Searching for long-lived particles with the CMS High Granularity Calorimeter

Jia Liu
The Enrico Fermi Institute, University of Chicago

Preliminary results working with Zhen Liu, Liantao Wang and Xiaoping Wang

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LLP motivation

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

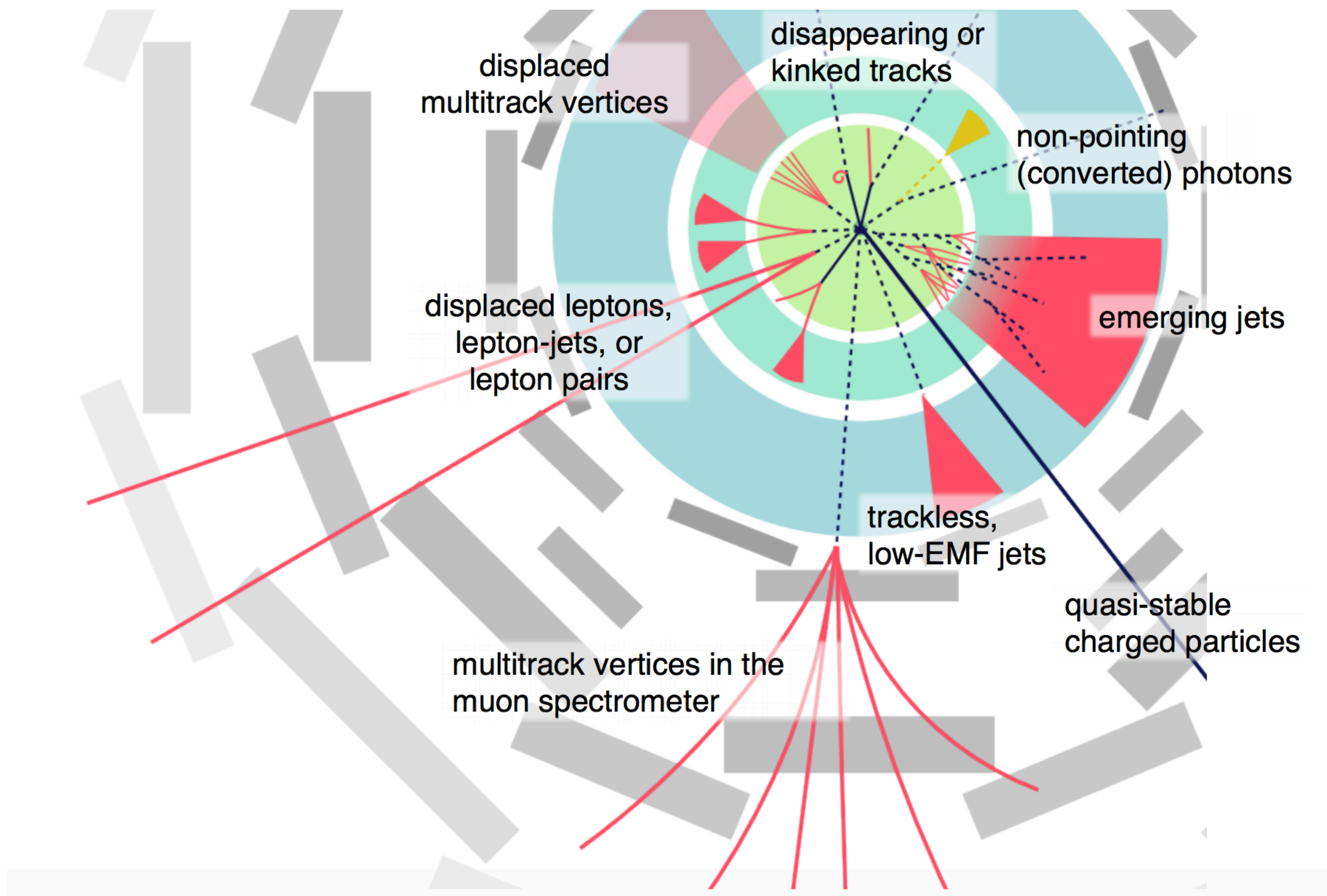
- Suppression from heavy mass scale:
  muon/charged pion, gauge mediated spontaneous breaking Supersymmetry

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

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

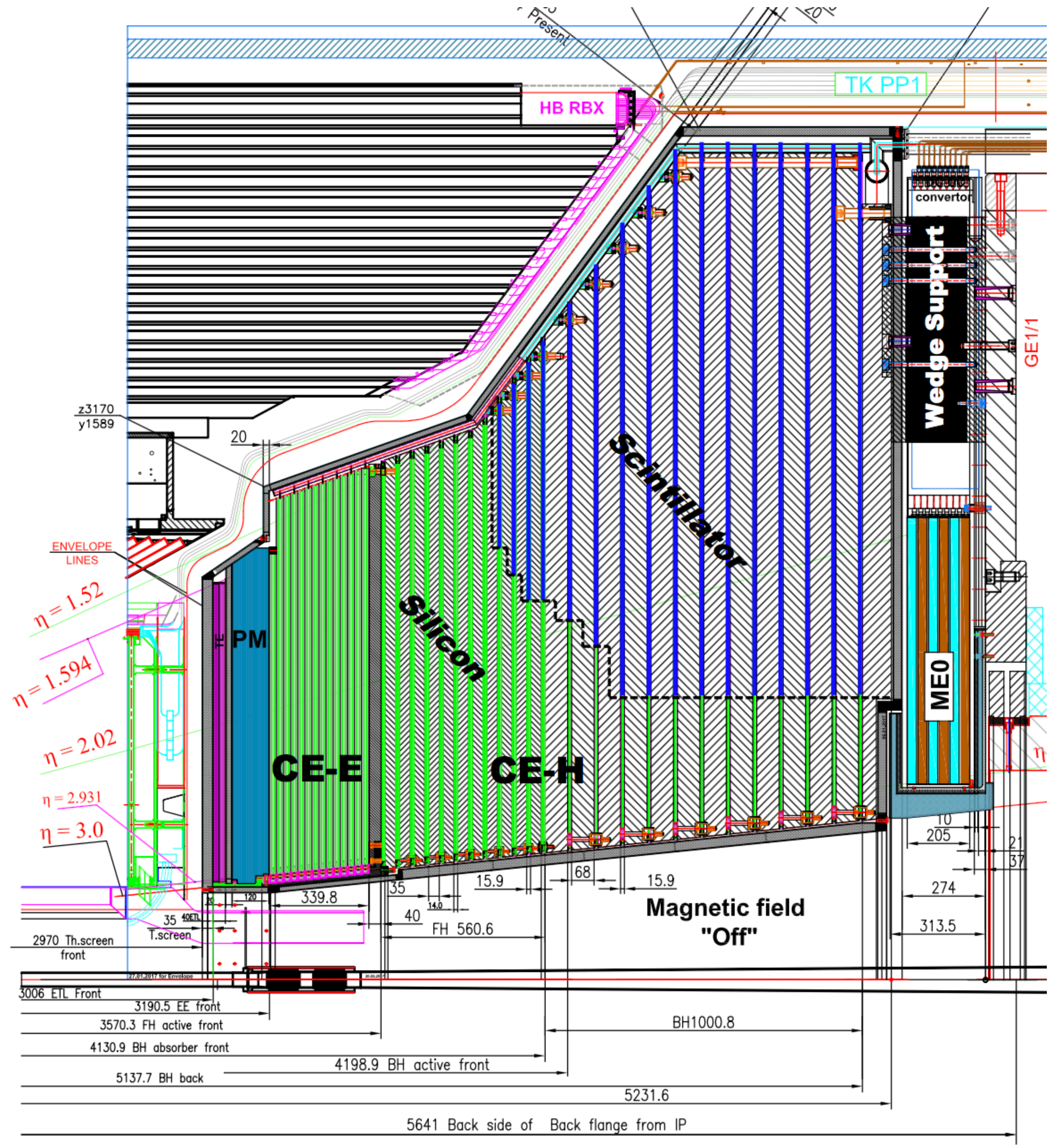
LLP searches at LHC

- ATLAS/CMS searches
  - Tracker system
  - Calorimeters
  - Muon system



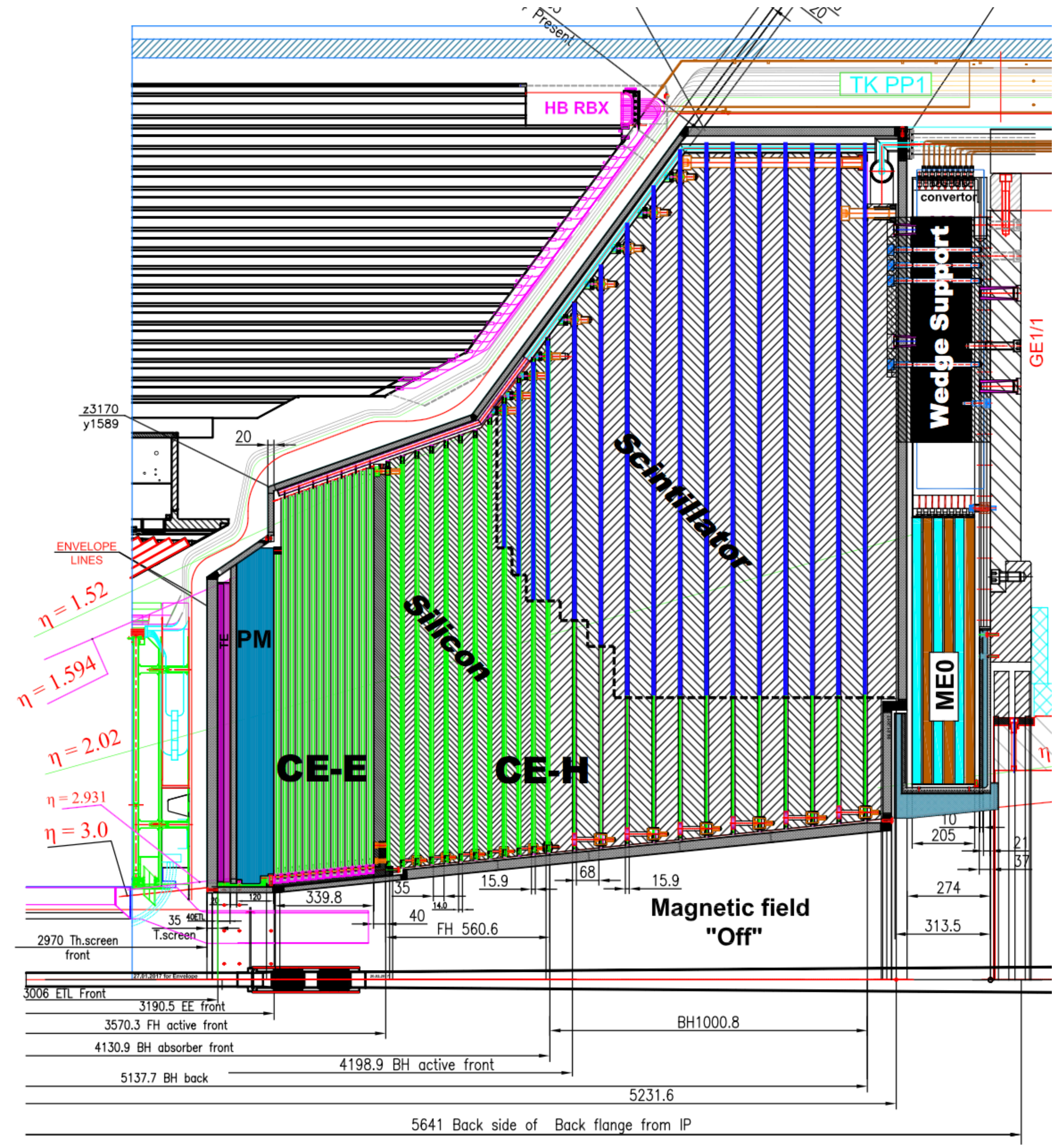
CMS High Granularity Calorimeter

- 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 @ 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

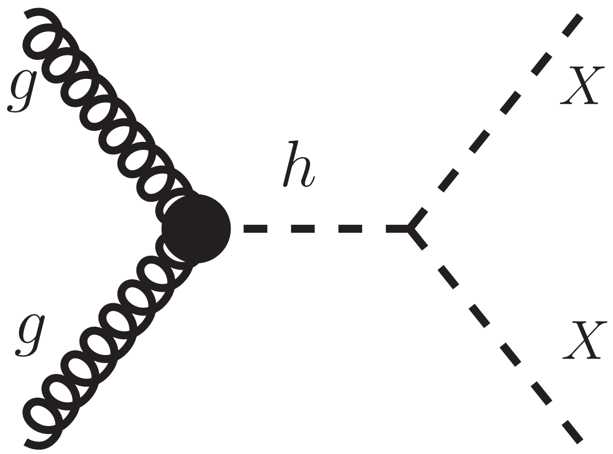


What is the HGCAL sensitivity for LLP?

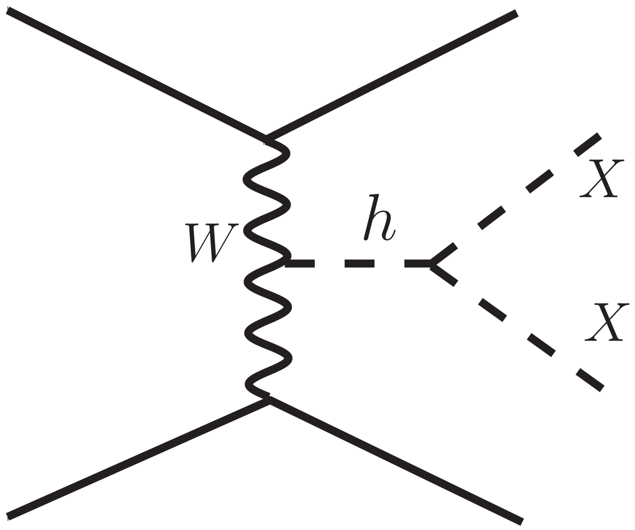
LLP model

- 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



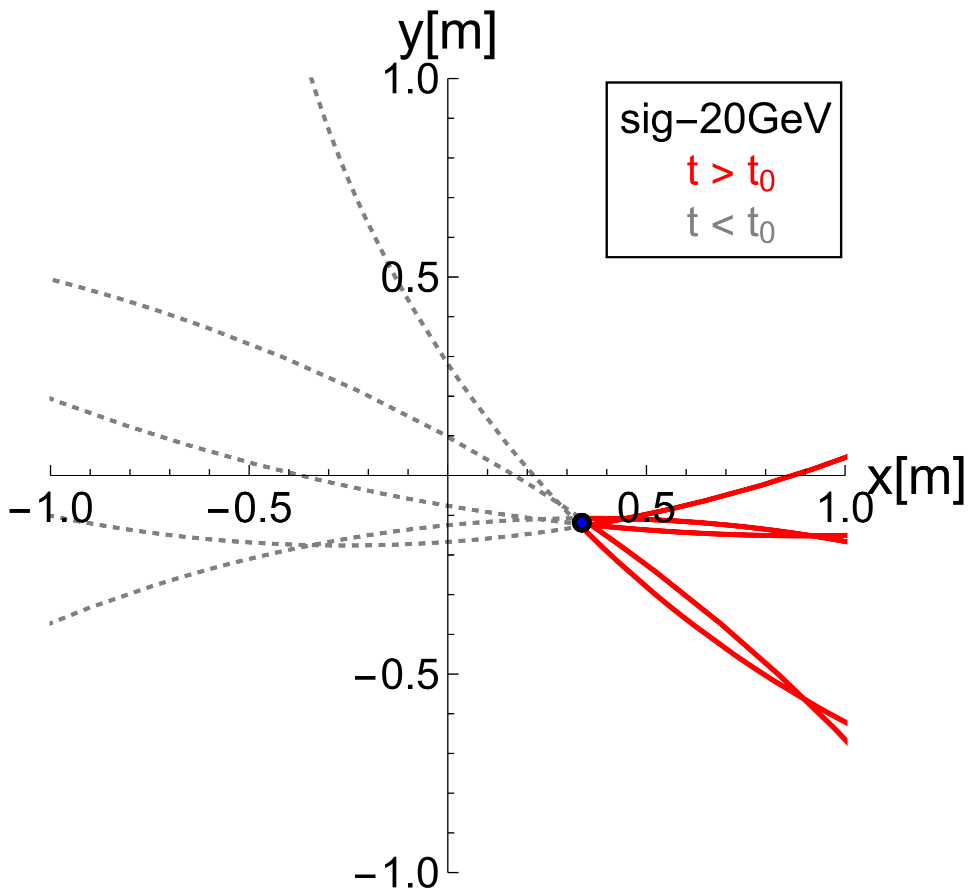
- LLP decay

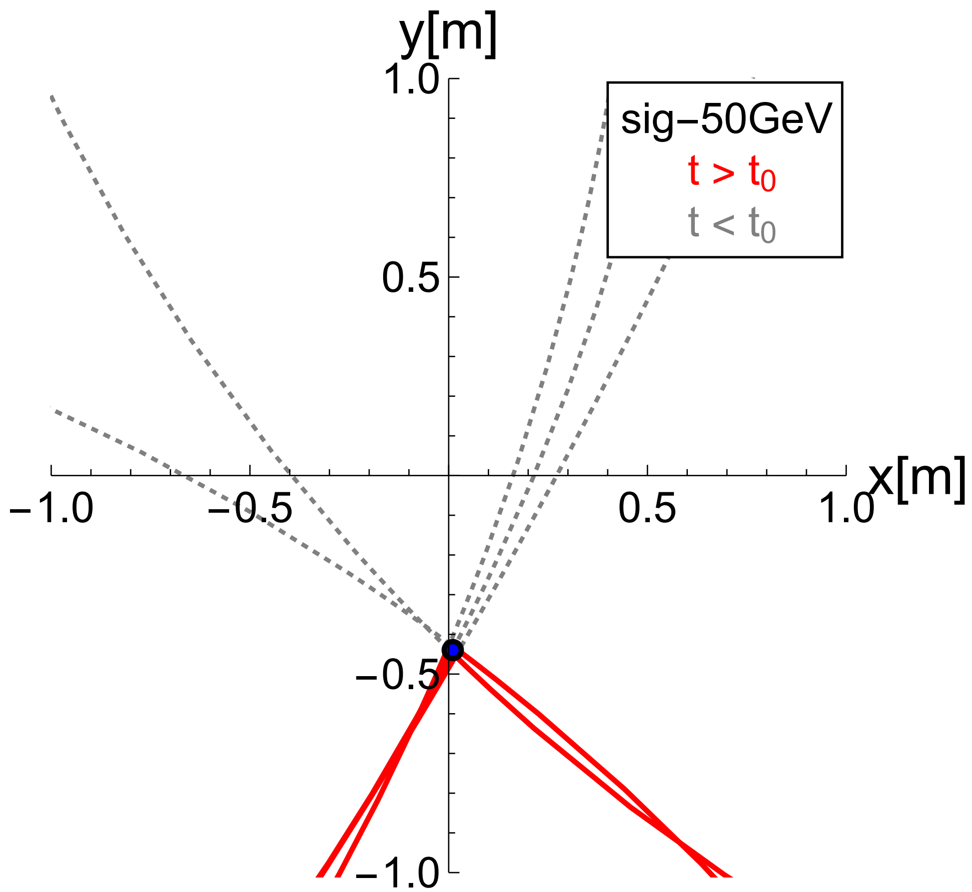
$$X \to \bar{b}b$$

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

The signature of the signal

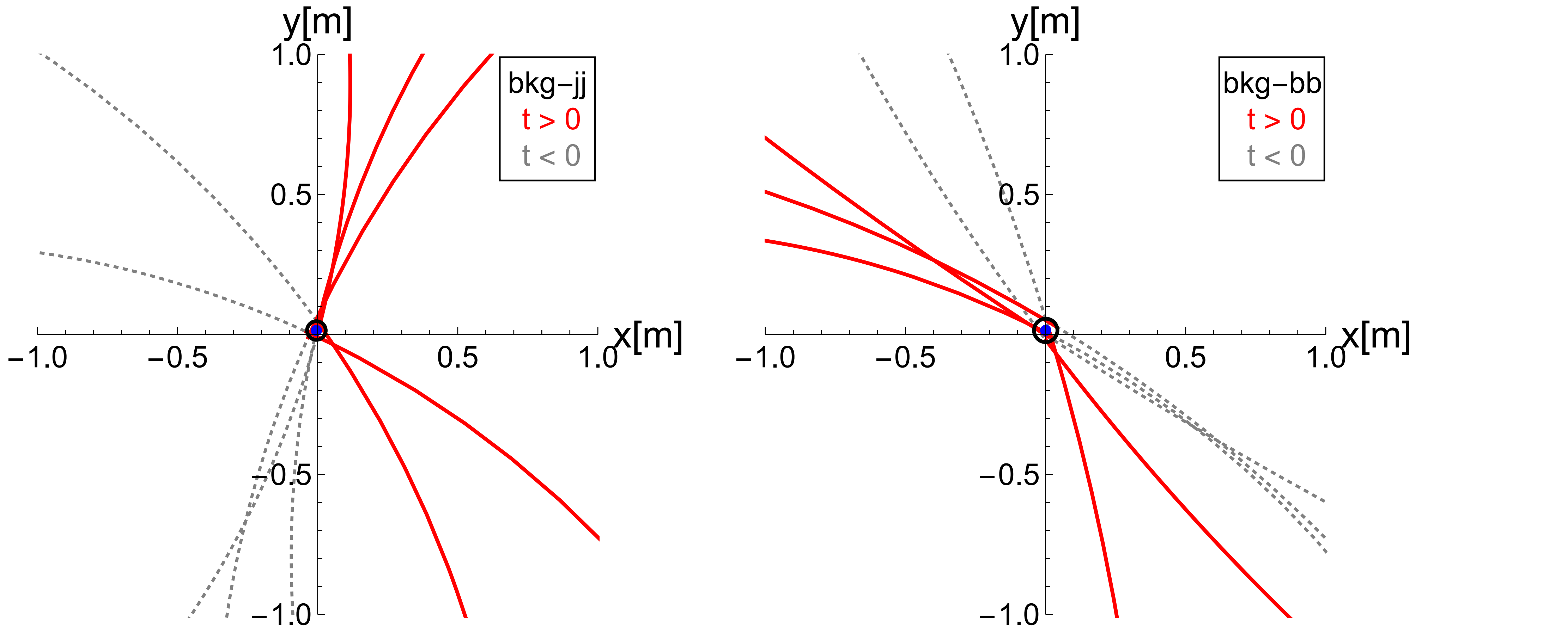
- Multiple tracks with large impact parameters from the same displaced origin





The SM backgrounds

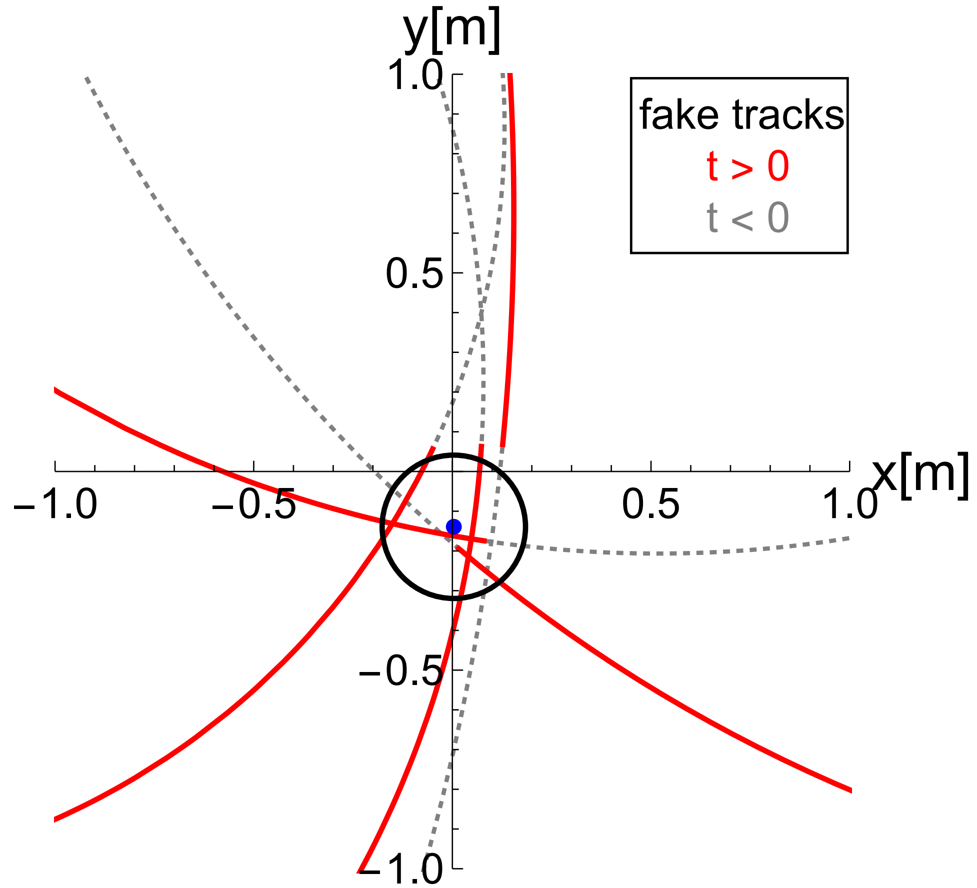
- QCD backgrounds
  - Most of them are prompt



- 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

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

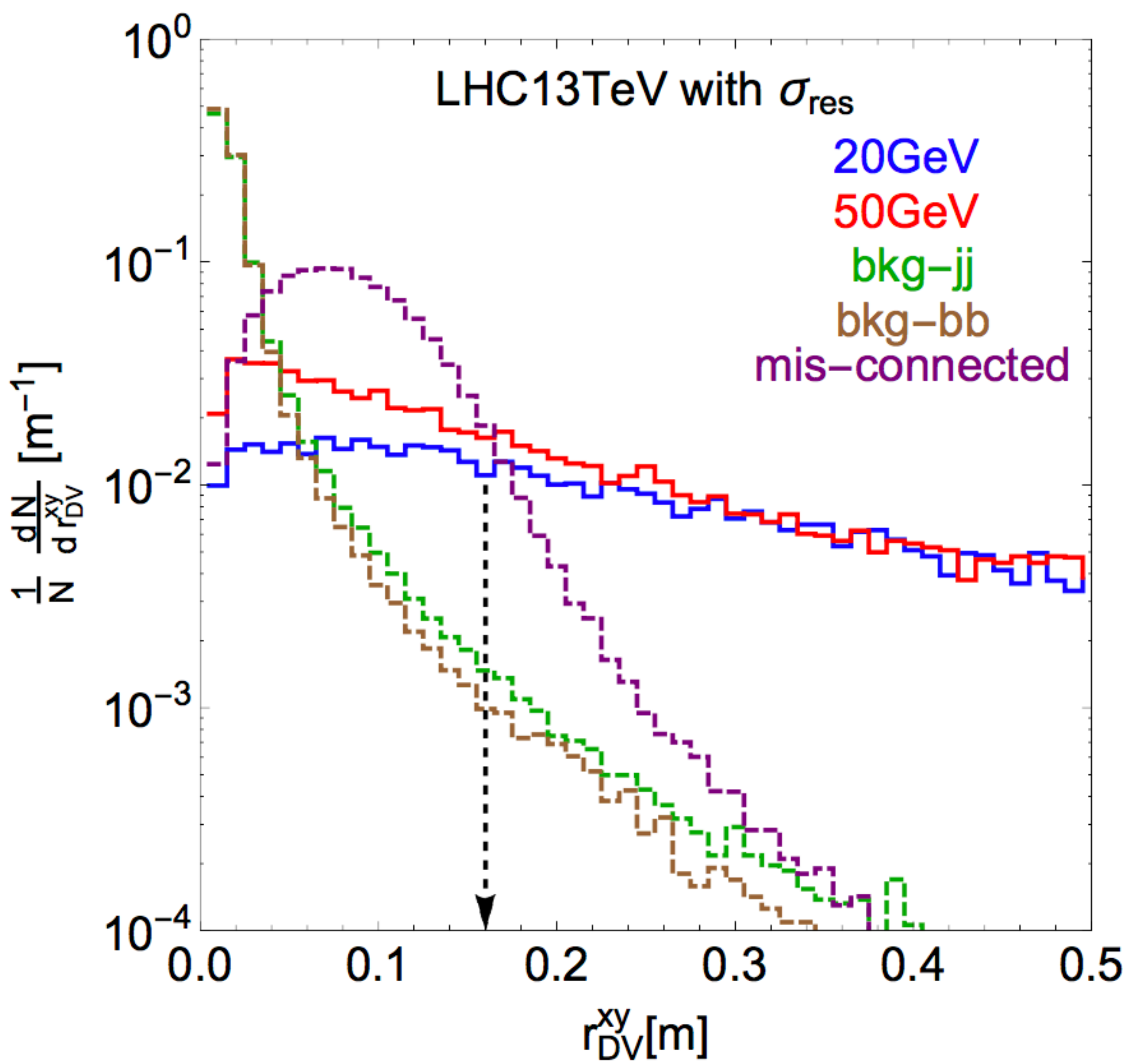
$$\Delta \mathrm{D} \equiv \sqrt{\sum_{i=1}^{5} \left(\sqrt{(x - x_i^{\mathrm{cen}})^2 + (y - y_i^{\mathrm{cen}})^2} - R_i \right)^2}$$

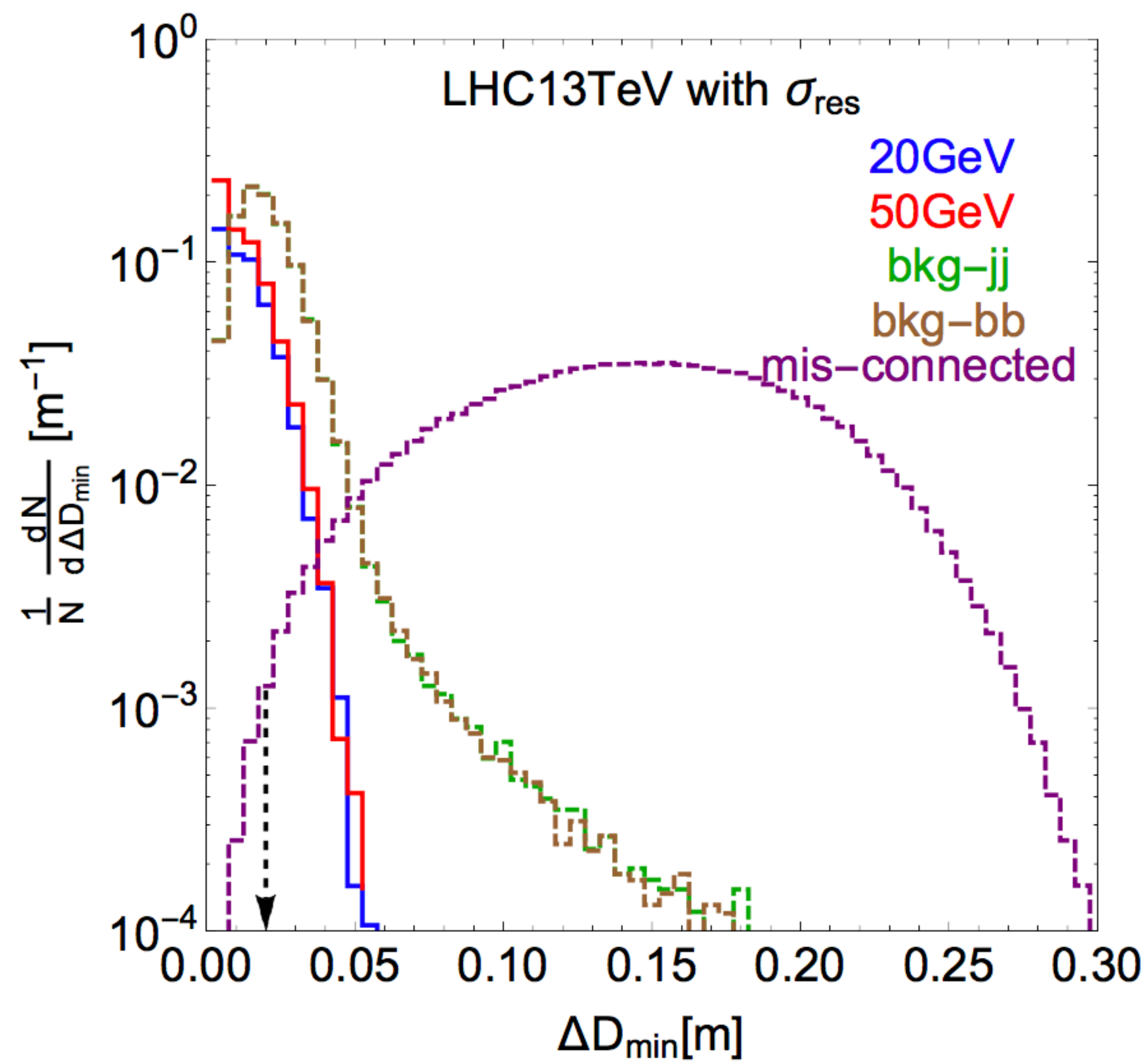
  - R_i is the curvature of the ith track, $\{x^{cen}, y^{cen}\}$ are the center of the track
  - We obtain the fitted DV {x, y}, and define $r_{\mathrm{DV}} = \sqrt{x^2 + y^2}$
  - The goodness of fit ΔD_{min}
- With the angular velocity of the track, we can determine the referencing point to DV for each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

Kinematic features

- Check the kinematic distribution for

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





Kinematic features

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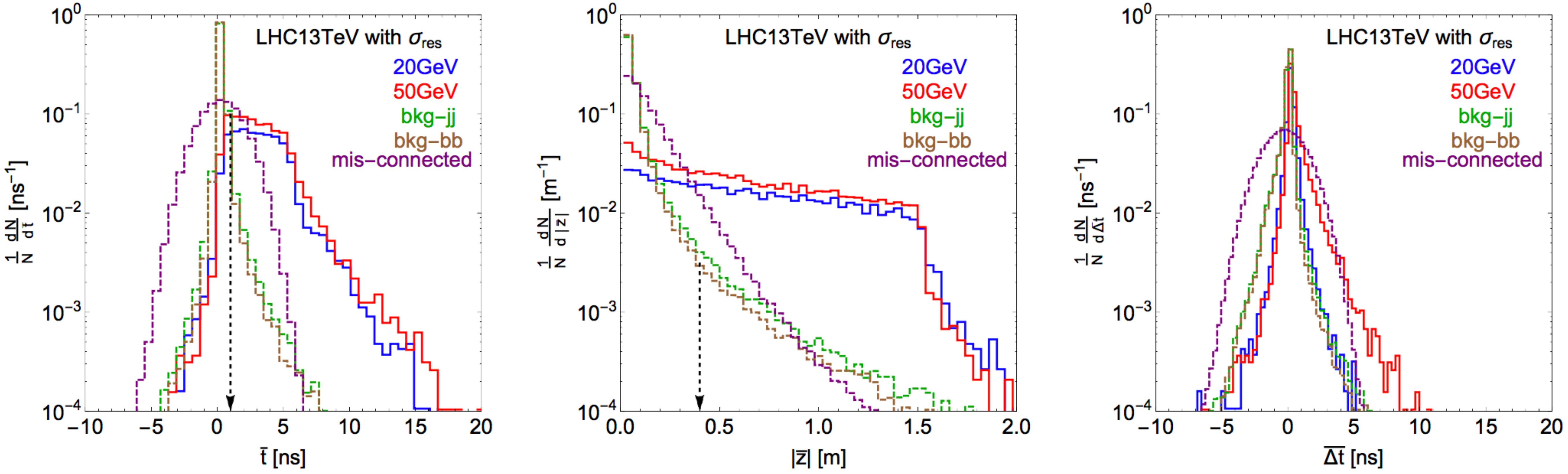
$$\mathrm{r_{DV}},\ \Delta\mathrm{D_{min}},\ \bar{\mathrm{t}},\ \bar{\mathrm{z}},\ \overline{\Delta\mathrm{t}},\ \mathrm{SD_t},\ \mathrm{SD_z},\ \mathrm{SD_{\Delta t}}.$$

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

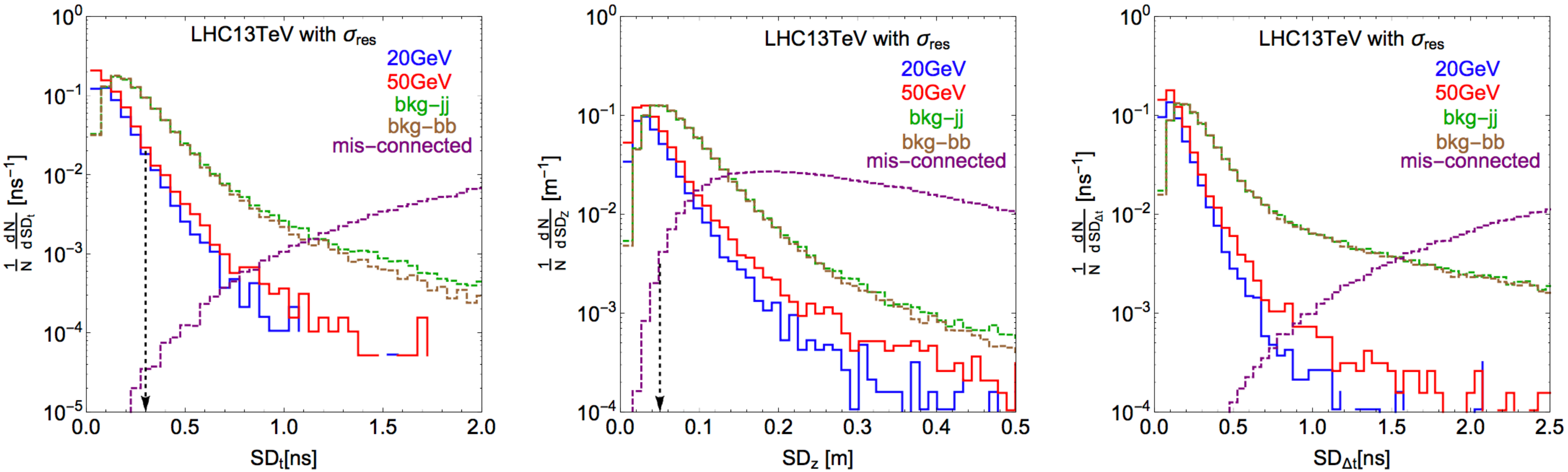


Kinematic features

- 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 (following Y. Gurstein 1705.04321), HL-LHC 10^8 sec

type of bkg	$N_{\rm ini}$	5 tracks	$r^{xy}_{\rm DV} > 0.16$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

Pre-cuts for DV fitting

type of bkg	$N_{\rm ini}$	5 tracks	$\rm r_{DV}^{xy} > 0.16m$	$\Delta \rm D_{min} < 0.02m$	$\bar{t} > 1$ ns	$\rm SD_t < 0.3$ ns	$\bar{z} > 0.4$ m	$\rm SD_z < 0.05$ m	$\epsilon_{\rm pre}$	$(d_0^T > 0.03\rm m)^5$	$N_{\rm fin}$
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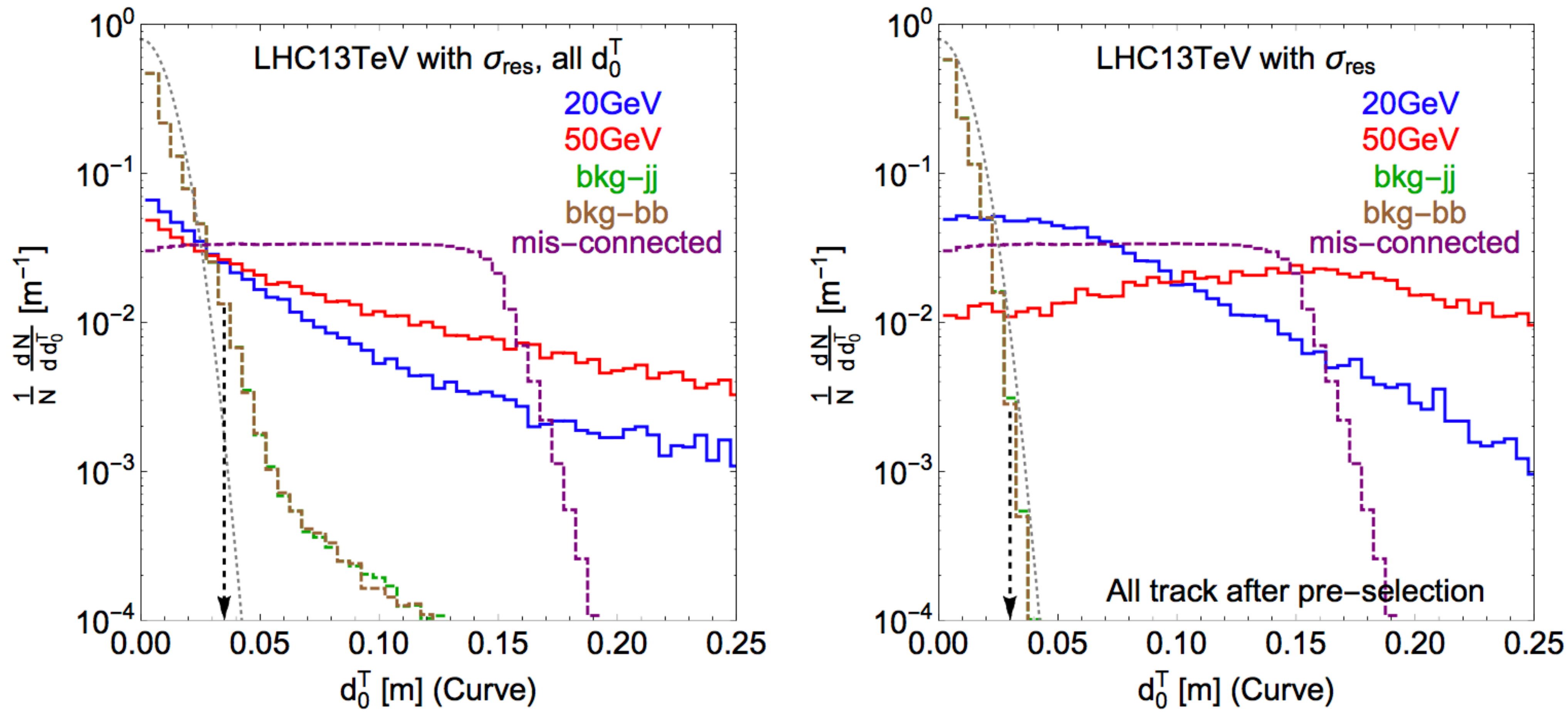
- Fake track bkg suppressed because its random origin

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	$N_{\rm ini}$	5 tracks	$\rm r_{DV}^{xy} > 0.16m$	$\Delta \rm D_{min} < 0.02m$	$\bar{t} > 1$ ns	$\rm SD_t < 0.3$ ns	$\bar{z} > 0.4$ m	$\rm SD_z < 0.05$ m	$\epsilon_{\rm pre}$	$(d_0^T > 0.03\rm m)^5$	$N_{\rm fin}$
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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	$\rm r^{xy}_{DV} > 0.16m$	$\Delta \rm D_{min} < 0.02m$	$\bar{t} > 1$ ns	$\rm SD_t < 0.3$ ns	$\bar{z} > 0.4$ m	$\rm SD_z < 0.05$ m	$\epsilon_{\rm pre}$	$(d_0^T > 0.03{\rm m})^5$	$N_{\rm fin}$
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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

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

  - ~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

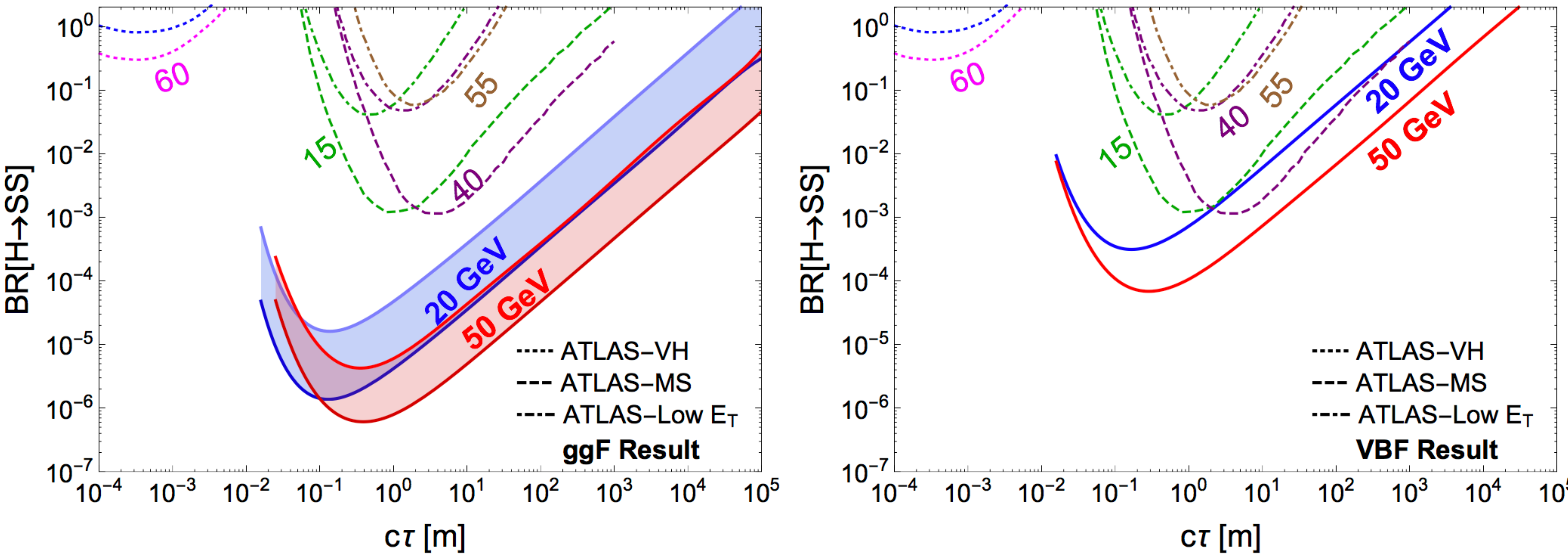
- Fake track bkg: pre-cuts are independent with each other

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

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

mis-connected	$r_{DV}^{xy} > 0.16$ m	$\Delta D_{min} < 0.02$ m	$\bar{t} > 1$ ns	$SD_t < 0.3$ ns	$\lvert\bar{z}\rvert > 0.4$ m	$SD_{\lvert z\rvert} < 0.05$ 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

The preliminary results for HL-LHC



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

Summary

- LLP signal in CMS HGCAL has been studied
- Signal signature: multiple tracks with large impact parameter from a common displaced vertex
- QCD background: suppressed by requirement of multiple large impact parameter
- Fake track background: suppressed by common displaced vertex fitting
- Trigger has large impact on sensitivity, low H_T and p_T cuts preferred
- ggF can reach BR~10^{-5} , while VBF BR~10^{-4}

Thank you!

Backup slides