Search for Long Lived Particles
A theory overview

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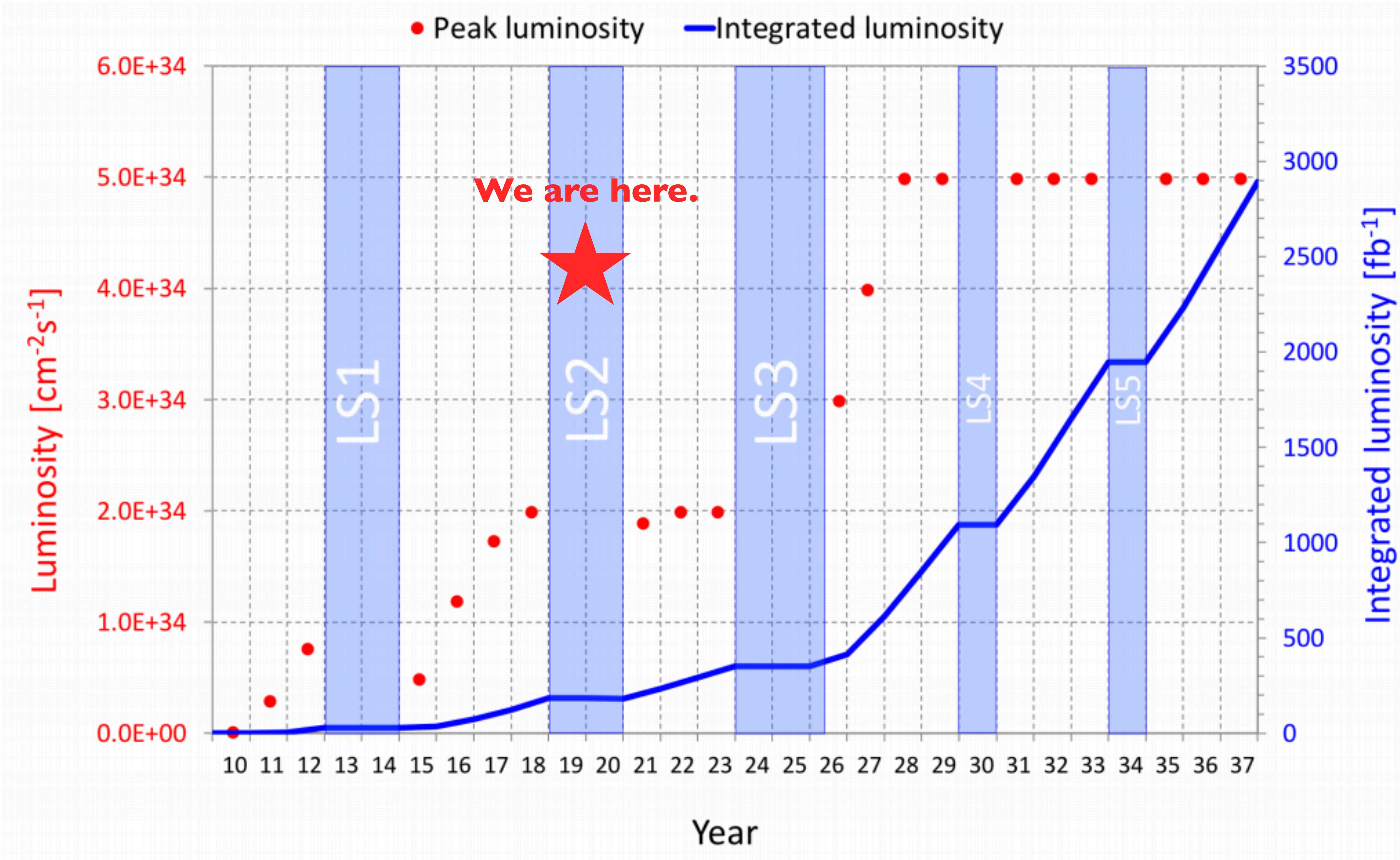
U. Chicago

5th workshop on LLP searches, CERN May 27, 2019



Peak luminosity
Integrated luminosity
We are here.
Luminosity [cm-2s-1]
Integrated luminosity [fb-1]
6.0E+34
5.0E+34
4.0E+34
3.0E+34
2.0E+34
1.0E+34
0.0E+00
3500
3000
2500
2000
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LS1
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LS4
LS5
10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37
Year

LHC is pushing ahead.

Exp. collaborations are pursuing a broad and comprehensive physics program: SUSY, composite H, extra Dim, etc.

New directions

The potential of a lot of data

- Very rare signal
  - E.g. dark sector, rare decays, ...
- Data can help with reducing systematics
  - Precision measurements.

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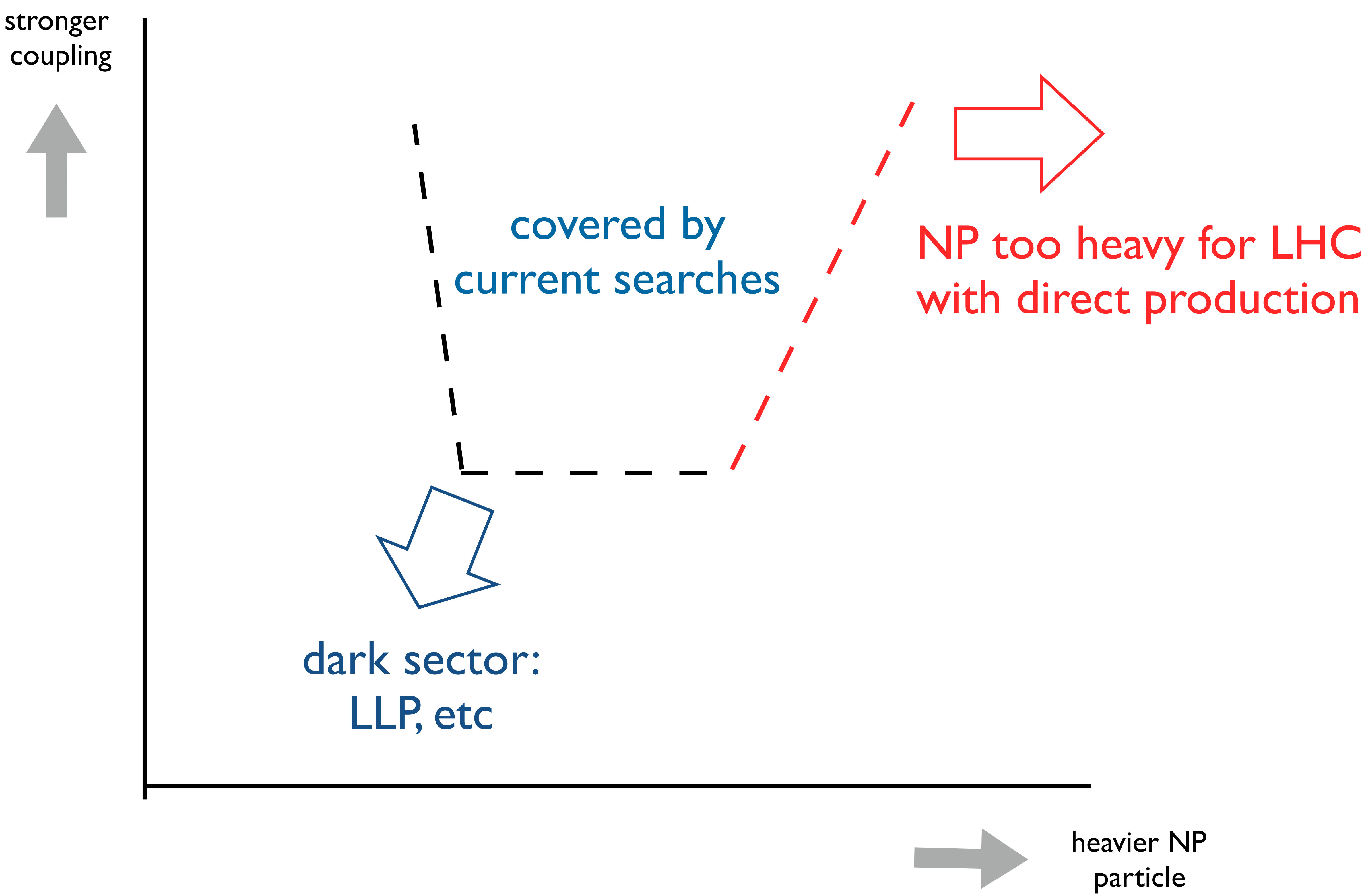
An important example:
Long lived particles

LLP: Largely unexplored territory



Great motivation to fully explore!

My talk

- A theory overview: models...

Well documented

Searching for long-lived particles beyond the Standard Model
at the Large Hadron Collider

March 6, 2019

Particles beyond the Standard Model (SM) can generically have lifetimes that are long compared to SM particles at the weak scale. When produced at experiments such as the Large Hadron Collider (LHC) at CERN, these long-lived particles (LLPs) can decay far from the interaction vertex of the primary proton-proton collision. Such LLP signatures are distinct from those of promptly decaying particles that are targeted by the majority of searches for new physics at the LHC, often requiring customized techniques to identify, for example, significantly displaced decay vertices, tracks with atypical properties, and short track segments. Given their non-standard nature, a comprehensive overview of LLP signatures at the LHC is beneficial to ensure that possible avenues of the discovery of new physics are not overlooked. Here we report on the joint work of a community of theorists and experimentalists with the ATLAS, CMS, and LHCb experiments — as well as those working on dedicated experiments such as MoEDAL, milliQan, MATHUSLA, CODEX-b, and FASER — to survey the current state of LLP searches at the LHC, and to chart a path for the development of LLP searches into the future, both in the upcoming Run 3 and at the High-Luminosity LHC. The work is organized around the current and future potential capabilities of LHC experiments to generally discover new LLPs, and takes a signature-based approach to surveying classes of models that give rise to LLPs rather than emphasizing any particular theory motivation. We develop a set of simplified models; assess the coverage of current searches; document known, often unexpected backgrounds; explore the capabilities of proposed detector upgrades; provide recommendations for the presentation of search results; and look towards the newest frontiers, namely high-multiplicity "dark showers", highlighting opportunities for expanding the LHC reach for these signals.

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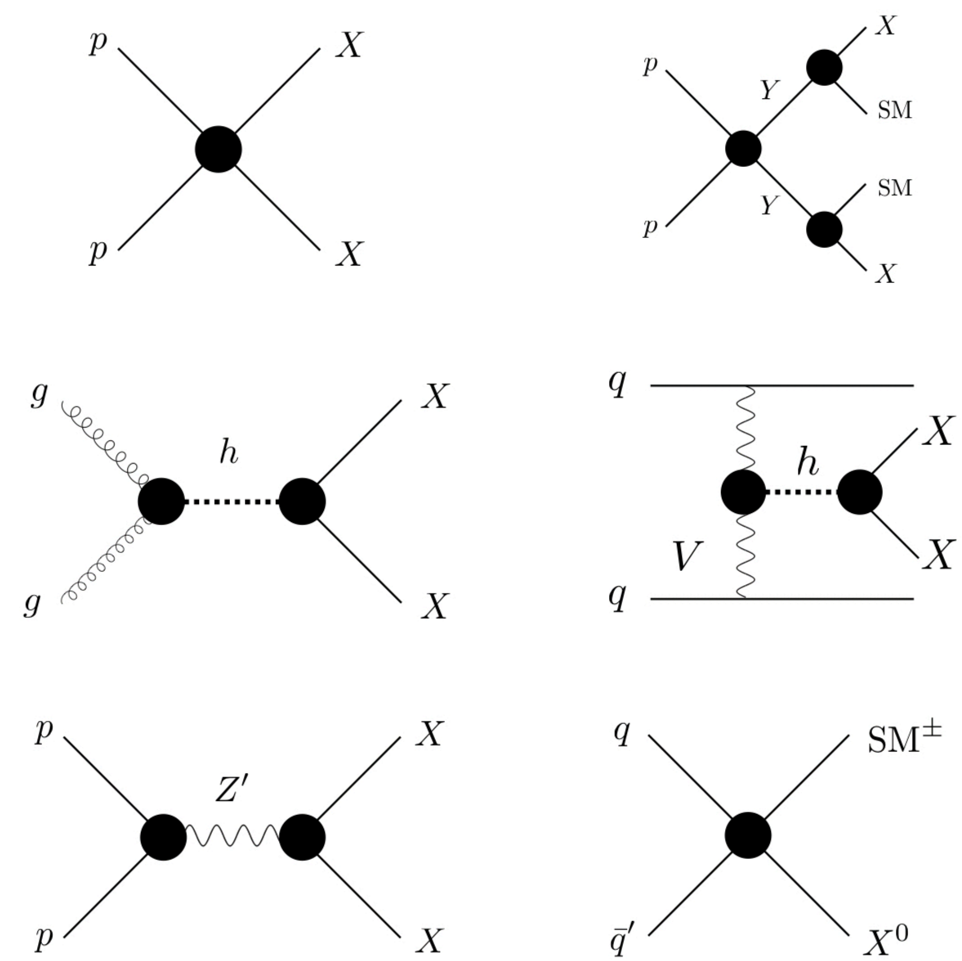
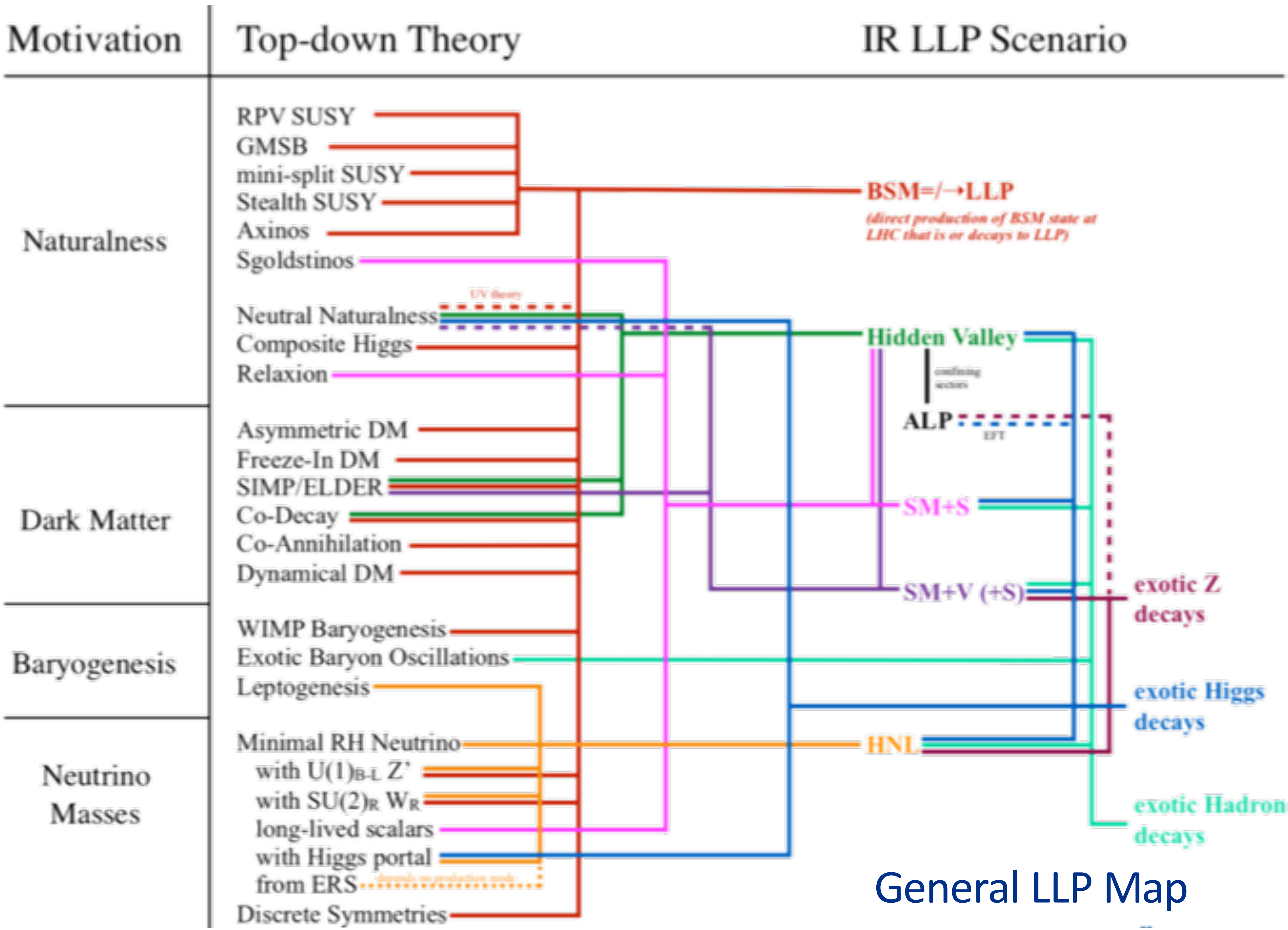


Simplified models, channels, signatures...

tons of models



General LLP Map

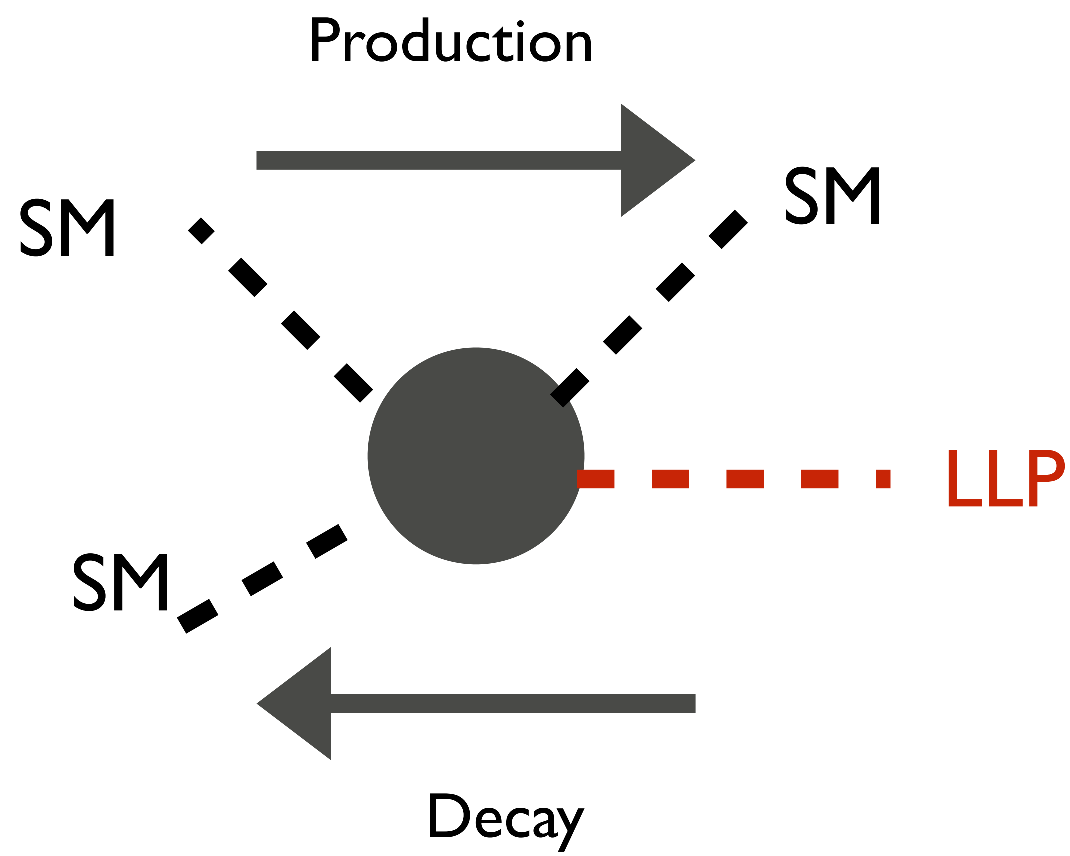
My talk

- Instead of reading the white paper to you...
- I review some estimates, reflect some (my) theory bias
  - What kind of life time we expect?
  - A lot of tuning, tricks?
- A theorist's view of experimental probes.
  - Direction for further developments.

Theory considerations (biases)

- Of course, anything is possible. But:
- TeV new physics is somehow involved in bridging the SM and the LLPs
    - Good physics motivation, TeV close to EW scale.
- LLP needs small coupling. But small number happens usually for some reason.
    - Something to do with dark matter? Dark means small coupling.
    - Neutrino mass? Small mass, small coupling.
    - Additional symmetries

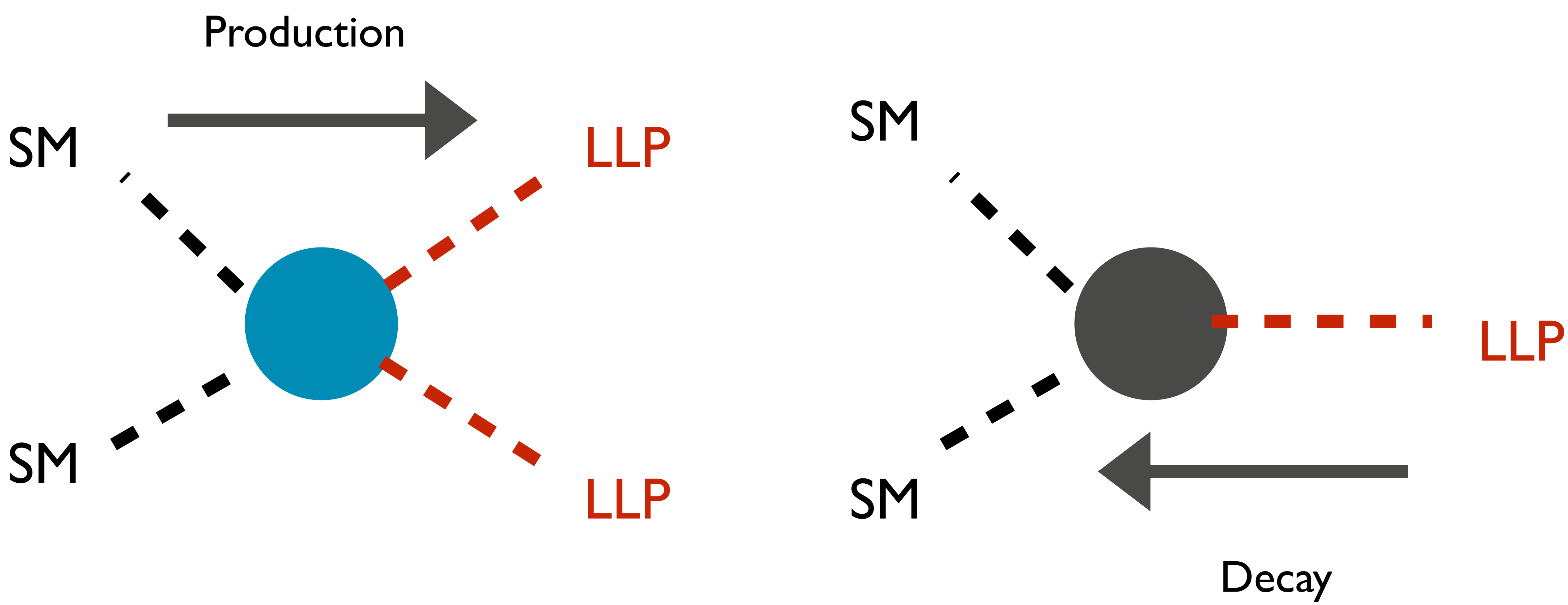
Production vs decay



Simplest model, one effective coupling

Can be difficult to have sufficient rate while maintaining long life time.

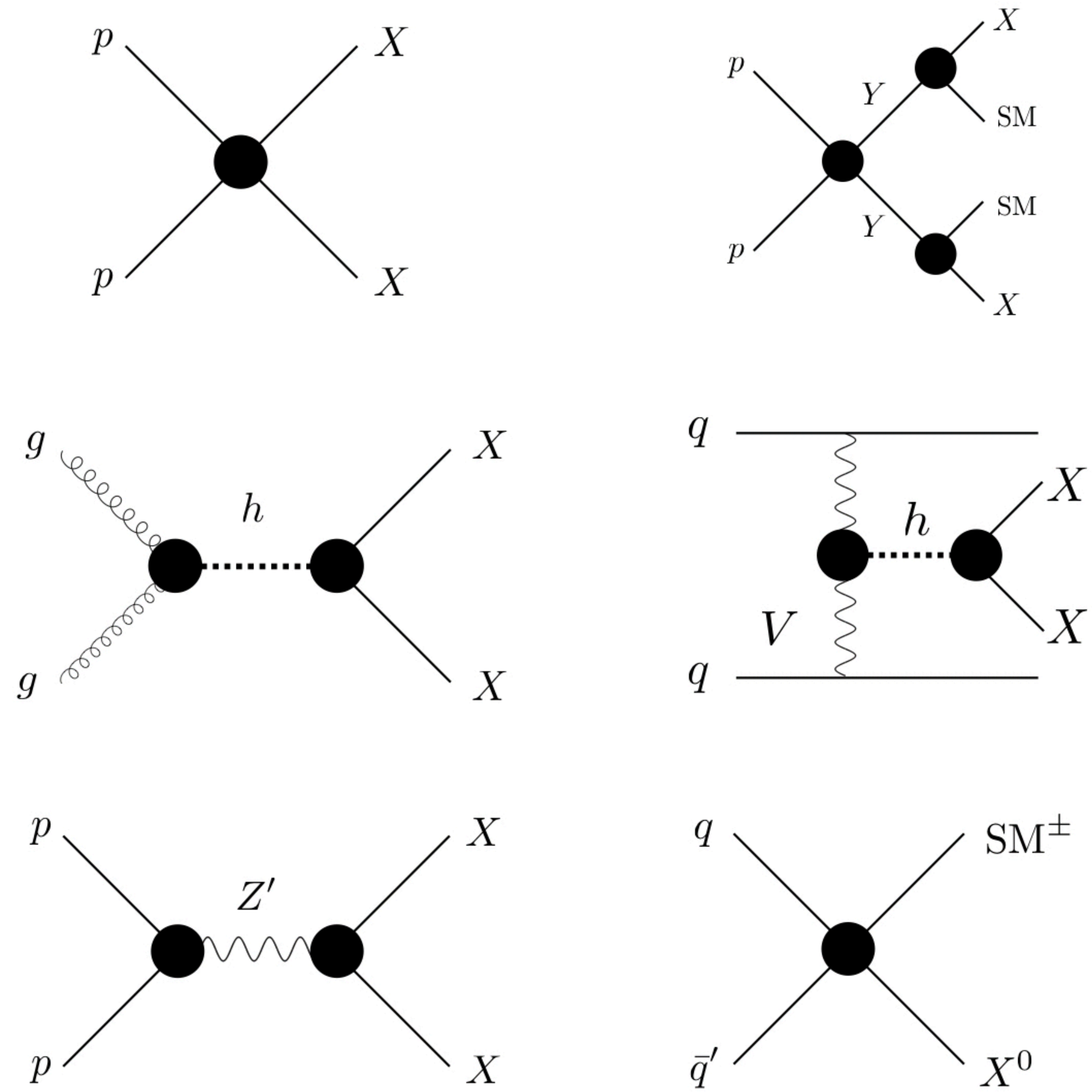
Production vs decay



More ideal, separate production and decay.

Pair production. Otherwise same coupling leads to decay.

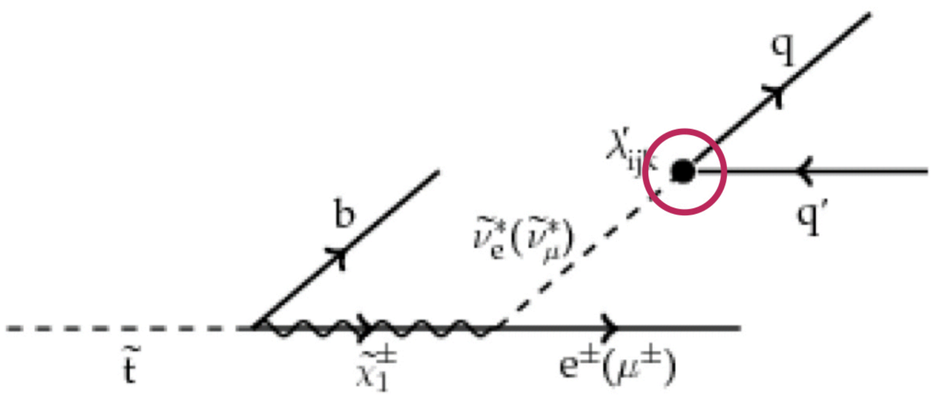
Production benchmarks



Mostly pair production.

LLP carrying SM quantum number

- Similar to SM matter field, generically expected to have renormalizable coupling to SM.
  - Typical example, RPV

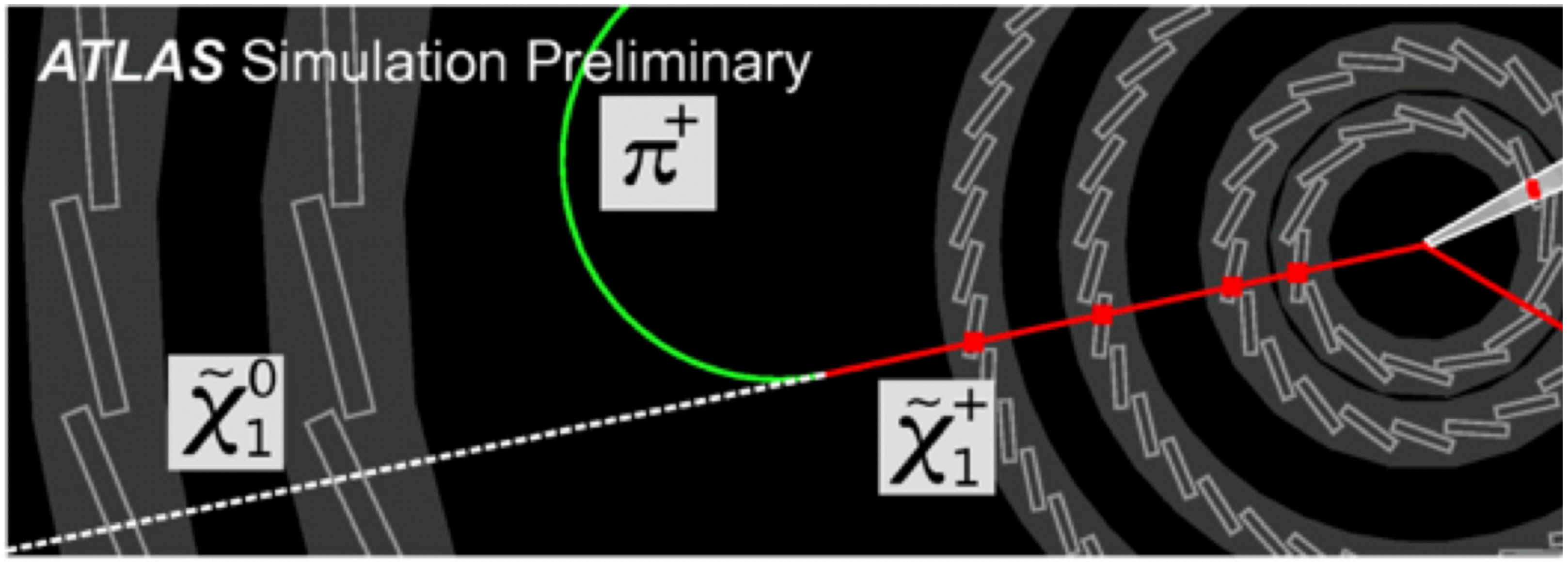


$$c\tau \sim 1 \text{ mm} \left(\frac{10^{-6}}{\lambda}\right)^2 \left(\frac{100 \text{ GeV}}{\text{m}}\right)$$

Need tiny coupling. RPV couplings typically constrained by other considerations.

Long life time possible, probably not very long

Interesting cases I

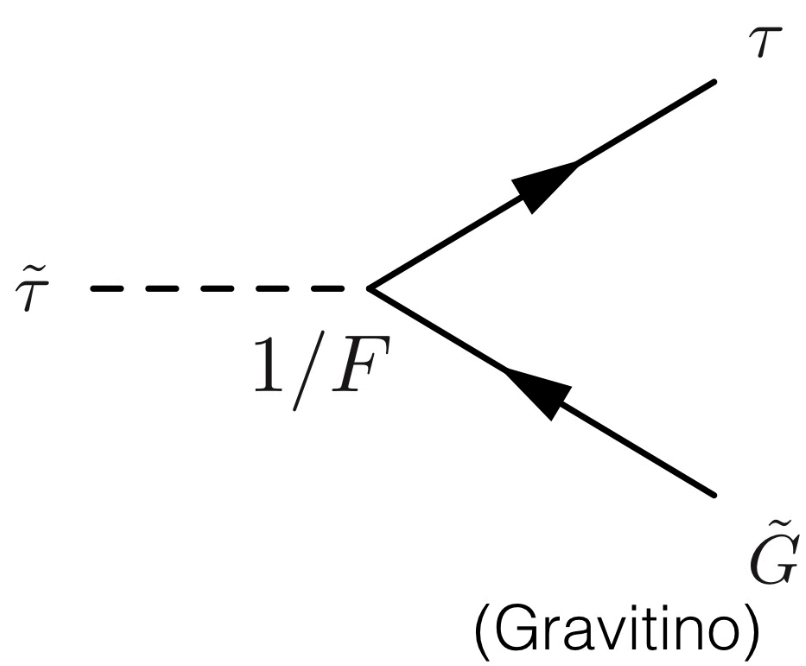


$$c\tau \simeq 1 \text{ cm} \left(\frac{(\mathrm{m}_\pm - \mathrm{m}_0)}{350 \text{ MeV}} \right)^3$$

Charge and neutral particles from a Electroweak triplet (e.g. wino)

Mass differences determined, no tuning and other model dependence.

Interesting cases II



$$c\tau \sim 1\ \mathrm{m} \left(\frac{\sqrt{\mathrm{F}}}{10^3\ \mathrm{TeV}} \right)^4 \left(\frac{100\ \mathrm{GeV}}{\mathrm{m}_{\tilde{\tau}}} \right)^5$$

Life time 10^{-4} - 10^4 m

Gauge mediation. 100 - 10^4 TeV SUSY breaking scale well motivated.

A good LLP candidate with a wide range of possible lifetime!

LLP is a SM singlet

- Many possibilities.
- Couple to SM gauge invariant operators
  - “Portal”s

$$\mathcal{O}_{\rm SM}: \;\; H^\dagger H, \;\; F^{\mu\nu}, \;\; H^\dagger W^{\mu\nu} H, \;\; HL, \;\; J_{\rm U(1)}, \; \ldots$$

$$\mathscr{L}_{\rm SM}, \quad \text{higher order} \ldots$$

Naively

$$X : \mathrm{LLP}\,.\ \mathrm{m_X} = 10\ \mathrm{GeV}, \quad \Lambda = 1\ \mathrm{TeV}$$

$$\mathrm{dim}-6:\ \frac{\mathrm{X}\mathcal{O}_{\mathrm{SM}}}{\Lambda^2} \rightarrow \Gamma \propto \frac{\mathrm{m_X^5}}{\Lambda^4} \rightarrow c\tau \sim 10^{-6}\mathrm{m}$$

$$\mathrm{dim}-7:\ \frac{\mathrm{X}\mathcal{O}_{\mathrm{SM}}}{\Lambda^3} \rightarrow \Gamma \propto \frac{\mathrm{m_X^7}}{\Lambda^6} \rightarrow c\tau \sim 1\mathrm{cm}$$

$$\mathrm{dim}-8:\ \frac{\mathrm{X}\mathcal{O}_{\mathrm{SM}}}{\Lambda^4} \rightarrow \Gamma \propto \frac{\mathrm{m_X^9}}{\Lambda^8} \rightarrow c\tau \sim 10\mathrm{m}$$

- LLP needs dim 7 or higher. A little contrived.
- But, couplings could be further suppressed. Some can even be well motivated.

Higgs portal.

$$\mu X H^\dagger H \quad H = \frac{1}{\sqrt{2}}(v + h)$$

$$\rightarrow \mu v X h \rightarrow \frac{\mu v}{m_h^2} \frac{m_b}{v} X b \bar{b}$$

Last step: integrating out Higgs

At the LHC: $pp \rightarrow h \rightarrow X \ldots, \quad X \rightarrow b\bar{b}$

If $\quad \frac{\mu v}{m_h^2} \frac{m_b}{v} \sim 10^{-7} \ \rightarrow \ c\tau \sim m$

- Too small a mixing with the Higgs?

A class of model

$$\mathscr{L} \supset \frac{\hat{\alpha}}{6\pi}\frac{v}{f}\frac{h}{f}\hat{G}^{\mu\nu}\hat{G}_{\mu\nu}$$

Dark sector dark QCD. Higgs couples to dark QCD through TeV new physics.

$\hat{\alpha}$: dark QCD coupling, $f \sim$ TeV $\sim m_{\mathrm{NP}}$, v/f : Higgs NP mixing

Dark QCD confines around m_0 = 10 GeV,
produces bound states X (e.g. glueball).

$$m_X \sim m_0 \sim 10\ \mathrm{GeV}$$

A class of model

$$\mathscr{L} \supset \frac{\hat{\alpha}}{6\pi}\frac{v}{f}\frac{h}{f}\hat{G}^{\mu\nu}\hat{G}_{\mu\nu}$$

$\hat{\alpha}$: dark QCD coupling, $f \sim$ TeV $\sim m_{\mathrm{NP}}$, v/f : Higgs NP mixing

$$\frac{\mu v}{m_h^2}\frac{m_b}{v} \sim \frac{1}{8\pi^2}\frac{m_b}{v}\frac{m_0^3}{f \cdot m_h^2} \sim 10^{-8} \qquad c\tau \simeq 18\mathrm{m} \times \left(\frac{10\ \mathrm{GeV}}{m_0}\right)^7 \left(\frac{f}{750\ \mathrm{GeV}}\right)^4$$

$$BR(h \to \text{dark glueballs}) < 1\,\%$$

A bit model building, but not so unreasonable

Signal pretty generic: hidden valley, twin Higgs...

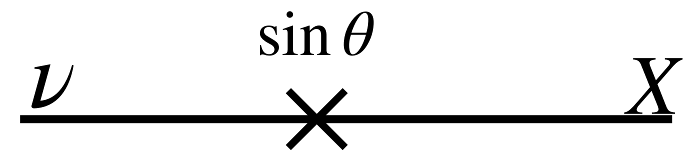
Other LLPs with small mixings to Higgs: ALPs, relaxion, extra-singlet...
With various degrees of motivation. Similar signal.

Neutrino

$$\mathcal{O}_{\text{SM}} = HL$$

See-Saw model

$$\lambda_\nu XHL + MX^c X + h.c.$$



$$\text{Basic See}-\text{Saw}: \ \sin^2\theta = 10^{-12}\left(\frac{m_\nu}{0.01\ \text{eV}}\right)\left(\frac{10\ \text{GeV}}{m_X}\right)$$

Larger mixing possible for extended models: inverse, linear...

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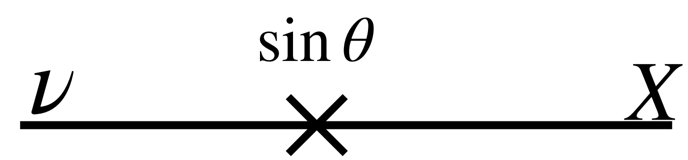

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Larger mixing possible for extended models: inverse, linear...

$$c\tau \simeq 1\ \text{m} \times \left(\frac{10^{-8}}{\sin^2\theta}\right)\left(\frac{10\ \text{GeV}}{m_X}\right)^5$$

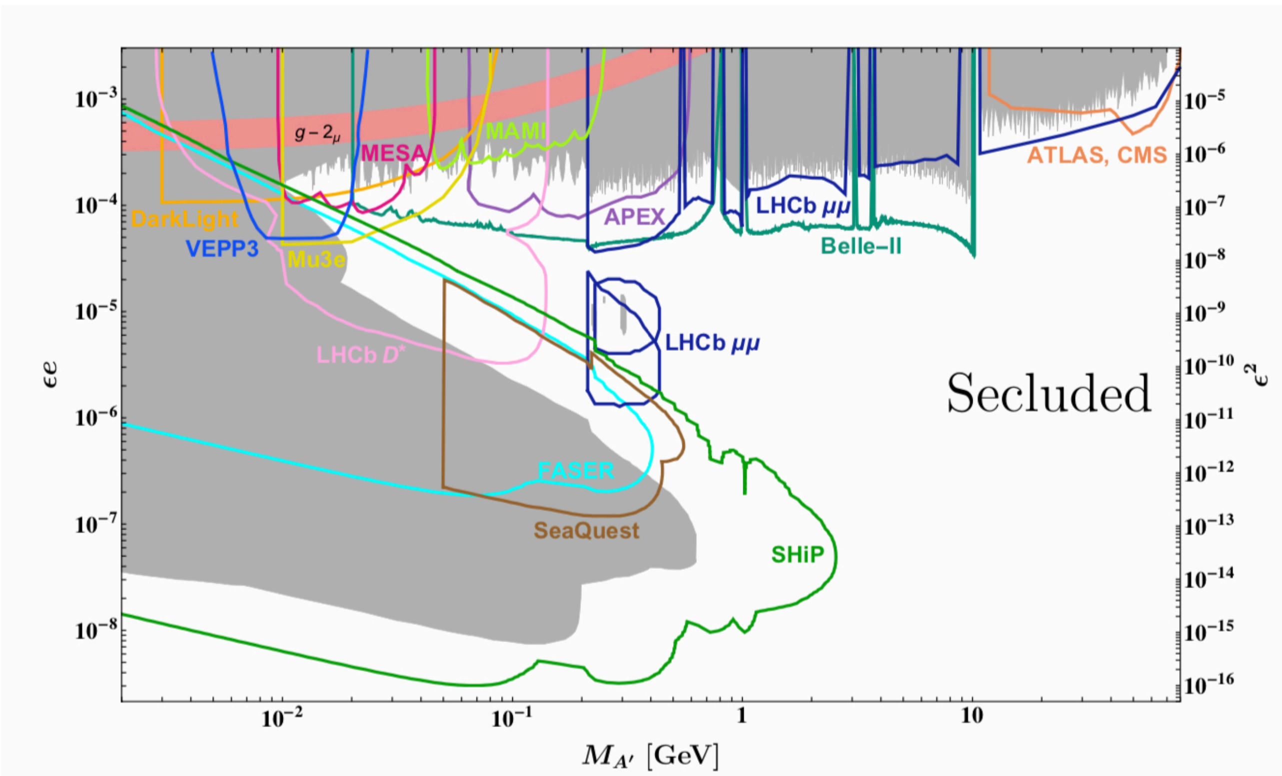
$$3\ \text{ab}^{-1} \times \sigma(pp \to W^\pm)\cdot BR(W^\pm \to \ell^\pm X) \simeq 2\times 10^3\left(\frac{\sin^2\theta}{10^{-8}}\right)$$

With trade-off between production and decay, LLP signal possible.

Difficult to reach the basic see saw model due to low production rate.

Dark photon

$$\mathscr{O}_{\rm SM} = F^{\mu\nu},\ J_{\rm U(1)} \quad \to \quad \mathscr{L} \supset \epsilon F^{\mu\nu} F'_{\mu\nu},\ \epsilon A' J_{\rm U(1)}$$



Bauer, Foldenauer, Jaeckel, 1803.05466

$$c\tau \sim 1\ \text{cm} \left(\frac{10^{-5}}{\epsilon}\right)^2 \left(\frac{m_{A'}}{\text{GeV}}\right)$$

Typically, coupling loop induced $\epsilon \sim 10^{-3\div4}$

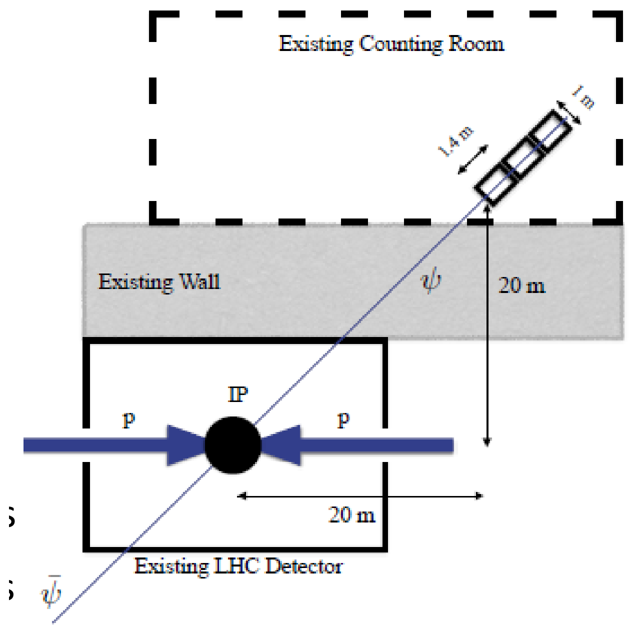
LLP signal possible (on the shorter side)

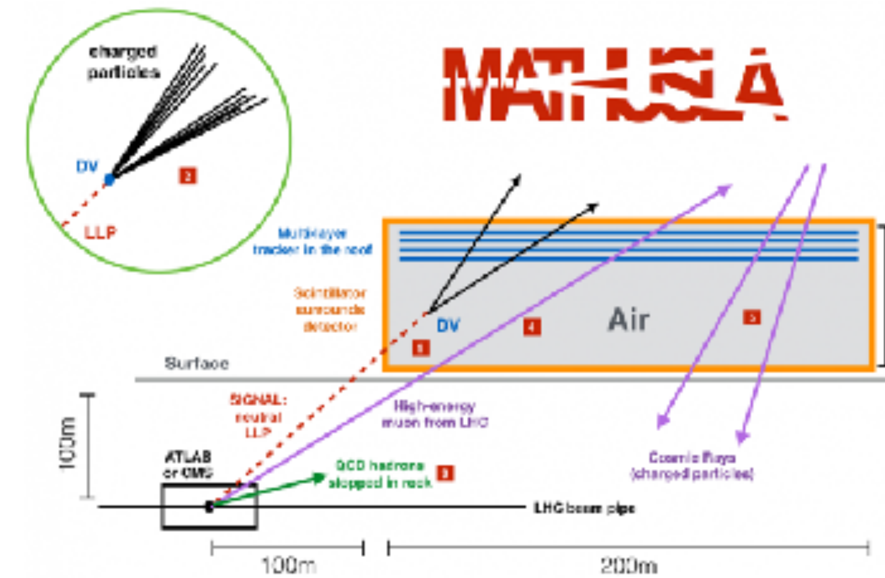
Lessons from models

- Simple motivations and relatively simple setups lead to models with LLPs.
  - Not inevitable, but quite generic.
- Covers a range of lifetimes (1 cm - 10^4 km), and GeV-ish masses (LHC can probe).
- Rich final states: bb, jj, met, lepton, etc.

Directions of experimental searches

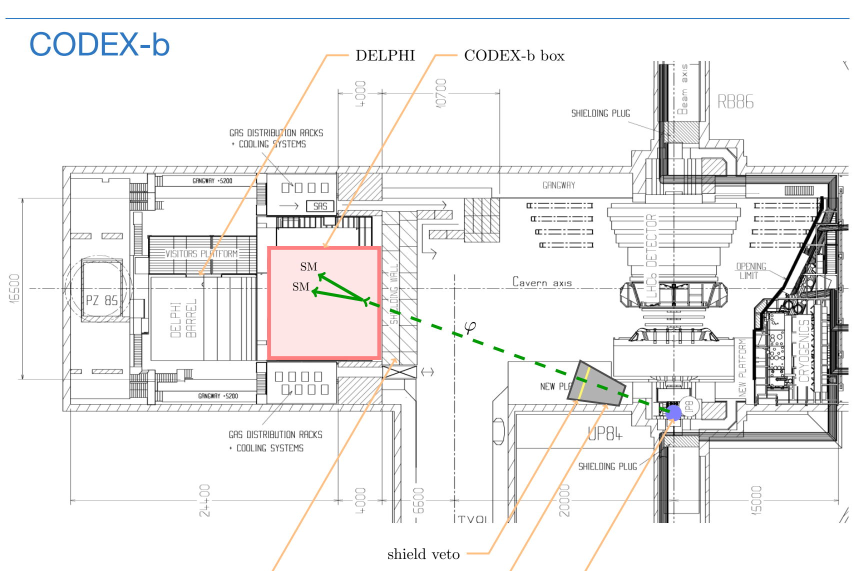
Far detectors

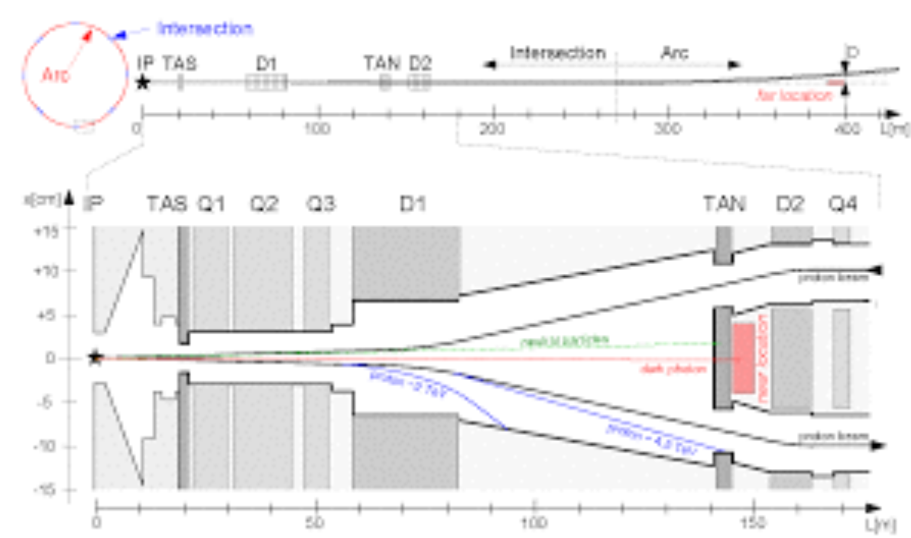




MATHUSLA

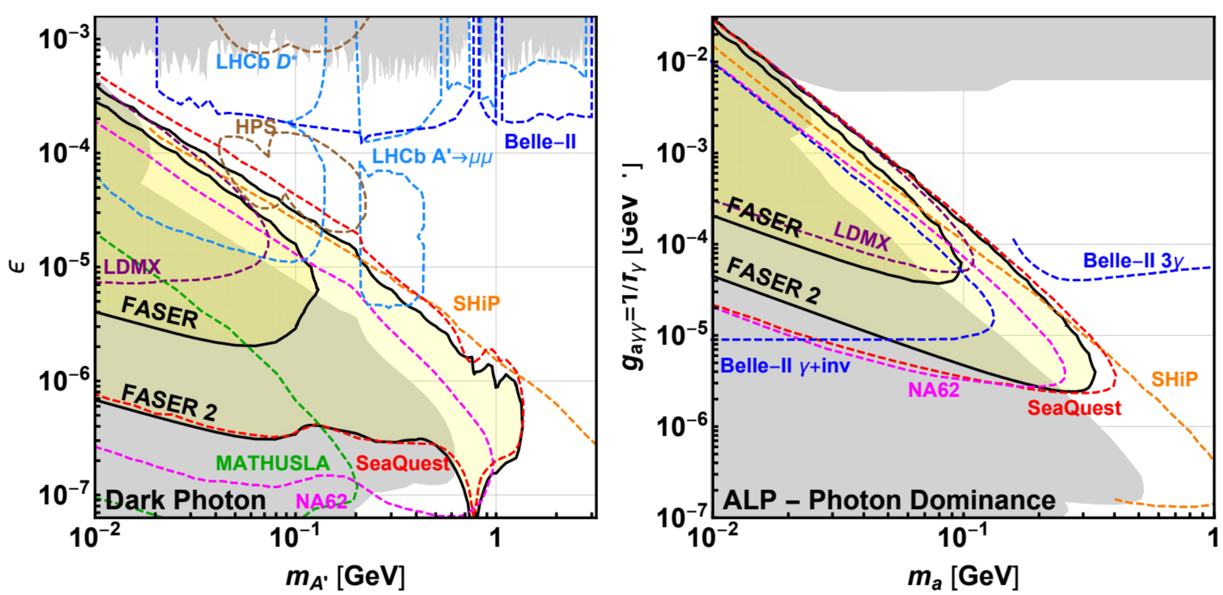
new detectors far
away from the interaction region

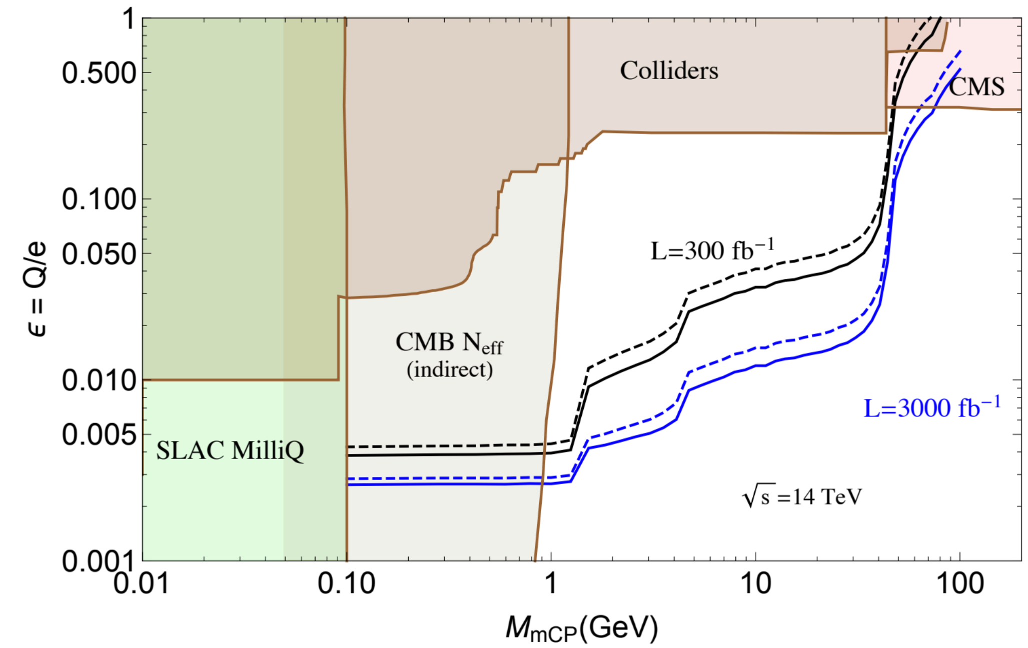


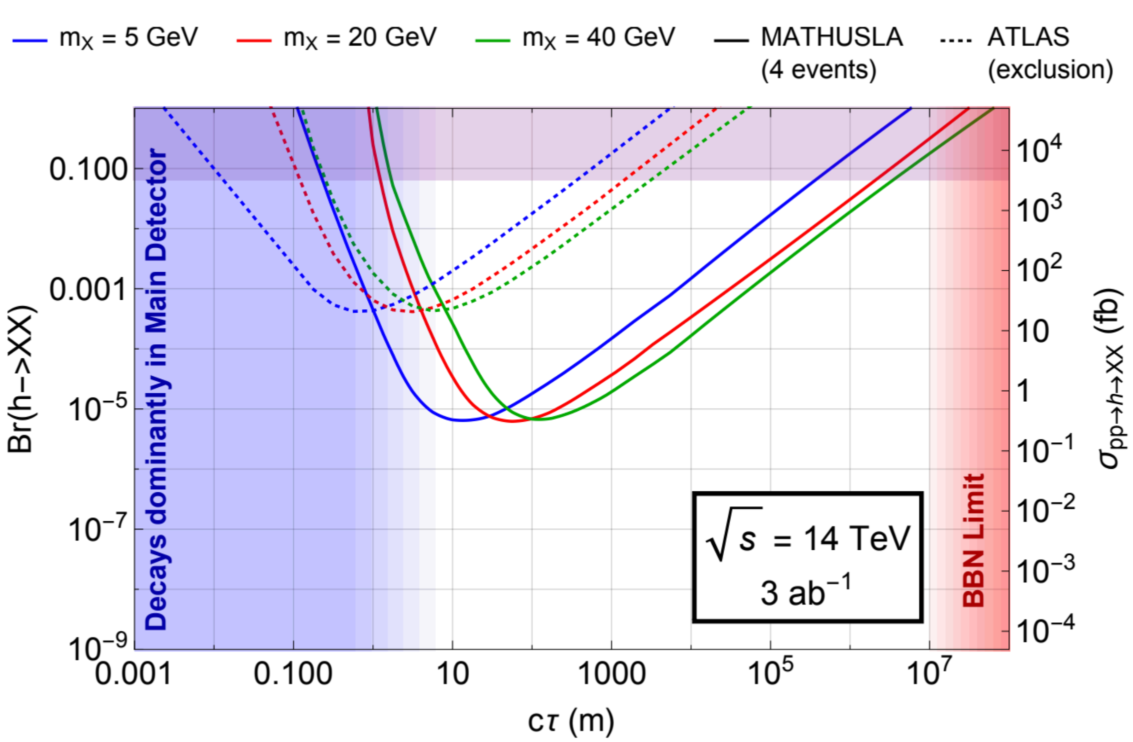


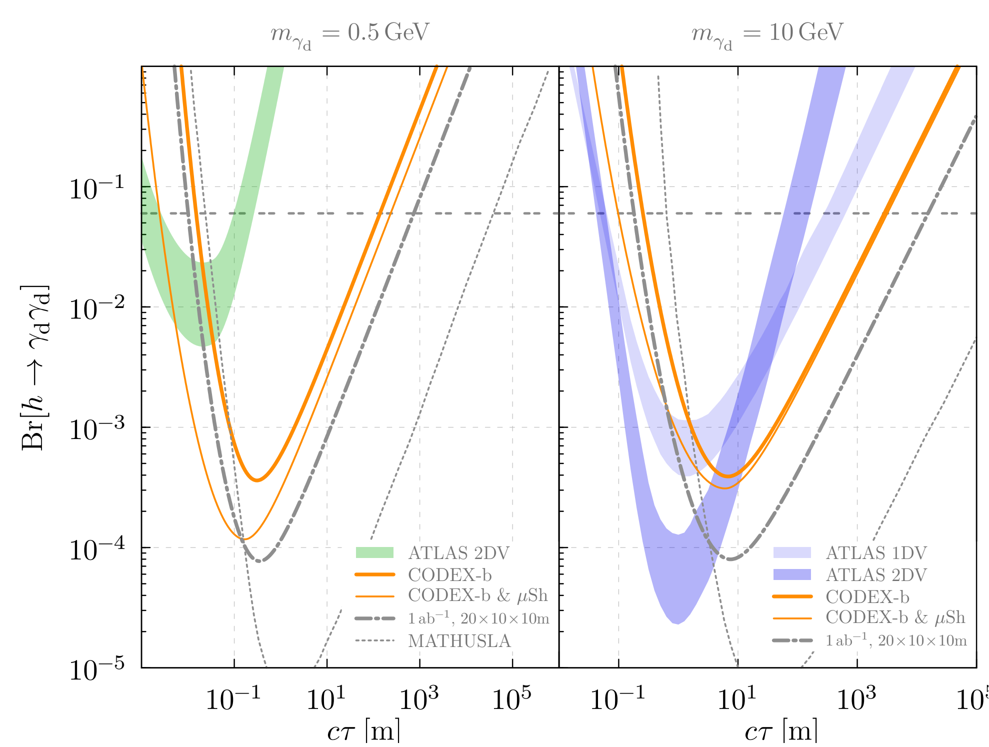
FASER

Broad coverage in mass and coupling

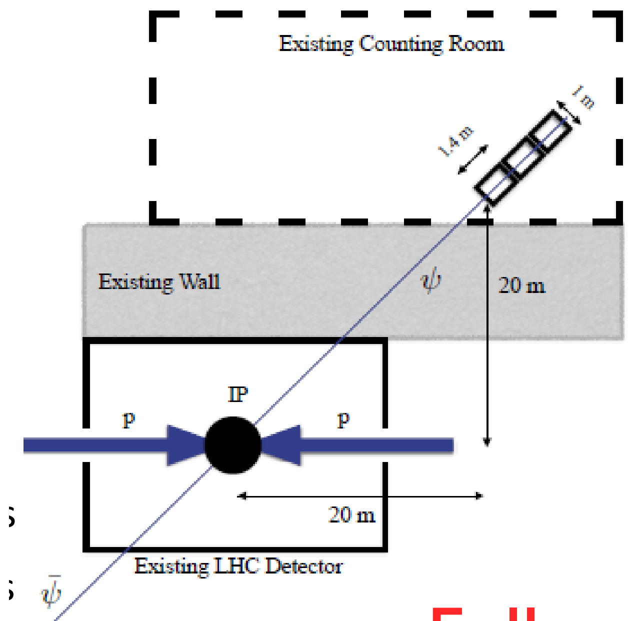


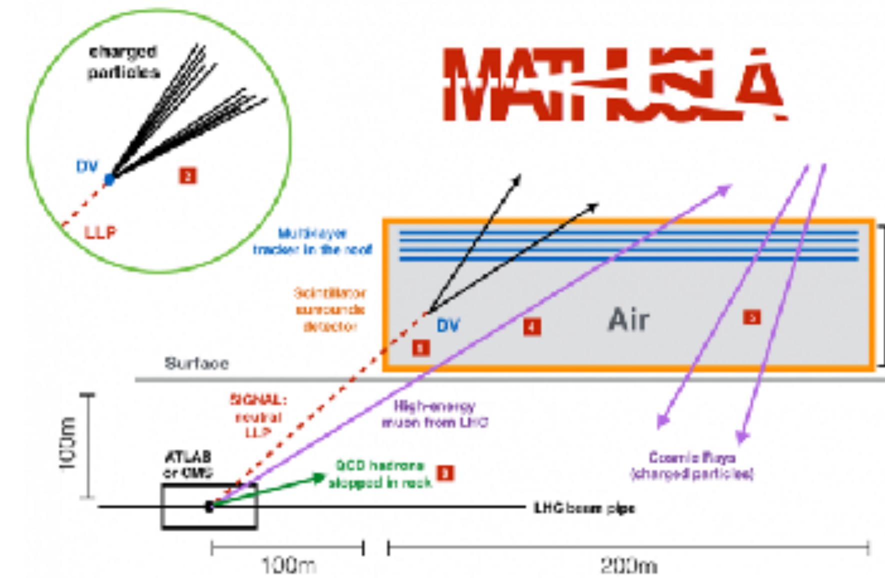






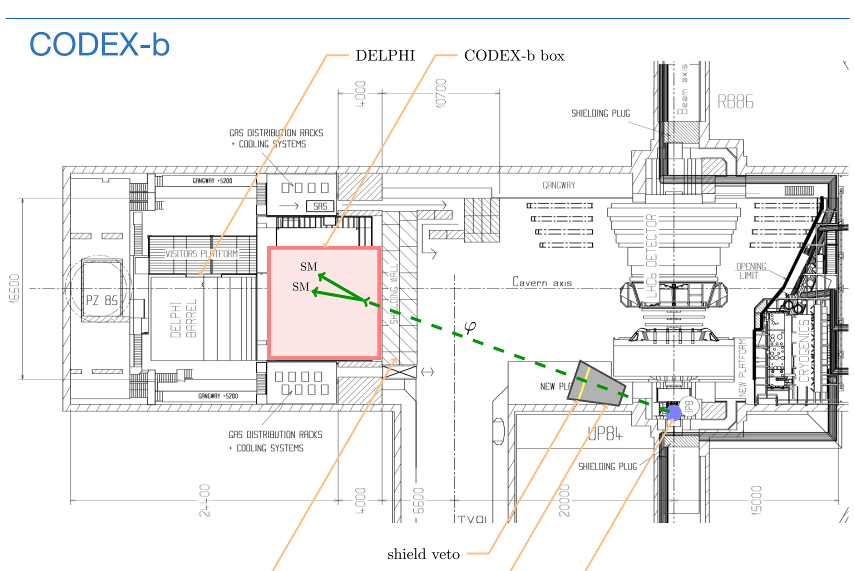
Far detectors

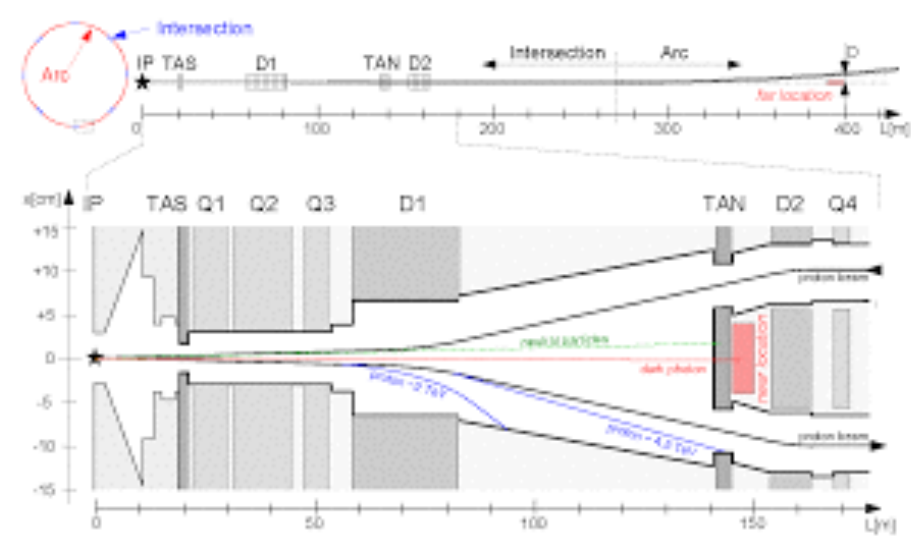




MATHUSLA

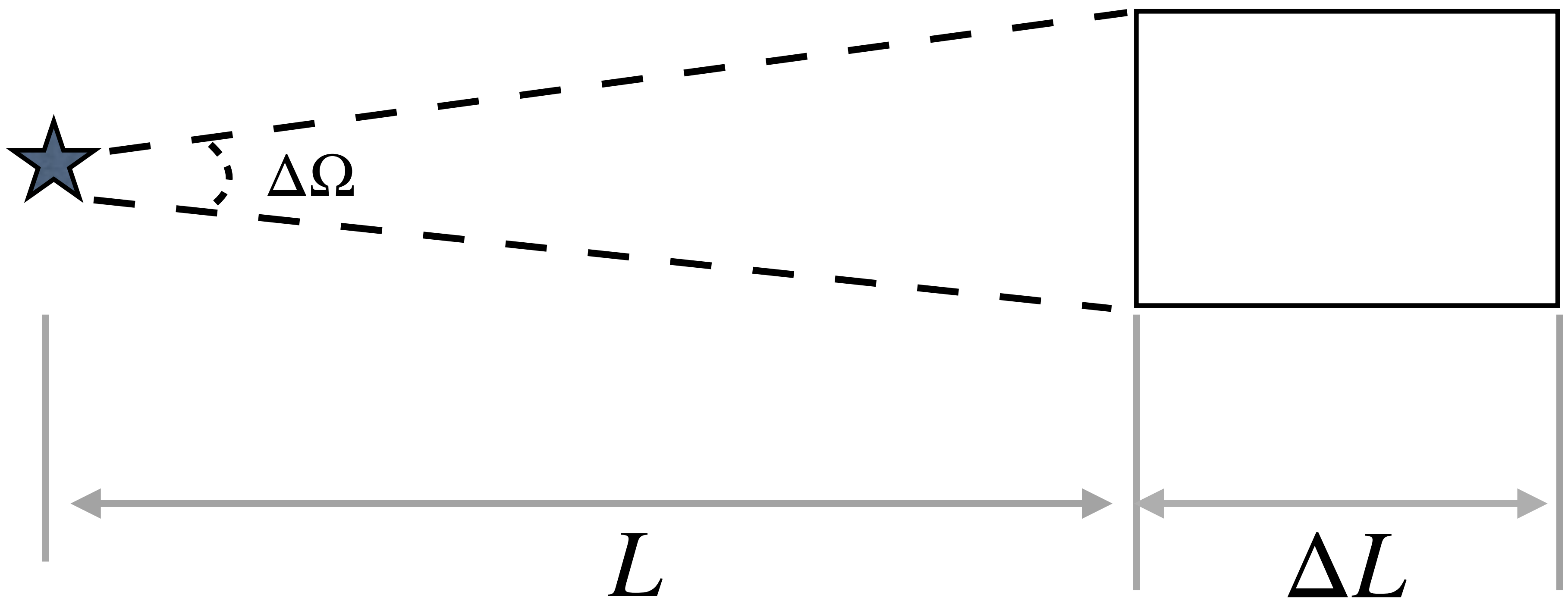
Fully optimized LLP searches at
the interaction points ATLAS, CMS, LHCb?





FASER

Optimal place to catch LLP



Number of particle decayed within detector volume:

$$\#_{\rm in} \simeq \#_{\rm produced} \times \frac{\Delta\Omega}{4\pi} \times \frac{\Delta L}{d} e^{-L/d}$$

$d = \gamma c \tau$ decay length $\quad d \gg \Delta L,\, L$

Very long lived: $\quad d \geq 100\text{s meters}$

Optimal place to catch LLP

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	ATLAS/CMS (LHCb)	Far detectors
$\Delta\Omega$	$\sim 4\pi$	< 0.1
ΔL	$1 - 10$ meters	$1 - 10$ meters
L	$1 - 10$ meters	$10 - 100$ meters

Optimal place to catch LLP

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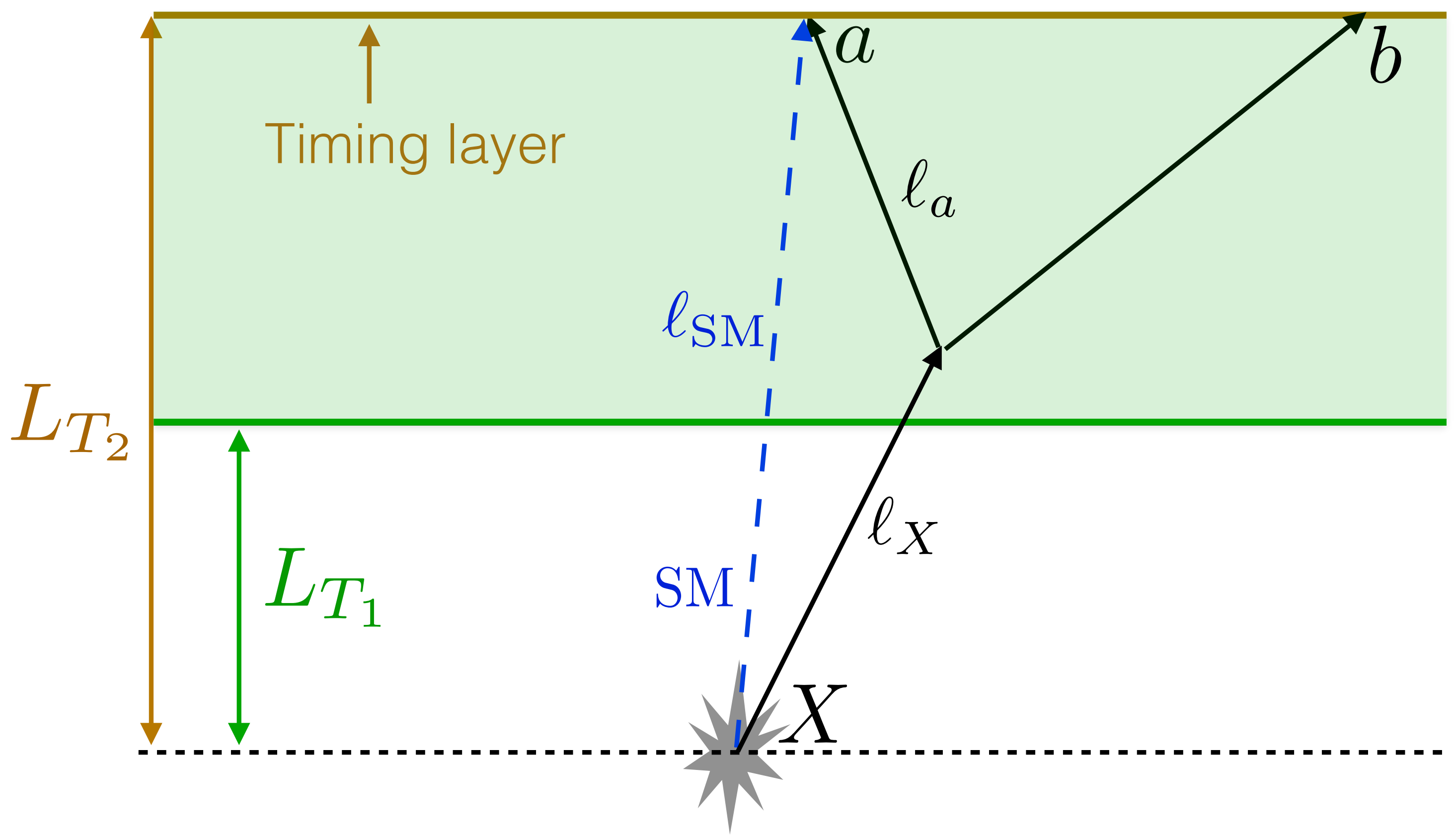
ΔL	$1 - 10$ meters	$1 - 10$ meters
L	$1 - 10$ meters	$10 - 100$ meters

Advantage of far detector?
Far away from interaction point, less background.

Room for new ideas: suppression bkgd near interaction point.

LLP decay products somewhat soft, different trigger strategy

Time delay



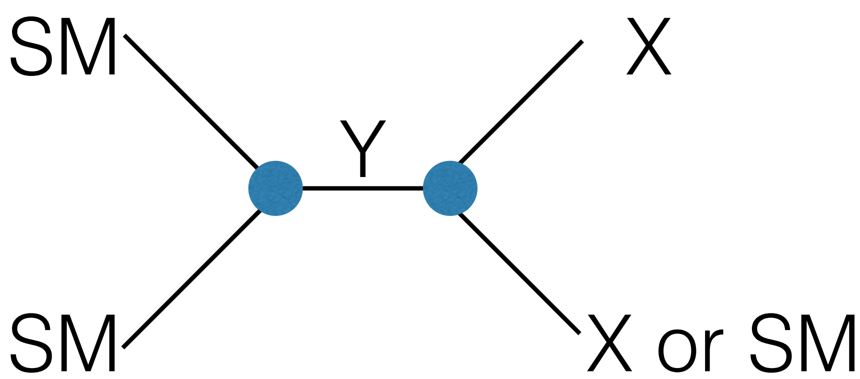
$$\Delta t = \frac{\ell_X}{\beta_X} + \frac{\ell_a}{\beta_a} - \frac{\ell_{\rm SM}}{\beta_{\rm SM}} \qquad \beta_a \simeq \beta_{\rm SM} \simeq 1$$

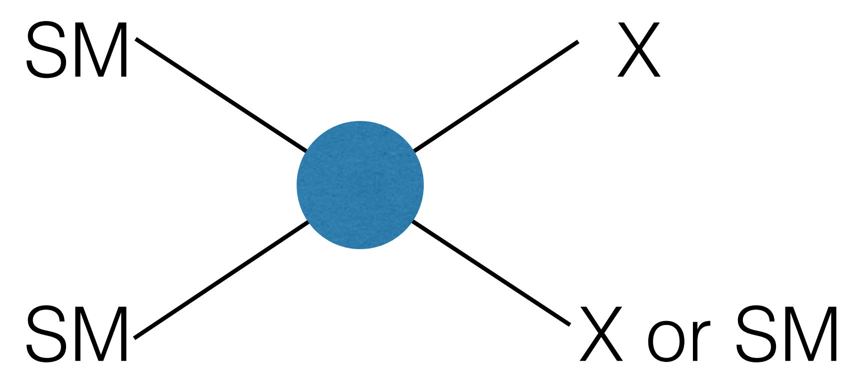
Good for massive LLP produced with small or moderate boost

$$\beta_X < 1$$

Basic topologies

X = LLP





boost: $\gamma \simeq \dfrac{m_Y}{2m_X}$

challenging for $m_X \ll m_Y$

benchmark: Higgs portal

$Y = \text{Higgs}$

$X \to \text{SM}$ Long lived

boost: $\gamma \sim 1$

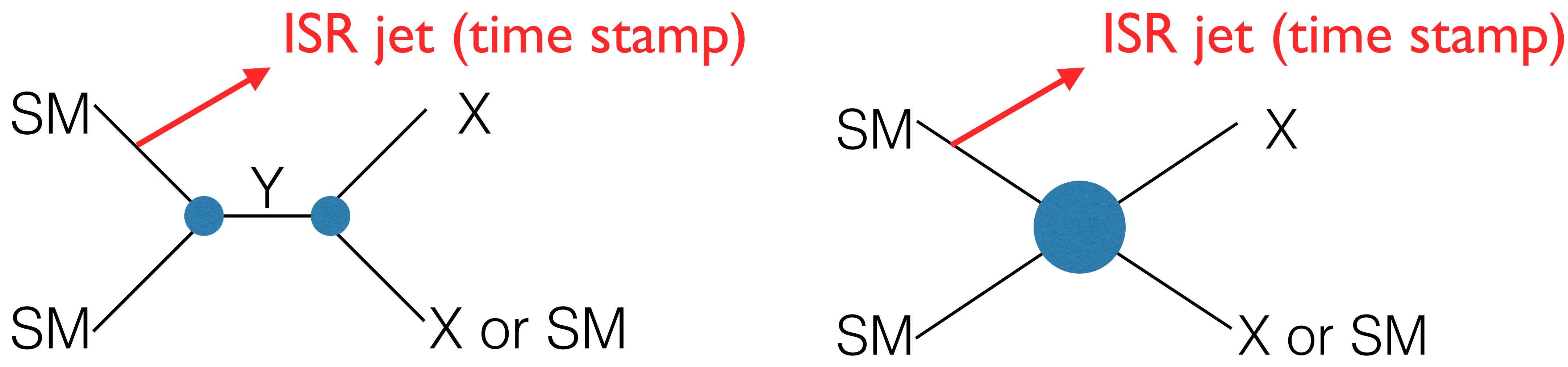
slow moving, sizable Δt

benchmark: SUSY

$X = \text{neutralino}$

$\chi_0 \to \text{gravitino} + \ldots$ Long lived

Signal



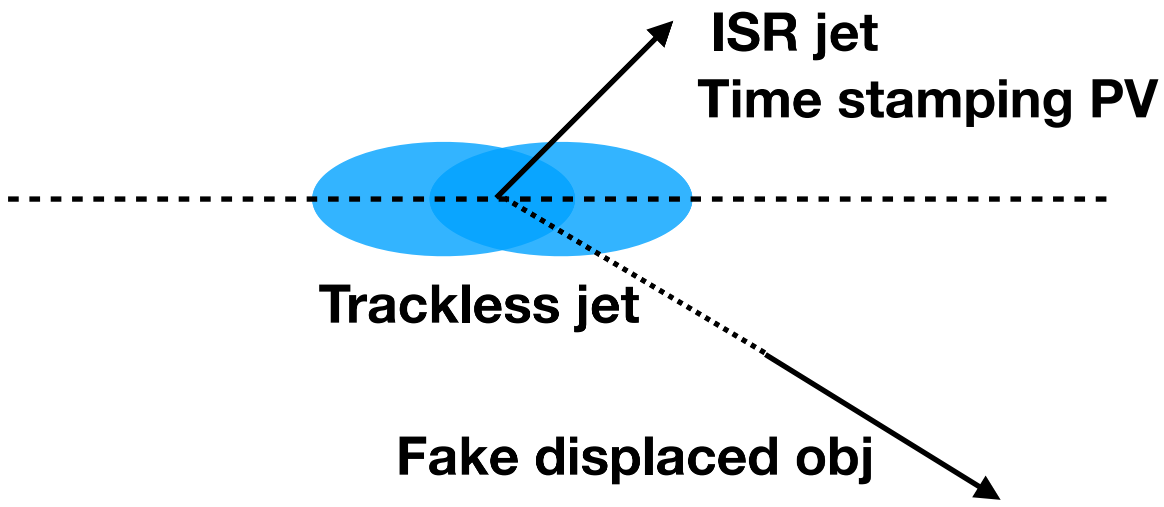
1. ISR jet provides the time for the hard collision

2. LLP decay before reaching timing layer.

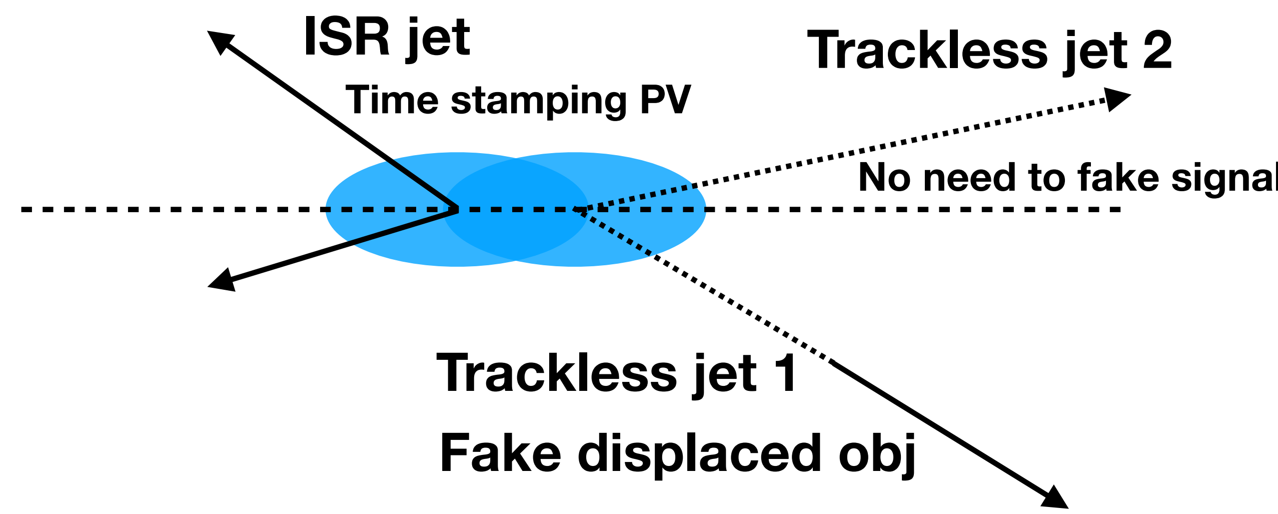
⇨ measurement of Δt

“physics” background

Same hard interaction



Pile up

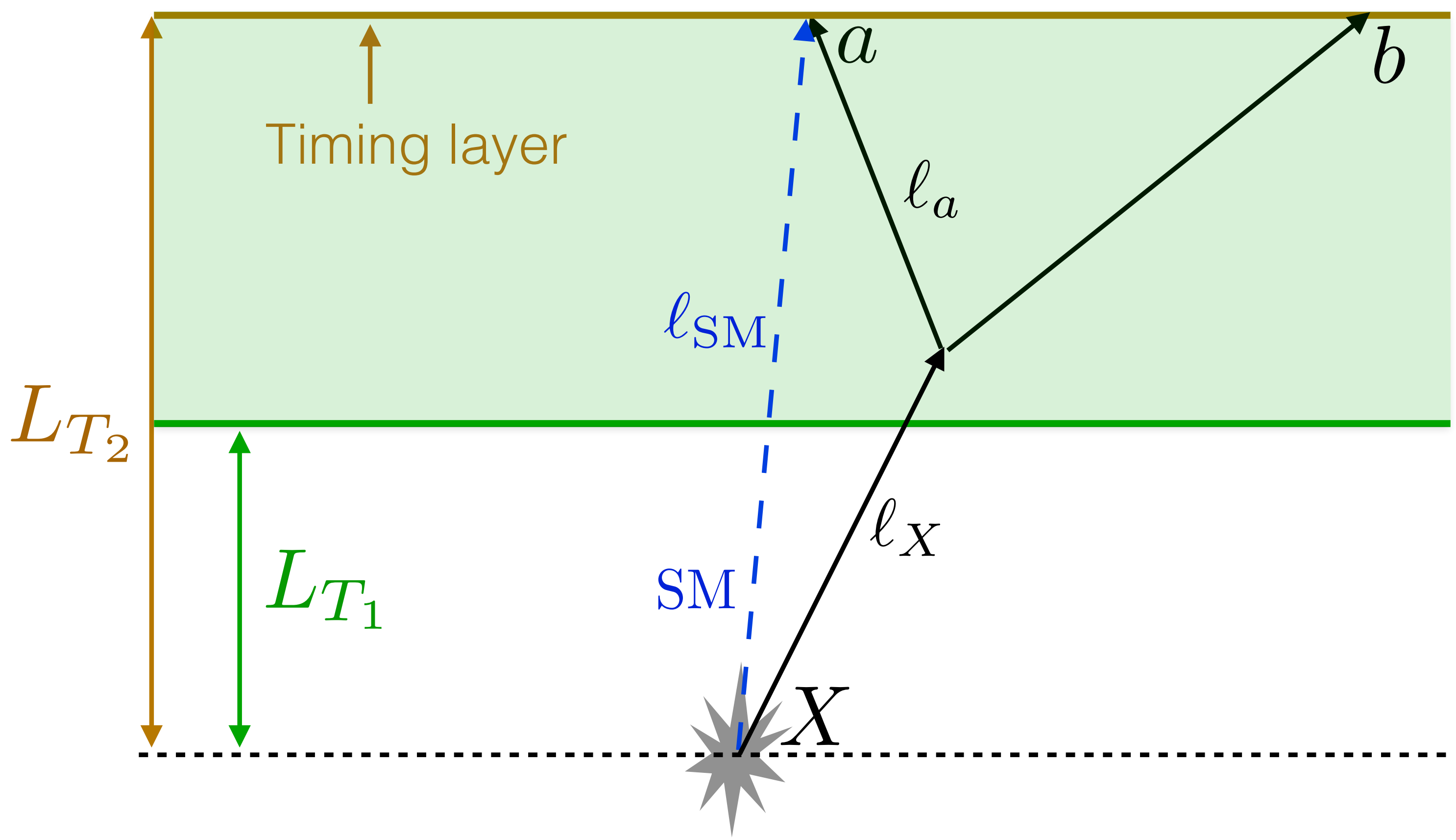


Time delay from
resolution of timing detector.

Time delay from
spread of the proton bunch

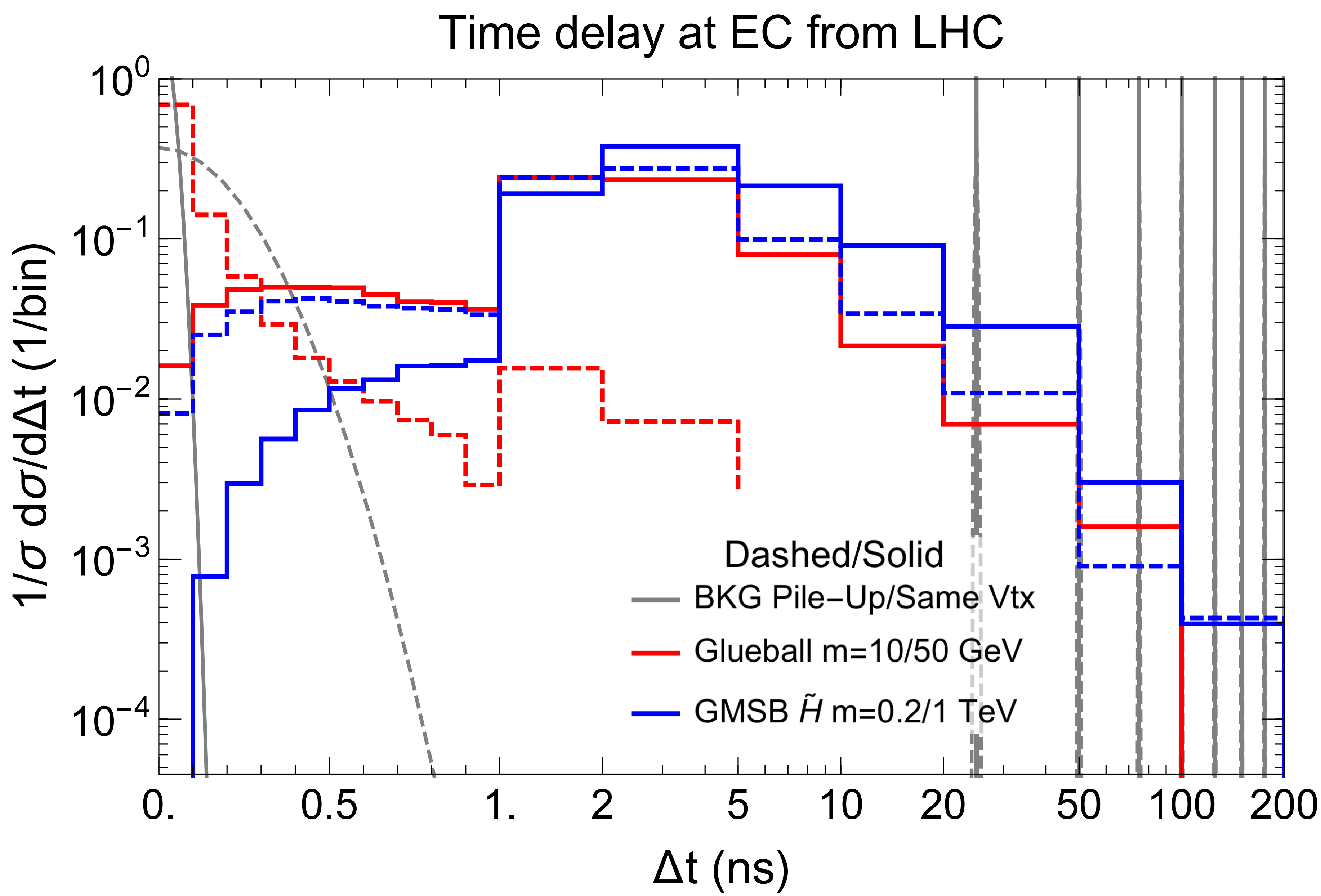
$\sim$ **190 ps**

Examples:



- **timing layers considered here:**
  - **CMS EC search: LT1 = 0.2 m, LT2 = 1.2 m (EC = Electromagnetic Calorimeter)**
    - **Resolution:** $\boldsymbol{\delta \mathrm{t} = 30\ \mathrm{ps}}$
  - **MS search (hypothetical): LT1 = 4.2 m, LT2 = 10.6m (MS = Muon Spectrometer)**
    - **Resolution: don't need to be as good (detail later)**

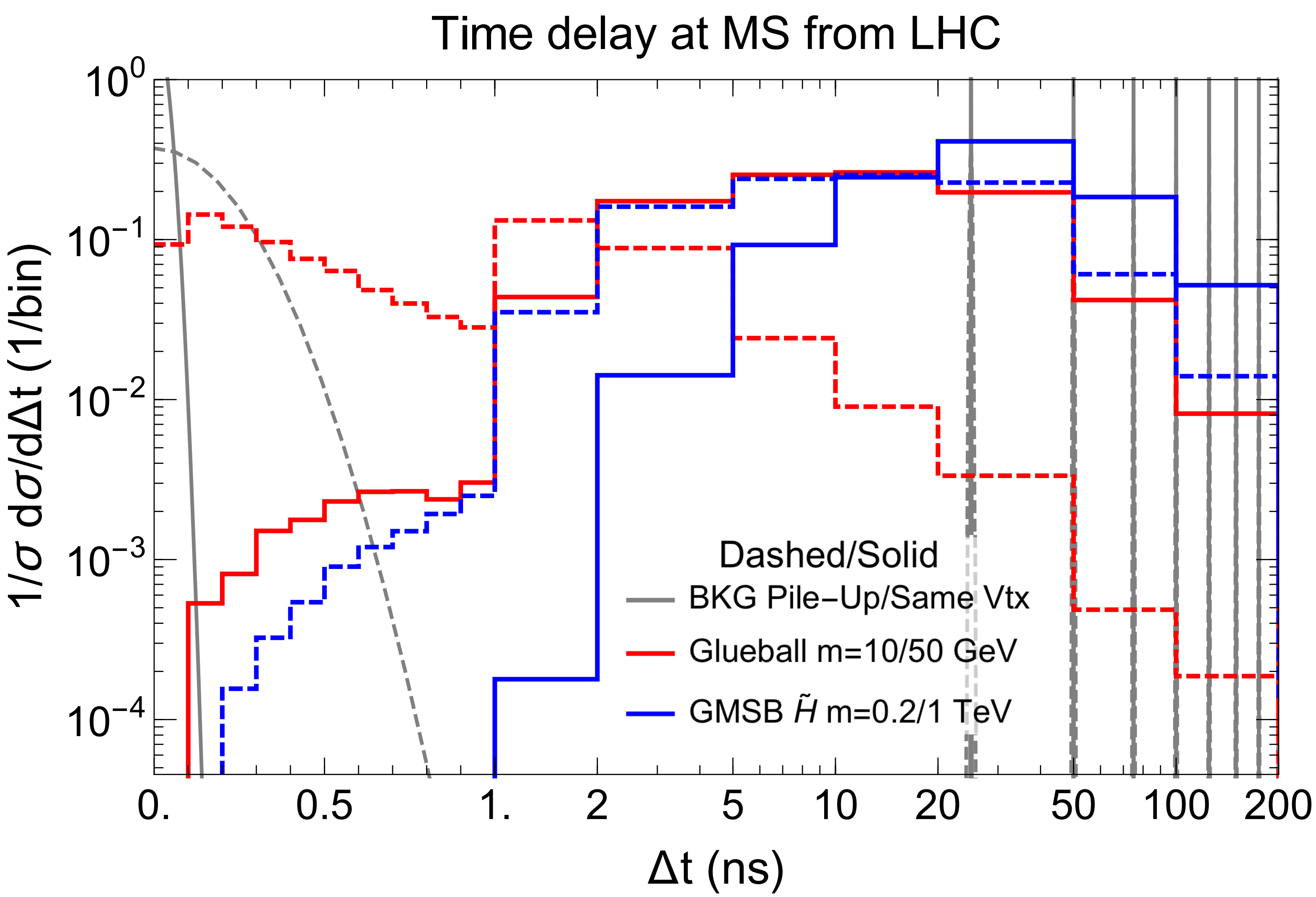
Search based on EC



After timing cut: $\Delta t > 1$ ns

Back ground dominated by pile up $\#_{\text{background}} \sim 1$

Search based on MS



Pile up background smaller, shielded by HCAL etc.

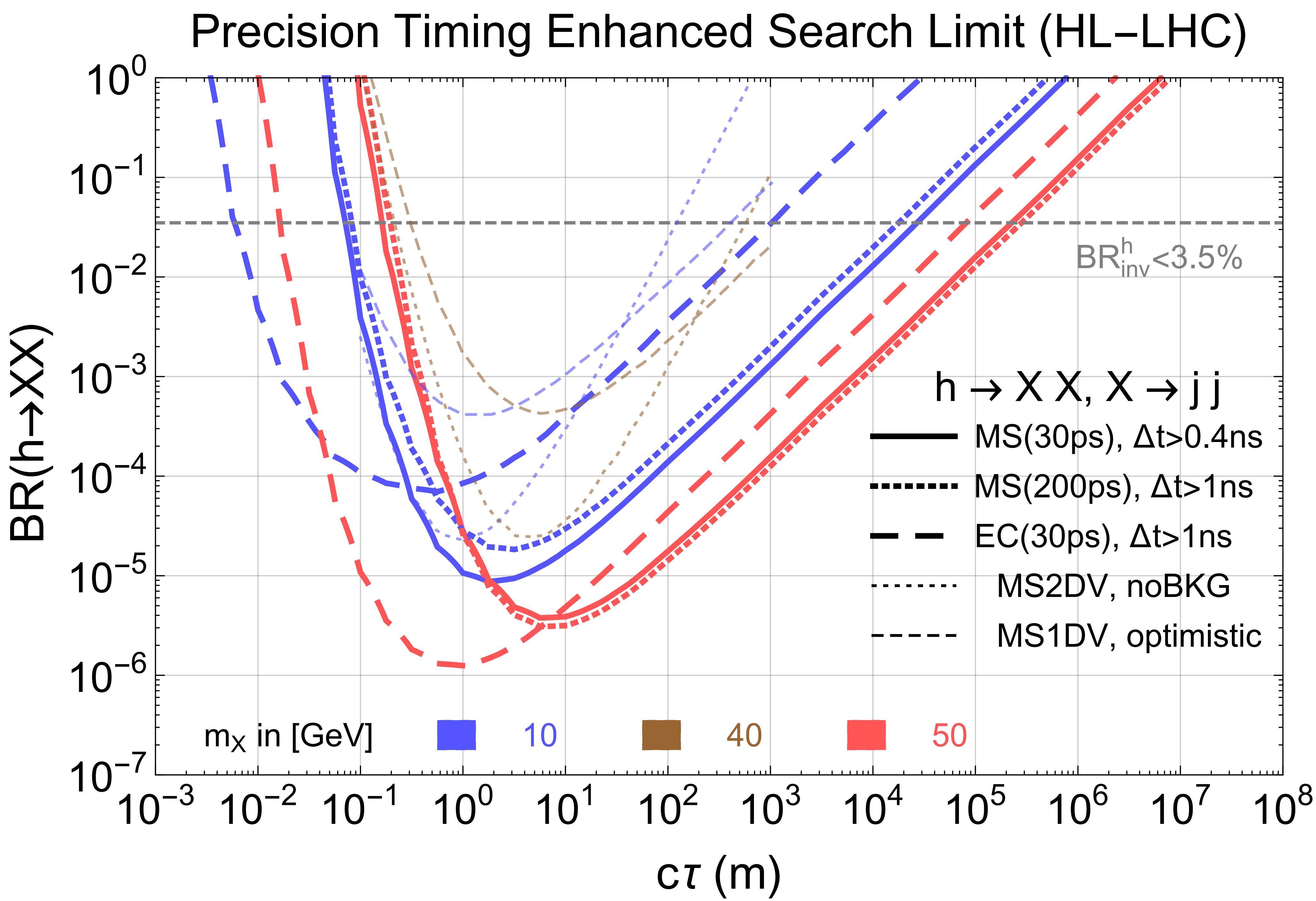
Before timing cut: ~ 50

After timing cut: $\Delta t > 1$ ns $\quad \#_{\text{background}} \sim 1$

Further away, larger Δt for signal.

Sensitivity to Higgs portal

Jia Liu, Zhen Liu, LTW

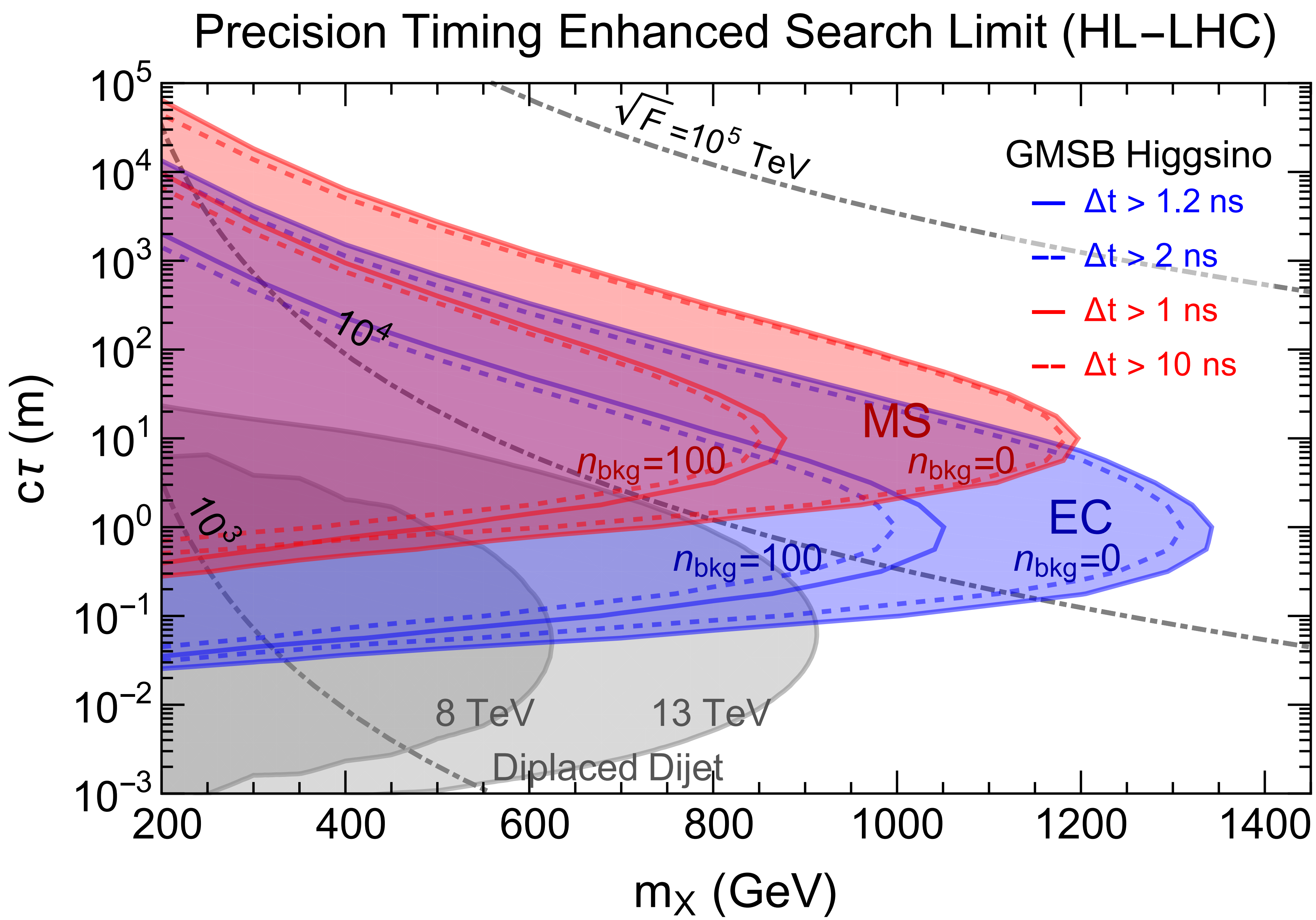


For example, for $\mathrm{BR}(h \to XX) \sim 10^{-3}$

EC(MS) reach can be $c\tau \sim 10^{3}(10^{4})$ meters

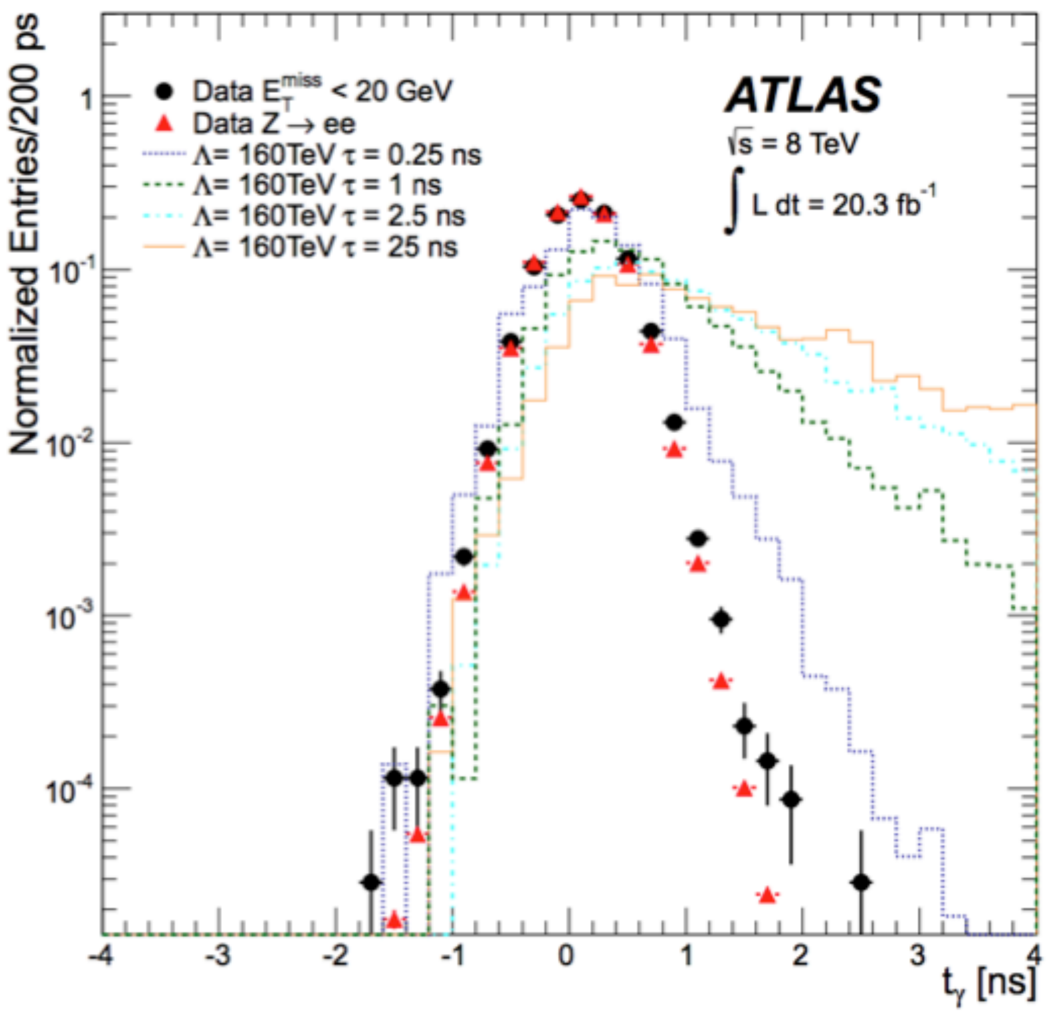
Sensitivity to SUSY

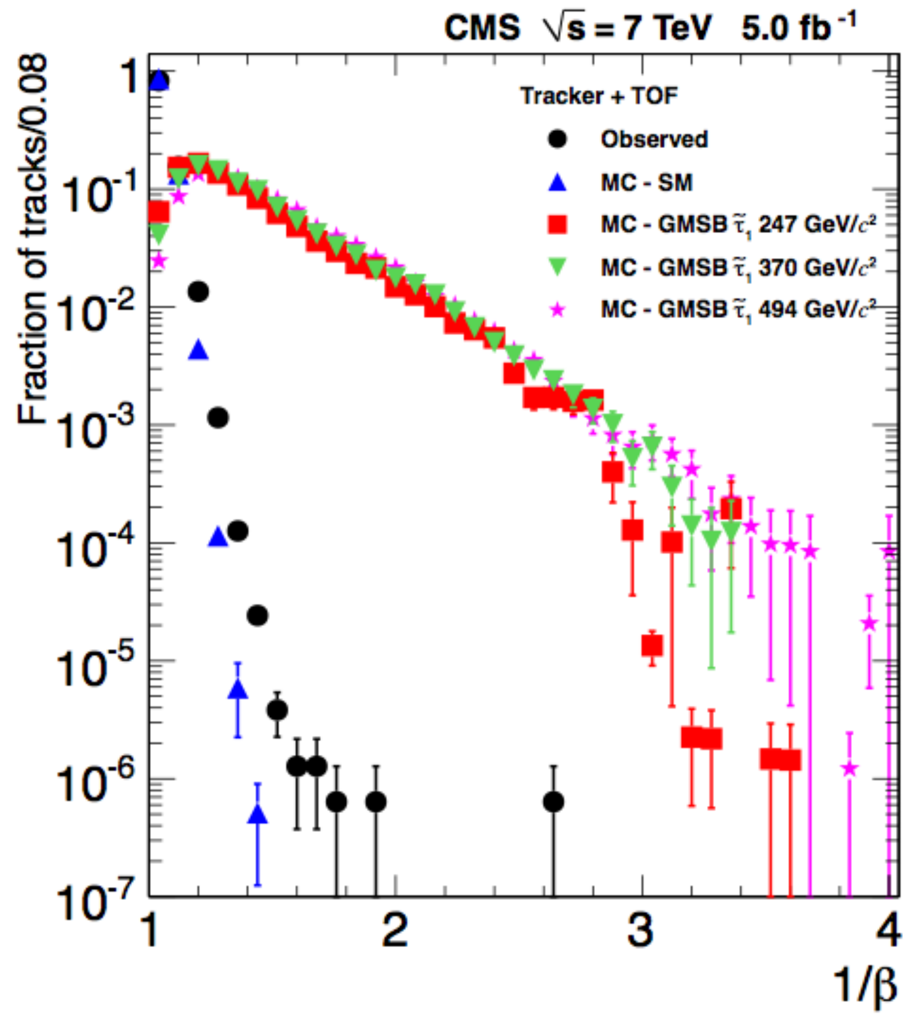
Jia Liu, Zhen Liu, LTW



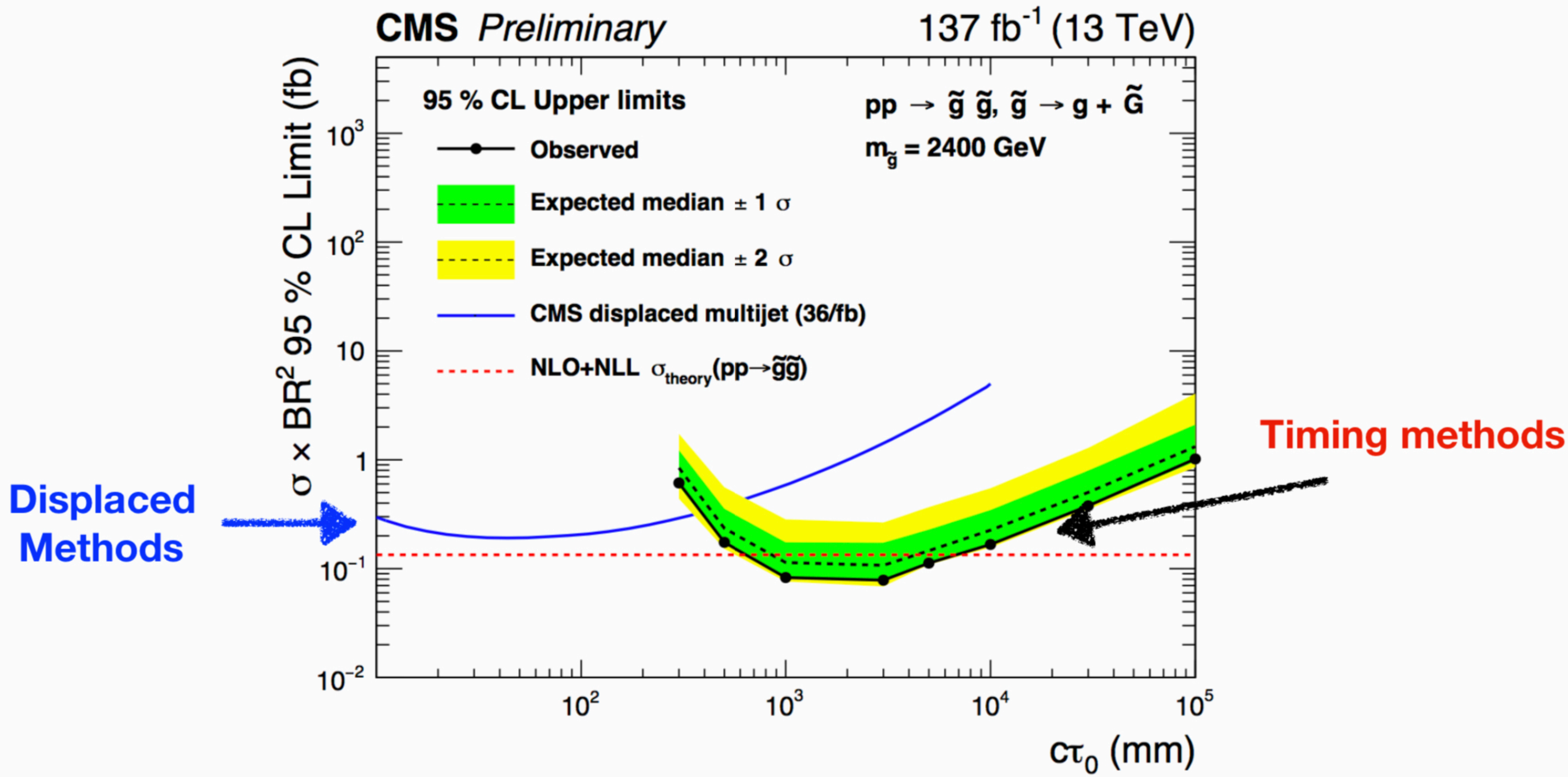
Slower moving LLP, timing cuts can be further relaxed.

Some timing info has been used





CMS EXO-19-001 applies the timing techniques



Going beyond

- Our studies demonstrated great potential of using timing.
- We have made idealized assumptions about background.
- But we also have not fully used the signal. Such as LLP decay to two delayed objects.
- More realistic triggering and background studies necessary (some under way).

New directions and ideas

- Apply timing to current LLP searches should already help.
  - e.g. muon-RoI based searches
- Removing the ISR jet for MS searches.
  - Higher rate. Larger dt = 1 ns cut, don't need precise hard collision time.
- High granularity, better pointing and vertexing
  - Would be at least as useful as timing.
  - HGCAL, MS RPC upgrade.
- Using timing info with the calorimeters, HGTD.

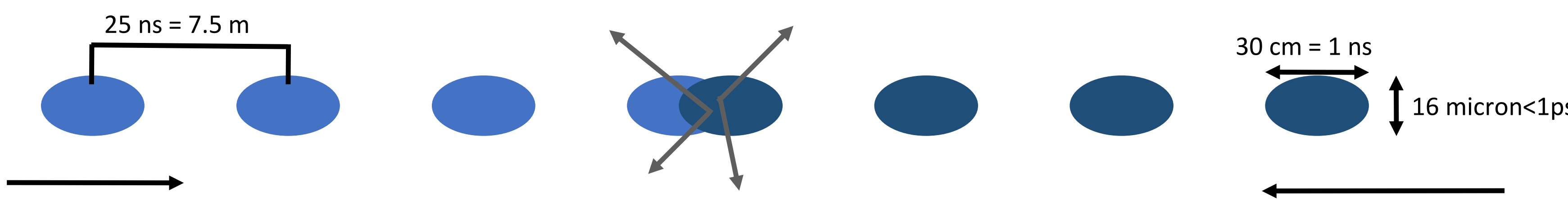
Conclusion

- LHC still has a lot to say.
  - 15+ years of operation, 95+% of data to come.
  - Need to think about how to new searches with this data. (In addition to looking else where.)
- LLP searches are a promising direction.
  - Theoretically motivated, a variety of models.
  - Cover a broad range of life-time, production mechanism and decay products.
- More work (and originality) needed.
  - In particular, optimize searches at ATLAS/CMS/LHCb

extra

Detector with timing information

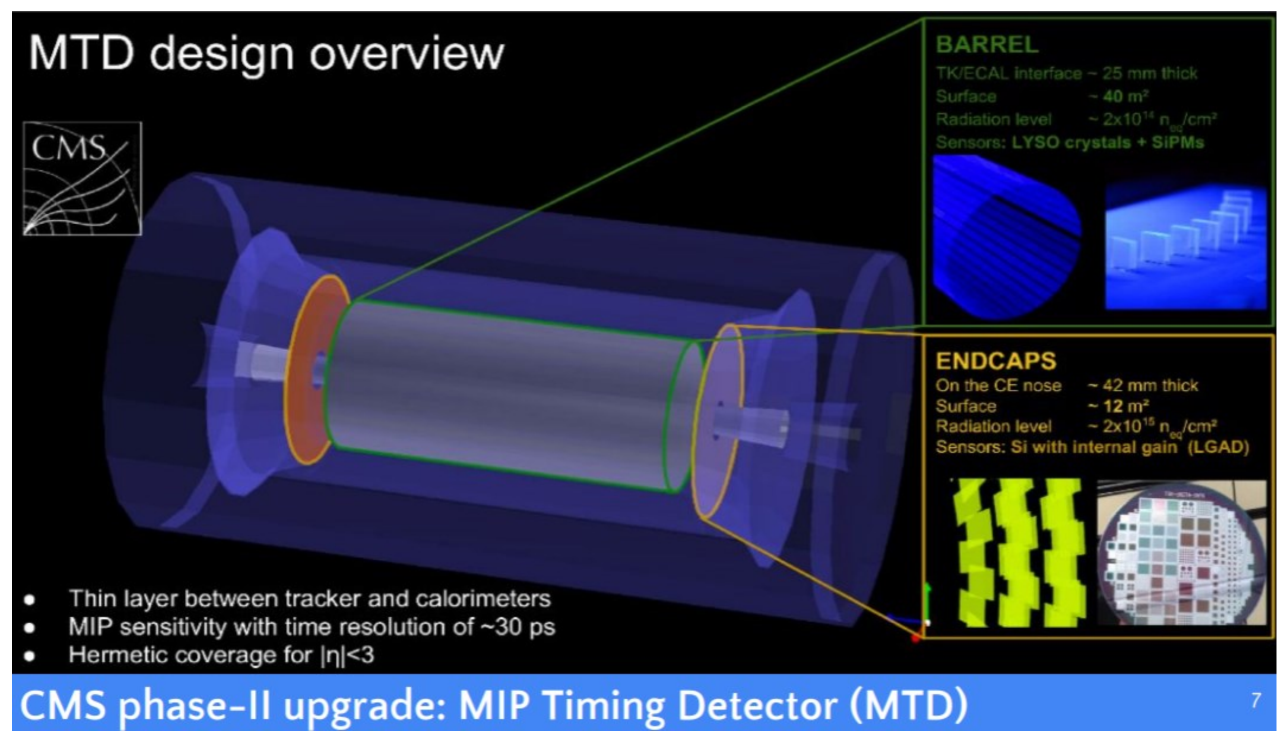
- Detector needs timing information to record event



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



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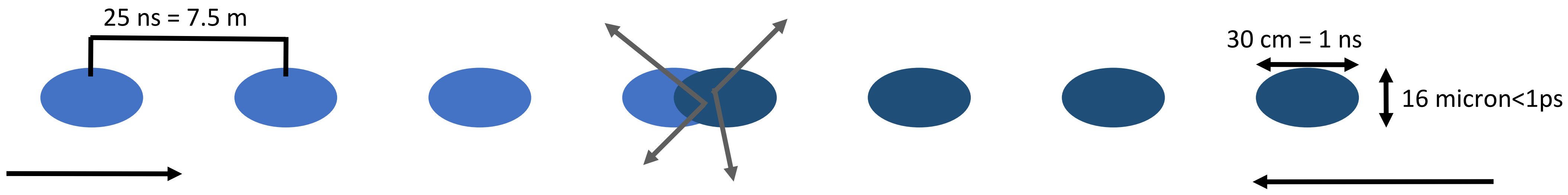

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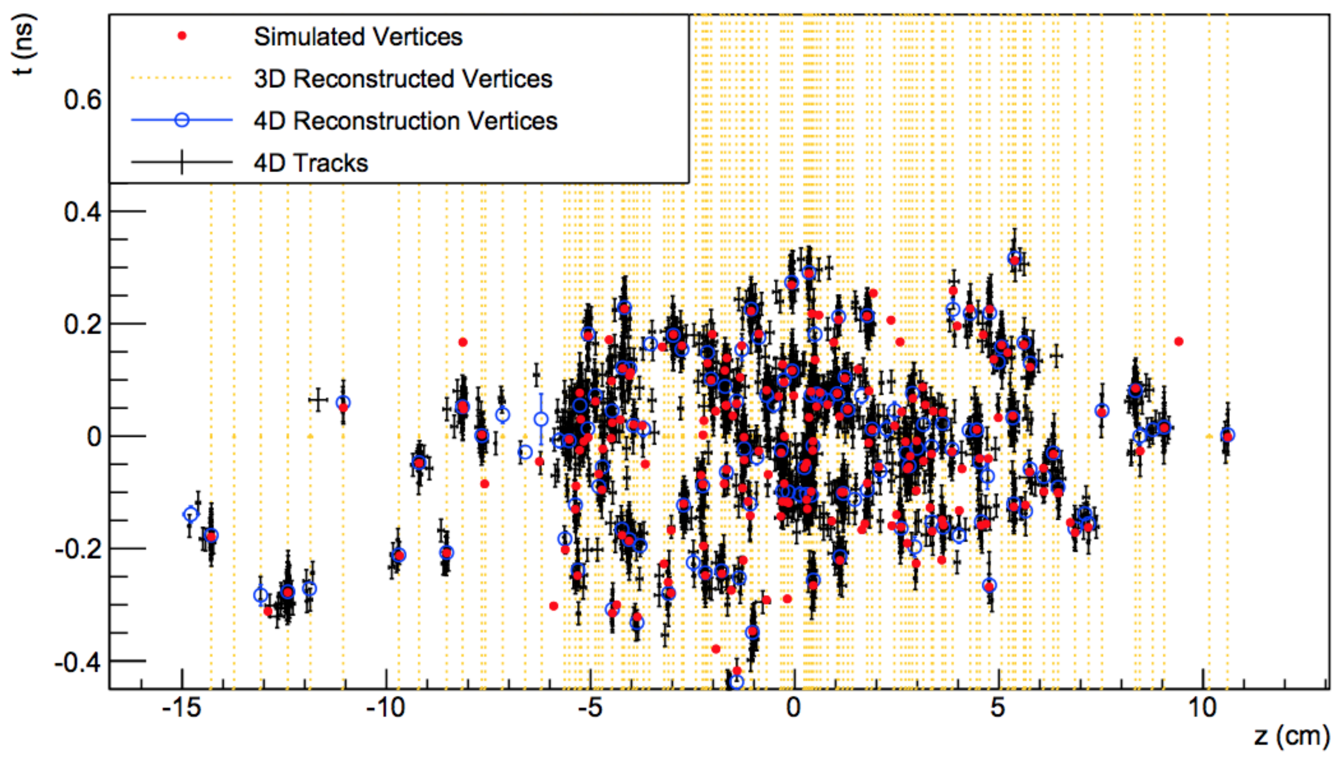


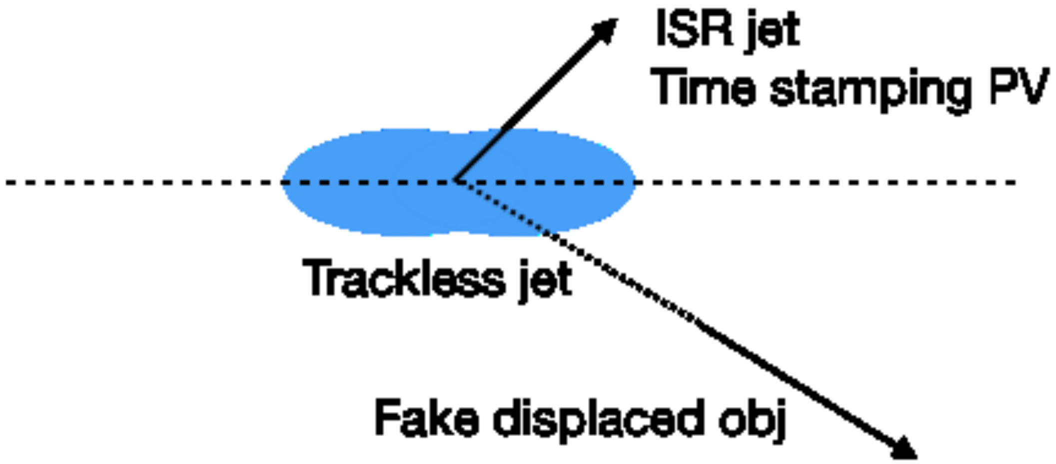
Late comers will be spotted easily:

	L_{T_2}	L_{T_1}	Trigger	ϵ_{trig}	ϵ_{sig}	ϵ^j_{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}

CMS MTD $|\eta| < 3.0$

ATLAS MS LLP search

(without timing)



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

Hard collision BKG: detector time resolution ~30 ps

MTD (30ps) cut: $\Delta t > 0.4$ ns

MS (30ps) cut: $\Delta t > 1$ns

BKG(SV) << 1

The detector time resolution for MS can be hundreds of ps

MS (200ps) cut:

$\Delta t > 1$ns

BKG(MS-SV) ~ 0.11

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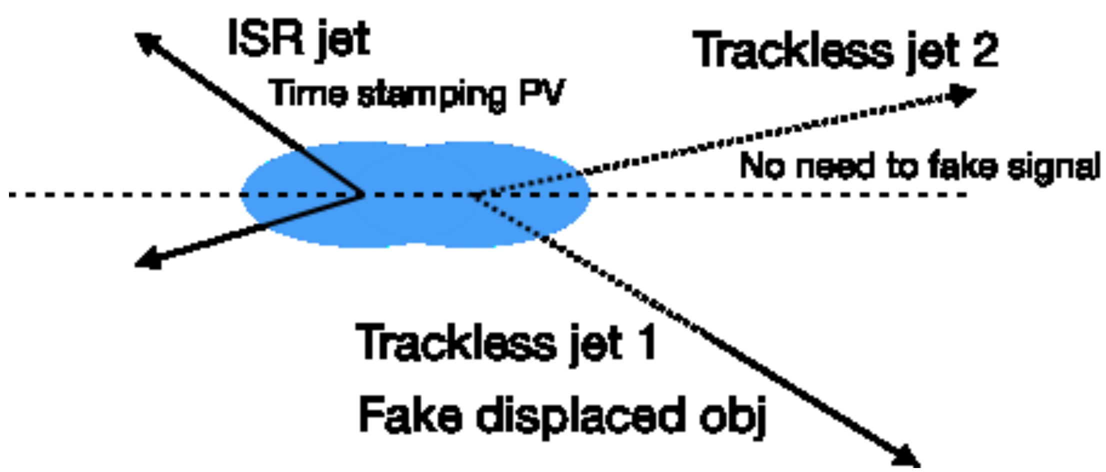


Pile-Up background, time spread

190 ps (beam property)

$$N^{\rm PU}_{\rm bkg} = \sigma_{\rm j}\mathcal{L}_{\rm int}\epsilon^{\rm EC}_{\rm trig}\left(\bar{n}_{\rm PU}\frac{\sigma_{\rm j}}{\sigma_{\rm inc}}\epsilon^{j,{\rm EC}}_{\rm fake}f^j_{\rm nt}\right) \approx 2\times10^7,$$

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

Pile-up BKG: intrinsic resolution ~190 ps

MTD (30ps) cut: Δt > 1 ns

BKG(MTD-PU) ~ 1.3

MS (30ps) cut: Δt > 0.4 ns

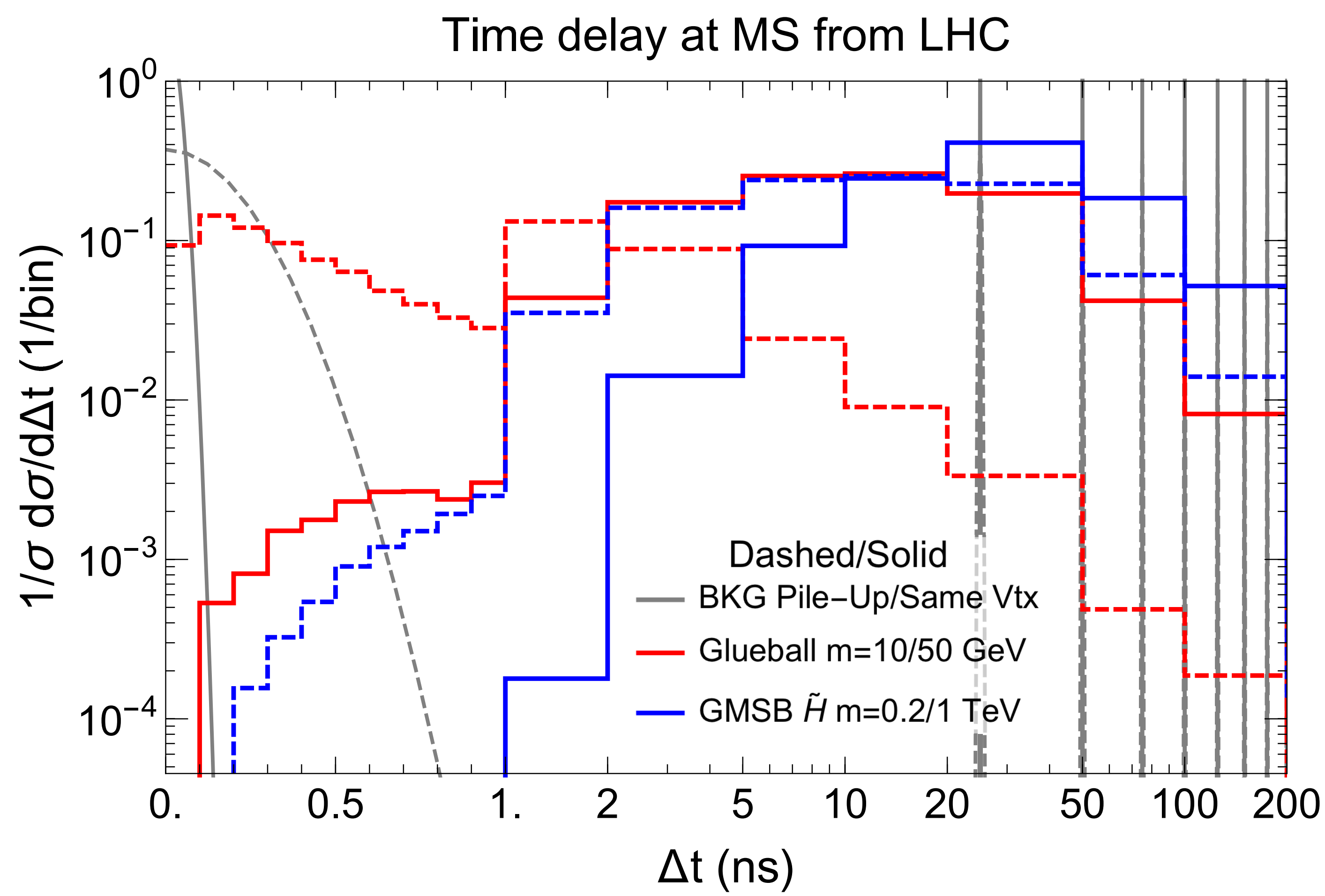
BKG(MS-PU) ~ 0.86

The detector time resolution for MS can be hundreds of ps, even ns

MS (200ps) cut: Δt > 1ns

BKG(MS-PU) << 1

Search based on MS



Pile up background smaller, shielded by HCAL etc.

$\Delta t > 1$ ns $\quad \#_{\text{background}} \sim 1$

Further away, larger Δt for signal.

no need for super good timing resolution

$\delta t \sim 200$ ps

will do