BSM Physics Benefiting from Superior Particle Identification

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IAS Program on High Energy Physics (HEP 2021)

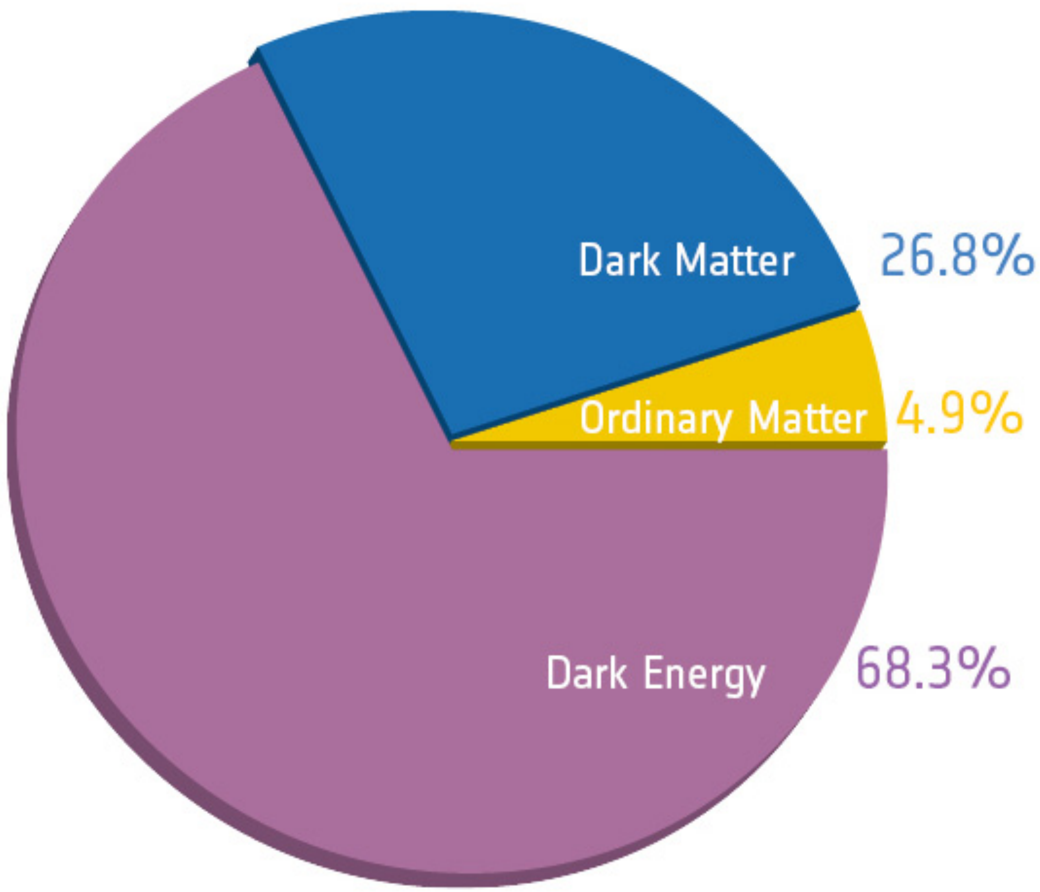
2021-01-14

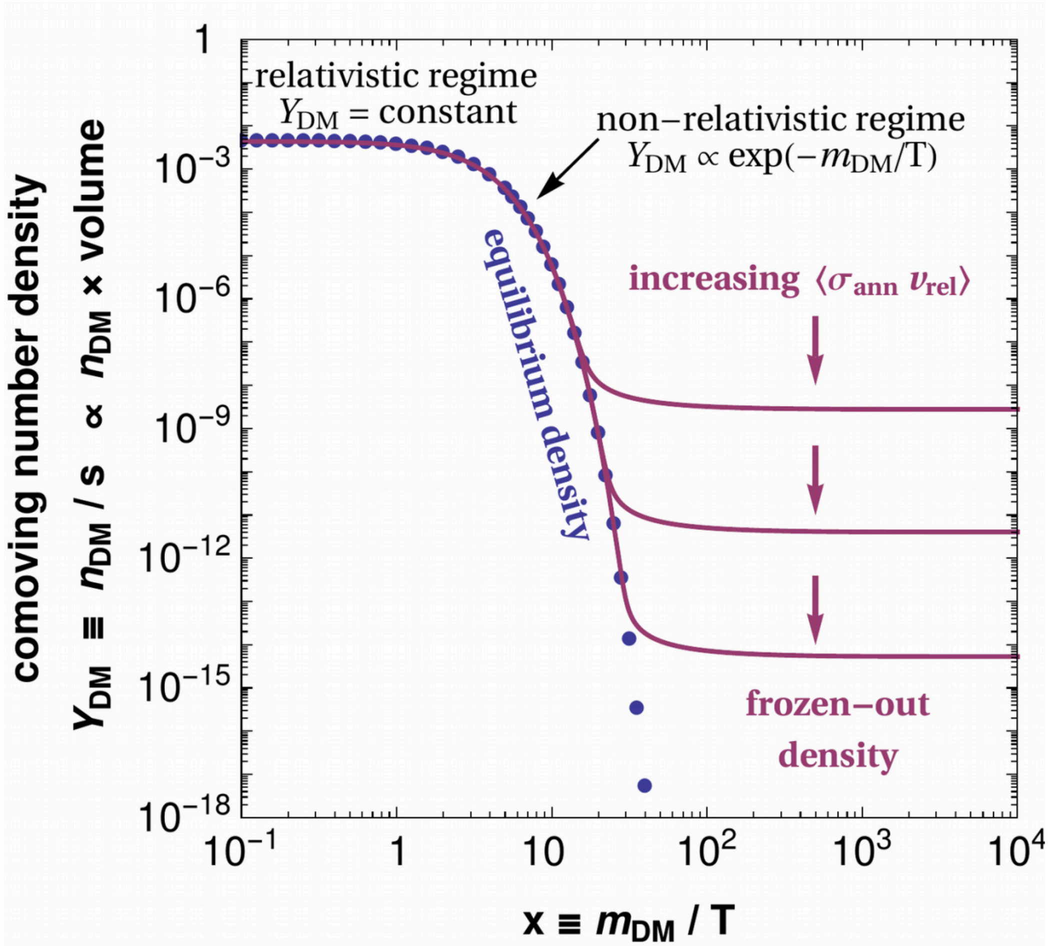
Outlines

- The motivation from light dark sector: softer and long-lived
- The timing detector and PID
- Triggers and PID
- The tau PID and g-2
- Summary

Dark matter and its particle nature

Courtesy of Kalliopi Petraki





- What is the particle nature of the Dark Matter?
- Not a particle in SM!

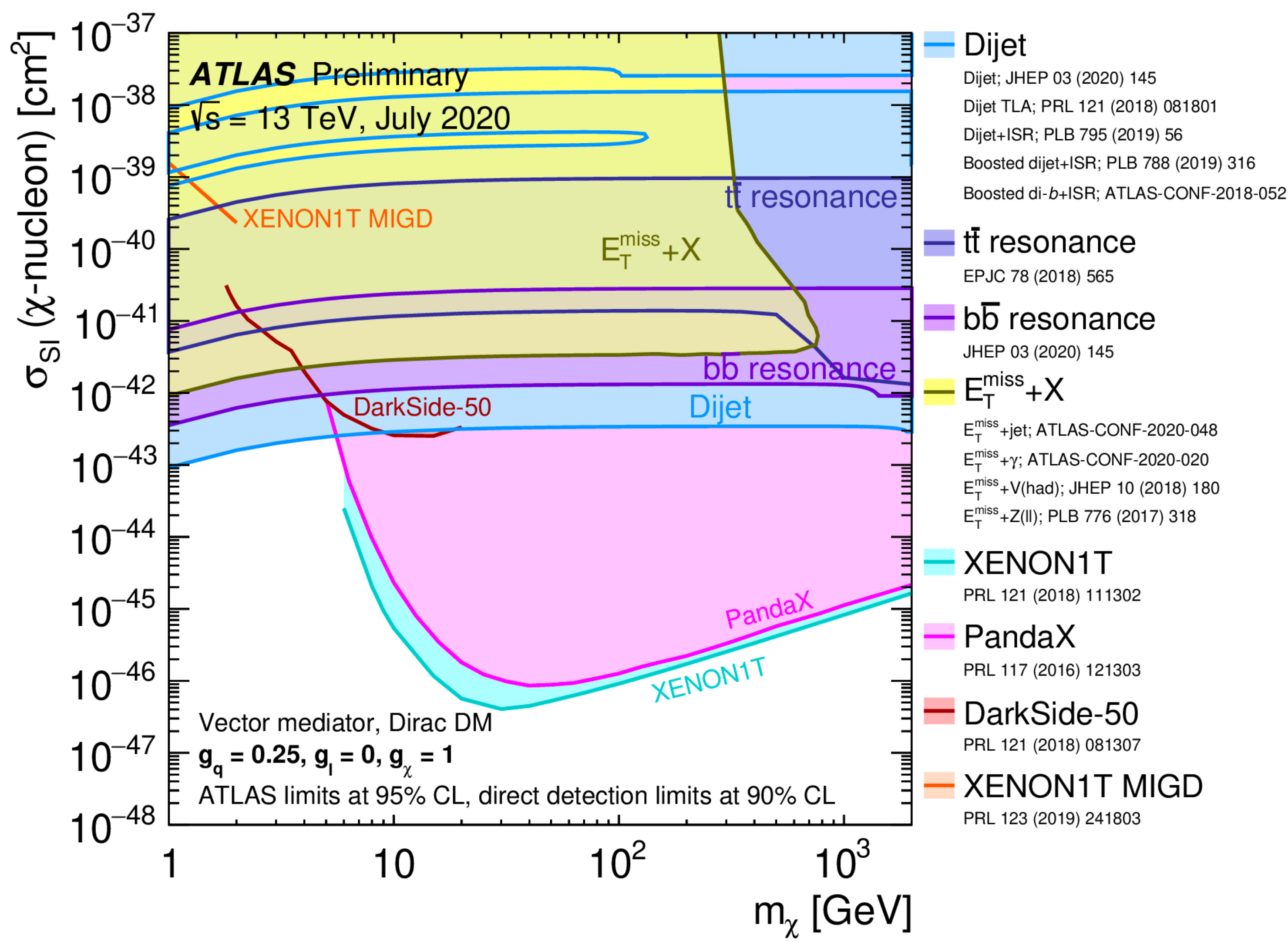
$$\mathrm{DM} + \mathrm{DM} \rightarrow \mathrm{SM} + \mathrm{SM}$$

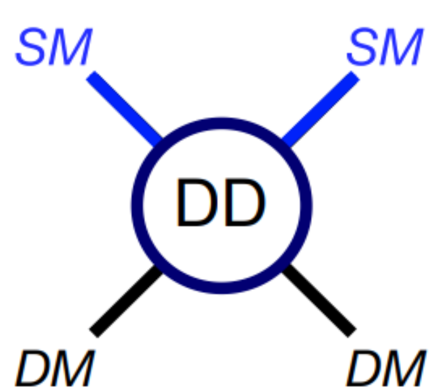
$$\langle \sigma v \rangle \sim 3 \times 10^{-26} \mathrm{cm}^3/\mathrm{s}$$
$$\sim \alpha^2 / m_W^2$$

- The WIMP miracle!

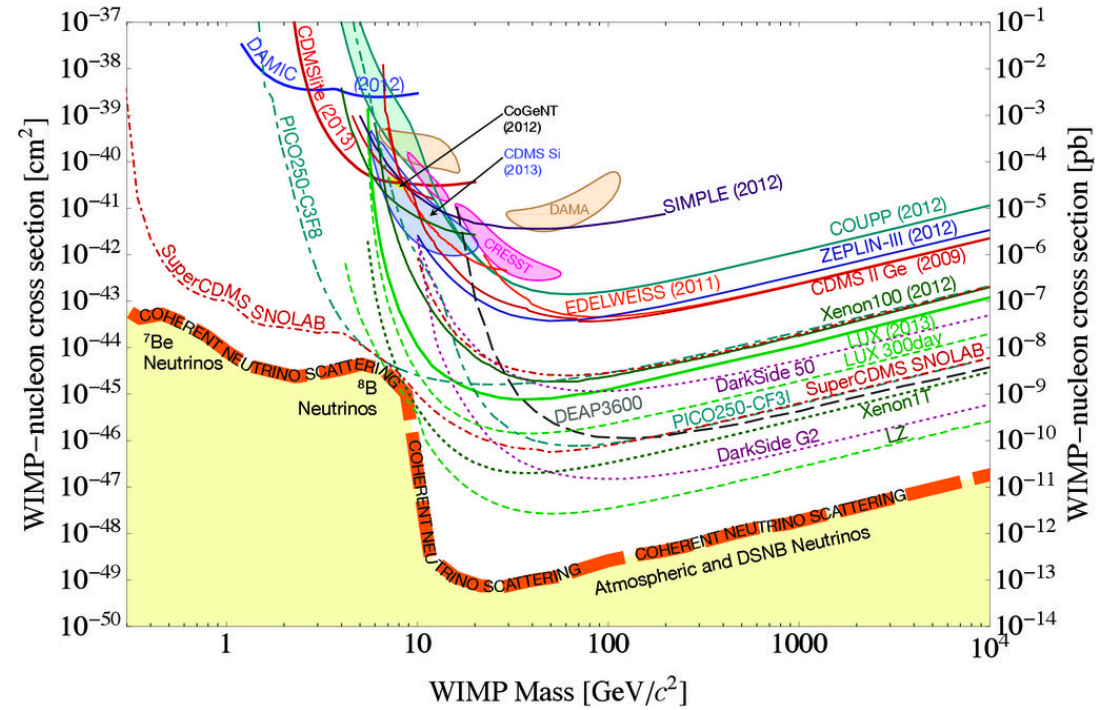
Dark matter at colliders

- The DM pair can be produced at LHC
  - mono-X search: X = photon, Z, jet, Higgs …
  - EFT operators
  - Simplified models
    - Mediator searches
- Direct synergy with DM direct detection

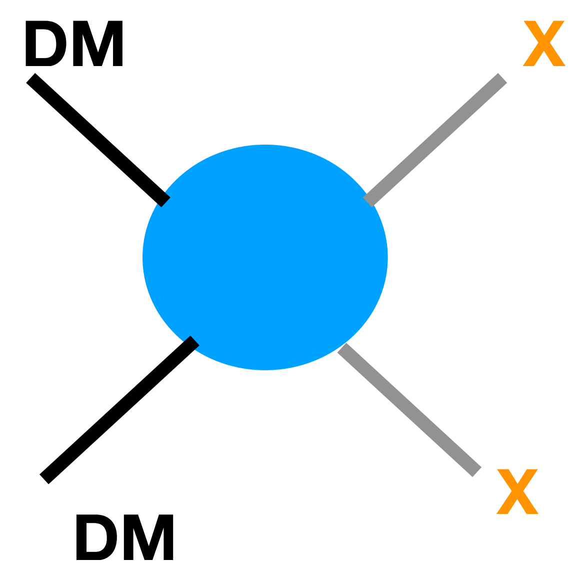


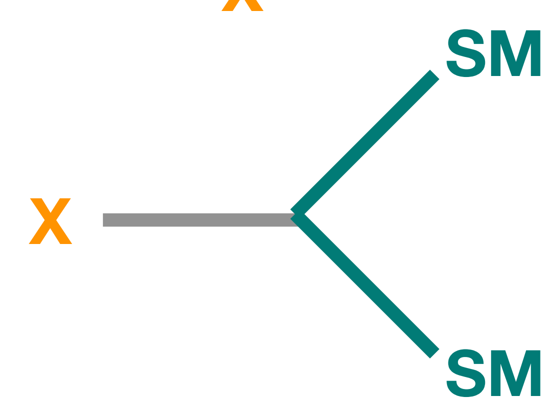


From dark matter to dark sector



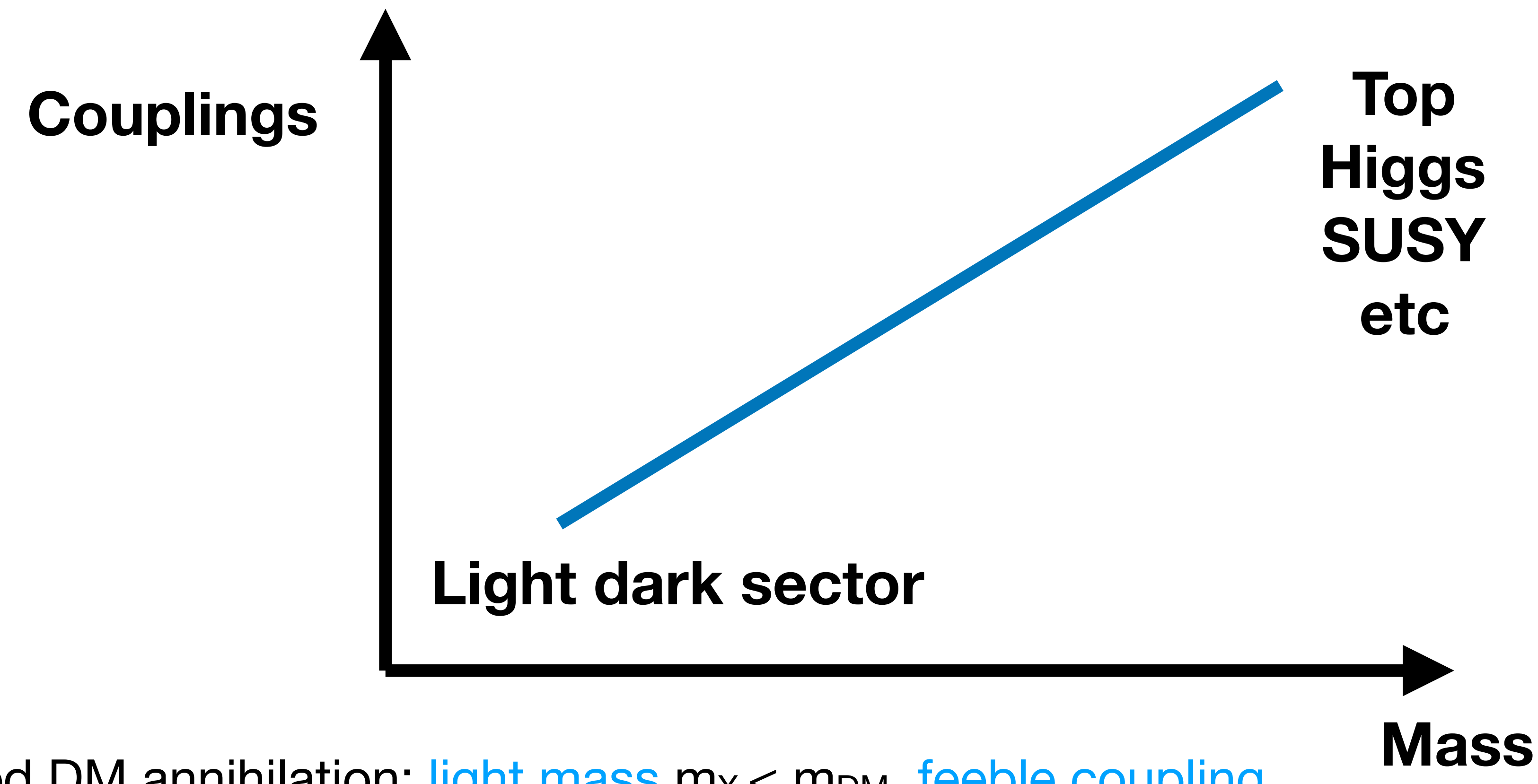
- The existence of dark matter
  - do not interact with strong, weak, or electromagnetic forces
  - A zoo of similar particles in the dark sector as in the visible sector
- The null detection of dark matter
  - Secluded annihilation: DM + DM → X + X
  - X is light and very weakly coupled to visible sector





X can be long-lived!

The motivation for light dark sector



- 1. Secluded DM annihilation: light mass $m_X < m_{DM}$, feeble coupling
- 2. It fits well with intensity frontier programs: beam dump, high-lumi searches from tau/charm factory, b factory, Z factory, Higgs factory
- 3. The low energy experiment hints
  - Lepton mu (e?) g-2 (light particles at ~ 100 MeV, coupling << 1) 1806.10252 Davoudiasl et al …
  - KOTO: neutral K decay into pi0 + MET (light scalar < 200 MeV) 1909.11111 Kitahara et al …
  - MiniBooNE: (dark neutrino/boson at 10~100MeV) 1807.09877 Bertuzzo et al …
  - Atomki: Be8/He4 decay into a 17 MeV ee resonance 1604.07411 Feng et al …

The examples of dark sector mediators

- Coupling through gauge singlet operators of SM
  - Vector mediator: kinetic mixing portal - Dark Photon

$$B_{\mu\nu}F'^{\mu\nu}$$

  - Pseudoscalar mediator: higher dimensional operators - Axion

$$\frac{a}{\Lambda}\tilde{F}F, \frac{a}{\Lambda}\tilde{G}G$$

  - Majorana fermion mediator: neutrino portal - Sterile neutrino

$$(LH)N_R$$

  - Scalar mediator: Higgs portal

$$\left(H^\dagger H\right)\left(\phi^1 \text{ or } \phi^2\right)$$

- Light → softer objects
- Feeble coupling → longer-lived objects

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Why long-lived particles?

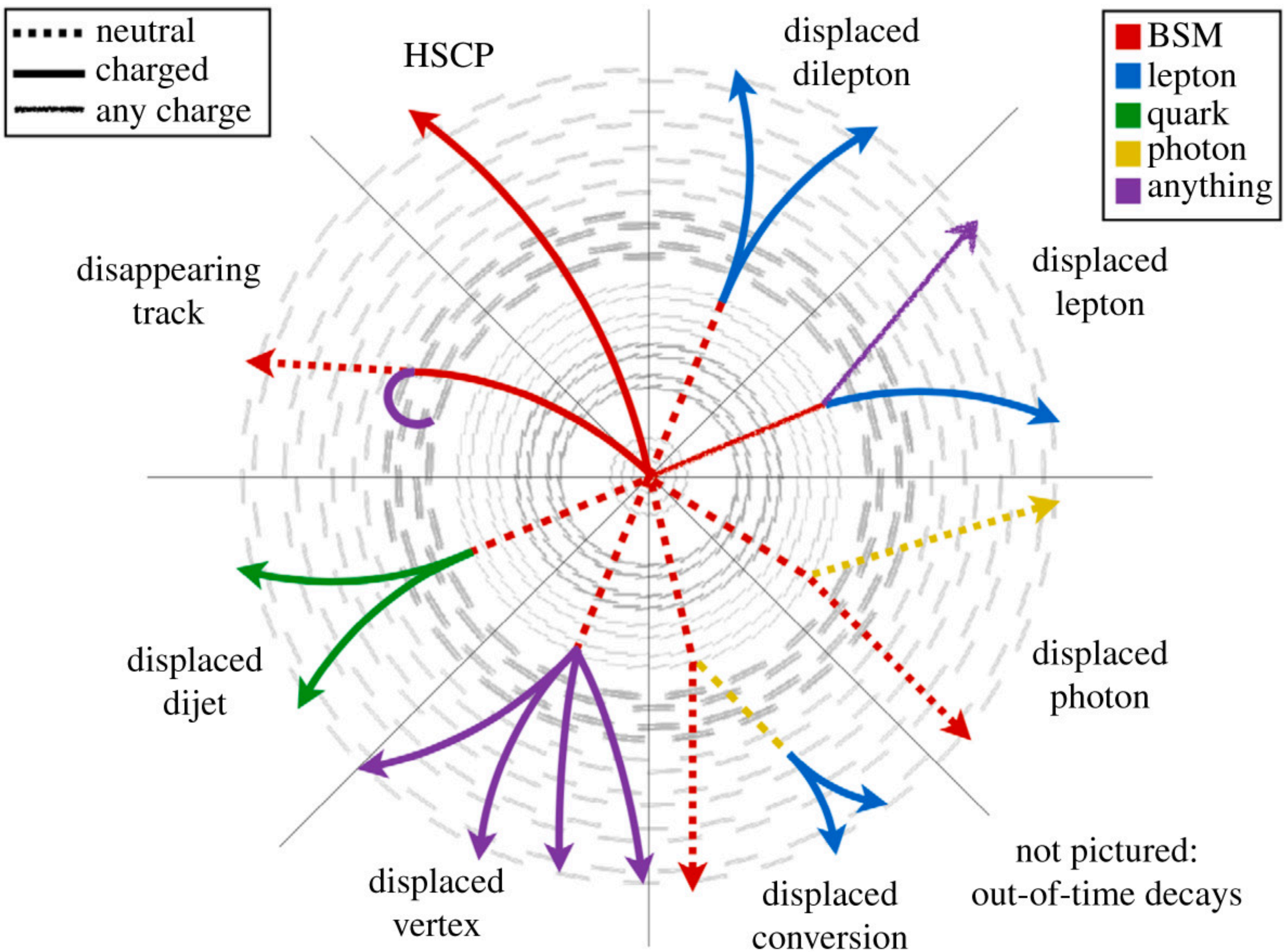
- Feeble couplings:
  Dark sector models, R-parity violating Supersymmetry, sterile neutrinos

- Suppression from heavy mass scale:
  muon/charged pion, gauge mediated spontaneous breaking Supersymmetry

- Near degenerate state:
  higgsino-like chargino/neutralino, or anomaly-mediated spontaneous breaking Supersymmetry

- Approximate symmetry:
  K_L to three pions (accidental PS suppression)

The spatial methods to search LLPs



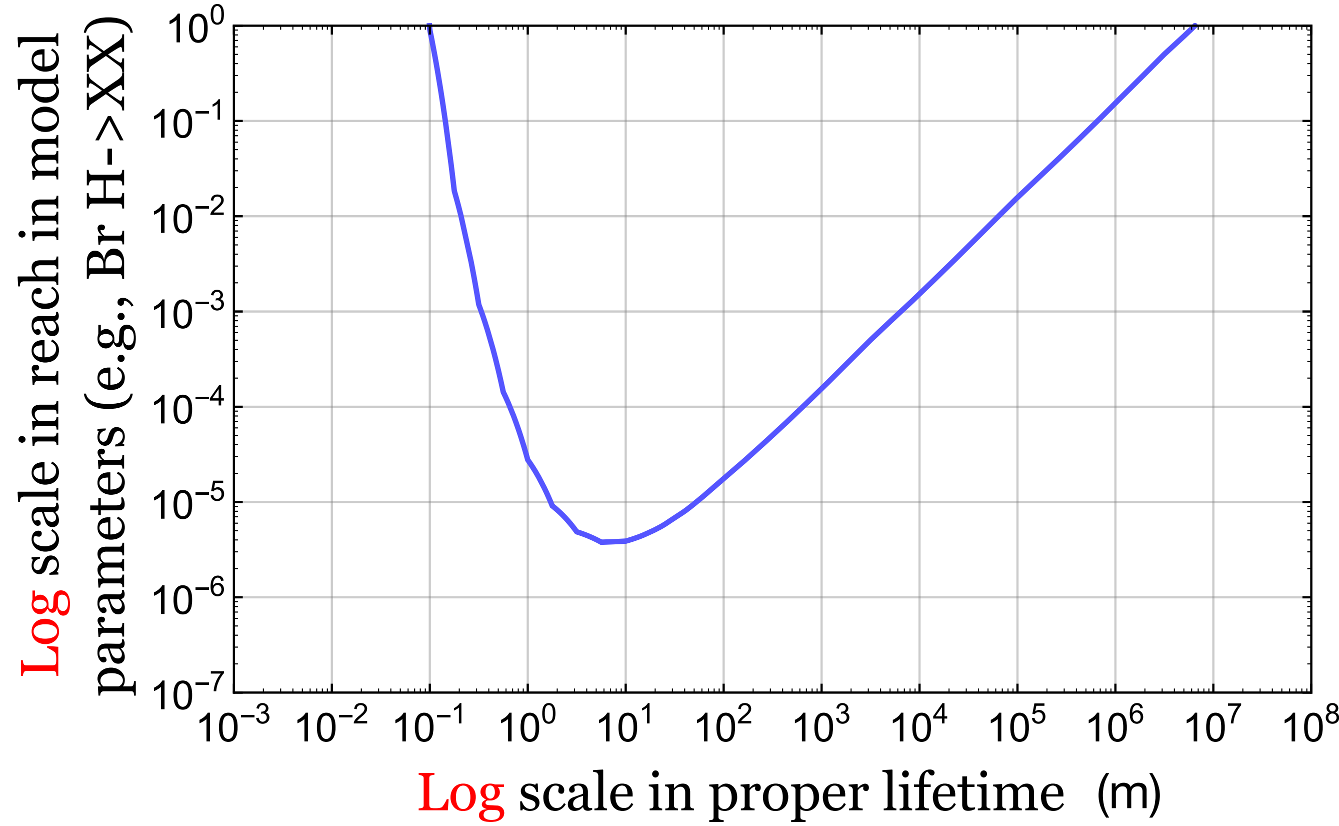
LLP experiment considerations

- Many far detectors proposals: CODEX-b, FASER, MATHUSLA, milliQan, SHiP …
- Searches at existing near detectors, e.g: ATLAS/CMS
  - Large geometrical acceptance ☺
  - But confronting large background ☹
    - Superior Particle Identification plays a role! 💪

LLP basics: Geometrical acceptance

- P_{in}: Geometrical acceptance

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



- The detector length L_2 - L_1
- d: expected decay length of LLP in lab frame $d = c\tau\gamma\beta$

LLP basics: Geometrical acceptance

- P_{in}: Geometrical acceptance

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

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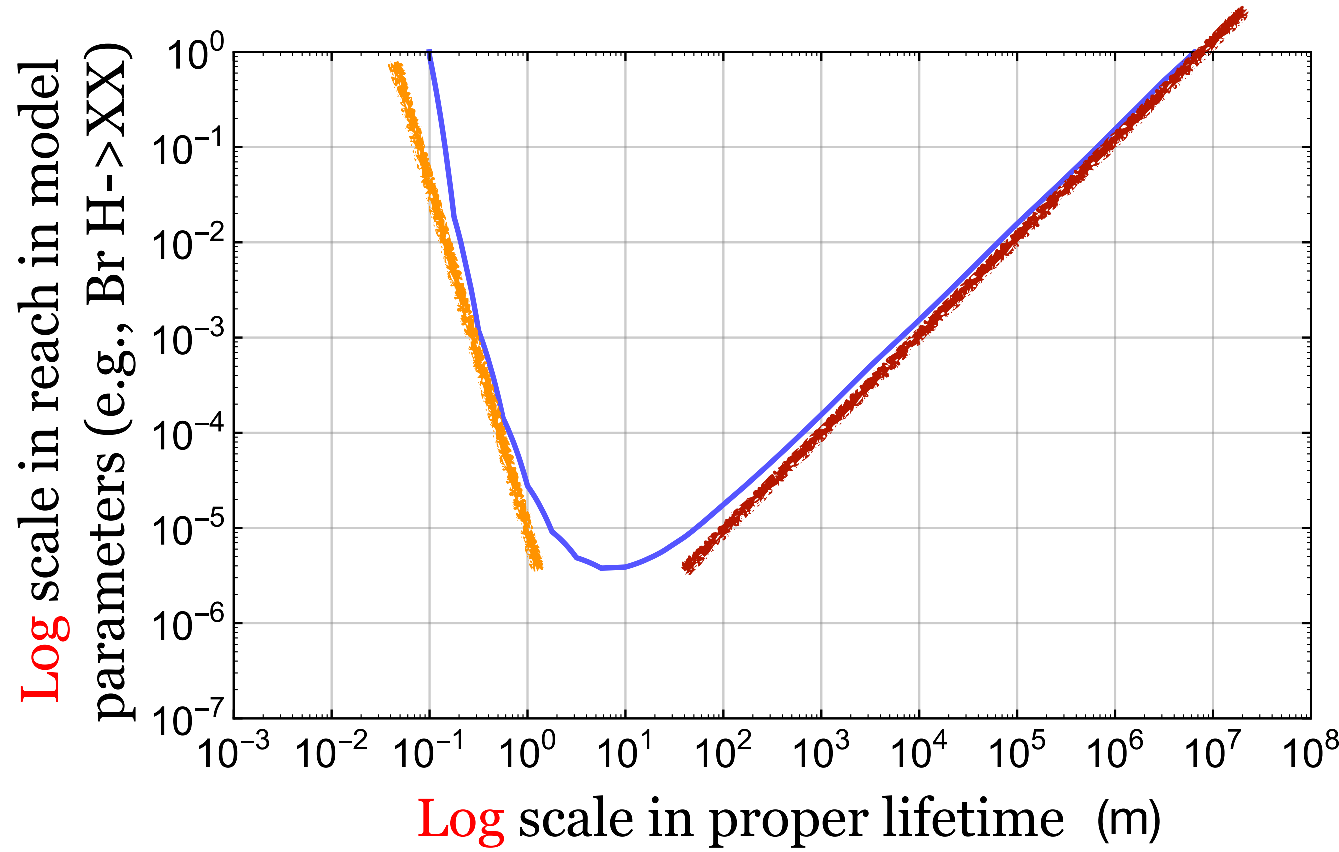
Solid angle **Detector length**



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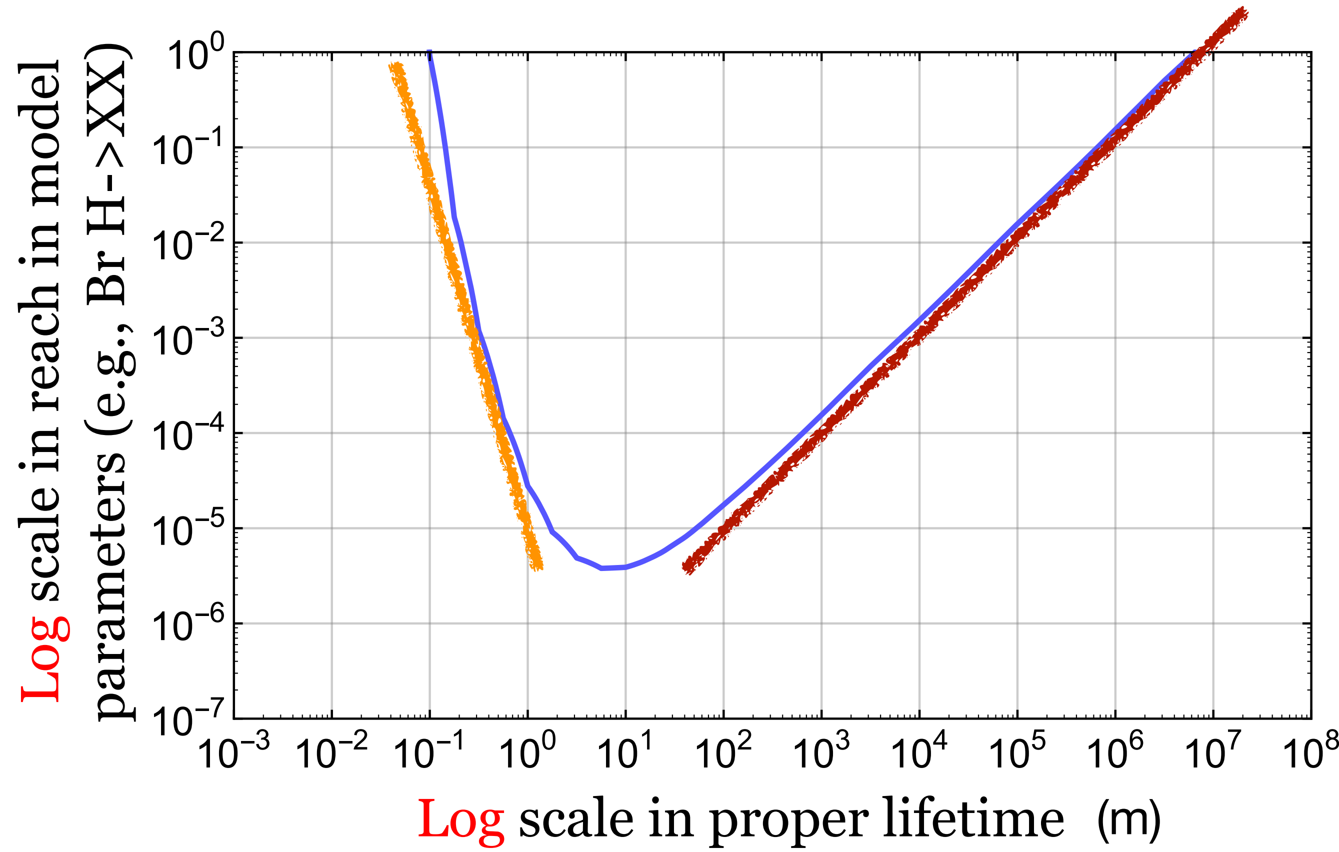


- The detector length $L_2 - L_1$
- *d*: expected decay length of LLP in lab frame

We need

- Closer to IP (for smaller lifetime)
- Longer detector (for larger lifetime)
- The larger solid angle (any lifetime)

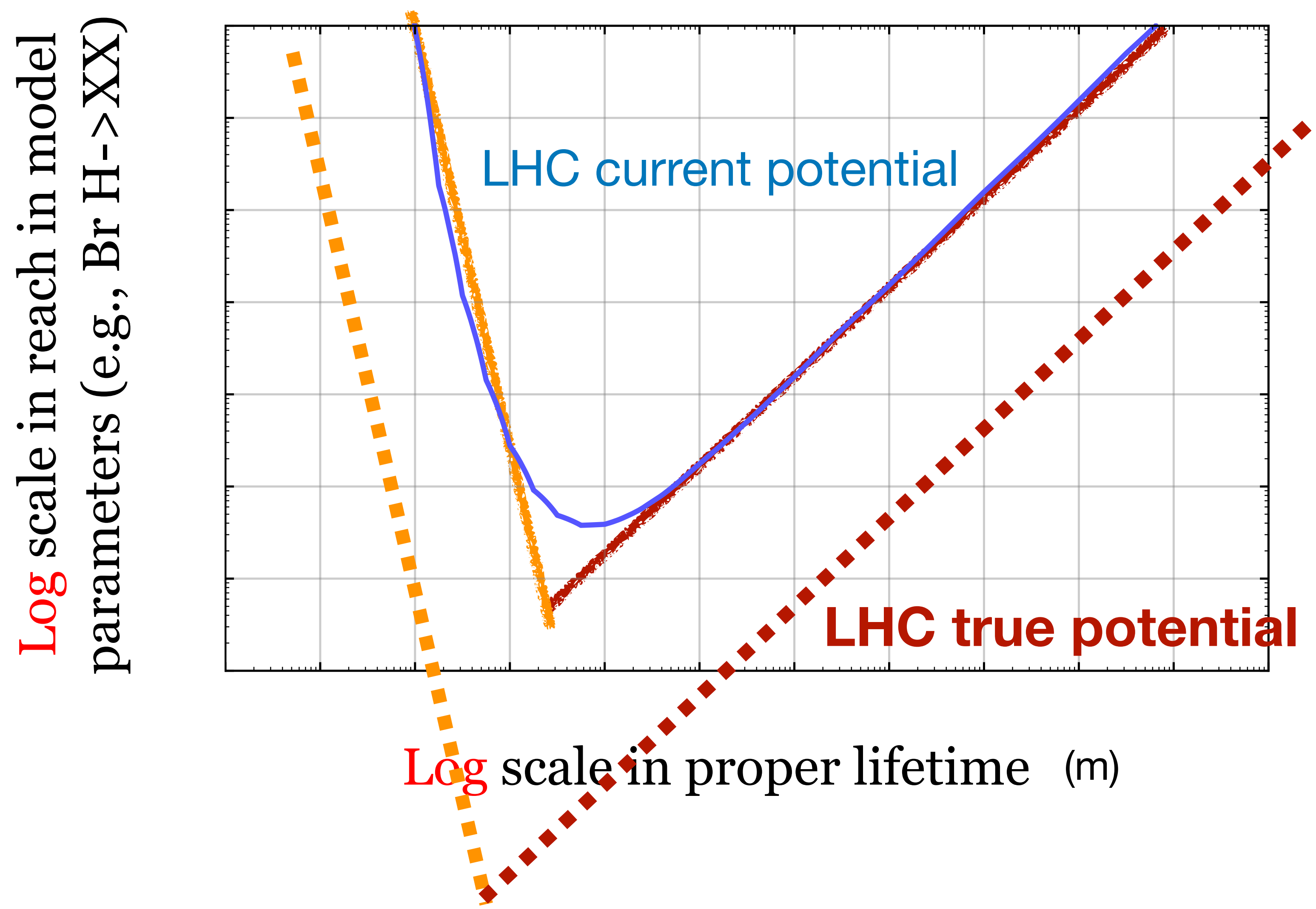
Challenges

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

geometrical acceptance | **trigger** | **signal efficiency** | **bkgd fake rate**

LHC already maximizes $\boldsymbol{P_{in}}$ in all aspects except longer detector length

Optimizing the efficiency factors to realize the full power of LHC



Timing upgrade proposals at LHC

LHCC-P-009

- CMS: MIP Timing Detector (MTD) in central region, High Granularity Calorimeter (HGCAL) in endcap region. CMS-TDR-019

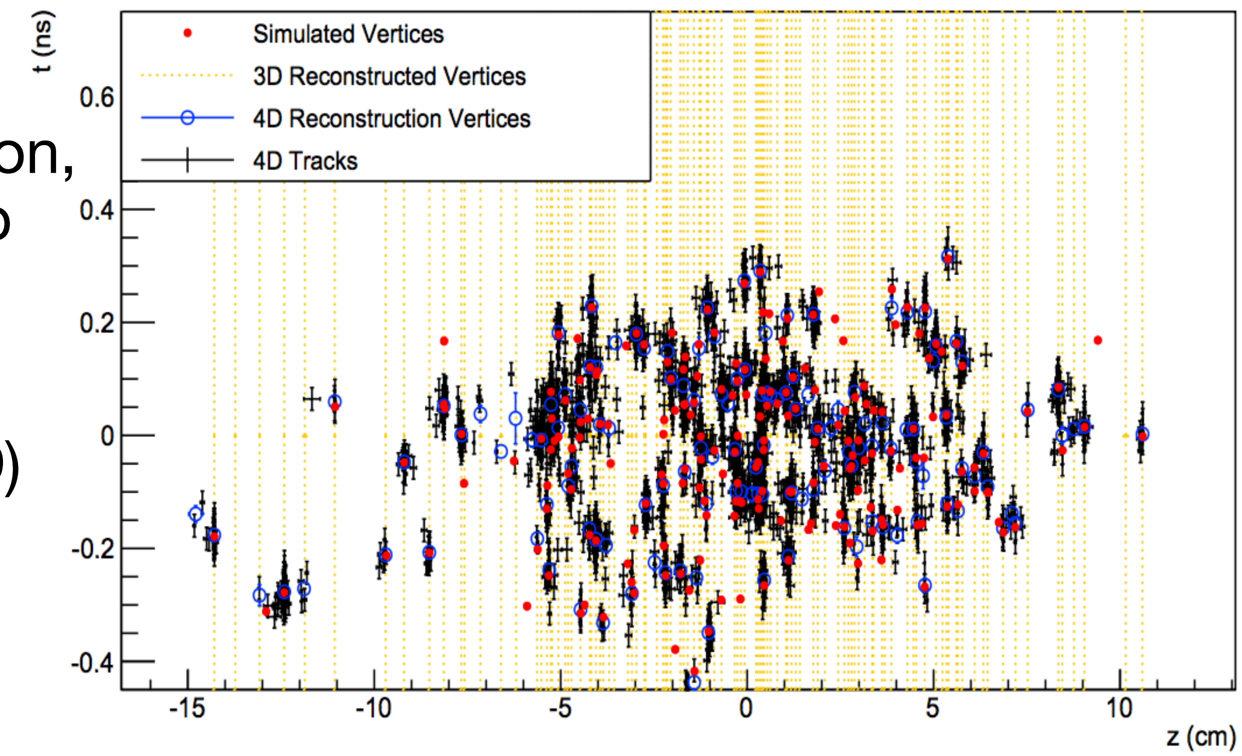
30 ps resolution!

- ATLAS: High Granularity Timing Detector (HGTD)

1804.00622

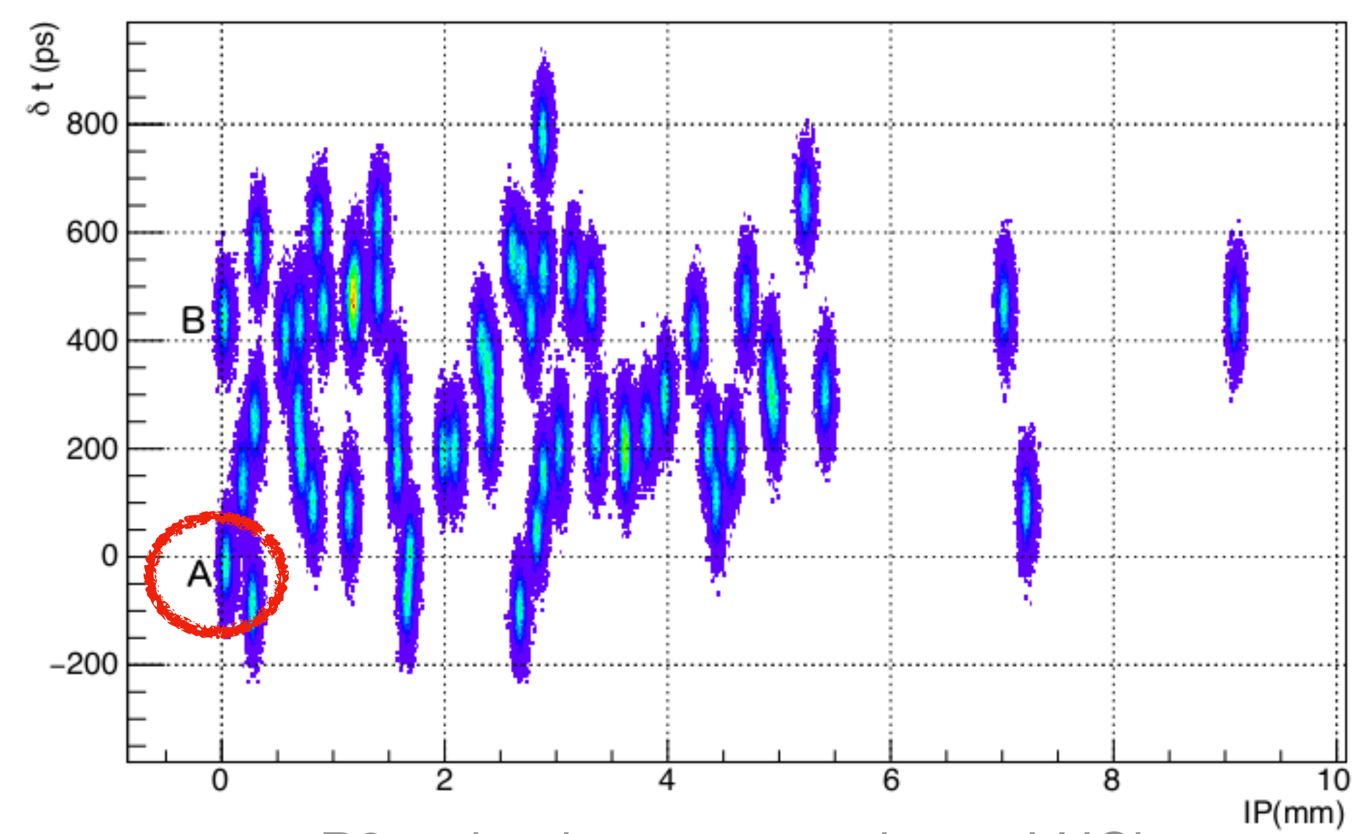
- LHCb: Vertex Locator (VELO), high granularity ECAL and Torch detector

LHCb: 1808.08865, B0->pi+ pi-



PV reconstruction at LHC

- Good potential to benefit new physics searches! (Rest of this talk)



B0->pi+ pi- reconstruction at LHCb

Time delay from LLP and detection proposal

- Long-lived particle X decay, X-> a b

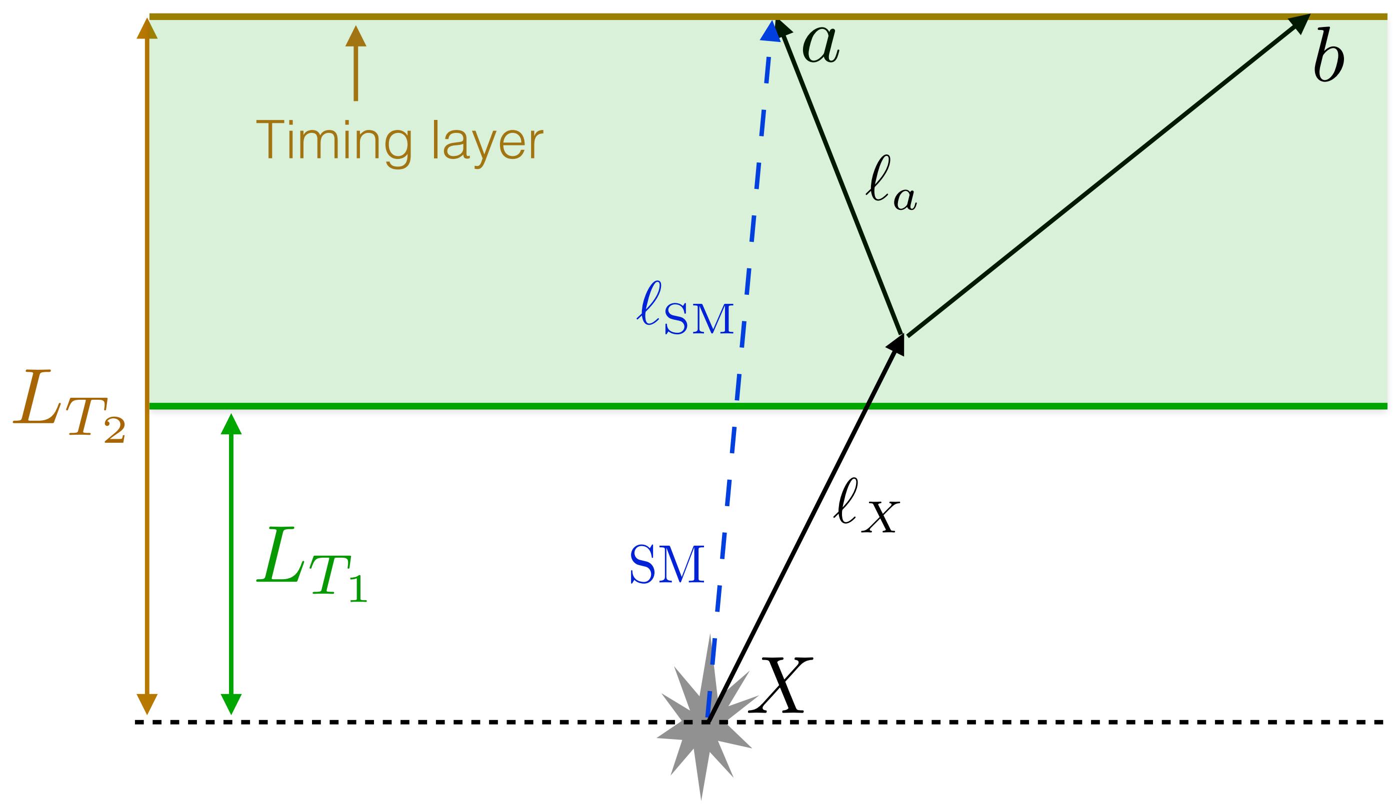
$$\Delta t = \boxed{\frac{\ell_X}{\beta_X} + \frac{\ell_a}{\beta_a}} - \boxed{\frac{\ell_{\rm SM}}{\beta_{\rm SM}}}$$

Signal arrival time - SM bkg ref time

$$\beta_X \lesssim O(1) \qquad \beta_a \simeq \beta_{\rm SM} \simeq 1$$

- Lower bound from slow X

$$\Delta t \geq \frac{\ell_X}{\beta_X} - \frac{\ell_X}{1} = \ell_X(\beta_X^{-1} - 1)$$

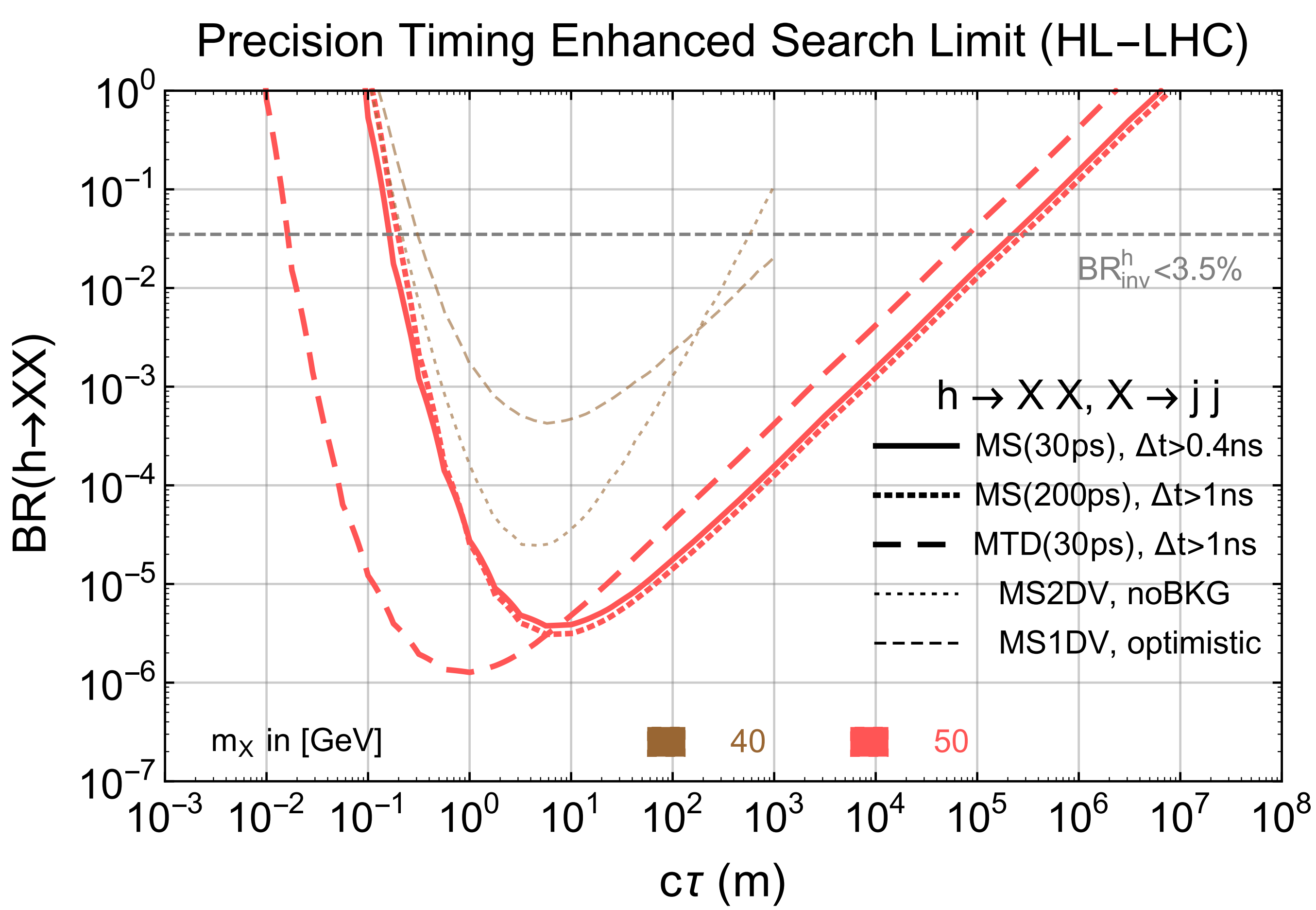


Z. Liu, JL, L.T. Wang, PRL 122 (2019) 131801

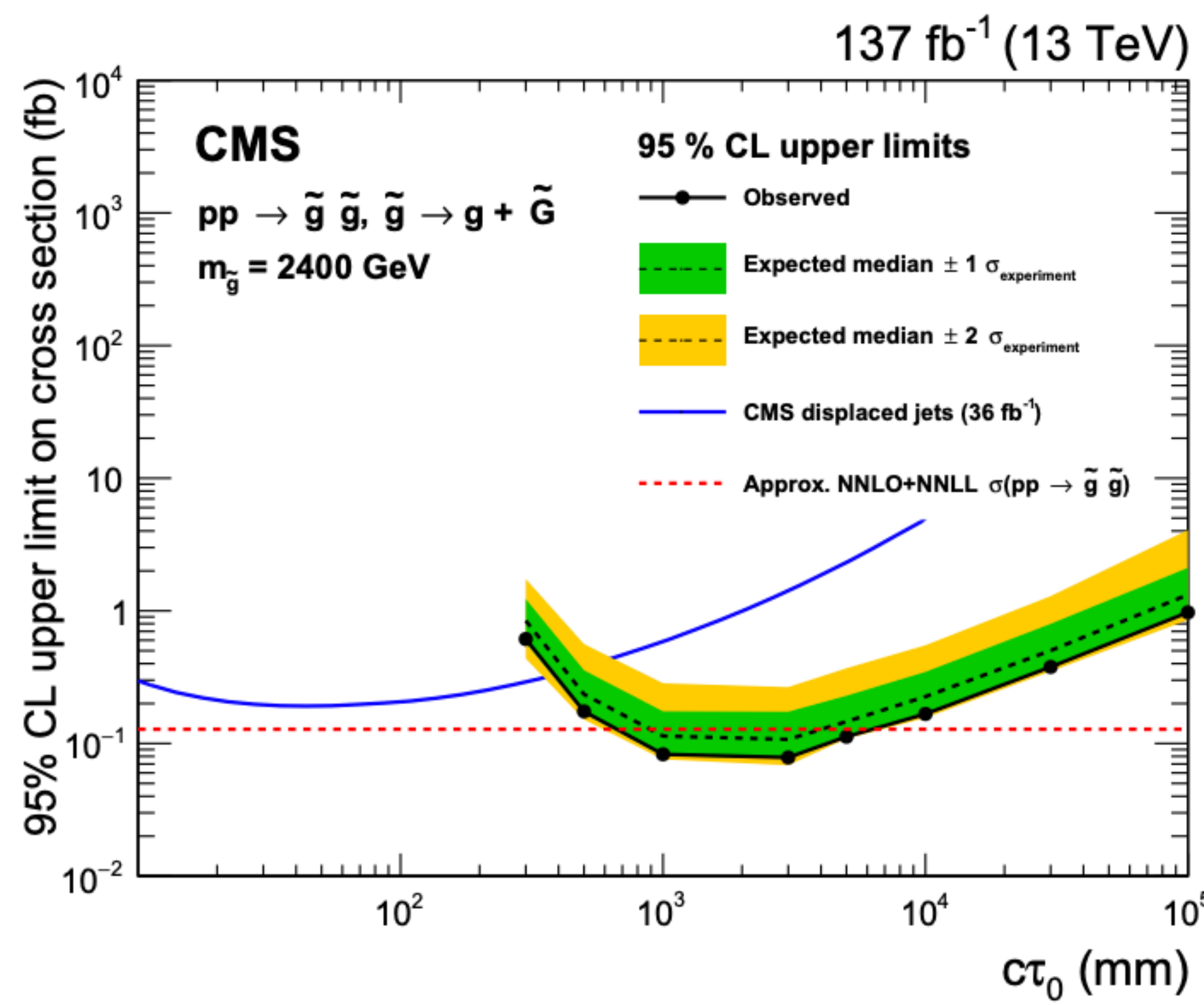
- For CMS MTD size, l_X ~ 1.2 m ~ 4 ns
  - LLPs (mass > 10 GeV) typically move much slower than c
- SM bkg time delay: Phase-2 time resolution 30 ps, Pile-up intrinsic resolution 190 ps
- LLPs are significantly delayed comparing with SM backgrounds!!!

LLP sensitivity benefits from timing PID

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



Z. Liu, JL, L.T. Wang, PRL 122 (2019) 131801



CMS, PLB 797 (2019) 134876

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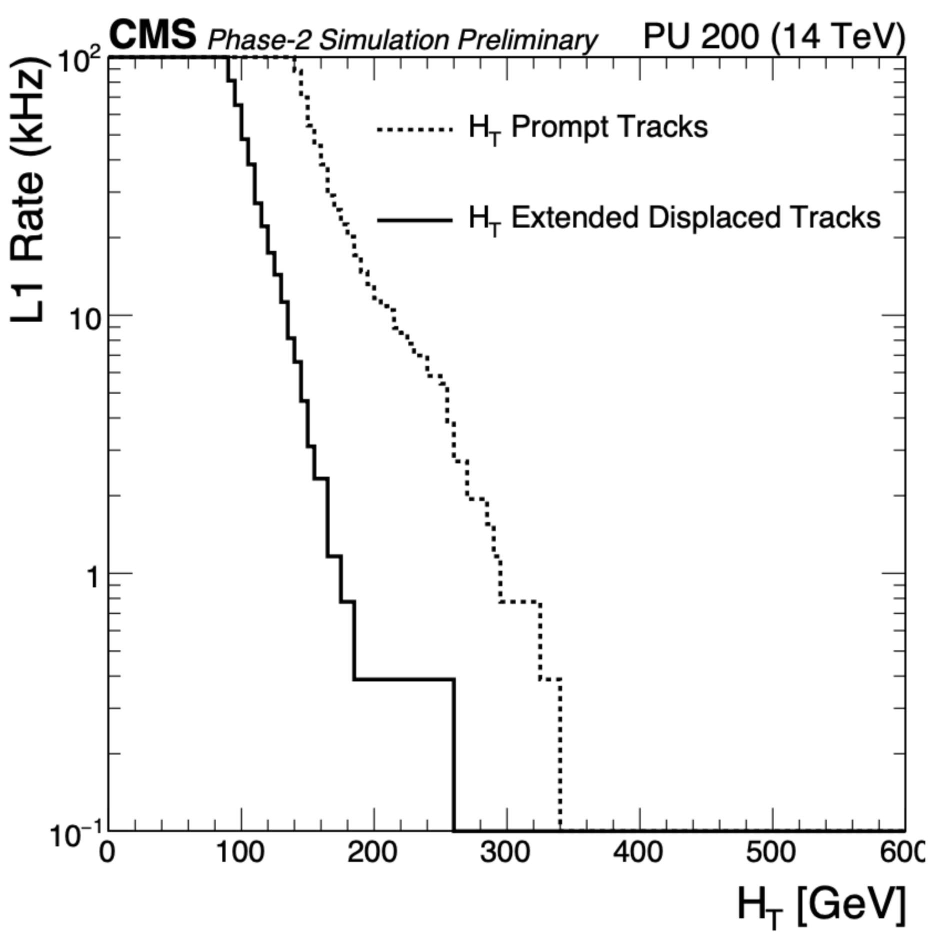
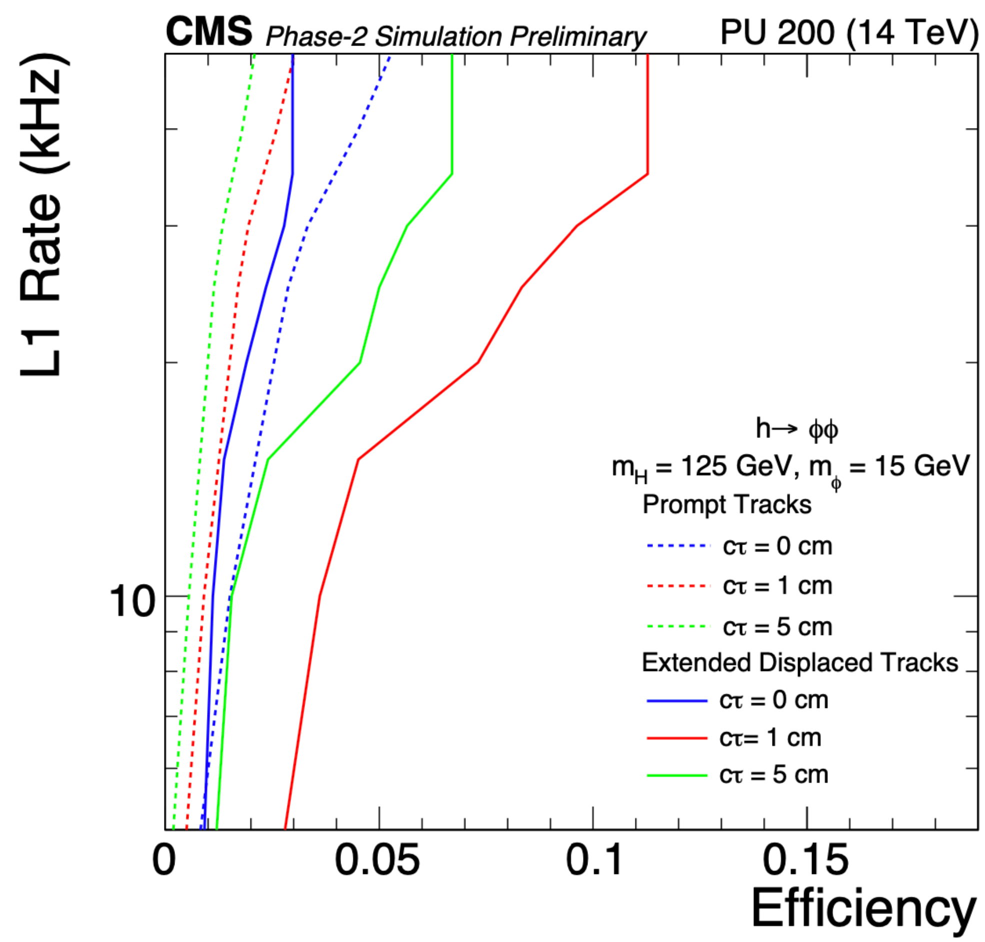
Triggers and PID

- Traditional triggers rely on large p_T , H_T and MET etc.
- Light dark particle, near degenerate states create soft object, suffering from hard cuts
- Unconventional triggers can help: track trigger, displaced vertex trigger, timing trigger etc

Track-based triggers

- Gershtein first worked on CMS hardware track trigger: new opportunity for LLP [1705.04321, PRD]
- CMS studied L1 Track Jet Trigger for Displaced Jets [CMS-PAS-FTR-18-018]





- Displaced track jet: >= 2 tight tracks in jet with $|d_0| > 0.1$ cm
- H_T can indeed be lowered

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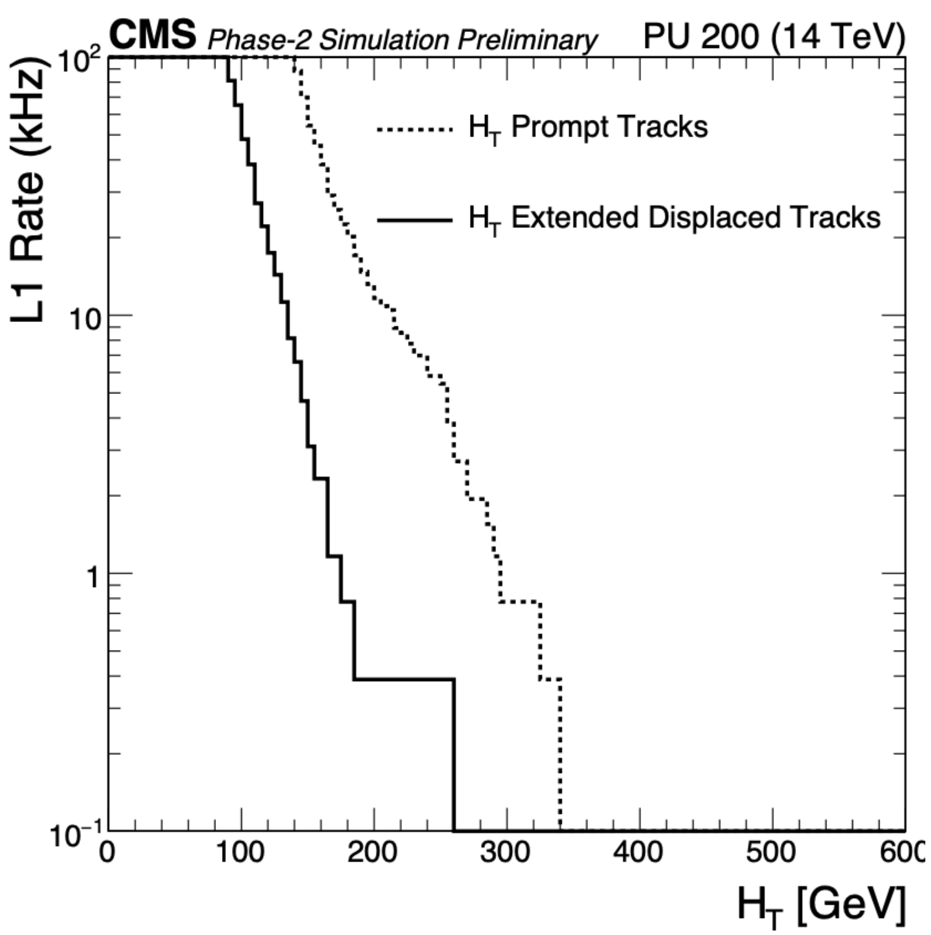
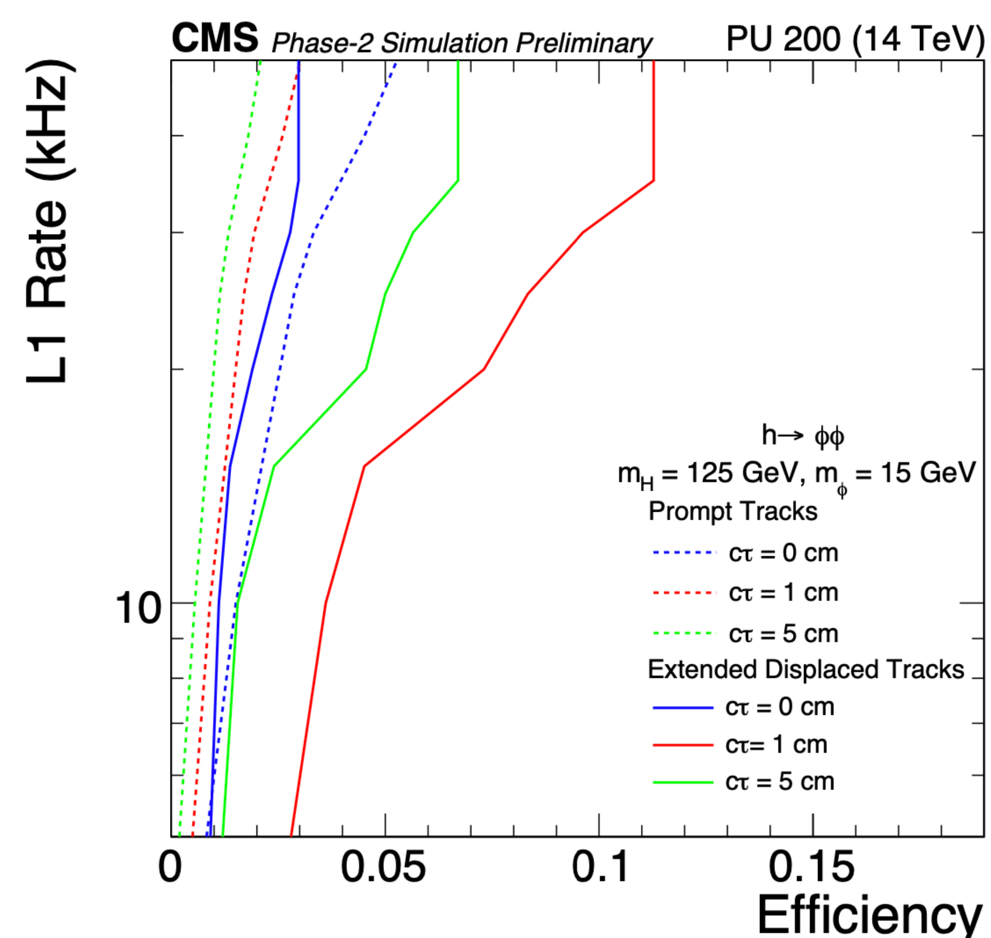


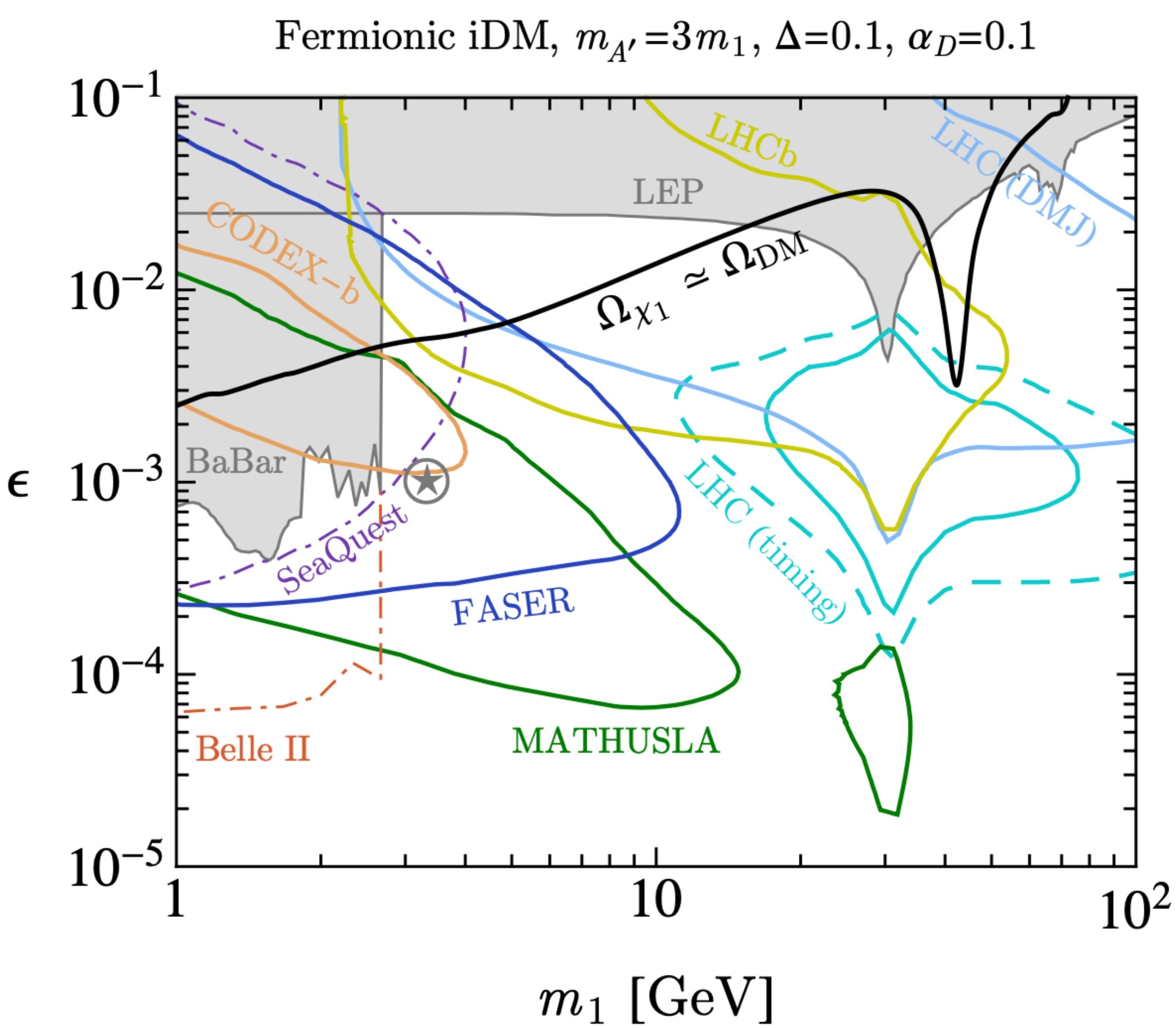


- Further development to displaced vertex trigger:
  - Very low mass displaced muon pair: Gershtein, Knapen [1907.00007]
  - Light singlets with a displaced vertex: Gershtein, Knapen, Redigolo2 [2012.07864]

Timing-based trigger

- Fermionic inelastic dark matter as LLP

Berlin and Kling, 1810.01879 [PRD]



$$\bar{q}q \to A' \to \chi_2\chi_1, \quad \chi_2 \to \chi_1 \bar{\ell}\ell$$

- Timing-based trigger

Timing (Δt) :
$$p_{T,j} > 30 \text{ GeV}$$
$$p_{T,\ell} > 3 \text{ GeV}$$
$$\Delta t > 0.3 \text{ ns}$$
$$5 \text{ cm} < r_{\chi_2} < 1.17 \text{ m}$$
$$z_{\chi_2} < 3.04 \text{ m}\,.$$

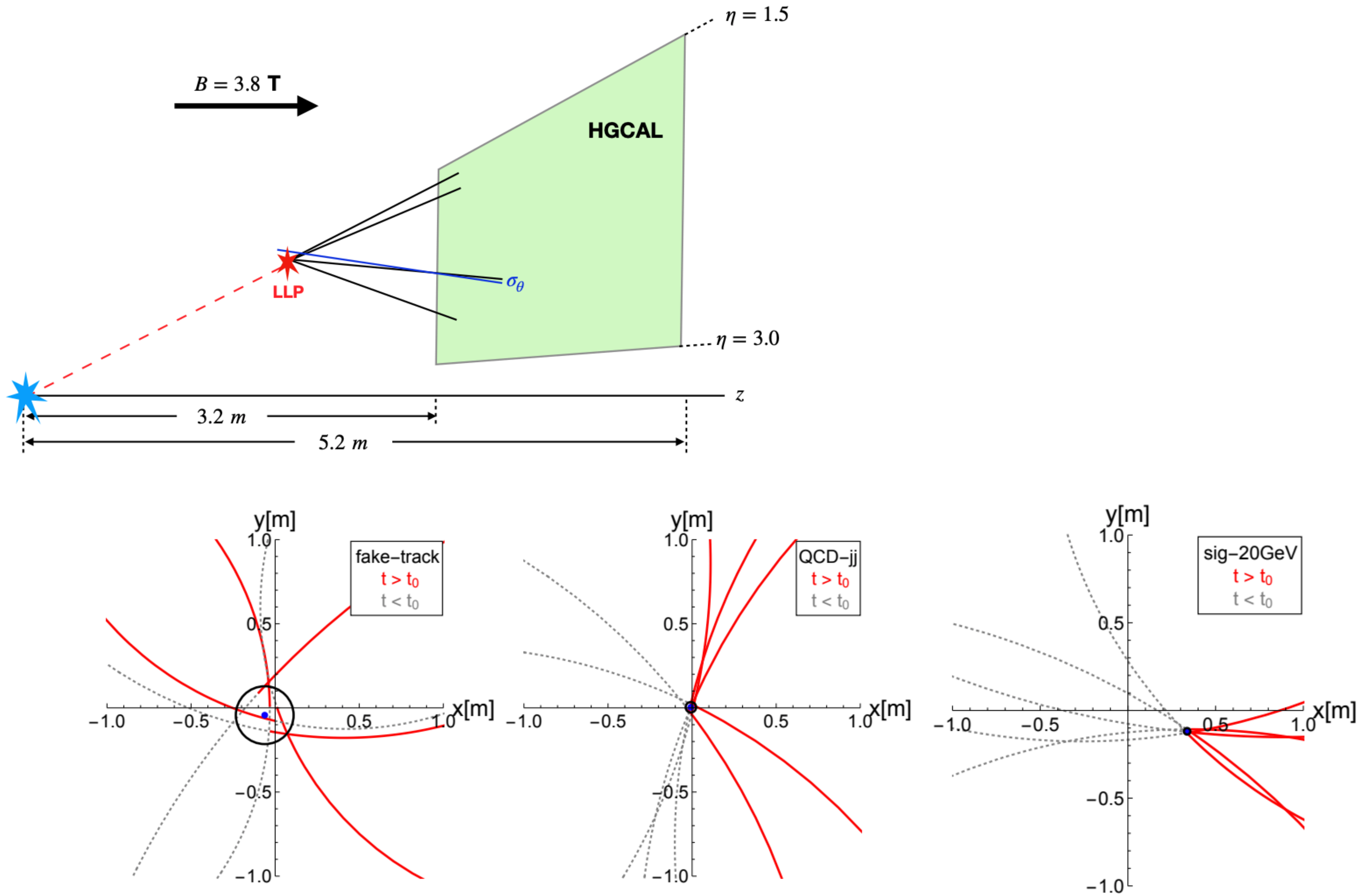
- Traditional trigger: monojet+MET

$$p_{T,j} > 120 \text{ GeV}$$

Track info and LLP search

- Track based LLP search at HGCAL

JL, Liu, Wang, Wang, 2005.10836 [JHEP]



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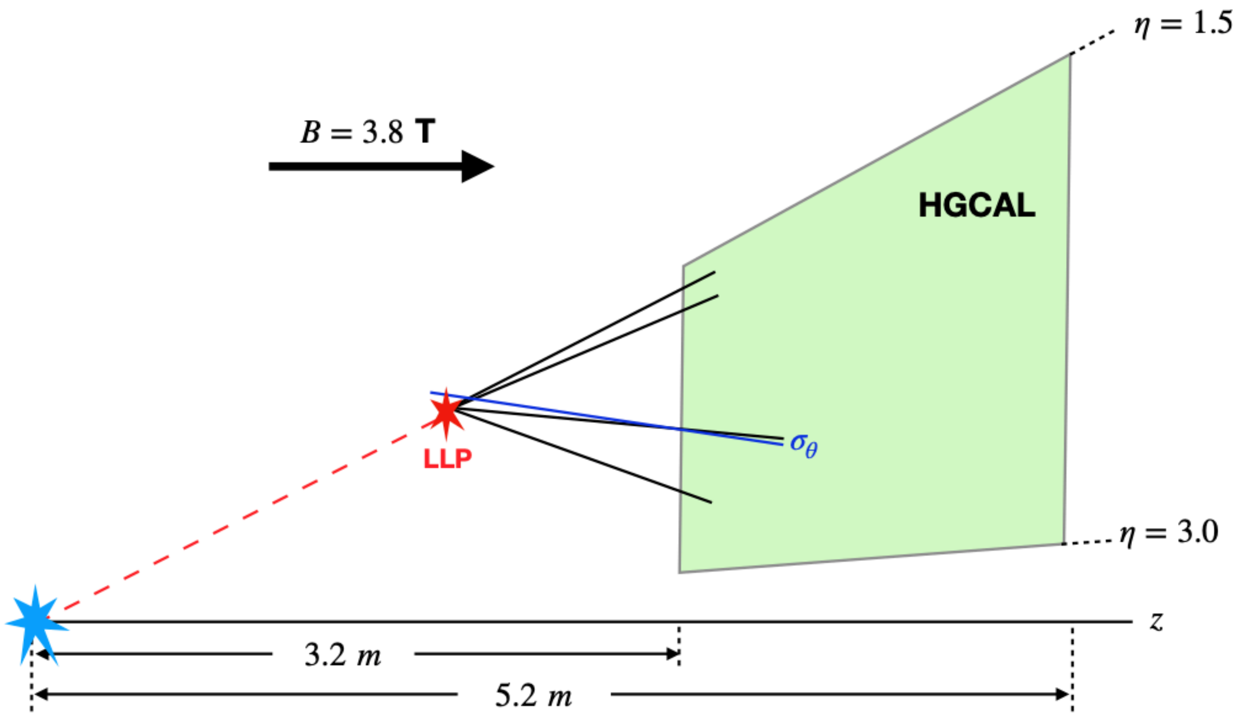

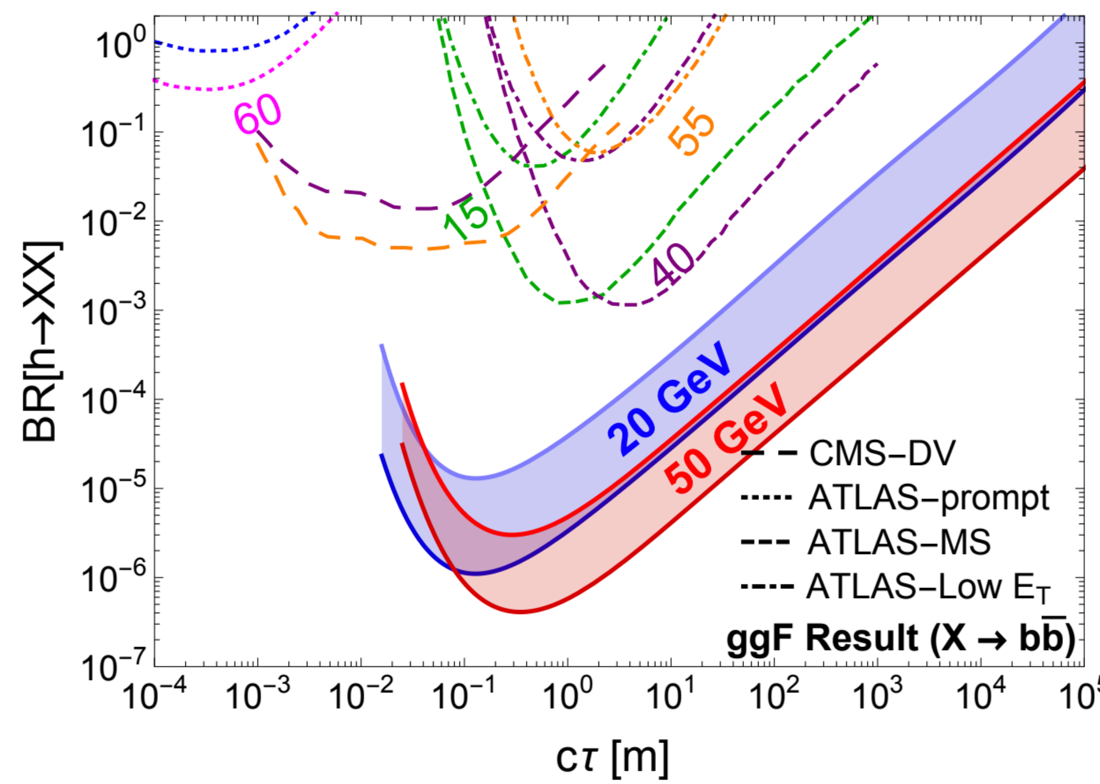

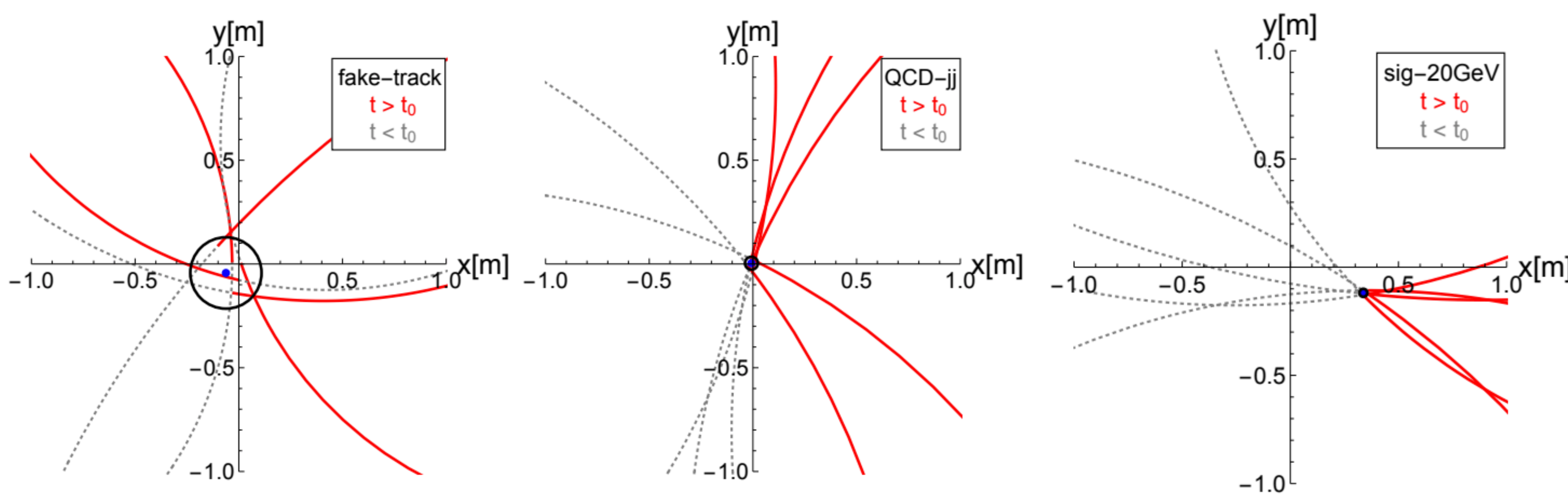

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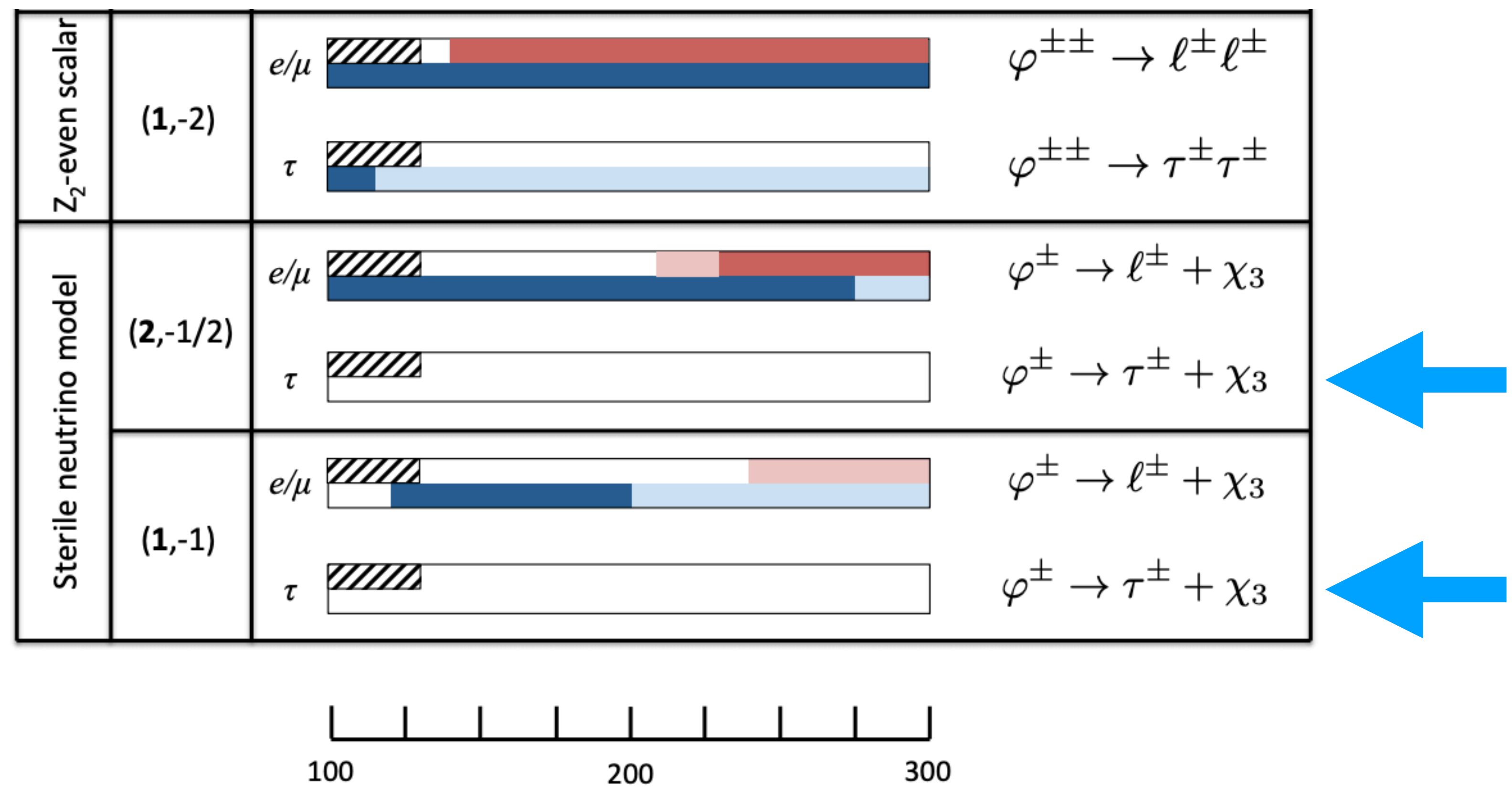
The importance of tau PID

- Tau is difficult for theorists

JL, Shuve, Weiner, Yavin, 1303.4404 [JHEP]

Leptonphilic dark matter

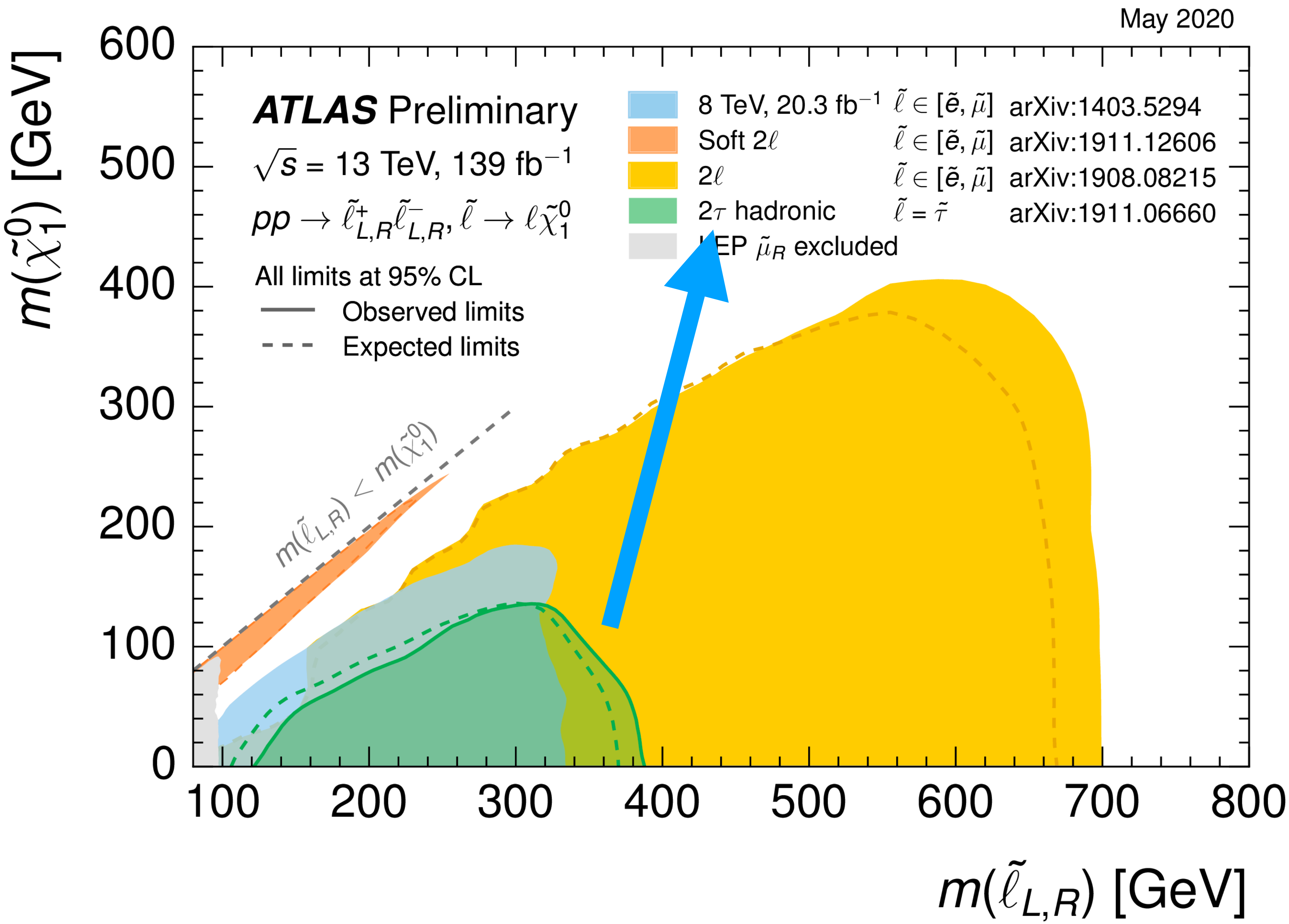
$$\mathscr{L} \supset \lambda \bar{\psi} \ell \phi$$



Collider search	Model
$\ell^+\ell^- + \not{E}_T$	Sterile neutrino model (φ coupled to e, μ)
$\geq 3\ell + \not{E}_T$	Odd scalar model (e and μ in final state) Odd fermion model (Type I 2HDM, triplet)
Same-sign dilepton + hadronic τ	Odd scalar model (doublet, τ in final state) Odd fermion model (Type IV 2HDM)
Same-sign dilepton + dijet resonance	Odd fermion model (triplet)
Disappearing charged tracks	Stable model
No distinctive signature	Sterile neutrino model (φ coupled to τ) Odd scalar model (singlet, τ in final state)

The importance of tau PID

- Improvement from hadronic tau PID



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Tau PID, leptophilic dark scalar and g-2$_\mu$

- SM Higgs portal model $H^\dagger H \phi^2$, $H^\dagger H \phi$

$$\mathscr{L}_{\text{int}} \supset \sin\theta \times \phi \left(\sum_q \frac{m_q}{v} \bar{q} q + \sum_\ell \frac{m_\ell}{v} \bar{\ell} \ell + \cdots \right)$$

Tau PID, leptophilic dark scalar and g-2$_\mu$

- SM Higgs portal model $H^\dagger H\phi^2,\ H^\dagger H\phi$

$$\mathscr{L}_{\rm int} \supset \sin\theta \times \phi \left(\sum_q \frac{m_q}{v}\bar{q}q + \sum_\ell \frac{m_\ell}{v}\bar{\ell}\ell + \cdots \right)$$

- Type-X 2HDM: one SM-like doublet coupling to quarks and one doublet coupling to leptons

$$\mathscr{L}_{\rm yuk} = -\lambda_u \bar{Q}\tilde{\Phi}_2 u_R - \lambda_d \bar{Q}\Phi_2 d_R - \lambda_e \bar{L}\Phi_1 e_R + h.c.$$

- The light scalar mixing independently with two doublets

$$\mathscr{L}_{\rm eff} \supset \epsilon_q \sum_q \frac{m_q}{v}\phi\bar{q}q + \epsilon_\ell \sum_\ell \frac{m_\ell}{v}\phi\bar{\ell}\ell + \epsilon_W \frac{2m_W^2}{v}\phi W_\mu^+ W^{\mu-} \qquad \epsilon_W \approx \epsilon_q$$

$$\to \epsilon_\ell \phi \sum_\ell \frac{m_\ell}{v}\bar{\ell}\ell$$

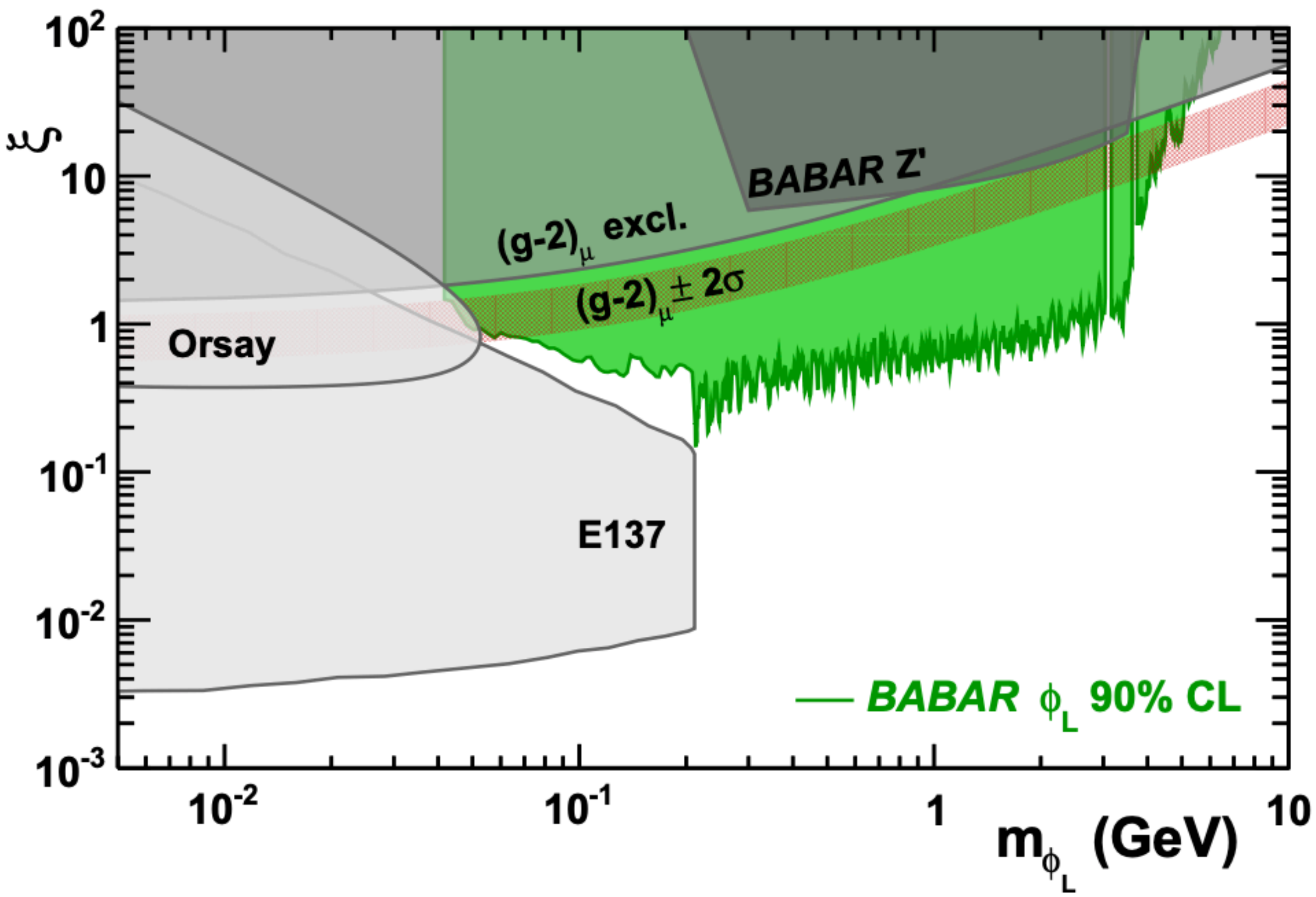
Leptophilic dark scalar model

Tau lepton has a much larger coupling to ϕ!

Tau PID, leptophilic dark scalar and g-2_μ

- Production at ee collider: $e^+ e^- \to \tau^+ \tau^- \phi$

Brian Batell et al [1606.04943, PRD]; BaBar [2005.01885, PRL]



$$\mathscr{L}_{\rm eff} = \epsilon_\ell \phi \sum_\ell \frac{m_\ell}{v} \bar{\ell}\ell$$

- ϕ decay channels considered

$$\phi \to e^+e^-, \mu^+\mu^-$$

Tau PID, leptophilic dark scalar and g-2_μ

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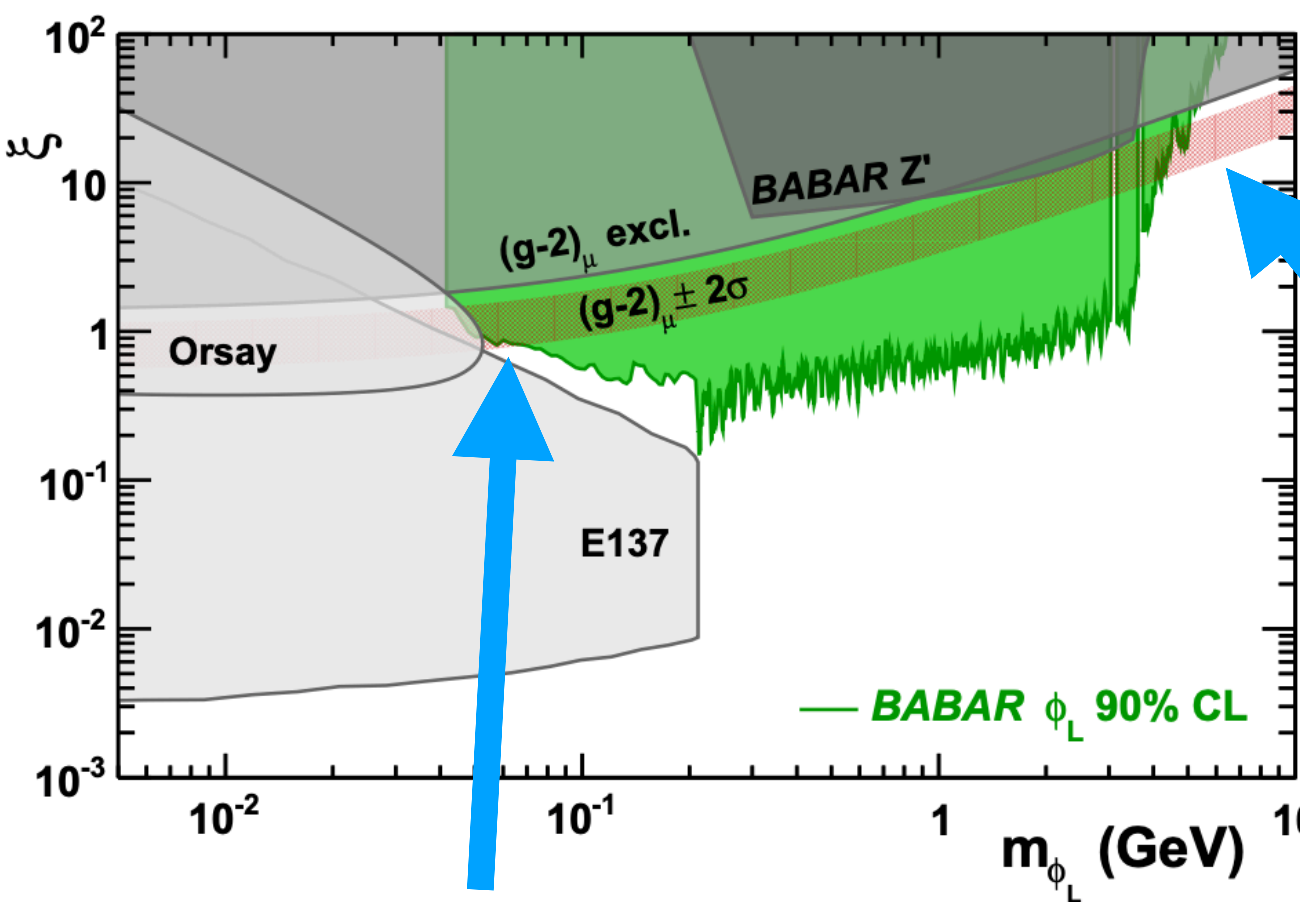


A silver corner m~50 MeV

$\phi \to e^+ e^-$, $c\tau \sim O(\mathrm{cm})$

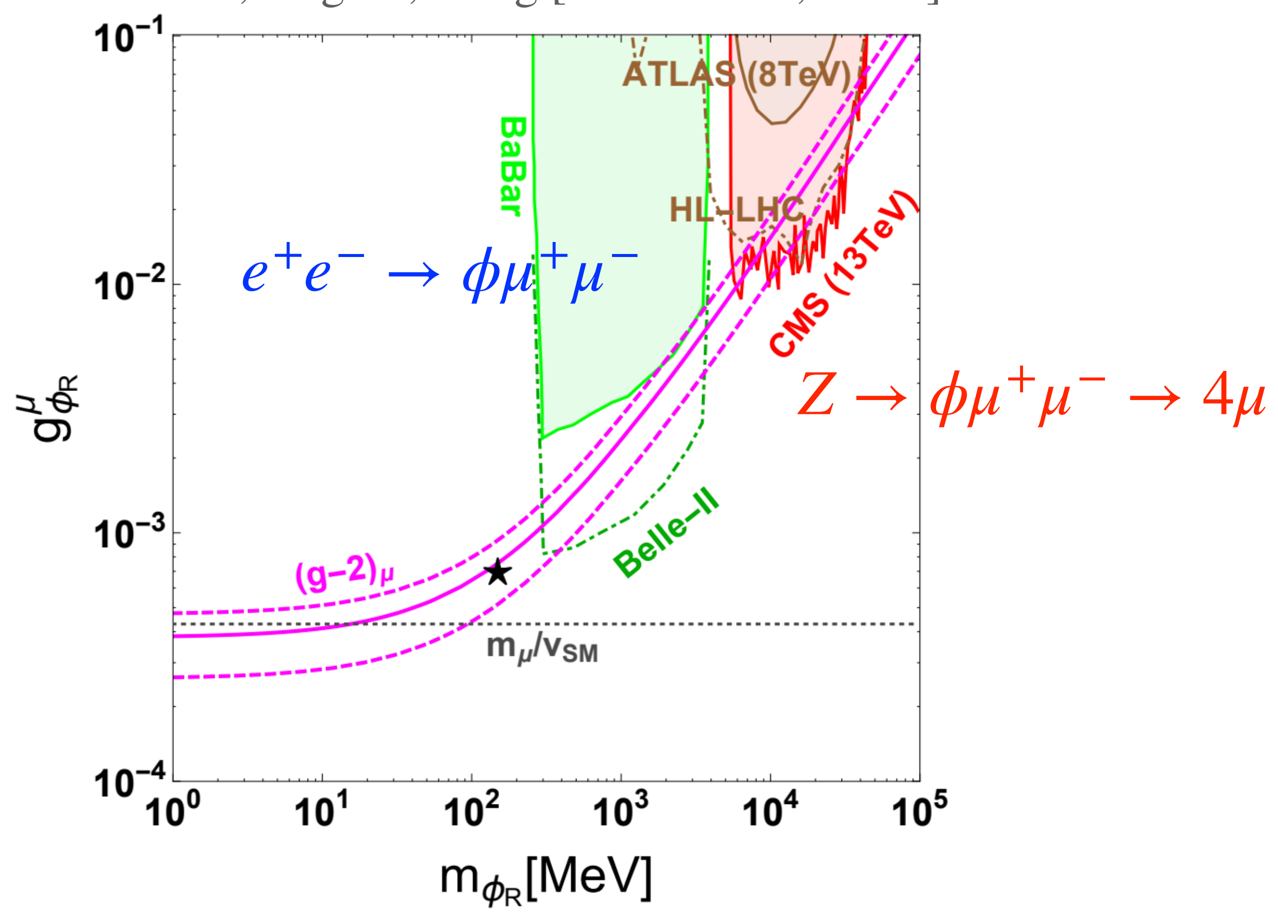
$$\mathscr{L}_{\rm eff} = \epsilon_\ell \phi \sum_\ell \frac{m_\ell}{v} \bar{\ell}\ell$$

- ϕ decay channels considered

$$\phi \to e^+e^-, \mu^+\mu^-$$

Opportunities at high mass

JL, Wagner, Wang [1810.11028, JHEP]



Tau PID, leptophilic dark scalar and g-2_μ

- Opportunities for future e+ e- collider

- Production channels

$$\text{Z factory}: Z \to \tau^+\tau^-\phi \to 4\tau$$

$$\text{H factory}: h \to \phi\phi \to 4\tau$$

$$\text{H factory}: e^+e^- \to \tau^+\tau^-\phi \to 4\tau$$

- Mass ranges

$$m_\phi \sim \mathcal{O}(50)\ \text{MeV}$$

$$m_\phi \sim [4,\ 5.5]\ \text{GeV}$$

$$m_\phi \gtrsim 40\ \text{GeV}$$

- Φ decay features
  - Prompt
  - Displaced
  - Missing energy
  - Collimated (lepton-jets)

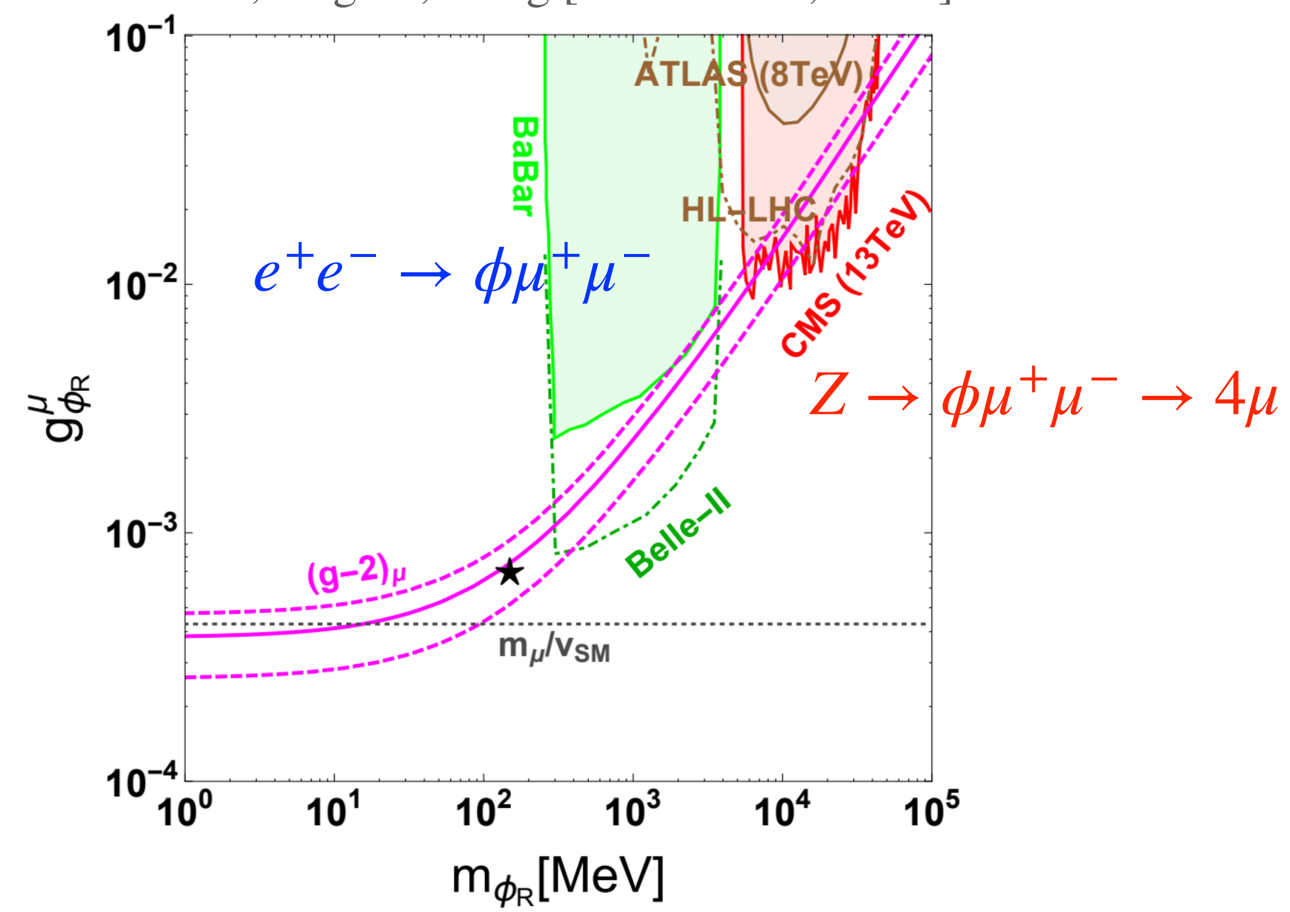
- Decay channels

$\phi \to e^+e^-$ Light mass, maybe long-lived

$\phi \to \mu^+\mu^-$ LHC competition, suffering low BR

$\phi \to \tau^+\tau^-$ ee collider: tau PID and low bkg

JL, Wagner, Wang [1810.11028, JHEP]



Summary

- PID is important for BSM searches, especially soft and long-lived objects
- Timing PID can be very useful in the LLP detection
- New triggers can be possible with superior PID
- Tau PID could be crucial for solving the $g\text{-}2_{\mu}$ problem

Thank you!

Backup slides