

Long-lived particle Searches at LHC



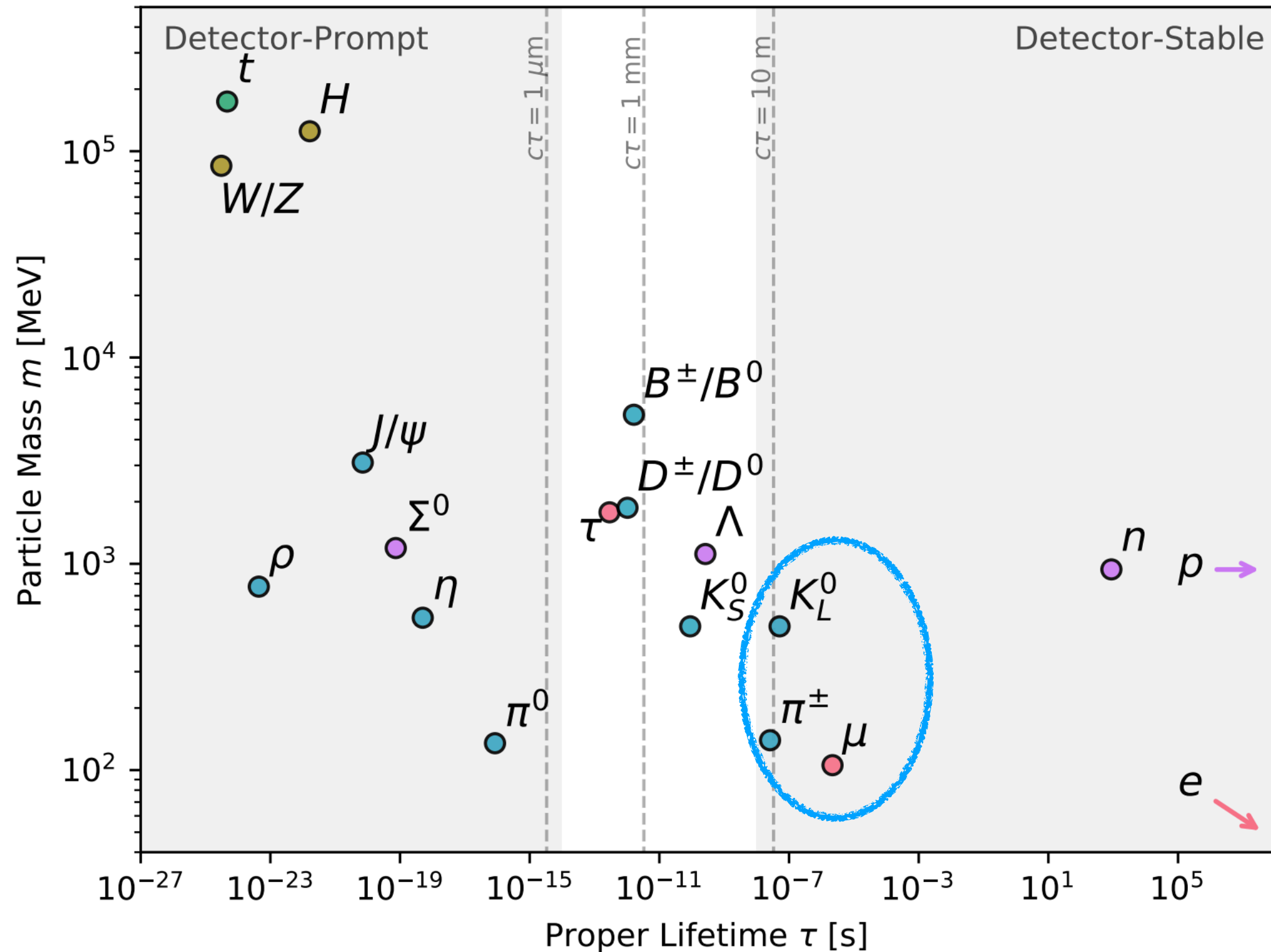
Xiao-Ping Wang
Argonne National Laboratory

Invisibles / Elusives Webinar | 25.02.2020

Outline

- Long-lived particle introduction
- Long-lived sterile neutrino search
- General long-lived particle search at CMS
HGCal

Why Long-lived Particles?



Why Long-lived Particles?

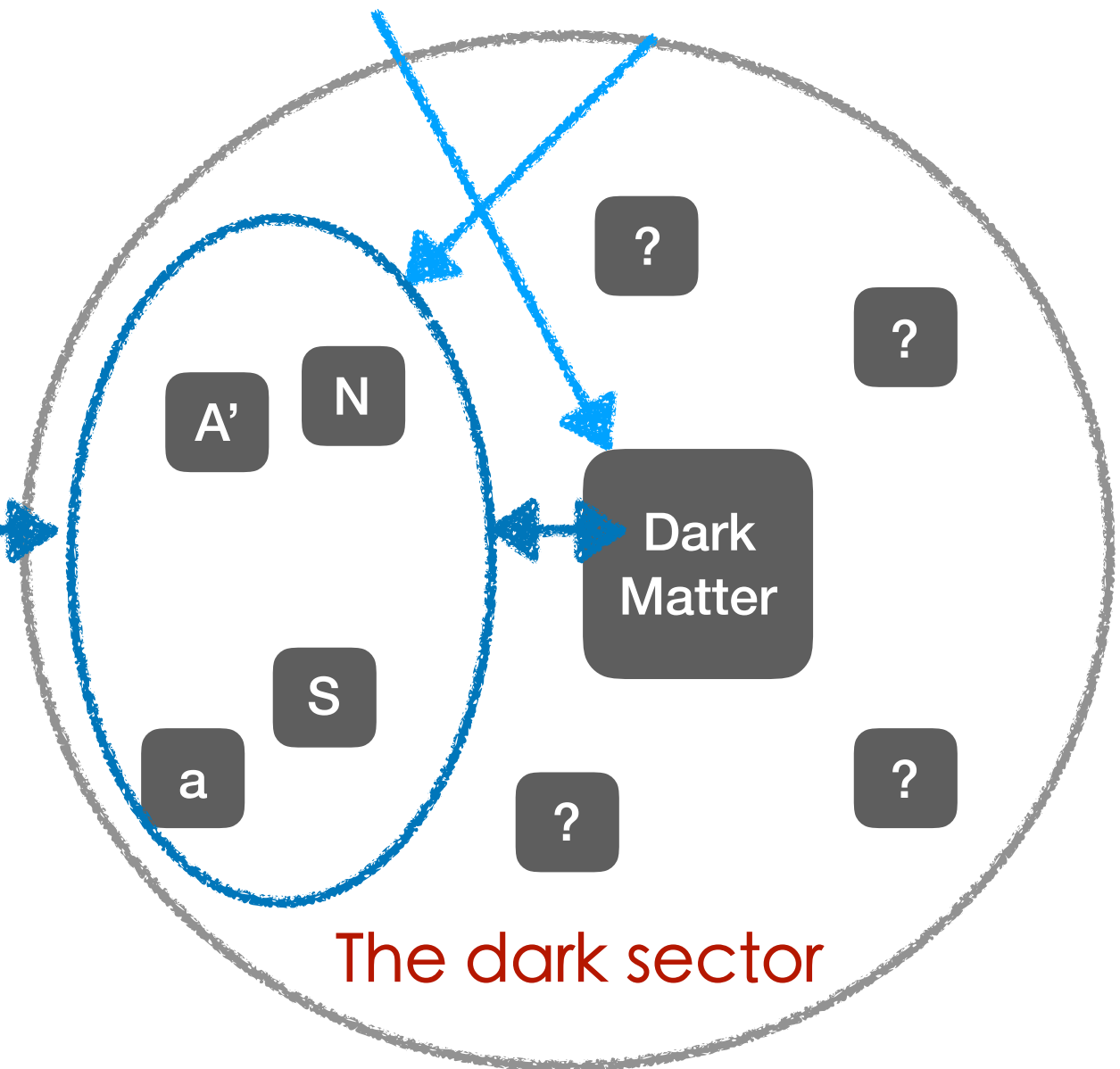
- Standard Model
= fermions + force mediators

- Dark sector
= DM + dark mediators

Standard Model of Elementary Particles

three generations of matter (fermions)			interactions / force carriers (bosons)	
	I	II	III	
mass	$\approx 2.2 \text{ MeV}/c^2$	$\approx 1.28 \text{ GeV}/c^2$	$\approx 173.1 \text{ GeV}/c^2$	$\approx 125.09 \text{ GeV}/c^2$
charge	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$	0
spin	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	0
	u up	c charm	t top	g gluon
	d down	s strange	b bottom	γ photon
	e electron	μ muon	τ tau	Z Z boson
	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	W W boson

QUARKS (purple boxes)
LEPTONS (green boxes)
GAUGE BOSONS VECTOR BOSONS (red boxes)
SCALAR BOSONS (yellow boxes)

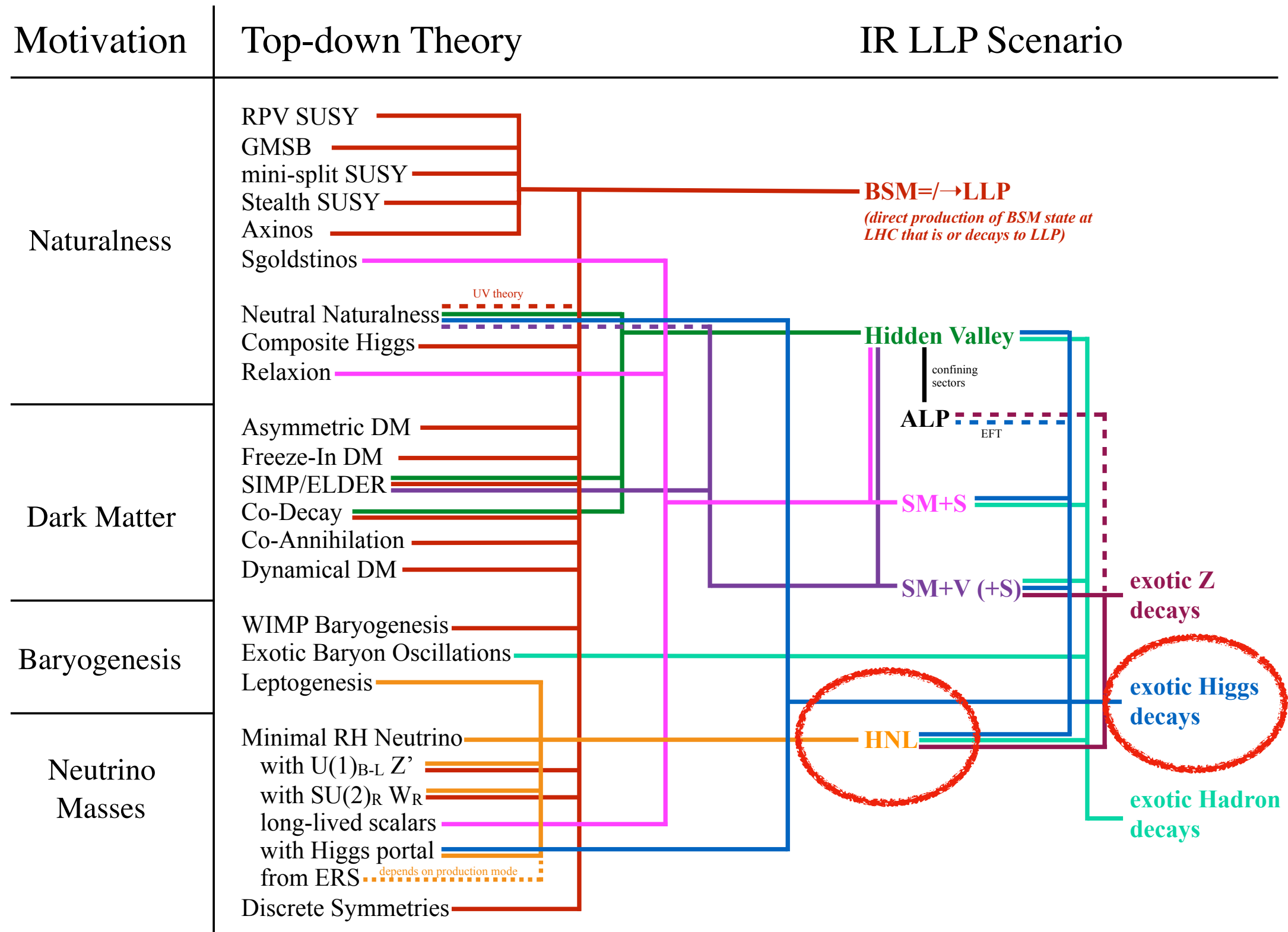


- Not a surprise: dark sector particles have a wide spread in lifetime

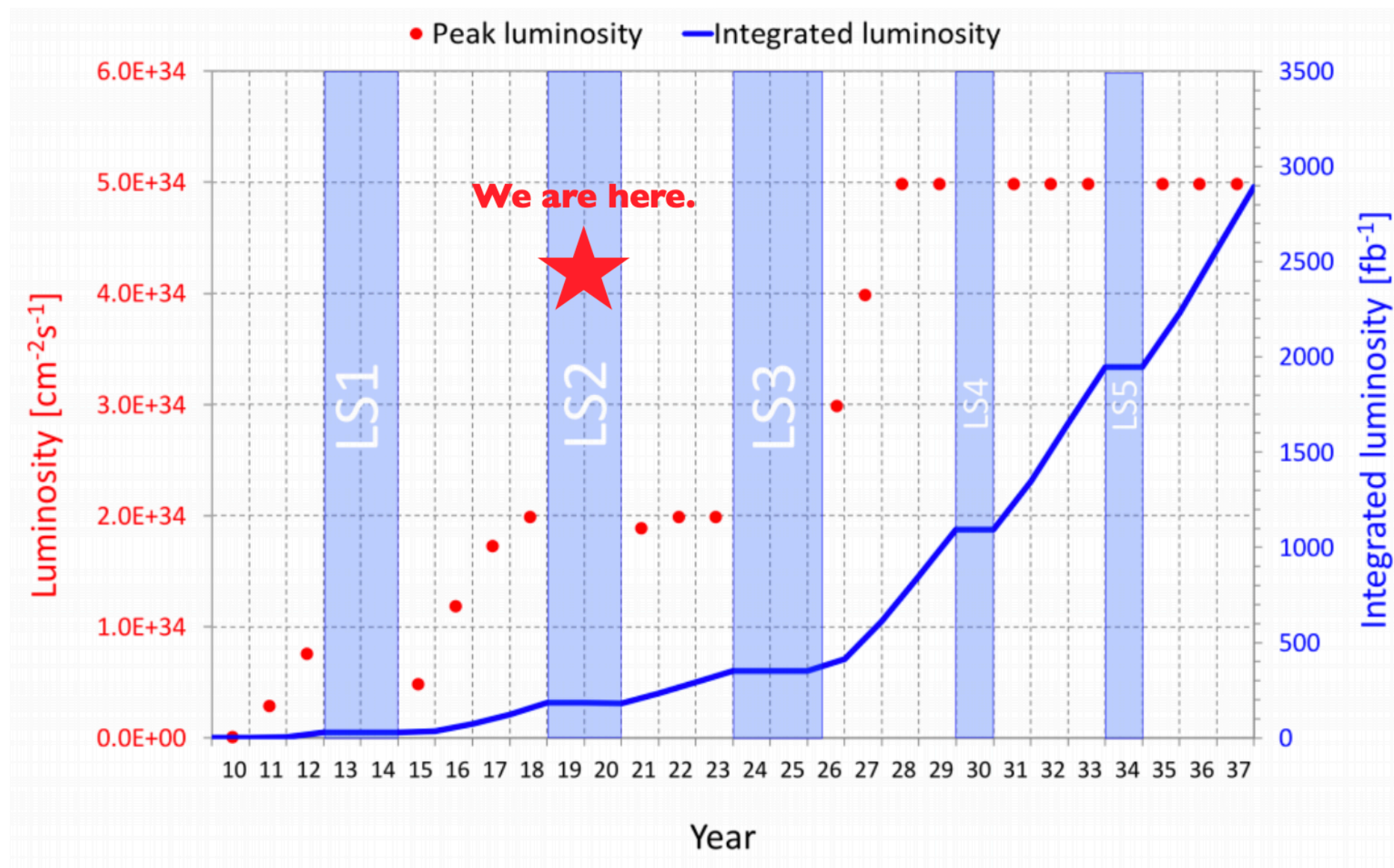
Why Long-lived Particles?

- **Feeble couplings:**
R-parity violating Supersymmetry, sterile neutrinos, portal models
- **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)

Why Long-lived Particles?



Why Looking for Long-lived Particle at LHC?

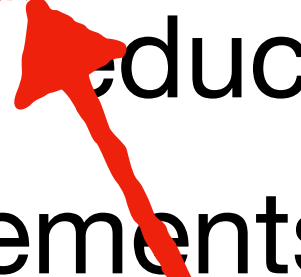


- LHC will accumulate more data
- Exp collaborations have broad physics programs: SUSY, composite H, extra Dim, etc.
- New directions?

Why Looking for Long-lived Particle at LHC?

- Physics potential from a lot of new data
 - Very rare signal
 - E.g. dark sector, rare decays, ...
- More data can help reducing systematics
 - Precision measurements

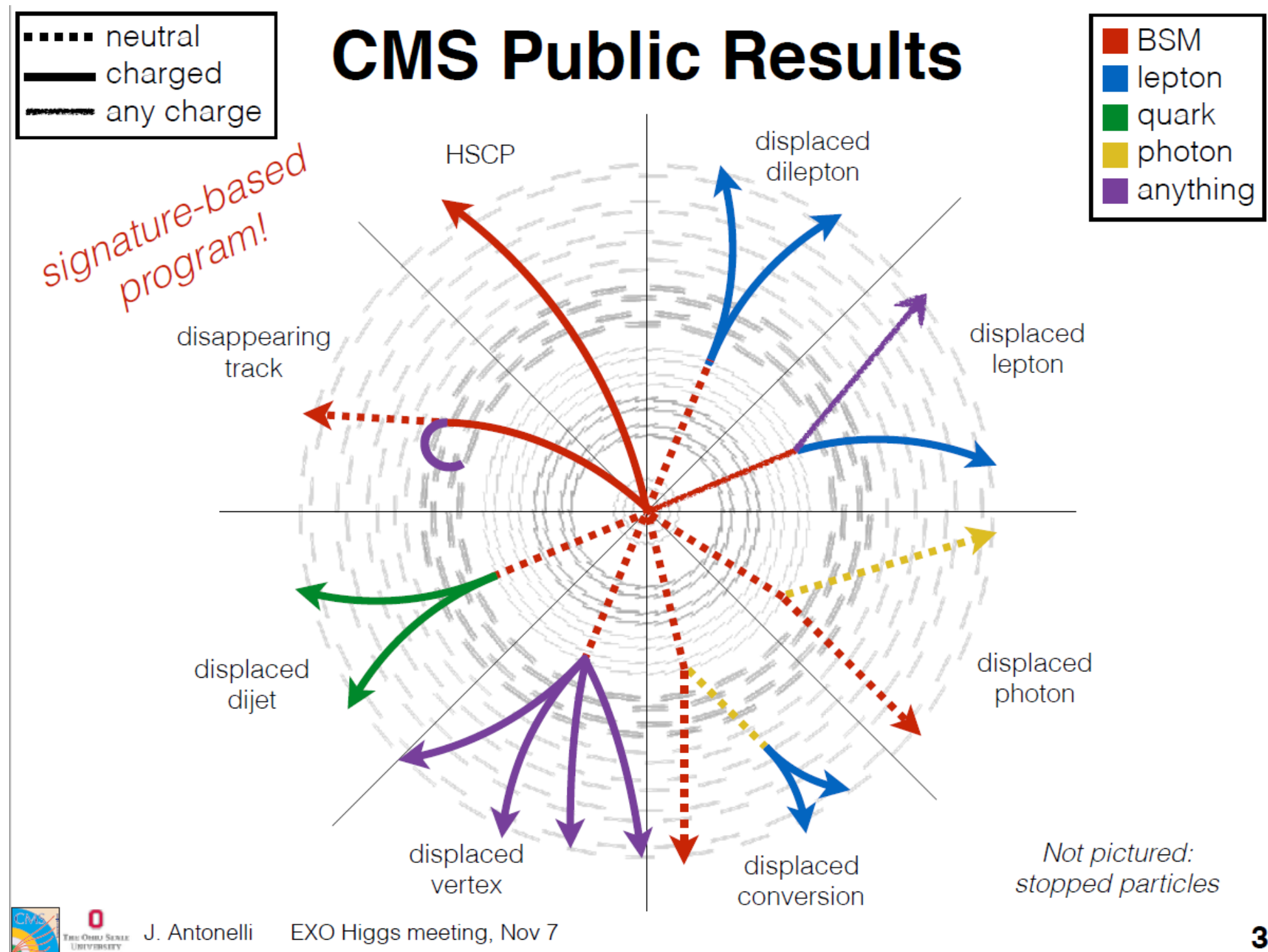
Why Looking for Long-lived Particle at LHC?

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- 

An important example:
Long-lived particles

How to Search LLP?

- Mostly related with displaced-vertex, less track-based



How to Search LLP?

- Mostly related with displaced-vertex, less track-based
- Our difference from previous work: focus on track-based observables

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Long-lived Sterile Neutrino Search

- ▶ Dec. 1930: W. Pauli hypothesizes the electron neutrino.
- ▶ Today: there are three active neutrinos that oscillate

⇒ Key question: Origin of neutrino masses?

- ▶ Heavy neutral leptons (HNL) naturally occur in Standard Model extensions toward neutrino masses.
- ▶ HNL with masses below m_W “easily” develop long lifetimes.

**HNL are a well-motivated prototype LLP
they have to be studied as thoroughly as possible!**

Sterile Neutrino Models

- Basic seesaw model

$$\Delta\mathcal{L}_\nu = -\lambda_\nu \bar{L}\tilde{H}N - \frac{m_N}{2}\bar{N}^c N + h.c.,$$

- Masses

$$m_D = \lambda_\nu v / \sqrt{2}$$
$$M_\nu = \begin{pmatrix} 0 & m_D \\ m_D & m_N \end{pmatrix} \quad m_\nu \equiv m_1 \simeq \frac{m_D^2}{m_N}, \quad m_2 \simeq m_N + \frac{m_D^2}{m_N} \simeq m_N$$

- Mixing

$$\sin^2 \theta \simeq \frac{m_\nu}{m_N} = 10^{-12} \left(\frac{m_\nu}{0.01 \text{ eV}} \right) \left(\frac{10 \text{ GeV}}{m_N} \right)$$

- Problem: production of N is suppressed by very small mixing

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- Inverse seesaw

$$\sin^2 \theta = \frac{m_\nu}{\mu} \quad m_\nu = \mu \left(\frac{m_D}{m_N} \right)^2$$

- Linear seesaw

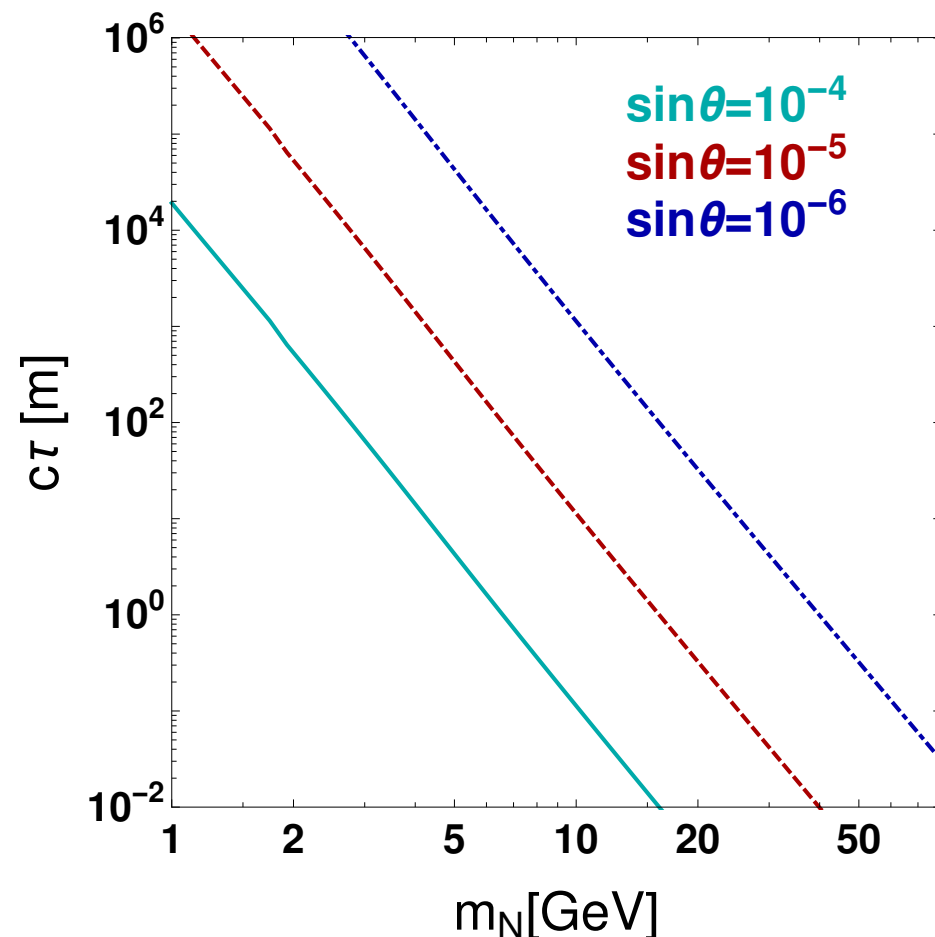
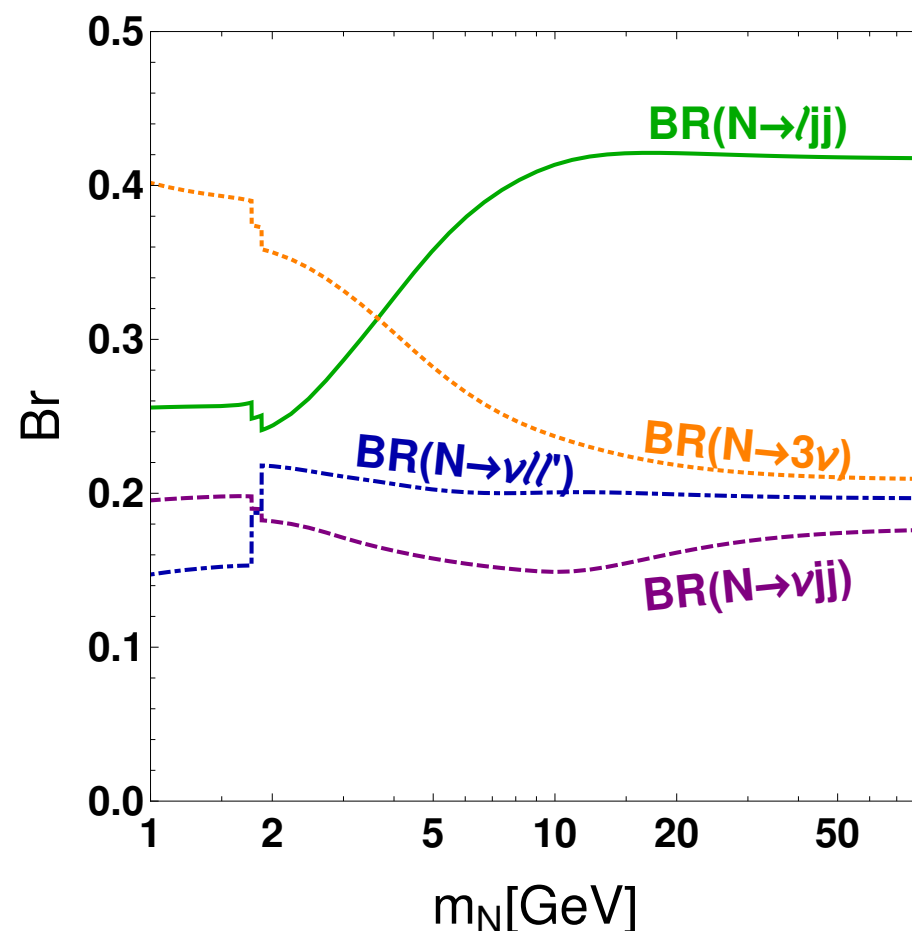
$$\sin \theta = \frac{m_\nu}{m_\psi}$$

Separate neutrino mass from mixing, realizing large mixing angle.

Sterile Neutrino Signal

- Free parameters: m_N , $\sin\theta$
- Long life-time

$$c\tau \simeq 12 \text{ km} \times \left(\frac{10^{-12}}{\sin^2 \theta} \right) \left(\frac{10 \text{ GeV}}{m_N} \right)^5$$



Sterile Neutrino Signal

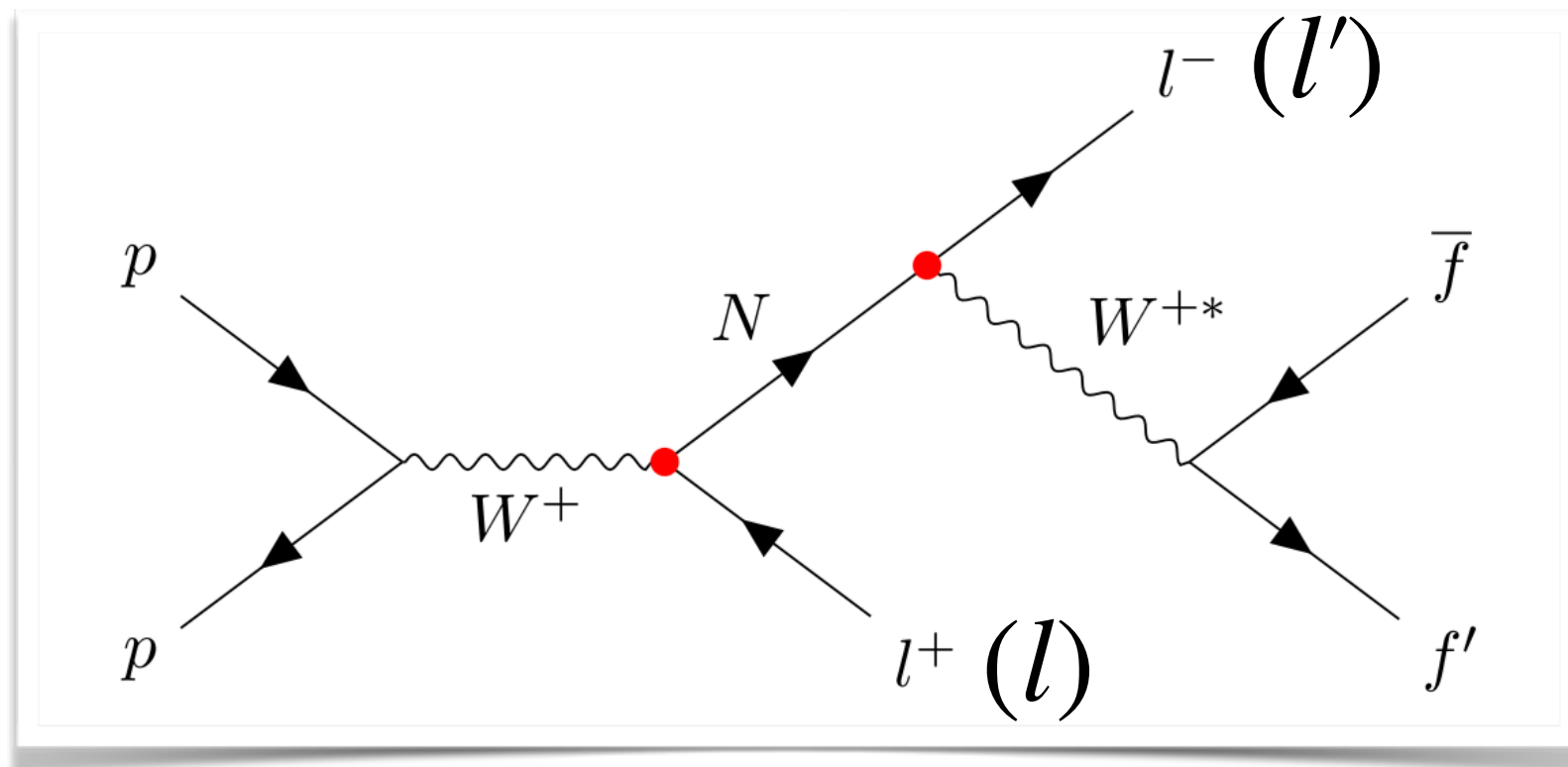
- Free parameters: m_N , $\sin\theta$
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$$c\tau \simeq 12 \text{ km} \times \left(\frac{10^{-12}}{\sin^2 \theta} \right) \left(\frac{10 \text{ GeV}}{m_N} \right)^5$$

- Event rate at HL-LHC

$$\mathcal{L} \times \sigma(pp \rightarrow W^\pm) \text{Br}(W^\pm \rightarrow \ell^\pm N) \simeq 1.8 \times 10^5 \left(\frac{\sin^2 \theta}{10^{-6}} \right)$$

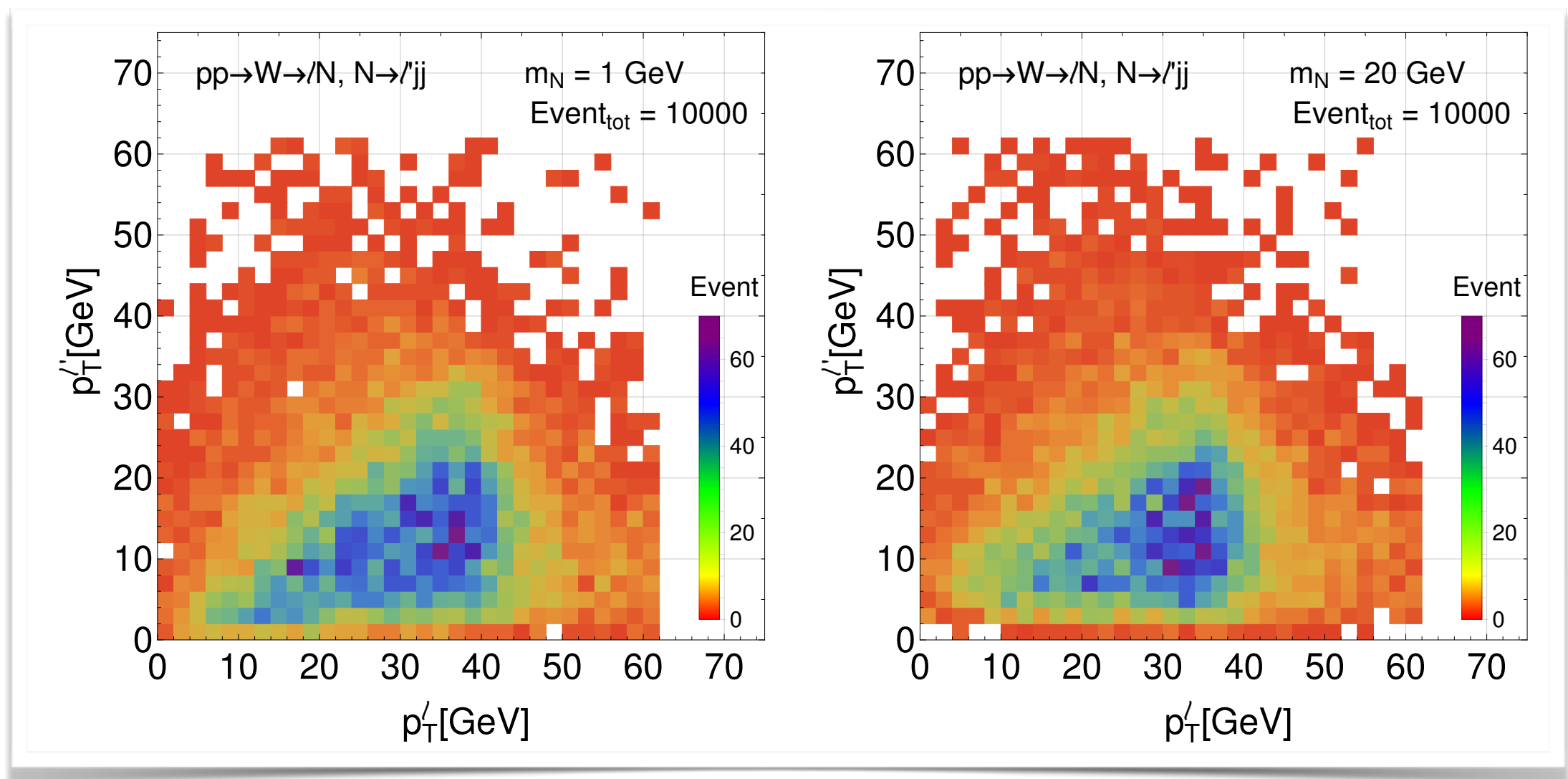
- Signal topology



The Lepton Behaviors

- Prompt lepton hard-ish
- Displaced lepton soft-ish

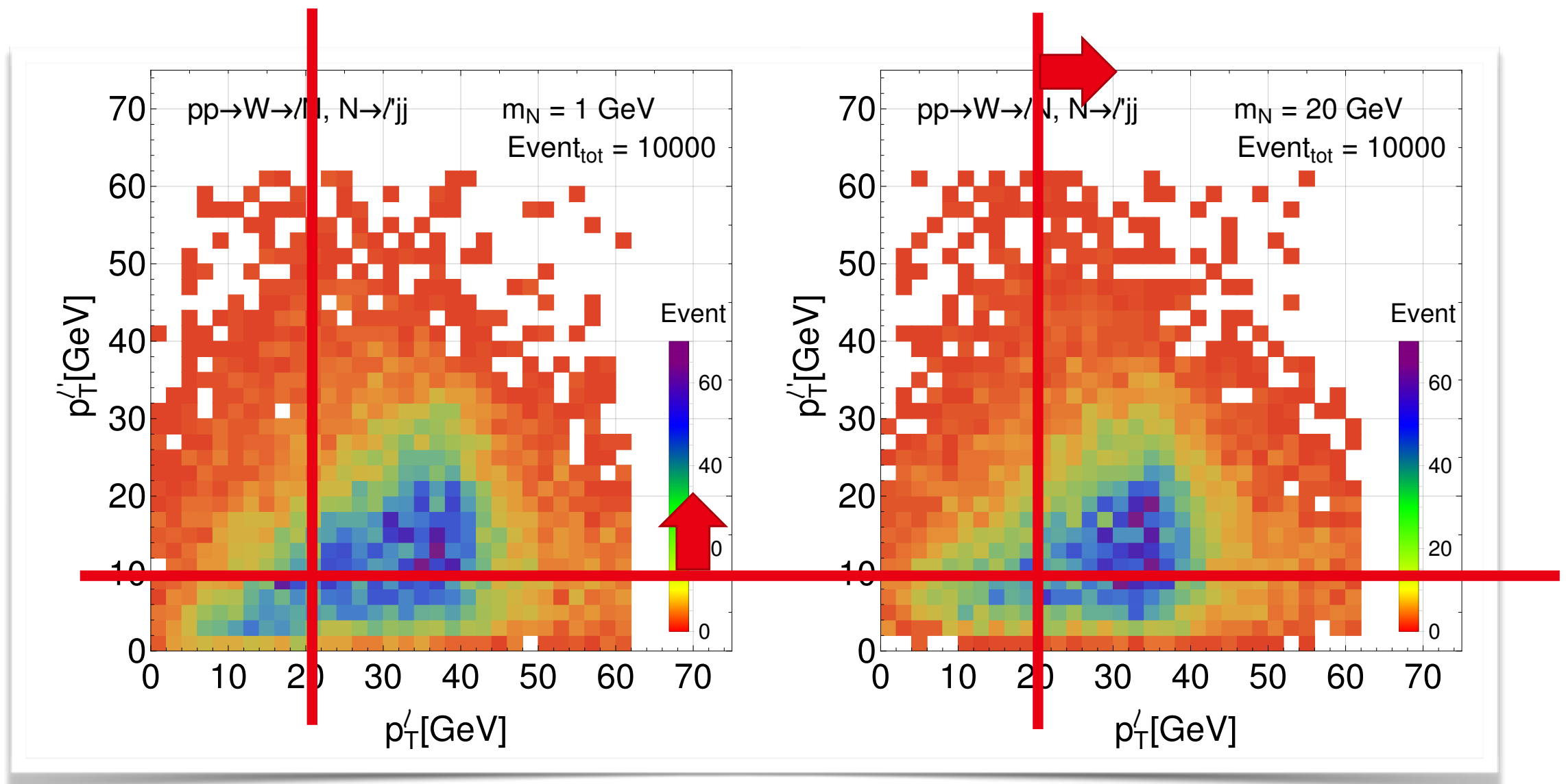
$$p_T^l = \frac{m_W^2 - m_N^2}{2m_W} \quad p_T^{l'} = \frac{1}{3} p_T^N = \frac{1}{3} \frac{m_W^2 + m_N^2}{2m_W}$$



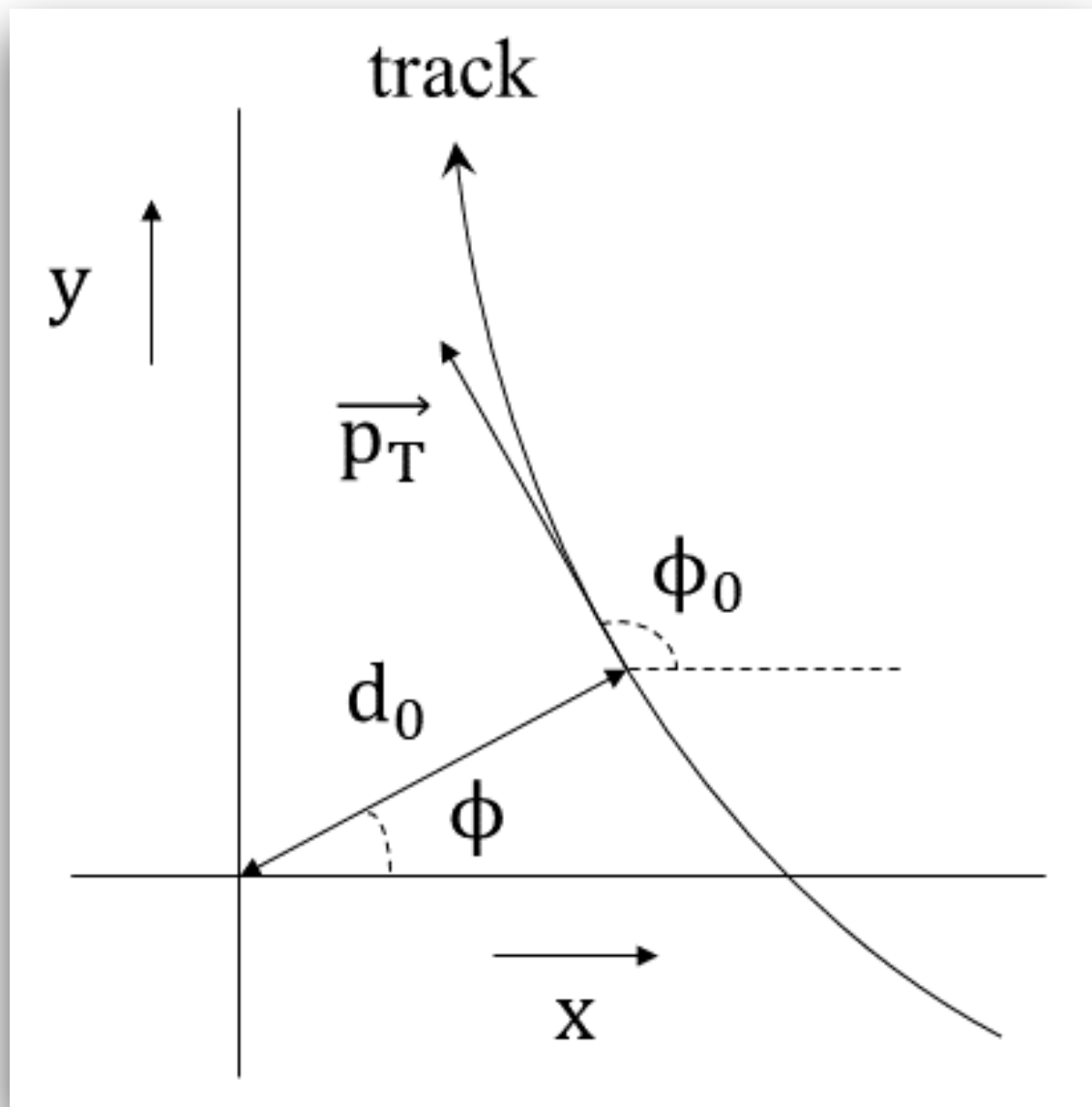
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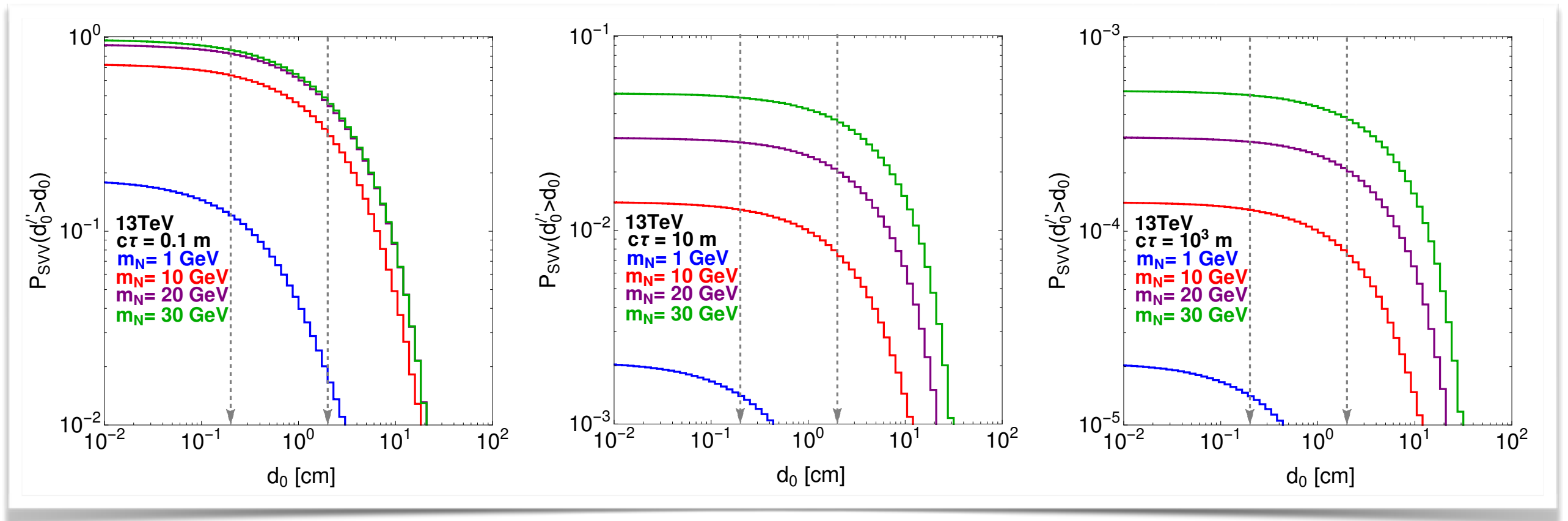


Impact Parameter



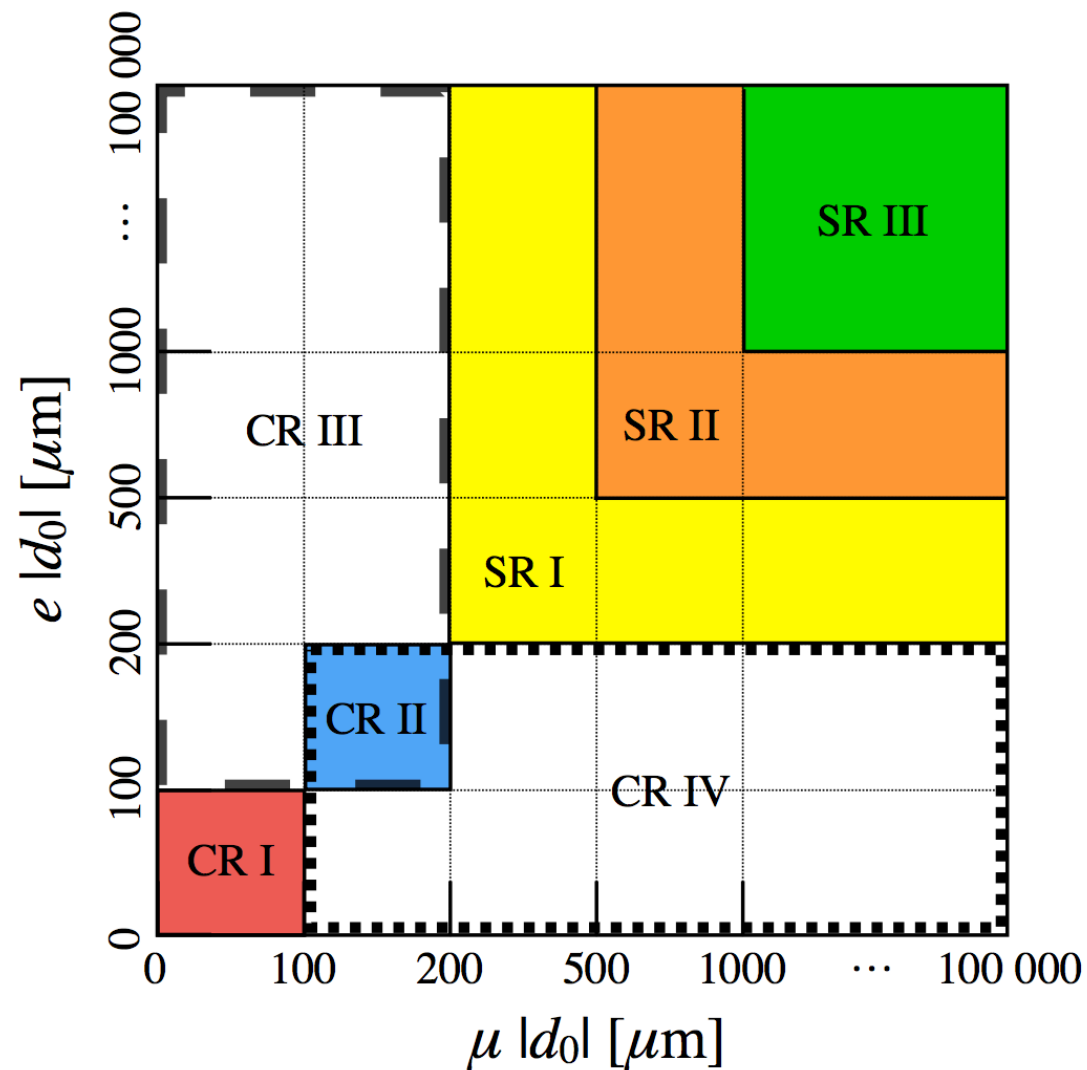
$$d_0 = \sqrt{x^2 + y^2 - \frac{(xp_x + yp_y)^2}{p_x^2 + p_y^2}}$$

The Lepton Behaviors



- Large d_0 cut, smaller signal efficiency;
- For short lifetime, $m_N > 10$ GeV sterile neutrinos behave similarly;
- For long lifetime, heavier sterile neutrinos are slower and hence higher decay probability within the tracker;
- For $m_N = 1$ GeV, decay product too collimated, suffering low d_0 ;

Valuable Knowledge from a SUSY Search



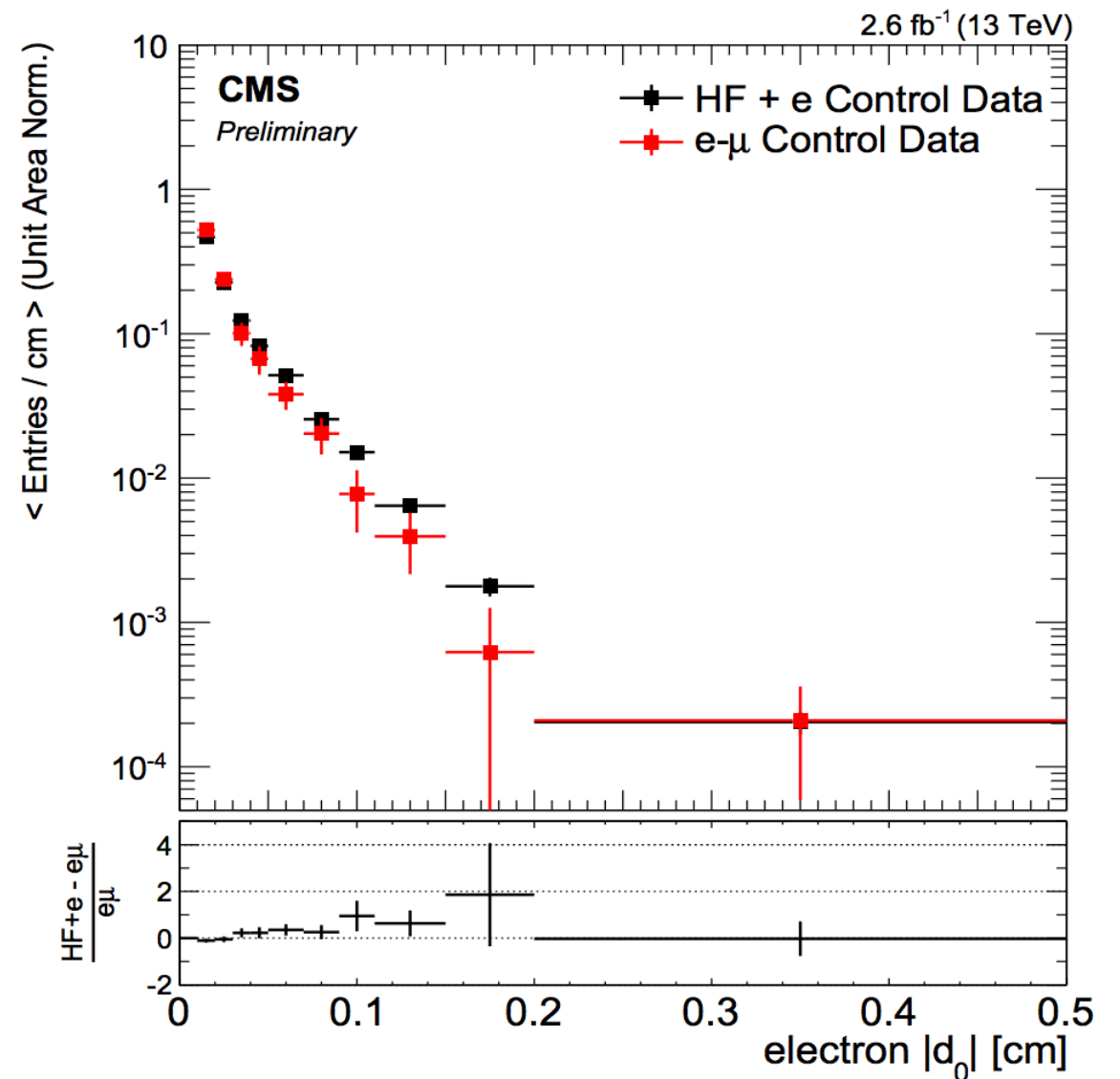
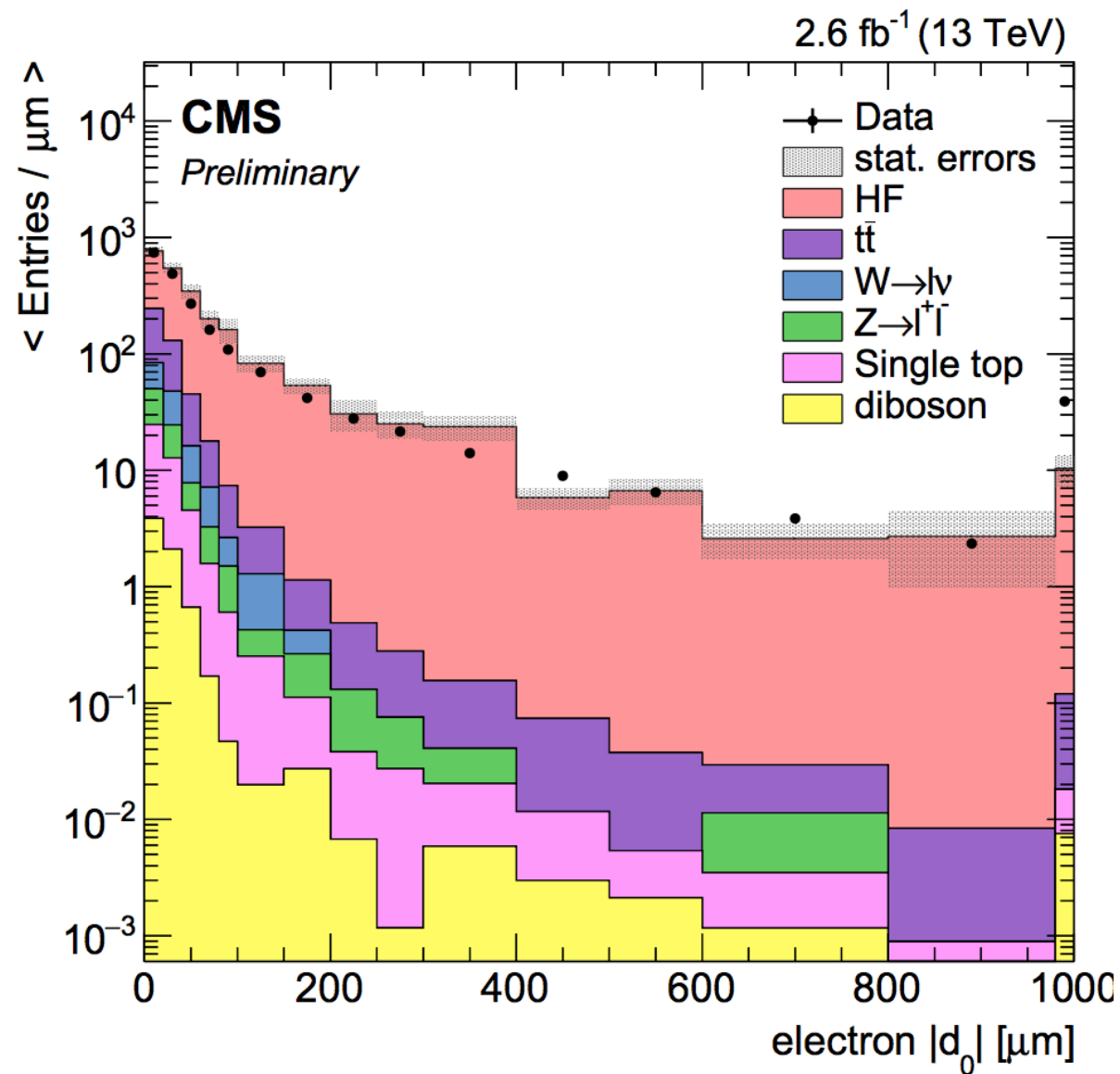
Prompt L+ displaced L

CR III: Heavy jet + displaced e

CR IV: Heavy jet + displaced muon

Displaced Electron Region (CR III)	Validation of HF Estimation	$ d_0 _e > 100 \mu\text{m}$ $ d_0 _\mu < 200 \mu\text{m}$
Displaced Muon Region (CR IV)	Validation of HF Estimation	$ d_0 _\mu > 100 \mu\text{m}$ $ d_0 _e < 200 \mu\text{m}$

Valuable Knowledge from a SUSY Search



HF+l: one tagged b jet + one displaced lepton from the other heavy flavor quark
Right plane: the agreement in the d_0 distribution between HF+l and e + μ data

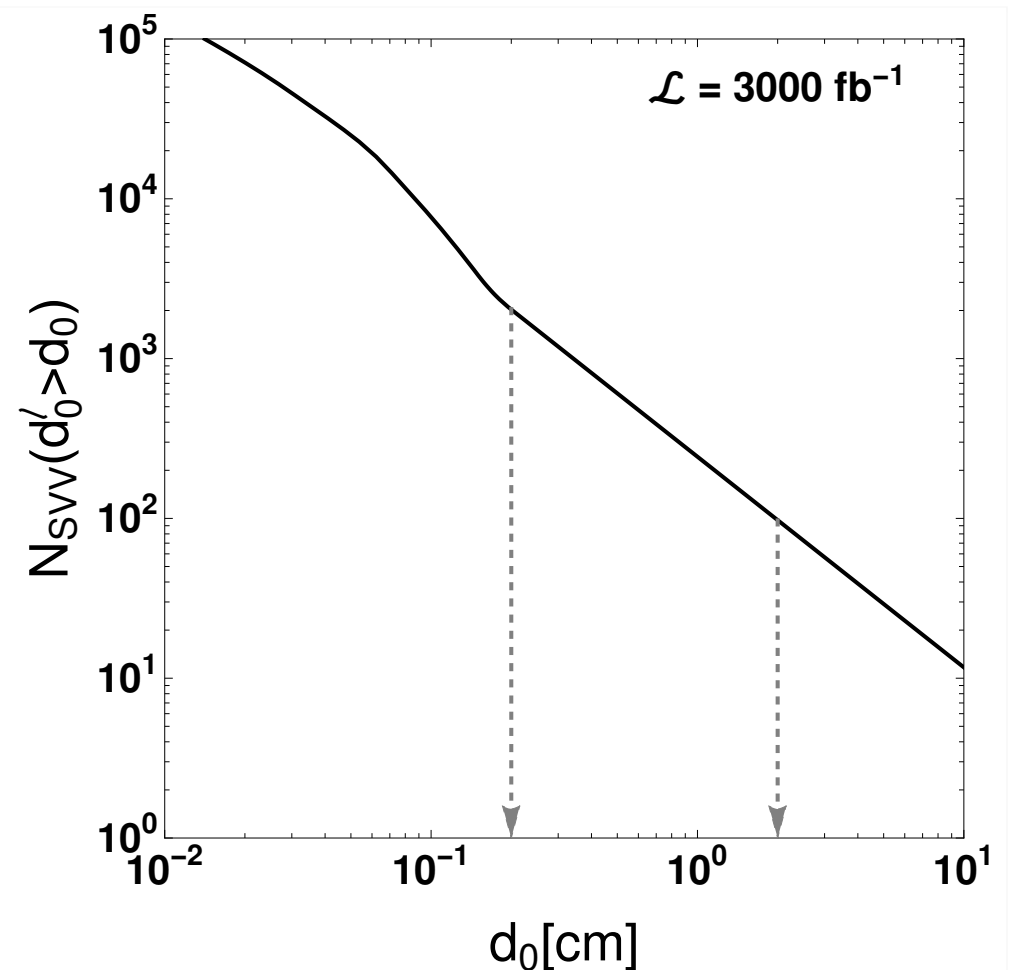
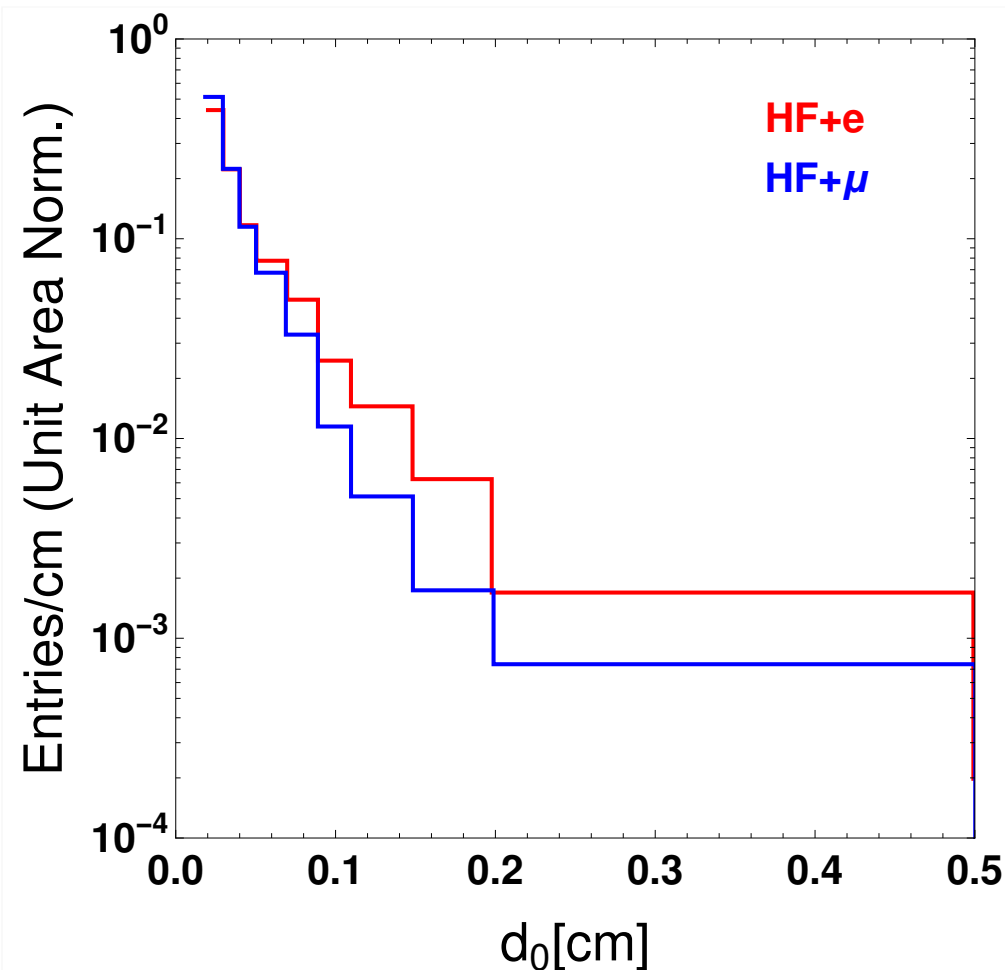
Valuable Knowledge from a SUSY Search

- Dominated by heavy flavor jets (b-jets) (data validated by using the “tag and probe”);
- The sub-leading background is from $t\bar{t}b\bar{b}$, still heavy flavor;
- The transverse impact parameter distributions are the same for isolated and non-isolated leptons.
- Different choices of the muon and electron p_T results in different background counting
- We reproduced the background behavior through simulation (simulation done via MG5NLO+Pythia8, signal sample jet-matched).

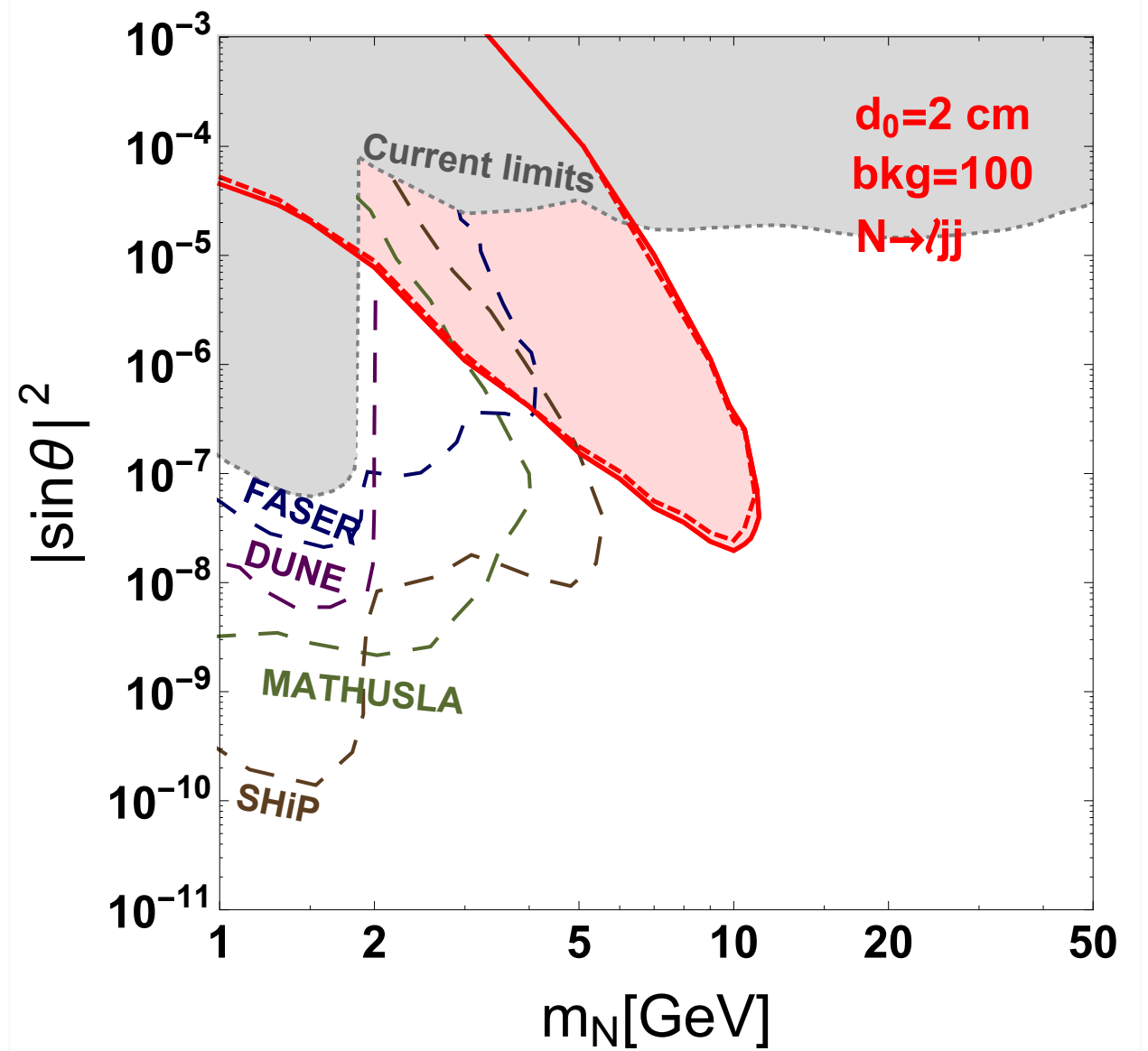
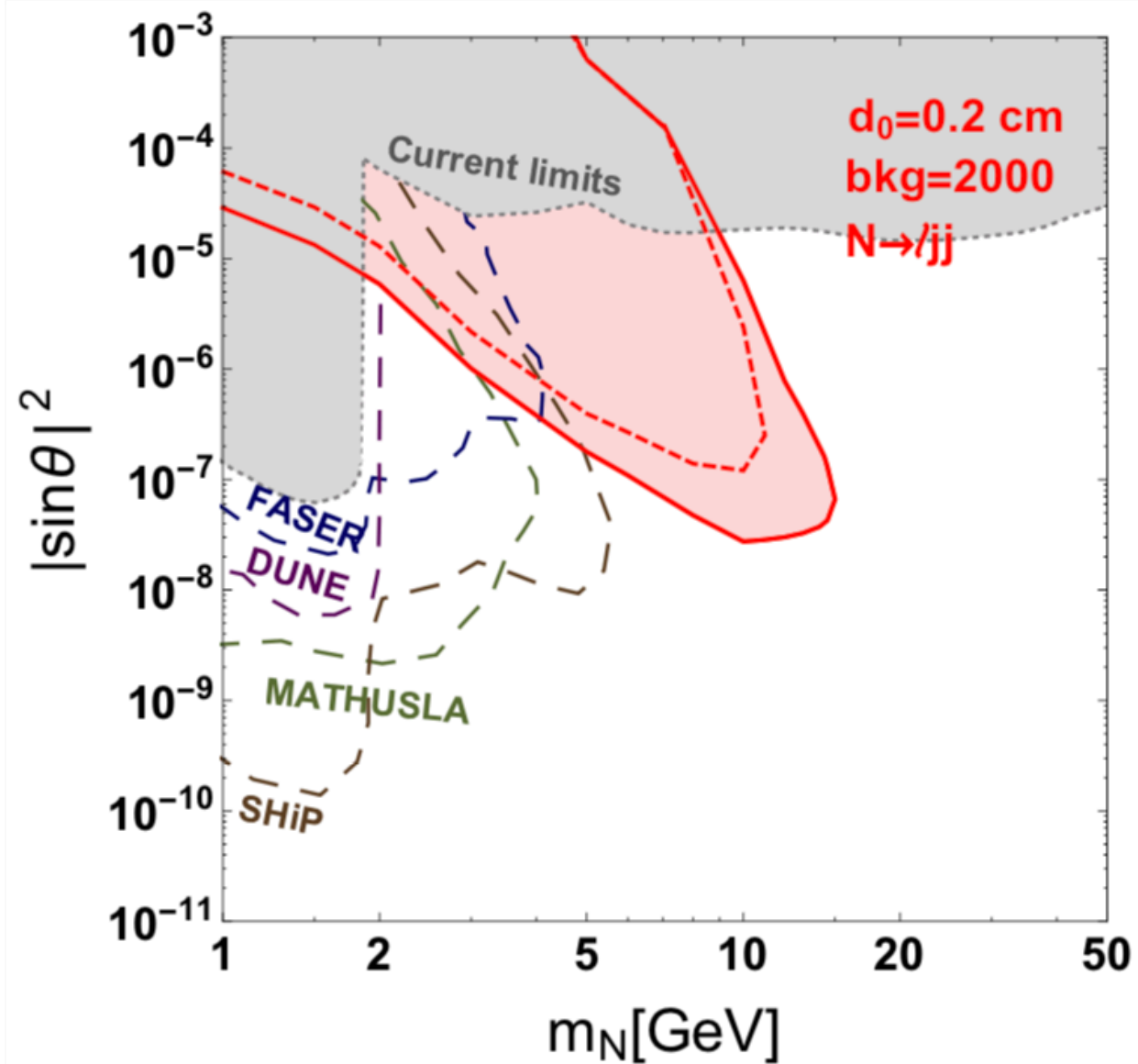
Background Estimation

Efficiency	σ^{ncut} (pb)	$N_b^{30} = 0$	$N_j^{20} < 2$	$N_j^{50} = 0$	$H_T^{\text{vis}} < 100$ GeV	$p_T^{\ell_1} > 19\text{GeV}$	$p_T^{\ell_2} > 10.5\text{GeV}$	ϵ_{opt}
$t\bar{t} \rightarrow b\bar{b} + \ell + X$	136	0.25	0.08	0.62	0.43	0.055	0.42	1.2×10^{-4}
$W + b\bar{b}, W \rightarrow \ell\nu$	3.8	0.40	0.60	0.76	0.40	0.27	0.29	5.7×10^{-3}

$$N_{\text{bkg}} = \frac{\sigma_{\text{HF}+e}^{\text{CMS}} + \sigma_{\text{HF}+\mu}^{\text{CMS}}}{\sigma_{b\bar{b}(e)}^{\text{icut}} + \sigma_{b\bar{b}(\mu)}^{\text{icut}}} \left(\sigma_{W+b\bar{b}, W \rightarrow \ell\nu}^{\text{ncut}} \times \epsilon_{\text{opt}}^{W+b\bar{b}} + \sigma_{t\bar{t} \rightarrow b\bar{b} + \ell + X}^{\text{ncut}} \times \epsilon_{\text{opt}}^{t\bar{t}} \right) \times \mathcal{L}_{\text{HL-LHC}}$$



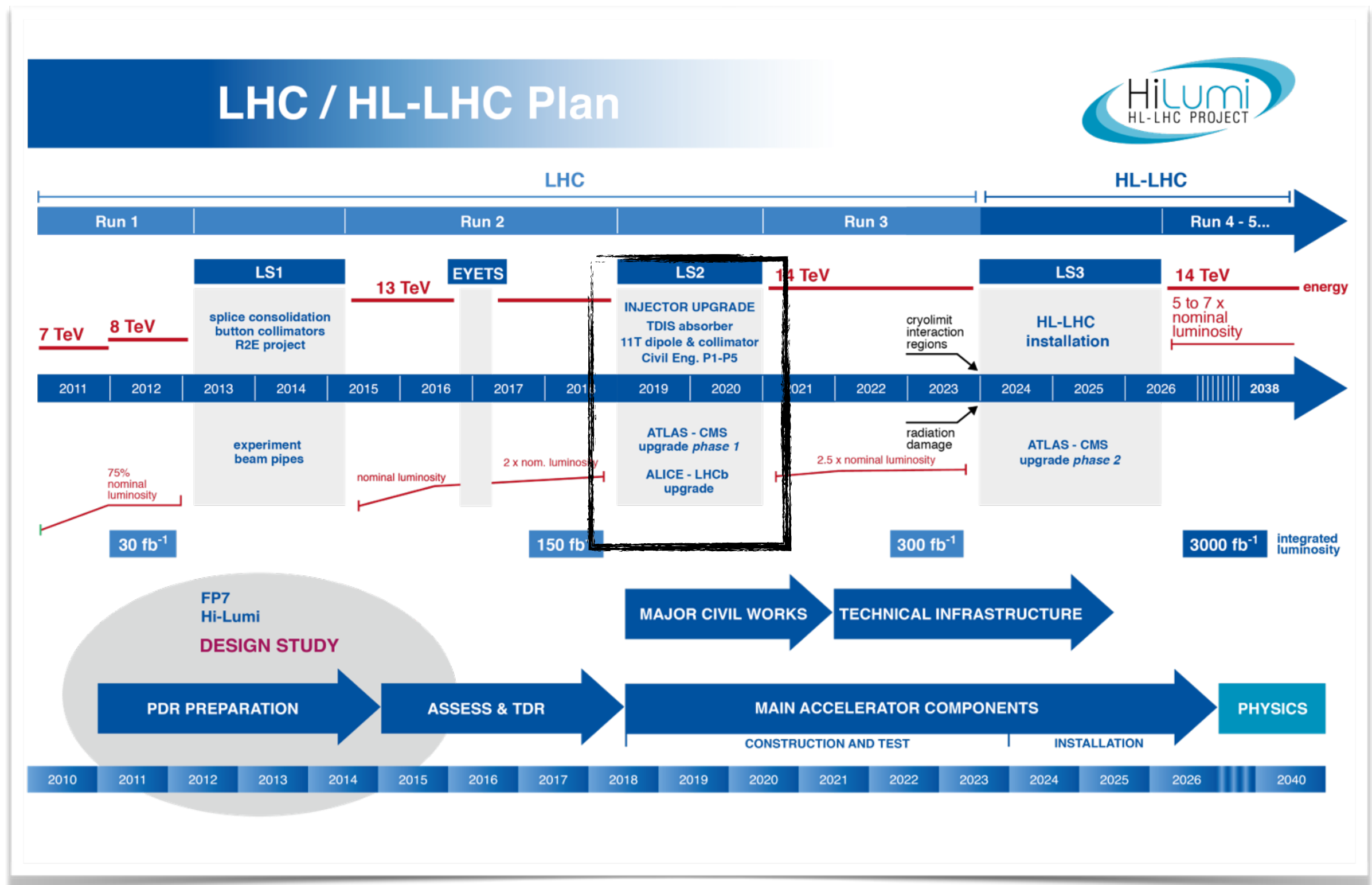
Results



Outline

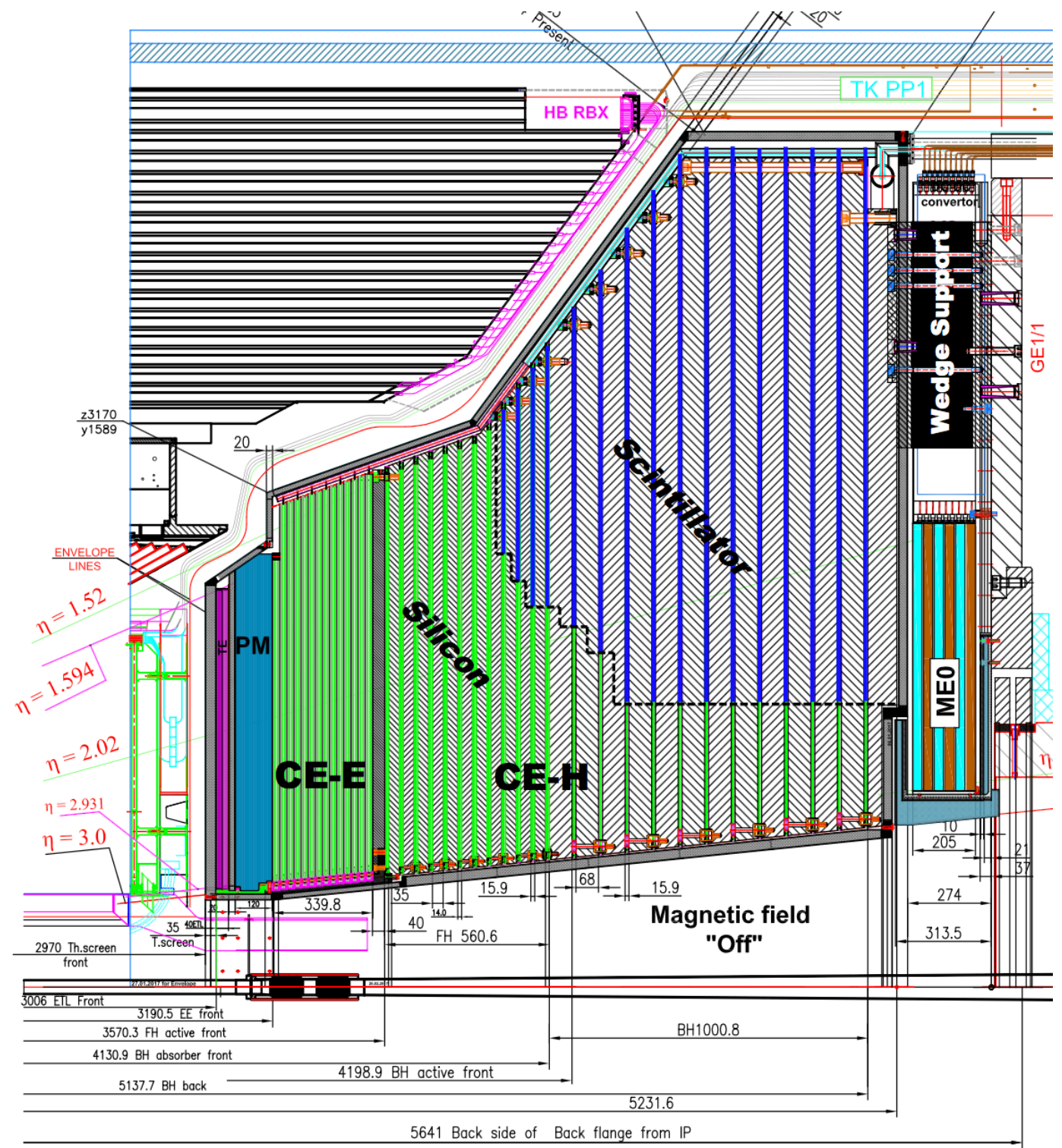
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LHC Timeline



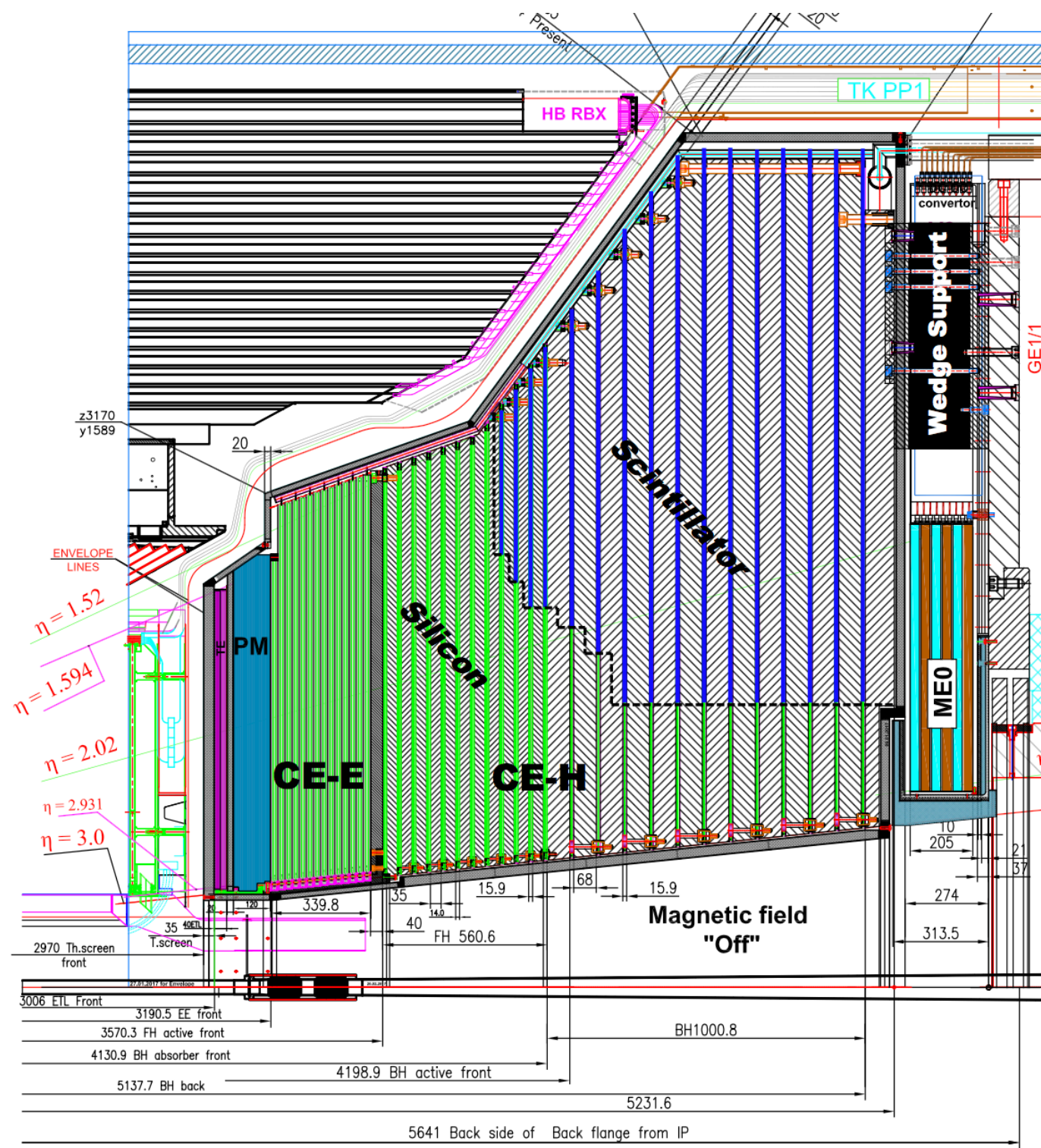
CMS High Granularity Calorimeter

- 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



LLP motivation @ HGICAL

- Own triggers
- Tracker with silicon cell 0.5~1 cm² for EM
- Angular resolution of 5×10^{-3} rad stand-alone from high granularity (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 HGICAL sensitivity for LLP?

LLP Model

- Higgs portal LLP: a very small mixing

$$\mathcal{L} \supset \lambda X^2 H^\dagger H$$

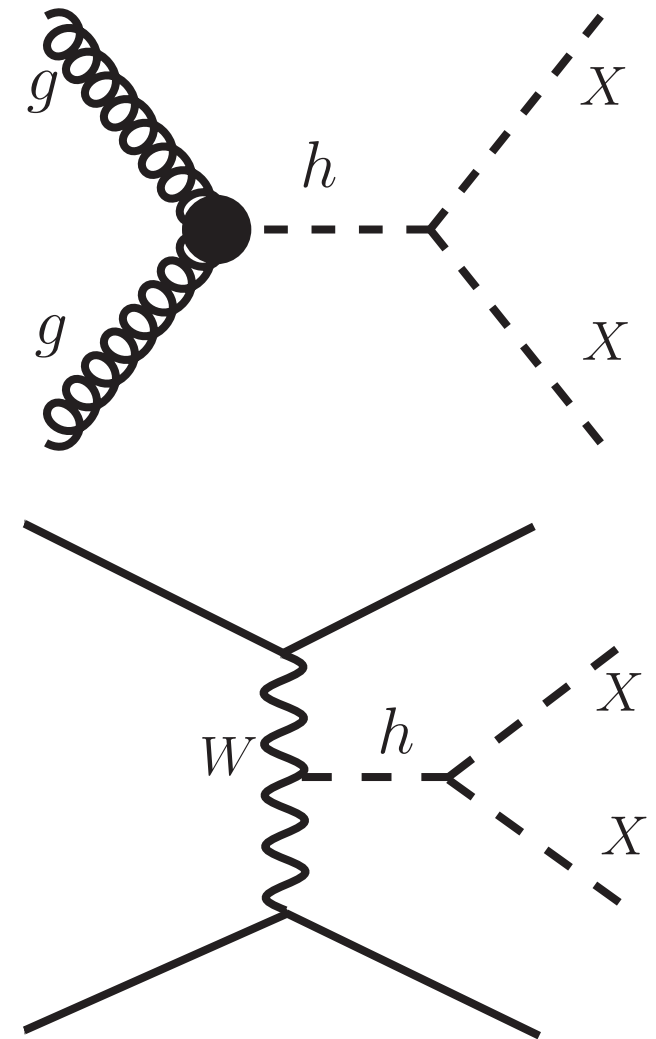
- LLP production from Higgs decay

- Gluon fusion
- Vector boson fusion

- LLP decay

$$X \rightarrow \bar{b}b$$

- Trigger: displaced track trigger with/without large H_T requirement, and traditional VBF trigger



The Search Strategy

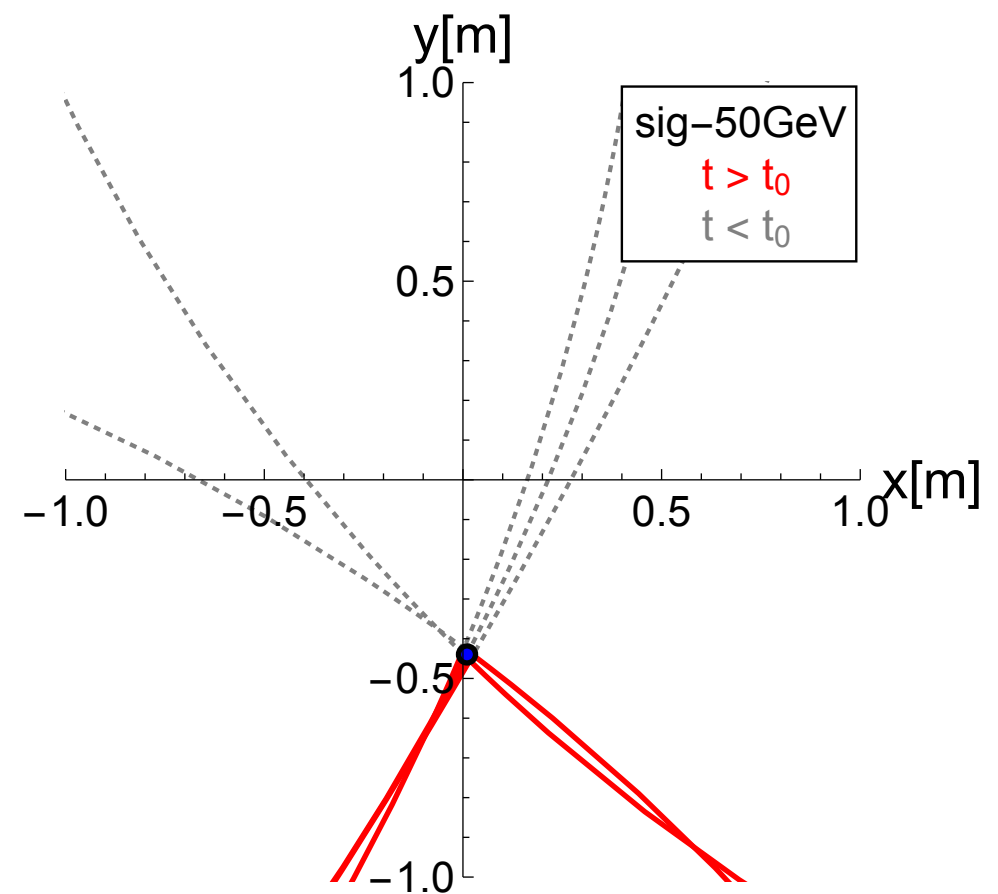
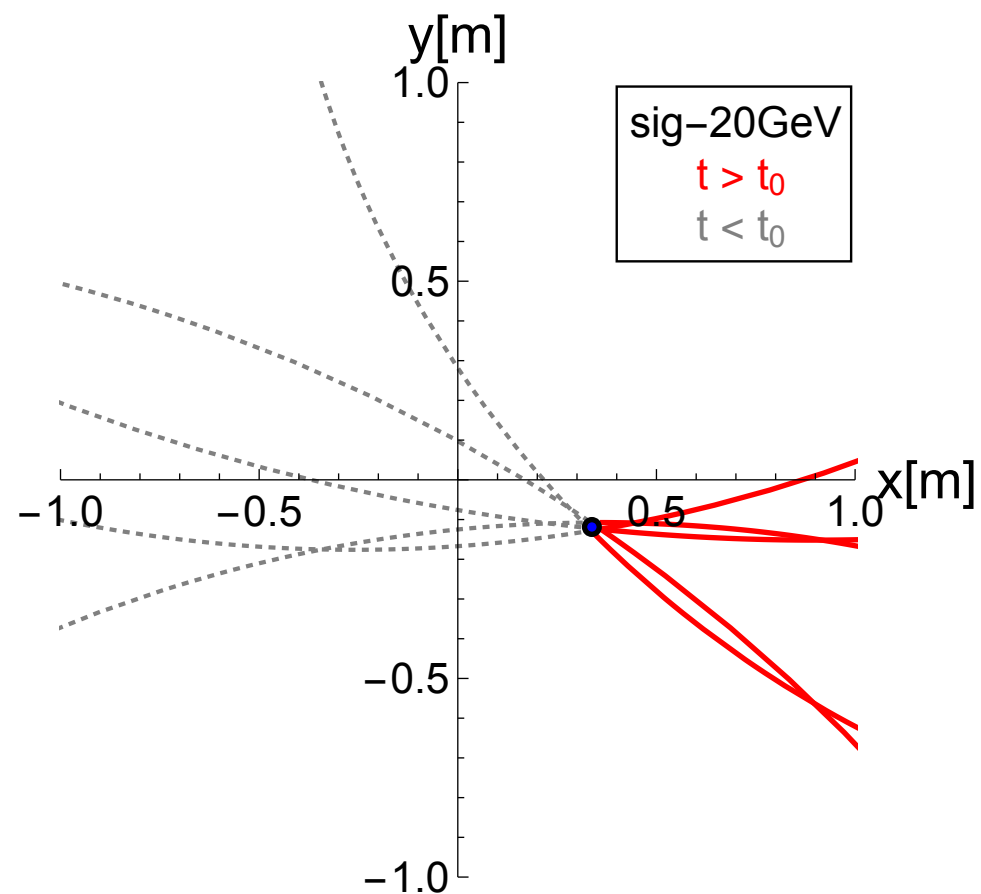
- Choose the leading 5 tracks (Pythia, p_T , hitting HGCAL) and calculate the 4D trajectories (including angular resolution effect)
- Perform a 2D track bundle vertex finder by minimizing the quantity

$$\Delta D \equiv \sqrt{\sum_{i=1}^5 \left(\sqrt{(x - x_i^{\text{cen}})^2 + (y - y_i^{\text{cen}})^2} - R_i \right)^2}$$

- R_i is the curvature of the i th track, $\{x^{\text{cen}}, y^{\text{cen}}\}$ are the center of the track
- We obtain the fitted DV $\{x, y\}$, and define $r_{\text{DV}} = \sqrt{x^2 + y^2}$
- The goodness of fit ΔD_{min}
- With the angular velocity of the track, we can determine the referencing point to DV for each track $\{x_i, y_i, z_i, t_i\}$
- A time delay quantity can be defined $\Delta t_i = t_i - \sqrt{x_i^2 + y_i^2 + z_i^2}$

The signature of the signal

- Multiple tracks with large impact parameters from the same displaced origin



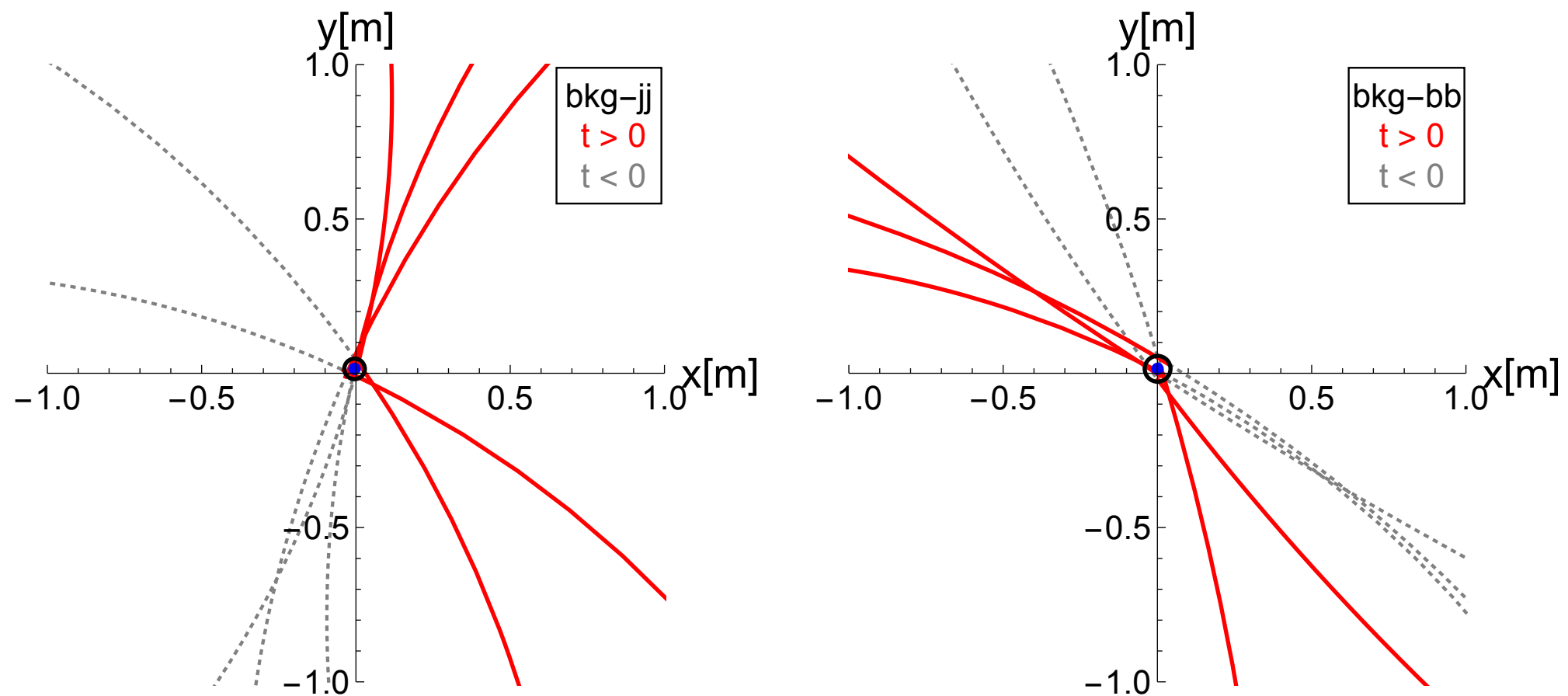
B=3.8T

X decay $|Z| < 1.5$ m

Tracks arrive at $|Z| = 3.2$ m

The SM Backgrounds

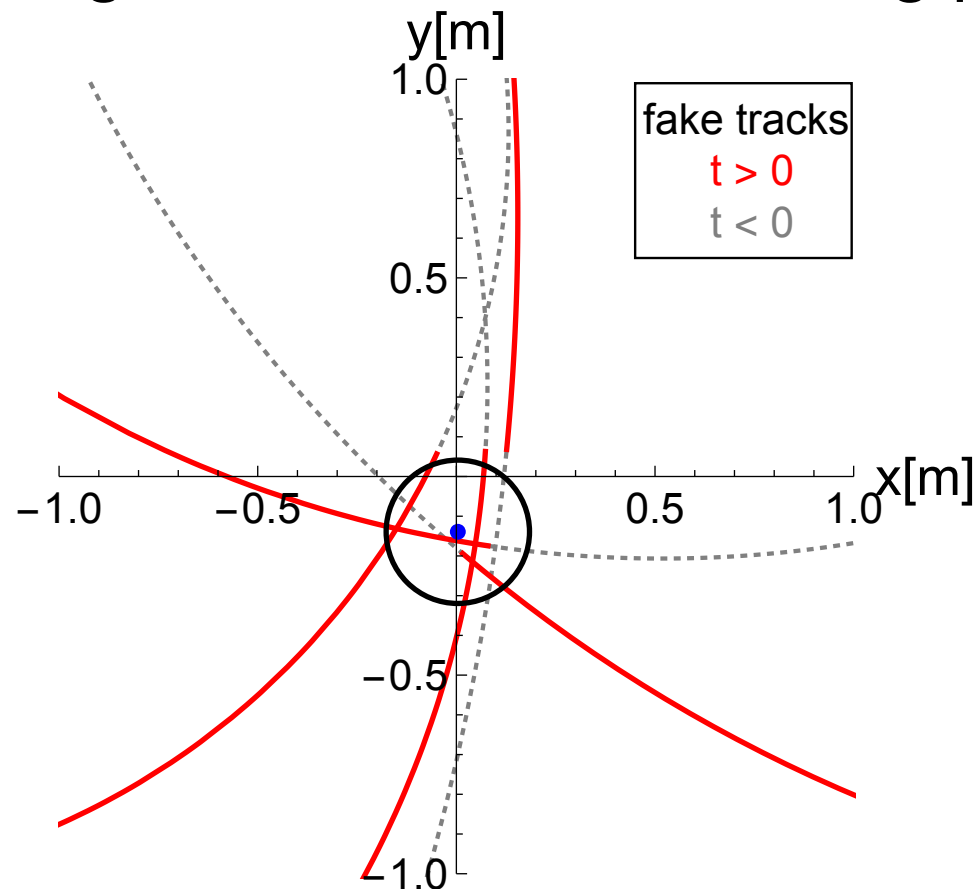
- QCD backgrounds
- Most of them are prompt



- Large impact parameter dominantly from K_S ($c\tau \sim 2.7$ cm)
 - B ($c\tau \sim 0.045$ m) and D meson ($c\tau \sim 0.03$ m) too small

The SM Backgrounds

- Fake track backgrounds
 - wrong connection of the hitting points in the tracker system



Flat distributions in

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

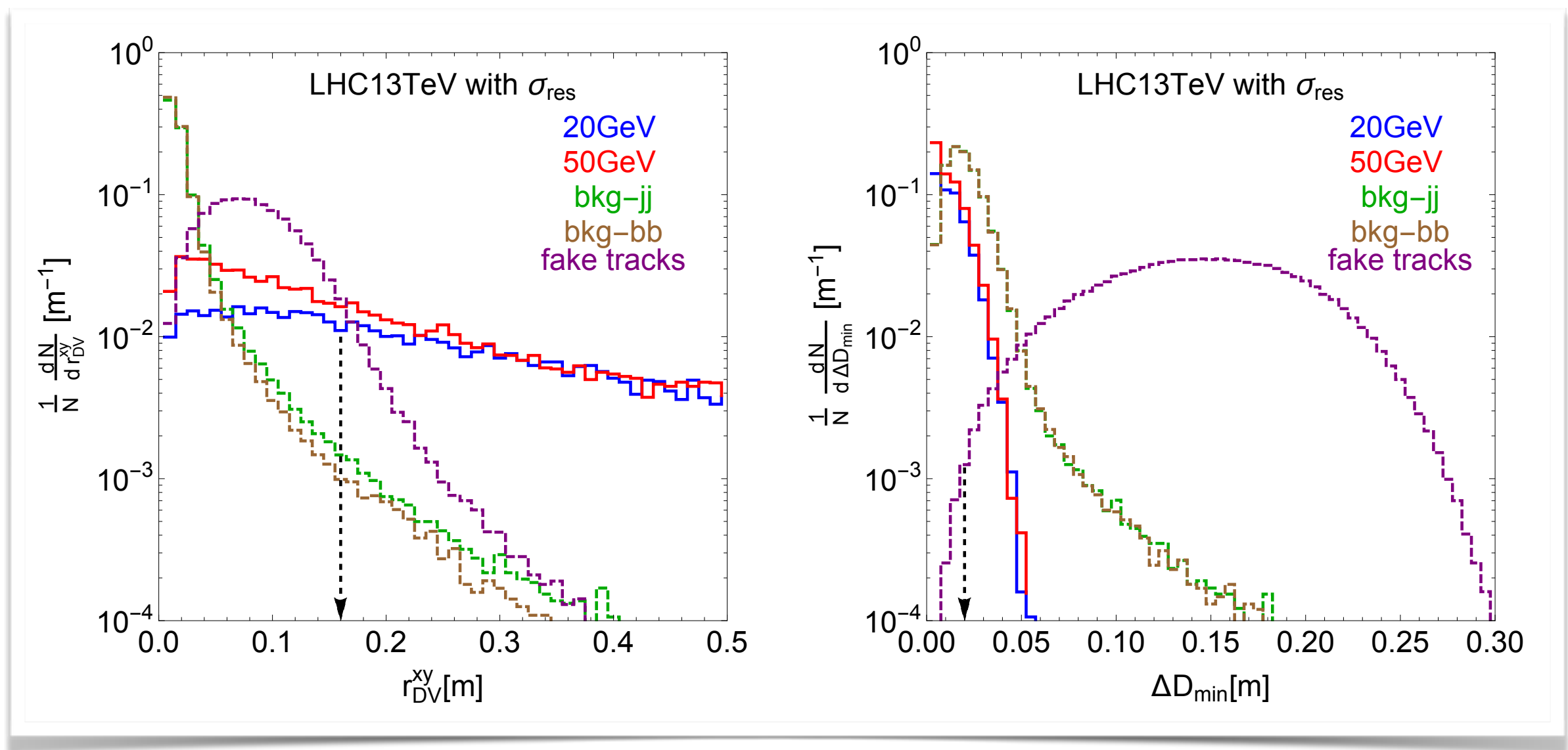
Generated following
Y. Gershtein and S. Knapen
1907.00007

- Very distinct features comparing with QCD backgrounds
 - Easy to have large impact parameter
 - Poorly fit to the same origin

Kinematic Features

- Check the kinematic distribution for

$$r_{DV}, \Delta D_{\min}, \bar{t}, \bar{z}, \overline{\Delta t}, SD_t, SD_z, SD_{\Delta t}.$$

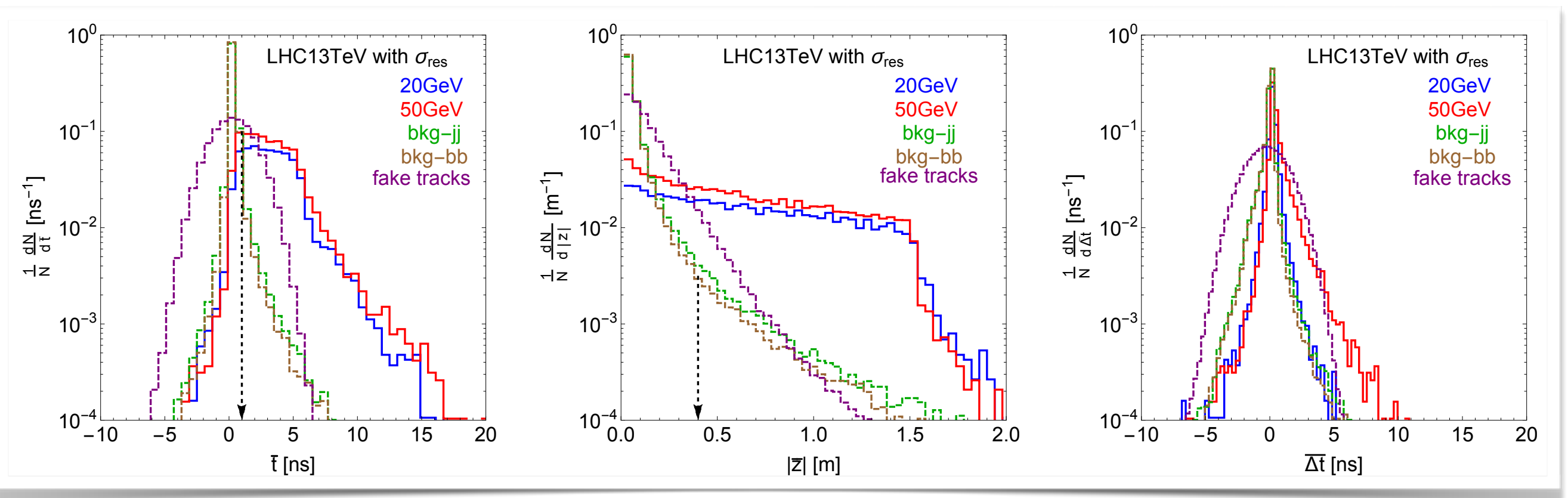


Kinematic Features

- Check the kinematic distribution for

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- Average of the tracks quantities (DV info from track based info)

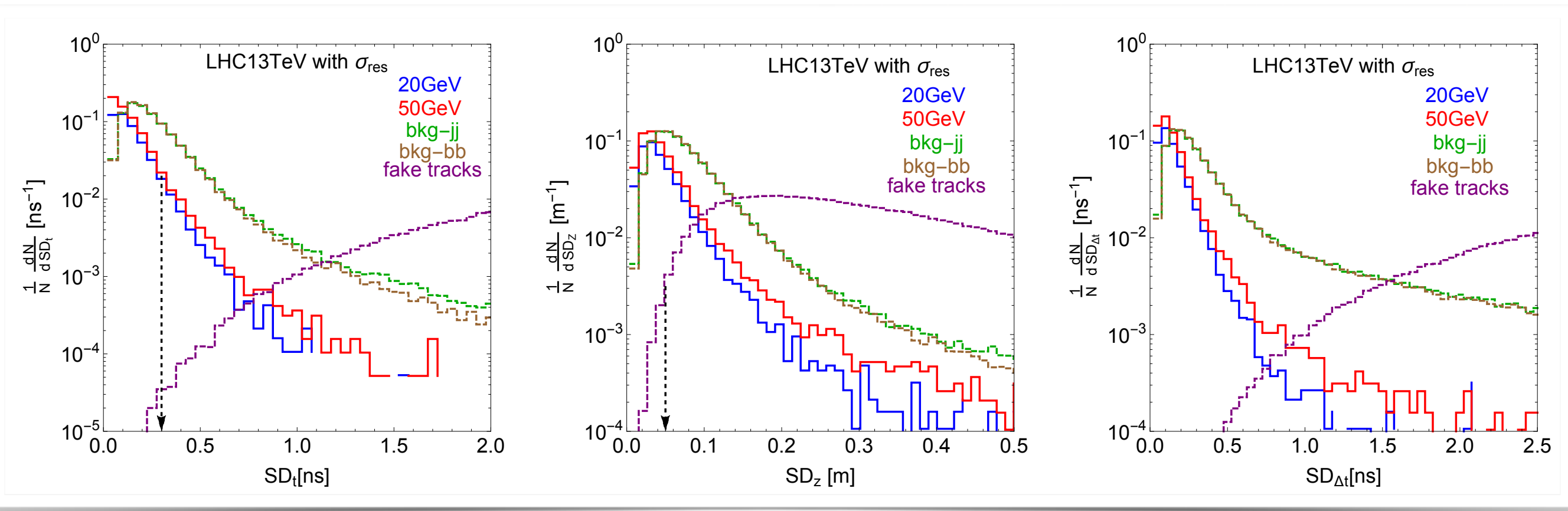


Kinematic Features

- Check the kinematic distribution for

$$r_{DV}, \Delta D_{\min}, \bar{t}, \bar{z}, \overline{\Delta t}, SD_t, SD_z, SD_{\Delta t}.$$

- Standard Deviation of the tracks quantities



The Cut Flow Table

- QCD bkg: $p_T > 20 \text{ GeV}$ with jet matching
- Fake track bkg: five displaced tracks and $H_T > 100 \text{ GeV}$
L1 trigger rate of 10 kHz (same as Yuri and Simon), HL-LHC 10^8 sec

type of bkg	N_{ini}	5 tracks	$r_{\text{DV}}^{\text{xy}} > 0.16 \text{ m}$	$\Delta D_{\text{min}} < 0.02 \text{ m}$	$\bar{t} > 1 \text{ ns}$	$\text{SD}_t < 0.3 \text{ ns}$
jj dijet	5.1×10^{14}	9.4×10^{-1}	$1.0 \times 10^{-2} (*)$	8.7×10^{-1}	$3.0 \times 10^{-2} (*)$	7.3×10^{-1}
$b\bar{b}$ dijet	1.1×10^{13}	1.0	$7.7 \times 10^{-3} (*)$	9.2×10^{-1}	$2.4 \times 10^{-2} (*)$	7.4×10^{-1}
fake track	1×10^{12}	5.6×10^{-1}	4.6×10^{-2}	2.2×10^{-3}	2.8×10^{-2}	6.2×10^{-5}
ggF $m_s = 20 \text{ GeV}$	$1.3 \times 10^8 \text{ BR}$	$0.36 \times 3.1 \times 10^{-1}$	5.3×10^{-1}	8.6×10^{-1}	9.9×10^{-1}	9.6×10^{-1}
ggF $m_s = 50 \text{ GeV}$	$1.3 \times 10^8 \text{ BR}$	$0.8 \times 3.5 \times 10^{-1}$	3.5×10^{-1}	8.8×10^{-1}	9.8×10^{-1}	9.5×10^{-1}

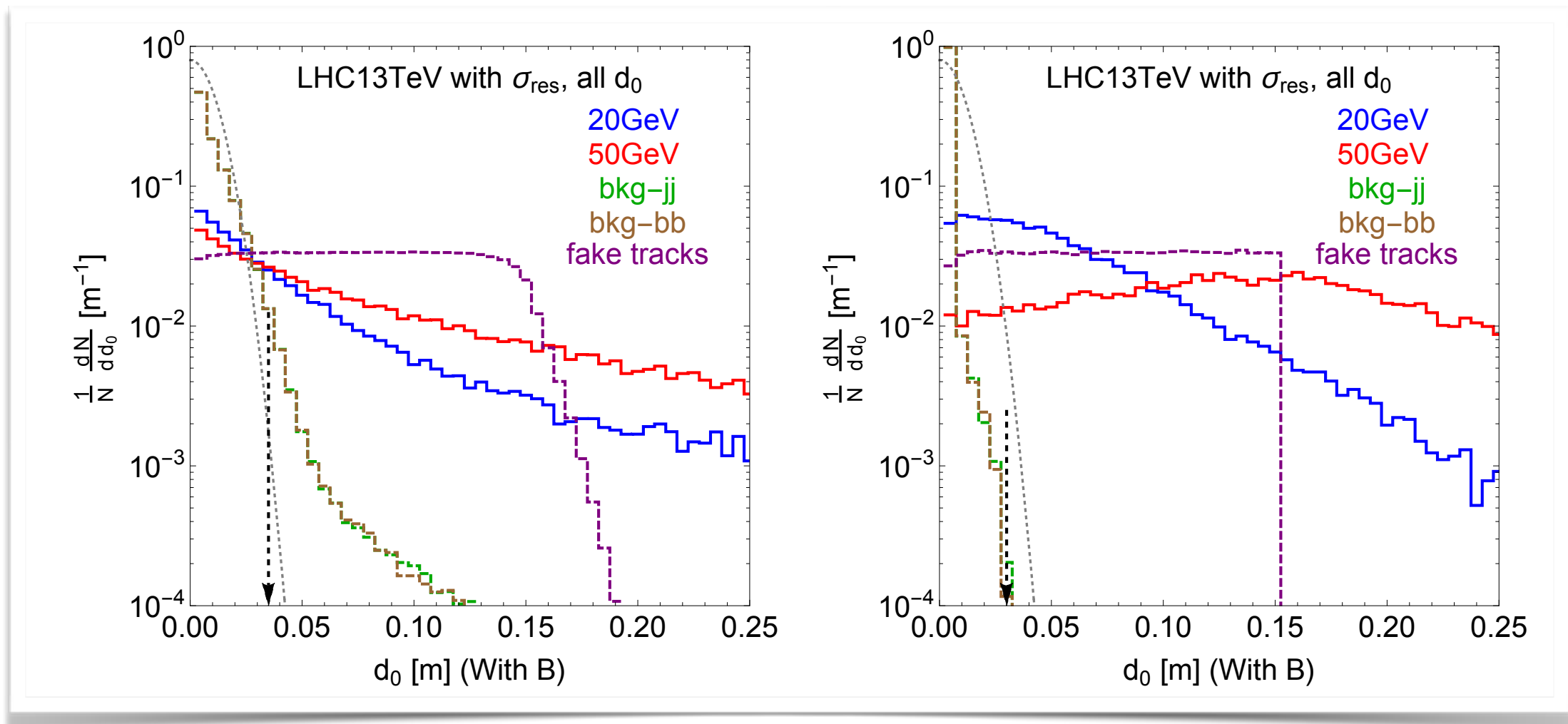
Pre-cuts for DV fitting

type of bkg	N_{ini}	5 tracks	$r_{\text{DV}}^{\text{xy}} > 0.16 \text{ m}$	$\Delta D_{\text{min}} < 0.02 \text{ m}$	$\bar{t} > 1 \text{ ns}$	$\text{SD}_t < 0.3 \text{ ns}$	$\bar{z} > 0.4 \text{ m}$	$\text{SD}_z < 0.05 \text{ m}$	ϵ_{vtc}	$(d_0^T > 0.03 \text{ m})^5$	N_{fin}
jj dijet	5.1×10^{14}	9.4×10^{-1}	$1.0 \times 10^{-2} (*)$	8.7×10^{-1}	$3.0 \times 10^{-2} (*)$	7.3×10^{-1}	$3.4 \times 10^{-2} (*)$	4.9×10^{-1}	3.0×10^{-1}	$(7.2 \times 10^{-4})^5$	2.8×10^{-2}
$b\bar{b}$ dijet	1.1×10^{13}	1.0	$7.7 \times 10^{-3} (*)$	9.2×10^{-1}	$2.4 \times 10^{-2} (*)$	7.4×10^{-1}	$2.7 \times 10^{-2} (*)$	4.9×10^{-1}	2.9×10^{-1}	$(6.5 \times 10^{-4})^5$	3.7×10^{-4}
fake track	1×10^{12}	5.6×10^{-1}	4.6×10^{-2}	2.2×10^{-3}	2.8×10^{-2}	6.2×10^{-5}	5.9×10^{-2}	5.4×10^{-3}	5.8×10^{-13}	3.4×10^{-1}	1.1×10^{-1}
ggF $m_s = 20 \text{ GeV}$	$1.3 \times 10^8 \text{BR}$	$0.36 \times 3.1 \times 10^{-1}$	5.3×10^{-1}	8.6×10^{-1}	9.9×10^{-1}	9.6×10^{-1}	9.8×10^{-1}	8.6×10^{-1}	1.2×10^{-1}	2.9×10^{-1}	$4.3 \times 10^6 \times \text{BR}$
ggF $m_s = 50 \text{ GeV}$	$1.3 \times 10^8 \text{BR}$	$0.8 \times 3.5 \times 10^{-1}$	3.5×10^{-1}	8.8×10^{-1}	9.8×10^{-1}	9.5×10^{-1}	8.9×10^{-1}	8.6×10^{-1}	9.0×10^{-2}	8.0×10^{-1}	$9.5 \times 10^6 \times \text{BR}$

- Fake track bkg suppressed because its random origin

Kinematic Features

- Transverse impact parameters



- QCD bkg has a good Gaussian shape because pre-cuts excludes K_S meson decays
- Gaussian width comes from angular resolution
 $3 \text{ m} \times 5 \times 10^{-3} \text{ rad} = 0.015 \text{ m}$

Independence Check is Necessary

- QCD bkg: impact parameter cuts are independent?
- Should be, because they are from angular resolution smearing

type of bkg	N_{ini}	5 tracks	$r_{\text{DV}}^{\text{xy}} > 0.16 \text{ m}$	$\Delta D_{\text{min}} < 0.02 \text{ m}$	$\bar{t} > 1 \text{ ns}$	$\text{SD}_t < 0.3 \text{ ns}$	$\bar{z} > 0.4 \text{ m}$	$\text{SD}_z < 0.05 \text{ m}$	ϵ_{vtc}	$(d_0^T > 0.03 \text{ m})^5$	N_{fin}
jj dijet	5.1×10^{14}	9.4×10^{-1}	$1.0 \times 10^{-2} (*)$	8.7×10^{-1}	$3.0 \times 10^{-2} (*)$	7.3×10^{-1}	$3.4 \times 10^{-2} (*)$	4.9×10^{-1}	3.0×10^{-1}	$(7.2 \times 10^{-4})^5$	2.8×10^{-2}
$b\bar{b}$ dijet	1.1×10^{13}	1.0	$7.7 \times 10^{-3} (*)$	9.2×10^{-1}	$2.4 \times 10^{-2} (*)$	7.4×10^{-1}	$2.7 \times 10^{-2} (*)$	4.9×10^{-1}	2.9×10^{-1}	$(6.5 \times 10^{-4})^5$	3.7×10^{-4}
fake track	1×10^{12}	5.6×10^{-1}	4.6×10^{-2}	2.2×10^{-3}	2.8×10^{-2}	6.2×10^{-5}	5.9×10^{-2}	5.4×10^{-3}	5.8×10^{-13}	3.4×10^{-1}	1.1×10^{-1}
ggF $m_s = 20 \text{ GeV}$	$1.3 \times 10^8 \text{ BR}$	$0.36 \times 3.1 \times 10^{-1}$	5.3×10^{-1}	8.6×10^{-1}	9.9×10^{-1}	9.6×10^{-1}	9.8×10^{-1}	8.6×10^{-1}	1.2×10^{-1}	2.9×10^{-1}	$4.3 \times 10^6 \times \text{BR}$
ggF $m_s = 50 \text{ GeV}$	$1.3 \times 10^8 \text{ BR}$	$0.8 \times 3.5 \times 10^{-1}$	3.5×10^{-1}	8.8×10^{-1}	9.8×10^{-1}	9.5×10^{-1}	8.9×10^{-1}	8.6×10^{-1}	9.0×10^{-2}	8.0×10^{-1}	$9.5 \times 10^6 \times \text{BR}$

Independence Check is Necessary

- QCD bkg: impact parameter cuts are independent?
- Should be, because they are from angular resolution smearing

type of bkg	N_{ini}	5 tracks	$r_{\text{DV}}^{\text{xy}} > 0.16 \text{ m}$	$\Delta D_{\text{min}} < 0.02 \text{ m}$	$\bar{t} > 1 \text{ ns}$	$\text{SD}_t < 0.3 \text{ ns}$	$\bar{z} > 0.4 \text{ m}$	$\text{SD}_z < 0.05 \text{ m}$	ϵ_{vtc}	$(d_0^T > 0.03 \text{ m})^5$	N_{fin}
jj dijet	5.1×10^{14}	9.4×10^{-1}	$1.0 \times 10^{-2} (*)$	8.7×10^{-1}	$3.0 \times 10^{-2} (*)$	7.3×10^{-1}	$3.4 \times 10^{-2} (*)$	4.9×10^{-1}	3.0×10^{-1}	$(7.2 \times 10^{-4})^5$	2.8×10^{-2}
$b\bar{b}$ dijet	1.1×10^{13}	1.0	$7.7 \times 10^{-3} (*)$	9.2×10^{-1}	$2.4 \times 10^{-2} (*)$	7.4×10^{-1}	$2.7 \times 10^{-2} (*)$	4.9×10^{-1}	2.9×10^{-1}	$(6.5 \times 10^{-4})^5$	3.7×10^{-4}
fake track	1×10^{12}	5.6×10^{-1}	4.6×10^{-2}	2.2×10^{-3}	2.8×10^{-2}	6.2×10^{-5}	5.9×10^{-2}	5.4×10^{-3}	5.8×10^{-13}	3.4×10^{-1}	1.1×10^{-1}
ggF $m_s = 20 \text{ GeV}$	$1.3 \times 10^8 \text{ BR}$	$0.36 \times 3.1 \times 10^{-1}$	5.3×10^{-1}	8.6×10^{-1}	9.9×10^{-1}	9.6×10^{-1}	9.8×10^{-1}	8.6×10^{-1}	1.2×10^{-1}	2.9×10^{-1}	$4.3 \times 10^6 \times \text{BR}$
ggF $m_s = 50 \text{ GeV}$	$1.3 \times 10^8 \text{ BR}$	$0.8 \times 3.5 \times 10^{-1}$	3.5×10^{-1}	8.8×10^{-1}	9.8×10^{-1}	9.5×10^{-1}	8.9×10^{-1}	8.6×10^{-1}	9.0×10^{-2}	8.0×10^{-1}	$9.5 \times 10^6 \times \text{BR}$

- Independence check

$$\text{IDd}_n \equiv \frac{\epsilon^n (1 \text{ track } d_0^T > 0.03 \text{ m})}{\epsilon (n \text{ tracks } d_0^T > 0.03 \text{ m})}$$

- ~ 1 independent, > 1 conservative
- In summary, ≥ 1 is conservative for bkg estimation

Independence Check

- QCD bkg: impact parameter for tracks are independent
- angular resolution smearing is independent for each track

jj dijets	$d_0^T > 0.01$ m	$d_0^T > 0.015$ m	$d_0^T > 0.02$ m	$d_0^T > 0.025$ m	$d_0^T > 0.03$ m
IDd ₁	0.96	0.95	1.0	1.1	1.3
IDd ₂	1.0	1.1	0.87	-	-
IDd ₃	1.2	0.95	-	-	-
IDd ₄	1.1	-	-	-	-
IDd ₅	0.9	-	-	-	-
$\bar{b}b$ dijets	$d_0^T > 0.01$ m	$d_0^T > 0.015$ m	$d_0^T > 0.02$ m	$d_0^T > 0.025$ m	$d_0^T > 0.03$ m
IDd ₁	0.96	0.95	0.98	1.12	1.8
IDd ₂	1.1	1.2	1.1	-	-
IDd ₃	1.3	0.90	-	-	-
IDd ₄	1.2	1.1	-	-	-
IDd ₅	1.1	-	-	-	-

Independence Check

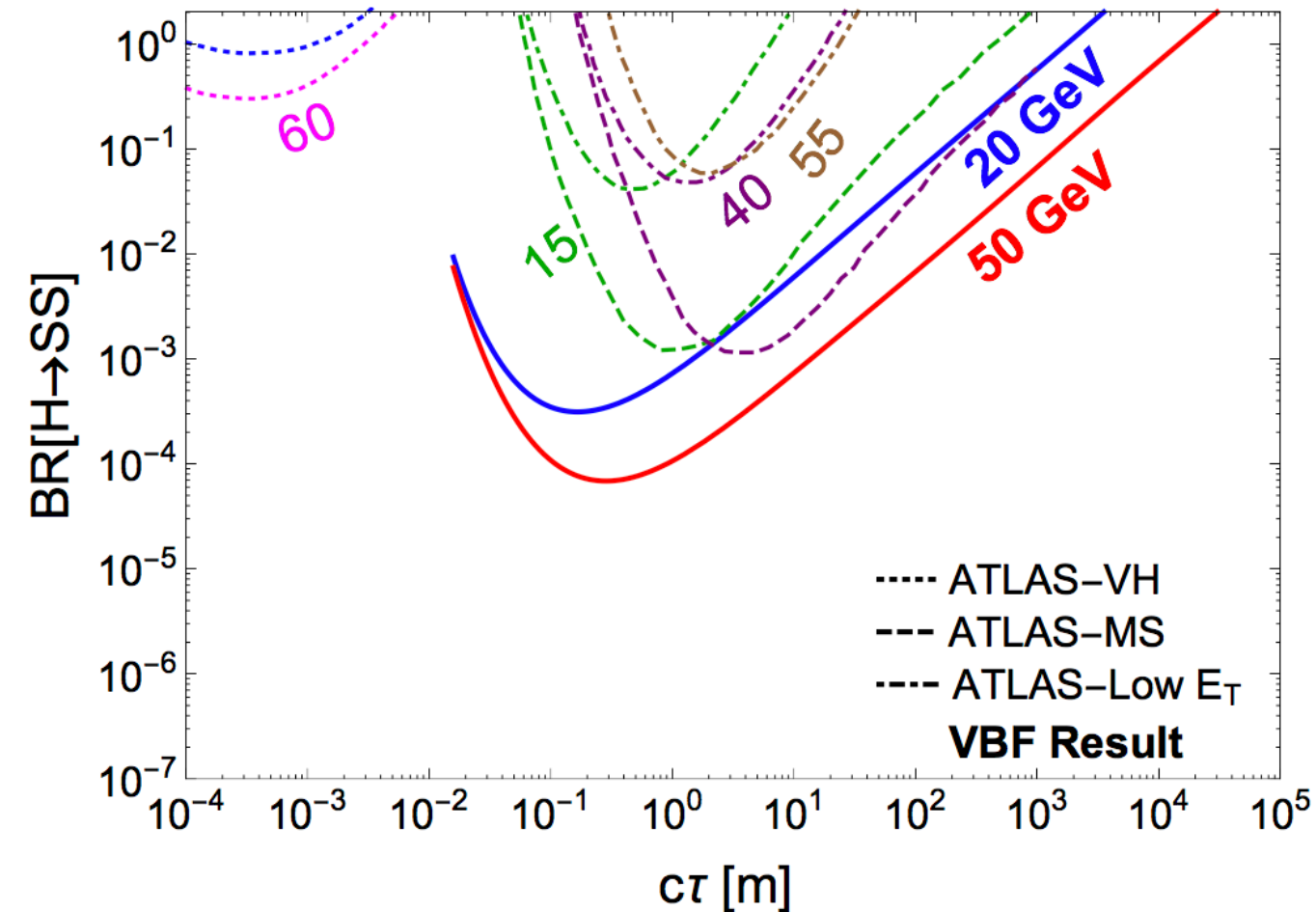
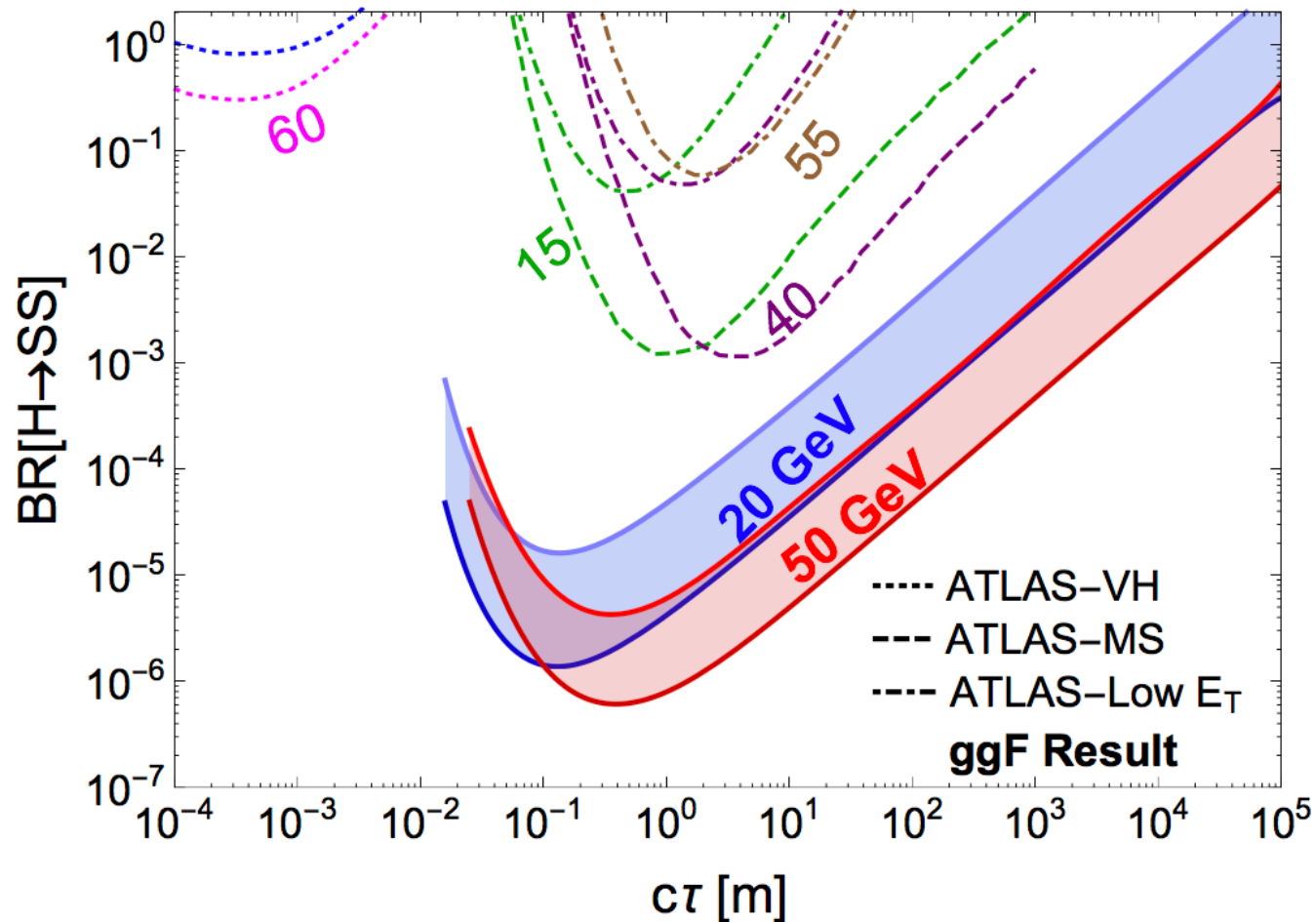
- Fake track bkg: pre-cuts are independent with each other

$$\text{ID}_{A,B} \equiv \frac{\epsilon(A)\epsilon(B)}{\epsilon(A\&B)}$$

mis-connected	$r_{\text{DV}}^{\text{xy}} > 0.16 \text{ m}$	$\Delta D_{\text{min}} < 0.02 \text{ m}$	$\bar{t} > 1 \text{ ns}$	$\text{SD}_t < 0.3 \text{ ns}$	$ \bar{z} > 0.4 \text{ m}$	$\text{SD}_{ z } < 0.05 \text{ m}$
$r_{\text{DV}}^{\text{xy}} > 0.16 \text{ m}$	-	0.56	0.86	1.1	0.15	-
$\Delta D_{\text{min}} < 0.02 \text{ m}$	*	-	0.99	-	0.64	1.6
$\bar{t} > 1 \text{ ns}$	*	*	-	0.88	0.81	1.0
$\text{SD}_t < 0.3 \text{ ns}$	*	*	*	-	1.48	-
$ \bar{z} > 0.4 \text{ m}$	*	*	*	*	-	21
$\text{SD}_{ z } < 0.05 \text{ m}$	*	*	*	*	*	-

mis-connected	$r_{\text{DV}}^{\text{xy}} > 0.16 \text{ m}$	$\Delta D_{\text{min}} < 0.02 \text{ m}$	$\bar{t} > 1 \text{ ns}$	$\text{SD}_t < 0.3 \text{ ns}$	$ \bar{z} > 0.4 \text{ m}$	$\text{SD}_{ z } < 0.05 \text{ m}$
$(d_0^T > 0.01\text{m})^1$	0.97	1.0	1.0	1.0	0.98	1.0
$(d_0^T > 0.03\text{m})^1$	0.91	1.1	1.0	1.1	0.95	1.1
$(d_0^T > 0.05\text{m})^1$	0.85	1.1	1.0	0.99	0.91	1.1
$(d_0^T > 0.03\text{m})^5$	0.65	1.0	0.99	1.4	0.79	1.2

The Preliminary Results for HL-LHC



- ggF result: with/without high H_T trigger requirement
- VBF result: standard VBF trigger

Summary

- Long-lived particle is well-motivated and is new direction of future LHC
- Track-based study is powerful
 - A sterile neutrino example
 - Increase the sensitivity by $10^2 \sim 10^3$
- CMS HGCal is a promising new calorimeter
 - Higgs portal LLP
 - Increase the sensitivity by $10^2 \sim 10^3$

Thank you!