Long-lived particle Searches at LHC

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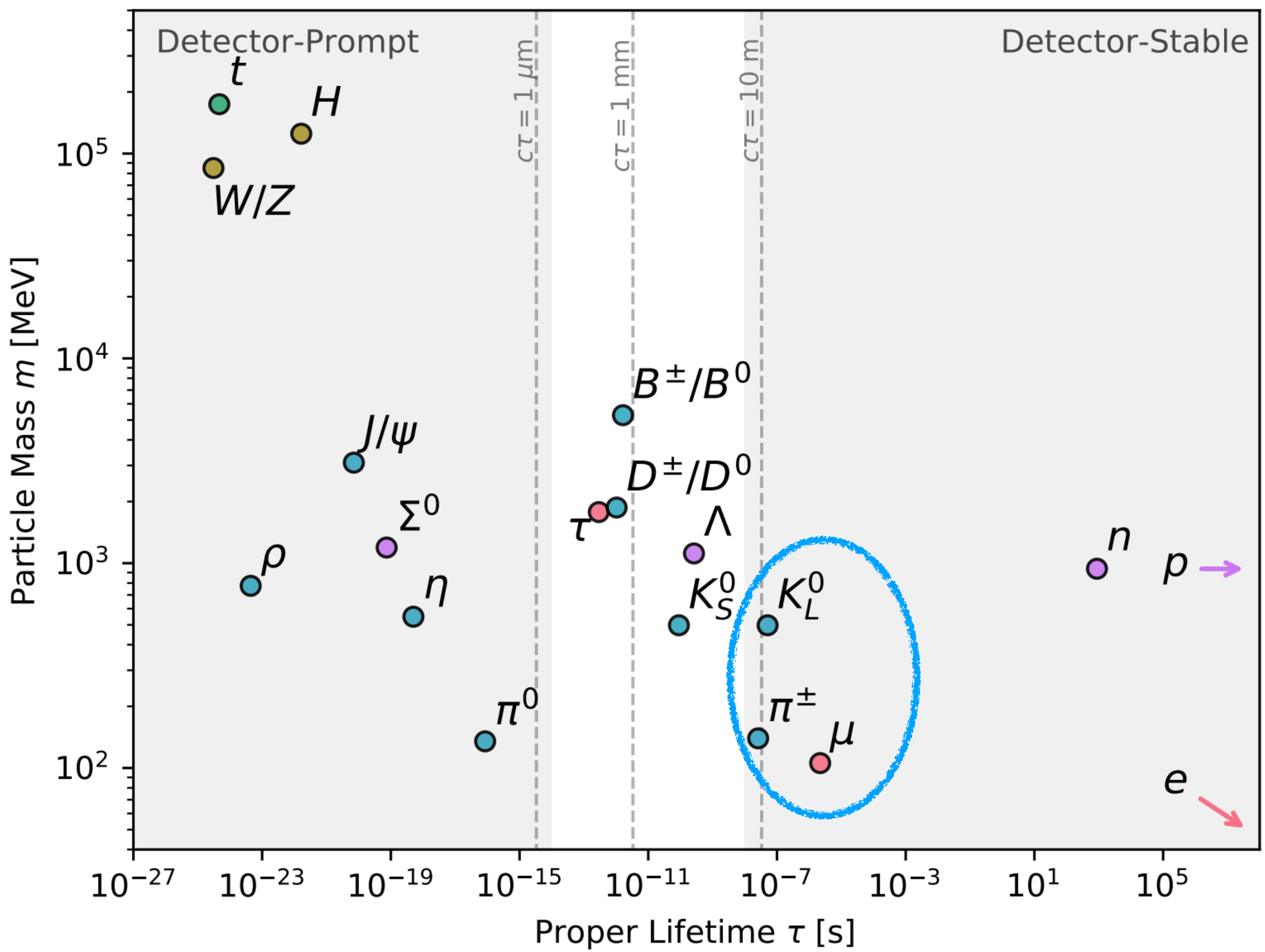
Seminar at CHEP@PKU, 22-12-2019

Outline

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

Why is there long-lived particles?



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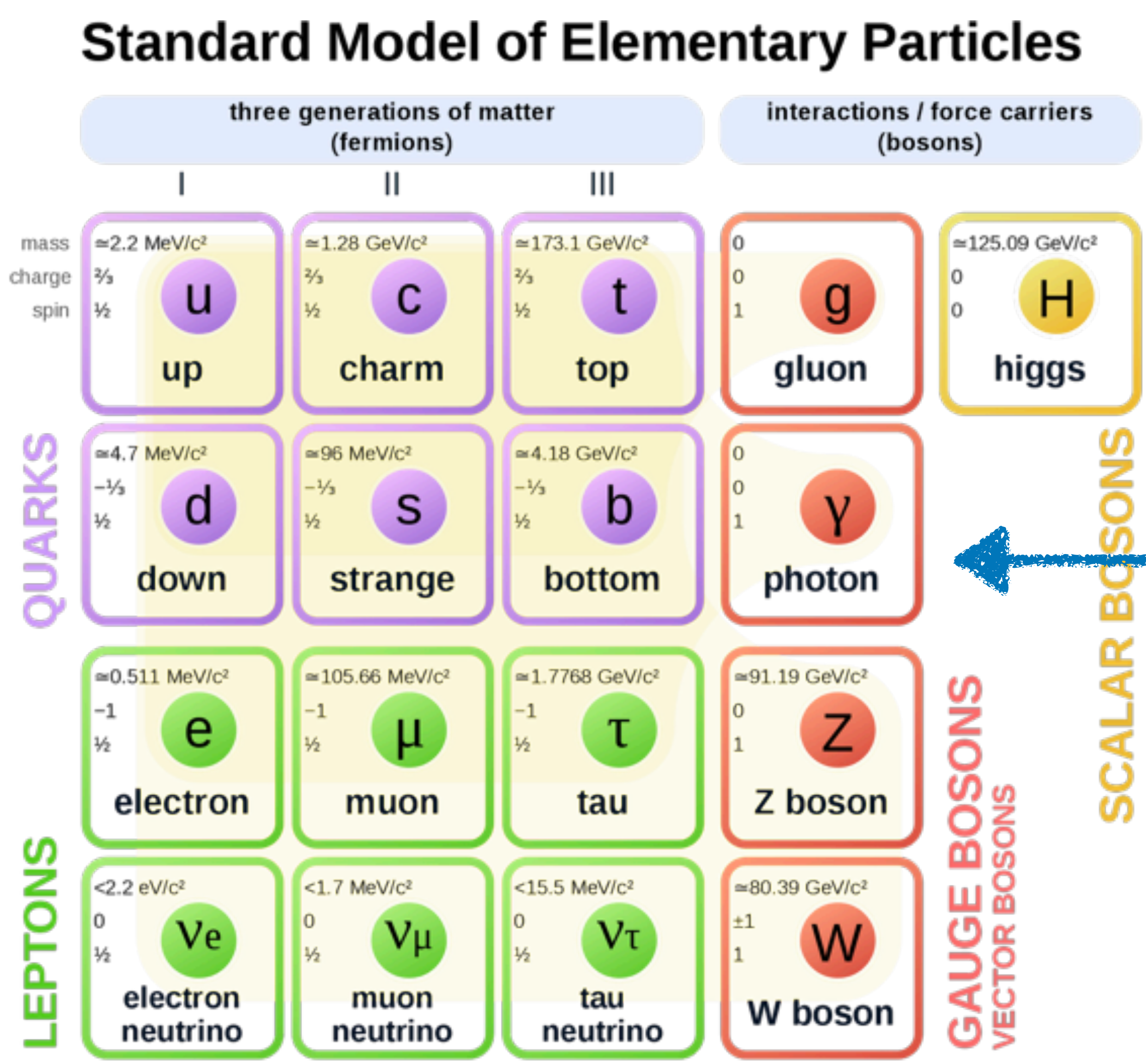
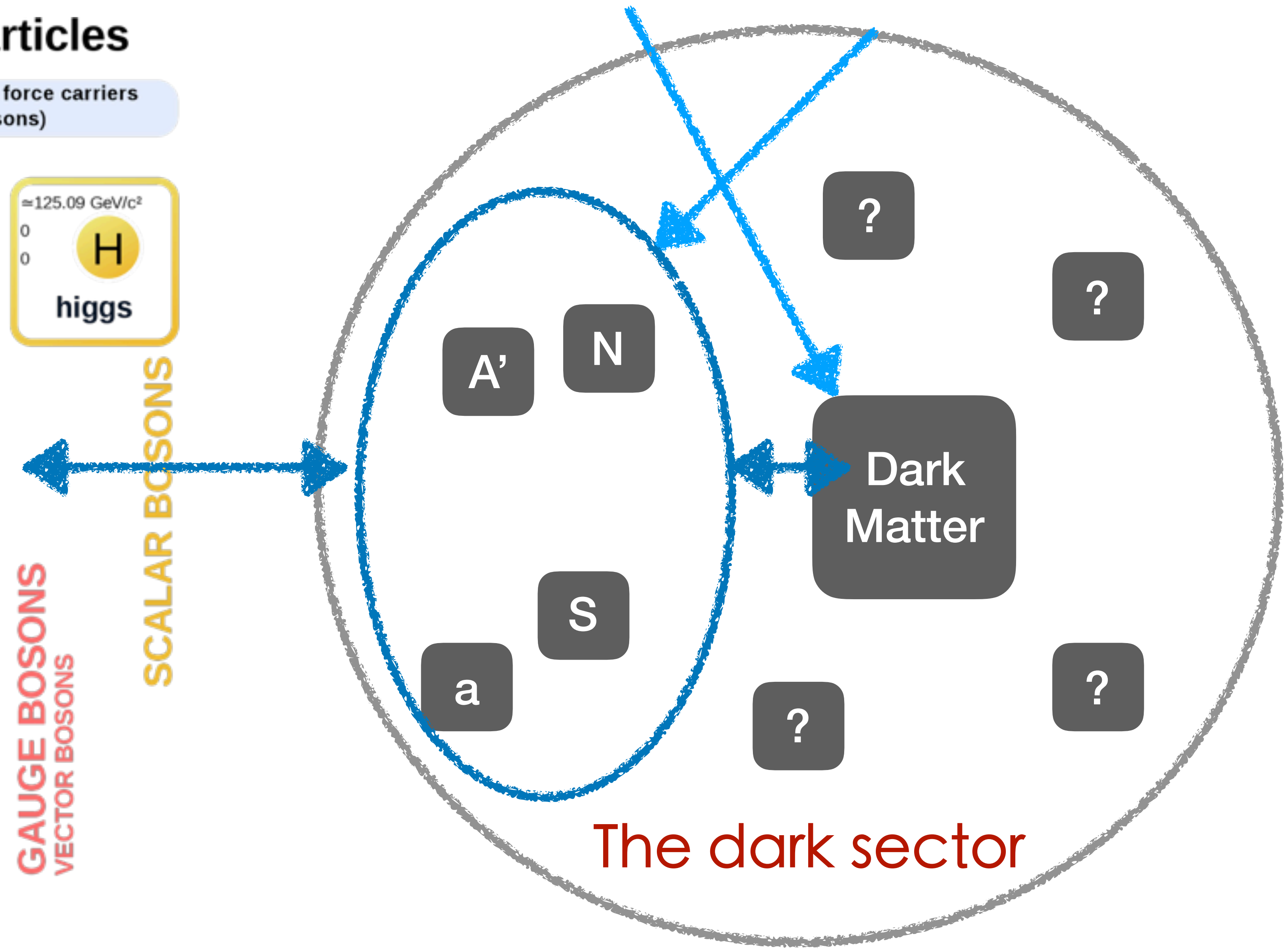
Why is there long-lived particles?

- Standard Model =fermions+force mediators
- Dark sector =DM+dark mediators





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

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Why is there 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)

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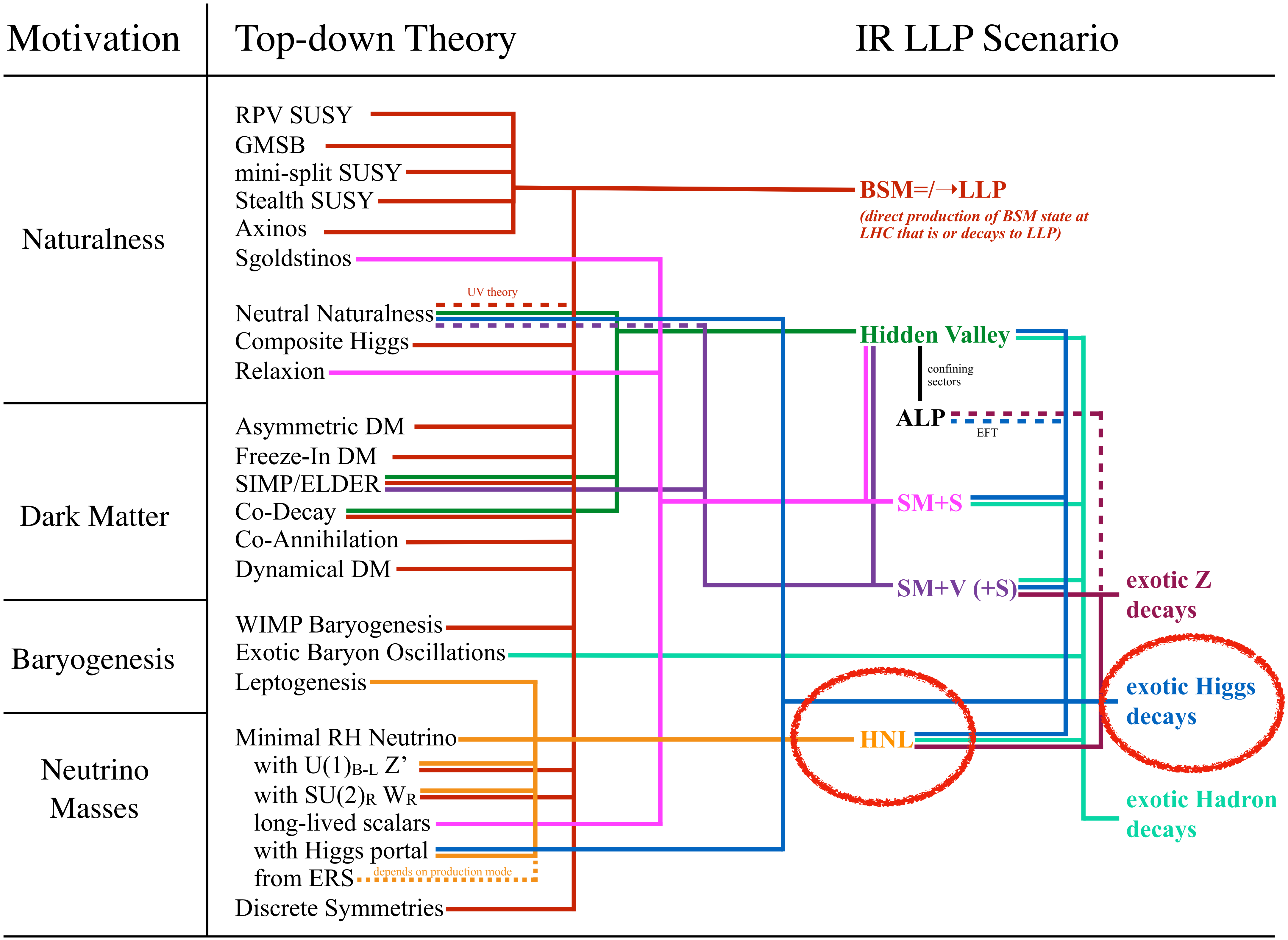
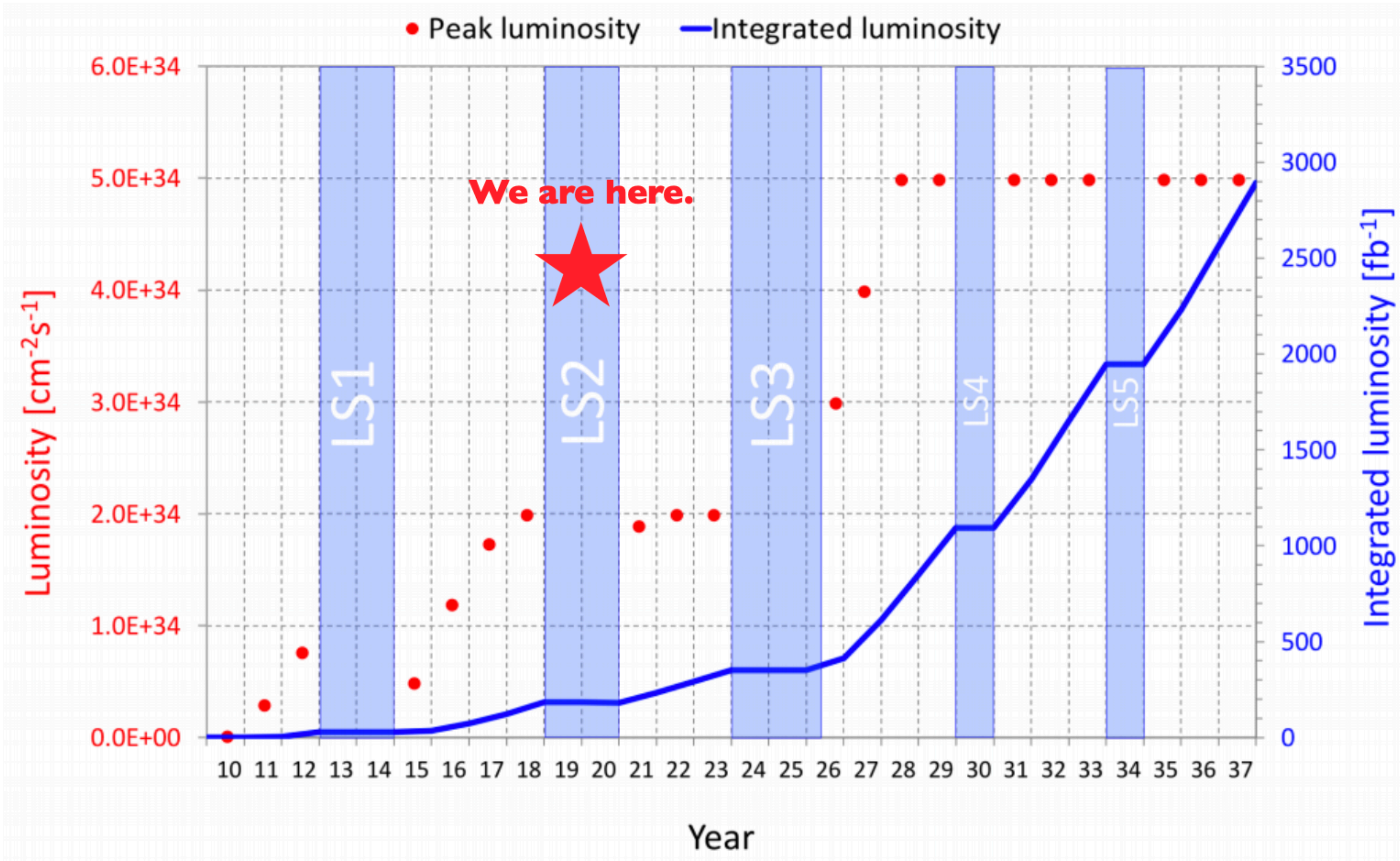
Why is there long-lived particles?



1806.07396: MATHUSLA Physics Case

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

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An important example:
Long-lived particles

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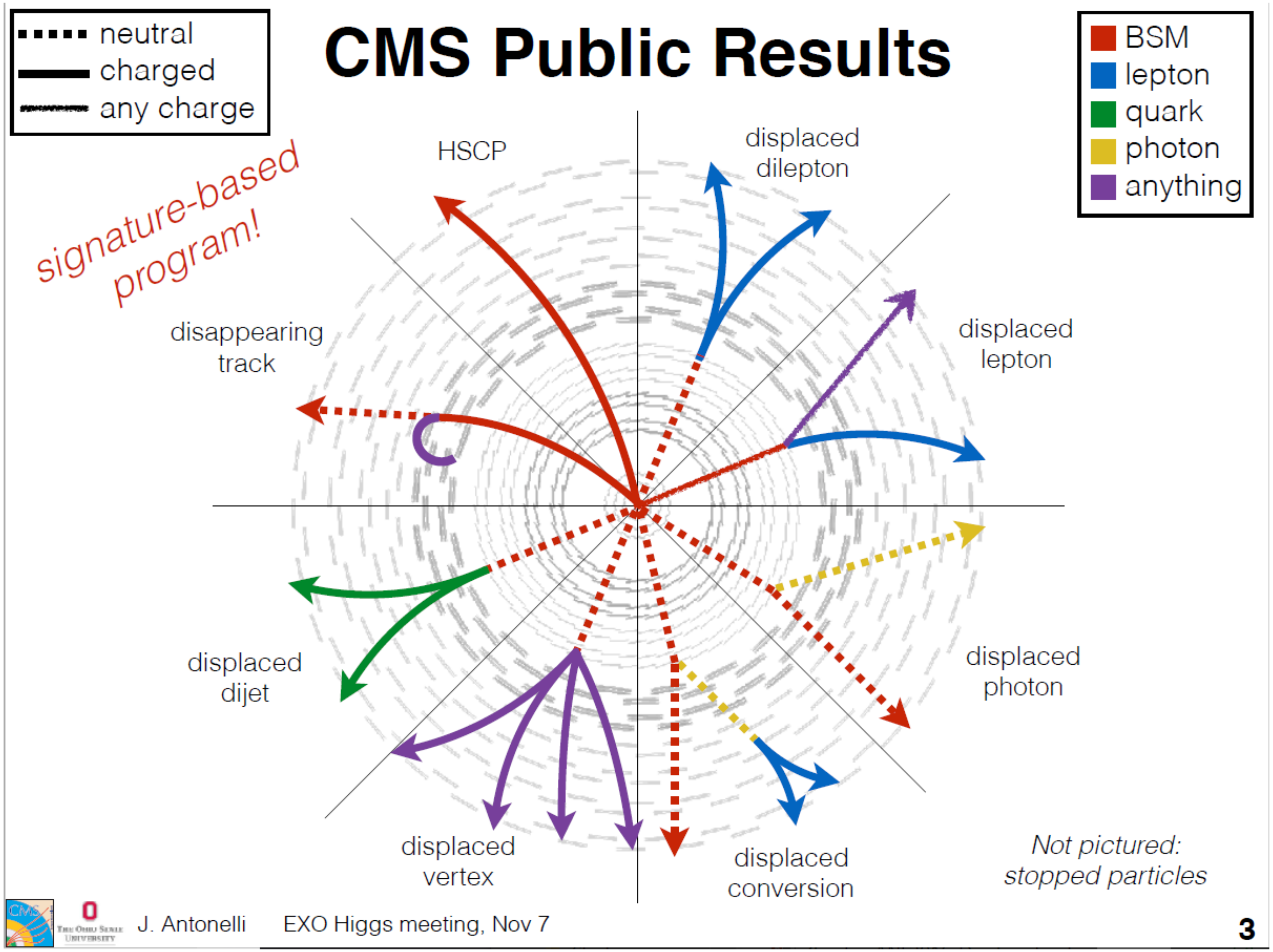
How to search LLP?

- 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

$\Rightarrow$ 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

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

- Masses

$$m_D = \lambda_\nu v/\sqrt{2}$$

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

- 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

Sterile neutrino models

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- Mixing

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

- Inverse seesaw

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

- Linear seesaw

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

Separate neutrino mass from mixing, realizing large mixing angle.

Sterile neutrino signal

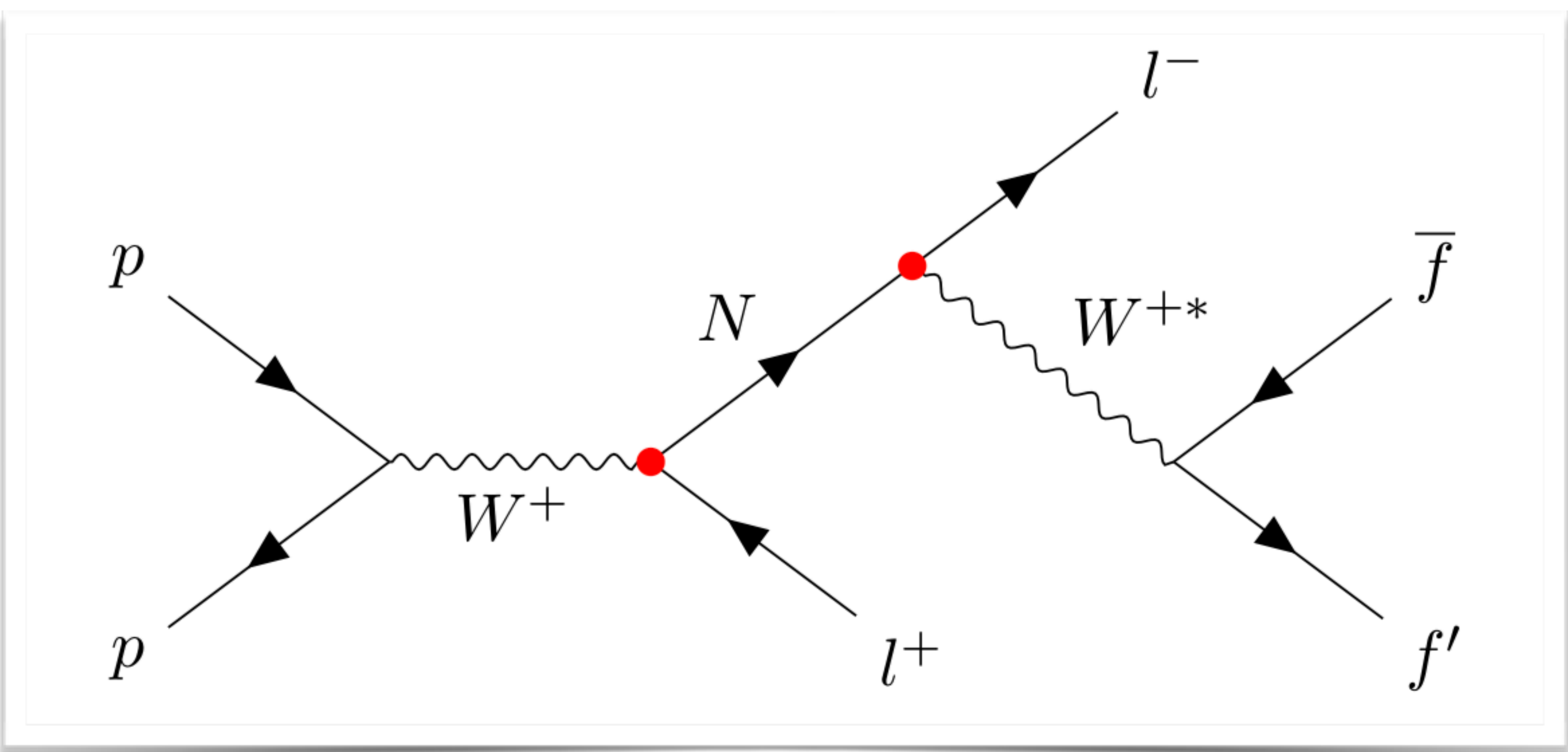
- Free parameters: m_N, sinθ
- Long life-time

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

- Event rate at HL-LHC

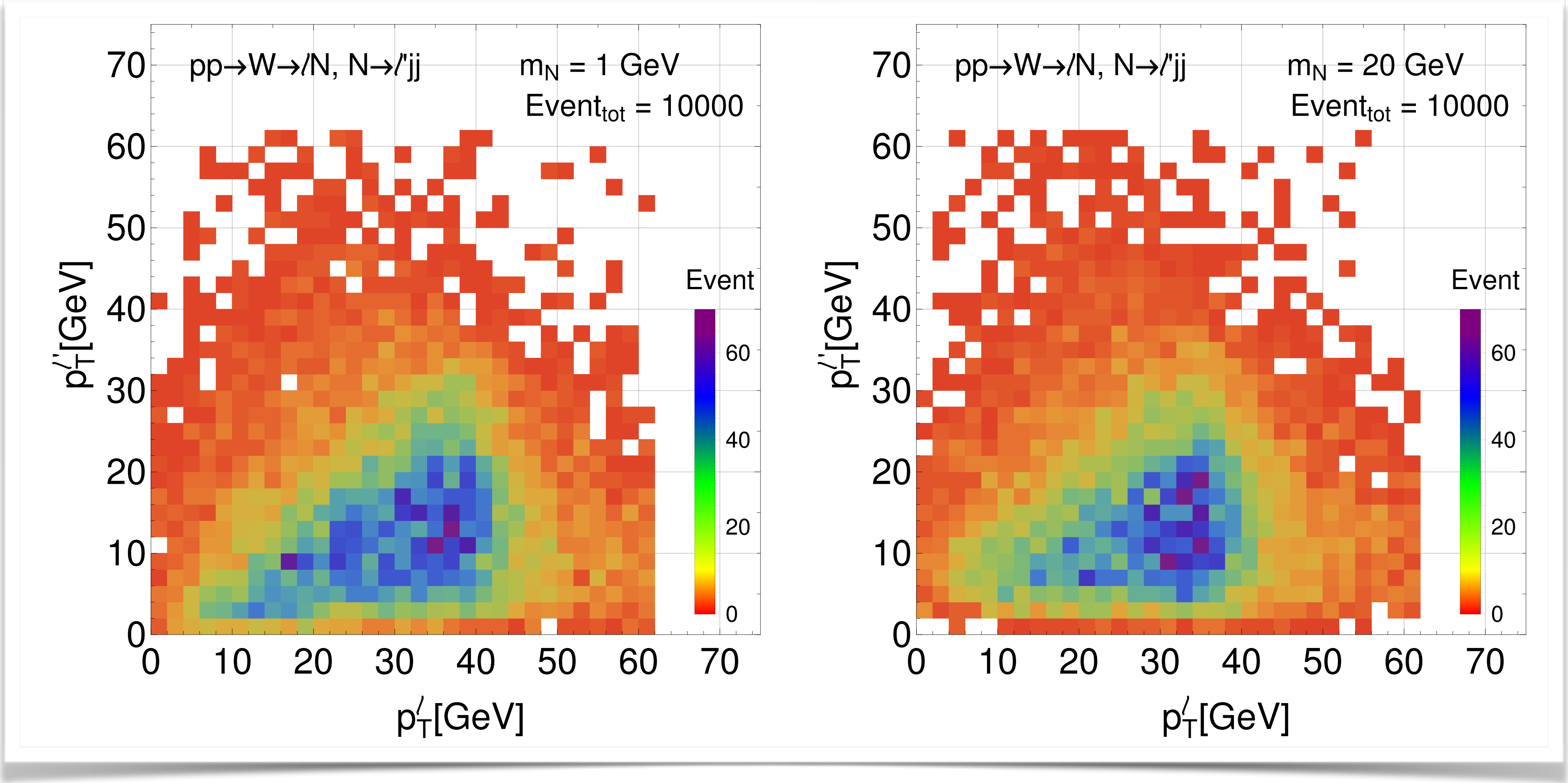
$$\mathscr{L} \times \sigma(pp \to W^\pm)\text{Br}(W^\pm \to \ell^\pm N) \simeq 1.8 \times 10^5 \left(\frac{\sin^2\theta}{10^{-6}}\right)$$

- Signal topology



The lepton behaviors

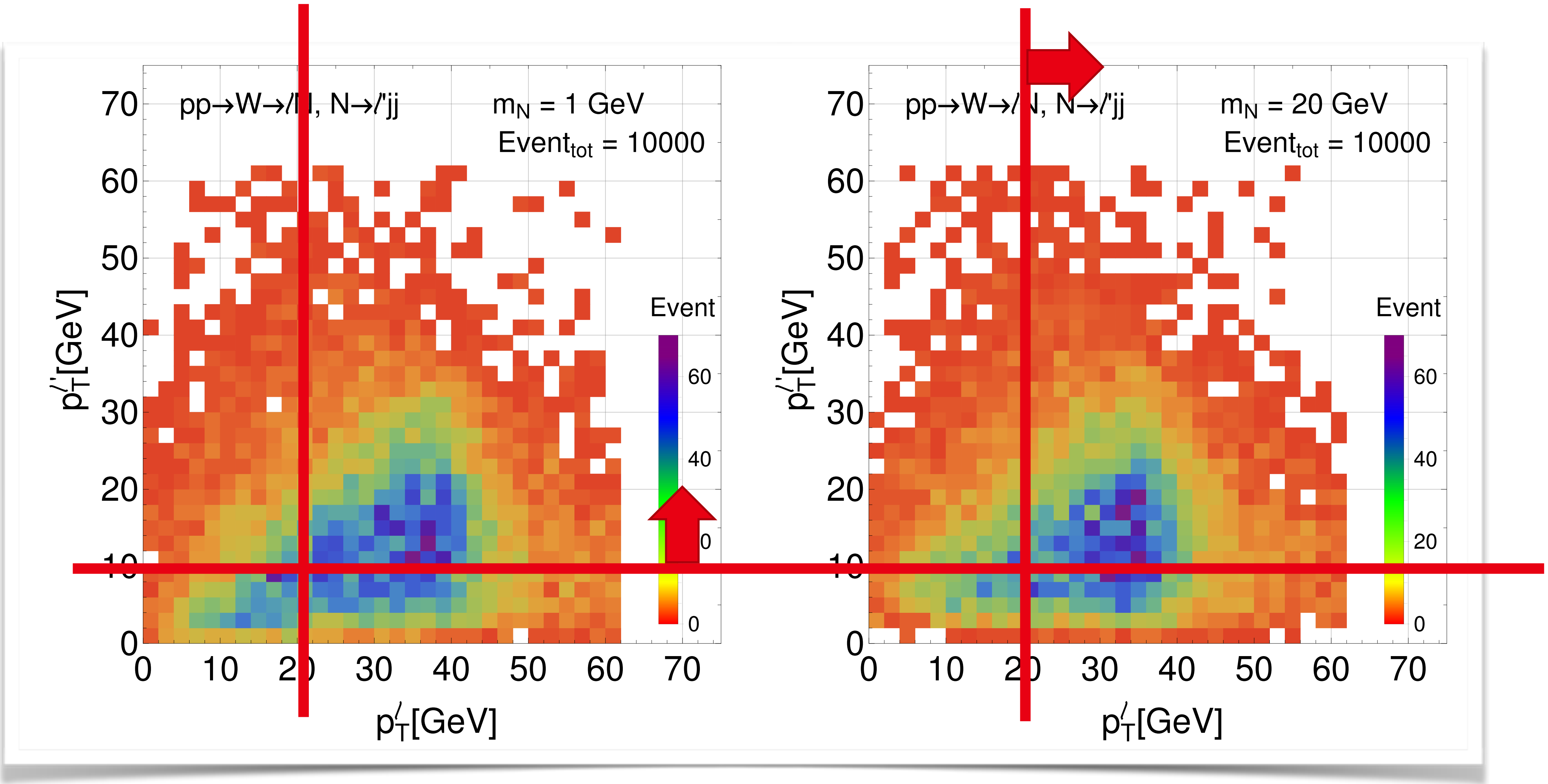
- Prompt lepton hard-ish
- Displaced lepton soft-ish



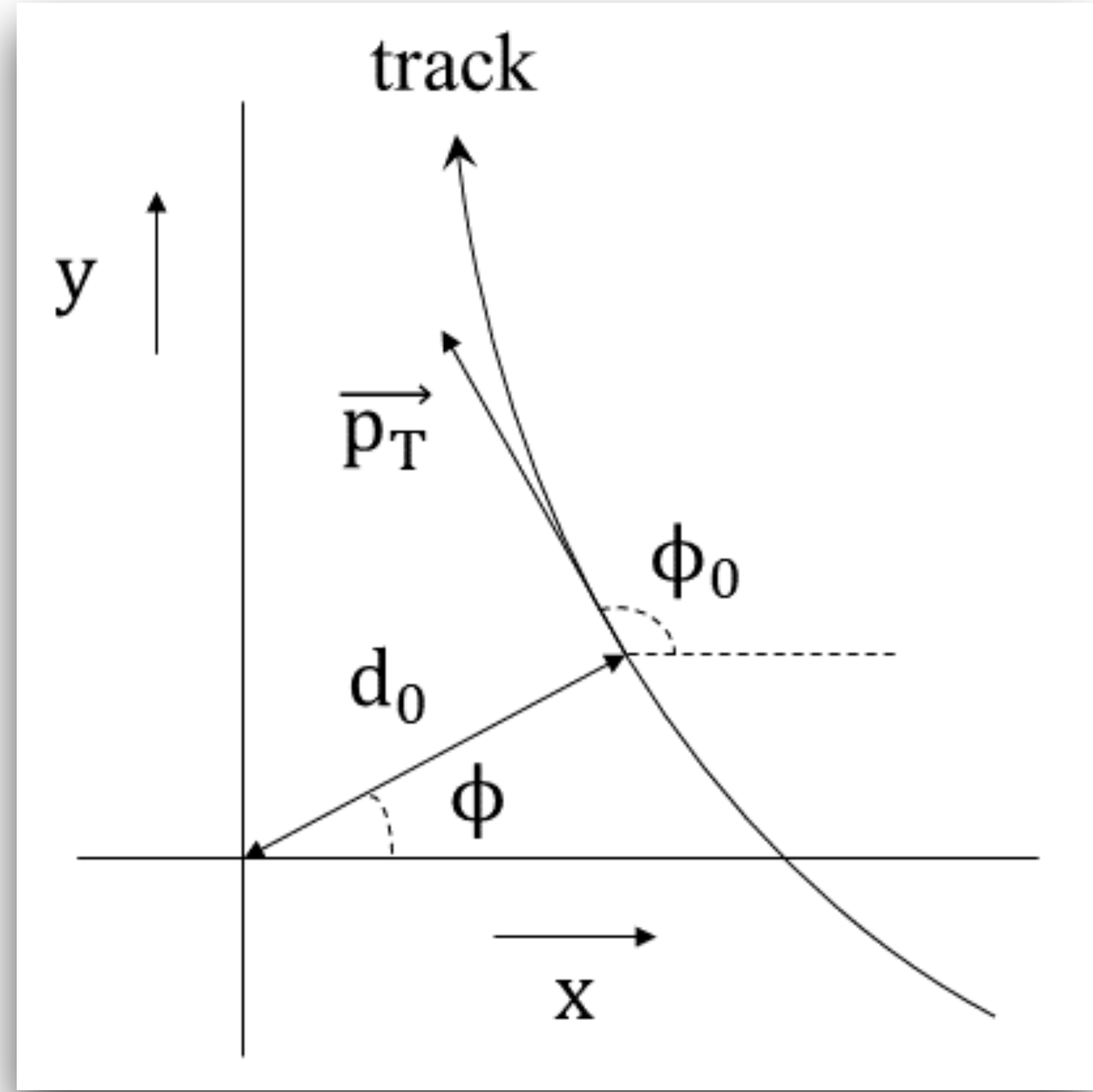
The lepton behaviors

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

$$p_T^l = \frac{m_W^2 - m_N^2}{2m_W} \qquad p_T^{l'} = \frac{m_W}{3}$$

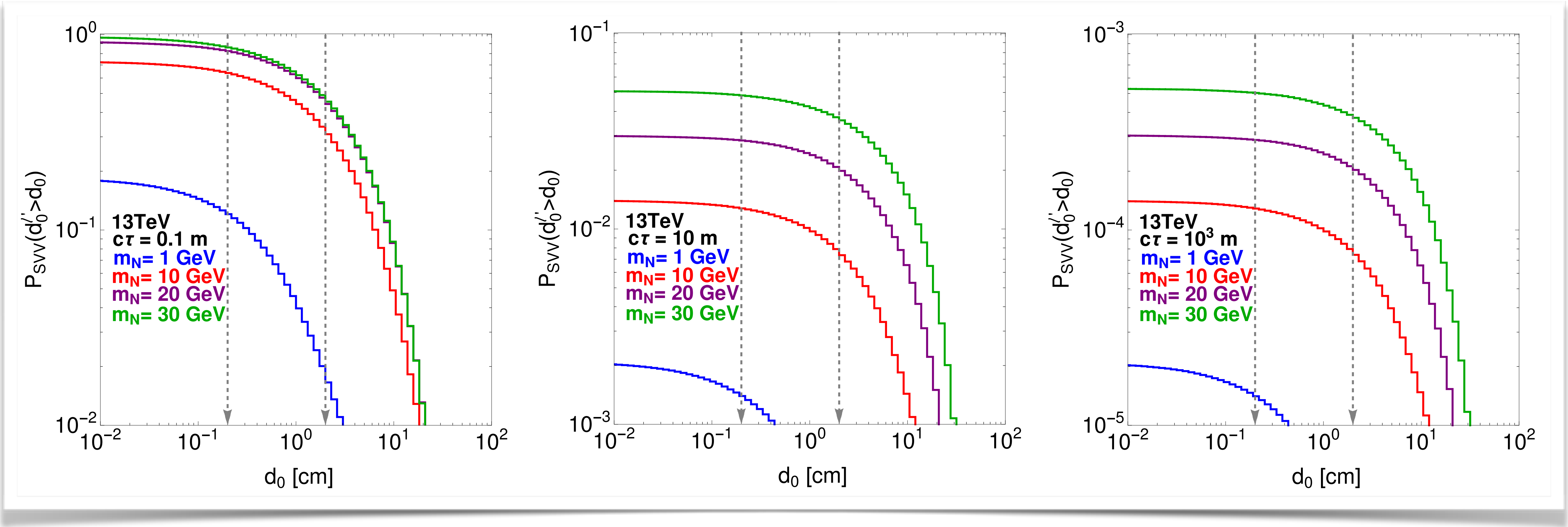


Impact parameter



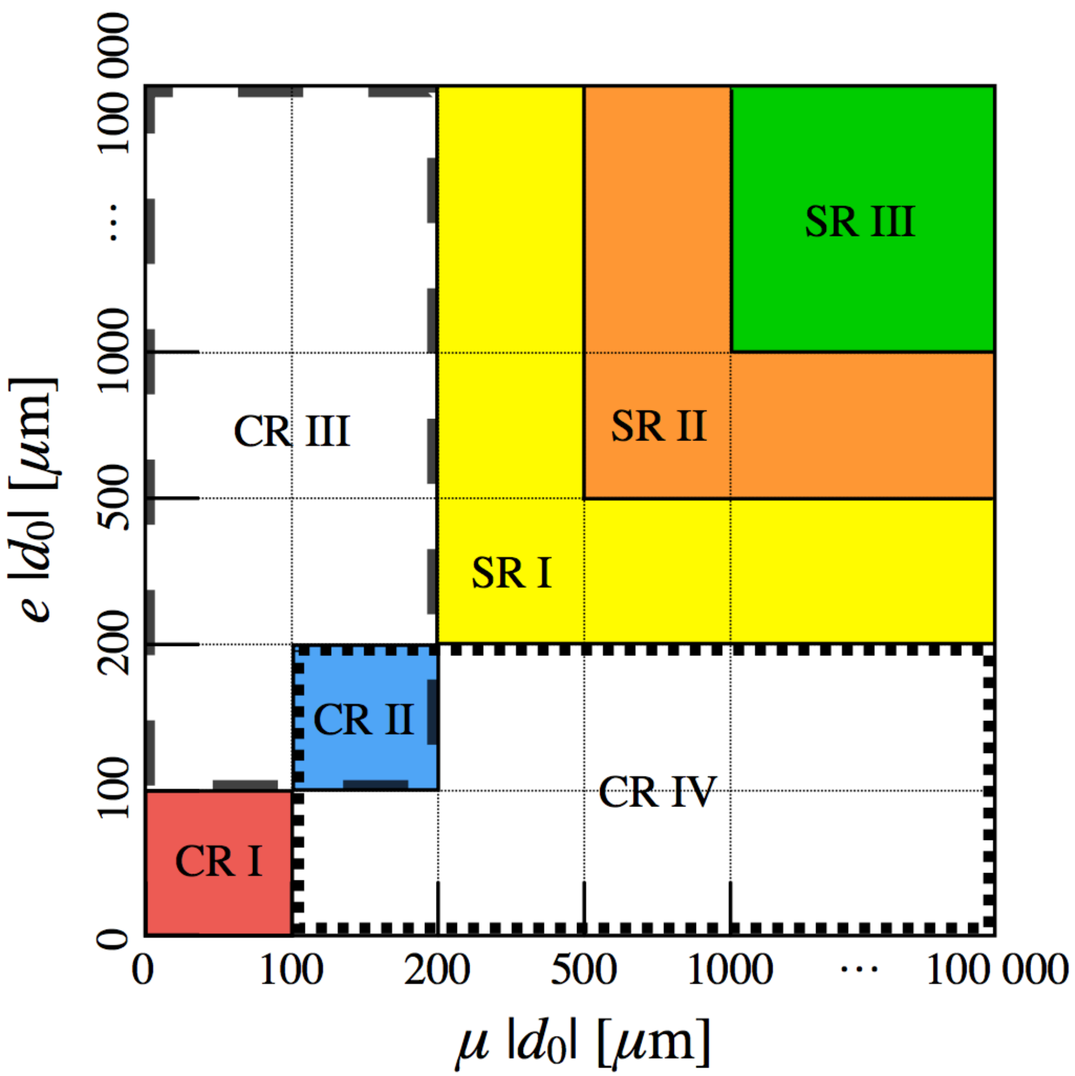
$$d_0 = \sqrt{x^2 + y^2 - \frac{(xp_x + yp_y)^2}{p_x^2 + p_y^2}}$$

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

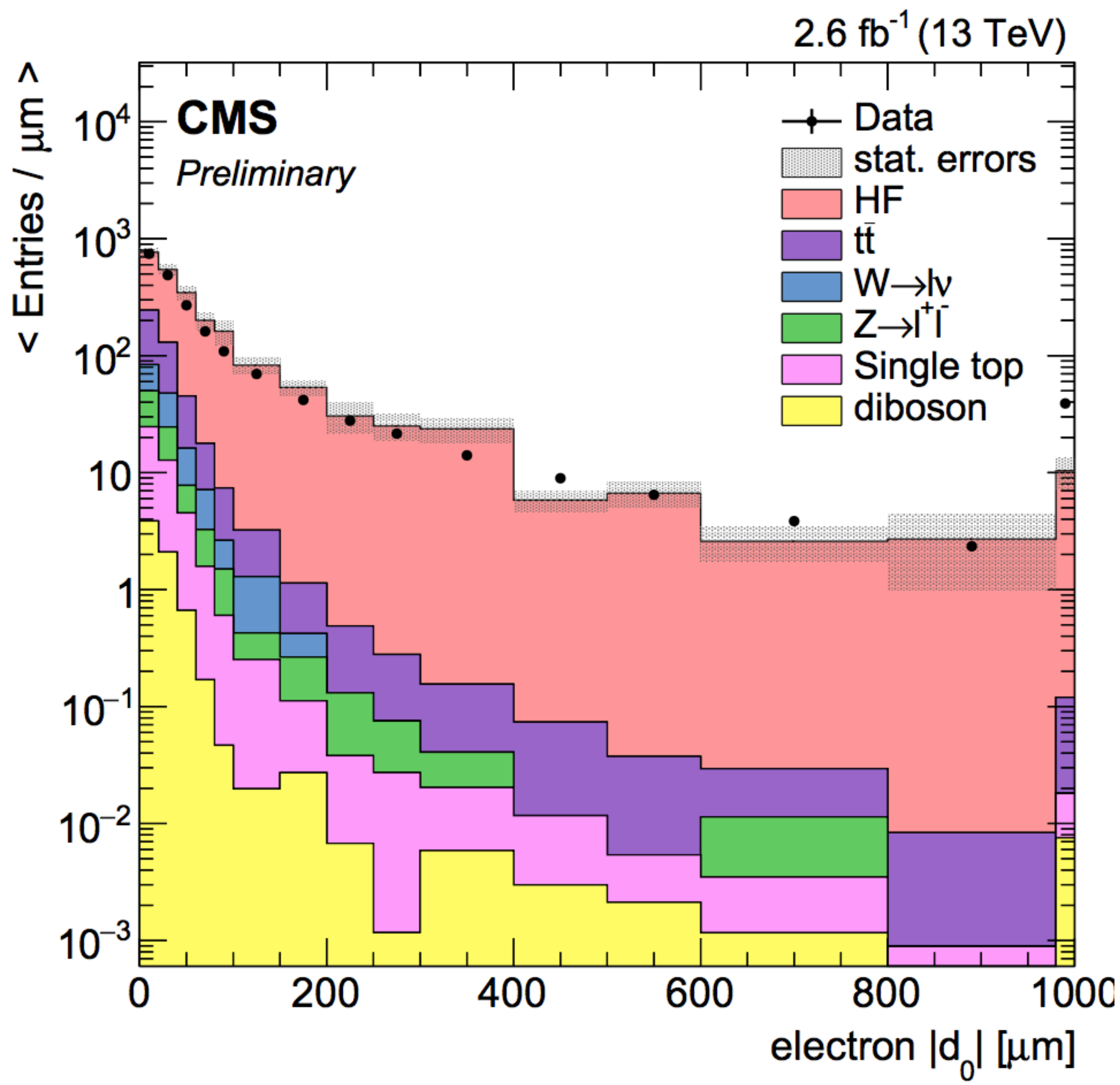


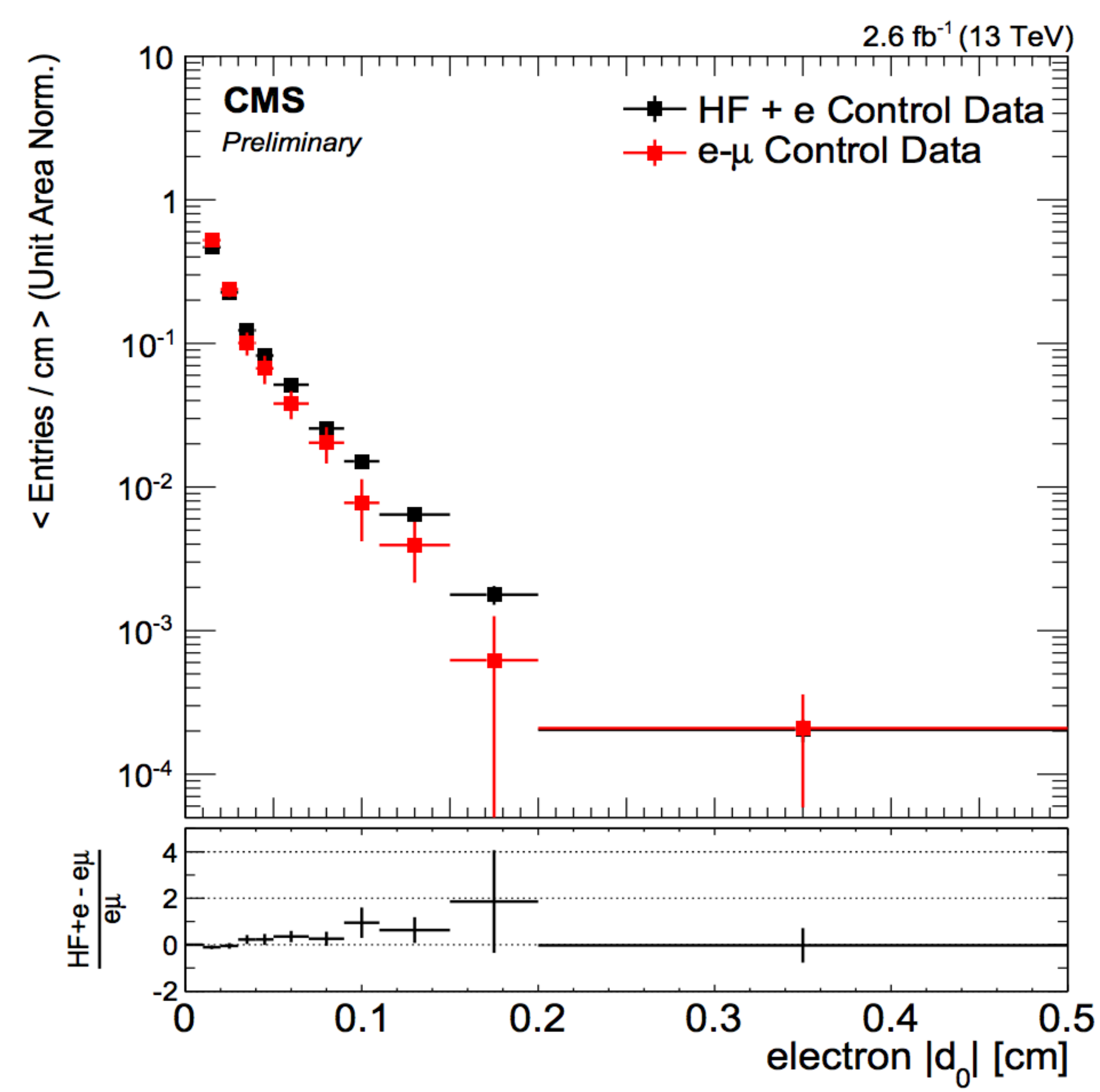
Prompt L+ displaced L

CR III: Heavy jet + displaced e
CR IV: Heavy jet + displaced muon

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

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

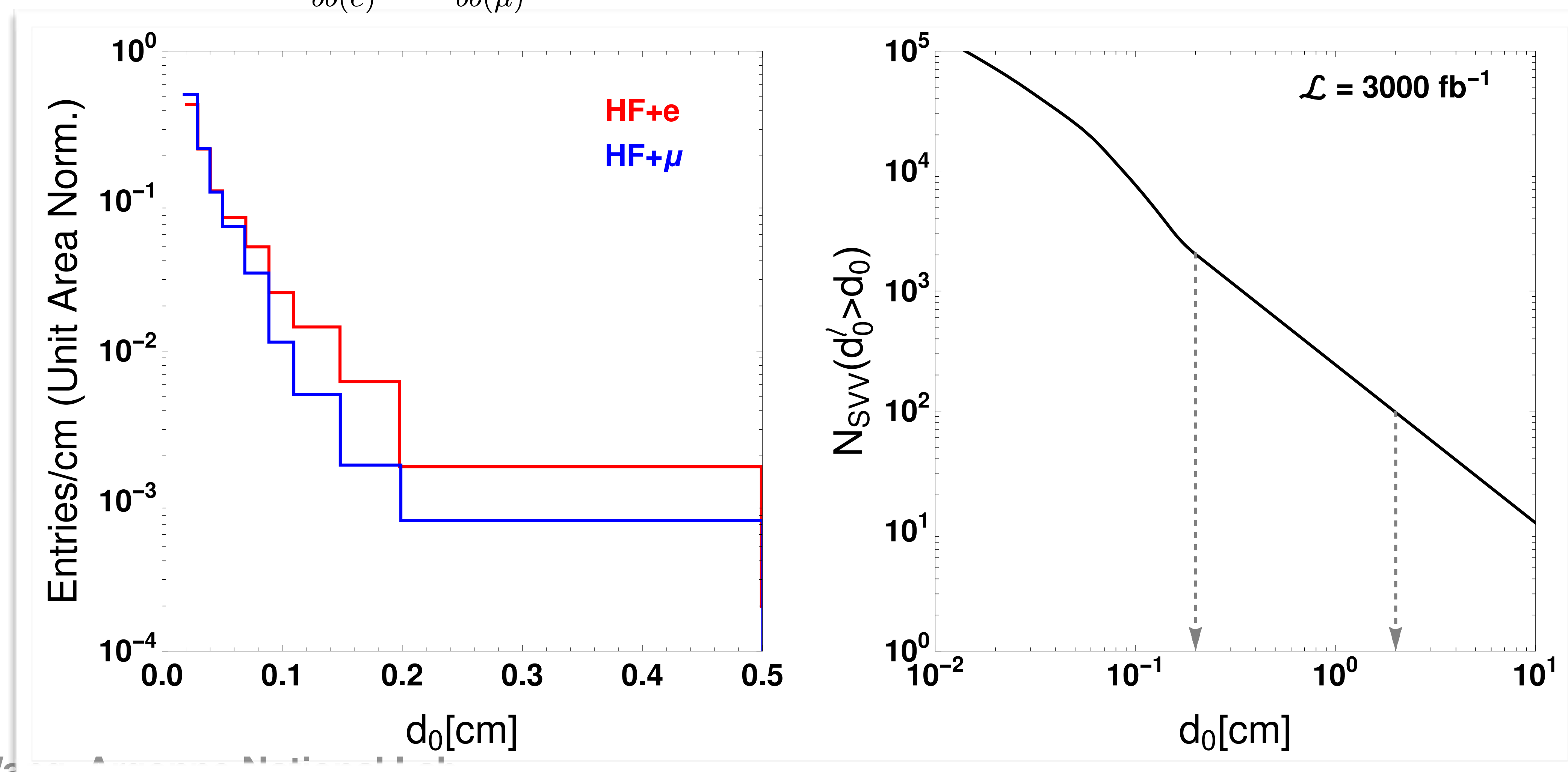
Valuable knowledge from a SUSY search

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

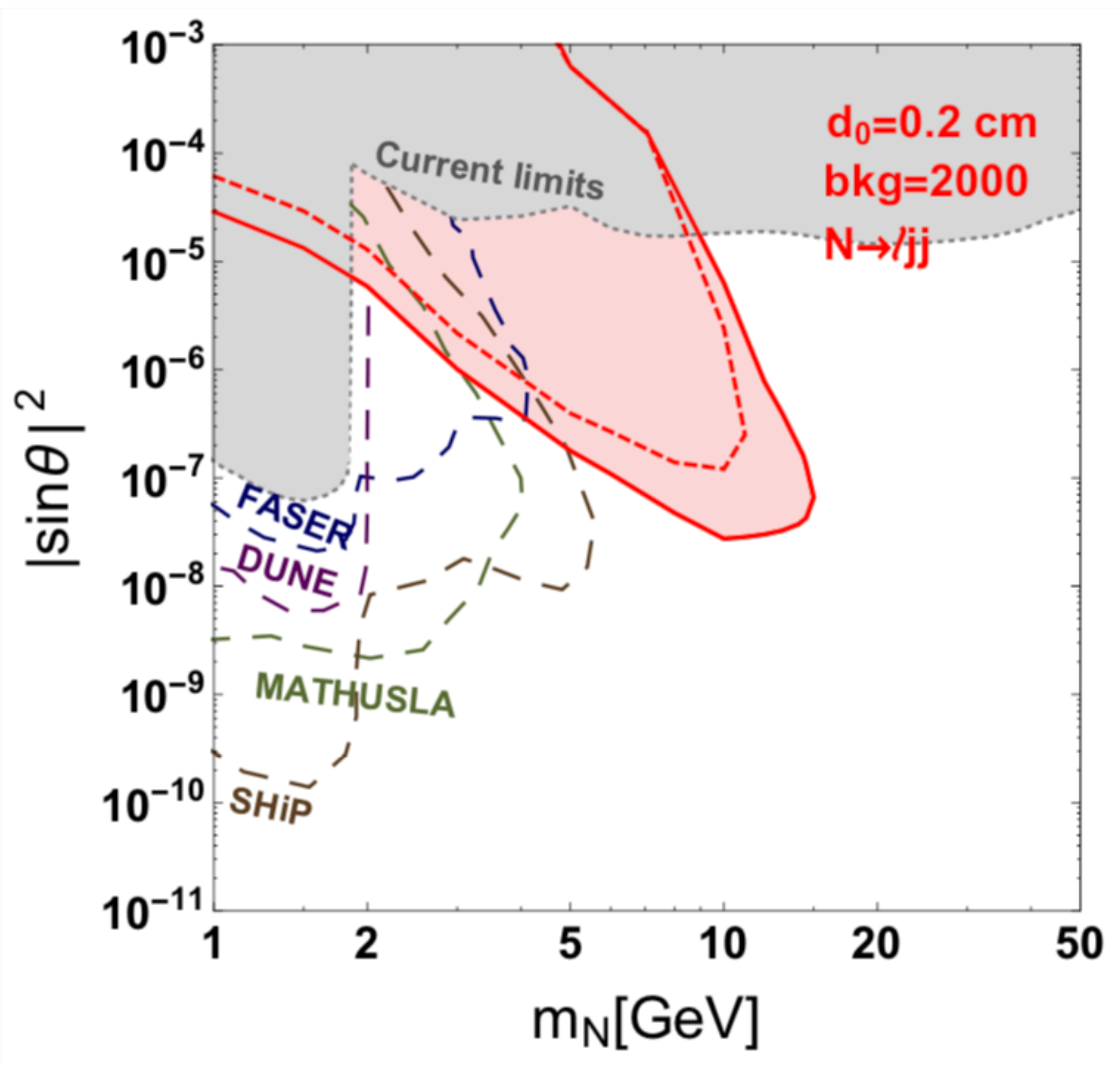
Background Estimation

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

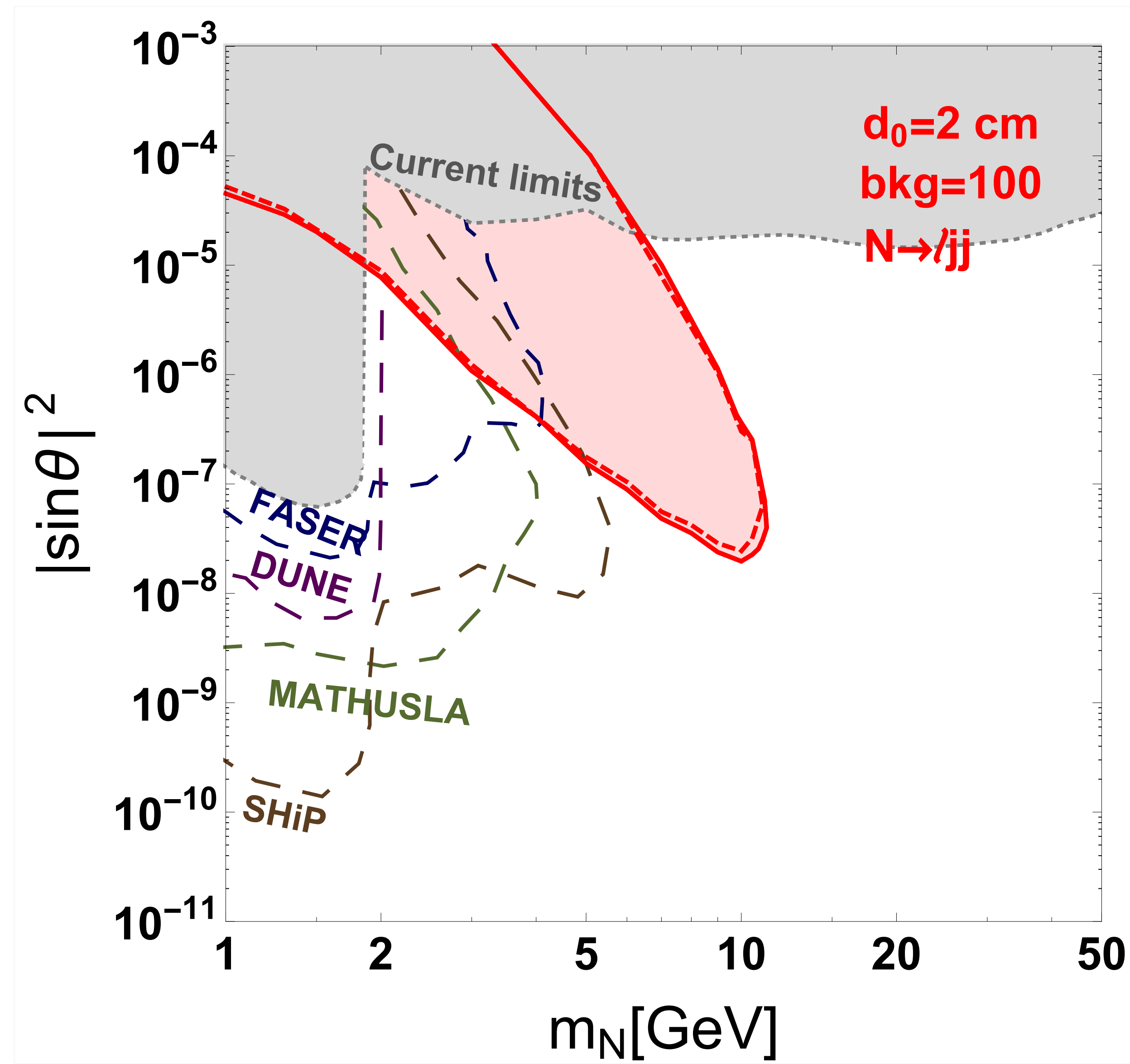
$$N_{\rm bkg}=\frac{\sigma^{\rm CMS}_{{\rm HF}+e}+\sigma^{\rm CMS}_{{\rm HF}+\mu}}{\sigma^{\rm icut}_{b\bar{b}(e)}+\sigma^{\rm icut}_{b\bar{b}(\mu)}}\left(\sigma^{\rm ncut}_{W+b\bar{b},W\to\ell\nu}\times\epsilon^{W+b\bar{b}}_{\rm opt}+\sigma^{\rm ncut}_{t\bar{t}\to b\bar{b}+\ell+X}\times\epsilon^{t\bar{t}}_{\rm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



Results



d0=0.2 cm
bkg=2000
N→νjj
Current limits
FASER
DUNE
MATHUSLA
SHiP
|sinθ|²
mN[GeV]



d0=2 cm
bkg=100
N→νjj
Current limits
FASER
DUNE
MATHUSLA
SHiP
|sinθ|²
mN[GeV]

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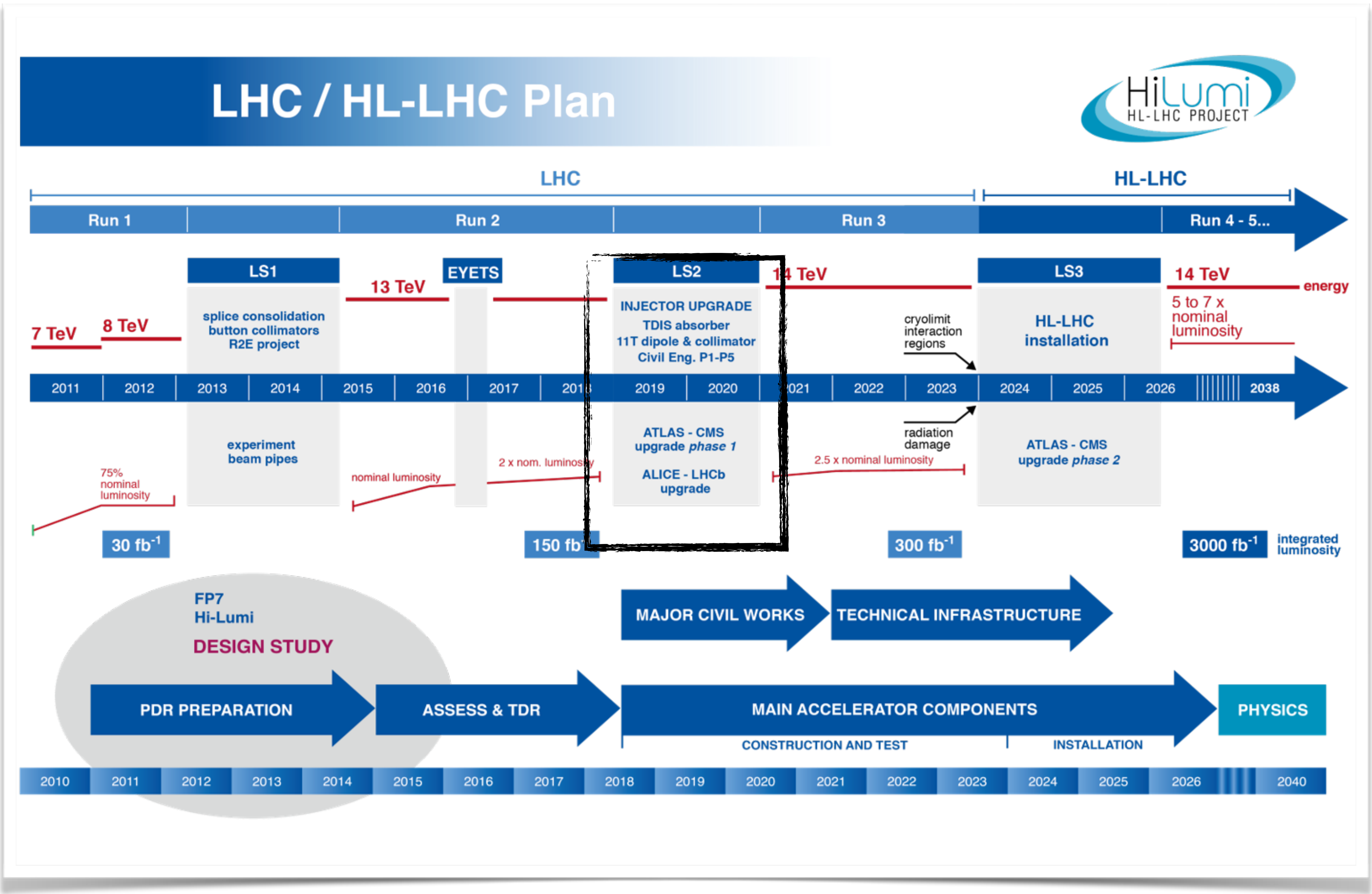
LHC Timeline



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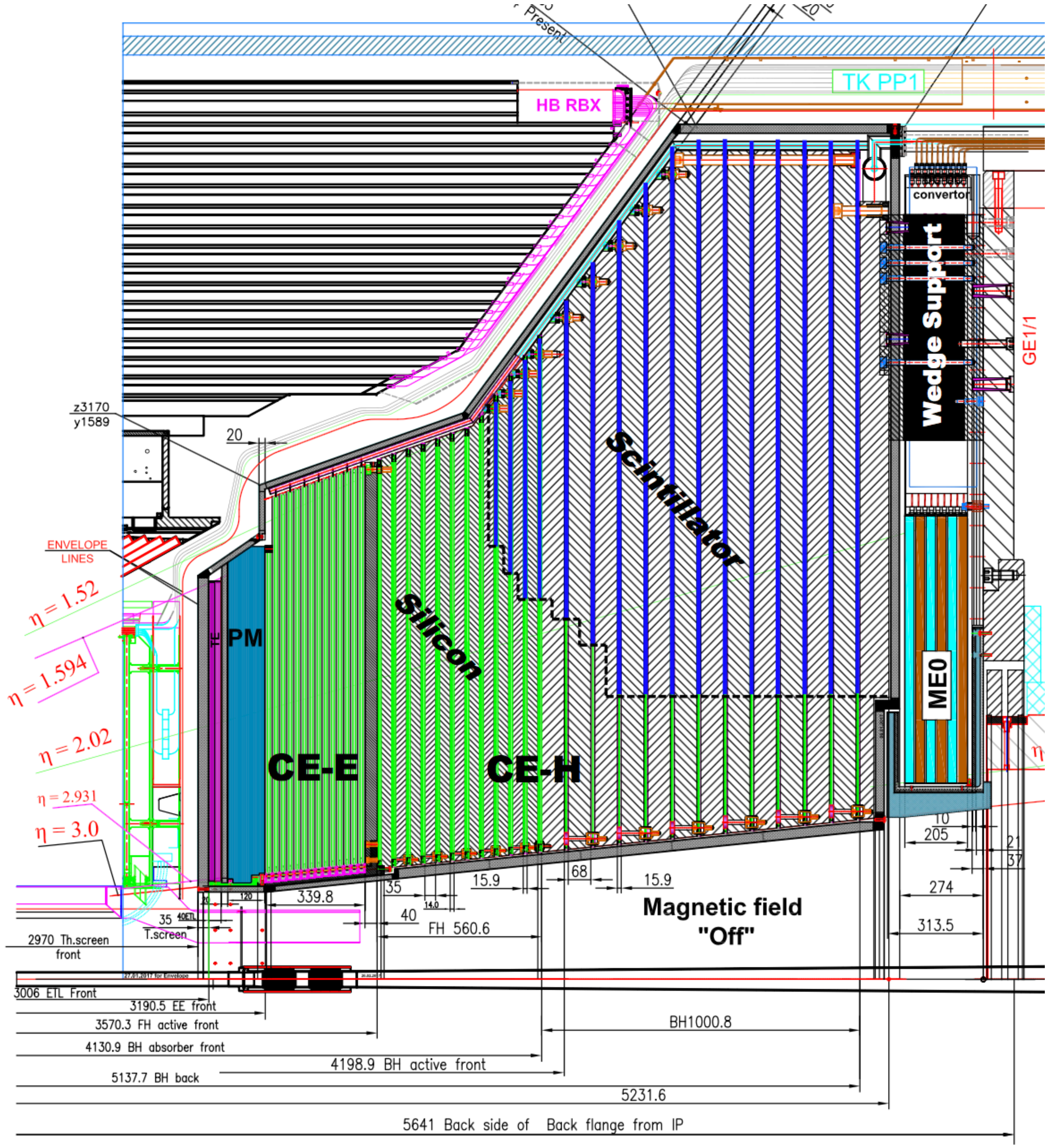
CMS High Granularity Calorimeter

- 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



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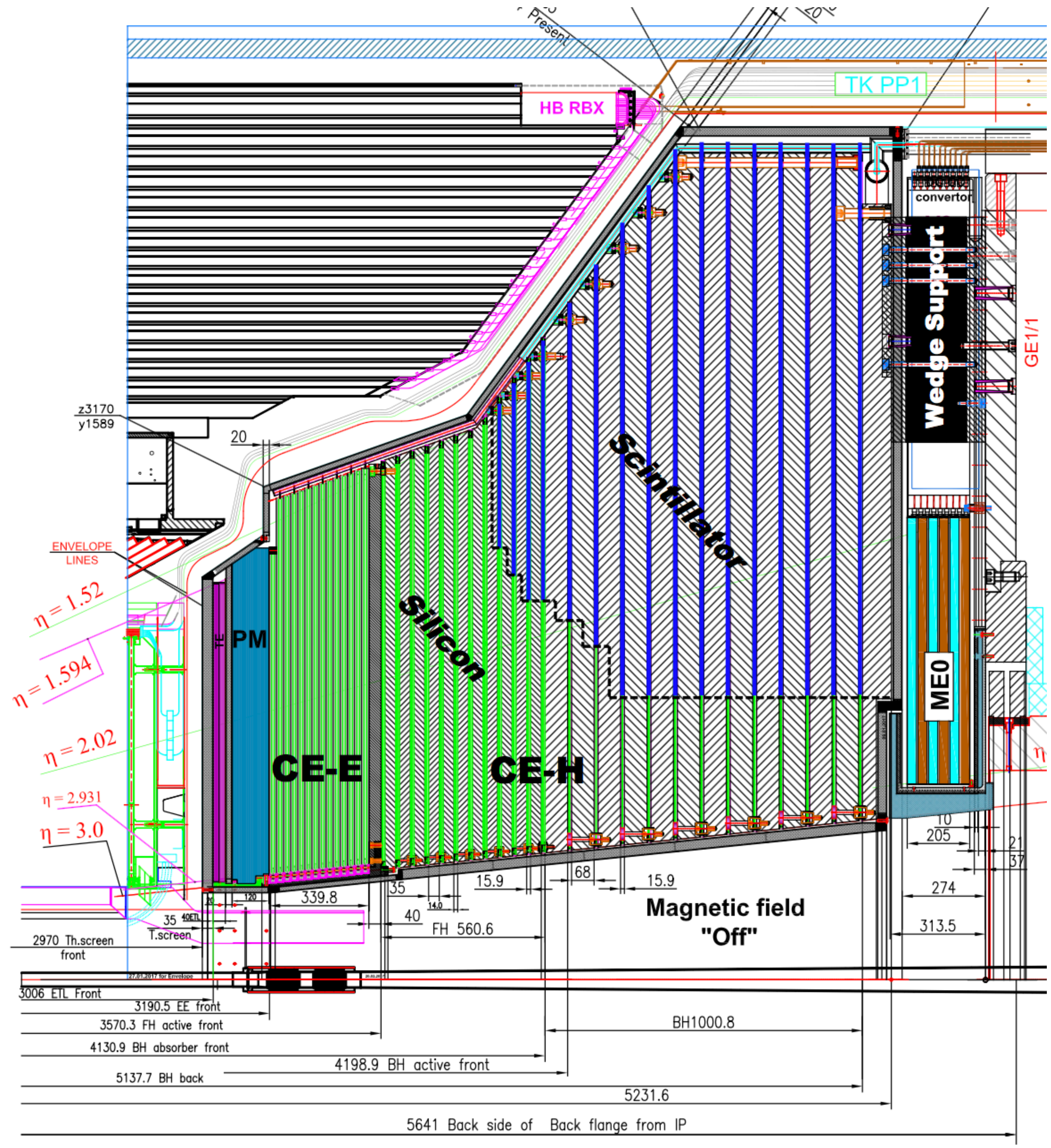
LLP motivation @ HGCAL

- Own triggers
- Tracker with silicon cell 0.5~1 cm^2 for EM and most HA calos
- Angular resolution of 5x10^{-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 HGCAL sensitivity for LLP?

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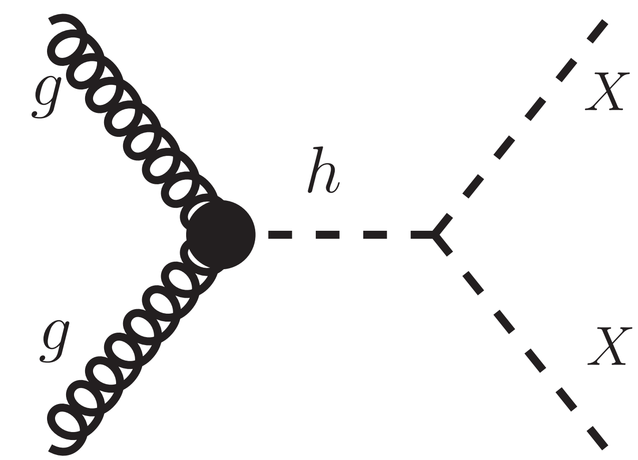
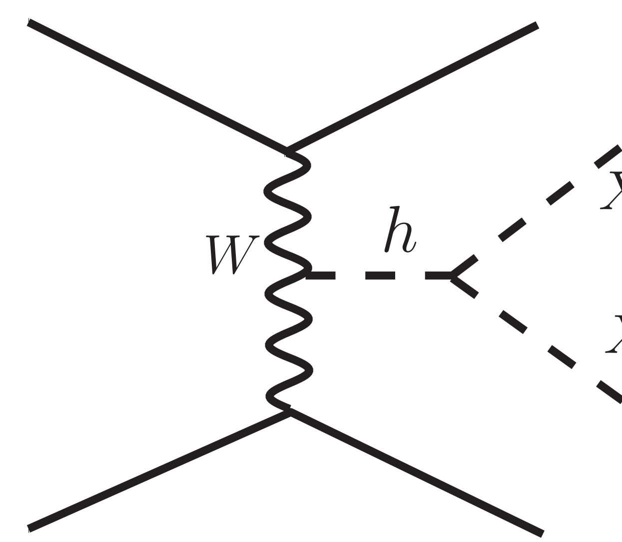
LLP model

- Higgs portal LLP: a very small mixing

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

- LLP production from Higgs decay
  - Gluon fusion
  - Vector boson fusion





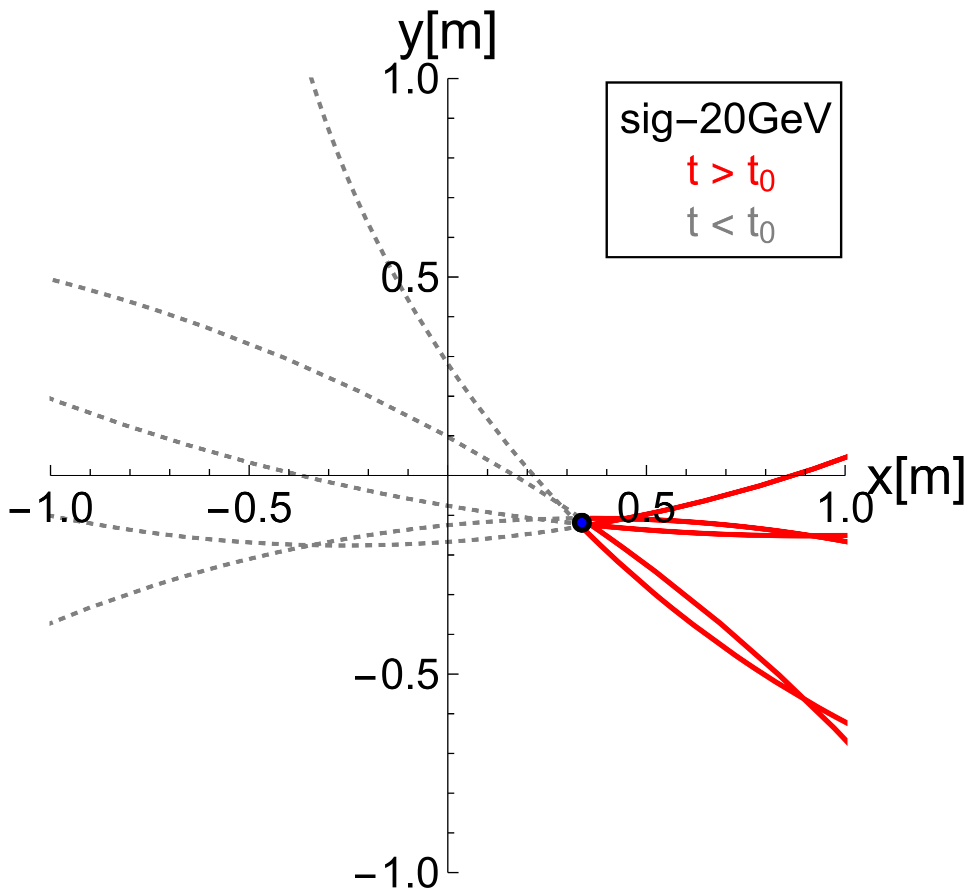
- LLP decay

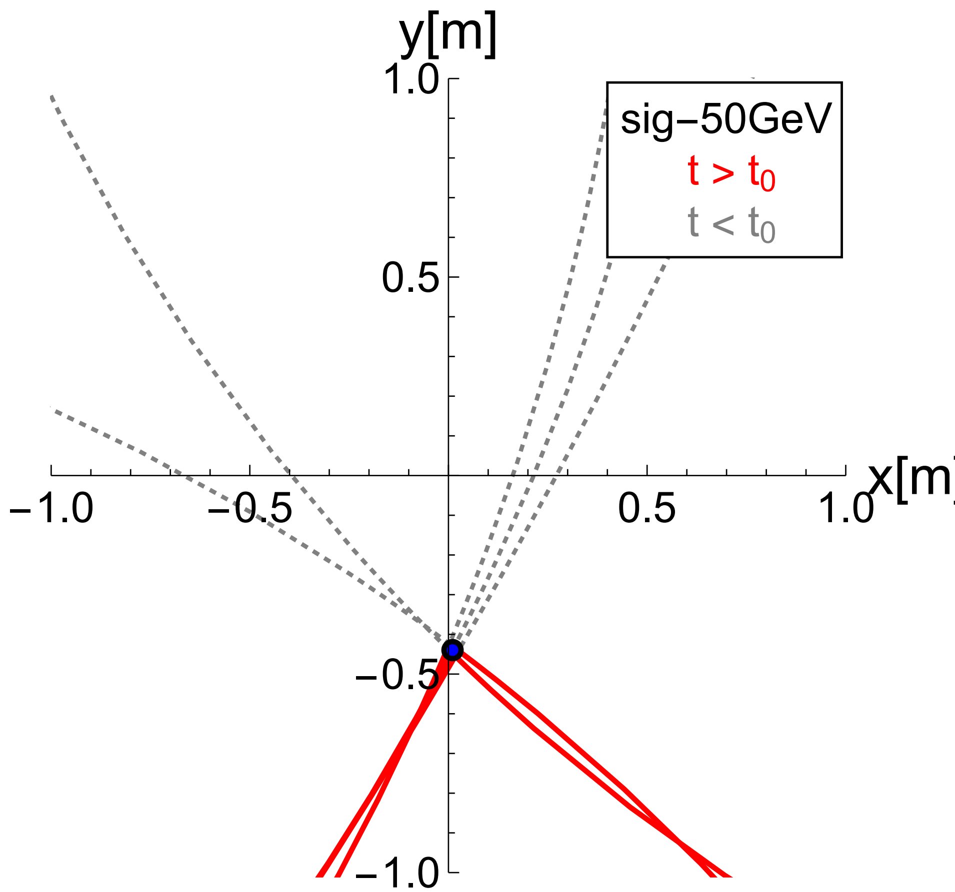
$$X \to \bar{b}b$$

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

The signature of the signal

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





B=3.8T
X decay |Z|<1.5m
Tracks arrive at |Z|=3.2m

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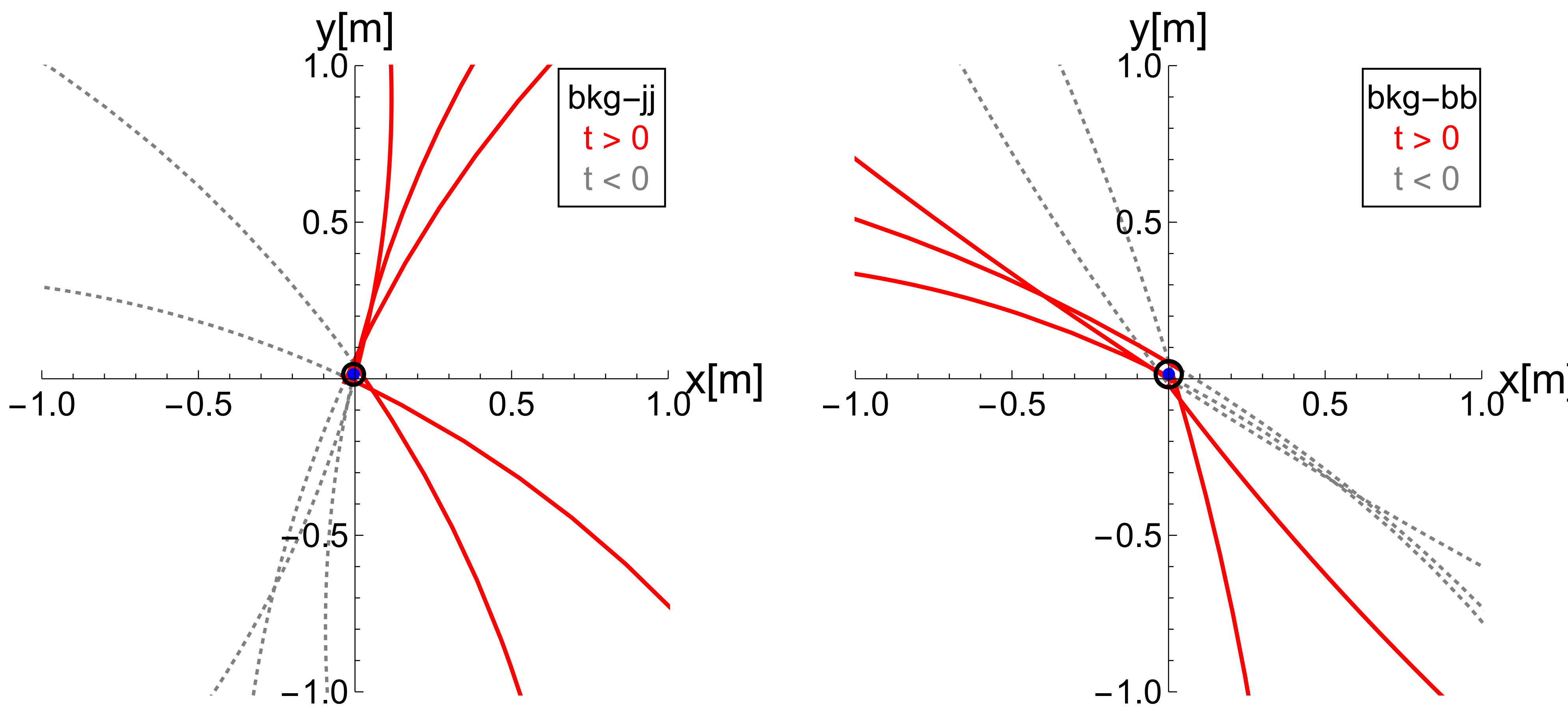
The SM backgrounds

- QCD backgrounds
  - Most of them are prompt



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

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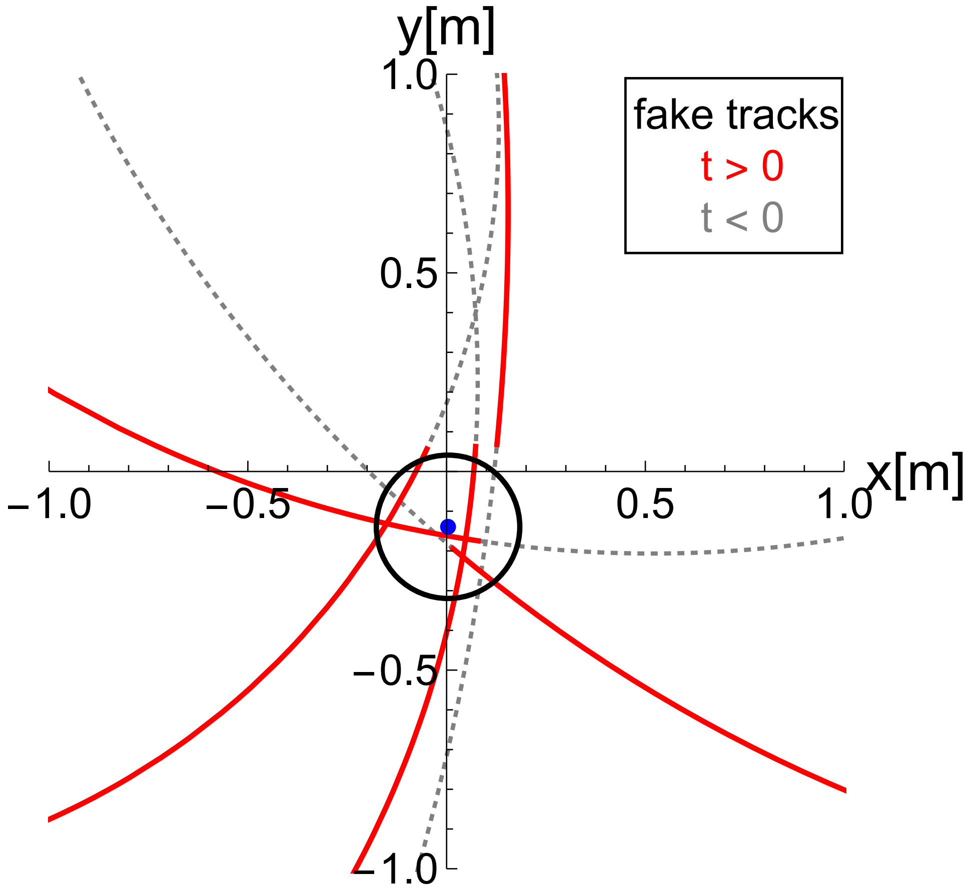
The SM backgrounds

- 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

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

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

  - R_i is the curvature of the ith track, $\{x^{cen}, y^{cen}\}$ are the center of the track
  - We obtain the fitted DV {x, y}, and define $r_{\mathrm{DV}} = \sqrt{x^2+y^2}$
  - 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 $\Delta t_i = t_i - \sqrt{x_i^2+y_i^2+z_i^2}$

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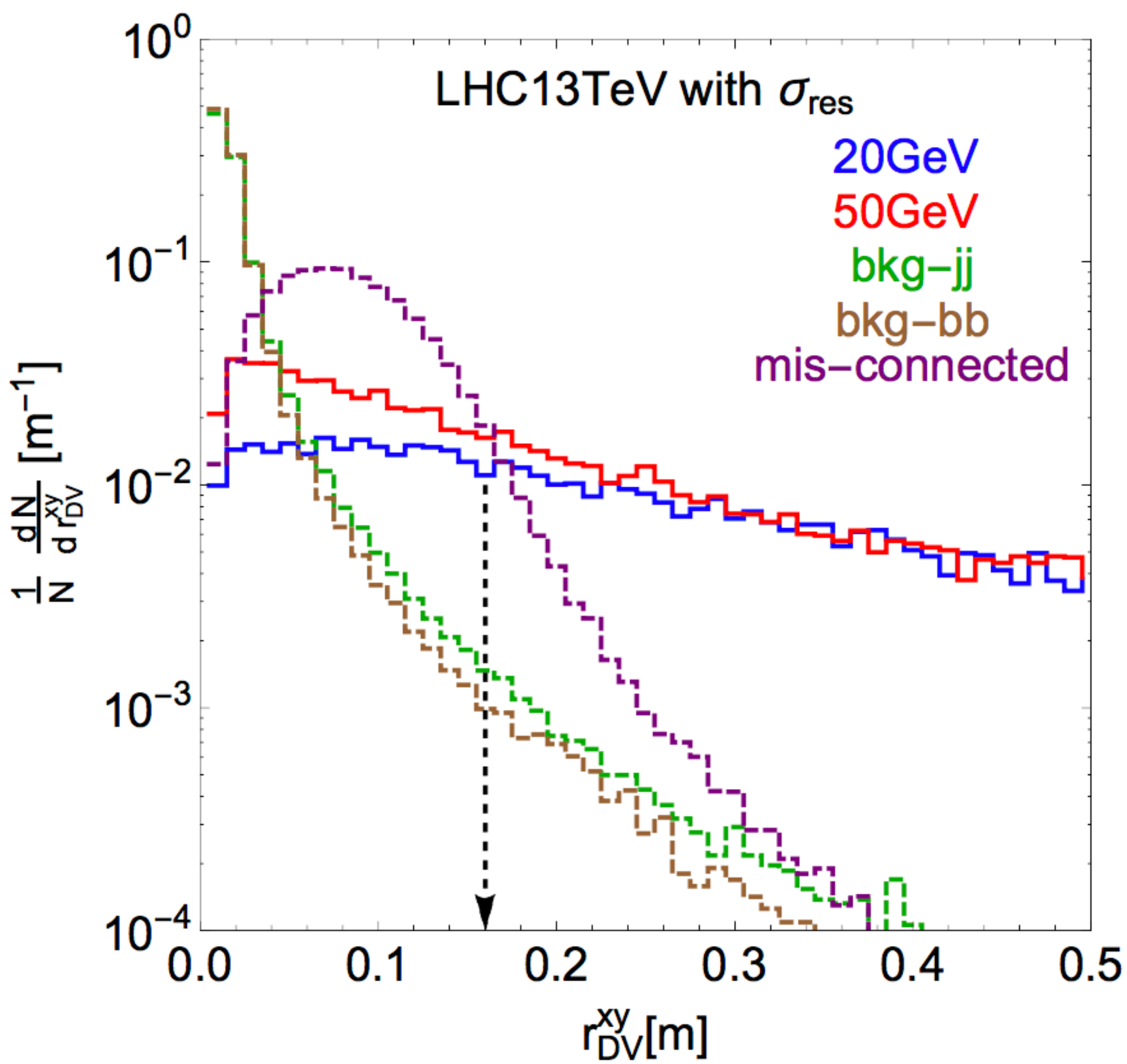
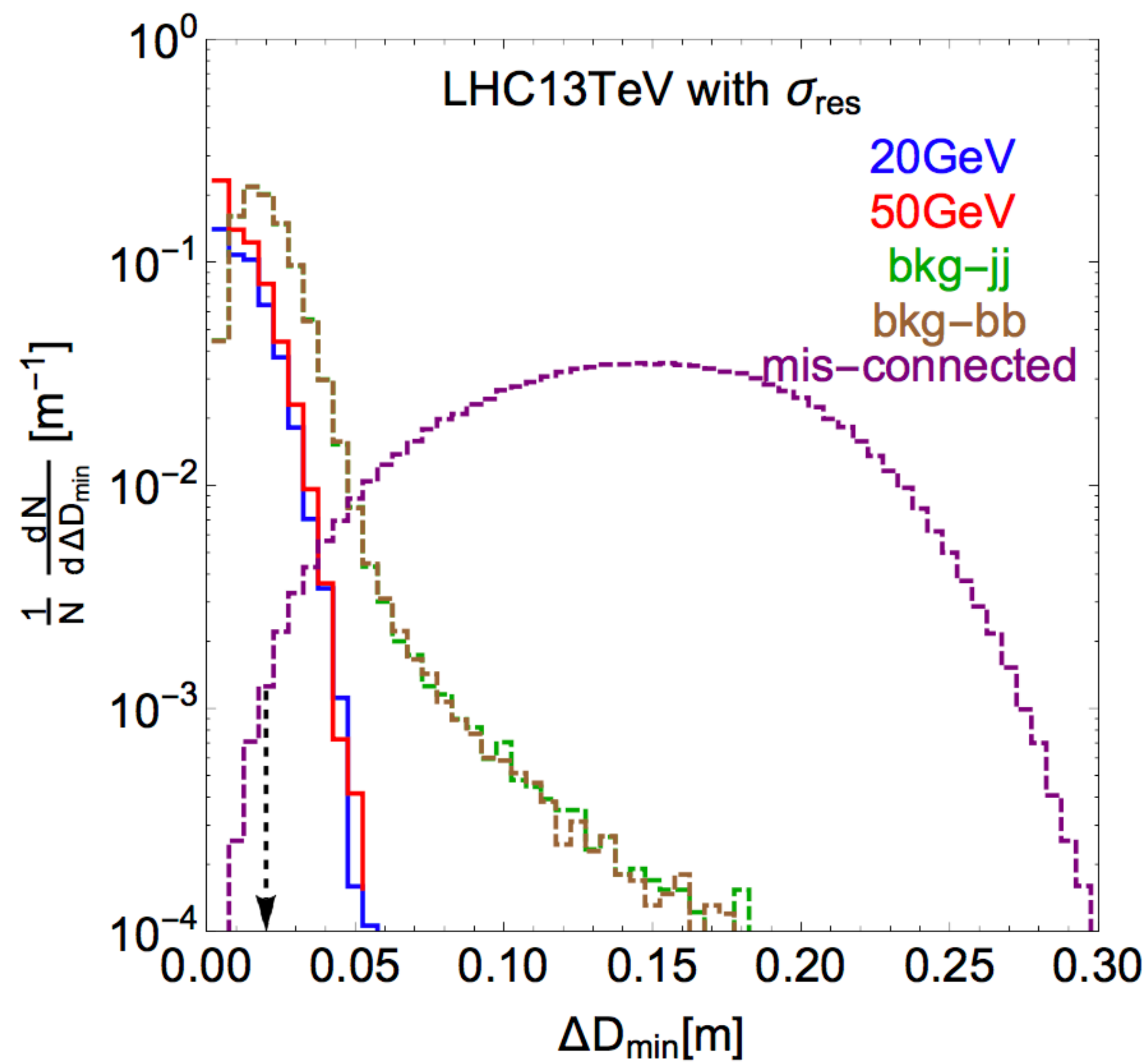
Kinematic features

- Check the kinematic distribution for

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





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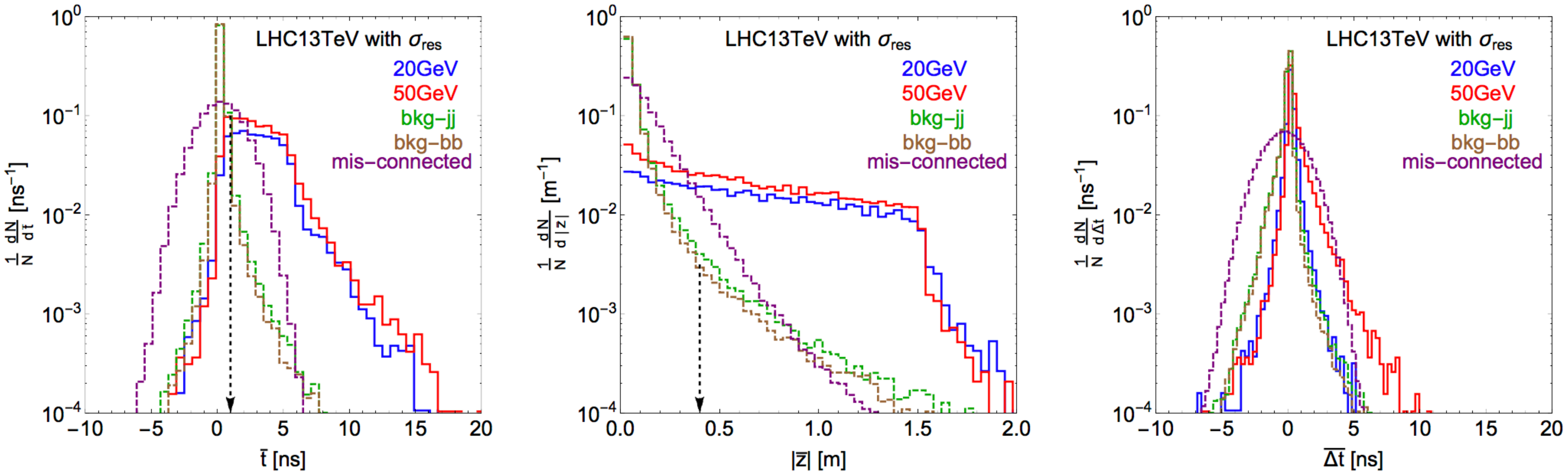
Kinematic features

- Check the kinematic distribution for

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

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



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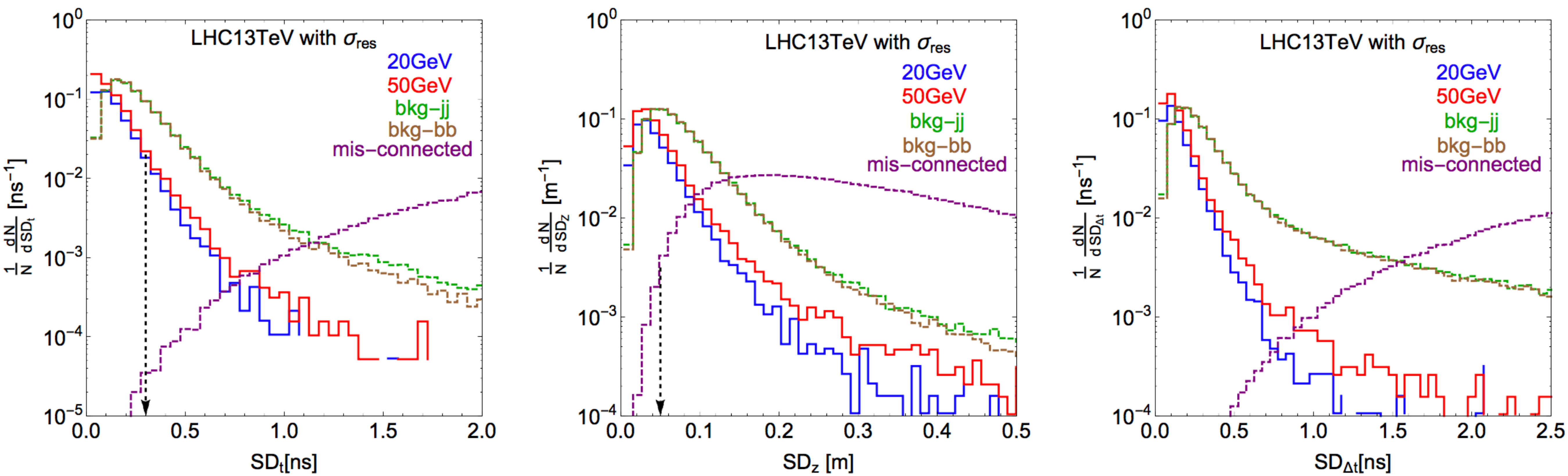
Kinematic features

- Check the kinematic distribution for

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

- Standard Deviation of the tracks quantities



The cut flow table

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

type of bkg	N_{ini}	5 tracks	$r_{\text{DV}}^{\text{xy}} > 0.16\text{m}$	$\Delta D_{\text{min}} < 0.02\text{m}$	$\bar{t} > 1$ ns	$\text{SD}_{\text{t}} < 0.3$ ns	$\bar{z} > 0.4$ m	$\text{SD}_{\text{z}} < 0.05$ m	ϵ_{pre}	$(d_0^T > 0.03\text{m})^5$	N_{fin}
jj dijet	5.1×10^{14}	9.4×10^{-1}	1.0×10^{-2} *	8.7×10^{-1}	3.0×10^{-2} *	7.3×10^{-1}	3.4×10^{-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	7.7×10^{-3} *	9.2×10^{-1}	2.4×10^{-2} *	7.4×10^{-1}	2.7×10^{-2} *	4.9×10^{-1}	2.9×10^{-1}	$(6.5 \times 10^{-4})^5$	3.7×10^{-4}
mis-connected	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 $m_s = 20$ GeV	1.3×10^8BR	$0.36 \times 3.1 \times 10^{-1}$	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}	$4.3 \times 10^6 \times$ BR
ggF$m_s = 50$ GeV	1.3×10^8BR	$0.8 \times 3.5 \times 10^{-1}$	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}	$9.5 \times 10^6 \times$ BR

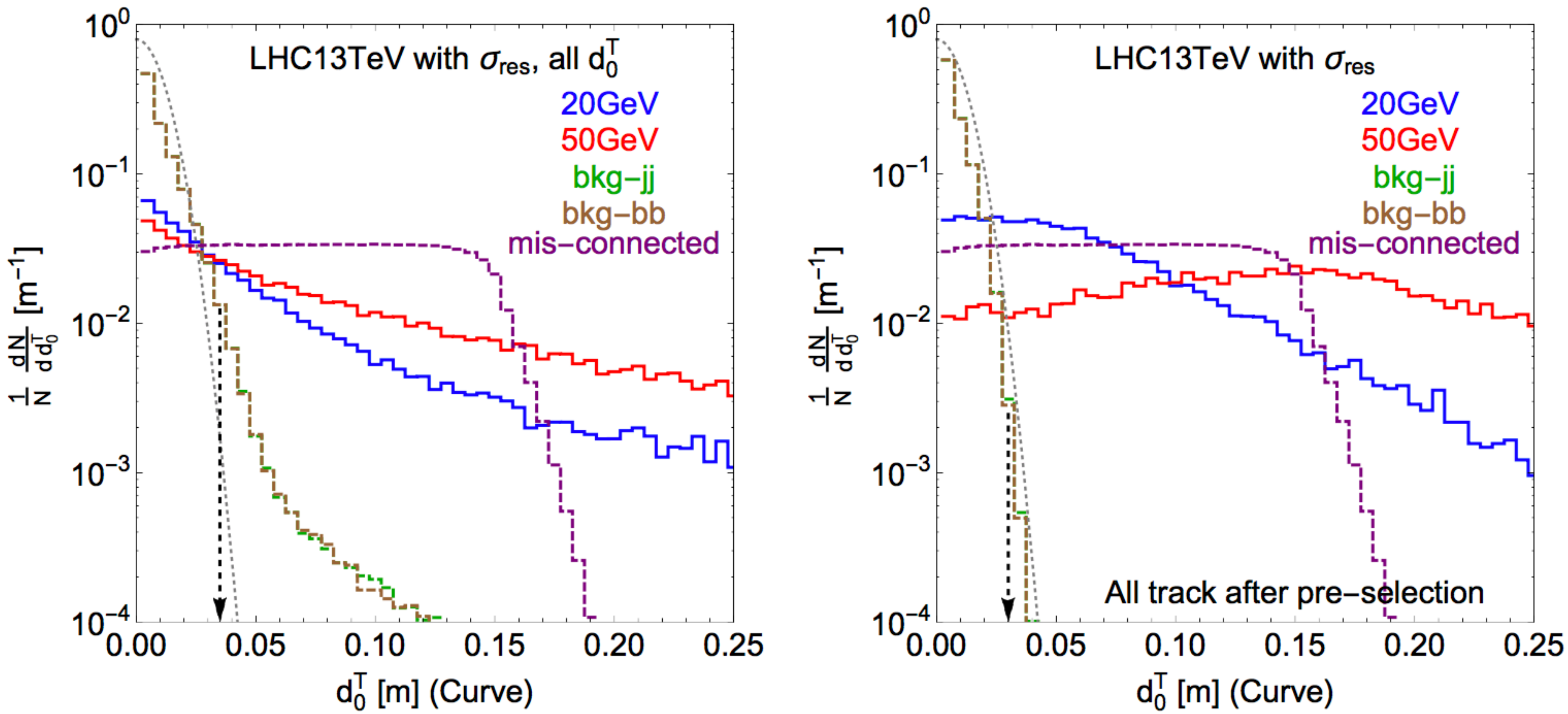
Pre-cuts for DV fitting

type of bkg	$N_{\rm ini}$	5 tracks	$r_{\rm DV}^{\rm xy} > 0.16$m	$\Delta D_{\rm min} < 0.02$m	$\bar{t} > 1$ ns	$SD_{\rm t} < 0.3$ ns	$\bar{z} > 0.4$ m	$SD_{\rm z} < 0.05$ m	$\epsilon_{\rm pre}$	$(d_0^T > 0.03{\rm m})^5$	$N_{\rm fin}$
jj dijet	5.1×10^{14}	9.4×10^{-1}	1.0×10^{-2} *	8.7×10^{-1}	3.0×10^{-2} *	7.3×10^{-1}	3.4×10^{-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	7.7×10^{-3} *	9.2×10^{-1}	2.4×10^{-2} *	7.4×10^{-1}	2.7×10^{-2} *	4.9×10^{-1}	2.9×10^{-1}	$(6.5 \times 10^{-4})^5$	3.7×10^{-4}
mis-connected	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 $m_s = 20$ GeV	1.3×10^8BR	$0.36 \times 3.1 \times 10^{-1}$	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}	$4.3 \times 10^6 \times$ BR
ggF$m_s = 50$ GeV	1.3×10^8BR	$0.8 \times 3.5 \times 10^{-1}$	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}	$9.5 \times 10^6 \times$ 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 m x 5×10^{-3} rad = 0.015 m

Transverse impact parameter cuts

- QCD bkg: impact parameter cuts
  - displacement comes from angular resolution

type of bkg	N_{ini}	5 tracks	$r_{\text{DV}}^{\text{xy}} > 0.16\text{m}$	$\Delta D_{\text{min}} < 0.02\text{m}$	$\bar{t} > 1$ ns	$\text{SD}_{\text{t}} < 0.3$ ns	$\bar{z} > 0.4$ m	$\text{SD}_{\text{z}} < 0.05$ m	ϵ_{pre}	$(d_0^T > 0.03\text{m})^5$	N_{fin}
jj dijet	5.1×10^{14}	9.4×10^{-1}	1.0×10^{-2} *	8.7×10^{-1}	3.0×10^{-2} *	7.3×10^{-1}	3.4×10^{-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	7.7×10^{-3} *	9.2×10^{-1}	2.4×10^{-2} *	7.4×10^{-1}	2.7×10^{-2} *	4.9×10^{-1}	2.9×10^{-1}	$(6.5 \times 10^{-4})^5$	3.7×10^{-4}
mis-connected	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 $m_s = 20$ GeV	1.3×10^8BR	$0.36 \times 3.1 \times 10^{-1}$	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}	$4.3 \times 10^6 \times$ BR
ggF$m_s = 50$ GeV	1.3×10^8BR	$0.8 \times 3.5 \times 10^{-1}$	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}	$9.5 \times 10^6 \times$ BR

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Independence check is necessary

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

type of bkg	$N_{\rm ini}$	5 tracks	$r_{\rm DV}^{\rm xy} > 0.16$m	$\Delta D_{\rm min} < 0.02$m	$\bar{t} > 1$ ns	$SD_{\rm t} < 0.3$ ns	$\bar{z} > 0.4$ m	$SD_{\rm z} < 0.05$ m	$\epsilon_{\rm pre}$	$(d_0^T > 0.03{\rm m})^5$	$N_{\rm fin}$
jj dijet	5.1×10^{14}	9.4×10^{-1}	1.0×10^{-2} *	8.7×10^{-1}	3.0×10^{-2} *	7.3×10^{-1}	3.4×10^{-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	7.7×10^{-3} *	9.2×10^{-1}	2.4×10^{-2} *	7.4×10^{-1}	2.7×10^{-2} *	4.9×10^{-1}	2.9×10^{-1}	$(6.5 \times 10^{-4})^5$	3.7×10^{-4}
mis-connected	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 $m_s = 20$ GeV	1.3×10^8BR	$0.36 \times 3.1 \times 10^{-1}$	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}	$4.3 \times 10^6 \times$ BR
ggF$m_s = 50$ GeV	1.3×10^8BR	$0.8 \times 3.5 \times 10^{-1}$	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}	$9.5 \times 10^6 \times$ BR

- Independence check

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

  - ~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

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

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

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

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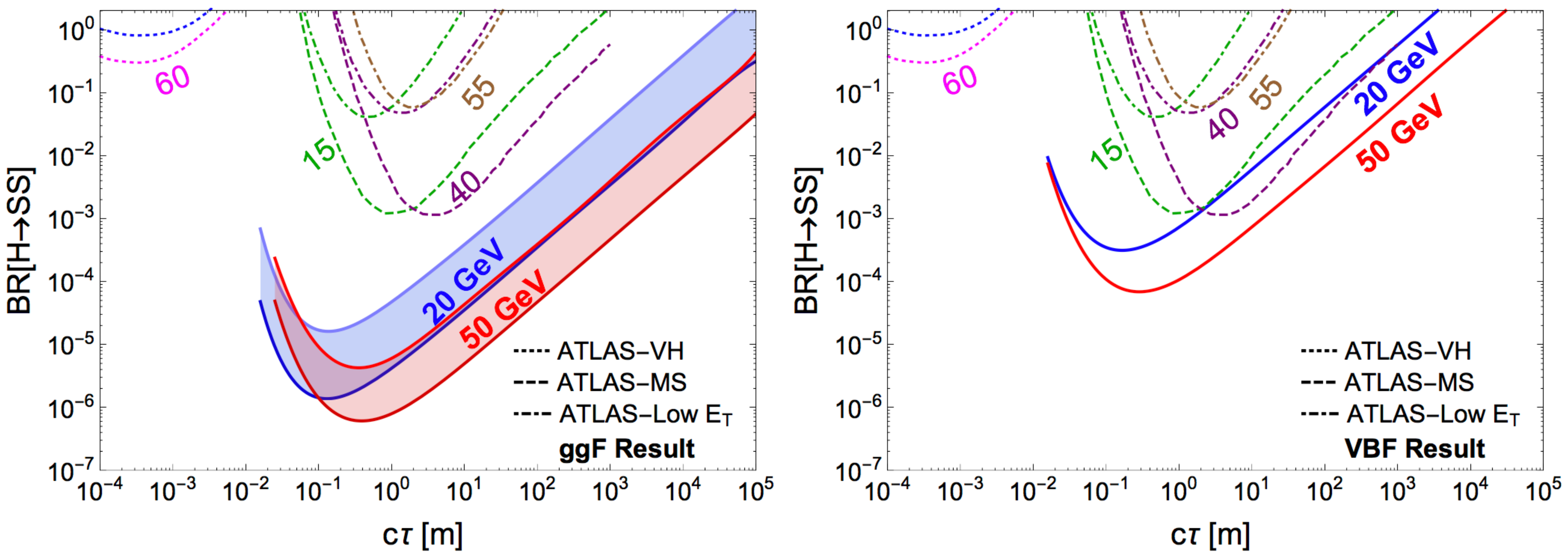
The preliminary results for HL-LHC



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

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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!