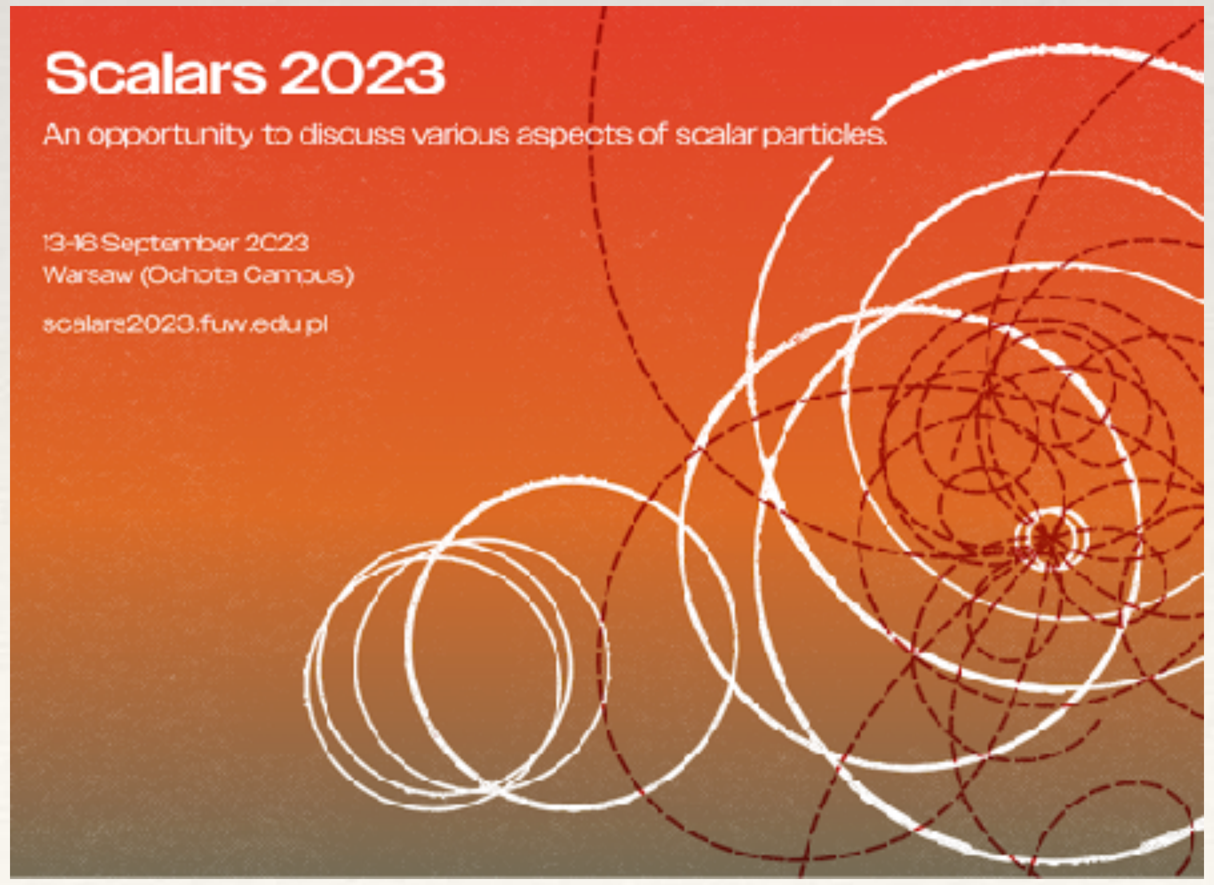
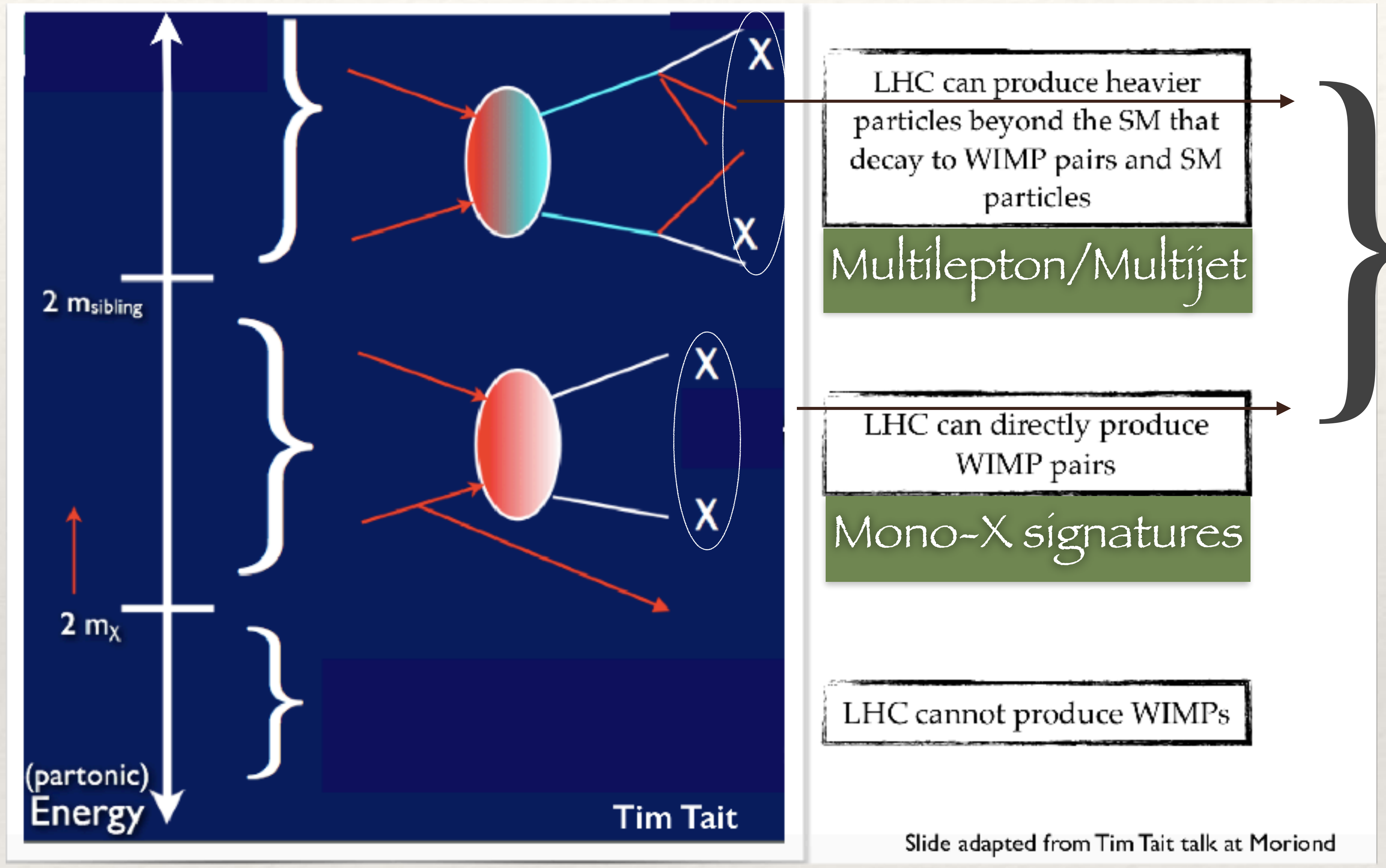
Scalars 2023, Warsaw, 15/09/23

Distinguishing Dark Matter components at Collider

Subhaditya Bhattacharya
IIT Guwahati



Collider Signal of Dark Matter



Missing Transverse Momentum (MET)

$$\not{E}_T = \sqrt{(\sum_{\ell,j,\gamma} p_x)^2 + (\sum_{\ell,j,\gamma} p_y)^2};$$

LHC, ILC
FCC,
Muon collider

Missing Energy (ME)

$$\not{E} = \sqrt{s} - \sum_{\ell,j,\gamma} E_{\text{vis}} \, ;$$

ILC/FCC
Muon collider

Missing Mass (MM)

$$\not{M}^2 = \left(\sum_i p_i - \sum_f p_f\right)^2$$

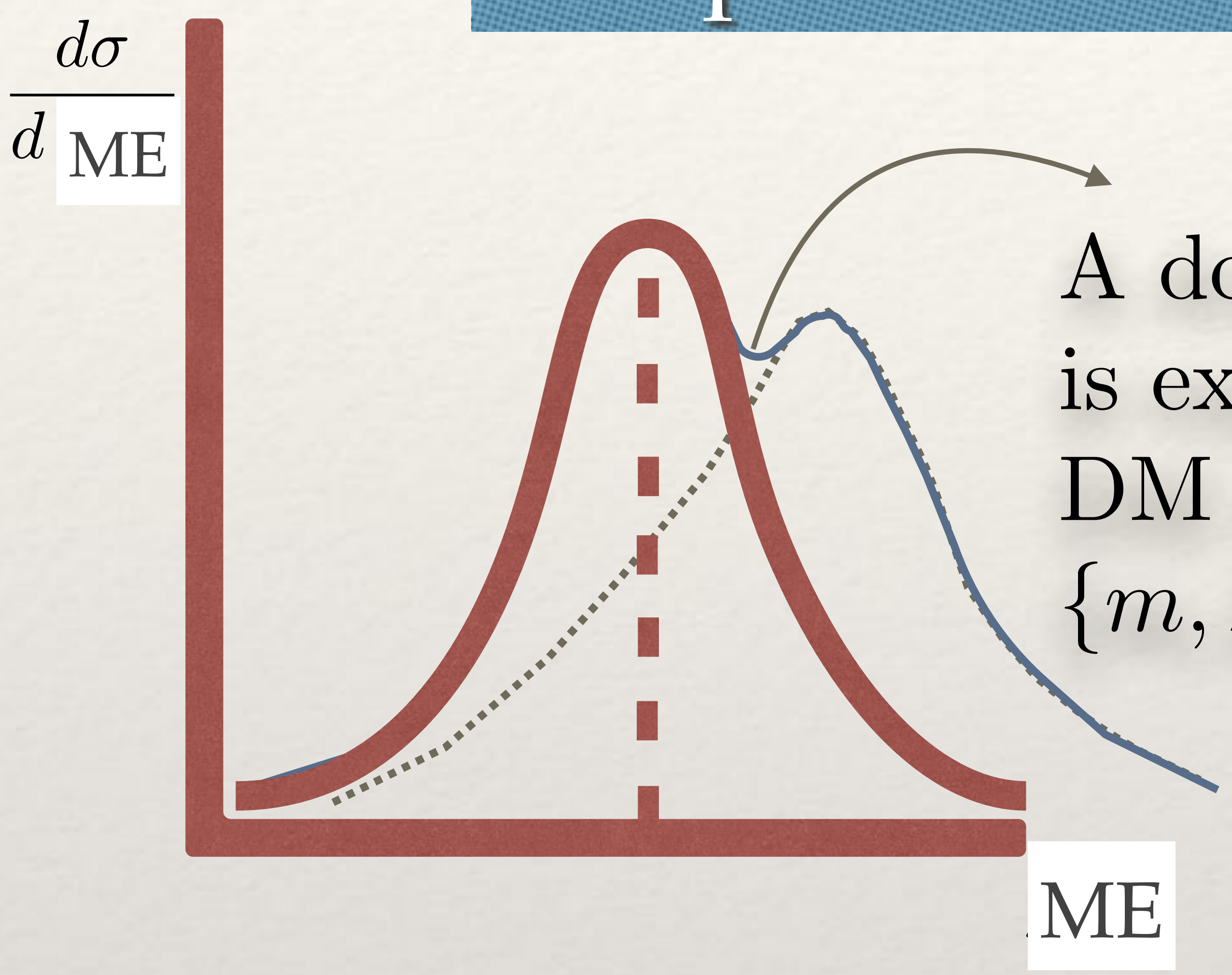
ILC/FCC
Muon Collider

Disappearing charge track, **displaced vertex signal** may also arise.

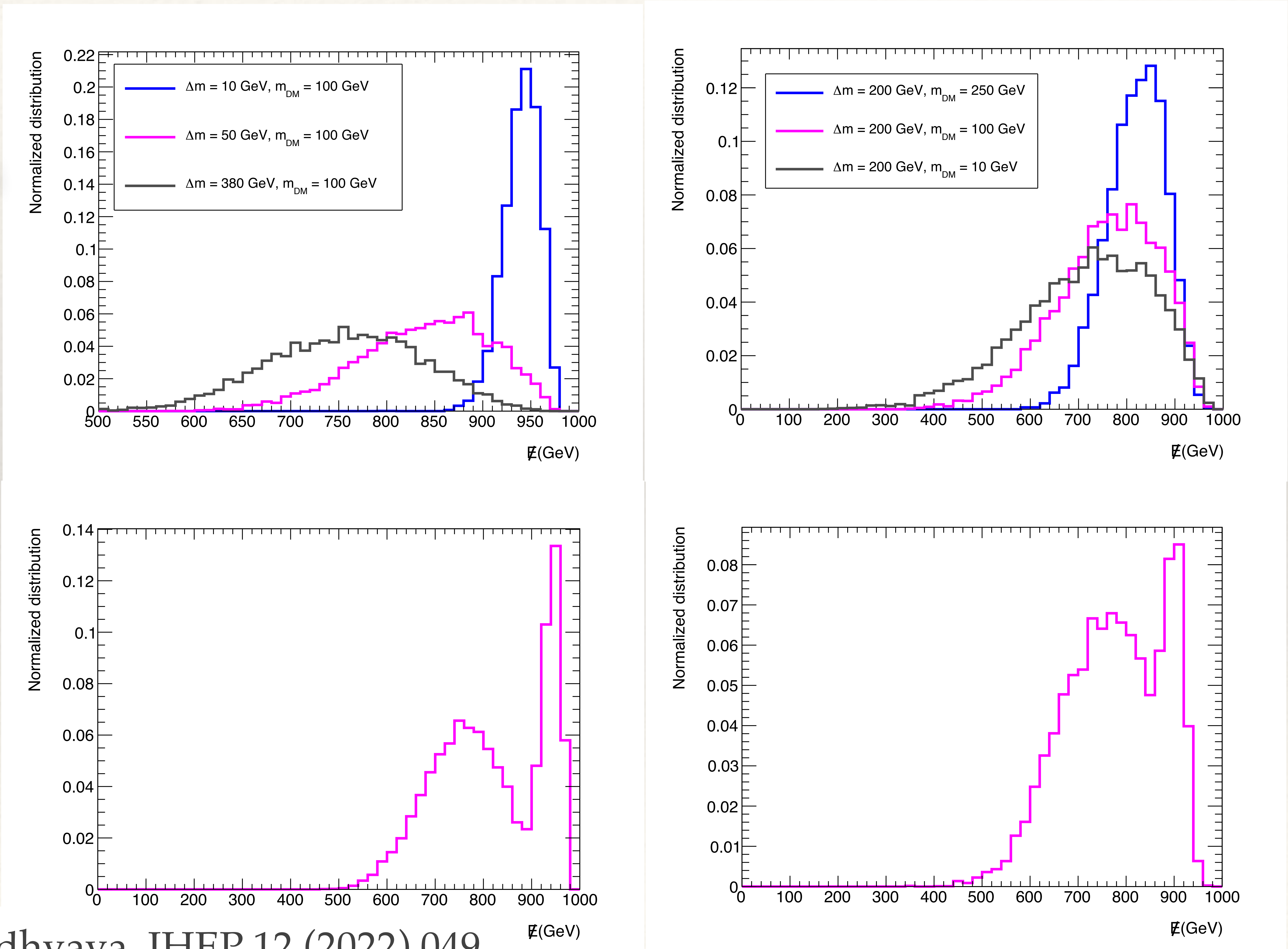
- Due to beam polarisation and longitudinal degrees of freedom, ILC has advantages over LHC.
- Due larger number of variables, multilepton signals from cascade turn more useful than mono-X signal.

If two WIMPs give rise to the same signal can we distinguish them ?

The peak of the ME distribution depends on both DM mass and splitting



A double hump is expected for different DM mass and splitting $\{m, \Delta m\}$.



Two peaks in ME/MET can be identified as a signal of the two component DM

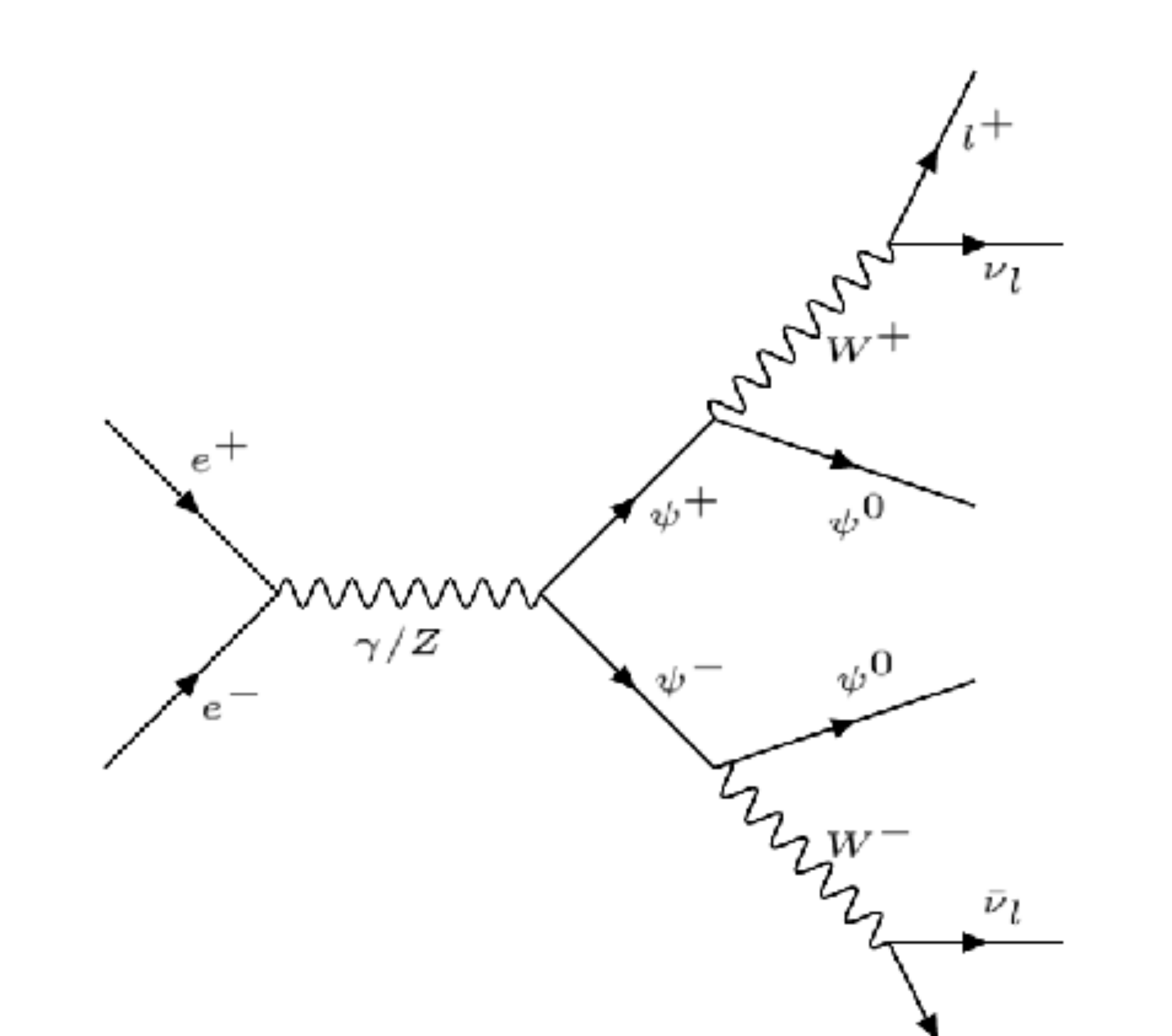
ME works better than MET as it is sensitive to DM mass plus splitting

SB, Purushottam Ghosh, Jayita Lahiri, Biswarup Mukhopadhyaya, JHEP 12 (2022) 049

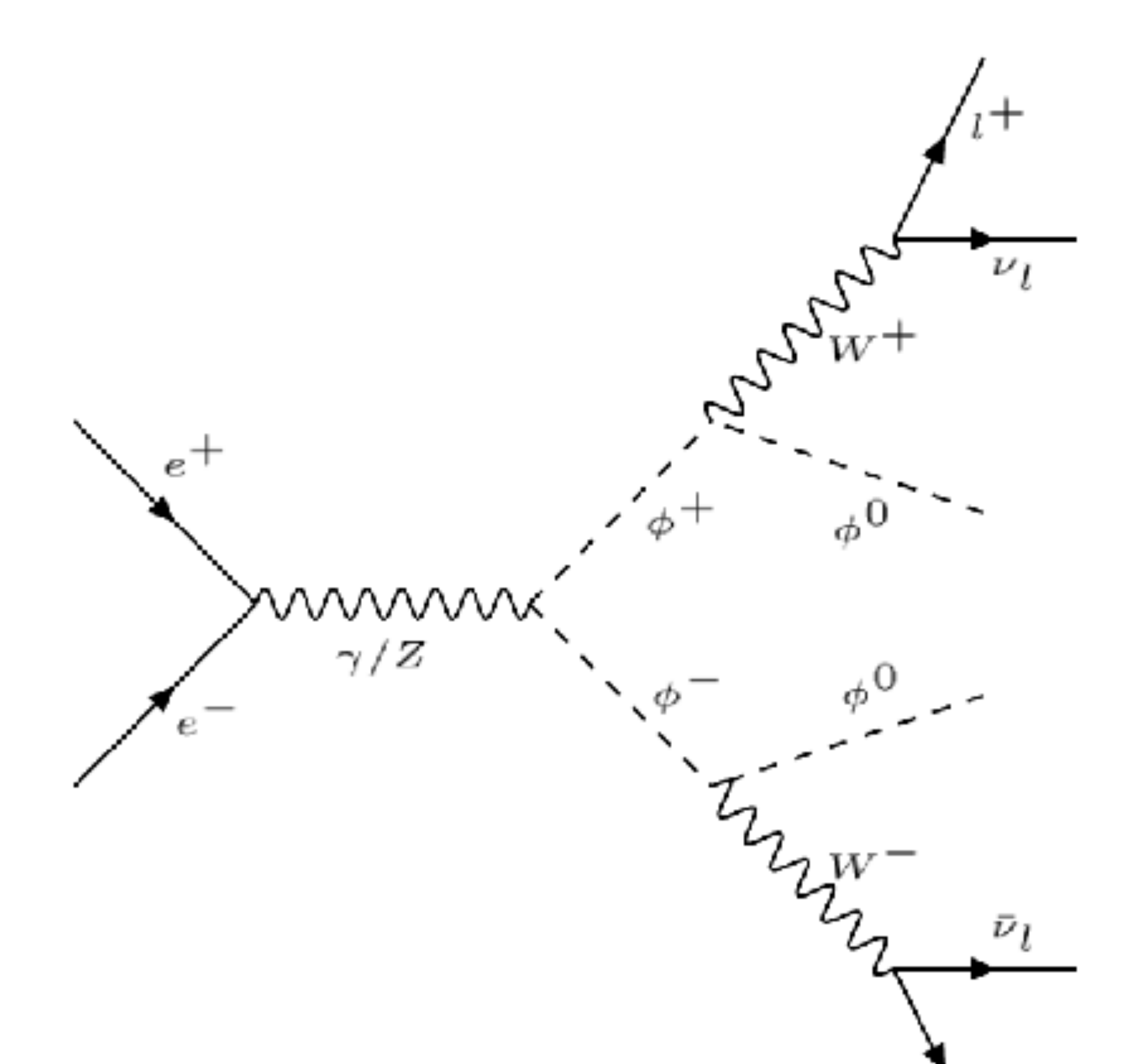
Signal plus background and beam polarisation

Hadronically quiet opposite sign dilepton

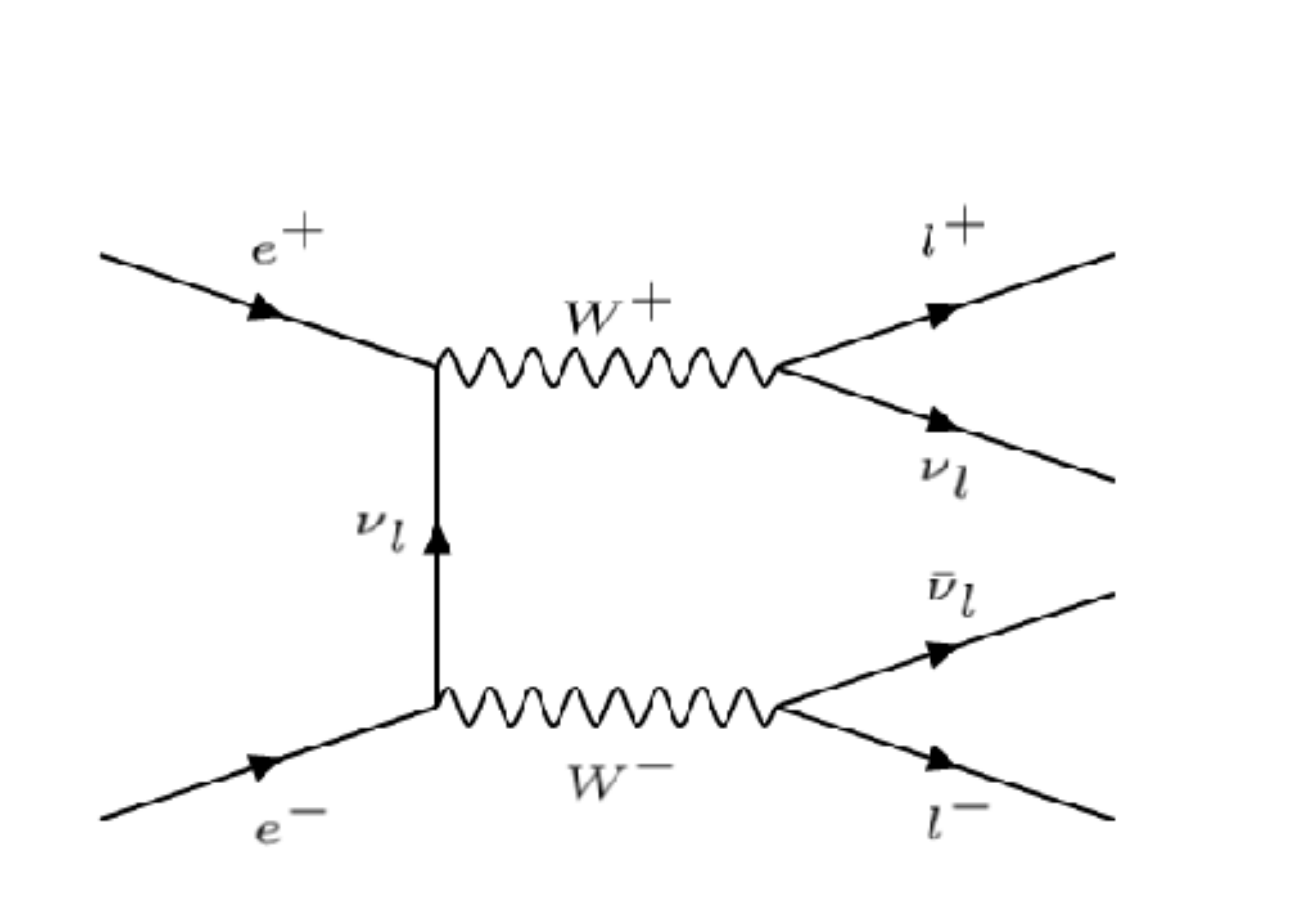
$\ell^+\ell^- + \; 0j + \; \text{ME}$



Fermion DM



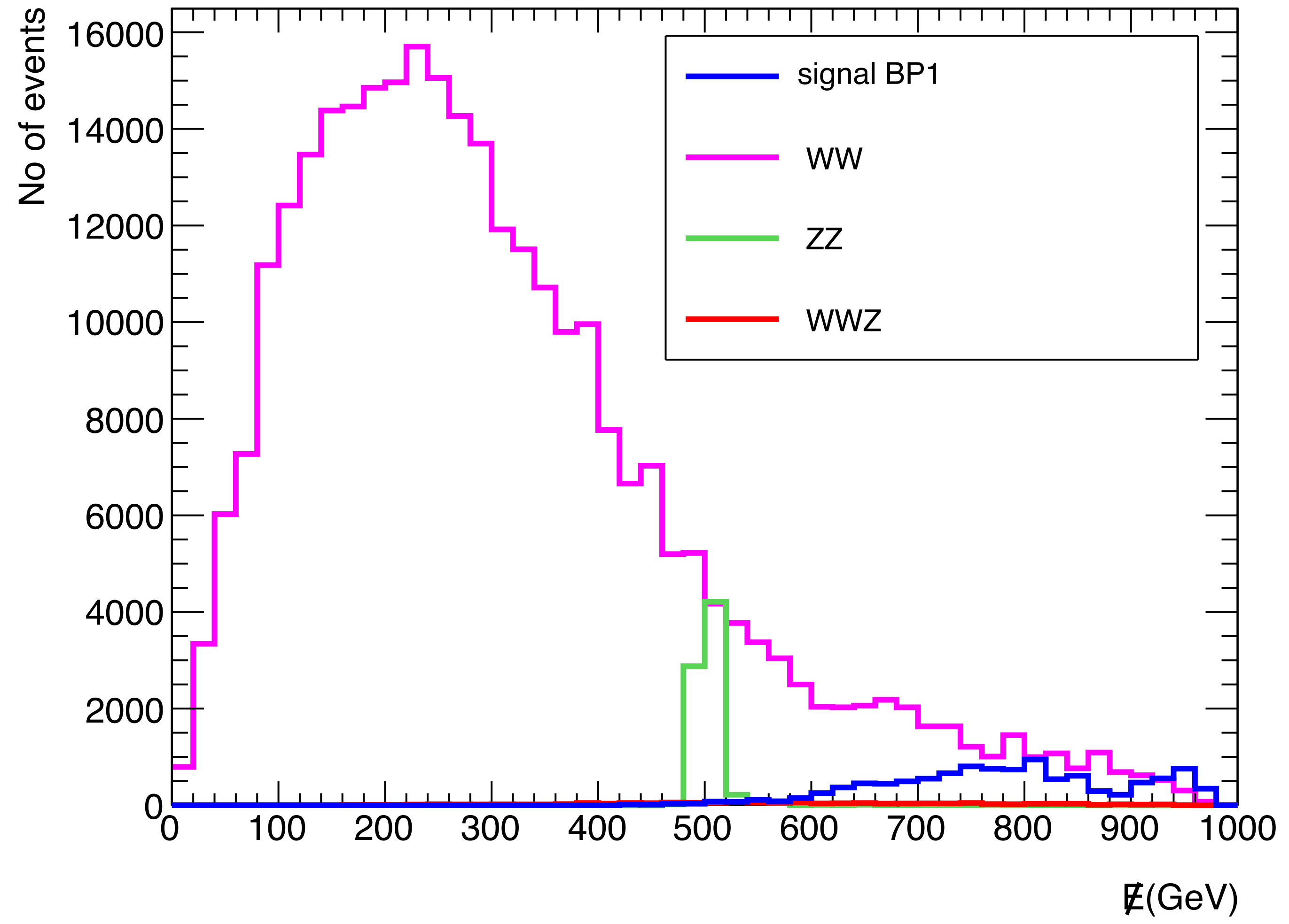
Scalar DM



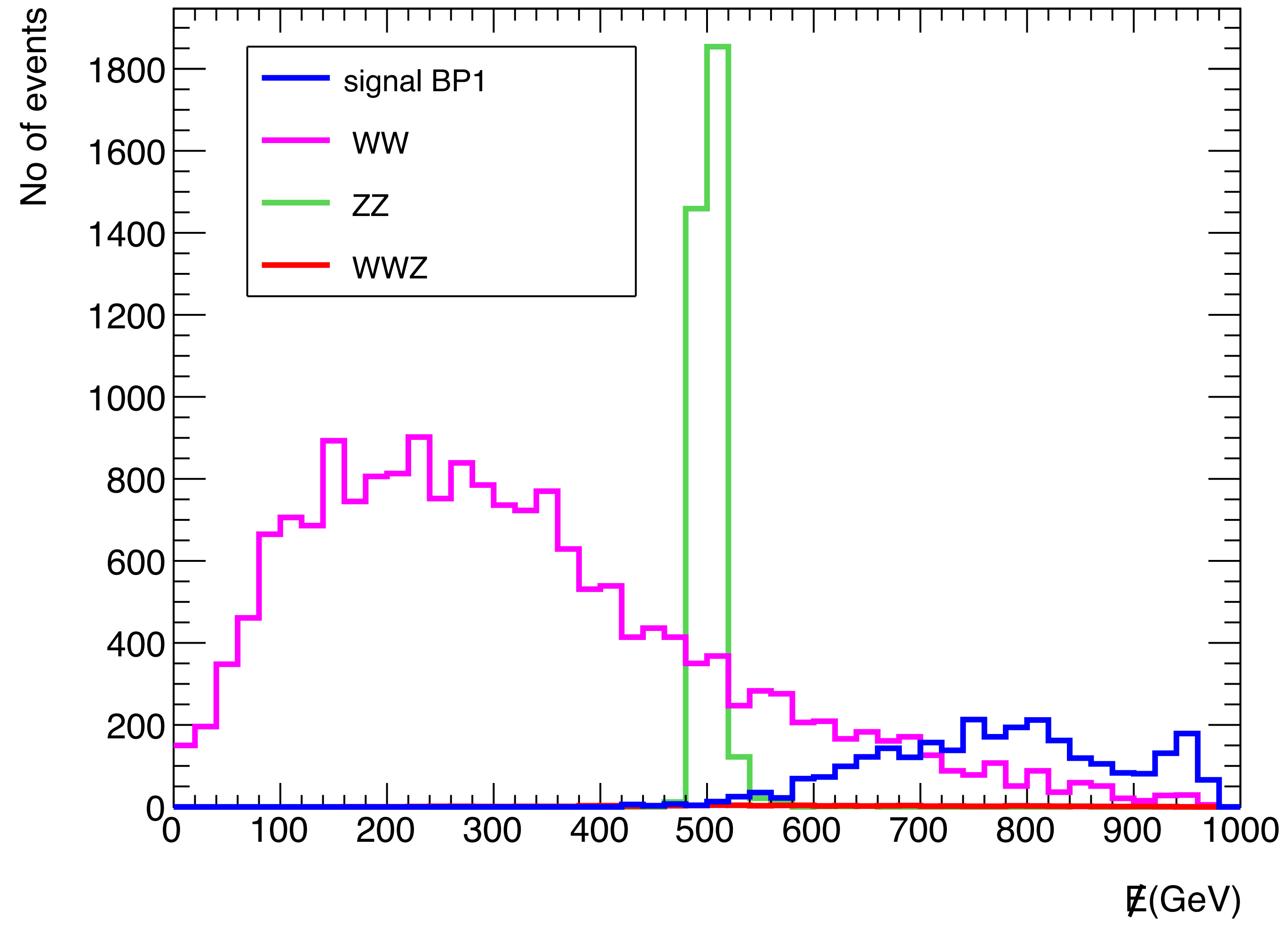
SM Background

Right polarised electron and left polarised positron beam helps in reducing background

$\text{P1} \equiv \{P_{e^-} : -0.8, P_{e^+} : +0.3\}$



$\text{P3} \equiv \{P_{e^-} : +0.8, P_{e^+} : -0.3\}$



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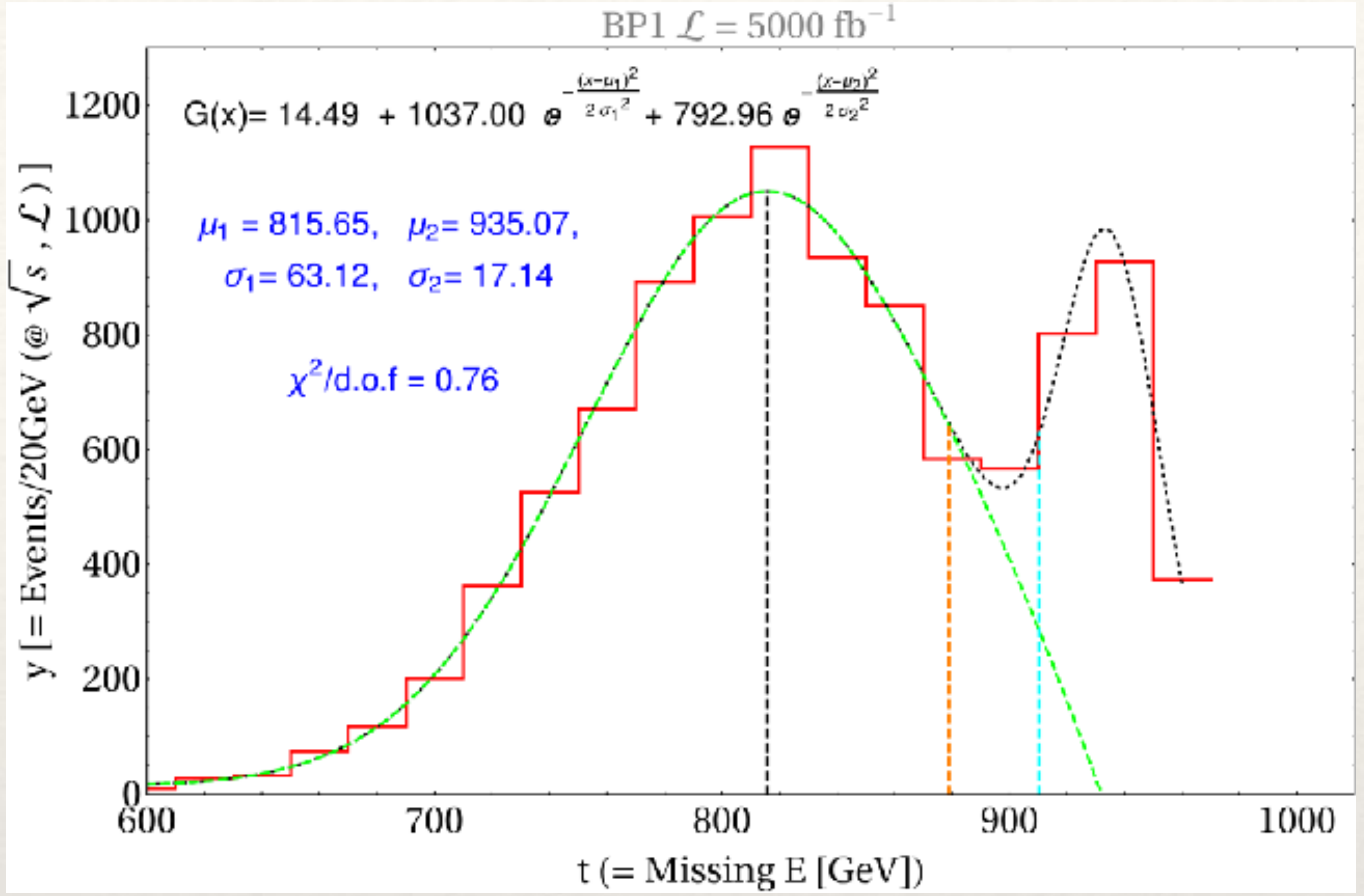
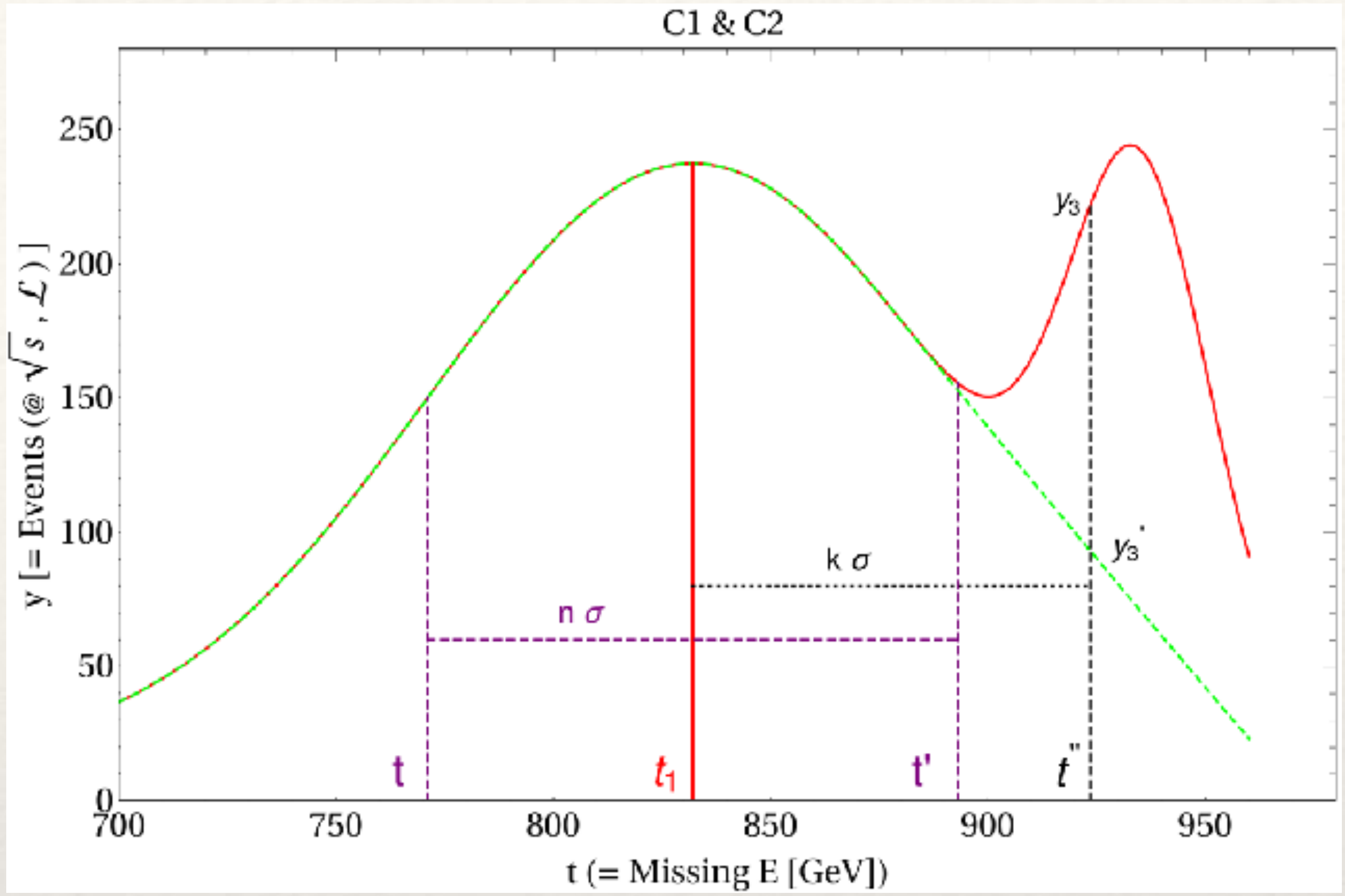
Conditions for segregating the peaks

Gaussian fitting of signal plus background distribution in ME

$$
\begin{aligned}
G(x) &= G_1(x) + G_2(x) + \mathcal{B} \\
&= A_1\, e^{-\frac{(x-\mu_1)^2}{2\sigma_1^2}} + A_2\, e^{-\frac{(x-\mu_2)^2}{2\sigma_2^2}} + \mathcal{B}\,.
\end{aligned}
$$



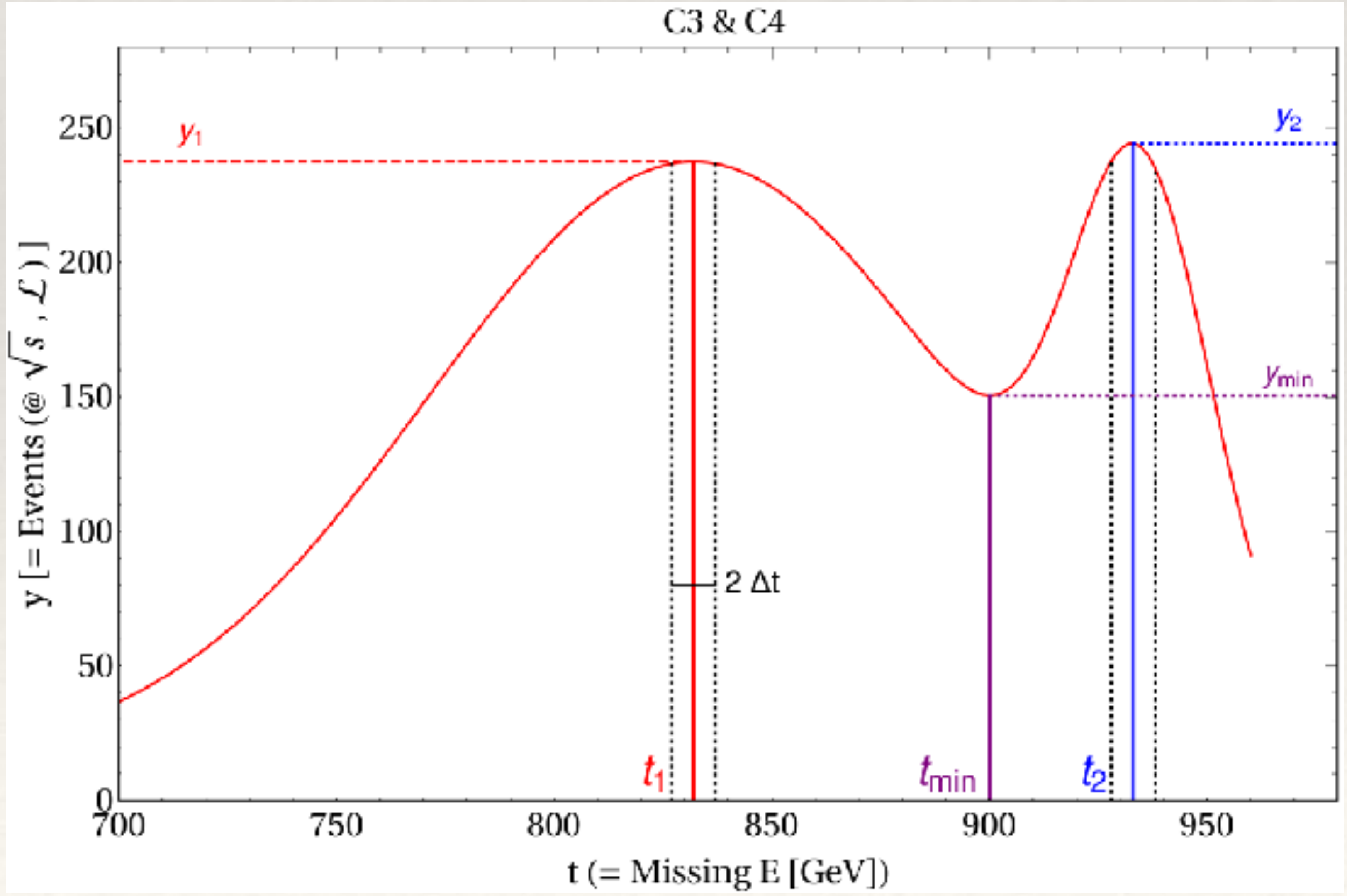


$$
C1:\ \Delta N_1 = \int_t^{t_1} y dt,\quad \Delta N_2 = \int_{t_1}^{t'} y dt\,;\ R_{C1} = \frac{|\Delta N_2 - \Delta N_1|}{\sqrt{\Delta N_1}} \to R_{C1} > 2\,.
$$

$$
C2:\ R_{C2} = \frac{y(t'') - y'(t'')}{\sqrt{y'(t'')}} \equiv \frac{y_3 - y_3'}{\sqrt{y_3'}}\ ; \to R_{C2} > 2
$$

$$
C3:\ R_{C3} \ = \ \frac{\int_{t_1-\Delta t}^{t_1+\Delta t} y dt - \int_{t_2-\Delta t}^{t_2+\Delta t} y dt}{\int_{t_1-\Delta t}^{t_1+\Delta t} y dt + \int_{t_2-\Delta t}^{t_2+\Delta t} y dt} \xrightarrow{\{\Delta t \to 0\}} \frac{y_1 - y_2}{y_1 + y_2}\,.
$$

$$
C4:\ R_{C4} = \frac{y(t_2) - y(t_{\min})}{\sqrt{y(t_{\min})}} \equiv \frac{y_2 - y_{\min}}{\sqrt{y_{\min}}} \to R_{C4} > 2\,.
$$



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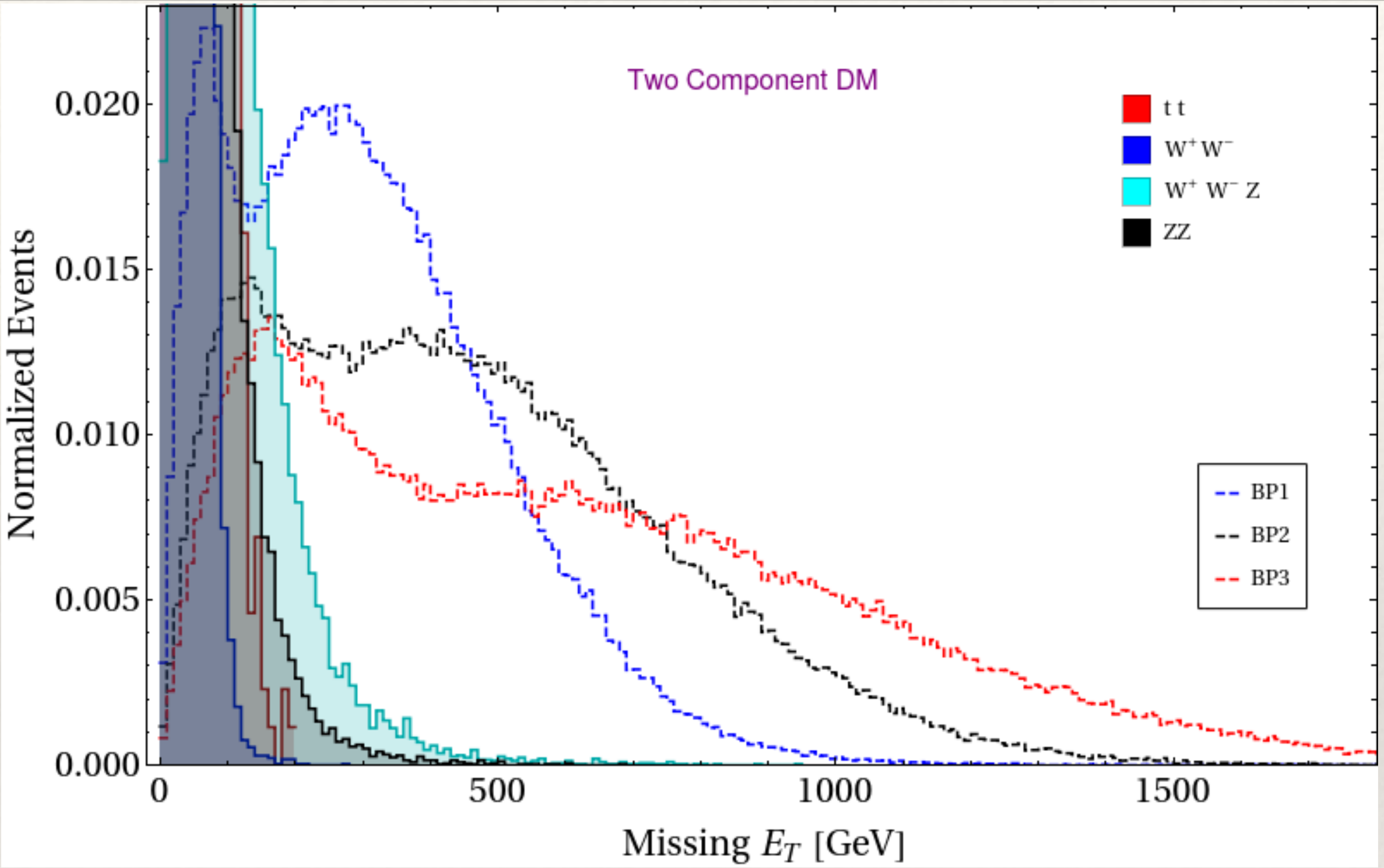
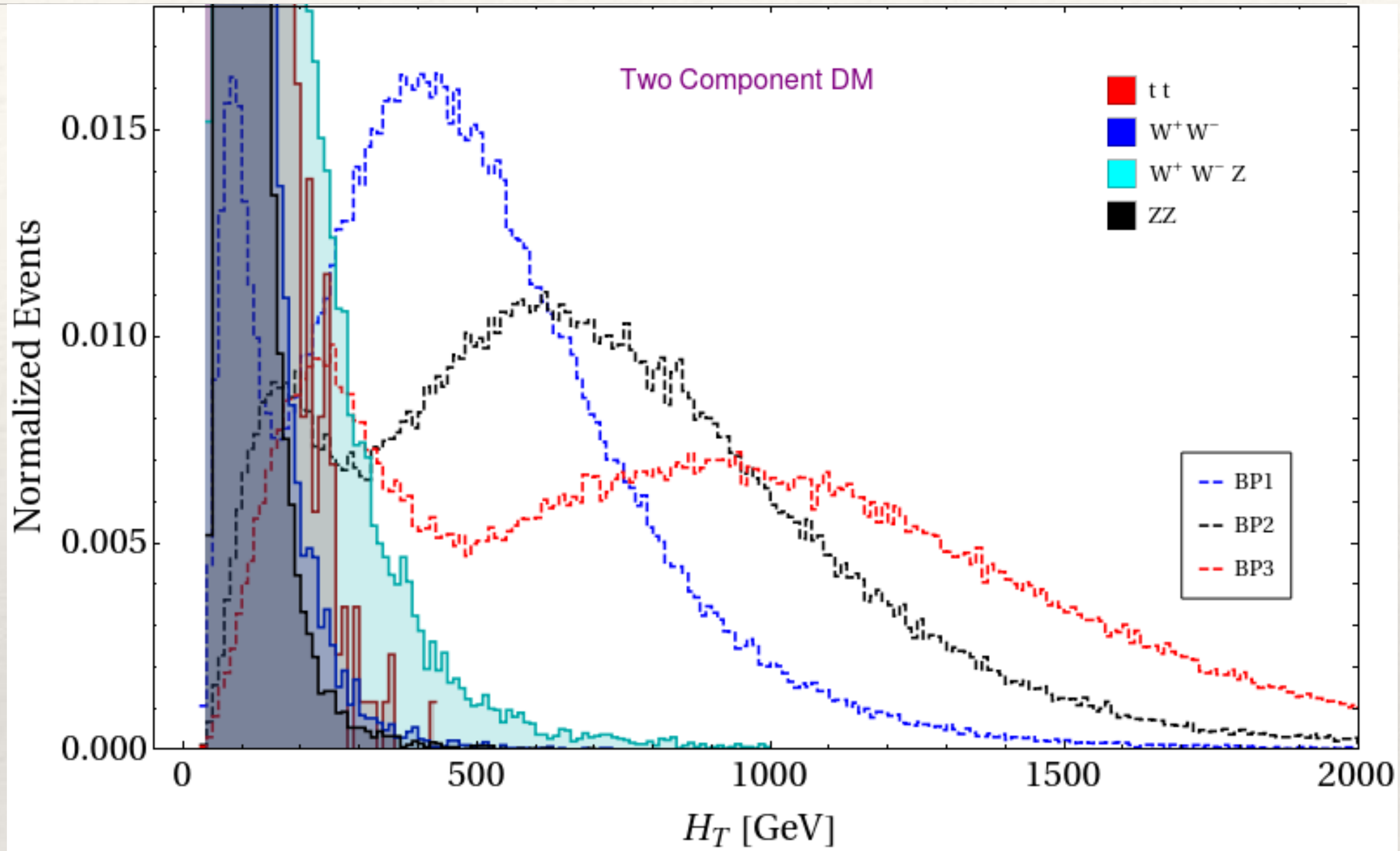
What happens at LHC ?



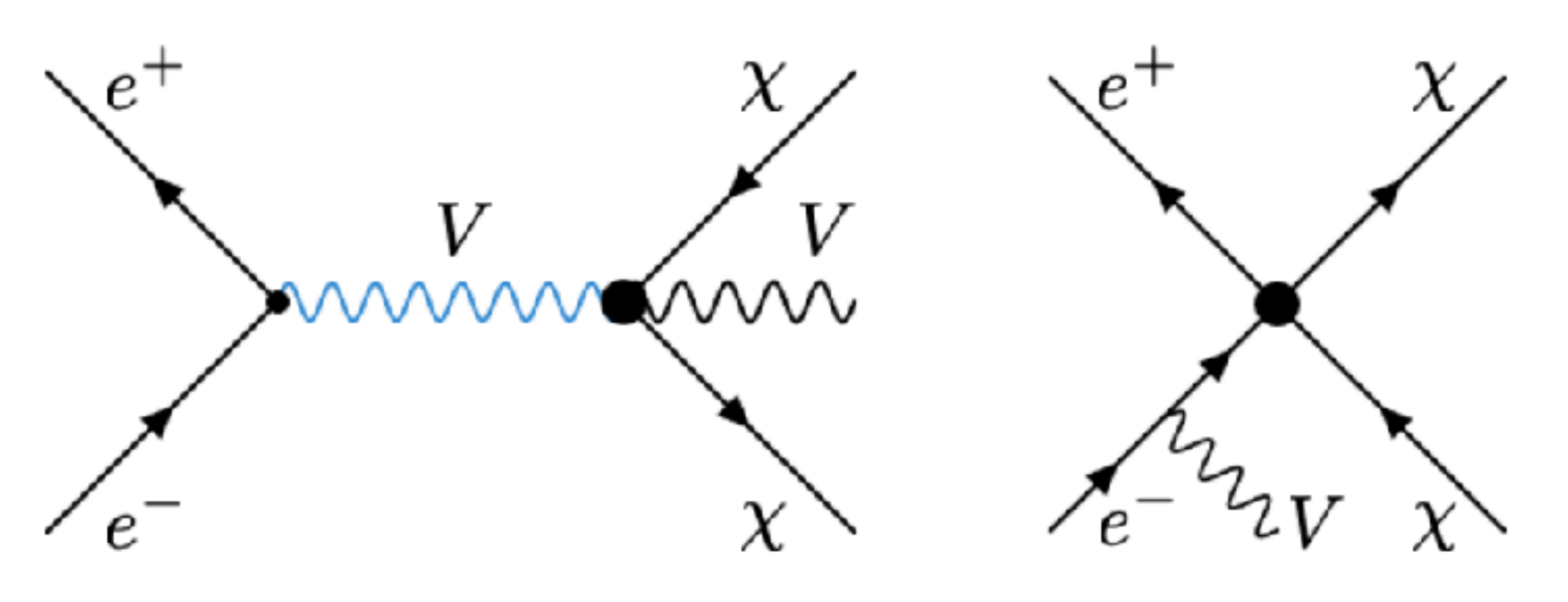


- The two peak behaviour in the signal can be seen.
- But the cross-section way below the SM background!
- Getting the first signal peak out of the background distribution is harder.

Work is in progress

Double Bump in mono-X signal

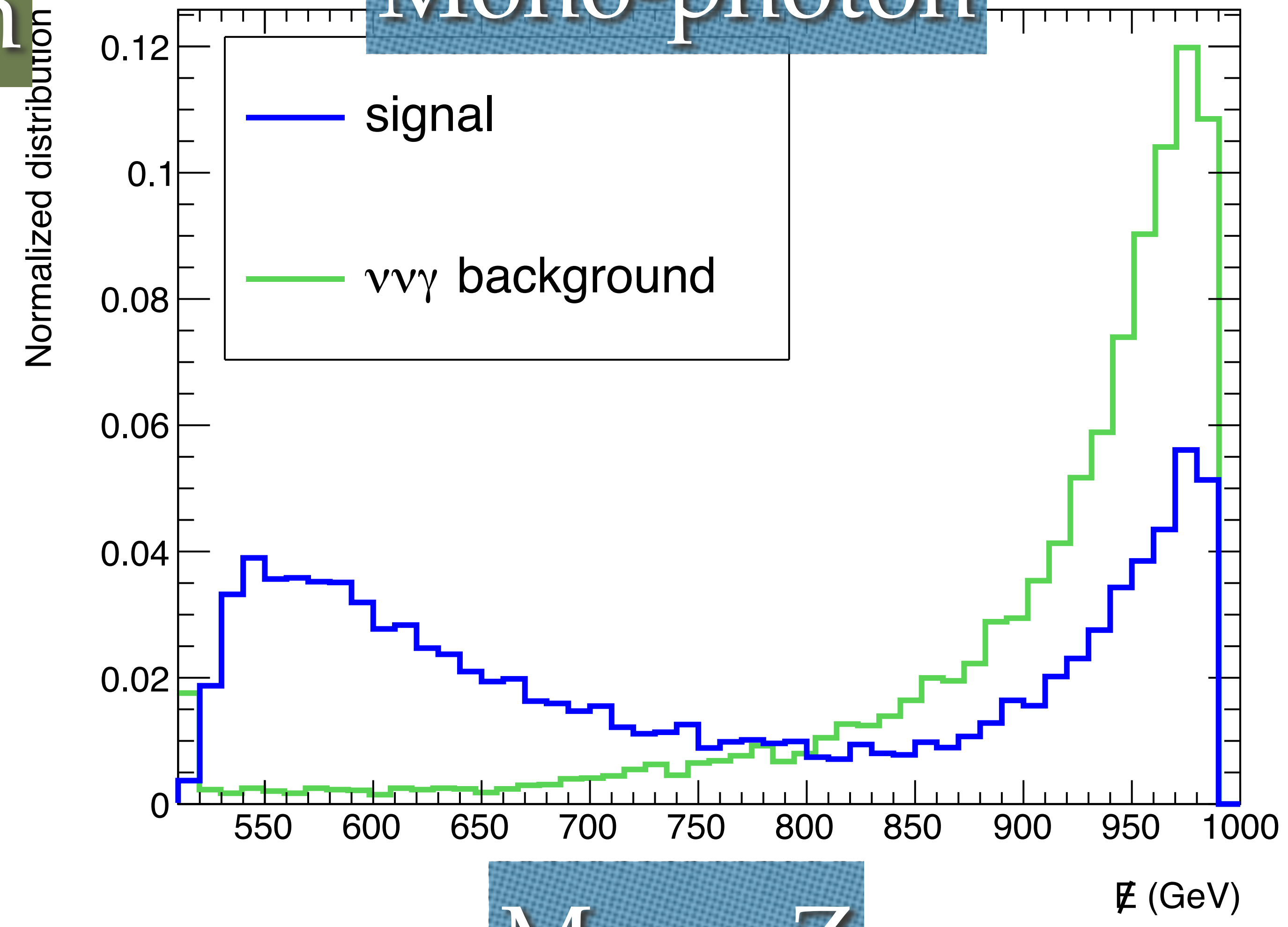
Much harder to find two peaks in ME distribution



Key properties that decide double peak behaviour in mono-X

- Angular momentum conservation
- Rotational invariance in Minkwoski space
- Colinear divergence
- Operator structure

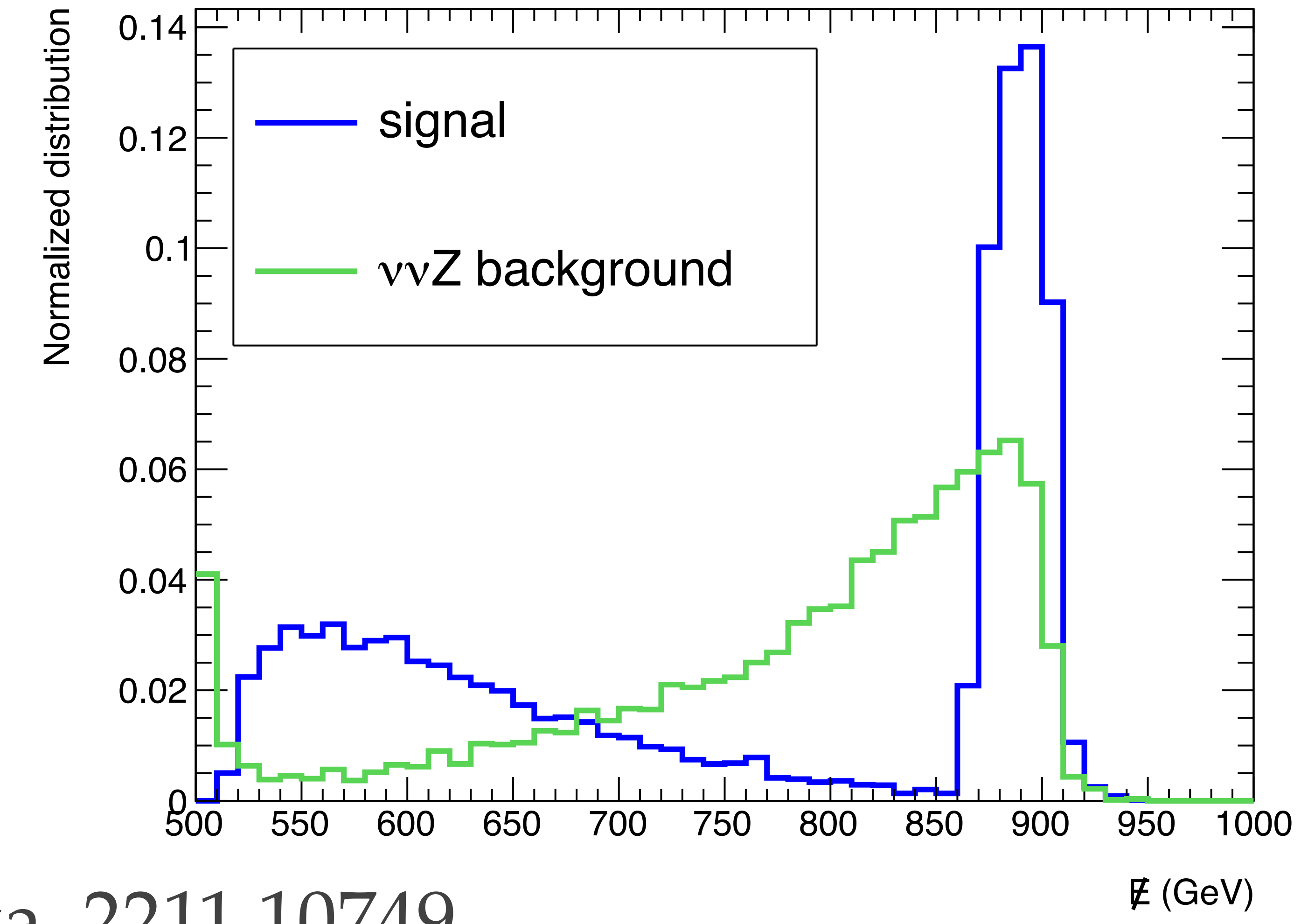
Mono-photon



$$\frac{1}{\Lambda^2}(B_{\mu\nu}B^{\mu\nu} + W^{(a)}_{\mu\nu}W^{(a)\mu\nu})\chi^2$$

$$\frac{1}{\Lambda^3}(\bar{L}\Phi\ell_R)(\bar{\chi}\chi)$$

Mono-Z



$$\frac{1}{\Lambda^2}(B_{\mu\nu}B^{\mu\nu} + W^{(a)}_{\mu\nu}W^{(a)\mu\nu})\chi^2$$

$$\frac{1}{\Lambda^2}(\bar{L}\gamma^\mu L + \bar{\ell}_R\gamma^\mu\ell_R)(\bar{\chi}\gamma_\mu\chi)$$

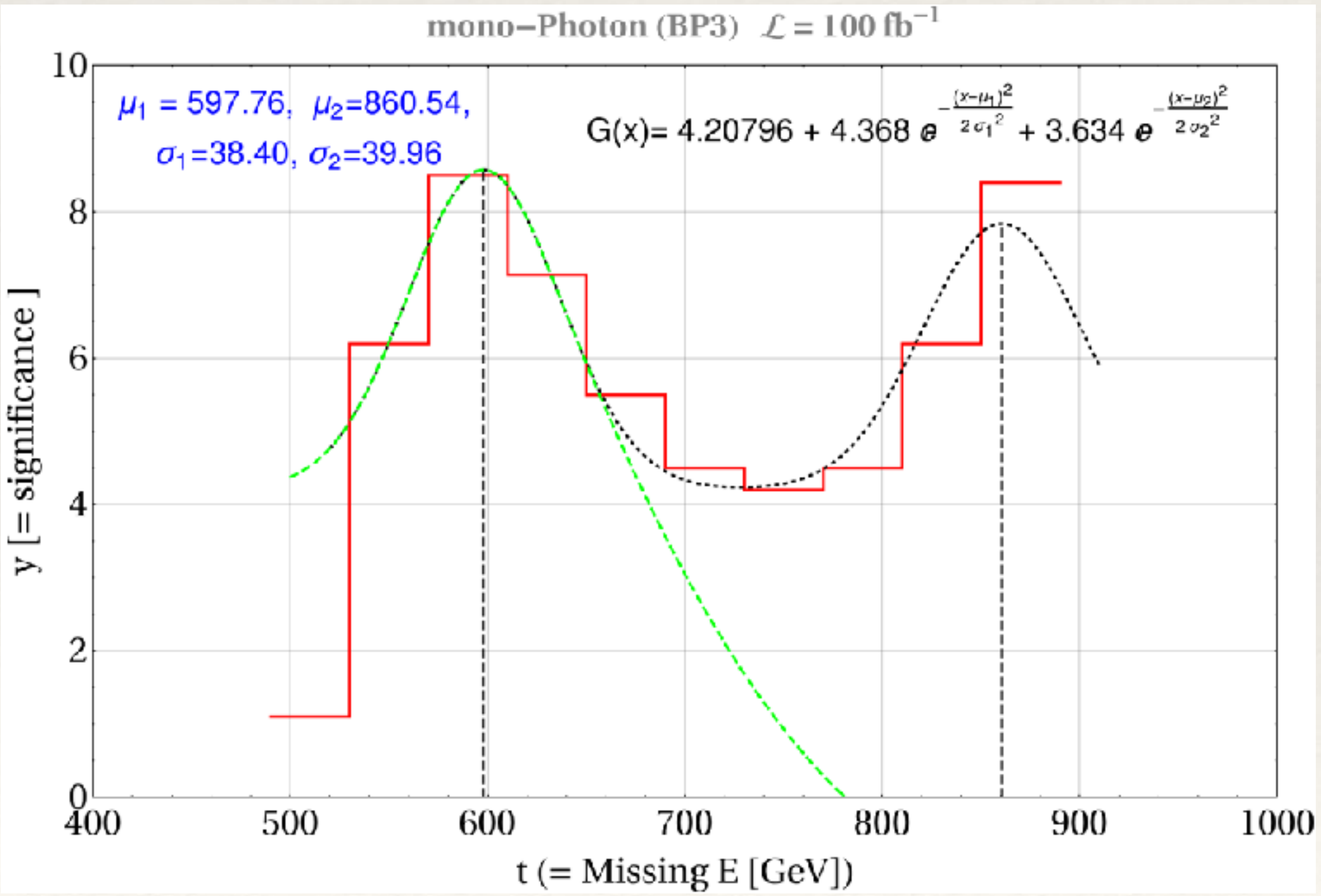
SB, Purushottam Ghosh, Jayita Lahiri, Biswarup Mukhopadhyaya, 2211.10749

Indomitable SM background!

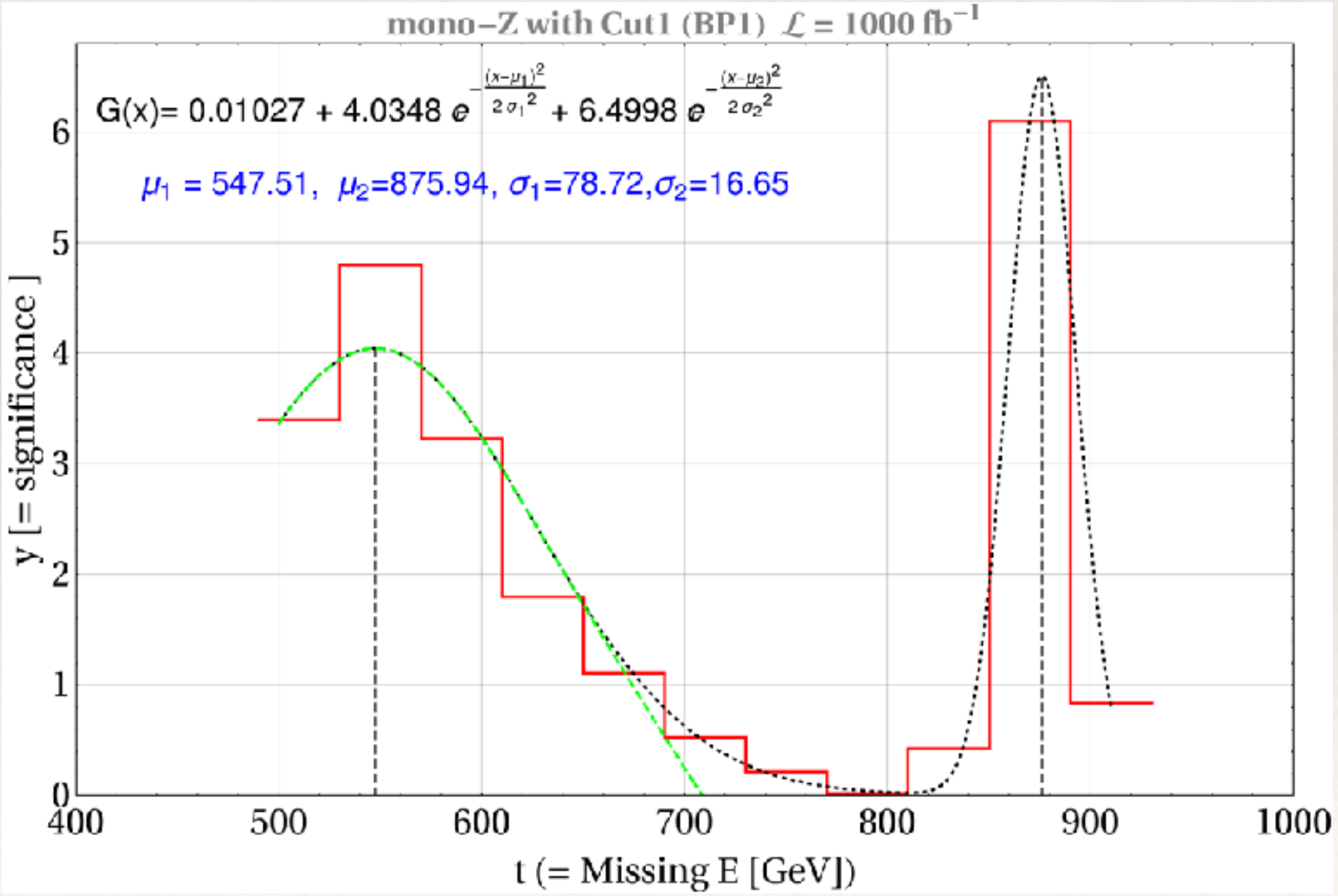
SM background is very large and can't be reduced beyond a limit

Signal+Background distribution can barely show two peak behaviour

We propose to look for bin wise signal significance!



$R_{C3} = 4, R_{C4} = 1.8$



$R_{C3} = 16, R_{C4} = 10.1$

2211.10749

Summary

- Two dark sectors producing DM via cascade decay can yield two bumps in the ME/MET spectra; ME does better than MET; thus ILC/FCC is a better machine explore such possibilities. Two bumps in mono-X is obtained with select few model combinations.

- The separation of the peaks depend on m, Δm (For mono-X only m); while the height also depend on them via production cross-section. Both are crucially controlled by DM constraints.

- SM background does play foul; beam polarisation and lepton energy cut for 2-lepton final state at ILC/FCC, comes handy. For mono-X the only way the two bump signal can be seen is via bin-by-bin signal significance.

- Conditions C1, C2, C3, C4 involving R_{C1}, R_{C2}, R_{C3} and R_{C4} variables respectively, can successfully distinguish double peak behaviour in the ME spectrum. For mono-X, R_{C3}, R_{C4} turns out to be relevant.

- Large luminosity helps avoiding statistical fluctuation and satisfying the conditions to segregate the peaks.

Also I would like to thank DST SERB grant CRG/2019/004078

Thank you

Additional Slides

Model Example: Scalar+Fermion

Fields		$SU(3)_C$	$\otimes SU(2)_L$	$\otimes U(1)_Y$	$\otimes Z_2$	$\otimes Z'_2$
SDM	$\Phi = \begin{pmatrix} \phi^+ \\ \frac{1}{\sqrt{2}}(\phi^0 + iA^0) \end{pmatrix}$	1	2	1	-	+
FDM	$\Psi_{L,R} = \begin{pmatrix} \psi \\ \psi^- \end{pmatrix}_{L,R}$	1	2	-1	+	-
	χ_R	1	1	0	+	-

$$\mathcal{L} \supset \mathcal{L}^{\rm SDM} + \mathcal{L}^{\rm FDM}.$$

$$\mathcal{L}^{\rm SDM} = \left|\left(\partial^\mu - ig_2\frac{\sigma^a}{2}W^{a\mu} - ig_1\frac{Y}{2}B^\mu\right)\Phi\right|^2 - V(\Phi, H)\,;$$

$$V(\Phi, H) = \mu_\Phi^2(\Phi^\dagger\Phi) + \lambda_\Phi(\Phi^\dagger\Phi)^2 + \lambda_1(H^\dagger H)(\Phi^\dagger\Phi) + \lambda_2(H^\dagger\Phi)(\Phi^\dagger H) + \frac{\lambda_3}{2}[(H^\dagger\Phi)^2 + h.c.]$$

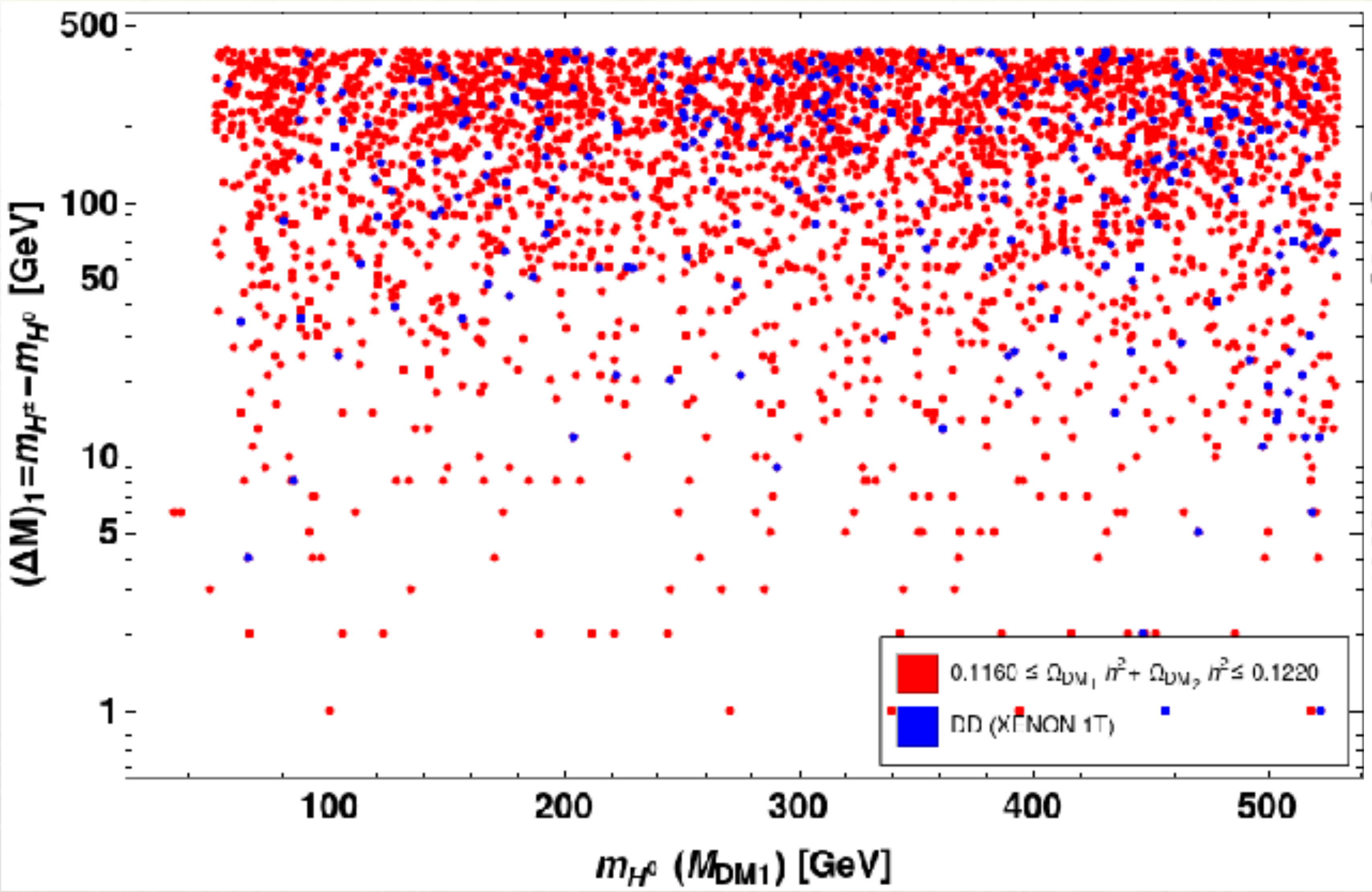
$$\{m_{{\rm DM}_1},\ \Delta m_1,\ \lambda_L\}.$$

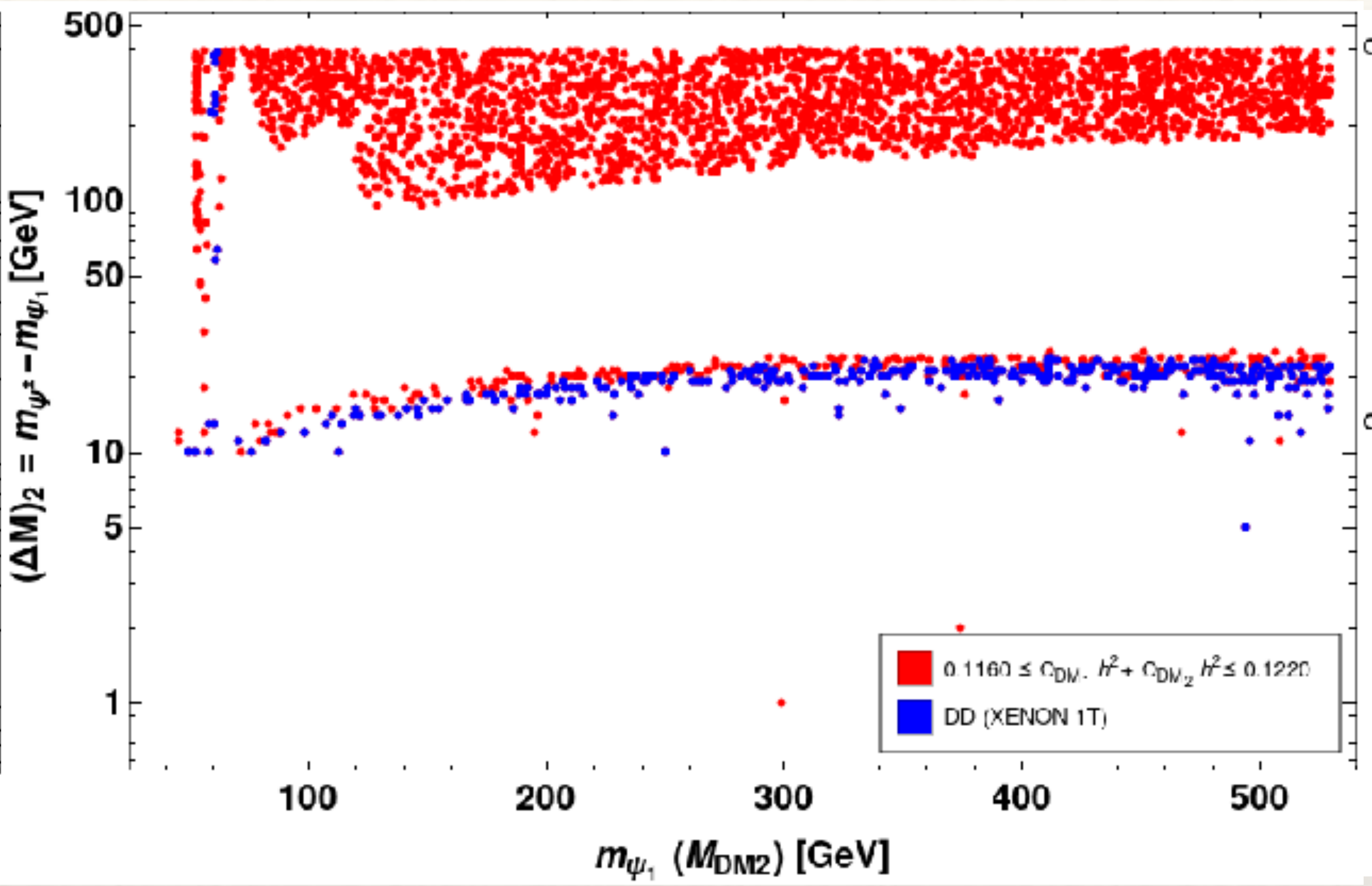
$$\lambda_1 = 2\lambda_L - \frac{2}{v^2}(m_{\phi^0}^2 - m_{\phi^\pm}^2)$$

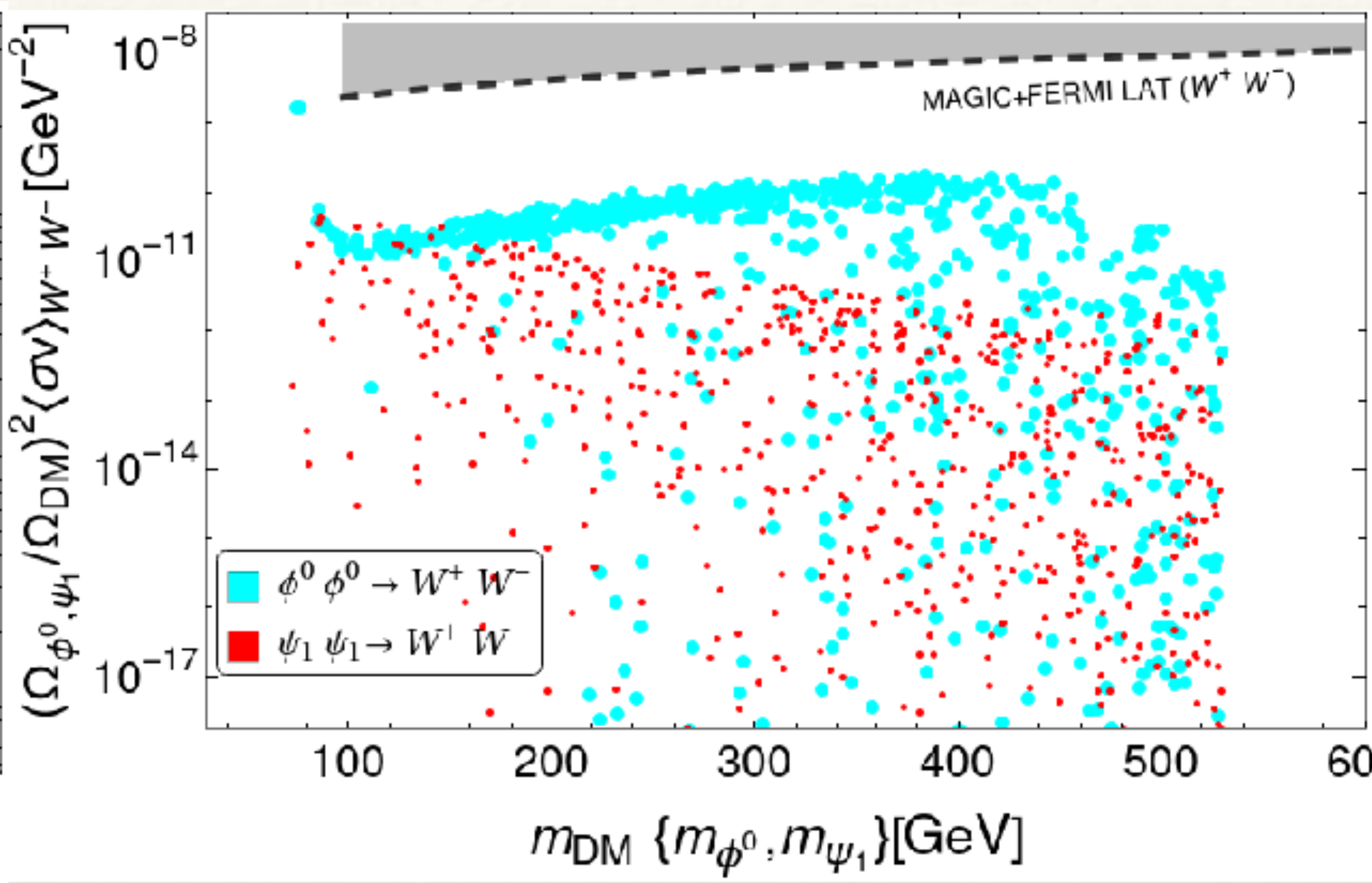
$$\mathcal{L}^{\rm FDM} = \overline{\Psi}_{L(R)}\ [i\gamma^\mu(\partial_\mu - ig_2\frac{\sigma^a}{2}W^a_\mu - ig_1\frac{Y'}{2}B_\mu)]\ \Psi_{L(R)} + \overline{\chi_R}\ (i\gamma^\mu\partial_\mu)\ \chi_R$$
$$- m_\psi\overline{\Psi}\Psi - \left(\frac{1}{2}m_\chi\overline{\chi_R}(\chi_R)^c + h.c\right) - \frac{Y}{\sqrt{2}}\left(\ \overline{\Psi_L}\ \widetilde{H}\chi_R + \ \overline{\Psi_R}\ \widetilde{H}{\chi_R}^c + h.c\right);$$

$$\{m_{{\rm DM}_2},\ \Delta m_2,\ \sin\theta\}\,;$$

DM constraints and Benchmark points





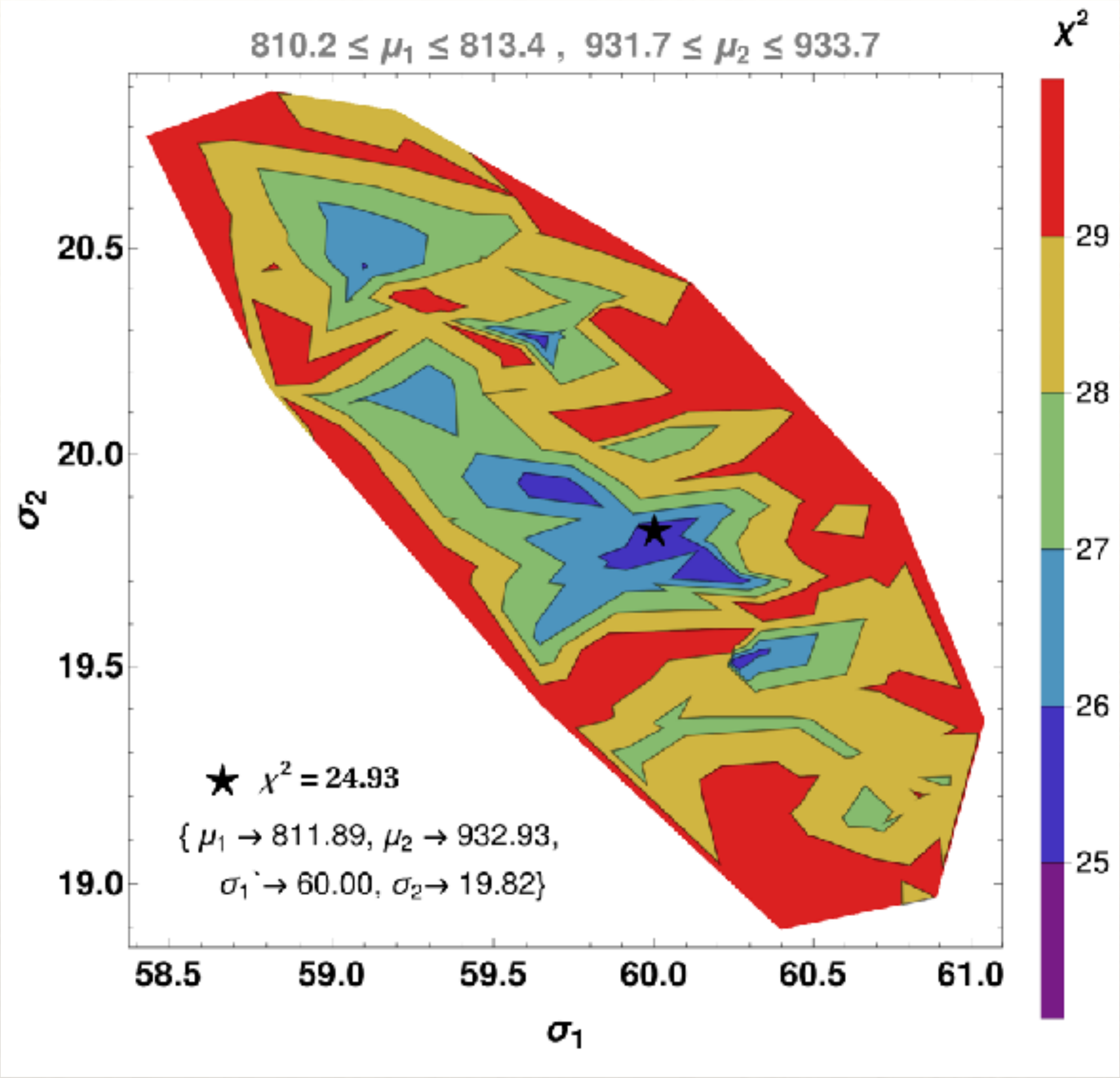


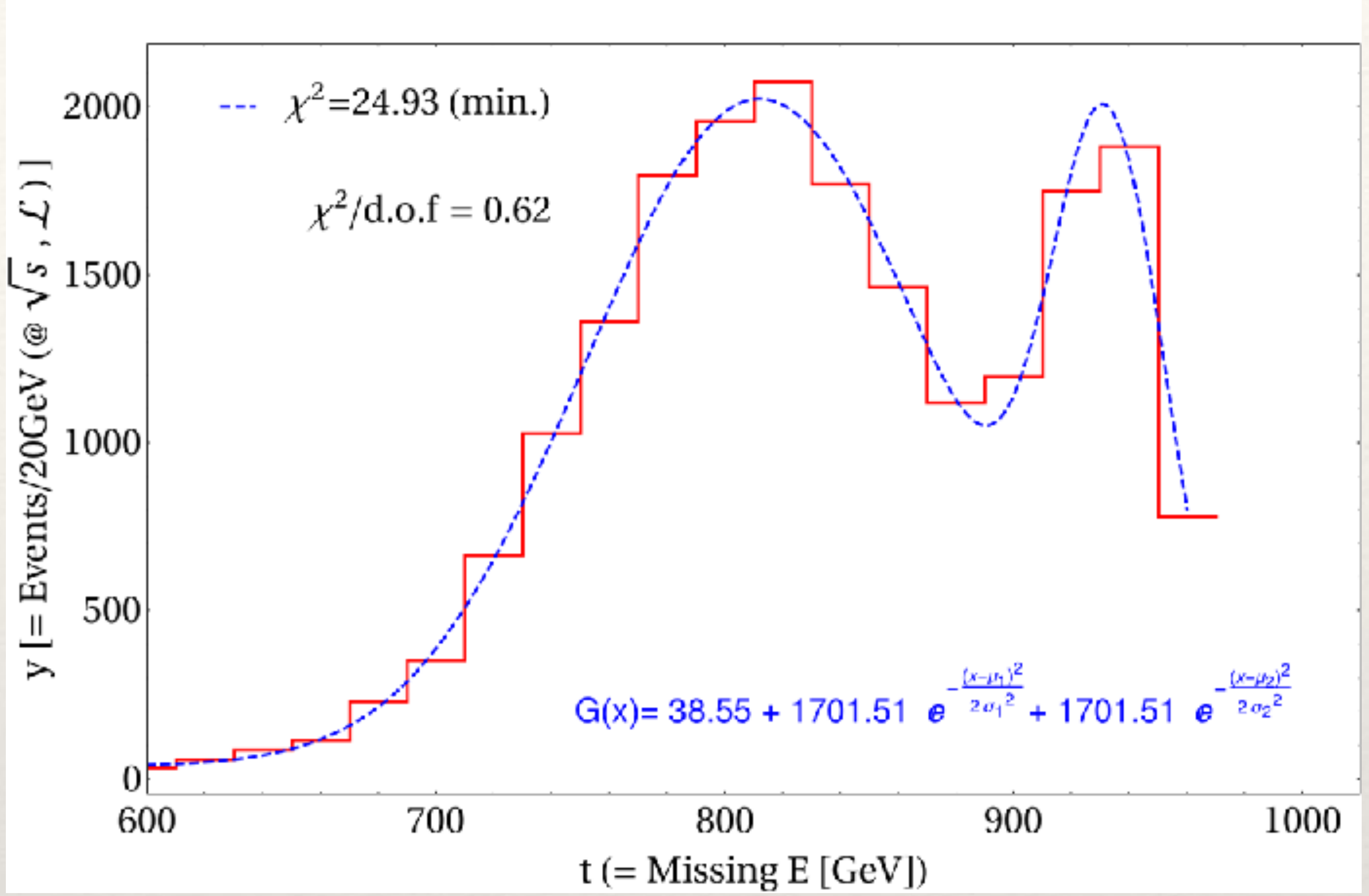
BPs	SDM sector $\{m_{\phi^0},\ \Delta m_1,\ \lambda_L\}$	FDM sector $\{m_{\psi_1},\ \Delta m_2, \sin\theta\}$	$\Omega_{\phi^0} h^2$	$\Omega_{\psi_1} h^2$	$\sigma^{\rm eff}_{\phi^0}$ (cm^2)	$\sigma^{\rm eff}_{\psi_1}$ (cm^2)	BR($H_{\rm inv}$)%
BP1	100, 10, 0.01	60.5, 370, 0.022	0.00221	0.1195	3.45×10^{-46}	2.03×10^{-47}	0.25
BP2	100, 10, 0.01	58.91, 285, 0.032	0.00221	0.10962	3.45×10^{-46}	5.38×10^{-47}	1.60
BP3	100, 10, 0.01	58.87, 176, 0.04	0.00221	0.11941	3.45×10^{-46}	5.00×10^{-47}	1.50
BP4	100, 10, 0.01	58.48, 190, 0.042	0.00221	0.1114	3.45×10^{-46}	7.01×10^{-47}	2.4

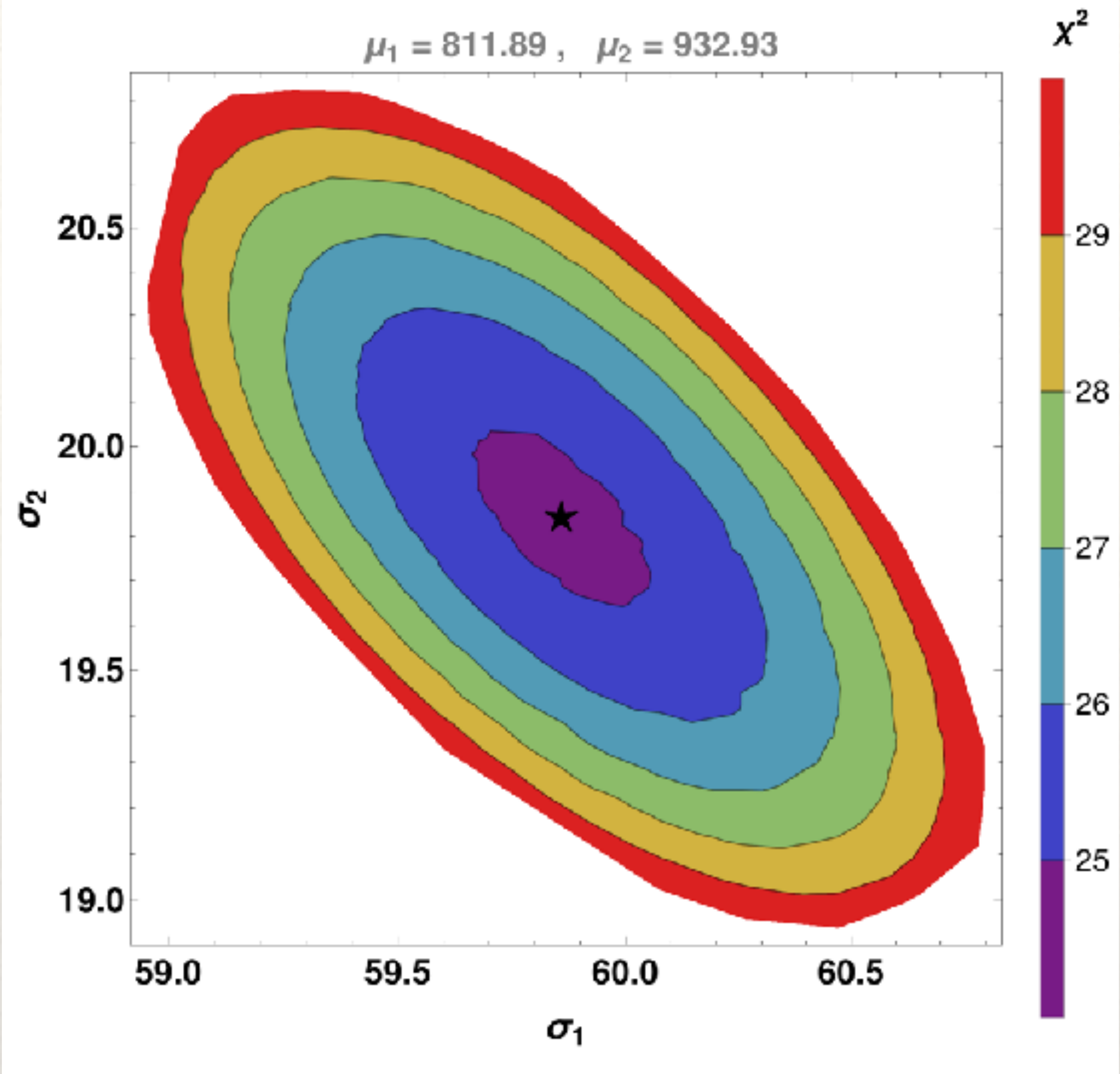
Benchmarks		Collider cross-section (fb)								
		$\sigma_{\rm total}$(OSD)			$\sigma_{\phi^+\phi^-}$(OSD)			$\sigma_{\psi^+\psi^-}$(OSD)		
$\sqrt{s}$	Points	P1	P2	P3	P1	P2	P3	P1	P2	P3
1000	BP1	232(10.8)	115(5.5)	58.5(2.75)	57.4(2.9)	28.9(1.5)	14.5(0.75)	173(8.4)	83.0(4.0)	44.0(2.0)
	BP2	276(13.4)	141(6.6)	70.0(3.3)	57.4(2.9)	28.9(1.5)	14.5(0.75)	218(10.4)	111(5.3)	55.5(2.7)
500	BP3	686(33.0)	339(15.9)	168.1(7.8)	180(8.9)	90.3(4.5)	44.3(2.3)	494(22.2)	253(11.3)	123.8(5.5)
	BP4	345(16.7)	170(8.4)	83.5(3.9)	180(8.9)	90.3(4.5)	44.3(2.3)	171.4(7.4)	82.4(3.9)	39.2(1.9)

- Higgs resonance region for FDM sector to account for DM constraints
- BP1, BP2 can be probed with 1000 GeV CM energy, BP3, BP4 at 500 GeV
- Polarisation P3 helps reducing the SM background

Gaussian Fitting







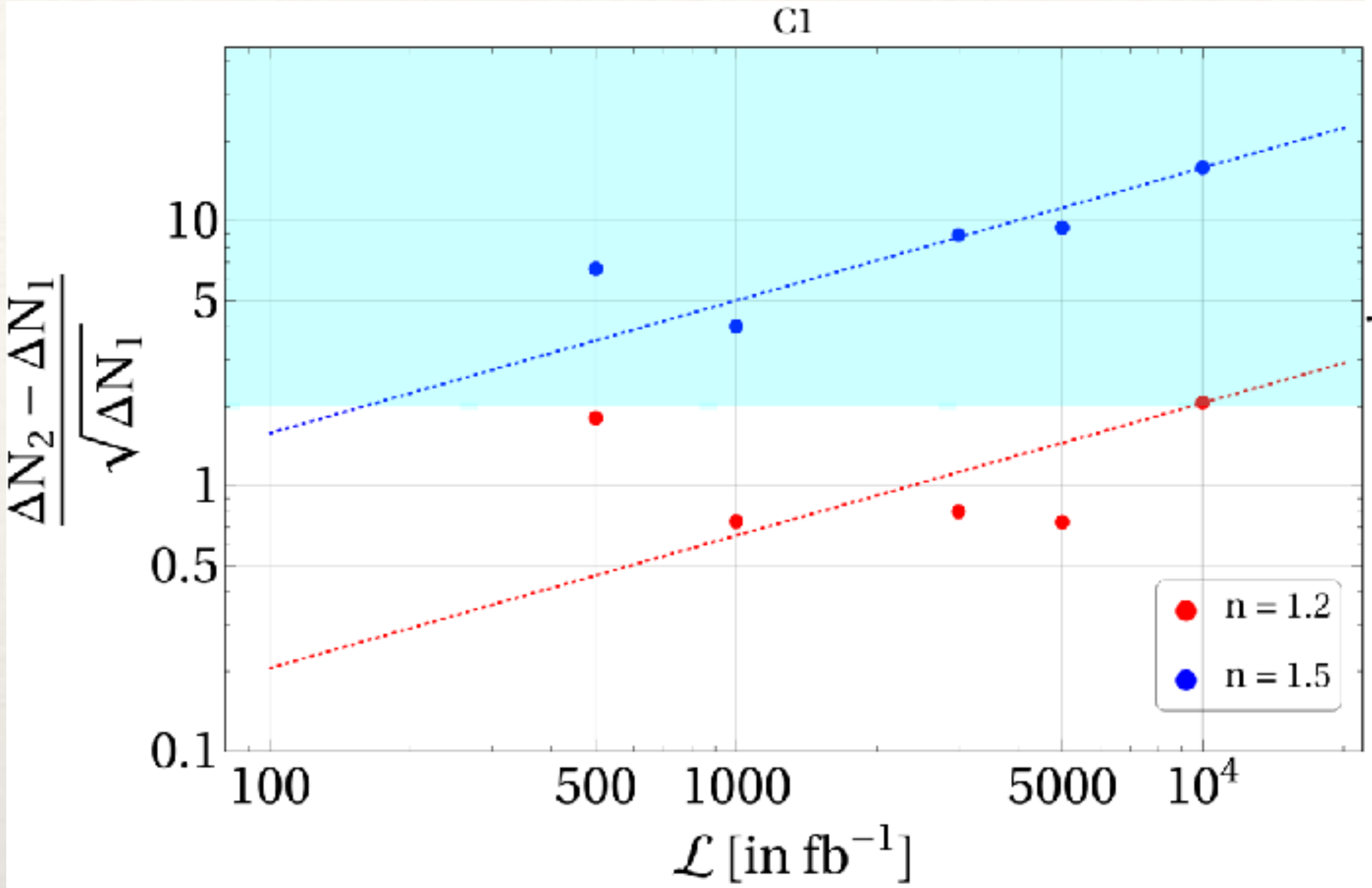
$$G(\mu_1,\sigma_1;\mu_2,\sigma_2) \;=\; A_1\, e^{-\frac{(x-\mu_1)^2}{2\sigma_1^2}} + A_2\, e^{-\frac{(x-\mu_2)^2}{2\sigma_2^2}} + \mathcal{B}\,.$$

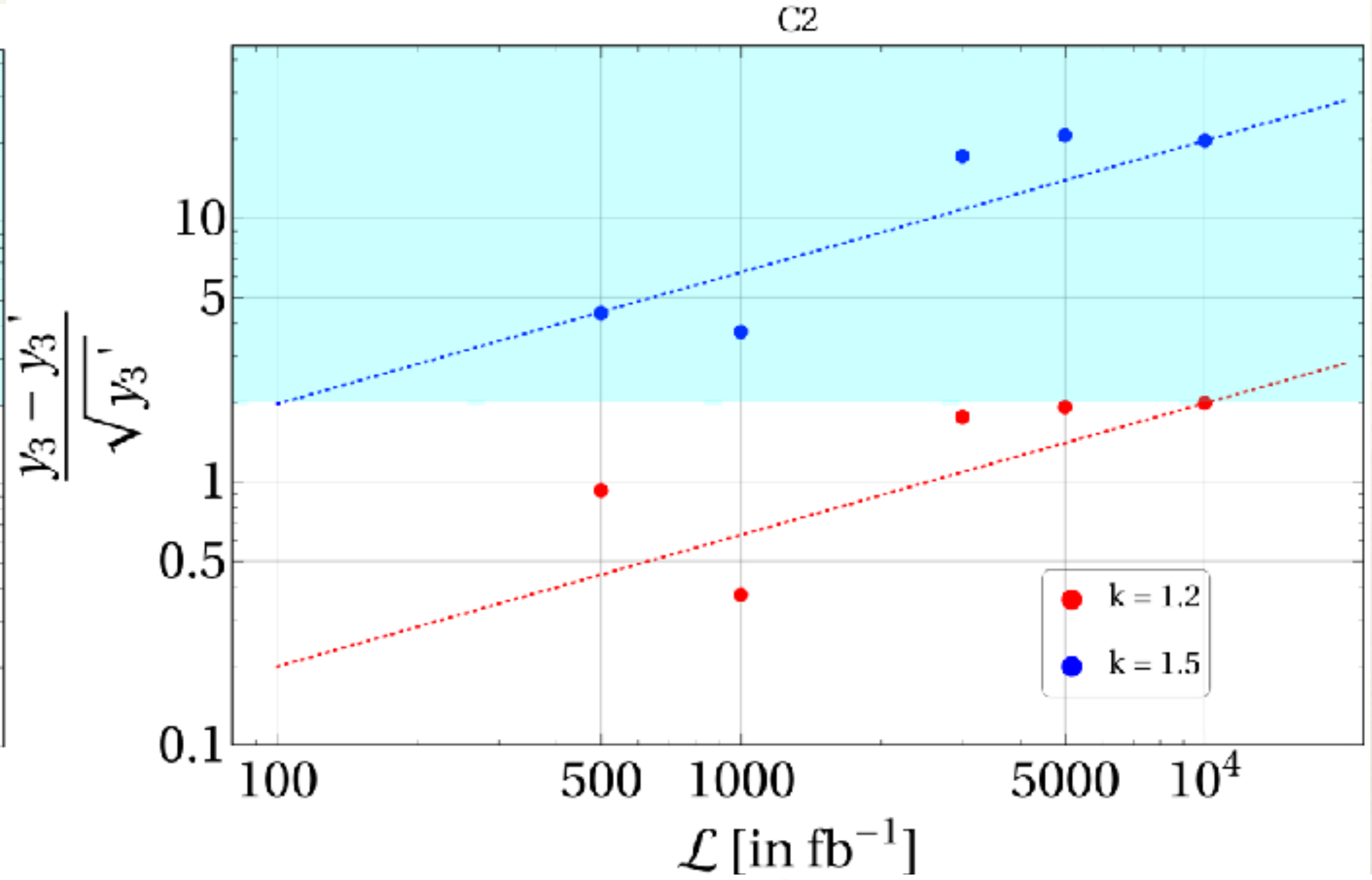
Minimize:

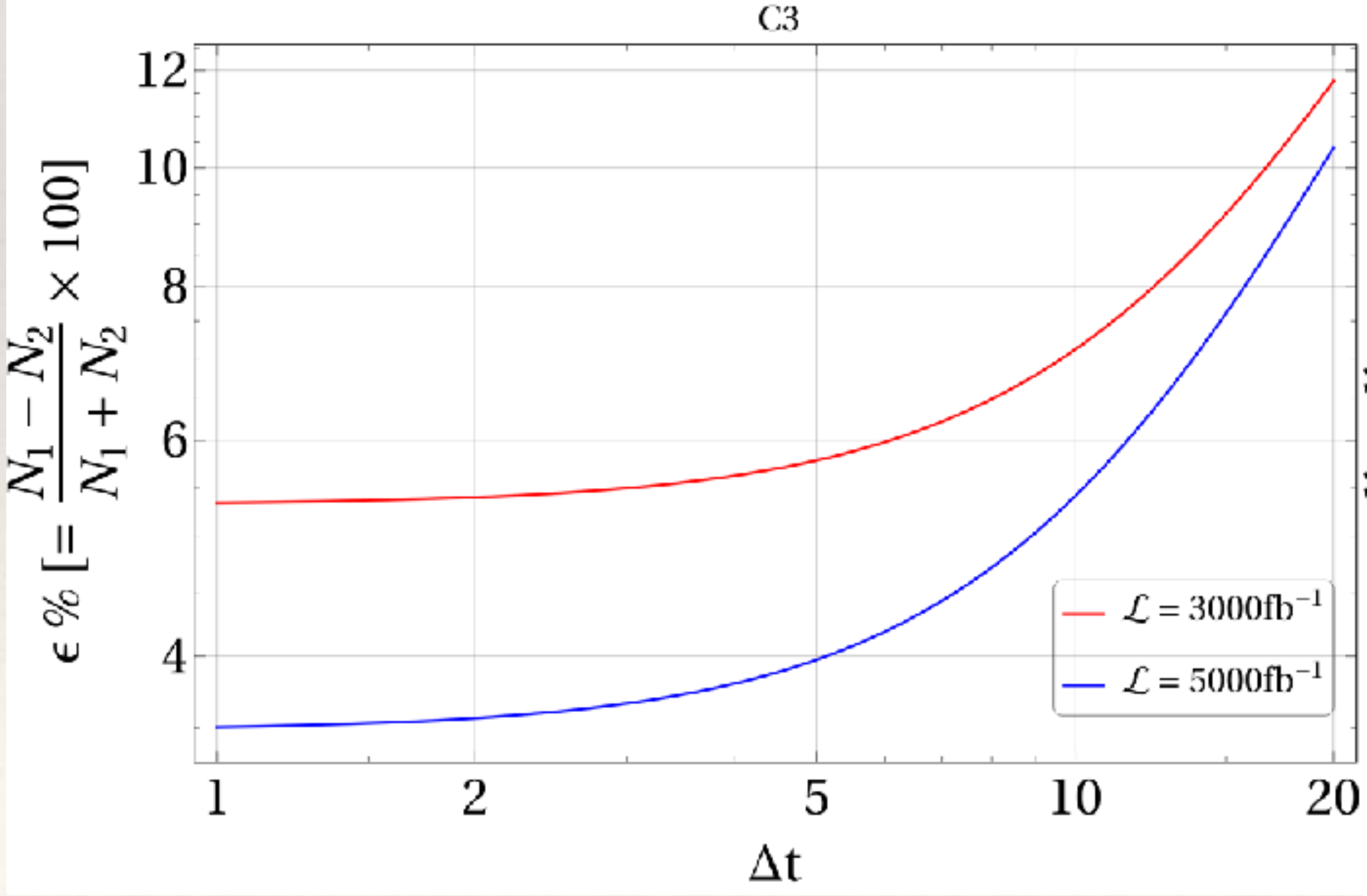
$$\chi^2(\mu_1,\sigma_1;\mu_2,\sigma_2) = \sum_{i=1}^{n} \frac{\left(G(\mu_1,\sigma_1;\mu_2,\sigma_2)[x_H^i] - y_H^i\right)^2}{y_H^i}$$

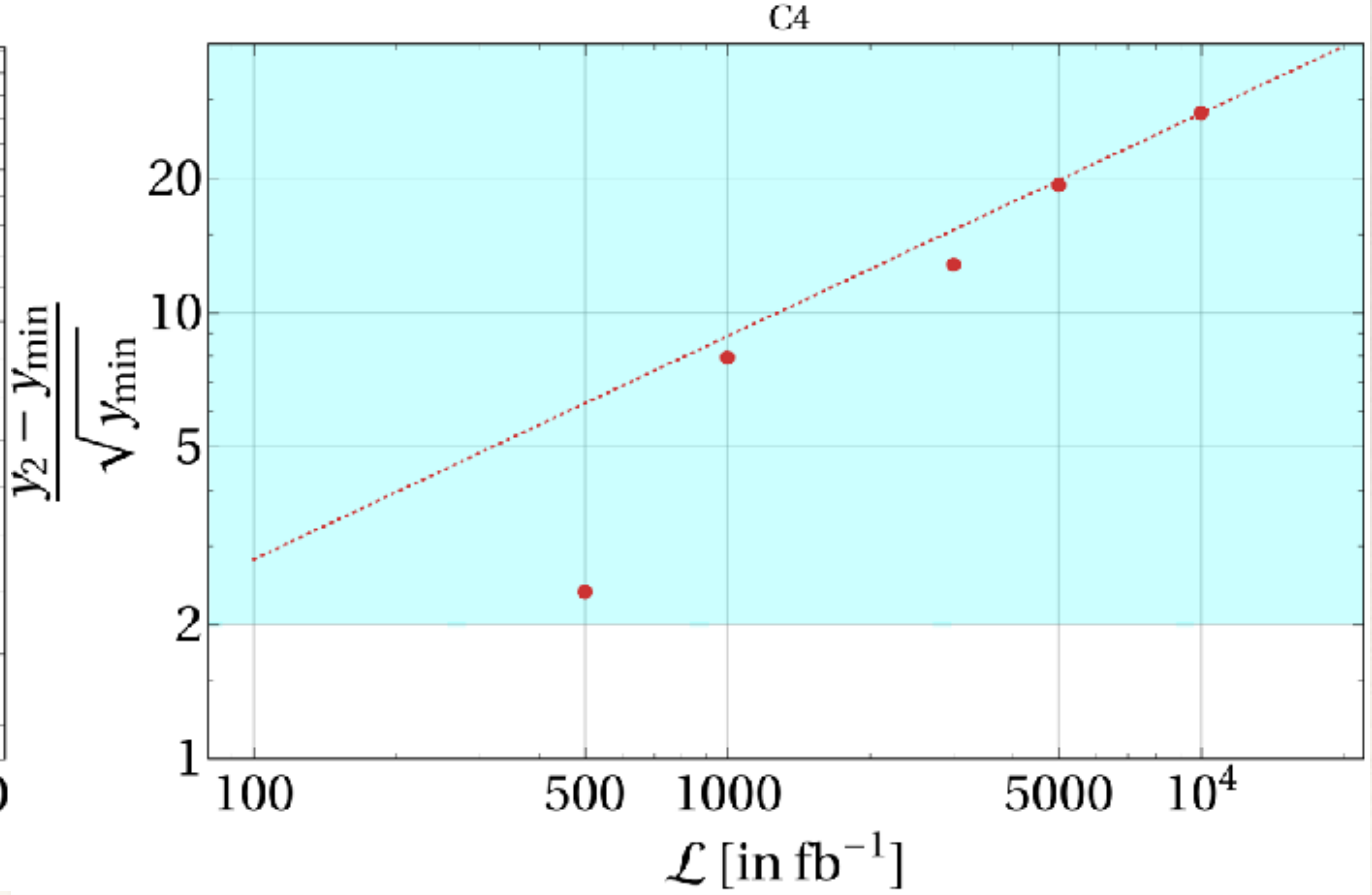
$\chi^2/\text{d.o.f} < 1$ is statistically acurate

Conditions as function of Luminosity





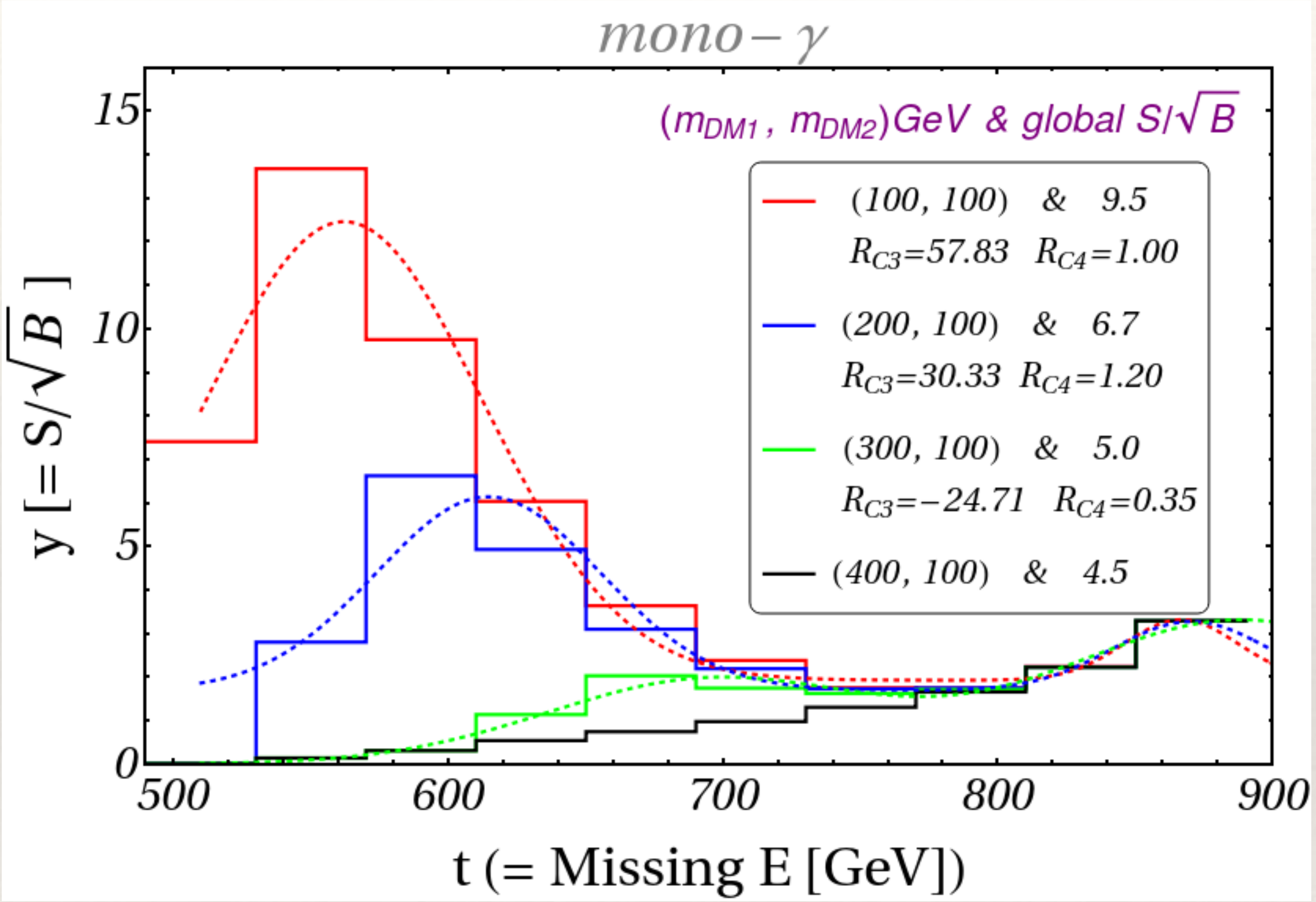




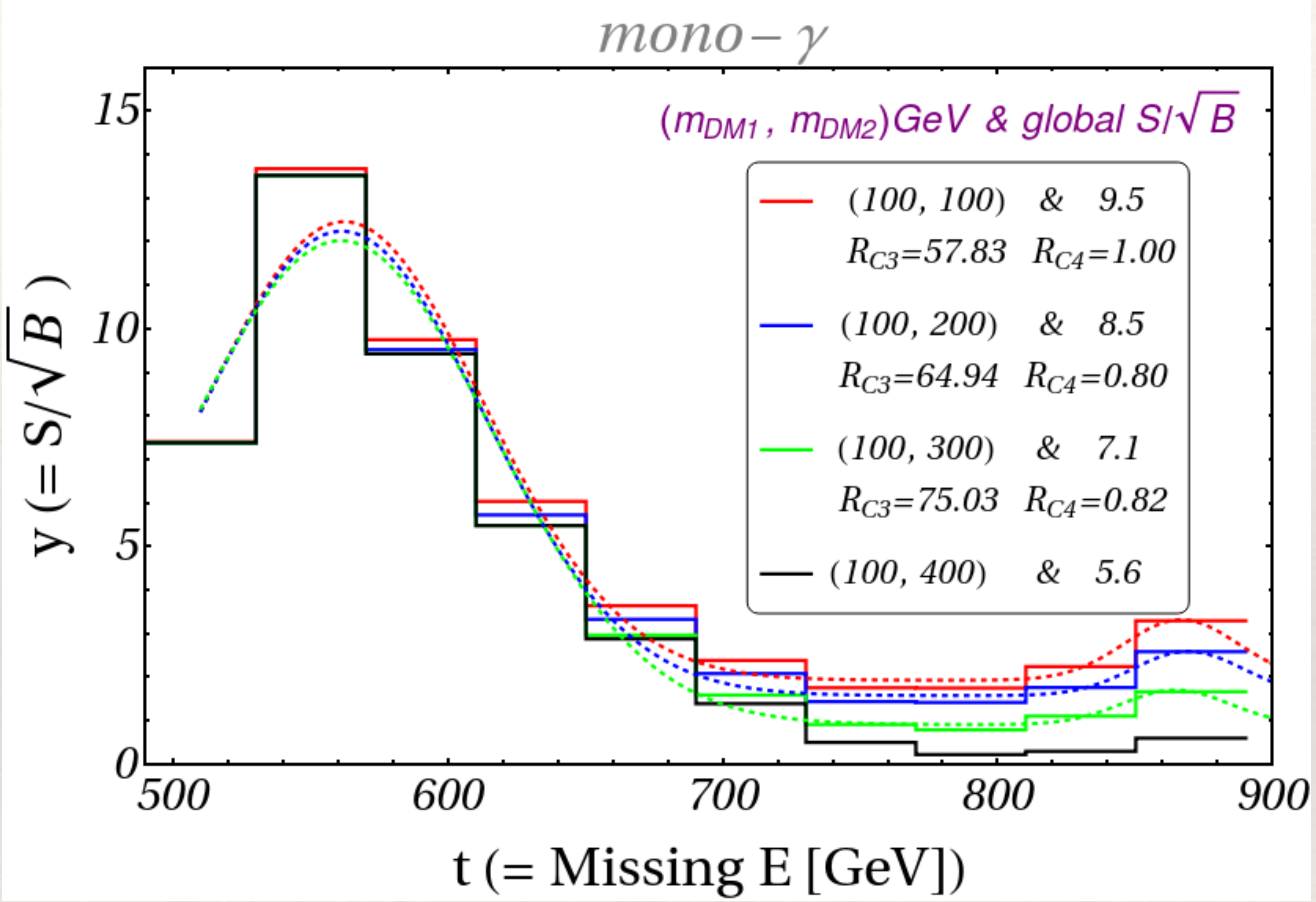
- The dots are simulated points.
- The lines are drawn by scaling with luminosity
- The sky blue region depicts 2 or more sigma statistical fluctuations.

2202.12097

Mass Effect



mono − γ
(m_{DM1}, m_{DM2})GeV & global $S/\sqrt{B}$
(100, 100) & 9.5
R_{C3}=57.83 R_{C4}=1.00
(200, 100) & 6.7
R_{C3}=30.33 R_{C4}=1.20
(300, 100) & 5.0
R_{C3}=−24.71 R_{C4}=0.35
(400, 100) & 4.5
y [= S/$\sqrt{B}$]
t (= Missing E [GeV])
0
5
10
15
500
600
700
800
900



mono − γ
(m_{DM1}, m_{DM2})GeV & global $S/\sqrt{B}$
(100, 100) & 9.5
R_{C3}=57.83 R_{C4}=1.00
(100, 200) & 8.5
R_{C3}=64.94 R_{C4}=0.80
(100, 300) & 7.1
R_{C3}=75.03 R_{C4}=0.82
(100, 400) & 5.6
y (= S/$\sqrt{B}$)
t (= Missing E [GeV])
0
5
10
15
500
600
700
800
900

Contribution from Individual Components