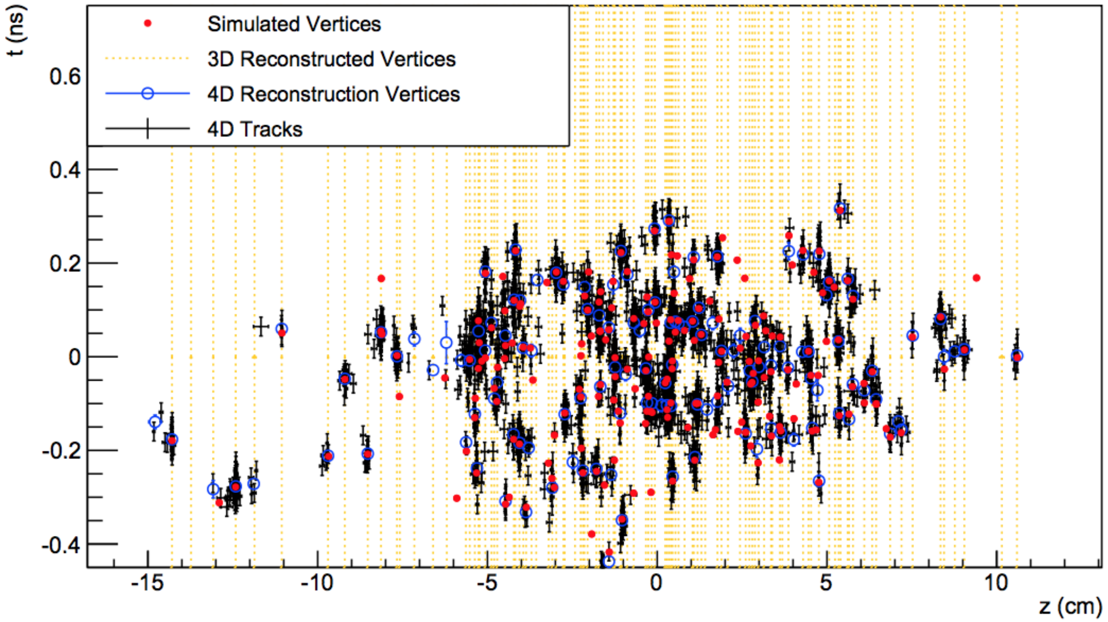
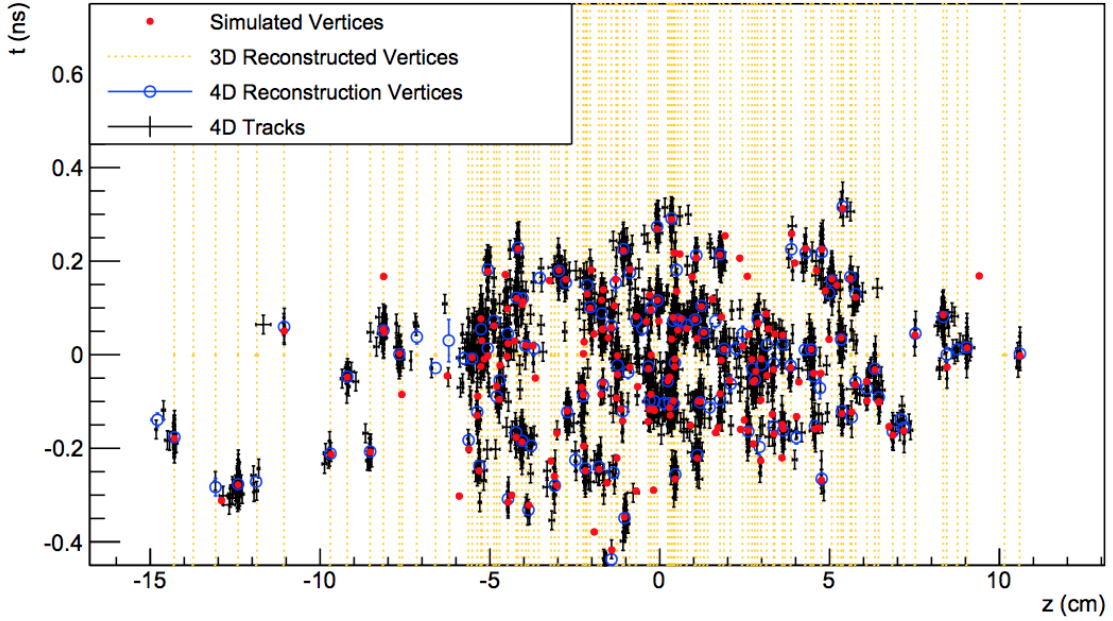
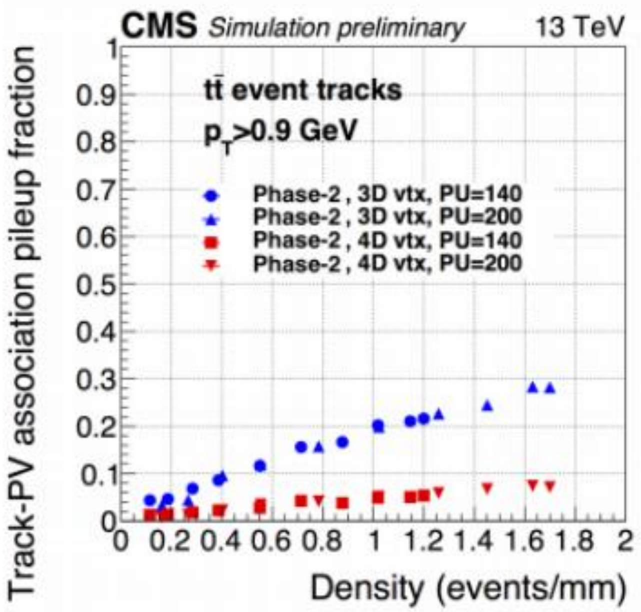


Detector with timing information

- CMS Phase-II upgrade:
  MIP Timing Detector
  both barrel and endcap

  - With 30 ps timing resolution, enable
  - Aim for reducing pile-up





TECHNICAL PROPOSAL FOR A MIP TIMING

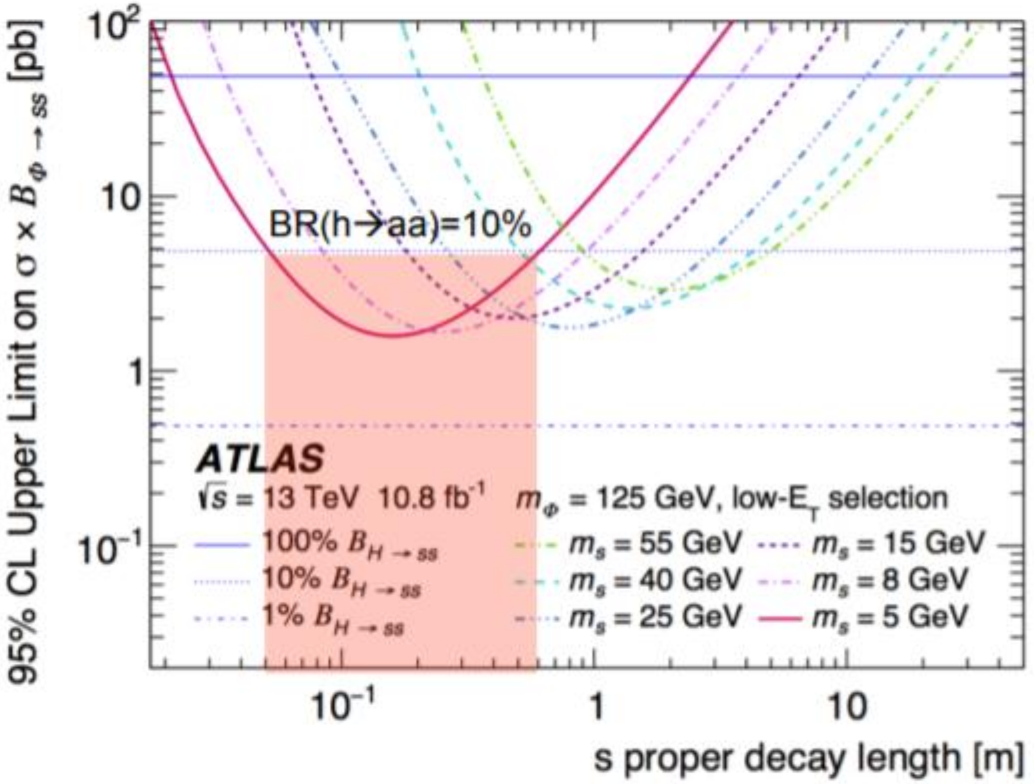
DETECTOR IN THE CMS EXPERIMENT

PHASE 2 UPGRADE

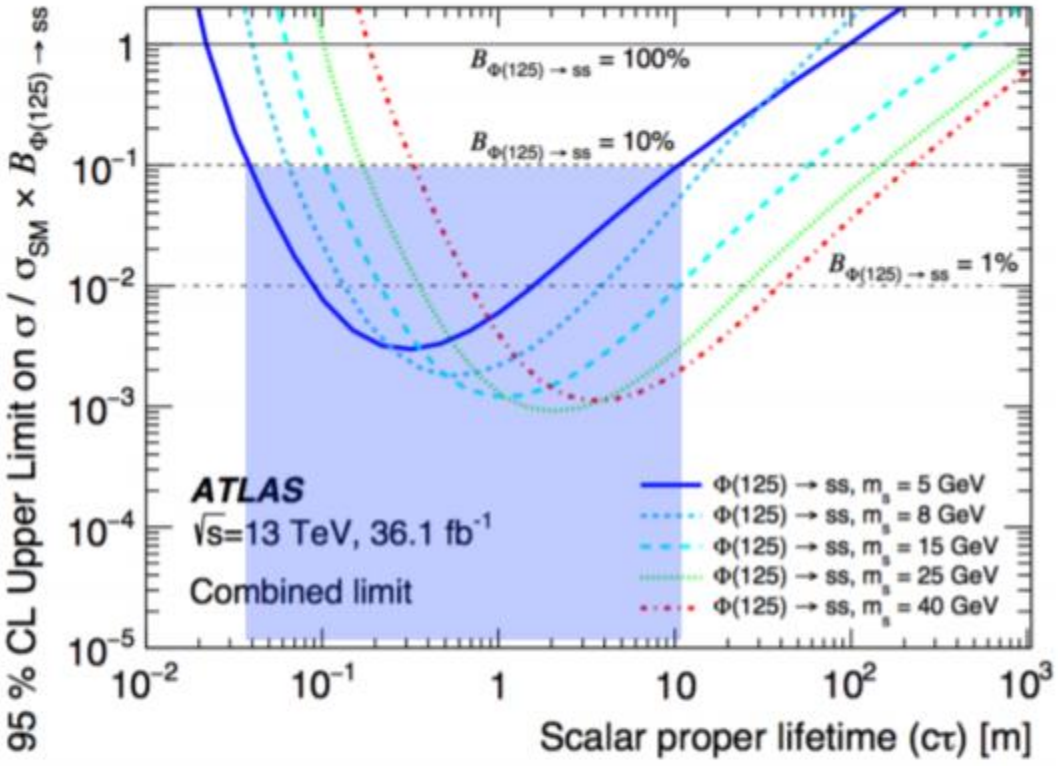
https://cds.cern.ch/record/2296612

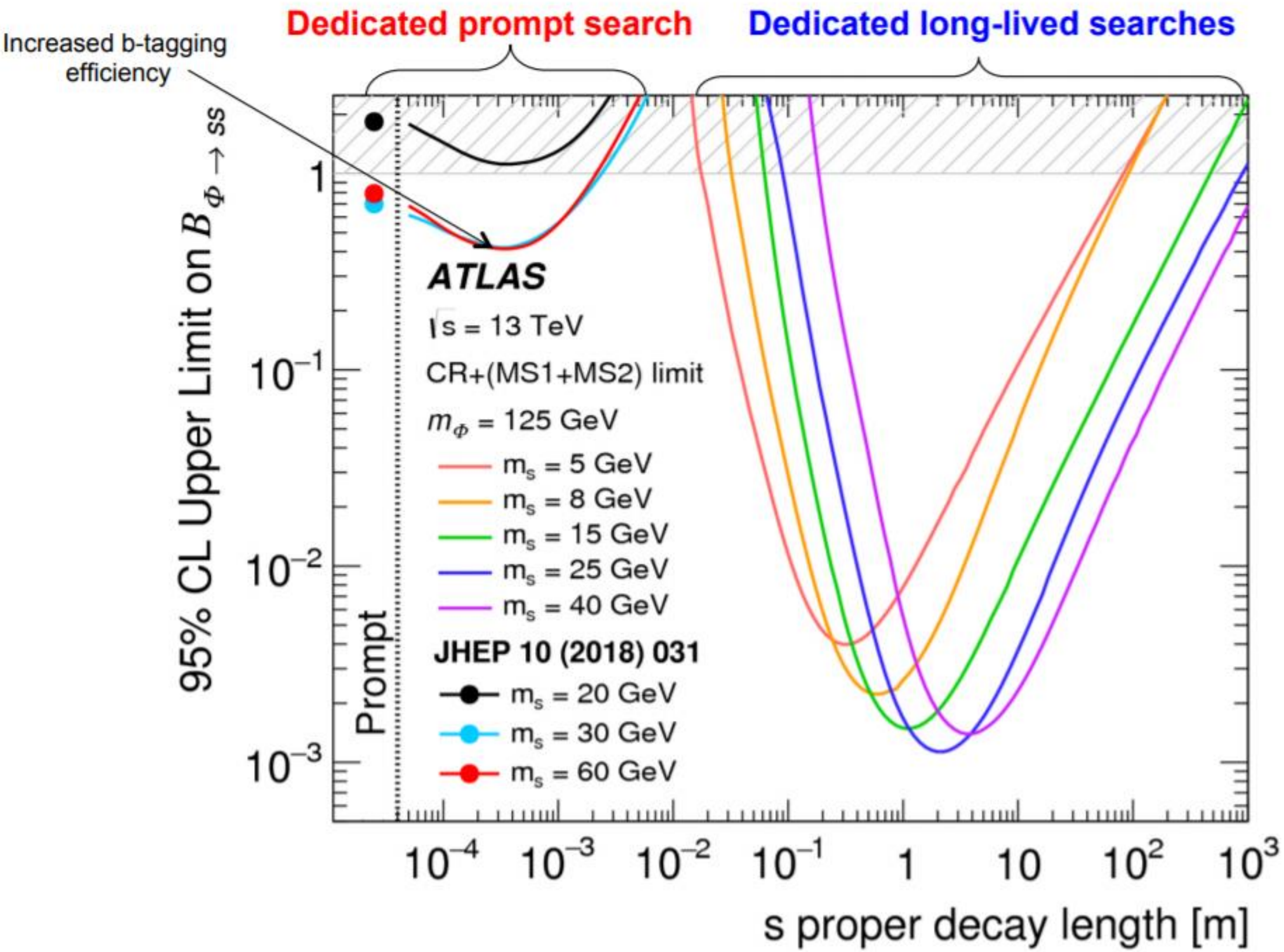
ATLAS and LHCb are also considering
timing detectors.
ATLAS: HGTD

arXiv:1902.03094



arXiv:1811.07370





Increased b-tagging efficiency
Dedicated prompt search
Dedicated long-lived searches
95% CL Upper Limit on $B_{\Phi \to ss}$
ATLAS
$\sqrt{s}$ = 13 TeV
CR+(MS1+MS2) limit
m_{Φ} = 125 GeV
m_s = 5 GeV
m_s = 8 GeV
m_s = 15 GeV
m_s = 25 GeV
m_s = 40 GeV
JHEP 10 (2018) 031
m_s = 20 GeV
m_s = 30 GeV
m_s = 60 GeV
Prompt
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
10
10^{2}
10^{3}
s proper decay length [m]