Soft Displaced Leptons at the LHC

7th LLP Workshop

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in collaboration with

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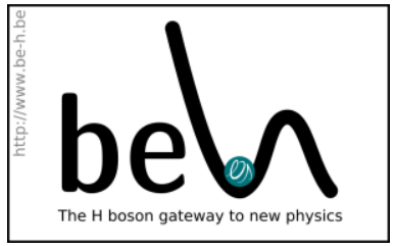
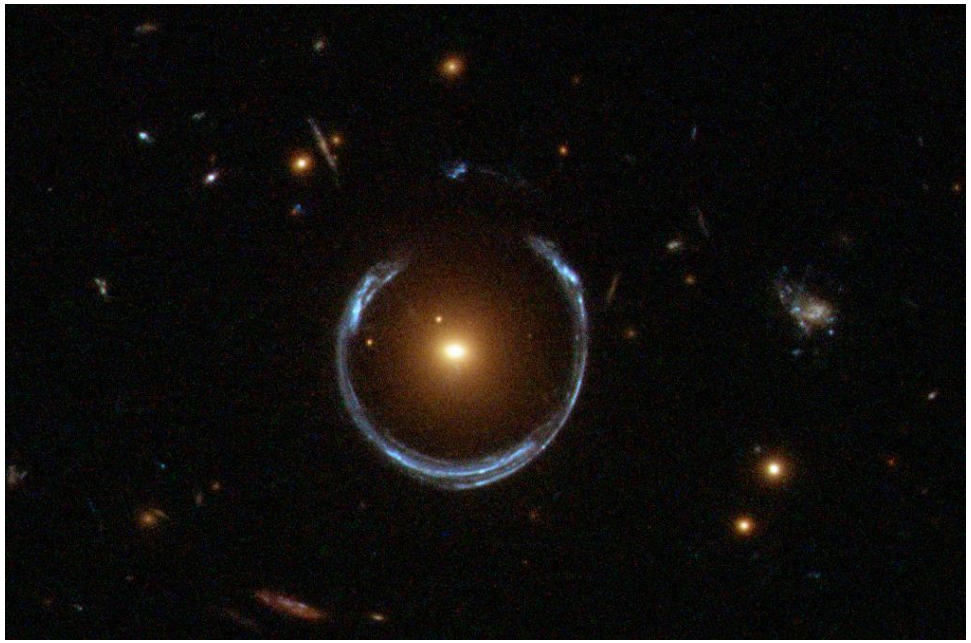


Thermal dark matter at the LHC

Credits: ESA/Hubble and NASA



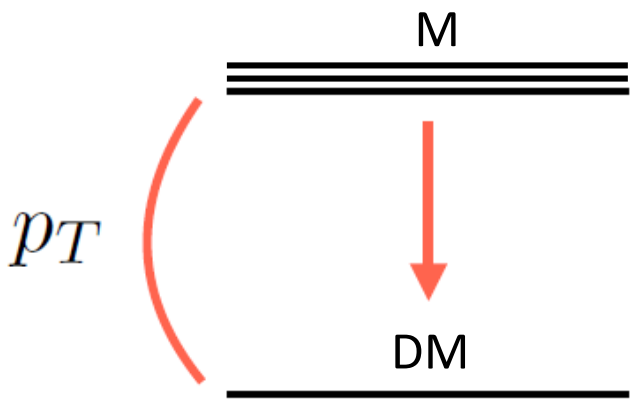
- Thermal relic through co-annihilation and co-scattering

  ⇨ compressed spectrum

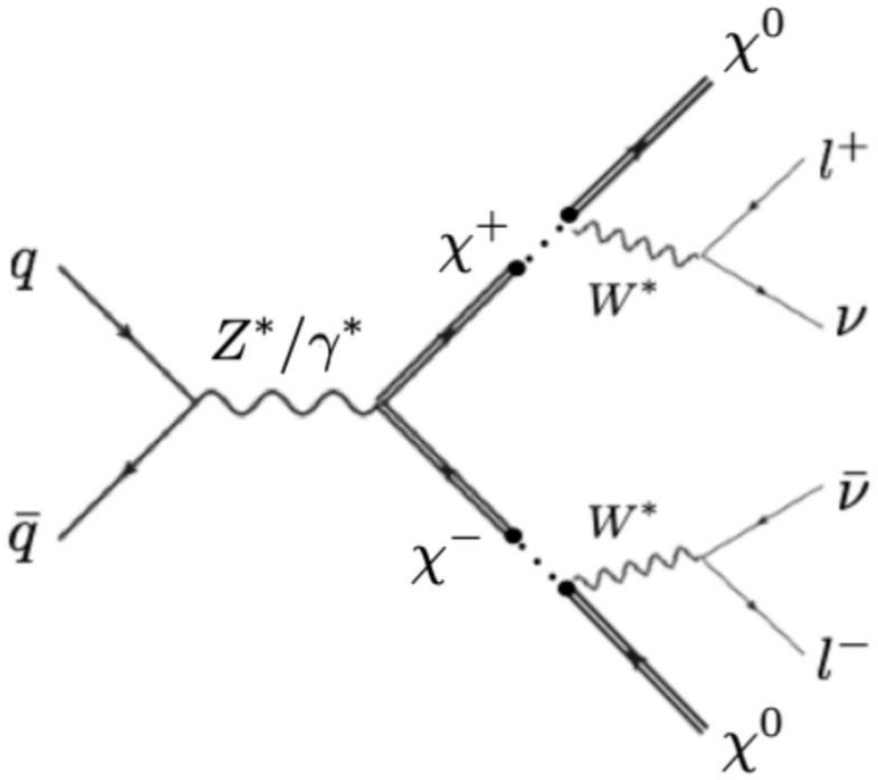
  DM mass ~ GeV – TeV

  Δm ~ *10 – 40* GeV

- At colliders:
  - Produce mediators (M)
  - M → DM + SM



Soft leptons from singlet-triplet model



New fermions:

- χ^0 – DM
- $\chi^{\pm}$
- χh

Filimonova and Westhoff [1812.04628]
Bharucha, Bruemmer and Desai [1804.02357]

Similar to bino – wino scenario in SUSY

Signal benchmark points

- Lepton kinematics depends on Δm.
- Detector acceptance is affected by $c\tau_c$.

#	m_c [GeV]	Δm [GeV]	$c\tau_c$ [cm]	$\mathcal{B}(\chi^+ \to \chi^0 \ell^+ \nu)$
1	324	20	2	0.025
2	220	20	3	0.014
3	220	20	0.2	1
4	220	20	2	1
5	220	20	20	1
6	220	20	200	1
7	220	40	2	1

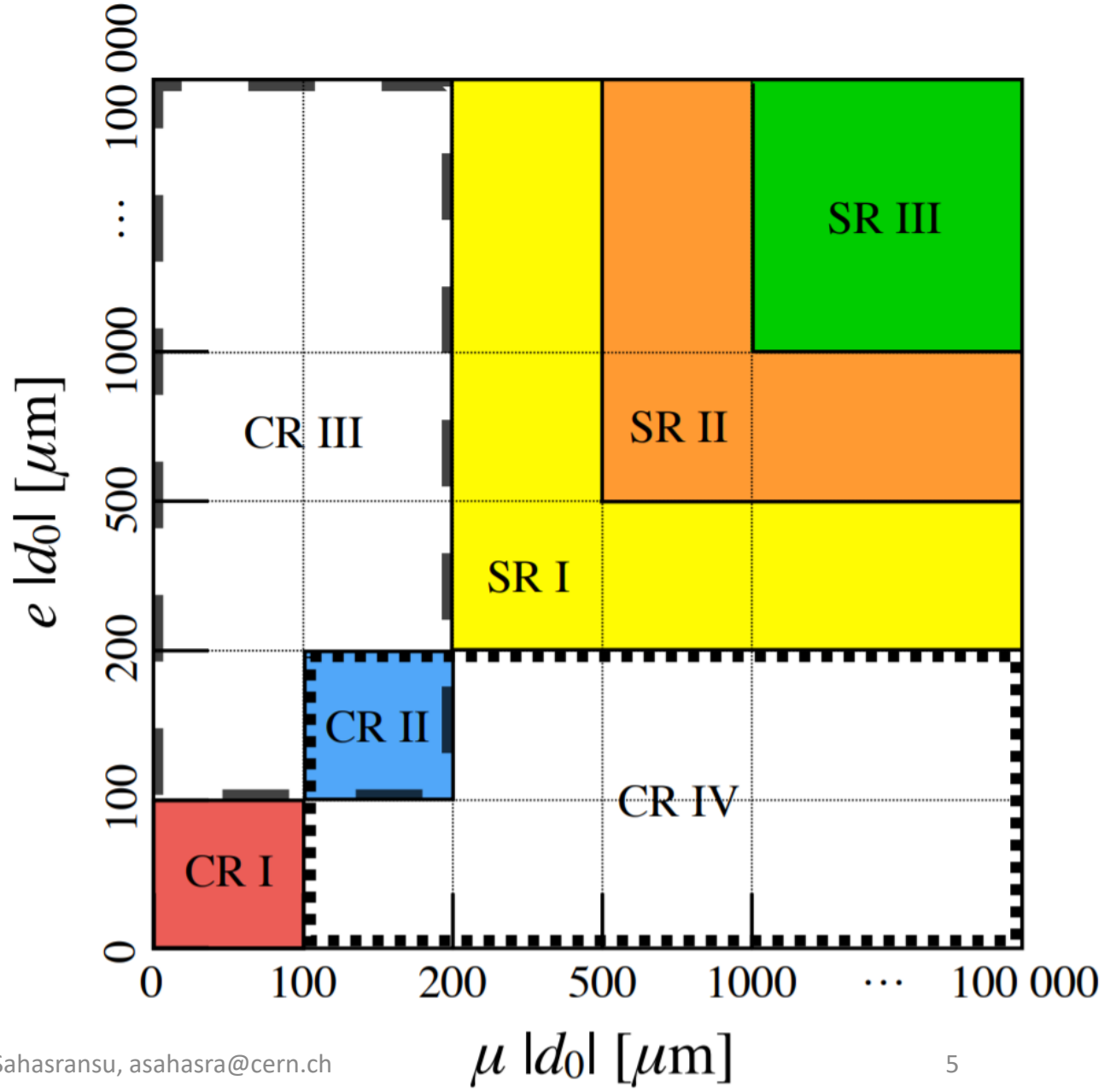
Event Generation: `Madgraph5_aMC@NLO 2.6.6` → Hadronization: `Pythia 8.243` → CMS effects: `Delphes 3.4.1`

Displaced di-lepton analysis at 13 TeV CMS-PAS-EXO-16-022

- 3 signal regions.
- Dominant background: **Leptons from heavy flavour jet**.
- Event selection:

Oppositely charged e and μ with ΔR > 0.5	1 muon	1 electron
	p_T > 40 GeV	p_T > 42 GeV
	η < 2.4	η < 2.4
	isolation < 0.15	isolation < 0.12

- p_T cut is too tight for the considered signature.

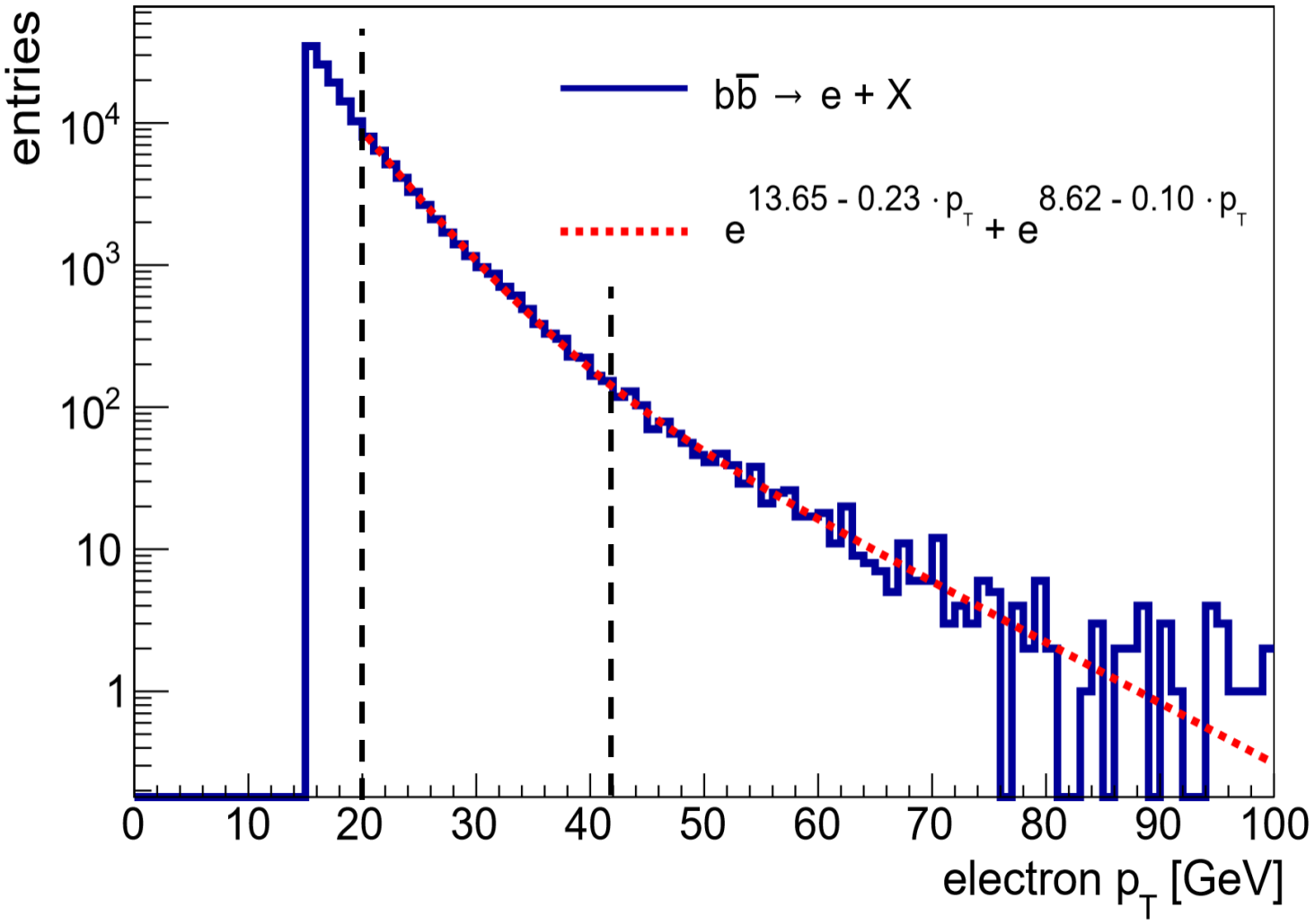


Background estimation

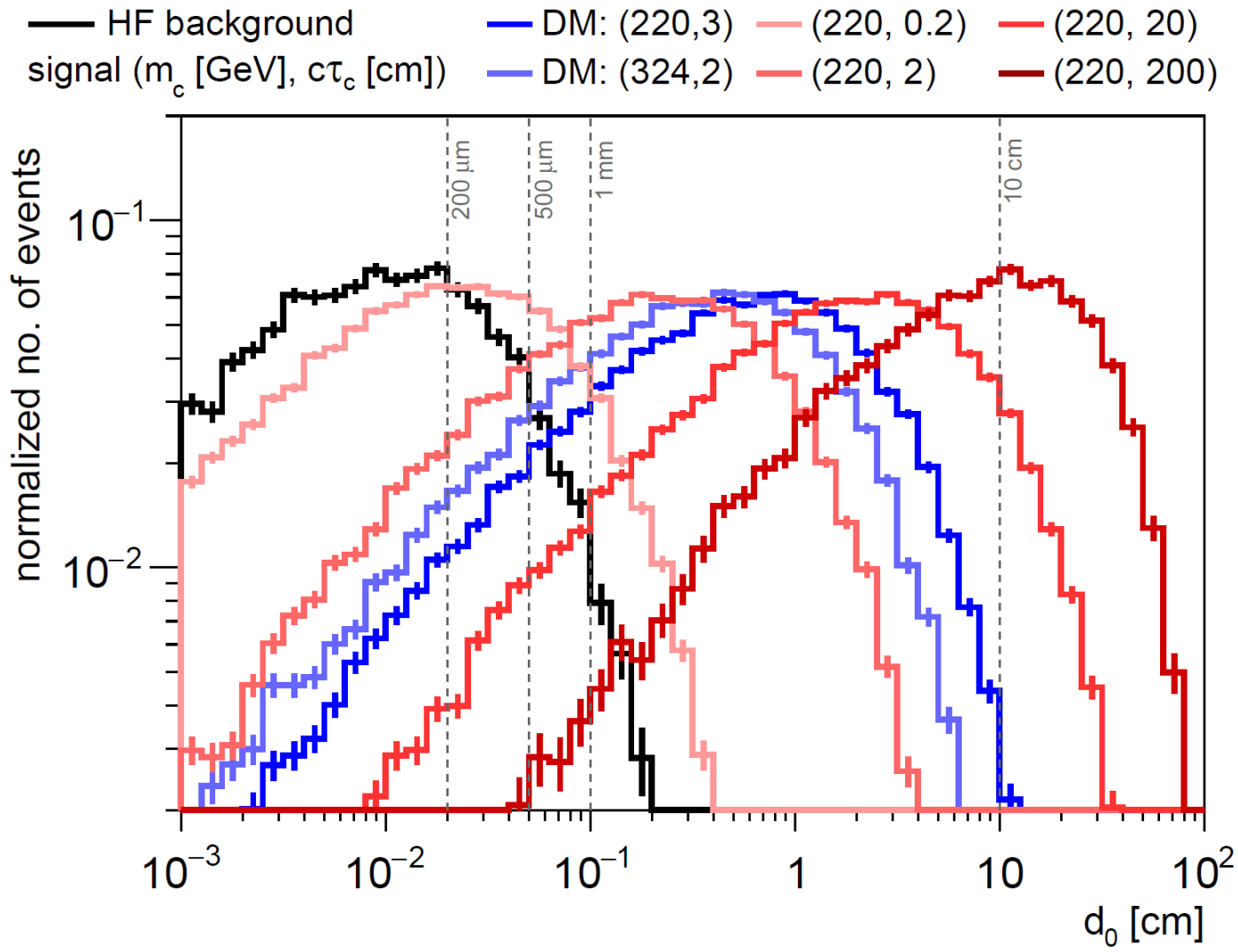
- Lepton enriched.
- e and μ transfer factor measured separately.
- p_T is independent of d_0 and isolation.

From CMS-PAS-EXO-16-022:

p_T(e, μ)	N_I	N_{II}	N_{III}
(42, 40)	<3.2	<0.5	<0.019
$\kappa_e(p_T) \times \kappa_\mu(p_T)$			
(20, 20)	<**4122.8**	<**644.2**	<**24.479**



Lepton d0 in benchmark points



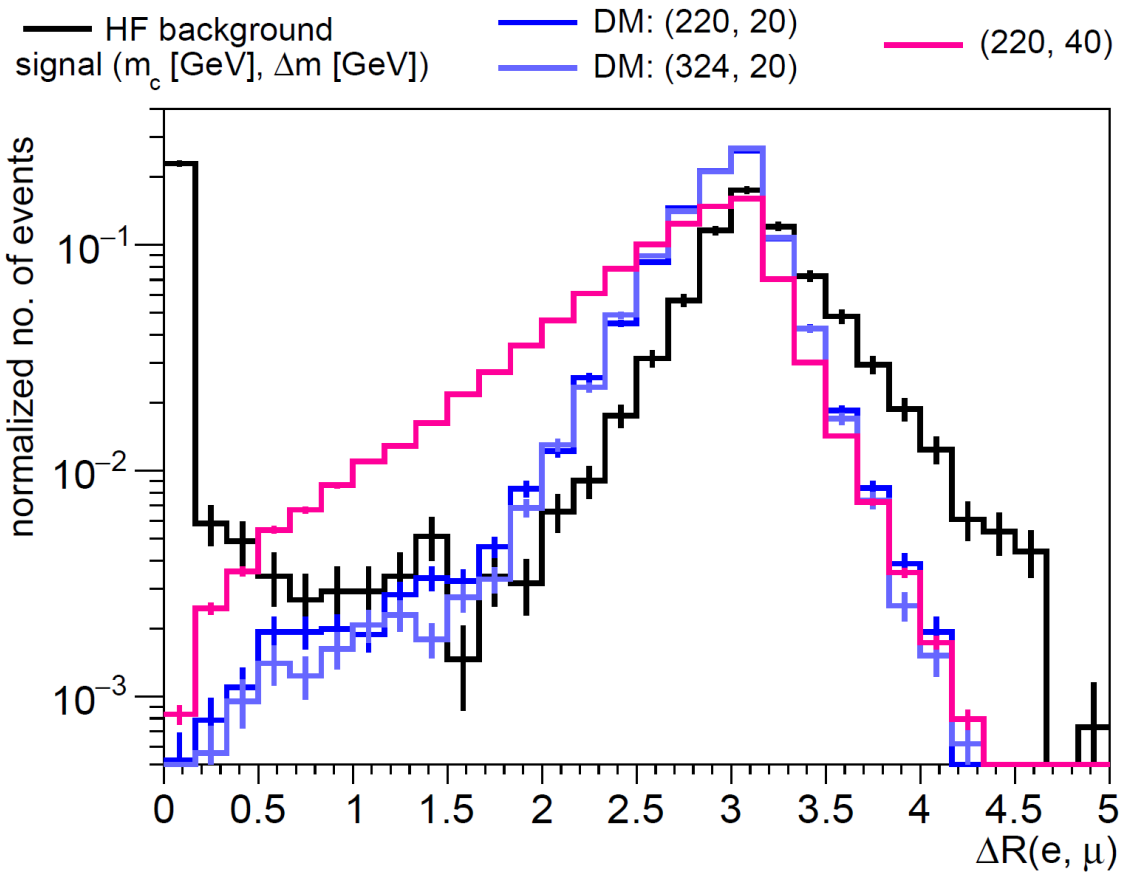
Signal Yields

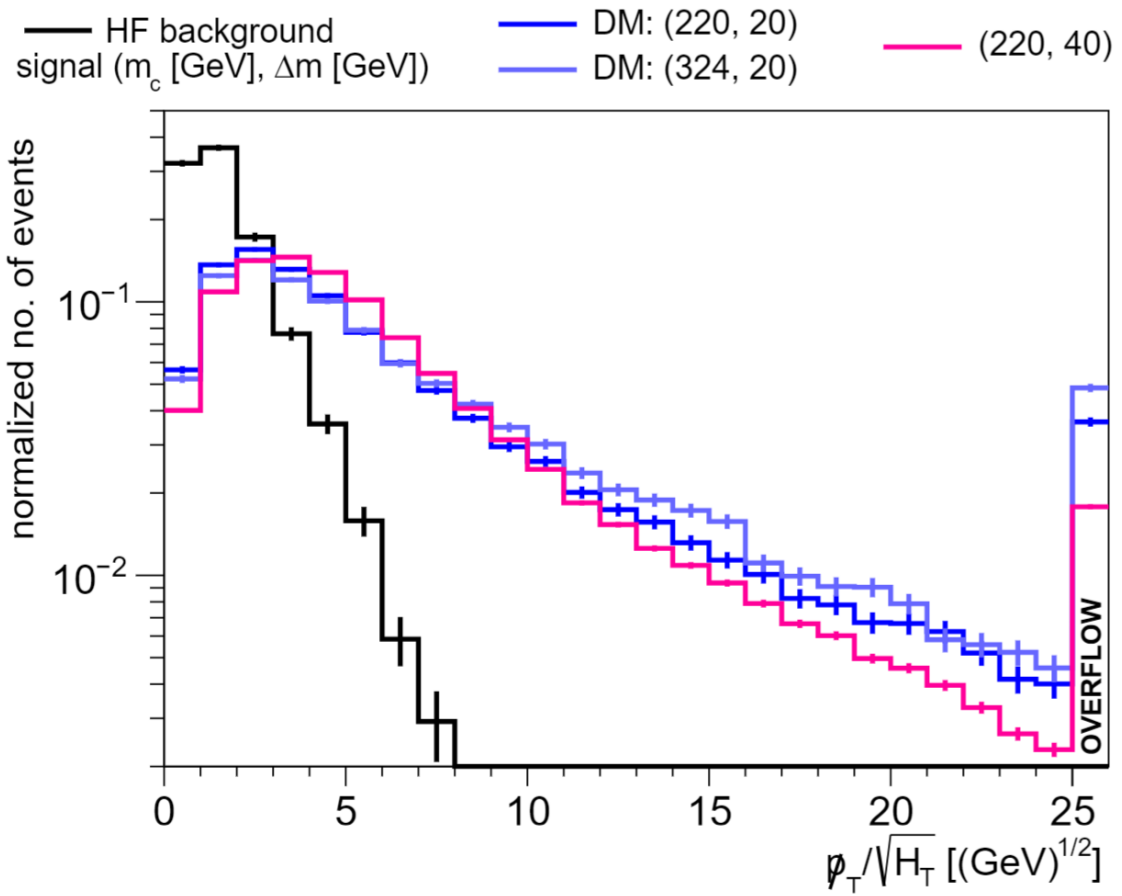
#	$(m_c\ ,\ \Delta m\ ,\ c\tau_c\ )$	N_{I}	N_{II}	N_{III}	$\mathcal{Q}/\mathcal{Q}_{\mathrm{lim}}\,(2.6\,\mathrm{fb}^{-1})$	$\mathcal{Q}/\mathcal{Q}_{\mathrm{lim}}\,(140\,\mathrm{fb}^{-1})$
	HF background	<4122.8	<644.2	<24.479		
1	(324, 20, 2)	0.009	0.010	0.035	0.000	0.000
2	(220, 20, 3)	0.030	0.036	0.182	0.000	0.012
3	(220, 20, 0.2)	3.023	0.832	0.149	0.000	0.038
4	(220, 20, 2)	4.029	3.713	7.723	0.342	18.397
5	(220, 20, 20)	0.926	1.181	14.398	1.027	55.262
6	(220, 20, 200)	0.049	0.067	2.074	0.028	1.497
7	(220, 40, 2)	24.760	23.160	49.938	7.746	417.028

- HF background: N_I <**4122.8** N_{II} <**644.2** N_{III} <**24.479**
- Signal << background for Δm = 20 GeV.

Discriminating signal from background

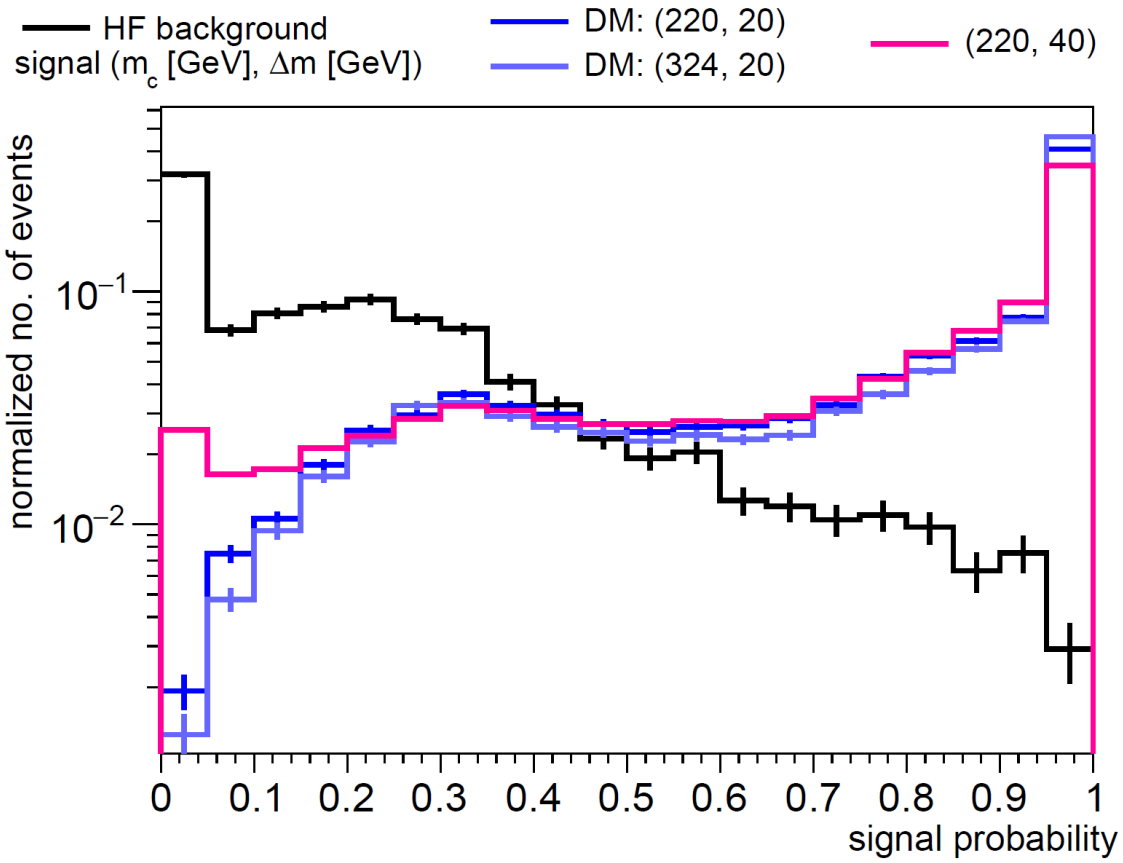
- Use multi variate analysis to gain discrimination.
- Using 9 input variables.

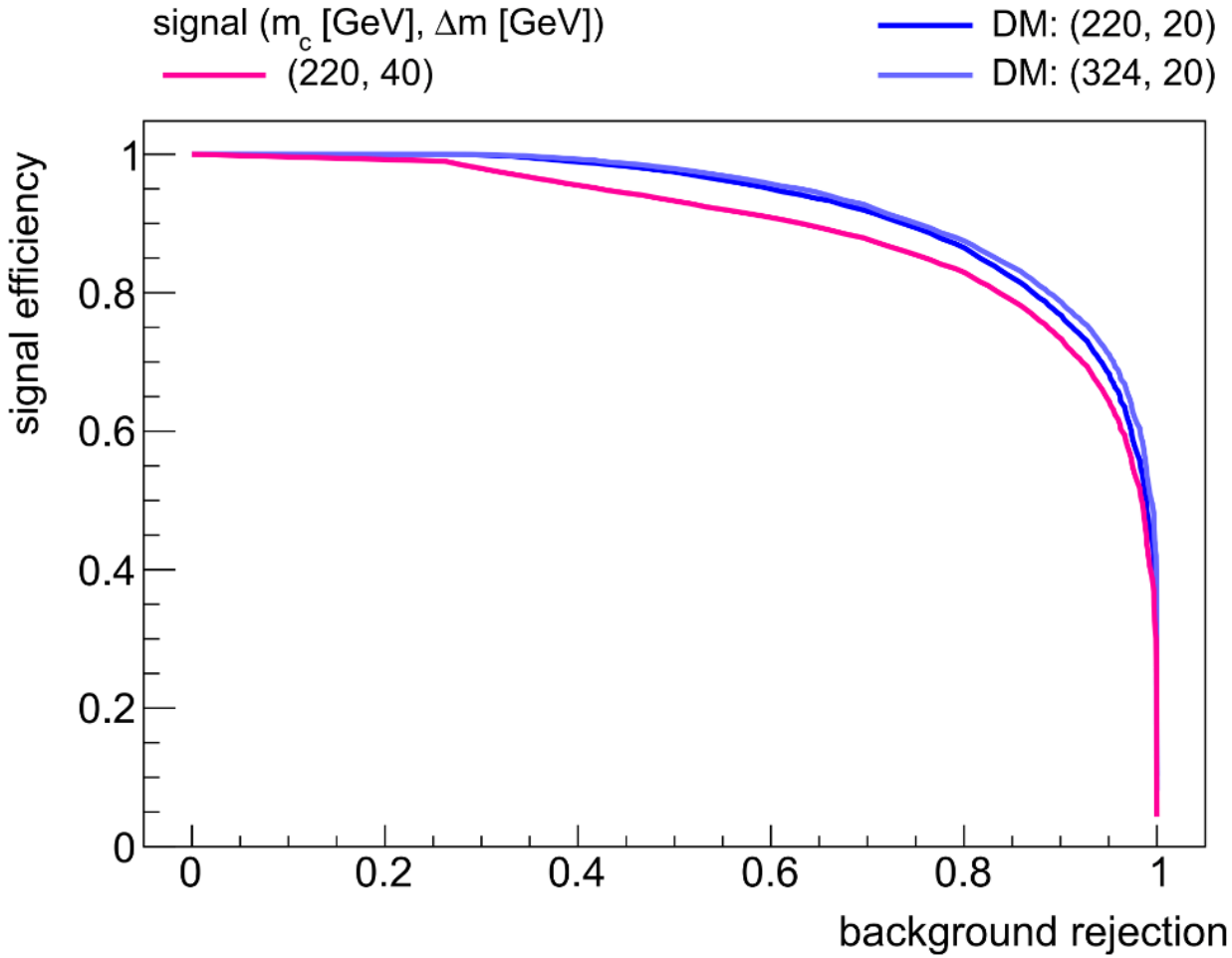




Neural network based classifier

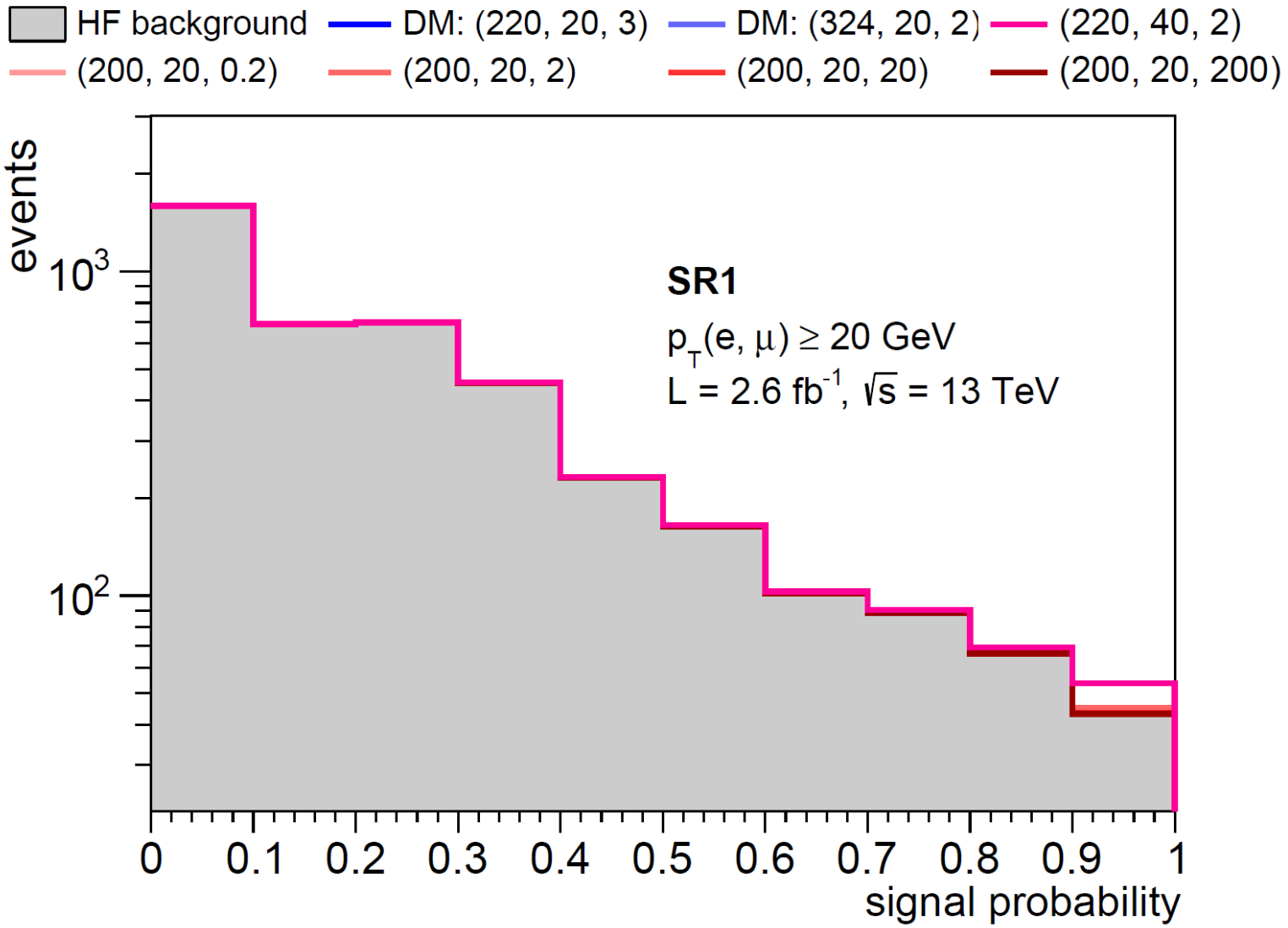
- Trained (80%) and tested (20%) on (324, 20, 2).



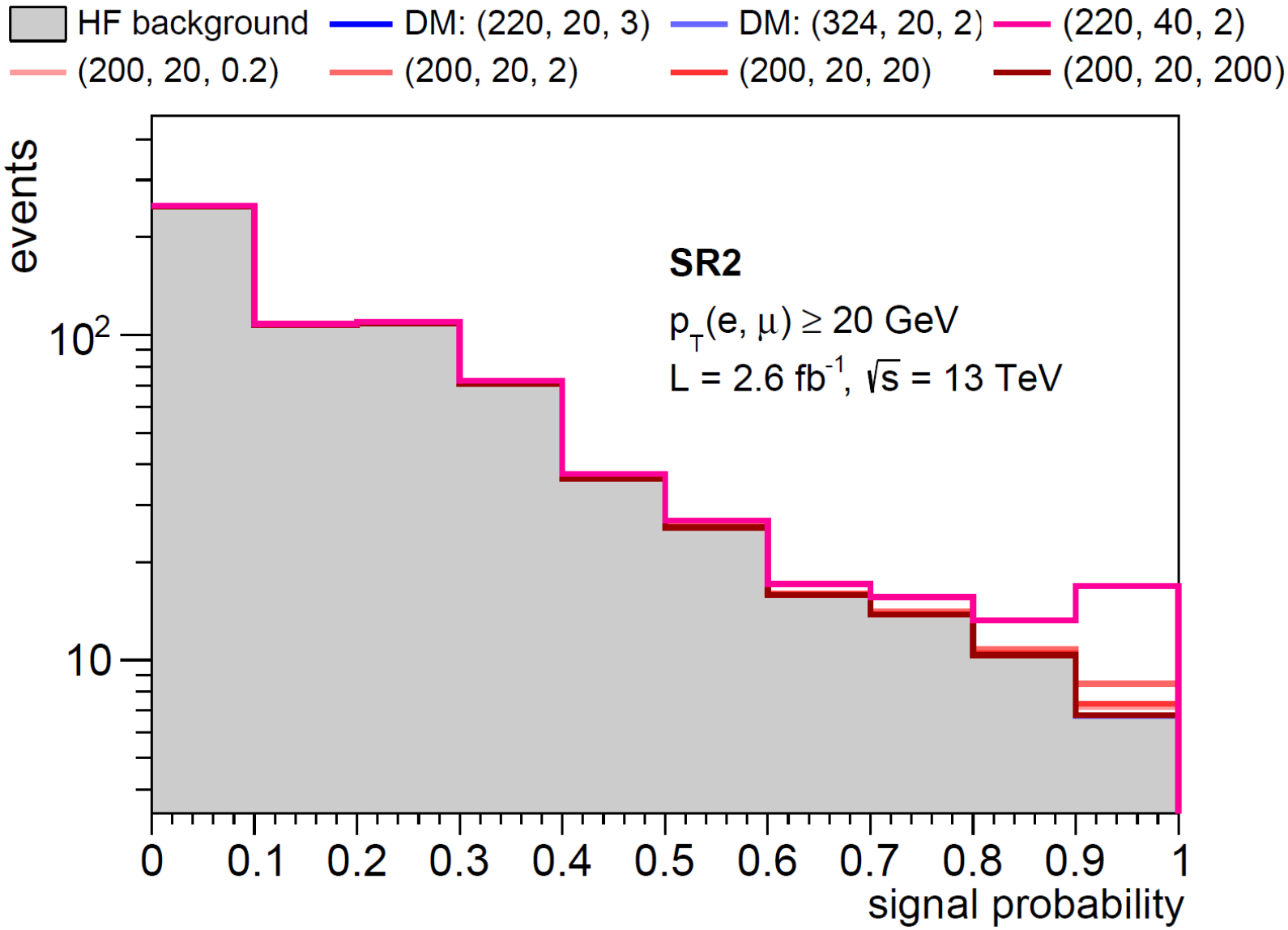


- One classifier for all benchmarks.

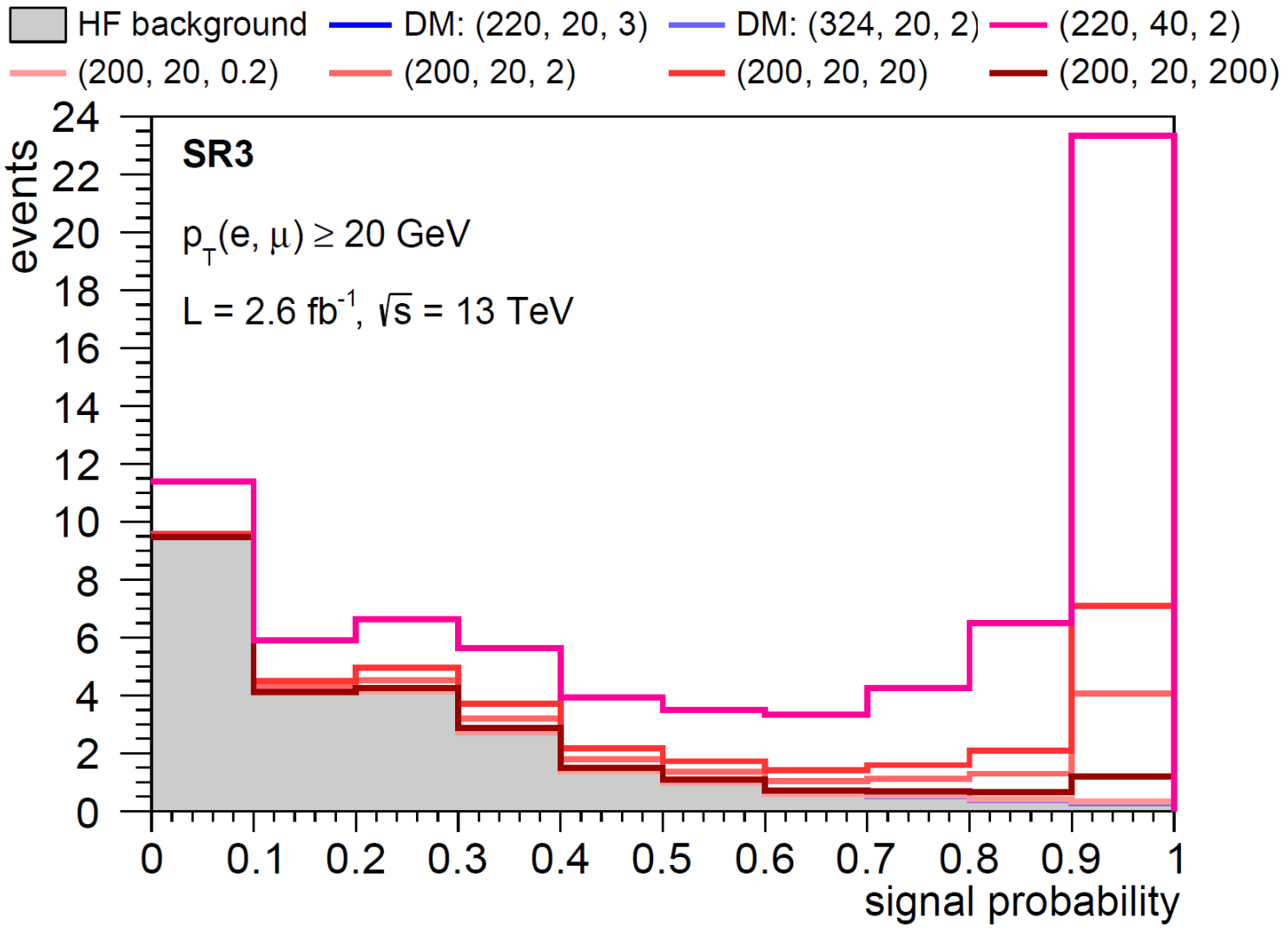
SR1


HF background
DM: (220, 20, 3)
DM: (324, 20, 2)
(220, 40, 2)
(200, 20, 0.2)
(200, 20, 2)
(200, 20, 20)
(200, 20, 200)
events
10^3
10^2
SR1
$p_T(e, \mu) \geq 20$ GeV
$L = 2.6\ fb^{-1}$, $\sqrt{s} = 13$ TeV
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
signal probability

SR2


HF background
DM: (220, 20, 3)
DM: (324, 20, 2)
(220, 40, 2)
(200, 20, 0.2)
(200, 20, 2)
(200, 20, 20)
(200, 20, 200)
events
10^2
10
SR2
$p_T(e, \mu) \geq 20$ GeV
$L = 2.6\ fb^{-1}$, $\sqrt{s} = 13$ TeV
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
signal probability

SR3

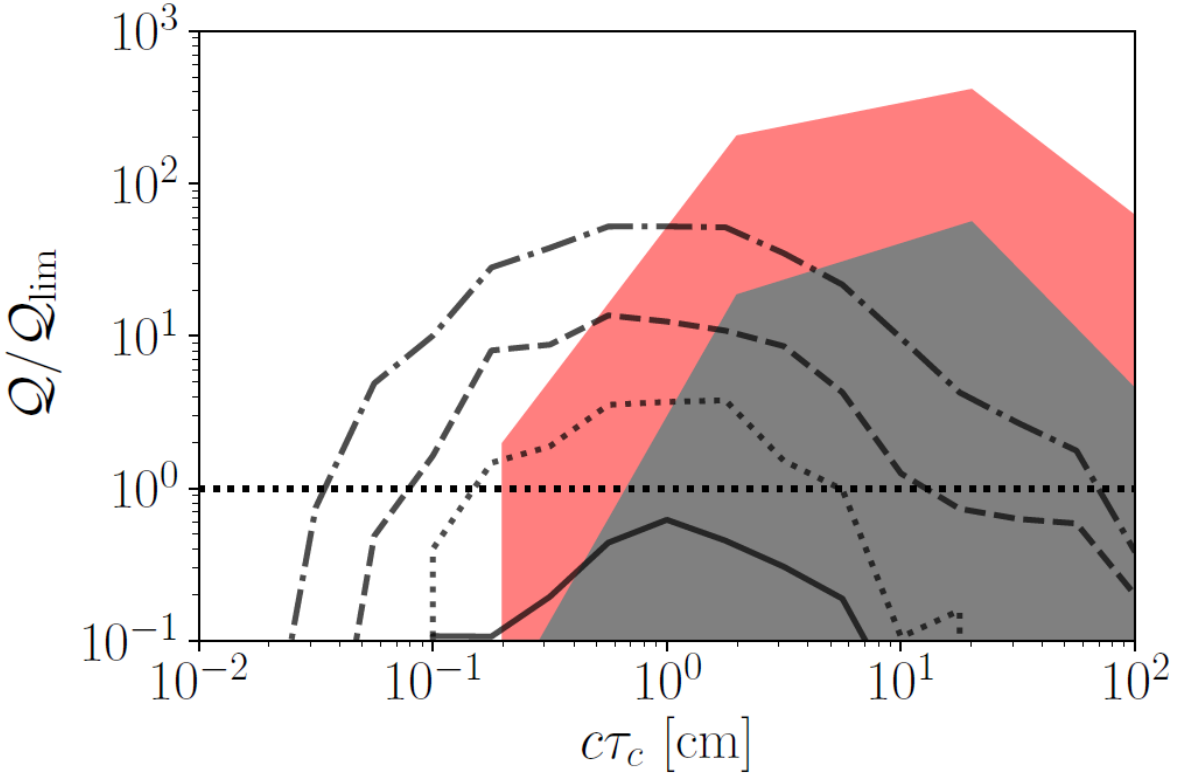

HF background
DM: (220, 20, 3)
DM: (324, 20, 2)
(220, 40, 2)
(200, 20, 0.2)
(200, 20, 2)
(200, 20, 20)
(200, 20, 200)
SR3
$p_T(e, \mu) \geq 20$ GeV
L = 2.6 fb^{-1}, $\sqrt{s}$ = 13 TeV
events
signal probability

Yield after discriminator cut shows significant improvement

- Discriminant cut = 0.9

#	$(m_c$ [GeV], Δm [GeV], $c\tau_c$ [cm])	N_{I}	N_{II}	N_{III}	$\mathcal{Q}/\mathcal{Q}_{\mathrm{lim}}\,(2.6\,\mathrm{fb}^{-1})$	$\mathcal{Q}/\mathcal{Q}_{\mathrm{lim}}\,(140\,\mathrm{fb}^{-1})$
1	HF background	35.13	5.49	0.21		
2	(324, 20, 2)	0.01	0.02	0.09	0.01	0.53
3	(220, 20, 3)	0.005	0.01	0.02	0.00	0.03
4	(220, 20, 0.2)	1.45	0.41	0.07	0.02	1.97
5	(220, 20, 2)	1.88	1.65	3.67	1.11	202.57
6	(220, 20, 20)	0.41	0.57	6.52	1.94	408.28
7	(220, 20, 200)	0.03	0.02	0.89	0.18	26.63
8	(220, 40, 2)	9.80	9.48	21.57	8.59	2016.47

Exclusion limit for the benchmarks



Displaced Lepton search; $m_c = 220$ GeV

- $\Delta m = 20$ GeV (8 TeV; 19.7 fb^{-1})
- $\Delta m = 25$ GeV
- $\Delta m = 30$ GeV
- $\Delta m = 40$ GeV
- $\Delta m = 20$ GeV (This work – with NN; Run 2)
- $\Delta m = 20$ GeV (This work – without NN; Run 2)

Conclusion

- Soft displaced leptons are typical signs of dark matter from co-scattering and co-annihilation.
  - To observe these signatures at the LHC, events with soft leptons need to be selected.
- LHC signal with soft displaced leptons are challenged by large heavy flavour background.
- Multivariate analysis effectively discriminates between signal and HF background.
  - Neural network reduces background by two orders of magnitude.
  - With 140 fb^{-1} $c\tau_c$ values between 2 mm and 2 m can be excluded.

Outlook

- CMS provides d_0 based efficiency for re-construction of leptons. `Delphes 3.4.1` doesn't take this into account. The event yield in each signal region needs to be re-weighted to account for this inefficiency.
- Exclusion limits to be calculated on the model benchmark points.
- Can be discovered with LHC Run 3 data.
  - Requires cross triggers with lower pT threshold and other objects.

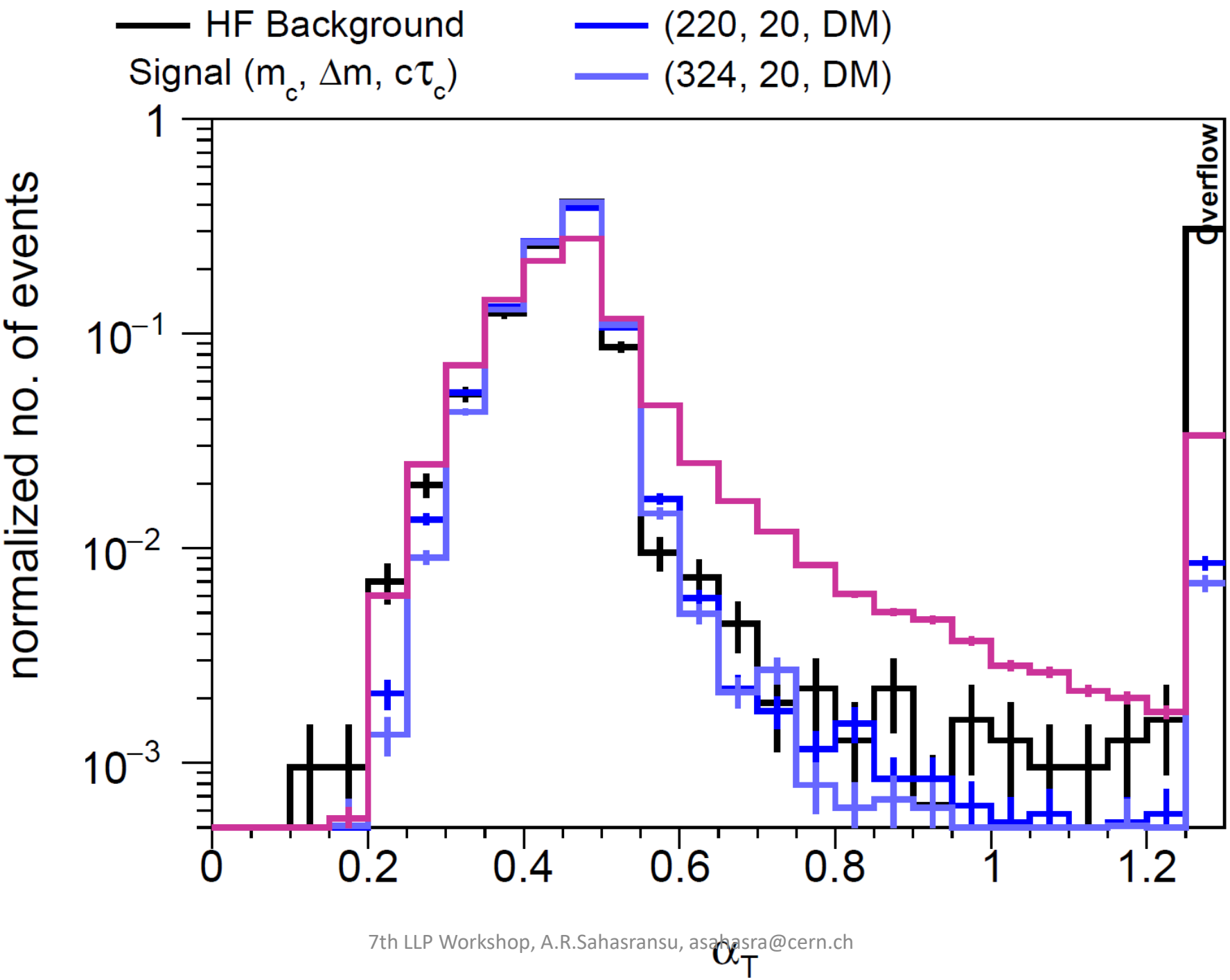
BACK-UP

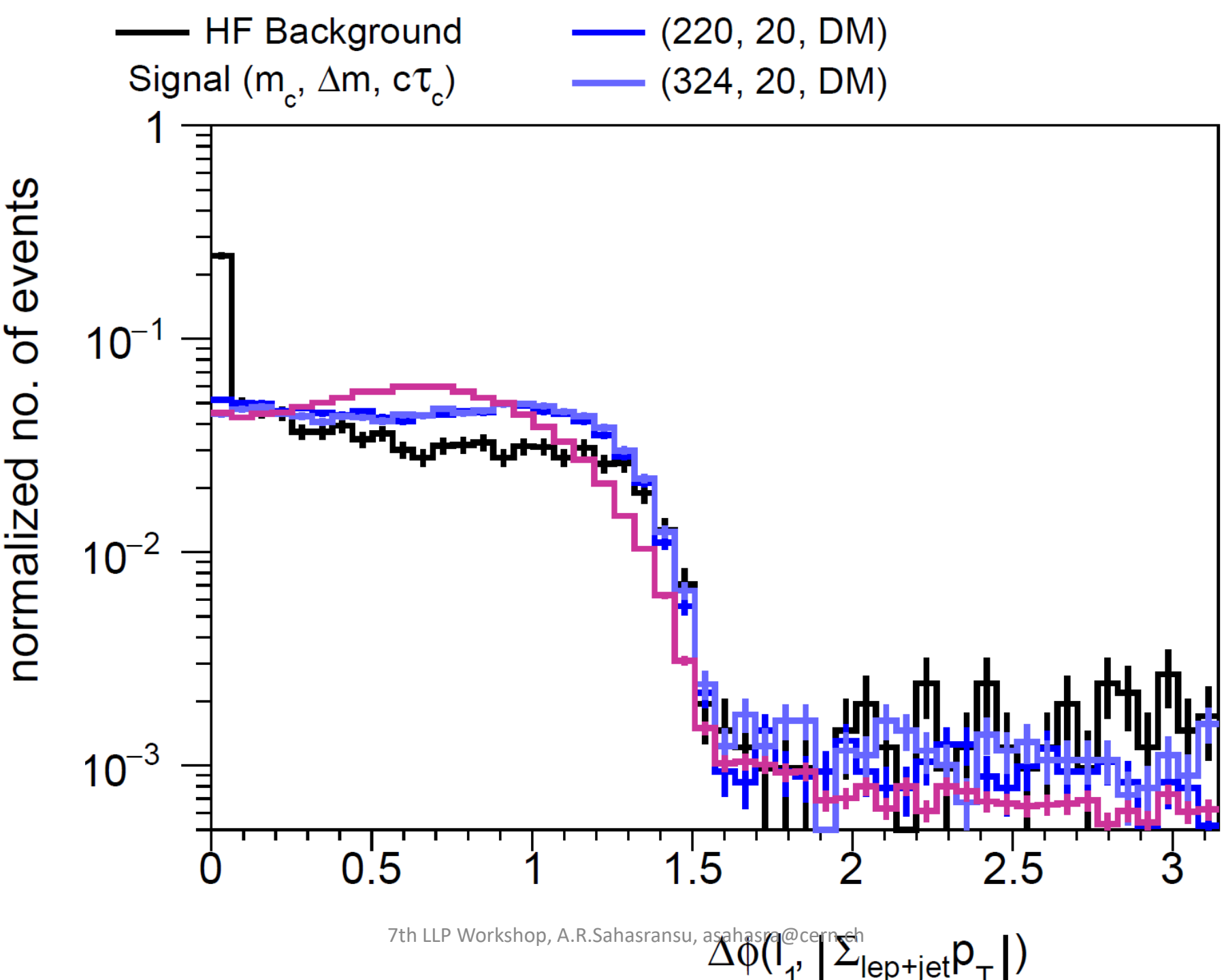
Ranking of Variables

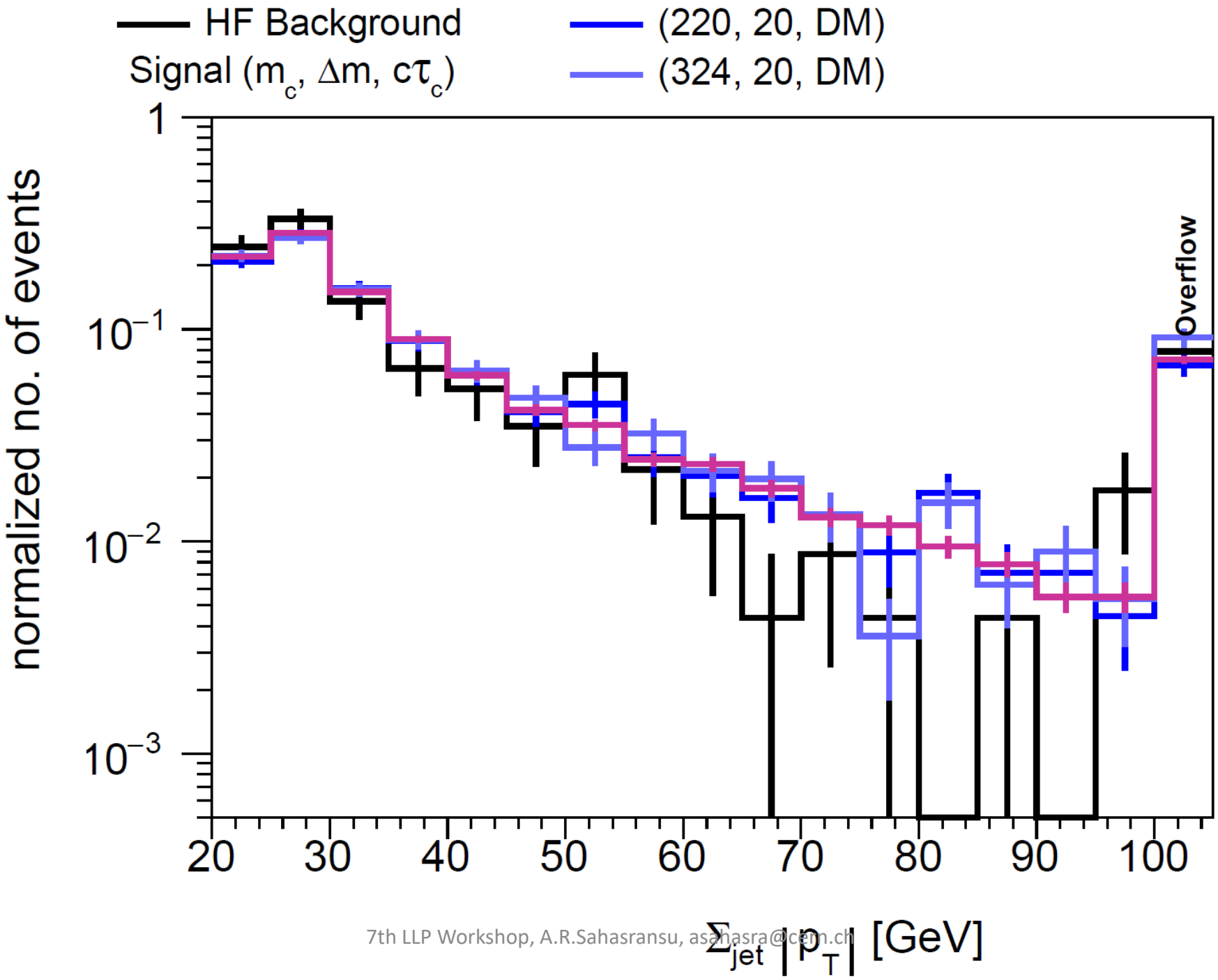
The ranking of the variables is based on overlapping co-efficient of the normalized histograms on each other.

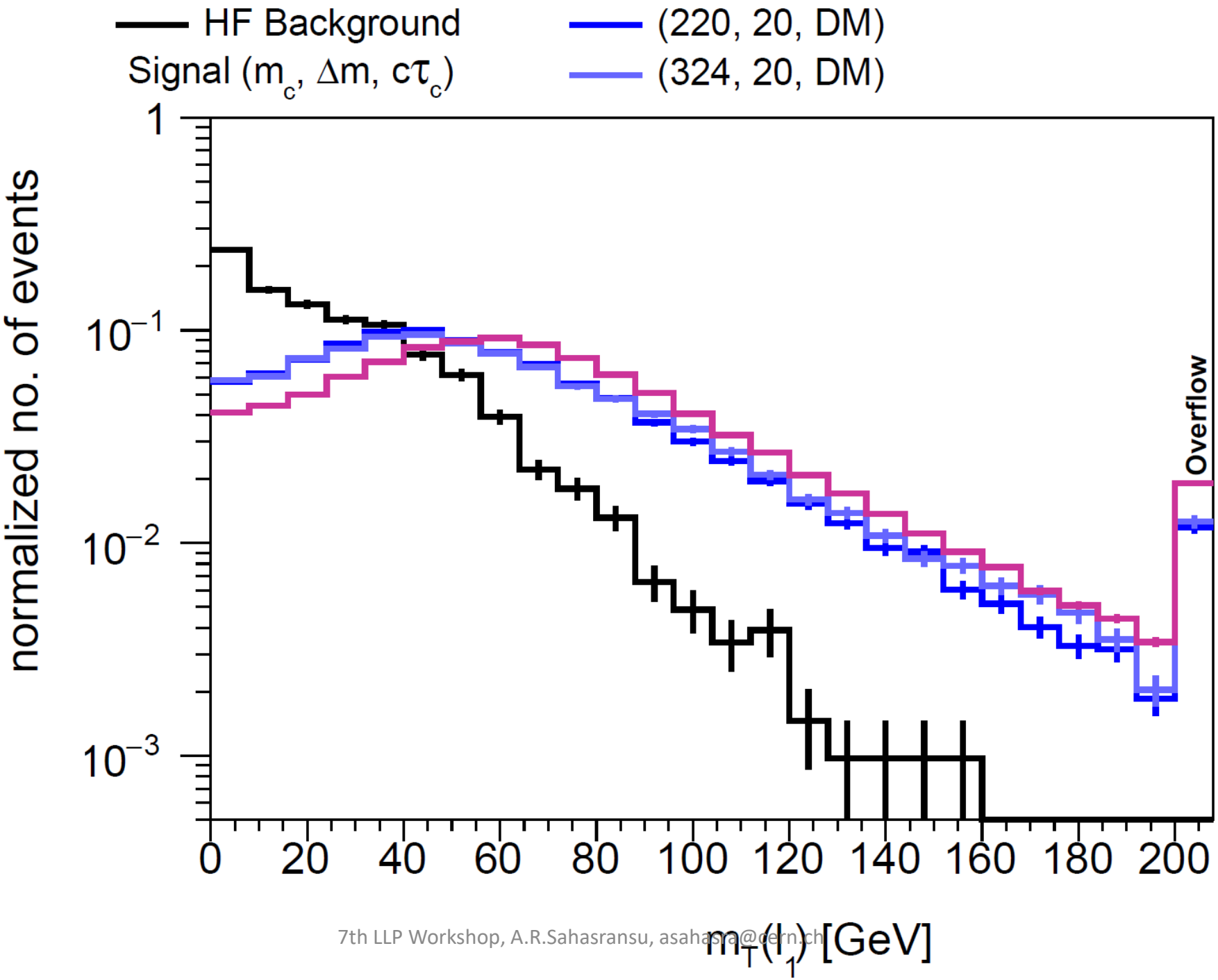
1. `YDelpObj` - 0.4764
2. `dRLL` - 0.596
3. `dPhiLepMET` - 0.6138
4. `Sphericity` - 0.7042
5. `Spherocity` - 0.7516
6. `YUserObj` - 0.7547
7. `dPhiLepMETSelObj` - 0.7705
8. `alphaT` - 0.7822
9. `EtaEl` - 0.8486
10. `EtaMu` - 0.8696

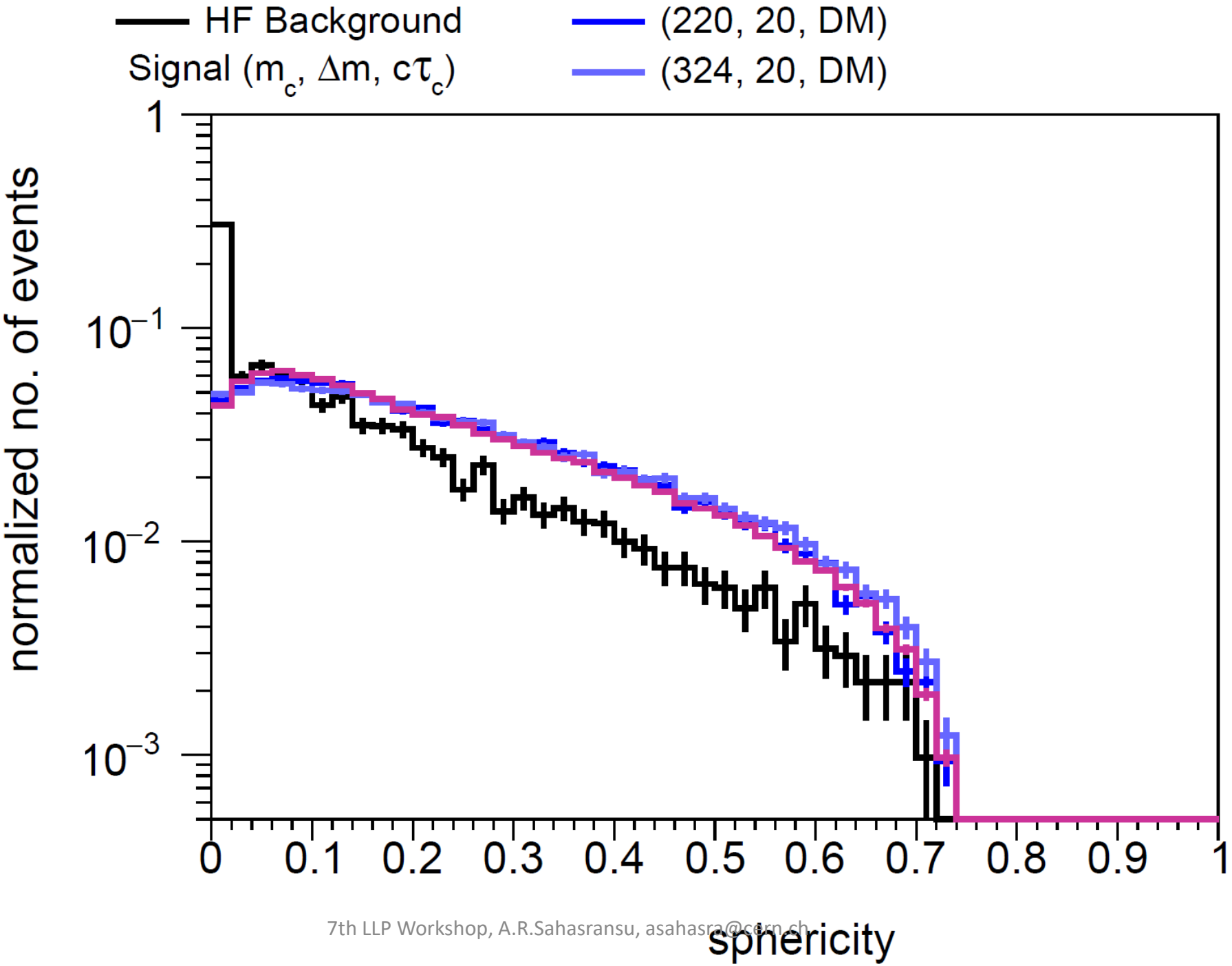
- $p_T/\sqrt{H_T}$, $\Delta R(e,\mu)$, $m_T(\ell_1)$,
- $\Delta\phi\ (\ell_1, p_T)$,sphericity, spherocity,
- $\sum_{\ell+j} |\vec{p}_T(i)| \,/\, \left|\sum_{\ell+j} \vec{p}_T(i)\right|$, α_T and h_T

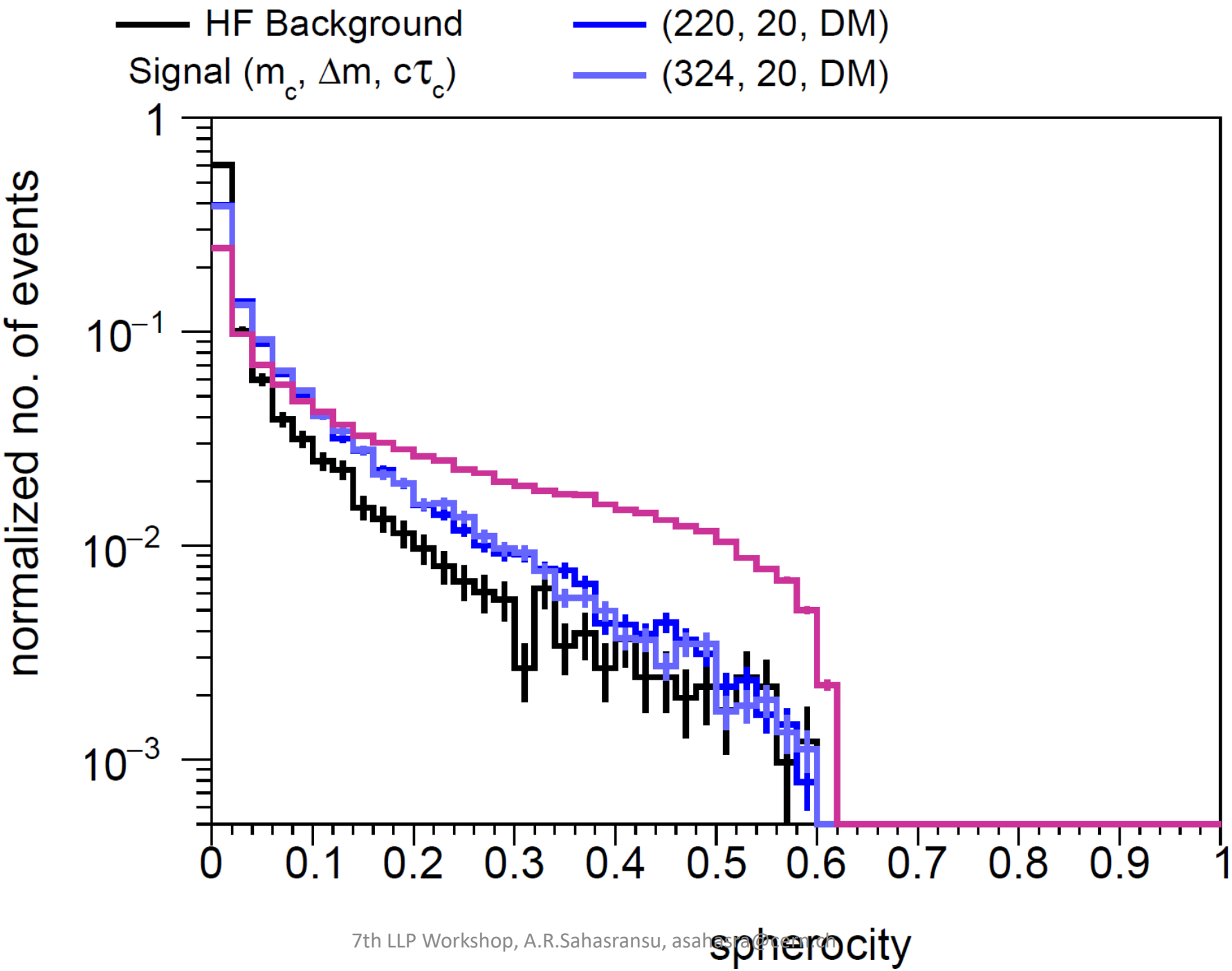

HF Background
Signal (m_c, Δm, $c\tau_c$)
(220, 20, DM)
(324, 20, DM)
normalized no. of events
1
10^{-1}
10^{-2}
10^{-3}
0
0.2
0.4
0.6
0.8
1
1.2
overflow
α_T

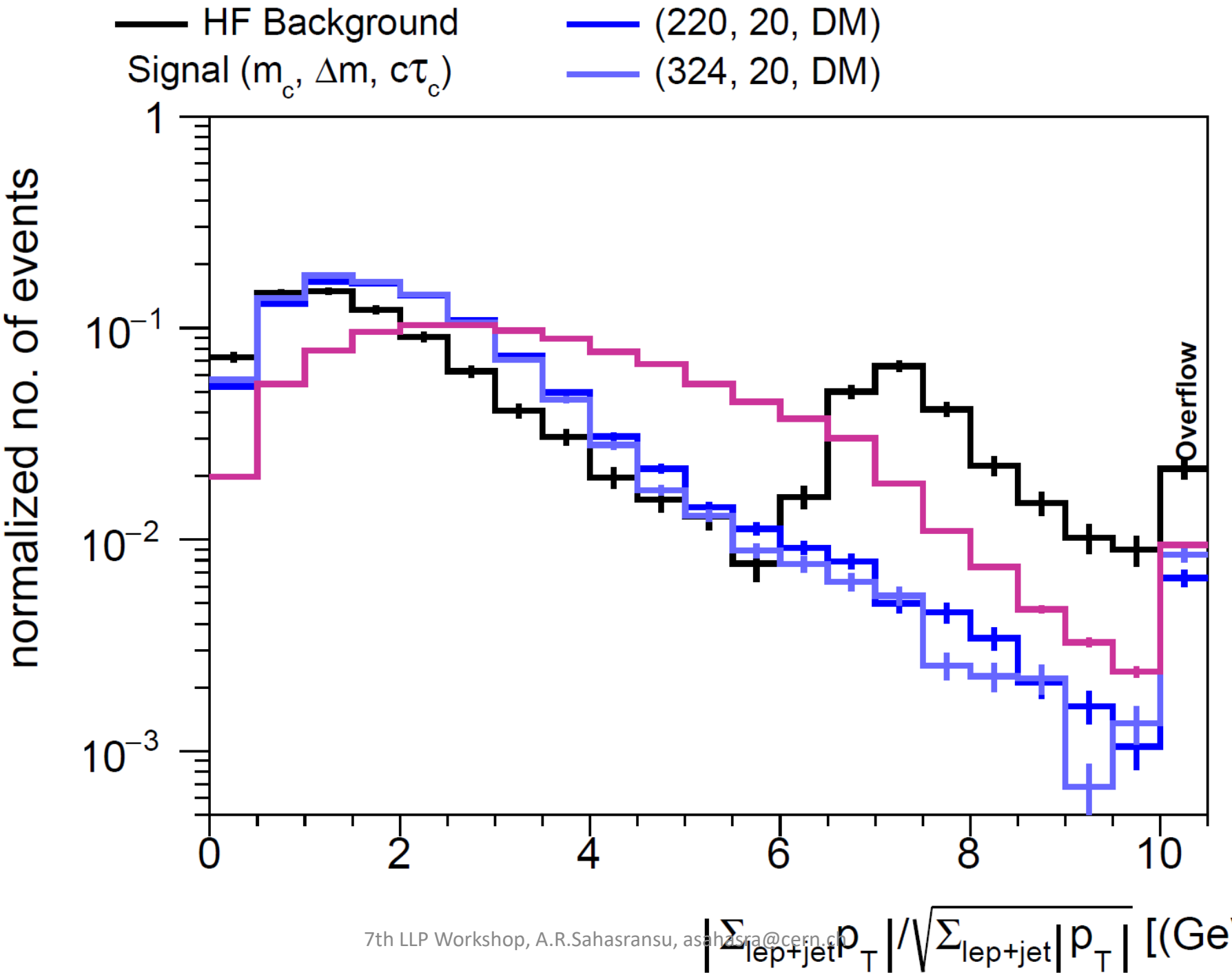

HF Background
Signal (m_c, Δm, $c\tau_c$)
(220, 20, DM)
(324, 20, DM)
normalized no. of events
1
10^{-1}
10^{-2}
10^{-3}
0
0.5
1
1.5
2
2.5
3
$\Delta\phi(l_1, |\Sigma_{lep+jet}p_T|)$


HF Background
Signal (m_c, Δm, $c\tau_c$)
(220, 20, DM)
(324, 20, DM)
normalized no. of events
1
10^{-1}
10^{-2}
10^{-3}
Overflow
20
30
40
50
60
70
80
90
100
$\Sigma_{jet} |p_T|$ [GeV]

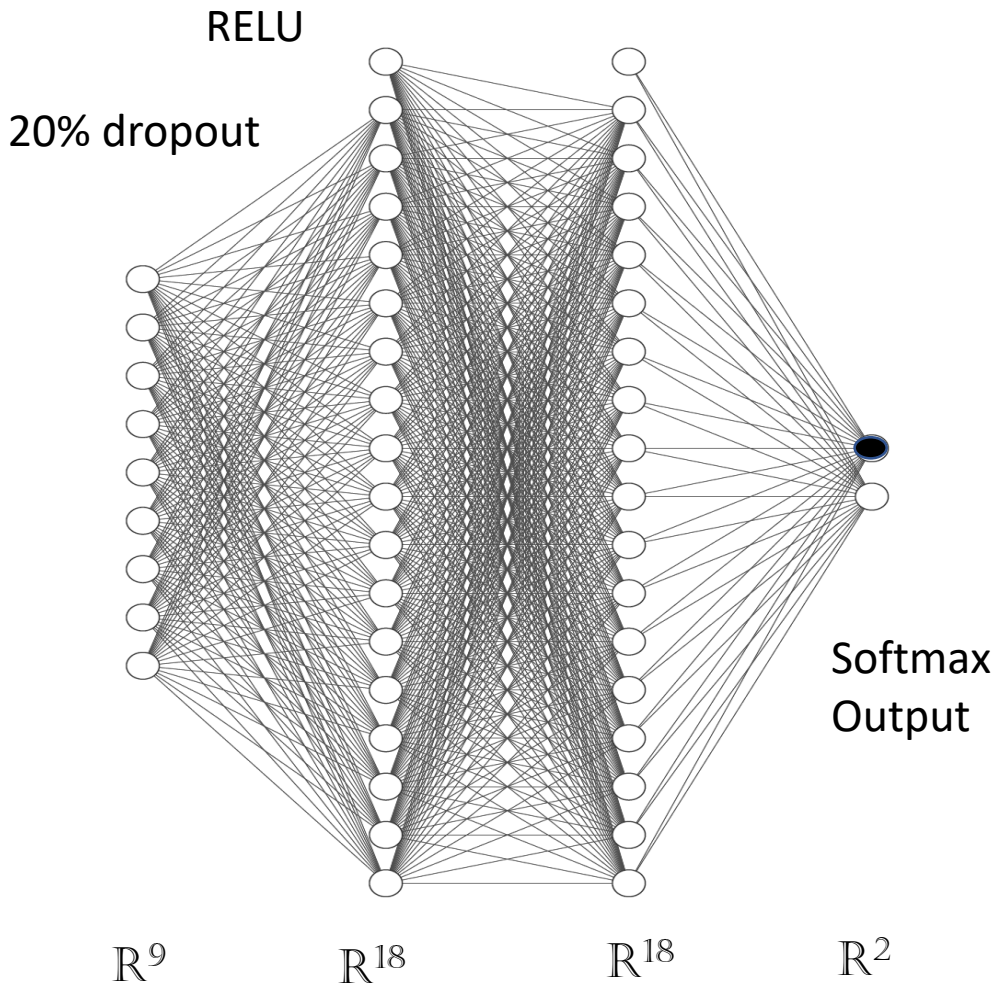

HF Background
Signal (m_c, Δm, $c\tau_c$)
(220, 20, DM)
(324, 20, DM)
normalized no. of events
1
10^{-1}
10^{-2}
10^{-3}
Overflow
0
20
40
60
80
100
120
140
160
180
200
$m_T(l_1)$ [GeV]

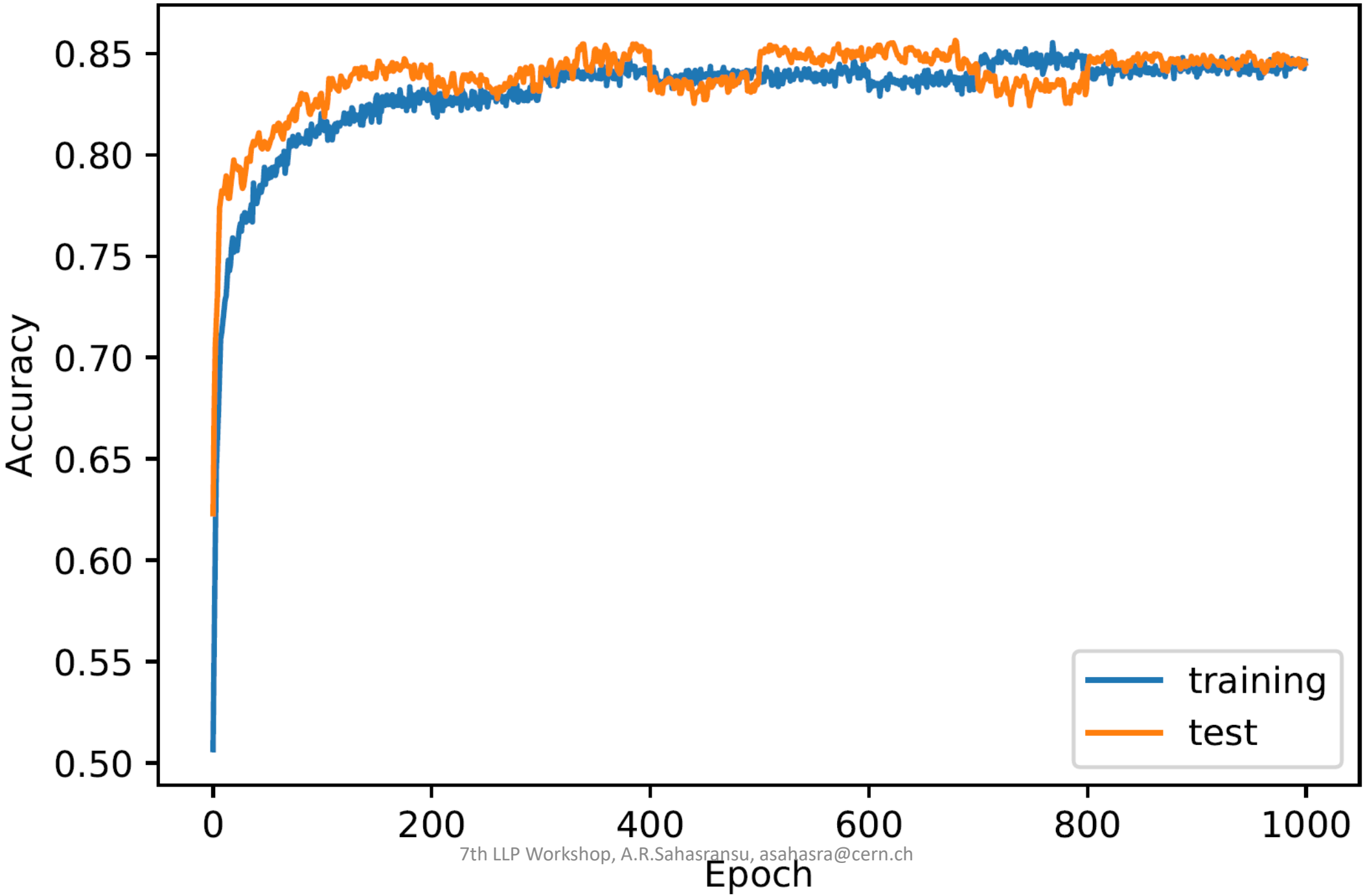

HF Background
Signal (m_c, Δm, $c\tau_c$)
(220, 20, DM)
(324, 20, DM)
normalized no. of events
1
10^{-1}
10^{-2}
10^{-3}
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
sphericity

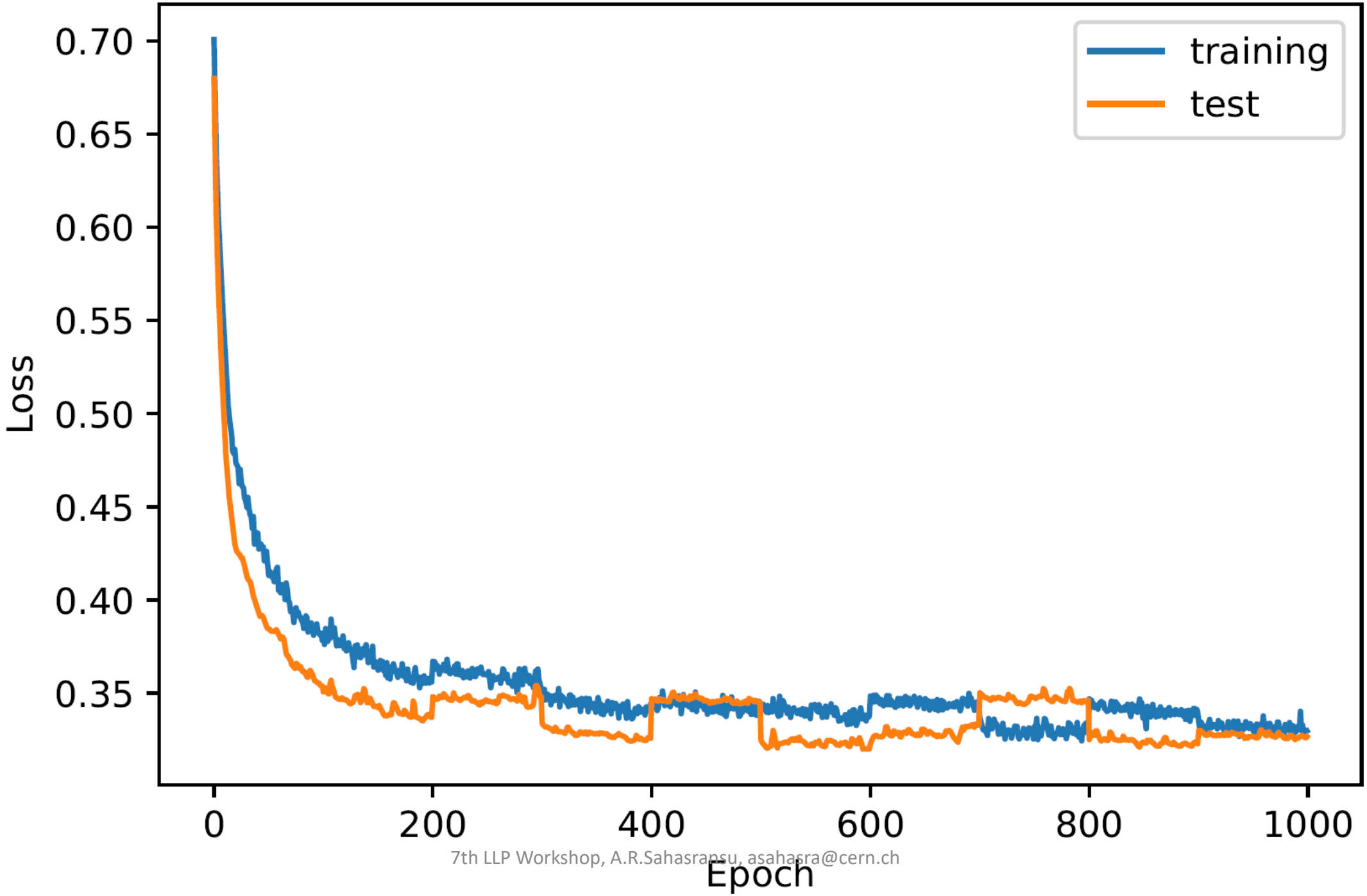

HF Background
Signal (m_c, Δm, $c\tau_c$)
(220, 20, DM)
(324, 20, DM)
normalized no. of events
1
10^{-1}
10^{-2}
10^{-3}
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
sphericity


HF Background
Signal (m_c, Δm, $c\tau_c$)
(220, 20, DM)
(324, 20, DM)
normalized no. of events
1
10^{-1}
10^{-2}
10^{-3}
0
2
4
6
8
10
Overflow
$|\Sigma_{lep+jet} p_T| / \sqrt{\Sigma_{lep+jet} |p_T|}$ [(GeV)$^{1/2}$]

4107 background events




0.85
0.80
0.75
0.70
0.65
0.60
0.55
0.50
Accuracy
0
200
400
600
800
1000
Epoch
training
test


training
test
Loss
0.70
0.65
0.60
0.55
0.50
0.45
0.40
0.35
0
200
400
600
800
1000
Epoch