TMD Studies in e^+e^- Collisions — Week 9 Progress

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Simulation study using PYTHIA8, FastJet, ROOT

Outline

- Recap & goals
- ancestry tracing
- New observables & plots

Recap of Week 8 & Goals for Week 9

Last week:

- Baseline jet shapes (thrust, sphericity) and jet multiplicity
- $\Delta\phi$ between leading jets and leading π/K spectra

This week (requested tasks):

- Investigate leading pion origins using PYTHIA ancestry tracing
- Plot thrust for several jet radii R (radius scan)
- Study p_T differences: $p_T(\text{jet}) - p_T(\pi)$ and $p_T(\pi) - p_T(\text{parent})$

Event setup: $e^+e^- \to d\,\bar{d}$

- The hard e^+e^- annihilation produces a down quark and an anti–down quark, seeding two back-to-back color strings.
- We show the early event record just after the hard process, before hadronization develops.

row	event	size	no	id	name	st	m1	m2	d1	d2	px	py	pz	E
0	3	134	0	90	system	-11	0	0	0	0	0.000	0.000	0.000	91.200
1	3	134	1	-11	e+	-12	0	0	3	0	0.000	0.000	45.600	45.600
2	3	134	2	11	e-	-12	0	0	4	0	0.000	0.000	-45.600	45.600
3	3	134	3	-11	e+	-21	1	0	5	0	0.000	0.000	45.600	45.600
4	3	134	4	11	e-	-21	2	0	5	0	0.000	0.000	-45.600	45.600
5	3	134	5	23	Z0	-22	3	4	6	7	0.000	0.000	0.000	91.200
6	3	134	6	1	d	-23	5	0	8	9	-44.829	7.850	2.821	45.600
7	3	134	7	-1	dbar	-23	5	0	10	10	44.829	-7.850	-2.821	45.600
8	3	134	8	1	d	-51	6	0	11	12	-41.505	0.505	4.102	41.711
9	3	134	9	21	g	-51	6	0	13	13	-0.289	6.813	-1.471	6.976

(showing rows 0 to 9 of 134 total)
More [Enter=+10, n=next event, q=quit]:

row	event	size	no	id	name	st	m1	m2	d1	d2	px	py	pz	E
10	3	134	10	-1	dbar	-52	7	7	16	16	41.794	-7.318	-2.630	42.513
11	3	134	11	1	d	-51	8	0	28	28	-34.400	4.792	5.001	35.092
12	3	134	12	21	g	-51	8	0	26	27	-7.156	-3.064	-1.163	7.871
13	3	134	13	21	g	-52	9	9	14	15	-0.237	5.590	-1.207	5.724
14	3	134	14	21	g	-51	13	0	25	25	-1.159	0.632	-3.075	3.346
15	3	134	15	21	g	-51	13	0	17	18	5.607	4.137	1.573	7.143
16	3	134	16	-1	dbar	-52	10	10	19	19	37.109	-6.498	-2.336	37.747
17	3	134	17	21	g	-51	15	0	20	21	14.413	4.424	2.258	15.245
18	3	134	18	21	g	-51	15	0	22	22	4.413	-2.604	-1.518	5.345
19	3	134	19	-1	dbar	-52	16	16	37	37	23.889	-4.180	-1.502	24.301

(showing rows 10 to 19 of 134 total)
More [Enter=+10, n=next event, q=quit]:

Most relevant PYTHIA8 status codes in this analysis

Code	Meaning
-11	Event record container ("system")
-12	Incoming beam particles (e^+, e^-)
-21	Incoming particles of the hardest subprocess
-22	Intermediate state of the hardest subprocess (e.g. virtual Z^0)
-23	Outgoing partons from the hardest subprocess (e.g. d, $\bar{d}$)
-51	Final-state shower products (FSR partons)
-52	Recoiler copies created by shower evolution
-71	Partons prepared for hadronization (pre-string state)
-83 / -84	Primary hadrons produced from string fragmentation

Reminder: negative code = particle already branched/decayed, positive = still present [1].

Event record structure (id, m1, m2, d1, d2)

- `id` = PDG particle ID, `m1,m2` = index of mother(s), `d1,d2` = index range of daughters in the event record [2].

QUARKS

d	1
u	2
s	3
c	4
b	5
t	6
b'	7
t'	8

LEPTONS

e^-	11
ν_e	12
μ^-	13
ν_μ	14
τ^-	15
ν_τ	16
τ'^-	17
$\nu_{\tau'}$	18

EXCITED PARTICLES

d^*	4000001
u^*	4000002
e^*	4000011
ν_e^*	4000012

GAUGE AND HIGGS BOSONS

g	(9) 21
γ	22
Z^0	23
W^+	24
h^0/H_1^0	25
Z'/Z_2^0	32
Z''/Z_3^0	33
W'/W_2^+	34
H^0/H_2^0	35
A^0/H_3^0	36
H^+	37

DIQUARKS

$(dd)_1$	1103
$(ud)_0$	2101
$(ud)_1$	2103
$(uu)_1$	2203
$(sd)_0$	3101
$(sd)_1$	3103
$(su)_0$	3201
$(su)_1$	3203
$(ss)_1$	3303
$(cd)_0$	4101
$(cd)_1$	4103
$(cu)_0$	4201
$(cu)_1$	4203
$(cs)_0$	4301
$(cs)_1$	4303
$(cc)_1$	4403
$(bd)_0$	5101
$(bd)_1$	5103
$(bu)_0$	5201
$(bu)_1$	5203
$(bs)_0$	5301
$(bs)_1$	5303
$(bc)_0$	5401
$(bc)_1$	5403
$(bb)_1$	5503

TECHNICOLOR PARTICLES

π^0_{tech}	3000111
π^+_{tech}	3000211
π'^0_{tech}	3000221
η^0_{tech}	3100221
ρ^0_{tech}	3000113
ρ^+_{tech}	3000213

LIGHT $I = 1$ MESONS

π^0	111
π^+	211
$a_0(980)^0$	9000111
$a_0(980)^+$	9000211
$\pi(1300)^0$	100111
$\pi(1300)^+$	100211
$a_0(1450)^0$	10111
$a_0(1450)^+$	10211
$\pi(1800)^0$	9010111
$\pi(1800)^+$	9010211
$\rho(770)^0$	113
$\rho(770)^+$	213
$b_1(1235)^0$	10113
$b_1(1235)^+$	10213
$a_1(1260)^0$	20113
$a_1(1260)^+$	20213
$\pi_1(1400)^0$	9000113
$\pi_1(1400)^+$	9000213
$\rho(1450)^0$	100113
$\rho(1450)^+$	100213
$\pi_1(1600)^0$	9010113

LIGHT $I = 0$ MESONS
($u\bar{u}$, $d\bar{d}$, and $s\bar{s}$ Admixtures)

η	221
$\eta'(958)$	331
$f_0(600)$	9000221
$f_0(980)$	9010221
$\eta(1295)$	100221
$f_0(1370)$	10221
$\eta(1405)$	9020221
$\eta(1475)$	100331
$f_0(1500)$	9030221
$f_0(1710)$	10331
$\eta(1760)$	**9040221***
$f_0(2020)$	**9050221***
$f_0(2100)$	**9060221***
$f_0(2200)$	**9070221***
$\eta(2225)$	**9080221***
$\omega(782)$	223
$\phi(1020)$	333
$h_1(1170)$	10223
$f_1(1285)$	20223
$h_1(1380)$	10333

Onset of hadronization

- Color strings fragment into resonances and hadrons along each jet axis — we track mothers $\rightarrow$ daughters in the PYTHIA record.

row	event	size	no	id	name	st	m1	m2	d1	d2	px	py	pz	E
20	3	134	20	21	g	−51	17	0	23	24	10.608	3.998	2.510	11.611
21	3	134	21	21	g	−51	17	0	69	69	4.804	−0.163	−0.595	4.843
22	3	134	22	21	g	−52	18	18	35	36	3.415	−2.015	−1.175	4.136
23	3	134	23	21	g	−51	20	0	47	48	4.109	1.534	−0.805	4.459
24	3	134	24	21	g	−51	20	0	34	34	6.381	2.529	3.002	7.492
25	3	134	25	21	g	−52	14	14	32	33	−1.041	0.568	−2.762	3.006
26	3	134	26	21	g	−51	12	0	29	30	−10.199	−2.470	−1.629	10.620
27	3	134	27	21	g	−51	12	0	31	31	−1.436	0.031	1.118	1.820
28	3	134	28	1	d	−52	11	11	50	51	−29.921	4.167	4.349	30.523
29	3	134	29	21	g	−51	26	0	40	40	−7.940	−0.852	0.547	8.004

(showing rows 20 to 29 of 134 total)
More [Enter=+10, n=next event, q=quit]:

Leading charged pions

- Identify the leading charged $\pi^{\pm}$ in each jet and record its ancestry chain (resonance $\rightarrow \pi$) for downstream Δp_T studies.

row	event	size	no	id	name	st	m1	m2	d1	d2	px	py	pz	E
70	3	134	70	21	g	-71	44	44	74	94	1.204	-0.840	-0.551	1.568
71	3	134	71	21	g	-71	45	45	74	94	7.440	-2.024	-0.505	7.727
72	3	134	72	21	g	-71	46	46	74	94	0.725	-0.188	-0.490	0.895
73	3	134	73	-1	dbar	-71	37	37	74	94	17.935	-3.143	-1.132	18.247
74	3	134	74	111	pi0	-83	57	73	107	108	-12.379	1.418	2.139	12.643
75	3	134	75	331	id331	-83	57	73	109	110	-6.073	1.072	0.605	6.270
76	3	134	76	111	pi0	-83	57	73	111	112	-5.161	0.835	0.887	5.305
77	3	134	77	-213	rho-	-83	57	73	95	96	-5.614	0.700	0.842	5.827
78	3	134	78	223	id223	-83	57	73	113	115	-4.959	-1.434	-0.383	5.235
79	3	134	79	2212	p+	83	57	73	0	0	-2.939	-0.420	0.067	3.115

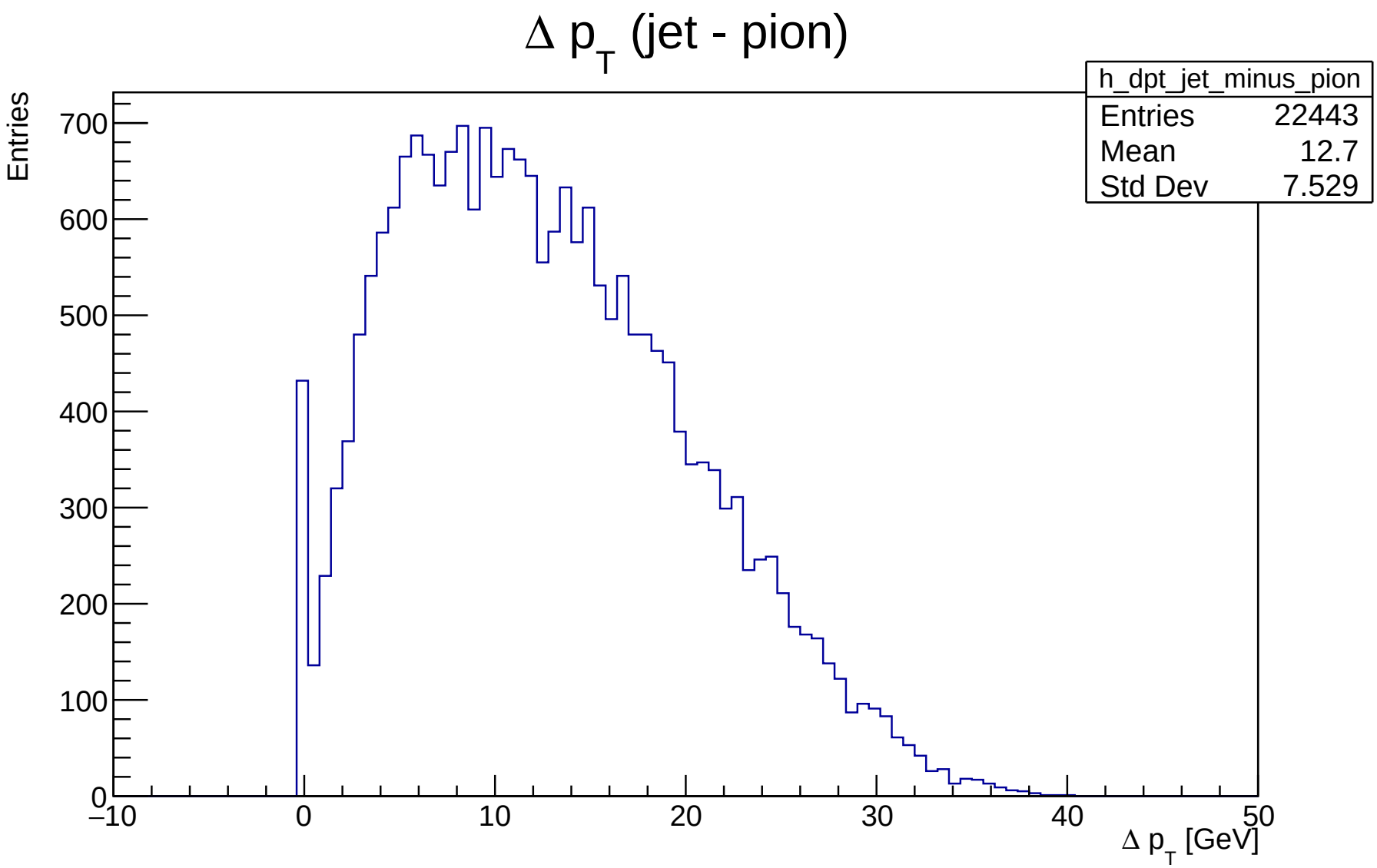
(showing rows 70 to 79 of 134 total)
More [Enter=+10, n=next event, q=quit]:

=== EVENT 3 ===

row	event	size	no	id	name	st	m1	m2	d1	d2	px	py	pz	E
80	3	134	80	-321	K-	83	57	73	0	0	-0.003	-0.112	-0.197	0.543
81	3	134	81	-3112	id-3112	-83	57	73	116	117	-3.258	0.221	-0.778	3.564
82	3	134	82	-211	pi-	83	57	73	0	0	-0.609	-0.776	0.336	1.051
83	3	134	83	211	pi+	83	57	73	0	0	-0.643	0.377	0.396	0.856
84	3	134	84	113	rho0	-84	57	73	97	98	0.230	0.721	-1.053	1.962
85	3	134	85	111	pi0	-84	57	73	118	119	0.908	0.129	-0.747	1.191
86	3	134	86	-213	rho-	-84	57	73	99	100	0.512	0.385	0.404	1.136
87	3	134	87	2212	p+	84	57	73	0	0	1.593	1.236	0.144	2.229
88	3	134	88	-211	pi-	84	57	73	0	0	0.647	-0.002	0.279	0.718
89	3	134	89	-2114	id-2114	-84	57	73	101	102	3.813	0.916	0.046	4.118

(showing rows 80 to 89 of 134 total)
More [Enter=+10, n=next event, q=quit]:

$\Delta p_T(\text{jet}) = p_T(\text{jet}) - p_T(\pi_{\text{lead}})$

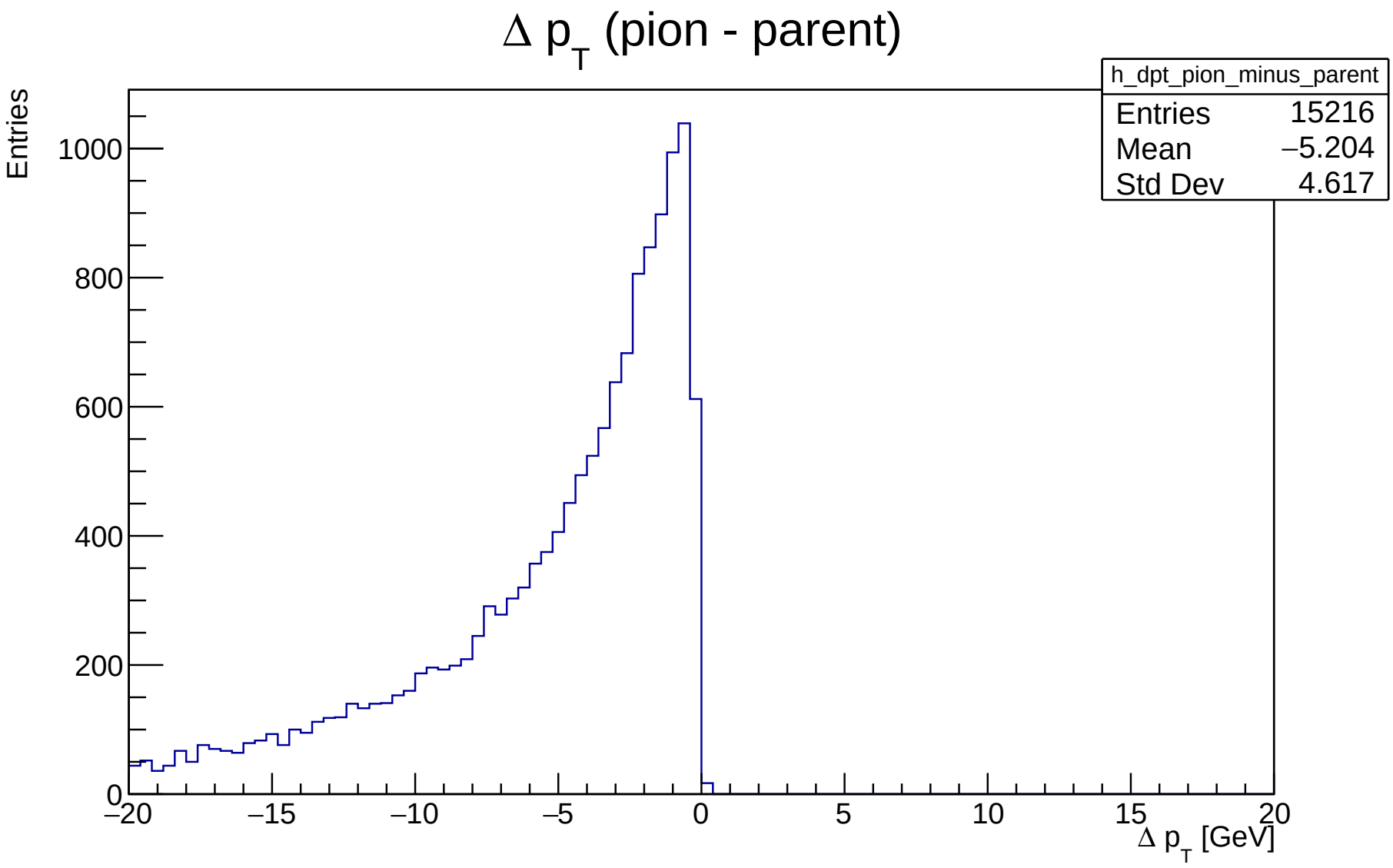


$\Delta p_{T,\text{jet}} = p_T(\text{jet}) - p_T(\pi_{\text{lead}})$

Implemented in code by looping over all reconstructed jets, locating the leading charged pion in each jet, and computing the p_T imbalance event-by-event.

- Identifies two highest-momentum pions per event
- Matches each pion to its parent jet via constituent tracking
- Calculates p_T difference: jet total minus leading pion
- Distribution shows momentum carried by other jet particles

$\Delta p_{T,\text{parent}} = p_T(\pi_{\text{lead}}) - p_T(\text{parent})$



Placeholder plot

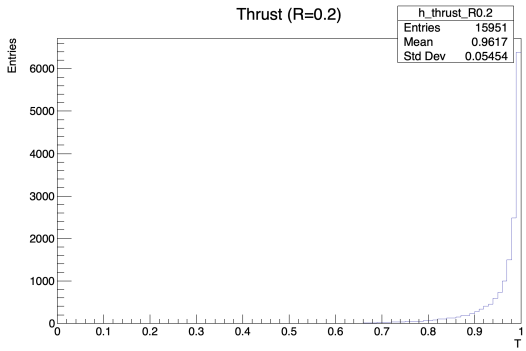
$\Delta p_{T,\text{parent}} = p_T(\pi_{\text{lead}}) - p_T(\text{parent})$

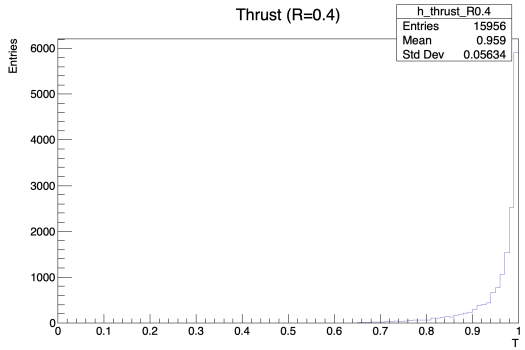
Implementation:

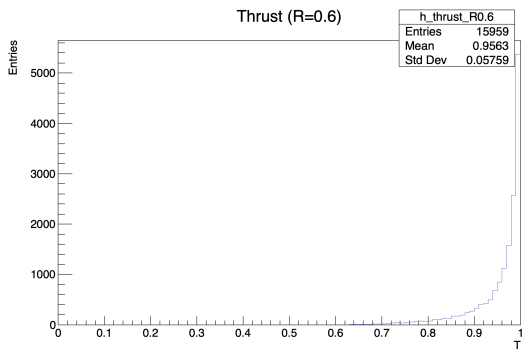
- Traces ancestry of leading pions via mother indices
- Identifies first hadronic parent (PDG 100–10000, excluding pions)
- Measures p_T gained/lost during decay process

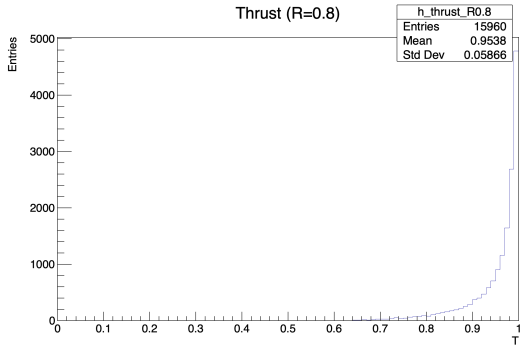
Thrust **vs** jet radius R

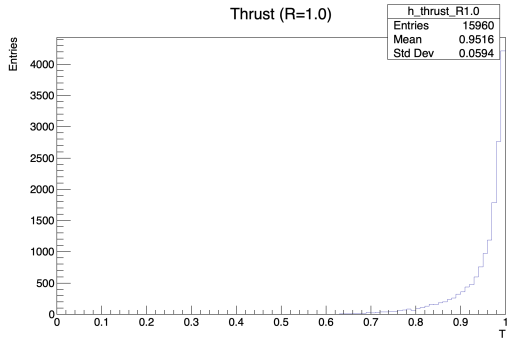
- Compared thrust across jet radii $R02, 0.4, 0.6, 0.8, 1.0$ to assess radius dependence of global event shape.











Thrust vs Jet Radius R

Implementation:

- Scans over jet radii: $R \in \{0.2, 0.4, 0.6, 0.8, 1.0\}$
- Clusters jets with anti-k_T algorithm at each R value
- Collects all jet constituents (minimum $p_T > 1$ GeV)
- Computes thrust from momentum tensor of jet particles
- Averages thrust over all events for each R setting

End

Questions?

References

1. "Particle status codes in PYTHIA 8", PYTHIA 8 Manual — ParticleProperties section. https://pythia.org/latest-manual/ParticleProperties.html
2. Particle Data Group, "Review of Monte Carlo Particle Numbering Schemes", https://pdg.lbl.gov/2007/reviews/montecarlorpp.pdf