Long-lived Particle Searches at Colliders

刘佳 (Jia Liu)
Peking University

27th Mini-workshop on the frontier of LHC
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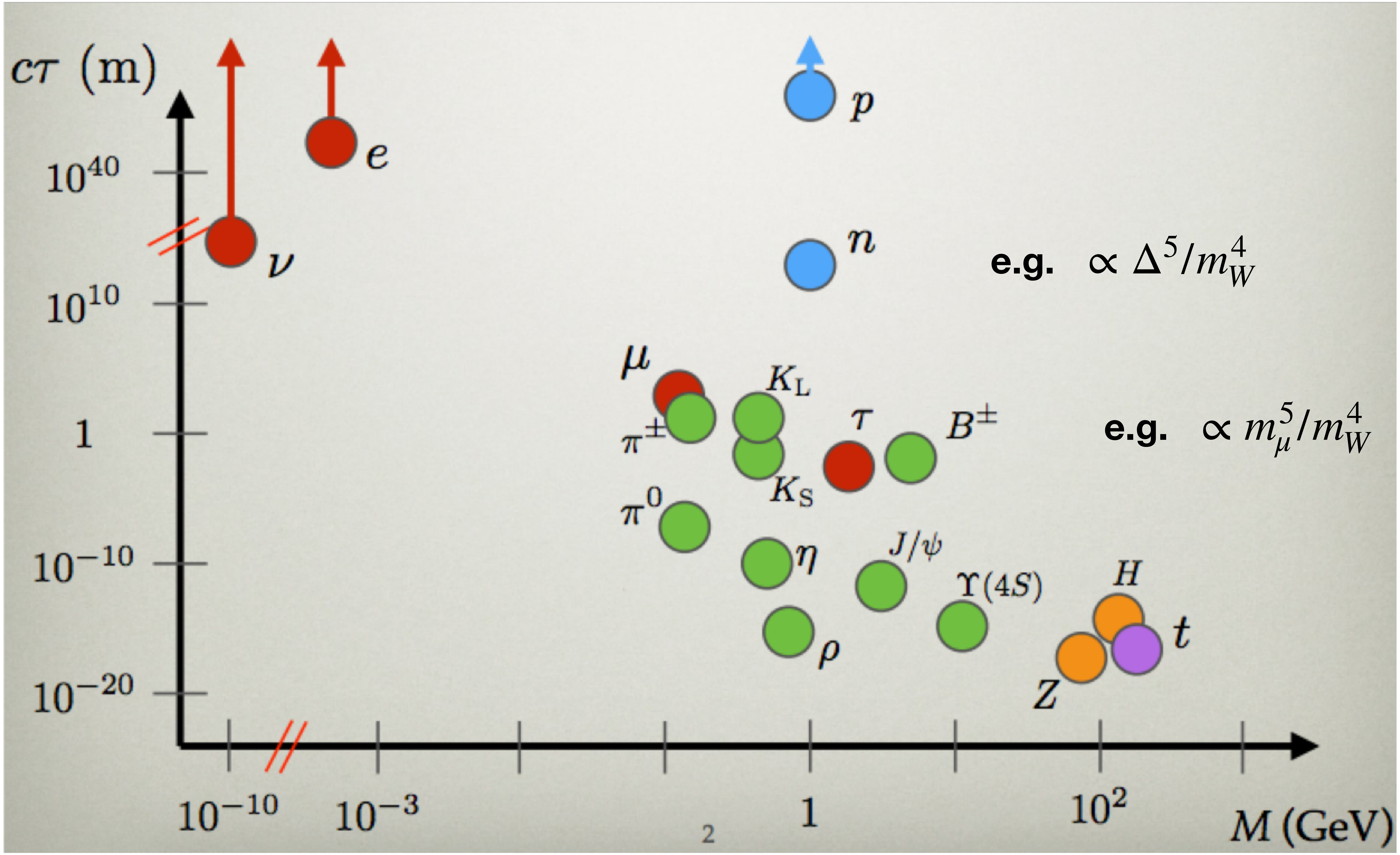
北京大学高能物理研究中心和中山大学物理与天文学院

Outline

- The motivation for long-lived particles
- Displaced searches for LLP
- Timing searches for delayed LLP
- Motivated long-lived candidates
- Summary

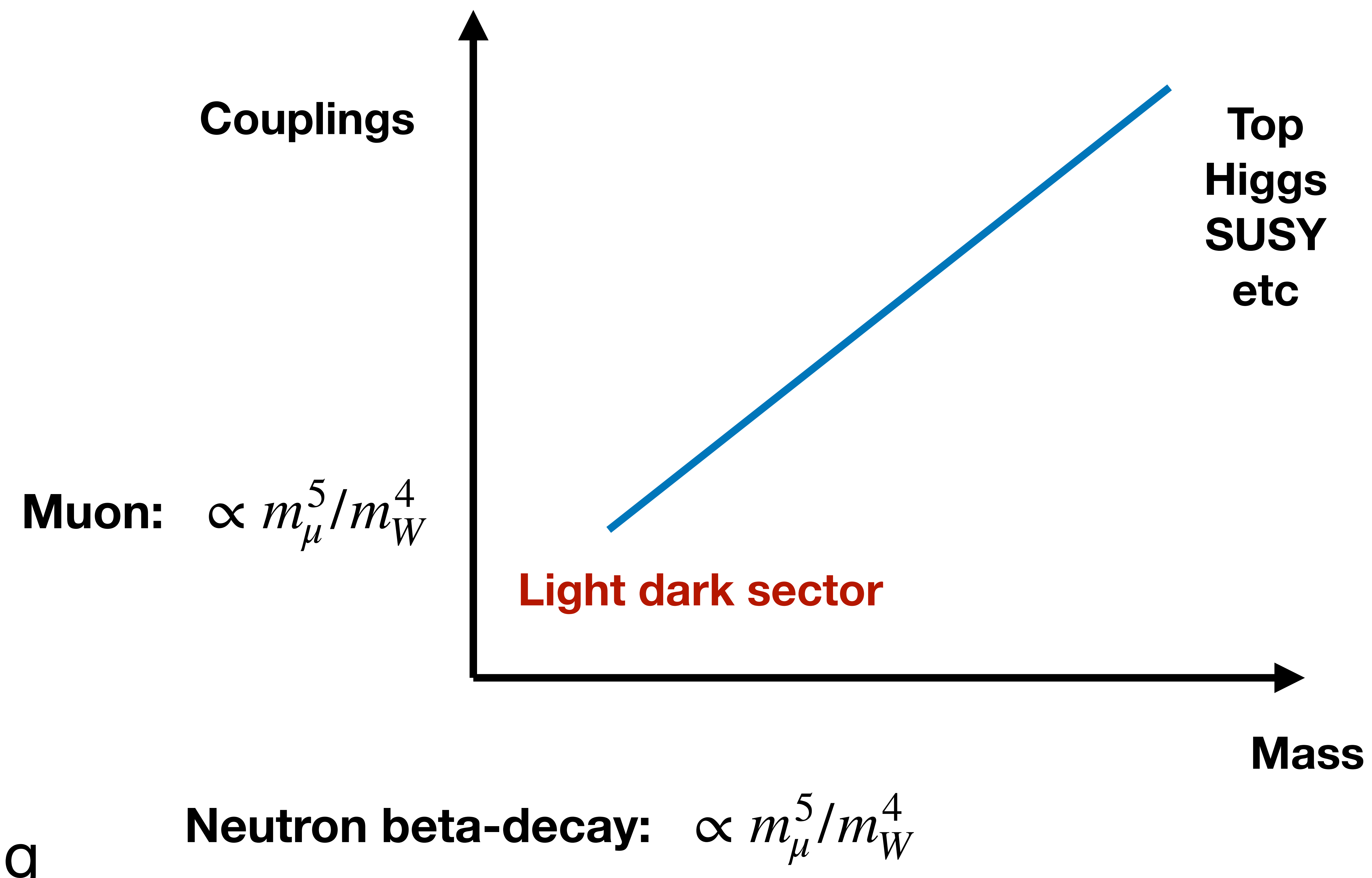
Long-lived particle in SM



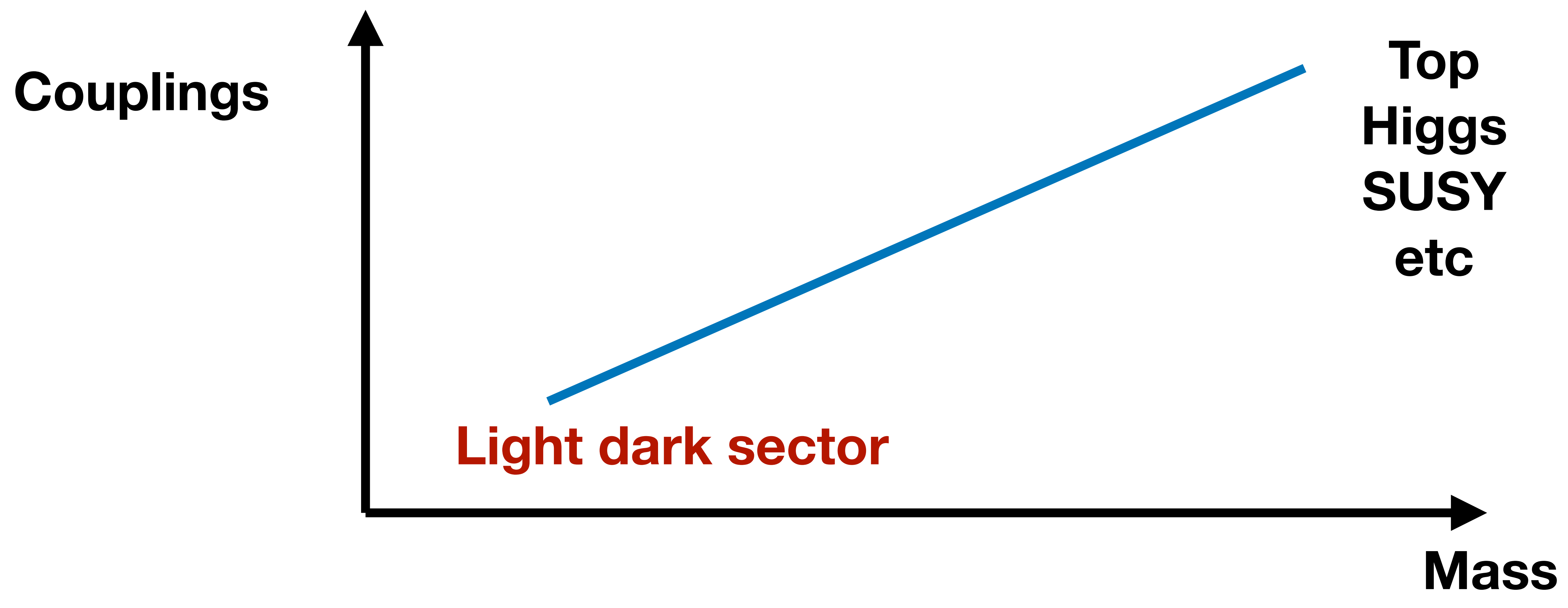
Credit: B. Shuve

Exotic features: Long-Lived Particles

- Why being long-lived?
  - 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 target for the Intensity Frontier



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

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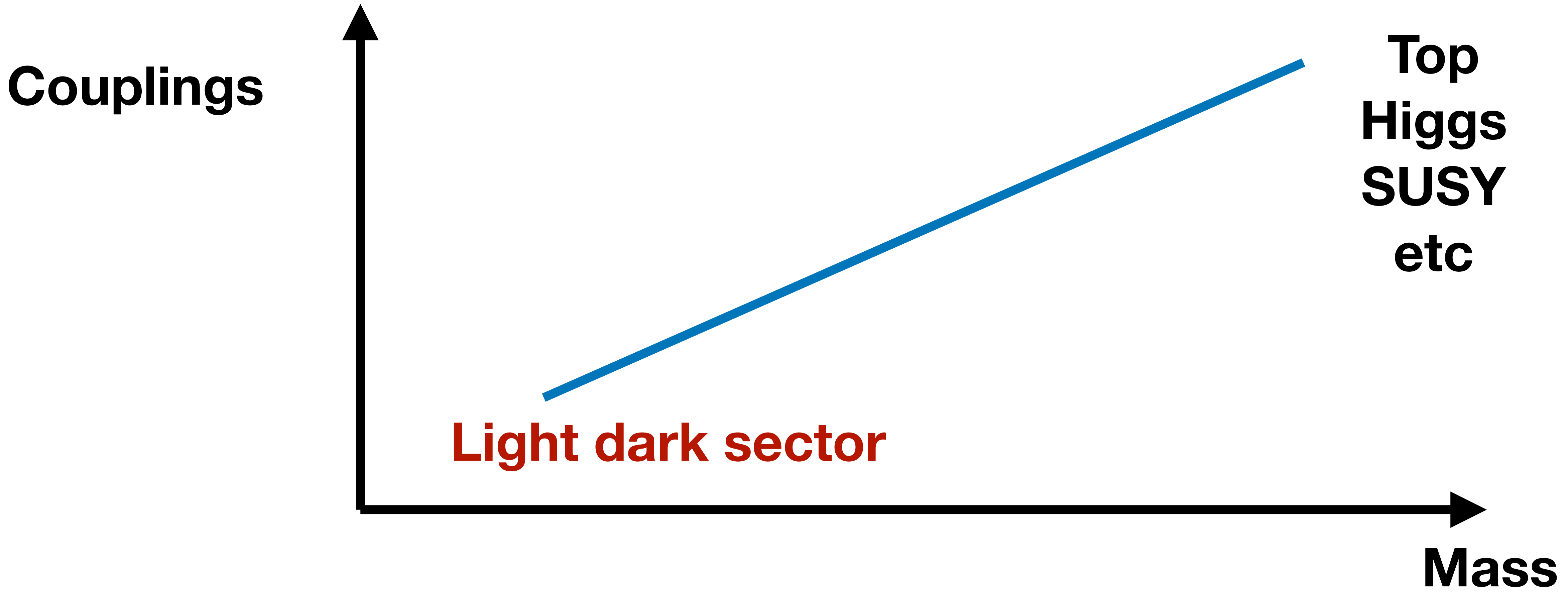
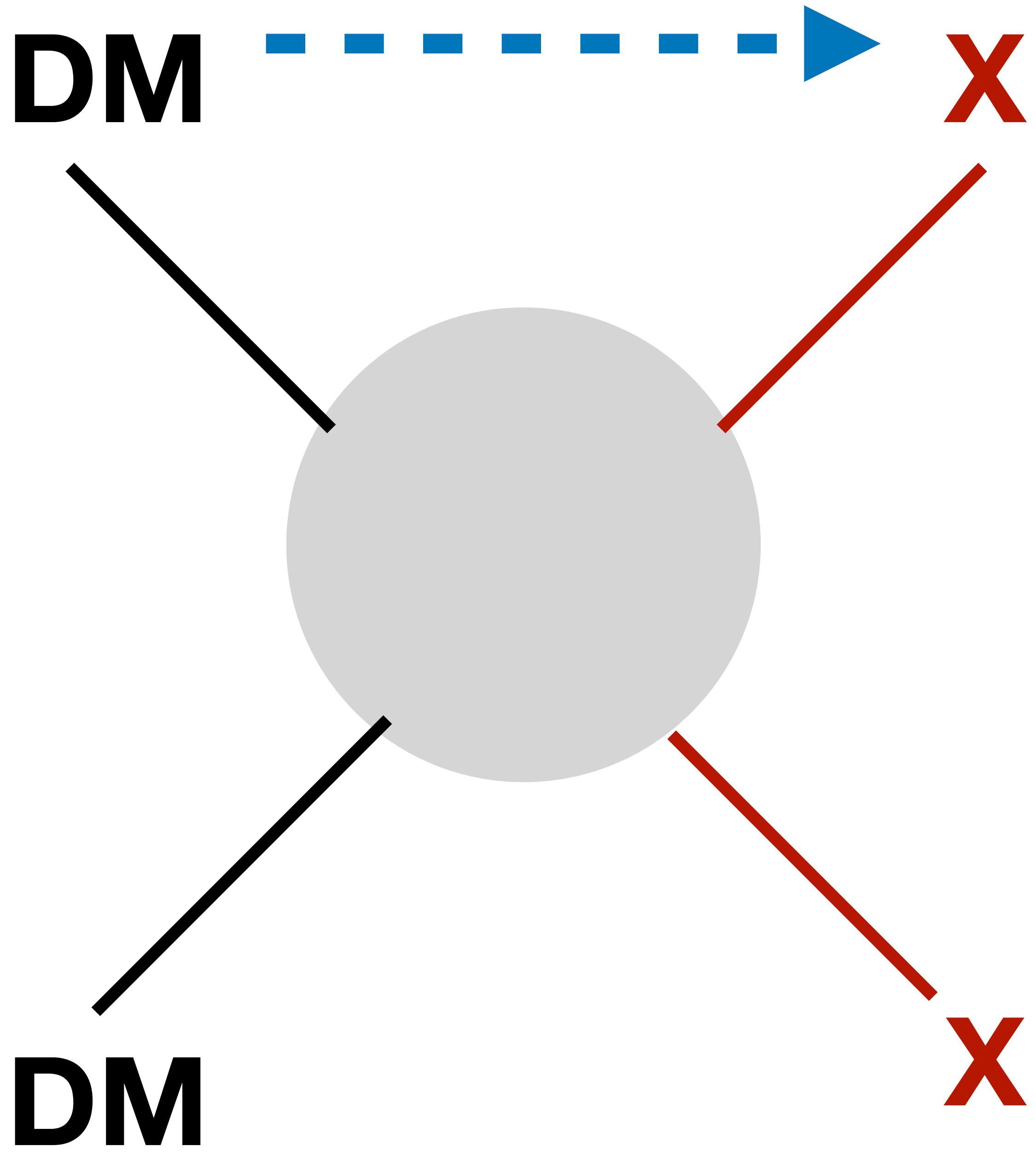
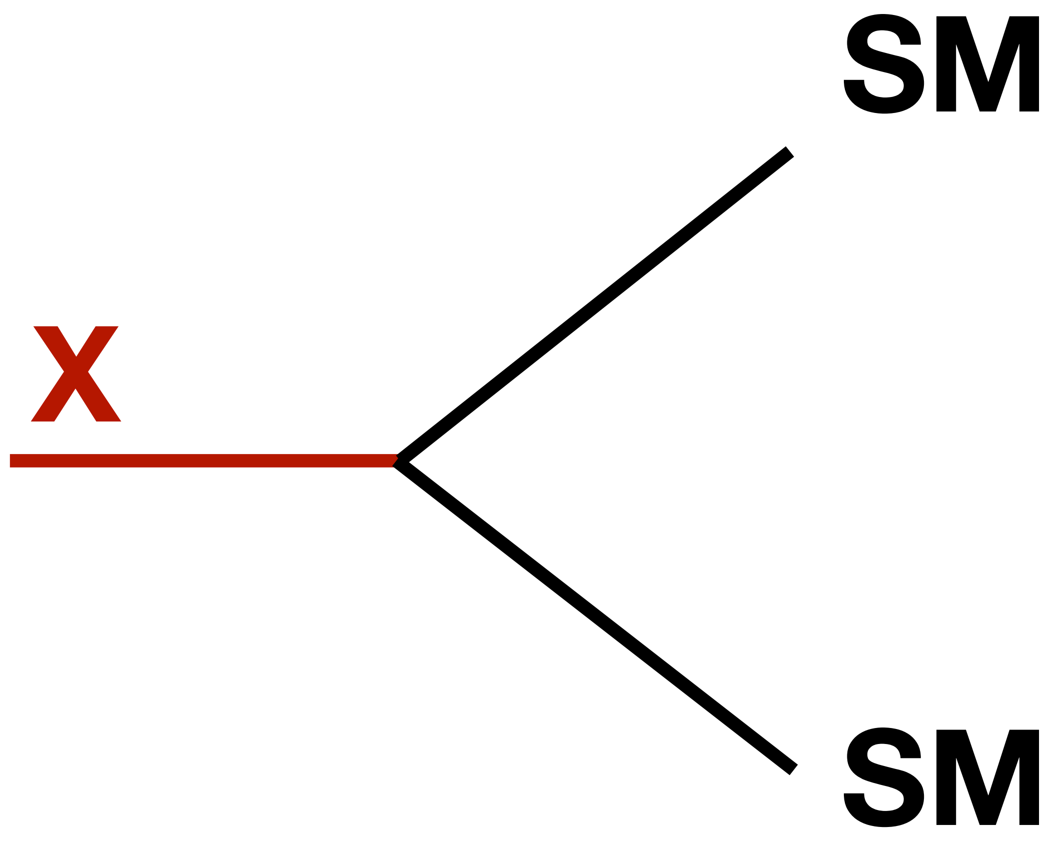


Secluded Annihilation





Search for X mediator directly

- 1. It fits well with intensity frontier programs: beam dump, high-Lumi searches from tau/charm factory, b factory, Z factory, Higgs factory
- 2. The low energy experiment hints
  - Lepton mu (e?) g-2 (light particles at ~ 100 MeV, coupling << 1)
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Exotic interactions: Various BSM portals

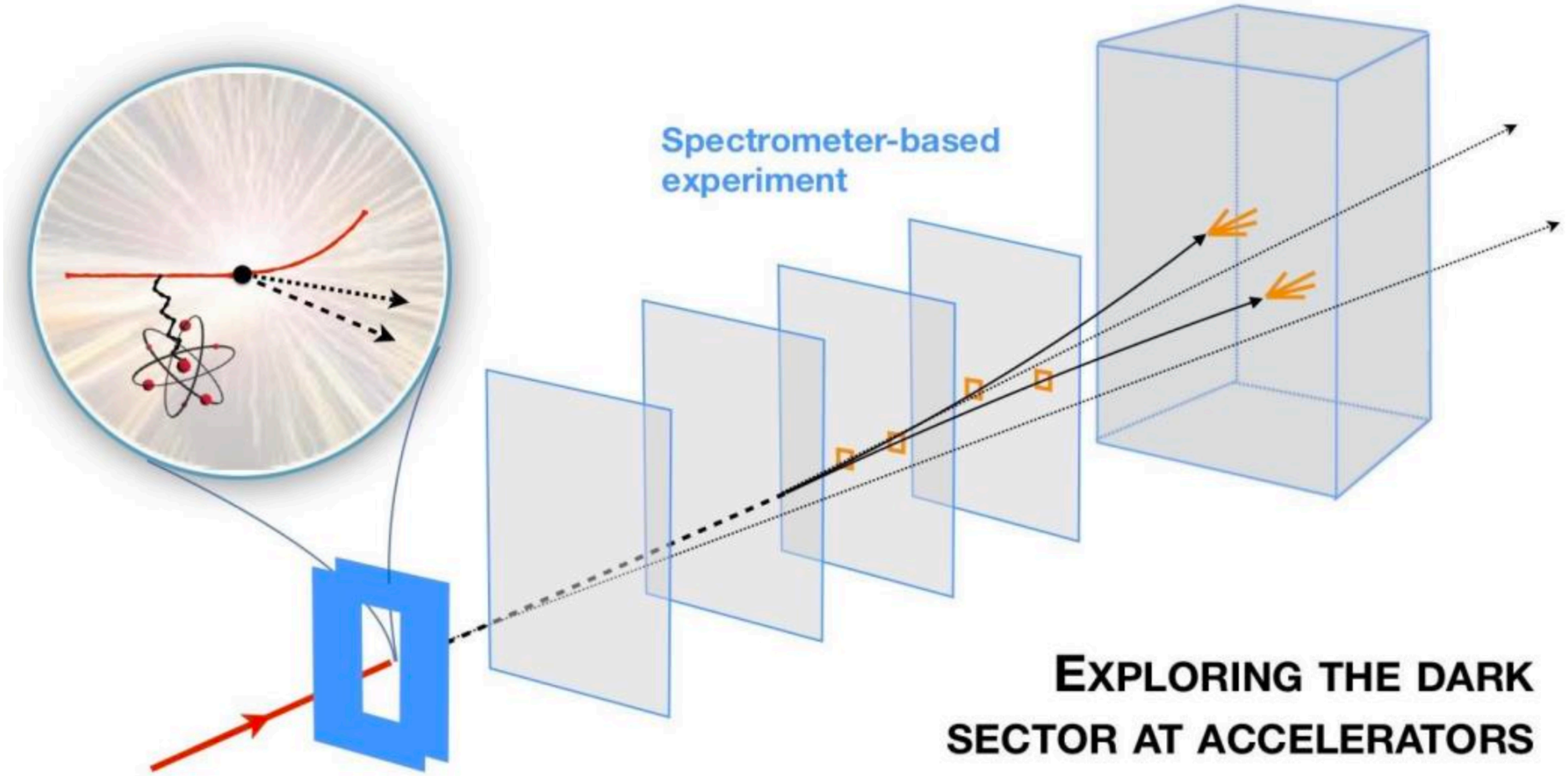
- Vector Portal: Kinetic Mixing Dark Photon
  $B_{\mu\nu}F'^{\mu\nu}$

- Pseudoscalar Portal: Axion, Axion-Like Particles $\frac{a}{\Lambda}\tilde{F}F, \frac{a}{\Lambda}\tilde{G}G$

- Scalar Portal (Higgs Portal): SM Higgs
  $\left(H^\dagger H\right)\left(\phi \text{ or } \phi^2\right)$

- Fermion Portal: Sterile neutrino, Vector-like Fermions
  $\left(\bar{L}H\right)N_R, \bar{L}\Phi\Psi, \bar{Q}\Phi\Psi$

- Millicharged Particles, Leptoquarks etc …



Long-lived particles are less explored

- CMS Exotica results

Exotica Publications

- Exotica Publications
  - Leptoquarks
    - First-Generation Leptoquarks
    - Second-Generation Leptoquarks
    - Third-Generation Leptoquarks
  - Randall--Sundrum Gravitons
  - Heavy Gauge Bosons
    - Sequential Standard Model
    - Superstring-Inspired Models
  - Long-Lived Particles
  - Dark Matter
  - Large Extra Dimensions
    - Arkani-Hamed--Dimopoulos--Dvali Model
    - Semiclassical and Quantum Black Holes
  - Compositness
  - Contact Interactions
  - Excited Fermions
  - Heavy Fermions, Heavy Righ-Handed Neutrinos
  - Colorons, Axigluons, Diquarks
  - Supersymmetry
  - Resonances
    - Multijets
    - Dijets
    - Dileptons
    - $t\bar{t}$
    - Dibosons, VV and VH
    - Boosted Topologies
  - Publications per Center-of-Mass Energy Datasets
    - $\sqrt{s}$ = 7 TeV
    - $\sqrt{s}$ = 8 TeV
    - $\sqrt{s}$ = 13 TeV

Additional Material from Exotica Physics Group

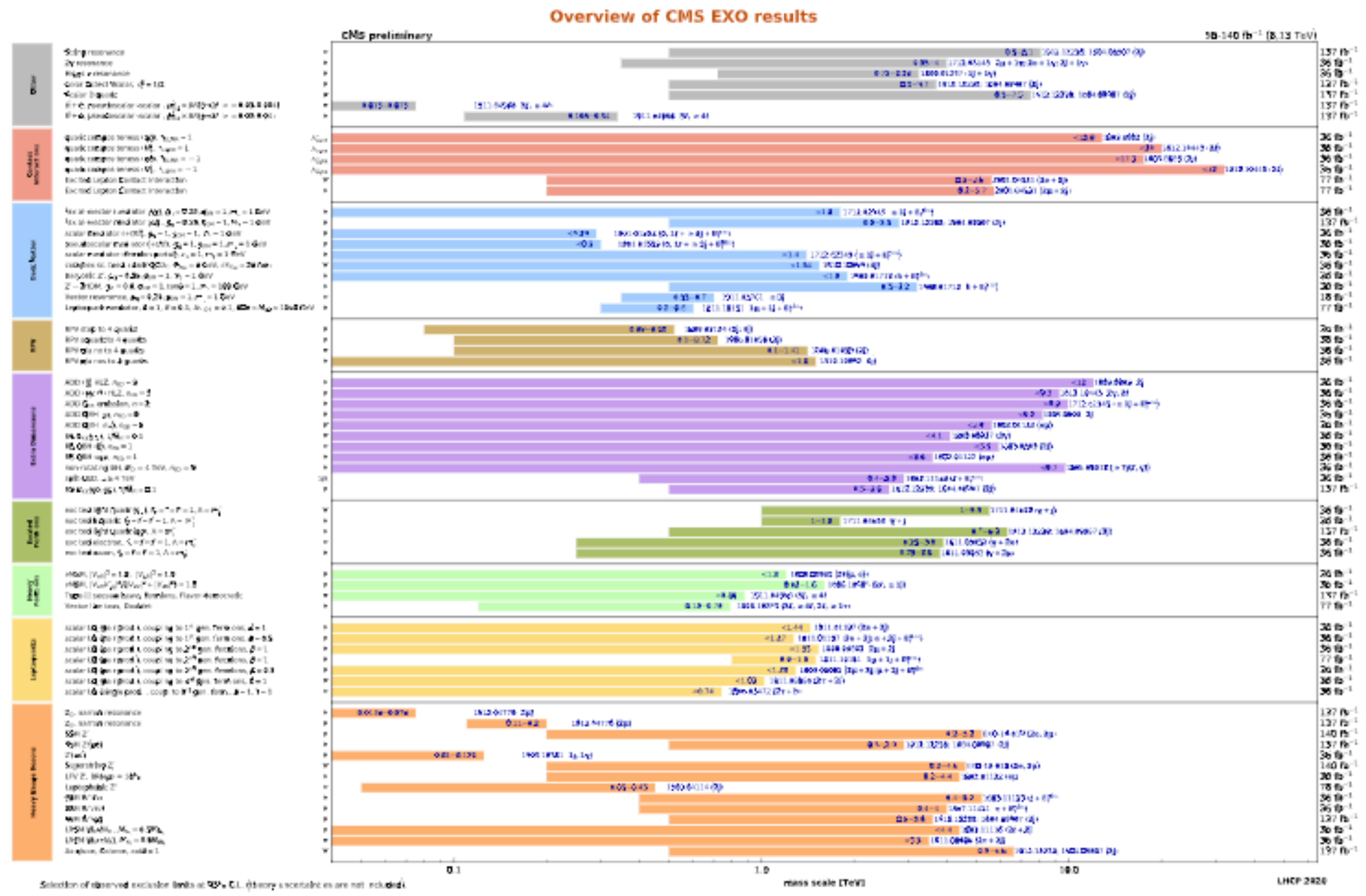
- Exotica Summary plots for 13 TeV data

Recent Preliminary Results in the Exotica Group

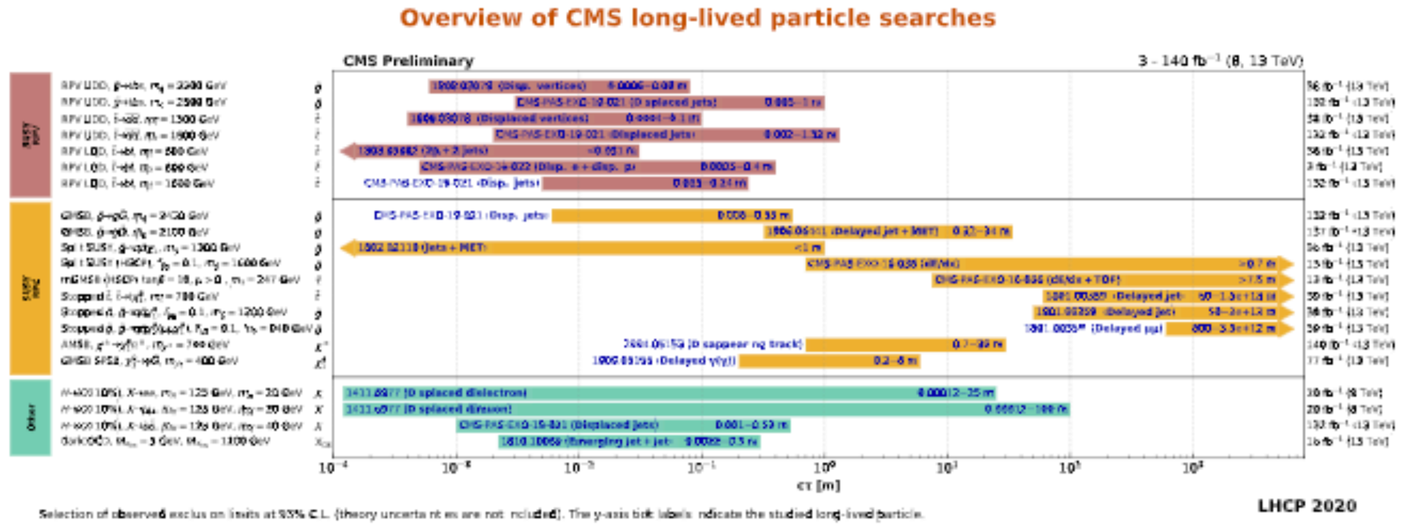
Publications in the Beyond 2 Generations Group

Exotica Publications in CDS

Prompt



Long-lived



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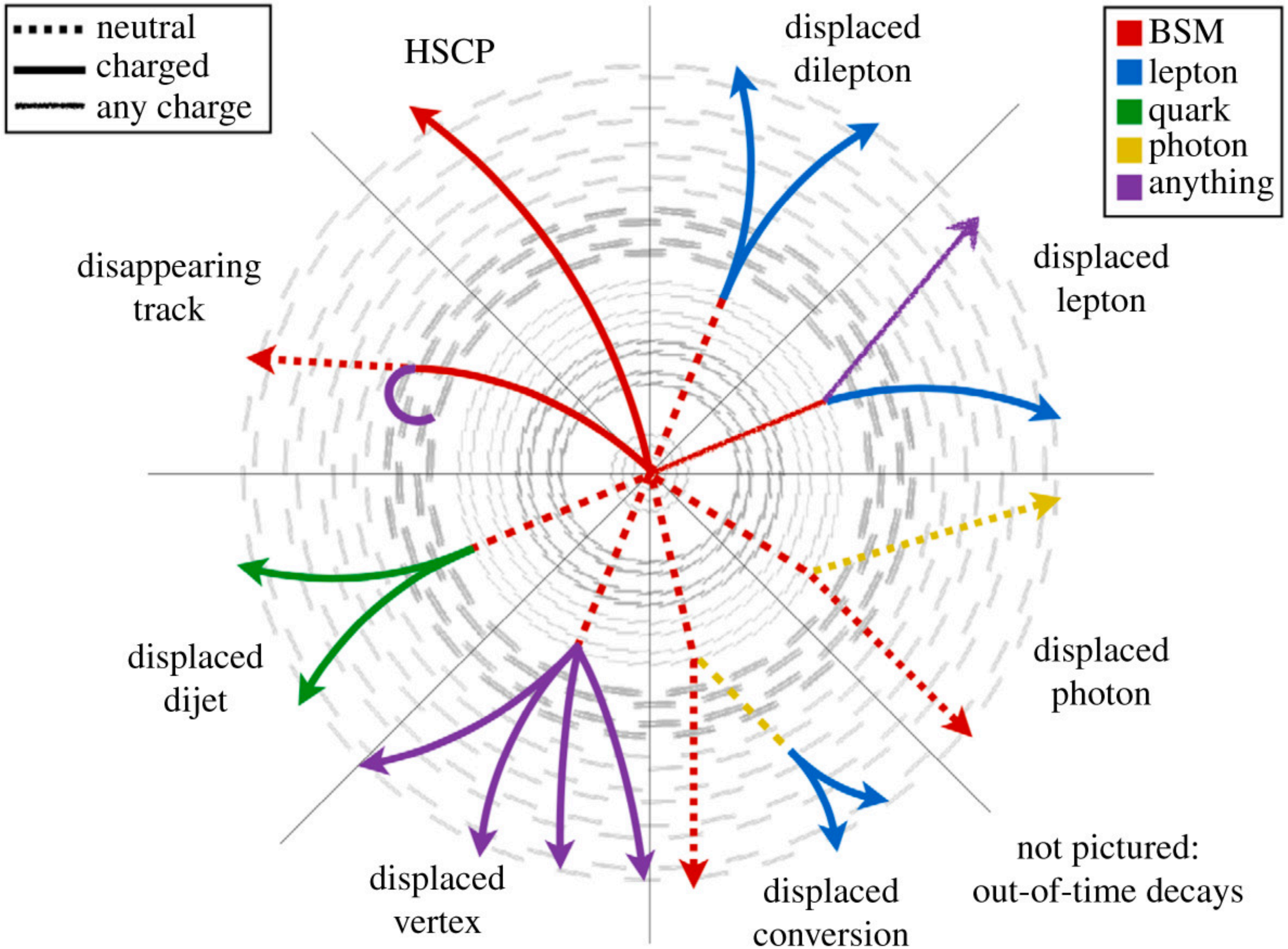
The spatial feature of long-lived particles

- Charged or Neutral LLP
- Charged particle is easier to search
  - Trackers > trajectories
- Neutral particles relies on displaced vertices feature



Hidden Sector Charged Particle exotic example

- ATLAS search for HSCP with high ionization $dE/dx > 2.4\text{MeV g}^{-1}\text{ cm}^2$
- Expected 0.7 ± 0.4, observed 7 events (3.6 σ)
-

ATLAS JHEP 06 (2023) 158

Target mass [GeV]	Mass window [GeV]	Signal region bin											
		SR-Inclusive_Low						SR-Inclusive_High					
		Exp.	Obs.	p_0	Z_{local}	$S^{95}_{\text{exp.}}$	$S^{95}_{\text{obs.}}$	Exp.	Obs.	p_0	Z_{local}	$S^{95}_{\text{exp.}}$	$S^{95}_{\text{obs.}}$
1200	[950, 2100]	6.7 ± 1.3	10	1.38×10^{-1}	1.1	$7.0^{+2.5}_{-2.3}$	10.2	0.9 ± 0.5	6	1.65×10^{-3}	2.9	$3.7^{+1.3}_{-0.6}$	10.4
1300	[1000, 2200]	6.1 ± 1.2	9	1.48×10^{-1}	1.0	$6.5^{+2.9}_{-1.4}$	9.7	0.8 ± 0.4	6	5.47×10^{-4}	3.3	$3.5^{+1.2}_{-0.5}$	10.3
1400	[1100, 2800]	5.2 ± 1.7	8	1.76×10^{-1}	0.9	$6.5^{+2.6}_{-2.0}$	9.6	0.7 ± 0.4	7	1.46×10^{-4}	3.6	$3.2^{+1.1}_{-0.1}$	11.9
1500	[1150, 2900]	4.9 ± 2.4	7	2.41×10^{-1}	0.7	$6.6^{+2.8}_{-1.9}$	9.3	0.6 ± 0.4	6	6.09×10^{-4}	3.2	$3.2^{+1.2}_{-0.1}$	10.7
1600	[1250, 3400]	4.2 ± 3.4	5	3.24×10^{-1}	0.5	$7.0^{+2.9}_{-2.2}$	8.4	0.54 ± 0.35	5	1.19×10^{-3}	3.0	$3.1^{+1.2}_{-0.1}$	9.5

Hidden Sector Charged Particle exotic example

- ATLAS search for HSCP with high ionization $dE/dx > 2.4\text{MeV g}^{-1}\text{ cm}^2$
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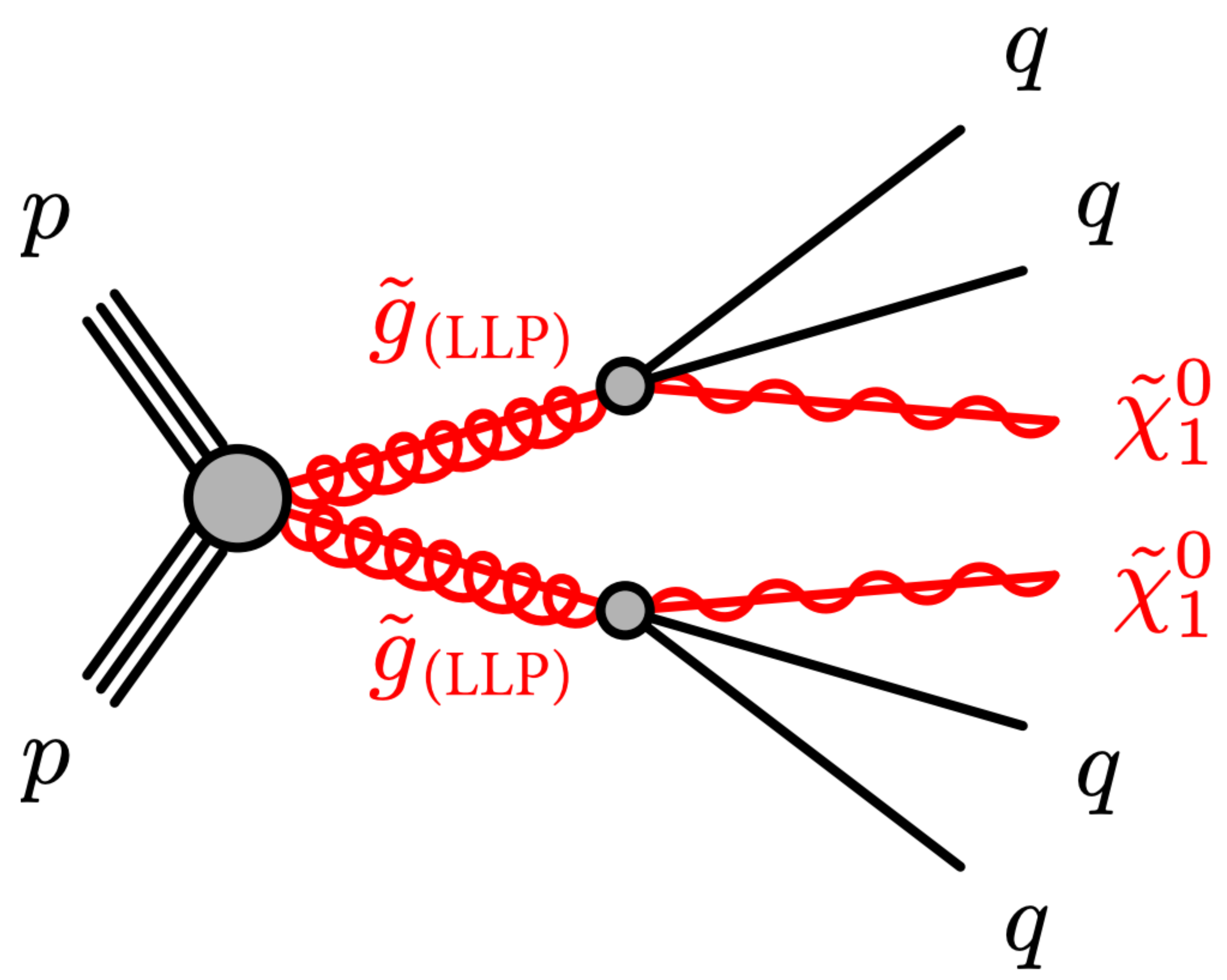
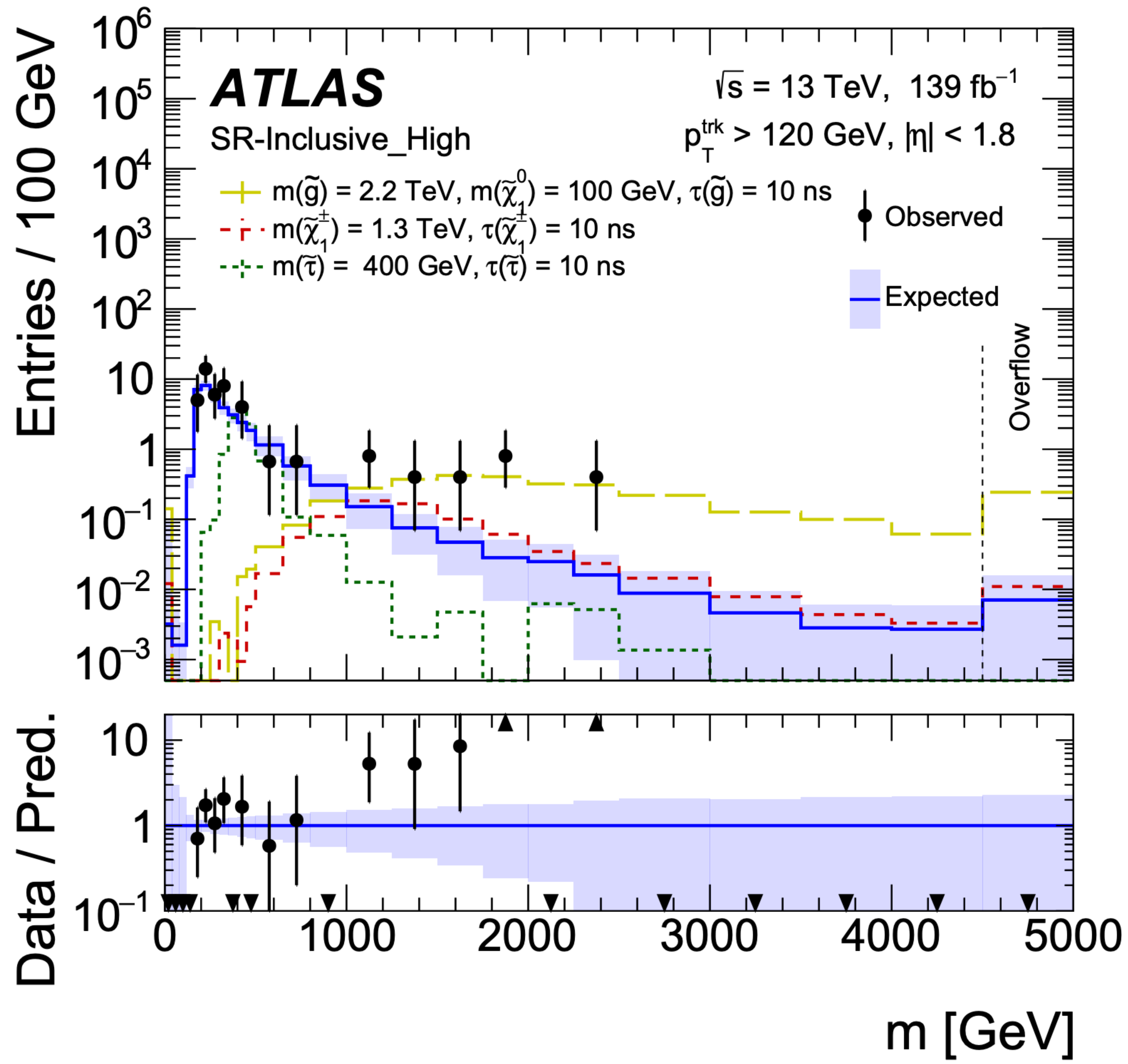
ATLAS JHEP 06 (2023) 158

- R-hadron with 2 TeV mass and 10 ns lifetime





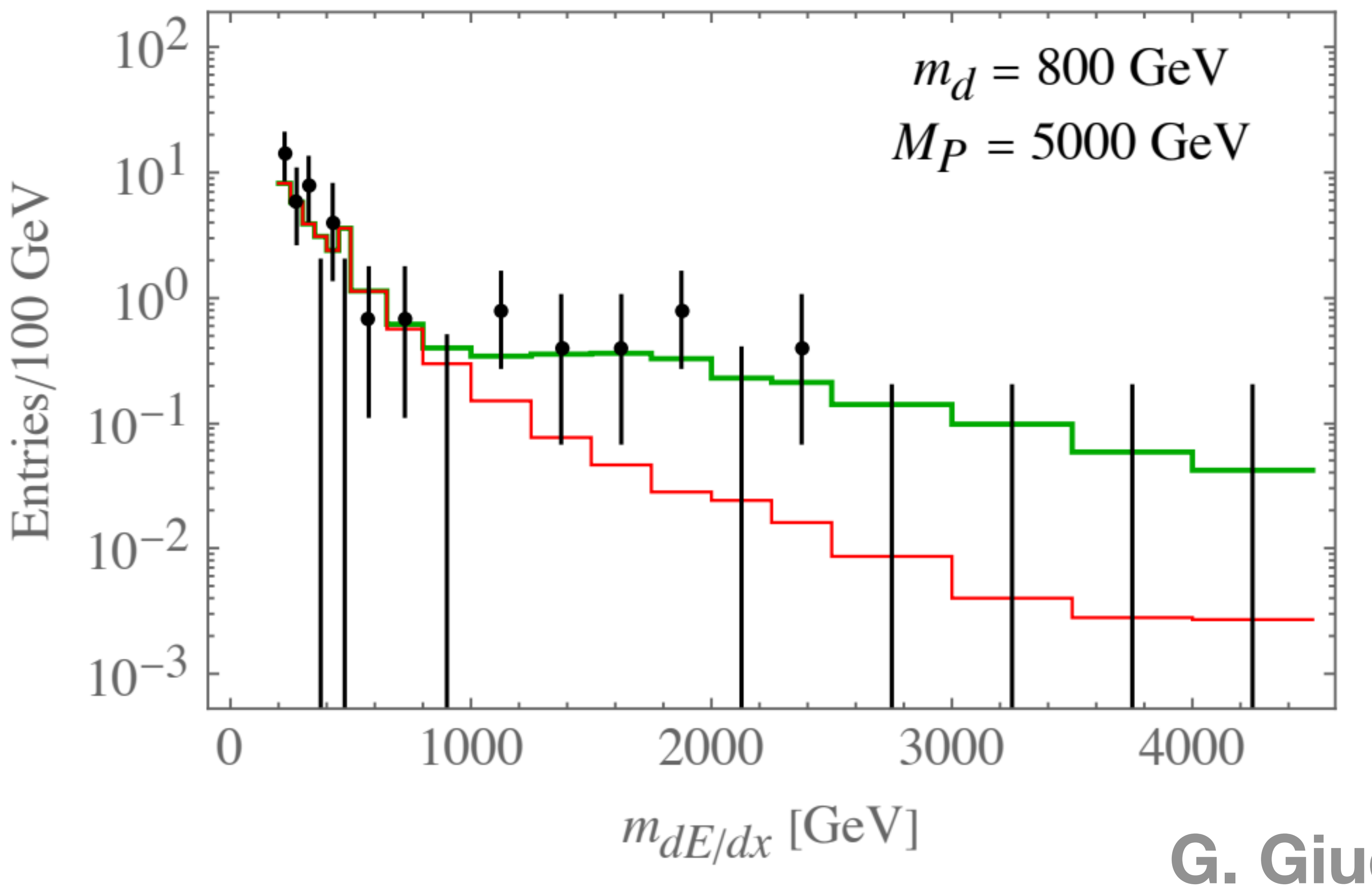
Hidden Sector Charged Particle exotic example

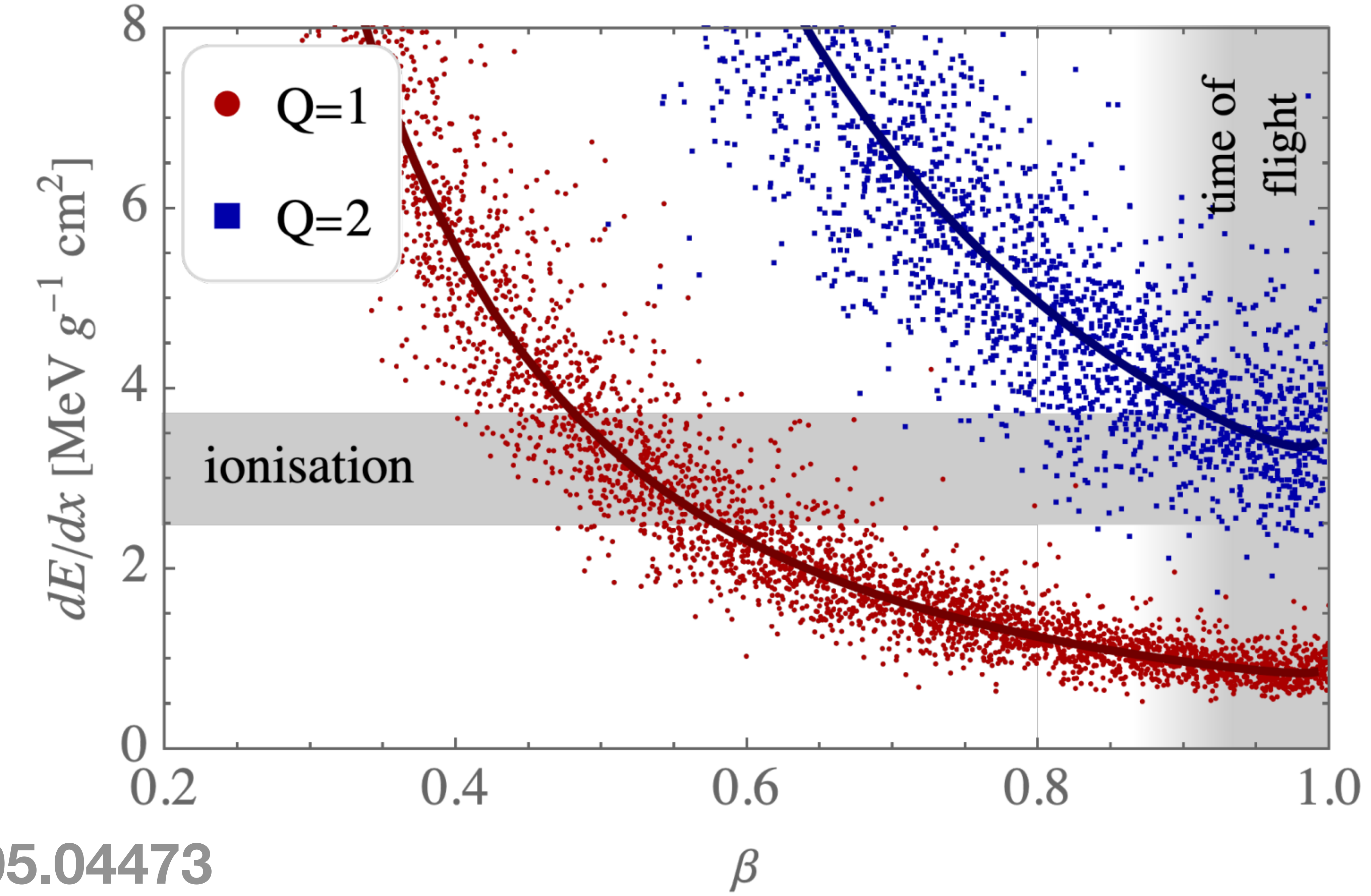
- ATLAS search for HSCP with high ionization $dE/dx/\rho > 2.4\mathrm{MeV\ g^{-1}\ cm^2}$
- Expected 0.7 ± 0.4, observed 7 events (3.6 σ)

ATLAS JHEP 06 (2023) 158

- R-hadron with 2 TeV mass and 10 ns lifetime
- Puzzle: Time of flight: $\beta = 1$ v.s. Ionization data $\beta \approx 0.7$

Q=2 BSM particles from heavy resonance?

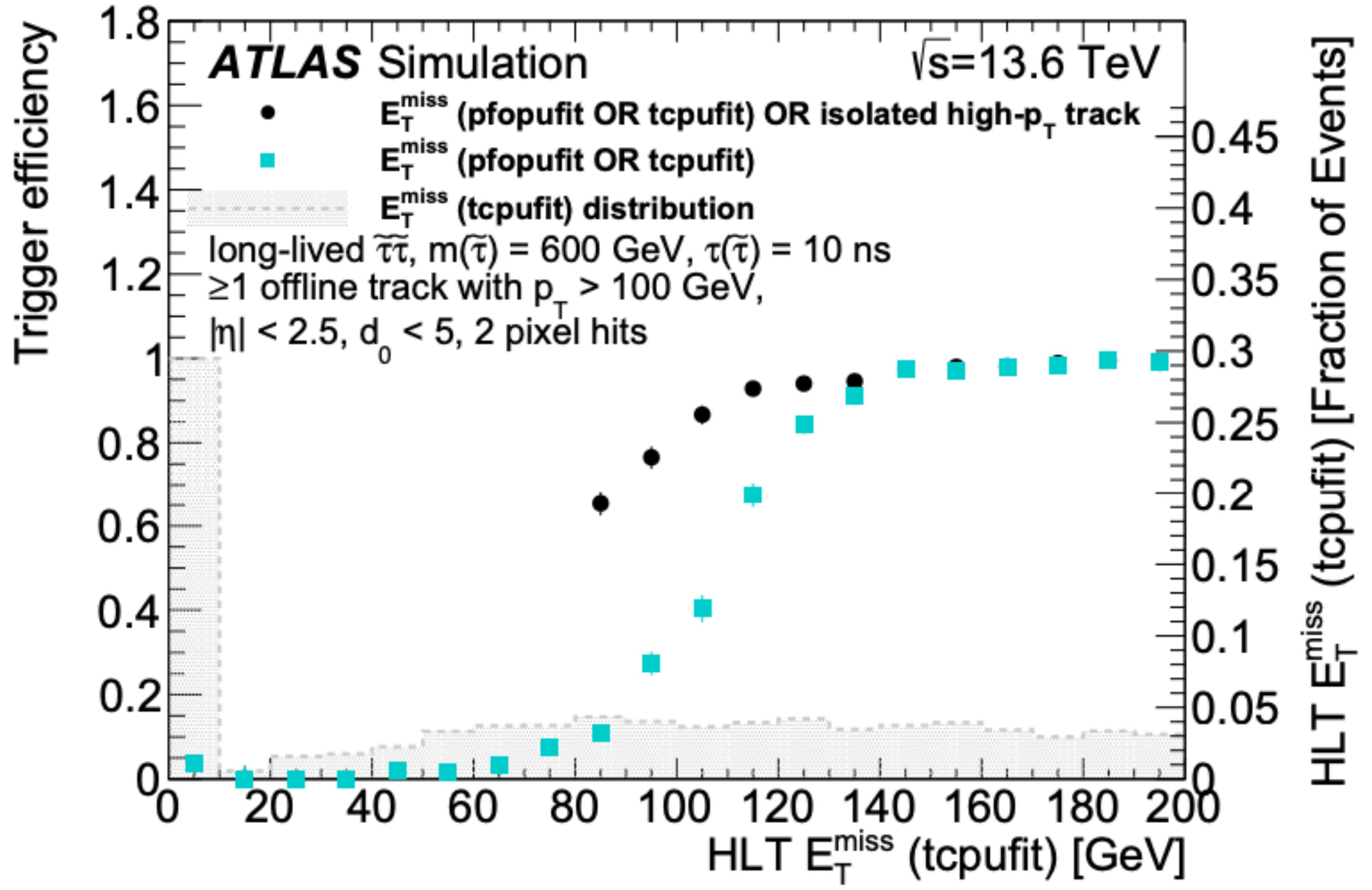


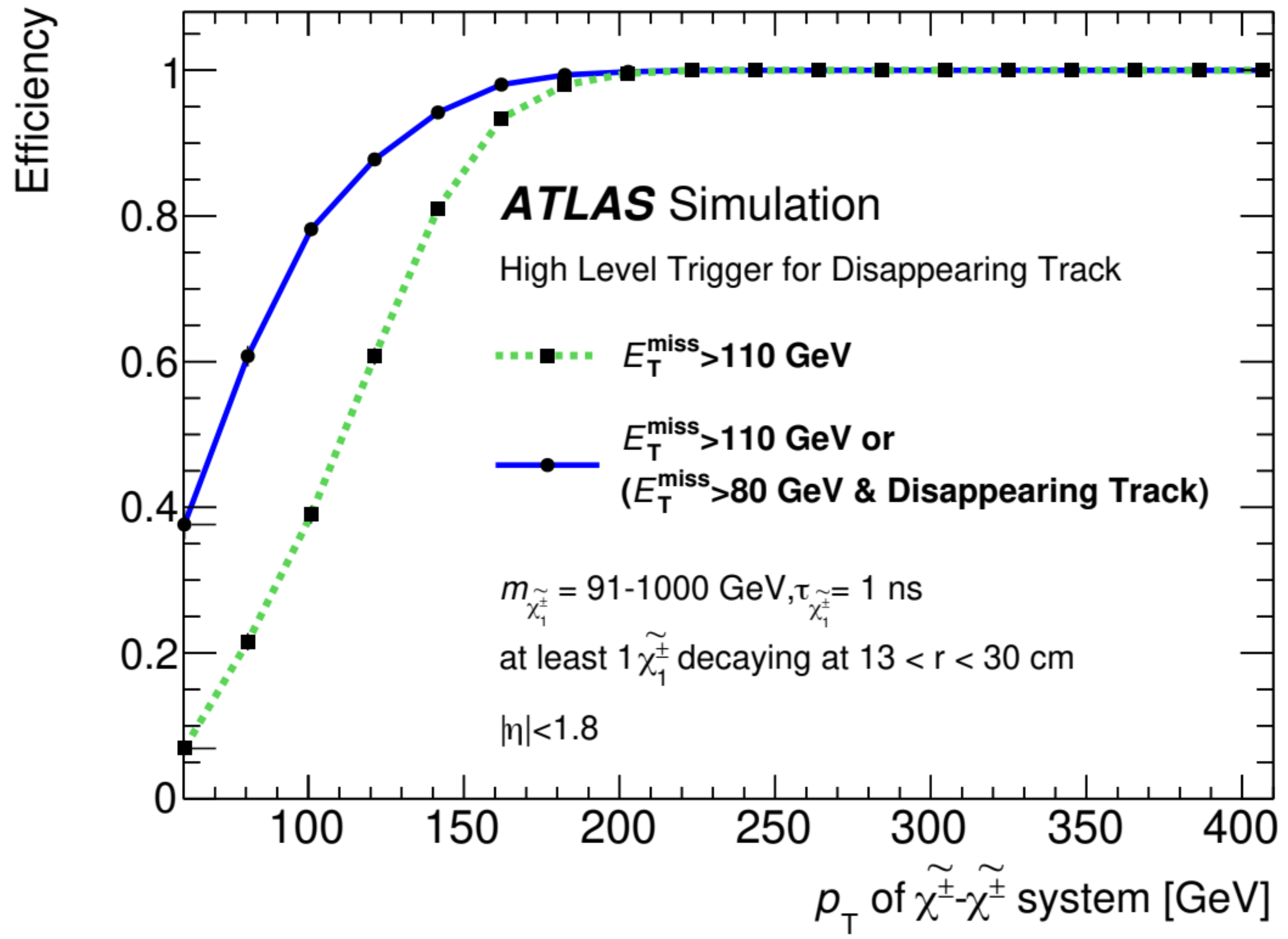


G. Giudice et al. 2205.04473

New trigger development for charged LLP

- Old triggers: large MET trigger
- New triggers:
  - High-pT isolated track
    $p_T > 120$ GeV + quality check
  - High $dE/dx > 1.7\mathrm{MeV/cm}$
  - Disappearing track trigger
    low-pT particles not reconstructed
- Dedicated trigger study expands the search range of LLP





ATLAS: 2401.06630

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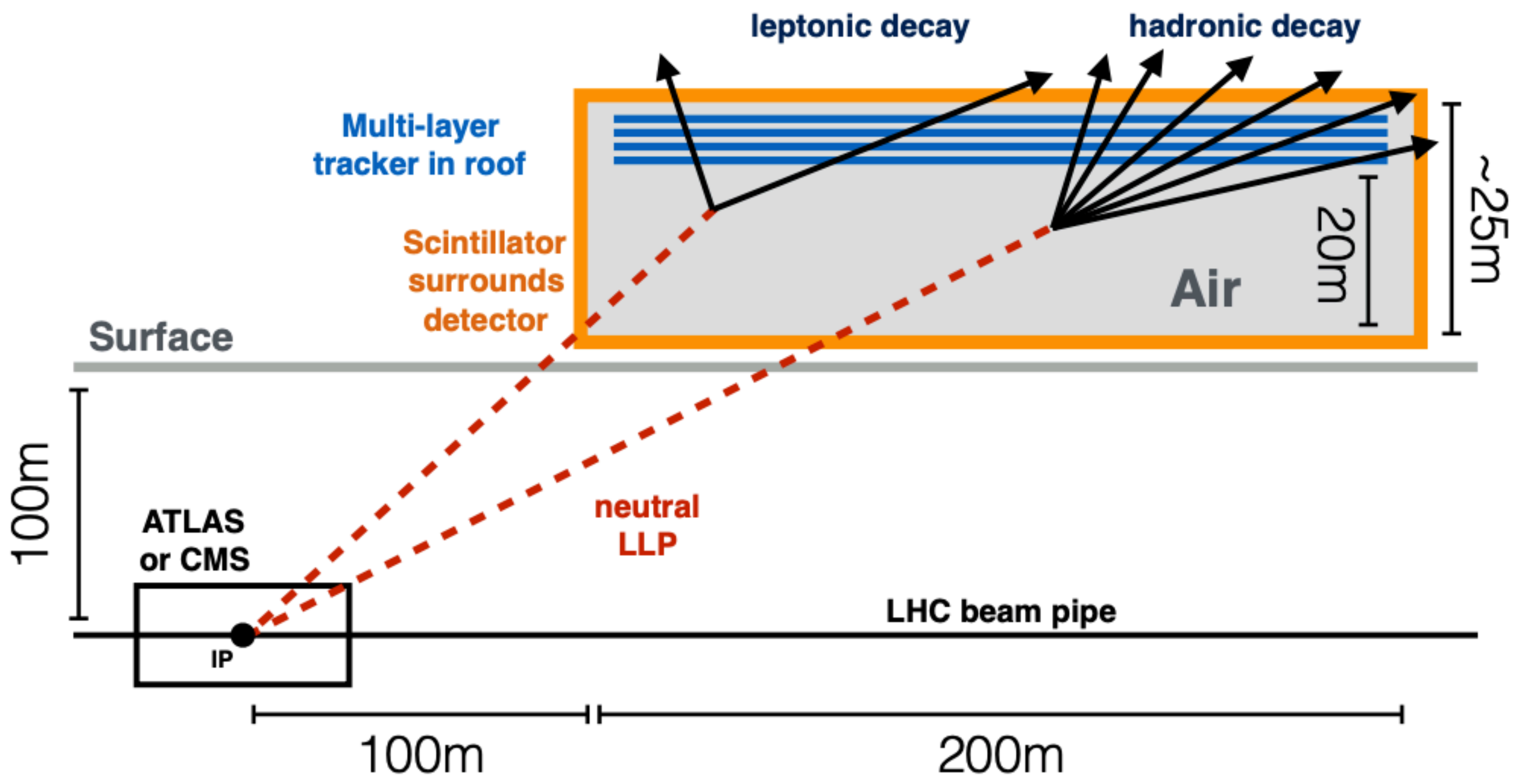
Far detector proposals



Arxiv: 1806.07396

- Mathusla, CODEX-b, FASER etc

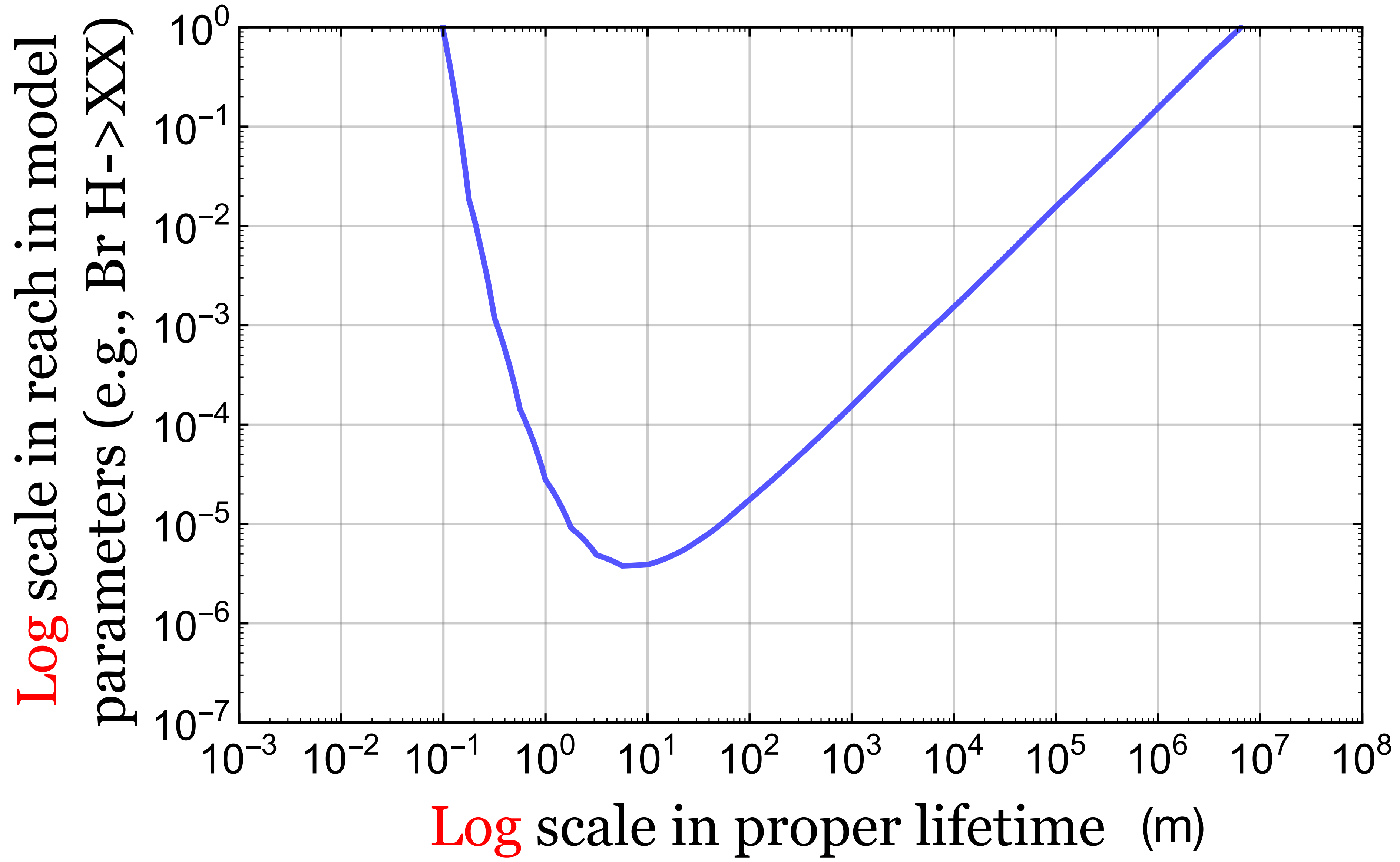
Experiment setup considerations

- Far detectors are expensive
  - Why not existing ones? ATLAS/CMS?
- We focus here on new approaches for searches at existing detectors, i.e., ATLAS and CMS.
  - Larger geometrical acceptance, but also large background.
  - Ample room for new ideas.

LLP basics: Geometrical acceptance

- P_{in}: Geometrical acceptance

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



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

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

LLP basics: Geometrical acceptance

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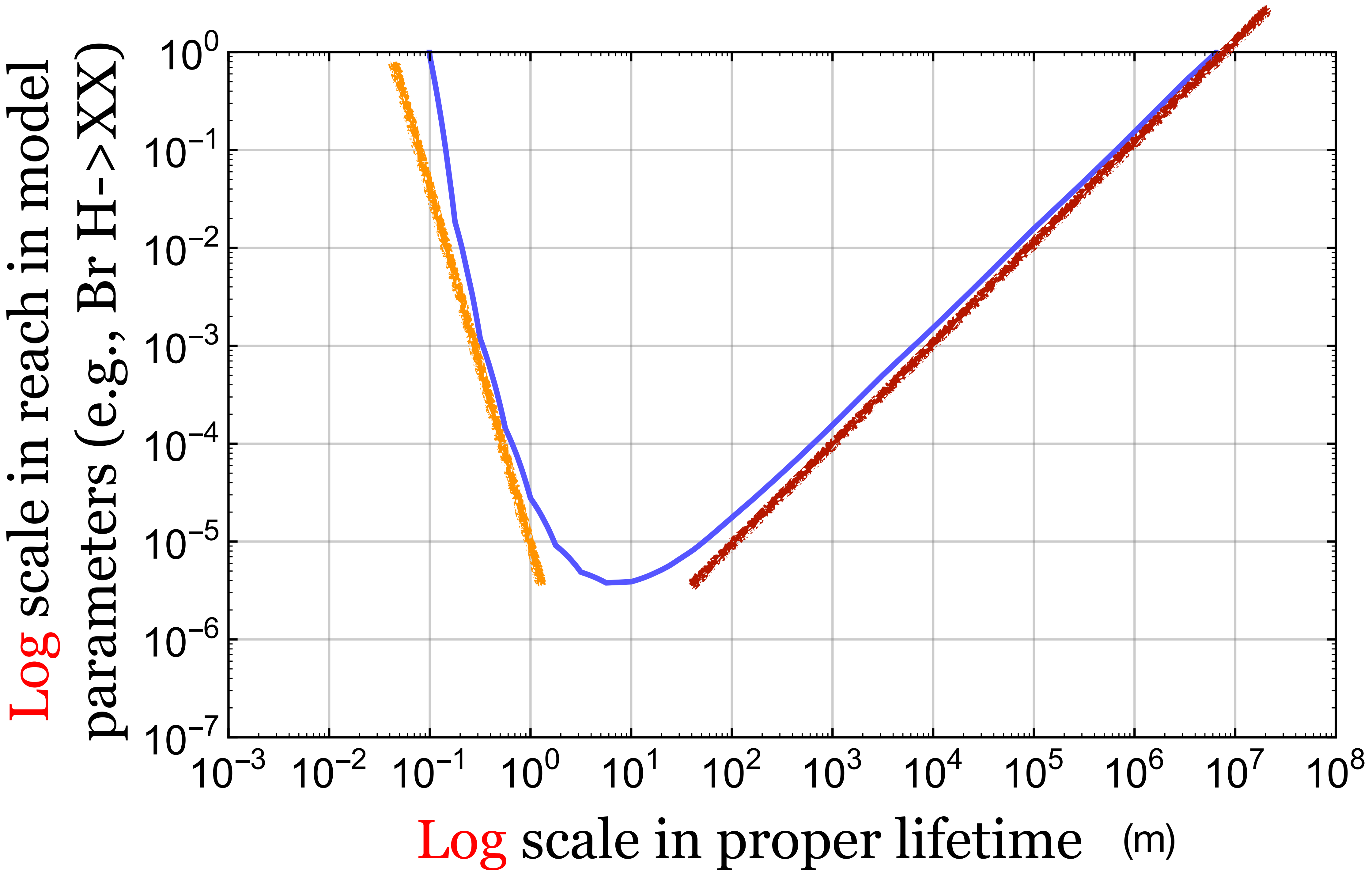
Solid angle

Detector length

- The detector length L_2 - L_1



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

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Solid angle **Detector length**

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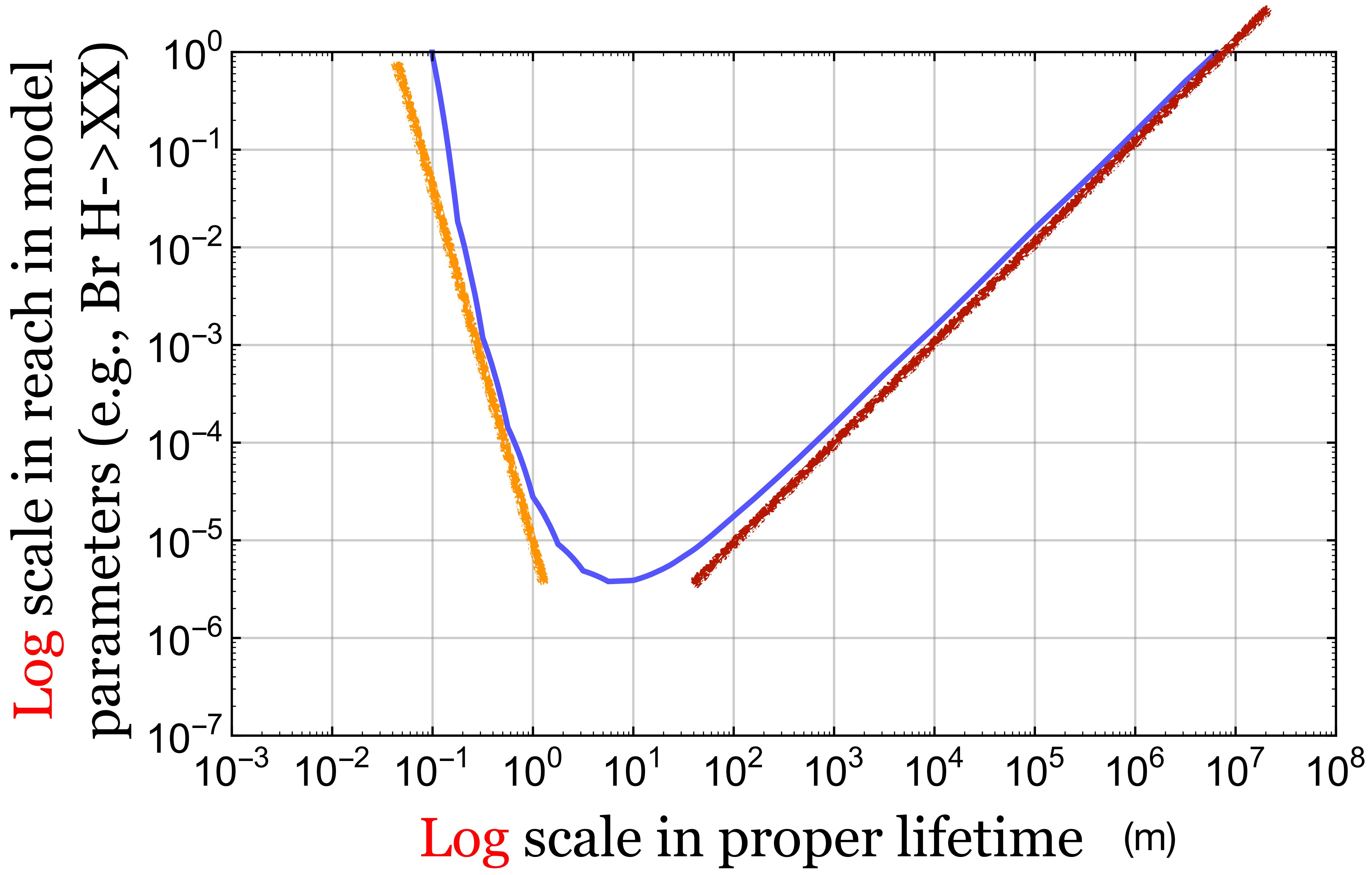


We need

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

LLP basics: Geometrical acceptance

ATLAS/CMS

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

- Inner detector, DV searches
- ~ meter(s)
- ~ 4 π

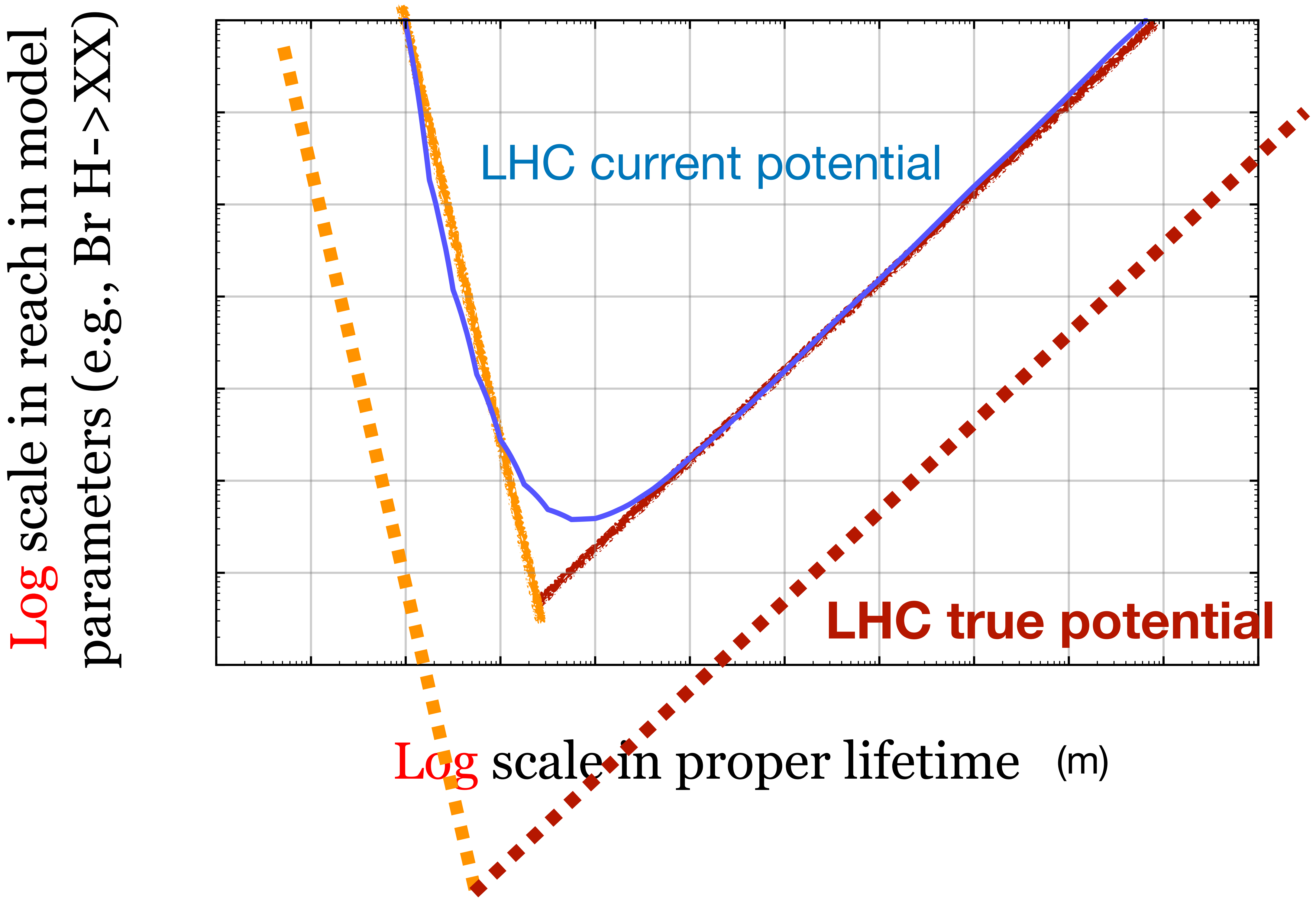
Challenges

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

geometrical acceptance | trigger | signal efficiency | bkgd fake rate

LHC already maximizes 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

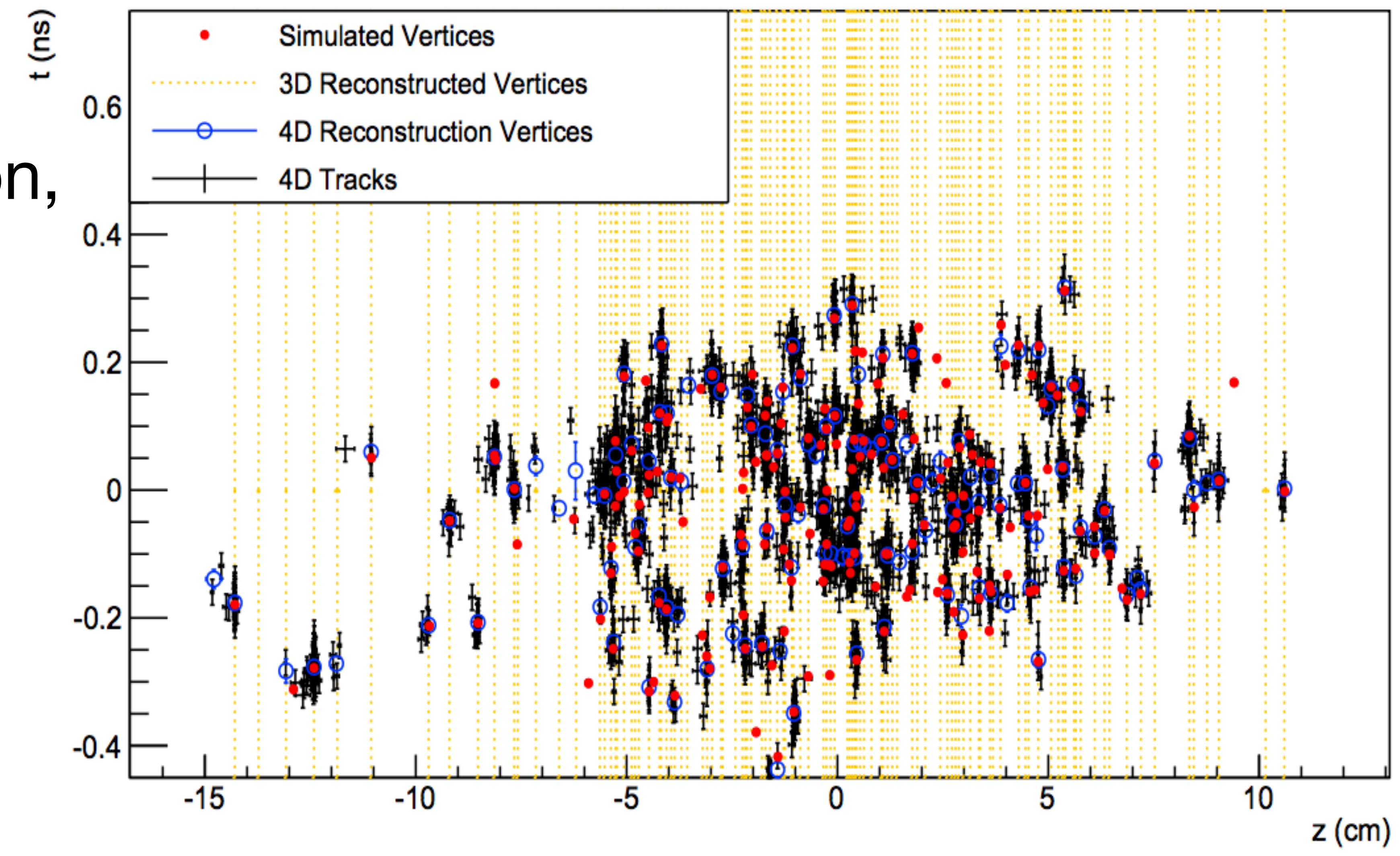
30 ps resolution!

- ATLAS: High Granularity Timing Detector (HGTD)

1804.00622

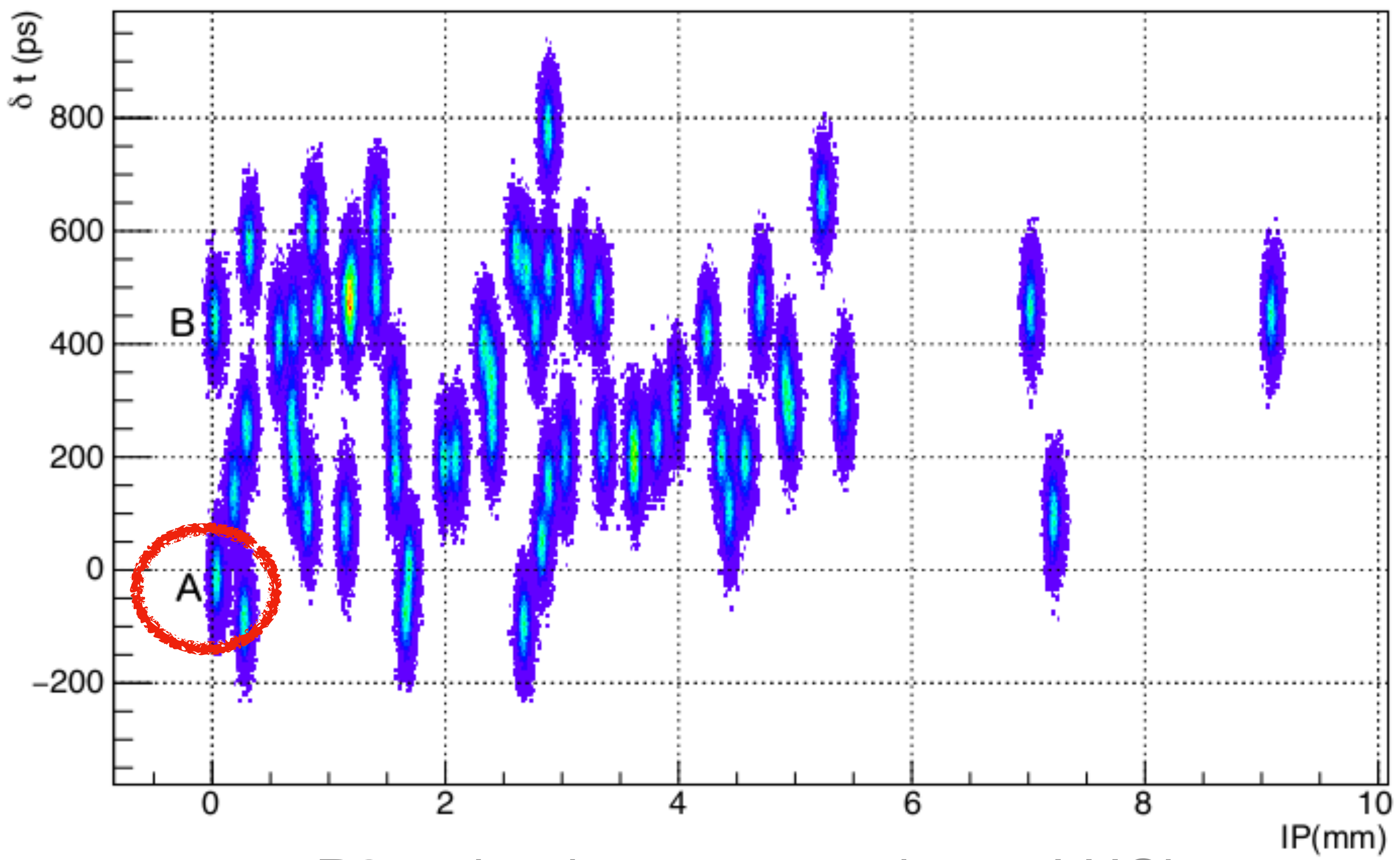
- LHCb: Vertex Locator (VELO), high granularity ECAL and Torch detector

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

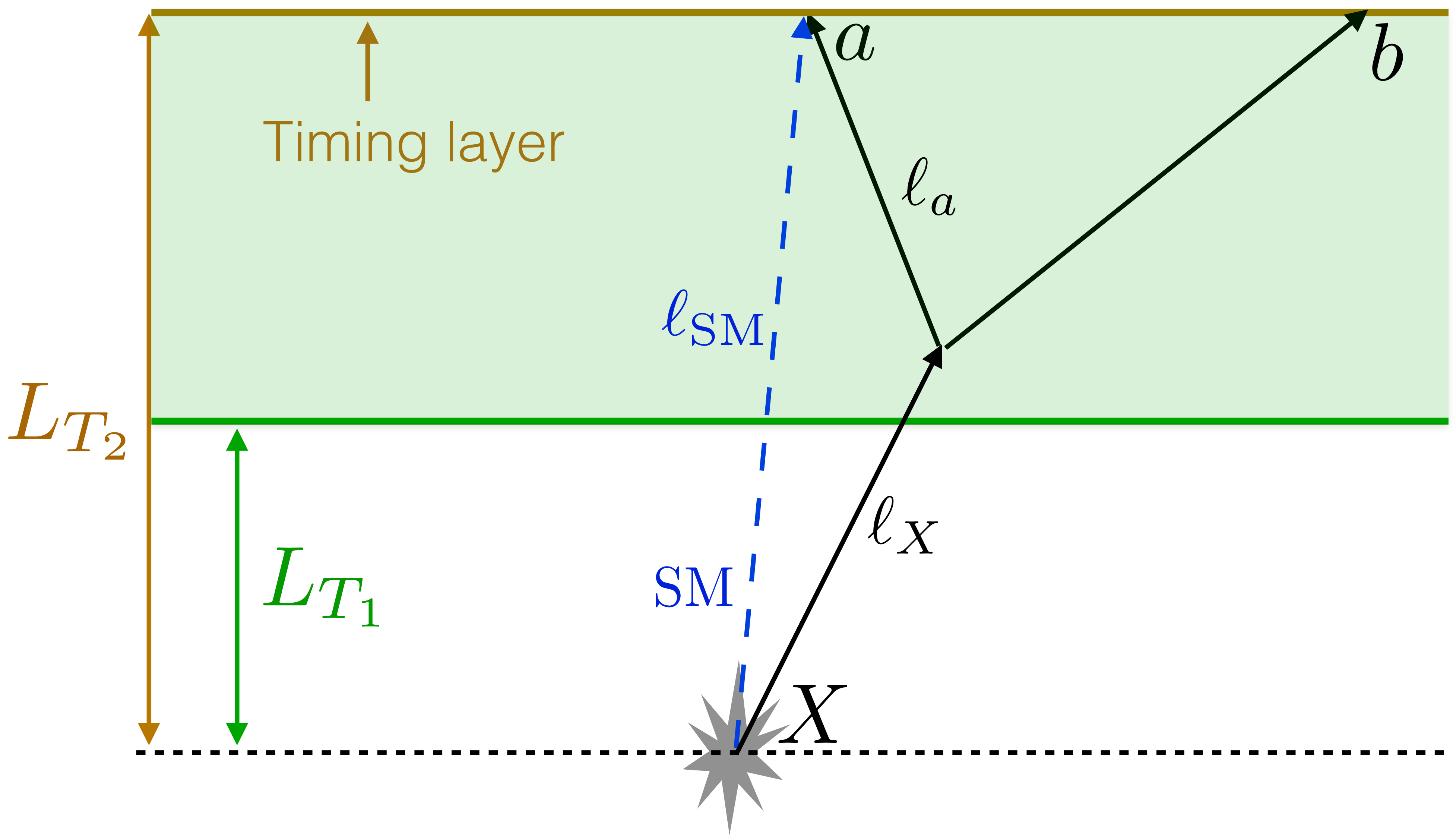
$$\Delta t = \frac{\ell_X}{\beta_X} + \frac{\ell_a}{\beta_a} - \frac{\ell_{\rm SM}}{\beta_{\rm SM}}$$

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

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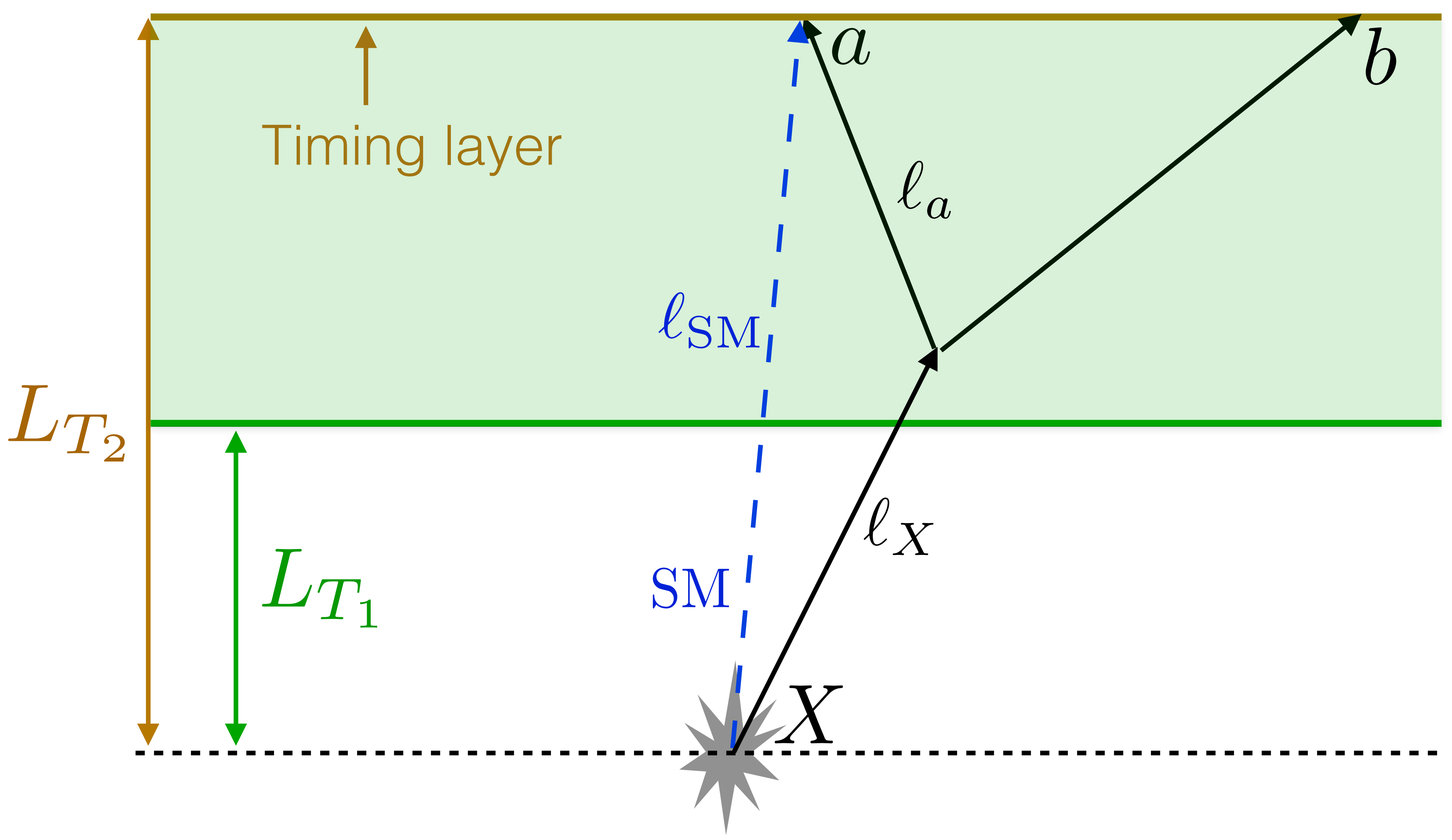
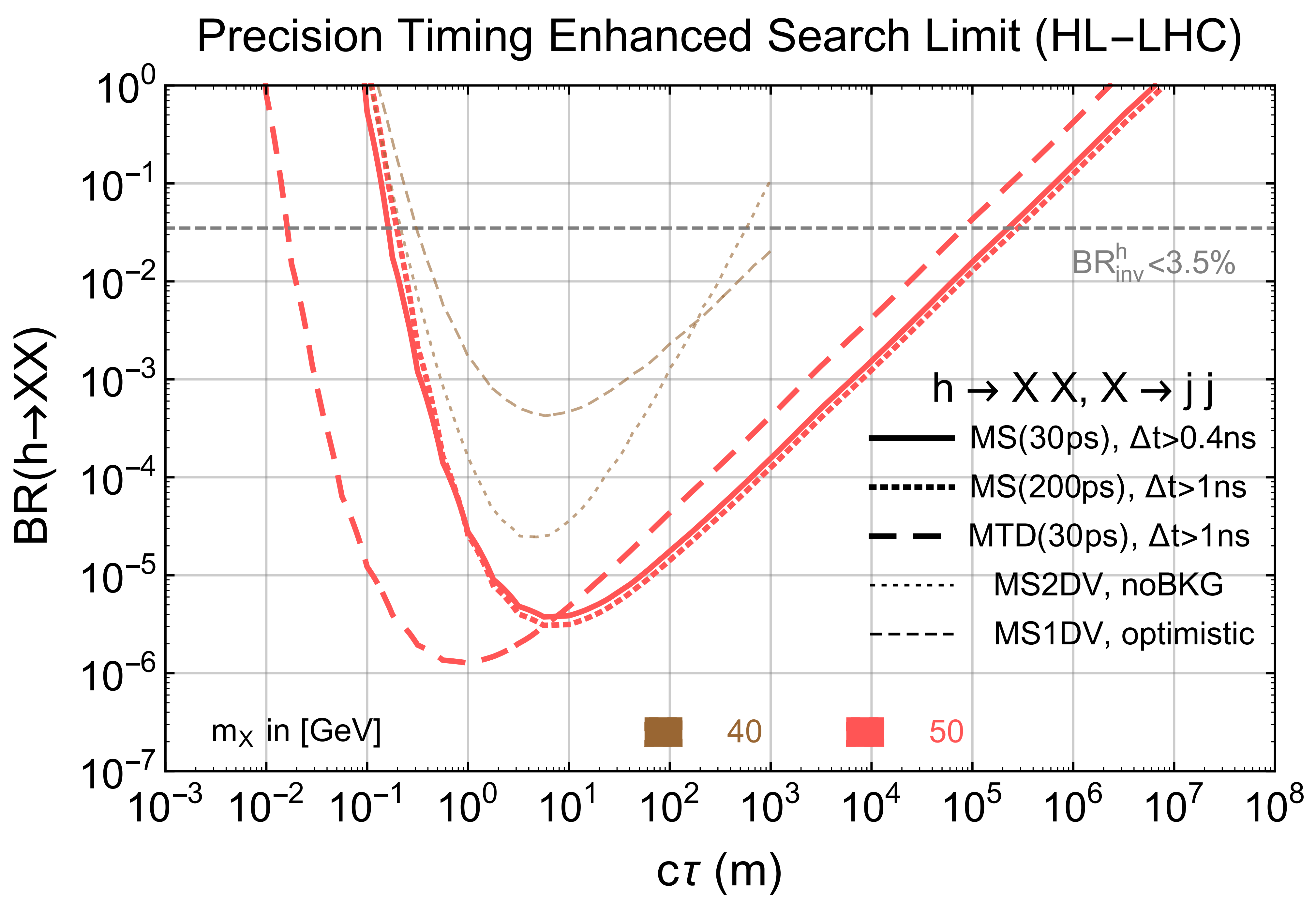


Z. Liu, JL, L.T. Wang, PRL 122 (2019) 131801

- 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!!!

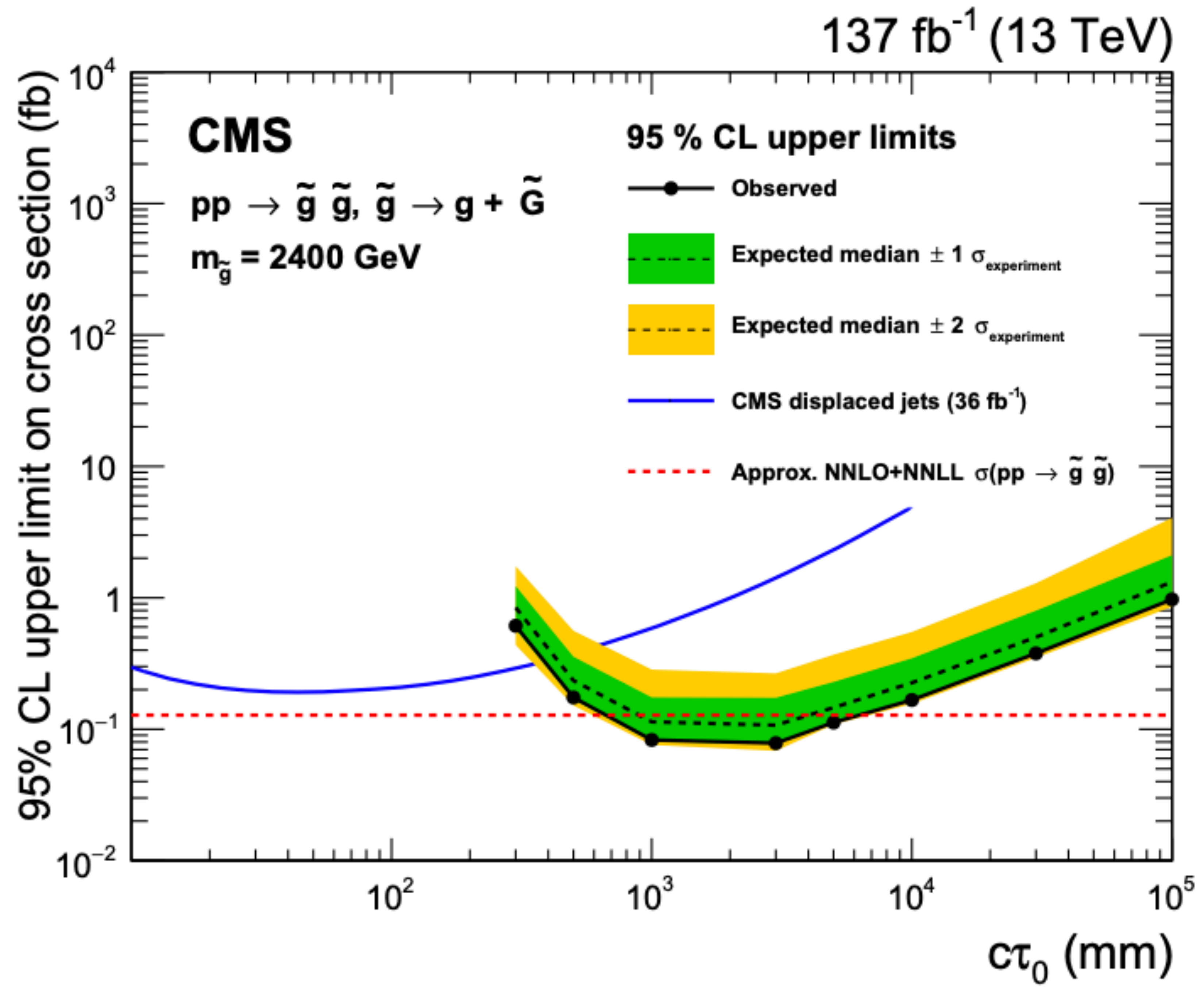
Performance of timing detection of LLP

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



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

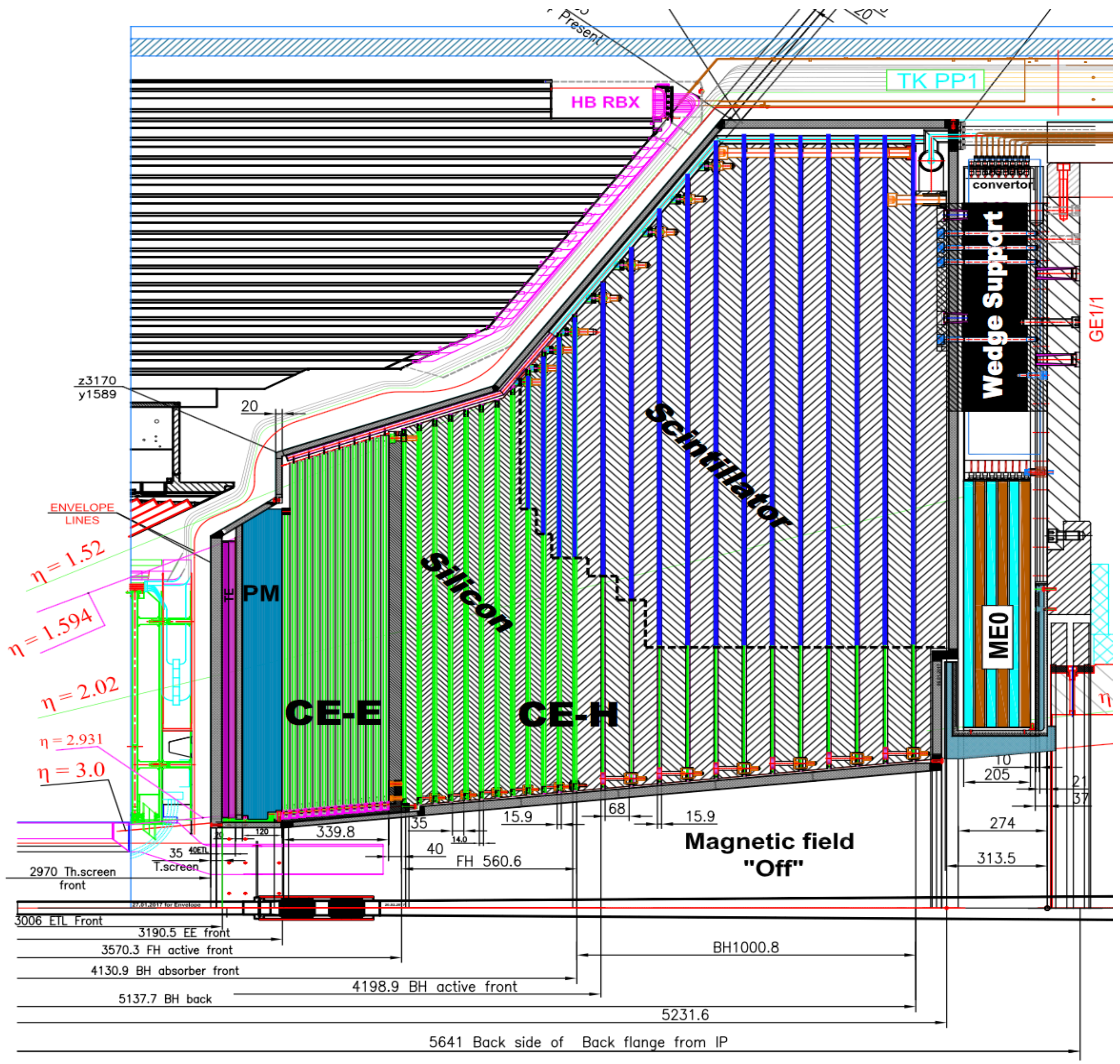
- The method works well in real CMS analysis
  - Good for long-lifetime LLP
  - Better sensitivity



CMS: PLB 797 (2019) 134876

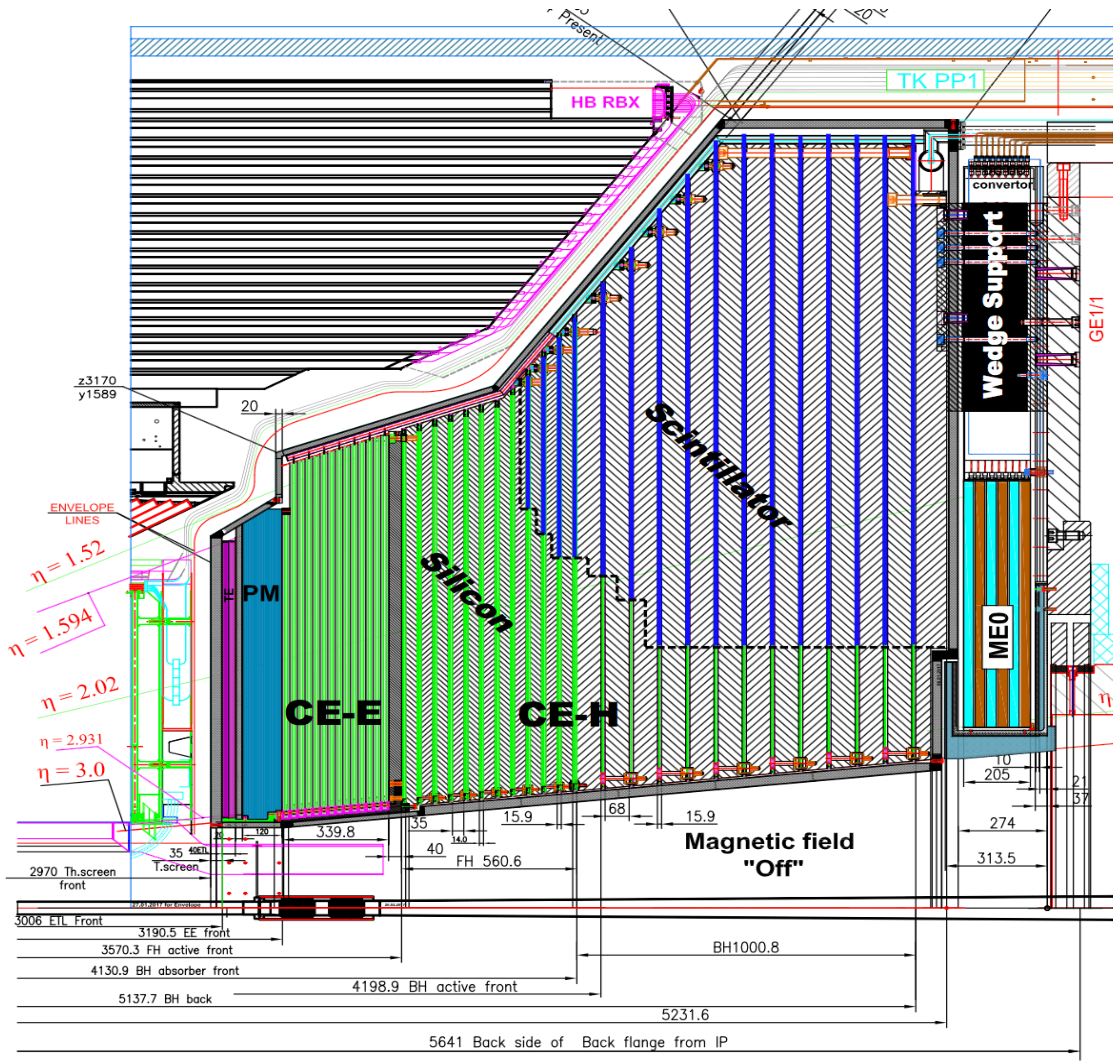
CMS High Granularity Calorimeter (HGCAL)

- Motivation
  - Upgrade for radiation tolerance and pile-up
  - Tracker, calorimeter and timing integrated in one detector
  - Will provide much more information than any previous calorimeters



CMS High Granularity Calorimeter (HGCAL)

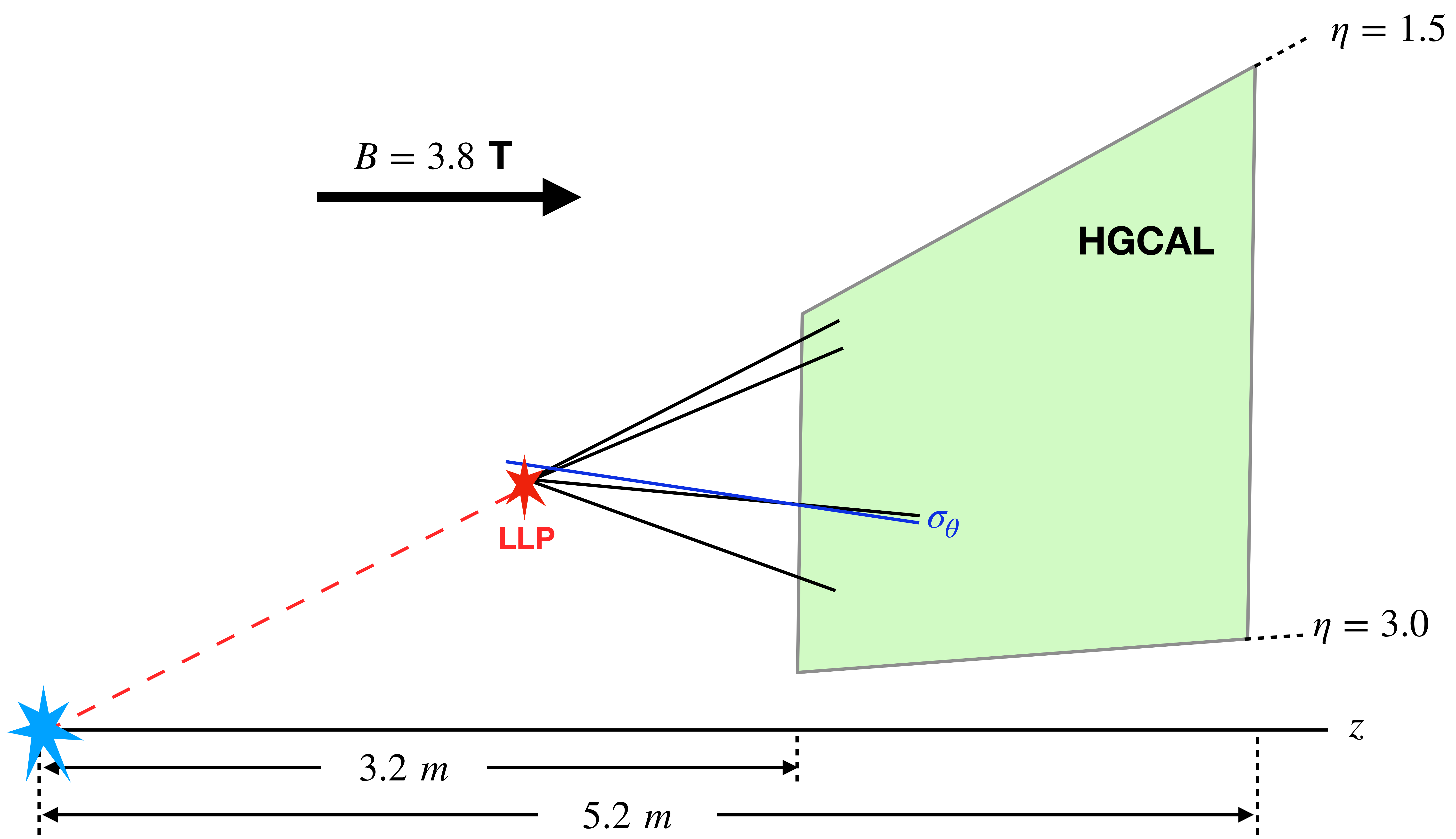
- Own triggers
- Tracker with silicon cell 0.5~1 cm^2 for EM and most HA calos
- Angular resolution of 5×10^{-3} rad stand-alone from high granularity (EM shower, improvement by combining with ID trackers)
- Timing resolution ~ 25 ps from silicon sensor
- Semi-central coverage good for forward LLP
  Collinear enhancement
  Pt PS suppression



What is the HGCAL sensitivity for LLP?

QCD background and LLP signal

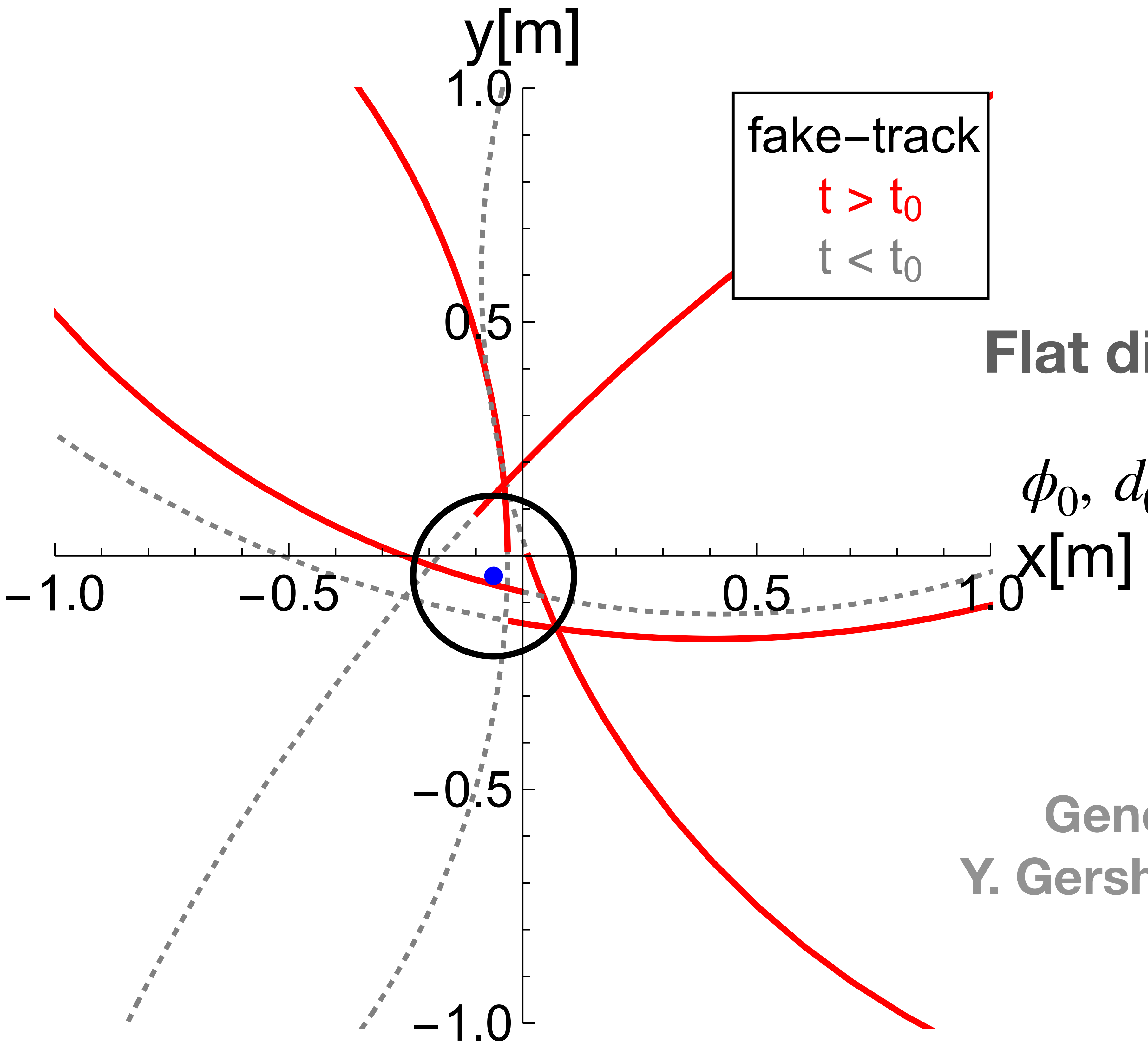
- Both spatial and timing difference



JL, Z. Liu, L.T. Wang, X.P. Wang, *JHEP* 11 (2020) 066

QCD background and LLP signal

- Both spatial and timing difference



Flat distributions in

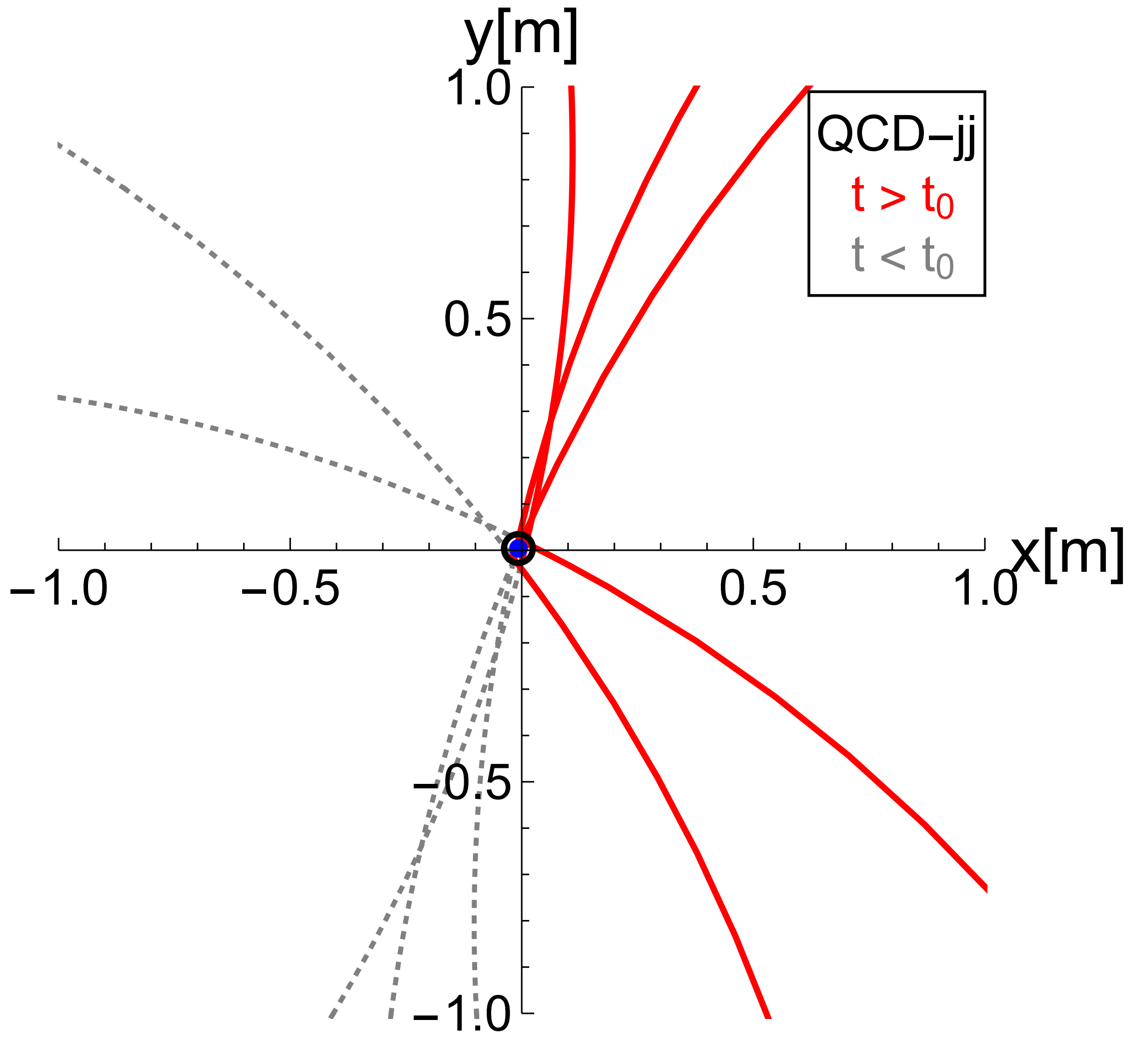
$\phi_0,\ d_0,\ 1/R,\ z_0, t_0, \eta$

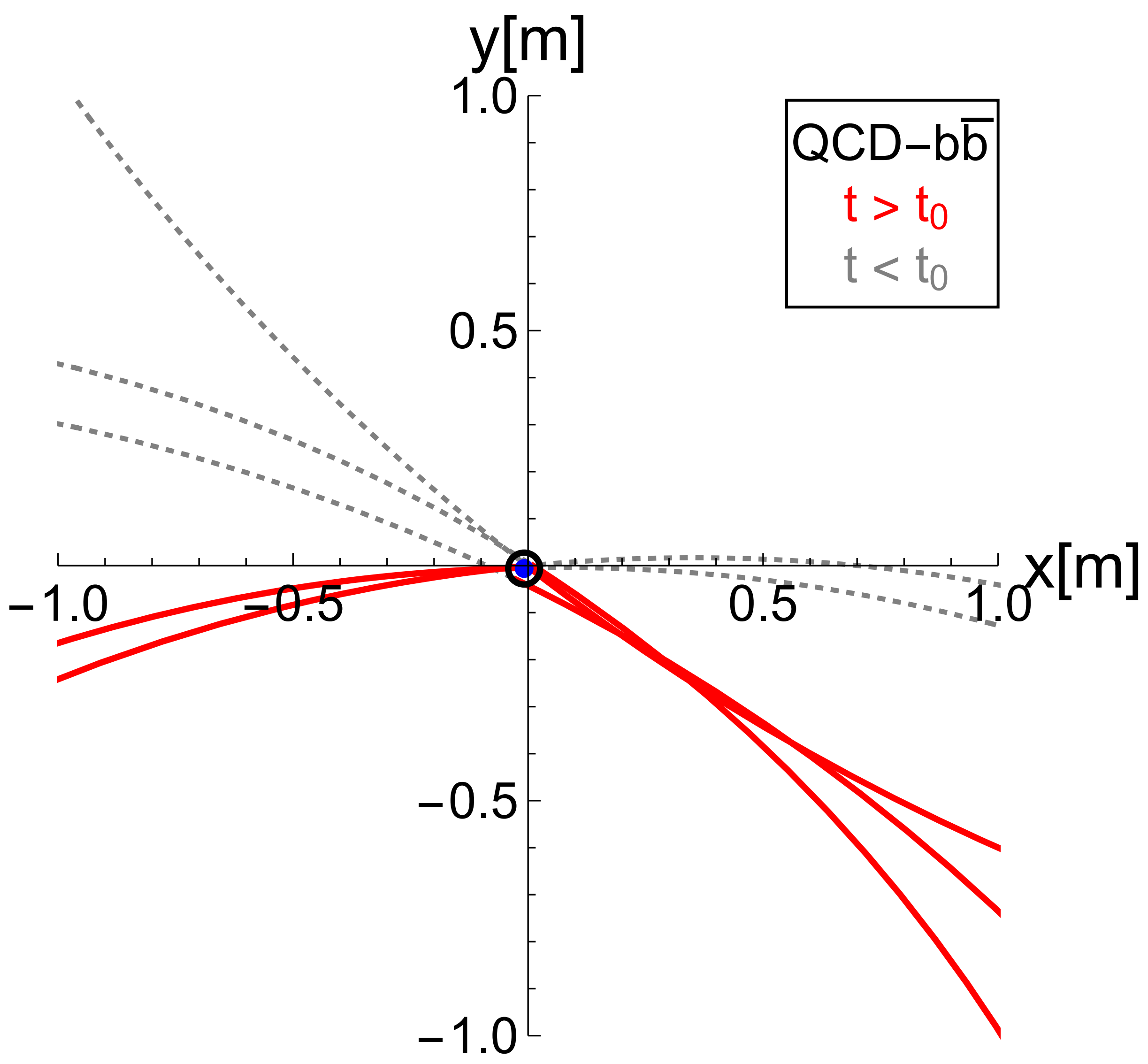
Generated following
Y. Gershtein and S. Knapen
1907.00007

- Fake track backgrounds
  - wrong connection of the hitting points in the tracker system
- Very distinct features comparing with QCD backgrounds
  - Easy to have large impact parameter
  - Poorly fit to the same origin

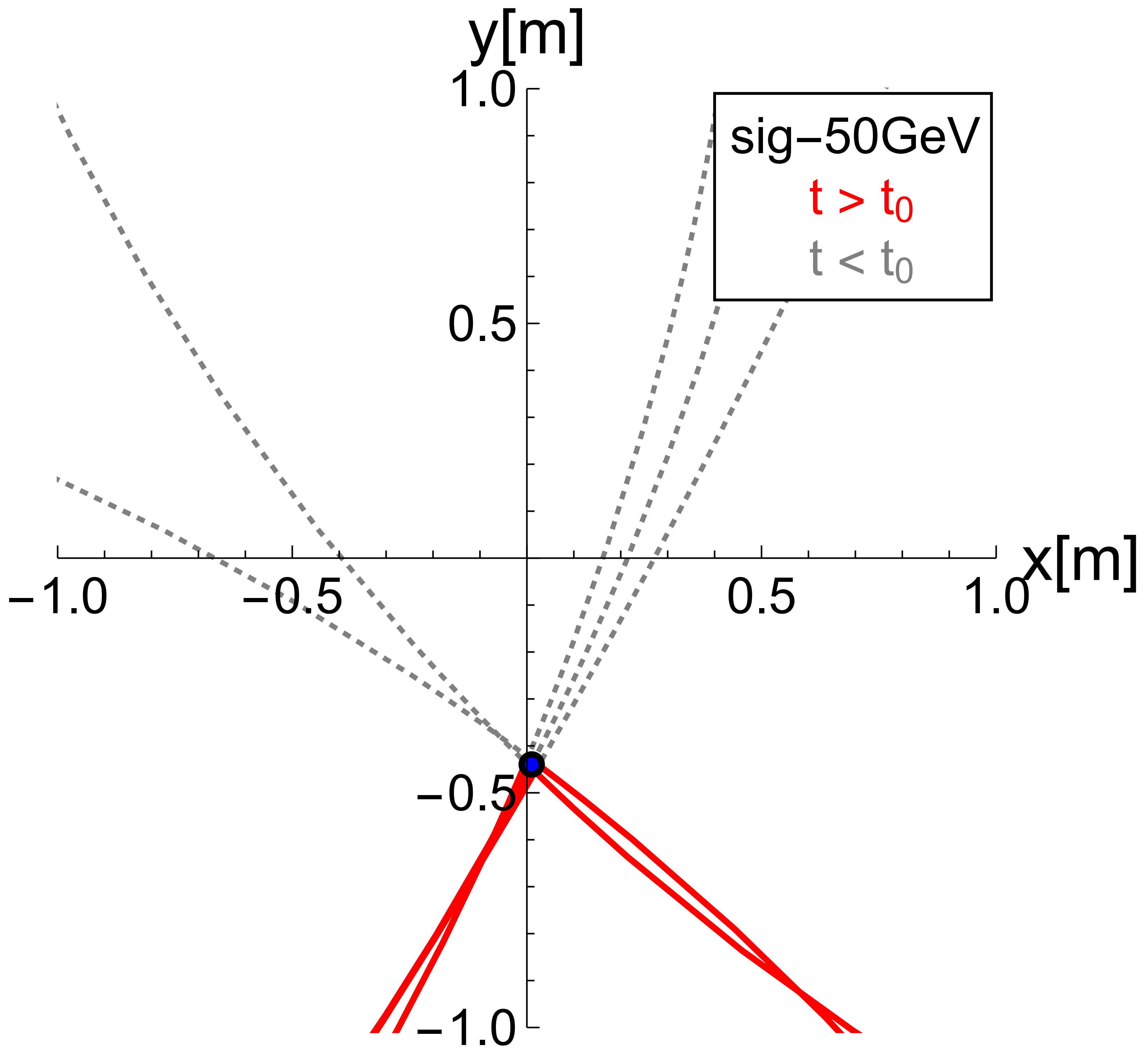
QCD background and LLP signal

- Both spatial and timing difference
  - QCD backgrounds
    - Most of them are prompt



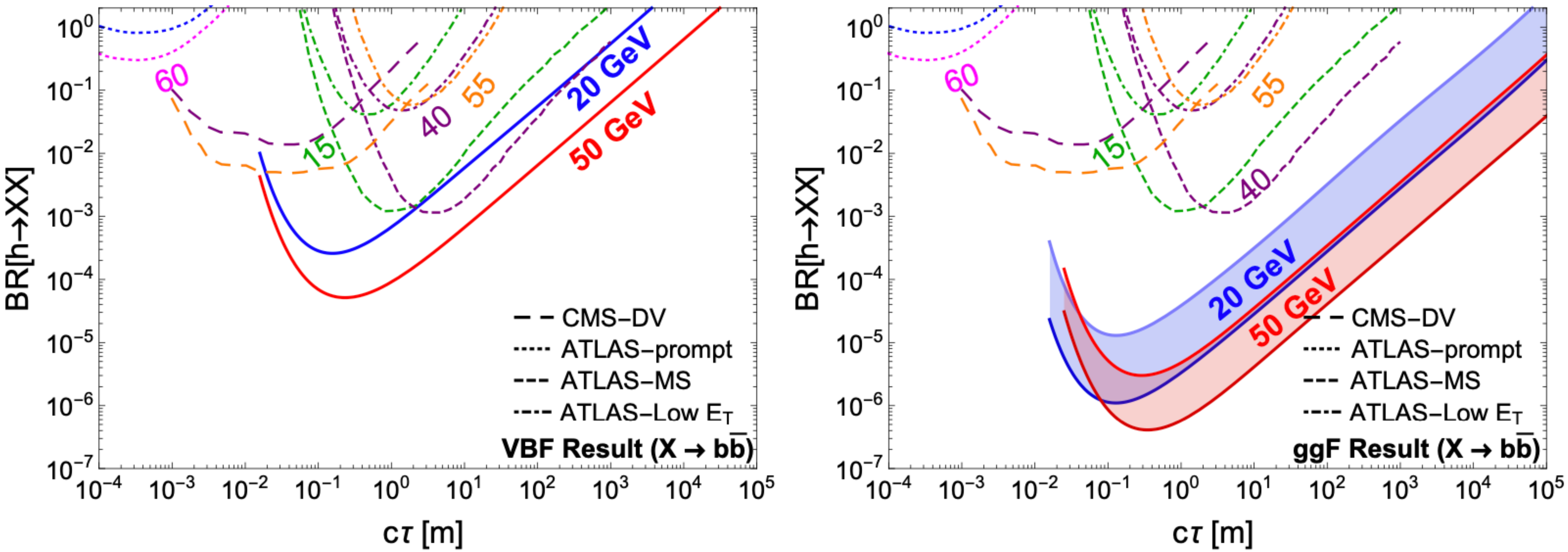


- Signal
  - Displaced and delayed



- Large impact parameter dominantly from K_S (cτ ~ 2.7 cm)
  - B (cτ ~ 0.045 cm) and D meson (cτ ~ 0.03 cm) too small

HGCAL search for $h \to XX$



- ggF result: with/without high H_T trigger requirement
- VBF result: standard VBF trigger
- Combined Displaced Vertex + Delayed Timing leads to good sensitivity
  - More ambitious: timing trigger?

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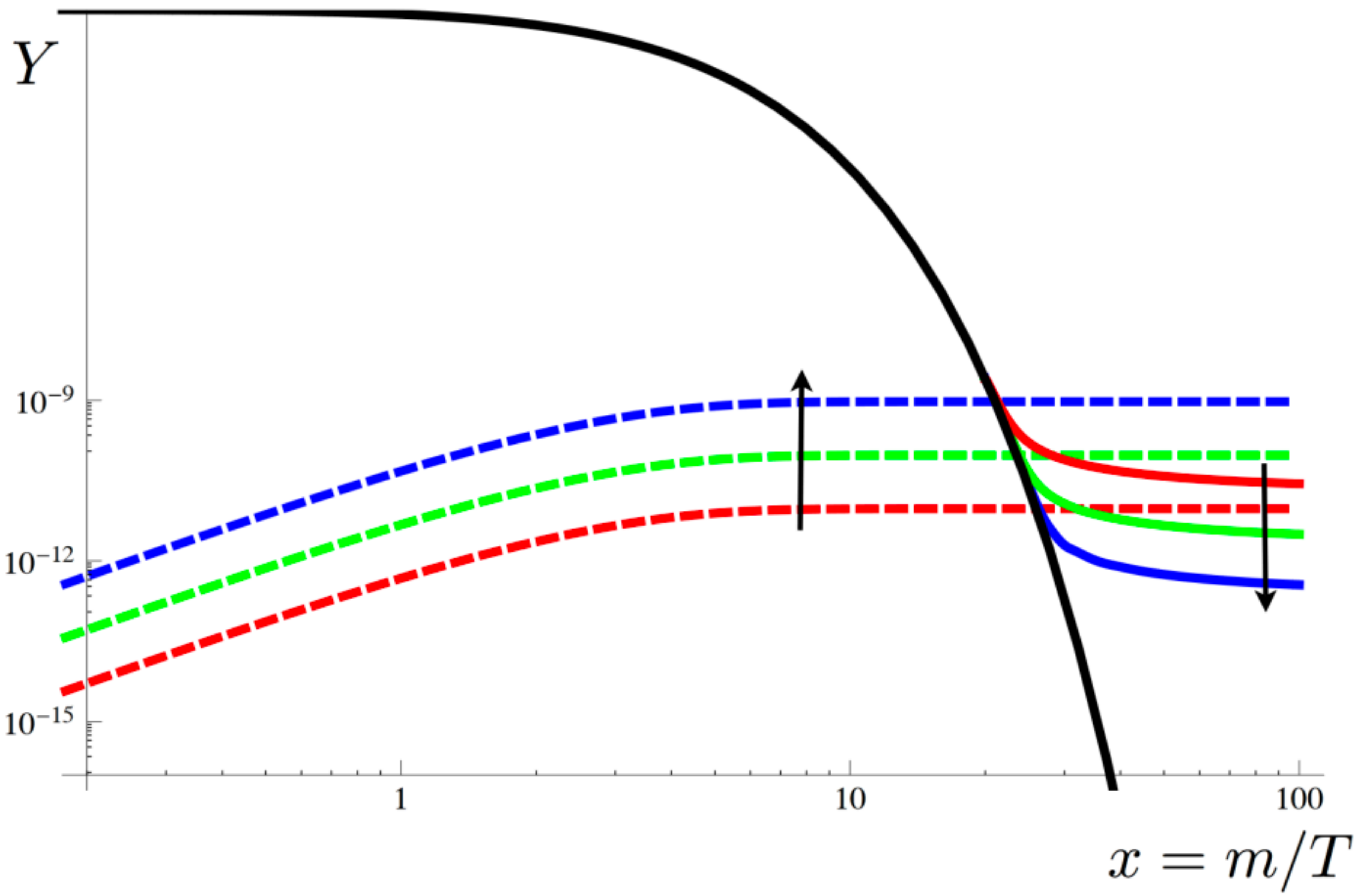
Friendly Freeze-in Dark Matter at Collider

- Freeze-in dark matter
  - Scattering: $a + b \to \chi\chi$
  - Decaying: $Y \to \chi + X_{\rm sm}$
- Interaction: fermion portal

$$y_\chi \, Y \, X_{\rm SM} \, \chi$$

	Y	$X_{\rm SM}$	χ
Z_2	**-1**	**+1**	**-1**
	F	ℓ/q	s



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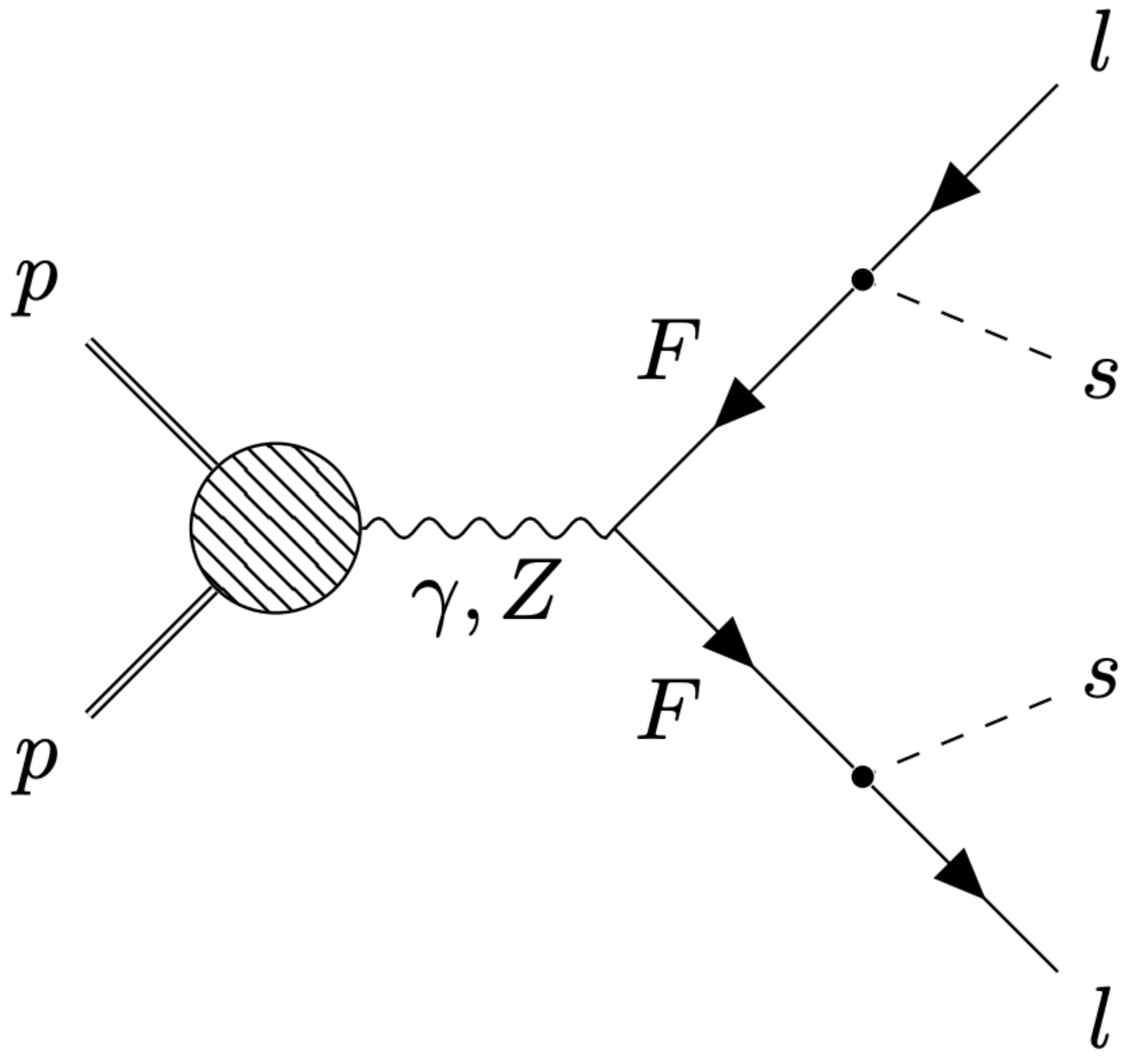
Friendly Freeze-in Dark Matter at Collider

- The thermal relic and the lifetime of Father particle



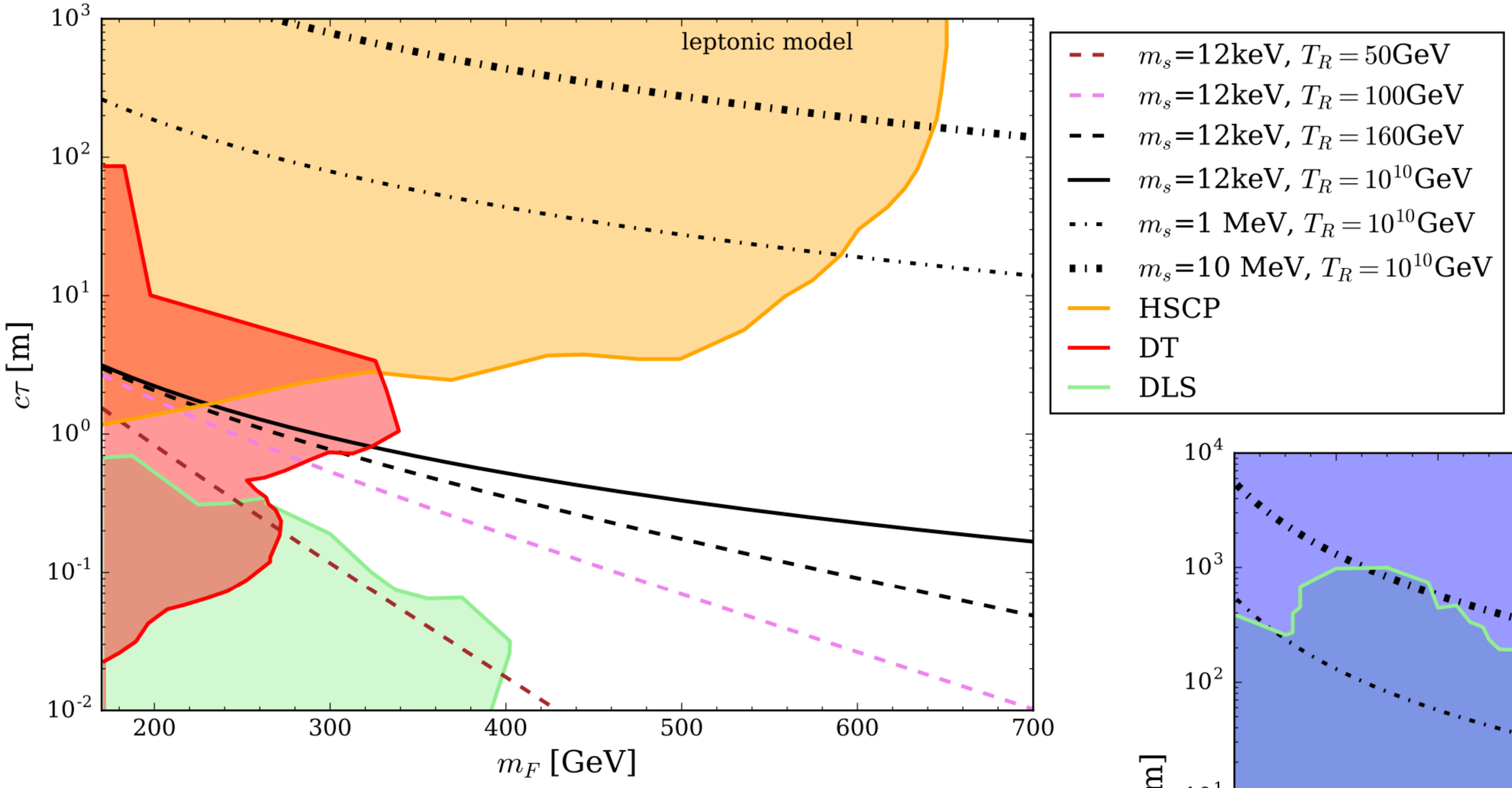
- Relic:

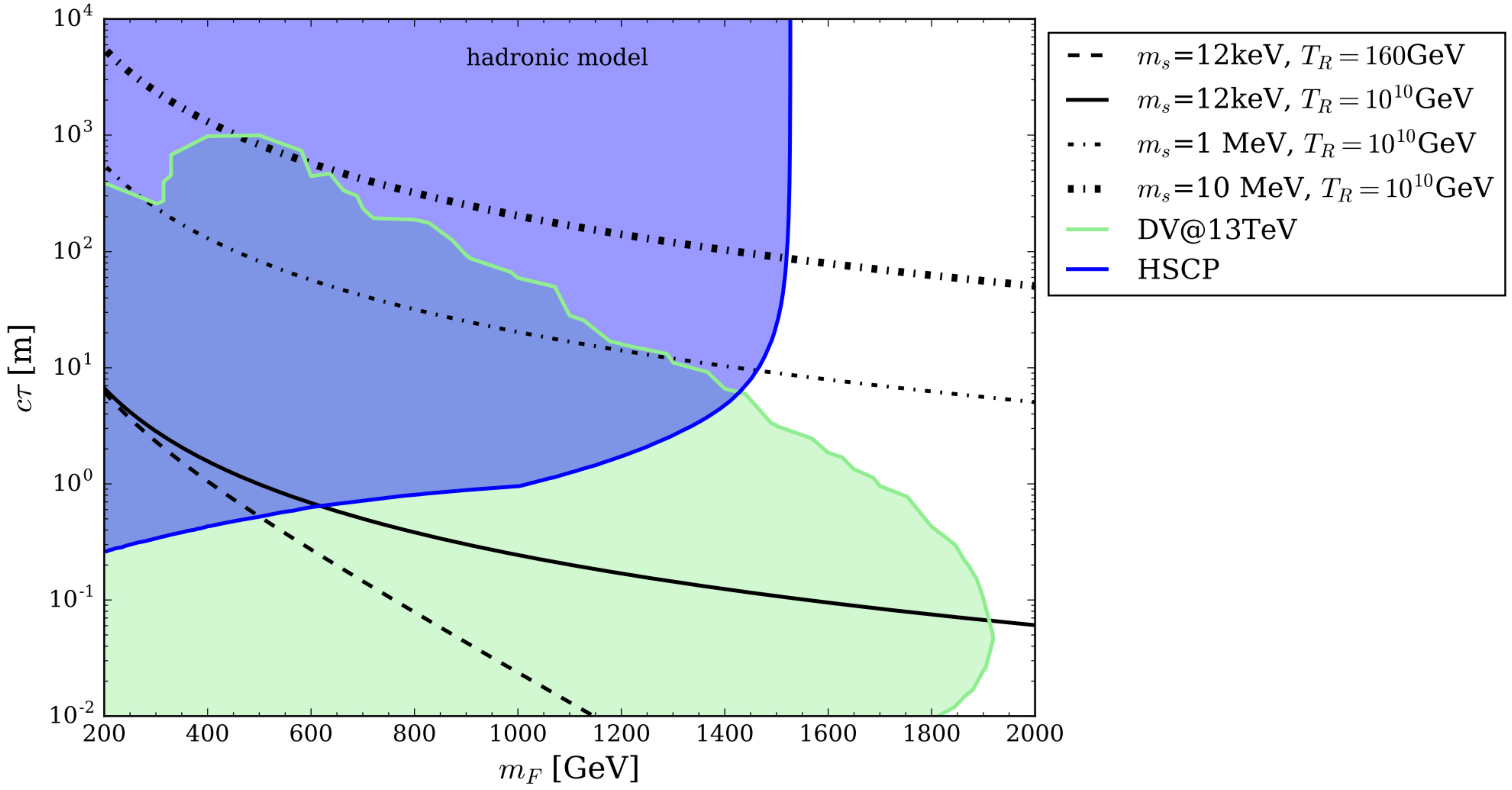
$$Y_s \approx \frac{45\,\xi\,M_{\rm Pl}}{8\pi^4 \cdot 1.66}\,\frac{g_F}{m_F^2}\,\Gamma \int_{m_F/T_R}^{m_F/T_0} dx\; x^3\, \frac{K_1(x)}{g_*^s(m_F/x)\sqrt{g_*(m_F/x)}},$$

- Lifetime:

$$c\tau[{\rm m}] \approx\; 4.5\;\xi\;g_F\;\left(\frac{0.12}{\Omega_s h^2}\right)\left(\frac{m_s}{100\ {\rm keV}}\right)\left(\frac{200\ {\rm GeV}}{m_F}\right)^2 \left(\frac{102}{g_*(m_F/3)}\right)^{3/2}\left[\frac{\int_{m_F/T_R}^{m_F/T_0} dx\; x^3 K_1(x)}{3\pi/2}\right],$$

Friendly Freeze-in Dark Matter at Collider





Outline

- The motivation for long-lived particles
- Displaced searches for LLP
- Timing searches for delayed LLP
- Motivated long-lived candidates
    - Freeze-in DM, Vector-like Fermion
- Summary

Vector-like fermion as natural LLP

- Only VLF is added
- E.g. F has right-handed lepton charges

$$\mathcal{L}_{\rm eff}^{F} \supset \bar{F}^0 iD_\mu\gamma^\mu F^0 + \bar{L}^0 iD_\mu\gamma^\mu L^0 + \bar{\ell}_R^0 iD_\mu\gamma^\mu \ell_R^0 - m_F^0 \bar{F}^0 F^0 - m_\ell^0 \bar{\ell}^0 \ell^0 - \boxed{(\delta \bar{F}_L^0 \ell_R^0} + \text{h.c.}),$$

- The mass eigenstates and mixing angles

$$m_F \simeq m_F^0 + \frac{\delta^2}{2m_F^0} \simeq m_F^0$$

$$m_\ell \simeq m_\ell^0 \left(1 - \frac{1}{2}\left(\frac{\delta}{m_F^0}\right)^2\right).$$

$$\tan\theta_R = -\frac{2m_F^0\delta}{(m_F^0)^2 - (m_\ell^0)^2 - \delta^2 + \sqrt{((m_F^0)^2 - (m_\ell^0)^2 + \delta^2)^2 + 4(m_\ell^0)^2\delta^2}} \simeq -\frac{\delta}{m_F^0},$$

$$\tan\theta_L = -\frac{2m_\ell^0\delta}{(m_F^0)^2 - (m_\ell^0)^2 + \delta^2 + \sqrt{((m_F^0)^2 - (m_\ell^0)^2 + \delta^2)^2 + 4(m_\ell^0)^2\delta^2}} \simeq -\frac{m_\ell^0\delta}{(m_F^0)^2} \simeq \frac{m_\ell^0}{m_F^0}\tan\theta_R,$$

$\theta_L \ll \theta_R$! Because of right-handed lepton charge

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Vector-like fermion as natural LLP

- Off-diagonal interactions are left-handed!

$$\supset \bar{F}(i\partial_\mu - eA_\mu + e\tan\theta_W Z_\mu)\gamma^\mu F - m_F\bar{F}F - m_\ell\bar{\ell}\ell$$
$$+\frac{1}{2}\frac{e}{\sin\theta_W\cos\theta_W}\theta_L Z_\mu(\bar{F}_L\gamma^\mu\ell_L + \text{h.c.}) - \frac{e}{\sqrt{2}\sin\theta_W}\theta_L(W_\mu^+\bar{\nu}_L\gamma^\mu F_L + \text{h.c.}),$$

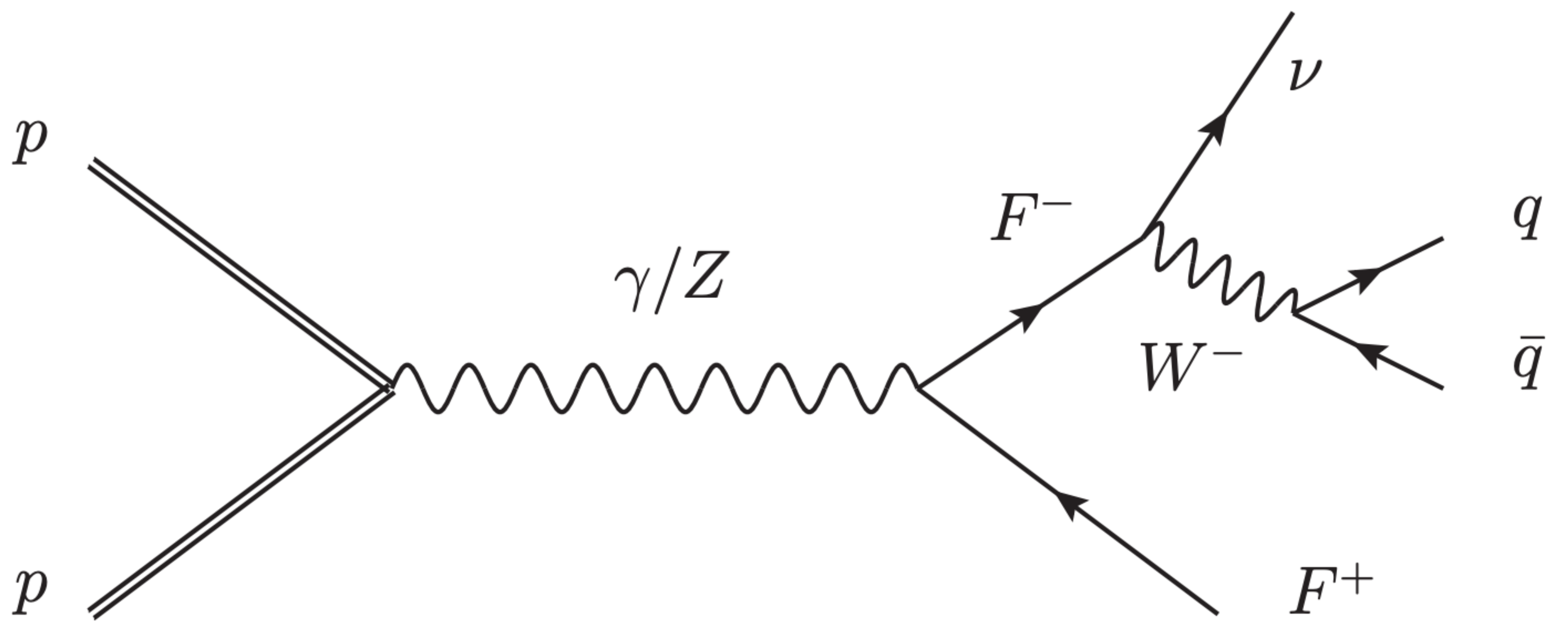
- Decay width are suppressed by θ_L^2

$$\Gamma(F^\pm \to \nu_\ell W^\pm) = \frac{\theta_L^2 g_W^2}{64\pi}\frac{(m_F^2 - m_W^2)^2(m_F^2 + 2m_W^2)}{m_F^3 m_W^2},$$
$$\Gamma(F^\pm \to \ell^\pm Z) = \frac{\theta_L^2 g_Z^2}{64\pi}\frac{(m_F^2 - m_Z^2)^2(m_F^2 + 2m_Z^2)}{m_F^3 m_Z^2}.$$

$$\propto \frac{\theta_L^2 g^2}{64\pi}m_F \approx \frac{g^2}{64\pi}\frac{m_\ell^2}{m_W^2}\frac{\delta^2}{m_F}$$

- Therefore, F is the natural charged LLP

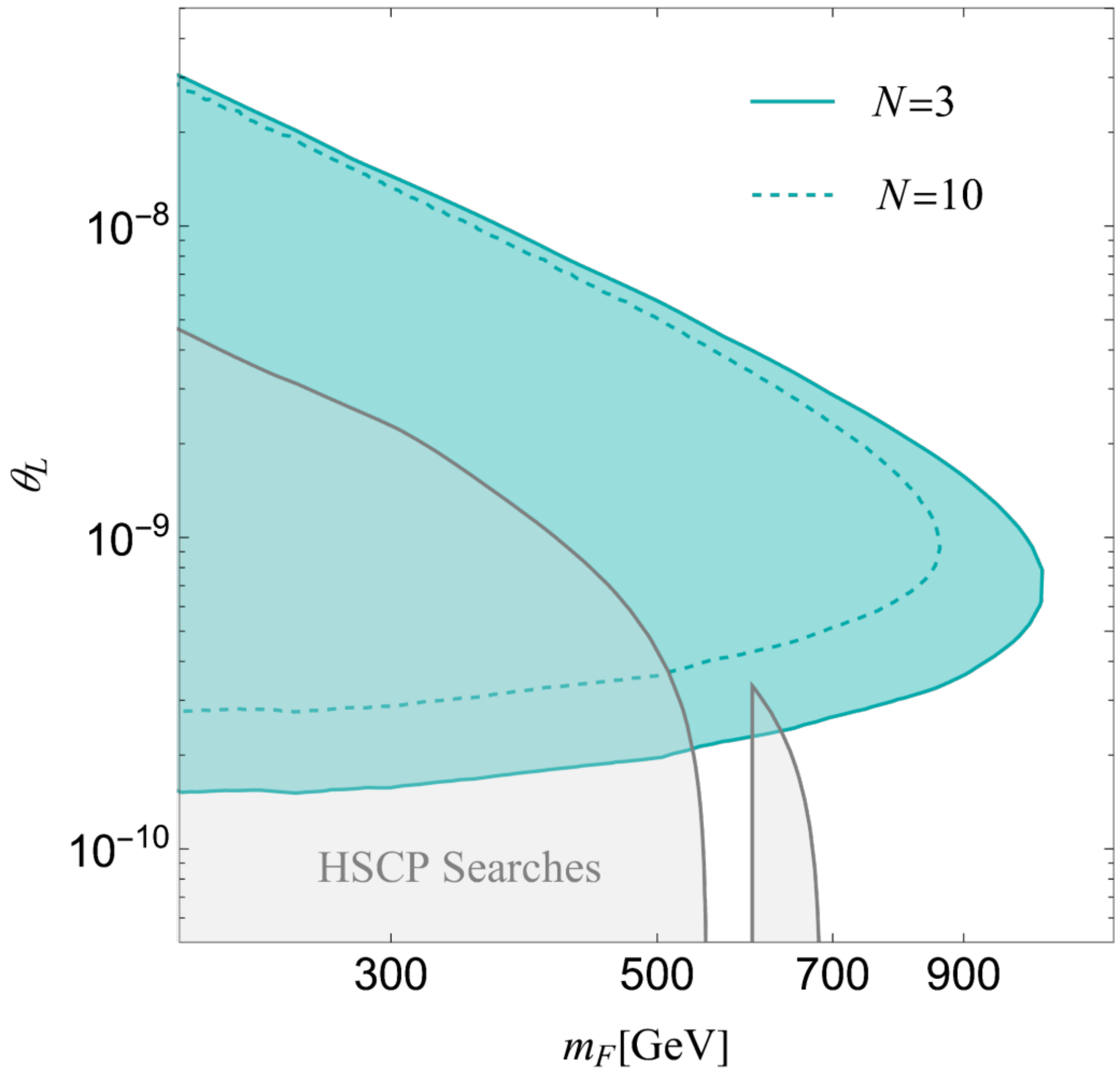
Vector-like fermion as natural LLP



- Ballpark: $\theta_L \approx \dfrac{\delta m_\ell}{m_F^2} \sim 10^{-9}$

- For electron or light quark: $\delta \sim 0.1$ GeV

- For muon lepton: $\delta \sim 1$ MeV



Vector-like fermion with light LLP scalar

- New interactions

$$\mathcal{L}_{\rm Int}^{\phi} \supset -y\phi \bar{F}_L^0 \ell_R^0 + \text{h.c.}$$
$$\simeq -y\phi\left(\bar{F}_L\ell_R + \bar{\ell}_R F_L + \theta_R \bar{F}F - \theta_L \bar{\ell}\ell\right),$$

- Prompt decay of F: $F \to \phi + \ell$, with $y \sim \mathcal{O}(1)$
- Naturally, long-lived ϕ

$$\Gamma(\phi \to \ell^+\ell^-) = \frac{(y\theta_L)^2 m_\phi (1 - 4m_\ell^2/m_\phi^2)^{3/2}}{8\pi},$$

$$\propto \frac{\theta_L^2 y^2}{8\pi} m_\phi \approx \frac{y^2}{8\pi} m_\phi \frac{\delta^2 m_\ell^2}{m_F^4}$$

$$\tau(\phi) \simeq \left(\frac{3\times 10^{-9}}{y\theta_L}\right)^2 \left(\frac{50\ \text{GeV}}{m_\phi}\right) \text{ns}.$$

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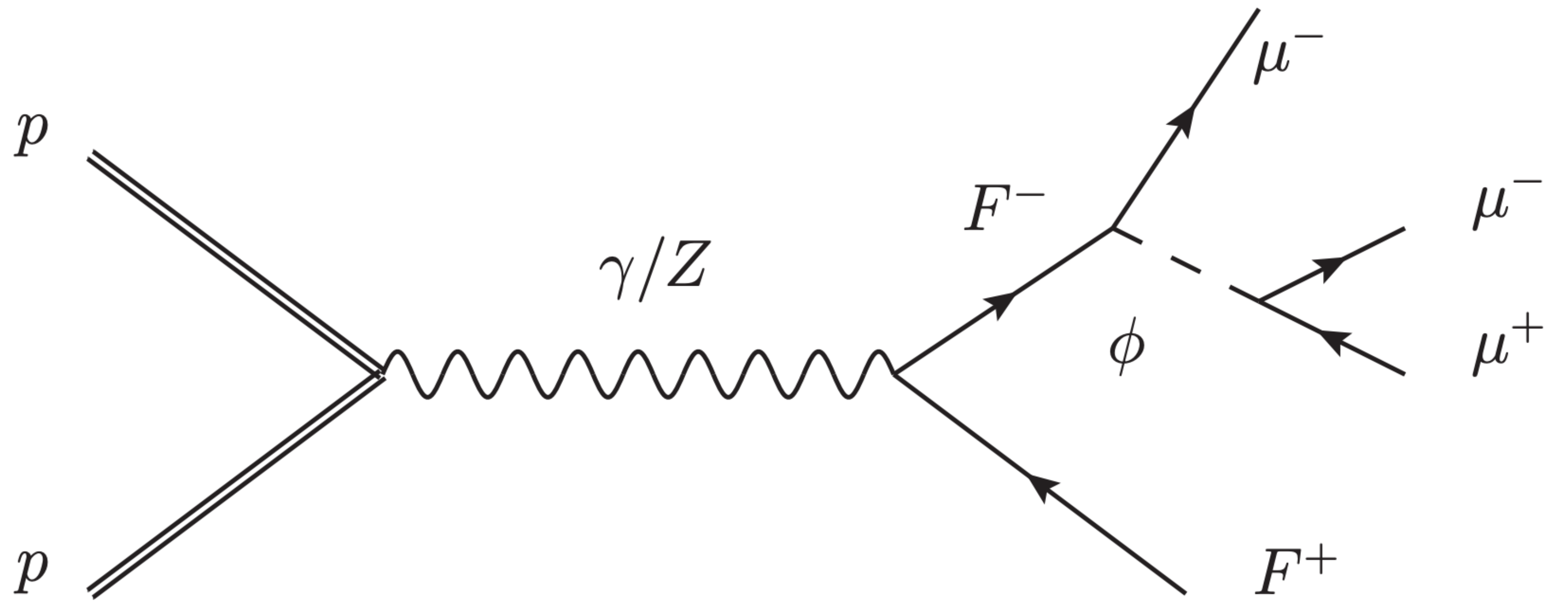
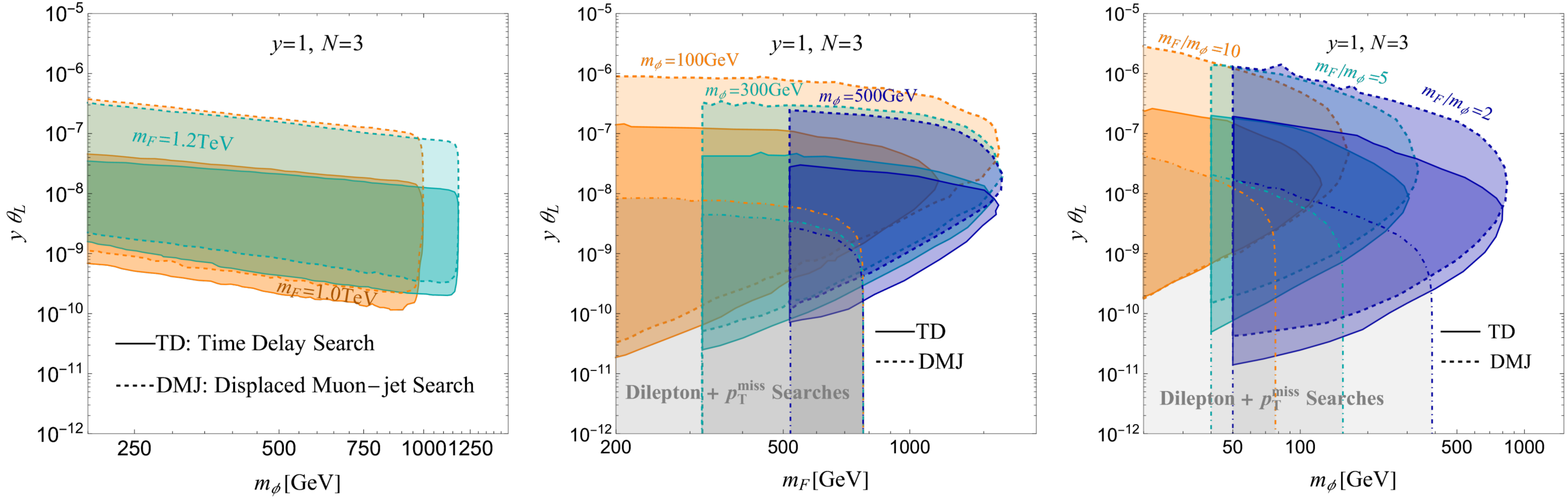
Vector-like fermion with light scalar

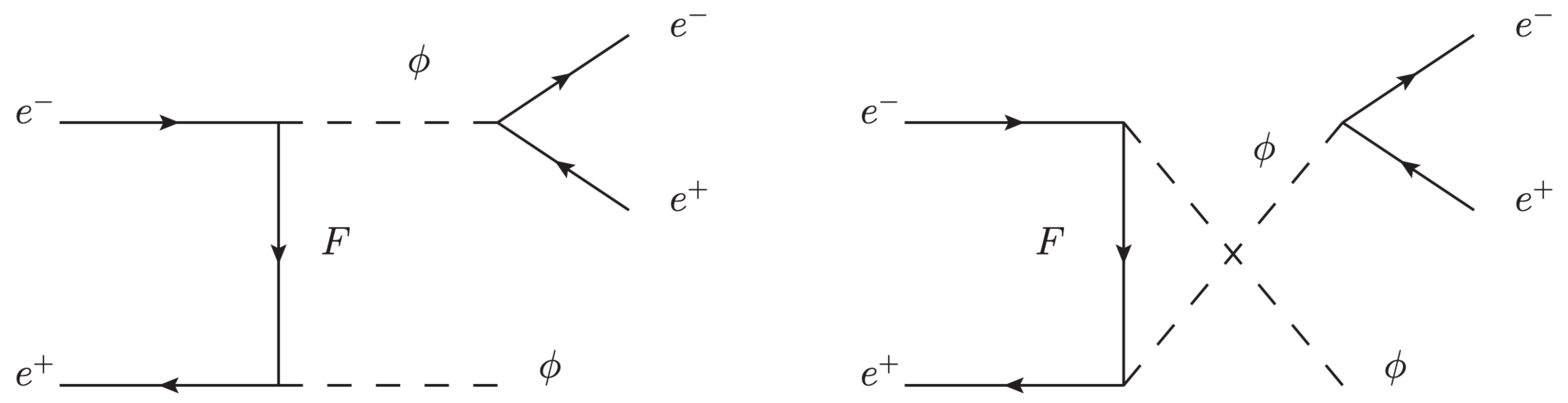
- If coupling to muons @ HL-LHC

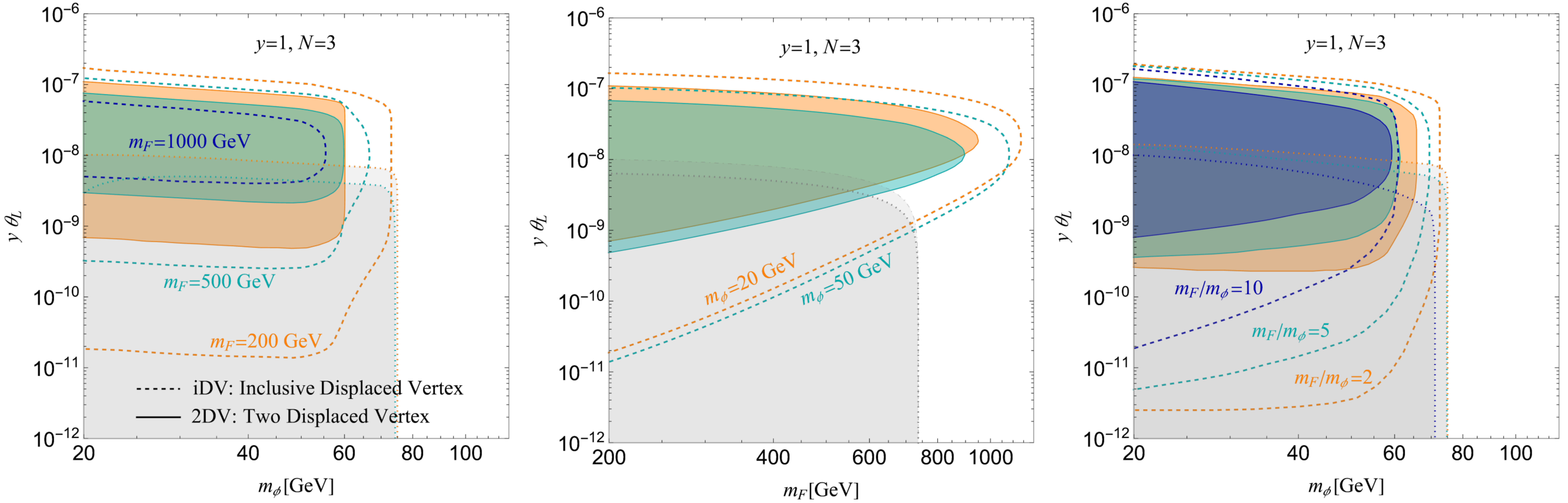




Vector-like fermion with light scalar

- If coupling to electrons @ CEPC





Summary

- The long-lived particle could naturally exist as in SM
- Displaced searches and time delay searches are both useful
  - Dedicated triggers are developed by experiments
- Some motivated LLP candidates can be naturally generated
  - Related to freeze-in dark matter
  - Vector-like fermion related suppressions
- A joint search program from intensity/energy/cosmic frontiers is necessary to hunt for long-lived particles.

Thank you!

Backup slides