

Search for $Z_c(3900)$ via Transformer at BESIII

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- $Z_c(3900)$ decay chain
 $e^+e^- \rightarrow Z_c(3900)^\pm \pi^\mp$
 $Z_c(3900)^\pm \rightarrow J/\psi \pi^\pm$
 $J/\psi \rightarrow e^+e^-(\mu^+\mu^-)$

- Signal MC sample (BOSS 7.0.3)

decay tree	decay model
$e^+e^- \rightarrow Z_c(3900)^\pm \pi^\mp$	PHSP
$Z_c(3900)^\pm \rightarrow J/\psi \pi^\pm$	PHSP
$J/\psi \rightarrow e^+e^-(\mu^+\mu^-)$	VLL

- Data Sample (BOSS 7.0.3)

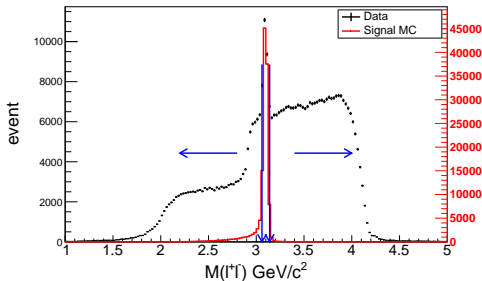
4.260 GeV Data at BESIII of 2013

sample	luminance	center-mass energy	Run number
4260	$828.4 \pm 0.1 \pm 5.5$	$4257.97 \pm 0.04 \pm 0.66$	29677-30367 31561-31981

- Good charged track selection
 - $|\cos\theta| < 0.93, |V_z| < 10\text{cm}, |V_r| < 1\text{cm}$
 - Four good tracks and zero net charge
- particle identification
 - $p > 1\text{ GeV}/c$ identified as lepton
 - $p < 1\text{ GeV}/c$ identified as π
 - The number of pions and that of leptons should be two in each event with zero net charge.
 - $E_{EMC} > 1.1\text{ GeV}$ identified as e
 - $E_{EMC} < 0.35\text{ GeV}$ identified as μ
- remove gamma-conversion background
 - $\cos(\pi^+\pi^-) < 0.98$
 - $\cos(\pi^\pm e^\mp) < 0.98$

Parameter Set

- Model : Transformer and Quantum Transformer
- Signal : Signal MC
- Background is form data :
 $M(I^+I^-) \in (0, 3.06) \cup (3.14, 5) \text{ GeV}/c^2$

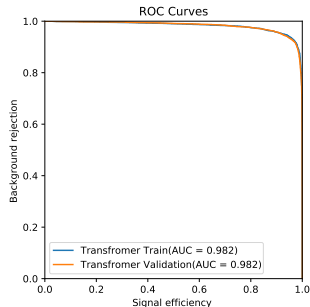
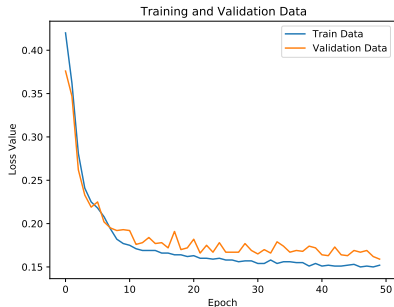


Parameter Set

- Data : 98577 event after preliminary cut
- Sideband data : 86609 event
- Signal : 124706 event
- Signal: background = 1:1
- Classical Transformer :
 - 20k events (10k for train, 10k for validation)
 - 50 epochs
- Quantum Transformer :
 - 20k events (10k for train , 10k for validation)
 - 6 epochs

Training Model–Transformer

- Parameter Set: 26 variables
- 16 variables: four-momentum of 4 charge tracks
- 4 variables: momentum of 4 charge tracks
- 4 variables : angles between tracks
- 2 variables : $\text{Num}(\gamma)$, $\text{Emax}(\gamma)$



Apply Model-Transformer

Data : 98k

Signal MC : 120k

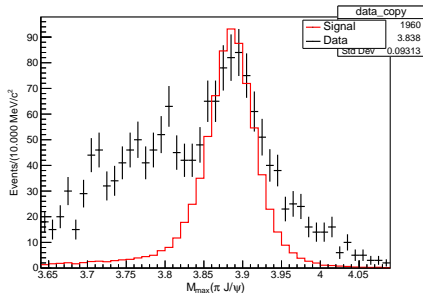
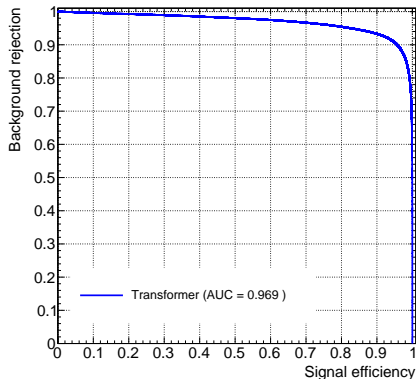
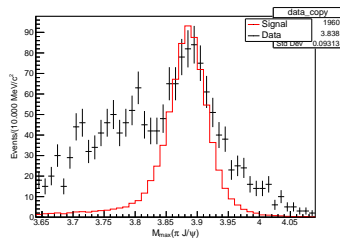
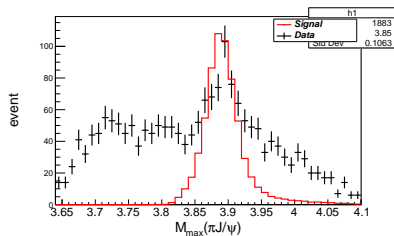


Fig : Apply the model to the real data and signal MC. ROC curve (left) and $M_{max}(\pi J/\psi)$ invariant mass distributions(right). In right panel, dots with error bars are data. The red curve is signal MC.

Apply Model-Transformer



$\epsilon = 231.63$ $\epsilon = 242.67$

Fig: $M_{max}(\pi J/\psi)$ invariant mass distribution. The left plot shows the result using classical cuts, while the right plot displays the Transformer result .

$$\epsilon = \frac{s}{\sqrt{s+b}}$$

Here, s represents the number of events in the signal MC, while b represents the number of events in the data.

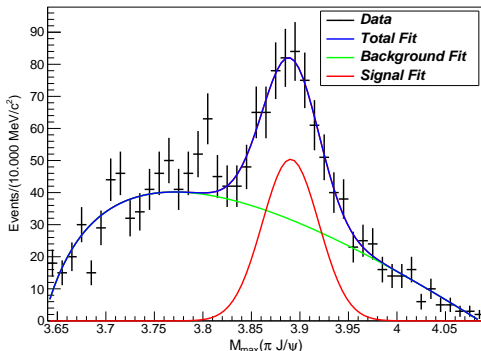
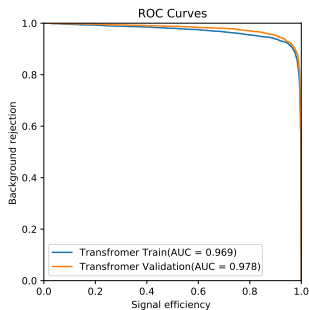
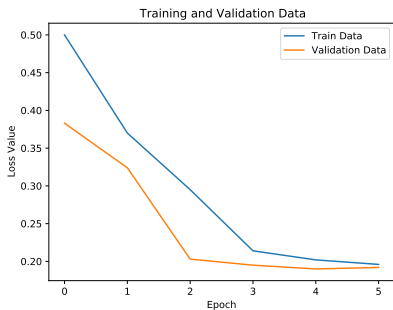


Fig : Fit to $M_{max}(\pi J/\psi)$ invariant mass distributions with Gaussian resolution as signal function and $a/(x - 3.6)^b + c + dx$ background trem . Dots with error bars are data. The blue curve shows the total fit, the green curve shows the background fit, and the red curve shows the signal fit.

Training Model—Quantum Transformer

- Parameter Set: 26 variables:
 - $\vec{p}, E, p, \theta_{l\pm\pi\mp}, \theta_{l+l-}, \theta_{\pi+\pi-}, N_\gamma, E_\gamma^{max}$
- Data Set :
 - 20k events (10k for train , 10k for validation)
 - 6 epochs



Apply Model-Quantum Transformer

Data : 60k

Signal MC : 120k

background rejection : 98%

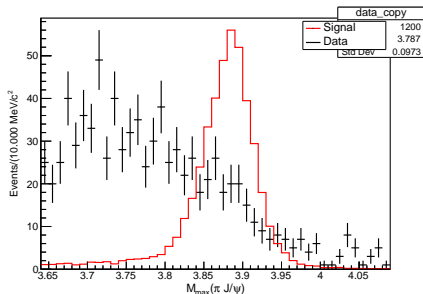
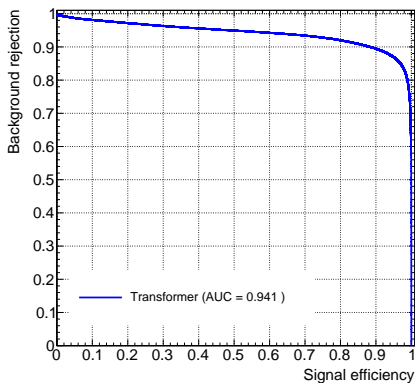


Fig : Apply the model to the real data and signal MC. ROC curve (left) and $M_{max}(\pi J/\psi)$ invariant mass distributions(right). In right panel, dots

Apply Model–Quantum Transformer

Data : 80k

Signal MC : 80k

background rejection : 97.7%

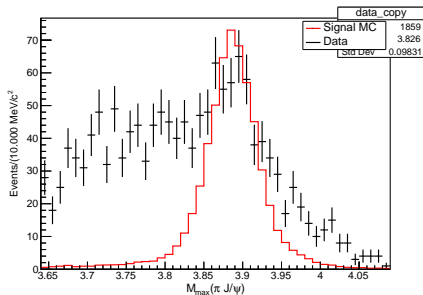
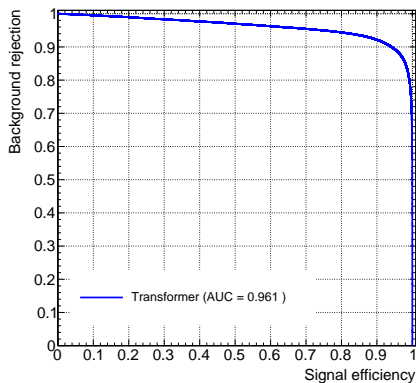


Fig : Apply the model to the real data and signal MC. ROC curve (left) and $M_{max}(\pi J/\psi)$ invariant mass distributions(right). In right panel, dots

Fit-Quantum Transformer

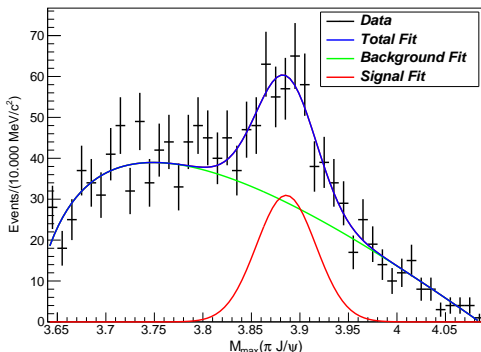
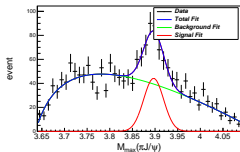
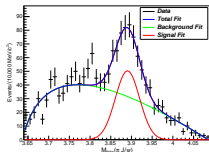


Fig : Fit to $M_{\max}(\pi J/\psi)$ invariant mass distributions with Gaussian resolution as signal function and $a/(x - 3.6)^b + c + dx$ background term . Dots with error bars are data. The blue curve shows the total fit, the green curve shows the background fit, and the red curve shows the signal fit.

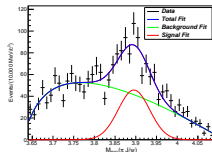
Summary



classical cut



Transformer

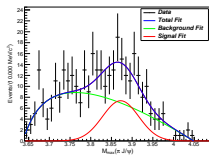


Quantum Transformer

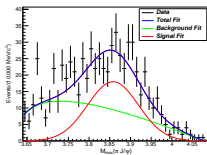
	classical cut	Transformer	Quantum
Signal	243.1	367.6	434.4
Background	1526.9	1197.0	1644.4
Total	1770.1	1546.7	2078.8
s	232.1	350.9	414.6
b	344.0	363.6	617.8
$\varepsilon = \frac{s}{\sqrt{s+b}}$	9.67	13.13	12.90

Here, s and b are obtained by fitting the data.

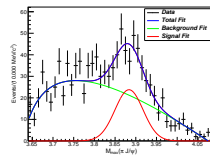
Quantum Transformer Result



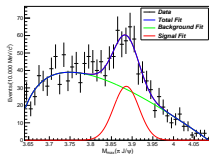
$\epsilon = 10\%$



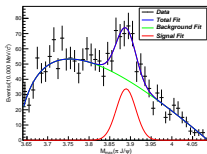
$\epsilon = 20\%$



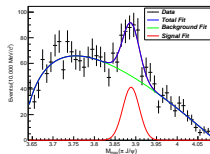
$\epsilon = 30\%$



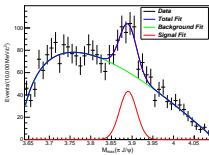
$\epsilon = 40\%$



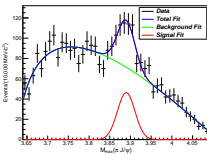
$\epsilon = 50\%$



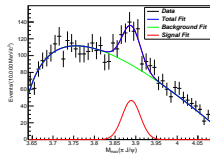
$\epsilon = 60\%$



$\epsilon = 70\%$



$\epsilon = 80\%$



$\epsilon = 90\%$

Fig: After applying the Quantum model to real data, I set different signal efficiencies, ϵ , to obtain $M_{max}(\pi J/\psi)$ invariant mass distribution plots.

Quantum Transformer Result

- Parameter Set:
 - Data : 80k
 - Signal MC : 80k

signal efficiency ϵ	background rejection	s	b	s+b	$\epsilon = \frac{s}{\sqrt{s+b}}$
5%	99.77%	49.75	54.77	104.51	4.87
10%	99.51%	77.20	118.26	195.46	5.52
15%	99.23%	176.66	187.65	364.31	9.26
20%	98.96%	264.32	223.55	487.88	11.97
25%	98.61%	183.99	269.63	453.62	8.64
30%	98.32%	193.37	284.53	477.89	8.85
35%	98.02%	188.76	303.22	491.98	8.51
40%	97.68%	226.50	354.27	580.77	9.40
45%	97.35%	209.64	364.89	574.54	8.75
50%	96.98%	189.64	373.22	562.86	7.99
55%	96.64%	202.11	371.68	573.80	8.44
60%	96.23%	198.74	400.45	599.19	8.12
65%	95.84%	209.73	444.54	654.28	8.20
70%	95.43%	213.67	496.62	710.29	8.02
75%	94.96%	232.16	563.46	795.61	8.23
80%	94.38%	233.97	597.78	831.75	8.11
85%	93.54%	243.94	649.81	893.75	8.16
90%	92.14%	243.68	773.01	1016.69	7.64
95%	89.31%	273.74	1022.22	1295.95	7.60

Transformer Result

- Parameter Set:
 - Learning rate : 0.0001
 - Data : 80k
 - Signal MC : 80k

signal efficiency ϵ	background rejection	s	b	s+b	$\epsilon = \frac{s}{\sqrt{s+b}}$
5%	99.72%	19.84	33.57	53.41	2.72
10%	99.49%	40.24	73.64	113.88	3.77
15%	99.28%	62.74	86.03	148.77	5.14
20%	99.08%	97.96	116.72	214.69	6.69
25%	98.90%	112.86	135.66	248.52	7.16
30%	98.69%	131.67	170.18	301.85	7.58
35%	98.45%	161.06	198.75	359.81	8.49
40%	98.20%	182.85	248.16	431.01	8.81
45%	97.95%	215.61	307.62	523.23	9.43
50%	97.71%	239.16	363.28	602.44	9.74
55%	97.44%	238.69	382.19	620.88	9.58
60%	97.12%	233.19	424.31	657.50	9.09
65%	96.75%	249.24	482.88	732.12	9.21
70%	96.34%	264.82	520.29	785.11	9.45
75%	95.81%	267.26	557.83	825.09	9.30
80%	95.19%	258.48	592.12	850.60	8.86
85%	94.32%	262.79	693.44	956.23	8.50
90%	93.31%	270.84	772.61	1043.45	8.38
95%	91.10%	297.70	978.29	1276.00	8.33

Transformer Result

- Parameter Set:
 - Data : 98k
 - Signal MC : 98k

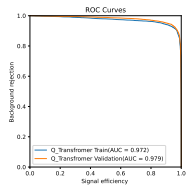
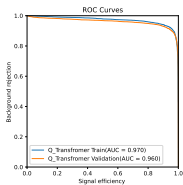
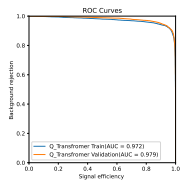
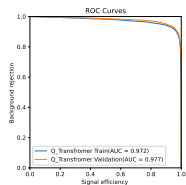
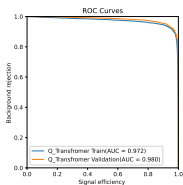
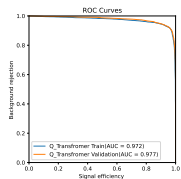
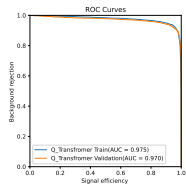
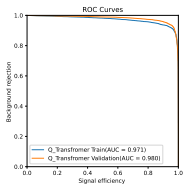
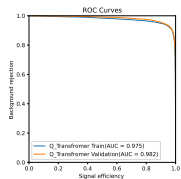
signal efficiency ϵ	background rejection	s	b	s+b	$\epsilon = \frac{s}{\sqrt{s+b}}$
5%	99.79%	43.56	37.01	80.56	4.85
10%	99.61%	76.79	58.64	135.43	6.60
15%	99.42%	114.97	103.04	218.01	7.79
20%	99.27%	122.31	121.31	243.62	7.84
25%	99.09%	180.71	160.97	341.68	9.78
30%	98.91%	199.82	190.00	389.82	10.12
35%	98.72%	239.75	226.21	465.96	11.11
40%	98.50%	301.93	280.43	582.37	12.51
45%	98.26%	331.83	305.86	637.69	13.14
50%	98.03%	347.60	359.36	706.95	13.07
55%	97.77%	362.57	420.57	783.14	12.96
60%	97.47%	381.42	503.97	885.39	12.82
65%	97.09%	380.62	575.22	955.84	12.31
70%	96.66%	399.35	635.83	1035.19	12.41
75%	96.13%	363.08	666.02	1029.10	11.32
80%	95.43%	334.80	713.30	1048.09	10.34
85%	94.52%	326.01	795.51	1121.52	9.73
90%	93.31%	342.47	925.12	1267.59	9.62
95%	90.71%	387.11	1140.04	1527.14	9.91

Transformer Result

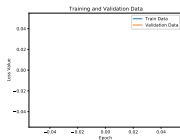
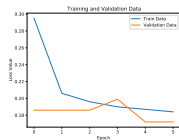
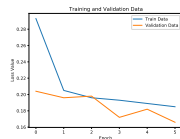
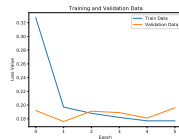
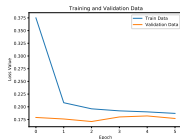
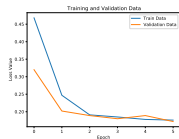
- Parameter Set:
 - Data : 98k
 - Signal MC : 120k

signal efficiency ϵ	background rejection	s	b	s+b	$\epsilon = \frac{s}{\sqrt{s+b}}$
5%	99.79%	46.03	35.63	81.67	5.09
10%	99.61%	81.18	59.92	141.09	6.83
15%	99.42%	118.77	102.33	221.10	7.99
20%	99.27%	127.04	120.53	247.57	8.07
25%	99.10%	183.63	156.71	340.34	9.95
30%	98.91%	204.36	187.70	392.06	10.32
35%	98.72%	244.64	224.07	468.71	11.30
40%	98.50%	305.77	278.10	583.87	12.65
45%	98.26%	340.66	306.33	646.99	13.39
50%	98.03%	357.63	361.37	719.00	13.34
55%	97.77%	371.53	423.47	795.00	13.18
60%	97.47%	388.12	503.90	892.01	13.00
65%	97.09%	395.21	588.34	983.55	12.60
70%	96.66%	414.36	649.26	1063.63	12.71
75%	96.12%	374.03	679.90	1053.93	11.52
80%	95.42%	343.99	727.70	1071.69	10.51
85%	94.51%	336.92	816.01	1152.93	9.92
90%	93.30%	354.34	950.11	1304.44	9.81
95%	90.70%	398.08	1163.93	1562.01	10.07

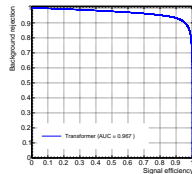
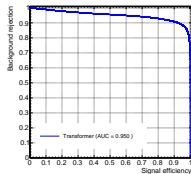
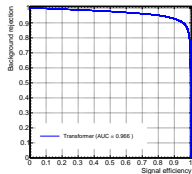
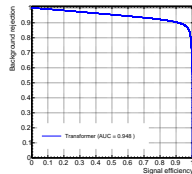
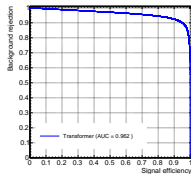
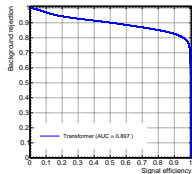
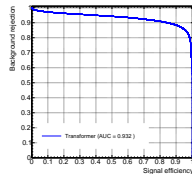
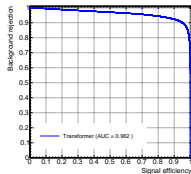
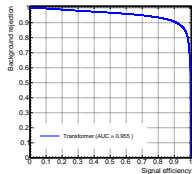
Training Model–Quantum Transformer



Training Model—Quantum Transformer



Apply Model-Quantum Transformer



Significance – Quantum Transformer

- Parameter Set:
 - Learning rate : 0.0002
 - Data : 80k
 - Signal MC : 80k

signal efficiency ϵ	background rejection	s	b	s+b	$\epsilon = \frac{s}{\sqrt{s+b}}$
5%	99.80%	24.77	20.83	45.60	3.67
10%	99.49%	108.63	123.94	232.56	7.12
15%	99.14%	131.74	186.35	318.09	7.39
20%	98.73%	93.28	199.92	293.20	5.45
25%	98.37%	123.00	225.29	348.29	6.59
30%	98.02%	135.62	262.33	397.95	6.80
35%	97.68%	148.89	282.48	431.37	7.17
40%	97.34%	164.73	298.98	463.71	7.65
45%	97.04%	181.95	338.74	520.69	7.97
50%	96.71%	196.21	381.07	577.27	8.17
55%	96.33%	187.90	415.26	603.16	7.65
60%	95.92%	215.93	496.50	712.43	8.09
65%	95.48%	205.74	527.87	733.62	7.60
70%	94.98%	228.80	604.82	833.63	7.92
75%	94.28%	220.88	653.04	873.92	7.47
80%	93.48%	215.22	699.66	914.87	7.12
85%	92.46%	240.96	810.18	1051.14	7.43
90%	90.69%	250.36	945.14	1195.50	7.24
95%	87.25%	290.88	1274.52	1565.40	7.35

Significance – Quantum Transformer

- Parameter Set:
 - Learning rate : 0.0003
 - Data : 80k
 - Signal MC : 80k

signal efficiency ϵ	background rejection	s	b	s+b	$\epsilon = \frac{s}{\sqrt{s+b}}$
5%	99.71%	28.59	33.62	62.21	3.63
10%	99.41%	34.90	61.19	96.09	3.56
15%	99.06%	52.50	115.30	167.80	4.05
20%	98.76%	64.38	139.79	204.17	4.51
25%	98.43%	88.57	175.10	263.67	5.45
30%	98.17%	98.41	209.46	307.88	5.61
35%	97.88%	99.16	248.11	347.27	5.32
40%	97.59%	133.61	269.18	402.79	6.66
45%	97.29%	167.49	313.52	481.01	7.64
50%	97.01%	163.96	316.92	480.88	7.48
55%	96.69%	162.78	349.21	511.99	7.19
60%	96.36%	171.63	382.49	554.12	7.29
65%	96.01%	185.03	422.60	607.63	7.51
70%	95.58%	202.42	472.84	675.26	7.79
75%	95.03%	224.64	561.23	785.87	8.01
80%	94.36%	260.64	686.14	946.78	8.47
85%	93.48%	270.84	791.87	1062.71	8.31
90%	92.30%	273.83	920.71	1194.54	7.92
95%	90.06%	255.10	1043.27	1298.37	7.08

Significance – Quantum Transformer

- Parameter Set:
 - Learning rate : 0.0008
 - Data : 80k
 - Signal MC : 80k

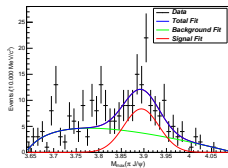
signal efficiency ϵ	background rejection	s	b	s+b	$\epsilon = \frac{s}{\sqrt{s+b}}$
5%	99.77%	29.33	15.04	44.37	4.40
10%	99.57%	157.30	17.74	175.04	11.89
15%	99.35%	144.13	93.36	237.49	9.35
20%	99.11%	182.04	152.49	334.54	9.95
25%	98.88%	162.13	155.42	317.55	9.10
30%	98.66%	194.82	201.23	396.05	9.79
35%	98.44%	209.27	229.82	439.09	9.99
40%	98.15%	217.56	269.29	486.85	9.86
45%	97.89%	203.26	302.57	505.83	9.04
50%	97.62%	222.82	351.92	574.74	9.29
55%	97.27%	258.08	488.14	746.22	9.45
60%	96.92%	254.25	530.93	785.19	9.07
65%	96.54%	269.77	558.59	828.36	9.37
70%	96.11%	275.13	579.81	854.93	9.41
75%	95.63%	268.29	561.03	829.31	9.32
80%	95.03%	270.45	614.20	884.65	9.09
85%	94.12%	270.84	710.05	980.89	8.65
90%	92.72%	263.44	810.79	1074.23	8.04
95%	90.31%	276.19	999.51	1275.69	7.73

Significance – Quantum Transformer

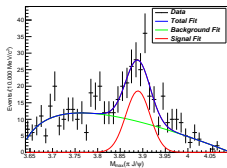
- Parameter Set:
 - Learning rate : 0.001
 - Data : 80k
 - Signal MC : 80k

signal efficiency ϵ	background rejection	s	b	s+b	$\epsilon = \frac{s}{\sqrt{s+b}}$
5%	99.81%	26.86	18.68	45.55	3.98
10%	99.61%	78.30	57.51	135.82	6.72
15%	99.41%	100.33	74.85	175.18	7.58
20%	99.22%	120.01	99.96	219.97	8.09
25%	99.00%	144.43	145.54	289.97	8.48
30%	98.74%	201.88	220.85	422.74	9.82
35%	98.49%	192.39	223.31	415.71	9.44
40%	98.22%	224.05	288.11	512.16	9.90
45%	97.95%	254.73	328.32	583.05	10.55
50%	97.67%	270.24	359.38	629.62	10.77
55%	97.36%	261.38	387.69	649.08	10.26
60%	97.02%	261.75	430.34	692.09	9.95
65%	96.64%	275.25	509.31	784.56	9.83
70%	96.24%	270.35	532.06	802.41	9.54
75%	95.72%	273.59	588.39	861.98	9.32
80%	95.15%	277.85	620.02	897.87	9.27
85%	94.41%	285.97	719.68	1005.65	9.02
90%	93.22%	269.65	792.21	1061.87	8.28
95%	90.52%	281.37	950.55	1231.93	8.02

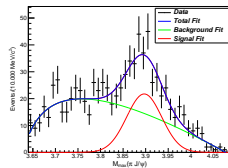
Apply Model-Quantum Transformer



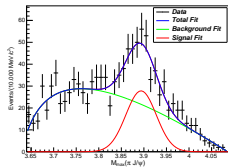
$\epsilon = 10\%$



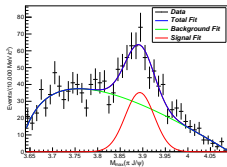
$\epsilon = 20\%$



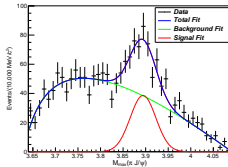
$\epsilon = 30\%$



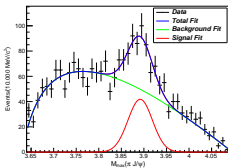
$\epsilon = 40\%$



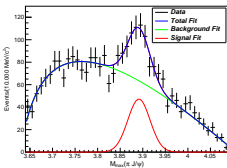
$\epsilon = 50\%$



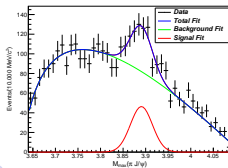
$\epsilon = 60\%$



$\epsilon = 70\%$



$\epsilon = 80\%$



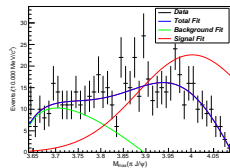
$\epsilon = 90\%$

Significance – Quantum Transformer

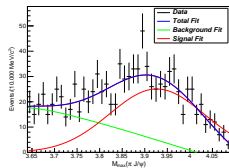
- Parameter Set:
 - Learning rate : 0.0001
 - Data : 98k
 - Signal MC : 98k

signal efficiency ϵ	background rejection	s	b	s+b	$\epsilon = \frac{s}{\sqrt{s+b}}$
5%	99.58%	105.00	53.26	158.27	8.35
10%	99.25%	660.32	-490.43	169.90	50.66
15%	98.93%	613.65	-67.43	546.22	26.26
20%	98.60%	627.34	196.55	823.89	21.86
25%	98.26%	-	-	-	-
30%	97.92%	373.27	581.56	954.83	12.08
35%	97.55%	427.77	678.31	1106.08	12.86
40%	97.21%	465.39	762.94	1228.33	13.28
45%	96.89%	536.32	852.63	1388.95	14.39
50%	96.53%	463.60	876.20	1339.80	12.67
55%	96.11%	400.95	834.36	1235.31	11.41
60%	95.73%	391.49	830.09	1221.58	11.20
65%	95.31%	356.56	854.38	1210.94	10.25
70%	94.80%	329.53	850.86	1180.39	9.59
75%	94.25%	323.56	847.80	1171.36	9.45
80%	93.61%	335.57	916.30	1251.87	9.48
85%	92.89%	352.13	930.29	1282.42	9.83
90%	91.94%	355.57	1062.32	1417.89	9.44
95%	90.10%	381.44	1297.48	1678.92	9.31

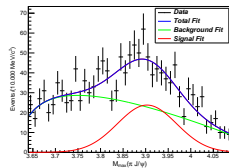
Apply Model-Quantum Transformer



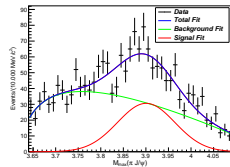
$\epsilon = 10\%$



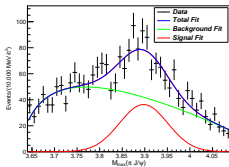
$\epsilon = 20\%$



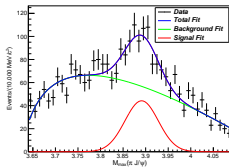
$\epsilon = 30\%$



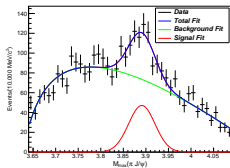
$\epsilon = 40\%$



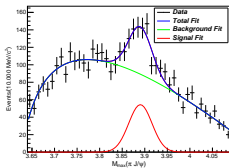
$\epsilon = 50\%$



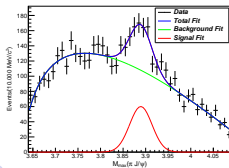
$\epsilon = 60\%$



$\epsilon = 70\%$



$\epsilon = 80\%$



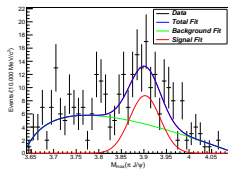
$\epsilon = 90\%$

Significance – Quantum Transformer

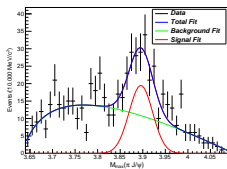
- Parameter Set:
 - Learning rate : 0.001
 - Data : 98711
 - Signal MC : 98711

signal efficiency ϵ	background rejection	s	b	s+b	$\epsilon = \frac{s}{\sqrt{s+b}}$
5%	99.82%	18.55	13.97	32.52	3.25
10%	99.63%	71.34	59.84	131.18	6.23
15%	99.43%	109.43	86.39	195.82	7.82
20%	99.25%	121.70	112.23	233.93	7.96
25%	99.02%	205.21	203.22	408.43	10.15
30%	98.82%	242.78	218.15	460.93	11.31
35%	98.55%	332.07	303.54	635.61	13.17
40%	98.30%	367.10	378.01	745.11	13.45
45%	98.01%	431.40	451.89	883.30	14.52
50%	97.73%	451.40	557.76	1009.16	14.21
55%	97.41%	454.88	619.24	1074.13	13.88
60%	97.10%	414.63	617.82	1032.46	12.90
65%	96.74%	400.77	666.80	1067.57	12.27
70%	96.36%	399.24	737.05	1136.29	11.84
75%	95.91%	409.05	785.51	1194.56	11.84
80%	95.41%	396.33	817.63	1213.96	11.38
85%	94.70%	384.24	886.84	1271.08	10.78
90%	93.48%	363.36	966.12	1329.48	9.97
95%	90.74%	368.43	1157.68	1526.11	9.43

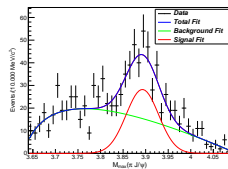
Apply Model-Quantum Transformer



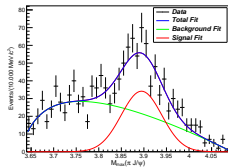
$\epsilon = 10\%$



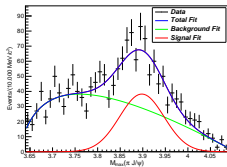
$\epsilon = 20\%$



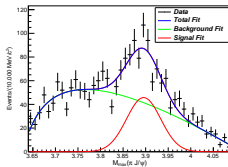
$\epsilon = 30\%$



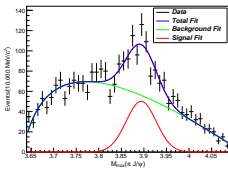
$\epsilon = 40\%$



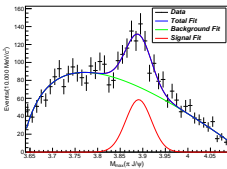
$\epsilon = 50\%$



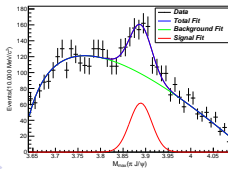
$\epsilon = 60\%$



$\epsilon = 70\%$



$\epsilon = 80\%$



$\epsilon = 90\%$